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ISABEL

Improving the sustainability of the European Magnetic Field Laboratory

Global Collaboration Strategy Paper

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DOCUMENT ABSTRACT

The aim of task 7.2 is to create a strategic roadmap for further research and development to address technical and material issues associated with the next generation of high-field magnets, already called for by the international research community and reports from prestigious research panels. This task is complementary to the technical roadmap elaborated in WP9. Continuous magnetic fields up to 45 T are currently generated by resistive magnets, using 20 MW or more of electrical power, without or with a superconductor outsert coil. Pulsed magnets can currently generate fields up to 100 T (repeated operation) and up 1000 T using magnets that can be used once. The next generation of high-field magnets requires substantial advances in our present state-of-the-art, taking place on a global scale and taking advantage of collaborations among the major organizations interested in the development of new magnet technologies. The development of new materials, including high-temperature superconducting (HTS) materials, will be necessary to push the possible fields to higher levels. Progress in this area has been reported on a number of international workshops and international conferences, as listed in D7.1 and D7.2. This document describes the state-of-the-art of magnets in the high-field facilities on different continents (East Asia, Europe and USA), as well as a roadmap how to realize the next generation high field magnets, including the analysis of whether global collaboration can contribute to this process.

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1. State of the Art

Worldwide there are only a small number of countries that offer user access to high-magnetic-field facilities for scientific discovery, with power supplies of 20 MW or more for static fields and more than 10 MJ stored energy for pulsed magnetic fields.

The EMFL (European Magnetic Field Laboratory) has four sites in Grenoble (LNCMI-G, Laboratoire National de Champs Magnétiques Intenses-Grenoble), Toulouse (LNCMI-T), Nijmegen (HFML, High Field Magnet Laboratory), and Dresden (HLD, Hochfeld-Magnetlabor Dresden). LNCMI-G and HFML offer DC fields with maximum fields of 37 and 38 T, respectively. LNCMI-G has demonstrated the operation of a 42 T Hybrid magnet and a high temperature superconducting insert coil reaching 32.5 T together with a resistive outsert coil. LNCMI-T and HLD offer pulsed magnetic fields with maxima near 100 T.

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The NHMFL (National High Magnetic Field Laboratory or MagLab) in the USA has three sites: The main site in Tallahassee offers static magnetic fields, the branch at the Los Alamos National Laboratory provides access to pulsed magnetic fields (*B*), and Gainesville enables measurements at ultra-low temperatures (*T*) in superconducting magnets, i.e., at large *B/T* ratios. The NHMFL produced 45 T using a hybrid magnet, 41 T using a purely resistive magnet, 32 T with a fully superconducting magnet and 100.7 T with a pulsed magnet.

China has invested heavily in the development of high-magnetic-field facilities, the static-field lab in Hefei and the pulsed-field lab in Wuhan. In Hefei, a hybrid magnet with fields up to 45.2 T and fully resistive magnets up to 41.5 T are advertised for users. Recently, a 35 T all-superconducting magnet has been successfully tested. At the WHMFC (Wuhan High Magnetic Field Center) in Wuhan, a suite of pulsed magnets with a record field of 90.6 T is provided. A WHMFC specialty is flat-top pulsing.

In Japan, a pulsed-field facility with user access is situated at the ISSP (Institute for Solid State Physics), University of Tokyo, offering pulsed fields in the range of 60 T for some 10 milliseconds (also with electronically stabilized flat top) and, uniquely, destructive fields using the electromagnetic flux-compression technique beyond 1000 T are produced. Another university-scale 60-T pulsed-field installation is run at Osaka University, mainly for bilateral ESR projects. Static fields beyond the commercially available fields of about 22 T produced by low-temperature superconductors are, at the moment, in Japan only offered at Tohoku University in Sendai, where cryogen-free superconducting magnets are installed (24 T in a 52 mm bore and 30 T in a 32 mm bore for an 8 MW hybrid magnet), using high-temperature super-conductors for the inner SC coils. These three laboratories have recently together created the Japanese High Magnetic Field Collaboratory (https://hf-colabo.jp/en/).

The table below shows an overview of the available magnets at the respective facilities.

Continent/ Country	Location	Hybrid	DC - resistive	DC - SC	Pulsed Non-destructive	Pulsed Destructive
Europe - EMFL	Grenoble	42 T	37 T	32 T**	-	-
	Nijmegen	45* T	38 T	-	-	-
	Toulouse	-	-	-	98 T	210 T
	Dresden	-	-	19 T	95 T	-
USA - NHMFL	Tallahassee	45 T	41 T	32 T	-	-
	Los Alamos	-	-	-	100.7 T	-
	Gainesville	-	-		-	-
China	Hefei	45.2 T	42 T			
	Wuhan	-	-	-	90 T	-
Japan	Tokyo	-	-	-	60 T	985 T
	Sendai	30 T		24 T	-	-
	Osaka					

*under construction **demonstrated

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2. Global Roadmap

The high-field magnet facilities are continuously working on upgrades of their magnets and the associated instrumental infrastructure to push forward the experimental capabilities and to create the best possible conditions for scientific discovery. The generation of such intense magnetic fields is very challenging due to the extreme forces and power densities that must be addressed. As such, modern high-magnetic-field installations require a high level of specialized technical and scientific expertise to operate, as well as major capital investments. To this end, the different countries and laboratories work with the formulation of roadmaps working towards new infrastructure, describing not only the scientific case but also the technological and operational challenges, and the investment and running costs. In recent years, several organizations have produced documents and white papers that address the future direction of high-magnetic-field science and technology. In the USA, the National Academy of Sciences and the National Science Foundation has issued an extensive report on the status and future direction of high magnetic field science and technology in the United States [1]. The report discusses the use of magnets in its broadest sense and is not limited to the highest possible fields, as discussed in section 1. It describes the development of materials (high-strength conductors and superconductors) to construct magnets for magnetic resonance-spectroscopy (NMR and MRI), fusion, condensed-matter physics and high-energy physics (accelerators), as well as how to implement these magnets in the scientific community. The Superconductivity Global Alliance (ScGA) has recently written a white paper to describe the prospects of new superconducting materials for Discovery Science [2], distinguishing High-Magnetic Field Science, High-Energy Physics and Nuclear Physics. The EMFL has described its ambitions for the further development of its infrastructure in its strategy document [3]. Part of this document will be updated, based on the outcome of the SuperEMFL project (all superconducting user magnets) and this ISABEL project, particularly of WP6 (specialty magnets), WP7 (global developments) and WP9 (EMFL magnet roadmap). The Asian countries (China and Japan) did not publish their future magnet technology and science programme, but they have announced substantial investments. In Japan, a five-year project with a budget of 6 M€ has been approved [4]. At the WHMFC, a project with a budget of about 270 M€ has been approved to be completed in 2028 [4]. The plans include a 110 T pulsed magnet, a 70 T pulsed magnet with flat-top, and a 9.4 T, 800 mm bore MRI system. In Hefei, the power supply will be upgraded from 28 MW to 42 MW within 2 years [4,5].

The plans for the different high-field facilities around the world differ in the details, but from the documents cited above [1-5] a general roadmap for the future magnets can be distilled.

- 100 T+ non-destructive pulsed user magnet
  Non-destructive pulsed magnets are amongst the workhorse instruments for research at the highest magnetic fields. Since a number of years, the maximum obtained field is 100 T. Higher fields are possible by the further development of existing technology. In the USA a recommendation has been made to develop a non-destructive magnet to a field of 120 T. Similar plans exist in China and at EMFL.

- MegaGauss generators
  To date, fields beyond 100 T can only be produced by pulsed magnets that are destroyed after use. Semi-destructive user magnets (the coil is destroyed, but everything inside the

coil remains intact) are offered in Japan and Europe with maximum fields up to about 250 T. In Japan, fully destructive user magnets reaching up to 1000 T are available. These highly specialized activities require specific operation of both the magnet installations as well as the experimental instrumentation for the actual measurements. Upgrades of the MegaGauss facilities for structural user operation are planned in Japan and Europe.

- 60 T-class DC magnet (Hybrid)
  DC magnets have been extremely instrumental to push forward our knowledge of matter, in particular for those experimental techniques or conditions that cannot be realized in pulsed magnets. Since more than two decades, the highest continuous DC field is 45 T. It would be extremely scientifically advantageous to push up this boundary, which would require the combination of resistive and superconducting technologies (Hybrid). In the USA a recommendation has been made to develop a 60 T Hybrid magnet and similar plans exist in China. In Europe no concrete plans exist currently to construct a Hybrid magnet beyond 45 T.

- 40 T-class all superconducting magnet
  With the further development of high-temperature superconductor-wire technology, 40 T -class superconducting magnets come within reach. Such magnets would allow long duration experiments at lower operational costs than resistive DC magnets and can be combined with the largest scope of experimental techniques and conditions. The development of the next generation of all-superconducting user magnets up to 40 T has been started in Europe, Japan, China, and the USA.

- Advanced magnets for specific applications
  Facilities for neutrons and advanced light sources, including those for X-ray and THz radiation, provide a platform for investigations of matter that cannot be done elsewhere. It is, therefore, important to develop high-field magnets that are compatible with such large-scale infrastructures. Worldwide the targets are 20 T+ DC Magnets and 40 T+ pulsed magnets for neutron and light sources (synchrotrons, free electron lasers and high-power lasers). Developments are planned in China, USA, and Europe.

Detailed descriptions of these magnets will be given in ISABEL-WP6 and ISABEL-WP9, together with the technological challenges to build them. This list is restricted to the magnets of interest to EMFL. Other developments such as large-bore superconducting magnets for applications in accelerators and fusion reactors or MRI magnets are not included.

3. Collaborations: Global and European

EMFL is involved in a number of global initiatives, in which the further development of high-field magnets is evaluated and discussed. EMFL is a founding member of the Global High Magnetic Field Forum HiFF (https://globalhighfieldforum.org/), which is a consortium of all major high-magnetic-field infrastructures in China (Hefei and Wuhan), Japan (Sendai and Kashiwa), the USA (Tallahassee, Los Alamos and Gainesville), and Europe (Nijmegen, Dresden, Grenoble and Toulouse). Together, these laboratories represent the research community that uses the highest magnetic fields available worldwide. EMFL is also member of the CERN-based High Field Magnet Network, which pursues accelerator-magnet research

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and development with low-temperature- and high-temperature superconductor technology. EMFL is involved in the Superconductivity Global Alliance (ScGa), which envisions to develop superconductivity and superconducting magnets to mainstream technological applications (https://scga.uk/). EMFL has an ongoing memorandum of understanding (MoU) with the Japanese High Magnetic Field Collaboratory. Within this MoU, the partners strive to encourage visits of their staff members from one institution to the other, strengthen their cooperation, exchange scientific information, and promote the use of the partner facilities in their respective scientific communities.

Despite these networks, true global collaborations on developing technology for high field science (the primary scope of EMFL) are scarce. The institutions in the USA and China have indicated that they have the ambition and capability to perform main developments mentioned in section 2 on their own, with perhaps the 60 T Hybrid as an exception. Furthermore, the current political climate is such that collaborations involving USA and/or China are quite difficult. Intense collaboration with Japan is feasible in the area of the MegaGauss fields, which will be pursued in the near future, as described below.

The situation described above implies that EMFL is forced to realize most of the developments alone or with its European partners, such as Institut Laue-Langevin (ILL) in Grenoble, ESRF in Grenoble, European XFEL in Hamburg, BESSY II in Berlin, Laser Mégajoule (LMJ) in Bordeaux, the ELBE free electron lasers at HZDR Dresden, the FELIX free-electron laser in Nijmegen and the FuSuMAtech consortium. Associated industrial partners in Europe are Oxford Instruments, Bilfinger Noell GMBH, Theva Duennschichttechnik GMBH, and I-CUBE Research. Within these partnerships EMFL plans the development of the following type of magnets.

- 100 T+ non-destructive pulsed user magnet
  Achieving non-destructive magnetic fields of 100 T has long been a strategic objective for the pulsed field facilities within EMFL. Two major initiatives are currently underway to surpass this threshold. New multi-coil designs, i.e., three- or four coil, systems are ready for testing, enabled by recent breakthroughs in reinforced conductor technology and the apparent increase of materials' strength. Further refinement of the coil materials will remain required to push up the highest magnetic fields strengths. Additional development efforts focus on new designs, such as reduced bore diameters for faster cooling cycles, and configurations capable of achieving higher peak fields.

- MegaGauss generators
  Currently, the ISSP in Kashiwa is the only place worldwide where fields beyond 200 T can be routinely used. Acces to this installation is now offered to European scientists through the EMFL access proposal procedure, facilitated through the ongoing MoU of EMFL with the Japanese High Magnetic Field Collaboratory. Furthermore, an official France-Japan International Research Project (IRP) on MegaGauss techniques and -science is ongoing between CNRS and the University of Tokyo. The IRP's purpose is to stimulate scientific-technical discussions, facilitate the sharing of experimental know-how, and to provide a framework for joint developments. The available financial means are used to organize a yearly workshop alternating between the partner sites, as well as regular exchanges including PhD students, younger and technical staff.

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- 40 T-class all superconducting magnet
  In the SuperEMFL project, EMFL and partners have formulated a roadmap for all-superconducting user magnets. SuperEMFL has designed three different 32 mm bore magnets, each of them consisting of an insert (containing a high temperature superconductor (HTS) part) within a low temperature superconductor (LTS) external magnet:
  [1] A 32 T magnet (13 T insert/19 T outsert magnet)
  [2] A 40 T magnet (21 T insert/19 T outsert magnet)
  [3] A 40 T magnet (25 T insert/15 T outsert magnet)

  Plans and (partial) funding exists in Grenoble and Dresden to finance and construct 32+ T prototype magnets, which makes it so that two prototypes may exist in 2027 in Europe. In the Netherlands, obtaining funding for a prototype is under consideration within the large-scale research Infrastructure (LSRI) programme. Oxford Instruments will be part of the realization of the prototypes. Identification of new industrial partners would be useful for a possible production as well as other research institutions, which would be interested to build further prototypes.

- Advanced magnets for specific applications
  ISABEL WP6 was aimed to structure the magnet aspects of high magnetic field science at advanced sources external to the European high-field facilities. 4 types of external sources were identified, i.e., neutrons (collaboration with ILL and possibly ESS in the future), X-rays (ESRF, BESSY II, and European XFEL), free-electron lasers (ELBE and FELIX) and high-power lasers (LMJ). The most efficient magnet developments would be those that satisfy many of the requirements of all four advanced source types. They were divided in three groups: scattering experiments (neutrons, synchrotrons, XFEL), spectroscopic experiments (IR/THz FEL, XFEL, laser, synchrotrons) and imaging experiments (IR/THz FEL, XFEL, laser, synchrotrons), each of them with specific requirements, as extensively discussed in WP6.
  These considerations resulted in five prospective magnet-design targets for advanced sources:
  [1] 25 T split-coil high-temperature superconductor magnet with a 50 mm room temperature bore for neutron and X-ray experiments.
  [2] 45 T split-coil pulsed magnet with a 20 mm cold bore for neutron and high power laser experiments.
  [3] 45 T solenoid pulsed magnet with a 20 mm cold bore and a wide conical aperture for synchrotron and neutron experiments.
  [4] 60 T radial-axial access pulsed magnet with a 15 mm cold bore; for X-ray and high-power laser experiments.
  [5] 36 T wide bore resistive magnet with a 50 mm room-temperature bore for IR/THz FEL experiments.
  (See deliverable D6.3 for more details.)

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