BILAN SCIENTIFIQUE

Laboratoire des Champs Magnétiques Pulsés
LNCMP – UMR 5147
Du 01/01/2005 au 31/12/08

Etablissements de rattachement :
Université Paul Sabatier Toulouse 3 (principale)
INSA Toulouse
CNRS – MPPU

A partir du 01/01/09 :

Laboratoire National des Champs Magnétiques Intenses
LNCMI – UPR 3228

Etablissement de rattachement : CNRS – MPPU
Lié par convention à l’Université Paul Sabatier Toulouse 3, à l’Université Joseph Fourier Grenoble 1
et à l’INSA Toulouse

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Table of contents

General overview 3
Overview of technical activities 7
Overview of scientific activities 15
Annex 1: Hygiene et sécurité 38
Annex 2: Formation 40
Annex 3: Enseignement, vulgarization, organization de colloques 41
Annex 4: Publication list 42
Annex 5: Organigramme 70
General overview

Short history
The Laboratoire National des Champs Magnétiques Pulsés (LNCMP UMR5147) was created on 1/1/2003 as a mixed research laboratory jointly operated and funded by the Centre National de la Recherche Scientifique (CNRS), the Université Paul Sabatier (UPS) and the Institut National des Sciences Appliquées (INSA) de Toulouse. Before that, it has existed as a mixed service unit, the Service National des Champs Magnétiques Pulsés (SNCMP, UMS5642) which was housed on the INSA campus until 2000, when it moved to a new building on the UPS campus, at the same time upgrading its capacitor bank to 14 MJ. The LNCMP ceased to exist on 1/1/2009, as at that date, the Laboratoire National des Champs Magnétiques Intenses (LNCMI, UPR3228) was created through the merger of the Laboratoire des Champs Magnétiques Intenses (LCMI UPR5021 in Grenoble) and the LNCMP, as part of the Très Grands Instruments de la Recherche (TGIR) of the CNRS.

Missions
The LNCMP has three major missions;
1) High quality research using high magnetic fields:
The scientists of the laboratory develop their own research in the main domains of solid state physics: semiconductors, metals and superconductors or magnetism where the quantum effects are studied. This 2005-2009 report presents the main developments of this research and of the technical improvements underpinning them. Since the LNCMP scientists also work as local contacts for visiting scientists, the number of topics studied at the LNCMP is necessarily large compared to the number of scientists, which is an inherent aspect of the operation of any user facility.
2) Providing access to external users:
The laboratory is open to the international scientific community. Any scientist wanting to use high pulsed magnetic fields can submit a project to use the relevant infrastructure of the laboratory with the help of the general support group of the laboratory and of a local contact.
All projects, including the internal ones, to be realized in high magnetic fields are evaluated by an international committee twice a year (June and December). Among around 70 projects submitted per year, the rejection or reduction of demanded time is around 15%, the total number of submitted French projects being around 30 (45 %).
3) Magnet development:
The laboratory has to develop and provide pulsed magnetic fields with the best possible performance for high quality scientific experiments. This can be in terms of the field strength, but also in terms of field homogeneity and stability, high repetition rate or by offering special magnet geometries. These are in general conflicting requirements and the optimal choice depends on the experiments to be performed. The developments in magnet technology allow us to remain competitive with facilities abroad and open our activities to other scientific domains, like pulsed field NMR, and other disciplines than physics.

Why high magnetic fields?
A magnetic field is a very powerful thermodynamic parameter to influence the state of any material system. Consequently magnetic fields serve as an experimental tool in very diverse research areas like condensed matter physics, molecular physics, chemistry and, with increasing importance, in biology. The versatility and universality of magnetic fields as a research tool lies in their coupling to the charge and spin of the particles that constitute the matter that surrounds us. Many magnetic field based research techniques are standard and can be done with conventional commercially available magnets and associated equipment (MRI-scanners, NMR and ESR spectrometers, conventional superconducting magnets, etc.). On the other hand there are many cases where very high magnetic fields, only available in a few specialized facilities, are essential and where the prospect of new discoveries is often the greatest. This scientific motivation has always formed a strong drive to develop techniques and installations to generate the highest possible magnetic fields and to perform experiments with them. In recent surveys, both by the European Science Foundation (ESF, "The Scientific Case for a European Laboratory for 100T Science", 1998) and by the USA National
Research Council (“Opportunities in High Magnetic Field Sciences”, COHMAG 2005), a compelling case has been made for high magnetic fields as a research tool for a wide variety of research topics and strong recommendations were made to stimulate high magnetic field large facilities. Since then, the recent developments in high magnetic field science have only further emphasised the importance and impact of high magnetic fields. The results obtained clearly illustrate the power, versatility and necessity of high magnetic fields as a research tool.

**National and international context**

The generation of very high magnetic fields is a technological challenge and their exploitation requires a high financial commitment. Therefore not many infrastructures exist where very high magnetic fields can be generated and used for research. Over the last twenty years, financial limitations and the complexity of such installations have resulted in a further concentration of these activities in less but larger infrastructures, very often operated on a national scale. For generating continuous magnetic fields in excess of 30 T, powered with 15+ MW power supplies, installations can be found in the USA (Tallahassee), Japan (Tsukuba) and Europe (Grenoble and Nijmegen). Large pulsed field installations based either on motor generators or large (> 5 MJ) capacitor banks are found in Los Alamos (USA), Tokyo (Japan), and in Europe in Toulouse and in Dresden (created in 2006). As the most recent step in this trend, in 2007 the Chinese government has created a 40 M€ national high magnetic field facility, consisting of a static field installation in Heifei and a pulsed field installation in Wuhan. Still the clearest example of this trend is the creation of the National High Magnetic Field Laboratory (NHMFL) in the USA, a three site organization that pioneers all aspects of high magnetic field generation, and its use for scientific experiments.

The current LNCMP installation was designed in 1992, and completed in 2000. Despite the continuous and gradual improvements that have been implemented since then, this installation is basically no longer up to the current standards and major investments are needed to improve its safety and to guarantee its international competitiveness in the future. To obtain the necessary investments, it is necessary to increase the weight and impact of high magnetic fields within the context of the French large facilities. Following the example of the NHMFL, it was therefore proposed to merge the LCMI and LNCMP into one Laboratoire National des Champs Magnétiques Intenses (LNCMI, UPR3228), on two sites. The new laboratory, with its increased size, scientific production and impact, and user community, will become a more important factor among the French large facilities, and it can be expected that through collaboration and synergy, the LNCMI will be more than just the sum of the LCMI and LNCMP, again improving the position of high field science in France and in Europe.

The LNCMI is the coordinator of the FP7 European infrastructure activity ‘EuroMagNET2’ (www.euromagnet2.eu) (2009-2012) that coordinates the activities of all European high field facilities (LNCMI, HLD Dresden, HFML Nijmegen). To further strengthen European collaboration, the LNCMI has been advocating the creation of a distributed European Magnetic Field Laboratory, uniting these four installations. This idea has been implemented through an ESRFI Roadmap Update proposal that was accepted last December (www.emfl.eu) and that will be elaborated in a future FP7 design study.
Funding
The LNCMP annual budget comes mainly from the CNRS (80%), the remainder from INSA (10%) and UPS (10%). During the last 5 years, the funds obtained from external sources, in particular from the ANR and from the European Community have greatly increased, and currently present more than 50% of the total budget of the laboratory.
Part of the new building and the 14 MJ capacitor bank were paid from funds obtained in the context of the Contrat Plan Etat Region 2000-2006 (CPER, Midi Pyrénées). The current CPER (2007-2013) foresees the funding of an extension of the building and an upgrade of the capacitor bank.

Summary of the technical activities at the LNCMP
The LNCMP develops in-house all technical aspects of the generation and the use of high pulsed magnetic fields. These activities can be grouped into five different categories:
- Ultrastrong conductors
  The maximum field strength of a pulsed magnet is limited by the mechanical properties of its conductor and the surrounding mechanical support. The LNCMP has an extensive in-house program to develop conductors for pulsed magnets that combine good mechanical strength (high field) with good electrical conduction (long pulses). The two main approaches developed are stainless steel jacketed copper conductors and nano-filamentary niobium copper composites. Both are examples of high level materials science aimed at specific applications.
- High voltage capacitor banks
  Pulsed magnets are most conveniently powered by high voltage, high energy and high power capacitor banks. The LNCMP engineers and technicians not only assure the maintenance and improvement of the main (home-built) 14 MJ capacitor bank, but they have also developed and constructed several mobile capacitor banks that are being used to perform pulsed field experiment at other installations, like the LULI in Palaiseau and the ILL and ESRF in Grenoble.
- Pulsed coil design and construction
  In order to obtain the highest fields and the longest pulses, pulsed field coils are operated very close to their destruction limit. The LNCMP engineers and technicians are strongly involved in pushing these limits to higher values. Over the last four years, the maximum field generated at the LCNMP has increased from 76 T to 82 T, and the foundations for further improvement have been laid. But the usefulness of a pulsed magnet for experiments is not only determined by field strength or pulse duration, but also by bore size, noise, homogeneity, cool down time, special geometries etc. and all these aspects are being covered and improved. During the last four years, these activities were largely developed in the context of a FP6 design study (DeNUF, www.denuf.org) and an ANR project.
- Cryogenics
  Both the pulsed magnet and the user experiments operate in general under (independent) cryogenic conditions. The large size of the magnets and the small size of the magnet bore impose non-standard cryogenics, further complicated by the presence of a strong time-varying field that often prohibits the use of metals as construction material. Proof of the strong performance of the cryogenics team is the fact that the LNCMP is the only pulsed field facility that routinely operates a (home-built) dilution refrigerator. The recent developments of the cryogenics for non standard coil configurations for optical and scattering experiments are another example.
- Mechanics
  All the above technical activities rely heavily on the presence at the LNCMP of a well equipped mechanical workshop, with highly skilled technical personnel.
  In order to go beyond the field limits imposed by the mechanical strength of current engineering materials, the LNCMP has recently installed a 60 kV, 1 MA capacitor bank that powers single turn coils (‘Megagauss’) This installation is based on controlled coil failure, but leaves the experiment unharmed. Values above 300 T can be generated by such an approach albeit with very short pulse durations, typically in the microsecond range.
  More details of these technical activities can be found below, or in greater detail in the annual reports (www.lncmp.org).
Summary of the scientific activities at the LNCMP

The scientific activities at the LNCMP cover a large area of condensed matter physics and go even beyond that. Over the last four years, they have resulted in 170 journal papers (‘ACL’), of which 21 Physical Review Letters and 6 papers in Nature, Nature Physics and Science. In view of the small number of scientists (9 equivalent full time permanent scientists in 2008), this is an excellent result, proving the large added value of pulsed magnetic fields as a research tool and the high quality of the LNCMP installation and researchers.

In the area of metals and superconductors, the first observation of quantum oscillations in high $T_c$ superconductors was certainly a highlight, generally acclaimed by the international scientific community. The study of quantum oscillations in organic conductors has allowed a better understanding of their Fermi surface.

The activities in nanophysics are focused on (i) (magneto)-transport properties of individually addressed carbon nanotubes and exfoliated graphene and graphene nano-ribbons, and (ii) NIR magneto-optical properties of carbon nanotubes in solution and epitaxial graphene. The activity in the domain of disordered systems consists mainly in the studies of the conduction mechanisms involved in macroscopic samples which conserve its nanometric-scale properties, that is networks of nano-objects obtained by self-organization on a surface.

The first results of $X$-ray and neutron scattering in high pulsed magnetic fields are coming out, and the LNCMP effort in this area is generally considered as pioneering. It allows the determination of structural and magnetic phases in high magnetic fields that cannot be addressed by any other means.

Pulsed magnetic fields also find applications outside condensed matter physics. The LNCMP is pioneering its use in experiments testing quantum electrodynamics. A setup to measure the long predicted magnetic birefringence of the quantum vacuum is under construction, and experiments on axion generation have allowed to push the existence limits of such particles to new values.

The activity in the semiconductor domain covers essentially three different aspects: one is focussed on the electronic bandstructure of semiconductors, mainly low dimensional systems, through the investigation of high magnetic field quantum effects on transport and spectroscopy in the VIS-FIR range, a second research axis is devoted to the study of the correlations in strongly interacting 2D electron systems and the third one concerns the properties of magnetic semiconductors.

All of the scientific activities outlined above are supported by the general support group, in terms of optics, electronics, sample preparation etc. This group also strongly contributes to the development of new experimental techniques for pulsed field measurements, examples of which are contact less resistance measurements by means of a tunnel diode oscillator and pulsed magnetic field NMR.

More details on these activities can be found below, or in even greater detail in the LNCMP annual reports (www.lncmp.org).

Summary of the other activities at the LNCMP

On average, the LNCMP hosts around 7 PhD or master students plus several stagiaires from engineering schools. Several members of the LNCMP staff teach at INSA Toulouse, UPS and ISAE. Several national and international meetings have been organized by the LNCMP during the last four years; a list can be found below.

The installation of the LCMI has some inherent risks, which in combination with the intrinsic presence of inexperienced external users, makes it important to pay special attention to security issues. The activities of the security officer (‘ACMO’) of the LNCMP to reduce the risks as much as possible are detailed below.

This report is organized as follows: A short account of all the technical and scientific activities is given below. The annexes 1-5 give details on security, training, popularization, the publication list 2005-2009 and the organizational chart.

Toulouse July 16th 2009

G. Rikken
High Field Installation

Personnel involved:

*Permanent*: Julien Billette (coils), Paul Frings (coils & generator), Franck Giguel (50%: coils), Bertrand Griffe (generator)

*Non permanent*: Jérôme Béard (coils), Julien Mauchain (X-coils)

*Collaboration*: mainly within DENUF: H. Jones, Oxford University; J. Perenboom, Universiteit Nijmegen; T. Hermannsdorfer, Hochfeldlabor Dresden;

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High Field Coils

Coils to generate high magnetic fields are subjected to enormous Lorentz forces that have a tendency to explode the coil. To contain these forces one can use stronger conductors or add internal (non-conducting, or at least not current carrying) reinforcement. These measures cause however higher losses and thus a more rapid rise of the temperature limiting the pulse duration. Optimized coil design for pulsed coils is therefore always a compromise between conductivity and mechanical strength.

**copper stainless steel coils**

The most evident, and in theory also the most efficient, way to contain the forces in a coil is to have wire of sufficient strength. The development of copper wire with a heavily cold-worked stainless steel jacket (UTS of the total wire ~1000MPa) permits in principle to wind straightforward coils with such a wire that can achieve fields in excess of 60T. However these coils showed short lifetimes, with a tendency of the lifetime to decrease with coil volume. We believe that this is due to insulation problems caused by high pressures inside the coil. This problem is probably the combination of a chemically inert stainless steel surface (difficult to adhere to) and the hardness of the surface. This combination is believed to promote “puncture” of the isolation at high contact forces. So for the time being the production of this type of coils is stopped.

**distributed reinforcement coils**

A flexible way to handle the balance between strength and conductivity is to reinforce every layer of the coil by the minimum required thickness of reinforcement. This reinforcement can easily cope with the hoop-stress but the axial load is difficult to transfer into the external reinforcement, and this is one of the factors (the other is the problem of plastic backflow) that limits the highest field that can be generated in such a way in a reliable manner.

**copper zylon**

This techniques was first tested with the combination of a ductile (and highly conductive) copper wire. After solving some minor technical problems (for instance the transition of one layer to the next), these coils turned out to be a reliable source for user fields up to 60 T. The inclusion of thermally not well conducting fibers caused unfortunately long cool-down times.

**glidcop zylon**

In order to pass the 60 T frontier for reliable user fields a stronger, but still ductile, conductor has to be used. By choosing glidcop we recently managed to generate 70 T user fields. The first coil has been tested elsewhere and is waiting to be installed in one of the specially adapted cells.

**stainless zylon**

To show the potential of this technique, we also produced a coil consisting of copper-stainless steel wire. With this combination of strong, but not so ductile wire, and zylon reinforcement a field of more than 79 T was realized, in agreement with the calculations. Due to the limitations of our generator these tests had to be performed at the NHMFL in Los Alamos (US). This approach can at this moment not be fully exploited in Toulouse due to the limitations of our generators. A project for an adapted generator is now underway.
rapid cooling coils

The distributed reinforcement coils have very low radial stresses. Therefore annular cooling channels can easily be integrated. By adding 1 cooling channel the cooldown time is decreased with a factor of 3.5 A simplified analysis, based on infinitely long coils and infinite heat of evaporation of the liquid nitrogen, gives a gain equal to \((n+1)^2\), \(n\) is the number of channels. The development of rapid-cooling coils has greatly enhanced the efficiency and ease of use for our users.

multi-coils

One way to obtain higher fields with existing materials is to build a set of nested coils that are energised consecutively. The increase in the number of free parameters for the coil design logically leads to coils with improved performance and permits moreover to use special wires that are only available in limited quantities or with limited sections. The drawback of this approach is however a more complicated system that is less easy to use since the field pulse has two (or more) largely different rise-times. This approach was tested and implemented with EU funding and permitted to generate fields above 75 T.

single-turn coils

The limit for the field that can be generated with the currently available engineering materials seems to be around 100 T. To go beyond this limit, one has to accept that the coil is destroyed during the pulse. By using a very fast (rise time sub microsecond) and high current (> 1 MA) generator, in combination with single turn coils, one can generate fields up to 300 T, without destroying the experiment inside the coil (which of course is destroyed). An installation of this type has been installed at the LNCMP and is currently under test.

special geometry coils

Sometimes an experiment needs a magnet where, contrary to the standard solenoids with a cylindrical axial hole, the field is not parallel to the access. Examples are diffraction on magnetic systems and experiments involving polarised radiation. The request for such type of coils was greatly enhanced by the construction of a transportable generator that permits the production of pulsed high magnetic fields at other large installations like high power lasers, neutron sources and synchrotrons (we performed experiments at the ERSF, LULI and ILL).

wide angle access

The first special coil for X-ray scattering increased the accessible scattering angles to ±30 degrees. The idea of for this coil was to obtain a conical bore by removing the wires close to the bore but far from the centre that are not very efficient anyhow. This resulted in a > 30 T coil that has at the moment produced more then 10000 pulses and is still in operation.

split coil

In order to have a full circle of diffraction angles accessible and to have at the same time the magnetic field perpendicular to the scattering vector a split coil for fields of over 30 T has been constructed and tested.

X-coils

In order to optimise the product \(B^2l\) (where \(B\) is the component of the magnetic field perpendicular to the path \(l\)) for birefringence experiments, a set of two slightly tilted racetrack coils has been developed. The first X-coils produced \(B^2l\) values of 25 T²m. Improved versions are under test that will surpass 150 T²m

Generator

To energise pulsed field coils one needs a lot of energy (several MJ) in a short time (~50 ms or less). Such powers can not easily be obtained from the electrical grid. The well known solution to this is intermediate stockage in a high-voltage capacitor bank.

14 MJ generator and two 0.17 MJ small generators

The main generator of the laboratory is a 14 MJ, 65 kA, 24 kV generator. This generator exists since ten years. It was built with an analogue control system. This analogue control proved to cause a lot of problems and moreover the company that produced the system disappeared. The overcome this problem and make the generator more reliable it was decided to replace the analogue control by a digital one realised by a series of distributed PLC’s (programmable controllers). After this major intervention the generator now works very reliable and has a more flexible interface for the users. Moreover, since all the control is programmed in software it can easily be adapted to new requirements. Recently we implemented a complete logging and access-control system. This is required by the EU funding for the visitor programme and allows at the same time to store
detailed information on coil behaviour and lifetime. Another technical improvement was the introduction of “home built” pneumatic switches. In a first time they replaced the (quite expensive) electro-mechanical relays for connecting the resistance measurement system. A much bigger version has now been developed to change the polarity of a complete generator. In addition we have two 0.17 MJ small generators that are used for testing smaller coils or to energise multi-coil systems.

**0.15 MJ transportable generator**

The 0.15 MJ transportable generator showed its versatility and its reliability in various experiments at other large installations. To make the setup of this generator more user-friendly (the first version needed a qualified technician to assemble the units after transport) this generator has been equipped with special high-voltage, high-power connectors and it can now be installed by a trained scientist without opening the generator modules.

**1 MJ transportable generator**

The success of the 0.15 MJ unit motivated us to build a 1 MJ transportable generator. This generator is equipped with an automatic system for polarity control that permits to change the direction of the magnetic field pulse. This is important for magneto-galvanic measurements and experiments using circular polarised X-rays. The generator was completely designed, built and tested in the laboratory, and is now in operation.

**6 MJ transportable generator project**

In order to produce field above 60 T one needs, due to the increased current density, shorter pulses than the actual 14 MJ generator can deliver. It was decided to build or acquire a 6 MJ generator with a shorter rise time. Design studies have been finished and a call for tender is expected to be announced soon.

**“Megagauss” generator**

The generator for the destructive single turn installation (“Megagauss”) has to be very fast and be able to supply a very large current. The assembly at the LNCMP of a 200 kJ, 60 kV, 2 MA, 0.5 µs rise time generator was recently successfully completed. It is located inside a Faraday cage for safety reasons and to limit the perturbation of other measurements in the building.

**Summary & Outlook: coils**

The standard (rapid-cooling, zylon reinforced 60 T coils) are performing well and have a typical lifetime of 500 pulses at maximum field. The production of these coils has been standardised and takes less than 3 weeks (1 week production of parts on a computerised machine, < 1 week coil winding, <1 week testing and installation).

**higher fields**

All main pulsed high-field laboratories are engaged in a competition for the highest fields. This competition is useful as far as it results in higher and reliable fields for our users but should not become the main activity of a user facility.

**multi coil system**

Multi-coil systems provide sufficient advantages to continue their development for the highest fields. The main advantages are: bigger parameter space, possibility to use wires of limited quantity or section, and possibly less risky since one can try to design the big outer coil in such a way that it has a longer lifetime as the much smaller, much lower energy containing and less expensive inner coil. A new and improved multi-coil system is designed, and its operation is foreseen for the end of 2009. The major improvements are the maximum field (80 T), the pulse duration and also a reduced difference between the two rise times, and finally this coil is foreseen to have several inserts: one for the highest field and one for lower field but longer pulse duration. Recently an 82 T record field has been produced in Toulouse by using a mini internal coil in a standard 60T coil. This technique can be promising for testing small batches of novel conductors and permits at the same time optical experiments that are compatible with the small bore size and the short pulse duration.

**Monolithic coils**

Combination of distributed reinforcement with stronger but yet ductile conductors will reduce the so-called “back-flow” problem (the conductor deforms so much plastically during the pulse that is deforms plastically again at zero field, due to the created permanent deformation of the conductor at maximum field). This repeated plastic deformation certainly limits the lifetime of a coil to a very low number of pulses. Another big improvement would be the introduction of some type of axial reinforcement (for the moment the fibre
reinforcement only reinforces in tangential direction, it does not reduces the axial stress in the wire). Such axial reinforcement would be most likely metallic and could as such introduce extra insulation problems, but it is worth to be tried.

**higher fields for users**

Higher fields for users make only sense if a reasonable lifetime (>100 pulses at maximum field) can be obtained. This is not only for reasons of coil efficiency but also because coil failures can damage the cryostat, data acquisition equipment and the sample. A good way to increase the lifetime is to downgrade the actual user field to 90% of the maximum field. This reduces the stresses by 20%. Moreover it turned out that every modification of a coil design, although beneficial in the long term, normally reduces the lifetime of the first few coils that are produced in that way. This means that modifications have to be performed in a prudent and systematic way and preferentially tested on small coils.

**rapid cooling and “high duty cycle” coils”**

It is quite likely that a lot of gain (10-50 times) can be obtained in rapid cooling techniques, either by optimising the existing technique or by using coil-construction techniques used for DC coils but now with liquid nitrogen cooling. This latter approach sounds very interesting and could be very fruitful since the laboratory has merged with the laboratory for DC fields in Grenoble. A minor concern might be the impedance of these coils since they are normally designed for voltages much lower than 24 kV. But we believe that this problem can be solved.

**Summary & Outlook: generator**

The generators are working fine and do not need a lot of modification or maintenance. In theory the idea of replacing the current limiting self-inductances by non-linear resistors (high-$T_c$ current limiters) seems interesting and efficient (more energy available, less rise-time limitations), but this technique is not very mature and still expensive, so it might be better to postpone its implementation for a few years.

**14 MJ generator**

The generator is now very stable and reliable. The aspects that could be improved, and should be if the number of users increases, is the duration of the charging and specially the duration of commutation between the boxes and the time it needs to change the polarity. This modification can be realised by installing pneumatic switches and at the same time reducing the number of thyristor stacks and replacing them by optical thyristors. Safety should always stay a major issue, and with the installation of more independent generators the interlock and grounding should be redesigned.

**6 MJ transportable generator**

Within two years this generator should become available, either (preferred) by acquiring a turnkey solution or by building the generator in house. This will greatly facilitate the test of medium size monolithic coils in the field-range from 70 to 90 T and the operation of a dual coil system.
Materials Science

Personnel involved:

Permanent: F. Lecouturier, N. Ferreira, L. Bendichou, J.P. Laurent, J.M. Lagarrigue, J. Billette

Ph.D Student: V. Vidal, J.B. Dubois

Non permanent: M. Mainson (CDD)

Collaboration: L. Thilly & P.O Renault (PHYMAT, Poitiers), V. Vidal (MTM-Leuven, ENSTIMAC-Albi), H. van Swygenhoven & S. van Petegem (POLDI-Paul Scherrer Institut, Switzerland), B. Schmitt (SLS-PSI, Switzerland), P. Olier (CEA-LTMEX, Saclay), A. Devred & C. Berriaud (CEA-SACM, Saclay), H. Jones (Clarendon Laboratory, University of Oxford), S. Svyagin (HLD, Dresden), C. Verwaerde (MSA-Alstom), M. Sandim (University of São Paulo, Brazil)

Ultra-high strength nanocomposite Cu/X (X=Nb, Ta) conductors

The development of reinforced conductors, with high electrical conductivity and high strength, is essential to provide non-destructive high pulsed magnetic fields over 80 Tesla: a compromise is obtained with Cu-based continuous nanofilamentary wires (2 GPa ultimate tensile strength and 0.6 µohm.cm electrical resistivity at 77K). The fabrication process of these nanocomposite wires is based on severe plastic deformation applied by accumulative drawing and bundling (ADB), leading to a multi-scale copper matrix containing up to N=85^3 (4.4 10^9) continuous and parallel niobium fibers. Three ways of optimization have been investigated and are summarized below: they deal with the geometry of the reinforcement, the material and the process.

Cu nanowhiskers embedded in Nb nanotubes inside a multiscale Cu matrix: the way to reach extreme mechanical properties in high strength conductors

For the development of non destructive resistive pulsed magnets over 80T, Cu/Nb/Cu wires with geometrical optimization, composed of a multi-scale Cu matrix embedding Nb nanotubes were produced by ADB. TEM reveals good co-deformation compatibility between the reinforcing Nb nanotubes and the multi-scale Cu. While a sharp single-component <110> fibre texture is developed in Nb nanotubes, a double texture with <111> and <200> orientations is observed in the copper matrix. The mechanical properties are improved compared to nanofilamentary Cu/Nb wires. The extraordinary strengthening of the co-cylindrical structure is related to: (i) an increase of Cu-Nb interfaces surface acting as dislocations barriers; (ii) a rapid and controlled access to nanometre scale where size effect operates on the plasticity mechanisms; (iii) the contribution of an additional reinforcing phase: the Cu-f nanofilaments embedded in the Nb nanotubes behave as whiskers with strong size dependence. The Cu/Nb/Cu system is therefore more efficient than the Cu/Nb system for the high-strength applications in magnets: it exhibits a controlled microstructure and an efficient strengthening in the nanocomposite zones, where size and also geometry play major roles (Scripta Mat 57 (3) (2007) 245-248).

Finally, the validity of the Cu/Nb/Cu nanocomposite wires (N=85^3, \( \phi1\text{mm} \)), insulated with Kevlar fiber), without any loss in strength, has been demonstrated in the thumb-coils configuration (Ph.D work of S. Batut). First neutrons diffractions experiments on Cu/Nb/Cu aged coils have been performed at the continuous spallation neutron source SINQ (POLDI, PSI, Switzerland).

(a), (b), (c) SEM image of the multi-scale structure of Cu/Nb/Cu co-cylindrical wires (N = 85^3, \( d=1.511\text{mm} \)). (d) High-magnification cross-section SEM image of the nanocomposite area showing the Nb nanotubes, the Cu fibers and the interfilamentary Cu.
Development of a new co-axial CuNbCuNb nanocomposite wires

A new nanocomposite structure has been designed with a superposition of Nb and Cu nanotubes. We have added nanometric phases reminding the extraordinary strengthening of the co-cylindrical structure. A conductor containing $85^3$ Nb nanowhiskers, Cu nanotubes and Nb nanotubes, embedded in a copper matrix has been obtained. The Cu/Nb/Cu/Nb system is therefore more efficient than the Cu/Nb filamentary and the Cu/Nb/Cu co-cylindrical system for high-strength applications in magnets: it exhibits a controlled microstructure and an efficient strengthening in the nanocomposite zones.

Effects of size and geometry on the plasticity of copper/tantalum wires

The material optimization procedure led to the use of tantalum to strengthen the copper matrix, instead of Nb because of the highest value of its shear modulus which is assumed to increase the whiskers effect. The microstructure of the Cu/Ta nanofilamentary conductors ($N=85^3$), cold-drawn to a diameter of 1.5mm, has been investigated and correlated to the mechanical properties. After heavy drawing, the Cu matrix is nanostructured and the Ta nanofilaments develop a strong ribbon-like shape resulting in an early microstructural refinement. The macroscopic strength is in excess from rule of mixtures predictions as confirmed by nano-hardness values. The strengthening is however lower as expected ($UTS_{RT}=711\text{MPa}$), because of the distorted ribbon morphology of the Ta fibers preventing them from behaving as nanowhiskers, like Nb fibers in Cu/Nb wires. This result shows that size and geometry play key roles in the plasticity of nanomaterials (Acta Mat 54 (4) (2006) 1063-1075).

Prevention of fracture during Accumulative Drawing and Bundling (ADB) process

The third way to improve the properties of Cu/X wires is to optimize the processing parameters. The cold-drawing of the Cu/Nb/Cu co-cylindrical conductors, reinforced by niobium nanotubes filled with copper nanowhiskers, has been improved with respect to the elimination of the central bursting defects following the conditions of the criterion of Avitzur and led to the obtention of more then 20 meters of conductors without fracture. Several attempts have been performed to insulate these conductors without loosing their strength with different kind of materials and different ways of application (heat-retractable PTFE sheath, PTFE in spray, Kevlar fiber…).

More details on the three ways of optimization of the CuX nanofilamentary can be found in the Ph.D thesis of Vanessa Vidal ("Optimisation des propriétés mécaniques des conducteurs nanofilamentaires CuX (X= Nb ou Ta) par l’étude des mécanismes élémentaires de déformation", Ph.D Thesis, INSA Toulouse, n°855, 2006)
Size and strain effects on the magnetic properties of heavily-drawn Cu-Nb (N=85\textsuperscript{5}) wires

We have studied the influence of strain applied via ADB on the superconducting properties for a series of Cu-3.5\%Nb nanocomposite wires, containing 85\textsuperscript{5} Nb fibers with diameter below 10nm, embedded in a Cu matrix, with interfilamentary spacing below 2nm. The increasing strain leads to only minor modifications of the superconducting Tc. Also, no major differences regarding the H\textsubscript{c2} data were observed among the investigated conductors. However, the main difference is the shape of the DC magnetization curves. Notably, the investigated samples exhibit a double-peak structure in the ascending branch of the magnetization curves. The first peak, which occurs at low magnetic fields, is related to the superconducting proximity effects in the Cu matrix and is enhanced as the interfilamentary spacing d\textsubscript{Cu-0} decreases, as expected. In an opposite manner, the second peak is almost suppressed as the dimension of Nb filaments d\textsubscript{Nb} decreases, a fact suggesting that the second peak is related mainly to the size of the Nb filaments (Superconducting Science & Technology 19 (2006) 1233-1239).

<table>
<thead>
<tr>
<th>Cu-3.5% Nb</th>
<th>d (mm)</th>
<th>d\textsubscript{Nb} (nm)</th>
<th>d\textsubscript{Cu-0} (nm)</th>
<th>RA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>2.416</td>
<td>6.7</td>
<td>1.2</td>
<td>88.71</td>
</tr>
<tr>
<td>A2</td>
<td>1.985</td>
<td>5.5</td>
<td>1</td>
<td>92.38</td>
</tr>
<tr>
<td>A3</td>
<td>1.571</td>
<td>4.4</td>
<td>0.8</td>
<td>95.23</td>
</tr>
</tbody>
</table>

DC magnetization curves for the Cu-3.5\%Nb nanocomposite wire: ascending branches of M(H) curves for T = 3 K. The inset shows details of the curves for low magnetic fields.

Evidence of internal Bauschinger test in Cu/Nb/Cu nanocomposite wires during in-situ macroscopic tensile cycling under synchrotron beam

In-situ multiple tensile load-unload cycles under synchrotron radiation have been performed at SLS (PSI) on nanocomposite Cu/Nb/Cu wires. The phase specific lattice strains and peak widths demonstrate the dynamics of the load-sharing mechanism where the fine Cu channels and the Nb nanotubes store elastic energy, leading to a continuous build-up of internal stress. The in-situ technique allows revealing the details of the macroscopically observed Bauschinger effect (APL 90, 241907 (2007)). The nature of the elasto-plastic transition is uncovered by the “tangent modulus” analysis and correlated to the microstructure of the Cu channels and the Nb nanotubes. Finally, a new criterion for the determination of the macroscopic work stress is given at the stress to which the macroscopic work hardening, \( \theta = \frac{d\sigma}{d\epsilon} \), becomes smaller than one third of the macroscopic elastic modulus (Acta Mat 57 (2009) 3157-3169).

Outlook

The improvement of the drawing conditions led us to apply the same procedure for the optimization of the extrusion conditions. The aim is the prevention of fractures during the extrusion step of the ADB process and the scale-up of the size of the nanocomposite billets. In collaboration with PHYMAT (L. Thilly), two CEA Laboratories (DAPNIA, LTMEX), and an industrial partner (Alstom/MSA), and funded by the ANR, we are joining forces, through the NANOFILMAG project, to master the parameters and processes of preparation and transformation of copper/niobium-based nanocomposite conductors. A Ph.D student, J.B Dubois, is involved in the project since October 2007 and shares his activity between LNCMI and PHYMAT.

Development of high strength macrocomposite copper/stainless steel (Cu/SS) conductors

- for 60T-1MJ and 3MJ magnets with optimized current distribution: 900 meters of Cu/SS macrocomposite conductors with two different SS contents (40, 58\%vol) and with different cross sections (2.00 * 3.15, 2.50 * 3.55 mm\textsuperscript{2}) were produced and checked the requirements for a 65T-1MJ prototype magnet with optimized current distribution. 600 meters of Cu/SS macrocomposite conductors with three different SS contents (42, 46, 58 \%vol) and with different cross sections (2.36 * 4.50, 2.65 * 4.50, 3.00 * 5.00 mm\textsuperscript{2}) have been especially produced in order to be wound in a "large bore" 65T-3MJ prototype magnet with optimized current distribution.

- for 80 T magnet with optimized reinforcement distribution: the development of 450 meters of Cu/SS macrocomposite wires with 40\% of SS and a cross section of 2.36 * 4.00 mm\textsuperscript{2} has been dedicated to the construction of a new type of magnet combining high strength wires and Zylon fibers, producing a new European record, in 2006, with a magnetic field of 78 T, powered by the capacitor bank of NHMFL (Los_Alamos-USA).
- for B > 80 T in the coilin/coilex system: the development of Cu/SS wires, for the coilin, with 60% of SS (UTS>1550 MPa) and a cross section of 2.00*1.25 mm² allows to reach 81 T (the LNCMI record) in spring 2009.

- for coil aging study within DENUF project (FP6): the study of the influence of the work-hardening on Cu/SS macrocomposite wires has been performed in order to determine the best compromise between strength and plastic strain with respect to the coil lifetime. Several small batches (50 meters) with different work-hardening ratio (RA= 65, 70, 75%, 80%) have been elaborated in-house and insulated by an industrial company with a double layer of polyimide films (Kapton).

Research & Development of high strength composite conductors

- Cu alloys for magnets with optimized current distribution: conductors made of Cu alloys like GlidCop (CuAl₂O₃) or CuAg (with low silver content 0.08%) have been provided by industrial companies in order to be combined with Zylon fibers in magnet with optimized reinforcement distribution.

- CuNbTi microcomposite wires for conventional magnets and split-coil:
A strong link has been developed with the industrial company MSA in order to adapt commercially available “raw materials” to the specifications of high pulsed field magnets. CuNbTi wires have been provided by MSA. First, a selection of round samples from LHC production has been characterized in liquid nitrogen at LNCMP. The good level of mechanical properties (UTS>1GPa at 77K) promotes them as potential candidates for pulsed magnets. Rectangular cross sections of 2.00mm * 3.15mm have been transformed.

Coil aging studies on CuSS and CuNbTi minicoils
In the framework of the European project DeNUF, “new” conductors and “new” insulators have been systematically aged using the mini-coil aging platform. During the period 2005-2009, we have performed aging experiments on CuSS (LNCMP), CuNbTi (MSA) mini-coils and also on in-situ CuNb wires provided by HLD (Dresden) and Bochvar Institute (Moscow).

Mini-coils wound with CuSS and CuNbTi have been tested in order to compare their aging performances. We have also compared two materials for insulation: polyester fibers and Kapton ribbons. Moreover, wet winding impregnation (LNCMP) and vacuum impregnation, performed in the Clarendon Laboratory (University of Oxford), were applied to the polyester insulated mini-coils.

Three CuNbTi coils, wet wound with polyester fiber braiding insulation, have shown electrical damages after winding. We observe an improvement by applying vacuum impregnation but the two coils have been damaged at low fields (4.7 and 13.8 T) due to an electrical failure. Two others coils insulated with Kapton ribbons have been successfully tested until a maximum field of 36.5 T and aged at 33.8 T (92%Bmax). The insulation method which is suitable to the obtention of high magnetic field is the Kapton insulation.

The electrical resistance monitoring data, for the CuNbTi wires insulated with Kapton, are compared to the ones of the CuSS wires. Bmax for the CuNbTi coils is comparable to the CuSS coils near 36 T. The increase of electrical resistance before the coil failure is much more important for CuNbTi (+15%) than CuSS (+5%). We can link this difference to the fact that the Cu matrix embedding NbTi filaments is free to deform whereas in CuSS wires, the deformation of the copper core is constrained by the stainless steel jacket. The same behaviour is observed during aging.

Nevertheless during aging after 60 shots at 92%Bmax, the resistance of the CuNbTi coil suddenly increases by 8%. The total resistance variation reaches 25% after 60 shots. The plastic aging of the CuNbTi coils seems to be more rapid than the plastic aging of CuSS coils, where ΔR= 9% after 100 shots (or even more) at 90%B max. The CuNbTi conductors are well adapted to generate high magnetic field, but their aging performances at high field are weaker than the CuSS conductors.
Strongly correlated electron systems

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Fermi surface of high temperature superconductors

A useful way to characterize the electronic properties of a metal is to map out their Fermi surface (FS). It can be done by measuring quantum oscillations in high magnetic field, either of the magnetoresistance (Shubnikov-de Haas –SdH- effect), or of the magnetization (de Haas -van Alphen –dHvA- effect) [1]. Other probes such as AMRO (angular dependence of the magnetoresistance) and ARPES (angle resolved photoemission spectroscopy) can also be used in such way.

In most metals, predictions of band structure calculations (LDA) are in good agreement with experimental measurements. This is also the case in the overdoped side of the phase diagram of high temperature superconductors (HTSC) where we have recently reported quantum oscillations in overdoped Tl$_2$Ba$_2$CuO$_6$+$\delta$ confirming that the FS consists of a large cylinder [2]. Fig. 1 shows interlayer resistance (top) and magnetic torque (bottom) with the field oriented close to the c-axis for two different Tl$_2$201 crystals at temperatures below their zero-field superconducting transitions. For both sets of data, the inset shows an expanded view near the field maxima, which reveals clear oscillations whose amplitude grows with increasing field strength. The frequency $F$ of the oscillations is directly related to the extremal cross-sectional area $A$ of the Fermi surface normal to the field. A Fourier transform of the data displays a single frequency of 18 100 T, which corresponds to $\Delta_R / B (T^{-1}) = 100 / B (T^{-1})$ in good agreement with band structure calculations.

These results are also in perfect agreement with AMRO [3], and ARPES [4] measurements.

By contrast, the underdoped regime is highly anomalous and appears to have no coherent Fermi surface, but only disconnected ‘Fermi arcs’ [5], whose origin would be in the high orbit predicted by the LDA calculations, with a pseudogap open around (O, $\pi$) et ($\pi$, 0). In this context, the observation of quantum oscillations in underdoped YBa$_2$Cu$_3$O$_y$ has created a lot of excitation in the community since it infers a more classical view based on a Fermi liquid picture.

Fig 1: Raw data of interlayer magnetoresistance (top) and torque (bottom) versus magnetic field. The insets show a magnified view of the oscillatory component of each quantity [2].
Thanks to the synthesis of high quality single crystals by the group of D. Bonn and the improvement in the signal/noise ratio measurement under pulsed magnetic field, we have reported quantum oscillations of the Hall resistance of the oxygen-ordered copper oxide YBa$_2$Cu$_3$O$_{6.5}$ [6]. With a $T_c$ of 57.5 K, these samples have a hole doping per planar copper atom of $p=0.10$, corresponding to the underdoped region of the phase diagram. Fig. 1 shows the magnetic field dependence of the Hall resistance at different temperatures between 1.5 K and 4.2 K, where clear oscillations of the resistance are observed beyond the superconducting transition. The oscillation frequency of 530 T implies a Fermi surface pocket that encloses a k-space area which represents only 1.9% of the Brillouin zone. The low oscillation frequency reveals a Fermi surface made of small pockets, in contrast to the large cylinder characteristic of the overdoped regime. dHvA oscillations have been observed at the same doping level [7, 8]. In addition, quantum oscillations have also been observed in the stoichiometric compound YBa$_2$Cu$_4$O$_8$ ($T_c=80$ K corresponding to a doping $p=0.14$) with a similar frequency $F=660$ T [9]. The sharp contrast between the sizes of the FS on opposite sides of the phase diagram is illustrated in Fig. 3. The main panel displays the Fourier transform of QO of underdoped YBa$_2$Cu$_3$O$_{6.51}$ (red) and of overdoped Tl2201 (purple).

The inset shows the area of the corresponding orbit in the FBZ. It is worth noting that quantum oscillations tell us neither the number of pockets, nor their location in the reciprocal space. This drastic dissimilarity of FS topology simply reflects the difference in carrier density on opposite sides of the phase diagram. While the large cylinder in the overdoped side corresponds to a carrier density of $1+p$, as predicted by band structure calculations, the band picture fails in the underdoped side, where the carrier number scales more closely with $p$. One fundamental question for our understanding of HTSC is what causes the dramatic change in FS topology from overdoped to underdoped regimes? Based on the observation of a negative Hall effect at low temperature in underdoped YBCO, the presence of an electron pocket in the Fermi surface has been suggested would naturally arise from a reconstruction of the large hole FS calculated from band structure.

Fig. 2 : Hall resistance as a function of magnetic field $B$ for YBa$_2$Cu$_3$O$_{6.5}$, at different temperatures between 1.5 and 4.2 K [5]

Fig. 3 : Fourier transform of the oscillatory part of the torque for underdoped YBa$_2$Cu$_3$O$_{6.51}$ (red) and for overdoped Tl2201 (purple). Insert: Sketch of the FS area deduced from the frequencies of quantum oscillations via the Onsager relation.
Different mechanisms have been proposed for this FS reconstruction, involving d-DW order [11], incommensurate antiferromagnetic order [8] or stripe order [12]. Each scenario predicts a different FS topology and the observation of an additional frequency would provide a stringent test. In particular, recent dHvA measurements in the same compound than the present work found evidence of a larger pocket which impose strong constraint on the ordering wave vector for the reconstruction [8].

In order to determine whether there are other closed FS, which is of fundamental importance to clarify the FS of HTSC in the pseudogap phase, we have performed high-precision measurements of the dHvA effect in underdoped YBa$_2$Cu$_3$O$_{y}$O$_{6.54}$. Raw data of torque for two slightly different compositions ($y=6.51$ and $y=6.54$) are shown in the inset of Fig. 4. Solid lines are fits of the Lifshitz-Kosevich theory, assuming that four frequencies are involved in the data. The main figure presents the Fourier analysis of the oscillatory torque for underdoped YBa$_2$Cu$_3$O$_{6.54}$. A broad peak with a maximum around 535 T is observed, in agreement with previous results. Our results do not support the existence of a larger pocket reported recently in the same compound [8]. The main frequency, so far believed to be a single frequency, is in fact composed of three closely spaced frequencies: $F_1=540$ T (black line in Fig. 4) and two satellites $F_2=450$ T (green line) and $F_3=630$ T (purple line). We attribute these frequencies to bilayer effect and corrugation of the FS, which point out for the first time in an underdoped cuprate the coherence of the quasiparticle along the interplane direction at low temperature.

Heavy-fermion systems
Activity on heavy-fermion physics was developed during the last years at the LNCMI-Toulouse. Among recent works, two studies performed at the LNCMI-Toulouse on the “hidden-ordered” paramagnet URu$_2$Si$_2$ and on the antiferromagnet CeRh$_2$Si$_2$ are summarized below.

Transport properties of the heavy-fermion URu$_2$Si$_2$ have been studied in pulsed magnetic fields [14]. Combination of magnetoresistance, Hall effect and Nernst effect measurements (see Fig. 5) permitted to outline the reconstruction of the Fermi surface in the magnetic field-temperature phase diagram. The zero-field ground state (called “hidden order state”) is a compensated heavy-electron semi-metal, which is destroyed by magnetic fields through a cascade of field-induced transitions. A large Nernst signal emerges in the hidden order state. A finite Nernst signal is indeed expected in a multi-band metal with different types of carriers. In addition, as illustrated by the case of elemental bismuth, the Nernst effect, which tracks the ratio of mobility to the Fermi energy, becomes particularly large in a clean semimetal. This signal was found to be suppressed above 35 T, when the magnetic field destabilizes the hidden order.

![Fig 4: Fourier analysis of the oscillatory torque (see inset) for underdoped YBa$_2$Cu$_3$O$_{6.54}$.](image)

![Fig 5: Nernst signal in URu$_2$Si$_2$ at different temperatures. The inset compares the phase diagram (T,B) obtained from the MR (square) and Nernst effect (triangles) studies in pulsed fields with steady field measurements of the MR (circles).](image)
Above 40 T, URu$_2$Si$_2$ appears to be a polarized heavy-fermion metal with a large density of carriers, whose effective mass rapidly decreases with increasing magnetic polarization. CeRh$_2$Si$_2$ is a heavy-fermion compound characterized by two successive transitions, at $T_{N,1} = 36$ K and $T_{N,2} = 26$ K, towards antiferromagnetic order [15]. Application of hydrostatic pressure induces a quantum phase transition to a paramagnetic Fermi liquid regime, in the vicinity of which an unconventional superconducting pocket develops [16]. Recently, we have studied the effects of high magnetic fields on this system (at ambient pressure) at the LNCMI-Toulouse [17]. Transport (see Fig. 6) and torque measurements have been performed in pulsed magnetic fields up to 60 Tesla, and thermal expansion measurements were performed in continuous fields up to 13 Tesla. Fig. 6 shows measurements of the magnetoresistance up to 50 Tesla and temperatures between 1.5 K and 80 K. At low temperatures, a step-like anomaly is observed at a critical field $H^*$ of around 26 T. This corresponds to a field-induced first-order transition to a magnetically polarized regime, where all the microscopic magnetic moments (on the Ce$^{3+}$ sites) are aligned ferromagnetically along the field direction. Additional torque measurements (not shown here) permitted to see in fact two transitions to the polarized state, at $H_{1}^* \approx 25.6$ and $H_{2}^* \approx 26.0$ Tesla (see also [18]). The strong change of resistance between the antiferromagnetic and the polarized phases may indicate an important modification of the electronic properties, which may be related to a reconstruction of the Fermi surface of the system. At higher temperatures, a magnetic anomaly characteristic of the field-induced transition between the antiferromagnetic and polarized states can be followed from our measurements: its characteristic field decreases with increasing temperature, and vanishes at $T_{N,1} = 36$ K. A change from a first order to a second order transition is observed at about 20 Kelvin. At temperatures higher than $T_{N,1}$, a broad anomaly (at $H_{pol}$) is associated to the crossover between the low-field non-polarized paramagnetic regime and the high-field polarized paramagnetic regime.

This study permitted to determine carefully the magnetic field-temperature phase diagram of CeRh$_2$Si$_2$, when a magnetic field is applied along the easy-axis $c$. The phase diagram shown in Fig. 6 was obtained from the combination of our transport, torque, and thermal expansion measurements. The transition temperatures $T_{N,1}$ and $T_{N,2}$ are found to decrease with increasing magnetic fields, before merging at about 24 T and 20 K. This point may correspond to a tetra-critical point, where two first-order transition lines reported below 20 K (and above 24 T) also end. Changes of the physical properties close to this point are not trivial since, from our resistance measurements, a reminiscence of the first order transition can be followed up to 25 Tesla, while the second order line can also be defined down to 15 Tesla. At higher temperatures, the characteristic field $H_{pol}$ of the crossover between the paramagnetic non-polarized and polarized regimes is found to vary almost linearly with $T$, which confirms that its nature is simply related to the Zeeman effect.
References

Due to their rather simple Fermi surface (FS), organic metals provide a powerful playground for the investigation of quantum oscillation physics. Indeed, in most cases, their FS can be regarded as networks of orbits coupled by magnetic breakdown (MB) giving rise to quantum oscillations spectra with numerous frequency combinations that cannot be accounted for by the semiclassical model of Falicov and Stachowiak. This phenomenon which is attributed to either the formation of Landau bands or (and) the oscillation of the chemical potential in magnetic field needs to be better understood.

**Frequency combinations in linear chains of orbits with high scattering rate**

The FS of \((BEDO)_{5}\text{Ni(CN)}_{3}\text{C}_{2}\text{H}_{4}(\text{OH})_{2}\) (see the opposite figure) corresponds to a linear chain of quasi-two-dimensional orbits coupled by MB. Remarkably, the scattering rate can be consistently deduced from the Shubnikov-de Haas oscillations data relevant to both the basic \(a\), the second harmonic \(2\alpha\) and the MB-induced \(b\) orbits. Its large value points to a significant reduction of the chemical potential oscillations. Despite of this feature, the oscillations spectrum exhibits many frequency combinations [1]. Their effective masses and (or) Dingle temperature are not in agreement with neither the predictions of the quantum interference model nor the semiclassical model.

**Frequency combinations in networks of compensated orbits**

According to calculations [2] chemical potential oscillations are strongly reduced for 2D metals with compensated orbits. 2D networks of compensated orbits are achieved in the compound \((ET)_{8}\text{Hg}_{4}\text{Cl}_{12}\text{C}_{6}\text{H}_{5}\text{Br})_{2}\) as displayed in the opposite figure where the two \(a\) orbits with different shapes are compensated while the \(d\) and \(D\) pieces are forbidden orbits. In agreement with the above statement, all the frequency combinations observed in early de Haas-van Alphen (dHvA) oscillations spectra up to 28 T data are consistent with the semiclassical picture [3]. Oppositely, recent dHvA data obtained from torque measurements up to 55 T exhibit many frequency combinations, most of them being forbidden within the semiclassical framework [4]. Otherwise, the pressure dependence of the effective mass linked to the basic \(a\) orbits scales with the coefficient of the \(T^2\) law of the zero-field resistance which is in line with a Brinkman-Rice scenario expected for strongly correlated compounds [5].

**References**

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The activity in the semiconductor domain covers essentially three different aspects: one is focussed on the electronic structure of semiconductors, mainly low dimensional systems, through the investigation of high magnetic field quantum effects on transport and spectroscopy in the Vis-FIR range, a second research axis is devoted to the study of the correlations in strongly interacting 2D electron systems and the third one concerns the properties of magnetic semiconductors. In the following section some results obtained in these different aspects are presented.

\(X_z\)-\(X_y\) valleys crossover in AlP-GaP quantum wells

We have established by high magnetic field spectroscopy and magnetotransport on 2DEG confined in AlP/GaP quantum wells (QW) that bulk AlP \(X\)-valleys are located exactly at the edge of the Brillouin zone and that in many respects, the valley symmetry in AlP quantum wells (QW) with GaP barriers is similar to that of the AlAs quantum wells with GaAs barriers. As expected for such systems, the valley degeneracy is lifted into a single \(X_z\)-valley and a twofold \(X_{xy}\)-valleys, due to on the one hand the valley-anisotropy confinement splitting and on the other hand the biaxial strain splitting caused by the lattice mismatch between AlP and GaP. In the present study, we have investigated the properties of quasi-two-dimensional electrons in a wide range of modulation-doped AlP quantum wells (between 3 and 15 nm) with GaP barriers by measuring cyclotron resonance (CR), quantum Hall effect, and Shubnikov de Haas oscillations. The experiments down to 1.55K were performed under high pulsed magnetic field while static fields were used for the low temperature transport measurements down to 280mK.

Figure 1 summarizes the CR data, obtained at 4K on two different samples, one being a 15nm wide multi-QW structure and the other a 4nm wide single-QW.

![Graph](image)

**Fig. 1.** Values of the resonant fields determined from CR at different excitation energies for the 15nm MQW structure (full circles) and the 4nm SQW (open circles).

The two straight lines indicate parabolic conduction bands in the investigated energy range for both \(X_z\) and \(X_{xy}\) valleys, the deduced cyclotron masses are \(m_{c1} = 0.30 \pm 0.02 m_0\) and \(m_{c2} = 0.52 \pm 0.01 m_0\) respectively. The iso-energy surfaces are then ellipsoids elongated along the \(\Delta\) line of the BZ with longitudinal and transverse effective masses: \(m_l/m_0 = 0.3\pm0.02\) and \(m_t/m_0 = 0.3\pm0.02\). Regarding the valley degeneracy, a direct determination is derived for each QW from combination of longitudinal and Hall resistances data.

Fig. 2 shows \(R_{xx}(B)\) and \(R_{xy}(B)\) for a 10nm wide QW at 1.55K and for a 3nm wide QW at 280 mK. In Fig 2a, standing for the wide QW having the \(X_{xy}\)-valley populated the sequence of integer filling factors is incremented by 4 at low magnetic fields, high Landau quantum numbers, and then by one at low quantum numbers.
Consequently, the Landau degeneracy equal to 4 gives \( g_v = 2 \) for the \( X_{\text{xy}} \)-valley. Accordingly, a valley degeneracy \( g_v = 1 \) is expected for the populated \( X_{\text{xz}} \)-valley of the 3nm sample. This is precisely displayed by the data in Fig. 2b showing a sequence of filling factors incremented by 2 at low magnetic fields and by one at high magnetic field. Further experiments have revealed that the the \( X_{\text{y}} \)-\( X_{\text{l}} \) valleys crossover occurs at AlP QW thickness between 4 and 5 nm.


High-pressure magneto-spectroscopy on the III-VI layered semiconductor InSe

Indium selenide is a layered semiconductor widely investigated in the last decades for its potential optoelectronic applications. In the past various experiments revealed the electron effective mass anomalous behaviour. Modern ab-initio band structure calculations combined with optical measurements under high pressure have explained this anomaly and have also unveiled new interesting features such as the onset of a ring-shaped valence band maximum above 2 GPa.

Taking advantage of a novel non-magnetic Diamond Anvil Cell (DAC) [1] we have performed both magneto-photoluminescence (MPL) and magneto-absorption (MA) investigations under high pressure up to 6 GPa providing a very deep insight on the electronic structure of n- and p-type InSe.

MA, excitonic and interband Landau-level absorption bands yielded an accurate determination of the diamagnetic coefficient and as well as the exciton effective Rydberg magnetic field dependence. The pressure behavior of the conduction band exhibiting a strong non-parabolicity can be well described within a specific k.p model. Moreover, the toroidal VBM has been unraveled through reentrant excitonic absorption at high field owing to a larger hole effective mass. Combining our MA experiments together with p-type MPL as a function of pressure allowed to establish the valence band structure with an overwhelming accuracy. Finally, the direct-to-indirect conduction-band crossover around 4 GPa has been characterized by effective mass, dielectric constant and Rydberg evolution [2].

Excitonic states in InP/GaP self-assembled quantum dots probed in high magnetic fields

InP quantum dots (QD) on GaP have been much less investigated than InGaAs/GaAs self-assembled (QD). Nevertheless, this system deserves a strong interest, for both a fundamental understanding of excitons in QD based on direct-indirect bandgap semiconductors, as well as for its potential applications to visible light emitters. We have performed magneto-photoluminescence (MPL) on InP/GaP quantum dots (QD) between 4 K and 200 K and up to 20 kBar, where a brutal quenching of the PL occurs. Both the ground and the first excitonic states are followed when both p, B, and T are swept [1].

The magnetic shift of the PL features unveils the nature of the discrete energy levels and gives access to the reduced effective mass and confinement energy. Using Fock-Darwin model which is found to match well with the ground state, we found a reduced excitonic mass $\mu = 0.094 m_0$. This value is found to be slightly larger than expected but agrees well with a biaxial strain induced valence band splitting. Besides, type-I band offset and the origin of the PL emission are further evidenced through the pressure energy shifts. In fact, strong built-in strain induced effects are evidenced in these highly mismatched structures by strongly affecting the pressure coefficient of the $\Gamma - \Gamma$ transition.

\[
\text{(Left) Magnetic evolution of the two-peaks PL feature up to 56 T. (Right) Pressure coefficient of the two lines, exhibiting very low pressure shifts and the enhancement of the confinement energy.}
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Spin susceptibility and polarization field in a dilute 2DEG in (111) silicon.

Anomalous properties of strongly interacting two-dimensional (2D) electron systems have attracted a lot of attention during the last years. While at high electron densities conventional Fermi-liquid behaviour is established, at very low electron densities qualitative deviations from the weakly interacting Fermi-liquid behavior are expected. Recently, the drastic increase of the effective electron mass with decreasing electron density has been observed in strongly correlated 2D electron systems. The strongest many-body effects have been found in bvalley (100)-silicon metal-oxide-semiconductor field-effect transistors (MOSFETs). This has stimulated a new series of experiments in (111)-silicon MOSFETs. Here we have studied low-temperature parallel-field magnetotransport in a 2D electron system in (111) silicon in a wide range of electron densities.

The measurements were done both in dc parallel magnetic fields up to 14T in a dilution cryostat down to 80mK and as well as under high pulsed parallel magnetic fields up to 50T in a He-4 pumped cryostat. We found that the polarization magnetic field $B_p$, obtained by scaling the weak-parallel-field magnetoresistance at different electron densities, tends linearly to zero at a finite electron density. It corresponds to a large increase of the spin susceptibility $\chi \propto gm$ at low densities which is consistent with the increase of the effective mass observed earlier in this electron system. The polarization field $B_{sat}$, determined by resistance saturation, turns out to deviate to lower values compared to $B_p$ at high electron density. This is explained by the parallel-field-induced filling of the upper electron subbands in the fully spin-polarized regime. The subbands splitting in our samples is estimated to be $\Delta = 2$ meV.

**Photoluminescence measurement of Er,O-codoped GaAs under magnetic field up to 60 T.**

Rare earth doped semiconductors show photoluminescence (PL) that originates from the intra-4f-shell transition by the photo excitation of the host semiconductor. Among the various rare earth elements, Er has attracted particular attention because the $^{4}I_{15/2} \rightarrow ^{4}I_{13/2}$ PL transition involving 4f shell of the Er$^{3+}$ ion ($4f^{11}$) occurs at the wavelength of 1.54 µm, which is important for applications. PL measurements have been performed on the magnetic semiconductor GaAs:Er,O under the pulsed magnetic field up to 60 T. We have succeeded in observing the Zeeman effect on the PL.

Our experimental results suggest that the Er center in GaAs:Er,O has a complicated electronic structure under high magnetic field. PL of mode A is attributed to the transition from the $^{4}I_{13/2}$ to the lowest state in $^{4}I_{15/2}$. Furthermore, the experimentally obtained effective $g$-factor is in good agreement with theoretically estimated one based on the crystal field theory.

**Fig. 1** Magnetic Field dependence of PL spectra at 4.2 K.

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Disordered systems

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The activity in the domain of disordered systems consists mainly in the studies of the conduction mechanisms involved in macroscopic samples which conserve its nanometric-scale properties, that is networks of nano-objects obtained by self-organization on a surface. Actually this domain of investigation covers two types of studies: one is devoted to the charge transport mechanisms in self-organized arrays of multi-walled carbon nanotubes (MWCNT) in the presence of high magnetic field, the second type is devoted to the high magnetic field properties of low-dimensional arrays of tin-dioxide nanoclusters.

**Topic 1: Charge transport mechanisms in the arrays of MWCNT**

Unlike the case of individual nano-objects, in arrays the intertube barriers and defects play an essential role in the electrical transport properties. Therefore, different charge transport mechanisms can be observed: metallic conductivity, variable range hopping (VRH), weak localization (WL), fluctuation induced tunneling, and combinations of the various mechanisms.

In thin layers of MWCNT the variation of the resistance as a function of temperature is negative in the whole investigated temperature range [4-300 K]. In the range [4-60 K], the resistance follows a Mott’s law of two dimensional (2D) VRH: \( R = R_0 \exp(T/T_0)^{1/3} \). Fig.1 shows the relative magnetoresistance \( \Delta R/R_0 \) in the temperature range in which the VRH is observed.

The minimum position of negative MR shifts to higher fields as the temperature rises. Both low-field NMR due to changing of phase between alternate hopping paths enclosing a magnetic flux (quantum interferences) and high-field positive MR (PMR) due to electronic orbit shrinkage are predicted for systems with hopping conductivity mechanism; i.e. \( \text{MR} = \text{NMR} + \text{PMR} \). In this model, the amplitude of the NMR declines as the temperature increases in the temperature range in which VRH can be responsible of the charge transport mechanism. From the other side, negative MR is inherent for the systems where conductivity can be described in the frame of WL theory. Therefore we made assumption that MR data are the sum of the positive and negative contribution due to MR effects in the VRH and WL regimes, respectively. We found that high-field positive part of MR can be approximated in frame of Kamimura model for spin-dependent VRH conductivity. This study demonstrates the role of the surface defects of the NT's by its spins.

**Figure 1 From left to right:** Relative magnetoresistance in the temperature range in which 2D VRH is observed, Kamimura’s model for PMR (spin dependent VRH) and NMR obtained by subtraction of the calculated PMR from the experimental results.
Topic 2: Two dimensional weak localization in polycrystalline SnO$_2$ films

The phenomenon of quantum interference in disordered conductors is well known and its effects on the electrical conductance are widely used to determine the inelastic scattering time of charge carriers and, thus, the mechanisms of inelastic scattering. Because of the prominent effects of weak localization in 2D systems, the last became an object of intensive studies. But, the reduced dimensionality and the presence of disorder lead not only to enhancement of interference effects, but also to the necessity to take into account the electron-electron interaction. It appeared that such characteristics as density of states, temperature and magnetic field dependences of electrical conductance could be described only if one takes into account the effects of electron-electron interaction in a disordered low-dimensional system [Altschuler B.L., Aronov A.G. «Electron-electron interaction in disordered conductors» in Modern problems in condensed matter sciences Vol 10 Efros A.L. & Pollak M. editors, North Holland 1985]. Moreover, the dephasing mechanisms in weak localization are strongly related to interaction effects: inelastic electron-phonon scattering, quasi-elastic electron-electron scattering with small energy transfer. The interplay of interference and interaction effects remains a puzzling problem that is still far from being solved [Pagnosin et al. Phys Rev B 78, 115311 (2008)].

In our SnO$_2$ polycrystalline films the low transverse magnetic field dependencies of conductance is positive and can be described in the frame of a 2D weak localization model, the phase breaking mechanism being electron-electron scattering with small energy transfer (not shown here).

In Fig. 2, the dependencies of magnetoconductance on the normalized magnetic field $B/B_\phi$, measured on the same sample, are presented in the full range of applied magnetic field up to 50 Tesla. Here, $B_\phi (T)$ is the value of magnetic field at which the flux of magnetic field through an area enclosed by the electron's paths becomes equal to the flux quantum $\hbar/2e$. From both the inset, where the curves are presented in linear coordinates, and from the main part of Fig. 2, one can see that at high fields (starting from 8 Tesla) the curves exhibit different behaviour and do not overlap any more. We thus suggest the necessity to take into account of the anisotropy of scattering potentials in order to describe the observed results. Different particularities of single scattering events may influence (manifest) at different temperatures in this high field region.

The experimental curves in Fig. 4 resemble those derived in [Zduniak A. et al., Phys Rev B 56, 1996 (1997) & Germanenko A.V., Minkov G.M., Sherstobitov A.A., Rut O.E. Phys Rev B 73, 233301 (2006)] where the weak localization model is extended beyond the diffusion limit. In the frame of this model, only small closed loops are believed to give contribution to the effect of weak localization at such high magnetic fields, the minimum number of collisions in each loop being 3. One can suppose that relative to electron-electron interaction effects, these triangles should be easier to study than any complicated electron's path with large number of collision. As in many materials the dephasing in the weak localization effect was found to be due to electron-electron interactions, the study of these materials in high magnetic fields should provide important information about these interactions (single electron's wave function interference is destroyed, so the interaction effects should give the main contribution to magnetoconductance).

![Fig. 2](image)

**Fig. 2** The magnetic field dependencies of magnetoconductance as a function of normalized magnetic field. Inset shows field dependencies of magnetoresistance in linear coordinates measured on the same sample.
An important trend in modern sciences is the investigation of individually addressed objects with properties determined by a nano-sized group of atoms or molecules. There is an increasing demand from the high magnetic field community to extend single-object measurements up to the highest magnetic fields, to benefit from the powerful combination of nanosciences and high fields. Indeed, the magnetic length, defined by $l_B = \sqrt{\frac{\hbar}{eB}}$ (3 nm at 74T), becomes comparable to typical dimensions of nano-objects, leading to significant changes in their energy spectrum: the magnetic field drastically lifts the spin and orbital motions of electrons allowing advanced magneto-spectroscopy experiments.

Our activities in nanophysics are focused on (i) (magneto)-transport properties of individually addressed carbon nanotubes and exfoliated graphene and graphene nano-ribbons, and (ii) NIR magneto-optical properties of carbon nanotubes in solution and epitaxial graphene. Note that individual nano-scale samples are usually extremely delicate to handle and can easily be damaged by the aggressive electrical environment inherent to the control of the capacitors bank. Specific procedures, shielding and filters are used to safely measure the 60T magneto-conductance of individual carbon nanotubes as well as graphene.

Carbon nanotube based devices under magnetic field
Carbon nanotubes have already demonstrated their wide potential in nanoelectronics and optoelectronics even if their large scale integration raises cumbersome issues. The unique electronic structure of a graphene sheet combined to a tubular confinement leads to remarkable one dimensional charge transport properties in carbon nanotubes. In a recent past, both theoretical and experimental evidences unveiled the large energy dependence of the transport regime in individual CNT (from ballistic to diffusive), by playing with the electrochemical potential level. In our study, we demonstrate that an applied magnetic field, along with a control of the electrostatic doping, drastically modifies the electronic band structure of a carbon nanotube based transistor [G. Fedorov & al., Phys. Rev. Lett. 94, 066801(2005)]. We give evidence of unconventional quantum phenomena like the giant Aharonov-Bohm modulation of the electronic density of states [B. Lassagne & al. Phys. Rev. Lett 98, 176802 (2007)] or the onset of propagative Landau states in the high magnetic field regime [B. Raquet & al. Phys. Rev. Lett. 101, 046803 (2008)].

In a parallel configuration (B applied parallel to the tube axis), a quantum flux threading the tube induces a giant Aharonov-Bohm conductance modulation mediated Schottky barriers which profile is magnetic field dependent (Fig.1). Recently, we explore the multi-period quantum flux modulation of the conductance in heavily doped and ballistic MWCNTs controlled by an efficient back-gate voltage [S. Nanot & al, C. R. Physique, in press (2009)]. In the perpendicular configuration, experiencing the Landau states by Hall measurements remains an unsolved technological challenge. By playing with a carbon nanotube based electronic Fabry-Perot resonator, we have recently demonstrated that the electronic transmission of the device can be modified by a moderate transverse magnetic field (35T) – Fig.2. The field dependence of the resonant states of the cavity reveals the onset of the first landau state at zero energy. New experiments under 60T give experimental evidence of propagative Landau states in both semiconducting and metallic CNTs. The two-probe conductance in the high magnetic regime evolves to a unique conducting state, independently of the electrostatic doping. This remarkable phenomenon is assigned to the onset of propagative electronic states in high fields along with the closing of the energy gap for semiconducting tubes.
Complementary studies, less central, have been also developed on the electronic properties of individually addressed DWCNT and MWCNTs.

- **Electronic noise measurements on DWCNTs.** We demonstrate that CNTs are low noise conductors once the structural quality, the gaseous environment and the contact transparency are under control [B. Lassagne & al., New J. Phys. 8(3) 2006].
- **Raman Spectroscopy of individual MWCNT versus the electrostatic doping.** The G-band, constituted of 4 peaks, is modified by shifting of the Fermi energy. We infer the efficiency of the electrostatic coupling from shell to shell in the multi-walled structure [S. Nanot, submitted].
- **Electronic transport under high hydrostatic pressure on an individual DWCNT based FET.** We study the conductance versus energy under pressure, up to 10kbar [S. Nanot & al, unpublished].
- **Preparation, characterization and electronic properties of α-Fe nanowires located inside Double Wall Carbon Nanotubes.** Capillary effect was used to fill DWCNTs with iron. We observe the presence of α-Fe nanowires inside DWCNTs, ferromagnetic at 300K [J. Jorge & al, Chem. Phys. Lett. 457, 347 (2008)].

**Electronic properties of graphene and few layers graphene**

Research exploring the physics of low-dimensional nano-objects is at the heart of a thriving world-wide effort, attempting to investigate how size effects, atomic arrangements and interactions can produce new and unexpected physical phenomena. Beyond its fundamental interest, the investigation of 2D or quasi-2D carbon-based materials (i.e. graphene and few-layer graphite) may end up with various promising applications. For instance, their integration into electronic circuits may provide a genuine alternative to overcome the fundamental limitations of conventional silicon-based technology. Nevertheless, this requires first a thorough understanding of these systems, and this is where fundamental research comes into play. For this purpose, magneto-transport experiments have been performed on few layer graphite and graphene at low temperature and under high...
magnetic field. In such system, the charge carrier density can be continuously tuned through the application of a back gate voltage, allowing fine investigations over a broad range of experimental conditions.

In few layer graphite, magneto-transport experiments have been performed to probe the co-existence of two types of charge carriers, namely massive and Dirac fermions, which dynamics reveal itself into different signatures in the Quantum Hall Effect. By mean of changing the carrier concentration and upon approaching the charge neutrality point (i.e. compensation of hole-like and electron-like charge carriers), the system tends to reproduce the peculiar behaviour of graphene, for which massless Dirac fermions govern its electronic properties [W. Escoffier & al, submitted].

Figure 3 a) Spectral intensity of oscillations of $\Delta R_{xx}(B)$ for selected gate voltages. Notice peaks labeled $\alpha$ and $\beta$, originating from Dirac and normal holes respectively. b) and c) Fan chart constructed from peak $\alpha$ and $\beta$ respectively for selected gate voltages ; the linear extrapolation intercepts the x-axis to index 0 and -1/2. d) frequency shift for peaks $\alpha$ and $\beta$ versus gate voltage, a linear fit is used to compute the charge carrier concentration and gate efficiency for massive and Dirac holes.

The electronic properties of graphene have been investigated in the Quantum Hall regime. In the limit of very low filling factors (low carrier density and very high magnetic field), a splitting of the spin and/or valley degeneracy is expected for this system. Up to now, very few experiments have demonstrated these predictions which remain a matter of debate. Actually, the main experimental difficulties lie in the fabrication of high quality graphene samples (high mobility) and the production of high magnetic fields to reach low filling factors. Recently, pulsed-field magneto-transport measurements with graphene have been performed in Toulouse and showed very peculiar features for the $n=0$ Landau Level at high magnetic field [J-M Poumirol, in preparation]. Even if the sample’s mobility was still too low to fully investigate the above-mentioned predictions, this experiment has demonstrated the feasibility of such an experimental method, while new samples with improved quality are being prepared.

Figure 4 Longitudinal resistance $R_{xx}$ and Hall resistance $R_{xy}$ simultaneously recorded as a function of magnetic field at $T=1.6K$ and $V_g=0V$. The charge carrier density is estimated to $n=4.1x10^{12} \text{ cm}^{-2}$ from the low field Hall resistance. Note that we find a slightly different carrier density when analysing the periodic structures of $R_{xx}(1/B)$, indicating local charge carrier inhomogeneities across the measuring electrodes. Insert: longitudinal resistance as a function of back gate voltage at $T=1.6K$: the charge neutrality point is located at $V_g=+52$. The sample’s mobility is estimated to about 1500 cm$^2$/V.s
Spectroscopy of carbon nanostructure in high magnetic fields

Using an InGaAs detector array we investigated the high-field optical and electronic properties of carbon nanotubes. For the photoluminescence (PL) experiments we used a titanium-sapphire Laser and various laser diodes. With this method we were able to show the effects of magnetic field on the electronic properties of carbon nanotubes, i.e. adding an Aharonov-Bohm phase on the band structure and modifying the PL spectra in fields up to 77 T [1]. The high-field PL spectroscopy of carbon nanotubes also revealed an increase in intensity of the PL peaks, the so-called magnetic brightening [2,3]. By using highly aligned films of carbon nanotubes, we have demonstrated that the rather weak brightening observed under the influence of a perpendicular magnetic field reflects only the residual disorder in the film. The brightening thus relates exclusively to the magnetic field component parallel to the tube axis [4]. We also were able to determine quantitatively the zero field splitting of the two lowest exciton states, responsible for the magnetic field induced brightening [4]. This has been achieved by fitting a theoretical model to the available high-field data and extrapolating the exciton energies to B=0.

![Fig. 5: PL peak evolution for highly aligned samples perpendicular and parallel to the magnetic field. The brightening for the field perpendicular to the sample reflects only the residual disorder in the film [4].](image)

The band structure of graphene yields to unconventional effects such as electrons behaving like massless Dirac fermions. Thus the Landau level structure is different from other 2-D semiconductors. At high fields and high energies theoretical models predict an asymmetry between electrons and holes. The absorption of circular polarized light should reveal it. The analysis of our NIR measurements of this effect is still in progress.


Dynamic alignment of single walled carbon nanotubes in aqueous suspensions

The main purpose of this work is to investigate the dynamic properties of carbon nanotubes in different aqueous suspensions. Due to different magnetic susceptibilities, for metallic and semiconducting tubes along the tube long axis and perpendicular to it, carbon nanotubes will align parallel to an external magnetic field.

To quantify this effect we analyse the field induced linear dichroism : a valuable method to detect magnetic anisotropies and to quantify it. A theoretical model based on the Smoluchovski equation for rigid rods were developed in order to determine quantitatively other effects governing the alignment such as temperature, viscosity, bundling or length distribution of nanotubes. [1]

![Fig. 6 Comparison between calculated (black) and measured (purple) linear dichroism (LD). The LD is following the magnetic pulse (green) [1].](image)

[1] Shaver et al, ACS nano 3 (2009), 1
Magneto optics

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Magnetic Birefringence of Vacuum (BMV)

1. Introduction

The activity of our group is devoted to perform experimental test of fundamental interest using high magnetic fields and optical techniques.

Since 2001 we are pushing forward collaboration with LCAR of Toulouse and LMA of Lyon to measure the vacuum magnetic birefringence (BMV Project), a QED prediction. From 2006 to 2008 we have also performed a measurement at LULI of the Ecole Polytechnique to search for photon oscillations into massive particles (Boson project) always in collaboration with the LNCMI of Toulouse. Photon oscillations into massive particle can be at the origin of effects mimicking an optical activity of vacuum, and therefore they are strictly related with the search for the Cotton-Mouton effect of vacuum.

2. BMV project

The BMV project goal is to measure the birefringence induced in vacuum by an external magnetic field (Birefringence Magnétique de Vide), a QED prediction which dates from 1935 and not yet experimentally proved. This magnetic birefringence, also known as Cotton-Mouton effect, has been measured in gases since the sixties and it exists in any medium.

The BMV project is a collaboration between the LNCMI of Toulouse and the LCAR. Our experiment is now fully operational in a clean experimental room hosted by the LNCMI and we have performed our first measurements. We will describe them in the following.

Our experimental setup is described in ref [1]. A Nd-YAG laser ($\lambda$=1064 nm) is locked on a 2.2 m optical resonant Fabry-Perot cavity using the Pound-Drever-Hall technique. The light is polarized by a high quality polarizer and the transverse magnetic field is delivered by two especially designed coils (Xcoil). To increase as much as possible the effect to be measured we need a very high finesse cavity. The polarization of the light transmitted by the Fabry-Perot cavity is analyzed by a second high quality polarizer.

As far as the optical cavity is concerned, we used different sets of mirrors in order to test more and more efficient configurations. Mirrors are characterised by their reflectivity from which we can deduce the nominal finesse of the cavity. We have locked our laser to cavities of finesse about 5 000 and about 130 000. We have also at our disposal mirrors built by the LMA of Lyon with which we collaborate since the beginning of the project in 2001. The finesse of the cavity realized using such mirrors is expected to be about 650 000.

The experimental finesse is measured by measuring the lifetime of photons in the cavity. We shut down the laser and we measure the intensity of transmitted light versus time. The transmitted light intensity decays exponentially. Once light lifetime in the cavity is known, finesse can be calculated. We have currently reached a cavity finesse of 131 000 (decay time of 306 $\mu$s). The full width at maximum of the cavity resonance line has a
typical FWHM of 500 Hz, which is one the smallest value ever reached in the optical region.

The second important point is the transverse magnetic field. We are using two identical coils developed especially for this experiment (ref [2]). Because the Cotton Mouton effect is proportional to the square of the magnetic field the pertinent factor for evaluating the coil performance is the product \( B^2 \times L_0 \) where \( L_0 \) is the length of the magnetic field region. Each coil can produce 10 T at the center which gives 30 T²m for each coil.

In order to test our apparatus, we measured the Cotton Mouton effect in nitrogen in July 2008. Our result is in a very good agreement with others existing data. Moreover, this is the first Cotton-Mouton measurement ever performed with pulsed coils. After this probing test, we have measured the smallest Cotton Mouton effect known in gases, the one given by helium gas. This measurement is quite difficult and only three measurements are published. Our preliminary measurements at different pressures give a birefringence corresponding to an anisotropy of the index of reflection at 1 T field and a gas pressure of 1 atm \( \Delta n_u = (2.1\pm0.4)\times10^{-16} \). The predicted value by \textit{ab initio} computational methods is \( \Delta n_u = 2.37\times10^{-16} \) (ref [3]).

In conclusion, 2008 has been the year of our first birefringence measurement. Our results are all in agreement with previous ones, and with theoretical ones. Our sensitivity in \( \Delta n_u \) is at the moment of the order of \( 10^{-17} \). In 2009 and 2010 we will test the limits of our present set up.

Major improvements are further needed to reach the Cotton Mouton effect of vacuum, such as the upgrade of the mechanical rotation and tip tilt of polarizers and of the cavity mirrors, the upgrade of the cavity finesse, the upgrade of the vacuum system and the upgrade of the magnetic field. A new coil has been designed with new wires, bigger size, in order to reach 25 T at the centre and a \( B^2L \) of 190 T²m in usual working conditions. Our goal is to put at least three of these coils on the experiment. A new bank of capacitors to supply the current for such coils is also needed.

To enter in this new phase, the experimental set up has to be accurately reshaped.

3. Boson project

In 2006, the Italian collaboration PVLAS announced the unexpected observation of a magnetic dichroism in vacuum, which they suggested might be due to photoregeneration of axionlike particle [4]. Identical energy in a transverse magnetic field, then blocking the photon beam with a wall. The axionlike particles hardly interact with the wall and are converted back to photons in a second magnet. Finally, the regenerated photons are counted with an appropriate detector. Such an experiment was conducted in the 1990s by the BFRT Collaboration without detecting any regenerated photon signal, which led to limits on the axion parameters [7]. Mainly motivated by the PVLAS astonishing results, several “light shining
The area below our curve is excluded. Our limits are compared to those from other experiments.. We have found that the axionlike particle two photons inverse coupling constant $M$ is $> 9 \times 10^5$ GeV for low axion masses. Our measurements also improved the existing limits on the parameters of a low mass hidden-sector boson usually dubbed "paraphoton" because of its similarity with the usual photon [9].

Experimentally, the main difficulty lies in detection. The expected regeneration rate is indeed very weak—less than $10^{-20}$—so that optical shielding has to be perfect and the detector background very low. We have found an original and efficient way to solve the detection problem as both the laser and the magnetic field were pulsed, as well as our detector. Contrary to other similar experiments requiring long integration times, we were not limited by the background of the detector as the photons were concentrated in very intense and short laser pulses. In collaboration with the LULI in Palaiseau and the LNCMI (Laboratoire National des Champs Magnétiques Intenses) in Toulouse, we rapidly set-up the experiment in the LULI2000 laser hall in Palaiseau, so that we were the first to present, in June 2007, the results of our pulsed "light shining through a wall" experiment, definitively invalidating the axion interpretation of the original PVLAS optical measurements with a confidence level larger than 99.9% [8]. Our latest results, obtained after 3 more weeks of data acquisition in September 2007 and January 2008, are presented in Figure 1: $3\sigma$ limits for the axion-like particle - two photon inverse coupling constant $M$, as a function of the axion-like particle mass $m_a$ obtained from our null result.

Figure 1: $3\sigma$ limits for the axion-like particle - two photon inverse coupling constant $M$, as a function of the axion-like particle mass $m_a$ obtained from our null result. The area below our curve is excluded. Our limits are compared to those from other experiments.

The area below our curve is excluded. Our limits are compared to those from other experiments.


**X-ray and neutron scattering**

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**High magnetic field synchrotron X-ray powder diffraction**

A mobile pulsed magnetic field installation has been developed at the LNCMI-Toulouse (LNCMI-T) to combine pulsed magnetic fields with an intense X-ray source. With this setup, high field X-ray powder diffraction experiments have been performed for the first time at the European Synchrotron Radiation Facility (ESRF, Grenoble) with magnetic fields up to 30 T [1].

**Direct observation of the high magnetic field effect on the Jahn-Teller state in TbVO$_4$**

During our pilot experiments, we have directly measured the effect that a 30 T magnetic field has on the Jahn-Teller (JT) state in terbium orthovanadate TbVO$_4$. This compound is a textbook example of a material exhibiting the cooperative JT effect driven by phonon-mediated interactions between the terbium quadrupole moments [2]. At high temperatures, it crystallizes in the tetragonal zircon structure whereas on lowering the temperature to less than 33 K it undergoes a cooperative JT transition and the crystal spontaneously distorts along the [110] direction, lowering the symmetry to orthorhombic. The balance between TbVO$_4$’s magnetic and quadrupolar effects can be tuned by varying the strength of an applied field. The effect of large external magnetic field on TbVO$_4$ has only recently been studied [3]. It was predicted that the JT distortion would be suppressed when fields more than 29 T were applied along the c-axis of the sample.

The data shown on figure 1 were collected on the DUBBLE CRG beamline (BM26B) by accumulating about 45 magnetic field pulses per powder diffraction spectrum. For each field pulse a mechanical shutter exposed the image plate detector for 4.9 ms centered around the maximum field.

The JT transition manifests itself as a splitting of some of the powder lines in the spectrum due to the distortion of the crystal lattice. Within the photon energy range studied, the (311)/(131) and (202)/(022) pairs of reflections are sensitive to the JT distortion (fig. 1). Spectra taken at different fields strengths (15 and 30 T) showed a reduction of the splitting below the JT transition (fig. 1, left) and the appearance of splitting above the transition (fig. 1, right), thus providing evidence for the modification of the JT distortions of TbVO$_4$ by magnetic fields.

![Fig. 1: Comparison between calculated and measured spectra for various fields (0-30T) and for temperatures 7.5 K (left) and 39 K (right). A T = 39 K and 30 T, the dotted curve (in red) corresponds to the calculations including the magnetocaloric effect, and the green line to the calculations with the magnetoelastic constant reduced by 25%.](image-url)
In order to quantitatively describe the effect outlined above we have performed comprehensive mean field calculations of the magnetoelastic distortion of TbVO$_4$ as a function of the strength and direction of the externally applied magnetic field [4]. The applied magnetic field was found to influence both the magnitude of the order parameter, as observed in the splitting of the (311)/(131) and (202)/(022) pairs of Bragg peaks, and the relative domain populations, reflected in the intensity ratio between the partners of a pair. Although the observed splitting followed the predicted spectra, the degree of splitting was lower than expected. Various theories to explain the quantitative difference have been proposed, one being sample heating due to the magnetocaloric effect.


**Magnetic field induced structural transition in the electron-doped manganite Ca$_{0.8}$Sm$_{0.16}$Nd$_{0.04}$MnO$_3$**

The physical properties of manganite compounds, $\text{R}_{1-x}\text{D}_x\text{MnO}_3$ (R = rare-earth La, Nd, Sm; D = alkaline-earth metals Sr, Ca, Ba,...), such as colossal magnetoresistance (CMR) effect, charge ordering, orbital ordering and phase separation have been extensively studied during the last ten years. One of the main results of manganite investigation is the discovery of tendencies toward inhomogeneous states, both in experiments and simulation models [1]. The colossal magnetoresistance effect appears to be closely linked to these mixed phase tendencies and to the coexistence of a strong competition between the ferromagnetic (FM) metallic state and the insulating antiferromagnetic (AF) charge and orbital orders.

In the present work, we have been interested to investigate the structural and magnetic phase separation aspects in the electron-doped manganite Ca$_{0.8}$Sm$_{0.16}$Nd$_{0.04}$MnO$_3$ [2] using our 30 T pulsed field synchrotron X-ray powder diffraction set-up, combined with resistivity and magnetization measurements. X-ray experiments were performed on ID20 at the ESRF whereas the resistivity and magnetization measurements were carried out at the Institute for Nanoscale Physics and Chemistry (INPAC) in Leuven. Upon lowering the temperature through 113 K, Ca$_{0.8}$Sm$_{0.16}$Nd$_{0.04}$MnO$_3$ exhibits a first order structural and magnetic transition, associated with a metal-insulator transition. Below 125 K, both low field magnetization data and zero field synchrotron powder diffraction showed the coexistence and competition of two magnetic and structural phases: a major AF monoclinic state and a minor FM orthorhombic one. Furthermore, high field X-ray and magnetization measurements at low temperature clearly revealed a field induced structural change (from a monoclinic to an orthorhombic phase, fig. 2 and 3) associated with a metamagnetic transition.

**Fig. 2:** Synchrotron X-ray powder diffraction patterns of Ca$_{0.8}$Sm$_{0.16}$Nd$_{0.04}$MnO$_3$ at $T = 7$ K obtained for different magnetic fields.

**Fig. 3:** Low temperature field dependence of the monoclinic phase fraction.

X-ray absorption spectroscopy (XAS) and magnetic circular dichroism (XMCD) in pulsed magnetic field

By coupling the mobile pulsed magnetic field device developed at the LNCMI-T to the fast acquisition possibilities of the ESRF energy-dispersive XAS beamline ID24, the feasibility of measuring X-ray magnetic circular dichroism (XMCD) in pulsed magnetic fields up to 30 T using long pulses has been investigated. Our first high field XAS and XMCD experiments on Gd foil (December 2006) and URhGe single crystal (February 2007) showed that the feasibility and the quality of the measurement strongly depend on the mechanical stability of the experimental setup. This high sensitivity to mechanical stability derives from the specific features of the beamline ID24, more particularly the use of a polychromatic dispersive light that is focused into a very small spot of 5 microns horizontally. In these geometrical constraints, the acquisition of absorption spectra under in-situ pulsed magnetic field is challenging because of potential vibrations and motions induced by the production of the high field pulse, therefore requires excellent sample homogeneity and position stability within the beam focal spot.

To reduce the observed vibrations effects in the setup, modifications of the cryostat design and mechanical improvements are under study. The vibrations effects have been already drastically reduced form the initial configuration (where it was exceeding 1mm) by consolidating cryostat internal tube with the chamber holding the coil. With this new configuration, XMCD measurements have been successfully performed on a GdSi$_{1.8}$Ge$_{2.2}$ powder sample. Data analysis are still under progress.

**High magnetic field neutron diffraction**

The magnetic properties of geometrically frustrated systems are among the hot topics in condensed matter physics. In such systems, a variety of unconventional phases appears due to a frustrated spin interaction that couples with lattice, orbital and charge degrees of freedom. We can tune the balance between them using strong magnetic field through the Zeeman interaction of spins, and various novel magnetic phases have been found in magnetic fields exceeding 20 T. Neutron scattering is a powerful and valuable technique to directly determine the space- and time-correlation of magnetic moments, and to have a deeper insight into the origin of the novel phases in high fields. So far, however, sufficiently high magnetic fields have not been accessible for neutron scattering studies. In view of the successful X-ray scattering experiments at the ESRF using a mobile pulsed field installation, capable of generating fields in excess of 30 T, we have decided to attempt a neutron scattering experiment using this installation, at the Institut Laue Langevin (ILL, Grenoble) in collaboration with Prof. Nojiri’s group from Sendai (IMR, Tohoku University, Japan).

**Neutron diffraction study of the frustrated antiferromagnet TbB$_4$[6]**

This new technique was used to investigate the magnetic structure of the geometrically frustrated system TbB$_4$, in magnetic fields up to 30 T. The experiment was carried out on the high-flux, low background triple-axis spectrometer IN22, with a neutron wavelength of 1.53 Å, using a transportable pulsed magnet system built up by Prof. Nojiri’s group and the mobile capacitor bank developed at the LNCMI-T.

At room temperature, TbB$_4$ crystallizes in the tetragonal structure $P4/nmbm$. The network of magnetic Tb ions consists of squares and triangles whose configuration within the $c$-plane is characterized by orthogonal dimers topologically equivalent to the two dimensional Shasya-Sutherland lattice (SSL) [1]. In zero field, TbB$_4$ exhibits two successive antiferromagnetic transitions at $T_{N1} = 44$ K and $T_{N2} = 24$ K [2]. The magnetic structure at $B = 0$ T is a XY-type noncollinear structure [3]. At low temperature and high fields (between 16 and 30 T), multi-step magnetization plateaus appear when the magnetic field is perpendicular to the magnetic easy plane (fig. 4) [4]. This behaviour is unusual since successive metamagnetic transitions in rare earth intermetallics are generally expected when the field is parallel to the Ising easy axis [5]. Therefore the determination of magnetic structure of TbB$_4$ in high magnetic field is essential to understand this phenomenon.

Within the constraints of the pulsed magnet system developed for neutron scattering, we have succeeded in measuring the field dependences of four Bragg reflections ($(100)$, $(200)$, $(110)$ and $(220)$) up to 30 T. The neutron counts and magnetic fields were measured simultaneously using a time analysing system so that the field dependence of Bragg peaks at fixed diffraction angle can be monitored and recorded as a function of time. The accumulation of 100-200 magnetic field pulses for each reflection was required to acquire statistically relevant data. As an example, the field dependence of the intensity of the $(100)$ peak is reported on figure 5. The relative intensity against the zero field intensity $I/I_0$ and the relative magnetization $M/M_S$ are reported in the figure. Stepwise changes which can be related to the magnetization process are clearly observed in the intensity of the magnetic $(100)$ reflection.

From these experimental results, different magnetic models have been calculated. They indicate a much weaker AF correlation in TbB$_4$ than the expected one in a conventional antiferromagnet and also suggest the presence of significant anisotropic interactions. A model introducing a biquadratic interaction term which stabilizes an
orthogonal configuration of magnetic moments was proposed to explain the multiple magnetization plateaus. Further investigations of the magnetic scattering diagram in high fields would be needed to confirm this model. Nevertheless, these results clearly demonstrate the large potential of pulsed magnetic fields for neutron diffraction experiments.

Fig. 4: Magnetization of TbB₄ at 4.2 K. Solid line: field direction is tilted 5 degrees from the c-axis, which corresponds to this study. The indicated fraction denotes the ratio \( M/M_S \). Inset: magnetic structure at \( B = 0 \) T for \( T_{N2} < T < T_{N1} \) (solid arrows) and \( T < T_{N2} \) (dashed arrows).

Fig. 5: Field dependence of the peak top intensity of (100) reflection at \( T = 4.1 \) K for ascending (open circles) and descending (closed circles) field. The dashed lines are guide for eye.


High field neutron diffraction study of the spin Jahn-Teller compound CdCr₂O₄

More recently, this emerging technique was used to examine the high magnetic field phase of the spin Jahn-Teller compound CdCr₂O₄. The latter is a highly frustrated spinel antiferromagnet consisted of frustrated tetrahedra. An unusual half-magnetization plateau was found above 28 T, independently of the field directions [1]. This phenomenon was attributed to the spin Jahn-Teller effect where a lattice distortion takes place to lift the magnetic frustration. With our pulsed field neutron diffraction experiment, we have succeeded in following the appearance at high field of magnetic Bragg reflections, which permits to distinguish between two possible magnetic structures at the half plateau.

Fig. 6: Field dependence of the magnetic Bragg reflection (1 -1 0) at \( T = 2.2 \) K for ascending (red circles) and descending (blue circles) field.

Annex 1 : ‘Hygiene et securité’

List of safety incidents at the LNCMP and the precautions taken.
25/06/2005: Road accident between home and work involving two days sick leave: Cycle accident, elbow bruised, damage on corrective glasses.
23/11/2006: Work accident involving one day off: Flesh wound on right thumb with haematoma, due to a wrong move with the dismantling tool of the milling machine. Measure taken: Impose the use of safety gloves.
08/02/2008: Work accident involving one day off; superficial burn on the right hand caused by the manipulation of a hot product coming out of the oven. Measures taken: Impose the use of safety gloves.
20/05/2008: Accident in workplace without sick leave: Wrong manipulation resulting in projection of irritating liquid into right eye. Measure taken: Impose the use of safety gloves and goggles.

Identification, analysis and countermeasures of specific risks in the laboratory
The laboratory has performed a professional risk assessment, available from the security officer (‘ACMO’). In summary, the mains specific risks are related to the presence of high voltage, the possibility of projectiles when a magnet fails and the presence of large quantities of liquid nitrogen:
*
**Electrical risk**: There are now no longer any galvanic connections between the high voltage circuit of the magnets and the command posts, but only optical fibres. The liquid nitrogen supply line has also been galvanically decoupled inside the magnet boxes.
**Ventilation**: Ventilation in the main experimental hall has been improved and oxygen detectors are installed.
**Projectiles**: Magnets are operated in closed boxes in which no personnel is allowed during a magnet shot. However the increasing energy of the magnets causes concern about the capabilities of the boxes to stop all projectiles in the case of a serious coil failure. Within the planned upgrade of the laboratory, new, more strongly reinforced magnet boxes are foreseen that will eliminate this concern.

Security risks that are specific to any laboratory are:
**Fire protection**: The ACMO organizes every year evacuation exercises, oven checks, hood checks and warning system checks. This year, a training “handling of fire extinguishers” had been done for all the staff. Staff doing welding jobs is equipped with aprons, gloves and safety masks.

**Handling risk**: lifting devices are controlled every year by APAVE, and are used only by well trained staff.

Organisation of the security structures of the laboratory
For assuring the safety rules, the director of the LNCMI is assisted by an ACMO (Agent in Charge of hygiene and safety). (The number of employees on the Toulouse site isn’t large enough to justify a committee hygiene and safety.) The ACMO is in contact with the hygiene and safety engineers of the CNRS, the UPS and the INSA. The CNRS doctor is regularly consulted for example concerning the arrangements of work stations. The ACMO of the LNCMP drafts the ‘document unique’, executes or organizes the security checks and the periodic controls. She is in charge of the safety registers, safety equipments, individual protection and equipment, organizes the first aids, and informs the new arrivals.

Arrangements for staff security training and in particular of new arrivals
Every year, an annual training plan is established by our training correspondent in the laboratory, according to the laboratory’s needs and the staff requirements. This plan is discussed with the laboratory council which defines the priorities. These last years, the accent was put on safety trainings and several training sessions were implemented:

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<th>High voltage safety</th>
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<td>Manipulation of fire extinguishers</td>
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<td>Competent person for radioprotection</td>
<td>Chemical risks</td>
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<td>Waste treatment</td>
<td>Evacuation guides</td>
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When a new collaborator arrives (permanent, PhD student, trainee), he is invited for a visit of the laboratory by the person in charge, who will indicate the specific laboratory risks and the means of protection, and who will inform him off the procedures and laboratory rules. A twenty page security manual is given to complete the visit. This manual summarizes risks, dangers and the different means of prevention.
The necessary SPUR (Individual Equipment and protection: coats, overalls, safety footwear, glasses etc.) are supplied to the staff by the ACMO (for example to work in workshops or specific laboratory rooms)
Annex 2 Formation

Les formations suivies, pendant la période 2005-2009, par les personnels du LNCMP étaient en partie issues d’offres de formation transversales en provenance des 3 tutelles. L’accent a été mis sur le suivi de cours d’anglais pour les personnels ITA amenés à interagir avec les visiteurs étrangers et sur l’initiation des chercheurs à l’utilisation des machines-outils (dans le cadre des PFU 2005/2006/2009, 3 sessions de formation ont été mises en œuvre dans nos locaux). Des formations techniques dans des domaines spécifiques permettant l’acquisition de connaissances et de compétences nouvelles dans le but d’accompagner de façon optimale les activités de recherche ont été mises en œuvre soit de façon individuelle (conception et caractérisation de circuit hyperfréquences, techniques de microbiologie, langage de programmation, logiciel de CAO/DAO…), soit de façon collective (stage d’électronique radiofréquence, stage de prise en main pour la fraiseuse à commande numérique suivi d’une formation au logiciel de programmation ESPRIT, stage d’instrumentation LABVIEW). L’accompagnement des nouveaux entrants s’effectue par des formations spécifiques à leur activité dans le laboratoire (XLab et Labintel pour le secrétariat et formation Web pour le gestionnaire réseaux). Des formations à l’encadrement ont aussi été mises en œuvre (management, conduite de projets…). De plus, des formations pour améliorer la sécurité au laboratoire ont été suivies par un grand nombre des membres du LNCMP (SST, conduite des ponts roulants, manipulation des extincteurs). D’autre part, plusieurs membres du laboratoire appartiennent aux réseaux de métiers (mécaniciens, électroniciens, opticiens, informaticiens) animés par le CNRS.

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<td>2007</td>
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<td>37 (of which 32 ITA)</td>
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<td>2008</td>
<td>18</td>
<td>28 (of which 18 ITA)</td>
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<td>01/01/2009 - 31/05/2009</td>
<td>7</td>
<td>56 (of which 38 ITA)</td>
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<td>Total</td>
<td>77</td>
<td>191 (of which 137 ITA)</td>
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Annex 3  Enseignement, vulgarisation, organisation de colloques

The LNCMP staff has six ‘enseignants chercheurs’ who teach at UPS and INSA. One of them is also director of the physics department at INSA, another director of the ‘unité formation & recherche’ Physics, Chemistry and Automation at the UPS. Two of the CNRS ‘chargé de recherche’ teach voluntarily at the ISAE.

The LNCMP organized each year the ‘journée portes ouvertes’ in the framework of the ‘Fete de la Science’, and also on other occasions provides tours for interested students and teachers.

During the last four years, the LNCMP has organised three international meetings;
- Narrow gap semiconductors 12 (July 2005, Toulouse)
- Workshop on Synchrotron Applications in High Magnetic Fields (November 2006, Grenoble)
- French-Russian seminar on Sources and Detectors of THz radiation (June 2007, Toulouse)

Furthermore, staff of the LNCMP was involved in the organisation of several national meetings in the context of GDR, Journées la Matière Condensée etc.
# Annex 4 Publication list

## Publications 2005-2008 / LNCMP

ACL : Articles dans des revues internationales ou nationales avec comité de lecture

<table>
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<th>Publication ID</th>
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<td>2005-ACL-023</td>
<td>Intergrain magnetoresistance up to 50 T in the half-metallic (Ba$<em>{0.8}$/Sr$</em>{0.2}$)$_2$FeMoO$_6$ double perovskite: spin-glass behavior of the grain boundary.</td>
<td>D. Serrate, J-M De-Teresa, P-A. Algarabel, M-R. Ibarra, <strong>J. Galibert</strong>.</td>
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<td>2005-ACL-032</td>
<td>O. Contreras, <strong>Ch. Power</strong>, M. Quintero, M. Morocoima, R. Tovar, E. Quintero, J. Gonzalez, V. Munoz-San Jose, <strong>J. M. Broto</strong> and E. Snoeck. Quantum dots of Cd0.5Mn0.5Te semimagnetic semiconductor formed by the cold isostatic pressure method.</td>
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<td>Z.A. Kazei, V.V. Snegirev, <strong>J.M. Broto</strong> and <strong>H. Rakoto</strong>. Jahn-Teller magnet TbVO4 in a strong magnetic field up to 50 T.</td>
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<td>2006-ACL-072</td>
<td>Krstic V., G.L.J.A. Rikken, M. Kaempgen, S. Roth and J. A. Beukes</td>
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<td>Advanced Materials</td>
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<td>2008-ACL-155</td>
<td>D. Vignolles, A. Audouard, R.B. Lyubovskii, M. Nardone, E. Canadell, E.I. Zhilyaeva, R.N. Lyubovskaya</td>
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<td>2006-ACT-005</td>
<td>High magnetic fiels study of 2D electron gas in AlP to be published in Int. Journal Modern Physics B.</td>
<td>M.P. Semtsiv, S. Dressler, W. T. Masselink, M. Goiran, V. V. Rylkov, J. Galibert, J. Leotin</td>
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**AFF: Communications par affiche dans un congrès international ou national**

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**Communications sans actes (COM):**

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<td>2006-COM-010</td>
<td>M. Goiran, J. Gallibet, V.V. Rylkov, J. Leotin, M.P. Semtsiv, S. Dressler, W.T. Masselink.</td>
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<td>2008-COM-043</td>
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<td>2008-COM-049</td>
<td>C. Proust</td>
<td>Fermi surface of underdoped cuprates revealed by quantum oscillations and Hall effect&quot;.</td>
<td>March meeting, New Orleans, Etats-unis (Mars 2008)</td>
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<td>2008-COM-050</td>
<td>C. Proust</td>
<td>Fermi surface of underdoped cuprates revealed by quantum oscillations and Hall effect.</td>
<td>Meeting de la société Suisse de Physique, Genève, Suisse (Mars 2008)</td>
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<td>2008-COM-053</td>
<td>C. Proust</td>
<td>Fermi surface of cuprates: What quantum oscillations can teach us ?</td>
<td>ICAM Workshop on Cuprate Fermiology, Maryland, USA (novembre 2008)</td>
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<td>2008-COM-054</td>
<td>C. Proust</td>
<td>Quantum oscillations in cuprates &quot;Canadian Institute for Advanced Research” meeting of the Quantum Materials Program, Vancouver, Canada (novembre 2008)</td>
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Conférence invitées (INV):
<p>| 2006-INV-002 | F. Lecouturier, V. Vidal. | Elaboration by severe plastic deformation, microstructural and mechanical study of Cu/X (X = Ta or Nb) nanofilamentary wires for use in high field pulsed magnet. CERN AT/MAS (Accelerator Technology/Magnets and Superconductors), 22 février 2006, Genève |
|  | B. Raquet, B. Lassagne, JM Broto. |</p>
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2007-INV-027  C. Proust.
« La surface de Fermi des supraconducteurs à haute température critique ». invitation du comité local de la Société Française de Physique à Toulouse (octobre 2007)


2007-INV-030  B. Raquet.

Light scattering in magnetic fields, IMCODE Council meeting, Grenoble 20/12/2007

Magnetic fields and chirality; 'Chirality at the Nanoscale', Sitges17-21 septembre 2007

Magneto-optics and symmetry; EuroMagNET School, Cargèse 27 August-7 septembre 2007

Magneto-optics and symmetry; invited to INLN, Nice 14 december 2007


T.A Dauzhenka, VK. Ksenevich, I.A. Bashmakov, J. Galibert
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| 2008-INV-037 | Quantum interference effect and the problem of localization phenomena in SnO2 granular films.  
GDR Physique Quantique Mésoscopique Réunion plénière Aussois 8-11 décembre 2008 |
ESRF Users’ Meeting, Grenoble, France, February 5-7, 2008 |
| 2008-INV-039 | O. Mathon, P. Van der Linden, M. Sikora, C. Strohm, K. Chesnel, F. Duc, S. Pascarelli S.  
XMCD Under Pulsed Magnetic Field Up To 30 Tesla And Low Temperature Down To 10 K. APS Users’ Meeting, Argonne National Laboratory, Chicago, May 4-8, 2008 |
| 2008-INV-040 | M. Millot. Photoluminescence under high pressure and high magnetic field. DCITIMAC.  
Universidad de Cantabria, Santander, Spain, October 2008. |
| 2008-INV-041 | M. Millot. Photoluminescence under high pressure and high magnetic field.  
| 2008-INV-042 | M. Millot. Photoluminescence under high pressure and high magnetic field.  
Grenoble High Magnetic Field Laboratory, Grenoble, France, May 2008. |
| 2008-INV-043 | M. Millot. Physics under pulsed magnetic field up to 60 T.  
Universidad Federal do Ceara, Fortaleza, Brazil, July 2008. |
| 2008-INV-044 | O. Portugall. General overview over investigations on low-dimensional carbon-based materials in magnetic fields above 50 T.  
18th Int. Conf. on High Magnetic Fields in Semiconductor Physics. Estancia de Sao Pedro, Brazil, 3.-8.8.2008 |
Fermi surface of underdoped cuprates revealed by quantum oscillations and Hall effect. |
Fermi surface of underdoped cuprates revealed by quantum oscillations and Hall effect. |
| 2008-INV-047 | G.L.J.A Rikken. Big news from big machines, magnetism in high magnetic fields, invited to JEMS08, Dublin 17/09/08 |
| 2008-INV-048 | G.L.J.A Rikken. High magnetic field facilities in Europe, invited to Physique en champ intense, SFP colloque 24/10/2008 |
### 2008-INV-049


### 2008-INV-050


### Ouvrages Scientifiques (OS):

#### 2006-OS-001

**F. Lecouturier.** Conducteurs nanocomposites multi-échelle ultra renforcés pour bobines de champ magnétique pulsé non-destructif supérieur à 60T. Les nanosciences 2 : Nanomatériaux et nanochimie, éditions Belin, collections Echelles (2006), Lahmani (Marcel) / Bréchignac (Catherine) / Houdy (Philippe)

#### 2008-OS-004


#### 2008-OS-005

**F. Lecouturier.** Thilly L. Applications of nanomaterials: mechanics : high field coils. Nanomaterials and nanochemistry, Springer editions, Lahmani (Marcel) / Bréchignac (Catherine) / Houdy (Philippe), (Feb 2008)

#### 2008-OS-006

Annexe 5 Organigramme 1/4/2009

Conducteurs renforcés
F. Lecouturier IR
N. Ferreira AJT
J. M. Lagarrigue T

Bobines & Generateur
P. Frings IR
J. Bilotte IE
F. Giqueul T
J. Béard IE CDD ANR
B. Griffe AI

Soutien général
G. Ballon AI échantillons
L. Drigo. IE électronique
L. Bosseaux T informatique
J.P. Nicolin IE CDD EMII
S. George T optique
J. Mauchain CDD IE BMV
F. Duranteau IE MegaGauss
Vacature IR CDD

Mécanique
L. Bendichou T
T. Schiavo AJT UPS
J.C. Desclaux CDD AI

Directeur
G. Rikken DR1
Directeur-adjoint
O. Portugall IR

Secrétariat-Administration
F. Moes T
S. Bories AJT INSA
A. Labrador, AJT CDD EMII
C. Feugeade IE 50% EMII

Cryogénie Vide Pression
M. Nardone IR
J.P. Laurent T INSA
A. Zitouni AI
J. Delescluse CDD T

Thésards
C. Jaudet UPS
S. Nanot UPS
N. Ubrig UPS
M. Millot UPS
J.B. Dubois (Poitiers)
J. Jorge UPS-Merida
P.Y. Solage UPS
J. Poumirol UPS
T. Dauzhenko UPS-Minsk

(Enseignants)-Chercheurs
A. Audouard CR1
R. Battesti MC UPS
J.M. Broto PR UPS
F. Duc CR1
W. Escoffier MC INSA
J. Galibert CR1
M. Gouran PR UPS
W. Knafo CR2
B. Raquet PR INSA
C. Proust CR1
D. Vignolles MC INSA

Accueil BMV-LCAR
C. Rizzo PR UPS
M. Fouché CR2

Post-docs
E. Klein FFC CNRS
B. Vignolle FFC CNRS
Vacature RMN-ANR
A. Kumar Graphene-ANR
BILAN SCIENTIFIQUE

Laboratoire des Champs Magnétiques Intenses
LCMI – UPR 5021
Du 01/01/2005 au 31/12/08

Etablissement de rattachement : CNRS – MPPU
Lié par convention à l’Université Joseph Fourier – Grenoble 1

A partir du 01/01/09 :

Laboratoire National des Champs Magnétiques Intenses
LNCMI – UPR 3228

Etablissement de rattachement : CNRS – MPPU
Lié par convention à l’Université Paul Sabatier Toulouse 3, à l’Université Joseph Fourier Grenoble 1
et à l’INSA Toulouse

AERES
Campagne d’évaluation 2011 - 2014
Summary

General overview of the LCMI 2005-2009 ................................................................. 1
Scientific Activities ........................................................................................................ 5
Publications ................................................................................................................... 23

ACL .................................................................................................................................. 23
ACTI ............................................................................................................................. 48
ACLN .......................................................................................................................... 67
INV ............................................................................................................................... 70
COM ............................................................................................................................. 75
AFF ............................................................................................................................... 81
OS, AP ......................................................................................................................... 86
Prix, distinctions, colloques ......................................................................................... 87

Organigramme ............................................................................................................ 89
Annexe 1 : Enseignement et formation par la recherche, information et culture scient. et tech. ............... 91
Annexe 2 : Action de formation permanente des personnels de l’unité .................................................. 93
Annexe 3 : Hygiène et sécurité ..................................................................................... 95
General overview of the LCMI 2005-2009

Short history
The Laboratoire des Champs Magnétiques Intenses (LCMI), was a "Unité Propre du CNRS, UPR 5021" associated with the University Joseph Fourier, UJF, and the Institut National Polytechnique, INP Grenoble. It belongs to the "Très Grands Equipements" of the CNRS since 2005 and depends primarily on the MPPU department of the CNRS, with a secondary attachment to the CNRS Chemistry department.

At its creation in 1972, the laboratory was operating as a "service". It was named "Service National des Champs Intenses" (SNCI) and a collaboration started with the Max-Planck-Institut für Festkörperforschung (MPI-FKF) in Stuttgart for both research and magnet development. In 1990/91, most of the technical installations were renewed, and the dc electric power and cooling capacity were increased from 10 to 24 MW. From 1992 a common laboratory, the LCMI, or Grenoble High Magnetic Field Laboratory (GHMFL), has been operated by the CNRS and the Max-Planck-Gesellschaft through the MPI-FKF in Stuttgart. This partnership extended to the end of 2004. From 2002 to the end of 2005 Gérard Martinez was director and he insured the transition to the new state of the laboratory in 2005. His successor was Jean-Louis Tholence, who directed the laboratory until end 2008. On 1/1/2009, the LCMI was merged with the Laboratoire National des Champs Magnétiques Pulsés in Toulouse (LNCMP), under the directorship of Geert Rikken.

This report starts in 2005, when the status of "Très Grand Equipement" (TGE) was given to the laboratory by the CNRS. As a consequence, the LCMI is since then supervised by a "Comité de Direction" replacing the previous "Comité Commun". This "Comité de Direction" meets once a year to evaluate the scientific activities of the laboratory, summarized in an annual report, and its technical and scientific projects. The CNRS has made a large effort to contribute to the budget of the laboratory and insured a reduced but reasonable access time to the magnets (3500 instead of 5000 magnet hours). Today 85% of the budget is coming from the CNRS and 15% from the European community in the framework of the "Large Scale Facilities".

Moreover some of the MPI technical employees have been admitted on technical positions opened by the CNRS, and the laboratory is now operating with 38 ITA (instead of 50 tens years ago). The number of scientists supported by the MPI used to be up to 25, but the LCMI was operating in 2008 with only 10 permanent scientists (CNRS, UJF and INSA Toulouse).

Missions
The LCMI has three major missions;
1) **High quality research using high magnetic fields:**
The scientists of the laboratory develop their own research in the main domains of solid state physics: semiconductors, metals and superconductors or magnetism where the quantum effects are studied. Some techniques like the high frequency and high field EPR and the high resolution NMR are of great interest for solid state chemistry and have been the objects of large efforts of the laboratory. This 2005-2009 report presents the main developments of this research and of the technical improvements underpinning them.

Since the LCMI scientists also work as local contacts for visiting scientists, the number of topics studied at the LCMI is necessarily large compared to the number of scientists, which is a necessary condition for the operation of any large facility.

2) **Providing access to external users:**
The laboratory is open to the international scientific community. Any scientist wanting to use large magnetic fields can submit a project to use the relevant infrastructure of the laboratory with the help of the "instrumentation service" of the laboratory and of a local contact.

All projects, including the internal ones, to be realized in high magnetic fields are evaluated by an international committee twice a year (June and December). Among around 150 projects submitted per year, the rejection or reduction of demanded time is around 15%. The fraction of internal projects has dropped with the departure of MPI scientists, the total number of submitted French projects being around 50 (33%).
3) Magnet development:
The laboratory has to produce continuous magnetic fields with the best possible performance. This can be in terms of the field strength, but also in terms of field homogeneity and stability, or by offering special magnet geometries. These are in general conflicting requirements and the optimal choice depends on the experiments to be performed. The developments in magnet technology allow us to remain competitive with facilities abroad and open our activities to other scientific domains, like high resolution NMR, and other disciplines than physics.

National and international context
The generation of very high magnetic fields is a technological challenge and their exploitation requires a large financial commitment. Therefore not many infrastructures exist where very high magnetic fields can be generated and used for research. Over the last twenty years, financial limitations and the complexity of such installations have resulted in a further concentration of these activities in less but larger infrastructures, very often operated on a national scale. For generating continuous magnetic fields in excess of 30 T, powered with 15+ MW power supplies, installations can be found in the USA (Tallahassee), Japan (Tsukuba) and Europe (Grenoble and Nijmegen). Large pulsed field installations based either on motor generators or large (> 5 MJ) capacitor banks are found in Los Alamos (USA), Tokyo (Japan), and in Europe in Toulouse and in Dresden (created in 2006). As the most recent step in this trend, in 2007 the Chinese government has created a 40 M€ national high magnetic field facility, consisting of a static field installation in Heifei and a pulsed field installation in Wuhan. Still the clearest example of this trend is the creation of the National High Magnetic Field Laboratory (NHMFL) in the USA, a three site organization that pioneers all aspects of high magnetic field generation, and its use for scientific experiments.

The last major upgrade of the LCMI installation this was done in 1992. Despite the continuous and gradual improvements that have been implemented since then, its installation is basically no longer up to the current standards and major investments are needed to guarantee its international competitiveness in the future. In particular, the construction of a hybrid magnet, combining a superconducting outsert with a resistive insert, in order to generate fields far above 40 T is the main priority for the coming years.

To obtain the necessary investments, it is necessary to increase the weight and impact of high magnetic fields within the context of the French large facilities. Following the example of the NHMFL, it was therefore proposed to merge the LCMI and Laboratoire National des Champs Magnétiques Pulsés in Toulouse (LNCMP, UMR5147) into one Laboratoire National des Champs Magnétiques Intenses (LNCMI, UPR3228), on two sites. The new laboratory, with its increased size, scientific production and impact, and user community, will become a more important factor among the French large facilities, and it can be expected that through collaboration and synergy, the LNCMI will be more than just the sum of the LCMI and LNCMP, again improving the position of high field science in France and in Europe. To strengthen the latter aspect, the LNCMI has been advocating the creation of a European Magnetic Field Laboratory, uniting the four major European high field installations (Grenoble, Toulouse, HLD Dresden, HFML Nijmegen). This idea has been implemented through an ESRFI Roadmap Update proposal that was accepted last December (www.emfl.eu). This proposal will be elaborated in the near future in the context of the FP7 design study.

Funding
The LCMI being a TGE since 2005, its annual budget has been more or less guaranteed at a constant level by the CNRS. However, increasing electrical energy cost, and an increase in the electrical energy consumption due to an increased use of the 24 MW magnets as compared to the 12 MW magnets make that the electricity bill consumes an ever increasing part of the LCMI budget. In addition, in order to realize the hybrid magnet project, which is considered to be vital to the long term survival of the laboratory, the LCMI has been obliged to take part of the necessary investments from its annual running budget. So far this budget allowed to hire post doc scientists to partly compensate the departure of staff scientists, but now we have reached a point that this is no longer possible. Either an increase of the annual budget or an additional contribution to the hybrid magnet project is necessary to assure that the laboratory can continue to operate at its current level of activity and quality.
In recent years, several scientific projects at the LCMI have been funded by the ANR. Unfortunately, the ANR refuses to fund project related to the high field installation. An ANR program to fund mid-scale investments at the French TGE is sadly lacking.

**Summary of the technical activities at the LCMI**

Presently the LCMI is equipped with an electrical power and cooling installation of 24 MW. It has eight magnet sites: five produce fields up to 23 T with 12 MW, three consume 24 MW and reach fields of respectively 35 T, 28 T and 18 T in bore diameters of 34 mm, 50 mm and 160 mm.

Over the last few years, a steady increase in maximum field strength has been realized by improving magnet design, materials developments and new cooling techniques. Thanks to these activities, the LCMI currently shares the world record resistive magnetic field with the NHMFL, in spite of a much lower budget.

The laboratory is currently heavily investing in the realization of a hybrid magnet producing 42 T in a 34 mm diameter. This project replaces an earlier project, in which the superconducting outsert, fabricated by an industrial partner, was defective and beyond repair. No alternative industrial supplier could be found and the laboratory is now obliged to coordinate the manufacturing of the superconducting cable and the construction of the magnet and its cryogenics.

During the last years, a large effort has been made to improve the stability of the power supply, now reaching values of $5 \times 10^{-6}$. This result mainly benefits the development of high resolution NMR at the LCMI.

A part from its in-house installation, the LCMI has been strongly involved in the development of other high magnetic field installations, in collaboration with other institutions. It has strongly contributed to the FP7 Design Study ‘ESRFUp’ in which, amongst others, the possibility of the construction of a new high field installation (40 MW, 30+ T) between the sites of the ESRF and the ILL is investigated. The results of this study confirm the technical feasibility of such an installation and the magnets necessary to perform neutron and X ray scattering experiments in fields above 30 T. In collaboration with the LPSC and using the unique LCMI magnet technology, a special magnet was designed that will constitute the heart of the new European electron cyclotron resonance ion source.

More details on these technical activities can be found below, or in greater detail in the annual reports (http://ghmfl.grenoble.cnrs.fr)

**Summary of the scientific activities at the LCMI**

The scientific activities of the LCMI are spread over many topics in condensed matter science. A more detailed overview will be presented later on. They are all related to the effects of a large magnetic field on the physical properties of materials or nanostructures, the other parameters being varied being typically temperature or pressure. The scientific production of the laboratory over the reporting period is 440 publications (ACL, ACT), of which 48 with an impact factor over 6 (Phys. Rev. Lett., JACS, etc) and 4 with an impact factor over 15 (Science, Nature etc). In view of the small number of scientists (10 permanent scientists in 2009), this is an extraordinary result, proving the large added value of high magnetic fields as a research tool and the high quality of the LCMI installation and researchers.

Several specific experiments have been developed to explore various new properties in high magnetic fields that are unique in the world. In the following paragraphs a few highlights will be given.

In semiconductor physics, including its modern "nano" and "spintronics" branches, magnetic fields are used as a powerful tool to study material properties or to create unique systems, unavailable by other means. Focusing on the effects of electron-electron interaction, the appearance of Stoner transition which drives 2DEG into a ferromagnetic state has been demonstrated with transport experiments. Electron-electron interactions have been also shown to be apparent in cyclotron resonance absorption of a 2DEG and to play an important role in determining the spin and charge state of optically probed single quantum dots and to affect the electronic transport of a 2DEG via plasmon excitations. The studies of anisotropic transport (ratchet effect) induced by microwave excitations in a 2DEG with an intentional anisotropic disorder, and of other microwave induced effects have revealed interesting mesoscopic phenomena which may be also important for applications.

The newly discovered graphene, essentially a carbon monolayer, has been a very fertile playground for the LCMI scientists; Raman scattering studies of multilayered graphene have confirmed its unique Dirac-like electronic like spectrum, previously uncovered with magneto-spectroscopy methods. The appearance of
“Dirac states” at the specific point of the Brillouin zone of graphite has been also shown. The high energy limits of Dirac spectrum have been studied with high-field magneto-optics and extremely high room temperature mobilities of the charge carriers have been observed. Very striking behavior in high magnetic fields has been observed for several metals and superconductors. High field de Haas-van Alphen effect, magnetization, torque as well as recently developed high sensitivity specific heat measurements have been used to explore high field phase diagram and electronic properties of a number of strongly correlated electron systems. The two step 26 Tesla metamagnetic transition in CeRh$_2$Si$_2$ has been shown to trigger a strong modification of the Fermi surface compatible with the change from localized to itinerant character of the 4f electrons, while the effective mass enhancement at the transition remains relatively small. The unconventional anisotropy of the superconducting gap of the non-magnetic LuNi$_2$B$_2$C and the mass-enhancement factor have been studied by dHvA effect and compared with band structure calculations. In ZrB$_{12}$, dHvA effect measurements have been used to verify its band structure in order to confirm the two-band BCS origin of superconductivity in this compound. Finally, large Shubnikov-de Haas oscillations in layered organic materials and their strong temperature and angular dependence confirmed the hypothesis of field-induced charge density wave transitions associated with Landau quantization. Other high field transitions of magnetic origin have been studied in a variety of new materials by magnetization measurements.

*Nuclear magnetic resonance* is rapidly gaining importance at the LCMI, which proposes the only set-up in the world allowing NMR measurements at 40 mK in magnetic fields up to 30 T. Very interesting phenomena in quantum magnets have been observed, in particular the magnetic structure of magnetization plateaus in SrCu$_2$(BO$_3$)$_2$. The persistence of this superstructure above the first magnetization plateau at 28 T points to the possibility of a “supersolid phase”. The NMR performance of the LCMI installation has been drastically improved, allowing for high field NMR measurements that also interest the chemistry community. More details on these scientific activities can be found below, or in even greater detail in the annual reports ([http://ghmfl.grenoble.cnrs.fr](http://ghmfl.grenoble.cnrs.fr)).

**Summary of the other activities at the LCMI**

On average, the LCMI hosts around 7 PhD or master students plus several stagiaires from engineering schools. Several members of the LCMI staff teach at INSA Toulouse, UJF Grenoble, IUT Grenoble or INP Grenoble. The small fraction of LCMI staff that teaches, plus the large geographic separation from the university campus make it difficult to attract students.

About 10 national and international meetings have been organized by the LCMI during the last four years; a list can be found below.

The installation of the LCMI has some inherent risks, which in combination with the intrinsic presence of inexperienced external users, makes it important to pay special attention to security issues. The activities of the two security officers (‘ACMO’) of the LCMI to reduce the risks as much as possible are detailed below.

Much attention is paid to the continuous training of the LCMI staff, in order to maintain a high level of technical skills, as detailed below.

This report is organized as follows: A short account of the scientific and technical activities is given, then followed by the list of publications 2005-2009 (based on data from ISI Web of Science, on July 10th, 2009) and communications according to the AERES classification. The organization chart is given at the end, before the annexes 1, 2 and 3.

Grenoble July 17th 2009 G. Rikken
SCIENTIFIC ACTIVITIES

Spectroscopy of nano- and meso-systems


Collaborators: A. Babinski (University of Warsaw, Poland), I. Bar-Joseph (Weizmann Institute, Israel), A-L. Barra (LNCMI-Grenoble), M. Bayer (University of Dortmund, Germany), C. Berger (Institut Néel, Grenoble, France), L. Bryja (Technical University of Wroclaw, Poland), Yu. Bychkov (Landau Institute, Chernogolovka, Russia), J-N. Fuchs, M. Goerbig (LPS, Orsay), Y. Guldner (LPA-ENS, Paris), P. Hawrylak (IMS-NRC, Canada), W.A. de Heer (Georgia Tech at Atlanta, USA), Y. Hirayama (Tohoku University, Japan), R.J. Nicholas (Oxford University, U.K.), A. Pinczuk (Columbia University, USA), S. Raymond (IMS-NRC, Canada), Z.R. Wasilewski (IMS-NRC, Canada), A. Wysmolek (University of Warsaw, Poland)

The physics of low dimensional systems (semiconductor structures and two-dimensional allotropes of carbon) in combination with spectroscopic methods and magnetic field techniques is the central theme of our research activity. Low dimensional systems had and continue to have a great impact on solid state physics and on technology. They are exceptionally suitable for studying the fundamental quantum mechanical phenomena and allow producing more and more efficient electronic devices. Applications of magnetic fields play an important role in the investigations of low-dimensional systems. This is best demonstrated by the discoveries of quantum Hall effects. These effects, representative for the physics of a two-dimensional electron gas in semiconductor heterostructures, are the consequence of the unique energy structure of two-dimensional systems in a magnetic field, which represent highly, \( eB/h \)-degenerate discrete (Landau) levels. The energy levels of zero-dimensional systems, such as semiconductor quantum dots, are already discrete in the absence of the magnetic field. Nevertheless, the application of this field introduces a characteristic (magnetic) length, which can be comparable with the size of the dot (extension of the electronic wave-function) what leads to essential modification of electronic orbitals and in consequence to important changes in the energy diagrams of these systems. Magneto-spectroscopy and/or electronic properties of low dimensional systems in magnetic field and under electro-magnetic wave excitation are the representative axis of our research activity.

The relevant part of our recent activity has been focused on studies of electronic properties of graphene (single sheet of graphite) and its derivatives. Our contributions to this emergent research area concerns magneto-optical studies which, in contrast to more common, electric transport methods, provide almost direct information on band structure of solids. Our group was the first to demonstrate the “Dirac like” electronic dispersion relations of graphene-based structures using magneto-spectroscopy methods [Sad06]. Importantly, our work has shown that the Dirac-like electronic spectrum is not only characteristic of a single graphene layer but persists in structures of multilayer graphene on C-terminated surface of silicon carbide (C-SiC), which were used in our experiments. This initially surprising conclusion has been later confirmed in our Raman scattering experiments [Fau08] and is today a well established, important fact.

The appearance of the Dirac-like electronic states in graphene structures on C-phase of SiC in combination with high, room temperature electron mobilities which we have reported in these systems [Orl08b] is important from the viewpoint of possible applications in electronics. Graphene on C-SiC may be also the material of choice to further explore the fundamental physics of Dirac fermions in solid state labs. Fermions in graphene are obviously not “real fermions” but only quasiparticles characteristic of band states in solids. Nevertheless, our more recent works [Plo08] show that Dirac-like states in graphene extend over a wide energy range (only small nonlinear effects occur, but far away from the zero Dirac point). Our magneto-optical experiments also show that the majority of the C-SiC graphene layers are practically neutral and that the electronic states from the immediate vicinity of the zero-Dirac point, which physics is perhaps the most spectacular, can be investigated in these structures [Orl08b].

A few of our recent works [Orl08a, Orl09, Sch09] have aimed at reviewing the electronic properties of graphite. This material is far more complex than graphene, but electronic states of graphite also involve
physics of Dirac fermions [Orl08a]. The nature of electronic states in graphene has been recently a matter of some controversy which we then clarified in our works. Our investigations show [Orl09] that from the viewpoint of magneto-spectroscopy experiments graphite behaves like a structure composed of a single graphene (with massless Dirac Fermions) and a graphene bilayer (with massive Dirac fermions). Such an image is in full accordance with the well established Slonczewski-Weiss-McClure model of the band structure of graphene. Our simplified view of electronic states of graphite [Orl09] is only valid with respect to magneto-spectroscopy experiments, whereas, for example, electronic transport measurements [Sch09] of this material are sensitive to its three dimensional character.

Very appealing seems to be our latest discovery [cond-mat/arXiv:0903.1612] of the unprecedented properties of the graphene flakes which can be found in nature, in the form of decoupled layers on the surface of natural graphite species. Quality of these graphene flakes, when expressed in terms of electron mobility, is found to be by two orders of magnitude higher then in any manmade graphene structures. This is a good prognostic for further development of the graphene-oriented research, since subtle physics to be discovered in graphene calls for significantly better quality of the manufactured structures.

Preliminary investigations of carbon-nanotubes have uncovered the intriguing high field behavior of polymer-embedded ensembles of these objects [Nis08].

Spectroscopy of quantum Hall systems is another important research direction of our group. Photoluminescence studies of a high mobility two-dimensional electron gas (2DEG) at low temperatures (50mK) and high magnetic fields (30 T) allowed us to identify optical signatures of a number of fractional quantum Hall states within the ν=1/2 family of composite fermions [Bys06]. Neutral excitons have been found to dominate the optical response when the 2DEG is in the incompressible (insulating) phase, whereas the effects of dressing of excitons with an additional electronic charge have been observed for the metallic phases. Formation of fractionally charged excitons in the vicinity of the filling factor ν=1/3 has been deduced. Quantum Hall ferromagnetism with long range order has been found to be a surprisingly fragile phenomenon [Plo09]. A small change in filling factor (ν = ±0.01) leads to a significant depolarization of the system. This, together with the temperature dependence, suggests that the itinerant quantum Hall ferromagnet at filling factor ν=1 is not robust, and collapses whenever possible, to a lower energy ground state with a large number of reversed spins. Nevertheless, small size spin textures seem to be characteristic of the ground state of the 2DEG at filling factors far apart from ν=1, and even in the presence of considerable disorder [Bry06]. Theoretical and experimental works on cyclotron resonance of a 2DEG at high magnetic fields have shown evidences for its magneto-plasmon character [Byc05, Fau07, Byc08]. Influence of the disorder on the magneto-luminescence of the 2D gas has been studied in details [Gla06, Ter05, Bab06c, Ter06, Bry07a]. Rayleigh scattering has been found to be another method to determine the role of disorder in two-dimensional systems [Bel07]. A number of studies have been devoted to magneto-transport properties of a 2DEG under microwave excitations [Stu05, Stu07, Mor07]. Exact waveform of microwave induced resistance oscillations (MIROs) has been worked out. Possible explanation of MIROs in terms of a quasi-classical model has been proposed.

Semiconductor quantum dots have been investigated with optical magneto-spectroscopy experiments in visible (interband transitions) and far infrared spectral range (interband and intraband transitions). Excitations of electrons between atomic-like orbitals of quantum dots have been shown to be strongly coupled to phonons of the surrounding matrix [Pre05, Pre06, Car06a]. Both single- and bi-polaron states have been observed in magneto-far-infrared absorption measurements on ensembles of n-type InAs quantum dots. Optical experiments in the visible range have been focused on single dot spectroscopy. Zeeman splitting of the ground state emission from single and quantum dot molecule has been investigated in details [Ort05, Bab06a]. Single dot, multieexcitonic emission due to s, p, and d-shells has been observed in highly excited self assembled InAs/GaAs structures. Surprisingly, the evolution of the multieexcitonic lines with magnetic field has been found to closely resemble the single particle Fock-Darwin diagram [Bab06b, Avi08, Pre09]. However, electron-electron interactions in combination with possible effects of an asymmetric confinement potential are deduced to lift the degeneracy of single particle states at zero magnetic field as well as at the crossing points induced by the magnetic field. More recent studies indicate the relevant role of the spin orbit interaction in understanding the optical response of quantum dots made of small bandgap materials [Kor07]. Other experimental and theoretical studies identify the method of optical readout of the spin state of the quantum dot. We now also believe to have a number of proofs which show that GaAs/AlAs bilayer structures may contain a new class of quantum dots which are characterised of strong 3D confinement and extremely low surface density [Pie07].
Magneto-transport techniques at high magnetic field (up to 32T) and low temperatures (down to 10mK) are employed to investigate numerous different systems with reduced dimensionality, strong anisotropy and/or strongly correlated charge carriers. Transport techniques can be combined with optics, high pressure, point contact spectroscopy, break junction spectroscopy, and resistively detected electron spin resonance (ESR) or nuclear magnetic resonance (NMR). We are currently developing force detected (cantilever) ESR and NMR to complement resistively detected techniques in quantum Hall systems. Selected topics are presented below.

The quantum Hall ferromagnet at high filling factors

Many body interactions are at the origin of the rich physics displayed by quantum Hall systems. Traditionally invoked for the fractional quantum Hall physics, it is now becoming apparent that electron-electron interactions play a dominant role throughout quantum Hall physics, even in the magnetic field, integer quantum Hall effect limit.

In this work we have shown that the appearance of spin splitting at high odd integer filling factor is a transition to a quantum Hall ferromagnet [Pio05]. The appearance of a ferromagnetic state requires that the disorder energy cost of populating higher energy levels by flipping spin, should be less than the gain in exchange energy, which therefore stabilizes the polarized state. The density of states at the Fermi level $D(E_F)$ increases as $B/\Gamma$, due to the $eB/h$ Landau level degeneracy and disorder-induced broadening ($\Gamma$). The underlying idea is that when increasing the magnetic field we reach a sufficient density of states at the Fermi level to reduce the spin flip energy cost, so that the spin system eventually becomes “ferromagnetic.”

As the Zeeman energy plays no role in this model, the appearance of spin splitting is simply the manifestation of an itinerant quantum Hall ferromagnet in the highest occupied Landau level. This can also be thought of as a Stoner transition, since the only role of the magnetic field is to modify the density of states at the Fermi energy. Using very high in-plane magnetic fields to tune the single particle Zeeman energy has allowed us to validate our zero parameter model for a Stoner transition to a quantum Hall ferromagnet [Pio07].

High Temperature superconductors Bi$_2$Sr$_2$Ca$_n$Cu$_n$O$_{x}$ ($n=1,2,3$)

The origin of superconductivity in HT superconductors remains controversial, notably the applicability of BCS theory remains the subject of considerable debate. The cuprate high temperature superconductors (HTSC) behave as a stack of Josephson junctions between layers of atomic thickness. Quasiparticle tunnelling spectroscopy in high magnetic fields can be used to probe the interlayer properties, the understanding of which is of fundamental importance with numerous potential applications of the Josephson effect (generation and detection of electromagnetic radiation, quantum logic). The behaviour of quasiparticles is directly related to the anomalous normal state of HTSC and to the mechanism of superconductivity. We have investigated both the in-plane and the inter-plane resistivity in HTSC single crystals Bi$_2$Sr$_2$CuO$_x$ (Bi2201), Bi$_2$Sr$_2$CaCu$_2$O$_x$ (Bi2212) and Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ (Bi2223) in the normal and superconducting states in high magnetic fields for a wide doping range and for temperatures down to 40 mK [Ved05a, Ved05b, Ved07, Ved08a, Ved08b].
In particular, we have used break-junction tunnelling spectroscopy, at temperatures 30-50 mK in high magnetic fields up to 28T, to directly probe the quasiparticle density of states within the energy gap in a single crystal Bi2212 HTC superconductor. The measured tunnelling conductances dI/dV(V) in the subgap region have a zero flat region with no evidence for a linear increase of the density of states with voltage. A number of tunnel break-junctions exhibited dI/dV(V) curves with a second energy gap structure at the average magnitude $2\Delta=13$meV. Our data cannot be explained by either a pure s-wave or a pure d-wave pairing [Ved05].

**Magneto-transport in graphite**

Recently, massless Dirac fermions have been observed at the K point of the Brillouin zone in graphene, a hexagonally arranged carbon monolayer with quite extraordinary properties. Historically, graphene forms the starting point for the Slonczewski, Weiss and McClure (SWM) band structure calculations of graphite. In graphite, the Bernal stacked graphene layers are weakly coupled with the form of the in-plane dispersion depending upon the momentum $k_z$ in the direction perpendicular to the layers. The carriers occupy a region along the H-K-H edge of the hexagonal Brillouin zone. At the K point ($k_z=0$), the dispersion of the electron pocket is parabolic (massive fermions), while at the H point ($k_z=0.5$) the dispersion of the hole pocket is linear (massless Dirac fermions). The observation of massless carriers with a Dirac-like energy spectrum, using magneto-transport measurements remains controversial, since in the SWM model, the electrons and hole carriers at the Fermi level are both massive quasiparticles.

We have investigated magneto-transport in natural graphite at very low temperature (T=10 mK). Due to the low temperatures used, the magneto-transport is much richer than previously published data. Quantum oscillations are observed for both majority electrons and holes with orbital quantum number up to almost $N=100$ [Sch09]. We have shown that these oscillations are fully consistent with the presence of majority electron and hole pockets within the three dimensional SWM band structure calculations for graphite. At high magnetic fields (B>2T), a significant deviation from 1/B periodicity occurs due to the well documented movement of the Fermi energy as the quantum limit is approached. This seriously questions the validity of using the high field data to extract the phase of the Shubnikov de Haas oscillations, and hence the nature of the charge carriers.

![Figure](image-url)

*Figure.* (a) Right axis: Resistance $R_{xx}$ versus B measured at T=10mK for natural graphite. (a-c) Left axis: Background removed data $\Delta R_{xx}$ showing quantum oscillations measured over different magnetic field regions. The high field electron (e) and hole (h) features are indicated. The vertical arrows indicate spin split electron and hole features.
Mesoscopic transport phenomena in 2DESs based on semiconductors

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We report on transport measurements in 2D electron systems at low temperatures ($T \geq 50$ mK), in high magnetic fields ($B \leq 34$ T) and exposed to microwave irradiation (GHz-THz range). Phenomena like the creation of a directed current in an asymmetric antidot lattice due to linear polarized microwave irradiation, quantum Hall liquid-insulator and plateau-to-plateau transitions in HgTe quantum wells, photoresistance in double quantum wells and interferometry in quantum wires under microwave irradiation as well as fractional quantum Hall effect in multilayer systems are presented.

- “Ratchet” effect in a 2DEG with artificial asymmetric scatterers

The generation of directed currents and mesoscopic photo-voltages (up to 100 mV), induced by linear polarized microwave irradiation (GHz to THz), is investigated in an asymmetric antidot lattice. This electronic "ratchet" effect is an original version of a universal effect existing in nature (motion in biological systems : bacteria, proteins…). In the absence of any macroscopic forces, the appearance of a directed transport induced by external energy sources in asymmetric systems is known as the “ratchet” effect. This effect has a generic nature and it has been observed recently in various physical systems. We have experimentally studied the ratchet electron transport induced by linear-polarized microwave irradiation in an asymmetric periodic antidot lattice (semi-circular antidots) in a semiconductor heterostructure (AlGaAs/GaAs) (Sa08, Sas07a, Sa07b). In the absence of any external current (or bias), a dc-current of a few µA is created in the ratchet antidot lattice exposed to MW irradiation. The electron motion due to scattering events of electrons in the asymmetric antidote lattice leads to that directed flow. We have found that (i) the direction of the induced current depends on the orientation of the linear polarization to the lattice , (ii) the effect is absent in symmetric lattices (with circular antidots) and (ii) exhibits linear power dependence. Therefore, we have possibilities in future to observe this effect in structures with smaller sizes and at higher temperatures.

- Conductance properties in the presence of weak and strong electronic interaction
(low and high electronic density), effects of the disorder in the transitions between insulating and metallic parts, the introduction of the disorder is controlled by artificial array of antidots (100 nm). (Ols06).

-Quantum Hall liquid-insulator and plateau-to-plateau transitions in HgTe quantum well

Owing to the advances in the fabrication technology of narrow gap semiconductors, a high mobility 2DEG in HgTe quantum wells (QW) has recently become available for experimental study. In the present work the magnetic field induced QH liquid-to-insulator and plateau-to-plateau transitions in a high mobility 2DEG in HgTe QW have been studied for the first time. The experimental samples were CdTe/HgTe/CdTe QWs with two different widths ($d$): $d = 16$ nm and $d = 21$ nm, grown on a GaAs substrate by means of the MBE technology. The first QW contained a 2DEG with the electron density $N_e = 2.2 \times 10^{11}$ cm$^{-2}$ and the mobility $\mu = 2.8 \times 10^5$ cm$^2$/Vs while in the second the 2DEG had the $N_e = 1.4 \times 10^{11}$ cm$^{-2}$ and $\mu = 1.5 \times 10^5$ cm$^2$/Vs. As can be seen a typical magnetic field induced transition is observed right after the Fermi energy crosses the lowest Landau level. The transition is characterized by a critical magnetic field $B_c = 10.9$ T and a critical diagonal resistivity value $\rho_{xx} = 0.9h/e^2$. At the same time the Hall resistivity has a sort of a plateau on the insulator side of the transition at the lowest temperatures. So, at a first glance, for $T < 1.6$ K the magnetic field induced transition in our 21 nm HgTeQW has main features observed earlier in AlGaAs/GaAs and Ge/SiGe structures shanetsky 7).

- Transport phenomena in multilayer systems

In the present studies, we report on transport phenomena in multilayer two-dimensional systems. Due to an extra degree of freedom, bilayer or trilayer systems open the possibility to a new kind of magneto-
resistance oscillation in low magnetic fields and to coherent states in fractional quantum Hall effect which occur due to an interlayer interaction between neighbored quantum wells. First, we focus on a bilayer system which is exposed to microwave irradiation and exhibits photo-resistance oscillations, caused by the interference of magneto-intersubband (MIS) oscillations and microwave induced resistance oscillations (MIROs, observed systems with one occupied subband). The investigated samples are GaAs double quantum wells (DQWs) with AlGaAs barriers and high total sheet electron density $n_s = 10^{12}$ cm$^{-2}$ and a mobility of $\mu = 10^5$ cm$^2$/Vs, coupled by tunneling. Transport measurements in a perpendicular magnetic field reveal MIS oscillations owing to the alignment of Landau levels which pass consecutively the Fermi level with increasing magnetic field. The MIS oscillation picture is strongly frequency dependent and shows enhanced MIS peaks for high frequency, damped features and inverted MIS peaks for low frequencies. The inelastic mechanism, generalized to the two-subband case explains behavior taking into account heating of electrons due to microwave irradiation and the characteristic scattering times $\tau_q$ (quantum lifetime), $\tau_{tr}$ (transport time) and $\tau_q$ (quantum lifetime) (Wie8).

Triple quantum wells (TQWs) consist of three quantum wells in a close proximity and coupled by tunneling. In contrast to single wells, new fractional quantum Hall states are predicted in these systems if the interlayer electron-electron interaction is comparable to the ordinary intralayer interaction, determined by the ratio of the layer separation $d$ to the magnetic length $l_B$ (ratio in the order of unity). The samples have an electron density of $n_s = 10^{12}$ cm$^{-2}$ and a mobility of $\mu \approx 0.5 \times 10^5$ cm$^2$/Vs and are separated by thin barriers. In this type of samples, density of the central well is 30% smaller than in the lateral wells. We have observed a collapse of integer quantum Hall effect as well as two phenomena in fractional quantum Hall effect: (i) emergence of fractional states and (ii) re-entrance on the right side of filling factor $\nu = 5/2$. Physics of FQHE for $n$ layers ($n = 3$: triple quantum well) with $n > 2$ opens interesting perspectives to study such coherent states by varying several parameters. New theoretical works about multilayer fractional quantum Hall states, e.g., the part on construction may lead to further studies of such systems.

- Quantum interferences of edge channels in magnetically confined quantum wires

We report on the observation of quantum interferences in a multichannel quantum wire coupled by a microwave field at two pinning sites where electrons experience forward scattering. We use a magnetic field to tune the phase difference between charge density waves propagating in each channel. Their interference gives a magnetic field dependent transmission through the second pinning site which we detect through oscillations in the magneto-resistance. Magnetically confined quantum wires (MCQW) were obtained by fabricating Dysprosium microstrips at the centre of narrow Hall bars made of a GaAs/AlGaAs quantum well. The depth of this MCQW was tuned between 0 and 25meV by applying a magnetic field in the plane to magnetize the strip. At low field, the energy separation between MCQW subbands is sufficiently small for microwave absorption through inter-channel transitions. At high magnetic field (B>9T), the energy gaps between 1D subbands become wider than the photon energy. As a result, there is no oscillatory structure in the magnetoresistance above 9T.

We have analyzed the oscillatory structure below 9T and conclude to the formation of 1D magnetic subbands in the gradient of magnetic field. Microwaves excite transport in 1D subbands above the Fermi level which results in 1D charge density waves. The magnetic field tunes the phase difference of the charge density waves circulating in each branch by changing the Fermi wavevector. Charge density excitations therefore interfere at two points (magnetic defects) in the manner of a Mach-Zehnder interferometer. The phase difference between the two arms of the Mach-Zehnder interferometer gives the magneto-resistance oscillations seen at low field. We have fitted the resistance peaks with the theoretical maxima of power absorption by the charge density waves and find as sole adjustment parameter the distance between the magnetic defects to be $d=11 \mu m$. We thus conclude to a mean free path of charge density waves at least equal to 3 times the electron mean free path. We have demonstrated microwave assisted interferences of edge channels.
Metals and Superconductors

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The most remarkable and significant results were obtained on the ferromagnetic superconductor URhGe. This compound undergoes a ferromagnetic transition at $T_{Curie}$ of 9.5 K, below which the magnetic moments align along the $c$-axis of the orthorhombic crystal structure. Superconductivity then emerges in high quality samples below $T_c$ of 250 mK, a temperature much lower than that of the ferromagnetic transition. We found that in URhGe there is a first order magnetic transition where the direction of the spin axis changes when a magnetic field of 12 Tesla is applied parallel to the crystal $b$-axis. We then discovered that a second pocket of superconductivity occurs at low temperature for a range of fields enveloping this magnetic transition, well above the field of 2 Tesla at which superconductivity is first destroyed. Remarkably, the re-entrant superconductivity is of an origin different from the Jaccarino-Peter effect. When the magnetic field is inclined towards the $c$-axis, both the spin rotation transition and the re-entrant superconductivity move to higher fields. The transition becomes broader and the spins are no longer aligned with the field above the transition. The magnetic transition changes to second order and then vanishes when the magnetic field is at a few degrees from $b$- to the $c$-axis giving rise to a quantum critical point. The field-induced superconductivity then disappears at a small angle of about 7 degrees. The established phase diagram implies that it is the quantum critical point that is at the origin of the field-induced superconductivity in URhGe. As the next step of our study, we applied the magnetic field in the crystal ($ab$) plane; $a$-axis is the hard magnetic axis. We found that in this case the spin-rotation transition does not depend on the $a$-component of the applied field and always occurs when the $b$-axis projection of the field reaches 12 Tesla. As regards the re-entrant superconductivity, it follows the spin rotation transition over a wide angular range and was observed up to 32 Tesla, the highest field available in the laboratory at the time of the experiment. Our findings strongly suggest that excitations in which the spins rotate stimulate superconductivity in the neighborhood of a quantum phase transition under high magnetic field. The analysis of the coherence length suggests that even the low field superconductivity is due to the tail of the excitations developing at the quantum critical point. This implies that both low and high field superconducting phases are of the same origin. This finding sheds light on the origin of superconductivity in other ferromagnets, notably recently discovered UCoGe.

The specific heat and magnetic torque of the layered organic superconductor $\kappa$-(BEDT-TTF)$_2$Cu(NCS)$_2$ have been studied in magnetic fields up to 28 T applied perpendicular and parallel to the superconducting layers. In parallel fields above 21 T, the superconducting transition becomes first order, which signals that the Pauli-limiting field is reached. Instead of saturating at this field value, the upper critical field increases sharply and a second first-order transition line appears within the superconducting phase. Our results give strong evidence that the phase, which separates the homogeneous superconducting state from the normal state, is a realization of a Fulde-Ferrel-Larkin-Ovchinnikov state.

In CeCoIn$_5$, an intriguing case of a heavy fermion superconductor, we performed high field measurements of the Nernst and de Haas-van Alphen effects at low temperature and up to 28 Tesla. The field-dependence of the Nernst coefficient in the 12 - 28 Tesla field range reveals new features emerging at high magnetic field. The anomaly detected at $H_K \sim 23$ T is similar to what is observed in CeRu$_2$Si$_2$ at $H_m \sim 7.8$ T where a metamagnetic transition occurs. Fourier spectra of the de Haas-van Alphen oscillations indicate that new frequencies also appear above 23 Tesla. Furthermore, the Dingle temperature was found to decrease by about 30% at 23 Tesla. Thus, two independent sets of evidence point to the existence of a new field scale in CeCoIn$_5$ at 23 T. Based on the Nernst coefficient anomalies and de Haas-van Alphen results, the previously determined magnetic phase diagram of CeCoIn$_5$ is revised. Later, we observed a similar behavior of the high field de Haas-van Alphen effect in another compound of the same family, CeIrIn$_5$. This suggests that it might be a common feature for the whole family of Ce 115 compounds.

In CeRh$_2$Si$_2$ we performed low temperature transport, specific heat, magnetostriction measurements in fields up to 28 Tesla as well de Haas-van Alphen effect measurements up to 32 Tesla. When a magnetic
field is applied along the crystallographic $c$-axis, two antiferromagnetic transition temperatures, $T_{N1} = 36$ K and $T_{N2} = 24$ K, decrease with applied magnetic field and finally merge into a two-steps metamagnetic transition at 26 Tesla. When a magnetic field is applied along the crystallographic $c$-axis of the tetragonal crystal structure, a complex two-step metamagnetic transition occurs at about 26 Tesla at low temperatures. The transition becomes strongly first order at low temperature. The low temperature Sommerfeld coefficient increases by a factor of two at the transition. The topology of the Fermi-surface changes above the transition due to suppression of the antiferromagnetic order. However, the $f$-electrons remain localized above the transition.

Related to the previous results, we have also performed a systematic study of the metamagnetic transition in the series of $\text{Ce(Rh}_{1-x}\text{Ru}_x\text{)}_2\text{Si}_2$ alloys by measuring the magnetoresistance of such alloys with magnetic field applied along the $c$-axis. With the concentration of Ru increasing, both transitions are found to move to lower fields with the low-field transition moving faster.

We have performed de Haas-van Alphen effect measurements in $\text{ZrB}_{12}$ in fields up to 28 Tesla. The discovery of two-band superconductivity in $\text{MgB}_2$ stimulated a substantial interest in other borides as potential candidates for multi-band high-temperature superconductivity. $\text{ZrB}_{12}$ becomes superconducting at $T_c = 6$ K. Recent measurements of the temperature dependence of the magnetic penetration depth, $\lambda(T)$, and the upper critical field, $H_{c2}(T)$, suggested that superconductivity in this compound can be explained within a two-band BCS model with different superconducting gaps and critical temperature. However, contrary to magnesium diboride, nothing was known so far about the Fermi surface topology of $\text{ZrB}_{12}$. We observed three different branches of the de Haas-van Alphen frequencies. Their angular dependence is well reproduced by theoretical band structure calculations. The analysis of the effective masses and their comparison with the calculated band masses support the two-band superconductivity model in $\text{ZrB}_{12}$.

In $\text{CeIrSi}_3$ with a non-centrosymmetric tetragonal structure, we have measured low-temperature electrical resistivity in a magnetic field as a function of pressure in order to investigate its superconducting properties. The compound is an antiferromagnet with a Neel temperature $T_N = 5.0$ K at ambient pressure. The antiferromagnetic ordering is completely suppressed at a pressure $P_c = 2.25$ GPa. In high quality samples, superconductivity appears over a wide pressure range from 1.8 to about 3.5 GPa, with a maximum transition temperature $T_{sc} \approx 1.6$ K at $P_c = 2.63$ GPa. At around $P_c$, the upper critical field, $H_{c2}$, for the magnetic field $H$ along the [001] direction is not destroyed by spin polarization based on Zeeman coupling, but possesses an upturn curvature below 1K, revealing a divergent tendency of $H_{c2}(0)$ at $P_c$. It extrapolates to a huge value of $H_{c2}(0) \approx 45$ Tesla. On the other hand, the upper critical field for $H \parallel [110]$ indicates a tendency of Pauli paramagnetic suppression, with $H_{c2}(0) \approx 9.5$ Tesla at 2.65 GPa. This might be a combined phenomenon between the electronic instability at $P_c$ and the characteristic superconducting property without inversion symmetry in the tetragonal structure.
Systems of strongly interacting electrons studied by high-field NMR

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The NMR investigations at the LNCMI-G cover a number of different physical systems focusing on magnetic field induced phenomena. We favour studies in very high magnetic fields and at very low temperature, that is, in conditions which cannot be accessed with other techniques (such as neutron diffraction) or with standard NMR setups. "Strongly interacting electrons" are meant to include: i) quantum spin systems (insulators), as model systems for collective phenomena of quantum magnetism, ii) low dimensional organic conductors and heavy fermions systems, for studies of magnetic field induced phases and, in particular, for field-induced superconductivity, as well as iii) thermoelectric cobalt oxides, where we address electron correlation effects and Na vacancy patterning. As the high-field NMR facility is open to visitors and their projects, the number of investigated systems is relatively large, many of them being studied in a collaborative effort. We mention here only our most important results and publications, mostly in the Phys. Rev. Lett. Several scientific projects have requested important technical developments of NMR probes and spectrometers. We note the construction of the narrow bore NMR probes for the dilution and 3He refrigerators for resistive magnets that provide the highest magnetic field, as well as the extension of the NMR frequency range above 1 GHz, namely up to 1.9 GHz which corresponds to the proton resonance in a field of 44 T.

Our principal research subject are the magnetic field induced phenomena in quantum spin systems. Most of them are antiferromagnetic Heisenberg systems of coupled (copper) spin $S=1/2$ dimers, where interesting physics is generated the field induced singlet–triplet crossing, provoking quantum critical phase transition to a polarized state. Important modification, which drives these systems away from the ideal Heisenberg Hamiltonian, is induced by the presence of anisotropic Dzyaloshinsky-Moriya (DM) interactions on the dimer bonds, as these mix the singlet and the triplet states. These effects were for the first time identified and understood in the Cu$_2$(C$_5$H$_{12}$N$_2$)Cl$_4$ "ladder" system [Cle06]. In [Miy07] we have explained how they also strongly influence the magnetic torque measurements. We have also quantified by NMR the presence of DM terms in SrCu$_2$(BO$_3$)$_2$ [Kod05]. This compound is regarded as the model compound for the "Shastry-Sutherland", 2D, strongly frustrated system of orthogonal $S=1/2$ dimers, and has been intensely studied to understand its magnetization plateaus at 1/8, 1/4 and 1/3 of the saturation magnetization. The torque measurements in this compound are indeed influenced by the DM terms [Lev08] which has even lead to a controversy about these results [Lev09]. Our most important results on SrCu$_2$(BO$_3$)$_2$ are NMR insights on the nature of phases between the plateaus, which may be an analogue of a supersolid phase, where the interstitial triplets undergo Bose-Einstein condensation (BEC) in the background of the commensurate superlattice. By high-field NMR we have proved the existence of such background, namely the spin superlattice formed in the 1/8 plateau is found to survive above the plateau, that is above 28.4 T [Tak08]. By NMR we have also discovered a new phase adjacent to the 1/8 plateau, and by torque measurements we identified this phase as a new plateau and determined its complete phase diagram [Lev08]. Most recent (unpublished) NMR investigation up to 34 T provides clear evidence for another plateau state attributed to the fraction 1/6.

The "Han purple" (BaCuSi$_2$O$_6$) compound was recently proposed to be an ideal candidate for the BEC of triplet excitations in a 2D coupled dimer spin system. Our NMR data in this compound revealed that there is a structural phase transition at ~90 K which not only introduces an incommensurate distortion within
the planes, but also leads to the existence of at least two types of planes, alternating along the c-axis, with different intradimer exchange couplings and energy gaps. As a consequence, the field induced BEC state appearing above 23.4 T is also modulated, with the boson density being very small in every second plane [Kra07]. This state turns out to be very special and is subject of further detailed NMR and theoretical investigation.

Very recently, a new spin ladder system was identified, CuBr₄(C₅H₁₂N)₂ (BPCB), in which by crystal symmetry the DM term on the rungs has to be zero. Our ¹⁴N NMR study showed that BPCB is a nearly perfect 1D system, and thus a unique candidate for controlling and probing the Luttinger Liquid (LL) physics. We have quantitatively characterized the variation of Luttinger parameters over the whole gapless phase of BPCB. This allowed us to fully account for the phase transition to a 3D ordered phase at temperatures below 110 mK, which takes place due to weak inter-ladder exchange coupling, in terms of weakly coupled LLs [Kla08 (labelled as "Editors' suggestion")].

The azurite, Cu₃(CO₃)₂(OH)₂, is the first recognized model system for a frustrated diamond spin chain. In its magnetization vs. magnetic field curve it presents a wide plateau at 1/3 of the saturation magnetization. By NMR we have given the first direct experimental evidence that this plateau is of pure quantum character and corresponds to a state in which, out of 3 spins in a unit cell, 2 spins are paired into a singlet state while the third one is fully polarized [Ai09].

Molecular magnetic clusters (zero-D spin systems) have also received enormous attention because of their spectacular quantum phenomena. The "CsFe₈" molecule, which realizes a ring of eight spin-5/2 Fe(III) ions, is the only antiferromagnetic ring system in which a new phase appears near the magnetic field induced molecular level crossings. Our ¹H NMR spectra and ¹T₁⁻¹ relaxation rate data showed that the novel phase is characterized by a huge staggered transverse polarization of the electronic Fe spins, and the opening of a gap, providing the first microscopic evidence [Schneizer 7] for the previously proposed interpretation in terms of a field-induced magneto-elastic instability.

In the organic charge transfer complex λ(BETS)₂FeCl₄ a field induced superconductivity appears between 18 T and ~45 T, with the maximum Tc at 33 T. The origin was assumed to be the Jaccarino-Peter compensation effect, where the applied external field is cancelled by a negative exchange field Hexch between the spins of the π (conduction) band and the localized spins of Fe³⁺ ions. We proved this mechanism by observing the cancelation of the total (effective) local field through high-field ⁷⁷Se NMR measurements of the hyperfine shift of the p electrons. The corresponding publication has been selected as the"Paper of Editors' Choice by JPSJ Editorial Board" [Hir07].

The heavy-fermion superconductor CeCoIn₅ was studied in the vicinity of the superconducting critical field, where a possible inhomogeneous superconducting (SC) state, the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state, is thought to appear. This phase was clearly identified and characterized first by the ¹¹⁵In NMR line-shift measurements as a function of temperature [Mit06], followed by the field dependence over an extended magnetic field range (2-13.5 T) at very low temperature (≅70 mK) [Kou08]. We have also proved that the first NMR data on this compound, published by the group of Kumagai, were erroneous because of excessive excitation power [Mit08b].

Recent studies of sodium cobalt oxides NaₓCoO₂ have revealed a rich phase diagram with superconductivity, anomalous magnetism and strong thermopower, where electron correlations play an essential role. We have studied several members of this cobaltate family, using ⁵⁹Co and ²³Na NMR. We identified the stoichiometric Na₃CoO₂ phase, which is shown to be a nonmagnetic insulator, as expected for homogeneous planes of Co³⁺ ions with S = 0. We also showed that for compounds with a slight average Na deficiency (x ≈ 0.95-0.98) there is a chemical and electronic phase separation into x = 1 and x = 0.8 phases: Na vacancies segregate into the well-defined, magnetic, NaₓCoO₂ phase [De Vaulx 5]. In the x = 0 compound (CoO₂) our data reveal a metallic ground state, at variance with the Mott insulator phase expected by many [deV07]. In the thermoelectric Naₓ₀.₇₅CoO₂, we demonstrate a remarkable impact of the Na⁺ vacancy ordering on the cobalt electronic states in Naₓ₀.₇₅CoO₂. At long time scales, there is neither a disproportionation into 75% Co³⁺ and 25% Co⁴⁺ states, nor a mixed-valence metal with a uniform Co⁴⁺ state. Instead, the system adopts an intermediate configuration in which 30% of the lattice sites form an ordered pattern of localized Co³⁺ states [Jul08]. This result raises the hope of tailoring electronic properties through the control of ion doping in these materials.
High-Field EPR for the study of transition metal ion complexes

Contributors: A.L. Barra, C. Duboc, P. Neugebauer

In the last decades, EPR has undergone a profound renewal, with the advent of High-Field and High-Frequency EPR (HF-EPR) as well as the development of pulsed techniques. HF-EPR has proven to be very powerful for the study of transition metal complexes from mononuclear systems to Single-Molecule Magnets (SMM). The domain has now grown up to establishing relations between electronic and molecular structures not only for mononuclear complexes but also for spin clusters and it allows determining the structural parameters governing the magnetic anisotropy. This is also an essential step to understand the reaction mechanisms for paramagnetic moieties from enzymes. Here we report our main results obtained during these last four years with the application of HF-EPR to topics of interest to chemistry and biology.

Mononuclear complexes

With its multifrequency operation, our HF-EPR spectrometer is particularly suited for the study of spin systems with $S>1/2$. Among these, the non Kramers ions, EPR-silent at standard EPR frequencies due to large Zero-Field Splittings (ZFS), are the main focus of study. An illustrative example involves two Ni(II) complexes ($S=1$), with very similar ligands derived from galactose which possess three O-CH2-pyridine pendant arms that chelate the Ni ion. [Cha07]. The analysis of the EPR spectra recorded at several temperatures and frequencies shows a striking change of sign for the axial term of ZFS (D parameter) whereas the rhombicity (E/D) is the same. Ligand field calculation for both complexes, within the Angular Overlap Model, allowed understanding the change of sign for D. The structural difference responsible for it results from the nature of the sugar scaffolds. In one case, the sugar scaffold imposes an intramolecular hydrogen bond with one of the atoms linked to the Ni II which leads to a distorted coordination sphere and a positive D, while the absence of such a hydrogen bond in the other complex results in a less distorted environment around the Ni center and leads to a negative D value.

HF-EPR is also useful for the study of half-integer spin systems with $S>1/2$, e.g. allowing approaching the high field limit where spectra are easy to analyze. Such studies have been performed on Mn(II) or Fe(III) complexes. In the case of Mn(II) numerous mononuclear complexes have been described. However, few studies existed on the precise determination of their electronic parameters, most of them being obtained from EPR spectroscopy. Several mononuclear Mn(II) complexes have been studied by HF-EPR, allowing the determination of the ZFS parameters, and the results were then analyzed with DFT model calculations [Duboc8]. They reveal that D is closely connected to the coordination number (5 or 6) of the Mn(II) ion, D being dominated by spin-orbit contributions for 5-coordination whereas spin-spin interaction gives the leading part for 6-coordination. In the case of halide complexes, D is correlated with the nature of the halide anion.

These studies illustrate the interest of combining HF-EPR spectroscopy with theoretical approaches relying on molecular calculation such as AOM or DFT. Beyond obtaining magneto-structural correlations for the magnetic anisotropy, this approach is fundamental for defining the best suited starting blocks for building up SMM with large anisotropies (bottom-up approach) or for the understanding of reactivity (for catalysis or for metalloenzymes when the metal center is the active site).

The previous examples deal with synthetic complexes, where quantities can be large. Taking advantage of the Quasi-Optical configuration of the HF-EPR spectrometer, it has been possible to extend this approach to a mononuclear high-spin ferrous iron centre in a protein. Rubredoxins are small iron-sulfur proteins (~6 kDa) that contain a mononuclear tetrahedral [Fe-4S] site. A frozen solution of the mutant Rm A44S of *Pyrococcus abyssi* in its reduced state has been measured at several frequencies and temperatures, leading to the first EPR determination of the magnetic anisotropy of a ferrous iron centre from a protein [Barra6]. It illustrates the interest of the Quasi-Optical multifrequency approach for the study of biologically relevant metal centres with large ZFS.
Single-Molecule Magnets

Recently, the progress realized experimentally and theoretically has allowed extending the studies of magneto-structural correlations to the magnetic anisotropy of complex magnetic systems, namely SMMs. SMMs are molecules which magnetization relaxes slowly at low temperature; they have attracted a lot of interest due to their behaviour similar to the one of superparamagnets together with quantum effects such as Quantum Tunnelling of the Magnetization (QTM)

A single-crystal HF-EPR study was performed on a truly axial SMM of the Mn$_{12}$ family to investigate the origin of its transverse magnetic anisotropy, a crucial parameter for QTM. The angular dependence of the resonance fields in the crystallographic ab plane shows the presence of high-order tetragonal anisotropy and strong dependence on the M$_z$ sublevels with the second-highest-field transition being angular independent. This behavior was explained considering fourth- and sixth-order transverse parameters with opposite effect in the Giant Spin Hamiltonian (GSH) describing the magnetic anisotropy in the S=10 ground state. To establish the origin of these anisotropy terms, the results were analyzed using a simplified multispin Hamiltonian which takes into account the exchange interactions and the single ion magnetic anisotropy of the Mn(III) centres. It has led to magnetostructural correlations with GSH parameters up to the sixth order. It shows that the transverse anisotropy originates from the multi-spin nature of the system and from the break-down of the strong exchange approximation leading to the S-mixing [Barra7b].

Another very important study deals with a family of tetrairon(III) SMM with a propeller-like structure and an S=5 ground state [Gregoli9]. They exhibit tuneable magnetic anisotropy barriers in both height and shape, and the first SMM to show magnetic hysteresis (at gold surfaces) belongs to this family. HF-EPR analysis allowed determining the dependence of the axial anisotropy parameter D on the propeller pitch over a series of twelve complexes. A similar relationship was first found to hold also for the fourth order axial term, but the uncertainty on the powder measurements didn’t allow extending this relation to all complexes.

Spectrometer developments

A pulsed HF-EPR spectrometer is currently being implemented, which will open important applications especially for distance measurements on spin labelled biological systems such as synthetic DNA strands. A Fabry-Pérot cavity has been built to operate with the Quasi-Optical set-up. It has a finesse of about 700 at 283 GHz. A new detection has also been implemented, with a mixer involving a heterodyne detection, with an intermediate frequency of 1.8 GHz. At 283 GHz, the resulting sensitivity is comparable to the bolometer one. This new set-up is already operative in continuous wave and will be soon available also for pulsed operation. A new magnet, with a much better homogeneity (~5 ppm) and a higher maximum field, will also allow extending the application of the spectrometer to radical species.
High resolution NMR in resistive magnets

Contributors: S. Krämer, M. Horvatić, C. Berthier, F. Debray, J. Dumas, Ch. Trophime, N. Vidal, P. Petmezakis, R. Barbier, E. Yildiz, P. Sala

Collaborators: P.-H. Fries (CEA, INAC, SCIB, RICC, Grenoble), O. Pauvert, A. Rakhatullin, F. Fayon, C. Bessada, D. Massiot (CEMTHI/CNRS, Orleans), M. Mehring (University of Stuttgart, Germany)

Contracts: CPER Rhône Alpes “Nanoscience et Matière”, FP7 EU contract EuroMagNET II (Nr. 228043)

The LNCMI intends to establish high resolution NMR in resistive magnets at fields of the order of 30-32 T as an innovative research and development activity. Its implementation will make the laboratory more attractive for a wider research community, in particular for chemists and material scientists. In the following we report on the first scientific and technical achievements within this framework.

NMR study of paramagnetic relaxation enhancements (PRE) above 1 GHz

We studied for the first time the PRE of $^1$H in diamagnetic species interacting with paramagnetic metal complexes in solution above 1 GHz and up to 1.36 GHz. This provides a deeper insight into the intermolecular recognition movements, in particular those governing the efficiency of contrast agents used in Magnetic Resonance Imaging (P.-H. Fries et al.).

Ultrahigh field NMR of quadrupolar nuclei at 30 T

High magnetic field can overcome the problem of line broadening in NMR spectra of nuclei with strong quadrupole interactions. As an example we recorded $^{91}$Zr NMR spectra of ZrF$_4$ at 30 T (left figure), a compound with application potential in nuclear industry (O. Pauvert et al., submitted to Inorganic Chemistry 2009).

Figure left: $^{91}$Zr NMR powder spectra of ZrF$_4$ at 17.6 T (a) and 30 T (b). The spectrum shows the central transition, dominated by second order quadrupole interaction that is strongly reduced at 30 T. The spectra (blue line) can be modeled (green and purple lines) assuming two different Zr sites. Figure right: Active, NMR based field stabilization of GHMFL M9 resistive magnet at 29.5 T acting directly on the main 24 MW power converter. The average field drift is completely suppressed and the remaining error of the closed control loop is 1.2 ppm.

Technical milestones towards implementation of high resolution NMR at LNCMI

The technical part of the activity comprises tailored NMR instrumentation and efforts to improve the intrinsic field inhomogeneity and instability of resistive high field magnets. The first experiment exploring an active NMR based field stabilization was performed in 2008 on LNCMI 24 MW M9 magnet at 29.5 T. The right figure shows a 90 minute record of the closed loop field stabilization performance. The long term field drift is completely suppressed and the short term field variations remain within the 1 ppm threshold during the entire experiment ($\sigma = 1.2$ ppm). In summary this result demonstrates that the long term field stability condition for high resolution NMR in resistive magnets (1 ppm) can be reached by active, NMR based field stabilization.
Magnetometry and magnetic properties under high continuous magnetic fields

Contributor: M. Guillot

Very deep collaborations with French and foreign groups have been developed in the frame of the magnetic measurements. Exchanges with different countries (China, USA, Poland, Turkey, Romania, Canada...) have been then maintained. Two examples of studies may be selected.

The magnetic phase diagrams of $\text{RFe}_2\text{Ti}$ compounds are strongly modified upon insertion of light elements (H, C, and N) within the crystal structure. Investigation of the magnetic properties of $\text{PrFe}_{11.04}\text{Ti}_{0.96}$ and $\text{PrFe}_{11.04}\text{Ti}_{0.96}\text{H}$ reveal the effect of H insertion on the magneto-crystalline anisotropies. For the first time a giant H, D isotope effect has been observed from the magnetic properties of $\text{Y}_{1-x}\text{R}_x\text{Fe}_2(\text{H,D})_{4.2}$ ($\text{R} = \text{Tb, Er, Lu}$) compounds. These compounds undergo a magnetovolumic transition at a temperature which is about 45 K higher in hydrides compared to the corresponding deuterides. A detailed study of the structural and magnetic properties of $\text{YFe}_2(\text{H,D})_{4.2}$ compounds, using magnetic measurements at high fields, Mossbauer spectroscopy and neutron diffraction versus temperature and pressure have allowed us to explain the magnetic transition by an itinerant electron metamagnetc behaviour of one Fe moment among eight, leading to a ferro-antiferromagnetic change of structure.

Some weeks ago a new magnetometer has been successfully controlled on the M9 magnet under 35 T in the 1.5-350K temperature range. It is worth noting that the two main challenges were i) one unique sample holder which can be used either in a 50mm bore or in a 33mm bore in Grenoble or in the Vibrating Sample Magnetometer in the NHMFL (Thallahassee USA). ii) Precise absolute calibration of the magnetometer was performed. this set sup offers the advantage of a good sensitivity in the order of $2 \times 10^{-3}$ e.m.u.; the relative accuracy is estimated to be 0.1 % when the M lies in the order of one e.m.u. while the reproducibility on the field and on temperature are 0.01 T and 0.2K, respectively. Note that the sample cavity volume is of about 125 mm$^3$.

Characterization of superconducting wires and tapes

Contributors: E. Mossang, J.P. Domps


Research plans focuses on the development of low $T_c$ superconductors strands and wires (NbTi, Nb$_3$Sn) and high-$T_c$ superconductors tapes and wires: $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (Bi-2212) and $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ (Bi-2223) in pure Ag and Ag alloys, $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ coated conductors and MgB$_2$. Studies in progress on low $T_c$ superconductors are performed wit many national and international collaborations [Zan05].

Significant effort has been put into the development of high performance Nb$_3$Sn strands over the last decade. This has been particularly motivated by the ITER reactor to be built in Cadarache. One focus has been to optimize the critical current density ($J_c$) of Nb$_3$Sn strands. $J_c$ is very sensitive to the axial strain ($\epsilon$). Characterizing the field, temperature and strain dependence of $J_c(B,T,\epsilon)$ is very important. We have measured the strain dependance of $J_c$ at different temperatures ($T$) in magnetic fields up to 28 T (LNCMI) and 15 T for the Nb$_3$Sn strands. These comprehensive measurements are essential to characterise strands for the ITER project and other large superconducting systems. $J_c(B,T,\epsilon)$ measurements are performed in collaboration with Durham University.

Variable temperature characterizations of NbTi strands are performed for JT-60SA TF coils. The mission of the JT-60SA Tokamak, to be built in Japan, is to contribute to the early realization of fusion energy by its exploitation in support of the ITER program. JT-60SA project is an
important part of the broader approach activity as a satellite program for ITER. The Toroidal Field (TF) coils are a European contribution and they will partly be built in France. This study is performed in collaboration with Alstom and IRFM, CEA, Cadarache, France.

High Tc superconductors open extremely interesting perspectives for very high field applications such as high field magnets for NMR or SMES, nuclear fusion or future colliders. These materials make possible to operate at temperatures higher than 4.2 K. Institut Néel and the LNCMI have decided to build a Variable Temperature Insert (VTI) for Ic measurements, in the frame of the “Super SMES” ANR project, in collaboration with Nexans, IRFU/CEA Saclay and the LNCMI. This VTI is an extremely useful tool for the very high field magnet developments with high Tc superconductors.

Magnesium Diboride (MgB2) is a potential alternative to the Nb-based superconductor due to its rather raw material costs, its possibility for cryocooler use at around 20 K and its reasonable upper critical field (Hc2) values. [Wan09], [Zha09], [Ma07], [Wan07] 1 [Mal08] These studies take place in the frame of projects on MRI.

The collaboration with NIN Xi’an takes place within the framework of a French-Chinese “Laboratoire International Associé” [Gao07a], [Gao07b], [Xu07], [Xu06], [Li07], [Fen05], [Xu05a], [Xu05b].

Magnetosciences

Contributor: F. Debray LNCMI,
Collaborations: E. Beaugnon CRETA UPS 2070,
JP Chopart LACM-DTI, LRC CEA, Université de Reims
Th. Alousséière LGIT, UJF

Magnetosciences concern the magnetic field effects in processes, including physical, chemical and biological processes. Such effects come from electromagnetic interactions that can be divided in two main categories: MHD (Magneto-Hydro-Dynamic) and MS (Magneto-Static). Effects also often combine both and include other kinds of interactions.

This activity has strongly developed at LNCMI during the last 4 years, leading to the creation of a dedicated branch of expertise in the program committee of the laboratory. About 15 projects are led now per year at the laboratory in this domain, which represents about 10 % of the total number of project. Considering the last 4 years of activity, we can subdivide this domain in three branches.

1- Electrochemistry under high magnetic field 1,2
2- Metallurgy under high magnetic field 3
3- Magnetohydrodynamics (turbulence under magnetic fields, Alfen waves).

Most of the experiments performed in Magnetosciences are made on large diameter bore magnet. Three configurations are used at the laboratory, 6 T in 284 mm (5MW), 13 T in 130 mm (10 MW) and 19 T in 160 mm (20 MW).

The need for large bore is a specific need of this field of research, it is easily understandable for domain 2 (need of oven to be inserted in the bore) and domain 3 (sufficient range of scale between viscous scale and apparatus scale.

For electrochemistry, part of the experiments could be performed at higher field, miniaturization of electrochemical cells is then an axis of development for this activity.

To strengthen this research domain in Europe, the CNRS has created in 2008 a GDRE (Groupement de Recherche Européen) called GAMAS. This is actually the CNRS’s largest structure of this kind. LNCMI and CRETA have contributed to the preparation of GAMAS and have promoted the creation of a transversal Working Package to promote the use of high magnetic fields in the four domains of the GDRE namely, Magneto static, Applied MHD, Magnetic fluids and Mageto electrolysis. The facility in LNCMI is
dedicated to experiments with the highest magnetic fields, while the superconducting magnets in CRETA are more devoted to long duration experiments in large bore but reduced fields (8 and 11 T). LNCMI and CRETA will encourage scientists of the others group to perform unique experiments in high magnetic field conditions in order to explore new frontiers of magneto-sciences. In addition, CRETA policy encourages the applications of magneto-sciences and promotes industrial collaboration. The proposals will be twice a year reviewed by the program committee of LNCMI following the classical procedure of this large scale facility. In the duration of the GDRE the new scientific investigations that will be led will contribute to identify the special requirement for future magnets and instrumentations that will be relevant for the development of magneto science (e.g.: split magnet, magnetic table, high gradient magnet (uniform grad B or grad B2), rotating magnet etc.).

1. Kinetics of Cu2O electrocrystallization under magnetic fields

2. Effect of natural and magnetic convections on the structure of electrodeposited zinc–nickel alloy

3. 3D Physical Modeling of Anisotropic Grain Growth at High Temperature in Local Strong Magnetic Force Field
High magnetic field development

Magnet development outcome: 2005/2009

From 2005 to 2009, the magnetic field available to researchers at the LNCMI has been increased from 28 teslas in a 50 mm bore to 35 teslas in a 34 mm diameter bore. This result was obtained by developing the polyhelix technology. The helix technology developed in Grenoble has proved to be able to produce the highest continuous resistive field in the world. Undergoing project is the preparation of a magnet with B > 30 teslas in a 50 mm bore and the standardization of the three sites 20 MW sites of the LNCMI (M8, M9, M10) so that they could accept any high field insert. Critical points of construction have been patented end 2007 by the laboratory to protect this efficient technology1. It consists of the optimization and realization of patterns in the helix cut itself. This construction procedure is suitable to form windings well adapted for electromagnet design (using metal alloys or massive superconductors) as the cut’s pattern can be optimized to hold mechanical constraints that originated from electromagnetic and/or thermal constraints. Such a design has been tested first in the 32 T magnet and is now fully operational in the 35 T magnet.

Table 1: The “high field” status of the LNCMI facility

<table>
<thead>
<tr>
<th>Magnet site</th>
<th>Magnetic field</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>M9</td>
<td>35 T in 34 mm</td>
<td>World record for resistive magnet (March 2009)</td>
</tr>
<tr>
<td>M10</td>
<td>28 T in 50 mm</td>
<td>B &gt; 30 T planned for 2010</td>
</tr>
<tr>
<td>M8</td>
<td>19 T in 160 mm</td>
<td>From 2010, the configuration will be available on M9 and M10, M8 site will then be free for the 42 T hybrid project</td>
</tr>
<tr>
<td>M1/M6</td>
<td>23 T in 50 mm</td>
<td>Field available on two sites, 25 T version for 2010</td>
</tr>
<tr>
<td>M7</td>
<td>20 T in 50 mm</td>
<td>Dedicated to applied superconductivity</td>
</tr>
<tr>
<td>M5</td>
<td>13 T in 130 mm</td>
<td>Mainly applied superconductivity and magneto-sciences</td>
</tr>
</tbody>
</table>

Top view of the 14 helix 35 magnet of the LNCMI

Optimized cut patterns have been applied in 2008 and 2009 on pair of helices that are radially cooled in series. These new technologies are available to researchers in 2009 on the new M1, 12 MW high field site. This new design leads to a better cooling of the inner most helices and consequently allows to apply higher current densities on the inner most helix. The validation of this technology has allowed to use it in the design study made in the frame of the ESRF upgrade study for high field magnet suitable for diffraction (cf § Magnet for diffraction studies). Undergoing optimizations aim at reducing the mechanical stress on the critical helices to be able to sustain the new specifications of the 42 T CEA/CNRS hybrid project. For this we develop high field magnets that will use a combination of the two helix technologies (namely, longitudinally and radially cooled). The first version of this “mixed insert” is planned to be available in 2010 in a 50 mm version with a magnetic field higher than 30 T. If successful we aim at developing a 38 Tesla magnet in a 34 mm configuration for 2011.

The successful development of the helix high field technology has permitted to propose the use of this technology in the heart of the projects that will contribute to define the future of the LNCMI. This technology will be combined in the future with the use of High Temperature Superconductors for the definition of the high field projects for the period 2015/2020.

These aspects are presented in the § “Perspectives for magnet development 2010/2014”.

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1 Chwalisz B., A.Wysmolek, R.Stepniewski, A.Babinski, M.Potemski and V.Thierry-Mieg
Magneto-luminescence of a single lateral island formed in the type-II GaAs/AlAs quantum well

Anisotropy of transport of 2D electron gas in parallel magnetic field

Tunneling between twodimensional hole layers in GaAs
Proc.13th Int. Symp. Nanostructures Physics and Technology, St Petersburg, Russia, ed. Ioffe Institute 2005, p.169

Temperature dependence of the Aharonov-Bohm effect in chiral Fermi-system
Proc. 13th Int. Symp. Nanostructures Physics and Technology, St Petersburg, Russia, ed. Ioffe Institute 2005, p.197

Electron transport through antidot superlattices in Si/Si0.7Ge0.3 heterostructures: New lattice-induced
magnetoresistance oscillations at low magnetic fields
Proc. 13th Int. Symp. Nanostructures Physics and Technology, St Petersburg, Russia, ed. Ioffe Institute 2005, p.209

The effect of the microscopic state of a ballistic ring on the Aharonov-Bohm oscillations temperature
dependence

7 Raymond S., S.Studenikin, A.Sachrajda, Z.Wasilewski, S.J.Cheng, W.Sheng, P.Hawrylak, A.Babinski,
M.Potemski, G. Ortner and M.Bayer
Excitonic Fock-Darwin spectra from electronhole droplets in self-assembled quantum dots
*Observation of quantum corrections to the transport coefficients of a 2DEG up to 110 K*
Proc. 13th Int. Symp. Nanostructures Physics and Technology, St Petersburg, Russia, ed. Ioffe Institute 2005, p.401

*Metal-insulator type transition in tunnelling between 2D electron systems induced by in-plane magnetic field*
Proc. 13th Int. Symp. Nanostructures Physics and Technology, St Petersburg, Russia, ed. Ioffe Institute 2005, p.418

* Steering of electron wave in three terminal small quantum dot*
Proc. 13th Int. Symp. Nanostructures Physics and Technology, St Petersburg, Russia, ed. Ioffe Institute 2005, p.8

*Mesoscopical behavior of Aharonov-Bohm effect in small ring interferometer*
Proc. 13th Int. Symp. Nanostructures Physics and Technology, St Petersburg, Russia, ed. Ioffe Institute 2005, p.205

*Anisotropic properties of Bi-2201 thin films grown on vicinal substrates*
2009

1  **2009 APS March Meeting**  
16-20 March 2009, Pittsburgh, PA, USA  
*Landau level spectroscopy of Dirac fermions in multilayer epitaxial graphene, graphite and graphene*  
**M. Potemski**

2  **International Workshop on the Emergence of Inhomogeneous Phases in Strongly Correlated Electron Systems**  
30 June - 3 July 2009, Paris, France  
*Coexistence of magnetic order and superconductivity in high temperature superconductors*  

3  **The 9th International Conference on Research in High Magnetic Fields (RHMF 2009)**  
22-25 July 2009, Dresden, Germany  
*New NMR insights into plateaus, BEC and other "exotic" phases in quantum spin systems*  
**Horvatić Mladen**, Berthier Claude, Krämer Steffen, Aimo Francesco, Raivo Stern, Takigawa Masashi, Matsubara Shinichi

4  **International workshop on “Emergent phenomena in quantum Hall systems”**  
25 - 28 June 2009, Villa Guinigi, Capannori (Lucca), Italy  
[http://epqhs3.sns.it/home.shtml](http://epqhs3.sns.it/home.shtml)  
**M. Potemski**

5  **International workshop on “Recent progress in graphene research”**  
Seoul, Korea, June 29 – July 2, 2009  
[http://workshop.kias.re.kr/RPGR/](http://workshop.kias.re.kr/RPGR/)  
**M. Potemski**

6  **Neuvièmes journées de cryogénie et de supraconductivité**  
25-27 mars 2009, Aussois, France  
*Champ magnétiques intenses et développement technologiques*  
**F. Debray**

7  **Training school of magneto-sciences, cost P17/GDRE GAMAS Riga**  
18-22 mai 2009, Latvia  
*High field Magnet for magneto-sciences*  
**F. Debray**

2008

1  **Deutsche Physikalische Gesellschaft Spring Meeting**  
25-29 February 2008, Berlin  
*High Field NMR in Low Dimensional Quantum Antiferromagnets*  
**C. Berthier**, H. Mayaffre, **M. Klanjšek**, S. Krämer, **M. Horvatić**, M. Takigawa
2. **6th Conference on Physical Phenomena in High Magnetic Fields (PPHMF-VI)**
   1-6 August 2008, Laulasmaa, Tallinn, Estonia
   *New NMR Insights in Quantum Spin Systems: SrCu$_2$(BO$_3$)$_2$ and CuBr$_4$(C$_6$H$_{12}$N)$_2*

   1-6 August 2008, Laulasmaa, Tallinn, Estonia
   *High-field NMR Studies of the Modulated BEC in BaCuSi$_2$O$_6$ and the Frustration Driven Magnetization Plateau of Cu$_4$(CO$_3$)$_2$(OH)$_2*
   S. Krämer, M. Horvatić, C. Berthier, R. Stern, T. Kimura, I. Fisher, M. Klanjšek, F. Aimo, H. Kikuchi

   *Field-induced Re-entrant Superconductivity in Ferromagnetic URhGe*
   I. Sheikin, A.D. Huxley, F. Levy

5. **6th Conference on Physical Phenomena in High Magnetic Fields (PPHMF-VI)**
   *HF-EPR for the study of Single-Molecule Magnets anisotropy*
   A.L. Barra, A. Cornia, D. Gatteschi, R. Sessoli, L. Sorace

6. **25th International Conference on Low Temperature Physics (LT25)**
   Amsterdam, Netherlands, AUG 06-13, 2008.
   *Coexistence and interplay of superconductivity and ferromagnetism in URhGe*
   F. Levy, I. Sheikin, B. Grenier, C. Marcenat, A. Huxley

7. **International Conference on Strongly Correlated Electron Systems (SCES 2008)**
   Buzios, Brazil, AUG 17-22, 2008.
   *Bismuth Beyond the Quantum Limit*
   Kamran Behnia, Benoit Fauqué, Aritra Banerjee, Luis Balicas, Ilya Sheikin, Yakov Kopelevich

8. **International Conference on Strongly Correlated Electron Systems (SCES 2008)**
   Buzios, Brazil, AUG 17-22, 2008.
   *Fulde-Ferrel-Larkin-Ovchinnikov State in the Organic Superconductor κ-(BEDT-TTF)$_2$Cu(NCS)$_2*
   A. Demuer, R. Lortz, Y. Wang, I. Sheikin, B. Bergk, J. Wosnitza, Y. Nakazawa

9. **Correlated Electron Systems in High Magnetic Fields**
   13-17 October 2008, Dresden, Germany
   *New NMR insights into plateaus, BEC and other "exotic" phases in quantum spin systems*
   M. Horvatić

10. **Correlated Electron Systems in High Magnetic Fields**
    13-17 October 2008, Dresden, Germany
    *From Luttinger Liquid to Bose Einstein Condensation in coupled spin ladders.*
    M. Klanjšek, H. Mayaffre, C. Berthier, M. Horvatić, T. Giamarchi

11. **Correlated Electron Systems in High Magnetic Fields**
    13-17 October 2008, Dresden, Germany
    *Landau level spectroscopy of Dirac Fermions in multilayer graphene and graphite*
    M. Potemski

12. **7th PAMIR International Conference on Fundamental and Applied MHD**
    8-12 September 2008, Giens - France,
    *Magnet development at the Grenoble High Magnetic Field Laboratory*
    F. Debray
1. **International Conference on Strongly Correlated Electron Systems 2007**  
13-18 May 2007, Houston, Etats-Unis  
*Spin susceptibility in the FFLO phase in CeCoIn$_5*, V.F. Mitrović, G. Koutroulakis, M. Horvatić, C. Berthier, G. Knebel, G. Lapertot, J. Flouquet  

2. **International School on Magnetic Fields for Science**  
27 Aug.-8 Sept. 2007, Cargèse, France  
*High Field NMR: Application to Solid State Physics*  
C. Berthier  

3. **10ème Journée Rhône-Alpes de RMN**  
5 Octobre 2007, Charavines (38), FRANCE  
*High resolution solid state NMR in resistive magnets at Grenoble High Magnetic Field Laboratory (GHMFL)*, S. Krämer, C. Berthier, M. Horvatić, C. Chauvin, F. Debray, C. Trophime, N. Vidal, P. Petmezakis, A. Richard, P. Sala  

4. **2nd Meeting Grenoble CNRS–Beijing IoP/Chinese academy of Science**  
19-21 November 2007, Beijing, Chine  
*High Field NMR in Low Dimensional Quantum Antiferromagnets*, C. Berthier, M. Horvatić, S. Krämer, M. Takigawa, S. Matsubara, R. Stern, H. Kageyama, Y. Ueda, T. Kimura  

5. **2nd Meeting Grenoble CNRS–Beijing IoP/Chinese academy of Science**  
19-21 November 2007, Beijing, Chine  
*High-Field EPR for the study of Single-Molecule Magnets*, A.L. Barra  

6. **2nd Meeting Grenoble CNRS–Beijing IoP/Chinese academy of Science**  
19-21 November 2007, Beijing, Chine  
*The Grenoble High magnetic Field laboratory facility*, J.-L. Tholence  

7. **4th International Symposium on High Magnetic Field Spin Science in 100 T**  
26-28 Nov. 2007, Sendai Japon  
*High Field NMR in Low Dimensional Antiferromagnets*, C. Berthier, M. Horvatić, S. Krämer, M. Takigawa, S. Matsubara, R. Stern, H. Kageyama, Y. Ueda, T. Kimura  

8. **4th International Symposium on High Magnetic Field Spin Science in 100 T**  
*Field-induced Re-entrant Superconductivity in Ferromagnetic URhGe*. 4th, I. Sheikin, A.D. Huxley, F. Levy  

9. **Japan-France Cooperative Science Program Seminar on Materials Processing under Magnetic Field**  
20-23 May 2007, NANCY, France  
*High field magnet development at the GHMFL*, F. Debray
2006

1 "Nanoelectronic 2006" International Conference
Lancaster, UK, 811 January, 2006
Crossing of Landau levels of a 2DEG in dilute magnetic semiconductor quantum wells
Potemski M.

2 EUROMAR 2006,
16-21 July 2006, York, United Kingdom
Ultra High Field NMR and Field Induced Quantum Phase Transitions
C. Berthier, M. Horvatić

3 17th Conf. on High Magnetic Fields in Semiconductor Physics
Würzburg, Germany July 30 - August 4, 2006
Spectroscopic studies of semiconductor structures in high magnetic fields
Potemski M.

4 17th Conf. on High Magnetic Fields in Semiconductor Physics
Würzburg, Germany July 30 - August 4, 2006
Infrared spectroscopy of twodimensional electrons in epitaxial graphene
Sadowski M.L., G.Martinez, M.Potemski, C.Berger and W.A.de Heer

5 Yamada Conference LX on Research in High Magnetic Fields RHMF 2006
16-19 August 2006, Sendai, Japan
High Field Phase Diagram of the Frustrated 2D Dimer Spin System SrCu$_2$(BO$_3$)$_2$
M. Takigawa, S. Matsubara, M. Horvatić, C. Berthier, H. Kageyama

6 Yamada Conference LX on Research in High Magnetic Fields RHMF 2006
High magnetic field facility in Grenoble
Aubert G., F.Debray, J.Dumas, W.Joss, S.Krämer, G.Martinez, E.Mossang, P.Petmezakis, P.Sala, J.L.Tholence, C.Trophime and N.Vidal

7 Training school on NMR, MRL, μSR and Mössbauer techniques (in the framework of the European Network of Excellence MAGMANet)
17-30 September 2006, Pavia, Italy
NMR in high magnetic fields
M. Horvatić

8 Workshop on Synchrotron Applications of High Magnetic Fields
Grenoble, France, NOV 16-17, 2006
Strong electron correlations in high magnetic field..
I. Sheikin

2005

1 The Canadien Institute for Advanced Research Nanoelectronics Program Meeting
Banff, Alberta, Canada, 1720 March, 2005
Optical spectroscopy of semiconductor quantum dots in magnetic fields
Potemski M.

2 Réunion du GDR 2757 "Nouveaux états électroniques des matériaux" (NEEM)
10–13/05/2005, Batz sur Mer, France
Magnétisme Quantique vu à travers la RMN: Quoi de neuf ?
M. Horvatić, C. Berthier, R. Stern, H. Kikuchi, A. Comment, M. Jansen
International workshop on "Electron interactions in semiconductor nanostructures"
Bad-Honnef, Germany, May 29 – June 1, 2005
Quantum dot excitons in GaAs/AlAs double layer structures
Potemski M.

Colloquium "Science in High Magnetic Fields"
13–14/06/2005, Grenoble, France
Quantum Magnetism Revealed by High-Field NMR
M. Horvatić and C. Berthier

Colloquium "Science in High Magnetic Fields"
13–14/06/2005, Grenoble, France
High Magnetic fields for Science
C. Berthier and M. Potemski

Colloquium "Science in High Magnetic Fields"
13–14/06/2005, Grenoble, France
High field EPR for biologists and chemists
C. Duboc, A.-L. Barra

International Symposium on Molecular Conductors ISMC 2005
17–21/07/2005, Hayama, Japan
Field Induced Phase Transitions in Quantum Spin Systems and low dimensional organic conductors
C. Berthier, M. Horvatić, H. Mayaffre, Y.F. Mitrović, S. Krämer, K. Kodama, M. Takigawa, R. Stern

24th International Conference on Low Temperature Physics (LT24)
10–17/08/2005, Orlando, Florida, USA
NMR Studies on Magnetization Plateaus in Dimer Spin Systems
M. Takigawa, K. Kodama, M. Horvatić, C. Berthier, H. Kageyama, Y. Ueda, and H. Tanaka

Physical Phenomena at High Magnetic Fields, PPHMF-V
5-9/08/2005, Tallahassee, Florida, USA
The Grenoble High Magnetic Field Laboratory: A user facility
W. Joss

International ICAM Workshop "NMR/EPR of Correlated Electron Superconductors"
15-21 October 2005, Dresden, Germany
Electronic ground states in Na$_x$CoO$_2$ probed by NMR
M.-H. Julien, C. de Vaulx, H. Mayaffre, M. Horvatić C. Berthier, C.T. Lin, P. Lejay

Meeting on Neutron scattering in High Magnetic Fields
October 2005, Grenoble France
Neutron scattering in steady high magnetic fields
W. Joss
2009

1. ESF-WFW Conference in Partnership with LFUI “Graphene Week 2009”
   Oberurgl, Austria, 2-7 March, 2009
   Electronic properties of graphitic layers: magnetic field studies
   http://www.esf.org/index.php?id=5255
   M. Potemski

2. 6èmes Journées scientifiques de l’Association Française de RPE (ARPE)
   Mars 2009, Autrans
   Combination of EPR and quantum chemistry for elucidating the electronic structure of mononuclear Mn(II) complexes
   C. Duboc, M.-N. Collomb, F. Neese

3. 6èmes Journées scientifiques de l’Association Française de RPE (ARPE)
   Mars 2009, Autrans
   Magnetostructural Correlations in Tetrairon(iii) Single-Molecule Magnets

4. 2009 APS March Meeting
   16-20 March 2009, Pittsburgh, PA, USA
   Controlling Luttinger Liquid Physics in Spin Ladders under Magnetic Field

5. 2009 APS March Meeting
   16-20 March 2009, Pittsburgh, PA, USA
   Coexistence of Superconducting and Magnetic Order in CeCoIn5
   Georgios Koutroulakis, Vesna Mitrović, Mladen Horvatić, Claude Berthier, Gerard Lapertot, Jacques Flouquet

6. 2009 APS March Meeting
   16-20 March 2009, Pittsburgh, PA, USA
   BEC of triplon in the complex quantum spin liquid BaCuSi2O6
   Raivo Stern, Steffen Krämer, Mladen Horvatić, Ivo Heinmaa, Enno Joon, Claude Berthier, Tsuyoshi Kimura, Joel Mesot

7. Journées scientifiques de l’IMBG
   Avril 2009, Autrans
   Investigation of the electronic properties of mononuclear Mn(II) complexes by multifrequency EPR and DFT
   C. Duboc, M.-N. Collomb, F. Neese

   12-15 May 2009, Lyon, France
   Frustration Induced New Quantum Phase in the Han Purple compound BaCuSi2O6
   S. Krämer, R. Stern, M. Horvatić, C. Berthier, F. Aimo, T. Kimura
The 9th International Conference on Research in High Magnetic Fields (RHMF 2009)
22-25 July 2009, Dresden, Germany
Towards General Purpose NMR in Ultrahigh Magnetic Fields up to 34 T
S. Krämer, M. Horvatić, C. Berthier, M. Klanjšek, F. Aimo, P.-H. Fries, O. Pauvert, A. Rakhmatullin, C. Bessada and D. Massiot

4th JAEA Synchrotron Radiation Research Symposium: X-ray and High Magnetic Field
5-7 March 2009 at SPring-8, JAPAN
Design study of high field continuous magnets suitable for diffraction experiments

Final EURISOL Town Meeting
30 March – 1 April 2009, Pisa, Italy
60 GHz Electron Cyclotron Resonance (ECR) Ion Source Prototype: calculus of the magnetic structure and CAD Design,
L. Latrasse, T. Lamy, T. Thuillier, C. Trophime, F. Debray, J. Dumas, P. Sala, C. Fourel and J. Giraud

2008

1 IUPAP Cross-Disciplinary
Toronto, Canada, 14-16 February, 2008
Symposium on “Ultracold Nanomatter”
Bose Einstein condensation of excitons but optics of semiconductor quantum dots
http://www.yorku.ca/ucn2008/
M. Potemski

2 Club Métalloprotéines et Modèles, Réunion annuelle
Mars 2008, Fréjus
Définition de corrélations magneto-structurales pour l’ion Mn(II) par RPE à haut champ et calculs DFT
C. Duboc, M.-N. Collomb, F. Neese

3 2008 APS March Meeting
10–14 March 2008, New Orleans, Louisiana, USA
Nature of the superconducting state of CeCoIn$_5$ as revealed by NMR

4 2008 APS March Meeting
10–14 March 2008, New Orleans, Louisiana, USA
Spin-Jahn-Teller effect in the antiferromagnetic molecular wheel CsFe$_8$
O. Waldmann, L. Schnelzer, B. Pilawa, M. Horvatić

5 QUEMOLNA Meeting
29 April 2008, Modena, Italy
Concept of Pulsed High Field EPR Spectrometer Operating at 283.2 GHz
P. Neugebauer, A.L. Barra

6 International Workshop on “Quantum Phases and Excitations in Quantum Hall Systems”
Dresden, Germany, 16-21 June, 2008
Landau level spectroscopy of graphene and graphite
http://www.mpipks-dresden.mpg.de/~qhsyst08/
M. Potemski
Magnetic Resonance Conference EUROMAR-2008
6-11 July 2008, St. Petersburg, Russia
91Zr NMR AT VERY HIGH FIELD IN ZIRCONIUM HALIDES
O. Pauvert, A. Rakhmatullin, C. Bessada, S. Krämer, M. Horvatić, C. Berthier, F. Fayon, D. Massiot

Low Temperature Physics, LT25
6-12 August 2008, Amsterdam, Netherlands
From Luttinger liquids to Bose-Einstein condensation in coupled spin ladders
M. Klanjšek, H. Mayaffre, C. Berthier, M. Horvatić, and T. Giamarchi

GDR MICO 3183 (Matériaux et Interactions en Compétition)
1-4 décembre 2008, Autrans, France
New Quantum Magnetic Phases in SrCu2(BO3)2: A Route to Supersolid Phases?

2008 Symposium, Laboratory for the Applications of Superconductors and Magnetic Materials
30 septembre - 2 octobre 2008, CNRS Grenoble, France
The Grenoble High Magnetic Field Laboratory: actual status of the high magnetic field magnets and opportunities for characterization of superconductors
E. Mossang

2007

1 2007 APS March Meeting
5–9 March 2007, Denver, Colorado, Etats-Unis
Complex 2D Oxide BaCuSi2O6: A NMR Study.

2 2007 APS March Meeting
5–9 March 2007, Denver, Colorado, Etats-Unis
Nature of a possible FFLO state in CeCoIn5 as revealed by NMR,

3 XXème congrès du GERM
25-30 Mars 2007, Alénya, France
High-field NMR studies of the field induced magnetic phase of BaCuSi2O6

4 GECOM-CONCOORD
Mai 2007, Plancoët
Etude des propriétés électroniques de complexes monouncléaires de Mn(II) par RPE à haut champ et par DFT
C. Duboc, F. Neese, M.-N. Collomb

5 Réunion du GDR "NEEM": Nouveaux états électroniques des matériaux
5-8 Juin 2007, Tours, France
La phase x=0 de Na4CoO2
M.-H. Julien, C. de Vaulx, C. Berthier, S. Hébert, V. Pralong

6 « LAW3M » Conference
Août 2007, Rio, Brésil
Symposium sur les champs magnétiques intenses : leur développement en Amérique Latine : High Magnetic Fields in Grenoble
G. Aubert, F. Debray, J. Dumas, W. Joss, S. Krämer, G. Martinez, E. Mossang, P. Petmezakis, Ph.
Sala. J.L. Tholence, C. Trophime and N.Vidal

7 GIRSE-ARPE, First joint meeting
Septembre 2007, Salerne, Italie
Investigation of the electronic properties of mononuclear Mn(II) complexes by high field EPR and DFT
C. Duboc, M.-N. Collomb, F. Neese

8 GIRSE-ARPE first joint meeting’,
Septembre 2007, Salerne, Italie
Origin of the transverse magnetic anisotropy in Mn12 Single Molecule Magnets
A.L. Barra, A. Cornia, D. Gatteschi, L.P. Heiniger, R. Sessoli, L. Sorace

9 2nd Beijing-Grenoble Meeting on Condensed Matter Physics
Pékin, Novembre 2007
High-Field EPR for the study of Single-Molecule Magnets
A.L. Barra

10 Réunion du GDR Magnétisme et Commutation Moléculaires
Gif-sur-Yvette, Dec. 2007
Origine de l’anisotropie transverse dans les ‘Aimants à 1 molécule’ de la famille Mn12
A.L. Barra, A. Cornia, D. Gatteschi, R. Sessoli, L. Sorace

11 Réunion du GDR Magnétisme et Commutation Moléculaires
Gif-sur-Yvette, Dec. 2007

2006

1 2006 APS March Meeting
13-17 March 2006; Baltimore, MD, USA
NMR Study of the Possible FFLO State in CeCoIn$_3$
V. F. Mitrović, M. Horvatić, C. Berthier, G. Knebel, G. Lapertot, J. Flouquet

2 Réunion du Groupe Français d'Etude des Composés d'Insertion GFECI 2006
28-30 mars 2006, Autrans, France
Etudes RMN du magnétisme dans Na$_x$CoO$_2$
M.-H. Julien, C. de Vaulx, H. Mayaffre, M. Horvatić, C. Berthier, P. Lejay, C.T Lin

3 QuEMolNa meeting
April 2006, Valencia
Magnetic characterization of SMM
A.L. Barra

4 Low Energy Electrodynamics in Solids (LEES 06)
2-6 July 2006, Tallinn, Estonia
NMR Study of the frustration induced $1/3$ magnetization plateau of Azurite (Cu$_3$(CO$_3$)$_2$(OH)$_2$)
S. Krämer, M. Horvatić, C. Berthier, A. Comment, H. Kikuchi
Low Energy Electrodynamics in Solids (LEES 06)
2-6 July 2006, Tallinn, Estonia

Complex quantum magnet BaCuSi$_2$O$_6$: A NMR Study

First International workshop on the physical properties of lamellar cobaltates
16-20 July 2006, Orsay, France

$x=0$ and $x=1$ phases of Na$_x$CoO$_2$ studied by NMR

Yamada Conference LX on Research in High Magnetic Fields RHMF 2006
16-19 August 2006, Sendai, Japan

High Field NMR Microscopic Investigation of the Field Induced BEC in the Han Purple BaCuSi$_2$O$_6$
S. Krämer, M. Horvatić, C. Berthier, R. Stern, H. Kikuchi

Yamada Conference LX on Research in High Magnetic Fields RHMF 2006
16-19 August 2006, Sendai, Japan

Field-induced spin rotation transition gives rise to re-entrant superconductivity in ferromagnetic URhGe
I. Sheikin, A.D. Huxley, F. Levy

International Conference on Magnetism (ICM 2006)
20-25 August 2006, Kyoto, Japan

Anomalous Field Induced Staggered Magnetization in the Quantum Antiferromagnet Compound Cu(Hp)Cl
C. Berthier, M. Clémançey, H. Mayaffre, M. Horvatić, B. Chiari, O. PIOvesana

International Conference on Magnetism (ICM 2006)
20-25 August 2006, Kyoto, Japan

Complex 2D Oxide BaCuSi$_2$O$_6$: a NMR Study

International Conference on Magnetism (ICM 2006)
20-25 August 2006, Kyoto, Japan

NMR Studies Towards the Magnetic Structure of the 1/3 Magnetization Plateau Phase in the Frustrated Diamond-Chain Compound Cu$_4$($CO_3$)$_3$(OH)$_2$
S. Krämer, M. Horvatić, C. Berthier, A. Comment, H. Kikuchi

International Conference on Magnetism (ICM 2006)
20-25 August 2006, Kyoto, Japan

High-field de Haas-van Alphen effect study of CeCoIn5 and CeIrIn5
I. Sheikin, D. Aoki, J. Flouquet

2006 Symposium, Laboratory for the Applications of Superconductors and Magnetic Materials
11-13 October 2006, Northwest Institute for Nonferrous Metal Research, Xi’an, P.R. China

Introduction to the GHMFL and high field measurement techniques
E. Mossang

2nd International Workshop on Materials Analysis and Processing in Magnetic Fields
19-22 March 2006, CNRS Grenoble, France

The GHMFL and its instrumentation for high field experiments
E. Mossang

Synchrotron Applications of High Magnetic Fields
16-17 November 2006, Grenoble-France

Radially cooled high field magnet for neutron scattering
F. Debray, M. Enderle, S. Labbé-Lavigne
2005

1. **APS March Meeting 2005**
   21–25/3/2005, Los Angeles, California, USA
   *NMR studies of quantum spin liquids using high magnetic fields: SrCu$_2$(BO$_3$)$_2$ and BaCuSi$_2$O$_6*

2. **Réunion du GDR 2757 "Nouveaux états électroniques des matériaux" (NEEM)**
   10–13/05/2005, Batz sur Mer, France
   *Etude par RMN du composé Na$_2$CoO$_2*
   **C. de Vaulx, M.-H. Julien, C. Berthier, M. Horvatić, V. Simonet, P. Bordet, C.T. Lin***

3. **QUEMOLNA meeting**
   12–14 May 2005, Paris, France
   *Electron Paramagnetic Resonance (EPR) in High Frequency and at High Frequency*
   **P. Neugebauer, A.L. Barra***

4. **Electron Paramagnetic Resonance at High Field and High Frequency: Technology and Applications**
   Budapest, Mai 2005
   *Magnetic and HF-EPR study of an antiferromagnetically coupled Cr$_8$Ni ring : $[(C_6H_{11})_2NH_2][Cr_8NiF_9(O_2CCMe_3)]_{18}$*
   **A.L. Barra***

5. **Journée thématique de l’IMBG : Le Ni et le Mn, deux métaux importants pour le monde vivant**
   Novembre 2005, Grenoble
   *Investigation of mononuclear Mn(II) sites by high field EPR*
   **C. Duboc, A. L. Barra***

6. **2ème réunion annuelle de l’ARPE**
   Décembre 2005, Autrans
   *Etude des propriétés électroniques de complexes polyoxométallates de Cu(II) et de Mn(II) par RPE multifréquence (34-285 GHz)*

   14-17 November 2005 Yokohama, Japan
   *Comparison of magnetic forces acting on electrochemical systems*
   **J.P. Chopart, L. Rabah, J. Douglade, J. Amblard, F. Debray, A. Harrach***
2009

1. **XXI Congrès du GERM**  
8-13 mars 2009, Fréjus, France  
*Towards General Purpose NMR in Ultra High Magnetic Fields up to 34 T*  
*S. Krämer, M. Horvatić, C. Berthier, M. Klanjšek, F. Aimo, P.-H. Fries, O. Pauvert, A. Rakhmatullin, C. Bessada and D. Massiot*

2. **ARPE meeting**  
15-18 mars 2009, Autrans, France  
*Concept of Pulsed High Field / Frequency Electron Paramagnetic Resonance Spectrometer Operating at 283.2 GHz*  
*P. Neugebauer, A.L. Barra*

12-15 May 2009, Lyon, France  
*Spin Configuration in the 1/3 Magnetization Plateau of Azurite Determined by NMR*  
*F. Aimo, S. Krämer, M. Klanjšek, M. Horvatić, C. Berthier, and H. Kikuchi*

4. **GECOM-CONCOORD**  
Juin 2009, Strasbourg-Albé  
*Etudes des propriétés électroniques de complexes de Mn par RPE multifréquence et chimie quantique*  
*C. Duboc, M.-N. Collomb, F. Neese*

5. **The 9th International Conference on Research in High Magnetic Fields (RHMF 2009)**  
22-25 July 2009, Dresden, Germany  
*Magnetic Field control of the Luttinger liquid physics in the weakly coupled spin ladder system CuBr₄(C₅H₁₀N)₂*  
*M. Klanjšek, H. Mayaffre, C. Berthier, M. Horvatic, and T. Giamarchi*

6. **The International Conference on Quantum Criticality and Novel Phases (QCNP09)**  
2-5 August 2009, Dresden, Germany  
*Quantum criticality in spin ladders: from Luttinger liquid physics to Bose-Einstein condensation*  
*M. Klanjšek, H. Mayaffre, C. Berthier, M. Horvatić, and T. Giamarchi*

2008

1. **ESF workshop on Materials for Frustrated Magnetism**  
3-5 March 2008, Grenoble, France  
*¹H and ⁶³,⁶⁵Cu high field NMR studies towards the microscopic structure of the frustration driven 1/3 magnetization plateau of Azurite Cu₃(CO₃)₂(OH)₂*  
*S. Krämer, M. Horvatić, M. Klanjšek, F. Aimo, C. Berthier, A. Comment, H. Kikuchi*

2. **Molmat 2008**  
Toulouse, Juillet 2008  
*Slow relaxation in a tetrairon(III) Single-Molecule Magnet*  
*A. Cornia, L. Gregoli, C. Danieli, A. Caneschi, R. Sessoli, L. Sorace, A.L. Barra, W. Wernsdorfer*
Magnetic Resonance Conference EUROMAR-2008
6-11 July 2008, St. Petersburg, Russia

High Resolution Solid State NMR in Resistive Magnets at Grenoble High Magnetic Field Laboratory
S. Krämer, M. Horvatić, C. Berthier, F. Debray, C. Trophime, N. Vidal, P. Petmezakis, A. Richard, P. Sala

18th International Conference on High Magnetic Fields in Semiconductor Physics and Nanotechnology,
Sao Pedro, BRAZIL, AUG 03-08, 2008

Magnetoresistance Oscillations In Double Quantum Wells under Microwave Irradiation

4th EPR Summer School
22 aug.-1 sept. 2008, St. Andrews, UK

Concept of Pulsed High Field EPR Spectrometer Operating at 283.2 GHz
P. Neugebauer, A.L., Barra

JMC11, 11ème journées de la Matière Condensée
25-29 août 2008, Strasbourg, France

New quantum Magnetic Phases in SrCu_{2}(BO_{3})_{2}; a route to supersolids?

ICMM 2008
Florence, Septembre 2008

HF-EPR study of Cu and Ni cubanes
C. Aronica, Y. Chumakov, E. Jeanneau, D. Luneau, P. Neugebauer, A.L. Barra, B. Gillon, A. Goujon, B. Cousson, W. Weversroder

International COST meeting on Advanced Paramagnetic Methods in Molecular Biophysics
Siena, Septembre 2008

HF-EPR study of a mononuclear Mn(III) model complex

Highly Frustrated Magnetism 2008
7-12 September 2008, Braunschweig, Germany

NMR investigation of Azurite, the frustrated diamond spin chain
S. Krämer, M. Klanjšek, F. Aimo, M. Horvatić, C. Berthier, H. Kikuchi

GDR MICO 3183 (Matériaux et Interactions en Compétition)
1-4 décembre 2008, Autrans, France

High-field NMR studies of the modulated BEC in BaCuSi_{2}O_{6}

GDR MICO 3183 (Matériaux et Interactions en Compétition)
NMR investigation of Azurite, a frustrated diamond spin chain
S. Krämer, M. Horvatić, C. Berthier, R. Stern, T. Kimura and I. Fisher

GDR MICO 3183 (Matériaux et Interactions en Compétition)
F. Aimo, S. Krämer, M. Klanjšek, M. Horvatić, C. Berthier, H. Kikuchi

Controlling Luttinger Liquid Physics in Spin Ladders under a Magnetic Field
2007

1. **Conférence ‘ESR-2007**
   Oxford, Mars 2007
   
   *EPR of the Single Molecule Magnet Mn12tBuAc: origin of transverse magnetic anisotropy*
   A.L. Barra, A. Janoschka, V. Schünemann, C. Schmidt

2. **ARPE meeting**
   20 March 2007, Paris, France
   
   *Electron Paramagnetic Resonance at 283.2 GHz*
   P. Neugebauer, A.L. Barra, J. Florentin

3. **XXème congrès du GERM**
   25-30 Mars 2007, Alénya, France
   
   *High resolution solid state NMR in resistive magnets at Grenoble High Magnetic Field Laboratory (GHMFL)*
   S. Krämer, C. Berthier, M. Horvatić, C. Chauvin, F. Debray, C. Trophime, N. Vidal, P. Petmezakis, A. Richard, P. Sala

4. **EUROMAR2007**
   1-6 July 2007, Tarragona, Spain
   
   *Fabry-Pérot Resonator for Electron Paramagnetic Resonance (EPR) Experiments*
   P. Neugebauer, A.L. Barra

5. **MT 20 – 20th International Conference on Magnet Technology**
   27-31 August 2007, Philadelphia, Pennsylvania, Etats-Unis
   
   *High resolution solid state NMR in resistive magnets at Grenoble High Magnetic Field Laboratory (GHMFL)*
   S. Krämer, C. Berthier, M. Horvatić, C. Chauvin, F. Debray, C. Trophime, N. Vidal, P. Petmezakis, A. Richard, P. Sala

6. **GIRSE-ARPE first joint meeting**
   30 sept-03 oct. 2007, Vietri-sul-Mare, Italy
   
   *Fabry-Pérot Resonator for Electron Paramagnetic Resonance (EPR) Experiments*
   P. Neugebauer, A.L. Barra

7. **GDR MCM (Magnétisme et Commutation Moléculaires)**
   3-5 December 2007, Gif-sur-Yvette, France
   
   *The Pulsed High Field / High Frequency Electron Paramagnetic Resonance Spectrometer Concept*
   P. Neugebauer, A.L. Barra

2006

1. **2006 APS March Meeting**
   13-17 March 2006; Baltimore, MD, USA
   
   *$^{51}$V-NMR investigation of the spin-frustrated magnet Ni$_3$V$_2$O$_8$*
   W.G. Clark, P. Ranin, Guoqing Wu, G. Gaidos, G. Lawes, A.P. Ramirez, R.J. Cava, M. Horvatić, C. Berthier

2. **EUROMAR 2006**
   16-21 July 2006; York, UK
   
   *High Filed EPR study of powder of a cubane Ni4 compound*
   P. Neugebauer, C. Aronica, A.L. Barra, D. Luneau
Yamada Conference LX on Research in High Magnetic Fields RHMF 2006
16-19 August 2006, Sendai, Japan

$^{77}$Se NMR studies at a wide magnetic field range on the field induced superconductor, $\lambda$-(BETS)$_2$FeCl$_4$

International Conference on Magnetism (ICM 2006)
20-25 August 2006, Kyoto, Japan

$^{77}$Se Microscopic Evidence for the Jaccarino-Peter Mechanism in the Organic Charge Transfer Complex $\lambda$-(BETS)$_2$FeCl$_4$

2$^{ème}$ conférence internationale de l’IMBG
Septembre 2006, Autrans

How high field EPR can be used for the study of mononuclear Mn(II) sites
C. Duboc, J. Michaud Soret, J. Pécaut et M.-N. Collomb

Conférence EFEP R
Madrid, Septembre 2006

High-Field EPR of ferrous high-spin iron center of a rubredoxin type electron transfer protein
A.L. Barra, A. Janoschka, V. Schünemann, C. Schmidt

5$^{ème}$ Réunion annuelle du Club Métalloprotéines et modèles
Octobre 2006, Aussois

Etude de la structure électronique de complexes mononucléaires de Mn(II) par RPE à haut champ et à haute fréquence
C. Duboc, J. Pécaut, T. Phoeung, C. Mantel, M.-N. Collomb

4$^{ème}$ International Workshop on Mechanical and Electromagnetic Properties of Composite Superconductors (MEM 06)
Durham University, UK, 2-5, Juillet 2006

The Grenoble High Magnetic Field Laboratory (GHMFL)
E. Mossang, F. Debray, W. Joss, G. Martinez, P. Petmezakis, P. Sala, J.L. Tholence, C. Trophime

2005

1 Workshop Manipulating Quantum Spins and Classical Dots
Les Houches, Avril 2005

HF-EPR study of the in-plane magnetic anisotropy of Mn12
A.L. Barra

2 4$^{èmes}$ Journées scientifiques de l’IMBG
Avril 2005, Autrans

Etude des propriétés électroniques de complexes mononucléaires de Mn(II) magnétiquement dilués par RPE multifréquence (9 - 285 GHz)
C. Duboc, T. Phoeung, J. Pécaut, M.-N. Collomb

3 International Symposium on Molecular Conductors ISMC 2005
17–21/07/2005, Hayama, Japan

$\pi$-$d$ interaction in $\lambda$(BETS)$_2$FeCl$_4$. $^{77}$Se NMR
4 12th International Conference on Bioinorganic Chemistry (ICBIC)
Août 2005, Ann Arbor, USA
High Field EPR: A powerful tool for the study of mononuclear Mn(II) sites
C. Duboc, J. Pécaut, T. Phoeung, C. Mantel, M.-N. Collomb

5 Physical Phenomena at High Magnetic Fields-V, (PPHMF-V)
6–9/08/2005, Tallahassee, Florida, USA
Quantum spin liquid BaCuSi2O6 and BEC of triplons: a NMR study

6 24th International Conference on Low Temperature Physics (LT24)
10–17/08/2005, Orlando, Florida, USA
Quantum spin liquid BaCuSi2O6 and BEC of triplons: a NMR study

7 4ème Réunion annuelle Club Métalloprotéines et modèles
Septembre 2005, Carry le Rouet
High Field EPR: A powerful tool for the study of mononuclear Mn(II) sites
C. Duboc, J. Pécaut, T. Phoeung, C. Mantel, M.-N. Collomb

8 COST P15 meeting
Budapest, Octobre 2005
High-field EPR of ferrous high-spin iron centers of a rubredoxin type electron transfer protein
A.L. Barra

9 Conférence « La RPE en France : Perspectives et Enjeux Scientifiques »
Autrans, Décembre 2005
Multifrequency EPR study of ferrous iron centers of a rubredoxin type protein
A.L. Barra, A. Janoschka, V. Schünemann, C. Schmidt

10 19th International Conference on Magnet Technology
Genova, Italy, 18-23 Sep 2005
The Grenoble High Magnetic Field Laboratory
G. Aubert, F. Debray, H. Jongbloets, W. Joss, G. Martinez, E. Mossang, P. Petmezakis, P. Sala, C. Trophime and P. Wyder
2007

1. M. Fontecave, C. Duboc
   *Metals in biocatalysis: from metalloenzymes to bio-inspired systems*

2005

1. Barra A.L. and A.K.Hassan
   *Electron spin resonance*

2. Bassani F., G.L.Liedl and P.Wyder
   *Encyclopedia of Condensed Matter Physics*
   Publisher: Elsevier Physics, eds. G.F.Bassani, G.L.Liedl, P.Wyder, 2005

3. de Brion S., M.D.Nunez-Regueiro and G.Chouteau
   *Orbital and spin order in the triangular S=1/2 layed compound (Li,Na)NiO2*

   *Electron Spin Resonance*

AP

Contribution to the upgrade program of the ESRF in the frame of ESFRI financed by the European Commission

*Steady magnetic fields for neutron and X-ray scattering*

*Variable temperature characterization of NbTi strands for JT-60 SA TF coils : manufacturing process optimization*, ref. AIM/NTT-2008.011
Prix et distinctions

Highlight ANR PNANO 2008 (www.r3n.org) pour “ANR MICONANO - ANR-05-NANO-059
Coordinateur : J.-C. Portal

Sami Sassine, Prix International "AIXTRON Young Scientist Award" 2007

Sami Sassine, Prix de la meilleure thèse INSA 2007 (ED GEET) Thèse effectuée au LCMI

C. Duboc, Médaille de Bronze du CNRS, section 13, 2007

C. Duboc, Prix de la division chimie physique de la SFC, 2007, C. Duboc

Organisation de colloques et de portée nationale/internationale

6èmes Journées scientifiques de l’ARPE (national)
A.-L. Barra, G. Blondin, C. Duboc, B. Guigliarelli, Mars 2009, Autrans (55 participants)

Ecole thématique du CNRS de RPE : techniques avancées (national)
A.-L. Barra, G. Blondin, C. Duboc, B. Guigliarelli, Juin 2008, Autrans (50 participants)

International workshop on Materials For Frustrated Magnetism (international)

European School : Magnetic Field for Science (international, in the framework of Euromagnetl)
M. Potemski, C. Faugeras, D.K. Maude, M. Sadowski, G. Ménéroud, R. Graziotti; A. Pic
Cargese, 27/08-08/09 2007 (90 participants)

2ème conférence internationale de l’IMBG (international)
C. Duboc (porteur du projet), M. Atta, C. Belle, F. Catty, M.-N. Collomb, M. Fontecave, S. Ménage, F. Thomas, Septembre 2006, Autrans (100 participants)

Ecole thématique du CNRS de formation à la RPE (national)

2ème réunion scientifique de l’ARPE (national)
A.-L. Barra, C. Duboc, S. Gambarelli, Décembre 2005, Autrans (50 participants)

Journée thématique de l’Institut des Métaux en Biologie de Grenoble (IMBG) sur "Le nickel et le manganèse : deux métaux importants dans la chaîne de la vie" (national)
C. Belle, M.-N. Collomb, C. Duboc, F. Thomas Novembre 2005, Grenoble (50 participants)

Colloquium “Science in High Magnetic Field (international)
G. Chouteau, Grenoble Juin 2005 (60 participants)

4èmes journées scientifiques de l’IMBG (national)
C. Belle, C. Duboc, J.-M. Mouesca, Mars 2005, Autrans (60 participants)
Annexe 1

Enseignement et formation par la recherche,
Information et culture scientifique et technique

Formations dispensées par les personnels du LCMI/LNCMI-G de 2005 à 2009

<table>
<thead>
<tr>
<th>Formation</th>
<th>Intervenant</th>
<th>Stagiaires</th>
<th>Durée</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enseignement Sciences Physiques</td>
<td>De Muer (maître de conférences)</td>
<td>Etudiants IUT 1 UJF</td>
<td>250 h / an</td>
</tr>
<tr>
<td>Travaux dirigés atelier électronique</td>
<td>Petmezakis Yildiz</td>
<td>Etudiants Polytech Grenoble UJF</td>
<td>130 h / an</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Etudiants</td>
<td>90 h / an</td>
</tr>
<tr>
<td>Encadrement projet</td>
<td>De Marinis</td>
<td>Etudiants PHELMA INPG</td>
<td>36 h / an</td>
</tr>
<tr>
<td>Travaux pratiques Chimie organique</td>
<td>Brefuel</td>
<td>Etudiants en licence UJF</td>
<td>32 h / an (équ. TP)</td>
</tr>
<tr>
<td>Communication et valorisation du laboratoire</td>
<td>Debray De Muer Faugeras Guillot Krämer Mossang Petmezakis Rikken Tholence</td>
<td>Grand Public (Fête de la Science), Scolaires, Universitaires</td>
<td>équ. 10 jours / an</td>
</tr>
</tbody>
</table>

Encadrement de stagiaires

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>BTS DUT</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Licence</td>
<td>4</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Master</td>
<td>7</td>
<td>4</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>
Annexe 2

Action de formation permanente des personnels de l’unité
Partie commune LCMI-LNCMP

Les activités du LCMI, issu de la fusion du LNCMP de Toulouse et du LCMI de Grenoble, sont très étendues. Les disciplines techniques incluent la conception et fabrication mécanique, la métallurgie, l’électrotechnique haute tension, la cryogénie et l’instrumentation. Au niveau scientifique, plusieurs domaines de la physique, dont le magnétisme, la supraconductivité, les semi-conducteurs et la nano-physique sont couverts par le LNCMI, utilisant des techniques de transport, d’optique etc... Etant donné le rôle international que joue le LNCMI, les agents se doivent d’entretenir et de développer leurs compétences et performances techniques et/ou scientifiques au meilleur niveau mondial.

Les formations suivies, pendant la période 2005-2009, par les personnels du LNCMP-Toulouse étaient en partie issues d’offres de formation transversales en provenance des 3 tutelles. L’accent a été mis sur le suivi de cours d’anglais pour les personnels ITA amenés à interagir avec les visiteurs étrangers et sur l’initiation des chercheurs à l’utilisation des machines-outils (dans le cadre des PFU 2005/2006/2009, 3 sessions de formation ont été mises en œuvre dans nos locaux). Des formations techniques dans des domaines spécifiques permettant l’acquisition de connaissances et de compétences nouvelles dans le but d’accompagner de façon optimale les activités de recherche ont été mises en œuvre soit de façon individuelle (conception et caractérisation de circuit hyperfréquences, techniques de microbiologie, langage de programmation, logiciel de CAO/DAO…), soit de façon collective (stage d’électronique radiofréquence, stage de prise en main pour la fraiseuse à commande numérique suivi d’une formation au logiciel de programmation ESPRIT, stage d’instrumentation LABVIEW). L’accompagnement des nouveaux entrants s’effectue par des formations spécifiques à leur activité dans le laboratoire (XLab et Labintel pour le secrétariat et formation Web pour le gestionnaire réseaux). Des formations à l’encadrement ont aussi été mises en œuvre (management, conduite de projets...). De plus, des formations pour améliorer la sécurité au laboratoire ont été suivies par un grand nombre des membres du LNCMP (SST, conduite des ponts roulants, manipulation des extincteurs). D’autre part, plusieurs membres du laboratoire appartiennent aux réseaux de métiers (mécaniciens, électroniciens, opticiens, informaticiens) animés par le CNRS.

Pendant la période 2005 – 2009, les personnels du LCMI Grenoble ont suivi 134 formations. Etant donné que le LCMI est un grand instrument avec des grosses installations techniques une grande partie des formations sont effectuées dans les domaines « techniques spécifiques » et « informatique (applications) ». De nouvelles compétences étaient notamment acquises par les personnels pour permettre le développement de nouvelles technologies dans le domaine de la conception des aimants résistif (conducteurs, éléments finis, CATIA), ainsi que dans le domaine de pilotage et supervision (Starter TiA, conception avec UML) en vu de modifications majeures sur les installations de puissance de 24 MW.

D’autres formations dans les domaines cryogénie, optique, Labview, instrumentation et électronique ont été effectuées pour améliorer l’accompagnement technique des visiteurs scientifiques et les activités de recherche dans le laboratoire. Une attention particulière a notamment été portée à la formation des agents de l’équipe informatique compte tenu de l’évolution rapide des techniques réseaux. La mise en place d’un centre d’usinage 4 axes ½ utilisé également pour la fabrication d’aimants a nécessité le développement de compétences de programmation des agents de l’atelier mécanique. Un autre agent a suivi une formation d’usinage mécanique dans le but d’améliorer le service auprès des chercheurs travaillant sur les aimants résistifs.

L’adaptation au poste de travail des nouveaux entrants a pu être facilitée par des formations notamment dans les domaines de la gestion de la recherche et la bureautique (XLAB, SIFAC, ACCESS, EXCEL, WORD).
Le laboratoire accueille chaque année un grand nombre de visiteurs étrangers pour des périodes de courtes ou moyennes durées. En effet, la maîtrise de la langue anglaise à l’oral et à l’écrit des personnels de toutes les catégories est d’une grande importance. D’autre part, un certain nombre de thésards et post-doc étrangers ont suivi une formation de la langue française. Plusieurs formations ont également été réalisées avec le but d’améliorer l’efficacité personnelle ainsi que le management et le travail en équipe (techniques de la communication, animer un groupe de travail, réaliser un entretien de carrière et rédiger un rapport d’activité, gestion du temps etc.). La forte proportion des formations dans le domaine de l’hygiène et la sécurité est en rapport avec la présence d’installations de puissance mais aussi liée aux activités dans les domaines de la cryogénie et chimie ainsi qu’aux travaux de manutention. De plus, un certain nombre d’agents participe aux réseaux de métiers CNRS (mécaniciens, informaticiens, opticiens et électroniciens).

Depuis le 2 février 2009, date de création du LNCMI (UPR3228) issue de la fusion du LNCMP de Toulouse et du LCMI de Grenoble, les 2 sites, toulousain et grenoblois, du LNCMI se concertent afin de mettre en place des synergies communes de formation pour les années à venir.
Annexe 3

Hygiène et sécurité
Laboratoire Champs Magnétiques Intenses, Grenoble

1. Bilan des accidents et incidents survenus dans l’unité :

<table>
<thead>
<tr>
<th>date</th>
<th>nature de l’accident</th>
<th>mesures prises</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Brûlure cryogénique de la main à l’hélium liquide</td>
<td>Visite à l’infirmerie du CNRS</td>
</tr>
<tr>
<td></td>
<td>Contact à mains nues avec un élément portant des traces d’acide fluorhydrique</td>
<td>Utilisation d’une ampoule de gluconate de calcium, rappel d’utilisation des EPI</td>
</tr>
<tr>
<td></td>
<td>Lombalgie</td>
<td>Arrêt de travail pendant 6 semaines</td>
</tr>
<tr>
<td>2006</td>
<td>Accident de trajet en vélo</td>
<td>Soins internes</td>
</tr>
<tr>
<td></td>
<td>Accident de trajet : chute en vélo sur sol glissant (entorse à la main)</td>
<td>Soins internes</td>
</tr>
<tr>
<td></td>
<td>Accident de trajet : l’agent, en vélo, a été percuté par un scooter sur la piste cyclable</td>
<td>Visite à l’infirmerie du CNRS et médecin du travail</td>
</tr>
<tr>
<td>2007</td>
<td>Chute dans l’escalier (entorse au pied)</td>
<td>Soins internes, rappel aux agents de tenir la rampe</td>
</tr>
<tr>
<td></td>
<td>Chute d’une plateforme élévatrice lors d’un contrôle visuel après l’installation (fracture du bras)</td>
<td>Appel des secours (pompiers) et transport à l’hôpital</td>
</tr>
<tr>
<td></td>
<td>Accident de trajet : chute sur piste cyclable (plaie à la tête)</td>
<td>Visite à l’infirmerie du CNRS, puis le médecin traitant</td>
</tr>
<tr>
<td></td>
<td>Accident de trajet : agent piéton renversé par un cycliste (fracture du coude, contusions)</td>
<td>Consultation du médecin du travail, puis médecin traitant, arrêt de travail pendant 2 mois</td>
</tr>
<tr>
<td></td>
<td>Chute dans l’escalier (contusion au bras)</td>
<td>Consultation du médecin du travail</td>
</tr>
<tr>
<td></td>
<td>Choc au tibia lors de la manutention d’une pièce métallique (déchirures musculaires)</td>
<td>Soins internes</td>
</tr>
<tr>
<td></td>
<td>Malaise (vertiges soudains) d’un agent au travail</td>
<td>Appel des secours (pompiers), transport et examen ORL à l’hôpital</td>
</tr>
</tbody>
</table>

2. Identification et analyse des risques spécifiques rencontrés dans l’unité :

L’évaluation des risques lors de la mise en place du Document Unique a montré que les principaux risques identifiés au LNCMI-G sont le risque électrique et magnétique, le risque d’incendie, le risque cryogénique, le risque chimique et le risque lié à la manutention.

3. Dispositions mises en œuvre en fonction des risques et priorités retenues :

Risque électrique : les zones des installations de puissance sont sécurisées (enclos grillagé englobant toute l’installation à l’intérieur duquel l’accès est interdit aux personnes non habilitées) et une procédure de consignation des installations est systématiquement appliquée pour toutes les interventions.

Chaque salle d'expériences est équipée d'un arrêt d'urgence général qui se trouve à l'extérieur de la salle concernée.

Risque magnétique : les zones à risque sont indiquées par des panneaux lumineux qui montrent si un aimant est en marche ou par des autocollants « attention champ magnétique » et « interdit aux porteurs de stimulateurs cardiaque » à l’extérieur des salles ainsi qu’aux entrées des différents bâtiments qu’occupe le laboratoire.

Risque cryogénique : Les sous-sols, qui présentent un risque d’anoxie et d’asphyxie liés aux gaz cryogéniques fréquemment utilisés au laboratoire, sont équipés de capteurs d’oxygène reliés à une centrale de détection. Un taux d’oxygène passant sous le seuil de 19% déclenche une alarme sonore et le fonctionnement de panneaux lumineux clignotants. Cette installation fait l'objet d'un contrat de maintenance avec une vérification trimestrielle.

Risque chimique : La venue d’un ingénieur chimiste a permis de réorganiser le laboratoire de chimie et d’actualiser l’inventaire des produits chimiques utilisés. Les produits non utilisés ou périmés ont été éliminés. Un stockage extérieur des solvants a été mis en place avec l’accord de l’IRPS. Par ailleurs, une liste des produits chimiques présents au laboratoire de chimie est accessible sur l’intranet.

Risque lié à la manutention : Les appareils de levage et de manutention (17 palans, 8 ponts-roulants, 4 chariots élévateurs) font l’objet de vérifications périodiques. En 2007, ces appareils ont également été vérifiés à charge nominale ou jusqu’à 5 tonnes. Par ailleurs, tous les équipements de manutention (sangles, chaines, crochets, manilles …) ont été contrôlés par l’APAVE en 2006.

4. Fonctionnement des structures d’hygiène et de sécurité propres à l’unité :

Le laboratoire compte 2 ACMO en raison de la forte potentialité de danger due à la complexité des installations. 10% de leurs temps de travail est consacré à la réalisation de leurs missions.

La commission hygiène et sécurité (CHS) se réunit une fois par an. Elle est présidée par le directeur de l'unité et se compose de l'Ingénieur Régional de Prévention et de Sécurité (IRPS), du médecin du travail, de l'infirmière, de l'assistante sociale, des 2 ACMO et de 5 membres nommés par le directeur parmi le personnel scientifique et technique du laboratoire qui représentent les différents services du laboratoire : 1 chercheur, 1 ingénieur de recherche en charge des utilisateurs des sites d'aimants, 1 technicien en charge des installations hydrauliques et 2 membres de l'équipe responsable des travaux des bâtiments.

Un registre d’hygiène et de sécurité ainsi qu’un registre de sécurité et des contrôles obligatoires est à la disposition des agents dans le bureau des ACMO.

5. Dispositions mises en œuvre pour la formation des personnels et des nouveaux entrants :

Les formations du personnel dans le domaine de la sécurité ont toujours été très encouragées par la direction du laboratoire. Elles sont également inscrites dans le Plan de Formation de l’Unité qui est établi chaque année.

L’accent est mis sur les formations suivantes : habilitations électrique, cariste, pontier-élargleur, secourisme. Les nouveaux entrants sont encouragés à suivre les formations initiales tandis que les agents déjà formés participent aux recyclages périodiques. Un certain nombre d’agents ont également réalisé des formations concernant le risque laser et l’utilisation des extincteurs.

En 2008, une sensibilisation au risque chimique rencontrés dans les ateliers mécaniques (bains d’acides, utilisation de solvants et colles) a été spécialement effectué par l’IRPS pour les techniciens du laboratoire, utilisateurs occasionnels de produits chimiques qui n’ont aucune formation dans le domaine de la chimie.

Une brochure d’information présentant un résumé de tous les risques présents au laboratoire est systématiquement distribuée aux nouveaux entrants et utilisateurs des sites d’aimants.

Les comptes-rendus des CHS, la brochure d’information sur les risques, des consignes concernant l’élimination des huiles usées ainsi que les listes des secouristes et caristes sont disponibles en permanence sur l’intranet du laboratoire dans la rubrique Hygiène et Sécurité.

6. Problèmes de sécurité qui subsistent :

Risque d'incendie : Suite à l’installation des alarmes sonores, il reste à planifier une organisation humaine et matérielle des secours (désignation de serre-fils, guides d’évacuation, définition de points
de regroupement, etc…). Ceci doit se faire avec l’IRPS dans le cadre plus global de l’ensemble du site du polygone CNRS.

**Signalisation** : La signalisation des personnes à appeler (responsable de la salle) en cas d’un problème matériel majeur dans une salle d’expérience doit être mise à jour.

**Risque électrique** : Il est nécessaire de refaire un diagnostic de l’équipement électrique du laboratoire par un organisme agrée. Les installations électriques en amont des disjoncteurs de chaque salle ont déjà été vérifiées.

**Nouveaux entrants** : Un certain nombre de thésards et post-doc ne maîtrisent pas suffisamment la langue française à leur arrivée au laboratoire. Les formations dans le domaine de la sécurité doivent notamment être suivies au début de la prise des fonctions, il est donc urgent de trouver du matériel de formation en langue anglaise.
PROJET SCIENTIFIQUE
2011-2014

Laboratoire National des Champs Magnétiques Intenses
LNCMI – UPR 3228

Etablissement de rattachement : CNRS – Institut National de Physique

Lié par convention avec
l’Université Joseph Fourier Grenoble 1
l’Université Paul Sabatier Toulouse 3
l’INSA de Toulouse

AERES
Campagne d’évaluation 2011-2014
<table>
<thead>
<tr>
<th>Table of contents</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>General overview</td>
<td>3</td>
</tr>
<tr>
<td>Technical perspectives</td>
<td>5</td>
</tr>
<tr>
<td>Scientific perspectives</td>
<td>15</td>
</tr>
<tr>
<td>Auto analysis</td>
<td>25</td>
</tr>
</tbody>
</table>
General overview

Introduction
The Laboratoire National des Champs Magnétiques Intenses (LNCMI) was created on 1/1/2009 through the merger of the Laboratoire des Champs Magnétiques Intenses (LCMI UPR5021 in Grenoble) and the Laboratoire National des Champs Magnétiques Pulsés (LNCMP UMR5147, Toulouse), as part of the Très Grands Instruments de la Recherche (TGIR) of the CNRS. Like its two predecessors, it has three main missions:
- to generate the highest possible magnetic fields for research purposes
- to use these fields for in-house research and to develop the necessary scientific infrastructure
- to provide access to qualified French and European users to these high magnetic fields and the surrounding scientific infrastructure.

The rationale behind the merger was the potential synergy between the two laboratories in terms of scientific programs and instrumentation and the increased weight and impact of a unified position in the negotiations with partners and funding agencies. The first implementations of the synergy and the consequences of the increased weight of the laboratory are becoming visible. For the coming years, the LNCMI will further expand upon this synergy.

Context
The generation of very high magnetic fields is a technological challenge, the maximum fields being limited by Joule heating and Lorentz forces. High field magnets operate very close to the engineering limits of these parameters. Further progress in this domain requires significant efforts in materials research, non-linear multi-physics finite element analysis and mechanical fabrication techniques, implying ever increasing design and manufacturing costs. Also the exploitation requires a high financial commitment, because of electrical power consumption for DC magnets and cooling by cryogenic liquids for pulsed magnets. Therefore not many infrastructures exist where very high magnetic fields can be generated and used for research. Over the last twenty years, financial limitations and the complexity of such installations have resulted in a continuous concentration of these activities in less but larger infrastructures, very often operated on a national scale. For generating continuous magnetic fields in excess of 30 T, powered with 15+ MW power supplies, installations can be found in the USA (Tallahassee), Japan (Tsukuba) and Europe (Grenoble and Nijmegen). Large pulsed field installations based either on motor generators or large (> 5 MJ) capacitor banks are found in Los Alamos (USA), Tokyo (Japan), and in Europe in Toulouse and in Dresden (created in 2006). As the most recent step in this trend, the Chinese government has recently funded a static field installation in Heifei and a pulsed field installation in Wuhan, which are currently under construction and which will become operational by 2010. Still the clearest example of this trend is the creation of the National High Magnetic Field Laboratory (NHMFL) in the USA, a three site organization that pioneers all aspects of high magnetic field generation, and its use for scientific experiments.

In Europe, for historical and political reasons, the high magnetic field landscape was much more finely distributed and therefore less effective and visible; The Netherlands have had separate DC and pulsed field laboratories, which were integrated into the new Nijmegen installation in 2003. The UK also has had DC (Oxford) and pulsed (Oxford and Bristol) installations, which are being shut down for lack of critical mass. Germany has withdrawn from the joint French-German DC installation in Grenoble, and has created a new pulsed field facility in Dresden (2006).

France has had separate DC and pulsed field infrastructures (LCMI and LNCMP respectively) until 1/1/2009. Although performing quite well as compared to their counterparts abroad in terms of publications and technical performance, the lack of recent major investments in their installations caused their long term competitiveness to decrease. A first major step towards improving France’s position in high magnetic field science was the merger of the LCMI and LNCMP into the LNCMI, per 1/1/2009. For the future, several large projects are being developed that will restore the leading role France has had in the area of high magnetic field research, as described below.
European perspectives
On a European scale, a major step was the funding in 2005 under FP6 of the EuroMagNET Integrated Infrastructure Initiative (I3), which united most of the European high field facilities, with a common transnational access programme, networking and joint research activities (www.euromagnet.org). Its successor, EuroMagNET II, has recently started (1/1/2009, for 4 years), this time integrating all major European high field facilities (LNCMI Toulouse/Grenoble, HLD Dresden and HFML Nijmegen) (www.euromagnet2.eu), with the LNCMI as coordinator. A further integration of these four installations into one distributed European Magnetic Field Laboratory (EMFL, www.emfl.eu) has been proposed, and this proposal is now part of the ESFRI Roadmap. The EMFL proposal also foresees the integration of high magnetic fields with the ESRF X ray source and the ILL neutron source in Grenoble. These two large facilities have proposed the construction of a joint high field faculty on their site in the context of their upgrade programs, which are also part of the ESFRI Roadmap. The EMFL proposal is currently being elaborated in the context of a FP7-Infrastructures-Preparatory Phase call, dedicated to the new arrivals on the ESFRI Roadmap (deadline 3/12/2009, result spring 2010).

Organigramme
Technical perspectives

Field generation

Introduction
The continuous quest for higher and higher magnetic fields is part of a more general trend of studying matter under more and more extreme conditions, like very high pressures or very low temperatures. At the same time, the ongoing improvements of superconducting magnet technology (state of the art 23.5 Tesla) force the high field facilities to increase the field strength they can propose to their users to higher values, in order to be able to offer sufficient added value and to provide a convincing reason for their existence. An ad-hoc criterion that has been respected over the last decades is that when going from superconducting magnets to resistive magnets to pulsed magnets, the maximum field strength doubles each time.

Recent developments in superconducting technology suggest that superconducting magnets will cross the 25 T mark within the next 5 years. High Tc superconductors offer in principle a potential to go much higher, but major materials processing issues have to be solved before such a potential can be realized. The current maximum value for a DC resistive magnetic field is 45 T (a hybrid magnet at the NHMFL in Tallahassee, with similar hybrid magnet projects underway in Grenoble (see below), Nijmegen and Heifei), whereas a 60 T hybrid project is being considered by the NHMFL. For purely resistive magnets, the field record is at 35 T (Grenoble and Tallahassee), but the LNCMI-G has an ongoing program to push this value towards 40 T by 2012 and a similar project exists at the NHMFL. For non-destructive pulsed magnets, the maximum field value is 89 T (obtained at the NHMFL in Los Alamos with a multi-coil system, with similar projects underway in Dresden and Toulouse). The Los Alamos and Dresden projects are aiming at 100 Tesla, and are steadily progressing towards that aim. The Toulouse facility can not currently develop a credible 100 T project, because of the limitations of its current high voltage capacitor bank and because of security issues with the magnet cells. In the context of the Contrat Plan Etat Region Midi Pyrénées 2007-2013, an extension of the building with explosion-safe cells and fast high voltage modules are foreseen, that will remedy these problems, which will open the route towards 100 T, and that will allow the LNCMI-T to maintain its long term international competitiveness.

To go beyond the field limits imposed by the mechanical properties of current engineering materials, one has to accept that the magnet is destroyed during a magnetic field pulse. The use of a very fast (sub microsecond rise time) high voltage (60 kV) and high current (2 MA) generator allows the use of single turn coils that are destroyed during a field pulse without harming the experimental setup inside the coil. Such an installation has been constructed at the LNCMI-T and will be progressively put into use to study matter under extremely high magnetic fields (up to 300 T).
**Materials research**

The maximum magnetic field that a well designed DC resistive magnet can produce is limited both by the Lorentz forces and by the Joule heating. Therefore a strong and low resistivity conductor is needed for such magnets, two requirement that are mutually exclusive.

Pulsed magnets partly free themselves from the latter constraint by limiting the magnetic field duration to a value that leaves the magnet after the pulse at an acceptable temperature. This allows to use stronger materials that enable the magnet to generate much higher fields. However, as the necessary pulse duration for a sensitive experiment cannot be arbitrarily reduced, also the materials for pulsed magnets should have a reasonable electrical conductivity.

The LNCMI-T has a long standing tradition in materials research and development for high strength conductors, whereas the LNCMI-G has so far relied on commercially available alloys. The merger allows the LNCMI-G to benefit from the know-how and conductors of the LCNMI-T. In particular the use of stainless steel jacketed copper conductors (CuXSSY) and of cold worked copper-silver alloys (CuAg) could contribute greatly to increasing the field strength of the DC resistive field magnets in Grenoble (see figure below). Part of the materials research effort at LNCMI-T will be directed towards such aims, and collaborations with industrial partners will be sought.

![Graph showing electrical conductivity and yield strength of different conductors](image)

*Summary of different conductors in use for resistive pulsed (red squares) and DC (other symbols) magnets at the LNCMI*

In order to limit the electrical power consumption of Grenoble DC high field installation, it will be necessary to participate in the development of superconductor materials that are capable to be used in hybrid magnets, or in stand alone 25+ T all superconducting magnets. To this aim, several collaborations are underway with external partners.
Evolution of standard DC resistive magnets

Based on the expertise that the LNCMI-G has acquired over the recent years with the polyhelix technology, on recent advances in commercial copper alloys and radial cooling techniques, and backed by extensive finite element modelling, it is extrapolated that DC resistive fields up to 39 T should be possible, within a time span of 5 years (see figure below). The R&D to realize this potential will be one of the priorities of the LNCMI-G for the coming years. Provided that the necessary financial means can be found, this will bring the LNCMI back to the leading position in high magnetic field technology.

The improved coil efficiency resulting from the above developments will also allow to generate somewhat more modest fields (28+ Tesla) with only 12 MW electrical power consumption. This will allow to operate two such magnets simultaneously, greatly increasing the LNCMI-G capacity and will allow to do high field experiments at reduced electricity consumption. In view of the long term sustainability of a high field facility, this latter aspect is becoming more and more important.

Another route to increasing the field strength available for experiments at constant electrical power consumption and with the available conductors would be to reduce the bore size e.g. to 25 mm. This will of course complicate cryogenics and other aspects of the experiments to be performed in such a magnet. By implementing the bore size reduction by means of a magnet insert that operates at lower temperature (e.g. cooled by liquid nitrogen), an even more significant gain in field strength, can be obtained. First estimates suggest fields in excess of 42 T for such a configuration, which will be studied and modelled in greater detail in the future.

![Graph showing the evolution of maximum static magnetic field available at LNCMI-G](image)

*Evolution, realized and expected, of the maximum static magnetic field available at LNCMI-G*
Hybrid magnet

Hybrid magnets, the combination of a resistive inner coil with a superconducting outer one, allow to generate the highest continuous magnetic fields for a given electrical power installation. The present state-of-the-art hybrid magnet system has been built by the NHMFL at Tallahassee in Florida and has produced the highest DC magnetic field equal to 45.2 T in a 32 mm bore.

<table>
<thead>
<tr>
<th>Place</th>
<th>Magnetic field</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsukuba, Japan</td>
<td>$35 , T = 14 , T , (\text{Nb3Sn}) + 21 , T , (15 , MW)$</td>
<td>Operational</td>
</tr>
<tr>
<td>Tallahassee, US</td>
<td>$45 , T = 11 , T , (\text{Nb3Sn}) + 34 , T , (30 , MW)$</td>
<td>Operational</td>
</tr>
<tr>
<td>Grenoble, France</td>
<td>$42 , T = 8.5 , T , (\text{NbTi}) + 33.5 , T , (24 , MW)$</td>
<td>Planned for 2013</td>
</tr>
<tr>
<td>Nijmegen, The Netherlands</td>
<td>$42 , T = 12 , T , (\text{Nb3Sn}) + 30 , T , (20 , MW)$</td>
<td>Planned for 2013</td>
</tr>
<tr>
<td>Hefei, China</td>
<td>$42 , T = 11 , T , (\text{Nb3Sn}) + 29 , T , (20 , MW)$</td>
<td>Planned for 2013</td>
</tr>
<tr>
<td>Tallahassee, USA</td>
<td>$36 , T = 14 , T , (\text{Nb3Sn}) + 22 , T , (12 , MW)$</td>
<td>Planned for 2012</td>
</tr>
</tbody>
</table>

Unfortunately, the last hybrid coil project of LNCMI-G, aiming to produce 40 T, failed because of a defect in the superconducting outsert coil produced in industry. In order to maintain the competitiveness and attractiveness of the LNCMI-G it was decided end of 2006 to replace the outsert coil instead of fully restarting a new project, mostly because of the shorter delivery time scale. The baseline for the coil sub-assemblies of the hybrid magnet is given in Table 2 together with their magnetic field contributions. Ultimately, the field produced by the poly-helix and Bitter coils is planned to be further increased, typically up to 36-37 T, which should allow for a 43-44 T hybrid magnet.

Table 2: Composition of the 42T hybrid magnet

<table>
<thead>
<tr>
<th>Hybrid subpart</th>
<th>Magnetic Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 series connected helix coils</td>
<td>$24.5 , T$</td>
</tr>
<tr>
<td>2 series connected Bitter coils</td>
<td>$9 , T$</td>
</tr>
<tr>
<td>1 superconducting pancake coil</td>
<td>$8.5 , T$</td>
</tr>
</tbody>
</table>

Table 3: Main parameters of the superconducting outsert coil

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner/outer radius</td>
<td>550/913 mm</td>
</tr>
<tr>
<td>Height</td>
<td>1400 mm</td>
</tr>
<tr>
<td>Inductance</td>
<td>3 H</td>
</tr>
<tr>
<td>Nominal current (8.5 T)</td>
<td>7100 A</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>76 MJ</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>1.8 K</td>
</tr>
</tbody>
</table>

A conceptual study for the new superconducting outsert of the hybrid coil project has been prepared in collaboration with IRFU-CEA, and reviewed by internal and external experts. The most important choices that have been made can be summarized in five key points:

- High current to minimize the coil self-inductance and reduce voltage levels during quenches,
- Nb-Ti superconductor at 1.8 K,
- Vacuum impregnated coil with internal cooling,
- Insulated conductor to increase the safety and reliability,
- A 30 K copper screen with stainless steel reinforcement to absorb a part of the induced field effects in case of sudden loss of the power of the resistive coils.

The already existing infrastructure of the hybrid magnet has fixed the maximal dimensions of the superconducting coil, which are listed in Table 3 together with the main parameters. To produce a
field in the range 8.5-9 T, the required overall current density should be slightly below 30 A/mm², which is a usual value for large scale superconducting magnets. The protection of the superconducting coil during a quench will be ensured by an energy dump resistor of 70 mΩ, limiting the maximum temperature to about 80 K for a maximum voltage of 500 V. The superconducting coil will consist of 37 double pancakes with 26 turns per pancake and will require a current of 7100 A to produce the design field value of 8.5 T in a 1100 mm bore diameter. The double pancakes are wound from a Rutherford Cable On Conduit Conductor (RCOCC) composed by a Nb-Ti/Cu Rutherford cable brazed on a Cu-Ag stabiliser. The required critical current of the cable is about 19 kA at 1.8 K in the peak field of 9.4 T. To ensure the internal cooling at 1.8 K of the fully impregnated coil winding, the stabiliser of each double pancake is equipped of a cooling channel (Fig.1) with both ends open to the static bath of pressurized superfluid He.

![Fig. 1. Rutherford Cable On Conduit Conductor (RCOCC) specially developed for the Hybrid coil project; a) 2D cross-section of the conductor (drawing not to scale and dimensions are given in mm; b) Example of a sample produced by Alstom and Aurubis.](image)

To produce the magnetic field of 8.5 T in the 1.1 m diameter bore, the maximal stress on the conductor was calculated to reach 170 MPa at 1.8 K, including thermal contraction effects. The elastic limit and the yield stress have been then measured at various temperatures (300 K, 77 K, 4.2 K) on various samples of stabiliser in CuOFE and Cu-Ag0.04% with the proper geometry and various hardening levels. They were obtained from extrusion process and hereafter submitted to a thermal treatment reproducing the brazing process. Tests results give an elastic limit larger than 300 MPa at 4.2 K, which provides a quite comfortable margin.

Concerning thermal stabilities of the superconducting coil, a dedicated analysis has shown that with the design parameters of the conductor the cryostability criteria is fulfilled, reducing to minimum the probability of quench occurrence. In case of a disruption of resistive magnets eddy current losses should be kept below the quench energy level of the superconductor. Numerical calculations of eddy current losses in this faulty mode have shown that, despite the addition of a Cu/stainless steel cylindrical shield cooled at 30 K, the Residual Resistive Ratio (RRR) of the stabiliser should be kept below the value of 50 to avoid quenching of the superconductor. This consideration has driven the choice of Cu-Ag0.04% for the stabiliser. To allow the tuning of the parameter used in numerical calculations, a sample of 3x5 RCOCC of 330 mm long have been vacuum impregnated with epoxy resin to be tested in compression. This mock-up was also used to test the electrical insulation between turns after the impregnation process and successful results were obtained. Results obtained from first conductor developments and tests have allowed to validate the design of the new superconducting outsert coil. The study of the industrialisation process to produce all required RCOCC unit lengths of 260 m long is in progress despite the fact that Alstom has decided to close its production lines of superconducting cables. The call for tenders for the RCOCC has been issue and the choice of the supplier is in progress. The ones related to the winding of the coil, the construction of the LHe cryostat and the cryogenics satellite with the caloduc are planned for 2010 together with the remaining infrastructures and the power converter. The first run at 42 T can be expected in 2012 just after the commissioning of the superconducting coil without resistive inserts.
DC magnet for 60 GHz ECRIS (IN2P3/INP collaboration)

The LNCMI is a partner in the “beta beam project”, one of the three likely scenarios considered in the EUROP program (2008-2012) for future neutrino oscillation facilities. The aim is to use the $\beta$-decay of radioactive ions to produce neutrino beams. The LNCMI is collaborating with the Laboratoire de Physique Subatomique et de Cosmology (LPSC Grenoble, IN2P3-UJF) to use its unique high field technology to develop a high frequency (60 GHz) pulsed electron cyclotron resonance ion source (ECRIS) for the beam preparation. For efficient ionization, the ion source volume has to be small, and the magnetic field high (6 T at the injection, 3 T at the extraction, a closed surface with $|B| = 2.1$ T). We have designed a prototype cusp magnetic structure using the polyhelix techniques for this magnet. 2D and 3D simulations were used to define the helix geometries. Calculations have shown that it is necessary to use two concentric radially cooled helices at the extraction side and 2 at the injection, using a variable pitch for the internal injection coil. An aluminium prototype of the internal injection coil has been constructed in 2008 and has been used to validate at low current density the calculation of the magnetic structure. The 60 GHz magnetic structure prototype (copper helices in their housing, electrical connections and water cooling environment) is now under construction and is expected to be tested at the beginning of 2010 at half field with a direct connection to two of the four power supplies of the LNCMI-G. If the test is successful, preparation of a test at full magnetic field, corresponding to 60 GHz ECR, that necessitates the use of the 4 power supplies will be organized in the second half of 2010. Afterwards a complete gyrotron experimental hall could be installed at the LNCMI-G in the framework of a collaboration between IN2P3 and INP. As the gyrotron will be pulsed, it may be considered to operate the magnet in a synchronous pulsed mode, thereby greatly reducing its average power consumption, taking advantage of the expertise of the LNCMI-T in this domain.

DC magnets with high temperature superconductors (CERN/CEA/Nexans collaboration)

The electricity bill is one of the major expenses of the LNCMI, so replacing part of the resistive magnet by superconducting coils is very worthwhile. As it is foreseeable that electricity prices will continue to go up, the LNCMI-G must dedicate part of its energy to the development of superconductor materials and coil technology, in collaboration with other laboratories. Based on the expertise of the LNCMI-G with the characterization of low and high $T_c$ superconductors, joint R&D projects were started for the development of prototype magnets using high temperature superconductors, as these are the only possible candidates for high field magnets.

The first one is funded by an ANR project (Stock E) that has started in 2009. The aim is to build insert coils using BISCO wires and to test it in a background magnetic field of 20 Tesla available at the LNCMI-G. The main partners are the CNRS (LNCMI/IN/CRETA), the CEA-IRFU and the NEXANS Company.

The second one is linked to the EUCARD project led by CERN that aims at defining the technologies that will be used for the next generation of accelerators. One of ultimate goal of this large international project is to design a HTS dipole to be inserted in a 12 T Nb$_3$Sn dipole constructed by the CEA. The deliverables from the CNRS for this project are BISCO and YBaCuO inserts to test in high field environment. Critical issues, such as winding and quench detection, are integral parts of the two projects. If successful, these projects will permit to define during the period 2012-2014 the technical basis for a future upgrade of the LNCMI hybrid currently under construction that could be operational in 2015. The aim of this upgrade would be to replace the outer resistive magnet nested in the NbTi large bore coils by high $T_c$ superconductors. This could give a field of 45+ Tesla or a compact hybrid magnet in the range of 40 Tesla with low power consumption. Such a magnet would be useful for experiments with long data acquisitions times, like NMR or neutron scattering. The use of MgB$_2$ superconductor for such a configuration will also be studied, in collaboration with an industrial partner.
Evolution of pulsed field magnets
The continuous increase of resistive magnetic fields obliges the pulsed field infrastructures to continuously strive for higher pulsed fields. It is clear that as a result of the large efforts devoted to this aim in the USA, Japan, China and in Germany, within the next 10 years, the ‘magical’ 100 T limit will be reached. This progress can be realized through three different aspects.
- Increase in electrical energy. The maximum field increases however only logarithmically with the electrical energy at constant mechanical stress. Furthermore, large stored energies pose serious security issues for coil operation and require very large investments.
- Improvements in material parameters. The LNCT-MI-T has an ongoing effort in developing conductors with a better trade-off between mechanical strength and electrical conductivity. In particular the development of nano-filamentary conductors has proven to be very promising and this effort will be continued.
- Improvements in coil design and fabrication. By a better understanding of coil failure mechanism and more detailed modelling, higher operating fields can be realized with the same energy and materials. By going to more elaborate multi coil designs, which allow for more design freedom, higher fields can be generated, at the expense of higher fabrication and operating complexity. During the last few years, the LNCT-MI-T has developed extensive software tools to do analytical and finite element modelling that will be put to good use to improve the design of such multi coil systems.

In order to continue to improve the performance of its magnets, the LNCT-MI-T will upgrade its installation through the purchase of a rapid mobile capacitor bank totalling 6 MJ of stored energy, bringing the total energy to 20 MJ. This purchase is planned in the context of the CPER Midi Pyrénées 2007-2013. The 6MJ bank alone will allow fast (10 ms) monolithic coils to reach 75 Tesla, and in combination with the slow original 14MJ bank, will allow for dual coil operation in the 90+ T range, whilst providing sufficient pulse duration for sensitive measurements. This would bring the LNCT-MI-T back to the front of the pulsed field installations in terms of performance.

The usefulness of pulsed magnets is however not only determined by their maximum field but also by other parameters, like geometry, bore size, noise and cool down time. Over the last few years, the LNCT-MI-T engineers have made great progress in reducing the cool down time, thereby providing more shots per day to the users. This strategy will be further pursued, in particular by using the polyhelix technology developed at the LNCT-G for static field coils, which allows for very efficient heat extraction. Although it is not expected that polyhelix technology permits the generation of very high fields, the high duty cycle could be very useful in experiments where long data acquisition times are needed and where DC magnets cannot provide the required field strengths.

Single turn coils
While the non-destructive generation of pulsed magnetic fields is currently limited to less than 90 T, destructive techniques have been used as early as 1973 to generate fields in excess of 150 T for scientific experiments. In particular capacitor-driven single-turn coils (STCs) have revealed considerable potential due to their cost efficiency, high repetition rate and the fact that the coil explodes outwardly, which - unlike flux compression experiments - leaves sample holders and cryostats intact. In 1985 a STC has therefore been installed at the ISSP Tokyo which has provided a considerable number of scientific publications. Due to their intrinsically short pulse duration of typically 5 to 10 us, STCs have nevertheless failed to emerge as a widely acknowledged research tool.

The rapid evolution of fast electronics and opto-electronics has recently renewed the interest in STCs. State-of-the-art high-speed data acquisition systems, the EMP-proof design of electronic circuits and the use of optical transmitters are effective means to cope with the induced voltages and the trigger noise generated during a discharge. Three major laboratories have therefore taken up the challenge to develop new measurement techniques for STCs: The NHMFL at Los Alamos, the ISSP Tokyo and, more recently, the LNCT Toulouse. In Toulouse we focus on optical techniques which are most appropriate for STCs. The development of a setup for wavelength-resolved measurements in the near-infrared using an InGaAs detector array has actually started. Making use of the recent boom in Terahertz-technology we will also establish a setup for EPR measurements. It has been agreed, that the results of these technical developments will be exchanged freely with the NHMFL at Los Alamos, which is pursuing complementary techniques such as wire-less conductivity measurements.
Scientific projects involving the Toulouse STC (also called MegaGauss) include the infrared spectroscopy of carbon-based nanostructures. Key issues for this class of materials are manifestations of the Aharonov-Bohm effect with and without quantum confinement, the breakdown of the quasi-relativistic regime in graphene and electron-hole asymmetries in the same material. We also envisage measurements on diamond whose low mobility forestalls the resolution of resonant transitions unless very high magnetic fields are applied. Another important class of materials, whose low mobility has foiled most attempts to investigate their electronic bandstructure, is that of organic conductors. We plan to investigate these systems either in-house or in collaboration with various national and international groups who have already expressed their interest in using the Toulouse STC.

**High magnetic fields for neutron and X-ray scattering (ESRF/ILL collaboration)**

Neutron and X-ray scattering are often used to characterize magnetic structures of materials, in particular at high flux large facility sources like the Institut Laue Langevin (ILL) and the European Synchrotron Radiation Facility (ESRF). The maximum magnetic field available at such facilities is typically around 15 T, provided by dedicated superconducting magnets, but a strong scientific need exists to extend this value to much higher fields, in order to study high field phenomena that have been identified in high field facilities. The LNCMI has been engaged for several years already to provide much higher fields, 30 T or more, for experiments at these two facilities.

The LNCMI-T has developed and constructed mobile high voltage capacitor banks (initially 150 kJ, since 2009, 1 MJ) and the corresponding pulsed field magnets to operate on beam lines at the ESRF and the ILL. Both large scattering angle solenoidal magnets and a radial access split coil magnet have been constructed and operated, together with the corresponding cryogenics, and the first scientific results obtained with this approach validate its usefulness and confirm the scientific case for high magnetic fields on neutron and X-ray beam lines. The ESRF has now partly dedicated one beam line (ID6) to operate with the LNCMI mobile pulsed field installation. The mobile generator has also been used at the kilojoule laser source at LULI (Palaiseau) and its use at SOLEIL and at the SLS (Switzerland) is being considered. This strategy will be further pursued in the future, aiming for even higher fields and larger duty cycles in order to more efficiently use the beam time at such facilities that has a very limited availability. Part of the upgrade of the LNCMI-T, funded by the CPER Midi Pyrenees 2007-2013, will provide fast capacitor bank modules totalling 6 MJ. These will be constructed and operated in sea containers, so that they can also be moved to other facilities, like ILL and ESRF, to perform pulsed field measurements. With such a configuration, fields in excess of 60 T are feasible at such facilities, opening entirely new possibilities for experiments.

However, not all scattering experiments provide sufficient signal to noise to give meaningful results with a pulsed field installation and a beam time of typically one week. Therefore, there is a clear need to install very high static magnetic fields on these beam lines. To define the technical basis of such an installation, a design study has started in 2007, in the framework of a work package in the FP7 design study ‘ESRFUpgrade’, uniting ILL, ESRF and the LNCMI. The conclusion of this design study is that the electrical power and the corresponding cooling capacity (40 MW) can be made available at the ILL-ESRF site. In the same work package two DC resistive magnets designs have been considered in detail:

1. a horizontal field magnet suitable for scattering and absorption experiments. The design is derived from the actual 35 T/34 mm vertical field magnet operating at the LNCMI-G using longitudinally cooled helix technology

2. a split magnet design. An innovative design has been proposed and studied that takes benefits from the experience of the LNCMI in operating radially cooled magnets. In this configuration, the high heat transfer coefficients required to cool high field magnets are obtained in radial channels arranged between the magnet turns. Consequently, the innermost windings can be cooled more efficiently than traditional longitudinally cooled windings. It is then possible to increase current densities in the innermost windings resulting in compact magnet designs. This is of primary concern, to be able to implant the magnet in the limited space available for instrumentation on neutron or X-ray beam lines. Moreover, the main cooling water stream flows in the direction parallel to the mid plane
which offers a larger flexibility for the design of the mechanical devices necessary to hold the attracting forces existing between the two halves of the magnet.

The results were reported in February 2009 in the final report of the WP 12 of the ESRF upgrade design study. As far as magnetic configuration are concerned they are the following: 40 Tesla could be reached in the horizontal configuration, 30 Tesla in the split configuration. Currently the lack of funding hinders the realization of a prototype to test the innovations proposed for the split coil. As an intermediate step, a 12 MW magnetic table design is proposed (see figure), that will help to secure the design proposed for the split magnet and that will give access to a maximum field of 25 T at a short distance from the surface (50 mm) as compared to the standard distance of 450 mm. The laboratory is now exploring the possibility to develop this prototype magnet in the frame of collaboration with the technological community interested to perform levitation studies (Air Liquide for the development of cryogenic rocket propellants).

The framework in which the realization of the ILL/ESRF installation can take place and its relation with the LNCMI remain to be developed. It seems logical to try to integrate the ILL/ESRF high field installation into the ongoing European Magnetic Field Laboratory project.
Instrumentation

Cryogenics
Almost all experiments performed at the LNMC I are done under cryogenic conditions. The limited space available inside high field magnets, and the presence of strong time varying fields in pulsed magnets that prohibit the use of metals for certain parts, make life difficult for the cryogenics engineers at the LNMC I. However, a large part of the success of the LNMC I is not only based on the presence of high fields, but also on the presence of very low temperatures (20 mK at LNMC I-G, 50 mK at LNMC I-T) that allow to study matter under very extreme conditions. In fact, the minimum bores size of a magnet, and thereby the maximum field that can be generated for a given electrical power or energy, is partly determined by the cryogenics. Therefore a significant effort will be devoted to the miniaturization of the cryogenics.

The cryogenics related to the hybrid magnet is also very demanding, not because of the low temperatures (operating temperature of the superconducting outsert is 1.8 K) or limited space, but because of the mass to be maintained at this temperature (around 20 tonnes) and the large consumption of liquid helium in the case of field variations (up to 100 l/h). The presence of a cryogenics group at the LNMC I is therefore of the essence.

Experimental techniques
Very often the magnetic field acts as a thermodynamic parameter that brings the system under study into a new state that is then characterized by other techniques (transport, optics, specific heat etc). It is therefore clear that the scientific interest of applying high fields depends also on the characterization techniques that can be used under such conditions. Each additional characterization technique opens new classes of systems that can be meaningfully studied under high magnetic fields, and thereby enlarges the potential user community of the LNMC I. The development of new characterization techniques in high magnetic fields, or the improvement of existing ones, is therefore part of the core activities of the LNMC I and should be considered in this light. Such developments are often done in collaboration with user groups or groups that are experts in such techniques outside magnetic fields. Examples of techniques that will be further developed in the coming years at the LNMC I are high resolution NMR, NMR in pulsed fields, ultrasound spectroscopy, magnetostriction measurements, photon correlation techniques, single nano-object transport and spectroscopy, and X ray and neutron scattering. Other techniques may be developed if the LNMC I users express sufficient interest and if the necessary financial support can be found.
Scientific perspectives

The scientific activities at the LNCMI-T and LNCMI-G show a large overlap in terms of systems studied and techniques used. It is therefore expected that there will be a strong synergy between the scientific and instrumentation efforts at the two sites and the first joint publications will appear soon. Below a unified vision of the future scientific activities is presented. It should however be noted the activities can be strongly influenced by new, unforeseen scientific developments. The previous four year perspectives of the LNCMP and the LCMI did not foresee the discovery of graphene, the high $T_c$ pnictide superconductors nor the revival of the cuprates, subjects that now together make up more than 50 % of the activities of the LNCMI.

Magneto-transport in nano- and meso-objects

Quantum phenomena in mesoscopic systems under microwave radiation and high pressure

The project is to study the electronic and physics properties of semiconductor mesoscopic systems whose characteristic size is less than 100 nm (2DEG, quantum wires, interferometers and systems with artificial scatters: anti-dots). These systems have proved to be unique, for studies of coherent and interaction effects in structures containing few and many electrons and also for studies of the response of these systems to external influences such a linear polarization microwave radiation and mechanical strength under high pressure effect. Microwave radiation will be investigated on clean mesoscopic systems with ballistic and quasi-ballistic transport (array with asymmetrical anti-dots, quantum wires, rings and open dots). By means of the so-called ratchet effect, such systems can convert microwave radiation into direct current and this phenomenon will be studied for its potential use in microwave nano-detectors and current generators. High pressure methods will provide a tool for the study of many-body effects in disordered 2D electrons systems for example, for the study of MIT, fluctuation potential, electron-electron correlations effects and magneto-tunnelling

Transport phenomena in multilayer systems

The fractional quantum Hall effect is a many-body phenomenon where electron-electron correlations occur and form states at fractional Landau level filling factors, in contrast to the single particle description of the integer quantum Hall effect. Such interactions can also occur if several layers are in close proximity, separated only by a thin barrier. This leads to new interactions between electrons in adjacent layers and to new correlated states in the fractional quantum Hall effect.

Additionally for low magnetic fields, an interference of multilayer subband scattering arises in the longitudinal resistance. If such systems are exposed to microwaves, microwave absorption can be observed. In general, multilayer two-dimensional systems consist of $n$ layers separated by tunneling barriers. Future work will focus on multilayer systems with $n > 2$, mostly triple quantum wells ($n = 3$) but also systems with more layers. Beyond the well-known Shubnikov-de Haas oscillations in single layers with one occupied subband, which occur when Landau levels are passing consecutively the Fermi level, a coupled bilayer system ($n = 2$) with two occupied exhibits additional magneto-intersubband (MIS) oscillations due to the alignment of Landau levels from both wells at the Fermi level. For low magnetic fields, it has been shown that photo-resistance in double quantum wells ($n = 2$) exposed to microwave can be explained by the inelastic mechanism, generalized to the two-subband case. The interference phenomenon of MIS oscillations and microwave induced resistance oscillations (MIROs) in a double quantum well appears because the photo-induced part of the electron distribution, which oscillates as a function of microwave frequency, is modified owing to subband coupling and becomes also an oscillating function of the subband separation. In a trilayer system, MIS oscillations occur due to three subbands which are aligned at the Fermi level with increasing magnetic field. Therefore, studies of MIS oscillations in triple quantum wells exposed to microwave irradiation will yield to further details. A multi-component quantum Hall system, which consists of multiple quantum wells separated by tunnelling barriers, have exhibited many interesting phenomena in a strong perpendicular magnetic field due to interlayer electronic correlations. Previous theoretical works suggested several possible ground states in multilayer systems. The first candidate state is the spontaneous coherent mini-band states in a super-lattice (SL) quantum Hall system. This state is an
analogue of the interlayer coherent state at Landau filling factor $= 1$ in double well structures. The second candidate state is the solid state phase (Wigner crystals) with different configurations depending on the interlayer separation. A third candidate state is a staged liquid state, which consists of independent layer states with unequal density. Recently, it has been argued that another ground state, a so-called dimer state, is favoured for a large number of layers with small interlayer distance. The superlattice separates into pairs of adjacent interlayer coherent states, while such coherence is absent between layers of different pairs.

**Magnetic quantum wires**

The aim of our research activity on magnetic quantum wires is to investigate the properties of a two dimensional electron gas in a gradient of magnetic field. The theoretical predictions to verify are numerous and one can safely expect that many more will appear when experimental results start stimulating further investigation. We have for example demonstrated theoretically that electrons oscillate in a gradient of magnetic field and thus undergo spin resonance. As electron oscillations are propelled by a direct electric field, spin resonance is induced without microwaves. In fact, we are currently measuring the microwave fluorescence of arrays of magnetic quantum wires. Another experiment is directed to coherently controlling the current channelled by snake orbits with resonant microwave irradiation. Further predictions concerning electron densities below the Mott transition suggest the formation of spin helices and the decoupling between charge and spin excitations. Future experiments will be designed with such effects in mind.

**Magneto-spectroscopy of nano- and meso-objects**

Below we briefly summarize the research topics in the area of spectroscopy of nano- and meso-object that we are planning to develop for the coming years. However, we will always adapt our strategy to the evolution in this area driven by outside developments and the needs of our external users

**Electronic properties of graphene and its derivative**

a) investigations of the dynamics of photocreated carries in graphene based structures by means of pump-probe experiments; studies of the effect of Landau quantization on the carrier dynamics.
b) investigations of the electron-phonon interaction in graphene by means of Raman scattering experiments in high magnetic fields; search for theoretically predicted effects of resonant interaction between electronic and phonon excitations
c) studies of thermal conductivity of the graphene membranes
d) search for a possible light emission from graphene structures including electrically driven cyclotron resonance emission in high magnetic fields
e) magneto-spectroscopic studies of the graphene bilayer, and of graphene deposited on different substrates
f) magneto-spectroscopy of large area graphene and hydrogenated graphene grown on Ni surface
g) polarisation resolved Landau level spectroscopy of graphene structures in pulsed magnetic fields
h) resonant magneto-Raman studies of carbon nanotubes

**Quantum Hall phenomena in II/VI CdTe quantum well structures** (with large Zeeman splitting)
a) investigations of the effects of electron-electron interactions in fully populated Landau levels, by means of magneto-photoluminescence experiments
b) studies of fully spin polarised quantum Hall states at fractional filling factors 4/3 and 5/3
c) investigations of resonant effects in electron-phonon coupling (in these strongly polar crystals)

**Quantum dot systems**

a) high field spectroscopy of CdTe quantum dots with single Mn$^{2+}$ magnetic ions
b) microwave manipulation of a single Mn$^{2+}$ ion in a single CdTe quantum dot
c) investigations of diffusion processes of two-dimensional excitons in a GaAs/AlAs bilayer by means of single dot spectroscopy
Development of photon correlation techniques in high magnetic fields.
We will study of semiconductor quantum dot structures, of single nanotubes, and of possible Bose condensate phases of excitons in Cu$_2$O

Metals and superconductors

The following presents the current vision of the scientific objectives in the area of metals and superconductors for the next several years. However, given that almost every year new compounds with fascinating physical properties are discovered or new exciting theoretical predictions are made, other experimental projects might emerge in the future.

Ferromagnetic superconductors
We are going to continue our investigations of ferromagnetic superconductors, in particular URhGe. Once high quality single crystals of the recently discovered ferromagnetic superconductor UCoGe become available, we plan to verify whether the same physics discovered in URhGe applies to this compound as well. To get further insight into the fascinating physics of these compounds, we plan to perform specific heat and de Haas-van Alphen effect measurements across the field-induced quantum critical point. Specific heat measurements will prove the bulk nature of the re-entrant superconductivity and provide the field dependence of the average effective mass leading to better understanding of the origin of the exotic superconducting phase. The de Haas-van Alphen effect measurements will depict the Fermi-surface topology both below and above the quantum critical point. It will additionally allow us to extract the effective mass of each separate sheet of the Fermi-surface as well as its field and spin-orientation dependence.

Heavy fermions
Metamagnetic transitions are quite common for heavy fermion materials. The transitions are usually of first order. A line of first order transitions terminates at a critical end point. By tuning one additional parameter, the critical end point can sometimes be driven to zero temperature. In this case, a quantum critical end point arises. This, in turn, often leads to the appearance of a new phase. The exact nature of the metamagnetic transitions in heavy fermion compounds remains obscure. Two competing theoretical scenarios have been proposed. The localization scenario proposes that the itinerant f-electrons suddenly localize at the metamagnetic transitions, and the heavy-fermion state disappears at that point. An alternative scenario is given by a continuous evolution of the Fermi surface, in which the localization of the f-electrons is not tied to the metamagnetic transition. Experimentally, one of the major obstacles in investigating field-induced metamagnetic transition in heavy fermion compounds is that they often occur at high field, well above 20 Tesla. In order to shed more light on the mechanism of metamagnetic transitions, we will carry out transport, de Haas-van Alphen and specific heat measurements in several Ce- and U-based heavy fermions. One such candidate is CeIrIn$_5$ where a field-induced metamagnetic transition occurs at 28 Tesla. One of the objectives is to verify whether the metamagnetic transition gives rise to a quantum critical (end) point and, eventually, new quantum phases. The application of high pressure might also be required to study these transitions. Other heavy fermion systems will be studied; in particular the “hidden-ordered” paramagnet URu$_2$Si$_2$ and the antiferromagnet CeRh$_2$Si$_2$ as well as compounds without inversion centre of symmetry, such as CeRhSi$_3$, CeIrSi$_3$ and CePt$_3$Si. Most of such compounds were studied only by transport measurements and at moderate magnetic fields so far due to the extremely difficult experimental conditions. Our plan is to advance further on by low temperature transport, specific heat, torque and Nernst effect measurements under high field and where possible under high pressure. One of the key theoretical predictions, the field dependent splitting of the Fermi-surface for non-centrosymmetric compounds, is still lacking experimental confirmation, most probably due to insufficiently high field of the previous de Haas-van Alphen effect measurements. To this end, we are going to extend such measurements up to the highest fields available at the LNCMI at very low temperatures.
**Pnictides**

Superconductivity with unexpectedly high critical temperatures was recently discovered in a whole new class of materials, iron-based pnictides. In some of them, superconductivity emerges already at ambient pressure, while an application of high pressure is required to induce a superconducting transition in some others. In spite of considerable experimental and theoretical efforts, the understanding of underlying mechanism of superconductivity in such compounds is still far from being achieved. One reason of slow progress is that high quality single crystals of these materials became available only very recently. Another one is that some of the key experiments require extreme experimental conditions such as very low temperatures, high magnetic fields and high pressures, as well as combinations of those. Such experimental conditions are not readily available in most of the laboratories worldwide. Built on our expertise of measurements under extreme conditions, we plan to contribute to answering some of the fundamental questions related to iron-based superconductors. Transport and specific heat measurements both under magnetic field and pressure will allow us to explore in some details the phase diagrams of these materials and investigate their superconducting and normal state electronic properties. de Haas-van Alphen effect measurements will be employed for the direct exploration of the Fermi-surface and determination of the quasiparticle effective masses, which are directly related to the strength of the electronic correlations. What's more, in superconductors, the comparison of the measured effective masses with the calculated band masses provides a direct access to the strength of the electron-phonon coupling. Such coupling is suggested as the origin of superconductivity in iron-based pnictides by some theories. Other theoretical models suggest a multi-band superconductivity in Fe-based superconductors. Moreover, they suggest that the pairing mechanism may be mediated by magnetic fluctuations due to the proximity to a spin density wave. Knowing the fine details of the Fermi surface topology, its tendency towards instabilities as well as the strength of the coupling of the quasiparticles to excitations is, therefore, essential for understanding the superconductivity in these compounds.

To realise the scientific objectives described above, we will both use the existing experimental set-ups and techniques and develop new ones. We plan to improve the performance of some of the existing set-ups (better sensitivity, wider range of temperatures/fields, etc). For instance, our set-up for specific heat measurements by relaxation is currently limited to about 1.5 K. We are going to adopt it to lower temperatures, 3He system (about 0.4 K) in the beginning with an ultimate goal of 0.1 K in the dilution refrigerator. Built on our experience in high pressures, we are going to develop a whole set of different type pressure cells for transport and specific heat measurements covering a wide range of pressures, and suitable for high fields and low temperatures. One of the techniques we are going to develop shortly is absolute measurements of magnetisation with high resolution and sensitivity in magnetic field gradients, both pulsed and DC. The objective is to develop such measurements up 35 Tesla DC and 70 Tesla pulsed and down to 40 mK.

**Cuprates**

The cuprates, although known as high $T_c$ superconductors for over 20 years, continue to provide surprising experimental data, and a complete theory for this phenomenon is still lacking. Recent advances in crystal growth and improvements in measurement techniques now allow the observation of quantum oscillations in these systems. We will continue our pioneering studies of the Fermi surface of these materials through quantum oscillation measurements in order to obtain a more complete picture of the fermiology of these compounds. Other techniques, like Nernst effect measurements, ultrasound spectroscopy and pulsed field NMR will be developed and applied to these systems, in the hope to finally resolve the mystery of high $T_c$ superconductivity in the cuprates.
High-field NMR

The most ambitious long term project of the NMR group is to develop high-resolution (1-0.1 ppm) NMR in resistive magnets at fields ~30 T (1.3 GHz for proton NMR), as an opening to the communities of solid state chemistry and of materials science. Regarding the solid state (broad-band) NMR activity, the three main future events are:

1) bringing together at LNCMI-G all the members of the NMR group involved in the DC high-field NMR. That is, Dr. H. Mayaffre and Dr. M.-H. Julien are about to transfer their activities and equipments from the Laboratoire de Spectrometrie Physique to LNCMI-G.

2) the acquisition of the second 15/17 T solid state NMR magnet. Putting in operation the second high-field superconducting magnet dedicated to NMR will considerably facilitate and increase our scientific throughput, permitting us to equilibrate the research activities for/with external visitors and our own in-house research

3) The development of a NMR spectrometer in pulsed magnetic fields at the LNCMI-T. Although this instrument will never reach the resolution or sensitivity of the LNCMI-G set ups, it will open the 35-70 T field range for certain solid state NMR experiments. Similar developments are ongoing in Dresden and Okayama.

Instrumentation

We continuously improve all the elements of our NMR equipment, that is, spectrometers and probes. A new generation of custom-built spectrometers and the corresponding software are being developed. A new generation of NMR probes will be built to allow more excitation power, and to have better thermal properties (i.e., smaller thermal link to 300 K and less temperature gradient at the sample space). Narrow bore NMR probes for the resistive magnets and the high-frequency probes will be equipped by a new type of sample rotator. Our dedicated dilution refrigerator for the 15/17 T magnets is planned to be equipped with "bottom tuning" circuit, as well as by a piezo driven sample rotator, enabling rotations in-situ in the mixing chamber. Ultimately, a second dilution refrigerator for the 15/17 T magnets will be built to ensure replacement of the old one and improve its performance. A special NMR probe will be designed and built for our recently purchased 3He refrigerator. We are also developing electronic components for very high frequency range NMR, i.e., above 1 GHz, for proton NMR above 23.5 T, for which commercial products do not exist. Many of these developments are directly coupled to the "High-resolution NMR in resistive magnets" project mentioned above, and/or supported by the EC contract EuroMagNET II, NMR joint research activities. Development of NMR probes will also be supported within our participation to the SOLeNeMaR, an EC project, lead by Zagreb University, Croatia.

At LNCMI-T, the development of pulsed field NMR will be pursued, in the context of an ANR project (2009-2011) after the recent successful proof of principle experiments. This project aims to develop solid state NMR in the 30-70 Tesla range, but will be limited to systems with fast nuclear spin dynamics and large concentrations of highly NMR-active nuclei.

Below we detail on some the systems that will be studied in the coming years, but depending on the demands of our users, others may be added to this list.

Quantum spin systems

1) Recently recorded high field NMR spectra in SrCu2(BO3)2, in the field range 28-34 T, should ultimately lead to the determination of the spin superstructure of magnetization plateaus. This applies both to previously identified 1/8 and 1/4 plateaus, as well as to 2/15 and 1/6 plateaus which we have clearly identified by NMR. Experimental determination of this superstructure is of paramount importance because our understanding of their stability is far from complete. If available 11B NMR spectra are not enough, some further 65Cu NMR spectra might be required to conclude.

2) In the Han purple compound, the high field 29Si spectra will be used to determine details of the "modulated" BEC phase, to verify recent theoretical predictions about very special, novel character of this phase. Namely, in one type of planes there should be BEC bosons, while in every second alternating plane some boson density should be induced, but these bosons should not be condensed.

3) Regarding the investigation of the Luttinger Liquid (LL) behaviour in spin chain systems,
a new compound BaCo$_2$V$_2$O$_8$ is thought to cover different regime of LL parameters as compared to BPCB. We will start the investigation of this system by an NMR study of the ($H$-$T$) phase diagram, and will proceed according to the obtained results.

iv) In the frustrated diamond chain azurite we now focus on the transition from the $1/3$ plateau towards the complete polarization, appearing in the 30-34T field range. According to theoretical predictions, the system should evolve through an incommensurate phase, and there might be a plateau at $2/3$ of polarization characterized by spontaneous breaking of translational symmetry (unlike the $1/3$ plateau). Based on the last proton high-field NMR spectra, we will try to determine the corresponding experimental spin structure - to be compared to predictions.

**Organic conductors**

The LNCMI participates in the new ANR project “¾ FILLED”, coordinated by the LPS Orsay (C. Pasquier), in collaboration with two chemists groups in Rennes (P. Batail) and Angers (M. Fourmigué) and with the CRPP at Bordeaux (C. Coulomb). The program bears on the study of non dimerized one-dimensional organic conductors, in which there is a strong competition between $2k_F$ and $4k_F$ instabilities which can lead to charge disproportionation, and to a very rich phase diagram as a function of pressure and temperature. As far as 2D organic conductors are concerned, using very high field resistive magnets we plan to study the possibility of Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) modulated superconducting phase close to $H_{c2}$, in particular in the compound $\kappa$-(BEDT)$_2$Cu(SCN)$_2$ which has already been studied at LNCMI by specific heat measurements. The investigations of the BPCB spin ladder will focus on the quantum critical behaviour near the critical fields $H_{c1}$ and $H_{c2}$, as seen by the $T_1^{-1}$ relaxation rate. The Fermi surface studies of organic conductors by means of quantum oscillations, and in particular the origin of frequency combinations, will continue.

**Metals and superconductors**

In this area, our activity will target four kinds of systems:

i) In cobaltates we will focus on the interplay between ionic and electronic textures. This implies NMR studies of new systems, such as the P3 phase of Na$_x$CoO$_2$ and Li$_x$CoO$_2$. One of our objectives is to unravel the real-space pattern of electronic and/or ionic states, by combining NMR measurements and ab-initio calculations (and possibly structural studies),

ii) The newly discovered iron pnictide superconductors will be studied with particular attention to the problems of inhomogeneous electronic states and the phase coexistence between magnetic and superconducting orders. This research is supported by the ANR project “TETRAFER” (6-months postdoctoral grant for the NMR group) and by the University J. Fourier of Grenoble (one-year postdoctoral grant). It will involve collaboration with the group of J.L. Luo and N.L. Wang from the Institute of Physics of the Academy of Science in Beijing.

iii) “Hidden” magnetism will be searched for in high temperature (cuprate) superconductors, especially in ultra-pure YBCO single crystals. Other unsolved questions regarding the presence of magnetic order and/or nematic (stripe-like) phases in superconducting samples will also be addressed.

iv) In the heavy fermion compound CeCoIn$_5$ we plan to extend our investigation of the FFLO phase to see if this phase is associated to instability towards a magnetic phase, as in the CeRhIn$_5$ compound of the same family.

All these measurements will particularly require the use of high magnetic fields up to 34 Tesla. A new project on $^{55}$Mn NMR coordination complexes should start in autumn 2009. Our aim is to resolve the local electronic structure of the transition metal in molecules of chemical and/or biological interest with our specific low temperature and high/variable magnetic field NMR techniques. This research is supported by the ANR project “MANGACOM”, in the interdisciplinary field since it also involves chemical synthesis, EPR measurements and quantum chemical computation. It is in line with the will of the LNCMI to open the high magnetic field facilities to other communities, beyond physics-oriented problems.

At this moment, the LNCMI-G is the only laboratory in the world capable of performing NMR experiments at 40 mK and 30 T which attracts many collaborations from all over the world. In the future, a lot of effort will be devoted to opening the NMR installation to chemists, providing a unique tool for high resolution NMR (1 ppm) at 30 T. The strong international reputation of the LNCMI NMR team is a strong advantage for the realization of the above projects.
Molecular magnetism

With the recruitment of a Professor in chemistry starting in September 2009 (UJF), ‘Molecular magnetism’ is now identified as a dedicated theme of the laboratory. During the forthcoming four years period, the activity on this theme will follow several lines, ranging from chemical synthesis to physical studies especially with High Field/High Frequency EPR (HF-EPR).

Following the important results obtained in enantiomerically pure chiral magnets [Tra08], a first topic will keep exploring the physical effects related to the simultaneous breaking of space (P) and time-reversal (T) symmetries within the same medium.

At the molecular level, the coexistence of electric and magnetic dipolar moments within a chiral molecule can be exploited to probe the Curie-de Gennes conjecture. This conjecture precises Pasteur's intuition concerning the possibility to obtain an enantiomeric excess (e.e.) from achiral reactants by applying an external magnetic field: it states that obtaining such an e.e. is indeed possible by applying simultaneously parallel electric and magnetic fields to the system under reaction in order to influence the transition energies leading to either enantiomers [Bar94]. In this sense, the combination of the two external fields acts as a chiral catalyst. We will concentrate on the interconversion reaction between the two enantiomers of a polar paramagnetic chiral complex. The synthetic target will be heteroleptic chromium(III) complexes using two different bidentate ligands. We will focus on the synthesis \([Cr(acac)_{3-x}(hfac)_x]\) (acac=acetylacetonate, hfac=(1,1,1,5,5,5)hexafluoroacetylacetonate; \(x=1,2\)) (Figure 1). Given that the effect is expected to be weak, the interconversion reaction will be studied in collaboration with the Magneto-optic group of G. Rikken by applying high magnetic field. The experimental demonstration of this effect will substantiate a possible mechanism to explain the homochirality of life.

In extended structures, the simultaneous breaking of P and T symmetries lead to the formation of multifunctional magnets that can exhibit, in addition to mere magnetic properties, magnetically induced Second Harmonic Generation (MFISHG) or ferroelectricity. The latter case corresponds to multiferroicity, a subject which undergoes an explosive exploration in solid state chemistry [Che07, Chu08]. In the framework of the Young Researchers ANR program "Ferromol" (leader: C. Train), we intend to exploit the versatility of molecular chemistry and crystalline engineering to design, synthesize and assemble polar and paramagnetic building blocks in order to obtain and study molecular multiferroics. The measurement of ferroelectric properties will be done in collaboration with B. Dkhil in Ecole Centrale Paris (Chatenay-Malabry). The interplay between magnetism and ferroelectricity will be explored by Piezoelectric Force Microscopy in Barthelemy's group at Thales (Palaiseau) and by measuring the influence of the electric field on the magnetisation by micro-SQUID at Institut Néel (Grenoble). In parallel with the synthesis of bulk materials, we intend to process them in nanoporous alumina (M. Woytasik, Institut d'Électronique Fondamentale, Orsay) in order to favour their integration in devices.

The second topic is the development of coordination chemistry of verdazyl radical [Tra09] in the framework of the Young Researchers ANR program "fdp magnets" (leader: V. Robert, Lyon). One of the synthetic targets will be one dimensional compounds where verdazyl radicals bridge anisotropic metal ions. The goal is to combine strong single-ion anisotropy with reinforced exchange interaction...
in order to obtain Single Chains Magnets (SCM) with high blocking temperatures. These systems indeed appear as an appealing alternative to Single Molecules Magnets (SMM). To reach our synthetic target, we will exploit the versatility of the verdazyl chemistry in order to favour bidentate bridging mode. Systematic theoretical studies will be performed in Lyon while slow relaxation dynamics and the microscopic parameters triggering the effect will be measured in Grenoble.

Figure 2: Nickel(II) inserted in a calix-6-arene as a BPT coordination mode [Sen04]

The third topic is somehow related to the second one. When metal ions with strong single-ion anisotropy are spoken of, everyone immediately thinks of cobalt(II) or lanthanide(III) cations. Nevertheless, in a recent paper [Reb08], it has been proposed that nickel(II) in BiPyramidal Triangular (BPT) coordination could exhibit D values of -100 cm$^{-1}$. This perspective is very appealing for topics related to slow relaxation of magnetisation. Though it is known, this coordination mode is rather scarce. To test the above hypothesis by magnetometry and high field EPR, we will rely on a mononuclear complex of nickel(II) where the metal ion is coordinated by three nitrogen atoms of a modified calix-6-arene and two different solvent molecules leading to the expected BPT coordination mode (Fig. 2) [Sen04]. Nevertheless, this complex is not well adapted for the synthesis of polymetallic complexes or coordination polymers as those leading to SMM and SCM behaviour. An important effort of ligands design and synthesis will be undertaken in order to obtain BPT coordination mode and bridging ability.

More generally the understanding of magnetic anisotropy, leading to its control and tuning, is now a crucial step for the study and elaboration of mononuclear complexes as well as for that of SMM [Gre09]. For SMM the understanding of the factors governing the anisotropy, which is responsible for the existence of the energy barrier and the dominant factor of the tunnelling, is of primary importance. To obtain magnetostructural correlations for the magnetic anisotropy, systematic HF-EPR studies on series of complexes from mononuclear to polynuclear entities will be performed. Part of this work will be performed in the frame of the ANR project ‘TEMAMA’ (coordinator: Dr N. Guihéry, Toulouse) dealing mostly with consistent series of Ni(II) complexes and relying on the combination of the experimental determination of the magnetic anisotropy and their theoretical characterization. These series will involve an increasing number of metal ions while keeping the same surrounding ligands responsible for the anisotropy of the single ion. Such systems can be seen as building blocks of SMMs. The underlying challenge of such a systematic construction of architectures of higher nuclearity is the rational improvement of their intrinsic features (a larger resulting anisotropy and/or a larger spin and a higher blocking temperature). Similarly, the theoretical progression performed by the theoretical groups involved (N. Guihéry, Toulouse, and H. Bolvin, Strasbourg) will start from the “exact” Hamiltonian which allows analysis and identifications of the key structural and electronic factors and then will proceed through simplifying modelizations and controlled approximations for the largest systems.

Another line of study will emerge with the development of a pulsed HF-EPR spectrometer which is now in its final stage of construction. Fundamentally, the pulsed operation at 283 GHz will allow measuring dynamical properties of paramagnetic species. These dynamical studies will focus on two kinds of objects. An important goal deals with the determination of the relaxation times of Single-
Molecule Magnets. Recent measurements on this matter have been obtained on two SMM [Sch08, Tak09], showing the accessibility of the information within the timescales of pulsed operation for HF-EPR. Following our studies of the magnetic anisotropy on most of the synthesized derivatives of Fe₄ SMM, a systematic study of their relaxation times will be performed, with the main idea of understanding the dominant factors governing the relaxation and the coherence time in these complexes.

Pulsed EPR spectroscopy associated to double site-directed spin labelling (SDSL) is now a well established research area and allows measurements up to several nanometres in biomolecules, opening up the possibility of global structural mapping via SDSL. In the case of DNA and RNA, well-established techniques exist for the labelling with nitrooxide radicals, and from the radical study structural and dynamic information are obtained. In collaboration with Dr. S. Gambarelli (CEA Grenoble) pulsed EPR studies about the conformational changes resulting of DNA-damages [Sic09], which can be induced by many genotoxic agents, will be performed on synthetic DNA strands marked by double SDSL. Such studies could also be applied to other systems, such as vesicles or membranes.

References
Optics, X ray and neutron scattering

Birefringence magnétique du vide (BMV)

The LNCMI-T has been engaged since 2001 in a very ambitious experiment to observe the magnetic birefringence of the quantum vacuum (birefringence magnétique du vide, BMV), an effect predicted in 1935 by Heisenberg and Euler, but never observed so far. The experimental setup has recently reached a phase where magnetic birefringence of dilute helium gas could be determined with precision, using pulsed magnetic fields. For the near future, this setup will be further improved, gaining several orders of magnitude in sensitivity. Major improvements will realize this, such as an upgrade of the mechanical rotation and tip tilt of polarizers and of the cavity mirrors, the upgrade of the cavity finesse and its mechanical isolation. Starting from 2011, the BMV experiment will enter in a new phase. The development and test phase will be completed and an improved apparatus has to be designed to eventually reach the final goal, the observation of the magnetic birefringence of the quantum vacuum. A new coil has already been designed for this next phase and tested. It has generated 31.7 T at the centre and a B²L of about 300 T²m. The goal is to put two of these coils on the experiment, which will provide sufficient sensitivity to observe the predicted BMV. A new bank of capacitors to supply the energy for such coils is needed, and is foreseen in the context of the upgrade of the LNCMI-T, in the form of 6 MJ rapid modules. Once all that in place and properly tested, a long period of data acquisition will start. A crucial point that has to be studied is if the current room will be able to host the next generation of set up. A new room can be planned in the context of the extension of the LNCMI-T building that is also part of the CPER Midi Pyrenees 2007-2013 upgrade project.

To optimally accompany this evolution, Carlo RIZZO, full professor at the University of Toulouse, and originator of the BMV project, will join the LNCMI starting January 2011. Human and financial support is also needed to accompany such an experimental effort. We plan to apply to the ERC to demand such support. The BMV experiment on Cotton-Mouton effect opens a new research line at the LNCMI. The group has shown that it is now possible to envisage a more general theme: the electro-magneto optics of dilute matter. We are therefore studying the feasibility of measurements of inverse Cotton-Mouton effects in gases and in vacuum, electro-magnetic Jones birefringence in gases, both standard and chiral. We plan to adapt the present set up of the BMV experiment to this new line of research.

X ray and neutron scattering

The use of magnetic fields on X ray or neutron beam lines to study magneto-structural or magnetic effects is quite common, but so far the field strengths were limited by superconducting magnets to around 15 T, although a clear scientific case exists to go to much higher fields. A large number of phenomena has been observed in fields above 15 T, the understanding of which would greatly benefit from the powerful characterisation possibilities offered by neutron and X ray scattering. A project is under study to create a static field installation between ILL and ESRF, capable of generating fields in excess of 30 T to make such fields available for X ray and neutron scattering experiments. If realized, this project will be completed around 2015. In the mean time, LNCMI-T has developed a portable pulsed field installation that is actually in use to do such experiments up to 30 T with pulsed magnetic fields. In collaboration with ILL and ESRF, this installation will be further improved (see Technical perspectives), new samples environments will be developed in terms of temperature, pressure and manipulation capabilities, and it will be used for experiments on systems like quantum magnets, multiferroics, high Tc superconductors etc. This will be done in collaboration between LNCMI and ILL/ESRF scientists, and qualified external users will also be granted access through the EuroMagNET Transnational acces procedure.
Auto-analysis

Strong points
The scientific production of the LNCMI, or rather of its two precursors, the LCMI and the LNCMI over the last four years totals up to 650 publications (ACL + ACT), of which of 65 in high impact journals like Physical Review Letters, and 10 in the highest impact journals like Nature and Science. In view of the small scientific staff (in total 18 full time equivalent scientists), this is an excellent productivity both quantitatively and qualitatively. The reasons behind this success are the quality of the technical installations and the scientists of the LNCMI and its strong international orientation and diversity, which attract many high level external users.

Weak points
Several senior members have left the LNCMI over recent years, and several more will leave in the coming years, mostly because of retirement. Insufficient new positions were given by the CNRS and associated universities to compensate this loss. Within the French system, the small number of staff implies limited political influence on the attribution of positions, for which criteria like productivity or excellence are not decisive.

The low number of teaching scientists is related to the fact that it is considered to be difficult to combine teaching obligations with working in a user facility. The geographical separation between the LNCMI installations and the university complexes, in particular in Grenoble, aggravates this problem. As a consequence, the LNCMI is not very well known amongst the local students, and only a small fraction of them chooses the LNCMI to do a PhD.

The installations of the LNCMI, both of its Grenoble and of its Toulouse site have not had a major upgrade since the early 1990’s, and are rapidly losing competitiveness with respect to the much better funded, and therefore better equipped, international competition. The absence of a structural investment scheme for TGE in France makes it difficult to find the necessary investments to improve this situation.

Opportunities
The use of high magnetic fields for research purposes is worldwide strongly increasing, as witnessed by the ongoing large investments in high field facilities in the USA, China, Japan, Germany and the Netherlands, and by projects to bring high magnetic field infrastructures to other large facilities, like synchrotrons (ESRF, APS, Spring-8) and neutron sources (HZB, ILL, ISIS, SNS). Another important development is the coupling of high magnetic field to large THz sources. THz radiation is a powerful probe of magnetically induced states by cyclotron resonance and electron spin resonance. With this in mind, the HLD has been constructed next to a THz free electron laser (ELBE), and the NHMFL and the HFML will both have their dedicated free electron lasers, the former being still in the planning stage, the latter being already in the construction phase.

In view of its long standing experience and very good reputation, the LNCMI has a high potential to play an important role in these developments and to see the size and scope of its user community increase. Realizing this potential will however require investments and additional manpower, which are seriously lacking, and above all, a consistent long term view of the development of the French TGIR.

Risks
The current LNCMI installations, both in Grenoble and Toulouse are essentially 20 years old, and have not had any major upgrades during this period. The rapid developments in high field technology make that the LNCMI will increasingly loose its international competitiveness and that it will be abandoned by its external users, French and other, in favor of the international competition that can offer better specifications and support. Several major projects to improve this situation have been launched, (hybrid project LNCMI-G, upgrade LNCMI-T) but these are still lacking a solid financial basis.
AERES report on the unit:
Laboratoire National des Champs Magnétiques Intenses (LNCMI) – UPR 3228
under the supervisory authority of the following institutions and bodies:
CNRS
INSA
University Paul Sabatier – Toulouse
University Joseph Fourier – Grenoble

Mars 2010
Unit

Name of the unit: Laboratoire National des Champs Magnétiques Intenses

Requested label: UPR

No. in case of renewal: 3228

Unit director: Mr Gerardus RIKKEN

Members of the expert committee

Chairperson:
Mr Jean-Yves MARZIN, LPN, CNRS, Marcoussis

Reviewers:
Mr Jean-Paul AMOUREUX, Université des Sciences et Technologies de Lille
Mr Marc BIRD, National High Magnetic Field Laboratory, Tallahassee, USA
Mr Jérôme LESUEUR, CNRS, Ecole Supérieure de Physique et Chimie Industrielles de la ville de Paris
Mr Noboru MIURA, National Institute for Materials Science, Tsukuba, Japan
Mr Eric PALM, National High Magnetic Field Laboratory, Tallahassee, USA

Reviewer(s) nominated by the staff evaluation committees (CNU, CoNRS, CSS INSERM …):
Mr Guy LE LAY, CNU
Mrs Olena POPOVA, CoNRS

Representatives present during the visit

Scientific delegate representing AERES:
Mr Claude LECOMTE

Research organization representatives:
Mr Charles SIMON, CNRS, Institut de Physique

Invited representatives:
Mrs Pascale BUKHARI DR11/CNRS, Grenoble
Mr Laurent DAUDEVILLE, Université Joseph Fourier, Grenoble 1
Mr Raoul FRANCOIS, INSA, Université Toulouse 3
Mr Alain MILON, Université Paul Sabatier, Toulouse 3
Report

1. Introduction

- Date and conduct of the visit:

The evaluation relies upon the documents provided and a visit at the Grenoble site of LNCMI which took place on March 8 and 9 2010. The first day was devoted to a general description of LNCMI by the direction, a virtual visit of Toulouse facilities and a real one of those of Grenoble, a discussion with LNCMI operators, with personals, and to seven scientific presentations of the activities. In the second day, five other presentations focused on scientific and technical aspects and the future plans were outlined by the laboratory director.

The prepared material and organization of the visit itself were of high quality thanks to the LNCMI direction as well as all contributors from Toulouse and Grenoble.

- History and geographical location of the unit and brief description of its field of study and activities:

LNCMI results from the merger, in January 2009, of the Grenoble High Magnetic Field Laboratory (LCMI) and the Toulouse National Pulsed Magnetic Fields Laboratory (LNCMP). The unit, implanted thus on both sites, is at the same time a national and international facility and a research laboratory. Operated by CNRS, it is associated to the INSA and University Paul Sabatier of Toulouse and to the University Joseph Fourier of Grenoble. It is active, through in house research and hosted projects, in all fields of science requiring high magnetic fields, as well as in related technical developments.

- Management Team:

The unit director is Mr G. Rikken, with two deputy directors: Mr C. Berthier and Mr O. Portugall.
• **Staff:** (according to the dossier submitted to AERES):

<table>
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<tr>
<th>N1: Number of professors (see Form 2.1 of the unit’s dossier)</th>
<th>In the project</th>
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<th>N2: Number of EPST, (Public scientific and technological institution) or EPIC, (Public industrial and commercial institution) researchers (see Form 2.3 of the unit’s dossier)</th>
<th>In the project</th>
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<th>N3: Number of other professors and researchers (see Form 2.2 and 2.4 of the unit’s dossier)</th>
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<th>N4: Number of engineers, technicians and tenured administrative staff members (see Form 2.5 of the unit’s dossier)</th>
<th>In the project</th>
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<tr>
<th>N5: Number of engineers, technicians and non-tenured administrative staff members (see Form 2.6 of the unit’s dossier)</th>
<th>In the project</th>
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<tr>
<th>N6: Number of doctoral students (see Form 2.8 of the unit’s report dossier and 2.7 of the unit’s project dossier)</th>
<th>In the project</th>
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<tr>
<th>N7: Number of persons accredited to supervise research and similar</th>
<th>In the project</th>
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<td>14</td>
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2. **Assessment of the unit**

• **Overall opinion:**

   The high magnetic field laboratories in Toulouse and Grenoble both have long tradition and history since 1960’s or early 1970’s, and have made steady progress for many years. Both institutions have been well known as representative high field facilities of France, for pulsed and steady fields, respectively. Recently, the visibility of the two laboratories has become very prominent, and especially after their merger in 2009 as LNCMI. This tendency was accelerated by many excellent achievements which have been made by inhouse staff and outside users, from both France and abroad, in diverse fields of science. The high quality of the research accomplishments is confirmed by the number of outstanding papers in journals with high impact factors. This fact demonstrates that the facility (the largest in Europe) is now being matured as a real national and international centre of the high magnetic field research. As outlined by the LNCMI direction, the laboratory (and Europe in this field) is nevertheless at a crossroads, where the choice is either to invest and grow, to remain competitive with similar centers in the US, Japan and China, or accept to rely upon the access to these facilities.

• **Strengths and opportunities:**

   The most important factor as a national research center is to provide unique and user-friendly facilities for the community. At the same time, the activity of the inhouse staff is also essentially important, since for the joint use of the facilities, the cooperation with the staff is essential. In these respects, the strength and opportunities of LNCMI are considered to be in quite a high level: the facilities of high field generators can produce world-top class magnetic fields both in steady and pulsed forms, they seem to be reasonably user-friendly, and the scientific level and skills of the inhouse staff are also very high.
Another big advantage of LNCMI is the vicinity, in Grenoble, of ILL and ESRF where strong beams of neutrons and synchrotron radiations are exploited. This proximity to ESRF and ILL, a strong materials development program and a larger dc power supply than labs in Nijmegen and Hefei will be critical advantages over the next few decades. When complete, the 42.5 T hybrid magnet will be the highest dc field in Europe and might rival the one in Tallahassee. There are also many other laboratories in France where the scientists need high magnetic fields. Collaboration with these institutions and researchers, as well as those in other nearby countries in Europe, the LNCMI would be able to produce many excellent results in future as long as the technology is regularly updated in due time. The hiring of new researchers in the chemistry or biology should further enlarge the community of users.

The set up of EHMFL, which is now included in the ESFRI roadmap, is a key point for the future of LNCMI, if it could secure the necessary funding for upgrades and developments.

**Weaknesses and threats:**

The main problem of the LNCMI is that some of the equipments including the field generators are becoming rather old since they were built. On the meanwhile, the other European facility in Nijmegen and Dresden are either new or much younger. Whereas three quarters of the projects led in European facilities are hosted in LNCMI, the lack of support is a real threat. For example, the capacitor bank of 14 MJ in Toulouse is now 15 years old, and the protection chambers for the pulse magnets which were built when the laboratory started do not look sufficiently robust for routinely generating higher fields safely at present. Renewal of some facilities would certainly be necessary.

Another point is the relatively low number of tenured researchers and professors attached to LNCMI, as compared to similar facilities. Although CNRS and universities consider as a priority to maintain the personnel at the present level, LNCMI did not yet recover the staff number it had when LCMI was associated with Max Planck.

A third weak point (linked to the previous one) is that there seem to be not so many students in the two laboratories at Grenoble and Toulouse. Though the number relative to that of tenured researchers is reasonable, the absolute number is low. It would be desirable to increase the number, especially in such excellent and unique facilities with many constituents, for further increasing the activity of the laboratories and to foster young scientists in the research field in the next generation.

The main threat is a possible lack of competitiveness in the future, if necessary investments in human and financial resources are not made in time.

**Recommendations for the unit director:**

It is a very good point that the amalgamation of the two high magnetic field facilities in France has so far been very successful to enhance the activity of the entire LNcMI. It is now a good opportunity to implement various new projects based on the excellent achievements so far acquired. The proposed plan looks very appropriate, though the committee recommends setting up priorities among the planned projects. Needless to say, the safety is the most important issue for such laboratories as high field facilities: the programs related to the safety guard (e.g. fail-safe site in Toulouse) should be given the first preference, as well as the completion of the hybrid project, which is clearly a very high priority.

As far as the advertising on the lab activity is concerned, it would be useful, to fix a scientific reference frame (common to Grenoble and Toulouse) and stick to it, accelerate the effectiveness of the Toulouse/Grenoble merger by defining common scientific and technical projects, and identify more clearly the inhouse and outside driven research.

On the medium term, the implication of LNCMI in ESRF and ILL high field projects and set-up of EMFL are strategic issues which need to be clarified and prioritized.

**Data on work produced:**
| A1: Number of *produisants* (professors and researchers whose names appear in a minimum number of “publications” over a 4-year period) listed in N1 and N2 in the project column | 26 |
| A2: Number of *produisants* among the other staff listed in N3, N4 and N5 in the project column |  |
| A3: Proportion of *produisants* in the unit \([A1/(N1+N2)]\) | 100% |
| Number of theses for accreditation to supervise research defended | 3 |
| Number of theses defended | 15 |
| Any other data relevant for the field (please specify) | | |

### 3. Detailed assessments

- **Assessment of work produced and scientific quality**:

  - Relevance and originality of the research conducted, quality and impact of the results:

    The research conducted in LNCMI reflects in a large part the research conducted by the community of researchers using high magnetic fields: it is thus diverse and ranges from solid state physics to the experiments to evidence the magneto birefringence of vacuum. It would thus be somewhat unfair to evaluate it as if disconnected from its community of users. This being said, the quality of this research is indeed excellent, with several important breakthroughs in the 2005-2008 period.

    It is also worth noting that: (i) the LNCMI, as a facility, is also evaluated on a yearly basis by an international scientific committee which shares the present committee opinion on the scientific quality, (ii) that all the research projects held have to go through a program committee (common to the 3 European facilities through the European network EuroMagNETII) to get magnet time. Often, these projects are jointly set up by in house researchers and external users, the whole procedure ensuring an optimal use of the facility.

  - Quantity and quality of publications, papers, theses and other work:

    The number of publications is of the order of 130 per year, among which about one fifth in letters, and 40 contributions to international conferences with proceedings + 20 invited talks in international events. These figures, much higher than in “normal” solid state physics laboratory and the journals where the results are published attest both the quality of the research held at LNCMI and the impact it has as a facility. 15 PhD theses were defended from 2005 to 2008. The visibility of LNCMI researchers is globally very good, with a high number of invited talks in conferences.

  - Quality and solidity of contractual relations over time:

    LNCMI has a long tradition in supporting external research teams (national or not) needing access to high magnetic fields. The laboratory staff is involved in preparing the projects to be submitted to the programm committee, thus increasing the success rate (some 85%). As far as the relationship with partner organizations is concerned, the associated universities did and do support LNCMI, which proves a long term fruitful partnership.
- Ability to recruit top-level researchers, post-doctoral and other students, especially foreigners:

LNCMI was well supported in the recent years and can benefit from the hiring of very good researchers. It suffers nevertheless from the low number of students in physics for attracting PhD students. This is made worse by the low number of faculties; mainly in Grenoble (being researcher, professor and local point contact does not provide an easy life). Other French laboratories, which have been taking benefit from the facility should be strongly encouraged (by the program committee) to share PhD students with LNCMI, in order to ensure a sufficient breeding ground for future recruitments.

- Ability to obtain external financing, to respond to or launch calls for tenders and to participate in the activities of competitiveness clusters:

The LNCMI has been and is very active in European projects as well as for national calls of the ANR. The ANR funding (500 k€/year) is at an excellent level, which will be difficult to increase further.

- Participation in international or national programs, existence of important collaborations with foreign laboratories:

Several international conferences were organized or co-organized by LNCMI in the report period. The international collaborations are obviously at a high level (80% of the projects come from abroad).

- Valuation of research and socio-economic or cultural relations:

One patent was issued in 2007: this number is rather low, if one refers to the number of technical staff and to the field covered (this may be due to the specificity of the technical innovations).

• Assessment of the strategy, governance and life of the unit:

- Relevance of the unit’s organization, quality of its governance and internal and external communication:

The LNCMI, despite its peculiar configuration, is running smoothly, and the personals appreciate the way it is governed. Although they have the difficult task to do their own research and serve as local point contacts, and for some of them teach also, the LNCMI researchers are dynamic and productive. A special mention should be given to the PhD students (half of them from abroad) who are enthusiastic about their work and conditions.

It should also be noted that the direction makes a large effort to increase the opportunity for the staff and workers in both sites of Grenoble and Toulouse to meet each other in order to enhance the good cooperation and communication. Actually, it should be very important to speed up the lab consolidation.

Despite the complicated institutional and international landscape, the LNCMI direction has succeeded in building a very positive atmosphere inside the lab.

• Project assessment:

- Existence, relevance and feasibility of a medium- or long-term scientific project:

The projects of LNCMI on the medium term are both in the scientific domain as well as for magnet technology. On the first one, the committee approves the will to enlarge the community of users, beyond its traditional solid-state basis, in the fields of chemistry, fundamental and plasma physics, and to magneto-science. The LNCMI indeed prepares already adequately this broadening by having attracted in-house researchers who will accompany this growth.
Concerning the magnet developments, the projects are considered as positive by the committee, both for pulsed and DC fields. In particular, the choice of 1 and 6 MJ banks for pulsed fields are adequate in the context of portability and user-oriented policy, as well as the future projects of hybrid 35T/12 MW and high Tc superconductors based magnets for the DC fields. Given the cost of developing new high field installation, one has also to pay attention to the proper development of state to the art instrumentation, and even new ones like NMR, RPE, US, thermoelectric probes, etc. The recent outstanding results in cuprates for instance, are directly related to the gain in signal/noise ratio in the measurements. It is important to keep investing in instrumentation on both sites.

- Originality and risk-taking:

The past and future scientific projects (which are again also those of the community, and selected by an international committee to check their relevance) are indeed original and for some of them risky (e.g. vacuum birefringence).

On the technical side, the LNCMI is developing an original hybrid magnet system that has high visibility (and high cost). Risks are being managed well. The lab is playing a leading role in the new field of combining pulsed magnets with x-ray scattering and in trying to install dc magnets at both x-ray and neutrons sources: this is a clear originality with respect to similar facilities.

4 Team-by-team and/or project-by-project analysis

4.1 Metals and Superconductors

- 5 chargés de Recherche CNRS
- 2 maîtres de Conférences

The physics of metals and superconductors is studied on both sites through transport and spectroscopic measurements. The most important subjects of interest for the scientific community nowadays are addressed that is: strongly correlated systems, heavy fermions and organic materials. The overall quality is very good, with some exceptional contributions for example in the physics of cuprates in Toulouse or the study of the superconducting-ferromagnet URhGe in Grenoble, and some very detailed work on the fermiology of organic conductors for instance. The magnetic field is a powerful tool to probe new and exotic electronic states in matter, providing an appropriate instrumentation is used. Such an effort has been made on both sites, where accurate measurements of magnetoresistance, Shubnikov de Haas (SdH), de Haas van Alphen (dHvA), Nernst, ultra-sound, NMR... in very high field and often very low temperatures can be made. This appears to be decisive to compete at the top international level.

Through very efficient collaborations worldwide, this activity generated high level scientific contributions, published in high impact factor journals (3 Nature, 2 Science, 27 PRL).

The most striking results are related to superconductivity. For the first time, the topology of the Fermi surface of cuprates has been determined by quantum oscillations measurements (SdH, dHvA) for different doping levels in the phase diagram, and electron pockets have been surprisingly discovered in these hole doped materials. A Fermi surface reconstruction therefore must occur, whose nature is under strong debate in the community. This LNCMI work is a real breakthrough in the field. An surprising and important result is the discovery of a ferromagnet at 9.5 K being a superconductor at 250 mK, namely the heavy fermion compound URhGe. Moreover, a field induced superconducting pocket has been found related to a quantum critical point. A detailed magnetic phase diagram has been made, where the orientation of the field with respect to the crystallographic axis plays a major role. Another field induced superconducting state has been observed in an organic conductor \((\text{BEDT-TTF})_2\text{Cu(NCS)}_2\). The competition between superconductivity and magnetism is also addressed in the heavy fermion compounds and the organic conductor, where hints of the FFLO* state have been observed by NMR in CeCoIn5 and magnetometry and torque measurements in \((\text{BEDT-TTF})_2\text{Cu(NCS)}_2\).

Other interesting results on the properties of exotic electronic phases has been obtained thanks to high magnetic fields, like the “hidden order” in heavy fermions like URu2Si2, the Luttinger physics in the organic CuBr4(CSH12N)2, or the determination of the Fermi surface in the two band superconductor ZrB12 for example.
Beyond metals, the physics of quantum spin systems studied by NMR at LNCMI has a major impact in the community. In antiferromagnetic Heisenberg systems of coupled $\frac{1}{2}$ spin dimers, quantum transitions occur under strong magnetic fields, where the Dzyaloshinsky-Moriya interaction has been found to play a key role, like in the ladder system Cu$_2$(C$_5$H$_{12}$N$_2$)$_2$Cl$_4$. The possible Bose-Einstein Condensation of triplets on the background of the commensurate spin superlattice has been explored in SrCu$_2$(BO$_3$)$_2$ and in BaCuSi$_2$O$_6$.

The above mentioned activities have their own strong dynamics, and there is no doubt that they will be fruitful in the future. They have to be strongly supported. The NMR group will be reinforced by two permanent researchers, which is a very good perspective.

4 • 2 Nano & Meso
- 3 professeurs
- 2 directeurs de recherche
- 4 chargés de recherche
- 1 maître de Conférences

The scientific contributions in this area is based, on the one hand on semiconductor physics, comprising low dimensional structures: basically, two-dimensional electron gas (2DEG), quantum wells and quantum dots, and, on the other hand, on the study of graphite, graphene and carbon nanotubes.

10 researchers (2 DR + 2 CR + 1 Pr from Grenoble and 2 PR + IR + 1 CR + 1 MCF from Toulouse, as of 01/01/2010) work in this area together with 6 students (on a total of 13), i.e., a large proportion.

The production is largely superior to the usual standards in this field and of high quality. Just for year 2009, it includes 14 in-house projects (11 on graphene, one on graphite, 3 on semiconductors) on a total of 39, 53 articles, among which 13 are related to carbon allotropes (comprising 4 Phys. Rev. Lett. : 2 on graphite, 1 on graphene, 1 on polymer-embedded single-walled carbon nanotubes).

Typically, the last theme of carbon-based nanostructures regroups in a very fruitful synergetic collaboration researchers from both previous laboratories, i.e., the LCMI in Grenoble and the LNCMP in Toulouse. Samples are prepared in house and studied in static and pulsed fields both in Grenoble and Toulouse.

Some highlights concern the study of the Aharonov-Bohm effect in ballistic multi-wall carbon nanotubes, the Landau level spectroscopy of in graphene-based structures.

Other highlights in semiconductor physics concern:
- The study of electron-electron interactions; e.g., in strongly interacting 2D electron systems, the Stoner transition which drives a 2DEG into a ferromagnetic state; their role affecting electronic transport in a 2DEG via plasmon excitations; their role in determining the spin and charge state of optically probed single quantum dots.
- The “ratchet effect”: anisotropic transport induced by microwave excitations in a 2DEG with intentional anisotropic disorder.
- The study of magnetic semiconductors.

The points to develop concern the relationship with the Universities, the Polytechnic Institute.

4 • 3 Magnetic Resonance
- 1 professeur,
- 2 directeurs de recherche
- 1 chargé de recherche
- 2 ingénieurs de recherche
The scientific contributions in this area are mainly in solid-state Physics (broad-band NMR) at very large variable magnetic fields (up to 34 T) and low temperature (a few tens of mK). They are also based on high-resolution NMR for material science at room temperature and 30 T; however, this is a starting new project.

Five permanent positions of researchers, three postdocs and two students work in this area. This is a small group, which nevertheless attracts several (6) regular visitors.

The production is very good and quite superior to usual standards.

The themes which have been developed for solid-state Physics concern: (1) High Tc superconductors Cobaltates and Pnictides; (2) Exotic superconductivity: FFLO phase in CeCoIn$_5$ and Jaccarino-Peter mechanism in $\lambda$-(BETS)$_2$FeCl$_4$; (3) Quantum anti-ferro-magnets: (i) Luttinger-liquid behavior in the spin ladder CuBr$_2$(C$_5$H$_{12}$N)$_2$, (ii) Wigner crystallization of bosons: magnetization plateaus in SrCu$_2$(BO$_3$)$_2$, (iii) Bose-Einstein Condensation of triplets/bosons in Han purple BaCuSi$_2$O$_6$.

The second topic, which concerns ‘classical’ NMR, has only started very recently by analyzing at 30 T, on a static ZrF$_4$ powder sample, the $^{91}$Zr spectrum.

Concerning the projects, which concern solid-state Physics, there are related to:

- Quantum spins: Ising chain of BaCo$_2$V$_2$O$_8$, NiCl$_2$-4SC(NH$_2$)$_2$ compound (DTN), High-field phase transition in Volborthite.
- High Tc’s, cobaltates and pnictides.
- Field-induced super-conductivity.

However, the main new project of this group concerns the application of very high-field NMR to ‘classical’ NMR. This project should be encouraged. Indeed, there is another TGE (based on the Federation 3050), which is devoted to ‘classical’ NMR. At least ¾ of its proposals are based on quadrupolar low-gamma nuclei, which can only be recorded with very large field NMR spectrometers. The two largest fields presently available for this purpose are 21.1 T (Lille) and 20 T (Orléans). Indeed, the 23.5 T magnet of Lyon is reserved for biology, which means $^1$H/$^{13}$C/$^{15}$N nuclei, all spin-1/2 nuclei. Even at 21.1 T, the 1D spectra of low-gamma nuclei remain very broad with all resonances overlapping. For such broad spectra, the resolution of c.a. 1 ppm accessible at Grenoble is quite sufficient. The resolution of such nuclei is proportional to the square of the magnetic field, and thus spectra recorded at 30 T are 2.25 more resolved than those recorded at 20 T.

It should thus be fine for the two TGEs (LCMI, Lille and Orléans) to work together on such project of low-gamma quadrupolar nuclei. This new topic would create links between LNCMI and the large community of people working in the field of material science. In order to do so, it means for LCMI to develop double-resonance ($^1$H-$^{19}$F/X low-gamma) MAS probes, with the shortest as possible dead-time. There are several very recent ‘tricks’ that can be used to improve such a development. This can thus be done in collaboration with the two groups (Lille and Orléans) of ‘classical’ NMR.

### 4.4 Molecular Magnetism

- 1 professeur
- 1 directeur de recherche
- 1 ingénieur de recherche

Besides a nice NMR experiment on CsFe8, which displays a field-induced phase transition, most of the research on molecular magnetism is made within the High-Field RPE group. The recent arrival of a chemist researcher will boost that already well known activity on molecular magnet and will be the opportunity to develop a new activity on new materials presenting ferroelectric or even multiferroic properties.

The main results to date refer to S=1 systems, where the multifrequency operation mode of the HF-RPE system is particularly suitable. For example, double Ni(II), Mn(II) or Fe(III) complexes have been studied, and their molecular configuration explored, and compared with models. These results are important in order to be able to build new molecular magnets. Biological systems have been also investigated, namely proteins with Fe-4S tetrahedras. The structure of Single Molecular Magnets which present quantum properties at low temperature has been studied.
In the future, study of P and T violation in chiral molecule will be studied, in collaboration with the magneto-optic group, which is a very appealing perspective. Complex materials like ferroelectrics and multiferroics will be also investigated. Single-chain Magnets may be an alternative to single molecule one, with higher blocking temperature. An important research program is proposed in that perspective based on verdazyl chemistry.

The development of a pulsed HF-EPR spectrometer up to almost 300 GHz will allows dynamical studies of these compounds like the magnetic relaxation for instance.

Whereas the spectroscopic group “RPE & NMR” is on the same site, the committee wonders whether this is just a cosmetic label “spectroscopy”, or if one can imagine interactions? This should be possible on molecular magnetism for instance … The committee does not see clear projects in that direction.

4.5 Magneto-Optics, Neutrons and X-Rays

- 1 professeur
- 1 directeur de recherche
- 1 chargé de recherche
- 1 maître de conférences

Another highlight is the magneto-spectroscopy of carbon nano-tubes and graphene. In carbon nano-tubes, a remarkable achievement is that the evidence of Aharonov-Bohm effect was observed in both optical and transport experiments in pulsed high magnetic fields. In graphene, magneto-optical transitions between Landau levels were observed, and most of the peculiar Landau level structures arising from the mass-less Dirac carriers were clarified. At present, the subject has become very popular and many experiments are going on competitively. At LNCMI, these results have been obtained from a rather early stage, so that LNCMI has been playing a leading role in this research field, and has given a large impact.

One of the great advantages of the LNCMI is that the Grenoble lab. is located very close to the neutron scattering facilities of ILL and the synchrotron radiation facilities of ESRF. Both machines provide extremely powerful techniques for condensed matter sciences. Neutron scattering is particularly useful for magnetism, and the synchrotron radiation is very useful as an intense radiation in the X-ray range. The combination of high magnetic fields with these facilities would open up many new possibilities, such as the investigation of magnetic phase transitions or exploration of new magnetic and crystal structures, magneto-optical processes, etc. The effort of the LNCMI towards this direction is highly evaluated. Various special types of magnets have been developed. Both for steady fields and pulsed fields, coils with a conical access or split coils were designed and are being developed. For pulsed fields, a 1 MJ portable capacitor bank was built to install in the vicinity of the beam lines.

In collaboration with the group of Tohoku University, Japan, magnetic structures of the plateau phases were investigated in CdCr2O4 and TbB4. The lattice deformation with temperature and magnetic fields was measured in NdFeAsO using the beam at ESRF. These nice results obtained in these experiments demonstrated a promising future, and hence the demand of high magnetic fields for these beam experiments will increase significantly from now on.

4.6 Magnets / Instrumentation

- 6 ingénieurs de recherche

Pulsed-field

- Assessment of work produced and scientific quality:

On the basis of the long-standing tradition of the pulsed magnet technology in Toulouse and the European “ARMS” project in which the Toulouse laboratory was intensively involved, high field pulse magnets have been successfully built. The magnet construction was made basically following the fibre reinforcement technique which has now become one of the standard techniques for the pulsed magnets, and wet winding method. Furthermore, the team leader introduced his technique developed at Amsterdam. The quality of these magnets is quite good in the sense that they are reliable and have reasonably long life.
A unique point of the LNCMI magnet technology group is that they are developing strong wires by themselves in the lab. It would be marvellous if these wires become really available for practical use, but it would take some more time to solve all the technically difficult problems which still exist. With the recent merger of the Toulouse and Grenoble labs, this expertise is now being applied to development of materials suitable for high-field dc magnets as well, which is a good point.

Also, the polyhelix magnet technology that was developed in Grenoble for dc magnets is being transferred to the Toulouse facility for application in pulsed magnets. This shows potential for reducing the cool-down time of the pulsed magnets which should allow the lab to combine long pulses with short cool-down times, a formidable combination which could propel the lab to the international forefront of the pulsed magnet community. The scientific productivity of the pulsed-field facility is already competing with much larger labs worldwide, including Los Alamos. Such a development might allow Toulouse to be recognized as the international leader in this field.

Concerning the power supply, the plan to build a new 6 MJ bank is a sensible decision, because it would be very useful for generating most of the necessary pulsed fields by itself, and also it can be used for generating really very high fields with a two-coil structure, by combining with the 14 MJ bank. The committee also places a high value on their good success in building a 1 MJ portable capacitor bank for X-rays and neutron experiments, since nice results have been obtained with it.

Another notable recent progress is seen in the single turn coil system. The entire system was moved from Berlin to Toulouse, and it is now in operation. The technique is very useful as very high pulsed fields well above 100 T (up to 300 T) can be generated rather easily without spending so much energy in the capacitor bank. Although it is a destructive method (“semi-destructive” in the sense that the samples are not destroyed), and pulse duration is very short, we can perform a lot of interesting experiments can be performed as demonstrated in Tokyo and Berlin. The system will provide useful means for obtaining high fields and will become one of the attractive facilities of LNCMI for users.

- Quantity and quality of publications, papers, theses and other work:

Besides the publication on the science in high fields, reasonable amount of the pulsed magnetic field technology of Toulouse has also been published and well accepted internationally.

- Assessment of the influence, appeal and integration of the team or the project in its environment:

  - Number and reputation of the prizes and distinctions awarded to the unit members, including invitations to international events:

Several series of international conferences are held periodically on high magnetic fields and related science, and LNCMI always plays principal roles including invited talks. It also has hosted some of these conferences.

  - Ability to recruit top-level researchers, post-doctoral and other students, especially foreigners:

Considering the attractive research environment and very high reputation at present, it will not be so difficult to obtain very good researchers, post-docs, or students, if there are available positions created in LNCMI with reasonable salaries.

- Assessment of the strategy, governance and life of the team or project:

  Some staffs in the lab are professors of universities and there are students in their groups. However, the number of students is relatively small.

DC fields
Assessment of work produced and scientific quality:

The largest project presently underway in magnet technology is the development of a 42.5 T hybrid magnet. This is a very ambitious and original activity. There have been only 15 hybrid magnets built worldwide. This compares with thousands each of NMR, MRI and accelerator magnets. The project includes collaboration with a highly respected magnet development group at CEA. The lab has taken a conservative approach in the design of the superconducting outsert by avoiding a high-field, small-bore Nb$_3$Sn approach and building a relatively low-field, large-bore NbTi magnet. The conductor design for the outsert shows a good balance of relying on proven concepts (Rutherford cable w/ additional stabilizer, superfluid helium, ventilated windings) while still incorporating new features to optimize the conductor for this application. This magnet shows great promise of being successful and, when successful, will be the highest field dc magnet in Europe. There is also some possibility of upgrading the resistive insert to allow the system to rival the 45 T system in the USA (Tallahassee).

The dc resistive magnets in Grenoble have for many years attained lower fields than those at other labs worldwide, but recently a series of upgrades have been successfully completed, with more expected soon. Grenoble now has the highest dc fields in Europe and is starting to challenge those provided in Tallahassee. This is a most welcome development; the new director is to be praised for it. The LNCMI is starting to organize collaborations in Grenoble and elsewhere in France focused on high-temperature (or high-field) superconductors. The US is well organized in this regard, with the Applied Superconductivity Center in Tallahassee playing a lead role. It is commendable that the Grenoble is trying to organize the development of these materials that show so much promise for the future.

- Quality and solidity of contractual relations over time:

The LNCMI did enter into an inappropriate contract with Oxford Instruments many years ago, however it was a guaranteed-performance contract and when OI failed to deliver, the money was returned. It appears that presently the labs contractual relations are robust.

- Ability to recruit top-level researchers, post-doctoral and other students, especially foreigners:

The magnet technology group in Grenoble recently recruited a researcher from CERN to play a leading role in the design and construction of the new hybrid magnet. This new staff has a strong track record spanning more than 10 years in superconducting magnet system development. He is a most welcome addition to the team and should be able to play a leading role in magnet development in both Grenoble and Toulouse as senior colleagues retire.

- Ability to obtain external financing, to respond to or launch calls for tenders and to participate in the activities of competitiveness clusters:

LNCMI has been quite successful in securing additional funds for the hybrid magnet project and shows great potential for securing funding for other new initiatives, particularly the development of magnets for neutron and x-ray scattering.
- Participation in international or national programs, existence of important collaborations with foreign teams:

LNCMI is leading the EuroMagNET II, collaboration between the European high-field facilities in Nijmegen, Dresden, Grenoble and Toulouse. This collaboration shows potential to allow the European labs to jointly rival the US lab. The lab also is developing collaborations with ILL & ESRF, both of which are international labs. This collaboration also shows great potential to lead transformational science. The Toulouse branch of the lab has a long-standing collaboration with Oxford University on development of high-strength, high-conductivity materials for use in pulsed magnets. At the national level, LNCMI has a major collaboration with CEA on the development of the hybrid outset for Grenoble. The new initiative in high-field superconductors is an international collaboration that shows great potential.

- Relevance of its organization, quality of its governance and internal and external communication:

The magnet development activities in Grenoble have been recently re-organized with the arrival of the new director. Since then, external communications have improved with more visibility at international conferences. The lab is communicating very well with its immediate neighbors developing collaborations in superconductivity as well as high-field magnets for x-ray and neutron scattering.

- Relevance of initiatives aimed at scientific coordination and the emergence and taking of risks:

The new initiatives with ILL & ESRF are focused on an emerging set of possibilities and that various organizations and nations (Japan, US, Germany) have been pursuing. LNCMI is one of the leaders in this field and shows great potential for the future, given the success to date w/ pulsed field at ESRF and the proximity of the Grenoble branch to ESRF & ILL. The collaboration w/ CEA on the hybrid project should greatly reduce the risk associated with the development of a hybrid magnet. The collaboration with Nijmegen and Dresden is a much-needed step to allow the European labs to compete with the American one. The collaboration on high-field superconductors is much needed to pull together the European efforts. These materials show great potential not only for higher-field, more economical magnets, but also in revolutionizing power transmission and production, which is an increasingly important issue in coming years.

- Involvement of the members in teaching activities and in organising research in the region:

The magnet development team is very active in organizing research combining high fields with neutrons and x-rays and research in high-field superconductors in the city of Grenoble. The Toulouse and Grenoble branches of the lab are now leading the research at high fields in southern France.

- Project assessment:

Existence, relevance and feasibility of a medium- or long-term scientific project:

The hybrid magnet project will take a few years to complete (2013) and will result in the highest field dc magnet in Europe, possibly rivalling the 45 T system in the US (Tallahassee). This magnet seems feasible as it uses a relatively low-risk technology (NbTi 8.5 T, large bore outset).

Existence and relevance of a resource allocation policy: The lab has been successful in undertaking a hybrid project along with resistive magnet upgrades, design of split magnets for neutron and x-ray scattering and continuing to push the limits of pulsed-field facilities with a relatively small staff and budget. It seems that resources are being allocated very well.

To conclude on this part, the Toulouse and Grenoble magnet labs have been very prominent in the international magnet development communities for decades. In recent years both labs have taken on major new initiatives that show great promise of coming to successful fruition. The future looks very promising!