EMFL
Annual
Report
2016

European Magnetic Field Laboratory

EMFL
European Magnetic Field Laboratory

Radboud University

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HZDR

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HFML
Science in High Magnetic Fields

LNCMI

HLD.

EPSRC
Engineering and Physical Sciences
Research Council

European Magnetic Field Laboratory

Annual report 2016

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Foreword

Dear reader

This is already the second annual report of the European Magnetic Field Laboratory. EMFL is rapidly becoming mature, now that it has obtained the ESFRI Landmark status, awarded so far to only 29 large research infrastructures of pan-European interest. We will do our best to prove ourselves worthy of this label, and to continue to provide the best possible service to our user community. I would like to use this opportunity to thank the staff and the users of the EMFL facilities for making it all possible.

As you will see in this report, 2016 has been marked by many scientific and technical highlights, and we are looking forward to an equally exciting 2017.

Geert Rikken

Chairman EMFL

Director LNCMI

EMFLdays (© EMFL).

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

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Developments 2016

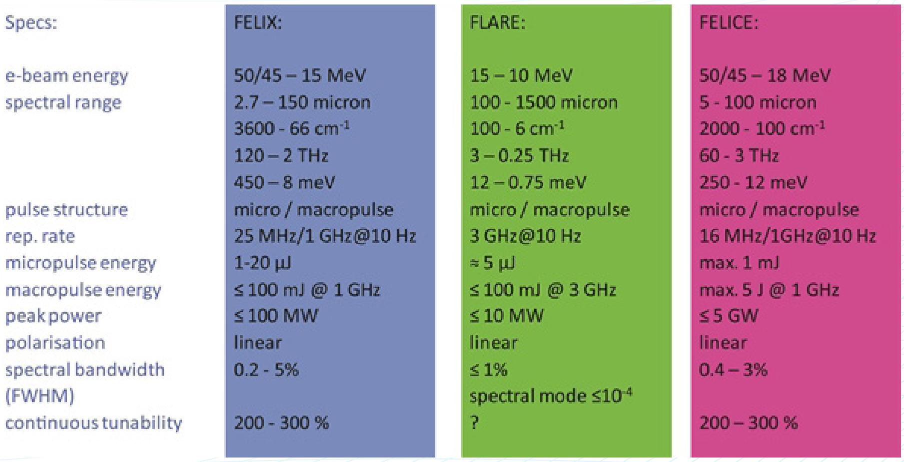
EMFL receives ESFRI Landmark status

The European Strategy Forum on Research Infrastructures (ESFRI) has awarded the European Magnetic Field Laboratory (EMFL) the “Landmark” status in the new ESFRI Roadmap list. EMFL is now one of the 29 Landmarks: pan-European research infrastructures which ensure that scientists in Europe have access to world-class facilities, enabling them to do cutting-edge research. The status represents full recognition of the established EMFL, with the formation of the EMFL AISBL legal entity, the incorporation of the Engineering and Physical Sciences Research Council (EPSRC) as a new member and an overall growth in the high field scientific domain.

The founding members of the EMFL are the French Centre National de la Recherche Scientifique (CNRS), the German research center Helmholtz-Zentrum Dresden-Rossendorf (HZDR) and the Dutch collaboration between Radboud University Nijmegen and the Foundation for Fundamental Research on Matter (FOM). Nigel Hussey (Director of the HFML and member of the EMFL Board): “Receiving the Landmark status by ESFRI underlines the success of the long-term cooperation among the EMFL partners, initiated by my predecessor Jan Kees Maan. Within the FP6 framework, this cooperation has evolved into the founding of EMFL during the FP7 project. EMFL is a clear example that a distributed network of research infrastructures, providing access to high quality experimental facilities through a single access point and selection committee, can be extremely beneficial for the researchers.“

The Nijmegen connection - all FELIX photons reach HFML

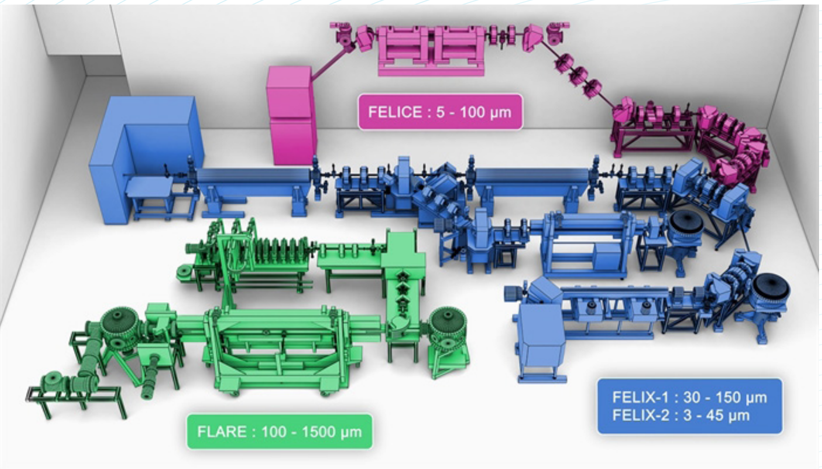
Due to the hard work of scientists, engineers, and technicians at the High Field Magnet Laboratory (HFML), the photons of the three beamlines of the FELIX Laboratory – FLARE, FELIX-1, and FELIX-2, now reach the magnet cells of the EMFL facility Nijmegen.



Specs:	FELIX:	FLARE:	FELICE:
e-beam energy	50/45 – 15 MeV	15 – 10 MeV	50/45 – 18 MeV
spectral range	2.7 – 150 micron	100 - 1500 micron	5 - 100 micron
	3600 - 66 cm^{-1}	100 - 6 cm^{-1}	2000 - 100 cm^{-1}
	120 – 2 THz	3 – 0.25 THz	60 - 3 THz
	450 – 8 meV	12 – 0.75 meV	250 - 12 meV
pulse structure	micro / macropulse	micro / macropulse	micro / macropulse
rep. rate	25 MHz/1 GHz@10 Hz	3 GHz@10 Hz	16 MHz/1GHz@10 Hz
micropulse energy	1-20 μJ	≈ 5 μJ	max. 1 mJ
macropulse energy	≤ 100 mJ @ 1 GHz	≤ 100 mJ @ 3 GHz	max. 5 J @ 1 GHz
peak power	≤ 100 MW	≤ 10 MW	≤ 5 GW
polarisation	linear	linear	linear
spectral bandwidth (FWHM)	0.2 - 5%	≤ 1% spectral mode $\leq 10^{-4}$	0.4 – 3%
continuous tunability	200 - 300 %	?	200 – 300 %

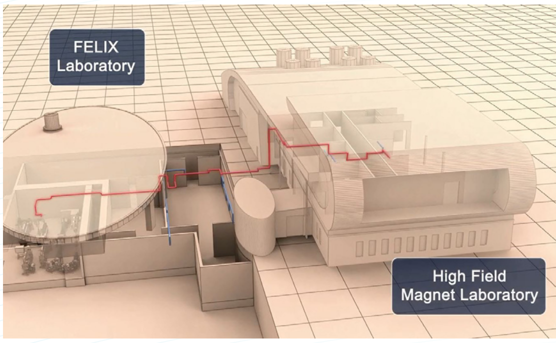
Specifications of the free electron lasers based at FELIX Laboratory in Nijmegen

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.



Overview of the four FELIX free electron laser beamlines. The beamlines FLAREm FELIX-1 and FELIX-2 are connected to the magnets at HFML

The infrared and THz radiation from the different FELIX beamlines travels more than 80 m from the free electron lasers into the magnets at HFML 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.



FEL beamline connection to the HFML

EMFL user meeting

The eighth annual User Meeting, for the fourth time organized under the EMFL flag, has been held at the Laboratoire National des Champs Magnétiques Intenses (LNCMI) in Toulouse on June 16th, 2016. The Meeting took place in a lively and pleasant atmosphere, with 35 participants, with an inspiring and informative program for the EMFL high-field users, and well organized by the local staff.

EMFL user meeting in 2016 (© EMFL).

The Meeting started with a welcome by Geert Rikken (chair of EMFL) who presented the current state of EMFL and future perspectives.
A technical session followed where Catalina Salazar (HLD), Ben Bryant (HFML) and Fabienne Duc (LNCMI) presented some of the instrumentation developments taking place at the EMFL facilities and the unique scientific results obtained with them. Afterwards, users from the facilities and key players in different research areas presented highlight results obtained an the EMFL facilities.

The User Committee this year was chaired for the last time by Amalia Patané (University of Nottingham), who will from now on be the UK representative in the EMFL Council. Raivo Stern (NICPB, Tallinn, Estonia) was nominated by acclaim as her successor as User Committee chairman. During the User Committee Meeting (open for all external users) suggestions for improvements at the EMFL facilities were discussed. The session was closed with an update by Amalia Patané to the lab directors and all users on the outcome of the User Committee Meeting.

To mark the entry of the UK high-field user community in the EMFL, it was decided to organize the next User Meeting in the UK, chaired by Amalia Patanè. The User Meeting ended with a visit to the new building in Toulouse.

Alix McCollam wins EMFL prize 2016

The EMFL prize 2016 went to Alix McCollam from the High Field Magnet Laboratory in Nijmegen. She was awarded for her outstanding research in Fermi-surface studies of various materials and the development of high-field magnetometry with extraordinary sensitivity. The EMFL prize was conferred during the User Meeting in Toulouse where Alix as well presented highlights of her recent work. Already since 2009, the EMFL members award annually the EMFL prize (up to 2012 called EuroMagNET prize) for exceptional achievements in science done in high magnetic fields.

Alix McCollam receiving the EMFL prize from Jochen Wosnitza

EMFL Days in Königstein

At the beautiful site of Königstein im Taunus the third gathering of the EMFL members took place. From 14th to 16th of September 2016 more than 130 people shared their scientific and engineering interests, discussed activities in managing and data-base issues, identified possibilities for future collaborations, had fun visiting Frankfurt am Main, and enjoyed delicious food and sport activities.

For almost two years now, the three laboratories at the four sites in Grenoble, Nijmegen, Toulouse, and Dresden are officially united as EMFL in an international non-profit organization. Last year, the British partner EPSRC (Engineering and Physical Sciences Research Council) joined the EMFL. In the German city of Königstein, we continued to learn more about each other’s work and tried to identify routes to further improve. This includes engineering and scientific activities, but as well our work on technological and administrative aspects. Besides this formal program, there also was time for sight-seeing

EMFL days in Königstein

Participants of the EMFLdays 2016 in Königstein im Taunus

during an informal visit to nearby Frankfurt am Main. In that way, the EMFL members not only had a chance to acquire new information on the EMFL activities, but also to get to know each other better on a personal level. The EMFL members definitely had a great time in the mountainous region of the Taunus.

HFML constructs new cooling tank

On Tuesday November 8, 2016, the HFML celebrated the milestone of reaching the deepest point of the construction of a new underground cooling water tank. HFML director Nigel Hussey "baptized" the tank by symbolically pouring in the first bucket of water, with representatives of the Radboud University and the contractor parties REEF infra, Croonwolterendros and Building Technology.

The HFML is in the process of expanding its cooling capacity by the construction of an underground cooling water tank of 2500 m^3. Excavation work started in early September, and recently the deepest point of the construction was reached. In the meantime, the concrete on the structure floor has been poured, providing a solid foundation. The cooling water tank will be operational in February 2017, allowing the HFML to make efficient use of the extra cooling capacity. Nigel Hussey: "The HFML offers its high magnetic fields to external users from all over the world, but to produce longer magnet times, expanding the cooling capacity was necessary. This will enable users to stay at maximum fields for up to four hours, significantly increasing the range of experiments that could be carried out at HFML. Moreover, we can now cool our magnets more efficiently by pre-cooling the water in the cooling tank during cold nights." But before that can happen, the tank needs to be filled first. "The first bucket of water is already in. The next 299.999 buckets needed to fill the tank will be in the hands of designated professionals."


© Victor Claessen (Radboud University)

Construction of the new cooling tank of HFML

The cooling tank will be filled beginning of February 2017, after a commissioning and testing period it will become available for external users.

Scientific Highlights

Magnetoelectric effect and phase transitions in CuO in external magnetic fields

Apart from being so far the only known binary multiferroic compound, CuO has a much higher transition temperature into the multiferroic state, 230 K, than any other known material in which the electric polarization is induced by spontaneous magnetic order, typically lower than 100 K. Although the magnetically induced ferroelectricity of CuO is firmly established, no magnetoelectric effect has been observed so far as direct crosstalk between bulk magnetization and electric polarization counterparts, prompting to call CuO a material with persistent multiferroicity without magnetoelectric effects.

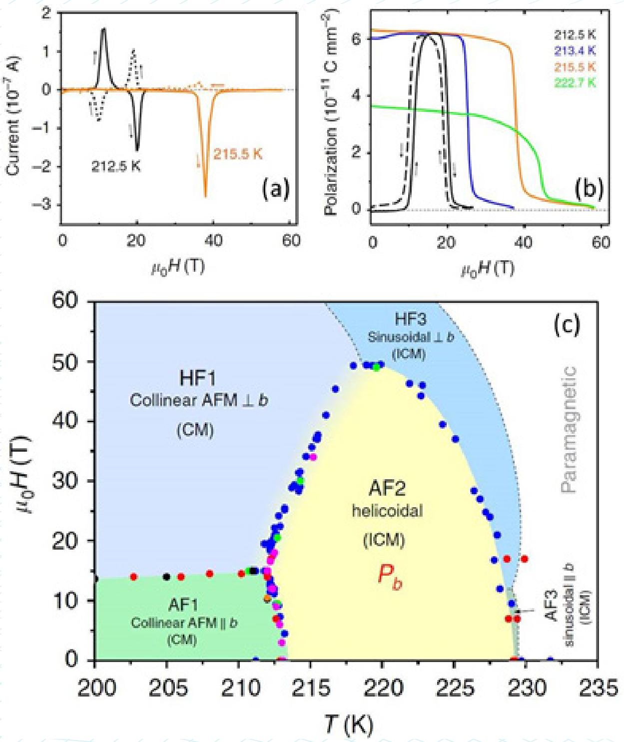


Figure: Electric polarization measurement results and the magnetoelectric phase diagrams of CuO. (a) Pyrocurrent as a function of magnetic field applied along the b axis at two selected temperatures (slightly below 213 K and in the incommensurate phase above it). (b) Electric polarization along the b axis at some selected temperatures, vs. magnetic field applied along the b axis. (c) Magnetic field temperature phase diagram for H || b, based on pyrocurrent (blue dots), capacitance (green dots), magnetostriction (pink dots), sound velocity (red dots) and bulk magnetization data (black dots).

By synergistic use of a number of experimental techniques combined with high magnetic fields – single-crystal neutron diffraction, electric polarization, ultrasound, magnetization, capacitance and magnetostriction measurements at the large scale European facilities (HLD-EMFL at HZDR in Dresden and ILL in Grenoble) – researchers from Dresden and Barcelona, in collaboration with colleagues from Grenoble and Moscow, were able to shed light on the puzzling magnetoelectric nature of CuO.

The results show that sufficiently high magnetic fields of about 50 T are able to suppress the helical modulation of the magnetic moments in the multiferroic phase and dramatically affect the electric polarization. Furthermore, just below the spontaneous transition from commensurate (paraelectric) to incommensurate (ferroelectric) magnetic structures at 213 K, even modest magnetic fields induce a transition into the incommensurate structure and then suppress it at higher field, causing remarkable polarization changes. Thus, hidden magnetoelectric features are uncovered, establishing CuO as a prototype multiferroic with abundance of competitive magnetic interactions. The magnetoelectric phase diagram of this multiferroic is sketched in the figure.

Magnetoelectric effect and phase transitions in CuO in external magnetic fields
Z. Wang, N. Qureshi, S. Yasin, A. Mukhin, E. Resouche, S. Zherlitsyn, Y. Skourski, J. Geshev, V. Ivanov, M. Gospodinov, and V. Skumryev, Nature Communications 7, 10295 (2016).

Pulsed-field broadband NMR of $SrCu_2(BO_3)_2$

The spin-dimer antiferromagnet $SrCu_2(BO_3)_2$ was investigated in great detail over the past two decades, as it represents the most prominent realization of the Shastry-Sutherland lattice model. In this material, electronic spins of Cu^{2+} ions within the $Cu_2(BO_3)_2$ layers form a lattice of mutually orthogonal spin-singlet dimers with significant interdimer interaction, giving rise to pronounced magnetic frustration.

At high magnetic fields, triplet states with reduced kinetic energy condense, resulting in a field-driven sequence of magnetic superlattices with corresponding plateaus in the macroscopic magnetization. The microscopic detection of these superlattice structures by means of NMR as a local probe is of great interest. To study all magnetization plateaus up to half of the saturation value, pulsed magnetic fields up to the regime of 100 T are required. A team of Estonian, Canadian, and German scientists from Leipzig University, the NICPB (Tallinn), McMaster University (Hamilton), and the HLD has performed NMR measurements on $SrCu_2(BO_3)_2$ in pulsed magnetic fields. The results are in very good agreement with a transition from a high-temperature, paramagnetic state to a low-temperature, commensurate superstructure of field-induced spin-dimer triplets in the 1/3 magnetization plateau. Moreover, the technical approach to measure broadband NMR in pulsed fields, that was developed in the course of this work, opens the door not only to the exploration of the higher-field ground states of $SrCu_2(BO_3)_2$, but also to studies of many other quantum magnets with complex interactions that stabilize new phases of matter in very strong magnetic fields.

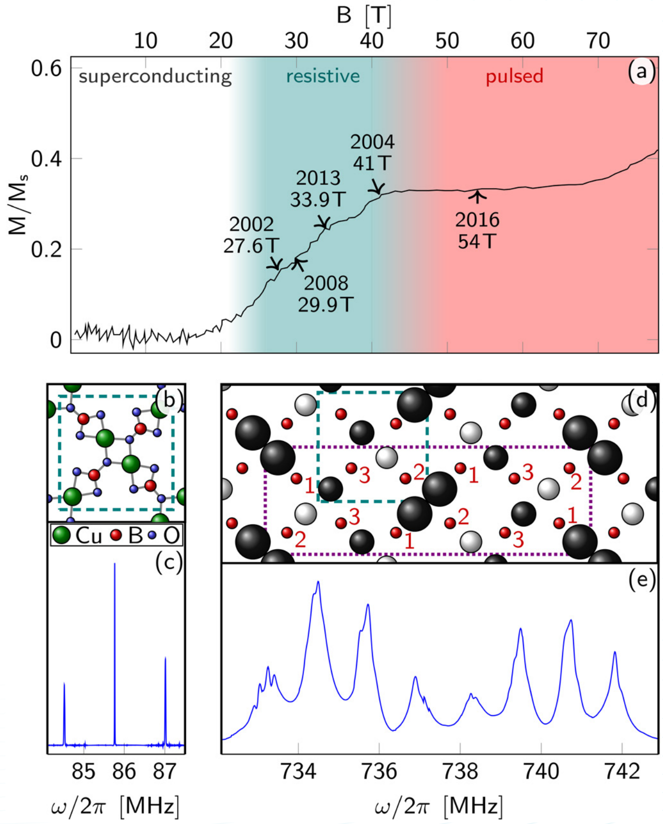


Figure: (a) Macroscopic magnetization of $SrCu_2(BO_3)_2$ at 2 K (from Matsuda et al.). (b) Unit cell of the $Cu_2(BO_3)_2$ plane and (c) the corresponding ^{11}B NMR spectrum at 6 T and 5 K. (d) Magnetic superlattice in the 1/3 magnetization plateau with three different ^{11}B sites (red spheres). White and black spheres represent negative and positive spin polarization, their size the magnitude. (e) ^{11}B NMR spectrum at 54 T and 2 K.

Field-stepped broadband NMR in pulsed magnets and application to $SrCu_2(BO_3)_2$ at 54 T.
J. Kohlrautz, J. Haase, E.L. Green, Z. T. Zhang, J. Wosnitza, T. Herrmannsdörfer, H. A. Dabkowska, B. D. Gaulin, R. Stern, and H. Kühne, J. Magn. Reson. 271, 52 (2016).

Pseudo-gap quantum phase transition in high-Tc cuprates

The microscopic origin of high-temperature superconductivity in the cuprates, despite its long history, is still under fierce debate. There is a conjecture that the so-called pseudo-gap phase, and in particular the critical fluctuations associated with it, are the underlying cause for high-Tc superconductivity. However, the existence of other phases, such as a spin density wave and a charge density phase complicate the picture considerably.

By performing Hall effect measurements in the field-induced low-temperature normal state of high-quality $YBa_2Cu_3O_x$ samples at very high magnetic fields (Figure 1), a team of Canadian and French researchers working at the EMFL in Toulouse has observed a sharp drop in the number of charge carriers exactly where the pseudo-gap phase sets in (Figure 2). This proves that the pseudo-gap state is accompanied by a transformation of the Fermi surface such that its volume suddenly shrinks by one hole per Cu atom. It is expected that a microscopic understanding of this transformation will elucidate the enigmatic behavior of electrons in the cuprate superconductors.

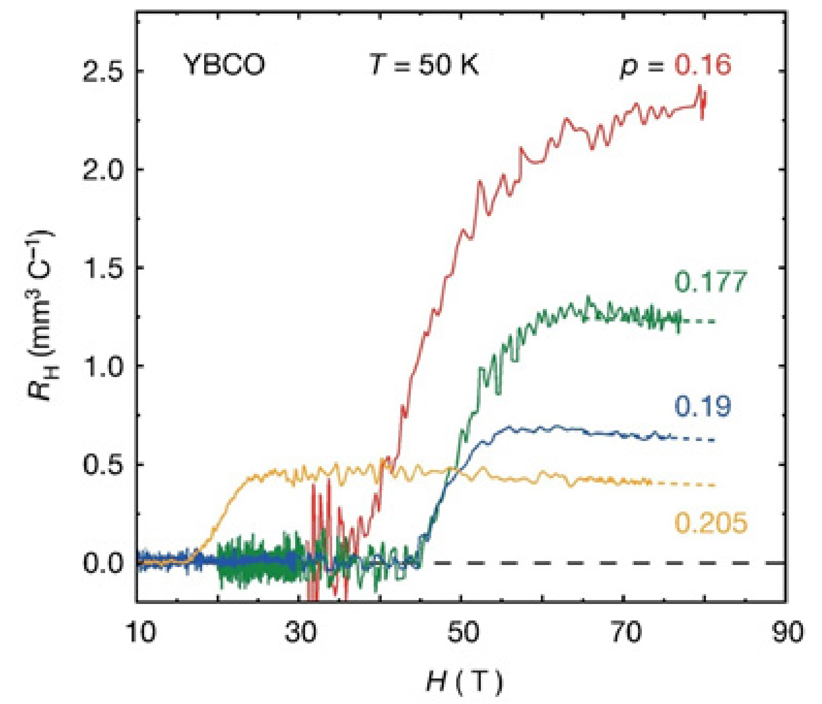


Figure 1: Hall effect measurements for samples with different doping level in pulsed magnetic field.

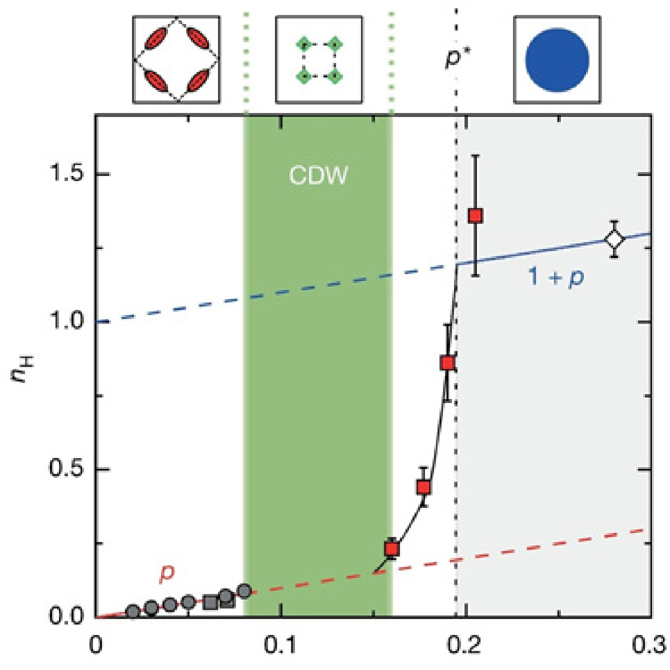


Figure 2: Charge-carrier concentration as a function of hole doping.

Change of carrier density at the pseudogap critical point of a cuprate superconductor

S. Badoux W. Tabis, F. Laliberté, G. Grissonnanche, B. Vignolle, D. Vignolles, J. Béard, D. A. Bonn, W. N. Hardy, R. Liang, N. Doiron-Leyraud, Louis Taillefer, and C. Proust, Nature 531, 210–214 (2016).

Collapse of ferromagnetism and Fermi surface instability near the reentrant superconductivity of URhGe

Quantum phase transitions (QPT) are a central topic in contemporary condensed-matter research. Their rich underlying physics plays an important role in explaining exotic low-temperature properties of a variety of strongly correlated materials such as high-T_c superconductors, quantum magnets or heavy-fermion compounds. URhGe is one of the four uranium-based heavy-fermion compounds where microscopic coexistence of ferromagnetism (FM) and superconductivity has been observed. A transverse magnetic field higher than the superconducting critical field H_{c2} applied along the hard magnetization b axis induces at low temperature a QPT induced by a reorientation of the magnetic moments from the c to b axis at H_R = 11.75 T. A field reentrant superconducting phase (RSC) appears in a narrow field window around H_R below T_{RSC} = 410 mK. Thus URhGe is a key case to study a ferromagnetic QPT.

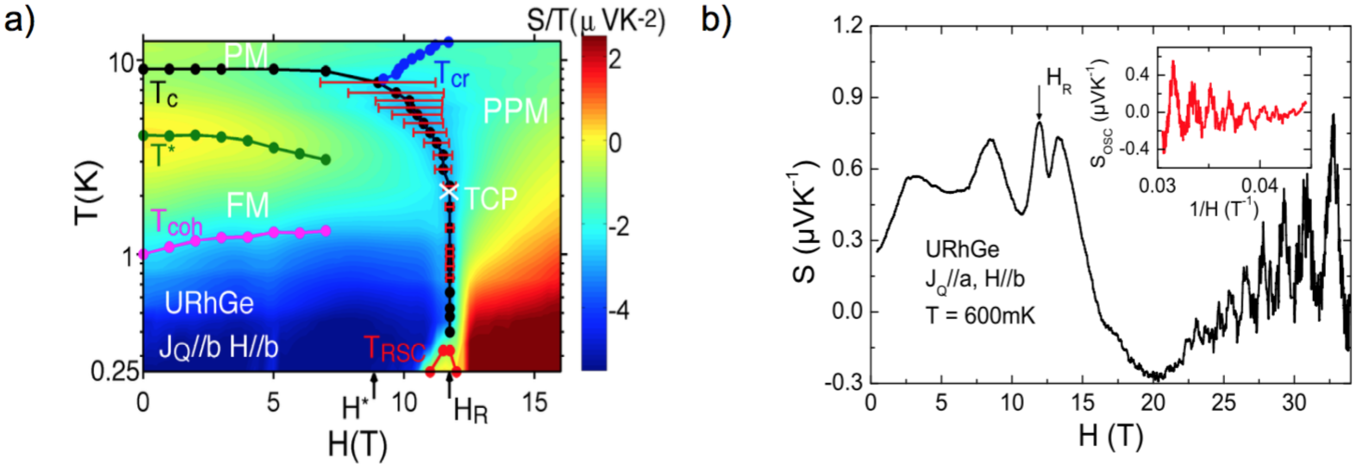


Figure 1: (a) Linear color map of S/T (TEP divided by T) in the (T, H) plane. The Curie temperature T_C (black circles), the reentrant superconductivity T_{RSC} (red circles) and the crossover line T_{cr} between the paramagnetic (PM) and the polarized paramagnetic (PPM) state (blue circles) are superimposed. The transition width observed in the TEP around H_R is also represented (red horizontal lines). (b) Magnetic-field dependence of the TEP for J_Q||a, H||b up to 34 T at 600 mK. S shows quantum oscillations above 22 T, represented as a function of 1/H in the inset. [1]

Recent thermoelectric power (TEP) measurements (Ref. [1]) performed for magnetic field applied along the hard magnetization b axis shows clearly the first-order nature of the QPT at H_R and the existence of a tricritical point (TCP, see Figure 1(a)). The abrupt change of sign of the TEP at H_R suggests that a topological change of the Fermi surface is associated to the QPT. The possibility of a Lifshitz transition at H_R in URhGe was already proposed in Ref. [2] from Shubnikov de Haas (SdH) experiments. Indeed, it has been observed that SdH oscillations below H_R, corresponding to a small orbit of only a few percent of the Brillouin zone, vanish on approaching H_R. It has been claimed that this Lifshitz-type transition, leading to the collapse of the Fermi velocity, is the driving force for the RSC. However, as shown in Figure 2(b), the TEP measured up to 34 T shows large quantum oscillations above 22 T. The corresponding frequency, ~ 500 T, is very similar to the frequency observed in the previous SdH measurements below H_R. This demonstrates that a Lifshitz transition as the sole driving force for the RSC seems unlikely. Our study presents clear evidence that both Fermi-surface instabilities and magnetic fluctuations occurring around H_R are the key ingredients for the apparition of the RSC.

[1] **Collapse of ferromagnetism and Fermi surface instability near reentrant superconductivity of URhGe**, A. Gourgout, A. Pourret, G. Knebel, D. Aoki, G. Seyfarth, and J. Flouquet, PRL 117, 046401 (2016)

[2] E. A. Yelland, J. M. Barraclough, W. Wang, K. V. Kamenev, and A. D. Huxley, Nat. Phys. 7, 890 (2011).

Field-induced spin-density wave beyond hidden order in URu$_2$Si$_2$

URu$_2$Si$_2$ is one of the most enigmatic strongly correlated electron systems and offers a fertile test ground for new concepts in condensed-matter science. In spite of more than thirty years of intense research, no consensus on the order parameter of its low-temperature hidden-order phase exists. Under a high magnetic field applied along c, a cascade of first-order phase transitions leads to a polarized paramagnetic regime above μ_0H_3 = 39 T. Here, thanks to a new cryomagnet (developed by the LNCMI-Toulouse, the CEA-Grenoble, and the ILL-Grenoble) allowing neutron diffraction up to 40 T, we have determined that URu$_2$Si$_2$ enters in a spin-density wave state in fields between 35 and 39 T. The transition to the spin-density wave represents a unique touchstone for understanding the hidden-order phase.

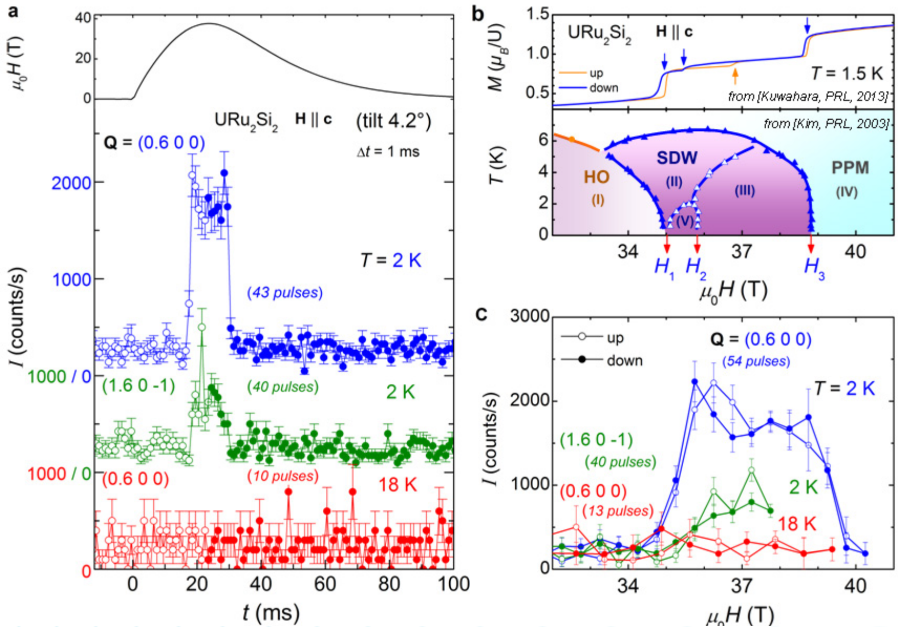


Figure: (a) Time profile of a magnetic field pulsed up to 38 T, and corresponding time-dependence of the neutron-diffracted intensity at Q = (0.6 0 0) and Q = (1.6 0 -1). (b) Magnetization versus magnetic field at T = 1.5 K and magnetic-field-temperature phase diagram of URu$_2$Si$_2$. (c) Field-dependence of the neutron-diffracted intensities in fields up to 40.5 T.

The Figure shows the diffracted neutron intensities recorded in magnetic fields up to 40 T at the momentum transfers Q = (0.6 0 0) and (1.6 0 -1), which are satellites of wavevector $k_1 = Q - \tau$ = (0.6 0 0) around the structural Bragg positions τ = (0 0 0) and (1 0 -1), respectively. The enhancement of the intensity at 2 K, absent at 18 K, shows that the spin-density wave with wavevector k_1 is established at high field and low temperature. In an itinerant picture of magnetism, a spin-density wave can be related to a partial or complete nesting of two parts of the Fermi surface. In URu$_2$Si$_2$, our observation of a spin-density wave in magnetic fields between 35 and 39 T will certainly push to develop models incorporating on equal basis the Fermi-surface topology and the magnetic interactions. To describe competing quantum instabilities between the hidden-order and long-range-ordered phases, such models will be a basis to solve the hidden-order puzzle.

Field-induced spin-density wave beyond hidden order in URu$_2$Si$_2$
W. Knafo, F. Duc, F. Bourdarot, K. Kuwahara, H. Nojiri, D. Aoki, J. Billette, P. Frings, X. Tonon, E. Lelièvre-Berna, J. Flouquet, and L.-P. Regnault, Nat. Commun. 7, 13075 (2016).

Disorder-induced stabilization of the quantum Hall ferromagnet

The quantum Hall ferromagnet (QHF) is a fascinating ground state of two-dimensional (2D) electrons in a magnetic field where exchange interactions can establish a long-range ferromagnetic order. In strong magnetic fields, electrons are "squeezed" close together, and thus experience strong Coulomb interactions creating a large energy gap which protects the QHF. Despite this large gap, the spin polarization P of the system, which should be full (P = 1) in the QHF state, may be reduced due to the appearance of peculiar spin textures known as Skyrmions, which can form as soon as charge are added or removed from the system. In practice, a fully polarized QHF is rarely observed, and recent experiments have shown a surprising fragility of the spin polarization which drops below 1 in the presence of charge fluctuations of about 0.1 % or at temperatures of a few hundred millikelvin. Our recent work gives an explanation for such fragility by showing that an optimal amount of disorder actually "protects" the QHF against depolarization. In simple words, a slightly dirty QHF is stronger than a clean one. When the amount of disorder is too high, however, the QHF, like other quantum Hall states, is eventually destroyed. This defines a small pocket in the disorder / interaction (magnetic field) / carrier density phase diagram of the 2D electron gas where the fully spin polarized state is stabilized. Our conclusions are reached by using state-of-the-art "frequency-pulsed-resistively-detected-NMR", enabling us to measure the electron spin polarization in an absolute way at very low temperatures as a function of the electron density and the magnetic field (see Figure), close to the complete filling of the lowest Landau level.

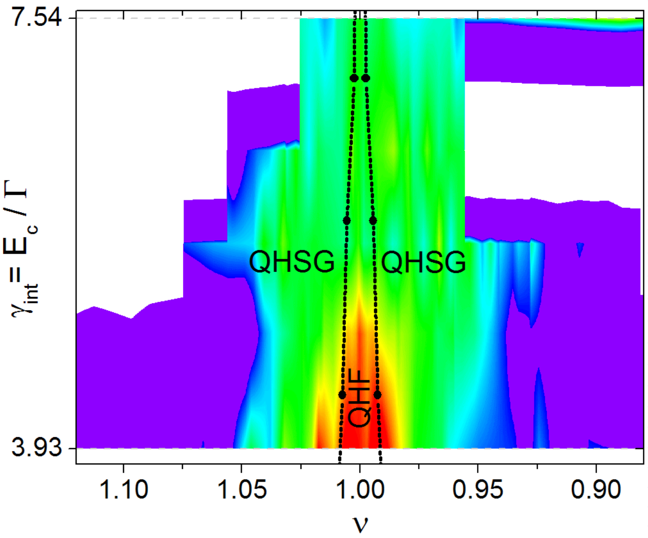


Figure: Color map of the electron spin polarization P as a function of the filling factor (number of filled Landau levels) and the interaction parameter γint. γint corresponds to the ratio between the Coulomb interaction Ec (tuned by applying a large magnetic field), and the sample disorder Γ. P < 0.7 (purple), P = 0.7 (blue) to P = 1 (red). Outside the theoretical narrow QHF region, delimited by the black-dotted lines, the QHF is destabilized with respect to the formation of Skyrmions (QHSG).

These findings explain why the QHF is so fragile in very clean (high-mobility) 2D systems, but also open ways to improve our control of the degree of spin polarization of collective 2D states.

Disorder-induced stabilization of the quantum Hall ferromagnet
B. A. Piot, W. Desrat, D. K. Maude, D. Kazazis, A. Cavanna, and U. Gennser, Phys. Rev. Lett. 116, 106801 (2016).

Magneto-optics of monolayer tungsten disulfide

Single layer transition-metal dichalcogenides, such as MoS_2, $MoSe_2$, WS_2, WSe_2, are two dimensional semiconductors, with a honeycomb lattice. Their bandstructures show a pair of inequivalent valleys (local extrema) at the +K and -K points of the Brillouin zone. The valleys in the conduction and valence bands are separated by a direct band-gap in the visible spectral range, resulting in efficient light absorption and emission. The existence of valleys results in charge carriers that exhibit, in addition to their real spin, an extra property called pseudospin, accompanied by a magnetic moment.

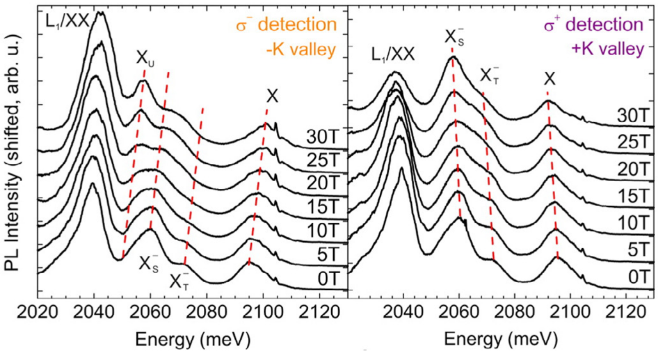


Figure 1. Left (σ−, left panel) and right (σ+, right panel) circularly polarized emission from monolayer WS_2 at 4.2 K and different magnetic fields. Neutral excitons (X) as well as different charged excitons, singlets (X^-_S) and triplets (X^-_T), can be distinguished.

In a collaboration between the University of Regensburg, the University of Münster and the High Field Magnet Laboratory Nijmegen the magneto-optical properties of monolayer WS_2 have been determined. The photoluminescence emission is dominated by neutral and charged electron-hole pairs (excitons). Two distinct types of charged excitons (trions), singlets (X^-_S) and triplets (X^-_T), have been observed, just below the emission line of the neutral exciton X (Figure 1). For all types of excitons the g-factors have been determined, while the observation of the diamagnetic shifts of the excitons gives insight into the real-space extension of these quasiparticles. The magnetic field induced valley polarization effects shed light onto the exciton and trion dispersion relations in reciprocal space.

A remarkable magnetic-field-induced rotation of the polarized light emission of neutral excitons has been observed (figure 2). A field-induced valley Zeeman splitting causes a rotation of the emission polarization with respect to the excitation by up to 35° and reduces the linear polarization degree by up to 16%. From these results it is deduced that coherent light emission from the valleys decays with a time constant of 260 fs.

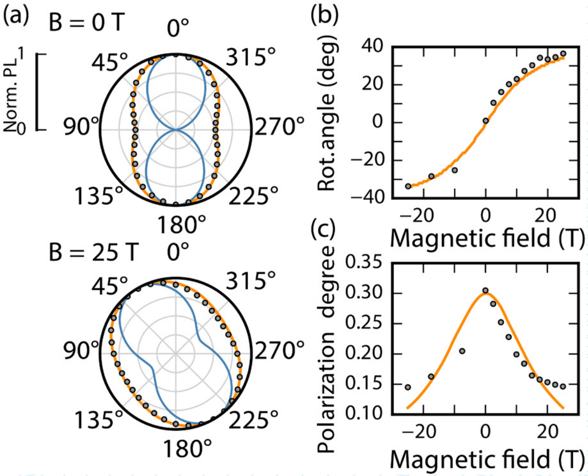


Figure 2. a) Measured normalized photoluminescence intensity (solid circles) for monolayer WS_2 as a function of the analyzer angle, under linearly polarized excitation for 0 and 25 T. The blue and orange lines indicate the polarization patterns obtained from different models. b) Relative rotation angle between the excitation and emission polarization for different magnetic fields. c) Linear polarization degree of the emission as a function of the magnetic field. The orange lines show the global fit to the data using a model taking into account exciton valley coherence.

These remarkable properties pave the way to study and utilize valley-dependent phenomena ("valleytronics") by optical means, which is very promising for novel opto-electronic applications.

Magnetic-Field-Induced Rotation of Polarized Light Emission from Monolayer WS_2, Schmidt et al., Physical Review Letters 117, 077402 (2016)

Trion fine structure and coupled spin–valley dynamics in monolayer tungsten disulfide, Plechinger et al., Nature Communications 7, 12715 (2016).

Excitonic valley effects in monolayer WS_2 under high magnetic fields, Plechinger et al., Nano Letters 16, 7899-7904 (2016).

Chirality of graphene electrons manipulated in high magnetic fields

Apart from the conventional properties charge and spin, electronsin graphene possess an additional degree of freedom: pseudospin which quantifies the contributions to the electronic wave functions from the two sublattices. Such electrons can then be described as chiral particles with their pseudospin locked to the direction of their momentum in a parallel or antiparallel fashion for electrons belonging to the K or K’ valley, respectively. This makes them promising candidates to perform new types of experiments as a basis of novel quantum-information devices. However, in general electrons with different chirality and pseudospin contribute to the transport phenomena in standard experiments on graphene, and it is not straightforward to observe and manipulate them individually in real devices.

Scientists from Manchester and Nottingham (United Kingdom), Chernogolovka (Russia) and the two EMFL Labs LNCMI-CNRS in Grenoble and HFML-RU/FOM in Nijmegen have now achieved both: Using vertical tunneling between two nearly aligned graphene sheets in strong magnetic fields they succeeded in observing and manipulating the chirality and pseudospin polarization. The devices used are van der Waals heterostructures consisting of two stacked graphene (Gr) layers with 3-5 monolayers of hexagonal boron nitride (hBN) acting as a tunneling barrier in between. Due to a slight misalignment (~1 degree) resonantly tunneling electrons between the two graphene layers can only originate from specific regions of momentum space although contributions from different chiral states remain indistinguishable.

However, when applying a large magnetic field of up to 30 T perpendicular to the tunneling direction, the Lorentz force leads to an additional momentum acquired by the tunneling electrons parallel to the graphene layers and perpendicular to the applied magnetic field. This so-called Lorentz boost Δp is defined by the thickness of the hBN, the tunneling direction, and the magnetic field. In particular, this makes it possible to overcome the momentum mismatch between the two slightly misaligned graphene layers, thereby enhancing the tunneling probability from a specific valley in one graphene layer to the same valley in the adjacent layer. Depending on the angle of the magnetic field, one specific chirality can tunnel easily thought the boron nitride whereas the other one is suppressed yielding a significant chiral selection of the tunneling electrons.

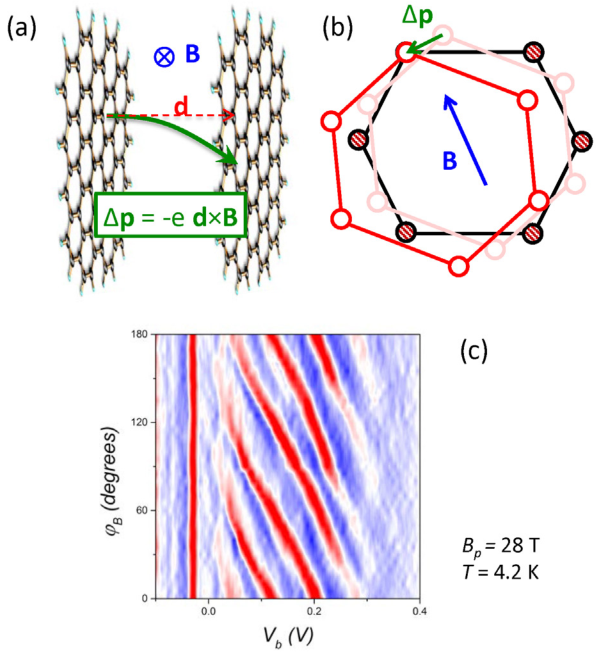


Figure: (a) Schematics of the Lorentz boost for electrons tunneling between two graphene layers.
(b) Momentum-space representation of the two slightly misalig-ned graphene layers. Due to the in-plane magnetic field the Brillouin zone of the second layer is shifted by Δ p , thereby bringing its top left valley in resonance with a valley in the adjacent layer.
(c) Differential conductance map of a Gr-hBN-Gr tunneling device as a function of bias voltage and angle of the in-plane magnetic field. The 60°-periodic pattern originates from resonances with one of the six K-valleys in the corners of the first Brillouin zone and the asymmetry in the pattern reflects the chiral selection.

Tuning the valley and chiral quantum state of Dirac electrons in van der Waals hete-rostructures
J. R. Wallbank, D. Ghazaryan, A. Misra, Y. Cao, J. S. Tu, B. A. Piot, M. Potemski, S. Pezzini, S. Wiedmann, U. Zeitler, T. L. M. Lane, S. V. Morozov, M. T. Greenaway, L. Eaves, A. K. Geim, V. I. Fal‘ko, K. S. Novoselov and A. Mishchenko, Science 355, 575 (2016).

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)
Gerard Meijer (RU/FOM)
Amina Taleb-Ibrahimi (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:

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

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

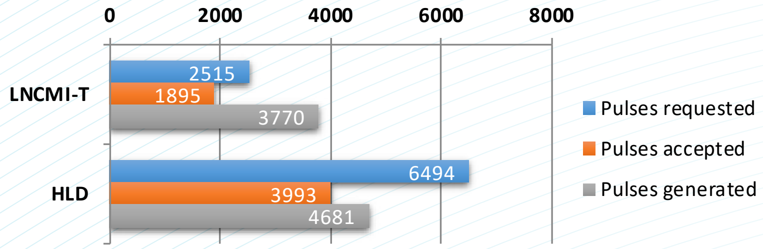
In order to represent the interests of the high field user community, members (all external to the infrastructures) are elected for a period of three years by the user community during the annual User Meeting. The chairman of the User Committee will report to the Board of Directors on behalf of the users.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

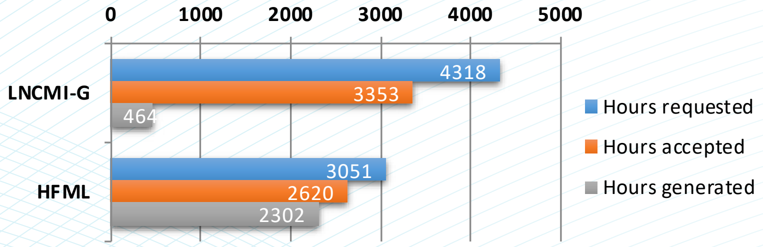
User Access

The 14th and 15th call for proposals closed in June and December, resulting in 305 applications from 24 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

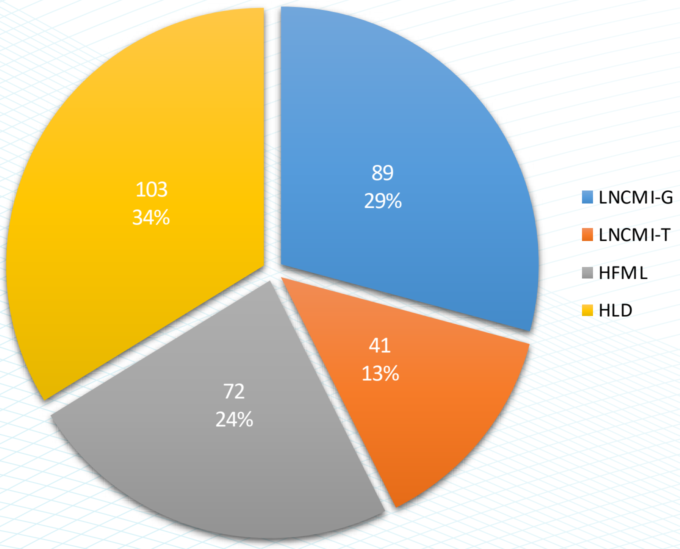


DC facilities

The EMFL facility in Grenoble generated less magnet hours then usually normally due to a down time period 2016 to be a able to perform a major upgrade of their power supply. 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 accepted amount of pulses by the Selection Committee as not only the scientific pulses are counted but also the test pulses for testing the experimental set-up.

Distribution by facilities
Number of applications

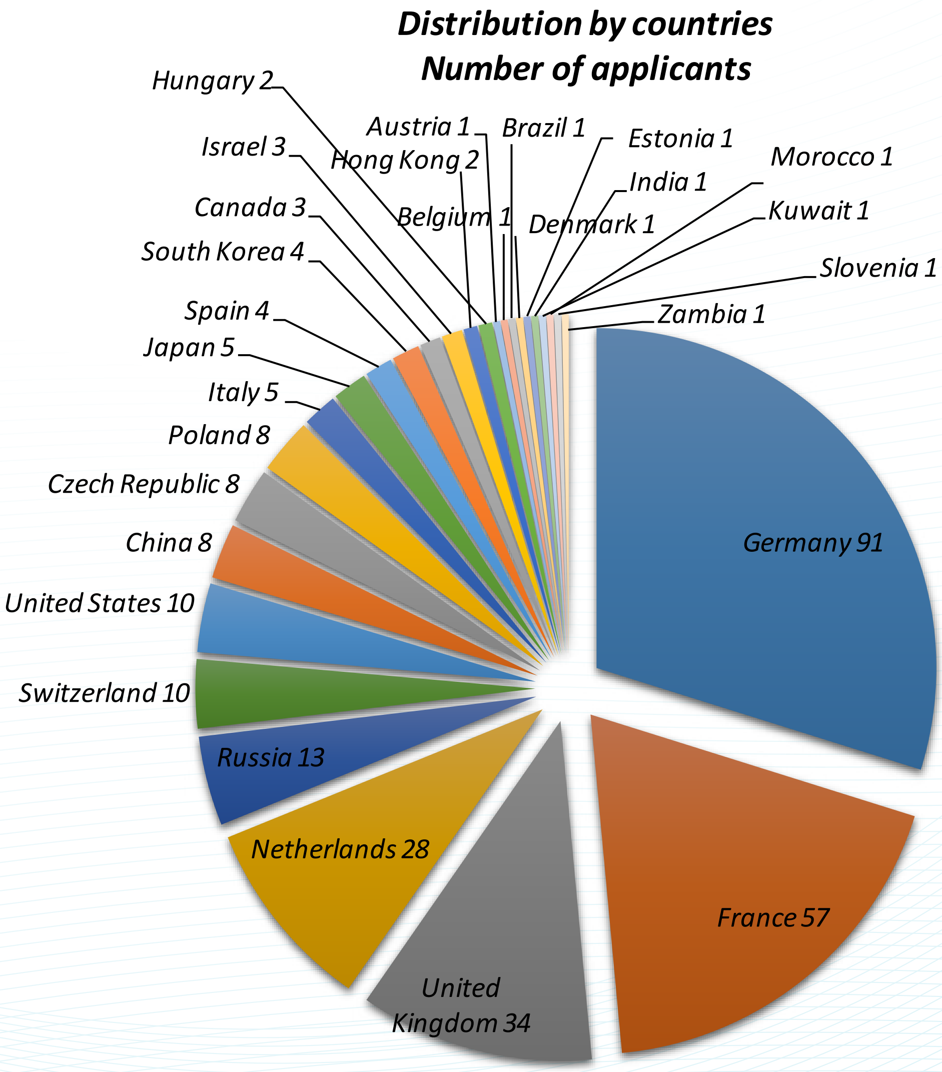


Evaluation of applications

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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