Report of the IUPAP working group on Facilities for Condensed Matter Physics : High Magnetic Fields

Foreword

At the beginning of 2004, the IUPAP organization nominated a working group to report on Facilities for Condensed Matter Physics: High Magnetic Fields.

The task of this committee was to produce a report summarizing:

- The existing possibilities in both static and pulsed high magnetic fields facilities.
- The scientific achievements, illustrated by a few examples, obtained in such facilities
- A list of ambitious projects that might be undertaken over the next ten years.

This working group was composed of:

Prof. P. Chaikin, Physics Department, Princeton
Prof. J. C. Maan, NHFML, Nijmegen
Dr. G. Martinez, GHMFL, Grenoble (Chair)
Dr. P. Monceau, LLB, Saclay (representative of IUPAP)
Prof. R. J. Nicholas, Physics Department, Oxford
Prof. F. Pobell, Forshungszentrum Rossendorf
Prof. N. Sullivan, Physics Department, Gainesville
Prof. S Takeyama, ISSP, Tokyo-Kashiwa

The following report attempts to answer the questions raised by the IUPAP.

It gathers the main ideas and information that the members of the working group have collected from a very large number of colleagues and/or users of high magnetic field facilities.
We would like to deeply thank all of them for their precious help and judicious advice.

July 2004

Report on High Magnetic Field Facilities

Contents

I. Introduction: how high is high field?

There is intense interest worldwide in research using high magnetic fields across a broad array of the sciences, in particular the condensed matter sciences, but also in chemistry, life sciences, geochemistry and environmental science. Most of these activities involve fields in the 3-20 Tesla range. The cost and availability of superconducting magnets up to 20 T has enabled, for example, the widespread use of NMR for chemical and biological studies and the use of MRI for medical diagnostics.

The greatest demand for high field research comes from the condensed matter sciences. Most laboratories performing condensed matter physics or materials research have magnets in the range 10-20 T which are used to characterize materials and to unravel new magnetic field dependent phenomena. The magnetic field is not simply a spectroscopic tool but is a thermodynamic variable which, along with temperature and pressure, controls the state, the phase transitions and the properties of materials. Therefore there has always been a search for higher magnetic fields to probe smaller lengths and create and explore new states of matter. With cleverly designed instruments and measurements, often the requirements of stability and homogeneity can be relaxed in the quest for field strength. Since DC resistive magnets can supply 2-5 times the field of conventional laboratory magnets and pulsed magnets another factor of 2-4, it has proven very productive to create dedicated large scale high magnetic field laboratories where such magnets are available. In this report we will define "high field" as being above 20 T and will concentrate on the magnet installations designed, built and used for science in these dedicated high field research centers with illustrative examples of scientific achievements.

A magnetic field has the unique ability of acting on both the spin and the orbital motion of charged particles, quantizing states and localizing free carriers on a length scale $l_B(\mathrm{nm})=25.6/\sqrt{B(\mathrm{T})}$ ~ 3.5 nm at 33 T. Moreover it allows characterization of the ground state, the symmetry and time reversal properties of many systems. Simultaneous use of high magnetic fields and low temperatures provides one of the most powerful means of changing the quantum properties generating new states of matter, cross-over of dimensionality of physical processes and even inducing quantum phase transitions. While the corresponding magnetic energy is often small (~3.5 meV at 30 T, for spin s=1/2, compared to a thermal energy of 25meV at 300K and bandwidths in solids of the order of 1 eV), this magnetic energy is nevertheless comparable to the scales of many interactions that drive important phase transitions.

The use of magnetic fields allows one to vary the relative strengths of kinetic, Coulomb and magnetic energies and to improve our understanding of the role played by these different energies in fundamental states of matter. The philosophy underlying physics in high fields is often the understanding of collective effects, implying the charge and spin of particles, which are responsible for the existence of unique properties in condensed matter physics such as magnetism, superconductivity, etc..

Modern condensed matter research in the last decade has gradually shifted to the study of ever smaller structures where the finite size becomes the determining factor for physical properties (nanoscience). In this area high magnetic fields also have a crucial role to play. Generally the study of properties in magnetic fields is a very successful approach to unravel the essential physics of the material studied. In the past, studies of bulk materials (de Haas- van Alphen, Fermiology) and of two dimensional systems (quantum Hall effects) in high magnetic fields have revealed these basic properties and often produced unexpected and challenging new scientific results. In this context magnetic fields are expected to be at least as important in the era of nano-science. More specifically the magnetic length at 30T is comparable to the size of nano-objects which makes the use of high fields particularly interesting for such objects.

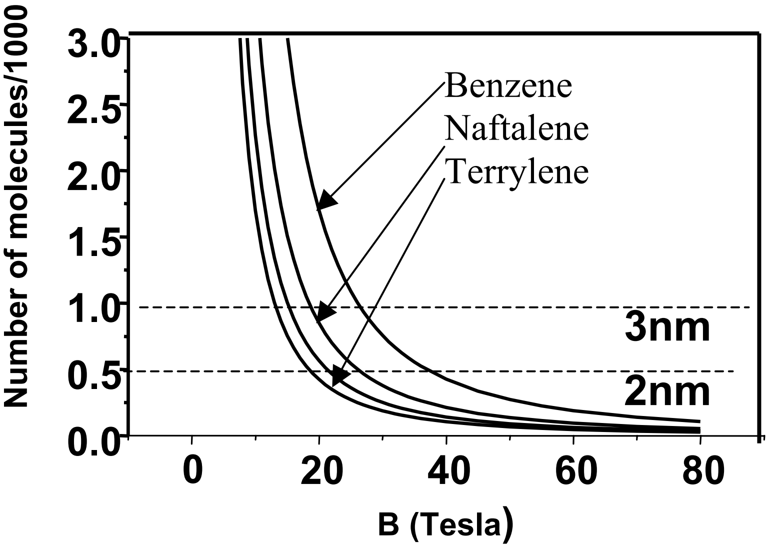


Figure1: Size of aromatic clusters for which the magnetic energy exceeds the thermal energy and which can be aligned in magnetic fields

In recent years there has been an increasing interest in high magnetic fields from scientists working in the field of nano-science. An important trend in chemistry is to construct molecular assemblies which, as a whole, contain desired functionalities. These molecular assemblies, often created by supramolecular chemistry have become increasingly large and often attain a size of a few nanometers. Consequently the (dia)magnetic forces on these assemblies at high fields can overcome thermal motion, which make high fields increasingly important in this area. As an illustration in Fig.1 the necessary cluster size needed for the magnetic energy to become larger than the thermal energy is shown as a function of the cluster size of aromatic molecules which demonstrates the importance of fields above 30 T for bottom-up nano-science.

In 1988-89 the US National Science Foundation, NSF, and the National Academy of Science, NAS, sponsored a committee to study the future of high field research in the US. The result was the Seitz-Richardson report which strongly recommended an expanded effort in high magnetic fields, primarily DC but also pulsed. This led to the creation of the American High Magnetic Field Facility (NHMFL) in Tallahassee. More recently (1998) a forward looking report was published by the European Science Foundation (ESF) “ESF study on large scale facilities in Europe: a scientific case for 100 T science” (http://www.esf.org/ftp/pdf/Pesc/100T.pdf) supporting, among others, a specific effort towards pulsed fields in the range of 100 T. This has encouraged the support of the Dresden-Rossendorf facility. A study is being currently undertaken by NSF/NAS to update the Seitz-Richardson report but the conclusions are not yet available.

This report will, first, review the present technical possibilities offered to the user community by leading user facilities all over the world. The next chapter will give a few specific examples of some scientific breakthroughs that the use of these facilities has provided in different classes of problems or materials. The last chapter will report on future developments either already funded or at an advanced stage of design.

I. Existing possibilities in high magnetic fields

The production of very high magnetic fields requires large power installations and for this reason can only be implemented in a limited number of places. This report will concentrate on the major installations which operate as user facilities either in DC and/or pulsed fields (a recent report from these facilities can be found in the special issue of the Journal of Low Temperature Physics (JLTP) **133** (2003)). Their implementation comprises a major capital investment. These are:

- The NHMFL (http://www.magnet.fsu.edu) located in Tallahassee for the DC facility, in Los Alamos for the pulsed field facility and in Gainesville for the B/T (Field/Temperature) facility.
- The GHMFL (http://ghmfl.grenoble.cnrs.fr) , a DC facility located in Grenoble.
- The HFML(http://www.hfml.kun.nl), located in Nijmegen, offering mostly DC fields but in addition some pulsed field facility.
- The TML (http://akahoshi.nims.go.jp/TML), located in Tsukuba, offering DC-fields.
- The HFLSM (http://www.hflsm.imr.tohoku.ac.jp), located in Sendai, offering DC fields.
- The LNCMP (http://www.lncmp.org), presently the leading pulsed field facility in Europe, located in Toulouse.
- The ISSP-MGL (http://www.issp.u-tokyo.ac.jp), world leader for pulsed fields in destructive mode, located in Kashiwa
- The Dresden pulsed field facility (http://www.fz-rossendorf.de/HLD/) under construction.

In order to produce an easy to handle document, the list detailed above includes only those laboratories which are routinely operating as a user facility.

Many other smaller scale laboratories (Oxford, Zaragosa, Berlin, Braunschweig, Wroclaw, Frankfurt, Osaka, Okayama, Kobe, Fukui, …) have developed pulsed field research, with sometimes a very innovative approach, and we apologize for having omitted their activity here (more information concerning the Japanese laboratories can be found on the Web site of the HFLSM). All these laboratories are involved in strong international collaborations, either between themselves or with the leading high field facilities.

A characteristic feature of high magnetic field research is that there exists a very large community of laboratory-based local experiments in the lower field (usually less than 20T) regime, which develop experimental techniques and systems and act as a filter and testing ground for new experiments. This enables highly efficient use to be made of the large user facilities.

When looking at the different possibilities for high fields, the maximum field value is not, *per se*, a goal: other important parameters have to be considered as the objective is to perform experiments which, often, require very low temperatures and/or high pressures or simply require specific quality of the field such as its spatial homogeneity or temporal stability (in particular for NMR experiments). For instance, the diameter of the bore where the field is produced, the pulse length for pulsed fields, or its "quality" dependent

on the homogeneity, vibration and noise levels, also play a crucial role. These characteristics will, *in fine*, determine the capability to obtain outstanding scientific results.
In the following we list the current possibilities offered to scientists in the facilities listed above. To avoid the use of acronyms, these facilities are labelled by location.

II.1 Static fields

Static fields beyond 20 T are produced either by pure resistive magnets or their combination with superconducting coils to form the so-called hybrid magnet. For a given power installation, this later combination provides the maximum DC field.

II.1.1 Hybrid magnets

The currently operational hybrid magnets are listed in Table 1 together with the power used for their operation.

Table 1 - Operating Hybrid magnets

Location	Maximum field (T)	Bore diameter (mm)	Homogeneity (ppm/cm dsv)	Power (MW)
Tallahassee	45	32	1500	40
Tsukuba	35	32	1500	15
Sendai	31	32	1500	8

They are characterized by a room temperature bore diameter which is sufficient for low temperature experiments. The homogeneity and the noise limit some refined investigations although technical improvements in the instrumentation could partially compensate this deficiency.

II.1.2 Resistive magnets

The most efficient resistive magnets are listed in Table 2 together with the power used for their operation.

Table 2 - Operating high field resistive magnets

Location	Maximum field (T)	Bore diameter (mm)	Homogeneity (ppm/cm dsv)	Power (MW)
High Field				
Tallahassee	33	32	1500	19
Grenoble	30	50	1500	22
Grenoble	34	34	1500	22
Nijmegen	33	32	1500	20
Tsukuba	25	32	1500	15
Sendai	20	32	1500	8
High Homogeneity				
Tallahassee	25	52	12	19
Large bore				
Tallahassee	19.5	195	400	20
Grenoble	20	180	400	20

Each facility has families of duplicate and different configuration coils adapted for specific measurement requirements. The detailed list of magnets can be found in their respective web-sites. Table 3 also reflects the possibilities in terms of field "quality". It is clear that increasing the homogeneity or the bore diameter leads to a decrease of the maximum field available.

II.2 Pulsed fields

With the existing high power installations in high field facilities, the limit in DC fields is probably of the order of 50 T. Beyond this value, higher fields can only be obtained in a pulsed mode. This requires a first stage of energy storage followed by a discharge in a high field coil.

There are two possibilities for these coils: either they remain operative after the shot (this is referred as a non-destructive operation) or they are destroyed.

II.2.1 Non destructive operation

In this mode of operation, the high field coils are cooled down, usually to liquid nitrogen temperature. Since the early work of Kapitza in 1938, the different ways to store the energy have been clearly identified: (i) either the energy is stored in a capacitor bank and discharged in the magnet (ii) or in a motor-generator system and discharged either directly or through an intermediate inductive storage system into the magnet. All these methods are indeed used and the results displayed in Table 3.

Table 3 - Operating pulsed magnets in a non-destructive mode (aimed at 100 shots at maximum field before destruction)

Location	Maximum field (T)	Bore diameter (at 77 K) (mm)	Duration	Stored energy in the magnet (MJ)
Motor-generator driven systems				
Tallahassee (Los Alamos)	60	32	100 ms flat-top (under re-construction)	90
Inductive storage				
Grenoble	60	24	15 ms flat-top	15
Capacitor driven systems				
Kashiwa	70	12	10 ms PWHM	0.9
Osaka	80	10	15 ms PWHM	1.7
Tallahassee	65	15	5 ms PWHM	1.6
Toulouse	77	15	5 ms PWHM	14
Dresden	61	15	10 ms PWHM	1

There are two different ways to qualify the duration of the pulse: either the pulse width at half maximum of the field or the time available for experiments at a given value of the field near its maximum value (within 1%) called, in Table 3, PWHM and flat-top respectively.

The actual limitations for this mode of operation derive essentially from the availability of materials: the conducting wires of the high field magnets have to fulfill the conflicting properties of high-conductivity and high tensile strength. In addition one has to face problems related to the ageing of these materials and their insulation. Of equal importance is the reinforcement material in the coils as available conductors do not have sufficient strength to withstand the forces in the coil during a field pulse.

II.2.2 Destructive operation

The actual state of the art for non-destructive mode operation is of the order of 75 T. At present, to go well beyond this field requires an operation which will lead to the destruction of the magnet. Such magnets use is either a single turn coil which is not expensive and preserves the instrumentation system (including the cryogenic environment and the sample) or use the technique of electromagnetic flux compression which is more destructive. The existing possibilities are listed in Table 4.

Table 4 - Operating pulsed magnetic fields in a destructive mode

Location	Maximum field (T)	Pulse duration (PWHM)
Electromagnetic flux compression		
Kashiwa	300-600	3 μs above 100 T
Single turn coil technique		
Kashiwa	80-200	6 μs

The details of this type of operation are described in J. Low Temp. Phys.,**133,** 39 (2003).

II.3 High fields and instrumentation.

Most of the spectacular advances, which will be illustrated in the next chapter, are not only due to magnetic field enhancements but also to the ability to carry out very sensitive measurements using advanced instrumentation such as newly manufactured micro-devices, strain gauges, miniature calorimeters, micro-coil NMR, high precision magnetization, advanced optical techniques etc. These instruments have to work *in-situ* for precise reliable measurements, in the hostile environment of pulsed magnetic fields. Here also each facility has a program to develop enhanced instrumentation. The results are available on their respective web-sites.

It is worth paying attention to the problem of combining high magnetic fields with low temperatures which is fundamental for many problems and in particular for new quantum phenomena. Such facilities exist, in particular, at the NHMFL High B/T facility at the University of Florida.

Finally, in view of the modern trend of nanoscience it is becoming increasingly important to develop tools which are able to address individual nanoparticles or objects. The most commonly used probes, single molecule spectroscopy, Scanning Near Field Optical Microscopy, Atomic Force and Magnetic Force microscopy and Scanning Tunnelling microscopy all require very low vibration levels to allow the necessary micro-positioning.

This additional experimental requirement raises a challenge for high magnetic field experiments where the necessary electrical and cooling powers tend to be noisy. Furthermore precise electrical measurements using Single Electron Tunnelling devices are extremely sensitive to field noise and this requires sophisticated field stabilization schemes to make such experiments possible. In the DC laboratories in Tallahassee, Grenoble and Nijmegen several projects are under way to create conditions which make these sensitive experiments possible.

II.4 High field superconducting magnets.

At present the Oxford Instruments and Bruker companies offer, on a commercial basis, magnets and NMR spectrometers operating at 900 MHz for the proton resonance frequency (field around 21 T). Beyond this field (or frequency) the next step is to reach 1 GHz (field about 23.4 T) with high homogeneity and stability. These magnets are mostly devoted to life sciences. They also correspond to a large capital investment exceeding ≅ 15 M$ and therefore they will probably be located be located in dedicated centers. Tsukuba is operating such a magnet at 930 MHz in a bore diameter of 54 mm whereas Tallahassee is installing a magnet for 900 MHz in a bore diameter of 105 mm. The next step will critically depend on the development of high Tc superconducting wires.

II.5 On-going technical programs in high field facilities.

Besides the effort in instrumentation, most of the high field facilities have a strong technical program to improve their capabilities and/or their efficiency. A more detailed review is given in section VI.

In DC magnetic fields, the main effort is concentrated on the design of magnets with specific instrumentation goals or attempts to make the high field operation less expensive. In this context, for instance, Sendai is heavily involved in the development of Cryogen-free superconducting and hybrid magnets (J. Low Temp. Phys.,**133**, 7 (2003)).

Another important route, followed by DC field facilities, is the development of efficient schemes to make very homogeneous magnets for NMR experiments, possibly at the 0.1 ppm level. The developments involve advanced active and ferromagnetic shimming techniques and field stabilization schemes. These developments are all based on the notion that high field NMR experiments (in principle 1.4 GHz in 33 T is possible) will only be possible in the near future with resistive DC magnets opening potentially new domains of research such as solid state NMR biology. Alternatively, high field NMR, as a probe of condensed matter science, will certainly benefit from improvements in the field range where new phases or phenomena appear.

Although static magnetic fields are obviously more suited to the NMR technique, an example of the instrumental improvement which can be achieved is the observation, at Dresden, of an NMR signal from Deuterium during a single field pulse at 46 T. This has been recently reported by J. Haase *et al.,* Physica B **346**, 514 (2004). This will provide a convenient way to calibrate pulsed field magnets, and, perhaps, open in the future the possibility of NMR studies above 45 T.

In pulsed field technology, the main effort is focused on programs aiming at the development of high conductivity-high tensile strength conductors. This is carried out in Tallahassee (Los Alamos), Toulouse and Dresden. New concepts for pulsed magnets have also been derived, for instance the principle of the coil-in-coil-ex design developed by the EU funded ARMS consortium.
Finally, as mentioned above, both Tallahassee and Tsukuba have a strong program to study and test high Tc superconducting wires.

II.6 Conclusion

In this chapter we have reviewed the most important facilities open to users who want to perform their research in high magnetic fields. The selection is far from complete, because not only many other magnets exist in these laboratories but each of them strives to provide users with outstanding experimental instrumentation.

The user community is continuously increasing due to the increase in of off-the shelf superconducting magnets in all laboratories, leading more scientists to explore magnetic field science in their own laboratories which naturally leads to the necessity to extend their research to higher magnetic fields. Furthermore the user community is evolving from primarily condensed matter physicists to other scientists exploring new issues at the frontiers of physics, chemistry and biology.

The following chapter will give a partial illustration of the wealth of information that can be obtained from investigation in high magnetic fields.

III. A few examples of current scientific achievements in high fields

Considering the wealth of information obtained from high field research in science, it is not an easy task to give an exhaustive report of all the highlights achieved in high magnetic fields. As already mentioned, the magnetic field can act in different ways on matter. Used as a spectroscopic probe which quantifies the spin and electronic states, it can promote the coincidence of induced transitions with internal excitation energies corresponding to specific interactions: this is the basis of EPR, NMR and ICR resonance experiments including optical measurements. What we learn in these conditions is related to the corresponding interaction mechanism. When the magnetic field is used as a thermodynamic probe inducing a new ground state of matter, leading to phase transitions, we obtain information about competing interaction mechanisms. This necessarily implies the relative evaluation of different correlation effects of great importance to understand the resulting field-induced new phase. It is, however, clear that the deeper the understanding of the signature of interactive mechanisms, the easier is the interpretation of results across a phase transition.

In the following, we review some major scientific information obtained from different classes of compounds studied under high magnetic fields.

III.1 Low Dimensional Semiconductors

III.1.1. Electron-phonon interaction

One of the simplest interaction mechanisms governing the collective properties of the matter is the electron-phonon interaction. Different mechanisms have been identified and conceptually described in terms of a one electron picture. This picture does not raise, a priori, fundamental questions when the interaction implies the deformation potential. It is however far from being trivial for Fröhlich type interaction with longitudinal optical (LO) phonons, which has led to the concept of polaronic mass.

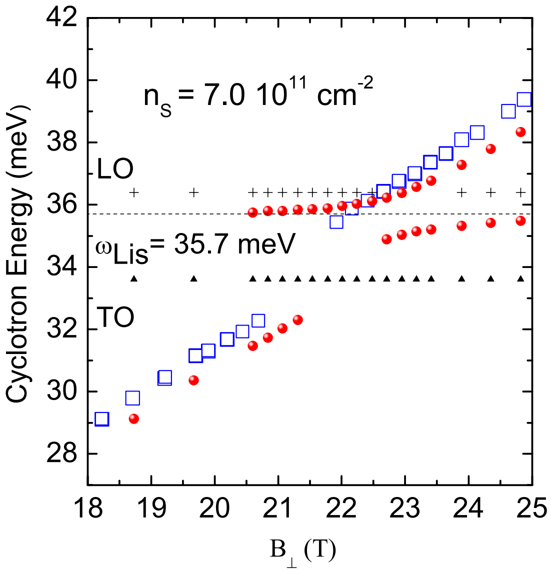


Figure 2. Cyclotron resonance energies of a doped GaAs Quantum Well (QW) for two configurations of the magnetic field perpendicular to the QW plane (squares) or tilted by an angle of 20.5° with respect to this plane.

Faugeras *et a*l. Phys. Rev. Lett., **92** ,107403,(2004)) Indeed, recent experiments of cyclotron resonance (CR) performed on especially designed high mobility n-doped single quantum wells of GaAs, demonstrate that this interaction does not exist in real metallic polar systems as seen in Fig. 2. The coupling with the LO phonons does not occur for fields perpendicular to the QW plane and, instead, a dielectric interaction with the hybrid plasmon-intersubband mode clearly develops for the tilted configuration. In fact the infra-red transmission spectra can be quantitatively interpreted without invoking any specific electron-phonon interaction. Therefore the Polaron concept may be questionable in real materials with free carriers. In addition, one observes some real interaction with the transverse optical phonons which is not explained by known theories.

These electron-phonon mechanisms are important to quantify not only on fundamental grounds but also for practical reasons. Indeed they are the main mechanisms governing the relaxation of excited carriers limiting, for instance, the efficiency of quantum cascade lasers.

III. 1.2. Interaction between localized and itinerant magnetic systems

This is the kind of interaction which occurs naturally in the family of diluted magnetic semiconductors such as CdMnTe with a low doping (0.2 %) of magnetic ions. This system can be viewed as composed of two paramagnetic subsystems with different transition spin energies, one originating from the Mn^{2+} ions and the second one from free electrons. When the magnetic field induces a coincidence of these energies, it has been found that there exists an anti-crossing of the spin transitions which demonstrate the collective character of the localized spins even for this diluted magnetic system (F. Teran *et al.* Phys. Rev. Lett., **91**, 077201 (2003)). These model systems are very simple and their study is of great importance to the understanding of the interactions between localized and itinerant magnetic systems.

III.1.3. Exciton complexes

The optical properties of undoped semiconductor quantum wells (QW) are dominated by coupled electron-hole excitations, i.e. excitonic resonances. Adding extra electrons to the quantum well leads to the formation of negatively charged excitons (trions), consisting of two electrons bound to one hole. A trion is a relatively simple three particle complex, analogous to H^-, and can therefore serve as a model system to investigate correlations between a few interacting electrons. Of particular interest is the limit of high magnetic fields, where the magnetic length is smaller than the typical interparticle distance. Reaching the high field limit of H^- is not possible because this would require much higher fields than those available nowadays.

At zero magnetic field the only bound state of negative trions is a singlet state in which the two electrons have opposite spin. In this case the photoluminescence spectrum exhibits only two emission lines due to the neutral exciton and the singlet trion. At finite magnetic fields this singlet state remains bound, but in addition spin-triplet states also (parallel electron spins) become bound. In the limit of high magnetic fields, a change of ground state occurs and one of the triplet trion states becomes lowest in energy. This has been studied in fields up to 45 T in doped GaAs QW systems (M. Hayne *et al.*, Phys. Rev. B **59** 2927 (1999)) and doped diluted magnetic semiconductor QW (S. A. Crooker *et al.*, Phys. Rev. B **61** R16307 (2000)).

III.1.4. Quantum Hall effects

The past decade has seen phenomenal discoveries, some deliberately researched and others quite unexpected. Many of these have been found using two dimensional electron systems, 2DES. The integer and fractional quantum Hall effects (IQHE and FQHE) were known from the 1980's, but the production of higher and quieter magnetic fields, along with the production of better quality samples have led to surprises and insights into the 2DES and the many body problem in general. Possibly the most profound, and not yet fully understood is the concept of "Composite Fermions" (CF). The idea is that the strong Coulomb repulsion between electrons can be treated by threading each electron with two flux quanta, treating the resulting system as noninteracting and allowing the properties of the fields to handle the complicated many body aspects of particle separation and exchange. This CF model has proven quite successful in addressing the relationship between integer and fractional quantum Hall effects as well as the even denominator FQHE states at high field.

Experiments to test this concept have been performed, measuring the spin polarization of a 2DES, by NMR measurements, at filling factors $\nu = 1/2$ and $2/3$ ($\nu = n_S/\Phi_0$, n_S and Φ_0 being the areal density and the flux quantum respectively). Indeed in this picture the relevant energy scale is the ratio η of the Zeeman to Coulomb energies. As can be seen in Fig. 3a, at $\nu = 1/2$ and beyond a critical value of η, η_{c1}, the polarization saturates and decreases linearly below, corresponding to a constant value of the CF effective mass not predicted by the simple theory of non-interacting CF. In addition for $\nu = 2/3$ (Fig. 3b), the polarization decreases abruptly below a second critical value of η, η_{c2}, which is not at all understood. Therefore much remains to be learned in this area of research.

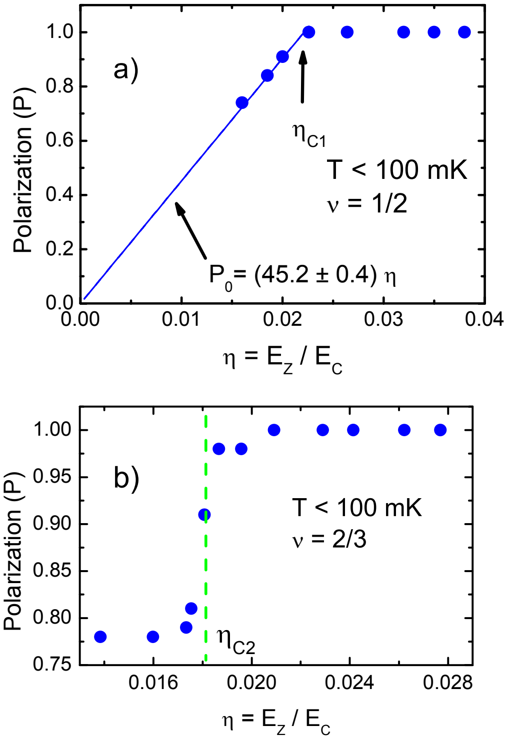


Figure 3. (a) Spin polarization at $\nu = 1/2$ and (b) at $\nu = 2/3$ versus the ratio η of Zeeman and Coulomb energies as determined by NMR measurements on multi-quantum well structure.
N. Freytag *et al.,* Phys. Rev. Lett., **89**, 246804 (2002)

Much of the high field 2DES work does not require the highest fields, but a combination of field and temperature stability, low electrical noise, good instrumentation and long measurement time. There had been a push for higher fields to observe the Wigner crystal which was predicted to lie at the high field limit of the FQHE steps, but the observation, in the 1990's, of insulating phases had to do as much with sample quality improvement. Further tests are needed to identify the nature of the insulating transitions and their sometimes reentrant competition with the FQHE. Many surprises were encountered in this matter. This was the case, for instance, of the existence of a new type of topological spin excitation, the skyrmion, which explains the difference in number of spins and number of carriers for partially fill Landau levels. More recent studies involve ferromagnetic phases between QHE transitions, radiation induced zero resistance states and many experiments where two 2DES layers are coupled either by Coulomb interaction or by tunneling. The latter experiments point to new states with a phase coherence analogous to superconductivity.

III.1.5. Nanotubes and the Aharanov-Bohm effect

Carbon nanotubes offer tremendous potential as electronic nanoscale building blocks. Because of their properties of chirality, magnetic fields are expected to have a dramatic effect on their electronic properties due to the effects on the electron phase within the tube. Magnetic flux inside a single wall nanotube is able to completely alter the band structure which is dependent on Φ/Φ_0, where Φ_0 is the flux quantum, transforming metallic nanotubes into semiconductors and vice versa. These effects can be seen in both the oscillations of the magnetoresistance with period Φ_0 (Aharanov-Bohm oscillations) but also in direct splittings of the interband magneto-optical spectra above 30 T, as has recently been reported (S. Zaric *et al.,* Science **304** 1129 (2004)). To date, the effects of excitonic interactions have not been identified, despite the fact that the excitonic binding energies are of order 100meV due to the one dimensional nature of the tubes. This is expected to be a very fruitful topic in the future.

III.1.6. Quantum dots

When growing InAs epitaxially on GaAs, self-organized quantum dots with a typical size of a few nanometers are formed. These structures can be filled with one or a few individual electrons or holes and are therefore often referred to as artificial atoms. Their electronic shell structure is then described in terms of a one electron Fock-Darwin (FD) spectrum. Depending on the number of electrons (and/or holes) contained in these dots, many different shells can be filled with the magnetic field lifting the initial degeneracy which reappear when levels with different angular momenta come into resonance. Indeed this one electron FD picture also applies to excitonic transitions and recent high magnetic field studies by magneto-optical measurements have clearly demonstrated this pattern (S. Raymond *et al.,* Phys. Rev. Lett., **92** 187402 (2004)). The resulting level shifting and crossing pattern in these systems show evidence of many-body effects such as the mixing of configurations and exciton condensation at the resonances.

These observations contribute to a deeper understanding of the shell structure in artificial-atoms and may finally lead to important applications in quantum-dot based spintronic semiconductor devices.

III.2 Molecular magnets.

Research into molecule-based-magnets has made large strides in recent years, with the discoveries of all organic molecular magnets, room temperature 3D ordered permanent magnets, and single-molecule nanomagnets (see Fig. 4), the latter exhibiting a host of spectacular quantum phenomena; for a review, see G. Christou *et al.*, MRS Bulletin, **25, No. 11**, 66-71 (2000). Single-molecule magnets (SMMs) represent a molecular approach to nanoscale and sub-nanoscale magnetic particles. They offer all of the advantages of molecular chemistry as well as displaying the superparamagnetic properties of mesoscale magnetic particles of much larger dimensions. They also straddle the interface between classical and quantum behavior; for example, they exhibit quantum tunneling of magnetization (QTM). Very little has been learned from experiment concerning the coupling of a nanomagnet to its environment, and how this coupling affects its quantum dynamics. Nevertheless, a large body of theoretical research has focused on this subject, and novel proposals exist for quantum computational devices that utilize SMMs as qubits for quantum computation [see M. Leuenberger, D. Loss, Nature (London) **410**, 789 (2001), S. Hill *et al.*, Science **302**, 1015-1018 (2003)].

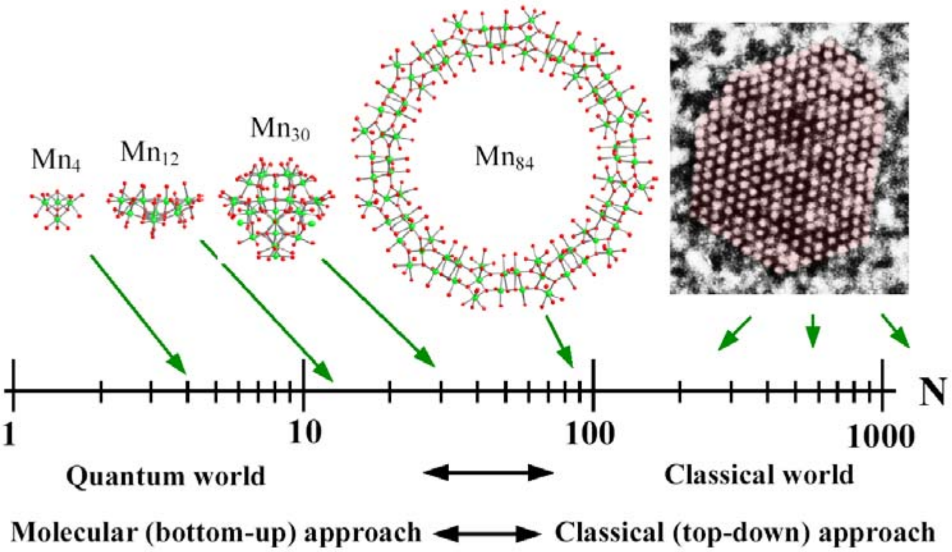


Figure 4. A comparison between molecular (bottom-up) and top-down approaches to nano-magnetism. N represents the number of spins per molecule/particle. Chemists have now bridged the size gap between the molecular and traditional top-down approaches to nano-scale magnetic particles. A. J. Tasiopoulos *et al*., Angew. Chem. Int. Ed., published on-line March 9th (2004).

Only by probing the dynamics of nanomagnets on appropriate time scales (10^2 to ~10^{-9} *s*) can one expect to address issues related to quantum magnetization dynamics. The large spin (up to $S = 13$) and anisotropy associated with a typical SMM necessitates high-frequency magnetic spectroscopies (> 100 GHz), i.e. high-frequency/high-field electron paramagnetic resonance (EPR). These techniques have been extensively used to characterize the relevant parameters describing each type of SMM.

Future research will demand several new experimental capabilities, including: i) continuous broadband frequency coverage in the range 20 GHz to 1 THz; ii) the ability to carry out pump/probe measurements in this frequency range using multiple powerful microwave sources, or a transient DC magnetic field; iii) and time domain capabilities with nanosecond resolution. Major microwave infrastructure for EPR can already be found at many high-field labs. The future of this research area will be dependent upon the development of bright coherent sources (30 GHz to 1 THz) which can be housed at a high magnetic field facility.

III.3 High Temperature Superconductors

High magnetic fields are needed to explore the full phase diagram and determine the ground state symmetries and correlations in high temperature superconductors. Progress in understanding these technologically important materials will come from extended studies at very high fields using several spectroscopic tools and transport measurements. High temperature superconductors can have critical fields that exceed the highest DC and most of the pulsed fields that can be generated at present. Both the superconducting and the “normal” state are very different from conventional normal metals and superconductors. Whereas conventional superconductors and metals can be treated as weakly interacting electronic systems, high Tc materials are apparently relevant from another paradigm, the electrons being strongly interacting and highly correlated. In order to understand the physics of these materials it is necessary to gain some insights into their non superconducting properties. To probe the “normal” state requires exceeding the critical field for low temperature studies or going above the critical temperature. Figure 5 shows the magnetoresistance of optimally doped $YBa_2Cu_3\,O_{7-\delta}$ sample measured with the contact less high frequency transmission technique used for the evaluation of the critical field H_{c2}. This compound remains superconducting at 4 K up to 250 T.

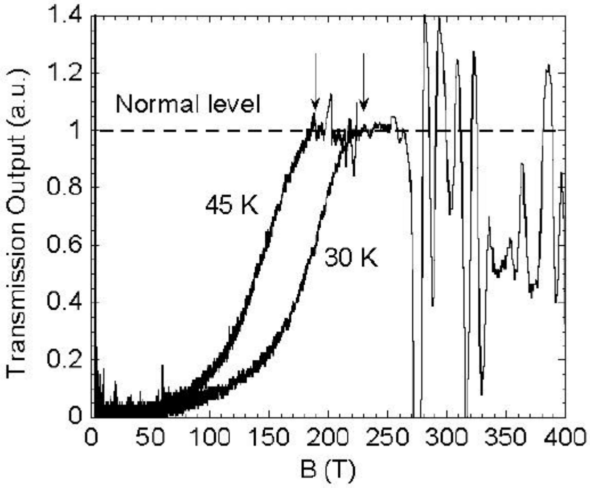


Figure 5. The magneto-resistance of doped $YBa_2Cu_3O_{7-\delta}$ measured by the high frequency transmission technique at 60 MHz in mega-gauss fields. The magnetic field was applied perpendicularly to the c-axis. The arrows indicate the value of the critical B_{c2} fields.

N. Miura *et al*. J. Low Temp. Phys., **133**. 139(2003)

In such conditions it is difficult to obtain information on its normal state. The understanding of the normal state of this class of compounds then requires refined techniques which are more easily implemented at lower magnetic fields. This, in turn, implies the study of materials with a lower T_c. As an example, Fig. 6 below displays the Hall signals measured, with 100 ms pulsed magnetic fields, on a $Bi_2Sr_{0.51}La_{49}CuO_{6+\delta}$ sample for which T_c = 33 K.

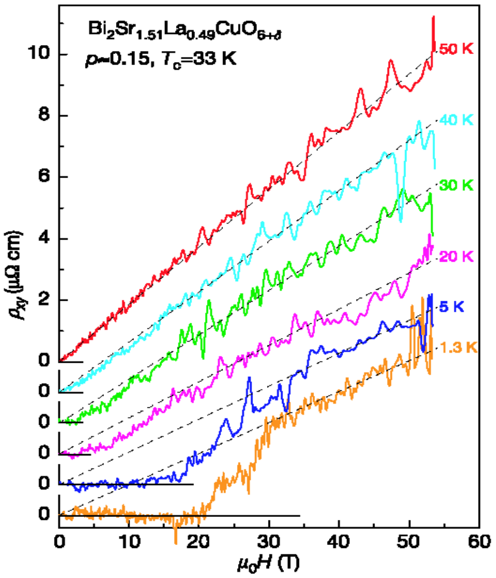


Figure 6. Hall conductivity in $Bi_2Sr_{0.51}La_{49}CuO_{6+\delta}$ high-T_c sample measured with pulsed magnetic fields. Data are shown for temperatures above and below T_c. Each temperature trace has been vertically offset for clarity. F.F .Balakirev *et al*. Nature **424**, 912 (2003).

At temperatures above T_c, the Hall effect yields a carrier density which is much lower than what could be expected from the amount of dopant. This is allegedly the result of strong correlations. When measured at low temperature at 70 T, above H_{c2}, the Hall coefficient corresponds to a value in line without correlations. A similar result is found at very high temperatures. This points to the unusual properties of the normal state and the interplay with superconductivity.

More insight into the superconducting state can be obtained from high field NMR experiments. Fig. 7 reproduces the NMR imaging of optimally doped $YBa_2Cu_3\ O_{7-\delta}$ where the electronic structure is spatially resolved inside and outside of the vortex cores.

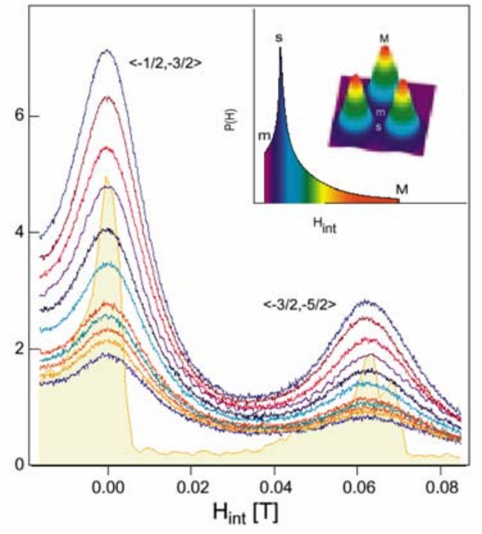


Figure 7. Solid state NMR studies at 37 T of the energy spectrum of vortices in a high temperature superconductor at various positions corresponding to the various internal fields. The inset is the spatial map of the magnetic field of the vortices generated from the spectra. V.F. Mitrovic *et al.*, Nature **413**, 505 (2001).

It is found that outside the cores the system develops strong antiferromagnetic fluctuations whereas inside these cores the electronic states are rather different from those found in conventional superconductors.

III.4 Low dimensional conductors: Superconductivity, Spin Density Waves and Charge Density Waves.

III.4.1 Organic 1D-2D conductors

Many of the unusual properties of organic conductors are high field effects or were revealed by high magnetic field studies. This is due to the close proximity of low dimensional energy scales and accessible magnetic fields, pressures, and temperatures. Molecular materials provide the opportunities to study physical processes in low dimensions, from one dimension where molecular chains have negligible interchain interactions, to two dimensions where interchain interactions begin to appear, to three dimensions where there is finite coupling between chains and planes. These systems occur as very high quality single crystals due to the self-organization that occurs during synthesis, and therefore they have long-range periodic order. The charge carriers are introduced in these compounds through stochiometric charge transfer. Hence, unlike polymers, they are not “doped”, and there is very little disorder.

In purely organic materials, with π-orbital bands partially filled by charge transfer, virtually all non-trivial ground states can be realized by chemical composition, temperature, magnetic field, and pressure. These states include spin-Peierls interaction, charge density waves (CDW) and spin density waves (SDW), metallic, and superconducting properties with a potentially unconventional Fulde-Ferrel-Larkin-Ovchinikov (FFLO), d-wave, and even triplet configurations. Through both Pauli spin and orbital coupling, the magnetic field may induce, enhance, or suppress these novel ground states, and this allows researchers to unravel their mechanisms and identity.

The discovery of quasi-two dimensional BEDT-TTF charge transfer salts, with closed orbits and very long mean free paths, led to qualitatively new magnetotransport phenomena: giant de Haas-van Alphen and Shubnikov-de Haas oscillations and angular dependent magnetoresistance oscillations, AMRO. These effects allow direct measurements of the Fermi surface shape and parameters. Since there are a wealth of Fermi surface instabilities and reconstructions, these measurements provide quantitative investigation of nesting vectors, spin effects and coupling parameters. With such clean low electron density anisotropic samples it has even been possible to observe the quantum Hall effect in bulk crystals.

Recent discoveries are equally exciting. These discoveries include field-induced superconductivity in BETS salts: Fig. 8 reproduces the effects observed in λ-(BETS)$_2$ FeCl$_4$ samples where the 2D sheet of electrons are sandwiched between magnetic layers. This compound, which is an antiferromagnetic insulator at 0 T, undergoes first a metal insulator transition around 10 T followed by a superconducting transition in the range of 20-25 T which in turn disappears at higher fields. This is a most beautiful example of the Jaccarino-Peter effect, compensation of an externally applied magnetic field by an internal exchange field.

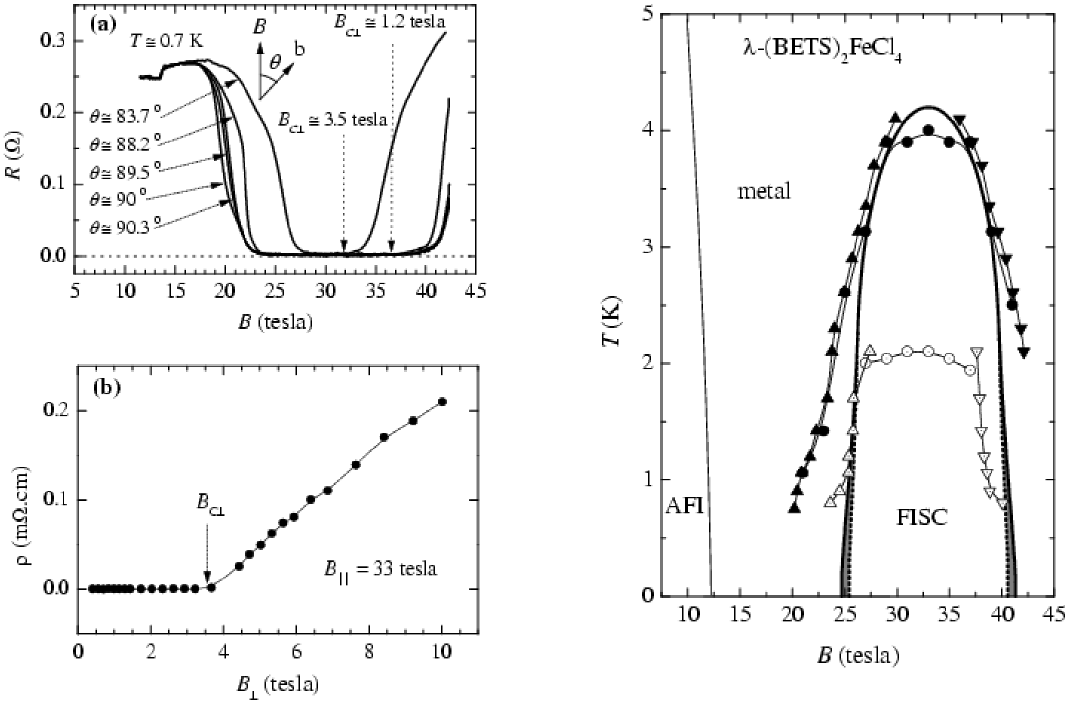


Figure 8. Field induced superconductivity in λ-(BETS)$_2$ FeCl$_4$. (Left) (a) Resistance as a function of magnetic field at T = 0.7 K and for five different angles θ between the applied field and the b-axis (b) Resistance for constant in-plane field $B_{//}$ versus transverse magnetic field $B_\perp$. (Right) Temperature-Magnetic field phase diagram.
S. Uji *et al.*, Nature **410**, 908 (2001) and L. Balicas *et al.*, Phys. Rev. Lett., **87**, 067002 (2001)

III.4.2. Inorganic low dimensional conductors.

Inorganic compounds can also reveal conductivity with a low dimensional character which demonstrates instabilities under high magnetic fields. As an example we report in Fig. 9 data obtained on NbSe$_3$, a quasi one-dimensional conductor. In the low temperature phase of this compound there remains only one small closed Fermi surface as a result of the band reconstruction due to two independent CDW transitions. This small Fermi pocket corresponds to the observed Shubnikov-de Haas oscillations below about 50 T. In the magnetic quantum limit, beyond this field, where only the lowest Landau level is occupied, the magnetoresistance displays a broad maximum at around 65 T decreasing monotonously beyond this field. This could be the result of the Harper broadening of the lowest Landau level due to magnetic breakdown beyond the CDW gap.

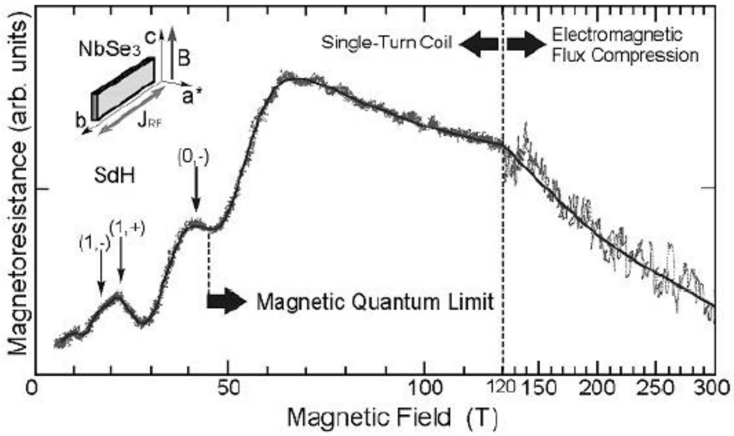


Figure 9. Magnetoresistance of NbSe$_3$ measured by the RF transmission technique under high magnetic fields.
N. Miura *et al.,* J. Low Temp.Phys.,**133**,139 (2003)

III.5 Highly correlated materials

Besides the high T_c superconductors which clearly could be included in this paragraph, there exists a very large variety of compounds having a ground state resulting from a genuine balance of spin and charge degrees of freedom with different degrees of localization. All of these compounds have properties very sensitive to the magnetic field which acts differently on the corresponding correlation effects.

III. 5. 1 Heavy Fermions compounds

Correlations are expected to dominate the physical properties of materials made with elements which naturally have strong localized electronic shells. In this context, during the past three decades, f-electron materials have proven to be a reservoir of novel correlated electronic states demonstrating extraordinary superconducting and magnetic phenomena, including Kondo many body singlet states, valence fluctuations, non-Fermi liquid (NFL) behavior, anisotropic superconductivity etc..

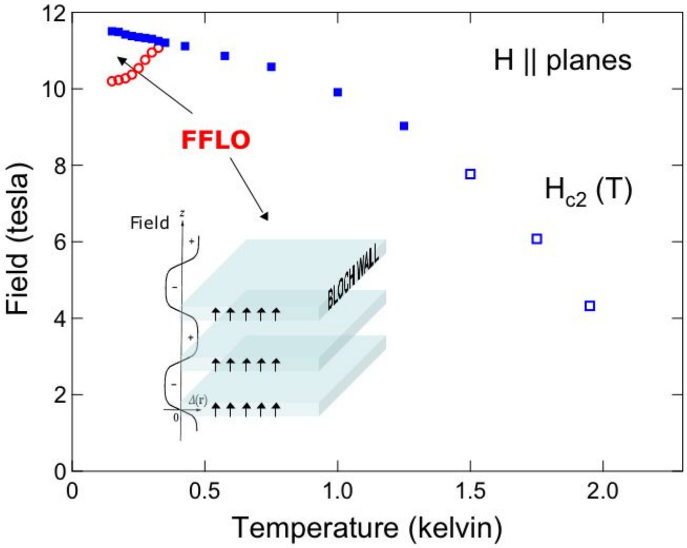


Figure 10. Observation of the FFLO state of magnetically enhanced superconductivity in CeCoIn$_5$. The closed symbols represent first order phase transitions and the open circles second order transitions.
H.A. Radovan *et al.,* Nature **425**, 51 (2003).

Just to illustrate the exotic character of phases which these compounds can exhibit, we show in Fig. 10 the phase diagram, as obtained from heat capacity measurements, of $CeCoIn_5$, a layered heavy Fermion compound. This result is the first clear demonstration of an effect, predicted more than 40 years ago, of the FFLO state resulting for a partial de-pairing of the superconducting state where the superconducting order parameter develops nodes in real space along the field direction. At these nodes the Cooper pairs are broken and spins align along the field resulting, for the superconductor, in a gain of spin polarization energy. It therefore lowers its free energy to remain superconducting. The inset in Fig. 10 shows schematically the arrangement of the ferromagnetic Bloch-type walls perpendicular to the applied external field.
We have a fairly accurate understanding of the non-interacting and weakly interacting electron gas as found in many "conventional" metals like Cu, Ag, Pb. Al, where the kinetic energy of the electrons is dominant. More interesting and complex systems involve strongly interacting electrons where typically the repulsive Coulomb energy and the Pauli exclusion principle play off one another to yield a material that is somewhat magnetic. The Pauli principle forbids the overlap of spin 1/2 particles. Thus electrons with aligned spins, as in a ferromagnet, stay away from each other reducing the Coulomb energy. The relative role of Coulomb and kinetic energy, and the different states they produce are a central question in solid state physics. Electron correlations are more important as Coulomb effects increase. Starting from this limit we expect a tendency toward localized electrons with a magnetic character. As we increase the relative importance of kinetic energy we expect more metallic and less magnetic behavior. There is a great deal of research related to the question of this crossover, which may not be a crossover but a "quantum phase transition' with a quantum critical point (QCP).

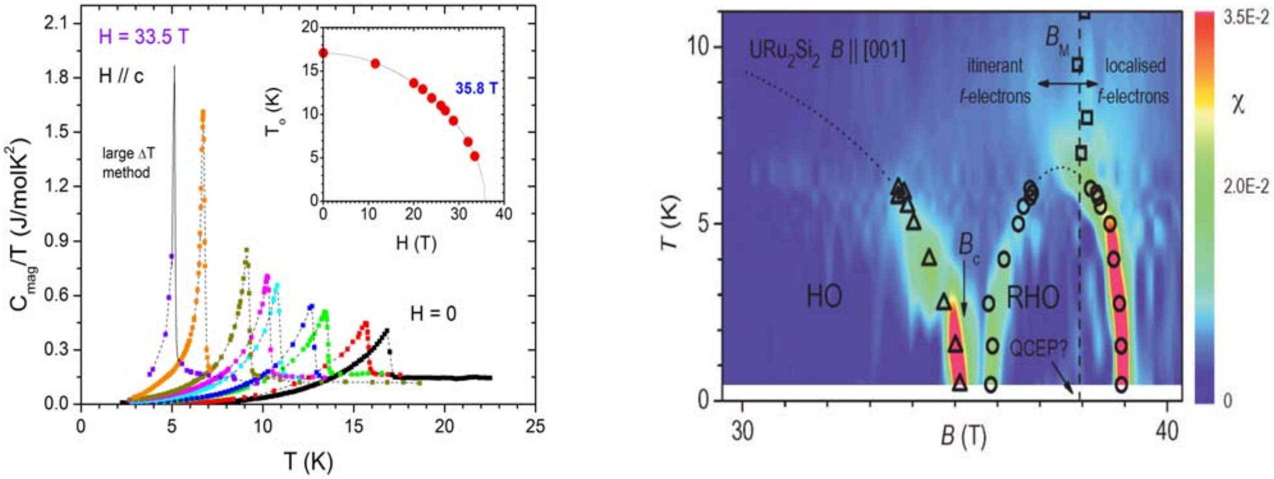


Figure 11. Study of high magnetic field-induced quantum criticality in the hidden order compound URu_2Si_2, Jaime *et al*., Phys. Rev. Lett. **89**, 287201 (2002), Harrison *et al*. Phys. Rev. Lett. **90**, 096402 (2003), and Kim *et al*., Phys. Rev. Lett. **91**, 269902 (2003).

"Heavy Fermion" systems are metallic compounds toward the magnetic side of this crossover. Since spin effects are decisive for these materials, high magnetic fields have been extensively used to both probe the systems and as a thermodynamic variable to change the state of the system.

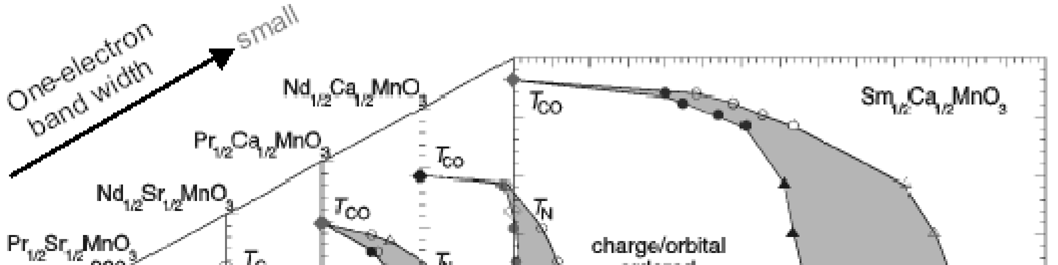
Figure 11 gives an example of the results obtained, by various techniques including specific heat measurements (left part of the figure) and resistivity and susceptibility measurements (right part of the figure) on the compound URu_2Si_2. In this material, rather than being localized giving rise to magnetism, f-electrons develop an itinerant character in a phase with an unknown order parameter, called *hidden* order parameter (HO), for fields below about 35 T. Above this field, both susceptibilitiy measurements (color plot in the right part of Fig. 11) and anomalies in resistivity plots suggest the appearance of a re-entrant phase between 36 and 39 T with another unknown order parameter (RHO). It has been proposed that this re-entrant phase "hides" a quantum critical point.

It is clearly apparent, including the vocabulary, that many things are unknown and therefore not understood in this kind of system: the fundamental aspects of the existence or not of a QCP, which is not only relevant to these Heavy Fermions compounds but also proposed for High T_c superconductors, are of great importance and further experimental investigations are necessary.

At present there are no spectroscopic techniques which have been applied to this kind of compound, especially at very low temperatures, and this is something which should be considered in the future.

III. 5.2 Doped Magnetic Oxides

Doped Magnetic Oxides are non-metallic compounds involving rare-earth and transition metals. They combine electronic features of conventional non-magnetic semiconductors with magnetic properties of conventional antiferromagnetic and ferromagnetic systems. From the physics point of view, these compounds are known as Mott insulators, following the seminal idea that, for partially filled band metals, electron-electron correlations may tend to localize electrons and drive the system to metal-insulator transition (MIT). Central to the properties of these compounds is the concept of orbital degree of freedom which mediates the various couplings between spin, charge and lattice. Just as an example, it mediates the coupling between structural distortion and magnetism in transition metal oxides. Magnetic field directly controls the magnetic ordering, which in turn affects the orbital ordering through hybridization with the neighboring d-orbitals. A prototype of this class of compounds is the family of doped perovskite manganites displaying colossal magnetoresistance (CMR) effects. The properties of these compounds under high fields have been recently review by Y. Tokura and N. Nagaosa (see Fig. 12). The shaded area in this figure corresponds to the hysteretic region expected for 1rst order phase transitions. The solid solution of two cations with different valence states leads, in a first approximation, to a mixed-valence state for the Mn namely Mn^{3+} ($3d^4$, S=2) and Mn^{4+} ($3d^4$, S=3/2).



The former deserves special attention: the 3d orbitals placed in the octahedral coordination of the perovskite structure are subject to partial lifting of the degeneracy into t_{2g} and e_g orbitals. The t_{2g} electrons are considered as localized with local spin S=3/2, even in the metallic state, whereas the e_g electron can become itinerant or may localize by giving rise to a metal-insulator transition and a charge ordered state. An important consequence of the apparent separation of charge and spin sectors is the strong Hund's rule interaction between the spin of the t_{2g} and the e_g electrons. The ferromagnetic interaction via the exchange of the conduction electron is known as double-exchange (DE) interaction, and has been invoked to explain the magnetoresistance singularities observed at around the transition temperature. Even this picture seems to be too simplistic to explain the nature of the phases encountered at low fields. In such conditions, the understanding of phases at higher fields is far from being complete.

III. 5.3 Quantum low dimensional antiferromagnets

Quantum effects are enhanced in magnetic systems with a low spin (S= 1/2 and S=1), and subject to antiferromagnetic couplings. Not only low dimensionality, in the magnetic interactions, magnifies the quantum effects but, in addition, the low temperature behavior of the low dimensional quantum spin systems is dominated by zero-point spin fluctuations. Sparkled by the synthesis of new materials, unusual ground states have been discovered in this class of compounds which have led to a revival of scientific activity in recent years. The largest class of low dimensional antiferromagnetic systems concerns quasi-1D spin systems where the magnetic interaction is dominant along one direction:

this covers, for instance, the spin-1 Haldane chains, spin 1/2 uniform or alternating chains. When frustration is also present, new features appear in the magnetization spectrum of the low-dimensional quantum systems as in $CuGeO_3$. When the magnetic interaction extends in two dimensions, one talks about 2D quantum systems such as $SrCu_2(BO_3)_2$.

Quantum effects strongly affect the response of these magnetic compounds to an applied magnetic field. For quasi-1D chains with a gap Δ (Δ is the singlet-to-triplet excitation gap) in their excitation spectrum (uniform S=1 or alternate S=1/2 chains), there is a critical field, $H_{c1} = \Delta / g\ \mu_B$, that must be exceeded to induce magnetization at T = 0 K.

As an example of quasi-1D systems studied in high fields, we report on the compound $CuGeO_3$ where the Cu^{2+} ions (spin 1/2), lying along chains parallel to the c-axis with an antiferromagnetic order at high temperatures (uniform phase). Below a temperature $T_{sp} \approx 14$ K, it undergoes a spin-Peierls transition with a dimerization of the Cu^{2+} ions resulting in a non magnetic singlet state (S = 0) (D phase). Under high fields and beyond H_{c1} a new phase develops which has a incommensurable magnetic character (I phase). This has been studied by NMR experiments with the results displayed in Fig. 13. It is found that, after the D-I transition, the magnetization develops a solitonic profile which progressively evolves towards a sinusoidal one at higher fields.

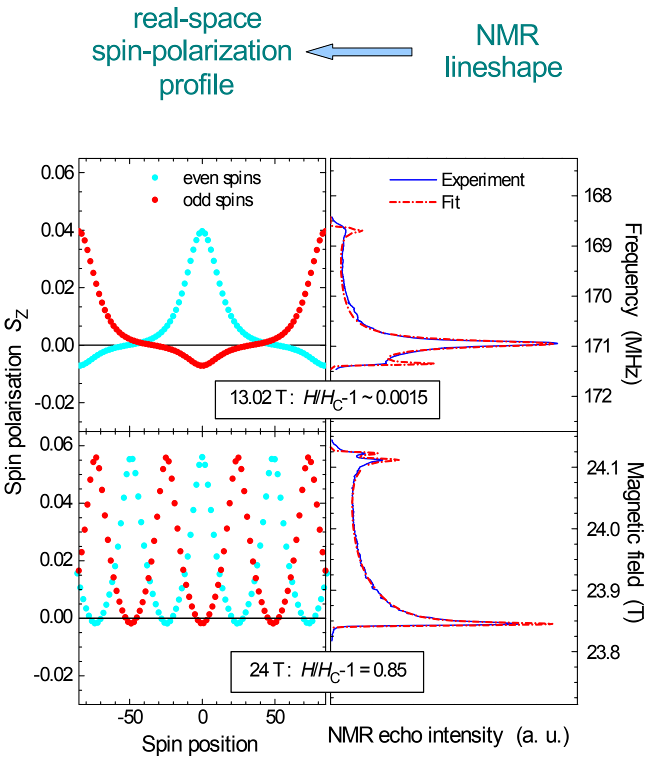


Figure 13. Real space reconstitution of the spin polarization profile (left panel) from the analysis of the NMR line shape (continuous lines in the right panel) for two different values of the magnetic field just above the D-I transition (upper part of the figure and much further away (lower part of the figure.

M. Horvatic *et al.*, Phys. Rev. Lett., **83**, 420 (1999)

Here and likewise in other studies of phase transitions, the approach of spectroscopic investigations at a fixed value of the field provides more insights into the properties of the new field induced phases.

In contrast with quasi-1D magnetic compounds for which many examples exist now, only a few 2D quantum antiferromagnets exhibit a singlet ground state with a spin singlet-triplet gap Δ. These are systems which develop plateaus in magnetization at fractional values of the total magnetization.

The most remarkable and widely studied in the last few years is $SrCu_2(BO_3)_2$: several plateaus are observed in magnetization as shown in Fig.14 (top left). This is a model compound for a 2D antiferromagnet characterized by two antiferromagnetic exchange energies J and J' coupling the nearest neighbor (intra-dimmer) and the next nearest neighbor (inter-dimmer) Cu 1/2 spins.

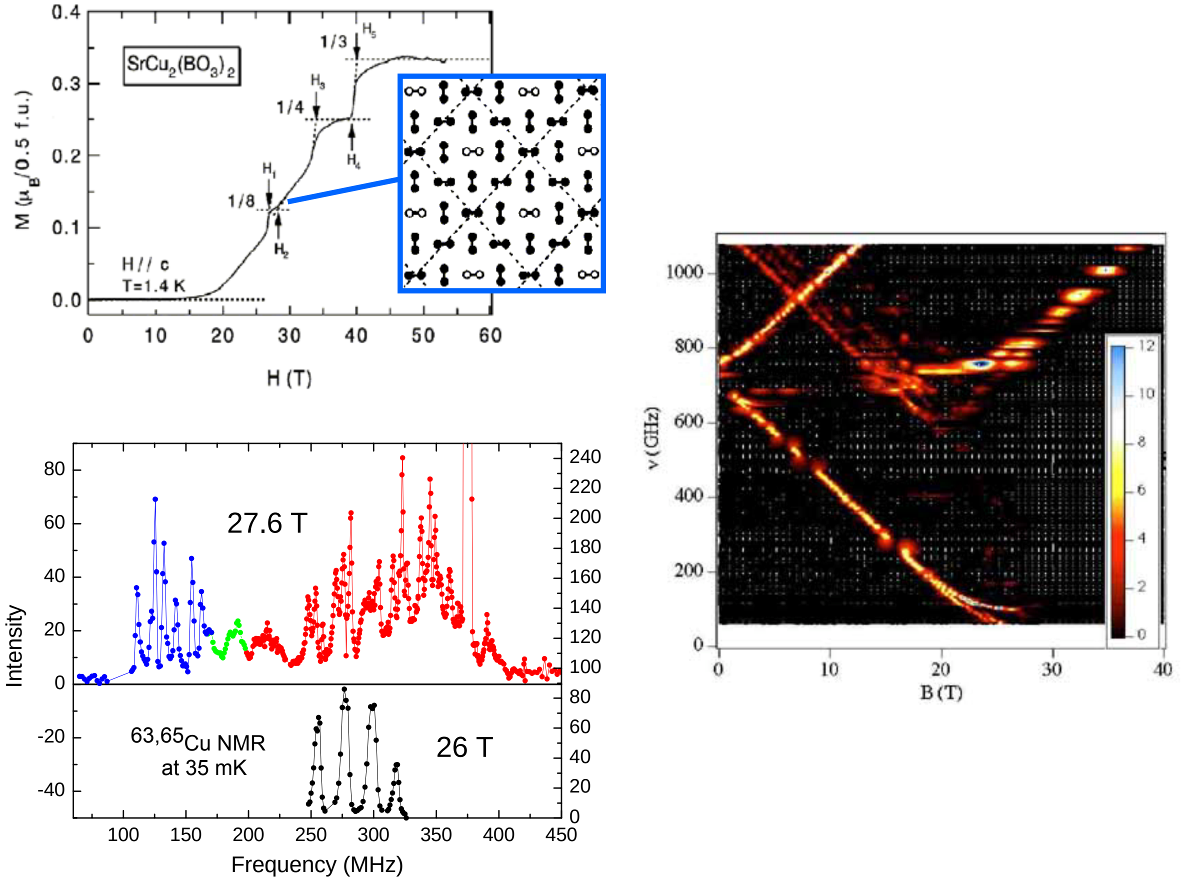


*Figure 14. (Top left) Magnetization of $SrCu_2(BO_3)_2$ showing plateaus at rational values of the total magnetization.*K. Onizuka *et al.*, J. Phys. Soc. Jpn., **69**, 1016 (2000)
(Bottom left) ^{63,65}Cu NMR spectrum at 27.6 T inside the magnetization plateau at 1/8 and at 26 T below the plateau. K. Kodama *et al.*, Science, **298**, 395 (2002)
(right) Energy structure of $SrCu_2(BO_3)_2$ as obtained from multi-frequency ESR spectroscopy in pulsed fields. H. Nojiri *et al.* J. Phys. Soc. Jpn., **72**, 3243 (2003)

The simplest model, derived by Shastry and Sutherland in 1981, which can mimic such a system predicts a ground state being a direct product of the dimer singlet states for J/J'< 0.7 which is the case in this material. When the spin gap is closed by a magnetic field (around 20 T), the magnetization is that of a gas of mobile triplets with a magnetic field dependent density. But the propagation of these triplets is limited by their repulsive interaction. When their density becomes commensurate with the underlying crystal lattice, the gas may crystallize into a superlattice with a magnetization density remaining constant during this process: the inset in Fig. 14 (top left) pictures the prediction of such crystallization at the 1/8 plateau. In reality and as clearly seen from the NMR experiments performed at 35 mK at fields below and inside this plateau, the situation is much more complex. Whereas below the plateau (Fig. 14 bottom left) four lines are observed with the two middle ones being common to both Cu isotopes, the spectrum becomes very complex inside the plateau: many sharp peaks, each related to a specific magnetic environment of Cu^{2+} ions, are distributed over a large frequency range, indicative of a commensurate magnetic order with a unit cell larger than that predicted with the simple model. It can only be explained by adding magneto-elastic contributions to the corresponding Hamiltonian. Multi-frequency ESR studies (Fig. 14 right) have provided information about the energy structure of magnetic excitations in such systems.

From these experiments we learn different things: (i) from a scientific point of view, it would be illusory to believe that the interaction with the lattice can be neglected in magnetic transitions, (ii) one needs to develop instrumentation capable of working in extreme conditions of field and temperature, (iii) we clearly feel the need to extend these investigations to higher fields in the 1/4 and 1/3 plateaus.

III.6 Beyond condensed matter science

Although the main effort of scientists working in high magnetic fields (during the last century) was concerned with solid state physics, there have been some domains at the frontier between physics and chemistry or bio-chemistry which have been explored at high magnetic fields and it is very likely that this trend will increase in the future. One scientific interest here is to use the magnetic field as a spectroscopic probe taking advantage of high fields to increase the resolution. In this domain, investigations in high fields are mainly driven by the determination of molecular structures, not only for themselves, but also to understand their chemical or biological *activity* through their conformation change upon reaction. In this matter, X-ray experiments could provide important information but they require crystallized samples, not always available and also not in their proper active environment. In that respect EPR and NMR probes can play a crucial role.

III. 6. 1. EPR investigations in bio-chemistry.

These studies are of course restricted to paramagnetic species but they benefit from a very significant resolution improvement in high magnetic fields as compared to standard X-band or Q-band investigations. All DC magnetic field laboratories have developed strong research activities in this domain, with possibilities for using multi-frequency spectroscopies from typically 100 GHz to 1000 GHz. Technically speaking these experiments are less demanding in terms of field homogeneity than NMR and therefore well suited to present field conditions in high magnetic fields laboratories.

There are two main classes of molecules which are studied by high field EPR: organic radicals and transition metal complexes.

Stable organic radicals such as the tyrosinyl, cystenyl, glycyl or tryptophanyl radicals appear in enzymes after oxidation of the amino-acid. The goal is to study their local environment through a precise determination of the components of the g-tensor which are fingerprints of the radical and often very sensitive to the presence or absence of H-bonds. An example of such studies has been recently reported for the glycyl radical (C. Duboc-Toia *et al.,* J. Am. Chem. Soc., **125,** 38 (2003)). Bio-chemists are also using stable radicals such as the nitroxyd radical , which can be attached, as a marker, to molecules allowing for studies of dynamical properties. Many issues related to protein denaturation or dimmerization and even to membrane formation can be addressed with such techniques.

A second class of interest for high field EPR research is that of transition metal complexes which play a central role to stabilize some proteins: ensuring the transport and storage of electrons, they often behave like catalyst centers. For example one can focus the discussion on the manganese superoxide dismutase, an anti-oxidant protein which catalyses the dismutation of the superoxide radical with a mononuclear Mn(III) (S=2) complex at the active site. High field EPR studies have been performed on a synthesized model system which mimics its activity: the Mn(III) is in a distorted octahedral site and can bind up to three azide ligands. Its chemical activity is related to the binding of such a ligand. What is learned in the present case is that, upon azide binding, the octahedron undergoes a distortion from compression to elongation along the symmetry axis (C. Mantel *et al.,* J. Am. Chem. Soc., 125, 12337 (2003)).

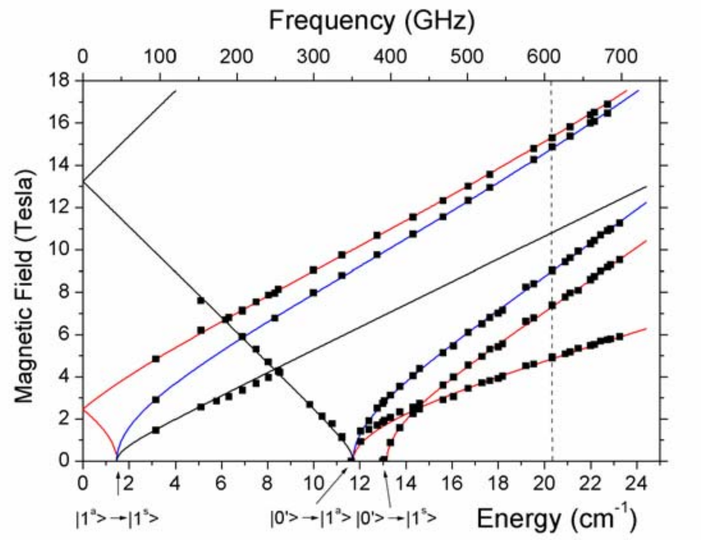


Figure 15. Results of high field EPR measurements for an high-spin Fe(II) complex. The lines are the results of the fitted Hamiltonian.
A. Ozarovski *et al.,* J. Am. Chem. Soc., (in print) 2004

Another example is the class of non-heme Fe proteins, in which Fe is often six-coordinate having two or more endogeneous histidine ligands. High-spin Fe(II) ($3d^6$, S = 2) is a non-Kramers ion with a large zero-field splitting and therefore high field/frequency EPR investigations are necessary to determine the parameters of the relevant Hamiltonian. We show in Fig.15 the comparison of EPR data (points) with the energies of the fitted Hamiltonian (lines) for a model system which approximates the non-heme proteins with other ligands. In the present case the system reveals a distortion of the octahedron very large.

It is interesting to note that in these transition metal complexes the system is very often "EPR silent" for standard EPR analysis because of their zero-field splitting. Therefore high field EPR can not only improve the experimental resolution but in some cases enable a previously impossible experiment to be performed.

III. 6. 2. NMR investigations in bio-chemistry: a first step

The NMR technique plays a central role in the determination of the molecule conformation: it is a local probe with a chemical (even isotopic) specificity able to provide structural information on the surrounding environment and dynamics of the atomic species without requiring any crystallized matter. It naturally gives access to anisotropic interactions like the chemical shift anisotropy (CSA), dipolar interaction (DI), scalar interaction (SI) and the quadrupolar interaction (QI) for nuclear spin larger than 1/2. The CSA provides information on non equivalent sites for a given species together with the coordination number and bond angles, the DI, on the distance between non equivalent sites, the SI, on the chemical bond, the QI, on the interaction between electric field gradient and nuclear quadrupole moment.

The spectacular development of NMR studies in this domain comes from the conjunction of two different improvements: the first one is the ability to perform such experiments in very homogeneous magnetic fields and the second, the introduction of various methodological techniques able to isolate some of the interactions described above by hiding other ones. As an example the use of the Magic Angle Spinning (MAS) technique which consists of rotating, at high speed, the sample at the magic angle $\theta_m = 54.7°$ with respect to the background field which results in a *coherent averaging* of the spectrum when it is dominated by a first order (DI) interaction. A broad spectrum is then transformed to sharp lines keeping only the trace of the CSA tensor. Many other techniques based on refined multi-frequency sequences of pulses have demonstrated the remarkable potential of the NMR technique.

Increasing the field results in different advantages because the CSA is directly proportional to the applied field B_0 whereas the QI varies like $1/B_0$ to second order. There is also a significant gain in the signal to noise ratio which varies as $B_0^{3/2}$. All these methodologies are known and need only to be adapted to the high magnetic field environment found in high DC field facilities. The challenge for these facilities is to provide the scientist with high fields having a good enough spatial homogeneity and temporal stability. As detailed in the next chapter, there are programs and projects aiming at that goal in these facilities.

In biology, there are two kinds of NMR investigations, ones related to the so-called liquid state NMR (L-NMR) and others related to the so-called solid state NMR (S-NMR). In the L-NMR investigations the required field homogeneity is believed to be of the order of 10^{-3} ppm which is far beyond any optimistic achievement that one could obtain with fields generated by resistive or hybrid magnets. On the other hand the possibilities for S-NMR investigations deserve to be analyzed and explored in more detail.

For instance, there has been recently a test experiment performed on the chemical compound $9(Al_2O_3)$-$2(B_2O_3)$ in the Tallahassee hybrid magnet using a MAS system and the evolution of the spectra for different fields up to 40 T is reproduced in Fig. 16.

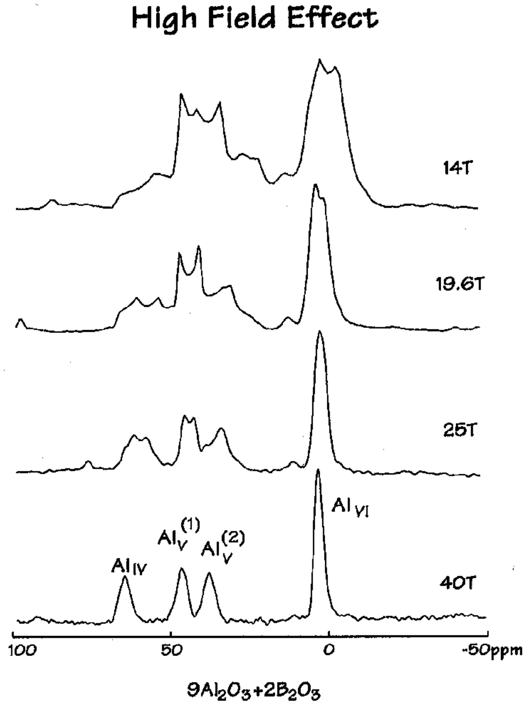


Figure 16. ^{27}*Al MAS spectra of* $9(Al_2O_3)$-$2(B_2O_3)$ *compound showing the spectacular increase of resolution for second order broadened quadrupolar nuclei.* Z. Gan *et al.*, J. American Chemical Society **124**, 5634 (2002)

These spectra have been obtained in a few seconds and it is interesting to note that the observed line width at 40 T is in the range of 5 ppm well below the intrinsic homogeneity of the magnet (see Table 1). Therefore, with specially designed magnets, one should be able to reach reliably 1 ppm homogeneity.

Indeed, there are a series of cases where less homogeneity would still provide acceptable and useful results in biologically relevant systems. Two of the most important and general examples are (i) deuterium NMR lineshape and relaxation studies, and (ii) characterization of (some) oriented peptides in certain membrane samples.

In the case of *deuterium NMR lineshape and relaxation studies*, the objective is to study suitable deuterium labelled samples to understand specific details and timescales of molecular motion that may be relevant to the mechanism of action of the proteins (or ligands) concerned. Deuterium lineshapes can extend over about 200 kHz (>1000 ppm) in the case of rigid groups, and the variations in lineshape induced by molecular motion provide an extremely sensitive probe of molecular dynamics. A 1 ppm (spatial and temporal) resolution is largely sufficient in these cases whereas high-field provides increased sensitivity to yield access to more complex systems. In the case of relaxation studies, the same is true, with the added factor that increased fields provide a different probe of the spectral density functions governing relaxation, and therefore contribute to greater reliability in spectral density mapping studies. Of course, this application is not limited to biological systems, but is applicable to the study of molecular dynamics in most organic systems (polymers, liquid crystals….).

In the case of the study of *peptides in oriented model membrane systems*, current studies concentrate on using nitrogen-15 chemical shifts to determine the orientation of fragments of the molecule compared to the membrane. This technique is increasingly widely used, and is based on observing changes in the nitrogen-15 spectrum of up to 200 ppm. Again, 1 ppm spatial and temporal resolution is largely sufficient here, and high fields yield access to more difficult, larger or more dilute, systems.

Therefore, in the future, DC High Field facilities will provide, the community of scientists working in S-NMR with very attractive opportunities.

III. 6.3. MRI Investigations in Biomedical Sciences

Major developments in the understanding of the biological processes at the most fundamental level will be realizable in the future from advanced instrumentation for high sensitivity Magnetic Resonance Imaging (MRI) at high magnetic fields. Major research frontiers include imaging the structure and process in living cells, functional imaging of human activities (learning, emotions), *in vivo* detection of stem cell incorporation, and developing a digital brain mouse atlas. Examples of systems currently being used an 11.1 T/40 cm horizontal magnet for small animal imaging, at the NHMFL Facility for Advanced Magnetic Resonance and Imaging and Spectroscopy at the University of Florida and micro-imaging probe development for sub-millimeter studies of living cells.

III.6. 4. Soft condensed matter

In soft condensed matter the most spectacular effect of the magnetic field on diamagnetic liquids is the magnetic orientation as a result of the diamagnetic anisotropy of molecules or suspended macromolecular complexes and larger particles: this is due to the intrinsic diamagnetic anisotropy of the constituent chemical bonds. The efficiency of the magnetic alignment is therefore strongly dependent on the system under study.

For instance, suitable chosen material, like Side Chain Polymer Liquid Crystals transform from the isotropic to nematic and subsequently to the glass phase when cooled in a magnetic field, giving rise to a macroscopically ordered, transparent and strongly birefringent material (see Fig. 17). The aligned samples retain their properties after the field is removed and can only be de-aligned by heating them to the isotropic phase. This fully aligned material is technologically interesting because of its strong birefringence and forms an ideal target for further scientific studies like X-ray or neutron scattering experiments. This magnetic field alignment has clear benefits over other techniques, such as mechanical stretching and the use of alignment layers: magnetic alignment has several advantages, since the field exerts a well defined, contact free, torque force on all molecules, and can therefore be used for thin films as well as bulk samples. Therefore not only the end product is interesting but the technique is also important to study the interactions within these materials and to the surface near the phase transition and provides quantitative information about these interactions.

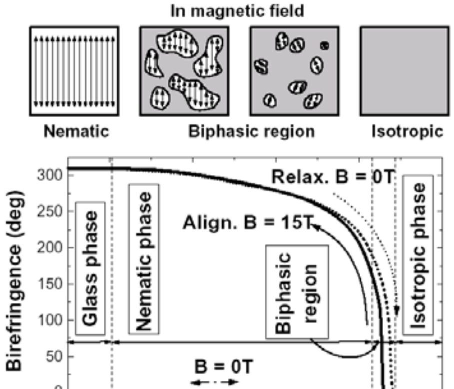


Figure 17. The ordering of side chain liquid crystal polymers in a magnetic field leads to a fully ordered strongly birefringent material, as observed in an in situ experiment. The aligning occurring at the phase transition from isotropic to liquid crystalline and is frozen in at room

An interesting application of these kinds of effects, not yet fully explored, would be the possibility to force the crystallization under magnetic fields of membranes proteins allowing their subsequent investigation by X-ray analysis.

III.7 Conclusion

These few examples, taken mainly from condensed matter physics and even not covering all its aspects, demonstrate that research in high magnetic fields is an extraordinary asset to the scientific understanding of the more challenging problems encountered in physics. This has been verified in the 20th century and remains clearly relevant for future investigations.

Knowing that new domains of science could be opened in a near future, it should be of great interest to carry on and expand this legacy along two main directions:

(i) by developing the corresponding technology to reach higher magnetic fields and/or high fields of better quality,

(ii) by developing new experimental techniques that may allow to consolidate and to further explore unique achievements at these high magnetic fields.

IV Future developments in High fields

Some of the examples described above as well as many other problems in science clearly call for higher fields. In this context the different high field facilities plan future developments. It is not always the highest field goal alone which is planned but often new technical improvements in experimental technology at high fields.

Of course, any new project requires financial support and for realistic purposes we shall first review the projects which are already funded and, in a second step, those which are at the level of "design studies".

IV.1 Projects in the construction phase

IV.1.1 Static magnetic fields

The major effort is currently focused on new hybrid magnets, or installations based on hybrid magnets. They are presented in Table 5.

Table 5 - On-going projects in DC fields installations

Location	Maximum field (T)	Bore diameter (mm)	Homogeneity (ppm/cm dsv)	Date of operation
Grenoble	40	34	1500	2004
Grenoble	24	160	1	2004
Nijmegen	30	52	10	2005
Sendai	35	12	1500	2006

The first project is a new high field hybrid magnet, with a field of 8 T provided by a NbTi based superconducting magnet and 32 T produced by the resistive magnet. In this hybrid system all instrumentation already available for resistive magnets in Grenoble will be operational.

The second project, based on the previous one, aims at the development of multi-frequency high resolution NMR experiments between 4 K and 300 K. The system will be equipped with a magic angle spinner. This magnet should be used for specific research programs at the frontier between physics and chemistry and also for the implementation of refined NMR instrumentation.

The hybrid magnet presently, being developed in Nijmegen, will be devoted to Solid State NMR. The relatively large bore is well suited to accommodate various field stabilization coils and shims to allow experiments at 1.2 GHz with 0.1 ppm resolution. The hybrid technology is used for energy saving since NMR experiments require long periods at constant high magnetic fields and for such an application, hybrid magnets are more cost effective.

In Sendai the effort is based on the development of a cryogen-free hybrid magnet.

IV.1.2 Pulsed magnetic fields

Most of the projects under construction focus on non-destructive mode operation. They are listed in Table 6. For Tallahassee, Toulouse and Kashiwa, they correspond to an extension of their existing capabilities. Projects aiming at 100 T require a significant technological effort for the development of high-strength conducting wires.

Table 6 - On going projects in pulsed fields in a non destructive mode

Location	Maximum field (T)	Bore diameter (77 K) (mm)	Duration (PWHM)	Date of operation
Motor-generator driven systems				
Tallahassee (Los Alamos)	100	15	7 ms	2007
Capacitor driven systems				
Toulouse	80	15	10 ms	2005
Dresden-Rossendorf	70 100	24 20	100 ms 10 ms	2006 2007
Kashiva	100	15	1 ms	2007

The Dresden-Rossendorf project is a new high field installation which has been under construction since 2003 at the Forschungszentrum Rossendorf near Dresden. Scheduled to become operational in 2006/2007, it will have the largest capacitor energy storage in Europe, with a modular (15 x 2.88 MJ, 4 x 1.44 MJ, 2 x 0.5 MJ) 50 MJ, 24 kV, 80 kA capacitor bank. The modular design of the power supply will allow coils to be driven as up to four sections with different pulse times.

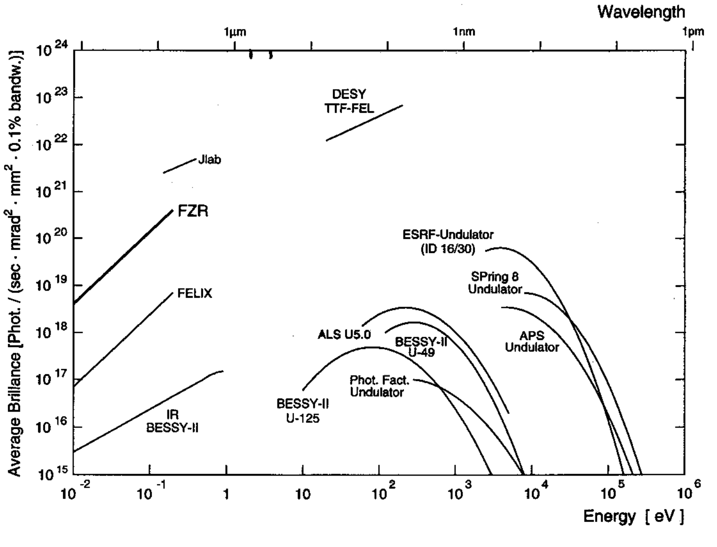


Figure 18. Comparison of the projected brilliance of the Rossendorf free electron laser (FZR) with other light sources existing in the world.

One of the unique features of this project is the combination of the pulsed high field facility with the adjacent free-electron-laser facility of the Rossendorf superconducting electron accelerator. With the projected brilliance of this source, (Fig. 18) this combination creates unique opportunities for high field infrared spectroscopy at wavelengths between 5 and 150 μm. The pulse repetition range of the free-electron-lasers (FEL) of 13 MHz will deliver about 10^5 FEL pulses during one magnetic field pulse of about 10 ms. The given wavelength range covers the range of impurity binding energies and cyclotron resonance energies of semiconductors, as well as semiconducting and high-T_c superconducting energy gaps. Exciting investigations of magneto-phonon effects, magneto-polarons, magneto-excitons, the magnetic limit of impurity levels and quantum confined levels in low-dimensional structures, as well as band gaps in narrow-gap and in diluted magnetic semiconductors will become possible. Taking into account that the Zeeman splitting of a magnetic ion with a typical magnetic moment of 2 μ_{Bohr} in a field of 100 T corresponds to an electromagnetic energy with a wavelength of 100 μm, it is obvious that this combination of magnetic field and infrared radiation will also enable entirely new high field infrared spectroscopy experiments in magnetism.

Some of the facilities involved in pulsed field operation in a non-destructive mode are developing strong programs of research on high strength conductors like Cu-SS macro-composites, Cu-Ag and Cu-Nb micro-composites. They collaborate closely on these topics.

IV.2 Projects at the level of design studies

Listed below are future projects which are at a level of preparation such that a design study has been proposed for support by different funding agencies. We restrict the description to those projects which require a major capital investment.

Two of the following projects aim at extending the investigations under high magnetic fields to new spectroscopic probes. This is a trend which was fostered by the conclusions of a special workshop organized at the ESRF (Grenoble) in 2001 to explore the scientific domains and technical possibilities of X-ray and Neutron studies in high magnetic fields (http://www.esrf.fr/conferences/proceedings/high-mag.pdf). Another workshop with the same goals was recently organized (May 2004) by the NHMFL to explore the combination of high magnetic fields and bright light sources. In this respect the Dresden-Rossendorf project described above was a precursor of this strategy. The possibility to have access to structural information of crystallographic and/or magnetic character for various phase transitions already identified in high fields (cf. chapter III) makes this approach particularly appealing. Therefore several different projects are attempting to couple high magnetic fields to X-ray or Neutron spectroscopy.

IV.2.1. The XDEMF project

The acronym of this project stands for X-ray Diffraction in Extreme Magnetic Fields. More specifically it aims at the development of structural studies under high-pulsed magnetic fields up to 60 T. This is a joint project between the European Synchrotron Radiation Facility (ESRF) and the Grenoble High Magnetic Field Laboratory (GHMFL).

As is clearly apparent from the illustrative examples described in chapter III, one needs to have information about the magneto-elastic properties of materials: this is not restricted to sample volume changes but also concerns how individual atoms react to magnetic (re)orderings. In this context the possibility to perform X-ray diffraction studies **in situ** is very attractive.

The core structure of the XDEMF project is based on the recent technological improvements that both facilities, the GHMFL and the ESRF have succeeded to implementing in their respective specialties.

- As sketched in Table 4, the GHMFL has succeeded in operating a pulsed field system based on inductive storage. The feasibility study was carried out, using a shock alternator installed in a private company, but it was designed to allow a direct connection to a high voltage power line. The results of this feasibility study were exceptional (G. Aubert *et al.*, IEEE transactions on applied superconductivity, **12**, 703 (2001)), providing fields with a standard pulsed magnet up to 60 T in a 24 mm bore diameter at 77 K with a “flat top” of the order of 15 ms, using only 15 MJ of stored energy out of the storage coil which has been tested up to 75 MJ. The limit was only determined by the high field coil as is usual.
- The ESRF on its side was able to demonstrate with the exceptional brightness of its source and standard detection systems the capability to perform diffraction studies on a time scale of a few ms.
- Combining these technological achievements, the ESRF proposes to dedicate a beamline to the diffraction studies in fields up to 60 T.

There exists already in Japan (Okoyama) a test experiment which demonstrates the feasibility of such studies. Fig. 19 reports results obtained at the Spring8 synchrotron with a portable pulsed field magnet (33 T) at the induced phase transition of $YbInCu_4$ which undergoes a transition from a mixed valence state to a monovalent localized state.

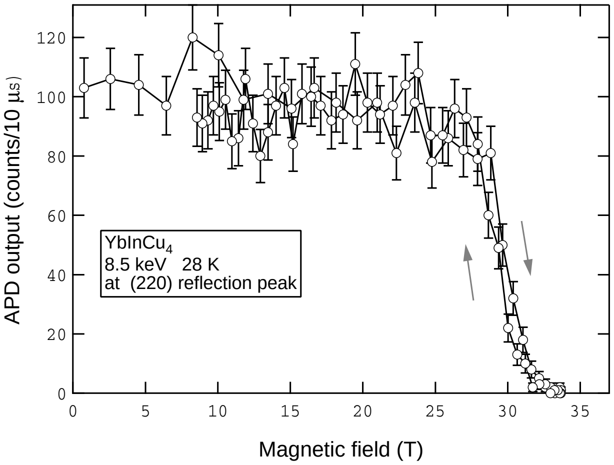


Figure19. Measured change of the lattice parameter of $YbInCu_4$ at the magnetic field induced phase transition.
Y. H. Matsuta *et al.,* Physica **B** 346-347, 519 (2004)

Knowing that in such experiments the field pulse width is just 1 ms, each point corresponding to 10 μs of signal integration, we can easily imagine the gain in signal to noise ratio that the XDEMF project could provide.

IV.2.2. High fields and neutrons

The Hahn-Meitner Institut Berlin and the Institute of Technical Physics of the Research Center Karlsruhe are pursuing a project to build a superconducting magnet with a DC field of about 25 Tesla for structure research with neutrons at the Berlin reactor. The magnet would be a horizontal solenoid with conical openings of 30 degrees at both ends and a warm central bore of 50 to 70 mm diameter. The solenoid should consist of three sections which - starting from the outside - would be wound from NbTi, Nb_3Sn and Nb_3Sn or a high-Tc-material. The outermost coil of NbTi would be operated at 1.9K, the other two coils at 4.2K.

There also exists the J-Parc project, in Japan, aiming at developing neutron scattering experiments combining the pulsed neutron source and pulsed fields for diffraction experiments up to 60 T and inelastic experiments up to 30 T. This project is proposed as a joint venture between Tohoku, Osaka and Tokyo universities.

IV.2.3. The SCH project.

The acronym of this project stands for Series-Connected Hybrid system. Proposed by Tallahassee, this project aims at providing users with a medium resolution NMR facility for biology and materials chemistry, high resolution EPR, condensed matter science requiring long durations at high fields, e.g., specific heat, condensed matter NMR, etc for which signal averaging is needed over extended period of time (tens of minutes to hours) for good signal to noise and measurements of dynamics and spin couplings (relaxation times).

The original idea is to obtain an *improved stability* (~5 ppm/s) of the magnetic field through series connection of an inductive superconductive magnet and a resistive powered magnet: this arrangement should reduce electrical "noise" and improve the "quality" of field for users requiring high homogeneity (~1 ppm), high temporal stability (<1 ppm), and long residence times at moderately high fields (~35- 40 T).

Based on a hybrid design with an outsert (superconducting magnet) providing 14.65 T, it could be configured in several ways with different options for the benchmark design as shown in Table 7.

Table 7 – Different configurations of the SCH project (Tallahassee)

Warm bore (mm)	Maximum field (T)	Field contribution from insert (T)	Field contribution from outsert (T)	Homogeneity (ppm/cm dsv)
40	35	20.35	14.65	1
32	40	25.35	14.65	1000
50	36	21.35	14.65	1000
100	27	12.35	14.65	20

In all variants, the resistive (insert) part is powered with 10 MW, which results in definite advantages: (i) it makes the operation of such a magnet more cost effective, and (ii) it allows the operation of other resistive magnets at the same time, thus increasing magnet time for users. The SCH is fundamentally a *new approach* to high field powered magnets.

IV.2.4. Coil-in/Coil-ex with a regulated coil-ex power source.

In Nijmegen (HFML), a new 20 MW power converter was built for the operation of the 20MW DC magnets and in the same building at the same time a 2 MJ 16 kV capacitor bank to operate liquid-nitrogen-cooled pulsed magnets has been installed.

The 20 MW DC power converter consists of two 10MW units which for the DC magnets operate at 2x20 kA and 500V with high stability. In pulsed operation the stabilization circuitry can be disabled and the two converters can be put in series giving a fast switching regulated output of 1000 V at currents up to 20000 A. This pulsed mode will be used to energize a large-bore platform field (coil-ex), while a small pulsed magnet (coil-in) in its bore will be fired from the capacitor source when the coil-ex has reached its design field.

Fields up to 30-35 T can be generated in a specially designed coil-ex with a bore of between 10 and 20 cm diameter and a time constant of a few seconds. The smaller pulsed magnet coil-in, with copper based conductor and ZYLON reinforcement coils is adapted to the existing capacitor bank and will give a 50-65 T peak field of typical duration 10 ms. Therefore the combination will provide total peak fields of 80-90 T and 10 ms duration. This rather unique combination of different power sources forms an alternative way of exploiting the route towards the goal of 100T field.

IV.2.5 Integrated initiative

In Japan, there is a plan to set up a collaborative program, in high magnetic fields, integrating three major laboratories (Sendai, Kashiwa, and Osaka).

There is a proposal to build, at the ISSP, a new free electron laser to operate with the megagauss facility of Kashiwa using the single turn coil and the flux compression instrumental systems.

A fly-wheel DC-power supply (210 MJ) is planned to be transferred from the Japan Atomic Research Center at Tokai to Kashiwa. In combination with the 1 MJ capacitor bank, it should allow to achieve a non-destructive 100 T pulsed magnet operation.

In this collaborative program, the following goals are planned:

1) Development of non-destructive 100 T magnet technologies,
2) Construction of a cryogen free-superconducting magnet aiming at generating 25 T,
3) Construction of a cryogen-free hybrid magnet (35 T) with a very high stability,
4) Development of micro-devices for high magnetic field measurements on various materials,
5) Development of ultra-high magnetic field electron spin resonance techniques for “spin labelling” oriented medical applications.

IV.3 Conclusion

In this chapter we have reviewed the future projects of high magnetic field facilities which are in the construction phase or are projected in the near future. We have restricted the list to those projects which correspond to a major capital investment. These plans for future developments in high fields try to respond to the needs clearly manifested by the user community at different levels. They demonstrate that these facilities strive to bring to the scientists more access and more refined conditions of work for their own research. In doing so, they continue to play a crucial role in the development of science in high magnetic fields.

V. General conclusions and recommendations

The examples, described in this report, of scientific achievements obtained recently in high magnetic field facilities clearly demonstrate that these facilities have played a very important role in the advancement of our understanding of major scientific problems in a number of different disciplines. These achievements clearly justify, *a posteriori*, the efforts made by different scientific agencies to promote and fund such high magnetic field facilities.

Although predominantly focused, up to now, on issues related to condensed matter physics, the activity of these facilities is taking more and more into account the possibilities for extending their work to other scientific domains and in particular to life sciences.

In all cases, it appears nowadays that there is clearly a need to enhance the accessible field range, to improve the quality of high field magnets and that of the associated instrumental probes:

- Improving the quality of high fields: towards a 3rd generation of high field magnets.

Until recently, the major investments in high magnetic field facilities were focused on the objective of increasing the value of the available fields. This is a prime goal before looking at further developments and refinements concerning the quality of the field. The present projects aim at designing and operating what can be called a *3rd generation of high field magnets*: in pulsed fields activities this would correspond to even higher fields and to longer pulses; in DC field activities to "ppm" magnets corresponding to high field homogeneity and temporal stability and/or "silent" magnets in which the electrical and vibration noise levels are reduced by one to two orders of magnitude with respect to the present capabilities. These 'high quality' fields will be needed to enable the implementation of high sensitivity instrumentation techniques such as scanning probe microscopy and ultra high field NMR. In addition, with new projects, increasing attention is being paid to the implementation of cost effective facilities which will enable more extensive access to high fields.

All these developments require advanced studies on material issues but also illustrate the need to pay attention to the quality of the power and cooling installations. There are a number of potential solutions to these challenges but they are almost all of a sufficiently complex scale to require exploration at the international level.

They clearly deserve to be encouraged.

- Improving the instrumental probes and techniques.

This is an essential effort which should be conducted in parallel with the need for field provision. New probes have to be developed or adapted for investigations in high fields. As critical examples, this covers *X-ray and neutron diffraction spectroscopies* but also *THz spectroscopies*, which often require the provision of multiple coupled complex installations.

New instrumental techniques have also to be implemented in high magnetic field facilities. The effort should be directed towards high speed electronics and detection systems but also towards nanotechnology based instrumentation. These latter aspects are of course not restricted to high field experiments and major advances are expected to emerge from studies performed in various laboratories. New ideas or technical achievements need however be adapted to the specific character of the high magnetic field environment. These efforts will be critical for increasing and extending the range of new outstanding information in high magnetic field science.

- Towards an international organization of the high magnetic field community.

This report was not written to provide a proscriptive road map for high magnetic field science, but to illustrate the many important advances that have resulted from research in this area. It is based on the actual technical and scientific achievements obtained in recent yeras in high magnetic field facilities all over the world. On this basis, the scientific community can judge the scientific significance of the advances which have been made.

As clearly evidenced by the contents of the report and all the discussions which have emerged during its preparation, the main developments in these facilities have come about, up to now, from national initiatives. As science ignores frontiers and as the scale of the expenditure needed for future advances increases, it may be wise to raise at this moment the question of the opportunity to have, at an international level, a committee in charge of discussing new developments and strategies to be adopted in high magnetic field science.

Given the very fruitful discussions among the members of the present working group, it is recommended that an "International Committee on High Magnetic Field Science and Technology" (ICHMFST) should be established which could meet periodically to provide advice to national and international funding agencies. The composition of this committee should, of course, be enlarged to be more representative of the user community in high fields and its creation should occur under the auspices of an international scientific organization.

We would like to thank the IUPAP for its initiative in nominating the present working group, and affording the opportunity to promote science in high magnetic fields.

July 2004