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ISABEL

Improving the sustainability of the European Magnetic Field Laboratory

Roadmap for magnet development

Start date of the project: 1st November 2020

Duration: 60 months

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DOCUMENT ABSTRACT

The present deliverable provides an overview over technical challenges, development objectives, and the expected implementation of next-generation high-field magnets in Europe. The document is based on prior analyses of the state of the art and expected progress in relevant technological areas as well as user communities and their practical needs. Economic limitations are likewise taken into account. Apart from performance specifications such as field strength, duration or experimental space, the energy-efficiency and durability of magnets is critically discussed. Standard magnets used in a wide range of applications are furthermore distinguished from custom developments requiring a more detailed cost-benefit analysis.

List of abbreviations:

AMSA	Advanced magnet for specific applications
DC	Direct current
EMFC	Electromagnetic flux compression
EMFL	European Magnetic Field Laboratory
ExFC	Explosive flux compression
GPM	General purpose magnet
HTS	High-temperature superconductor
LTS	Low-temperature superconductor
MG	Megagauss
NHMFL	National High Magnetic Field Laboratory
STC	Single-turn coil
TED	Transient electromagnetic disturbance

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I. Introduction

High magnetic fields are one of the most powerful tools available to scientists for the study, modification and control of states of matter, and in order to compete on the global scale, Europe needs state-of-the-art high magnetic field facilities which provide the highest possible fields (both continuous and pulsed) for its many active and world-leading researchers.

Taking state-of-the-art magnet technology as a starting point, the present document considers the effect of new concepts and emerging raw materials, cf. deliverable D9.2[1], on the further evolution of high-field infrastructures. Concrete recommendations for developing or improving magnets take are based on an in-depth analysis of

- their technical feasibility;
- user requirements, cf. deliverable D9.1[2];
- operational and financial constraints.

The document is organized in two parts. The first part considers magnets providing the highest possible fields in a moderate volume without additional restrictions. Building these magnets represents the core activity of the EMFL facility. The second part of the document refers to developments for specific applications whose implementation requires a more detailed cost-benefit analysis and generally depends on local activities in the EMFL facilities.

II. General-purpose magnets (GPM)

GPM are magnets built with no specific application in mind. They are characterized by a simple cylindrical bore of moderate size that can accommodate a wide range of interchangeable experimental setups.

GPM account for the vast majority of experiments performed in high-magnetic-field facilities around the world. Their continuous improvement, maintenance and replacement occupies a preeminent position in these facilities' technical activities. In the particular case of superconducting magnets, whose operation does not require large technical infrastructures, GPM are also developed and commercialized as independent laboratory tools by industrial producers.

While the transition towards more specialized magnet designs is often fluent, we refer here to the following practical criteria to distinguish GPM:

Table 1: Defining properties of GPM	
Openings	simple cylindrical bore
Opening diameter	8-35 mm
Homogeneity	1% within the experimental volume

The listed properties are typical for both commercially available superconducting solenoids and standard user magnets operated in high-field research infrastructures. All values are furthermore endorsed by the results of a recent survey among EMFL users[2].

1. Design objectives

High magnetic fields can amplify small physical effects above the experimental perception threshold or even give rise to entirely new phenomena. Providing the highest possible fields thus represents a central goal for GPM as well as other types of magnets. The extensive use of GPM furthermore calls for a high degree of operability under conditions that are both ergonomically and economically acceptable. As GPM are mostly operated close to their performance limits, their aging and necessary replacement also represent an important cost factor that needs to be controlled. The foremost objectives when designing new GPM are therefore:

Table 2: Design objectives for GPM
Maximum field in routine operation
High operability
Cost-efficient operation
Cost-efficient production

2. Basic technological approaches

High magnetic fields are generated by passing strong currents through a helical conductor arrangement, in the simplest case a wire-wound coil. The current heats the conductor and, in combination with the generated magnetic field, gives rise to forces that tend to radially expand and axially compress the helices. The underlying effects, dissipation and magnetic pressure, are at the origin of the limited service life and ultimate, sometimes violent, destruction of high-field magnets. Their control is an essential part of the engineering of any type of magnet, irrespectively of the categories discussed further on.

In ordinary magnets, the effect of dissipation and magnetic pressure changes with the duration of the field. On a sufficiently short timescale a magnet can sustain the accumulation of heat generated by a strong current, and on an even shorter timescale its inertia can delay the expansion caused by the respective magnetic pressure. It is, thus, possible to trade field duration against field intensity.

A notable exception are superconducting magnets where dissipation occurs spontaneously, when the superconducting quantum state breaks down. Apart from critical temperatures, currents, and magnetic fields, this so-called quenching occurs at high field-sweep rates, making shorter durations impossible. Superconducting magnets are therefore strictly limited to quasi-static fields.

The relationship between field duration and field intensity is at the origin of distinct operating regimes for high-field magnets, as illustrated in Figure 1. While each regime comprises several types of magnets and extends over a certain time range, it also remains clearly distinct from its neighbours. This

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separation reflects fundamental technological differences between the respective magnets, energy and power supplies, as well as supporting infrastructures. High-field facilities, therefore, tend to specialize in one or two, but generally not all, operating regimes.

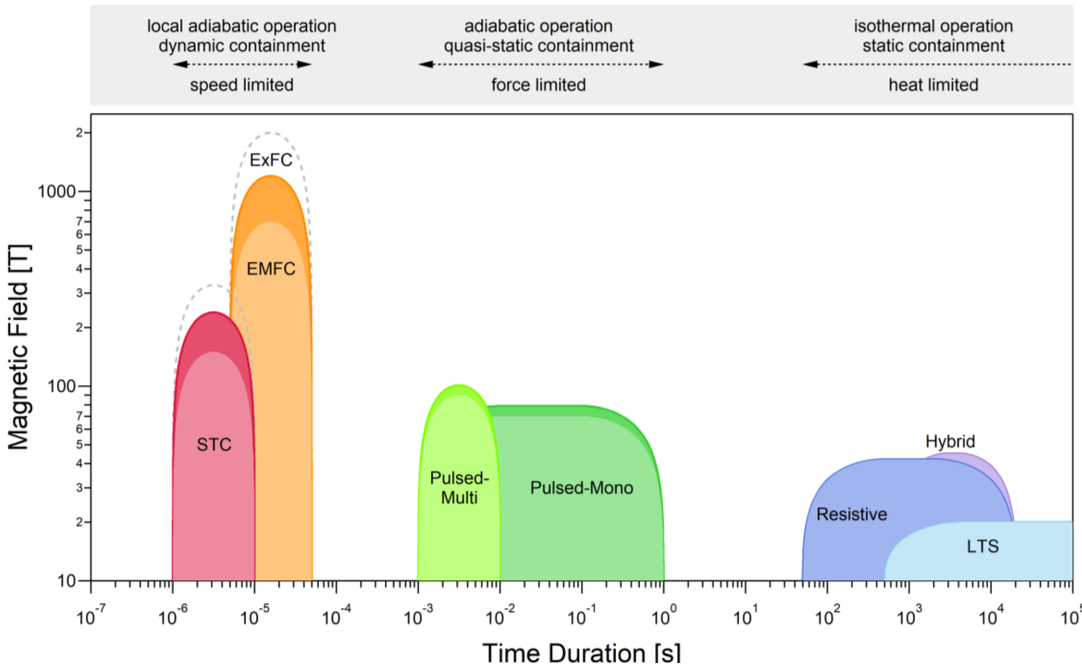

Figure 1: State-of-the-art performance and technological grouping of different types of magnets

STC stands for single-turn coils, ExFC for explosive and EMFC for electromagnetic flux compression, LTS for low-temperature superconducting magnets. Known ExFC records are indicated, although use of the technique seems to have been abandoned or at least restricted to secret military applications. Darker areas near the top of each category represent the offset between fields available for routine applications and one-time records. For STC, an additional dotted line represents records obtained in volumes that are too small to accommodate scientific experiments. The distinction between speed, force, and heat limitation is indicative as thermal and mechanical constraints are present in all cases.

Quantitatively, Figure 1 reflects the global situation as of 2025. For a comparison between fields obtained in and outside Europe, see Figure 2. In both figures, the difference between one-time field records and standard user fields is also indicated. As a rule, one-time records attract attention and are interesting as benchmarks to test and demonstrate the technical progress in magnet or generator design. In many cases, record fields are difficult to reproduce reliably and, hence, unsuitable for routine applications. Throughout the rest of the document, we, therefore, primarily focus on reproducibly achievable user fields.

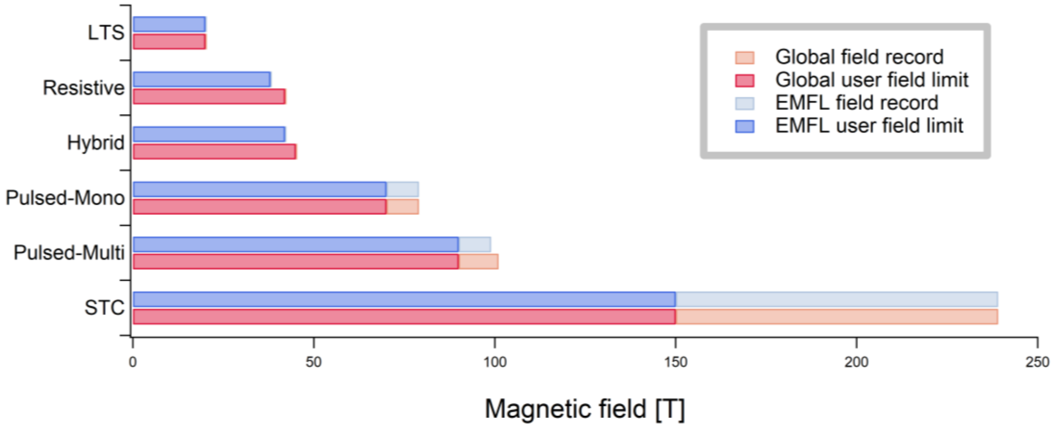

Figure 2: Comparison of the highest record and user fields in and outside Europe

The displayed EMFL hybrid values refer to the design field of installations in Grenoble and Nijmegen, whose commissioning is expected for 2025. The graph does not include EMFC, which is developed exclusively in Kashiwa, Japan. As of 2024, the Japanese installation is linked to EMFL via a formal agreement including arrangements for accommodating European users.

3. Basic improvement strategies

Over the past decades, the design and production of high-field magnets has been increasingly professionalized, both in industry and publicly funded research facilities. State-of-the-art magnets are devised and produced by teams of specialized engineers making use of advanced design tools, concepts and materials. The margins for technical improvements by simply optimizing magnets under otherwise identical conditions have, therefore, become very narrow. This leaves four principal levers that can be used to extend the available field range:

- *Scaling*. The generation of high magnetic fields is ultimately limited by the capability to procure, contain, and sustain adequate amounts of magnetic energy. Although simple theoretical scaling rules do not always hold exactly in practice, it stands to reason that larger energy and power supplies provide additional design freedom to obtain higher magnetic fields in a given volume. However, in order to produce a significant improvement, this approach would require a new level of facilities with substantially larger technical installations and, hence, higher capital investment and running costs.

  The inverse approach - scaling down a magnet while keeping the stored magnetic energy constant - can also permit higher fields as long as the effects of dissipation and magnetic pressure remain under control. Apart from that, the miniaturization of magnets is obviously subject to practical constraints associated with the necessary experimental space that has to be retained in their centre.

- *Intermediate operating regimes.* As indicated in Figure 1 and discussed above, all currently existing magnets fall into three operating regimes with characteristic peak fields and timescales. In the simplest case, technical solutions bridging the gaps between these regimes can shift the balance between mechanical and thermal constraints to obtain slightly higher fields on a shorter timescale. More importantly, sufficiently rapid processes can prompt unusual dynamic material behaviour that may help to postpone the destructive limit of advanced magnets. This possibility remains practically unexplored. Investigating possible magnet, energy, and power designs for intermediate timescales may bear some promise for the future.

- *New materials.* Advanced magnets rely on advanced materials, in particular as far as high strength and low resistivity are concerned. The advent of new materials with these properties can thus give rise to spontaneous improvements in magnet technology. Inversely, the use of exotic materials with a comparably small market exposes high-field facilities and industrial manufacturers to procurement uncertainties, and bears the risk of shortages and production stops that may generate a de-facto regression in terms of magnet performance. New concepts based on emerging materials, thus, have to take into account their development, future production, and reliable procurement.
- *New architectures.* Despite the relatively simple structure of GPM, conceptual innovations have occasionally produced unexpected performance breakthroughs in the past. Typical examples are pulsed magnets with distributed fibre reinforcement and the so-called Florida-Bitter plates for DC magnets, both invented in the 1990s. However, the comparatively steady evolution of magnet technology over the last 30 years suggests a level of maturity that now makes comparable ground-breaking innovations less likely or, at the very least, impossible to anticipate. This does not mean that speculative, highly disruptive theoretical concepts do not exist. In particular, force-free or quasi-force-free magnets tend to attract sporadic attention. However, with their complex winding structures, inherently higher current densities, and dissipation that arises from it, force-free magnets are currently a theoretical playground rather than a realistic technological option.

4. State of the art

4.1. All-superconducting DC magnets in research and industry

- *Basic facts*. Superconductivity is a material-specific quantum-phenomenon characterized by the lossless flow of electricity up to a critical temperature, current density, and magnetic field. Within these limits, the complete absence of dissipation permits the design of compact magnets that do not require large power supplies, which makes them suitable for small and mid-sized laboratory environments. For comparison, the resistive equivalent of a top-range 24 T superconducting magnet would need a large infrastructure providing 8 MW electrical power, plus the same amount for cooling.

  The absence of large power supplies also suggests that superconducting magnets are more economic to operate than their resistive counterparts are. This effect is partially compensated, however, by the need to maintain cryogenic temperatures. An important question in this respect is whether a magnet can be ramped, switched off, and, hence, needs cooling only while it is in use, or whether it has to be permanently kept cold and, possibly, also kept at constant field. Economic considerations notwithstanding, the latter restriction would also disqualify a magnet as GPM and, therefore, represents a key issue for emerging magnet technologies.

  In terms of failure modes, superconducting magnets are prone to spontaneous transitions into a resistive state, giving rise to an almost instantaneous dissipation of the stored magnetic energy that can fatally damage the system. So-called quench-protection circuits and the robustness of superconducting materials and junctions are, therefore, essential design issues.

  Building high-field magnets with low-temperature superconductors (LTS) is a mature technology employed by companies. Over the last 30 years, the maximum field that can be obtained with materials such as NbTi and Nb_3Sn has evolved from 20 to 24 T, but the remaining margin for further progress is accordingly small. LTS magnets dominate the lower end of the field scale, see Figure 1, but cannot be expected to compete with resistive magnets in terms of field strength anytime in the future.

High-temperature superconductors (HTS) tolerate higher magnetic fields and, thus, represent an extremely interesting perspective for next-generation high-field magnets. However, processing HTS to obtain a workable raw material and assembling a magnet with it, both turn out to be technically challenging and expensive. Currently, only one industrial provider is commercializing all-superconducting magnets containing both HTS and LTS, with a maximum field of 28.2 T available and an advanced version extending to 30.5 T in progress. However, these magnets are only available for one specific type of experiment (NMR) that, unlike most other applications in materials research, does not require field sweeps. As far as true HTS-based GPM are concerned, only 2 pilote projects have so far produced notable results: the first is an all-superconducting 32 T magnet built at the NHMFL Tallahassee (USA) that, at the time of writing, is out of operation for repairs; the second is the "Nougat" HTS-demonstrator insert built in Grenoble that has barely topped this record, albeit in an 18 T background field produced by a resistive DC magnet.

In practice, superconducting magnets are built with composite wires or tapes that consist of a continuous length of superconductor embedded or sandwiched in a copper matrix with, possibly, one or more intermittent buffer layers. The use of copper improves the composite's ductility, and provides a resistive current bypass and heat sink that, in case of a quench, reduces the risk of an immediate burnout. An important difference between LTS and HTS materials for high-field magnets lies in the fact that the first are metallic and well-compatible with copper, whereas the second resemble ceramics that are substantially more difficult to integrate in a composite.

- *Users.* Based on the results of surveys performed as part of the ISABEL and SuperEMFL projects, the user community for superconducting magnets comprises 3 groups.

  A majority of potential users currently works with resistive magnets and simply wants to perform the same types of experiment with superconducting systems. The principal motivations of this group are the possibility to stay at high fields for a longer time, while consuming less electrical energy, and the perspective to obtain better-quality data in an experimental environment less affected by mechanical vibrations and electrical perturbations.

  The second group consists of potentially new users, whose experiments are particularly sensitive to vibrations or require ultra-low temperatures and, hence, hardly feasible using resistive magnets.

  The third category finally concerns users requiring extended measurement times at constant magnetic field. This group includes the solid-state NMR community.

- *Commercial products.* Superconducting GPM available on the market are based on the LTS materials NbTi and Nb_3Sn. As outlined above, the only commercially available HTS-systems are operated at constant field and hence do not qualify in this respect.

- NbTi and Nb_3Sn become superconducting are 9.2 K and 18.3 K, respectively. For systems with regular cooling, i.e., 4.5 K, NbTi can be used up to 9 T, while for fields between 9 and 20 T Nb_3Sn is the material of choice. In the latter case magnets mostly consist of inner coil layers made from Nb_3Sn and outer coil layers made from NbTi, as the cost for Nb_3Sn is much higher. The major markets for superconducting applications are MRI-systems and commercial NMR-systems. With MRI systems the majority of fields used is systems with 1.5 T, 3 T and 5 T. Small numbers of devices are sold with 7 T and beyond. NMR systems are available up to 900 MHz, which correspond to a magnetic field of 21.1 T for LTS-only systems.

  GPM with cold bore diameters between 20 and 60 mm are commercialized up to 20 T. These systems offer persistent current operation and are operated as standalone systems. A special deviation in this area are the large bore series magnets offering 15 T in a cold bore of 240 mm and

19 T in 150 mm. Companies offering these types of magnets are located either in the UK, USA or Japan. There are no manufacturers in continental Europe.

- *Challenges (1) - raw materials.* While cable strands and wires containing filaments of Nb-Ti or Nb_3Sn have long-since become the customary solution for building LTS magnets, compelling standards for HTS have yet to be established. A key challenge in this respect is brittleness. To compensate the respective lack of strength, ductility, and hence workability, HTS need to be embedded in composite structures featuring a metallic substrate or matrix. Inevitably, this has inspired different technical approaches and manufacturing strategies[1]. The respective coexistence of competing technical solutions with uncertain market perspectives complicates the long-term planning and development of HTS magnets.
- *Challenges (2) - HTS workability and aging.* Although the combination with metallic substrates or matrices makes HTS more workable, their further processing remains complicated. Apart from the necessary shaping of wires or tapes to form a magnet, this notably concerns the lack of splicing techniques to produce superconducting junctions between current leads. Moreover, few aging studies have been performed on HTS magnets and materials. This concerns the effect of thermal cycles, magnetic forces, and failure modes producing cumulative damage in materials, interfaces and electric contact areas. So far, the only relevant study in this respect has been performed at the NHMFL Tallahassee, where an all-superconducting 32-T magnet was exposed to multiple ramps and forced quenches. To reach the status and reliability of GPM operated in a user facility, HTS magnets continue to require substantial investments into research, development, and prototyping.
- *Challenges (3) - metrology issues.* Current flowing in a wire is more confined than in a conducting tape whose width can permit inhomogeneous current densities, in particular in the presence of inductive couplings. HTS tapes are, thus, prone to screening currents that modify the local current distribution and, hence, the field profile compared to calculated performances. In addition, quench protection circuits can introduce variable resistances between turns with the consequence that the magnetic field is not directly proportional to the injected current, except after a long settling time. The need to monitor the real field value tends to complicate the use of HTS magnets as Hall or NMR probes have to be integrated in the experimental setup.
- *Challenges (4) - HTS-LTS integration.* Superconductors featuring higher critical fields are generally more costly and less workable. This is not only true for HTS as opposed to LTS, but also holds for Nb_3Sn and Nb-Ti based wires and strands. It is, therefore, customary to reserve high-performance materials for the innermost part of a magnet, while choosing a more cost-efficient solution for the larger outer part. The principal downside of this approach is that different magnet sections have to be protected differently, giving rise to relatively complex quench detection and management circuits. This is particularly true for HTS-LTS combinations. With the recent price drop of HTS materials driven by fusion research, HTS-only magnets thus tend to shift back into focus.
- *Challenges (5) - running costs and sustainability.* Superconducting magnets require a trade-off between operating temperature and magnetic-field strength. Despite their naming, even high-field HTS magnets are, therefore, liquid-He cooled which not only concerns their immediate operation, but also stand-by times during which the magnet is kept at low temperature or cooled down. As the direct power consumption of superconducting magnets remains marginal, running costs are, thus, dominated by expenses for He liquefaction and the occasional compensation of He losses. In the latter respect, it is important to note that He is a non-renewable resource, whose availability has previously been subject to intense price fluctuations caused by shortages and changes in the export policies of the main producer countries. Although superconducting magnets

are still cheaper to operate than their resistive counterparts, this dependence calls for adequate investments in cryogenic infrastructures and an efficient utilization management.

4.2. Resistive DC magnets

- *Basic facts.* Although the containment of magnetic pressure plays an important role in their design, the foremost limitation of resistive DC magnets is dissipation. Their operation thus resides on 2 pillars: The availability of sufficient electrical energy to compensate resistive losses, and the technical means to extract and dump the generated heat. State-of-the-art facilities are equipped with rectifiers and transformers providing 20 to 30 MW of electrical power, and large hydraulic cooling circuits pumping deionized water through the magnets to maintain their operating temperature, typically between 50 and 100 °C.
- The inherent restriction of power and current densities, as well as the incorporation of cooling conducts, make resistive DC magnets bulkier than other GPM. Furthermore, their architecture is characterized by large conductor cross sections and a limited number of windings, giving rise to mechanical stability and a low inductance. As a consequence of the latter, these magnets require relatively low operating voltages and are correspondingly easy to insulate. More importantly, they can also be ramped quickly, thereby saving electrical energy and reducing the turn-around time for serial measurements.
- Bitter and poly-helix magnets, see Figure 3, are the principal practical implementations of resistive DC magnets. The first consist of stacked plates with perforations for cooling and mounting, while the second are composed of nested helices with intermediate gaps. Both systems have their particular technical strengths and weaknesses, but exhibit little difference as far as performance and, in particular, field-strength is concerned. In both cases, copper and copper alloys are the materials of choice.
- *Users.* Resistive DC magnets have motivated the construction of large facilities accommodating external users long before the advent of superconducting or pulsed magnets. Together with seminal discoveries, such as the integer and fractional quantum Hall effects, this professionalization has promoted the development of stable academic user communities. Many researchers using resistive DC magnets are regular users having a high level of competence in the use of intense magnetic fields.

  The large and easily accessible room-temperature bore of resistive magnets represents an important asset for various user groups. This notably concerns cross-disciplinary research and industrial projects. While users from other scientific disciplines are rare and often require special preparations, their role as potential forerunners for future activities makes them important. Likewise, testing the magnetic field compatibility of industrial products is of dual interest, as the respective devices and materials may be useful for technical developments in a magnet facility. An obvious illustration are HTS-tapes and wires whose testing permits first-hand relationships with companies producing raw materials for next-generation superconducting magnets.

  Although experiments are normally performed with onsite equipment and the help of a local contact, DC fields can, in principle, be provided as a pure service for independent users bringing their own equipment. Of obvious interest for industrial clients, this possibility distinguishes DC from pulsed fields, as the transient nature of the latter and parasitic phenomena require counselling and a closer supervision by experienced staff. It also makes DC fields generally more accessible for new users.

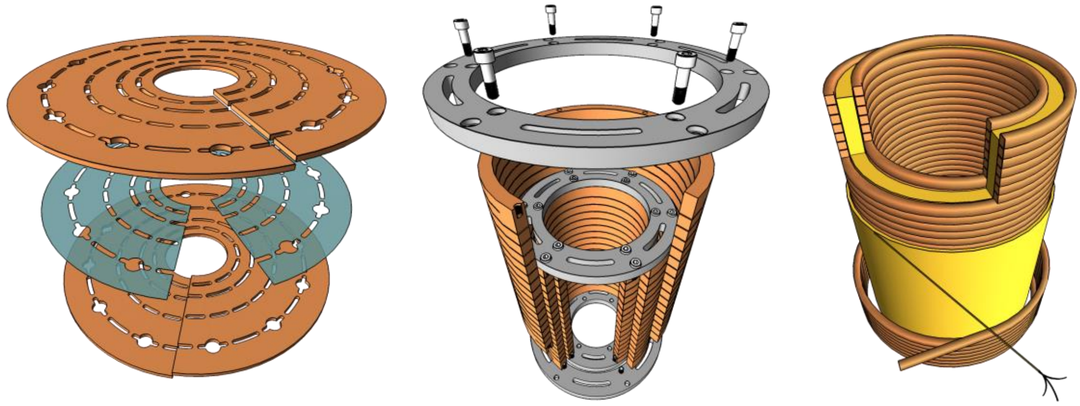

Figure 3: Schematic illustrations of Bitter (left), poly-helix (middle), and a wire-wound pulsed magnet with distributed fiber reinforcement (right, see description below)

- *Challenges (1) - peak field.* To obtain substantially higher fields with resistive DC magnets invariably requires larger power supplies. In China and the US 42 T have thus been obtained with 32 MW while the European record of 38 T refers to 21 MW of electrical power. While ongoing or planned upgrades of the EMFL installations may help to reduce the existing difference, it stands to reason that catching up with the international top level will not be possible without additional capital investments. This is currently unrealistic.

  Apart from larger power supplies, a few technical alternatives for improving the performance of resistive DC magnets exist, albeit at a more moderate level. These are considered in the following challenges (2) to (4).

- *Challenges (2) - scaling.* Resistive DC magnets dispose of a well-established standard of 32 to 34 mm as far as their bore size is concerned. By comparison, pulsed magnets exist with inner diameters ranging from 28 mm at 60 T all the way down to 9 mm for a maximum field around 90 T. While the operating mode of DC magnets definitely excludes a comparable gain, the question arises whether reducing the bore can still produce a significant, albeit moderate, advantage, and whether this advantage justifies the substantial workload and investment associated with the necessary renewal of hydraulic chassis, cryostats and experimental probes.

- *Challenges (3) - heat transfer optimization.* The power density of DC magnets is naturally by the transfer of heat between the electrical conductor where it is generated and the cooling liquid that evacuates it. Improving the heat transfer would permit higher power, current and hence magnetic flux densities. While the technical margin for improving the heat exchange in Bitter and polyhelix magnets is relatively narrow, measures such as an adequate surface structuring could nevertheless help to increase the field that can be generated with a given amount of electrical power.

- *Challenges (4) - materials.* In terms of conductor materials, copper and copper-alloys are irreplaceable when it comes to finding a compromise between low resistivity, high strength, workability and affordability. The principal interest of copper-alloys is to obtain better mechanical strength, albeit at an inevitable sacrifice in conductivity. More promising in this respect are advanced production processes for pure copper, whose ongoing development has given rise to a simultaneous improvement of mechanical and electrical properties. A recurrent problem in this case is the lack of industrial standards that requires magnet facilities to characterize and test advanced materials rather than just purchasing them based on guaranteed specifications.

- *Challenges (5) - energy consumption.* Environmental issues notwithstanding, the procurement of electrical energy represents an important cost factor for DC magnet facilities, whose control is not only complicated by experiments requiring extended sweep times or plateaus at maximum field, but also suffers from downright imponderabilities associated with fluctuating electricity prices. Although the technical margins for mitigating such operational difficulties are limited, energy efficiency arguably represents the most important actual challenge for new resistive DC magnet designs, infrastructures and operating modes.

4.3. Hybrid DC magnets

- *Basic facts*. Hybrid magnets usually combine a superconducting outsert with a resistive insert magnet. Compared to fully resistive magnets, hybrid magnets tend to offer similar or higher magnetic field strengths at lower electrical power. While resistive magnets usually catch up with hybrid magnets within one or two decades, this is normally achieved by implementing stronger power supplies with an accordingly larger energy consumption.

  At the time of writing, both EMFL DC-field facilities have commissioned hybrid magnets offering magnetic fields of 42+ T or are about to do so. The strongest operational magnets in this class are 45 T hybrid magnets at NHMFL in Tallahassee, USA and Hefei, China.

  The fact that existing hybrid magnets are composed of a resistive insert nested inside a superconducting outsert, accounts for the fact that LTS materials cannot withstand the field strength close to the centre. With the arrival of HTS conductors, a reversed arrangement might be possible, although the larger bore of the resistive outsert would invariably increase the system's energy consumption. A far more important perspective with regard to HTS materials is, therefore, the possibility to nest resistive coils inside HTS coils, which in turn are nested in LTS coils. Such systems have been dubbed tribrid magnets as they use three different conductor types. Preliminary design studies to reach 60 T with such a system have been performed. As hybrid magnets are large, technically complex, and store substantial amounts of magnetic energy, failures generally give rise to long outages, expensive repairs and, possibly, the total loss of the installation. Safety margins are accordingly high and designs tend to be more conservative than for other types of magnets.

- *Users.* Hybrid magnets mainly provide the possibility to extend measurements beyond the highest fields available with resistive magnets. The respective user groups are, in principle, identical. However, hybrid users are generally required to provide additional justification for their demands, most likely by presenting preliminary results obtained at lower fields that warrant their proposals.

- *Challenges (1) - constituent magnets.* Hybrid magnets depend crucially, though not exclusively, on the state of the art of technologies governing their constituent magnets. The advent of HTS magnets bears a lot of promise in this respect, but does not yet provide the level of maturity that would permit the safe integration into a hybrid system. New hybrids without HTS technology, on the other hand, would bear the risk of becoming rapidly obsolete. At the present stage, the design effort for new hybrid magnets is, therefore, limited to conceptual planning.

- *Challenges (2) - nesting issues.* Nested magnets are coupled mechanically and inductively. In the first case, extreme magnetic forces and force distributions can arise that require robust mechanical support structures. The inductive coupling, on the other hand, affects hybrid-magnet failure modes as trips in the resistive part may cause quenching of the superconducting coil. While a hybrid-magnet insert and outsert are, in principle, independently operated, their inductive coupling also requires that ramping and, in particular, emergency shut-downs in either part are coordinated.

- *Challenges (3) - funding and partnership.* Hybrid magnets are bigger than other types of magnets, require a larger infrastructure, and are technically more complex than just the sum of their constituents. As a consequence, building a hybrid magnet requires extensive technical competences, substantial capital investment, and a long-term commitment that might exhaust a single high-field facility's capabilities. Funding and partnership strategies are, therefore, an essential part of future hybrid projects.

4.4. Pulsed magnets

- *Basic facts.* The standard way of producing pulsed magnetic fields is to discharge a capacitor bank into a resistive magnet. In the past, flywheel generators, providing substantially larger energies, have also been used, but the respective activities are either temporarily or permanently discontinued. Capacitor banks are more economic in terms of initial investment, operation, and maintenance and represent the more reliable choice for user facilities.

During a pulse the coil buffers heat produced by the current and subsequently releases it during a much longer cool-down time. Larger currents produce higher fields, but generate more heat and thus require shorter pulses to avoid overheating. To control pulse durations, coils are specifically designed for the generators, i.e., capacitor banks or flywheel generators, that power them. The generation of pulsed fields is limited by mechanical stresses, arising from the Lorentz force on the conductor. Magnets are designed to limit repeated plastic deformations that lead to aging and ultimate failure. The respective safety margins represent a trade-off between maximum performance and the cost for producing replacement magnets. Depending on type and size, magnets typically deliver 100 to 1000 pulses at full field.

In many cases, monitoring coil parameters and discharge characteristics permits a decommissioning of older magnets prior to imminent failures. The risk of violent failures with collateral damage inflicted on the surrounding infrastructure nevertheless persists. This and the periodic investment associated with their replacement are strong motivations to limit the size of pulsed magnets, i.e., their volume and magnetic energy content. In terms of generators, this calls for power supplies capable of injecting the necessary energy more rapidly.

The moderate size and frequent replacement of pulsed magnets incidentally also limits costs, when a new design does not perform as anticipated. Therefore, new features can easily be incorporated, in particular, in magnets aiming at extreme performances. This not only concerns materials and architectures, but also relevant parameters for scientific experiments, such as pulse duration and bore size. As a consequence, pulsed magnets have not developed clear standards, such as their DC counterparts, and their qualification as "user magnet" rather depends on whether experimental equipment can be adapted and researchers accept them as such.

Advanced pulsed magnets can consist of a single or several nested coils. The latter provide additional design freedom for the magnet's stress and heat distribution, as each coil is separately optimized and driven by a different capacitor bank. This permits higher fields, but also gives rise to shorter transit times through the maximum, and complex pulse shapes as different field contributions are superimposed. By comparison, mono-coils provide less field but a smoother pulse shape, which is crucial for some types of measurements. Both coil types are an important part of advanced high-field facilities.

- *Users.* Pulsed magnets originally existed in smaller laboratories as a low-budget approach, and their utility for academic research was occasionally questioned. Their full recognition as a scientific tool and the formation of a broader academic user community dates back to the turn of the millennium when larger facilities made their appearance. Despite this evolution, working with pulsed magnets remains less comfortable than with DC magnets, as the intrinsic time-dependence requires a case-by-case analysis of side effects. Users are, therefore, counselled by experienced local contacts even before submitting a proposal for magnet time.

In the case of new users, the initial clarification of experimental conditions and constraints generally gives rise to extended lead times. Inversely, regular pulsed magnet users are accustomed to experimental adaptations and are willing to trade technical comfort against higher fields. This motivates new developments and makes it easy to valorise them.

When analysing pulsed-field data, it is necessary to distinguish effects caused by the field's magnitude from those caused by its time derivative. While users working in condensed-matter physics are able to make the distinction based on theoretical knowledge and previous experience, it can be a serious obstacle for cross-disciplinary and industrial projects.

- *Challenges (1) - peak field*. The principal routes for improving the maximum field of pulsed magnets without compromising their bore size or pulse duration are material related, see challenges (3) and (4) below. It is, however, safe to assume that such improvements will not produce spectacular changes exceeding a few percent.

  By comparison, the downscaling of magnets to produce shorter pulse durations could be a veritable game changer: as the mechanical strength of metals and some other materials increases at ultra-fast deformation speeds, magnets operating in a sub-millisecond regime are expected to sustain substantially larger magnetic pressures and hence fields. This approach remains currently unexplored, see Figure 1.

  Smaller magnets are also interesting from an economic and methodological point of view, as they permit systematic experimental developments. On the other hand, the inevitable reduction of bore size and the various side effects of a shorter pulse duration also require a consequent adaptation of scientific experiments, see below challenge (6).

- *Challenges (2) - turnaround time.* Pulsed magnets feature a compact structure to concentrate magnetic energy near the centre and resist the respective forces. A disadvantage of this principle is the magnet's inefficient heat exchange with its environment, giving rise to extended downtimes for cooling after each pulse. On-site experiments performed by external users are particularly affected by this.

  While magnet designs with advanced cooling mechanisms have been introduced in the past, improving the effective repetition rate of pulsed magnets remains a challenge to be addressed in the future. This is particularly true for magnets providing the highest fields, as their mechanical design leaves little room for other optimizations.

- *Challenges (3) - conductor materials*. Building state-of-the-art pulsed magnets requires wire that combines good electrical conductivity with superior tensile strength up to 1 GPa and sufficient ductility to permit winding. The principal materials satisfying these criteria are copper-based alloys and composites. To avoid potentially fragile joints inside the magnet, the conductor should be available in large continuous stretches, corresponding to several hundreds of kilograms.

  While industrial products are usually not limited in quantity, their mechanical properties are rarely pushed to the extreme, as increasing scrap rates and warranty issues would complicate their commercialization. Manufacturing high-strength wire as part of ongoing R&D activities in academic institutions, on the other hand, suffers from the inability to supply large quantities, both in terms of length for a single magnet and mass production to keep an entire facility operational. Apart from conceptual advances, an important challenge is, therefore, to elaborate sustainable procurement strategies, including industrial partnerships, technology transfer, and mutualized purchasing.

- *Challenges (4) - reinforcement materials*. The standard way of building pulsed magnets is to alternate conducting and reinforcement layers such that the latter compensate forces generated in the first. The reinforcement layers consist of a fibre-epoxy composite that derives its unique strength from Zylon®, a synthetic polymer exclusively produced by Toyobo Co., Ltd.

Following its withdrawal from the profitable body-armour business in 2005, Zylon® has been under threat of disappearing from the market, leaving no alternative with comparable performance for building pulsed magnets. Given the already substantial workload associated with the further improvement and production of GPM, as well as the occasional development of AMSA for specific projects, this problem arguably receives little attention.

- *Challenges (5) - generators*. Unlike DC magnets that only require an adequate power input, pulsed magnets and capacitor driven generators are dynamically coupled. Their combined electrical parameters determine the system's pulse duration and current, and, hence, the magnet heating and magnetic field. Although capacitor banks normally dispose of a modular structure to make them more flexible, magnets are specifically designed for them. As a consequence, constructing new generators, whose typical life cycle ranges from 20 to 30 years, represents a long-term commitment that calls for a clear strategy concerning the magnets that should be operated. Apart from technical considerations, this notably includes the anticipation of future user demands, making the overall assessment fairly complex.

- *Challenges (6) - related experimental developments.* As outlined above, miniaturizing magnets has many advantages from an engineering point of view. However, reduced bore sizes and pulse durations also require complementary developments as far as sample preparation, measurement technologies, and cryogenic equipment are concerned. It is, therefore, save to say that such developments represent an inseparable part of future improvements in pulsed-magnet technology.

4.5. Megagauss (MG) generators

- *Basic facts*. When a pulsed magnet breaks during operation, arcs bridge the nascent gaps and permit current to flow until most of the discharge is complete. A direct manifestation of Lenz's law, this self-stabilization opens a door for generating high magnetic fields in conductor arrangements that are destroyed in the process.

In a breaking magnet, electric energy is no longer converted to magnetic energy and waste heat, only. The coil's expansion causes additional kinetic energy losses and, at the same time, allows the remaining magnetic energy to spread over a larger volume. STC limit this effect by injecting current fast enough to avoid a substantial expansion up to peak field. The inverse process is used in ExFC and EMFC, where an imploding current-carrying ring converts kinetic energy back into magnetic energy, and squeezes the latter into its shrinking metallic enclosure. In either case, the relevant mechanical property is inertia, giving rise to characteristic timescales of the order of microseconds.

MG techniques make use of simple conductor arrangements to generate the field. The principal technical challenge lies in the construction of generators capable of producing megaampere currents with microsecond rise times. Ultimately, this calls for operating voltages of 40 kV or more, combined with a compact design leaving very narrow margins for high-voltage insulation.

The practical use of MG fields is challenging due to various side effects of the intrinsically short pulse duration. This notably includes transient electromagnetic disturbances caused by the trigger-and-discharge process. The substantial development effort that is necessary to implement scientific experiments under these conditions makes MG fields an emerging or niche application, albeit with increasing potential due to the rapid evolution of more and more robust ultra-fast electronics.

Figure 4: Single-turn coil before and after the pulse

- *Users.* The currently active MG facilities in Toulouse and Kashiwa dispose of a relatively small, albeit evolving, user community. One reason for this limitation is that many experimental techniques cannot be, or have not yet been, implemented in MG fields. Potential users also remain sceptical in view of the short duration and other technical issues. On the other hand, the actual non-destructive field record, 100.8 T obtained at the NHMFL in Los Alamos with an installation that is now out of service, dates back to 2012 and has not been reproduced by other facilities. The current perspectives for addressing a number of prominent scientific cases requiring even larger fields are, therefore, highly unfavourable. In this context, several initiatives involving experienced users are underway with the aim to improve measurement conditions and to extend the range of available experimental techniques for MG fields.

  Technical issues notwithstanding, MG fields also suffer from an information deficit that primarily concerns potential new users without preliminary experience. At present, there exists a large span between first-time proposals that are too unrealistic on the one hand, and projects that are never submitted because potential users are overly sceptical, or unaware of the existing experimental possibilities, on the other hand.

- *Challenges (1) - MG-compatible experimental techniques.* The foremost problem of MG generators is not to reach a certain field level, but to be able to use it in scientific experiments or other applications. As side effects such as large time derivatives and transient electromagnetic disturbances (TED) are intrinsic and impossible to avoid, the primary challenge is to develop new, MG-compatible, experimental techniques. This notably involves measurement circuits making use of advanced screening, filtering, modulation, and miniaturization techniques.
- *Challenges (2) - TED reduction.* By comparison, the margins for improving MG generators themselves, i.e., their high-voltage trigger and discharge circuits, are narrow. The most likely objective in this respect would be the design of an advanced high-voltage trigger generator whose emission of TED after the initial trigger pulse decays more rapidly, thereby reducing the impact on measurements during the up-sweep of the magnetic field.
- *Challenges (3) - destruction thresholds.* While the explosion of STC giving way to the applied magnetic pressure has surprisingly little effect on experimental equipment in the bore, a premature sublimation of conductor material can produce substantial damage. This second destruction threshold occurs at the highest fields when the surface current density exceeds a

critical value before the coil has started to expand and copper vapour accumulates inside the bore. Whether this effect can be reduced by structuring or otherwise modifying STC is subject to debate.

- *Challenges (4) - replacement of generator components.* As MG-generators operate at higher voltage than conventional capacitor banks, their construction relies on industrial components, whose market share is low and who are generally made to order. In practice, the affordability of components such as energy-storage capacitors therefore depends on whether an industrial supplier disposes of a stock of surplus equipment, most often from a previous, generally much larger, production campaign for military applications. This restriction calls for a careful long-term maintenance strategy.
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5. GPM roadmap

The GPM roadmap outlines strategic responses to the challenges previously identified and provides a concise overview of the implementation plans within the EMFL framework.

5.1. Superconducting magnets

The advent of high-temperature superconducting (HTS) technology has sparked optimism that superconducting GPMs may not only rival but eventually surpass resistive DC magnets. This shift holds promise for significantly reducing the high operational costs associated with resistive magnets, while also enabling experiments—such as those sensitive to mechanical vibrations—that are difficult to conduct in resistive environments.

As a result, the development of standalone HTS magnets or hybrid systems combining HTS with low-temperature superconducting (LTS) technology has become a strategic priority for high-field laboratories worldwide. Although integrating HTS and LTS components presents notable technical challenges (cf. 4.1), one clear advantage is that a single LTS outsert can be used to test and refine multiple HTS prototype inserts, streamlining development and reducing costs.

Building on the success of the "Nougat" demonstrator, which achieved 32.5 T in a resistive DC magnet, EMFL laboratories have adopted this modular approach for the development of all-superconducting user magnets. At LNCMI Grenoble, the first phase involves adding a HTS insert composed of two double-pancake coils (targeting 5–6 T) to a 19 T LTS outsert. Subsequent phases will incrementally increase the field strength through enhanced HTS inserts, with the goal of reaching 32 T while optimizing coil parameters such as bore diameter and field homogeneity. Funding for this initiative has been secured, and procurement of the 19 T LTS outsert and cryostat is currently underway.

HLD Dresden already operates a similar 19 T outsert and has outlined comparable plans to construct a 32 T all-superconducting magnet. Although funding is not yet secured, it is anticipated in the coming years. HFML-FELIX intends to follow suit, leveraging the experience gained at LNCMI and HLD.

Looking ahead, further increases in magnetic field strength — potentially up to 40 T — are envisioned. Achieving this will require advanced design optimization and a reassessment of funding requirements.

5.2. Resistive DC and hybrid magnets

Resistive DC magnets represent the most mature class of high-field magnet technology, and as such, offer limited scope for future breakthroughs. Nonetheless, recent upgrades to power infrastructure —

such as those at LNCMI Grenoble— have enabled efforts to push the field limits incrementally, with tests anticipated to reaching 39 T. However, these gains remain modest and are increasingly constrained by soaring energy costs, particularly in light of the recent surge in electricity prices across the EU.

Current development efforts are therefore focused on optimizing cooling systems and refining power distribution across the multiple coils that comprise these magnets. The overarching goals are to enhance power efficiency and improve field sweep rates. Achieving these objectives requires advanced modelling of coolant flow dynamics and the development of novel materials capable of withstanding the intense mechanical stresses within the coils, without significantly increasing electrical resistance.

Regarding hybrid magnets, LNCMI has been operating a 42 T hybrid magnet since 2024. A series of in-house experiments is planned for 2026 to validate its performance, with user access expected to begin in 2027. This magnet features a modular design that accommodates particularly large sample volumes and holds promise for even higher fields in future testing.

At HFML-FELIX, development is underway on a hybrid magnet targeting a maximum field of 45 T.

While initial design studies have explored the integration of HTS materials for future hybrid systems, EMFL currently does not anticipate developments beyond the 45 T threshold. There is broad consensus that such advancements would require a coordinated international effort, as the complexity of the technology exceeds the present capacity—both in terms of funding and personnel—of individual laboratories.

5.3. Pulsed magnets

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.

At HLD, a new triple-coil system designed to reach 100 T is ready for testing. However, further refinement of the coil materials is required to ensure mechanical integrity and performance under extreme conditions.

Meanwhile, LNCMI Toulouse is advancing a four-coil, quadruple-pulse design aimed at exceeding the 100 T mark. This effort has been propelled by recent breakthroughs in reinforced conductor technology and the apparent increase of materials' strength at deformation speeds reaching a sub-millisecond timescale. Both the generator and magnet systems for this configuration have already been developed, with initial testing scheduled for 2026.

Additional development efforts focus on specialized coil designs, including those with reduced bore diameters for faster cooling cycles, and configurations capable of achieving higher peak fields. There is also ongoing work to tailor coil systems for integration into other large-scale infrastructures, such as AMSAs, expanding the versatility and scientific reach of pulsed field technology.

5.4. Megagauss generators

Compared to applications involving superconducting, resistive-DC and pulsed magnets, experiments in MG-fields represent a niche activity and will probably not evolve beyond this status for some time to come. On the other hand, they are the only guaranteed technical solution for obtaining field strengths well beyond 100 T.

This disparity gives rise to 3 principal objectives for their further progress: (1) to possibly reduce side-effects associated with the transient nature of MG-fields at the source; (2) to develop techniques and methods that reduce the impact of such side-effects on measurement circuits, respectively experimental data; (3) to address metrology and other relevant issues determining the quality and reliability of experimental data. The emphasis for future developments in the MG range therefore lies on experimental techniques and a possible improvement of generator components such as high voltage triggering sources.

III. Advanced magnets for specific applications (AMSA)

Unlike GPM, AMSA are adapted to the requirements of one or more specific application right from scratch. Their deviations from GPM may reach from simple modifications, such as a larger bore, over magnets providing additional or modified openings, all the way to advanced designs allowing the control of field profiles in space or time. The presence of additional design criteria implies that AMSA generally provide less field than GPM.

Recommendations to develop a particular type of AMSA cannot be given in general. In view of the additional design and production effort, new projects of this type should rather be subject to a cost-benefit analysis taking into account the broader scientific importance. This usually implies that one or more of the following criteria must be valid:

- The project strengthens an existing or emerging scientific activity;
- The project responds to the expression of interest of a sufficiently large, or otherwise relevant, external science community;
- The project concerns the on-site combination of a high-field magnet with complementary equipment such as an advanced radiation source;
- The project concerns the remote installation and combination of a high-field magnet with complementary equipment at another research facility, generally in the framework of a formal collaboration.

Apart from the expected benefit, the development of new AMSA is evidently also subject to a careful analysis of available resources. Priorities given in the following list represent a snapshot of a situation that may be subject to changes.

1. Magnets with extended or additional experimental access

1.1. Wide bore magnets

Given the availability of multiple wide-bore configurations for resistive magnets—including the 42 T hybrid magnet at LNCMI-Grenoble, whose modular design enables exceptionally large sample volumes at the expense of peak field strength—the development of new wide-bore magnets is not currently a strategic priority for EMFL.

1.2. Conical bore magnets

Development of conical bore magnets are of interest only for the development of high magnetic fields at advanced sources such as ESRF and have been discussed in D6.3[3].

1.3. Radial access magnets ("split-coils")

Development of radial access magnets are of interest only for the development of high magnetic fields at advanced sources and have been discussed in D6.3[3].

2. Magnets with specific field profiles

2.1. High-homogeneity magnets

At present, EMFL does not consider the development of magnets with higher homogeneity a strategic priority, given that existing systems already meet current scientific requirements.

2.2. Levitation magnets

Magnetic levitation plays an increasingly important role in soft condensed matter physics, where strong magnetic forces are employed to manipulate soft materials and organize them across various length scales through magnetic alignment and levitation. At HFML-FELIX, high magnetic fields are used to study their effects on living biological cells—a line of inquiry that is not only vital for fundamental research but also holds promise for advancing clinical technologies such as magnetic resonance imaging. One particularly innovative application is the use of magnetic levitation to enable scaffold-free biofabrication of tissue spheroids. This technique represents a key milestone toward constructing complex organ structures and lays the foundation for scaffold-free 3D bioprinting. To support this research, a new levitation magnet is currently under development at HFML-FELIX. For this purpose, a 50 mm wide bore magnet is planned, capable of generating very high magnetic forces. The magnetic force is given by the product of the magnetic field strength (B) and the magnetic field gradient (gradB) and the new magnet aims to reach BgradB values as high as 10000 T2/m. A further requirement of such experiments is that the gradient is present within a sufficiently large volume (about 10 mm3) to contain the samples under study, and to accommodate in-situ techniques to monitor the object by optical microscopy or confocal fluorescence microscopy. This magnet will pave the way for studying the effect of weightlessness in a large variety of systems. It will permit to reach the effective levitation of unicellular organisms (Paramecium, Euglena) in water and statoliths in plant roots and to study the self-assembly of different biologically relevant materials into various shapes, sizes and topology (scaffold-free biofabrication). Moreover, such a magnet will be used to effectively tune the gravitational force over a large range (g-force ranging from -6g to +8g for water) and study physical, chemical and biological processes as a function of the size and direction of the effective gravitational pull, not only allowing the same types of experiments currently done at the ISS but going far beyond them. Beyond levitation, this setup will also unlock new possibilities for magnetic separation and advanced magnetometry, enhancing sensitivity in the study of delicate magnetic phenomena.

2.3. Racetrack-shaped ("dipole") magnets

Racetrack-shaped magnets have originally been developed for bending charged-particle beams in circular accelerators. Owing to the presence of lateral inlets and outlets for passing the beam they also share the principal characteristics of "split"-coils. The somewhat confusing name "dipole" magnet stems from their neighbourhood with quadrupole magnets in an accelerator environment.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 871106

High-field magnet facilities are generally not involved in the development of magnets for particle accelerators, as the latter require large production capacities and the compliance with strict standards rather than extreme performances. However, pulsed racetrack-shaped coils are part of an ongoing project to optically investigate diluted matter, whose weak coupling with light requires an extended interaction path. As an extreme case of dilution, the project notably attempts to test an essential prediction of quantum electrodynamics regarding the existence of a magnetic birefringence of vacuum. Pulsed racetrack-shaped coils thus represent a typical example for a project-based development whose continuation depends on the subject's overall evolution.

Table 3: Racetrack-shaped pulsed magnets	
Scientific case / users	magnetic birefringence of vacuum, spectroscopy of diluted matter
State of the art (EMFL)	operational foil-coil with 80 cm lateral extension available and tested up to 12 T
Perspective	depending on overall project evolution and scientific necessity to improve performance

3. Magnets with specific time dependences

By its very nature, this category primarily concerns pulsed magnets. Only the first type (3.1 below) concerns a mixed operation mode involving static fields for specific experiments. The following three examples (3.2 – III.3.4) are possibilities to extend the usability of pulsed fields by eliminating specific side effects. The last type in the list (III.3.5) makes explicit use of field variations to process metallic objects in an industrial environment.

For the sake of completeness, we note here that in the past also installations for repetitive pulsed fields and damped oscillations have been conceived. The first are primarily interesting for neutron facilities and advanced light sources and will be discussed in section III.4. Damped field oscillations are a normal phenomenon in single-turn coils, see subsection II.5.4, where they are used for various purposes. Their generation with non-destructive magnets is more complex, as it requires specific capacitors supporting large voltage reversals and a discharge circuit without crowbar. This and the absence of a clear scientific case make oscillating fields a too unlikely objective to be listed here.

3.1. Pulsed magnets with quasi-DC background fields

Combining static and pulsed magnetic fields is of hypothetical interest for investigating materials in a pre-polarized magnetic state whose build-up is too slow to be achieved with, for example, a long-pulsed magnetic field. While the idea has received moderate attention in the ISABEL user survey [2], it remains to be determined whether its practical implementation can be endorsed by a sufficient number of concrete scientific cases.

Technically, the project is attractive and fairly easy to implement, as it could be based on a combination of existing equipment. A pilot setup would consist of a transportable capacitor bank installed in a DC facility and a small pulsed magnet providing fields in the 40 T range. Owing to its initial simplicity the project is listed here as an interesting option.

Table 4: Pulsed magnets with quasi-DC background field	
Scientific case / users	to be determined
State of the art (EMFL)	subsystems / components available
Implementation effort	integration & testing of existing systems
Perspective	implementation possible on demand

3.2. Long-pulsed magnets

The principal interest of constant or slowly varying fields lies in the averaging of weak signals, the resolution of phenomena occurring in a small field range, and measurements involving intrinsically slow processes. Notable examples that limit the use of conventional pulsed fields are thermal-conductivity and specific-heat measurements, as well as the free-induction decay in NMR experiments.

A straightforward approach to combine the field strength of a pulsed magnet with quasi-static conditions is to upscale existing GPM designs to obtain 50 to 60 T with a pulse duration of typically 1 second. The downside of this approach is that longer pulses create more heat, while larger magnets cool down more slowly. Long-pulsed magnets, therefore, exhibit substantial turnaround times that severely limit their practical use. While this situation may change with the development of advanced cooling techniques, investments in alternative solutions including advanced measurement techniques are preferred in the meantime.

It is important to note that this choice is based on previous experience and stands in contrast with requirements expressed by a fairly large number of users, including participants of the ISABEL survey. However, the past has shown that, once commissioned, long-pulse magnets are rarely requested more than once by the same users. It is therefore reasonable to make their further development subject to additional conditions regarding improved turnaround times.

Table 5: Long-pulsed magnets	
Scientific case / users	NMR, specific heat …
State of the art (EMFL)	existing prototypes
Challenges	limited turnaround due to extended cooling times
Perspective	no further development unless advanced cooling techniques become available

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 871106

3.3. Flat-top pulsed magnets

Different technical approaches have been pioneered to generate magnetic-field pulses with a plateau-like top. While controlled waveforms are sometimes advertised as an essential advantage of flywheel generators, setting up such a device at one of the EMFL facilities is not realistic.

For generating flat-top pulsed fields with capacitors, two approaches can be envisaged: the first is to use a transformer to inject a reverse current into the discharge circuit, such that the total current flowing through the magnet is limited. The second method is similar, but uses a nested coil producing a magnetic field in the opposite direction to obtain the desired effect. In either case, an auxiliary capacitor bank is needed that sequentially fires capacitors to mimic the curvature of the main capacitor bank's discharge near its maximum. The result is a magnetic-field pulse, whose top is approximately flat and whose total duration remains short enough to avoid excessive heating.

While capacitor-based flat-top generators have been built in China and Japan, European laboratories currently follow a different strategy favouring advanced experimental techniques. For example, distortions in NMR signals arising from a varying magnetic field can be mathematically corrected.

Table 6: Flat-top pulsed magnets	
Scientific case / users	NMR, specific heat, …
State of the art (EMFL)	basic knowledge of existing technical solutions
Implementation effort	construction of an auxiliary bank and coupling with the main generator
Perspective	low priority, no concrete plans without prior cost-benefit analysis; prioritize the adaptation of measurement techniques

3.4. Slow-start pulsed magnets

Heating is not only a problem for magnets, but also for conducting samples and cryogenic equipment exposed to a pulsed field. The principal difference is that samples and cryostats primarily heat at the beginning of the pulse, when the initial field rise produces strong eddy currents. In the best case, the subsequent measurement thus refers to a higher temperature than desired; in the worst case, the entire experiment is left in an undefined state, as temperatures are often challenging to monitor on short timescales. It has, therefore, been suggested to consider ways to smoothen the onset of pulsed fields.

As outlined above, controlled waveforms require advanced generator designs and, hence, a substantial investment in terms of finance and workload. As a simple route to implement slow-start pulsed magnets, passive solutions in analogy to shims used in NMR magnets are an alternative. These could consist of ferromagnetic materials giving rise to hysteretic behaviour at low magnetic fields, or eddy-current shields.

Apart from its efficiency that has yet to be shown, the principal obstacle of this approach lies in the fact that screening a magnetic field invariably gives rise to strong local gradients that manifest as magnetic forces. Whether slow-start versions of non-destructive pulsed magnets are practically feasible thus remains unclear.

It is noteworthy that, in the particular case of MG fields, slow-start fields exist already. Here flux-compression techniques naturally produce an exponential field rise, albeit at the expense of destroying everything inside the bore, when the field reaches its maximum. Whether the use of a thin liner in STC can also smoothen the onset of the magnetic field and at the same time delay any destruction at least until the end of the pulse, is not clear.

Table 7: Slow-start pulsed magnets	
Scientific case / users	high-T_c superconductors, metallic samples
State of the art	Preliminary reflections regarding passive screening techniques in non-destructive and MG fields
Challenges	Efficiency to be tested; magnetic forces acting on parts inside the magnet
Perspective	no concrete plans for non-destructive pulsed magnets; preliminary tests for STC in preparation

3.5. B-dot magnets for industrial applications

Pulsed magnetic fields are interesting for a variety of industrial processes such as magneto-forming and magnetic welding. The common principle is that a strong time-dependent magnetic field initially propells a metallic workpiece towards a target in such a way, that it adapts its shape and possibly fuses with the latter.

As a rule, B-dot magnets need to be adapted to the specific process they are designed for, and part of their specifications can differ considerably from magnets built for scientific research. Apart from geometric constraints and room-temperature cooling, this notably concerns the magnet's design life and long-term reliability as part of an industrial production line. On the other hand, the same fundamental technical principles apply, i.e., the control of heating and magnetic forces. B-dot magnets are therefore an excellent example for collaborations involving academic and industrial partners, and the subject of successful ongoing projects.

Table 8: B-dot magnets	
Industrial applications	Magneto-forming, magnetic welding

State of the art	Existence of a privileged partnership with several funded projects; design and operation of a prototype magnet for magneto-forming
Perspective	Collaboration ongoing; high priority

4. Magnets and installations for advanced photon or particle sources

Outside its own facilities, EMFL operates mobile and stationary satellite installations in other large research infrastructures whose further development is discussed in a separate roadmap[3].

IV. Summary and conclusion

The European Magnetic Field Laboratory (EMFL) is currently entering a pivotal phase marked by significant advancements in magnet technology. Several key developments have already been successfully implemented, including the commissioning of the 42 T hybrid magnet at LNCMI-Grenoble and the installation of upgraded power infrastructures to support the operation of high-performance DC magnets.

In parallel, promising progress is being made on multiple fronts:

Pulsed Field Technology: Ambitious initiatives are underway to surpass the 100 T threshold in non-destructive pulsed magnetic fields, with novel multi-coil designs nearing the testing phase.

All-Superconducting Magnets: EMFL laboratories are actively developing next-generation superconducting magnets, combining HTS and LTS technologies to achieve fields up to 40 T with improved efficiency and experimental flexibility.

Infrastructure Integration: High magnetic field capabilities are increasingly being extended to other large-scale research facilities, broadening the scope of interdisciplinary applications.

These technological breakthroughs are opening new frontiers for experimental science. They enable previously inaccessible regimes of magnetic field strength and precision, fostering novel research opportunities across condensed matter physics, materials science, biophysics, and beyond. As EMFL continues to push the boundaries of magnet design and performance, it lays the foundation for transformative discoveries and deeper insights into the fundamental properties of matter.

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