

EMFLNEWS N°1 2018





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DEAR READER

Being active on the global scale is an important ingredient of the EMFL strategy. This comprises, for instance, the organization of international conferences (such as the HFM-23 to be held in Toulouse from 22 to 27 July 2018) and the collaboration within the Global High Magnetic Field Forum (HiFF). Being in contact with the high-field labs around the world, we got aware on the spectacular achievement of reaching almost 1000 T in an in-house experiment that our colleagues from the Institute of Solid State Physics (ISSP) of the University of Tokyo could proudly report. More first-hand information on this world record you may find inside this issue in an article written by the responsible ISSP scientists.

MEET OUR PEOPLE

Dr. Florence Lecouturier, LNCMI, France

I am group leader for the development of high-strength materials at the French National Center for Scientific Research (CNRS), Laboratoire National des Champs Magnétiques Intenses.

I obtained an Engineer diploma in physics/materials science from the National Institute for Applied Sciences in Toulouse (INSA) in 1991, concurrently to receiving a Master's degree from the University of Toulouse. I received a PhD degree in Materials Science in 1995 from the National Institute for Applied Sciences in Toulouse. During my PhD work, related to R&D of high-strength conductors, I had strongly interacted with the two industrial research centers: TREFIMETAUX Research Center (Sérifontaine, FR) and Alcatel ALSTOM Recherche (Marcoussis, FR).

I am primarily active in metal processing by use of severe plastic deformation, physical properties and modeling of copper/stainless steel macrocomposites, copper alloys, copper/X (with bcc/fcc combination as Cu/Nb, Cu/Ta, Cu/Ag) and carbon nanotubes-copper nanocomposite; all high-strength materials for high magnetic field applications.

Within the EMFL, I am the leader for the thematic network "Materials for high-field magnets" and I organized the first international workshop on "Materials for high-field magnets" in 2011, which was followed by a second one organized by the National MagLab in 2015.

In the EMFL, I am also actively involved in fostering and strengthening the relations with industrial partners with the ambitious goal to set up a strategy for bringing EMFL innovations to market. Further to that, you will find, as usual, articles on a number of outstanding scientific results obtained by using the EMFL facilities. We as well are happy to announce the opening of the nineteenth call for access. And, we start with a new rubric in this issue of the EMFL News, compiling upcoming events and conferences that might be of interest for you.

I hope to see many of you during this-year EMFL user meeting hosted by the HFML, Nijmegen, in June 21.

Have a stimulating reading, Jochen Wosnitza Director HLD, Chairman EMFL



🔰 Dr. Florence Lecouturier

http://www.toulouse.lncmi.cnrs.fr/spip.php? page=rubrique&id_rubrique=33&lang=en

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HOW CHARGE ORDER WEAKENS SUPERCONDUCTIVITY IN YBa₂Cu₃O_v

Marc-Henri Julien, LNCMI Grenoble

The upper critical field, H_{c2} , is a fundamental, and technologically important property that measures the ability of a superconductor to withstand magnetic fields. Recently, there has been a controversy regarding H_{c2} values in high- T_c copper-oxides, particularly in the context of the competition between superconductivity and charge density wave (CDW) order in YBa₂Cu₂O₂.

We have addressed this question by using for the first time a local probe, ¹⁷O NMR, to measure the spin susceptibility χ_{spin} of the CuO₂ planes at low temperature in charge-ordered YBa₂Cu₃O_y. The central result of this study is the observation of an essentially linear increase in χ_{spin} up to a magnetic field in the range of 20 to 40 T (depending on the hole-doping level), followed by a constant value. These saturation fields agree remarkably well with H_{c2} values determined in the work of [G. Grissonnanche et al., Nat. Commun. 5, 3280 (2014) and EMFL News n°3 (2014)], showing a minimum around the hole doping p = 0.12, where the CDW is strongest (Figure). This result is consistent with the interpretation that the CDW reduces H_{c2} in underdoped YBa₂Cu₃O_y.

Our data also yields quantitative information on the electronic density of states that should be benchmarked against theories and other measurements such as specific heat. We find that the "residual" χ_{spin} at H_{c2} in the zero-temperature limit is a small fraction (~16%) of χ_{spin} of near-optimally doped YBCO. This shows that the non-superconducting ground state has a large pseudogap, distinct from the superconducting gap. Second, the absence of a visible impact of the field-induced CDW transition on χ_{spin} suggests that the

Spin susceptibility of charge ordered YBa₂Cu₃O_y across the upper critical field,

R. Zhou, M. Hirata, T. Wu, I. Vinograd, H. Mayaffre, S. Krämer, A. P. Reyes, P. L. Kuhns, R. Liang, W. N. Hardy, D. A. Bonn, and M.-H. Julien, PNAS **114**, 13148 (2017). observed modifications of H_{c2} and of the Fermi-surface topology do not occur abruptly but rather gradually as a function of field. They must essentially be rooted in the presence of short-range (but static) CDW correlations already in zero field.



Figure: Saturation field in ¹⁷O Knight-shift measurements (blue dots, this work) at T = 2-3 K, compared to H_{c2} values extrapolated to T = 0 from resistivity data [B. Ramshaw et al., Phys. Rev. B 86, 174501 (2012)]. The agreement leads to the identification of the saturation field as H_{c2}, in the zero-temperature limit.

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GATE-TUNING ACROSS THE SUPER-CONDUCTING DOME OF MONOLAYER WS,

Sergio Pezzini, Maarten R. van Delft, Nigel E. Hussey, Steffen Wiedmann, HFML Nijmegen

Compared with three-dimensional superconductors, atomically thin superconductors are expected to be easier to engineer for electronic applications. In this project, researchers from University of Groningen (Netherlands) together with colleagues from HFML and Hong Kong have used field-effect gating to trace out a 'dome-shaped' superconducting phase in a monolayer of the semiconducting transition-metal dichalcogenide, WS_2 . The remarkable doping range allows access to a cascade of electronic phases from a band insulator, a superconductor, to a reentrant insulator at high doping. The large spin-orbit coupling of 30 meV makes WS_2 arguably the most strongly protected superconducting state against external magnetic field. The wide tunability revealed by spanning over a complete superconducting dome paves the way for the integration of monolayer superconductors to functional electronic devices exploiting the field-effect control of quantum phases.

In the initial state with very few carriers, WS₂ behaves as an insulator. The electric field adds carriers to this normal band insulator which increases the conductivity. At low enough temperatures, a superconducting state can then be realized. In the superconducting phase itself, the temperature at which superconductivity occurs first goes up with the increase of electric field, but then goes down again (Figure 1). This kind of dome-shaped curve was observed in many superconductors over several decades. Especially, this is one of the hallmarks of hightemperature superconductivity itself is exceptional in that it is robust to an intense magnetic field applied parallel to the monolayer plane. As shown in Figure 2, a field of 35 T only suppresses the superconductivity by 0.1 K. Even more surprising, however, was that as the electric field increases even further, the system goes from superconductor to insulator again, albeit a different kind of insulator.

Full superconducting dome of strong Ising protection in gated monolayer WS₂, J. Lu, O. Zheliuk, Q. Chen, I. Leermakers, N. E. Hussey, U. Zeitler, and

J. Ye, Proceedings of the National Academy of Sciences **115**, 3551 (2018).



Figure 1: Phase diagram of monolayer WS₂. Superconducting critical temperatures T_c are plotted (solid circles) as a function of the effective back gate. Quasi-metal (qM) regime is bounded by metal-insulator crossover temperature (empty squares).

The authors suggest that the charge carriers in the material eventually become localized by the high electric field. Thus, they can no longer move through the material and it becomes an insulator. This is somewhat counter intuitive since higher gating typically means more carriers and hence improved metallicity. This discovery could pave the way for the rational design of two-dimensional superconducting devices that function at relatively high temperatures.





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HIGH-FIELD CHARGE ORDER ACROSS THE PHASE DIAGRAM OF YBCO

F. Laliberté, M. Frachet, S. Benhabib, B. Borgnic, C. Proust, D. LeBoeuf, LNCMI-Toulouse

In hole-doped cuprates there is now compelling evidence that inside the pseudogap phase, a charge density wave (CDW) breaks translational symmetry. In YBa₂Cu₃O_y (YBCO) this CDW emerges in two steps: a two-dimensional (2D) order found at zero field and up to high temperatures inside the pseudogap phase, and a 3D order that is superimposed below the superconducting transition T_c when superconductivity is weakened by a magnetic field. It has been established by NMR and x-ray measurements that these CDWs coexist at low temperatures but it raises interesting questions: Do both CDWs share the same critical doping? What is their respective impact on the Fermi surface at low temperature?

We studied the doping dependence of the 3D CDW onset temperature and field using sound-velocity measurements in high magnetic fields. A jump is seen in the temperature dependence of the sound velocity measured at high field, as expected for a second-order phase transition. In the figure, we compare the doping dependence of the onset temperature T_{co} of the 3D CDW (red circles) with the onset temperature of the 2D CDW observed by x-rays (open green triangles) and we find that both CDWs coexist at low temperature in the same doping range. In addition, the critical doping of the CDWs appears distinct from the critical point of the pseudogap, suggesting that the two phenomena are separate.

The exact mechanism of the Fermi-surface reconstruction by the CDW is still debated. We assume that the sign change of the Hall effect (observed in the same doping range of YBCO where CDWs exist) is a signature of the presence of an electron pocket due to

High field charge order across the phase diagram of YBCO, F. Laliberté, M. Frachet, S. Benhabib, B. Borgnic, T. Loew, J. Porras, M. Le Tacon, B. Keimer, S. Wiedmann, C. Proust, and D. LeBoeuf, npj Quantum Materials **3**, 11 (2018).

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a Fermi-surface reconstruction. The facts that i) the onset of the 3D CDW barely affects the temperature dependence of the Hall coefficient and ii) the Hall coefficient changes sign at a temperature T_0 (open black diamonds) which can be 20 K higher than the onset of the 3D CDW, point towards a minor role of the 3D CDW for this reconstruction.



Figure: Temperature – doping phase diagram of charge orders in YBCO. X-ray diffraction (down green triangles) and resonant x-ray scattering (up green triangles) give the onset temperature of 2D CDW in zero field. The onset temperature of 3D charge order in high fields is given by NMR (blue squares) and sound velocity (red circles). A comparison is made with T_o (black diamonds) the temperature of the sign change of the Hall effect, a signature of an electron pocket in the reconstructed Fermi surface. The solid black line is the pseudogap temperature T* in YBCO determined from a resistivity curvature map. The dashed black line is a guide to the eye.

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EXPERIMENTAL OBSERVATION OF BETHE STRINGS

Zhe Wang, HZDR Dresden and A. Loidl, University of Augsburg

In his seminal work entitled "Eigenwerte und Eigenfunktionen der linearen Atomkette" (eigenvalues and eigenfunctions of a linear chain of atoms), published in 1931 in "Zeitschrift für Physik", Hans Bethe succeeded in finding an exact solution to the one-dimensional spin-1/2 Heisenberg model, and predicted the existence of bound states of two magnons in this model. The method that Bethe introduced was later further developed theoretically, and in general bound states of n magnons (string of length n; n is an integer) were predicted for the spin-chain model. Today, the so-called Bethe ansatz is an important mathematical tool of statistical physics.

The lack of suitable one-dimensional materials and appropriate experimental methods has made experimental verification of the many-body string states so far impossible. Impressive progress in material synthesis on one hand and the development of optical spectroscopy in the terahertz frequency range in very high magnetic fields on the other hand have now made this experimental detection possible for the first time.

In a first step, $SrCo_2V_2O_8$ crystals were synthesized and characterized at the Helmholtz-Zentrum in Berlin and at the Dresden High Magnetic Field Laboratory in the Helmholtz-Zentrum Dresden-Rossendorf. These crystals, in which the cobalt ions form a one-dimensional Heisenberg-Ising spin chain with spin S = 1/2, were then studied with terahertz spectroscopy in the University of Augsburg and the High Field Magnet Laboratory of the Radboud University in

Experimental Observation of Bethe Strings,

Zhe Wang, Jianda Wu, Wang Yang, Anup Kumar Bera, Dmytro Kamenskyi, A.T.M. Nazmul Islam, Shenglong Xu, Joseph Matthew Law, Bella Lake, Congjun Wu, and Alois Loidl, Nature **554**, 219 (2018).

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Nijmegen in a wide magnetic field range up to 30 T. By comparing to theory results obtained by scientists from the University of California at San Diego with the Bethe ansatz, length-2 and length-3 string states (Figure) were finally identified in the terahertz spectra of $SrCo_2V_2O_8$. Bethe's result is important not only in the field of quantum magnetism but also more broadly in the study of cold atoms and in string theory. Hence, the identification of the string states will shed light on the study of complex many-body systems in general.



Figure: (a) Illustration of ferromagnetically-aligned spins of the cobalt ions in SrCo₂V₂O₈ compared to a spin chain with (b) two-or (c) three-string excitations.

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OPENING OF THE NINETEENTH CALL FOR ACCESS

The 19th call for proposals has been launched in April, 2018 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 90 T and on the microsecond scale to beyond 180 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

The next deadline for proposals for magnet time is May 15, 2018.

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)"

> 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



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.



MAGNETIC FIELD APPROACHING 1000 T ACHIEVED BY ELECTROMAGNETIC FLUX COMPRESSION.

S. Takeyama, D. Nakamura, H. Sawabe, i-MgsL, ISSP, University of Tokyo

The ISSP research group has broken the world record for the highest magnetic field generated in an indoor experiment, achieving 985 T and approaching 1000 T. This is applicable to the measurement of physical properties by the electromagnetic flux compression (EMFC) method.

Since the 1970s, the ISSP has been carrying out research into the generation of ultra-high magnetic fields using the EMFC method and their application to unprecedented research in condensed-matter physics. With the aid of the quasi-three-dimensional mesh modelling simulation [1], the seed magnetic fields were adjusted to achieve the highest efficiency of flux-compression in a copper-lined main coil which we devised [2]. Faraday rotation of quartz was used to monitor the magnetic fields that were measured close to the highest value. Record magnetic fields, close to 1000 T, were detected showing that it is possible to generate such flux densities and indicating that it is also possible to measure physical properties in super-strong magnetic fields in the region of 1000 T (Figure). The spatial homogeneity and temporal evolution of the peak magnetic field are highly controllable, so they can be utilized for various reliable and precise physical measurements.

Experimental evidence of three-dimensional dynamics of an electromagnetically imploded liner, D. Nakamura, H. Sawabe, and S. Takeyama, Rev. Sci. Instr. 85, 036102 (2014).
 An approach to 1000 T using the electro-magnetic flux compression,
 D. Nakamura, H. Sawabe, and S. Takeyama,
 Rev. Sci. Instr. 89, 016106 (2018).



Figure: Time evolution of the light intensity of the Faradayrotation transmission signal (upper panel) and the magnetic field (lower panel). The inset shows the flux-compression coil system.

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SUPERCONDUCTING COIL FOR HFML'S 45 T HYBRID MAGNET

In the beginning of March 2018, a major milestone in the development of the 45 T hybrid magnet at HFML in Nijmegen has been achieved with the completion of the superconducting coil for the outsert magnet. The building process of the coil, with an outer diameter of 1.2 meter, a height of 1 meter and a weight of 7.5 ton, started in 2012 with the manufacturing in the USA of 225 km of high-current density superconducting Nb₃Sn strands with a diameter of 0.8 mm. Together with high-purity copper strands produced in Finland, these wires were assembled, cabled, inserted into special stainless-steel tubes and compacted into 2.5 km of rectangular shaped Cable-in-Conduit conductor (Figure), all done by 3 different Italian companies.







Figure: The superconducting coil is made out of 3 types of Nb₃Sn/Cu Cable-in-Conduit conductor (typical size 3 x 1.5 cm)

Early 2015, 5 conductor lengths were shipped to our colleagues from the National High Magnetic Field Laboratory in Tallahassee (FL, USA) who are capable of processing such large coils. The coil-manufacturing process, which took more than 2.5 years, comprised coil winding, section and lead joint processing, reaction heat treatment at 640 °C, vacuum impregnation with epoxy resin, connection of the tubing required to guide the flow of cryogenic coolant to and from the coil and finally the installation of voltage taps for quench protection.



The NHMFL team with the finished coil. (courtesy NHMFL)

Shipping the cold mass from Tallahassee to Nijmegen was the last but certainly not the least step towards its final destination. The coil will be built into its cryostat and integrated in the electrical, electronic and cryogenic hybrid magnet system in the coming year. After completion of the insert magnet the commissioning of the 45 T hybrid is scheduled at the end of 2019.



The completed outsert coil's cold mass reached its destination at HFML in Nijmegen. (courtesy HFML)



EMFL USER MEETING 2018

The yearly user meeting of the European high field magnet facilities for

> continuous fields (LNCMI Grenoble and HFML Nijmegen) and

> pulsed magnetic fields (HLD Dresden and LNCMI Toulouse)

will be hosted by Prof. Nigel Hussey (HFML) and will take place in the High Field Magnet Laboratory, Nijmegen, The Netherlands **Thursday, 21st of June 2018**.

The aim of this one-day meeting is to update our users on recent developments in the EMFL facilities, exchange ideas and experiences, present scientific results, and discuss possibilities for joint research programs and improving the facilities attractiveness.

During the meeting several talks will be given by the users and the directors of the EMFL to inform the user community about recent scientific and technical developments in high magnetic fields. Users are also invited to present their scientific work on posters.

Registration is free of charge.

http://www.emfl.eu/meetings-and-events/ user-meeting-2018.html

We would like to involve you, our users, in the process of defining the meeting's agenda; please inform us of the specific needs in terms of new equipment or facility developments you have today or may have in the future, so that we could provide you with the corresponding information during the meeting. Do not hesitate to suggest themes that you would like to discuss during the meeting. The User Committee has an online feedback form for all users: www.emfl.eu/user/user-committee.html

Also, users can contact the User Committee directly via e-mail: UserCommittee@gmail.com

The User Committee will meet with the users during the day. Chair of the User Committee is Prof. Raivo Stern (National Institute of Chemical Physics & Biophysics, Tallinn, Estonia).

UPCOMING EVENTS

- EMFL User Meeting 2018, HFML, Nijmegen, The Netherlands, June 21, 2018.
 http://www.emfl.eu/meetings-andevents/user-meeting-2018.html
- 2. RHMF 2018, 12th International Conference on Research in High Magnetic Fields Santa Fe, New Mexico, USA, June 24-28, 2018 http://www.cvent.com/events/rhmf-2018/event-summary-17867d9917 bb4aa989dc3063ee44231e.aspx
- ICM, International Conference on Magnetism, San Francisco, USA, July 15-20, 2018 http://icm2018sf.org/

- HMF23, Toulouse, France, July 22-27, 2018 http://www.hmf23.eu/
- 5. EMFL Summer School, Arles, France, September 26-30, 2018 http://www.emfl.eu/meetings-andevents/emflschool-2018.html
- MG-XVI, 16th International Conference on Megagauss Magnetic Field Generation and Related Topics, Kashiwa, Japan, September 25-29, 2018
 https://www.issp.u-tokyo.ac.jp/public/MG-XVI/index.html

16TH INTERNATIONAL CONFERENCE ON MEGAGAUSS MAGNETIC FIELD GENERATION AND RELATED TOPICS (MG-XVI)

25-29 September 2018, Kashiwa, Japan

The 16th International Conference on Megagauss Magnetic Field Generation and Related Topics (MG-XVI) will take place at the University Tokyo, Kashiwa campus, Chiba, Japan, September 25-29, 2018.

The aim of this conference is to provide a platform for scientists to exchange information and ideas among the members of the international scientific community in the domain of generation and application of ultra-high magnetic fields (above 100 T), ultra-high magnetic field applications in basic and applied research in solid-state physics, high-energy and high-current pulsed power physics and technology, magnetic-flux compression technologies for the production of multimegagauss fields, atomic physics and chemistry, high-energy density physics and for other related and novel technical applications. The MG-XVI conference encourages opportunities for a strong interaction and networking among experienced and young scientists, engineers, and students involved in this extremely interesting and unique research area.

Important Dates:

Abstract submission deadline: April 30th, 2018 Early bird registration deadline: July 15th, 2018 MG-XVI conference: September 25th-29th, 2018

Contact information:

https://www.issp.u-tokyo.ac.jp/public/MG-XVI/ index.html











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