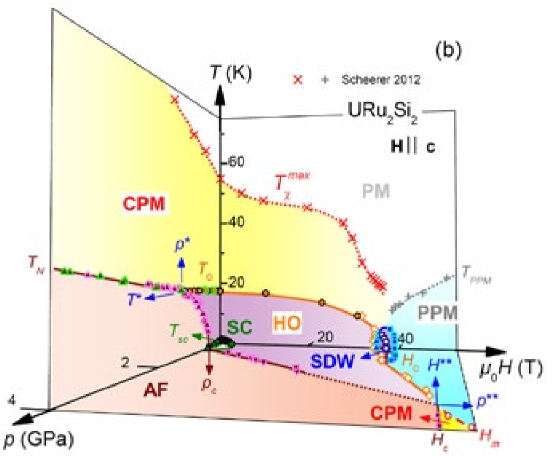
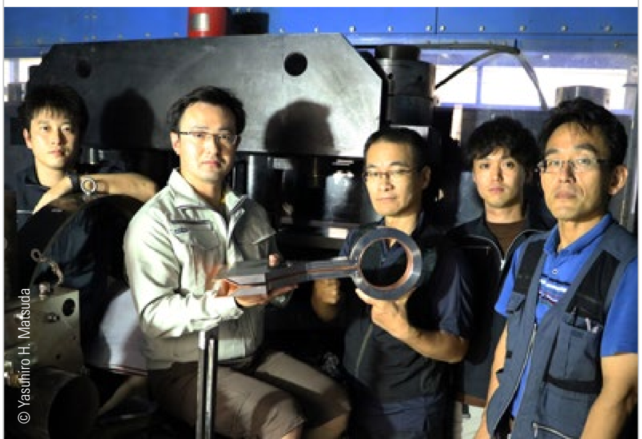
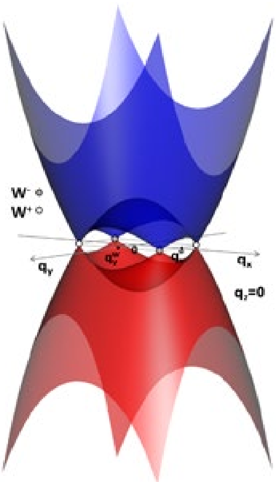
European Magnetic Field Laboratory

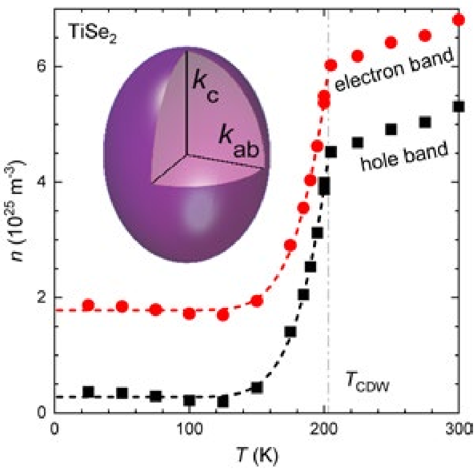
EMFLNEWS

N°2 2020









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DEAR READER

The previous EMFL News came to you in the middle of the COVID-19 crisis, and all EMFL facilities were either completely stopped, or could not receive external users. Some user experiments still have been performed, with mailed-in samples, and real-time online presence of the user, but in most cases this cannot replace an on-site experiment.

I am happy to tell you that now all sites have resumed user operation. There are still some restrictions on the number of people allowed on-site, but we can once again host external users. Only international travel restrictions may still pose problems for some of you when coming to the EMFL sites. All our staff is working hard to cope with the backlog of user proposals that were canceled or rescheduled, and we ask for your understanding if your experiment cannot be performed at the time that would suit you best. In order to help solving this backlog problem, our selection committee has been particularly attentive to the urgency aspects of the proposals of the last call.

Take good care of yourselves and your family and friends, and we hope to see you again soon in one of our EMFL facilities.

Geert Rikken, Director LNCMI, Chairman EMFL

MEET OUR PEOPLE

Caitlin Duffy, HFML Nijmegen

I started last October with my PhD work in Nijmegen, in the group of Nigel Hussey. My research is focussing on the quantum critical point in thin-film cuprates, in the hope they reveal information that tell us more about high-temperature superconductivity. For part of my PhD, I intend to use high fields and the intense THz laser from the FELIX Laboratory to break Cooper pairs. The combination experiments will be challenging, but I like a challenge.

I studied Physics at the University of St Andrews. For my Masters, I looked into the charge density wave in 1T-$TiSe_2$ and the fabrication of a novel STM sample holder. I like the open atmosphere at HFML and in my group. I haven't been to the other labs and with the current situation it might take a while, but I would like to visit for example the pulsed-field lab in Toulouse. And hopefully I will meet many EMFL postdocs and PhD students at the EMFL school or hands-on workshop when it is possible again.

Caitlin Duffy, HFML Nijmegen

RECONSTRUCTED FERMI SURFACE IN THE CHARGE-DENSITY-WAVE STATE OF $TiSe_2$

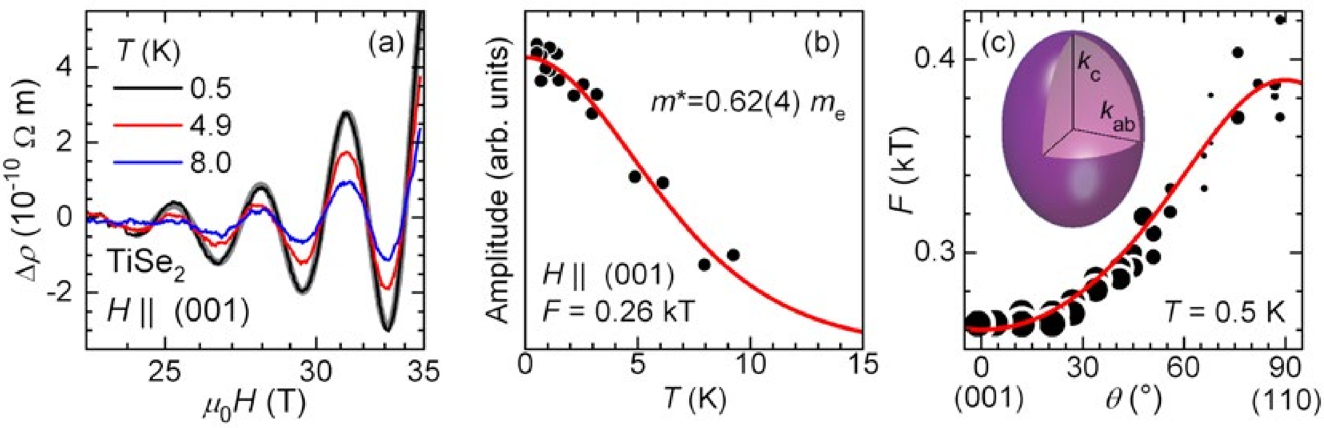
Owen Moulding and Sven Friedemann, University of Bristol

$TiSe_2$ features a charge density wave (CDW) driven by condensation of excitons, i.e., pairs of electrons and holes, alongside electron-phonon coupling. The CDW transition at 202 K gaps out most of the Fermi surface. Quantum-oscillation measurements at the HFML Nijmegen provide a clear view of the newly formed Fermi surface inside the CDW state.

Above the CDW transition, the Fermi surface consists of a hole-like cylindrical pocket and an electron-like distorted and tilted ellipsoidal pocket. The formation of electron-hole pairs gaps out the complete hole pocket but leaves a small part of the electron states. Indeed, our quantum-oscillation measurements show that the low-temperature state contains a single electron-like ellipsoid without tilt.

Identifying the size and shape of the Fermi surface was done with angular-dependent measurements in magnetic fields up to 35 T and using a rotator probe inside a 3-He cryostat at the HFML, Nijmegen. The increase of the quantum-oscillation frequency shows that the Fermi surface is approximately ellipsoid, and the semi-axes have been extracted from the data (Figure). Together with the effective mass determined from the temperature dependence of the quantum-oscillation amplitude, this allows detailed comparison with specific heat, ARPES, and our 2-band transport analysis which shows that this is the only pocket.

This knowledge of the Fermi surface of $TiSe_2$ enabled a study across the Fermi-surface reconstruction at the CDW transition. The team of Dr. Friedemann analyzed magnetoresistance and Hall resistivity measurements performed at the University of Bristol to trace the elimination of the hole pocket and the shrinkage of the electron pocket. They found that electron scattering is maximum right at the CDW transition and, thus, probably driven by the CDW fluctuations and highlights that the CDW is dominating the electronic properties of $TiSe_2$.



Fermi Surface Reconstruction and Electron Dynamics at the Charge-Density-Wave Transition in $TiSe_2$, P. Knowles, B. Yang, T. Muramatsu, O. Moulding, J. Buhot, C. J. Sayers, E. Da Como, and S. Friedemann, Phys. Rev. Lett. **124**, 167602 (2020).

Figure: Highest resolution in the quantum oscillations measurements were realized with samples optimized for large resistance signal and using low-noise transformers. (a) The oscillations show a single frequency in $TiSe_2$ at lowest temperatures. (b) From the temperature dependence of the amplitude the effective electron mass was extracted. (c) The angular dependence of the quantum-oscillation frequency is fitted by an ellipsoid model (red line).

Contact: sven.friedemann@bristol.ac.uk

BEYOND THE CONICAL BAND APPROXIMATION OF A WEYL SEMIMETAL

A. Akrap, University of Fribourg, A. V. Pronin, Universität Stuttgart, and M. Orlita, LNCMI-Grenoble

Experiments have demonstrated many gapless electronic phases with conical bands. These phases exist within diverse classes of systems comprising graphene and many different topological materials. Low-energy excitations in such conical bands somewhat resemble truly relativistic particles. This resemblance creates a non-trivial analogy between two branches of modern physics that were only loosely connected before. Thereby, condensed-matter physicists can now explore low-energy phenomena which were previously thought to happen only in high-energy physics.

The conical bands appear at specific locations in the Brillouin zone, where two or more bands cross each other. These crossings represent only a small part of the whole Brillouin zone. The particular properties of conical bands such as their position, degeneracy, tilt, anisotropy or the departure from linearity are closely related to the crystal symmetry and overall characteristics of the momentum-periodic band structure. Conversely, the presence of the valley-degenerated conical bands means that other features, typical for Lifshitz transitions, such as local extrema or saddle points of merging cones, will also show up.

Three-dimensional Weyl semimetals from the monopnictide family (TaAs, NbAs, TaP, and NbP) are representative examples of materials which are extensively explored today and which display multiple valley-degenerated conical bands in their band structures. In these materials, the Weyl cones emerge in quartets, due to the complex interplay of band inversion appearing at certain positions of the Brillouin zone with spin-orbit interaction. This necessarily leads to the local extrema of bands, and two types of saddle points as illustrated in the Figure, panel (a).

Recent high-field experiments on tantalum phosphide, realized in a broad collaboration of researchers from Stuttgart, Grenoble, Paris, Dresden, and Fribourg, and supported by theoretical modelling, show that such specific features in the band structure can be traced via their characteristic magneto-optical response (Figure, panel b). Most notably, the band inversion, leading to the appearance of the local extrema, is found to be responsible for a highly unusual series of inter-Landau-level excitations, which decrease their energy with increasing magnetic field.

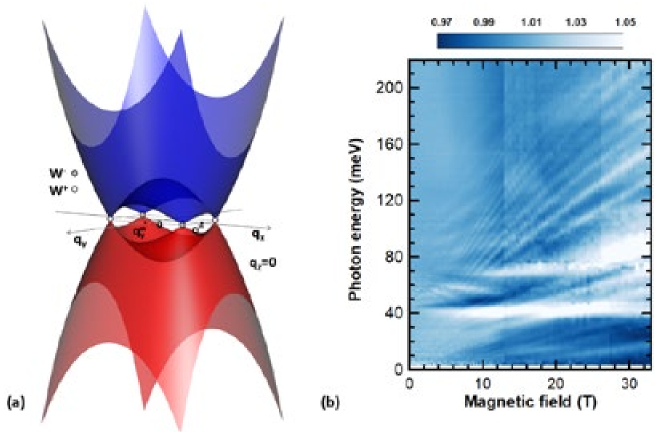


Figure: (a) Band structure of a time-reversal-invariant Weyl semimetal displaying a quartet of cones. (b) Infrared magneto-reflectance of the Weyl semimetal TaP in high magnetic fields.

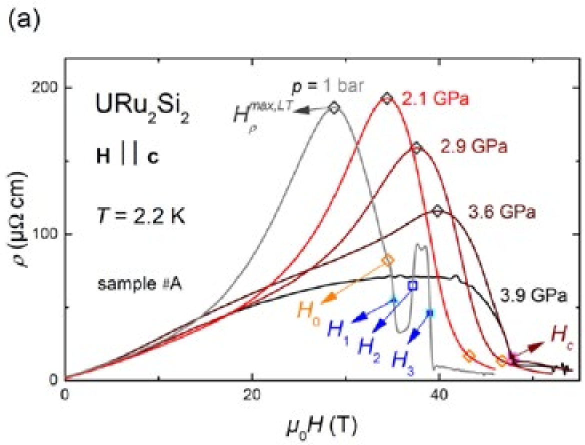
Magneto-Optics of a Weyl Semimetal beyond the Conical Band Approximation: Case Study of TaP, S. Polatkan, M. O. Goerbig, J. Wyzula, R. Kemmler, L. Z. Maulana, B. A. Piot, I. Crassee, A. Akrap, C. Shekhar, C. Felser, M. Dressel, A. V. Pronin, and M. Orlita, Phys. Rev. Lett. **124**, 176402 (2020).

Contact: Milan.Orlita@lncmi.cnrs.fr

SQUEEZING OUT FIELD-INDUCED REENTRANT HIDDEN-ORDER IN URu_2Si_2

William Knafo, LNCMI-Toulouse, Shingo Araki, Okayama University, and Daniel Braithwaite, CEA-Grenoble

The mystery of the hidden-order (HO) phase in the correlated electron paramagnet URu_2Si_2 is still unsolved. To address this problem, one strategy is to search for clues in the subtle competition between this state and neighboring magnetically ordered states. It is now well established that long-range antiferromagnetic order can be stabilized in this metal when it is under pressure and that a spin density wave manifests itself when a magnetic field is applied along the easy magnetic axis c. However, the complete boundaries of the HO phase in the pressure-magnetic-field plane of the phase diagram have not been determined so far. In this work, we have extracted the three-dimensional magnetic-field-pressure-temperature phase diagram of URu_2Si_2. Its magnetoresistivity was measured in magnetic fields up to 60 T combined with pressures up to 4 GPa. We find a rich phase diagram indicating a subtle competition between the different types of electronic interactions. The main features are the disappearance of the field-induced spin-density-wave phase and a squeezing out of the HO phase under high pressure. We emphasize that many of the boundaries of the 3D phase diagram are controlled by the field and pressure dependences of a single parameter characterizing the electronic correlations. This gives new constraints for theories that model the electronic correlations and ordered phases in URu_2Si_2.



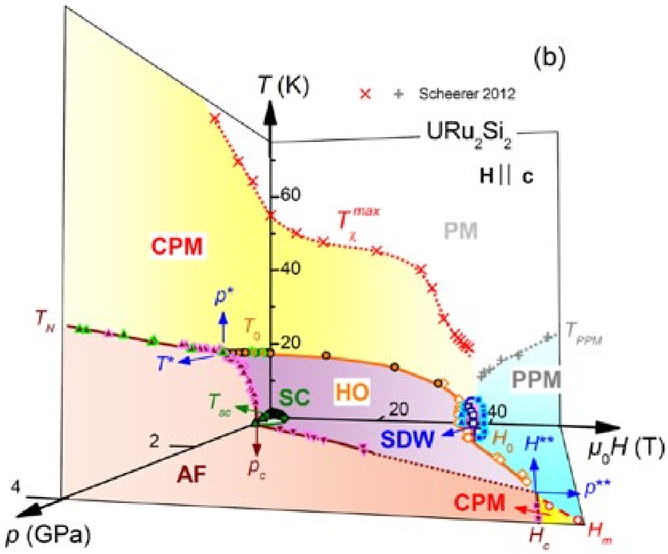


Figure: (a) Low-temperature electrical resistivity versus magnetic field and (b) three-dimensional phase diagram of URu_2Si_2 under pressure and magnetic field applied along c.

Destabilization of hidden order in URu_2Si_2 under magnetic field and pressure, W. Knafo, S. Araki, G. Lapertot, D. Aoki, G. Knebel, and D. Braithwaite, Nat. Phys. (2020), in press; https://doi.org/10.1038/s41567-020-0927-4.

Contact: william.knafo@lncmi.cnrs.fr
araki@science.okayama-u.ac.jp, daniel.braithwaite@cea.fr

NATURE OF MAGNETIC EXCITATIONS IN THE HIGH-FIELD PHASE OF α-$RuCl_3$

Sergei Zvyagin, HLD Dresden

Spin systems with honeycomb structures are attracting a great deal of attention, in particular in connection with the famous Kitaev-Heisenberg model. This model predicts a variety of magnetic phases, ranging from the conventional Néel state to a quantum spin liquid, with the spin dynamics determined by spin-flip excitations fractionalized into gapped flux and gapless Majorana fermion excitations.

α-$RuCl_3$ has been proposed as one of the prime candidates to test this model. One striking peculiarity of the spin dynamics in α-$RuCl_3$ is the presence of a broad excitation continuum, which was interpreted as a potential signature of fractionalized Majorana excitations. Apart from that, a very rich excitation spectrum was revealed in the field-induced, magnetically disordered phase below the continuum, whose identification has remained an open question. In particular, it was unclear whether the observed excitations correspond to bound magnons or to bound Majorana spinons and, for the latter case, whether the spinons are confined or simply bound.

In cooperation with our partners from Oak Ridge, USA, we performed comprehensive electron spin resonance (ESR) studies of high-quality in-plane oriented single crystals of α-$RuCl_3$ at HLD, focusing on its high-field spin dynamics. Combining our findings with recent inelastic neutron- and Raman-scattering data, we identified most of the observed excitations (Figure). Most importantly, we obtained firm evidence that the low-temperature high-field ESR response is dominated by single- and two-particle processes with magnons as elementary excitations.

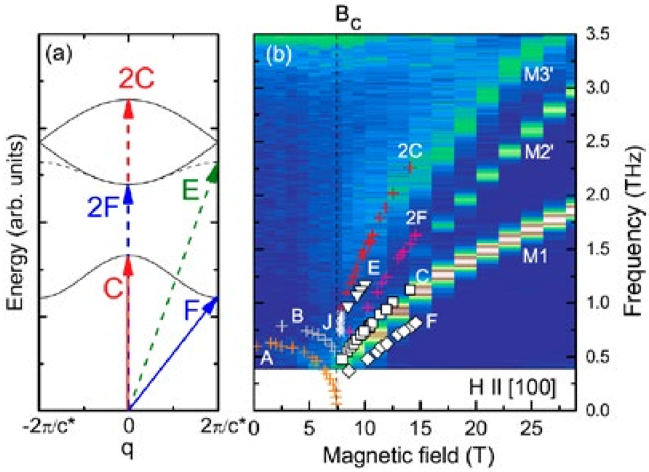


Figure: (a) Schematic energy diagram for α-$RuCl_3$ in an arbitrary magnetic field above the critical field B_c. The modes C and F are single-magnon excitations, while the modes 2C and 2F correspond to two-magnon excitations. The mode E corresponds to an excitation of a two-magnon bound state. (b) Frequency-field dependences of selected ESR modes and the color contour plot of the high-field Raman scattering intensity (latter data are from D. Wulferding et al., Nat. Commun. **30**, 1603 (2020); work done at LNCMI-Grenoble).

Nature of magnetic excitations in the high-field phase of α-$RuCl_3$, A. N. Ponomaryov, L. Zviagina, J. Wosnitza, P. Lampen-Kelley, A. Banerjee, J.-Q. Yan, C. A. Bridges, D. G. Mandrus, S. E. Nagler, and S. A. Zvyagin, Phys. Rev. Lett. **125**, 037202 (2020).

Contact: s.zvyagin@hzdr.de

RESULTS OF THE TWENTY-THIRD CALL FOR ACCESS

On May 15th, 2020, the 23rd call for access ended. Proposals for research activities requiring access to the large-scale high magnetic field facilities collaborating within EMFL were submitted to be ranked on a competitive basis.

Our four facilities

- LNCMI - Grenoble - France: Static magnetic fields to 36 T
- HFML - Nijmegen - the Netherlands: Static magnetic fields to 37.5 T
- HLD - Dresden - Germany: Pulsed magnetic fields to beyond 95 T
- LNCMI - Toulouse - France: Pulsed magnetic fields of long duration to over 90 T, and on the microsecond scale to beyond 180 T

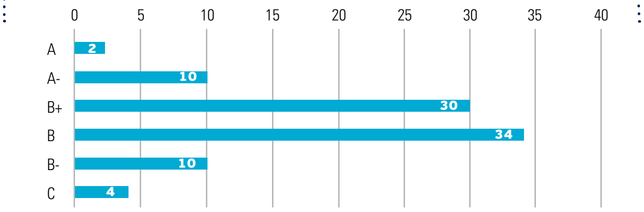
are open to users worldwide. EMFL operates a joint transnational access program, which grants full access to these installations and all associated scientific infrastructure to qualified external users, together with the necessary support from the scientific and technical staff on site.

For this 23rd call, 90 applications were submitted, only about half the number we regularly received in pre-COVID-19 times. The proposals came from 15 different countries and were evaluated by the EMFL selection committee until June 15th, 2020. The Selection Committee consists of 18 specialists covering the following five scientific topics:

- Metals and Superconductors (32 applications),
- Magnetism (33 applications),
- Semiconductors (20 applications),
- Soft Matter and Magnetoscience (3 applications),
- Applied Superconductivity (2 applications).

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

NEXT CALL :
Launch: October 15th, 2020
Deadline: November 15th, 2020



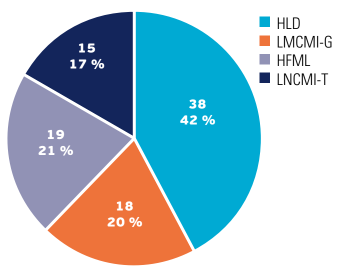
Evaluation of applications

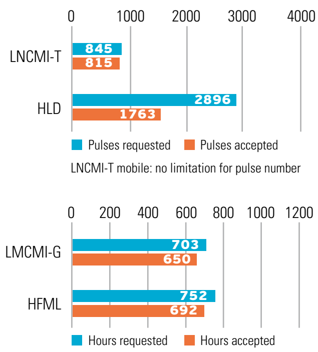
The proposals are ranked in three classes:

A (excellent proposal to be carried out),
B (should be performed but each facility has some freedom considering other constraints),
C (poorly crafted proposal, or one that does not need any of the four unique high-magnetic-field laboratories).

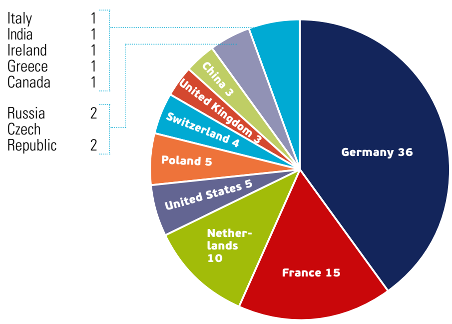
In the B category, the ranking + or - serves as a recommendation to the facility. This degree of freedom is necessary to allow the facilities to consider other aspects such as available capacity and equipment necessary for the successful outcome of a project.

Distribution by facilities
Number of applications





Distribution by country of PI affiliation



INVITATION TO "1000 T SCIENCE"

Yasuhiro H. Matsuda, IMGSL-ISSP Kashiwa, University of Tokyo

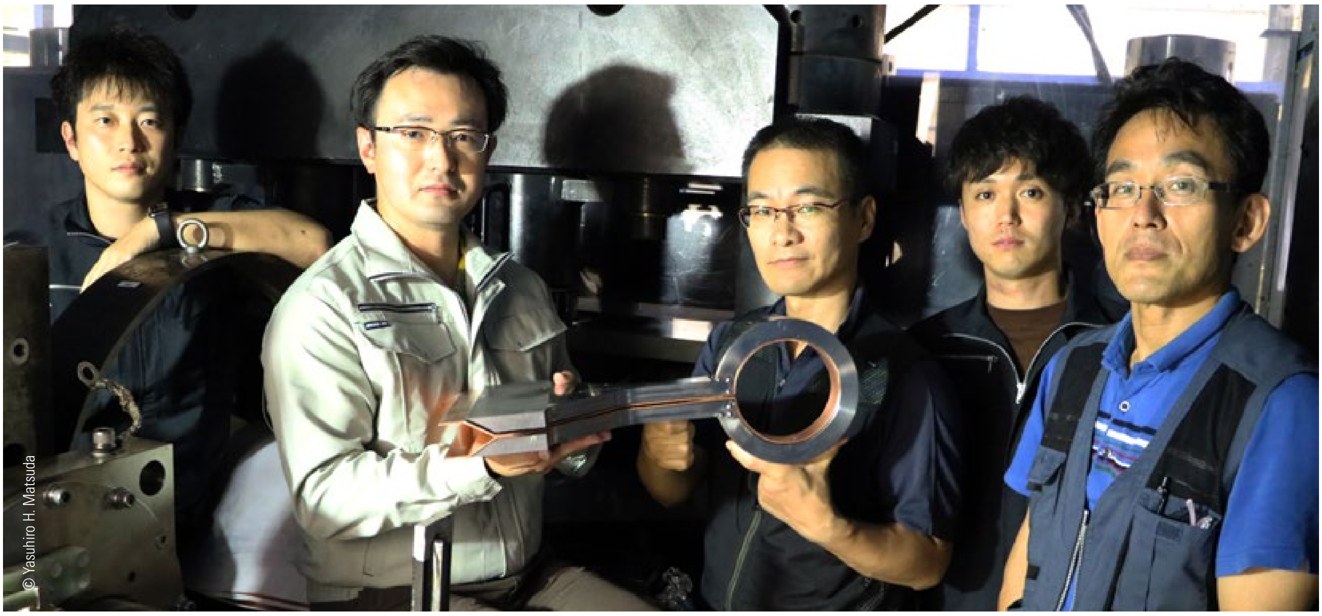
40 years ago, Prof. Chikazumi launched a project to realize extremely high magnetic fields by using electromagnetic flux compression (EMFC) at ISSP, and the project was taken over by Profs. Miura and Takayama. In 2018, a magnetic field of 1200 T was produced using EMFC pushing the frontiers of science (see also [1,2]). By producing 1000 T in an indoor experimental environment, several kinds of precision measurements have become possible even in this ultrahigh field range.

The multi-megagauss field research offers opportunities to challenge many intriguing physical topics, including (i) the full spin control of strongly correlated electrons, (ii) research on the low-temperature normal-state nature of high-T_c superconductors, (iii) investigation of effects of wave-function shrinkage on molecules and atoms, and (iv) the study of quantum spin physics with strong interactions. In relation to (i), we recently found a novel field-induced insulator-metal transition in W-doped VO_2 at 500 T [3]. We may also find further intriguing topics in interdisciplinary areas collaborating with chemists, biologists, or astrophysicists.

To explore and develop ultrahigh magnetic field science, we are delighted to collaborate with researchers in the user community of the European Magnetic Field Facility who are interested in the 1000 T environment. We like to discuss possible collaboration with those who have specific ideas for ultrahigh fields exceeding 300 T, which cannot be reached by the single-turn coil technique. Moreover, we are seeking to deepen the cooperation of ISSP with EMFL in a more formal way.

[1] **Record indoor magnetic field of 1200 T generated by electromagnetic flux-compression**, D. Nakamura et al, Rev. Sci. Instrum. **89**, 095106 (2018).
[2] **Magnetic phases of a highly frustrated magnet, $ZnCr_2O_4$, up to an ultrahigh magnetic field of 600 T**, A. Miyata et al., Phys. Rev. Lett. **107**, 207203 (2011).
[3] **Magnetic-field-induced insulator-metal transition in W-doped VO_2 at 500 T**, Y. H. Matsuda et al., Nat. Commun. **11**, 3591 (2020).

Contact: IMGSL-ISSP (http://www.issp.u-tokyo.ac.jp/labs/mgsl/index.html)



EMFC instrument at ISSP with responsible staff members.

NATIONAL ROADMAP GRANT FOR HFML-FELIX

HFML-FELIX has been awarded 15.1 million euros for the development of advanced instrumentation and new experimental techniques. The grant is part of the National Roadmap for Large-Scale Research Facilities of the Dutch Research Council (NWO) which enables the building or renovation of research facilities with international allure.

HFML-FELIX represents a world-unique research infrastructure in the Netherlands, working at the forefront in science and technology with respect to magnets and free-electron lasers. It serves as an open-access, international user facility, which hosts more than 500 guest researchers per year. Then again, HFML itself is one of the three European Magnetic Field Laboratories, joined in EMFL.

The awarded grant is dedicated to the development and exploitation of the facility (jointly operated by the Radboud University and NWO) as well as to develop experimental infrastructure and new instrumentation. The work will be executed in close collaboration with several partners from Dutch universities, institutes, companies, and hospitals.

Peter Christianen (director HFML): "We are delighted to have received this grant, which allows us to further develop pioneering technology and instrumentation. The innovative equipment will enable breakthroughs in a wide range of scientific domains and will contribute to solving societal challenges in the areas of Health, Energy, and Smart Materials. To give two examples: we will build instrumentation to image biomarkers in tissue to diagnose diseases and we will develop new experimental techniques aiming to reduce the energy required for magnetic data storage."

Britta Redlich (director FELIX): "These plans have been defined by identifying the most pressing requests from existing and prospective users to extend our experimental possibilities. In all projects, we work closely together with universities, institutes, companies, and medical centers across the country taking advantage of their expertise and experience in the corresponding areas. Ultimately, these developments will be opened to the research community worldwide."

FORMER PHD STUDENT OF HFML AWARDED EPSRC FELLOWSHIP

Experimental physicist Jake Ayres, a former PhD student at HFML, has been awarded a two-year fully funded EPSRC Doctoral Prize Fellowship to determine whether the elusive origin of high-temperature superconductivity can come from a newly revealed incoherent variety of electrons.

"Using the high fields at the HFML during my PhD, I found signs that there appear to be two 'varieties' of electrons in high-temperature superconductors. One type behaves as we would expect 'normal' electrons to behave in magnetic fields, but the other variety is very unusual and appears to be incoherent. It's potentially very exciting because understanding high-temperature superconductivity is a 30 year old problem and one that numerous Nobel prize winners have contributed towards. Incoherent transport and how it might be linked to high-temperature superconductivity is a new line of thinking. I hope the planned thermodynamic measurements will tell us something new and fundamental about the problem."

Ayres is now working as a postdoc in the group of Nigel Hussey at the University of Bristol, but he will be visiting Nijmegen frequently (when possible) to use thermodynamic measurements developed for high-field measurements at the HFML.

EPSRC Doctoral Prize Fellowship

The EPSRC fellowship supports recent PhD graduates' transition into early career research. It is for recently graduated or final-stage outstanding PhD researchers who have been funded by the Engineering and Physical Sciences Research Council (EPSRC) for their research. They can launch their research career in a supportive environment. Doctoral Prize Fellows propose their own bespoke program to conduct innovative, ground-breaking research.

EMFL PRIZE WINNER 2020: ZHE WANG

Due to the Corona pandemic, this year´s EMFL award ceremony took place less festive as usual. This time, Dr. Zhe Wang, junior group leader at the University of Cologne, had the honor to receive the prize. Due to the unusual circumstances, Jochen Wosnitza, Director of the Dresden High Magnetic Field Laboratory and chair of the prize committee, was forced to hand over the award via mail.

Dr. Zhe Wang received the award for his pioneering work in the field of quantum magnetism, in particular for the experimental detection of Bethe strings using terahertz spectroscopy at very high magnetic fields.

The German Physical Society had previously nominated him as laureate for the Walter Schottky prize 2020 for his contributions to the field of solid-state physics. Due to the pandemic and oddly enough, this award ceremony got affected as well and had to be postponed to a later date.

Since 2009, the EMFL members award annually the EMFL prize for exceptional achievements in science done in high magnetic fields.

› The EMFL Prize winner 2020, Zhe Wang.

UPCOMING EVENTS

Due to the dynamics of the current situation, some of these conferences might get canceled in due course.

1. International Conference on Strongly Correlated Electron Systems (SCES 2020), Guarujá, Brazil, September 20-25, 2020. **POSTPONED**
https://sces2020.org/

2. 65th Annual Conference on Magnetism and Magnetic Materials, Palm Beach, USA, November 2-6, 2020. **VIRTUAL**
https://magnetism.org/

3. IRMMW-THz 2020, 45th International Conference on Infrared, Millimeter, and Terahertz Waves, Buffalo, USA, November 8-13, 2020. **VIRTUAL**
https://irmmw-thz.org/current-conference/home

4. Symposium „Materials for Extreme Conditions", 2020 MRS Fall Meeting & Exhibit, Boston, USA, November 28 – December 4, 2020.
https://www.mrs.org/meetings-events/fall-meetings-exhibits/2020-mrs-spring-and-fall-meeting/call-for-papers

5. International Conference on Magnetism (ICM), Shanghai, China, July 4-9, 2021.
http://www.icm2021.com/

6. MT27, International Conference on Magnet Technology, Fukuoka, Japan, November 15-19, 2021.
http://csj.or.jp/conference/MT27/

› Hakata Bay, Fukuoka, Japan.

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

Centre National de la Recherche Scientifique (CNRS)
LNCMI Toulouse
143 avenue de Rangueil
31400 Toulouse
France

Centre National de la Recherche Scientifique (CNRS)
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

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Helmholtz-Zentrum Dresden-Rossendorf
Bernd Schröder
Phone: +49 351 260-2711
Email: b.schroeder@hzdr.de
contact@emfl.eu

Editorial Staff:
EMFL Board of Directors, Christine Bohnet, Martin van Breukelen, Benjamin Piot, Bernd Schröder, Larysa Zviagina

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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