EMFL Annual Report 2017

European Magnetic Field Laboratory

European Magnetic Field Laboratory
Annual report 2017

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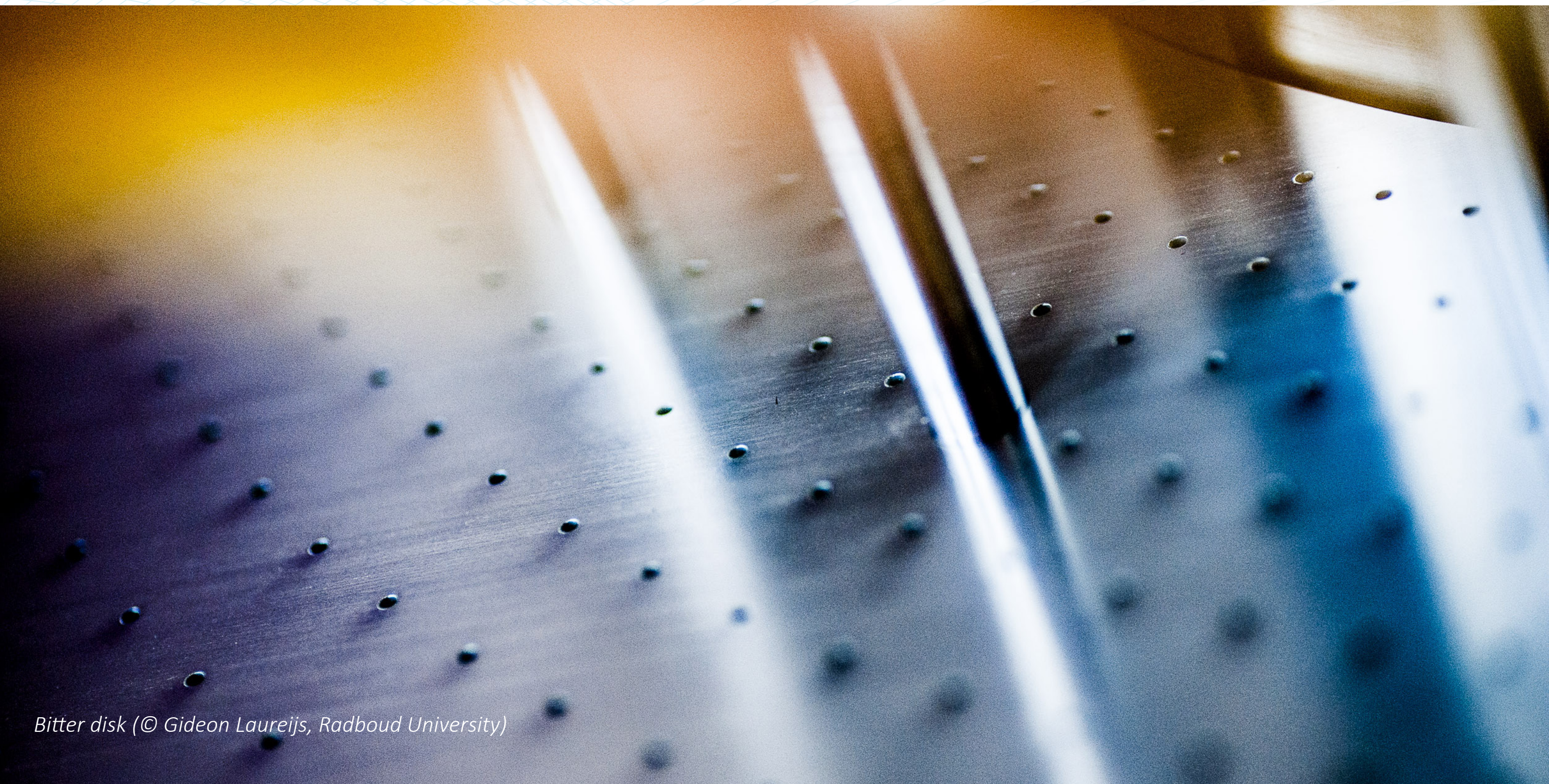


Bitter disk (© Gideon Laureijs, Radboud University)

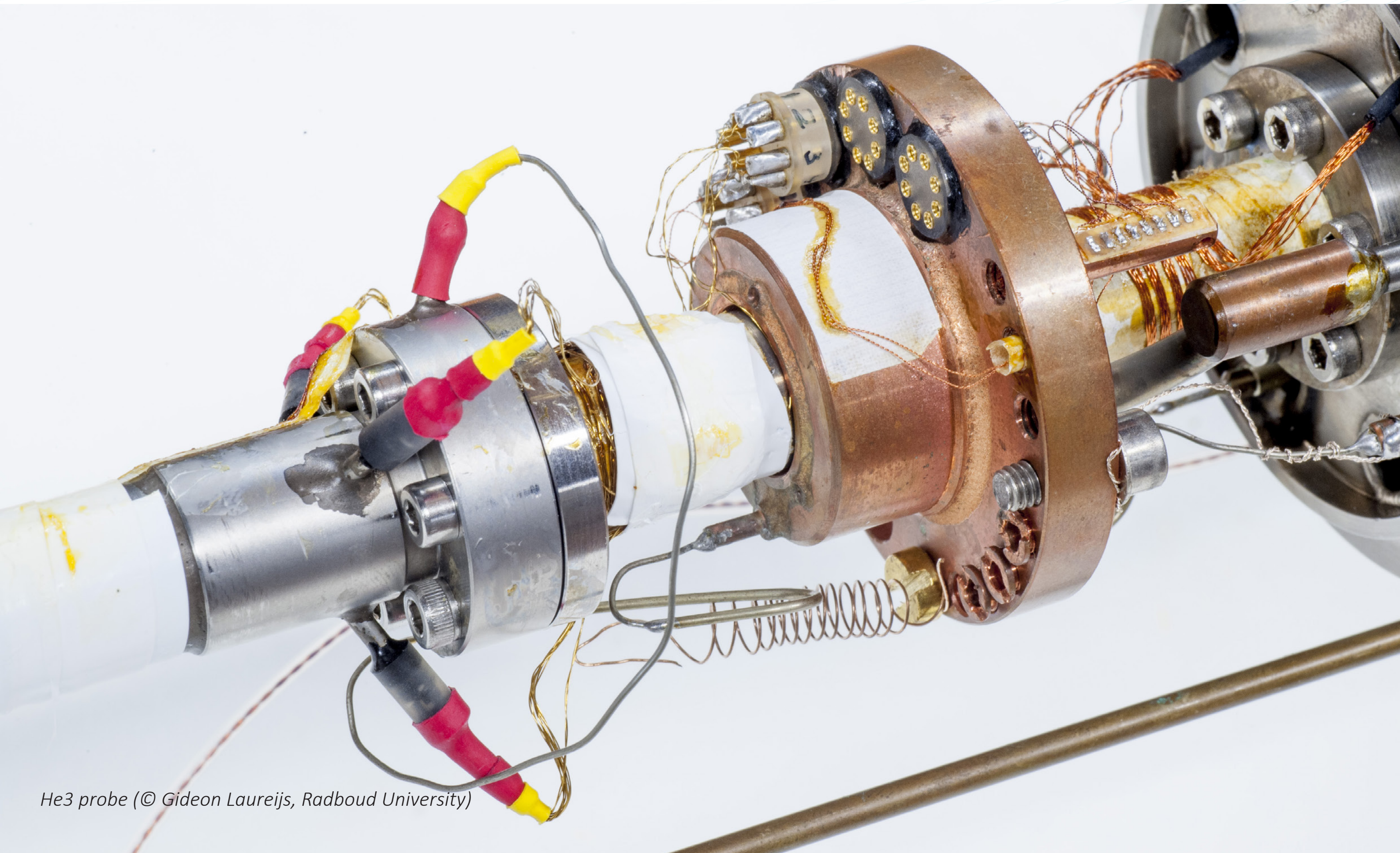
Foreword

Dear reader

Jochen Wosnitza

Chairman EMFL

Director HLD



He3 probe (© Gideon Laureijs, Radboud University)

Mission

The EMFL develops and operates world class high magnetic field facilities, to use them for excellent research by in-house and external users

High magnetic fields are one of the most powerful tools available to scientists for the study, the modification and the control of the state of matter.

The European Magnetic Field Laboratory (EMFL) was founded in 2015 and awarded the Landmark status in March 2016 during the ESFRI Roadmap presentation in Amsterdam. EMFL provides the highest possible fields (both continuous and pulsed) for its researchers. The EMFL is dedicated to unite, coordinate and reinforce the four existing European high magnetic field laboratories – the Dresden High Magnetic Field Laboratory (Germany), the Laboratoires National des Champs Magnétiques Intenses in Grenoble and Toulouse (France), and the High Magnetic Field Laboratory in Nijmegen (The Netherlands) – within a single body as a world-leading infrastructure.

The missions of the EMFL are:

- to develop, construct and operate world class high field magnets
- to do world class scientific research in very high magnetic fields
- to act as a European user facility, for the scientists of the participating countries, and for other scientists
- to act as the European centre of excellence for different magnetic field based material characterisation techniques in very high fields

Current lead (© Gideon Laureijs, Radboud University)

Developments 2017

Winter School: New Frontiers in 2D Materials – Approaches & Applications

The Winter school and Workshop "New Frontiers in 2D materials: Approaches & Applications" took place from 15 to 20 January 2017 in Villard-de-Lans, France (https://www.ceitec.eu/winter-school-new-frontiers-in-2d-materials/). The school attracted about 90 participants (including 16 invited speakers) from European countries (France, UK, Germany, Czech Republic, Poland…) and outside Europe (Brazil, USA). The School covered theoretical, experimental and technological aspects of current research on novel 2D materials (graphene, silicene, transition-metal dichalcogenides, topological insulators & semiconductor nanostructures) and other emerging systems (multiferroics, materials for spintronics, semiconductor quantum dots and quantum fluids in polariton structures).

New European Record for Nondestructive Pulsed Magnetic Fields

On February 10, 2017, the EMFL team in Toulouse has managed to generate, non-destructively, 98.8 T as shown in Figure 1. To obtain this result it was necessary to combine three independent concentric coils, shown in Figure 2, energized by the three main capacitor banks of the laboratory. The total amount of energy required to generate this field is close to 20 MJ. The next objective is to go beyond the symbolic limit of 100 T and the current world record of 100.75 T held by the Los Alamos National Laboratory since June 2012. Our engineers are now working to improve on this record later this year.

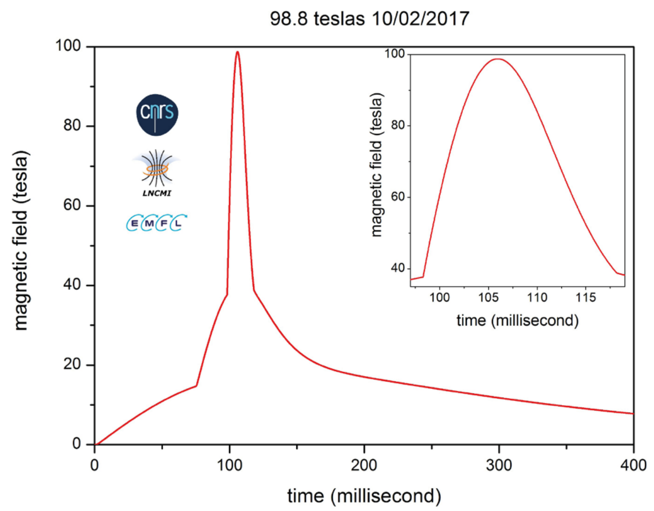


Figure 1: Temporal profile of the magnetic pulse. Only 400 milliseconds are represented, the field decay still continues during one second. The inset represents a zoom on the innercoil pulse.

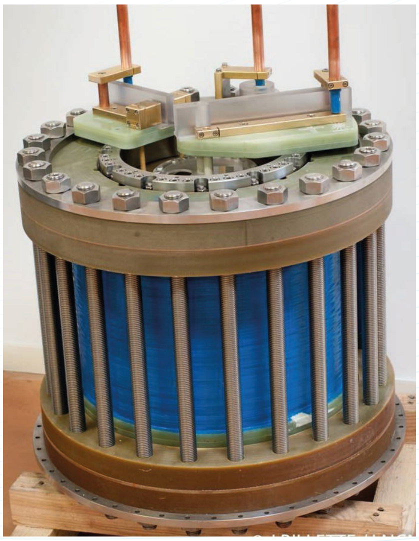


Figure 2: Picture of the magnet before installation in its nitrogen cryostat. The magnet measures about 70 centimeters in diameter and weights near to 600 kilograms.

This magnet is, most importantly, a tool for scientific research and the pulse duration of the new LNCMI magnet is the world's longest at such a high field. Most of the existing experimental techniques, as transport or optical measurements will be feasible down to 1.4 K in its 8 mm free bore diameter.

Beamline connects FELIX laboratory with the high field magnets

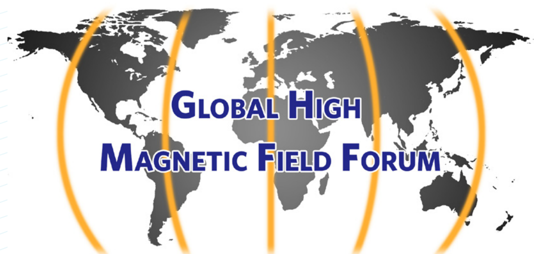
Due to the hard work of scientists, engineers, and technicians at FELIX Laboratory and the EMFL site Nijmegen, the photons of the three beamlines of the FELIX Laboratory – FLARE, FELIX-1, and FELIX-2, now reach the magnet cells of the EMFL facility Nijmegen.

This combination of intense, tunable infrared and THz radiation with high magnetic fields allows to study matter in magnetic fields up to 33 T irradiated with radiation in the range from 0.25 – 120 THz. A dedicated HFML-FELIX research team has started to explore and exploit this world-unique combination. Researchers use (far-)infrared and THz spectroscopy for measuring low-energy optical excitations in high magnetic fields, for instance electron magnetic resonance (ESR), cyclotron, and antiferromagnetic resonance.

The infrared and THz radiation from the different FELIX beamlines travels more than 80 m from the free electron lasers into the magnets at EMFL-Nijmegen through a quasi-optical transport system consisting of more than 40 mirrors. One of the technical challenges is that the diffraction of laser radiation is proportional to its wavelength and, therefore, needs to be refocused approximately every 8 meters to accommodate the longest wavelength of 1.5 mm that the FLARE laser of the FELIX Laboratory produces. The new optical transport system does not only warrant high transmission of the intense radiation but also maintains the short pulse lengths of the lasers providing excellent opportunities for time-resolved experiments in high magnetic fields.

Global High Field Forum: website launched

High magnetic field research is inherently multidisciplinary and spans physics, materials science, engineering, chemistry, biochemistry,and biomedicine. The historic and still dominant application of high magnetic field research is in condensed-matter physics, in which pioneering discoveries, including Nobel Prize winning discoveries, have resulted due to the unique interaction of magnetic fields on the electronic and magnetic states of all forms of matter.



The Global High Field Forum (HiFF), with EMFL being the European partner, was launched in November 2014 to unite the world's high magnetic field laboratories to work together to:

- Promote top-level science through the use of high magnetic fields
- Facilitate access of external users to the facilities best suited to advance their science
- Improve efficient operations of high magnetic field installations
- Stimulate the development and dissemination of new experimental techniques utilizing high magnetic fields
- Cooperate to advance magnet technologies, including the development of new materials specially designed for constructing improved high-field magnets
- Promote the development of new high-field magnets and laboratories
- Serve as a global representative of the high-magnetic-field research community and the laboratories that support their research.

This new collaboration seeks to:

- Bring together world expertise on the operation of facilities dedicated to the generation of the highest magnetic fields for scientific research
- Expand the knowledge base for technologies needed to generate such magnetic fields
- Stimulate worldwide activities promoting scientific research and technology development using the highest magnetic fields.

The next generation of high-field magnets, already called for by the international research community and reports from prestigious research panels, will require substantial advances in our present state-of- the-art; advances best achieved by a global commitment to communication, coordination, and collaboration among the leaders of the world's high-magnetic-field facilities.

You may find more and regularly updated information on the recently launched HiFF website: http://globalhiff.org

EMFL user meeting - Nottingham

The ninth EMFL User Meeting, organized for the 5th time under the EMFL flag, was held at the University of Nottingham on 23rd June 2017. This was the first time that the User Meeting was held outside one of the EMFL high-field facilities and, with over 50 participants, represented one of the best attended as well. Nottingham was chosen as the venue to underline the increased collaboration of the UK community with EMFL, through the EPSRC mid-range facility grant that is being coordinated by Prof Amalia Patanè, who also hosted the meeting. The User Meeting included two scientific and one technical session, to showcase some of the most recent scientific highlights as well as new technical and instrumentational developments at the high-field facilities, prior to the User Committee meeting.

The technical session focussed on recent progress and developments in magnet technology: François Debray (EMFL-Grenoble) reviewed reaching the highest fields using HTS materials, Sergei Zherlitsyn (EMFL-Dresden) novel possibilities with non-destructive and Atsuhiko Miyata (EMFL-Toulouse) with semi-destructive methods. Jonathan Buhot (EMFL-Nijmegen) also presented recent advances to the high-field Raman spectrometer that is now available to users. The scientific highlights were of very high quality and covered many areas of topical interest including 2D materials, high-temperature superconductivity, hybrid photovoltaics, quantum computation, and frustrated magnets. The talks illustrated the wide variety of research topics that can be performed using intense magnetic fields.

The User Committee meeting was chaired by Prof Raivo Stern (NICPB, Tallinn, Estonia) who reported the outcome of the meeting and the suggestions of the Committee back to the Board of Directors at the end of the meeting.

Report from the annual EMFL User Committee meeting - Nottingham

The EMFL User Committee meeting was held on the 23rd June 2017 at the University of Nottingham as part of the annual EMFL User Meeting. Six of the nine members of the User Committee (R. Stern, M. Doerr, C. Putzke, K. Prokes, S. Tozer, V. Skumryev) and several users attended the meeting with Prof. Stern chairing the committee. The meeting was followed by a discussion meeting with the Board of Directors of the EMFL and the user community. Several matters were discussed and recommendations made to the Board of Directors, as outlined below.

Members of the User Committee and its Mandate

Currently, the User Committee consists of 9 members, 3 new members (A. Arora, A. Pourret, V. Skumryev) started in 2017. With the user community of EMFL steadily growing, the new User Committee is asking for a renewed, much stronger mandate to represent the interests of the high-field users better. To allow users a more effective magnet use and to advise the Directors on all issues affecting users of the facilities the User Committee relies on more detailed information about the weaknesses and plans at the laboratories and, in particular, on continuous and informative user feedback. User feedback Following earlier recommendations of the User Committee, the EMFL has adopted an online user feedback form for all the laboratories of the EMFL. While on the first years this has facilitated a larger number of users providing feedback and comments on their experience at the installations of the EMFL, this year's outcome was close to nothing. To resolutely improve the amount and quality of feedback forms, the User Committee has requested

a) all EMFL facilities to stimulate the users to provide their feedback to the User Committee;
b) to implement a feedback-request procedure with reminders within the next 6 months.

A revised and improved feedback form should include additional questions centered on scheduling experiments with the local contacts and assignment of magnet time.

EMFL membership

There are still various opportunities for new members to join the EMFL. Members of the EMFL are able to shape the EMFL policy, including future developments and user access. In December 2015, the UK has officially become a member of the EMFL with the support (2015-20) of The Engineering and Physical Sciences Research Council (EPSRC), the UK's main agency for funding research in engineering and the physical sciences. Other users from other countries (in particular Spain, Poland, and Estonia) should engage with their research councils to discuss a possible membership first to strengthen the EMFL and further to lay the basis for future funding opportunities within Horizon2020, which has identified high magnetic fields as a topical area for development of research infrastructures.

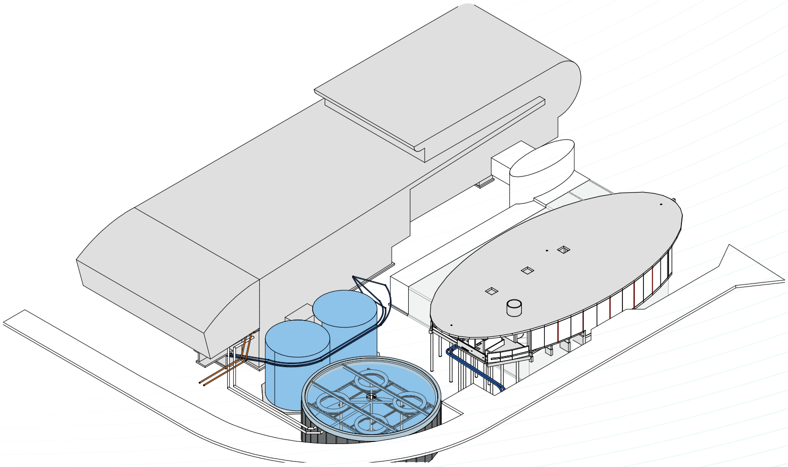
Finally, the User Committee acknowledged the Board of Directors for arranging an excellent user workshop where both users and representatives of the EMFL reported on recent developments of high-magnetic-field infrastructures/equipment, Raman spectroscopy in high magnetic fields, and research in topical areas ranging from transition-metal dichalcogenide (TMDC) monolayers to frustrated magnets and novel material systems of fundamental and technological interest. The user community received this rich program very well.

Sven Badoux wins EMFL prize 2017

The EMFL Prize 2017 went to Sven Badoux from the Physics department at the Université de Sherbrooke (CA). He was awarded for his outstanding research on "Transport signatures of the pseudogap critical point in cuprate superconductors" using high magnetic fields.

Additional cooling tank for HFML magnets now operational

On March 30, 2017 the site-acceptance test (SAT) of the new underground cooling-water tank took place at the high-field lab in Nijmegen. The HFML has now 2.500 m3 additional water available to cool its magnets, increasing its total cooling capacity thereby significantly. The contractor parties (REEF infra, Croonwolterendros and Building Technology) have shown during the SAT that all installed items (pumps, valves, etc) work according to the specifications and are integrated and functioning via the control software.



This third buffer already proved its use during some tests and internal experiments. However, before the scientists can use the buffer on a regular basis, some parameters need to be fine-tuned and the safety system thoroughly tested. We are confident that by the time this EMFL News is published the third buffer is available for external users. Currently, not much can be seen of the enormous pit dug out and the underground construction of the tank. The only remainder is an inspection hatch to access the tank. With the park and picnic seats on top of it, inspiring ideas might appear here, and we hope the new buffer together with the other great HFML infrastructure can help to realize them.

Scientific Highlights

Quantum Hall effect in few-layer InSe

The discovery of graphene in 2004 with its spectacular electronic properties has opened one of the fastest rising research fields in contemporary materials science. Indeed, graphene and other two-dimensional materials offer promising application perspectives for e.g. high-speed electronics beyond silicon. Specifically, graphene, with its ultra-high mobility even at room temperature has been proposed to replace silicon, but the absence of an energy gap makes it rather unsuitable for switching applications.

Researchers from Manchester and Nottingham (United Kingdom) have now fabricated and measured devices made from ultra-thin layers of InSe encapsulated in hexagonal boron nitride with roomtemperature mobilities of more than 1000 $cm^2 V^{-1} s^{-1}$. Since InSe is a semiconductor with a large energy gap these devices open new venues for super-fast switching of transistors in next-generation electronics.

On a more fundamental point of view, experiments performed in collaboration with EMFL scientists at Nijmegen have revealed a fully developed quantum Hall effect at B = 30 T with spin-resolved Landau levels (see Figure). They have shown that electrons in InSe behave like classical massive particles (rather than massless Dirac fermions known in graphene). Using temperature-dependent Shubnikov-de Haas experiments the effective cyclotron mass of electrons in 6-layer InSe was determined as m*= (0.14 ± 0.01) me and their Landé g-factor to g* ≈ 2.

These first results obtained on the quantum Hall effect in InSe indicate that this material might be another fascinating playground for studying the fundamental properties of low-dimensional electron systems in view of promising applications in future high-mobility nanoelectronics of ultra-thin devices.

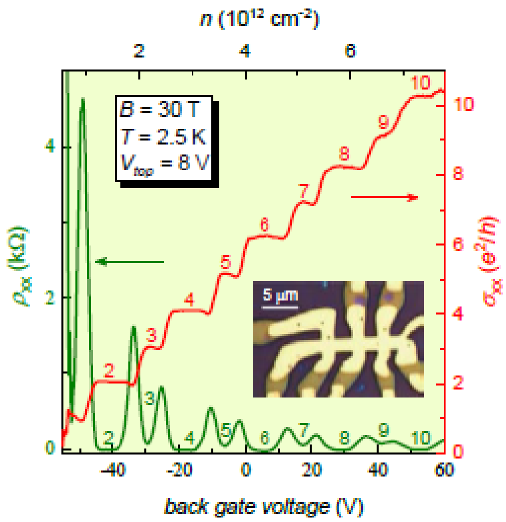


Figure: Resistivity ρ_{xx} (green, left axis) and Hall conductivity (red, right) of a 6-layer InSe field-effect transistor with a top gate and a back gate in a magnetic field B = 30 T. The numbers mark the integer filling factors of the corresponding quantum Hall states, with even numbers corresponding to Landau-level splitting and odd numbers to Zeeman spin splitting. The inset shows a micrograph of the device with the top gate and contacts in yellow and the encapsulated InSe in brown.

Reference

Bandurin, D. A., Tyurnina, A. V., Yu, G. L., Mishchenko, A., Zólyomi, V., Morozov, S. V., Krishna Kumar, R., Gorbachev, R. V., Kudrynskyi, Z. R., Pezzini, S., Kovalyuk, Z. D., Zeitler, U., Novoselov, K. S., Patane, A., Eaves, L., Grigorieva, I. V., Fal'ko, V. I., Geim, A. K. and Cao, Y. (2017). "High electron mobility, quantum Hall effect and anomalous optical response in atomically thin InSe". *Nature Nanotechnology* 12: 223 - 227.

Supersolidity in bond-frustrated $MnCr_2S_4$

Frustrated magnets provide a promising avenue for realizing exotic quantum states of matter, such as spin-liquid, spin-ice, and even supersolid states. A supersolid is an ordered solid which, due to quantum phenomena, has also superfl uid properties and, under some conditions, can thus behave as a liquid without viscosity. This can be considered as an example of a Bose-Einstein condensate (BEC). Active search for the supersolidity has been performed in solid helium and, very recently, in ultracold trapped atoms. Researchers from the Center for Electronic Correlations and Magnetism at the University of Augsburg and EMFL-Dresden have chosen another way by investigating the spin states in the frustrated magnet $MnCr_2S_4$.

In this material, prominent anomalies in the magnetization and sound velocity have been observed in high magnetic fi elds, which reveal two fascinating features: (i) an extremely robust magnetization plateau with an unusual spin structure stabilized by fi eld-induced lattice distortions (Figure 1) and (ii) two intermediate phases, indicating possible realizations of a supersolid state (Figure 2).

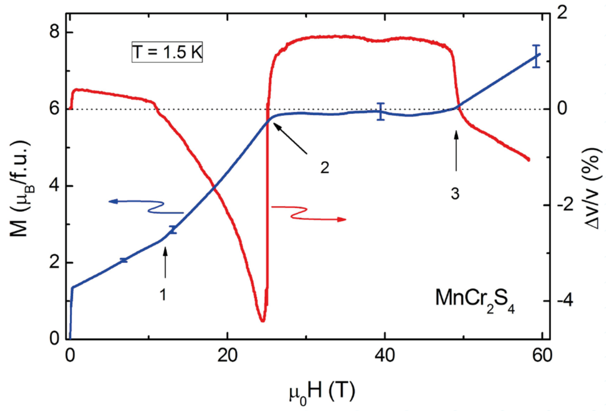


Figure 1: Field dependence of the magnetization and ultrasound velocity in $MnCr_2S_4$ at 1.5 K.

The measurements reveal that $MnCr_2S_4$ exhibits a manifold of competing spin states as a function of external magnetic fi eld. Thereby, the chromium moments are always aligned parallel to the external field, but the manganese spins exhibit different types of transverse and longitudinal order, which, by analogy with bosonic systems, can be described as superliquid and supersolid phases.

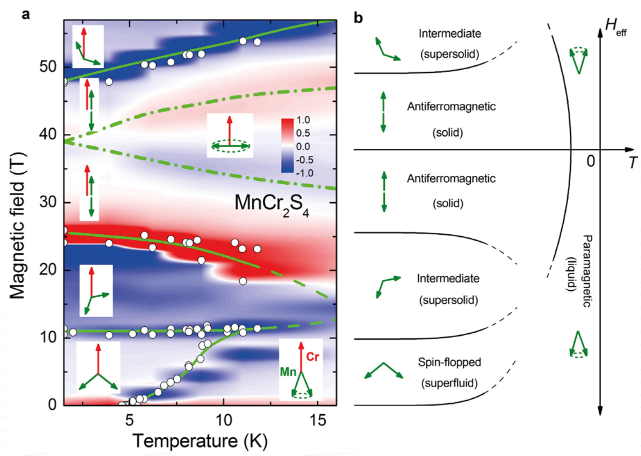


Figure 2: (a) Experimental and (b) theoretical phase diagram. (a) Color-coded plot of the derivative of the sound velocity. Open circles represent anomalies in the field-dependent magnetization. The solid lines denote maxima in the field derivatives of the sound velocity. The most probable spin configurations are shown for the different magnetic phases.

Indeed, the comparison of the phase diagram with respect to the manganese spins with theoretical predictions from the quantumlattice-gas model suggests the existence of extended supersolid phases, in addition to superfl uid and crystalline phases (Figure 2).

The work shows that magnetic systems under extreme conditions are prime candidates for the emergence of coherent quantum phenomena.

Reference

Tsurkan, V., Zherlitsyn, S., Prodan, L., Felea, V., Cong, P. T., Skourski, Y., Wang, Z., Deisenhofer, J., von Nidda, H.-A. K., Wosnitza, J. and Loidl, A. (2017). "Ultra-robust high-field magnetization plateau and supersolidity in bond-frustrated MnCr2S4". *Science Advances* 3(3).

A breakthrough for extreme conditions: combined high pressure and pulsed magnetic field

Combined extreme conditions of high pressure and strong magnetic field are an extremely powerful tool to tune microscopic interactions in order to attain and study new states of matter. While high-pressure measurements in static magnetic fields are a state-of-the-art technique up to the maximum available static fields, specific challenges (eddy currents, small accessible space, etc.) need to be overcome for the combination of high pressures with much higher magnetic fields, i.e., pulsed fields. Up to now, no setup allowed routine measurements of this kind at pressures higher than 1.5 GPa.

A French-Japanese collaboration between the EMFL-Toulouse, the CEA Grenoble, and the University of Niigata recently succeeded to develop a pressure cell allowing resistivity measurements in combined pulsed magnetic fields up to 60 T, pressures up to at least 4 GPa and temperatures down to 1.5 K. The first study permitted to establish the full three-dimensional (T, H, p) phase diagram of an Ising-type antiferromagnetic system ($CeRh_2Si_2$), with a systematic and careful comparison of pressure and magnetic-field-induced quantum phase transitions.

This new tool, unique worldwide, opens many perspectives in a wide range of subjects including the study of itinerant quantum magnets, high-temperature superconductors, and the new and exciting topic of exotic topological states.

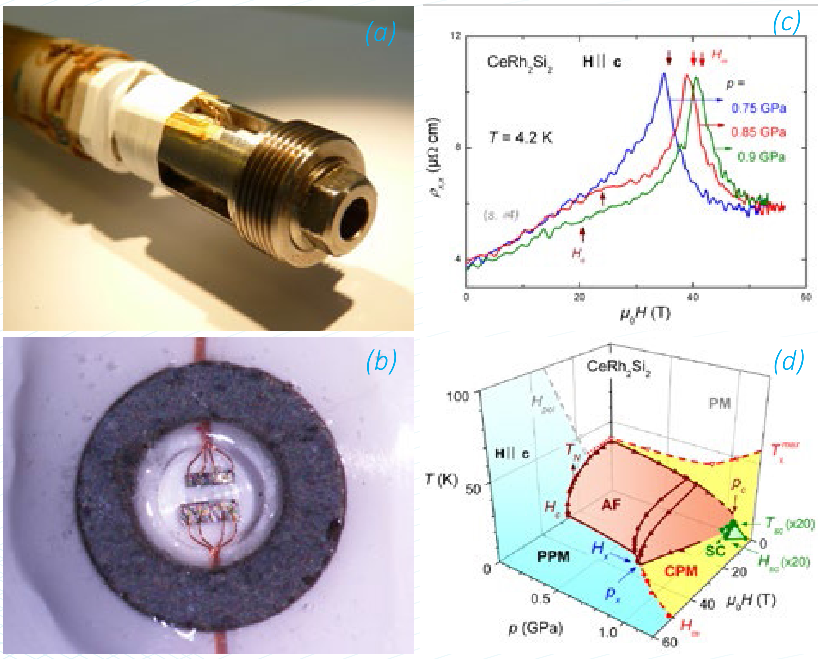


Figure: (a) Pressure cell on the pulsed field probe. (b) A sample in the pressure chamber together with a Pb gauge used as a manometer. (c) Magnetoresistance curves up to 60 T of the antiferromagnetic system CeRh2Si2 at several pressures close to the critical pressure. (d) Phase diagram of CeRh2Si2 illustrating how the antiferromagnetic order can be suppressed by temperature, pressure, and magnetic field.

Reference

Development of Bridgman-Type Pressure Cell for Pulsed High Magnetic Field, R. Settai, W. Knafo, D. Braithwaite, S. Kurahashi, D. Aoki, and J. Flouquet, Review of High Pressure Science and Technology / Koatsuryoku No Kagaku To Gijutsu 25, 325 (2015).

Pressure cell for transport measurements under high pressure and low temperature in pulsed magnetic fields, D. Braithwaite, W. Knafo, R. Settai, D. Aoki, S. Kurahashi, and J. Flouquet, Rev. Sci. Instrum. 87, 023907 (2016).

Three-dimensional critical phase diagram of the Ising antiferromagnet CeRh2Si2 under intense magnetic field and pressure, W. Knafo, R. Settai, D. Braithwaite, S. Kurahashi, D. Aoki, and J. Flouquet, Phys. Rev. B 95, 014411 (2017).

European Magnetic Field Laboratory

Impurity-induced disorder can generate long-range order in high magnetic fields

In the two back-to-back articles published in Physical Review Letters, experimentalists from LNCMI Grenoble and theorists from the Laboratoire de Physique Théorique in Toulouse have demonstrated that, contrary to previous expectations, disorder can help to order quantum matter. To show this, they have studied the spin-chain based material NiCl2-4SC(NH2)2, also called DTN, which at low temperature reveals a magnetic-field-induced ordered phase, described as a Bose-Einstein condensate (BEC). So far it was believed that, close to this BEC phase, chemical disorder created by doping Br impurities to substitute Cl ions in DTN would lead to localization, namely the so-called Bose-glass state. However, building on nuclear magnetic resonance (NMR) experiments on doped DTN at high magnetic fields, combined with state-of-the-art quantum Monte Carlo simulations, a radically different scenario was discovered: from a strong peak observed in the NMR relaxation rate, attributed to the crossing of energy levels of the impurity states, and an impurityinduced local spin-polarization value determined from the NMR spectra, a very precise microscopic image of the impurities could be established. Theoretical modelling then showed that the mutual pairwise effective interaction of the impurity states leads to a global quantum coherence over the full sample, which results in a new type of BEC ordering of these impurity states, in sharp contrast to a localized Bose glass. The existence of this new, “order-from-disorder” phase is now definitely confirmed by further NMR data: in a higher-doped DTN sample, this new phase appears at experimentally accessible temperatures, and the corresponding experimental phase diagram is currently being determined. This remarkable discovery is thus rewarding a very successful collaboration between experimental and theoretical teams.

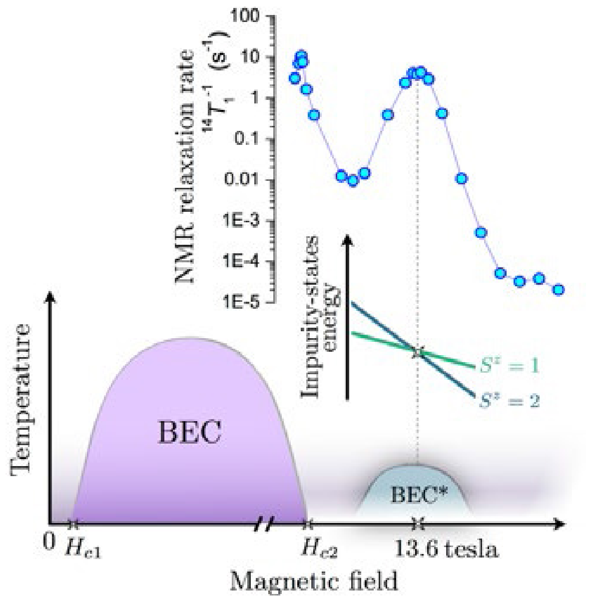


Figure: Besides the Bose-Einstein Condensate (BEC) extending between Hc1 = 2.1 T and Hc2 = 12.3 T, a new type of condensate (BEC) appears near 13.6 T. This new quantum state, induced by disorder and revealed through a strong peak in the magneticfield dependence of the NMR relaxation rate, emerges from the interaction between the localized impurity states.*

Reference

Orlova, A., Blinder, R., Kermarrec, E., Dupont, M., Laflorencie, N., Capponi, S., Mayaffre, H., Berthier, C., Paduan-Filho, A. and Horvati ć ć, M. (2017). “Nuclear Magnetic Resonance Reveals Disordered Level-Crossing Physics in the Bose-Glass Regime of the Br-Doped Ni(Cl_{1-x}Brx)2- 4 SC(NH2)2 Compound at a High Magnetic Field”. *Phys. Rev. Lett.* 118: 067203-067203.

Dupont, M., Capponi, S., Horvatić, M. and Laflorencie, N. (2017). “Competing Bose-glass physics with disorder-induced Bose-Einstein condensation in the doped S=1 antiferromagnet Ni(Cl_{1-x}Brx)2)- SC (NH2)2 at high magnetic fields”. *Phys. Rev. B* 96: 024442-024442.

Frustrated electrons refuse to tunnel

Scientists of the European Magnetic Field Laboratory in Nijmegen have shown that decoherence between layers of a metallic system is linked to a loss of long-range magnetic order in the material. It is the first time that the cause of loss of interlayer coherence was experimentally shown.

Many of the most topical and interesting metallic systems, such as the high-temperature superconductors, have a layered crystal structure. As a result, an electrical current flows much more easily within the layers than between them. In certain extreme cases, electrons are prevented from tunneling coherently (i.e., preserving their periodic wave-like motion) across adjacent layers; the electrons essentially become confined to individual layers and their motion between layers becomes diffusive. What induces this loss of interlayer coherence, however, has not been established in any material, though there has been much theoretical speculation as to the possible origin(s).

In a high-field study at the EMFL-Nijmegen it was now discovered that a key signature of interlayer coherence in the frustrated triangular antiferromagnet $PdCrO_2$ vanishes precisely at the temperature at which long-range magnetic order is lost. Moreover, through comparison with the isostructural non-magnetic $PdCoO_2$, the scientists were able to demonstrate that it is the loss of long-range magnetic order (and the subsequent development of short-range magnetic fluctuations) that destroy interlayer coherence of the conduction electrons and not the loss of interlayer coherence that destroys the long-range magnetic order.

Thus, while the spins on the Cr ions are ordered, the conduction electrons within the Pd-O plane are able to tunnel coherently from one layer to the next. However, above the ordering temperature, the now-fluctuating spins begin to scramble (scatter) the conduction electrons sufficiently to inhibit their ability to move coherently between the layers.

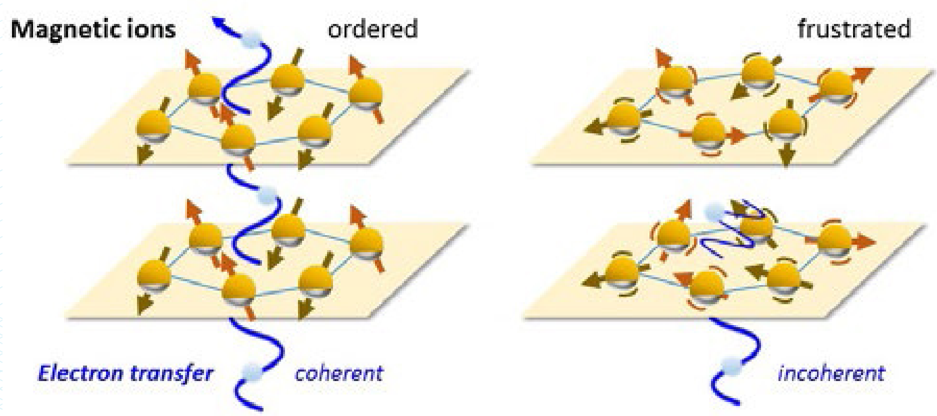


Figure: Schematic of the transition from coherent interlayer tunneling in the ordered state of PdCrO2 below the Néel temperature TN to incoherent tunneling in the frustrated state above TN

This study represents the first time that the cause of decoherence has been experimentally linked to a fundamental change in a material, in this case the loss of long-range magnetic order. By establishing this link, this study may have major implications for our understanding of interlayer coherence in a host of other low-dimensional metals that lie in close proximity to an ordered phase, be it of magnetic, electrostatic or orbital origin.

Reference

Ghannadzadeh, S., Licciardello, S., Arsenijević, S., Robinson, P., Takatsu, H., Katsnelson, M. I. and Hussey, N. E. (2017). "Simultaneous loss of interlayer coherence and long-range magnetism in quasi-two-dimensional PdCrO2". *Nature Communications* 8: 15001.

Evidence for spin nematicity in $LiCuVO_4$

Frustrated magnetism has generated interest over the years due to the emergence of novel states, most notably when exposed to high magnetic fields. According to theoretical work, bound magnon pairs can condense in cases where competing exchange interactions occur, thus forming a new quantum phase, referred to as a quantum spin-nematic state. Spin nematicity can be compared to the classical nematic order found in liquid crystals. Some years ago, it was proposed that $LiCuVO_4$, a frustrated magnetic compound consisting of spin-½ Cu^{2+} chains, was a good candidate for exhibiting spin-nematic order. However, experimental evidence remained elusive due to the high magnetic fields required and the sensitivity of spin nematicity on sample defects.

A high-quality $LiCuVO_4$ sample was grown at the Max-Planck-Institute for Solid State Research in Stuttgart and together with scientists from three of the EMFL facilities (Toulouse, Dresden, and Grenoble), clear evidence was provided in support of the presence of the spinnematic state. The experiment posed a technological challenge due to the short data-acquisition time. For the H || b orientation, magnetic fields above 51 T were necessary, thus precluding the possibility of measurements in DC magnetic fields. A newly constructed homogeneous pulsed-field magnet with a rise time of 70 ms was utilized in combination with a spin-echo sequence with sufficiently short pulses to allow for a bandwidth of 1.2 MHz.

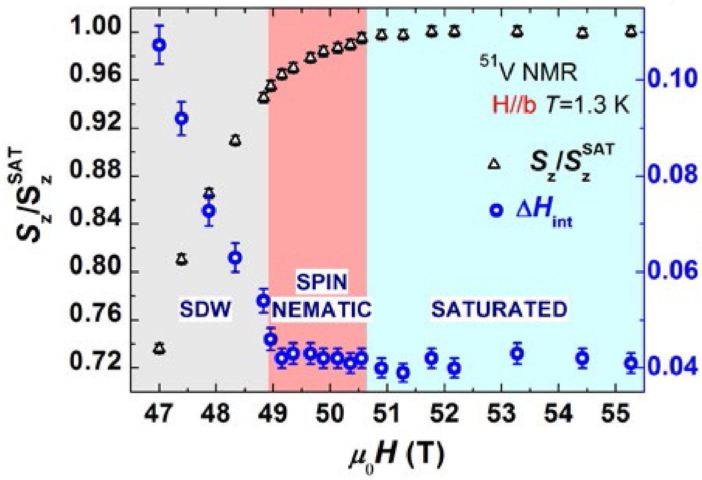


Figure: Open triangles represent the normalized spin polarization, Sz/Sz SAT, up to 56 T for H//b, shifting in accordance with high-field magnetization. However, the NMR linewidth (open blue circles) is not changing around 49 T, as expected in theory.

The "tour de force" 51V nuclear magnetic resonance (NMR) measurements were performed in pulsed magnetic fields up to 56 T which demonstrate the developing homogeneous local magnetization without any transverse dipolar (vector-type) order (see Figure), in agreement with theoretical predications for a spin-nematic state. These results not only prove the efficacy of NMR in pulsed magnetic fields, but also highlight the successful scientific cooperation within EMFL.

Reference

Orlova, A., Green, E. L., Law, J. M., Gorbunov, D. I., Chanda, G., Krämer, S., Horvatić, M., Kremer, R. K., Wosnitza, J. and Rikken, G. L. J. A. (2017). "Nuclear Magnetic Resonance Signature of the Spin-Nematic Phase in LiCuVO4 at High Magnetic Fields". *Physical Review Letters* 118(24): 247201.

Closing in on a magnetic analog of liquid crystals, Viewpoint article by Frédéric Mila featured in: Physics 10, 64 (2017).

Magnetic excitations in the honeycom-lattice material α-$RuCl_3$

The Kitaev-Heisenberg model of interacting magnetic spins is one of the few quantum-mechanical models which can be solved exactly. Such spin arrangements may be realized in materials with honeycomb-lattice structures and strong spin-orbit coupling. The magnetic phase diagram for the Kitaev-Heisenberg model as function of interaction parameters is rather complex, encompassing a variety of magnetic ground states, ranging from conventional Néel order to a quantum spin liquid. One of the most important peculiarities of the Kitaev quantum spin liquid is the presence of exotic excitations and fractionalized Majorana fermions, obeying non-Abelian statistics.

α-$RuCl_3$ appears to be a prime candidate to exhibit Kitaev physics. In spite of its almost ideal two-dimensional structure, this material undergoes a transition into an antiferromagnetically ordered zigzag state at 7 K. Remarkably, the ordered state can be suppressed by a magnetic field of around 7 to 8 T, applied along the honeycomb planes and transforming the system into a gapped, magnetically disordered (quantum paramagnetic) phase. The nature of the ground state and the spin dynamics in the field-induced phase have remained open questions.

High-field electron spin resonance (ESR) experiments have been performed at the EMFL-Dresden. A rich excitation spectrum was observed at low temperatures (see Figure). Two antiferromagnetic-resonance modes were detected in the ordered phase. Four ESR modes appear in the field-induced quantum paramagnetic phase. The data obtained in the field-induced phase were compared with results of recent numerical calculations, performed by a group from Frankfurt University (S. Winter et al., arXiv:1707.08144). Very good agreement between the calculated results and the experimental data is found. Most importantly, our studies reveal a very coherent, multiparticle nature of the spin excitations in α-$RuCl_3$. A strong ferromagnetic Kitaev coupling may be the reason for such unusual spin dynamics, facilitating the formation of bound states split from a two-magnon continuum.

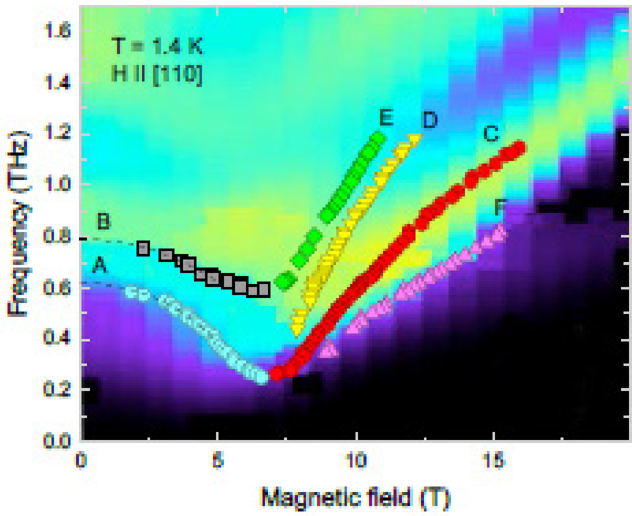


Figure: Frequency-field diagram of ESR excitations in α-$RuCl_3$. The experimental data (symbols) are shown together with the ESR response obtained numerically (color scale).

Reference

Ponomaryov, A. N., Schulze, E., Wosnitza, J., Lampen-Kelley, P., Banerjee, A., Yan, J. Q., Bridges, C. A., Mandrus, D. G., Nagler, S. E., Kolezhuk, A. K. and Zvyagin, S. A. (2017). “Unconventional spin dynamics in the honeycomb-lattice material α–RuCl3: High-field electron spin resonance studies”. *Physical Review B* 96(24): 241107.

Ultrasound measurements in the quantum limit of graphite

In presence of a magnetic field, the charge carriers of a Fermi sea group into Landau levels. At high enough magnetic field, the so-called quantum limit is reached when the carriers are confined into the lowest Landau level. In such limit, electronic correlations are at work to generate new electronic states, such as composite fermions and topological states in the fractional quantum Hall effect in two-dimensional systems. In three dimensions, this limit is still largely unexplored but exotic states of matter have been predicted to emerge. The exploration of this limit in the semimetal graphite started more than three decades ago. Renewed interest arose recently with magnetoresistance measurements that revealed unexpected transitions [B. Fauqué et al., Phys. Rev. Lett. 110, 266601 (2013)]. Mostly studied with transport measurement so far, the exact nature of those phases and the mechanism responsible for their appearance remain elusive.

We report the first study of the elastic constant and ultrasound attenuation of graphite in DC and pulsed magnetic fields. With the ultrasound technique, we were able to provide the first thermodynamic evidence for the existence of a series of phase transitions in the quantum limit of graphite. By performing a thermodynamic analysis of the sound-velocity anomaly, we conclude this electronic phase is likely to have a significant coupling to the lattice. In addition, we performed magnetostriction measurements in collaboration with the HFML Nijmegen (M. Berben and S. Wiedmann) and resistivity measurements. The combination of those techniques made it possible to build the phase diagram shown in the Figure. This diagram highlights the surprising richness of graphite. The role of the lattice in the formation of those states has so far been overlooked theoretically. Our results have profound implications for the understanding of quantum-limited electron fluids.

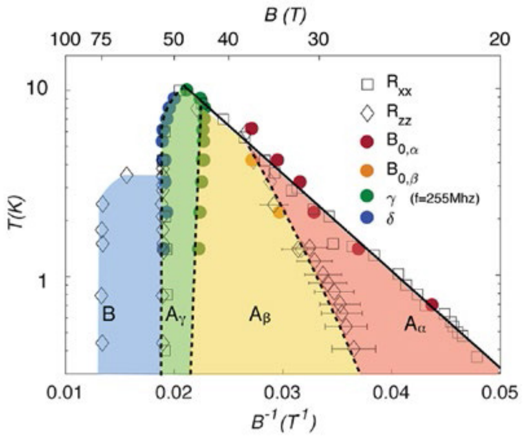


Figure: Phase diagram beyond the quantum limit of graphite, extracted from ultrasound (colored circles) and magnetoresistance measurements (open symbols). In this work we focused on the phases Aα, Aβ and Aγ.

Reference

LeBoeuf, D., Rischau, C. W., Seyfarth, G., Küchler, R., Berben, M., Wiedmann, S., Tabis, W., Frachet, M., Behnia, K. and Fauqué, B. (2017). “Thermodynamic signatures of the field-induced states of graphite”. ***Nature Communications*** 8: 1337.

Organisational structure

EMFL's objective, without profit aim, is to unite world-class high magnetic field facilities and to make them available for excellent research by users. More specifically EMFL is responsible for the management of access, networking and coordination activities of high field facilities in Europe.

Council

The Council is the highest governing body of EMFL and consists of the EMFL Member representatives. The council does:

- appoint and dismiss the Directors and approve the candidacy of the executive manager,
- admit and dismiss EMFL Members,
- approve the progress report, annual accounts and the budget presented by the Board of Directors,
- amend the Statutes and approve the vision, mission and definition of values of the Association,
- discuss and develop strategic, scientific and technical plans of the EMFL.

The Council exists of:

Roland Sauerbrey (HZDR, chair)
Han van Krieken (RU/NWO)
Emmanuelle Lacaze (CNRS)
Amalia Patanè (University of Nottingham)

Board of Directors

The board of directors, composed of the laboratory directors, where needed seconded by an executive manager has the following tasks:

- define the vision and mission,
- execute the strategic operation,
- prepare the budget, the annual accounts and the progress report.

The Board of Directors exists of:

Jochen Wosnitza (HLD, chair)
Nigel Hussey (HFML)
Geert Rikken (LNCMI)

Selection Committee

The task of the EMFL selection committee is to ensure that from the proposed experiments only those that are of excellent scientific quality and clearly benefit from the access to a high field facility are performed in the EMFL facilities.

The Selection Committee evaluates the scientific proposals on the following three criteria:

- scientific quality and originality of the proposal;
- necessity for the use of the infrastructure;
- track record and past performance of the user group.

Xavier Chaud	LNCMI-G	Applied Superconductors
Jens Hänisch	KIT	Applied Superconductors
Andries den Ouden	HFML	Applied Superconductors
Toomas Rõõm	NICPB	Magnetism
Mathias Doerr	IFP	Magnetism
Yuri Skourski	HLD	Magnetism
Uli Zeitler	HFML	Magnetism
Tony Carrington	Univ. Bristol	Metals and Superconductors
Mark Kartsovnik	WMI	Metals and Superconductors
Alix McCollam	HFML	Metals and Superconductors
Ilya Sheikin	LNCMI-G	Metals and Superconductors
Duncan Maude	LNCMI-T	Semiconductors
Amalia Patanè	Univ. Nottingham	Semiconductors
Marek Potemski	LNCMI-G	Semiconductors
Steffen Wiedmann	HFML	Semiconductors
Yves Fautrelle	INP Grenoble	Soft Matter and Magnetoscience
Hans Engelkamp	HFML	Soft Matter and Magnetoscience
Richard Hill	Univ. Nottingham	Soft Matter and Magnetoscience

User Committee

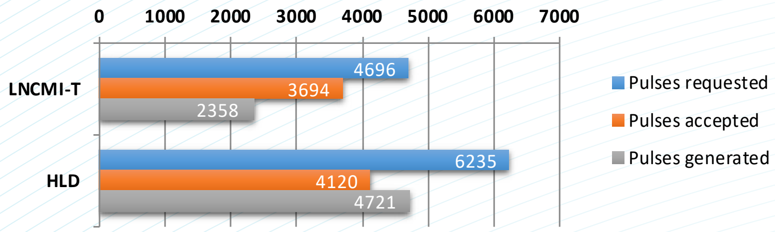
In order to represent the interests of the high field user community, members (all external to the infrastructures) are elected for a period of three years by the user community during the annual User Meeting. The chairman of the User Committee will report to the Board of Directors on behalf of the users. During the User Meetings the User Committee will report to the users and collect the feedback.

Raivo Stern (Chair)	NICPB, Tallinn	NMR/ESR
Ashish Arora	University of Münster	(Magneto)-optics of 2D semiconductors
Mathias Doerr	TU Dresden	Magnetism
Karel Prokes	Helmholtz-Zentrum Berlin	Magnetism
Carsten Putzke	Univ. Bristol	Metals/Superconductors
Antonio Polimeni	Sapienza Università di Roma	Optics/Semiconductors
Alexandre Pourret	IMAPEC-PHELIQS-INAC CEA	Magnetism/Superconductivity
Vassil Skumryev	ICREA, Barcelona	Magnetism/Magnetic materials
Stan Tozer	MagLab	CMS

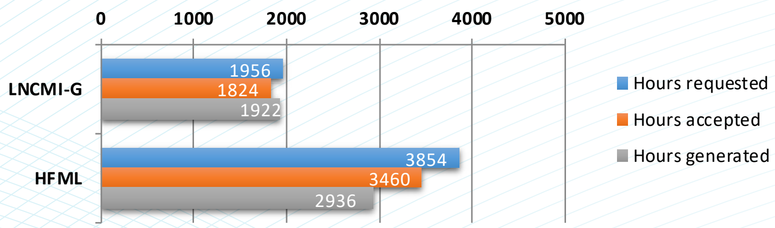
User Access

The 17th and 18th call for proposals closed in June and December, resulting in 332 applications from 28 different countries in total. The Selection Committee (see page 21) has evaluated the proposals, covering the five types of scientific topics:

- Metals and Superconductors
- Magnetism
- Semiconductors
- Soft Matter and Magnetoscience
- Applied Superconductivity



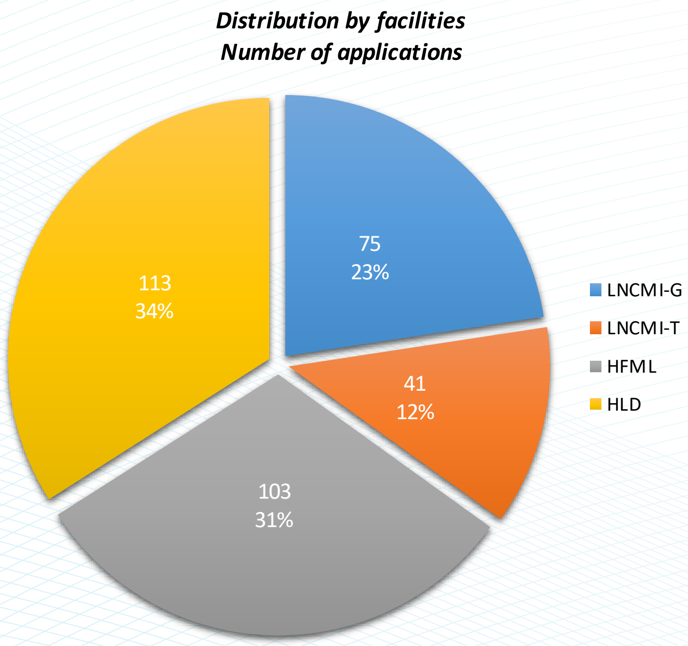
Pulsed facilities



DC facilities

The EMFL facility in Grenoble has supplied much less magnet hours than usual because a major upgrade of the power supply is in progress. In Grenoble >1000 hours have been used for testing the installation and the upgrade of their powersupply.

The amount of generated pulses is larger then the amount of pulses accepted by the Selection Committee as not only the scientific pulses are counted but also the pulses for testing the experimental set-up.

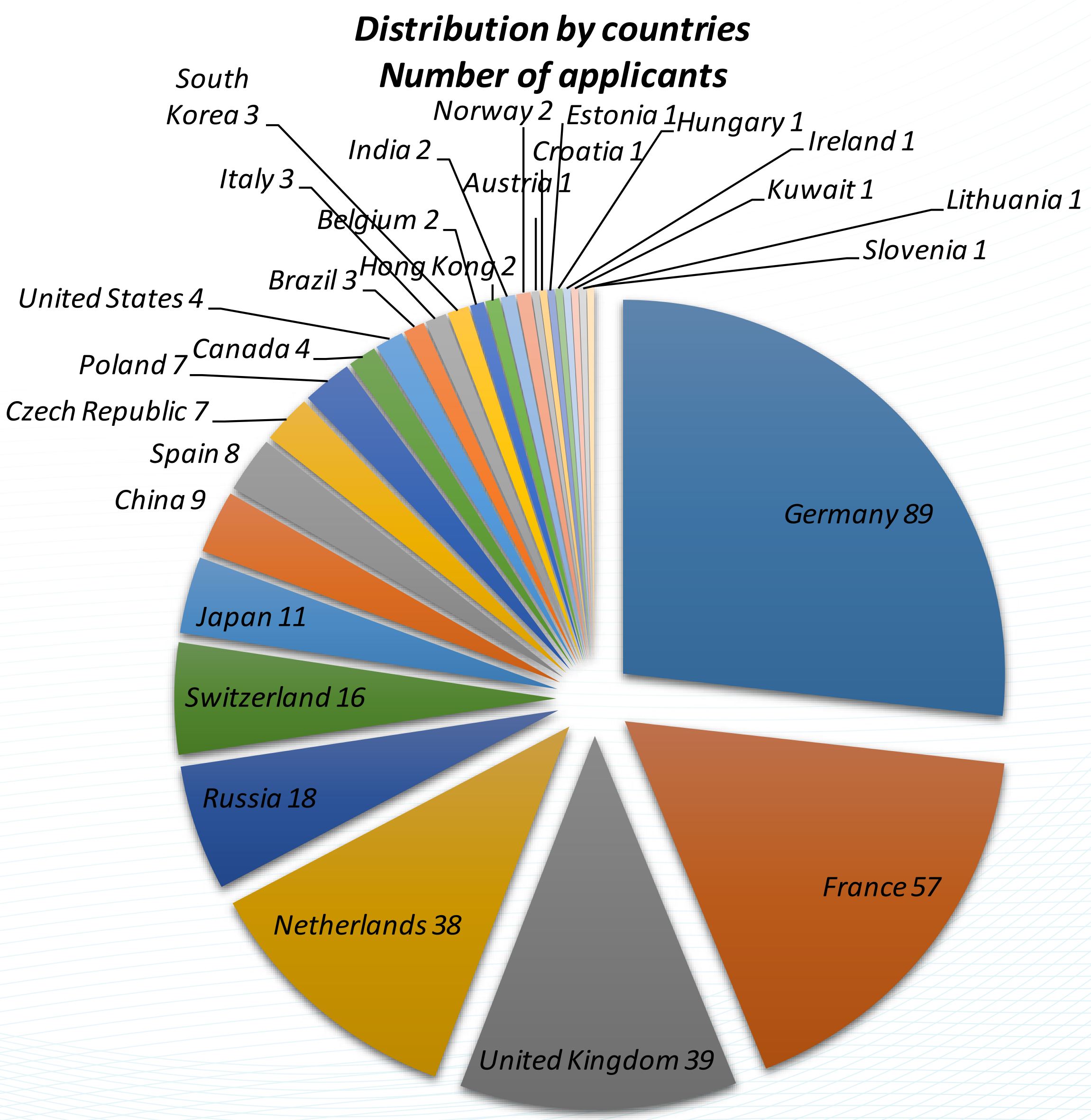


Evaluation of applications

Projects are classified in three classes:
A (excellent proposal to be performed in any case),
B (should be carried out but each facility has some freedom considering other constraints),
C (inadequate proposal or one that does not need any of the four unique high magnetic field laboratories).

In the B category, the ranking + or- serves as a recommendation to the facility. This freedom within the B category is necessary to allow the facilities to consider other aspects such as for instance available capacity and equipment necessary for a successful project. Besides of ranking the proposals the Committee recommends on the number of accepted magnet hours or number of pulses.

Information about the proposal application procedure can be found at www.emfl.eu/user.html



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