The Toulouse pulsed magnet facility

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Abstract. The ‘Laboratoire National des Champs Magnétiques Pulsés’ (LNCMP) is an international user facility providing access to pulsed magnetic fields up to and beyond 60 T. The laboratory disposes of 10 magnet stations equipped with long-pulse magnets operating in the 35–60 T range and a short-pulse system reaching magnetic fields in excess of 70 T. The experimental infrastructure includes various high and low-temperature systems ranging from ordinary flow-type cryostats to dilution refrigerators reaching 50 mK, as well as different types of high-pressure cells. Experimental techniques include magnetization, transport, luminescence, IR-spectroscopy and polarimetry. The LNCMP pursues an extensive in-house research program focussing on all technological and scientific aspects of pulsed magnetic fields. Recent technical developments include the implementation of 60 T rapid-cooling coils, an 80 T prototype, a pulsed dipole magnet for optical investigations of dilute matter and a transportable horizontal access magnet for small angle x-ray scattering experiments. Scientific activities cover a variety of domains, including correlated electron systems, magnetism, semiconductors and nanoscience.

1. Introduction
The ‘Laboratoire National des Champs Magnétiques Pulsés’ (LNCMP) is an international user facility jointly financed by three national institutions (CNRS, UPS, INSA) and the European Community in the framework of the EuroMagNET and DeNUF collaborations. Between 2003 and 2005 the LNCMP has accomodated researchers from 23 countries and carried out 190 research projects including roughly 30 % of in-house activities. Both in-house and external projects are subject to the same evaluation procedure by an international advisory board. Calls for proposals are issued twice a year via www.lncmp.org or the EuroMagNET website www.euromagnet.org.

The LNCMP user facility is mainly equipped with magnets generating 60 T with pulse durations of >100 ms in 26 mm bore. A short pulsed system providing fields in excess of 70 T is equally available. Magnets can be equipped with different types of cryostats providing temperatures between 50 mK and 300 K. High pressure cells for a variety of experiments are available or under development. For a detailed description of facilities, technical and scientific research activities of the LNCMP the reader is referred to previous publications [1] or the LNCMP website www.lncmp.org. In the present paper we merely provide an update concerning the most recent developments in Toulouse. Section 2 is therefore devoted to technical improvements while selected scientific topics are presented in section 3.

2. Recent technical improvements
The implementation of pulsed magnetic fields in a growing number of large user facilities has given rise to new technical objectives. The classical targets of pulsed magnet design – peak field and pulse
duration – are nowadays complemented by considerations concerning reliability, ergonomics and the suitability of magnets for specific types of experiments.

2.1. **Coil aging and coil monitoring**
In an effort to comprehend and suppress mechanisms limiting the lifetime of pulsed magnets the LNCMP pursues an active research program focussing on materials aging. A separate facility has been set up that permits investigations of degradation processes in small test coils under realistic conditions. As a first indication of the progressive aging of coils during normal operation irreversible resistance changes have been monitored that are witnessing the simultaneous hardening and fragilisation of conductor material. Subsequent post-mortem studies of the local conductivity and micro-hardness of samples recovered from the test coils permit conclusions concerning the spatial distribution of plastic deformations in different parts of the coil body. Similar post-mortem analysis have also been performed on larger user magnets [2].

More recently the direct real-time monitoring of local deformations inside pulsed magnets has become possible by incorporating fiber Bragg gratings between the coil windings. By simple detection of shifts of the Bragg resonance we have succeeded in (a) observing directly the thermal contraction of the coil due to liquid nitrogen cooling and the dynamic expansion due to the applied magnetic pressure and heating during a pulse and (b) deducing the amount of plastic and elastic deformation involved in either of these processes. A final account of these studies is now ready for publication.

2.2. **Ergonomics of user coils and record magnetic fields**
In order to improve the duty cycle of its magnet stations and hence their efficiency for external users visiting the laboratory for a limited time, we have recently started to install a number of rapid cooling coils. The new coil type is equipped with cooling channels that reduce cool-down times by a factor of 3.2 without reducing the 60 T peak field.

As far as record fields are concerned the LNCMP has now started to combine the technique of fibre-reinforced magnets with its in-house development of reinforced wire. In 2006 a first prototype magnet has been constructed making use of stainless-steel reinforced Cu-wire and additional Zylon fibre reinforcement. Prior to its failure at 82 T, the magnet has successfully produced 79 T at the NHMFL at Los Alamos where a sufficiently fast capacitor bank is available. We are now planning to build an up-scaled version of the same type that can be operated with the Toulouse capacitor bank and that will be available to external users.

2.3. **Magnets for special purposes**
Apart from the development of conventional pulsed magnets for its user program the LNCMP has two projects involving special magnet designs. The first project concerns the construction of a horizontal access magnet for small angle x-ray scattering experiments that is used in conjunction with an optical cryostat and a transportable capacitor bank both constructed at the LNCMP. The system has been used successfully for a first measurement campaigne at the ESRF Grenoble [3,4].

The aim of the second project is to investigate the magnetic birefringence of dilute matter and the quantum vacuum. The latter part of the project refers to a fundamental prediction of quantum electrodynamics, namely the magnetic birefringence of the vacuum due to virtual electron-positron pairs. In order to deal with the extremely small magnitudes involved in this effect we have designed a pulsed dipole magnet that provides lateral access for an optical cavity in which the light beam is exposed to the magnetic field over a length of 25 cm. The magnet consist of two race-track shaped coils that are slightly tilted in opposite directions out of the mid-plane so as to create the necessary opening for the cavity while generating a magnetic field in the perpendicular direction. The magnet has so far reached 14 T and is currently installed in the necessary clean-room environment together with the optical cavity.

3. **Current scientific activities**
The scientific activities of the LNCMP cover all areas of physics where high magnetic fields play an important role, including biophysics, magnetism, nanoscience, superconductivity and other correlated electron systems and semiconductors, and make use of a large variety of experimental techniques. For an up-to-date overview, we refer to the laboratory website www.lncmp.org. Below we will describe some recent highlights.

3.1. *Transport and optical spectroscopy studies of carbon nanotubes*

We are performing magneto-transport experiments in pulsed fields up to 60T on individual carbon nanotubes. The aim is to probe the electronic transport properties by combining different magnetic field orientations and electrostatic doping of the tube by a back-gate.

Recently, we have reported on the first experimental study of the magneto-resistance of double-walled carbon nanotubes under magnetic field as large as 60 Tesla [5]. By varying the orientation of the field with respect to the tube axis, or by a gate-mediated shift of the Fermi level position, evidences for unconventional magneto-resistance fingerprints have been presented. Calculations suggest that this phenomenon results from conflicting trends between a magnetic field-modulated density of states and quantum interferences effects at the origin of weak localization.

The electronic bandstructure of carbon nano-tubes (CNTs) is essentially determined by the phase coherence requirement for quantum states enfolding the tube circumference. By applying a magnetic field, one can lift the degeneracy as each quantum state acquires a revolution-dependent phase factor, that is commonly referred to as Aharonov-Bohm (AB) phase and that, at extremely high magnetic fields, gives rise to a metal-semiconductor transition. In order to study this phenomenon, we have performed luminescence and absorption experiments on micelle suspended and thin film semiconducting single wall CNT, in fields up to 70 T.

Our experiments have clearly shown a splitting of absorption peaks at B>50T, thus confirming the effect of the AB-phase on the electronic bandstructure of CNTs [6]. However, in our samples, the magnetic field not only changes the bandstructure but also aligns the initially disordered ensemble of suspended CNTs. At each magnetic field, one thus observes a superposition of splittings corresponding to the actual degree of alignment, which in turn depends on the preceding dynamic orientation of the tubes. Unless the alignment of CNTs saturates, this mechanism complicates a quantitative analysis of the observed splitting. The latter would be quite important, however, as a refined theoretical picture of the electronic properties of CNTs predicts optical transitions to be excitonic with the prevalent Coulomb interaction giving rise to a mixing of quantum states with opposite sense of revolution. More importantly, only one of the emerging excitons is expected to be optically active while the other is supposed to be dark.

As an alternative to the solution samples, we have recently started to study the optical properties of thin films of aligned CNTs, that have now become available and where the aforementioned difficulties do not occur. With these experiments we expect to indirectly confirm the existence of dark excitons at zero magnetic field and to directly observe their brightening at finite magnetic fields.

3.2. *Magnetic field induced structural phase transition observed by high field X ray diffraction*

Until recently, X-ray scattering experiments were limited to static fields of around 12 T, although many magnetically induced transitions are known to take place at higher fields, ad deduced by indirect methods. TbVO$_4$ is a textbook example of a cooperative Jahn-Teller transition, mediated by interactions between the Tb 4f magnetic moments. A high temperature, TbVO$_4$ is tetragonal, and around 33 K it becomes orthorhombic. By means of the mobile pulsed field installation described, installed on a beamline of the ESRF in Grenoble, and capable of producing fields up to 30 T, we have studied the effect of the magnetic field on this transition by real time x ray diffraction measurements. We find that below 33 K, the field reverses the structural transition [4].

3.3. *THz ESR spectroscopy of quantum magnets*

THz spectroscopy is a natural tool in high magnetic field studies, as many magnetically induced energy differences, like the Zeeman or the Landau energy, correspond to the THz energy scale.
We have studied the $s=1/2$-Heisenberg pseudo-ladder magnet CaCu$_2$O$_3$ in pulsed magnetic fields up to 40 T by THz ESR. CaCu$_2$O$_3$ has a crystal structure similar to the two-leg spin-ladder compound SrCu$_2$O$_3$ which exhibits a large spin gap of about 420 K and is nonmagnetic at low T. However, in contrast to the Sr counterpart where Cu spin chains parallel to the $b$ axis are coupled in the $ab$ planes into ladders via a strong rung AF exchange, in CaCu$_2$O$_3$ the Cu-O-Cu bond angle in the rungs deviates significantly from 180°, resulting in a reduced rung coupling. Remarkably, no hint for a spin gap in the Ca compound was obtained so far. This suggests that the corrugation of the ladders changes the spin topology from nearly isolated two-leg ladders to pseudo-ladders with significant interladder interactions, i.e. the coupled spin chains in this pseudo-ladder compound form anisotropic bilayers parallel to the $bc$ plane. We observe an ESR signal originating from a small amount of uncompensated spins residing presumably at the imperfections of the strongly antiferromagnetically correlated host spin lattice. By mapping the frequency/resonance field diagram we have determined a small gap for magnetic excitations below $T_N$ of the order of $\Delta \approx 0.3$ – 0.8 meV. Such a small value of the gap explains the occurrence of the spin-flop transition in CaCu$_2$O$_3$ at weak magnetic fields $H_{sf} \approx 3$ T. Qualitative changes of the ESR response with increasing the field strength give indications that strong magnetic fields reduce the antiferromagnetic correlations and may even suppress the long-range magnetic order in CaCu$_2$O$_3$ [7].

References
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