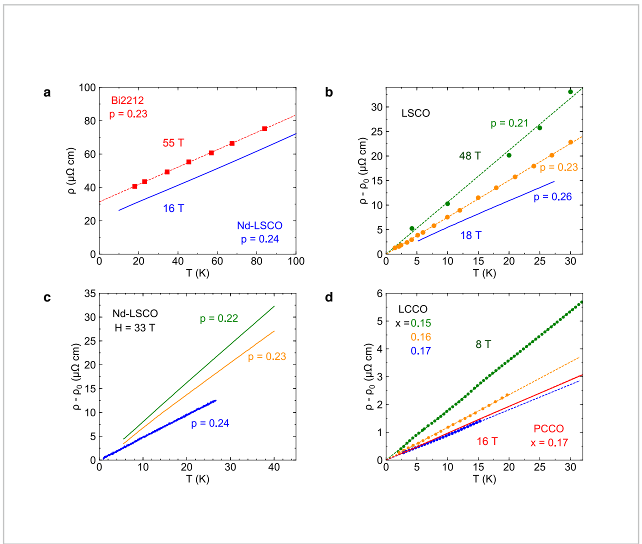
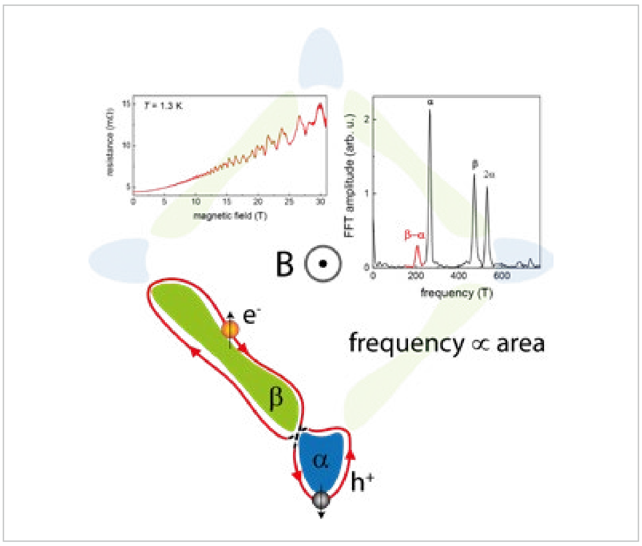
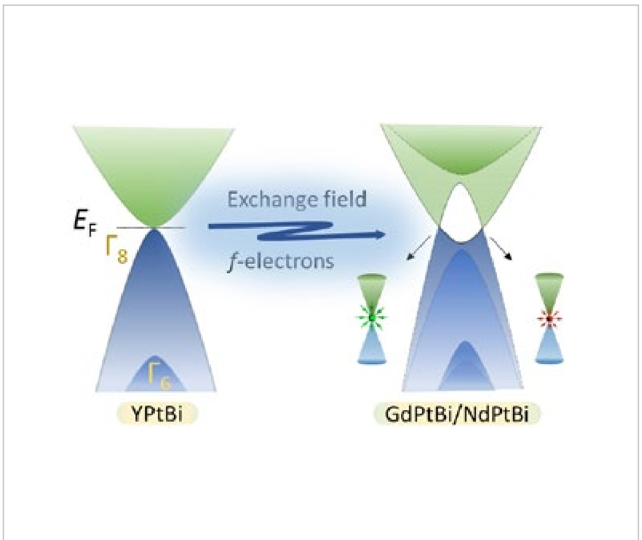
European Magnetic Field Laboratory

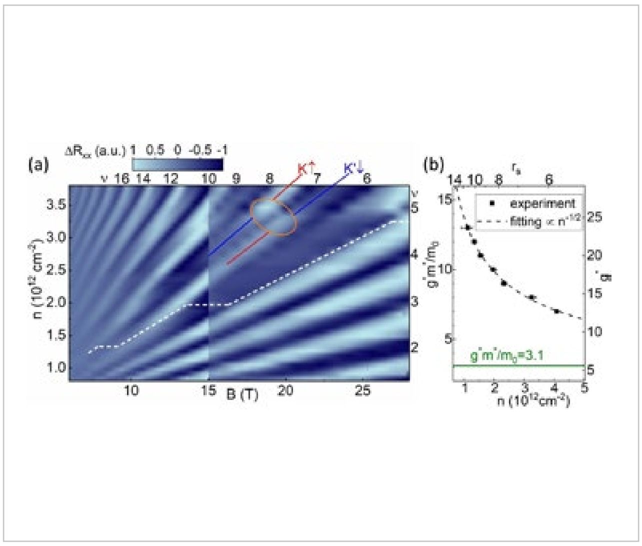
EMFLNEWS

N°4 2018









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DEAR READER

First of all, on behalf of the whole EMFL staff, let me wish you a prosperous and healthy New Year. Indeed, for EMFL the year 2019 has started with excellent news. We are happy to announce that Poland has become the newest member of the EMFL. A consortium of Polish high-magnetic-field users, represented by the University of Warsaw, has received funding by the Ministry of Science and Higher Education in Poland. Adam Babiński is the coordinator of the Polish membership and will be representing the Polish user community in EMFL. After our UK colleagues, this is the second user group that has lobbied in support for the development of high magnetic field science in Europe. In this respect, the European idea indeed is working. We are looking forward to further attract new members to EMFL in the years to come. You will find more information on the Polish membership in a news article in this issue.

As usual, a number of recent scientific highlights and the outcome of the latest call for access are as well presented in this issue. Again, we can announce a new record number of proposals in 2018. Finally, we are planning to have the next user meeting in the new EMFL member country Poland. Adam Babiński kindly has agreed to organize the meeting. We will inform you later on the exact date of this event.

Have a stimulating reading,

Jochen Wosnitza
Director HLD
Chairman EMFL

MEET OUR PEOPLE

Toni Helm – Scientist at HLD Dresden

I joined the EMFL as an employee rather recently, but I am both new and old to the European high-field community. During my graduate school at the TU Munich and PhD work at the Walther Meissner Institute in Garching (Germany) I have spent quite some time in most of the labs of the EMFL as an external user. Later, as a postdoctoral researcher in Berkeley, CA (USA) and at the MPI in Dresden, I continued working on various topical materials, such as unconventional and high-temperature superconductors, semimetals, and quantum magnets. High magnetic fields have always been one of the key tools for my research. My most recent works are based on an innovative approach, assisted by focused ion beams (FIB) that can be applied to create microscale experiments from a wide range of single-crystalline materials. With the capability to structure crystals with nanometer precision in three dimensions, we can build a bridge between the macroscopic and the nano-world.

From my point of view, the EMFL is very attractive because it brings together scientists from all over the world independent of their cultural, ethnical, or economic backgrounds. In our work, we try to reach beyond of what we currently accept as and believe is the truth, by pushing experiment and theory to their limits. We explore new and unknown territories and uncover black spots on an incredibly huge map. I am particularly excited about the potential of my work to discover effects and material properties that break with existing theories and might open up completely new research pathways.

In one of my projects, we combine FIB-microstructured devices for magnetotransport with diamond-anvil pressure cells and pulsed magnetic fields. With this, we can map out the high-field/high-pressure phase diagrams of unconventional metals, such as heavy-fermion antiferromagnets. The HZDR provides not only high magnetic fields for my research: The nearby ELBE - Center for High Power Radiation Sources and the Ion Beam Center, together with the Dresden High Magnetic Field Laboratory offer a unique science landscape plus a tremendous amount of expertise. I am looking forward to fruitful collaborations and experiments as part of the EMFL community.

› Toni Helm

PLANCKIAN DISSIPATION IN HIGH-T_C SUPERCONDUCTORS

Cyril Proust, LNCMI-Toulouse and Louis Taillefer, University of Sherbrooke

Measuring the electrical resistance of a new material is often the first experiment that researchers do, but also often the last to be understood. Nevertheless, the temperature dependence of the electrical resistance gives essential information on the ground state of materials. Whereas in usual metals the resistance exhibits a T^2 dependence at low temperature, some compounds called quantum materials show a linear temperature dependence of their resistance. This is the case for the cuprates where such a linear dependence has been observed in a wide range of doping, corresponding to a phase called "strange metal". Strong electronic interactions are certainly at the origin of this phenomenon, but no consensual explanation has been found to date.

To address this issue, a group of EMFL-T and Canadian researchers have measured the resistivity of thin films of $Bi_2Sr_2CaCu_2O_{8+\delta}$ in magnetic fields up to 60 Tesla. The latter weakens the superconductivity significantly and reveals the underlying properties of the material. It was observed that the electrical resistivity remains linear down to very low temperatures. This result shows first of all the universal character of this remarkable behavior over a wide temperature range (Figure 1). In addition, a quantitative analysis of the linear term of the resistivity in several cuprate families has revealed a universal mechanism called Planckian dissipation, a consequence of quantum physics which says that the minimum time to dissipate energy is given by the Heisenberg uncertainty (Figure 2). This limit implies that the electron scattering rate $\hbar/\tau$ is simply given by $k_B T$. This behavior appears at the same doping level as the superconductivity, which suggests that the mechanism at the origin of the Planckian dissipation is also at the origin of the electronic interaction giving rise to high-temperature superconductivity.

This mechanism is certainly the consequence of a new quantum state of matter in these materials. A similar mechanism, called minimal viscosity, is also encountered in the quark-gluon plasma and the most recent theoretical developments, called holography, are at the boundary between strongly correlated electron systems, string theory, black-hole physics, and the theory of quantum information. Progress in these latter disciplines could therefore directly benefit the understanding of systems where electronic correlations are strong, such as the cuprates.

Universal T-linear resistivity and Planckian dissipation in overdoped cuprates, A. Legros, S. Benhabib, W. Tabis, F. Laliberté, M. Dion, M. Lizaire, B. Vignolle, D. Vignolles, H. Raffy, Z. Z. Li, P. Auban-Senzier, N. Doiron-Leyraud, P. Fournier, D. Colson, L. Taillefer, and C. Proust, Nat. Phys. (2018); https://doi.org/10.1038/s41567-018-0334-2

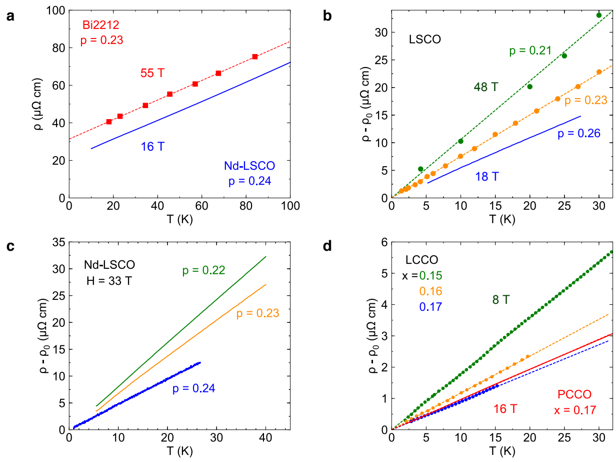


Figure 1: Experimentally observed temperature dependence of the resistivity of different cuprate superconductors, submitted to high magnetic fields.

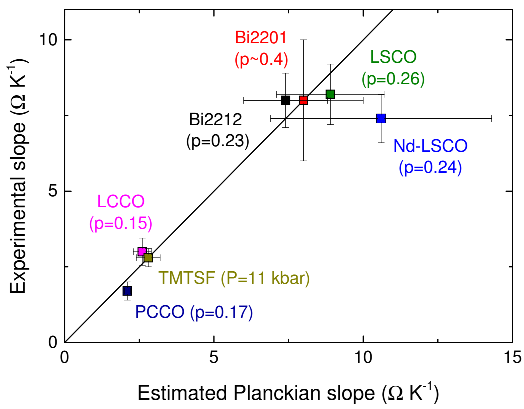


Figure 2: Experimental versus predicted slope of the linear temperature dependence of the resistivity of different superconductors. The solid line corresponds to a slope of unity.

Contact: cyril.proust@lncmi.cnrs.fr, Louis.Taillefer@USherbrooke.ca

ELECTRON-HOLE TUNNELING IN MOMENTUM SPACE REVEALED BY QUANTUM OSCILLATIONS

M. van Delft, S. Pezzini, T. Khouri, C. Müller, N. Hussey, S. Wiedmann, HFML Nijmegen

Researchers from Germany, USA, UK, and the HFML Nijmegen have found evidence for electron-hole tunneling in momentum space in the nodal-line semimetal HfSiS. This specific tunneling phenomenon is revealed in quantum oscillations of the electrical resistance at low temperatures and in high magnetic fields, and can be illustrated as a 'figure-of-eight orbit' enclosing one electron and one hole pocket. Their finding suggests that electron-hole tunneling in momentum space is a generic property of semimetals with adjacent electron and hole pockets, provided that the applied magnetic field is strong enough to overcome their k-space separation.

Quantum oscillations are a very powerful tool to determine the Fermi surface of metals, semiconductors, and semimetals in the presence of a high magnetic field. For charge carriers subjected to such high fields, the energy levels become quantized and are referred to as Landau bands. If the magnetic field is varied, these bands cross the Fermi energy resulting in oscillations, for instance, in the electrical resistance as a function of magnetic field.

The Fermi surface of HfSiS, a nodal-line semimetal, consists of both hole (α) and electron (β) pockets. In the presence of a magnetic field up to 31 T applied parallel to the c axis, quantum oscillations originating both from orbits of individual electron and hole pockets, and from magnetic breakdown between these pockets are observed. These orbits can be visualized in the fast Fourier transform (FFT): the peaks in the FFT amplitude correspond to the individual hole pocket (α), its harmonic (2α), the electron pocket (β), and the orbit enclosing one electron and one hole pocket (β-α) in the form of a 'figure of eight' (Figure).

Electron-Hole Tunneling Revealed by Quantum Oscillations in the Nodal-Line Semimetal HfSiS, M. R. van Delft, S. Pezzini, T. Khouri, C. S. A. Müller, M. Breitkreiz, L. M. Schoop, A. Carrington, N. E. Hussey, and S. Wiedmann, Phys. Rev. Lett. **121**, 256602 (2018).

This particular breakdown β-α orbit is a manifestation of 'Klein tunneling in momentum space', though in a regime of partial transmission as the pockets are separated. The occurrence of this orbit above a threshold magnetic field, the observed strong dependence of the oscillation amplitude on the field angle with respect to the c axis, and the cyclotron mass of this orbit are in agreement with theoretical predictions for this novel tunneling phenomenon. Although magnetic breakdown has been extensively studied in simple elements, and in organic metals, this specific type of magnetic breakdown between adjacent electron and hole pockets has been observed for the first time.

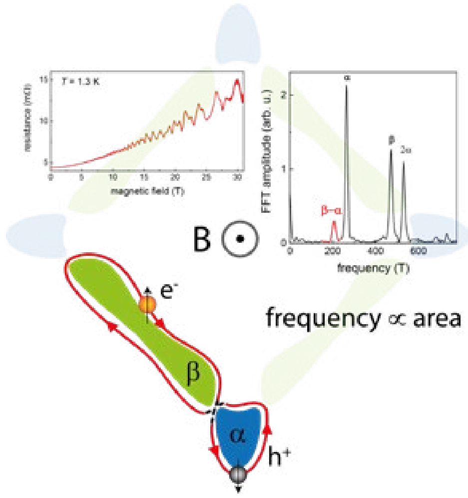


Figure: Field-dependent resistance with quantum oscillations, corresponding FFT, and sketch of the Fermi surface perpendicular to the magnetic field B.

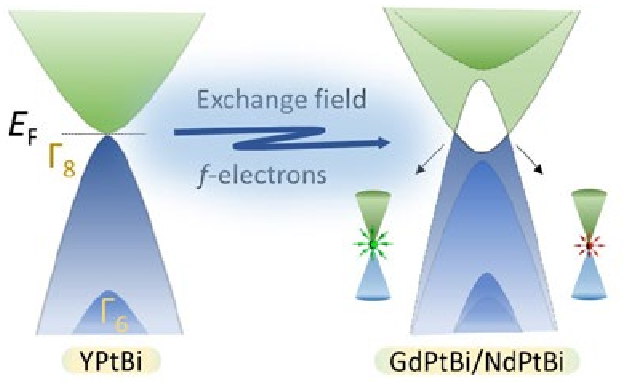
Contact: steffen.wiedmann@ru.nl

A DROSOPHILA FOR WEYL PHYSICS: GdPtBi

C. Shekhar, MPI CPfS Dresden and Y. Skourski, HLD Dresden

In 1929, Hermann Weyl discovered that massless spin-1/2 particles are solutions of the Dirac equation. After many decades, these Weyl particles were finally experimentally revealed in 2015 in simple semimetallic materials such as TaAs. Weyl fermions are low-energy quasiparticle excitations in the vicinity of the unavoidable touching points of a valence band and a conduction band: these materials are "Weyl semimetals". These touching points always come in pairs with opposite chiralities (right and left) and, moreover, act as large fictitious magnetic fields, so-called Berry fields, for electronic charge carriers.

A group of researchers from the Max Planck Institute for Chemical Physics of Solids in Dresden, in collaboration with the Technische Universität Dresden, the high magnetic field laboratories HLD in Dresden and HMFL in Nijmegen, and the PSI Switzerland have performed magneto-transport experiments at low temperatures and high magnetic fields up to 70 T. The observations directly indicate Weyl-fermion-mediated transport properties in GdPtBi and NdPtBi, two members of the Heusler family. The key properties are an extremely large chiral-anomaly effect due to pumping of Weyl fermions between pairs of Weyl points and a large anomalous Hall effect due to a non-zero Berry curvature. The temperature dependence of these two observations follow a similar trend (Figure), thereby revealing their common origin in Weyl fermions. Moreover, this study reveals that there is a crucial role of magnetism in creating Weyl fermions via exchange splitting of bands.



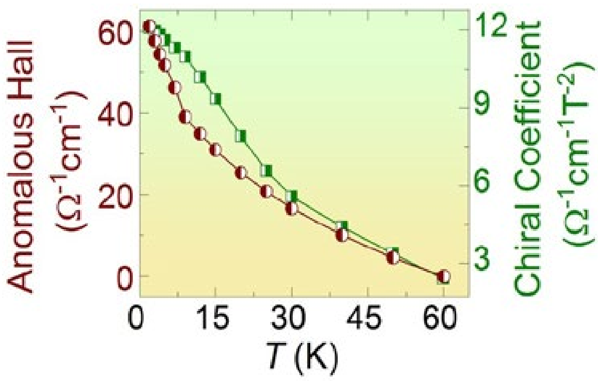


Figure: Evolution of Weyl points (left) evidencing Weyl fermions and measured anomalous Hall effect and chiral-anomaly effect in GdPtBi (right).

Anomalous Hall effect in Weyl semimetal half-Heusler compounds RPtBi (R = Gd and Nd), C. Shekhar, N. Kumar, V. Grinenko, S. Singh, R. Sarkar, H. Luetkens, S.-C. Wu, Y. Zhang, A. Komarek, E. Kampert, Y. Skourski, J. Wosnitza, W. Schnelle, A. McCollam, U. Zeitler, J. Kübler, B. Yan, H.-H. Klauss, S. S. P. Parkin, C. Felser, PNAS **115**, 9140 (2018).

Contact: Chandra.Shekhar@cpfs.mpg.de

STRONG INTERACTION EFFECTS IN MoS_2 LANDAU LEVELS

Jiangxiazi Lin, Ning Wang, Hong Kong University of Science and Technology and Benjamin Piot, LNCMI-Grenoble

Semiconducting two-dimensional transition-metal dichalcogenides (TMDCs) have been a recent hot research topic in physics, for their novel optical/electronic properties and potential applications. While phenomena such as direct-to-indirect band-gap transition, spin-orbit coupling, and symmetry-controlled valleytronics have attracted wide studies, investigations on interaction effects in TMDCs are scarce.

Our recent work focuses on the K-valley electrons in spin-orbit coupled MoS_2, with inversion symmetry broken by a back-gate voltage. We fabricated hBN-encapsulated bilayer MoS_2 devices of outstanding quality, showing a high electron mobility of 24000 cm^2/(V·s) at 1.2 K and quantized Hall resistance plateaus in high magnetic fields. Shubnikov-de Haas (SdH) oscillations were observed down to a filling factor ν (the number of occupied Landau level) of $\nu = 2$. In the density-field mapping of the SdH oscillations (Figure 1a), Landau-level (LL) crossings were observed at different carrier densities, and can be explained by a density-dependent interaction-enhanced effective g-factor g*. The giant g* gives a large Zeeman-to-cyclotron energy ratio E_z/E_c which leads to a spin-polarized transport regime. From the filling factor sequence in the mapping, we determined the dependence of g* on carrier density n (Figure 1b).

In higher magnetic fields, anticrossings were found near integer ratios of E_z/E_c where the LLs of opposite spins come close in energy (Figure 2). This may indicate a strongly interacting quantum Hall ferromagnetic behavior. Both the density-dependent g-factor and the LL anticrossings point to a strong electron-electron interaction scenario in MoS_2.

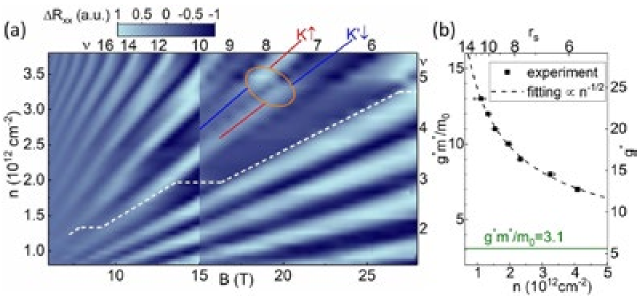


Figure 1: (a) Density-field mapping of the SdH oscillations. Filling factors are marked along the right and top edges. Red and blue lines mark one pair of spin-up and -down LLs. Crossings (orange oval) between LLs of opposite spins are due to the density-dependent E_z/E_c ratio. The white dashed line marks the upper boundary of the low-lying polarized LLs. (b) Density-dependent interaction-enhanced spin susceptibility extracted from (a).

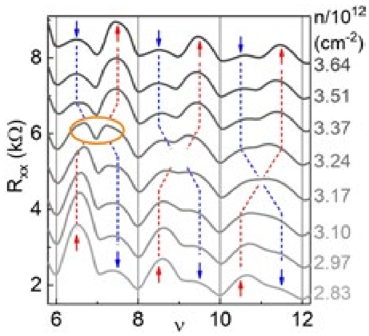


Figure 2: Waterfall plot of SdH oscillations at different density n near integer E_z/E_c. An obvious anticrossing gap at $\nu = 7$ is marked by the orange oval.

Probing Landau levels of strongly interacting massive Dirac electrons in layer-polarized MoS_2, J. Lin, T. Han, B. A. Piot, Z. Wu, S. Xu, G. Long, L. An, P. K. M. Cheung, P-P. Zheng, P. Plochocka, D. K. Maude, F. Zhang, and N. Wang, arXiv:1803.08007 (2018). Under review.

Contact: benjamin.piot@lncmi.cnrs.fr, phwang@ust.hk

RESULTS OF THE NINETEENTH CALL FOR ACCESS

On November 16th, 2018, the 20th call for access ended inviting proposals for research requiring access to the large installations for high magnetic fields collaborating within EMFL.

Our four facilities

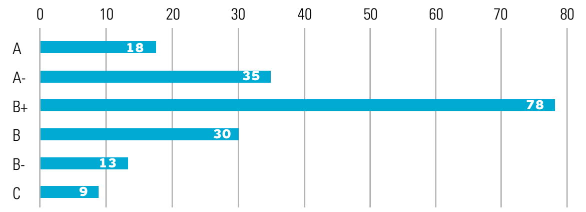
- LNCMI - Grenoble - France: Static magnetic fields to 37 T
- HFML - Nijmegen - the Netherlands: Static magnetic fields to 38 T
- HLD - Dresden - Germany: Pulsed magnetic fields up to 95 T
- LNCMI - Toulouse - France: Pulsed magnetic fields of long duration up to 99 T and on the microsecond scale up to 200 T

are open to users worldwide. EMFL operates a joint transnational access program, which gives full access to these installations and all associated scientific infrastructure to qualified external users, together with the necessary support from the scientific and technical staff.

For this 20th call 183 applications from 28 different countries were received which have been evaluated by the EMFL selection committee until December 17th, 2018. The Selection Committee consists of 18 specialists covering the following five types of scientific topics

- Metals and Superconductors (47 applications),
- Magnetism (64 applications),
- Semiconductors (54 applications),
- Soft Matter and Magnetoscience (13 applications),
- Applied Superconductivity (5 applications),

Besides of ranking the proposals the committee decides on the number of accepted magnet hours or number of pulses.



Evaluation of applications

Projects are classified in three classes:

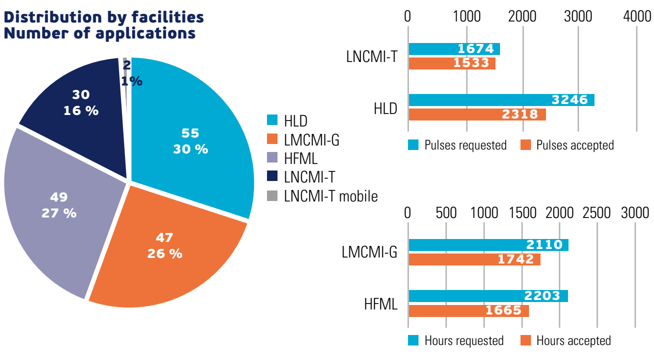
A (excellent proposal to be carried out),

B (should be performed but each facility has some freedom considering other constraints),

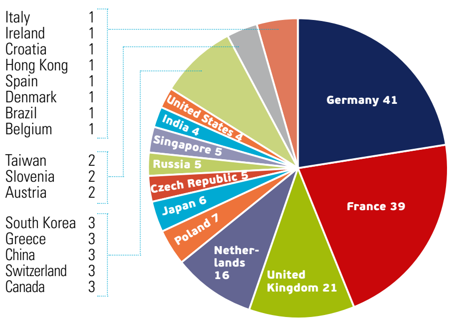
C (poor proposal or one that does not need any of the four unique high-magnetic-field laboratories).

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.

Distribution by facilities
Number of applications



Distribution by countries
Number of applicants



NEXT CALL :
Launch: April 15, 2019
Deadline: May 15, 2019

REPORT FROM THE ANNUAL EMFL USER COMMITTEE MEETING - NIJMEGEN 21ST JUNE 2018

The EMFL User Committee meeting was held on the 21st June 2018 at the EMFL facility Nijmegen (HFML) as part of the annual EMFL User Meeting. Five of the nine members of the User Committee (R. Stern, M. Doerr, A. Arora, S. Tozer, V. Skumryev) and a number of 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, no changes compared to 2017. With the user community of EMFL steadily growing, the new User Committee repeats their request for a renewed, much stronger mandate to represent the interests of the high-field users better. To allow users a more effective facility use and to advise the Directors on all issues affecting users of the facilities the User Committee needs access to more detailed information about the weaknesses and plans at the laboratories and, in particular, on informative user feedback, infrastructure improvements such as probe development (e.g. transport probes), new capabilities (e.g. FIB, high pressure, dilution-refrigerator temperatures, etc.), and available magnets and magnet construction schedules.

User feedback

Following earlier recommendations of the User Committee, the EMFL has in use an **online user feedback form** for all the laboratories of the EMFL. This year this has facilitated a largest number (20) of users providing feedback and comments on their experience at the installations of the EMFL, which is still only a small fraction of the total number of users/visitors. To further improve the amount and quality of feedback forms, the User Committee has requested:

a. all EMFL facilities to stimulate the users to provide constructive feedback to the User Committee;
b. to implement a feedback-request procedure with reminders within the next 6 months.
c. to make the comment fields mandatory, since plain grades give only very rough feedback.
d. to send the feedback form out automatically toward the end of the user's magnet time so that any issues are fresh in their mind.
e. A revised and improved feedback form should include additional questions centered on scheduling experiments with the local contacts and assignment of magnet time.

Other open issues

There were open data strategy and online safety regulations and trainings addressed. To attract new users and help them to design their experiment, an even better overview of the "instrumentation highlights" for participating labs should be available. There is a need for part-week test experiments and/or for testing new perspective samples in advance of full proposals. The user community is also concerned about a shortage of "workhorse" equipment and magnets. Having not only backup workhorse magnets, but fully built up magnet cells in the event of failure would make the best of the users time. It would also be useful to have dedicated magnets for some experimental methods.

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 2015, the UK has officially become a member of the EMFL with the support (2015-20) of EPSRC, the UK's main agency for funding research in engineering and the physical sciences. Other users from other countries (in particular Spain, Poland (s. page 10), and Estonia) should engage with their national research councils to discuss joining the EMFL 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, THz spectroscopy in high magnetic fields, NMR in pulsed magnets, and research in topical areas ranging from topological phosphides to halide perovskites and novel material systems of fundamental and technological interest. The user community received this rich program very well.

AN ULTRA-COMPACT LOW-TEMPERATURE SCANNING PROBE MICROSCOPE FOR MAGNETIC FIELDS ABOVE 30 T

Lisa Rossi, Lijnis Nelemans, Ben Bryant, HFML Nijmegen

Together with technicians and scientists from HFML Nijmegen, PhD student Lisa Rossi designed and built a scanning probe microscope (SPM) for operation at cryogenic temperatures in extremely high magnetic fields. It is the only one in the world that can measure in fields above 30 Tesla. Moreover, it is very compact, only 14 x 76 millimeter. Rossi: "With this SPM we can have a much better look at what happens with matter in high fields. But is has been a challenge. For instance: an SPM does not function well with noise. Therefore, we had to think for a solution for the noise the magnet makes. In addition, the instrument should be able to oscillate a bit, so we needed room. But you still have to be able to put it inside a magnet. So every millimeter counts."

Until now, the maximum field for scanning probe microscopy has been limited to 20 T. This leaves many field-induced phase transitions of materials out of reach. Rossi: "I made this because scanning probe microscopy is one of the best techniques to analyze 'hidden structures' in materials and the technique behind it is fascinating. A tip, connected to a lever that oscillates close to its resonance frequency, scans the surface of your sample. We try to keep the frequency or the amplitude of the oscillation constant, but the interaction of the atomic forces between tip and sample causes the amplitude or the frequency of the cantilever's oscillation to change. We translate this effect in an image of the surface. There are of course different kind of forces that can play a role in these kind of measurements, and with some variation on the technique, we can 'paint' all the different stories that the surface of the sample wants to tell."

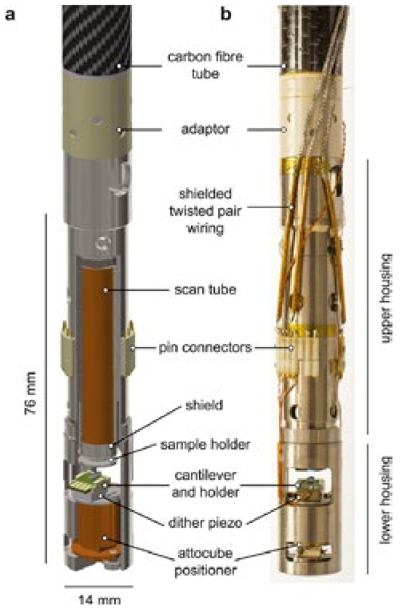


Figure 1: (a) Diagram and (b) image of the HF-SPM head, with the main components indicated.

An ultra-compact low temperature scanning probe microscope for magnetic fields above 30 T, L. Rossi, J. W. Gerritsen, L. Nelemans, A. A. Khajetoorians, and B. Bryant, Rev. Sci. Instrum. **89**, 113706 (2018).

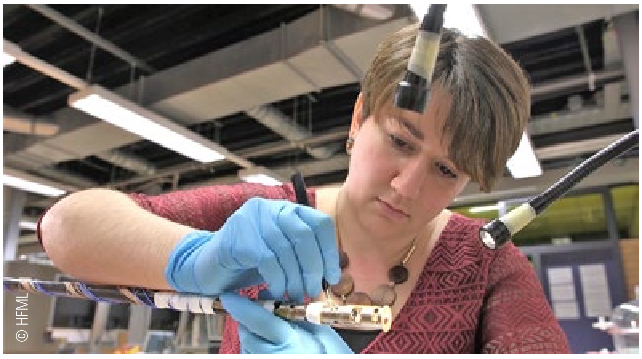


Figure 2: Rossi working on the scanning probe microscope.

POLAND NEWEST MEMBER OF THE EUROPEAN MAGNETIC FIELD LABORATORY

The Ministry of Science and Higher Education in Poland has awarded funding to the University of Warsaw to secure access to the European Magnetic Field Laboratory (EMFL) for the Polish user community.

The other members of the EMFL are the French Centre National de la Recherche Scientifique, with sites in Grenoble and Toulouse, the Dutch Radboud University/NWO in Nijmegen, the German Helmholtz-Zentrum Dresden-Rossendorf and the University of Nottingham representing the UK research community.

University of Warsaw

The EMFL was formally founded in January 2015 with support from the European Community through the ESRFI Roadmap. It aims to develop and operate world class high magnetic fields – both continuous and pulsed - and to use them for excellent research by both 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 University of Warsaw will represent Poland in the EMFL for a duration of five years, starting from 1st of January 2019. The membership enables Polish users access to all the EMFL installations and measurement techniques, expert support from local staff members, as well as funding for travel and subsistence.

Prof. Adam Babiński (University of Warsaw): "The continuous involvement of Polish researchers in high-magnetic-field studies has been substantially supported by the Ministry of Science and Higher Education of Poland. The grant from the Ministry, which is managed by the University of Warsaw, allows Poland to join EMFL as a member. We believe that this will significantly support the Polish high-field research community as it opens new perspectives for co-operation within this unique European infrastructure. We expect that our contribution is also a benefit for EMFL, as we add new people and ideas. It confirms the significance of research in high magnetic fields in creation of the European Research Area."

Wosnitza: "Our scientific collaboration with the Polish user community has always been very strong. This grant from the Polish ministry and the EMFL membership is a reward for our longstanding relationship and scientific achievements."

Prof. Adam Babiński will be representing the Polish community including the University of Warsaw and indirectly the Polish Ministry for Science and Higher Education, and will be participating in the EMFL Council meetings.

UPCOMING EVENTS

1. APS March Meeting, Boston, USA, March 4-8, 2019.
https://www.aps.org/meetings/march/

2. Gordon Research Conference: Superconducting Materials and Phenomena, Les Diablerets, Switzerland, May 12-17, 2019.
https://www.grc.org/superconductivity-conference/2019/

3. Superstripes 2019, Ischia, Italy, June 23-29, 2019.
https://www.superstripes.net/

4. Joint European Magnetic Symposia (JEMS) 2019, Uppsala, Sweden, August 26-30, 2019.
https://jems2019.se/

5. IRMMW-THz 2019, 44th International Conference on Infrared, Millimeter, and Terahertz Waves, Paris, France, September 1-6, 2019.
https://irmmw-thz2019.org/

6. EASTMAG-2019, VII Euro-Asian Symposium "Trends in Magnetism", Ekaterinenburg, Russia, September 8-13, 2019
http://eastmag2019.imp.uran.ru/

7. MT26, International Conference on Magnet Technology, Vancouver, Canada, September 22-27, 2019.
http://mt26.triumf.ca/

8. SCES 2019, International Conference of Strongly Correlated Electron Systems, Okayama, Japan, Sep. 23-28, 2019.
http://sces2019.org

9. EMFL 2019 User Meeting, Poland, June, details to be announced

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European Magnetic Field Laboratory

HFML
Radboud Universiteit Nijmegen
Toernooiveld 7
6525 ED Nijmegen
The Netherlands
www.ru.nl/hfml

CNRS – Centre National de la Recherche Scientifique
3, rue Michel-Ange
75794 Paris cedex 16
France
www.lncmi.cnrs.fr

LNCMI Toulouse
143 avenue de Rangueil
31400 Toulouse
France

LNCMI Grenoble
25 rue des Martyrs, B.P. 166
38042 Grenoble cedex 9
France

Helmholtz-Zentrum Dresden-Rossendorf (HZDR)
Dresden High Magnetic Field Laboratory
Bautzner Landstrasse 400
01328 Dresden
Germany
www.hzdr.de/hld

IMPRINT

Publisher / Contact:
Helmholtz-Zentrum Dresden-Rossendorf
Caroline Obermeyer
Phone: +49 351 - 260 2062
Email: c.obermeyer@hzdr.de
contact@emfl.eu

Editorial Staff:
EMFL Board of Directors, Christine Bohnet, Martin van Breukelen, Caroline Obermeyer, Benjamin Piot

Responsible for the content:
Peter Christianen (peter.christianen@ru.nl),
Geert Rikken (geert.rikken@lncmi.cnrs.fr),
Joachim Wosnitza (j.wosnitza@hzdr.de)

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