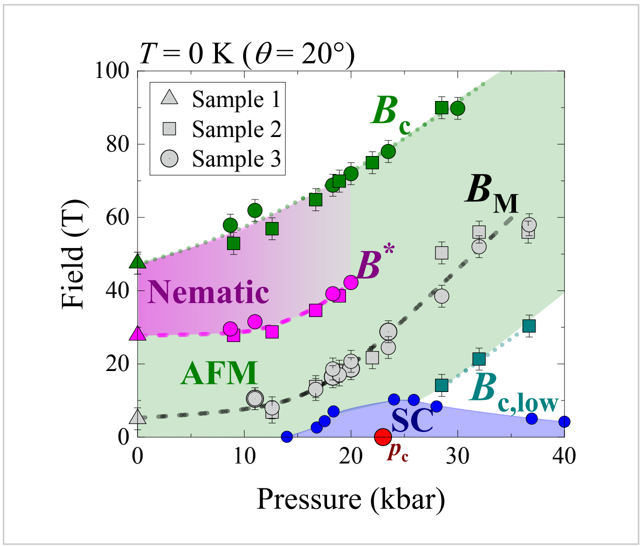
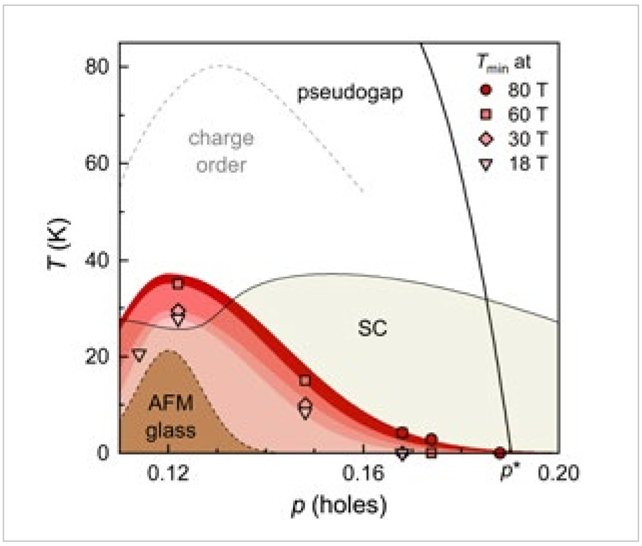
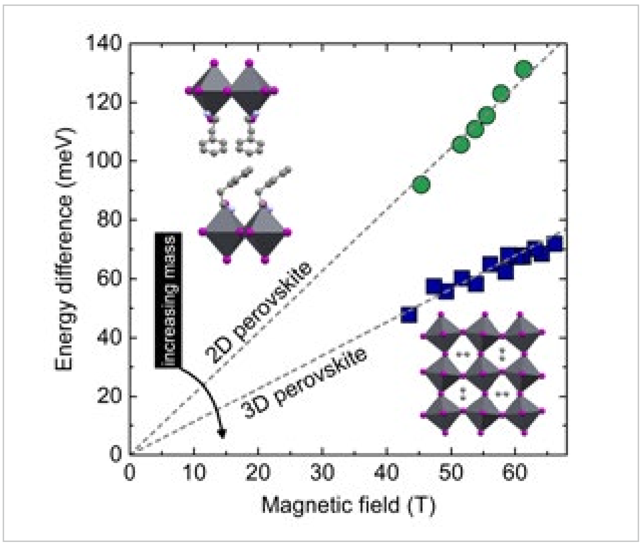
European Magnetic Field Laboratory

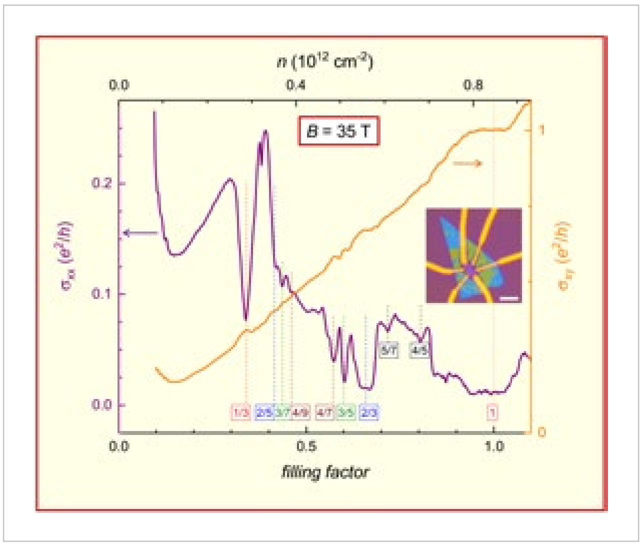
EMFLNEWS

N°3 2020









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DEAR READER

The previous EMFL News came to you just after the first COVID crisis, when things seemed to be returning to normal, and our greatest concern was handling the backlog of proposals that you could not carry out, so far. We have been working hard on that, but recently, the sanitary situation has started to degrade again, imposing new restrictions on the operation of our facilities and on international travel. We fear that even more severe restrictions may follow in the coming weeks.

Still, we issued our bi-annual call for proposals, and ask the principal investigators to explain the urgency of their proposal clearly, and to try to foresee its realization with mail-in samples. This puts extra strain on our staff, and cannot replace an on-site experience in all cases, but you will understand that these exceptional circumstances do not leave much alternative.

If you have any other questions concerning the EMFL user operation, please check the EMFL web site (www.emfl.eu) or contact the local contacts in the facilities.

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

Geert Rikken
Chairman EMFL

MEET OUR PEOPLE

Maurice Bal, HFML Nijmegen

I started with my PhD at HFML in September 2019, in the group of Uli Zeitler. I study the THz AC conductivity in semiconductors, while at the same time I develop an experimental setup that is capable of resistively detecting cyclotron resonances. Consequently, most of my work so far is related to optimizing the setup, both electrically as well as optically. The fact that the IR radiation of the FELIX Laboratory plays such a prominent role in my research makes it a challenging and interesting project, especially considering that the combination of static high magnetic fields and free-electron lasers is unique in the world.

In summer, I was looking forward to the EMFL hands-on workshop in Dresden, but unfortunately, it was cancelled in the wake of the COVID-19 pandemic. Hopefully, I can meet some of you in another way.

› Maurice Bal, HFML Nijmegen

FRACTIONAL QUANTUM HALL EFFECT IN CVD GRAPHENE

Uli Zeitler, HFML Nijmegen

The fractional quantum Hall effect (FQHE), observed in low-temperature magnetotransport experiments in two-dimensional (2D) electron systems and caused by the electron-electron interaction, can be regarded as an ultimate proof of device quality in terms of quantum mobility, homogeneity, and low residual impurities. Until recently, the observation of a FQHE in graphene, the two-dimensional form of carbon, had been limited to devices based on mechanically exfoliated graphene, whereas there was a controversial discussion if graphene produced by chemical vapor deposition (CVD) could support FQH states at all.

Using low-temperature high-field magnetotransport experiments up to 35 T, scientists from RWTH Aachen in collaboration with HFML-EMFL researchers have now succeeded to observe the FQHE in CVD-grown graphene (Figure). The devices used for these experiments consist of hexagonal-boron-nitride / CVD-graphene / hexagonal-boron-nitride heterostructures patterned into µm-sized field effect transistors in the form of a Hall bar.

Several well-pronounced FQH states are resolved and their excitation gaps are comparable to high-quality devices based on exfoliated graphene. We regard these results as an unambiguous prove that the high quantum mobility in CVD-grown graphene equals that of mechanically exfoliated graphene flakes. This can open a pathway to a new generation of large-area ultra-high-quality devices using a scalable growth of 2D materials based on CVD techniques.

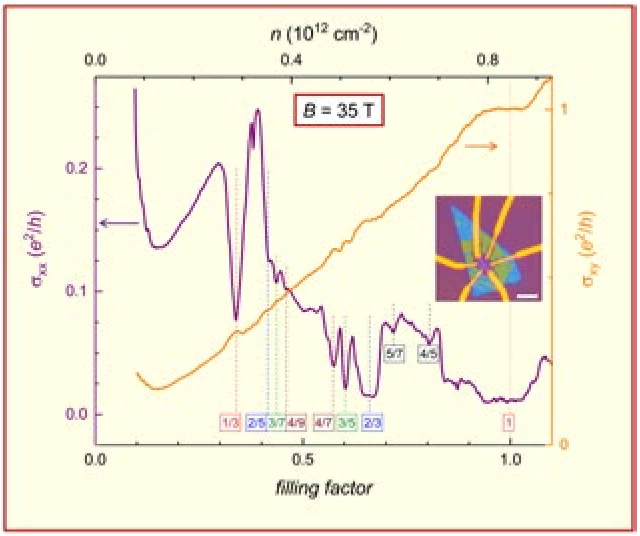

Figure: Longitudinal conductivity σ_{xx} (left axis) and Hall conductivity σ_{xy} (right axis) in the lowest Landau level of a high-quality CVD-grown graphene Hall bar as a function of filling factor (bottom) or electron concentration (top). The vertical lines mark the fractional quantum Hall states observed, indicating an exceptionally high quantum mobility. The inset shows an optical-microscope image of the etched and contacted h-BN/CVD-Gr/h-BN Hall-bar structure with a 10 µm scale bar.

Fractional quantum Hall effect in CVD-grown graphene, M. Schmitz, T. Ouaj, Z. Winter, K. Rubi, K. Watanabe, T. Taniguchi, U. Zeitler, B. Beschoten, and C. Stampfer, 2D Materials **7**, 041007 (2020).

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HIDDEN MAGNETISM AT THE PSEUDOGAP CRITICAL POINT OF A CUPRATE SUPERCONDUCTOR

David Leboeuf and Marc-Henri Julien, LNCMI-Grenoble

Extensive studies of cuprate superconductors have shown that, after three-dimensional Néel order disappears upon hole doping (p), there are still remnants of spin order at low temperature in the form of a glass-like freezing of incommensurate antiferromagnetic correlations. However, the importance of the coexistence of incommensurate spin order with superconductivity has been unclear. The glass-like characteristics and material-dependent phase boundaries of this 'antiferromagnetic glass' suggest that it is favored by disorder and that it is not unequivocally connected to either charge order, the pseudogap phase, or superconductivity.

We have used local (nuclear magnetic resonance, NMR) and bulk (ultrasound) measurements to show that, once competing effects from superconductivity are removed by high magnetic fields, the spin-glass phase of $La_{2-x}Sr_xCuO_4$ survives up to a hole-doping level much higher than hitherto believed: Actually, up to the critical doping level p* that defines the end of the pseudogap phase at zero temperature. This means that, in the non-superconducting ground state, this end of the pseudogap phase coincides with a quantum phase transition from glassy antiferromagnetic order to a correlated metal with only short-lived antiferromagnetism.

This discovery has implications for the interpretation of high-field experiments performed in La-based cuprates: The frozen striped antiferromagnetic pattern should influence low-lying electronic states up to p*, which could affect transport or thermodynamic measurements at low temperatures and high fields. A fascinating issue is whether this is related to the quantum critical behavior observed at p*. More generally, our results exemplify that the properties of the field-induced normal state may not necessarily serve as a proxy for the whole pseudogap state. Here, in $La_{2-x}Sr_xCuO_4$, the field-induced normal state at zero temperature is an ordered antiferromagnet (albeit freezing like a glass) but the temperature-induced normal state above Tc shows only short-lived antiferromagnetic correlations.

This work further shows that the spin-glass phase spans from the weakly doped insulator at p = 0.02 all the way up to p* ≈ 0.19. This suggests that the same local-moment antiferromagnetism as that found in the doped Mott insulator survives throughout the pseudogap state, which provides a connection between the pseudogap and the physics of the Mott insulator.

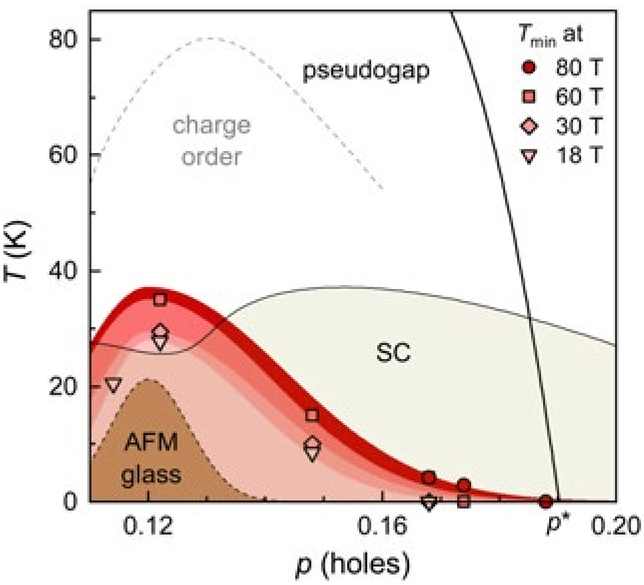

Figure: Temperature – doping phase diagram representing T_{min}, the temperature of the minimum in the sound velocity, at different fields. Because superconductivity precludes the observation of T_{min} in zero-field, the dashed line (brown area) represents the extrapolated zero-field T_{min}, which is close to the freezing temperature at the NMR and ultrasound time scales of about 10^{-8} s.

Hidden magnetism at the pseudogap critical point of a cuprate superconductor, M. Frachet, I. Vinograd, R. Zhou, S. Benhabib, S. Wu, H. Mayaffre, S. Krämer, S. K. Ramakrishna, A. P. Reyes, J. Debray, T. Kurosawa, N. Momono, M. Oda, S. Komiya, S. Ono, M. Horio, J. Chang, C. Proust, D. LeBoeuf, and M.-H. Julien, Nat. Phys. **16**, 1064 (2020).

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BROAD TUNABILITY OF CARRIER EFFECTIVE MASSES IN TWO-DIMENSIONAL HALIDE PEROVSKITES

Mateusz Dyksik, Wroclaw University and Paulina Plochocka, LNCMI-Toulouse

Two-dimensional organic-inorganic halide perovskites have generated tremendous interest in the field of optoelectronics for applications in low-cost and efficient light absorbers and emitters. Similar to their three-dimensional (3D) ancestors, the layered perovskite derivatives exhibit promising performance in photovoltaic and light-emitting devices, while presenting enhanced stability at ambient conditions, a haunting burden yet for their 3D counterparts. The enhanced environmental stability stems from the large hydrophobic organic cation L – a building block of two-dimensional perovskites – serving also as a spacer between consecutive inorganic sheets (see Figure for structure schematics). In contrast to 3D hybrid organic-inorganic perovskites, where the organic molecules cannot be chosen arbitrarily, there is a plethora of available large organic cations L leading to stable compounds. This makes 2D perovskites an unprecedented material system regarding tuning flexibility of its optoelectronic properties, because the large organic spacers provide control over the dielectric confinement as well as crystal and band structure and, as a result, the effective mass.

The effective mass is of specific interest as a fundamental parameter characterizing any semiconductor, governing the charge transport and optical-absorption phenomena, yet to date not measured for 2D perovskites. Such lack of experimental reports results in an unnecessary confusion as the estimated values of effective mass span over a broad range. Here, we demonstrate, for the first time, a direct experimental determination of the effective mass in 2D $(PEA)_2PbI_4$ and $(PEA)_2SnI_4$ perovskites (PEA = phenethylamine). Using high-magnetic-field spectroscopy, we observe interband Landau-level transitions. The energy separation of the Landau levels provides a direct handle for the reduced effective mass of the charge carriers μ. Combining our results with first-principles calculations, we find that μ can be tuned from a very low value of 0.05 m_0 to 0.15 m_0 by metal composition, which is a much wider range than that previously reported for 3D perovskites. Furthermore, we observe that the effective mass in 2D halide perovskites can be even lower than in the corresponding bulk material (Figure), which is in striking contrast to what is known for classic epitaxial quantum wells. Our direct experimental approach to determine the effective mass together with our calculations render a broader perspective on the available ways to modify effective masses in this fascinating material system.

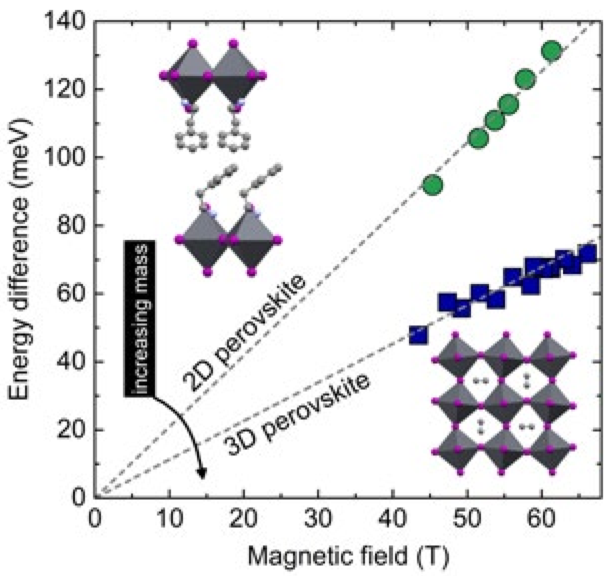

Figure: Energy difference between consecutive Landau levels versus magnetic field. Circles represent the 2D perovskite (PEA_2SnI_4), squares stand for 3D $FASnI_3$ (FA = formamidinium). Dashed lines are fits with $\Delta E = eB/\mu$, from which we directly determine the value of μ. The smaller the slope of the fitted curve the higher the effective mass. Although both compounds belong to the tin family, the 2D structure shows a lower reduced effective mass, atypical when the quantum confinement plays a role. The inset shows the crystal structure (c axis pointing upwards) of 2D (top left) and 3D (bottom right) perovskites. The sheets of inorganic cages of 2D perovskite are separated by large organic molecules containing phenyl rings.

Broad Tunability of Carrier Effective Masses in Two-Dimensional Halide Perovskites, M. Dyksik, H. Duim, X. Zhu, Z. Yang, M. Gen, Y. Kohama, S. Adjokatse, D. K. Maude, M. A. Loi, D. A. Egger, M. Baranowski, and P. Plochocka, ACS Energy Letters, in press.

Contact: paulina.plochocka@lncmi.cnrs.fr, mateusz.dyksik@pwr.edu.pl

PRESSURE DEPENDENCE OF HIGH-FIELD NEMATICITY AND MAGNETISM IN $CeRhIn_5$

Toni Helm, HLD Dresden

Strongly correlated electron materials, in particular heavy-fermion compounds, offer a huge playground for research on fundamental concepts in condensed-matter physics. The antiferromagnetic (AFM) metal $CeRhIn_5$ provides a textbook example of quantum criticality in a heavy-fermion system: Pressure suppresses local-moment AFM order and induces superconductivity in a dome around the associated quantum critical point (QCP) near $p_c \approx 23$ kbar. Magnetic fields also suppress the AFM order at a field-induced QCP at $B_c = 50$ T. At $B^* = 28$ T, a novel phase characterized by a large in-plane resistivity anisotropy emerges. Its two-dimensional electronic character and the absence of both, significant structural and magnetic changes, suggests a nematic high-field phase. Hence, the question arose if there is an intimate relation between the low-pressure high-field nematic behavior and the high-pressure low-field superconductivity in $CeRhIn_5$.

In cooperation with our colleagues in Tallahassee and Los Alamos (USA), Lausanne (Switzerland) and Dresden, we investigated the interrelation between these phenomena via magnetoresistance (MR) measurements under high pressure. Experiments were performed in pulsed magnetic fields combining focused-ion-beam (FIB)-structured devices (Figure, panel a), plastic diamond anvil pressures cells, and ^{3}He temperatures.

We made three observations: First, the nematic onset field B^*, characterized by an anisotropy jump and a first-order-like hysteretic behavior, grows with applied pressure from 28 T at ambient pressure to around 40 T close to 20 kbar. At the same time, the hysteretic transition, hallmark of entrance into the nematic state, continuously diminishes until p^*, at which it vanishes completely. Second, the critical field for the AFM transition, B_c, also shifts to higher fields upon pressure increase. Our third observation suggests a field-induced reentrance of antiferromagnetism at pressures above p_c. The critical field, B_c, and the critical pressure, p_c, both terminate the symmetry breaking AFM dome and, therefore, must be connected by a continuous line of phase transitions. Indeed, we do observe a discontinuity in the slope of the MR above p_c, tracing out an upward line $B_{c,low}$ that increases with increasing pressure. We associate this field with the field-induced reentrance of AFM order as expected. We reveal a phase diagram, much richer than the common local-moment description of $CeRhIn_5$ would suggest (Figure, panel b).

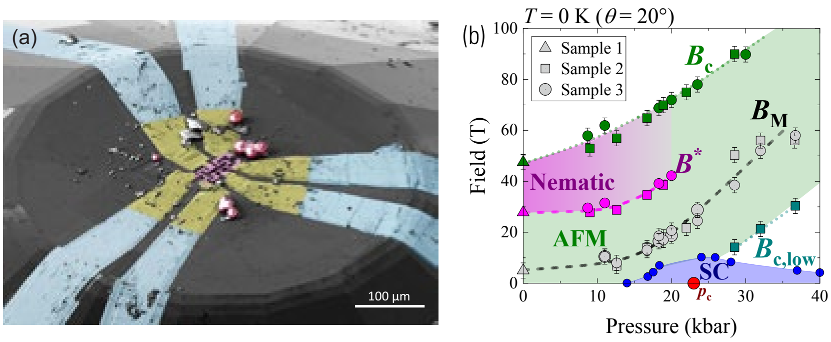

Figure: (a) False-color scanning-electron-microscope image of a FIB microstructure transport device (purple) on a diamond anvil with 6 terminals connected via gold/platinum tapes. (b) Schematic (field-pressure) phase diagram of $CeRhIn_5$.

Non-monotonic pressure dependence of high-field nematicity and magnetism in $CeRhIn_5$, T. Helm, A. D. Grockowiak, F. F. Balakirev, J. Singleton, J. B. Betts, K. R. Shirer, M. König, T. Förster, E. D. Bauer, F. Ronning, S. W. Tozer, and P. J. W. Moll, Nat. Commun. **11**, 3482 (2020).

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OPENING OF THE CALL FOR ACCESS NO. 24

With temporary signs of alleviation of the COVID-19 crisis across Europe during summer, all EMFL sites had resumed user operation. To facilitate the handling of all proposals and to provide maximum clarity to all users in this regard, the Board of Directors decided to revert to the regular policy that proposals will remain valid for one year. Users with older proposals are asked to resubmit them, including those granted in the 119 and 219 calls, which could not be carried out due to the COVID-19 crisis.

The 24th call for proposals has been launched on October 15, 2020, inviting researchers worldwide to apply for access to one of the large installations for high magnetic fields collaborating within EMFL.

The four facilities

- LNCMI - Grenoble - France: Static magnetic fields up to 36 T
- HFML - Nijmegen - the Netherlands: Static magnetic fields up to 37,5 T
- HLD - Dresden - Germany: Pulsed magnetic fields to beyond 90 T
- LNCMI - Toulouse - France: Pulsed magnetic fields of long duration to beyond 99 T and on the microsecond scale to beyond 200 T

run a joint proposal program, which allows full access to their installations and all accompanying scientific infrastructure to qualified external users, together with the necessary support from their scientific and technical staff.

Users may submit proposals for access to any of these installations by a unified procedure. The online form for these proposals can be found on the EMFL website.
www.emfl.eu/user

Please note that each experiment carried out on our high magnetic field installations must be followed up by a progress report and your publication record filled out online on the EMFL website. Please be aware that this information will also be made available to the Selection Committee.

To further improve our user program, your feedback to the user committee is highly appreciated.

Please find the form on the EMFL website.
https://emfl.eu/SelCom/UserCommittee/feedbackform.php

The deadline for proposals for magnet time is November 15, 2020.

Proposals received after the deadline, that are considered of sufficient urgency, may be handled as they arrive and fit into any available time.

The proposals will be evaluated by a Selection Committee. Selection criteria are scientific quality (originality and soundness), justification of the need for high fields (are there good reasons to expect new results) and feasibility of the project (is it technically possible and are the necessary preparations done). It is strongly recommended to contact the local staff at the facilities to prepare a sound proposal and ideally indicate a local contact.

Please do acknowledge any support under this scheme in all resulting publications with „We acknowledge the support of the HFML-RU/FOM (or HLD-HZDR or LNCMI-CNRS), member of the European Magnetic Field Laboratory (EMFL)." UK users should, in addition, add "A portion of this work was supported by the Engineering and Physical Sciences Research Council (grant no. EP/N01085X/1)."

- You may find more information on the available infrastructures for user experiments on the facility websites.

www.hzdr.de/hld
www.lncmi.cnrs.fr
www.ru.nl/hfml

EMFL European Magnetic Field Laboratory

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

ISABEL: IMPROVING THE SUSTAINABILITY OF EMFL

One of the great challenges of society is innovation through the development of new and advanced materials. We need such tailored materials in all key-technological areas, from renewable energy concepts, through next-generation data storage to bio-compatible materials for medical applications. Furthermore, many of these future materials will be synthesized on a nano-scale. In order to reach these goals, researchers are in need of state-of-the-art analytical tools. High magnetic fields are one of the most powerful tools available to scientists for the study, modification, and control of states of matter, and EMFL provides such fields (both continuous and pulsed) to Europe's many active and world-leading researchers.

In recognition of the importance of the EMFL, and in order to assure its long-term sustainability, the EU has decided to fund the H2020-ISABEL project (**I**mproving the **S**ust**A**ina**B**ility of the **E**MF**L**).

This project unites 18 partners, both academic and industrial, and aims to strengthen the long-term sustainability of the EMFL through the realization of three objectives:

> strengthening the EMFL structure by enlarging its membership and by improving several organizational aspects, such as data management, outreach, and access procedures.
> strengthening the socio-economic impact of the EMFL, by bridging the gap with industry.
> strengthening of the role of high magnetic field research in Europe and worldwide.

The project is coordinated by Geert Rikken (LNCMI) with a total budget of 4.9 M€, and it will start on 1/11/2020, for a duration of 4 years, with the kickoff video-meeting on 20/11/2020. We will keep you informed of its progress in these pages.

DELIVERY OF THE SUPERCONDUCTING COIL FOR THE 43+ T GRENOBLE HYBRID MAGNET

Pierre Pugnat, Rolf Pfister, and Luc Ronayette, LNCMI-Grenoble

The hybrid magnet in construction at LNCMI-Grenoble is based on the combination of resistive inserts, made of Bitter and polyhelix coils, with a large-bore superconducting outsert. It will produce in a first step, an overall continuous magnetic field of 43 T in a 34 mm warm bore opening. The superconducting coil will provide a nominal magnetic field of 8.5 T in a 1.1 m cold-bore diameter.

It relies on the novel development of a Nb-Ti/Cu Rutherford Cable On Conduit Conductor (RCOCC) cooled down to 1.8 K by a bath of superfluid helium at atmospheric pressure. The novelty of the RCOCC development concerns the assembly and the induction soft soldering of the multi-strand Rutherford cable on a Cu-Ag hollow stabilizer (Figure 1). This allows for a strict control of the interstrand contact resistance and, therefore, of the AC losses within the superconductor to prevent a magnet quench in case of resistive-insert voltage trips. Thorough tests and validation phases were conducted at LNCMI-Grenoble as well as in industry prior to the in-house industrial production of the RCOCC [1]. This included the trial production of the hard-drawn Cu-Ag hollow stabilizer in continuous lengths of 325 m as well as studies, developments, and integration of the industrial production line at LNCMI-Grenoble. The production of 43 RCOCC unit lengths wound in a single pancake of 2 m internal diameter was completed end of July 2017 and sent to the coil manufacturer Bilfinger Noell GmbH. We consider this as one the first great achievements of the project.

[1] In-house Industrial Production of the Superconducting Conductor for the 43 T Hybrid Magnet of LNCMI-Grenoble, P. Pugnat, T. Boujet, T. Disparti, P. Hanoux, C. Peroni, R. Pfister, M. Pissard, L. Ronayette, and J.M. Tudela, IEEE Trans. Appl. Supercond. **28**, 4301005 (2018).

[2] From Manufacture to Assembly of the 43 T Grenoble Hybrid Magnet, P. Pugnat, R. Barbier, C. Berriaud, R. Berthier, T. Boujet, T. Disparti, P. Graffin, C. Grandclément, B. Hervieu, K. Juge, B. Mallery, F. Molinié, H. Neyrial, M. Pelloux, C. Peroni, R. Pfister, L. Ronayette, Hans J. Schneider-Muntau, and B. Vincent, IEEE Trans. Appl. Supercond. **30**, 4300605 (2020).

A few months ago, a new milestone was achieved with the delivery of the superconducting coil at LNCMI-Grenoble. It consists of the thorough assembly of 37 double pancakes, vacuum impregnated separately (Figure 2), which can be exchanged in case of a serious damage during operation [2].

We focus now on:

- The construction of the cryogenic line connecting the cryogenic satellite to the magnet cryostat and
- The final assembly expected to end 2021.

This project is funded by the CNRS, the French Ministry of Higher Education and Research in the framework of the "Investissements pour l'avenir & Equipements d'excellence" Equipex LaSUP (Large Superconducting User Platform), the European Funds for Regional Development (FEDER) and the Rhône-Alpes region.

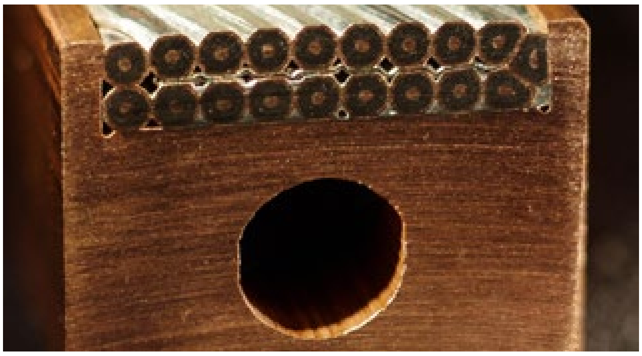

Figure 1: Cross section of the produced RCOCC of dimensions 17.92 x 12.96 mm².

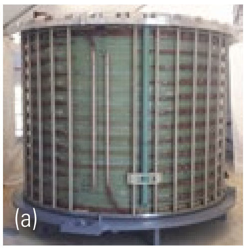

Figure 2: (a) The outsert superconducting coil (Weight = 21 tons, total height = 1551 mm and overall outer diameter = 2180 mm) delivered to LNCMI Grenoble together with (b) six spare double pancakes.

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ARIES: JOINT POSITION PAPERS

EMFL is a member of the Analytical Research Infrastructures of Europe (ARIEs) consortium. The ARIEs are centers of scientific and technological excellence, delivering services, data, and expertise to a growing and diverse user community of more than 40,000 researchers in academia and industry, across a range of domains: the physical sciences, energy, engineering, the environment and the earth sciences, as well as medicine, health, food, and cultural heritage. They include powerful photon sources, such as synchrotrons, laser systems and free-electron lasers; sources of neutrons, ions, and other particle beams; and facilities dedicated to advanced electron microscopy and high magnetic fields.

2020 saw the publication of two crucial joint position papers. The first one, „A Key Resource for the Five Horizon Europe Missions", highlights how a common, complementary approach will strengthen the European analytical research infrastructures collectively and will address societal challenges of the Horizon Europe Missions framework program.

With the second joint position paper, „Viral and Microbial Threats", the consortium enhances its cross-border, multidisciplinary collaboration to offer Europe a strong and valid weapon against the present COVID-19 challenge and other possible, similar future crises.

Further Information:

A Key Resource for the Five Horizon Europe Missions
https://www.lens-initiative.org/wp-content/uploads/2020/07/ARIE-PosPaper-2020-07-07-14.00.pdf

Viral and Microbial Threats
https://leaps-initiative.eu/wp-content/uploads/2020/09/Viral-Threats-Paper-09.2020-FINAL.pdf

UPCOMING EVENTS

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

1. 65th Annual Conference on Magnetism and Magnetic Materials, Palm Beach, USA, November 2-6, 2020. **VIRTUAL**
   https://magnetism.org/

2. 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

3. Symposium „Materials for Extreme Conditions“, 2020 MRS Fall Meeting & Exhibit, Boston, USA, November 28 - December 4, 2020. **VIRTUAL**
   https://www.mrs.org/meetings-events/fall-meetings-exhibits/2020-mrs-spring-and-fall-meeting#announcement

4. ARHMF 2020 and KINKEN Materials Science School 2020 for Young Scientists, Sendai, Japan, December 1-3, 2020. **VIRTUAL**
   http://arhmf.imr.tohoku.ac.jp/eng/index.html

5. Joint European Magnetic Symposia (JEMS), Lisbon, Portugal, December 7-11, 2020. **VIRTUAL**
   https://www.jems2020.com/

6. CM&LTP 2021, Condensed Matter and Low Temperature Physics 2021, Kharkiv, Ukraine, June 6-12, 2021.
   http://ilt.kharkov.ua/cmltp2021/index.html

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

8. International Conference on Magnetism (ICM), Shanghai, China, July 3-8, 2022. **SHIFTED**
   http://www.icm2021.com/

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