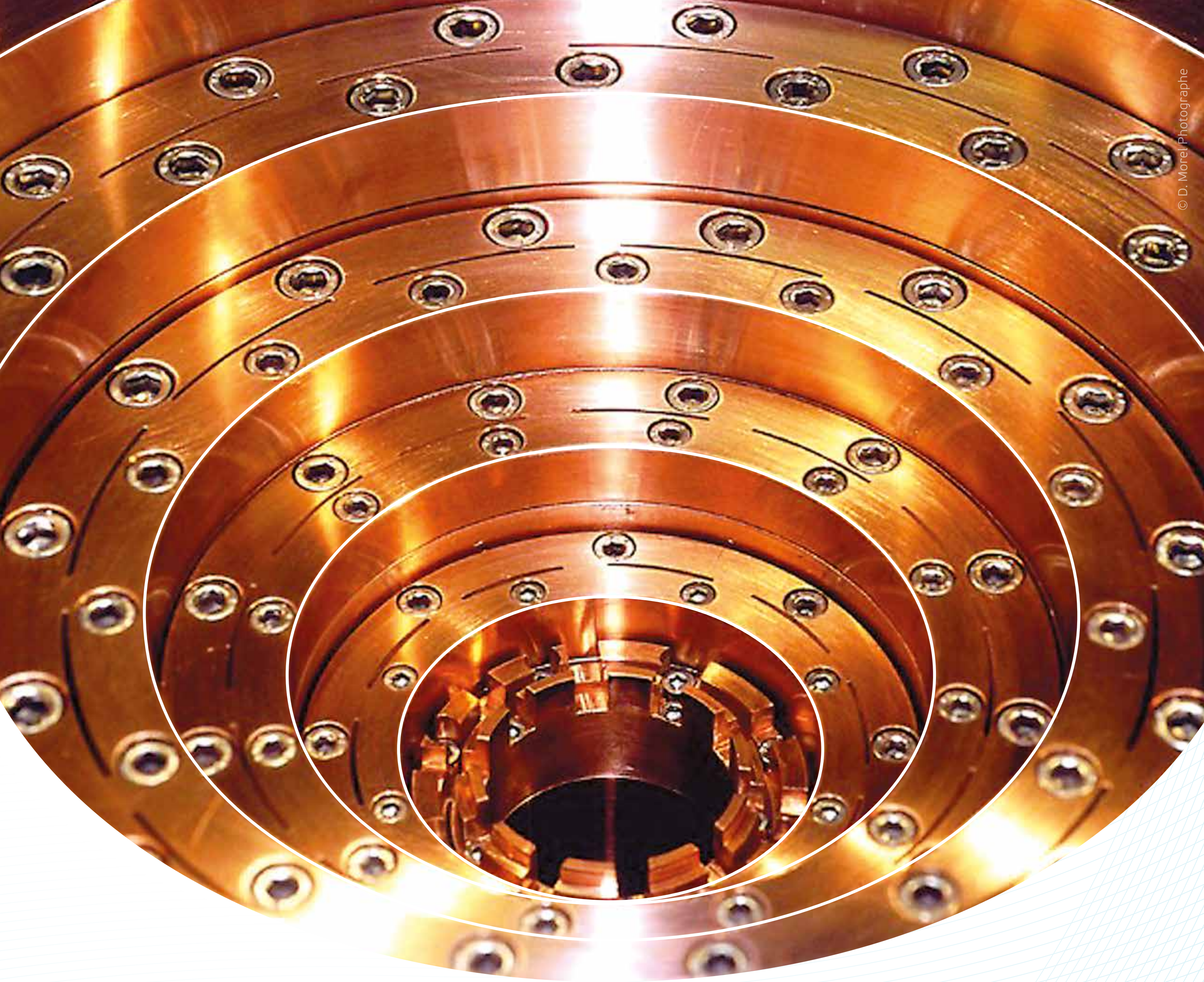
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MAGNIFICENT MAGNETS

SCIENCE IN HIGH MAGNETIC FIELDS

EMFL
European Magnetic Field Laboratory

1 HFML Nijmegen
2 LNCMI Toulouse
3 LNCMI Grenoble
4 HLD Dresden

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WELCOME TO THE EUROPEAN MAGNETIC FIELD LABORATORY

High magnetic fields are powerful tools used to study, modify, and control the different states of matter. It is the mission of the European Magnetic Field Laboratory (EMFL) to generate the highest possible magnetic fields for use in scientific research and make them available to the scientific community.

A EUROPEAN COLLABORATION

In a truly European spirit, the three European major high magnetic field laboratories are working together as a single unit: the EMFL. Located in the heart of Europe, the unique magnets attract scientists from all over the world who are in need of these extreme fields for their research. The EMFL's high magnetic fields help scientists reveal sometimes unexpected – but always highly valuable – properties of the materials they are studying. The strong fields can be arranged in such a way that they are even able to turn gravity upside down! No need to conduct research in a spaceship when you have a strong magnet you can use instead.

INNOVATIONS

High magnetic field experiments are the ideal way to gain insights into the matter that surrounds us. Magnetic fields allow for the systematic manipulation and control of material properties – which is why these kinds of experiments are conducted on new materials so that their fundamental properties can be explored and so that they can be optimised for future application. Very commonly, materials research provides the basis for innovations that help boost the economy while offering clean technology solutions to problems we are finding ourselves faced with in today's world. Think only of energy-efficient data storage, solar cells, sensors – the list goes on.

16 NOBEL PRIZES IN PHYSICS, CHEMISTRY, AND MEDICINE ARE CLOSELY LINKED TO MAGNETIC FIELD RESEARCH.

AMONG MANY OTHER THINGS, THE EMFL SCIENTISTS …

TAME EXTREMELY STRONG FORCES

The forces acting within the EMFL magnets are incredibly powerful. In a strong magnetic field of about 100 teslas, the magnetic force inside the conductor would generate a pressure that equals 40,000 times the air pressure at sea level. However, one should always bear in mind that these magnets are research tools and that their utility doesn't depend exclusively on the field strength. Other factors such as pulse duration and bore size are also important for realizing state-of-the-art high-field measurements.

CREATE MAGNETS FOR OTHER EUROPEAN OR NATIONAL LARGE RESEARCH FACILITIES

Transportable pulsed magnets and generators allowing fields of up to 40 teslas to be combined with large neutron, X-ray, or laser sources have been developed at the EMFL labs. Neutron and synchrotron experiments in pulsed fields allow researchers to reveal the microscopic properties of matter; they are conducted jointly between the EMFL and a number of large facilities that are leaders in their field, such as the Institut Laue-Langevin and the European Synchrotron Radiation Source in Grenoble, France, both of them European research facilities.

FIGHT CANCER

Magnetic fields can help defeat cancer. Not only are they used to trace tumours with the help of magnetic resonance imaging (MRI), EMFL researchers also want to use them to come up with a compact and inexpensive alternative to present-day cancer therapies – such as proton beam therapy using laser-particle acceleration. Pulsed magnets, developed and built in the EMFL labs, could be used to focus the rays on the tumour with high precision so that the energy can be discharged in exactly the right spot. However, until these new developments find their way into hospitals and to patients, a lot more research has to be done.

FORM METAL

Along with their external partners, EMFL researchers are investigating possibilities for forming, joining, and welding metals, which could otherwise not be welded. How is this supposed to work? By using very short and intense magnetic-field pulses, large compressive forces may act on materials. For that reason, work pieces can be deformed at enormous speeds – even to the point where they get joint or welded together although not heated. Pulsed electromagnetic field forming, joining, and welding is an energy-efficient cutting-edge technology with many extra benefits for economy and environment.

EMFL RESEARCH IN YOUR HANDS

Your mobile phone is actually made up of a lot of different materials and technologies that all originated in materials research. The processor consists of many tiny transistors in the nanometre range. The bright screen that so brilliantly shows your pictures is most likely made from a thin film. Electrons run through this film, in the process changing the colours so that you end up getting this very brilliant image. And the memory is made from materials designed with insights gained from magnetic field research.

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WHAT DOES IT TAKE TO CREATE A MAGNETIC FIELD?

Electric currents generate a magnetic field. By winding a metallic wire into a coil, the magnetic field is concentrated at its centre. Enormous currents are needed to create a strong magnetic field.

The EMFL labs' capacitor banks in Toulouse and Dresden are capable of generating the large currents necessary to produce pulsed high magnetic fields.

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DR KAMRAN BEHNIA

LABORATOIRE DE PHYSIQUE ET D'ÉTUDE DES MATÉRIAUX, PARIS

»Over the past couple of decades, I've been exploring the way entropy is carried by electrons travelling in a solid body. One particularly interesting phenomenon is the ›Nernst effect‹, a tiny voltage, which appears when heat flows in the presence of a magnetic field. The Nernst effect is particularly significant in such semi-metals as bismuth and graphite, which have a low concentration of conduction electrons. In these solids, a single mobile electron is shared by several thousand atoms, which gives it a rather long wavelength. Moreover, each single one of these electrons is extremely mobile and capable of carrying a lot of entropy.

My group has become a regular visitor at the EMFL high field facilities where we are able to study the Nernst effect. For our investigations, we need strong magnetic fields. A magnetic field confines electrons to quantized orbits. The larger the magnetic field, the smaller the quantized orbit. A particularly interesting situation arises when the orbit's radius becomes comparable to the electron wavelength. This is the quantum limit when the electron's particle- and wave-like personalities clash. Our Nernst experiments have shown that the physics become highly complex in this case – much like an intricate puzzle with many different pieces that have to all be arranged in the proper order.

Over the last few years, we have performed experiments on various systems ranging from superconductors to insulators in world-class facilities at Grenoble, Toulouse, and Nijmegen. Not only did our hosts at these facilities grant us access to their powerful magnets, they also shared with us their impressive technical know-how. We greatly appreciate the user-friendly atmosphere, which is very welcoming to people like us wishing to implement a new, unusual experimental technique in strong magnetic fields. We hope to be regular visitors at the EMFL facilities also in the future.«

WHY ARE MAGNETIC FIELDS SO USEFUL FOR RESEARCH?

Anyone who has ever played with a magnet will have witnessed its ability to attract iron from a distance. Magnetic fields force materials to change the orbit and magnetic spin of their electrons. This allows for changing and controlling of material properties, with many benefits for applications and research. The tailored manipulation of material properties make high magnetic fields a perfect research tool.

Today, strong magnets are used almost routinely in medical diagnostic equipment like MRI scanners, which expose patients to magnetic fields 50,000 times more powerful than Earth's own magnetic field.

HIGH MAGNETIC FIELDS ALLOW SCIENTISTS TO:

EXPLORE THE PROPERTIES OF NEW MATERIALS

Soon after Andre Geim and Konstantin Novoselov first created graphene – a carbon sheet one atom in thickness – in Manchester, they rushed across the Channel to investigate the properties of this extraordinary material in a high magnetic field. At the Nijmegen EMFL magnet lab, they soon discovered graphene's remarkable electronic and conductive properties, a feat which ultimately led to their winning the 2010 Nobel Prize in Physics. The first commercially available technological applications of graphene – such as mobile phones with flexible screens – are now only a matter of time.

MANIPULATE MATTER

Synthetic or organic materials are frequently made up of long, entangled molecules. Their structure resembles a plate of cooked spaghetti. When these molecules are exposed to a magnetic field, they can be aligned in one direction – like boxed dry spaghetti. This can change an opaque into a transparent material or improve the electrical conductivity of organic materials. Because like the spaghetti, the molecules will all be pointing in the same direction, and they'll transport energy much more efficiently. Using this technique, coronene molecules were used to create an organic transistor.

WHAT DOES TESLA MEAN ANYWAY?

The tesla (abbreviated T) is the international standard unit of the magnetic field or, more precise, of the magnetic flux density. A traditional horseshoe magnet is one tenth of a tesla. Earth's magnetic field is considerably smaller (thirty thousand times smaller than a tesla). The EMFL magnets range from 37.5 teslas for a continuous field to 94 teslas for a non-destructive pulsed field all the way up to 180 teslas for semi-destructive fields.

MANIPULATE GRAVITY

Every single molecule on this planet is formed in the realm of gravity, regardless of whether it's nature-made or man-made. This makes it very difficult to discern the influence of gravity on the molecules' form and function. Because the EMFL magnets are so strong, they can, for instance, levitate a droplet of water – which makes them ideal tools for studying the effects of gravity. As an extra-added bonus, the gravitational force can be scaled or even reversed.

DEVELOP SUPERCONDUCTOR APPLICATIONS

Superconductivity is a unique property of matter, which corresponds to a state of zero electrical resistivity where a magnetic field can be completely expelled from the material. This phenomenon is usually restricted to low temperatures, and the highest-temperature superconductors discovered to date exist in this state only at temperatures lower than minus 100 degrees Celsius. In the EMFL labs, a lot of effort goes into the application of high-temperature superconductivity to energy storage and transport, but also into developing magnetic levitation.

SEARCH FOR NEW PERMANENT MAGNETS

Most magnets used in everyday applications such as super strong kitchen magnets or the magnets found in wind turbines and cars contain neodymium, a rare-earth element. Because one day, we will be running out of this element and because its use is bad for the environment, alternative options are needed. As such, researchers are working on developing materials with neodymium-like properties or brand new magnetic materials that can be used to create smaller, more efficient electric motors. Magnetic fields can help scientists reveal the hidden physical properties of such materials.

PROF LOUIS TAILLEFER &
DR NICOLAS DOIRON-LEYRAUD

DÉPARTEMENT DE PHYSIQUE, UNIVERSITÉ DE SHERBROOKE, CANADA & CANADIAN INSTITUTE FOR ADVANCED RESEARCH

»High-temperature superconductivity is widely regarded as one of the great mysteries of physics and a field of research with immense technological potential in areas as varied as energy transport, communication, and medicine. The cuprate high-temperature superconductors are the focus of our research programme. To better understand their underlying normal state, we suppress superconductivity and reveal the normal state in our specimens by exposing them to a high magnetic field. Because exceptionally high magnetic fields on the order of tens of teslas are necessary for cuprate materials, the experiments have to be performed at designated high field facilities. The scientific journal *Physics* recently remarked on the fact that ›the most important breakthrough [on cuprate superconductivity] was the detection of definitive quantum oscillations in high magnetic fields in 2007 by Taillefer's group‹. Without the high magnetic fields available at the Toulouse site, this breakthrough would not have been possible.

High magnetic fields provide a unique window into the normal state of high-temperature superconductors. There is no way around it, only high fields can do this. And as new and more sensitive high field experiments are under way, this will continue to be the case for years to come. Access to high field facilities through the EMFL network will remain essential to our field of research.

We chose the Toulouse and Grenoble high field laboratories because they are world-class facilities that provide some of the most intense, quiet, and reliable magnets available for research in condensed matter physics. Over the last decade, we've been regular visitors at both sites, working closely with our local hosts. In this respect, the Canadian Institute for Advanced Research (CIFAR) represents a direct bridge between the Canadian community and the European Magnetic Field Laboratory.«

?

PULSED OR CONTINUOUS?

Two of the EMFL labs – Toulouse and Dresden – specialise in pulsed magnetic fields, meaning they generate huge magnetic fields of up to about 100 teslas using non-destructive magnets for a short period of time – on the order of tens of milliseconds. At the Toulouse site, even higher magnetic fields, up to 180 teslas, are generated by semi-destructive magnets (the coil but not the sample is destroyed during the pulse) within microseconds. Of course, these magnets are used for measurements that can be performed very quickly.

The continuous field magnets at the Grenoble and Nijmegen EMFL sites are capable of maintaining a constant maximum field (currently up to 37.5 teslas and, in a few years, up to 45 teslas), which makes these magnets ideal for measurements that require a longer time scale. The coils can be used for thousands of hours before they need to be replaced.

INVITING THE WORLD'S BEST SCIENTISTS

Every year, the excellent infrastructure of the four EMFL sites attracts hundreds of scientists from all over the world. An international panel of experts, often affiliated with external institutions, reviews all applications. Due to the large number of applicants, only the best scientists with the most promising projects are invited.
The scientists are looking for modern laboratories, a range of experiments, and assistance with their research projects. Once they have been selected to work at one of the three EMFL labs, they're very enthusiastic because they end up getting much more than they bargained for:

- four of the most successful labs of their kind worldwide
- state-of-the-art experimental technology and instruments
- world-class support by highly motivated researchers, engineers, and technicians
- a fruitful and innovative atmosphere
- a global scientific exchange with top scientists

But that's not all. In order to stay globally competitive – similar laboratories exist in the US, Japan, and China – there's still a lot more work to be done. That is why the EMFL scientists are always looking to move forward. They continuously construct new coils, reach higher fields, develop experimental techniques to make new results possible, and reach unprecedented sensitivities.

International users can always count on getting help from motivated and experienced staff.

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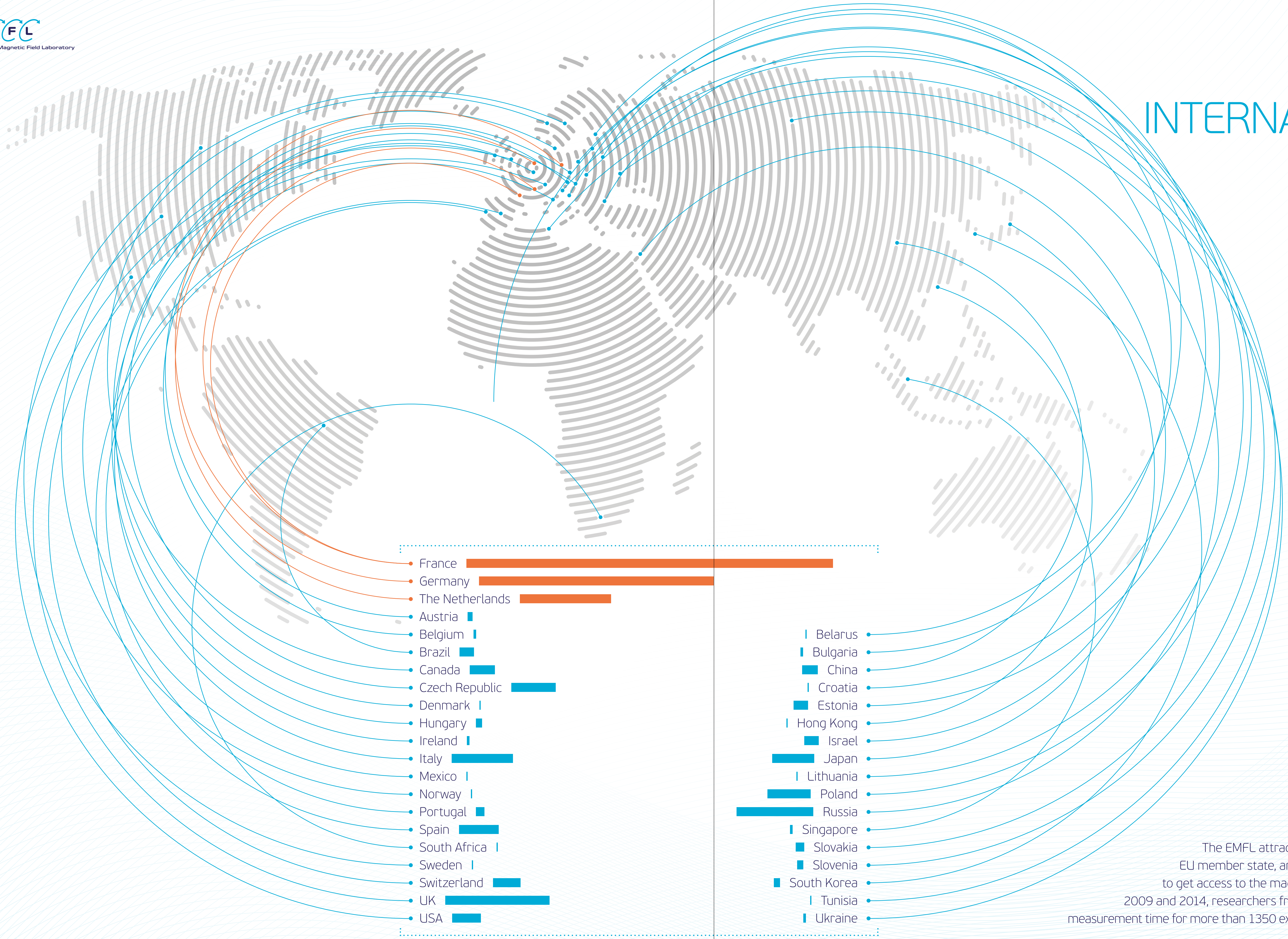
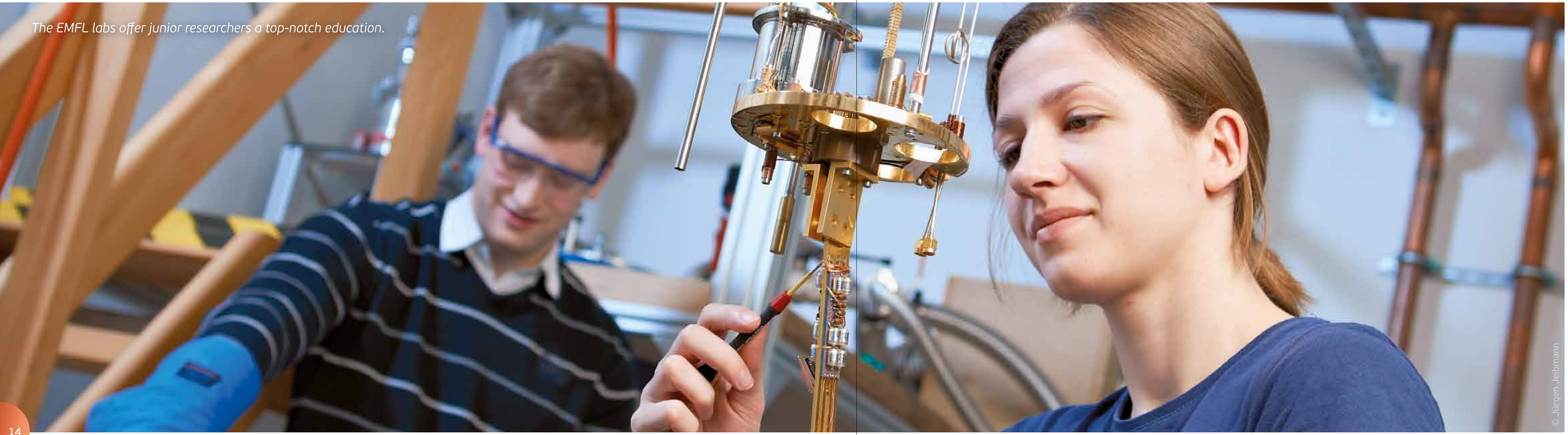
INTERNATIONAL USERS



The EMFL attracts users from almost every EU member state, and many travel even further to get access to the magnificent magnets. Between 2009 and 2014, researchers from 38 countries applied for measurement time for more than 1350 experiments in the EMFL labs.



The EMFL labs offer junior researchers a top-notch education.

© Jürgen Jeibmann

TRAINING YOUNG RESEARCHERS

The EMFL attracts not only physicists, chemists, biologists, materials scientists, and engineers, but also young scientists including university and even high school students. They're all fascinated by the EMFL's magnificent magnets and groundbreaking discoveries. And they want to be part of a creative, global scientific research community.

The EMFL partners motivate the younger generation to choose a career in the sciences by exposing them to exciting and internationally oriented research. Dozens of bachelor, master, diploma, and Ph.D. students as well as postdocs are finding excellent working conditions and intense training here.

MAHDIYEH GHORBANI ZAVAREH
PHYSICIST, IRAN

»I studied physics in Iran, and I'm now a Ph.D. student at the Dresden EMFL lab. Since I come from a theoretical physics background, for me, experiments in high magnetic fields are completely new territory. At first, I was a little bit concerned. But since I've been here, I really like it. My supervisor is simply wonderful – he supports me to the outmost and explains everything. I'm still only at the very beginning of my three-year journey here at Dresden. My research is focused on the magnetocaloric effect. The MCE is defined as the heating or cooling of a magnetic material in the magnetic field. It's a powerful experimental tool in solid state physics.

But it also has direct applications in magnetic refrigeration and heat transfer. Since we have extreme magnetic fields available here, we plan to investigate phase diagrams of novel materials. And the pulse duration of our magnets provides versatile and realistic conditions for magnetic refrigeration applications.«

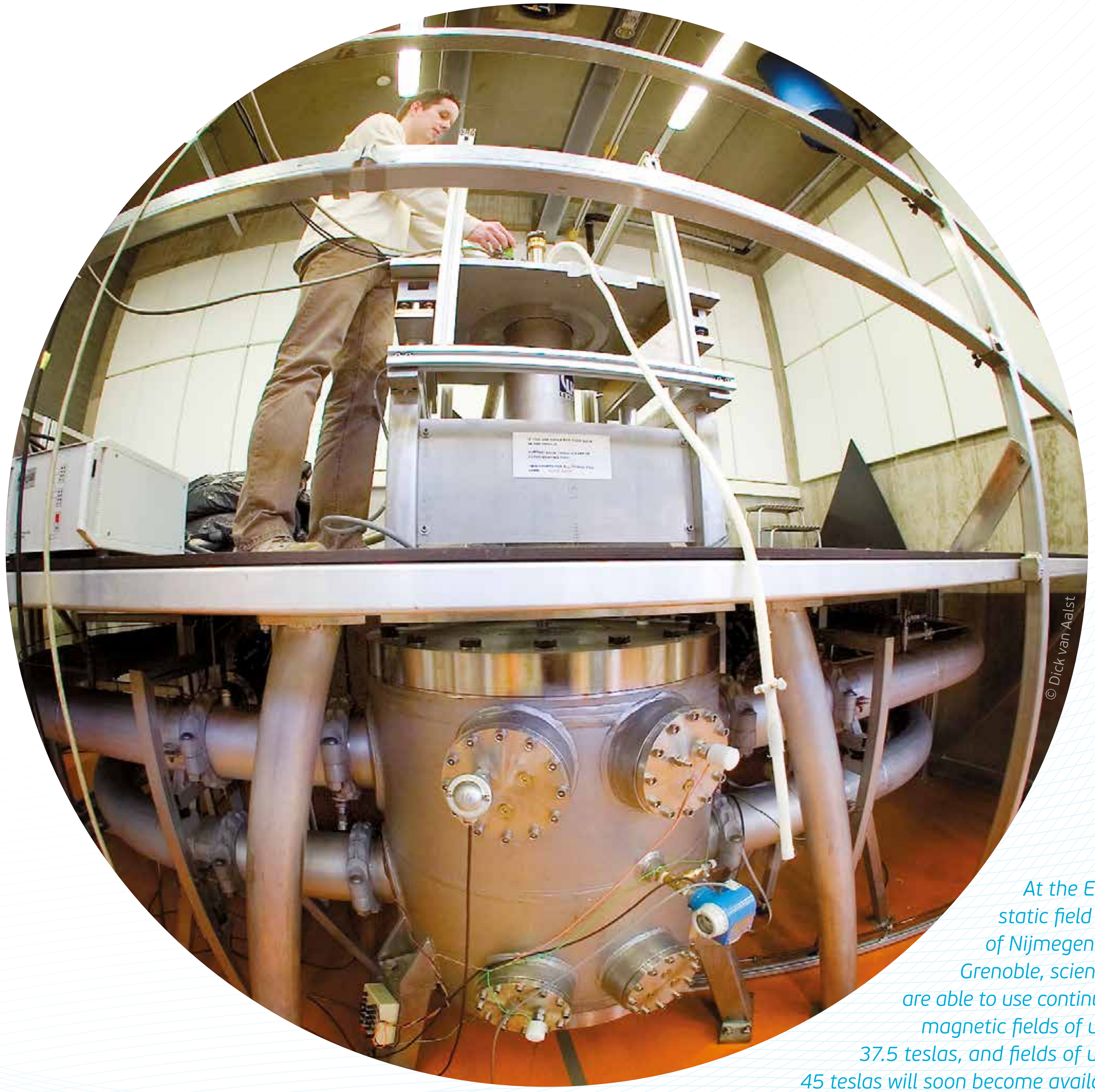
© Gerard Verschooten

SIR KONSTANTIN NOVOSELOV, WHO, TOGETHER WITH SIR ANDRE GEIM, **WAS AWARDED THE 2010 NOBEL PRIZE IN PHYSICS** FOR THE DISCOVERY OF THE TWO-DIMENSIONAL VERSION OF CARBON, WHICH IS NOW KNOWN AS GRAPHENE, WAS A **PH. D. STUDENT** AT THE DUTCH EMFL SITE, THE HIGH MAGNETIC FIELD LABORATORY AT RADBOUD UNIVERSITY IN NIJMEGEN. HE RECALLS THE DAYS WHEN HE FIRST ARRIVED FROM RUSSIA IN 1999:

»The magnet lab was a really buzzing community. International, young, friendly, a range of available projects, visitors with exciting experiments and techniques you had never heard of before, and complex equipment, which always required an extra bit of imagination. All you needed to do was to keep your eyes wide open (especially because my supervisor at the time – Andre Geim – is one in a million) and learn. The group put together by Jan Kees Maan really pushed you hard, with everybody being at the same time supportive yet informal, demanding yet encouraging – from Ph.D. students and post-docs all the way to technicians and academics.

A good example was our movie club. We had to start the club sessions fairly late. For one, because we typically ran our experiments until late, but also because we essentially had to break into one of the auditoriums with a data projector. These get-togethers, which also attracted people from other groups and departments, quickly transformed into heated discussion forums about anything and everything: science, politics, movies, relationships, etc.

Later, when I was already in Manchester, I always enjoyed my visits to Nijmegen, where I could conduct my experiments in high magnetic fields. Helpful and hard-working staff made those visits even more enjoyable. In 2005, we took our first graphene device over to the magnet lab and obtained detailed measurements of the quantum Hall effect in this material. High fields allowed us to observe this effect even at room temperatures, which was the topic of our publication in the journal Science in 2007.«



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At the EMFL static field labs of Nijmegen and Grenoble, scientists are able to use continuous magnetic fields of up to 37.5 teslas, and fields of up to 45 teslas will soon become available.

WHY ARE THE LABORATORIES SO BIG?

Regardless of whether you find yourself at Nijmegen, Grenoble, Dresden, or Toulouse – each EMFL site is a big, factory-like building filled with cutting-edge technology capable of generating the highest magnetic fields, and with sophisticated equipment for measuring tiny signals in the small samples. Next, the researchers will proudly explain to you that their magnets' bore sizes are between five millimetres and five centimetres in diameter. That doesn't sound impressive? Oh, but it is! To create a magnetic field that is high enough to lift a droplet of water, the electrical power normally used by the inhabitants of an entire city district or a village is released and concentrated in one coil to create this high magnetic field. And handling the power and energies requires a lot of space.

To keep the continuous-field magnets from melting, large amounts of water are pumped through them – roughly one bathtub full per second, at a high enough pressure to make a 300 metre fountain.

Inside the pulsed-field labs, the coils are cooled down to a temperature of around minus 196 degrees Celsius using liquid nitrogen.

Europe's highest magnetic fields are produced using the pulsed-field facilities of the EMFL laboratories in Dresden and Toulouse.

© Uwe Tölle

REACHING OUT: BEING A DRIVING FORCE FOR SCIENCE AND THE ECONOMY

To develop magnificent magnets and unique power supplies, innovative technology solutions have to be continuously unearthed. In this field, for many years now, the EMFL labs have set new standards – on an international scale. This, of course, is only possible through the close-knit collaboration with a number of regional and international partners from industry and the sciences.

The challenges EMFL scientists and technicians are finding themselves faced with often lie at the cutting edge of technological feasibility. It does pay off, though, as the acquired expertise can be used for a number of high-tech applications – say, for forming processes in industry or for a more efficient use of liquid hydrogen fuel in Ariane rockets. In addition, a number of scientific institutions use these developments for their own research projects – in many cases using technologies that were unthinkable only a few years ago.

WHY DO THE RESEARCHERS SOMETIMES WORK AT NIGHT?

The electricity required to generate continuous magnetic fields is so high that often the magnets have to be run at night to prevent brownouts, which would depress the voltage in the surrounding region's power grid. Incidentally, the energy generated by the cooling systems is not lost but recovered. In Nijmegen, for example, the nearby Faculty of Science is heated during the winter and cooled during the summer using stored heat from the high magnetic field lab.

Normally, scientists working with pulsed-field magnets don't need to work at night. Since a pulsed magnet experiment only runs for a few milliseconds, it's a relatively inexpensive affair. Recharging the capacitors that store the energy for the high-performance coils takes but a few minutes – and, in most cases, costs less than 10 euro cents per pulse.

REACHING OUT: MAKING SCIENCE A HANDS-ON EXPERIENCE

What is magnetism? How are magnetic fields generated? And what are they good for? The EMFL scientists are confronted with these and other questions whenever they open their doors to students and other interested parties. With great passion and creativity, they show visitors the work they do, the huge magnet coils, and the exciting experiments that are currently being conducted. The result: answers to many questions, a lot of astonishment, and a better sense of what goes on here.

- The EMFL labs welcome school classes and student groups on a regular basis
- Every second year, the Dresden High Magnetic Field Laboratory organizes an Open House Day and participates annually in the »Dresden Long Night of the Sciences«
- Each year, the labs in Grenoble and Toulouse open their doors to the public during »La fête de la science«
- During »La nuit des chercheurs«, Toulouse scientists regularly present their research to the general public
- Nijmegen is open for guided tours, is featured in many international popular science programmes on magnetism (BBC, CNN, Eurochannel), and offers lectures to schools and to the general public
- A team of EMFL scientists regularly visits kindergartens and shows the kids in a playful way what a magnet is

Open doors: EMFL staff share their knowledge and their passion with children, students, and anyone else who is interested.

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IMPRINT

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

The EMFL is operated by its Board of Directors: Jan Kees Maan (Chairman of the Board), Nigel Hussey (Director of the HFML), Geert Rikken (LNCMI Director), and Joachim Wosnitza (HLD Director).

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