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ISABEL

Improving the sustainability of the European Magnetic Field Laboratory

Roadmap for the development of high magnetic fields at advanced sources

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Project Coordinator: Geert Rikken – CNRS LNCMI (P1 - CNRS)

Contact: geert.rikken@lncmi.cnrs.fr

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DOCUMENT ABSTRACT

This roadmap outlines a 20-year vision for integrating cutting-edge magnet technologies with advanced external sources, ensuring that Europe remains at the forefront of high-magnetic-field science. Our goal is to identify and prioritize magnet developments that deliver maximum scientific and technological impact for a broad user base, while addressing practical constraints in materials, expertise, and funding.

High magnetic fields are essential for advancing materials science—critical for the fields of energy, quantum computing, AI, and healthcare. While many high-resolution techniques (such as NMR, Raman, and optical spectroscopy) are already supported by existing high-field facilities, others require integration with advanced sources (synchrotrons, XFELs, neutron sources, and THz facilities) to unlock new capabilities and efficiencies.

To meet these needs, we propose five strategic magnet design targets:

A 25 T split-coil high-temperature superconducting magnet with a 50 mm room-temperature bore;

45 T split-coil and solenoid pulsed magnets (0.01 % duty cycle, 20 mm cold bore), including a wide conical aperture option;

A 60 T radial-axial access pulsed magnet with a 15 mm cold bore;

A 35-38 T wide-bore resistive magnet for HFML-FELIX, featuring a 50 mm room-temperature bore.

These ambitious targets will push the boundaries of current science and technology, fostering innovation that benefits both advanced sources and in-house high-field facilities. By aligning development efforts, we create a synergistic strategy that maximizes impact for a diverse and expanding user community.

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1. Executive summary

The most efficient magnet developments would be those that satisfy many of the requirements of all advanced source types listed below. One can divide them coarsely in three groups for which five magnet design targets are defined (see Table 1 below):

Magnet	Field	Type	Duty cycle	Bore diameter & temperature	Advanced sources	
1	25 T	Split HTC		50 mm 300 K	Neutrons	X rays
2	45 T	Split pulse	0.01 %	20 mm 77 K	Neutrons	Lasers
2'	45T	Solenoid conical bore pulse	0.01 %	20 mm 77 K	Synchrotrons	Neutrons
3	60 T	Split pulse	0.01 %	15 mm 77 K	X FELs	High power lasers
4	35-38 T	Resistive		50 mm 300 K	IR/THz (FEL)	

Table 1 Magnet design target for advanced sources

Scattering experiments (neutrons, synchrotrons, XFEL): These experiments require extended spatial access to the field center for incident and scattered beams and the neutrons experiments also require long data acquisition times (seconds to hours). These requirements limit the maximum field strength that can be achieved. Important progress beyond state of the art would be possible using 20+ T split-coil HTc magnets and high duty cycle (ratio useful field duration/experiment duration) 40+ T split pulsed magnets, both with large bore size (> 20 mm). In synchrotron and XFEL facilities, coils #2 and #3 (Table 1) are useful for elastic scattering, while coils #1 and #4 are suitable for inelastic x-ray scattering. In addition, time-resolved measurements using pump-probe techniques are, in general, compatible with coils #1 and #4. But, when combined with single-shot time-resolved schemes, coils #2 and #3 could also be used for such experiments at XFELs. Scattering-based microscopy techniques require coil #1 or #4.

Spectroscopic experiments (IR/THz FEL, XFEL, laser, synchrotrons): These experiments mostly require only short data acquisitions times (nanoseconds to seconds) and narrow access to the field center, parallel and perpendicular to the field. This allows for high maximum fields. Important progress beyond state of the art would be realized by magnets with axial and radial access and with modest bore size, i.e., 60+ T pulsed magnets (~15 mm bore size) and 25+ T DC magnets (50 mm bore size). A special and unique case is the IR/THz FEL coupled to a DC magnet at HFML-FELIX, which will be a wide-bore magnet (50 mm) to allow for multiple scattering geometries (coil #4). At synchrotron and XFEL facilities, utilizing different types of magnets tailored for specific spectroscopy techniques would be useful. Coils #1 and #4 are useful for spectroscopy experiments in the nonlinear regime, absorption-based element-specific microscopy techniques, and pump-probe absorption experiments. Coils #2 and #3 would allow to measure x-ray absorption spectroscopy in the linear regime.

Imaging experiments (IR/THz FEL, XFEL, laser, synchrotrons): These experiments require both long acquisition times and large bore sizes (to accommodate positioners, etc.). Measurement can be based on detection of force or current, but also on spectroscopy. Related instrumentation could enable understanding of domain structures in high-field phases. Important progress beyond the state of the art would entail wide bore sizes at high fields and vibration-free environments, which could be realized in coils #1, #2, #3 and #4.

These considerations suggest, therefore, five magnet design targets for advanced sources:

1) 25 T split-coil HTc magnet with a 50 mm RT bore;
2) 45 T 0.01 % duty cycle split coil pulsed magnet with a 20 mm cold bore;
1) 45 T 0.01% duty cycle solenoid pulsed magnet with a 20 mm cold bore and a wide conical aperture;
2) 60 T radial-axial access pulsed magnet with a 15 mm cold bore;
3) 35-38 T wide-bore resistive magnet for HFML-FELIX with a 50 mm RT bore.

These ambitious targets would provide magnetic fields beyond the current scientific state of the art at the advanced sources, but also require challenging technical developments that would also benefit the high-field facilities for their in-house magnets. This synergy renders such a strategy beneficial for a very large user community.

2. Introduction

2.1 Aim of the roadmap

This roadmap aims to structure the magnet aspects of high magnetic field science at advanced sources external to the European high-field facilities for the next two decades. It aims to identify what magnet types would be most beneficial and feasible for use at such advanced sources by the largest possible user communities, and what would be required to implement their development. This roadmap attempts to provide a tentative planning for the design, realization and exploitation of such magnets, taking into account foreseeable possibilities and limitations concerning materials, manpower and funding.

2.2 Context of the roadmap

Development of new materials for energy needs, quantum information technology, artificial intelligence, and health needs to better understand these materials and high magnetic fields are of prime importance to perform high-resolution spectroscopies. Some of these techniques are developed in high magnetic field facilities (NMR, Raman, infrared, thermal and transport

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measurements, (time-resolved) optical spectroscopy, etc.) but some other techniques need advanced sources (Synchrotrons, XFEL, neutrons, intense lasers, THz sources) to be efficient. The need of development of such high magnetic fields at advanced sources is well demonstrated.

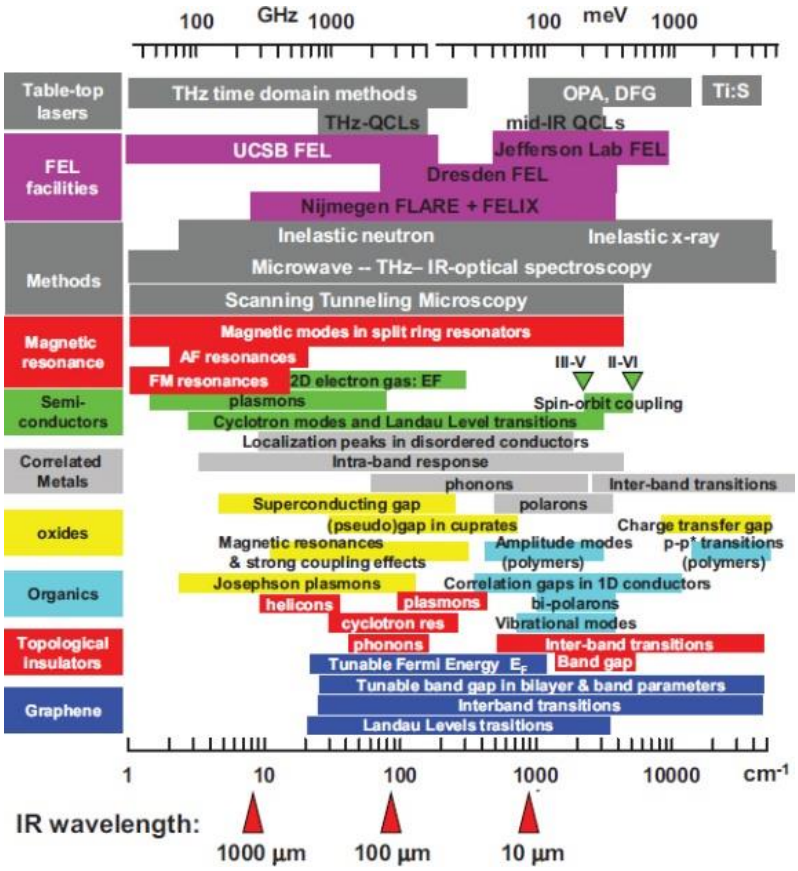

Figure 1 Characteristic energy scales in solids. NOTE: DFG, difference frequency generation; OPA, optical parametric amplifier; QCL, quantum cascade laser. *Adapted from D.N. Basov, R.D. Averitt, D. van der Marel, M. Dressel, and K. Haule, 2011, Electrodynamics of correlated electron materials, Reviews of Modern Physics 83:471, copyright by the American Physical Society [1].*

Figure 1 summarizes the type of sources, which are used to study advanced materials and gives a few examples of such materials. In the following, high magnetic fields are defined as "magnetic fields that are not commercially available". The field value depends on the geometry and the size of the magnet. Technical difficulties also depend on the precision of positioning the sample with respect to the beam (sample size and beam size), the important question of vibrations, but also the demand on the sample temperature.

Since all these magnet designs are highly specialized, it may be difficult to build an economical model in which industry will have a reasonable economical return. The EMFL facilities are in a unique position to satisfy the high magnetic field needs of advanced sources at reasonable cost, as they already possess the very specialized know-how to design such prototype magnets and the tools to construct them as a result of their in-house magnet programs.

The approach of this roadmap is then to focus on a few (five) prototypes of magnets based on strong scientific cases and to try to develop these prototypes by joining efforts on this list of objects.

Once the expression of needs is defined, the questions of financing the design studies, financing the construction phase, and financing the exploitation phase have to be discussed.

3. Science cases for high magnetic field experiments at advanced sources

3.1 Coupled charge, spin and lattice effects

3.1.1 General aspects

A universal feature of quantum materials is the strong coupling between charge, spin and lattice degrees of freedom. These interactions, occurring on comparable energy scales, result in nearly degenerate states of matter, that either compete or coexist, leading to the emergence of novel exotic properties [2]. This delicate competition also facilitates the 'tuning' of quantum materials, and, historically, the discovery of new quantum phases has been intertwined with the ability to carry out experiments at the highest available magnetic fields. Recent experiments at current-record fields have, indeed, revealed new phases and the community continues to thrive as experiments reach ever-increasing field strengths [3]. Although neutron and x-ray scattering experiments provide well-established and powerful methods for determining charge, spin and lattice order in to-date available magnetic fields of up to 14.5 and 17 T, respectively, using conventional superconducting magnets, studies at higher fields remain very rare. Consequently, the microscopic properties of many high-field phases are still poorly understood.

3.1.2 Some examples of scientific cases

Intermetallic compounds containing *f* electrons are exemplary in this regard, displaying a range of phases such as unconventional superconductivity [4,5], nematicity [6,7], "hidden" [8] and topological [9] electronic phases and intricate magnetic orders [10]. These systems are governed by the Kondo interaction, which couples localized 4*f* or 5*f* electrons with conduction electrons to form heavy quasiparticles. The significant spin-orbit coupling in 4*f* and 5*f* systems introduces an anisotropic character to the electronic wavefunctions, strongly coupling spin and lattice degrees of freedom. The strength of the Kondo coupling determines the degree to which this anisotropy appears in the electronic structure [11–13].

The spin-lattice coupling is further modulated by 4*f* valence fluctuations/transitions in systems such as *Ce, Yb, and Sm-based heavy fermions*. These transitions, occurring under high magnetic fields due to the closure of the correlation gap, directly influence the hybridization between local moments and conduction states. Advanced techniques such as element-selective x-ray absorption spectroscopy in pulsed magnetic fields at synchrotrons now allow direct detection of these hybridization effects, shedding light on the competition and cooperation between charge, spin, and lattice.

Spin-lattice and field-induced phenomena in complex oxides

3*d*, 4*d*, 5*d*, and 4*f*-based oxides such as pyrochlore compounds with stoichiometry $T_2R_2O_7$ or $T_2R_2O_6$ (where T = transition metals, R = rare-earths) and iridates are another highlight example displaying strong spin-electron-lattice coupling.

In pyrochlore materials, localized magnetic moments on corner-sharing tetrahedra are forced into an Ising state by crystal electric fields. A delicate balance of dipole-dipole and exchange interactions between nearest/next-nearest neighbors leads to a rich spectrum of emergent excitations and frustrated magnetic ground states. For example, spin-ice behavior and monopole-like excitations are observed in compounds such as $Ho_2Ti_2O_7$ at low temperatures. Using x-ray diffraction in pulsed magnetic fields up to 30 T, a spin liquid to structural transition was observed in $Tb_2Ti_2O_7$, driven by magnetoelastic coupling. X-ray magnetic scattering under these fields provides element-selective magnetization data at fields driving the 4*f* moments into saturation. High-field x-ray magnetic circular dichroism (XMCD) will enable disentangling 4*f* (*R*) and 3*d* (*T*) electron magnetic contributions and studying the sublattice interactions. Combining XFELs with even higher pulsed fields will enable advanced experiments on actively studied materials, such as $Nd_2Mo_2O_7$, $Yb_2V_2O_7$, and $Nd_2Ir_2O_7$.

Similar to the magnetic field-induced quantum spin-liquid phase emerging from the magnetically ordered state upon application of about 10 T in the 4*d*-Kitaev material α-$RuCl_3$, the onset of a field-induced quantum spin liquid has been theoretically proposed in 5d iridium oxides such as Na_2IrO_3. However, the latter is predicted to require substantially higher magnetic fields, on the order of 50 T, to access this exotic regime. Resonant x-ray magnetic scattering using strong pulsed magnetic fields would provide a powerful experimental probe to investigate these intriguing field-induced quantum spin-liquid phenomena.

3.2 Superconductors and field-induced order

3.2.1 General aspects

Conventional superconductors, which are well-described by the Bardeen-Cooper-Schrieffer (BCS) theory, mostly exhibit low transition temperatures and critical magnetic fields that fall within current experimental capabilities. This accessibility allows the entire superconducting phase to be investigated using neutron and x-ray scattering techniques. However, for BCS materials with high critical temperatures, such as Nb_3Sn (T_c = 18 K, H_{c2}= 30 T) and MgB_2 (T_c = 39 K, H_{c2} ~ 74 T), their critical fields exceed the limits of present experimental techniques, restricting comprehensive studies.

Unconventional superconductors, including heavy-fermion systems, cuprates, and iron-based superconductors, pose a similar challenge due to their extremely high critical magnetic fields, often exceeding 40 T, or remaining undefined experimentally [14]. For instance, in the case of cuprates superconductors, it is challenging to reconcile quantum oscillation studies of the Fermi surfaces, heat-capacity measurements and the diffraction signatures associated with charge and spin density waves observed in these materials.

In addition to directly probing superconducting responses, magnetic fields can induce changes to the underlying state. These include field-induced textured superconducting states such as the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) [15–17] state or the emergence of spin or charge density wave states.

3.2.2 Some examples of scientific cases

Spin density wave states

For instance, in $CeCoIn_5$, applying a magnetic field in a specific direction induces spin density wave order just below the critical field of 11.6 T [18–20]. The diffraction signals from such magnetically ordered states are typically weak, and so to date chasing down clear related excitation signatures from inelastic neutron scattering has been challenging. Access to higher fields, coupled with the enhanced neutron flux provided by facilities such as the European Spallation Source, will permit the exploration of the characteristic excitations underlying these states.

Iron-based superconductors also provide an important platform to investigate the interplay between superconductivity and spin density wave order. Zero-field studies have revealed a competition between these phenomena, arising from strong magnetoelastic effects in the orthorhombic lattice phase. However, since the upper critical field exceeds 15 T, tuning this competition via magnetic fields has been impeded by limitations of conventional steady-field coils at synchrotrons. The advent of 60 T pulsed magnets at synchrotrons and XFELs will enable tackling these issues. Moreover, exploring magnetically disordered regimes near the quantum critical point, where field-induced magnetism emerges, is also compelling. Strong magnetoelastic coupling in the orthorhombic phase permits probing such magnetism through induced lattice distortions.

Charge density wave states

In addition to investigations of magnetic order, high magnetic fields would also provide an avenue to explore the charge density wave (CDW) behavior seen in the cuprates by x-ray diffraction [21,22]. At low fields, CDWs are typically short-range ordered and primarily two dimensional in nature. Although CDW diffraction from these signals have also been detected using neutron scattering, their intensity is generally too weak for a detailed, systematic analysis. However, at fields above 15 T (e.g., for $YBa_2Cu_3O_{6+x}$), the CDW state develops a stronger order, becoming more three dimensional [23,24]. This enhanced ordering makes CDWs more accessible to both x-ray and neutron diffraction studies, enabling more comprehensive mapping of their behavior under extreme conditions. High-field experiments also open up opportunities to investigate the phonon response to the induced order in these materials, and searching for characteristic excitations, such as amplitudon and phason modes. Furthermore, the electronic order in the high-field phase of cuprates is unidirectional, transitioning from the bidirectional CDW order [25] in the zero-field phase. This suggests that magnetic fields drive a transition from an isotropic electronic phase to an electronic nematic phase. Such field-induced nematicity has not only been observed in cuprates but has also been suggested in other complex quantum materials, including iron-pnictide and heavy-fermion superconductors. This indicates that nematic electronic order may be a universal feature in complex quantum materials, especially those with intertwined magnetic and electronic instabilities. Consequently, high magnetic fields are essential for unraveling the connection between electronic liquid-crystal phases and unconventional superconductivity.

To advance this research, it is crucial to measure superlattice reflections such as those associated with a CDW, which are significantly weaker than fundamental Bragg peaks derived from the crystal structure. Such measurements can benefit greatly from the use of high-intensity x-ray free-electron lasers (XFELs) in combination with pulsed high magnetic fields, offering the sensitivity required to probe the intricate interplay between CDW order, phonon dynamics, and superconductivity.

Combining diffraction and inelastic measurements at higher fields will also help to reconcile the discrepancies between quantum oscillation measurements at high fields and scattering measurements at lower fields. This remains an open question for the underdoped cuprate superconductors, but also applies to a range of other materials, such as for the Kondo insulator SmB_6, where quantum oscillations are seen only in the magnetization and not in the resistivity [26].

Nematic and spin-triplet phases in unconventional superconductors
Putative nematic and chiral *p*-wave superconducting phases represent also highly exotic phases believed to arise from the intricate interplay of spin, charge, and lattice couplings in strong magnetic fields. While the microscopic mechanism underlying theses phases remain poorly understood, magnetic-field control has been shown to alter the strength of the Kondo interaction, changing the effects of hybridization. One notable example is $CeRhIn_5$, where an electronic nematic order has been revealed. Yet, the origin of nematicity in this material remains unclear, with coupling to both the spin and the crystal-field states being proposed. Notably, extensive neutron scattering experiments in zero and low-magnetic fields demonstrate that spin and charge degrees of freedom are closely coupled and possibly result in the emergence of a state, where the electronic structure of the material becomes spontaneously layered. This may be used for devices, in which the electronic properties can be changed *in-situ.*

Similarly, in UTe_2, three superconducting phases have been identified in magnetic fields exceeding 60 T [27,28]. Superconductivity mediated by conventional spin-singlet Cooper pairing is incompatible with such fields, as they disrupt antiparallel spin alignment. However, in itinerant ferromagnetic states, the large energy splitting between the majority and minority spins allows for the pairing of electrons with parallel spins within each of the spin-split Fermi surfaces. This spin-triplet Cooper pairing avoids magnetic pair-breaking and is thought to be mediated by longitudinal low-energy spin fluctuations [29,30]. However, such fluctuations require a strong uniaxial magnetic anisotropy that is typically provided by the spin-orbit coupling, which in turn couples to the crystal lattice. A recent STM study suggests that even at zero magnetic field the superconductivity has chiral *p*-wave character [5], a property proposed for the design of topologically protected (decoherence-free) qubits [31] and hence for implementing topological quantum computing [32]. While again no microscopic information is available for UTe_2 at high fields, several neutron scattering experiments at zero and low-field have revealed the existence of a spin-resonance showcasing the importance of spin degrees of freedom for this exotic superconducting state [33,34].
Both the nematic phases of $CeRhIn_5$ and the chiral *p*-wave superconductivity of UTe_2 illustrate the need for scattering experiments at elevated magnetic fields to optimize and exploit their properties for future applications.

3.3 Multiferroics

3.3.1 General aspects

Multiferroics are materials that exhibit both ferroelectric and magnetic order parameters. However, these order parameters do not merely coexist, but are found to be coupled, resulting in both exciting new fundamental physics and novel potential applications [35], such as memory devices, magnetic field sensors, small antennae, and others.

Neutron and x-ray scattering play a key role in elucidating ferroelectric properties of multiferroics by being able to study the detailed underlying crystal structure. More importantly and thanks to the spin degree of freedom of the neutron, neutron scattering is the key method to unambiguously determine the magnetic structures and spin dynamics. In addition, the application of magnetic fields is crucial to tune and optimize the coupling between both degrees of freedom, to understand how strongly the magnetic and ferroelectric order parameters are coupled [36].

3.3.2 Some examples of scientific cases

Several multiferroic materials highlight the importance of combining advanced scattering techniques with high-field capabilities to unravel their microscopic properties and the origin of their magnetoelectric coupling.

$BiFeO_3$ is well-established as a practical candidate, and yet the true nature of its putative metamagnetic transition has never been investigated microscopically apart from preliminary studies with pulsed field and very poor statistics [37].

One family of materials displaying rich multiferroic phenomena are the lithium orthophosphates, $LiMPO_4$ (M = Fe, Ni, Me, Co), which have antiferromagnetic and magneto-electric (ME) ground states below 20-50 K. A prime example is $LiNiPO_4$, a type-II multiferroic, in which the complex magnetic texture drives the electronic order due to strong lattice coupling. The resulting control of electrical properties by an applied magnetic field, and of magnetic properties with an electric field, offers a wide potential for applications in rewritable high-density storage and also in processing of both classical and quantum information. Neutron diffraction at high fields can be used quite generally to understand how the spiral order in type-II multiferroics "unwinds" to become ferromagnetic at saturation. In $LiNiPO_4$, the magnetic phase diagram shows multiple reentrant ME effects below 12 T, at 19-21 T and above 40 T [38,39]. Different physical mechanisms have been proposed for the complex coupling of spin and charge giving rise to such behavior, including the inverse Dzyaloshinskii-Moriya interaction, spin currents and *p*-*d* hybridization. To date, however, the magnetic structures in the ME phases [40] of materials like this remain poorly understood due to the difficulties inherent in neutron and synchrotron diffraction studies above 15 T. Because phenomenological models for the induced electric polarization suggest rather dramatic changes to the magnetic interactions both in and between the ME phases, higher field scattering capability is a necessity for investigating the physics of this system.

3.4 Molecular nanomagnets and molecule-based magnets

3.4.1 General aspects

Purely organic magnets with π-electron spins have essentially negligibly small spin-orbit couplings and are attractive materials because they are archetypical Heisenberg spin systems, in which quantum fluctuations play an important role. The spin size and the connectivity of the network is the key factor of the novel magnetic states arising from quantum fluctuations. Among the representative stable organic radical skeleton, the nitroxide (-N-O·) radical has the advantage of making antiferromagnetic spin networks [41,42]. The positive and negative partial charges on the N and O atoms, respectively, easily give the intermolecular contact between the NO groups on which the singly occupied molecular orbital (SOMO), that is the molecular orbital with the unpaired electron, is distributed.

The stacking of planar π-conjugated molecules gives a 1D chain. When two or more NO groups are substituted on a molecule, a double spin chain with different spin size is formed [42,43]. After extensive studies on the 1D Heisenberg antiferromagnet, there is a growing attention to the effect of the quantum fluctuations in 2D or 3D Heisenberg antiferromagnets, but the experimental realization is still rare.

Today, magnetic structure and collective-excitation studies are needed to understand the complex phase diagram found in purely organic magnets, which are badly understood due to the limited accessible magnetic fields. These experiments often require ultra-low temperature and the highest available field because the measured signal is proportional to the applied field.

Molecular nanomagnets are molecular metal-organic compounds that can serve as model systems for correlated magnetic systems [44]. In addition, they have fascinating properties of their own, such as extremely slow dynamics of the magnetic moment of purely molecular origin. These properties arise from the interplay of the (Heisenberg) exchange coupling and the local anisotropy, often in the form of zero-field splitting. High magnetic fields play a role in antiferromagnetic molecular nanomagnets, e.g., to study field-induced magnetic level crossings. Secondly, high magnetic fields are important for the full understanding of high-anisotropy systems, engendered by access to a regime where the Zeeman energy is comparable to the anisotropy energy. THz radiation and inelastic neutron scattering play an important role in studying magnetic excitations in such systems. In addition, intense THz radiation can be used to selectively excite phonon transitions in the study of spin–phonon coupling and its influence on magnetization dynamics (see 3.6.2).

3.4.2 Some examples of scientific cases

Organic Heisenberg Spin Ladders, whose magnetic behavior lies in the crossover region between one and two dimensions, have been at the focus of intensive research towards its understanding, since peculiar phenomena, such as superconductivity in a hole doped $S = 1/2$ two-leg spin ladder, are expected to appear [45–49]. A major challenge in studying these systems is the difficulty in accessing the spin gap, which is often too large for experimental measurements. Only in certain organometallics [50–55], the spin gap is small enough to permit a comprehensive investigation of the spectrum through the application of a magnetic field up to 20 T by using inelastic neutron scattering techniques at very low temperatures. To the best of our knowledge, only one purely organic (BIP-BNO) [56,57] compound has been synthesized that can really be described by the two-leg Heisenberg antiferromagnetic ladder model. Correlated spin systems composed of organic high-spin building blocks [58] are essentially unstudied and provide a potentially very fruitful avenue of research.

Organic triangular Heisenberg spin lattices: Multiferroic behavior has been demonstrated in trimerized Mott insulators through the interplay between spins and electric dipole moments resulting from electronic charge fluctuations in magnetically frustrated units [59]. The model consists of stacked triangular layers of trimers with small intertrimer exchange interactions. High magnetic fields (~20 T) and very low temperatures (< 250 mK) are needed to explore them with neutron scattering techniques and understand the complex phase diagram found in these triangular lattices.

Antiferromagnetic Clusters: In these systems, the ground-state spin in the absence of field is zero or very small. Magnetic anisotropy typically plays a minor role. Field-induced spin-state crossings have been investigated in some detail in these systems [60–62]. Open questions include level mixing at the crossing points (avoided crossings) and magnetoelastic effects. Techniques to study these include torque and Hall-bar magnetometry, as well as specific-heat measurements.

Single-Molecule Magnets: These materials feature slow relaxation of the magnetic moment of purely molecular origin, where the (antiferromagnetic) Heisenberg interaction leads to an uncompensated, large ground-state spin. Here, the magnetic anisotropy is large creating an energy barrier towards inversion of the magnetic moment. A corollary of the large anisotropy is that magnetic dipole spin excitations are located in the THz and sub-THz regime, and high-frequency electron spin resonance spectroscopy has been often used for the investigation [63,64]. In recent years, anisotropy values have been pushed to very high values and the corresponding excitations into the far infrared [65,66]. The necessity for high magnetic fields is implicit in the high frequencies of electron spin resonance measurements, but also for torque magnetometry, where for in-depth analysis the Zeeman and anisotropy energies should be similar [67]. Further opportunities for intense THz radiation lie in the investigation of spin–phonon coupling and its influence on magnetization dynamics, e.g., by selective excitations of specific molecular vibrations.

3.5 Semiconductors and 2D materials

3.5.1 General aspects

The combination of infrared and far-infrared (IR/THz) radiation and high magnetic fields have played a crucial role in the understanding of semiconductors and their nanostructures. Key examples are cyclotron-resonance (CR) experiments to determine the effective mass of charge carriers and electron spin resonance (ESR) to study their spin properties. With increasing magnetic fields, the required frequencies for CR and ESR shift in the THz regime, in which high intensity, narrow-band, pulsed sources are rather scarce (the so-called THz gap). Combining IR/THz FEL radiation with high field magnets is, therefore, ideally suited for high field CR and ESR experiments, provided the experimental infrastructure can be optimized and the optimal magnets can be designed and fabricated.

3.5.2 Some examples of scientific cases

Quantum-information technology

Donor atoms in a semiconductor host, such as Si:P, provide a way to test and realize quantum computing schemes. It has been shown that THz free-electron laser radiation can be used to control the dynamics of the quantum states of the donor states by optical interference, and subsequent electrical read-out [68]. In a next step, control of the orbital wavefunctions could be obtained by gating the magnetic exchange interactions between adjacent impurities. Such control is feasible in Si:P in magnetic fields up to 30 T [69].

THz electronics

Modern electronic devices, such as Si-based processors and memories in computers, work at several GHz. A further acceleration towards THz electronic devices requires new materials, new experimental methods and to develop a fundamental understanding in this new electronic ac-conductivity regime, where the typical electron scattering rates become comparable to the excitation frequencies [70]. Graphene has shown a very fast electronic response in the THz regime [71]. Combining intense, ultrafast FEL pulses with the highest magnetic fields is ideal to perform the required pump-probe experiments [72], relevant for THz emitters, detectors, transistors, plasmonic devices and modulators in graphene, transition metal dichalcogenides and other materials [73].

Organic semiconductors

Correlated spin pairs play a key role in many fundamental processes studied in biology, chemistry and physics. In organic optoelectronics, spin-triplet pairs are shown to mediate the spin-allowed conversion of a spin-0 singlet exciton into two spin-1 triplet excitons in a process called singlet fission. Singlet fission can be used to sensitize anorganic solar cells in order to surpass the Shockley-Queisser limit or in organic molecules to break the electroluminescence quantum-efficiency limit. Recently, the spin-pair coupling strength was determined by optical means in the material TIPS-tetracene [74]. This required magnetic fields up to 65 T due the strong intermolecular coupling. In a next step, the properties of these spin pairs should be addressed, which needs pulsed ESR techniques at highest magnetic fields, that only can be done by combining FELs and high-field magnets.

3.6 Magnetic materials

3.6.1 General aspects

Magnetic materials have revolutionized modern-day technology, e.g., driven by the continuous development of magnetic storage. The ever-increasing amount of data that is created poses an enormous challenge, not only to store it at high densities and at the fastest possible way, but also by using the least amount of energy. In the last decades, enormous progress has been made to switch magnetic bits by all-optical methods using femtosecond laser pulses [75], also at high magnetic fields [76]. This has boosted our understanding of the underlying mechanisms of light-matter interaction in solids, i.e., the interaction of photons with charges, spins, the lattice and the angular momentum transfer between them. Now, the attention is partially shifting from optical towards THz frequencies, to decrease the response time of the materials and to explore whether it is possible to effectively switch bits using phonons or magnons.

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3.6.2 Some examples of scientific cases

Magnetic switching by phonons

Recently, it was shown that the magnetic state of a material can be reversed by resonant pumping of phonon modes [77,78]. Utilizing the coupling between spin and lattice excitations for magnetic switching is especially attractive, because it requires substantially less energy than normal switching methods. Typically, these experiments utilize an intense THz source, such as a free-electron laser, to resonantly pump an optical phonon, but so far, the measurements have been restricted to zero magnetic field. Application of high magnetic fields gives access to more magnetic phases and allows to determine the actual strength of the magnetic component of the light pulse. Interestingly, this type of switching also applies to ferroelectric and multiferroic compounds [79].

Antiferromagnetic materials

Historically, most studies in magnetism were directed towards the understanding of ferro- and ferrimagnetic materials. Recently, it was realized that also antiferromagnetic materials exhibit quite some interesting characteristics for future spintronic applications [80]. Due to the absence of a net magnetization, they are robust against magnetic perturbations, and they produce no stray fields. Very importantly, they can display ultrafast dynamics, because of their magnetic resonance frequency in the THz range. To this end, to fully understand light-matter interactions in antiferromagnetic materials, the investigations should be extended to higher magnetic field values and combined with narrow-band pulsed free-electron-laser radiation [81,82].

3.7 High energy density physics (HEDP)

3.7.1 General aspects

We list here some scientific cases that can be addressed with pulsed fields in the range of 40 – 100 T. HEDP (density > 10^{20} cm^{-3}, temperature > 1 keV) can be easily produced by high-power lasers. This allows for experimental science to enter this extreme regime (pressure > 1 Mbar) and answer questions regarding, for instance, hydrodynamic or thermodynamic properties of matter, which are of crucial importance for the realization of inertial confinement fusion (ICF) and for improving our understanding of astrophysical phenomena.

3.7.2 Some examples of scientific cases

Planetology

It has been shown very recently, that by applying an initial high pressure to a sample of interest for planetology, and then compressing it to extreme pressures (by means of laser power), the conductivity is modified [83]. This result, coupled with the fact that higher conductivity gradients could favor multipolar magnetic fields with shallower density stratification, may have a major impact on our knowledge of (i) planetary interiors and (ii) their associated magnetic field. Here, the goal would be to use a high magnetic pressure (~ 1 GPa,

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corresponding to a field of the order of 40 – 70 T) in order to see how the conductivity is modified and how this modifies our knowledge of the structure of the planets.

Particle acceleration in magnetized collisionless shock

The acceleration mechanisms that occur in collisionless shocks require very strong magnetization. These make it possible, in particular, to better understand the spectrum of cosmic rays measured on Earth. In order to increase this magnetization, it is necessary to increase the imposed magnetic field to explore different regimes and acceleration schemes [84].

MHD turbulence

MHD (magnetohydrodynamic) turbulence is ubiquitous in the Universe. However, our theories for describing it are still very fragmented. This is considered as a major unsolved problem in plasma physics. Observational data are often limited and, therefore, the study of MHD turbulence on small spatial scales must be performed in laboratory experiments. In order to obtain different degrees of magnetization, it is necessary to have, in the laboratory, a magnetic field of up to 100 T (magnetization of 10^{-2} – 10^{-3}) [85].

Cataclysmic variables of POLAR type

Accretion processes play a crucial role in a wide variety of astrophysical systems. Of particular interest are magnetic cataclysmic variables, where plasma flow is directed along the star's magnetic field lines onto its poles. A stationary shock is formed, several hundred kilometers above the stellar surface; a distance far too small to be resolved with today's telescopes [86]. This is the reason why scaled laboratory experiments are essential to get new insights on these systems. In order to fully collimate the plasma flow onto an obstacle using a magnetic field (as in the astrophysical system) it is necessary to have, at least 20 T. In increasing the field up to 60-70 T, it will be possible to explore different accretion processes.

Magnetic reconnection

Despite significant progress in the study of HEDP, one question remains open: How the dynamics of strong self-generated magnetic fields (> 1 MG) influence plasma properties, especially with respect to heat flow? This issue is not well understood due to the inadequacy of current diagnostics and the difficulty of modeling these configurations in codes. Experimental objectives can be to gain a clear understanding of (i) the magnetic field growth and diffusion, as well as of its influence on heat transport, to clarify several long-standing issues regarding magnetic reconnection (the process through which anti-parallel magnetic field lines rearrange their topology to obtain a less-energetic state), (ii) the role played by the non-planar magnetic-field component (i.e., Hall component) on the rate of reconnection and on the energy balance between the directed and thermal components of the plasma outflow and (iii) the macroscopic large-scale consequences of reconnection events, such as happening in the solar corona.

Inertial confinement fusion – ICF

During an integrated ICF experiment, very intense magnetic fields (of the order of 100 T) can be self-generated due to the Biermann-Battery effect [87]. These fields then influence the dynamics of the implosion (heat transport, hydrodynamic instability, etc.). It is, therefore, necessary to study the microphysics associated with these implosions to validate numerical simulations in having a controlled magnetic field of the same order of magnitude. An alternative way to ICF and MCF (magnetized confinement fusion) is currently emerging: magnetized inertial confinement fusion [88]. Here, unlike for ICF, a stabilizing field (with regard to hydrodynamic instabilities for example) makes it possible to increase the number of neutrons in comparison with a conventional scheme [89]. Thus, it is necessary to perform experiments to verify the underlying microphysics. In this scheme, the magnetic field can be compressed to extreme values (> 5000 T). It is, therefore, necessary to be able to calibrate the simulation codes at least in fields of the order of 100 T.

4. State of the art

4.1 Superconducting Magnets

4.1.1 At synchrotron and neutrons facilities

All-superconducting coils enable the use of mobile magnets on neutron instruments, measuring complementary data over extended periods of time with limited cost. Superconducting split-pair magnets, the most demanded design for neutron scattering experiments, currently reach 13.5 T using conventional low-Tc superconductor (LTS) technology, and up to 15 T by expensive sub-cooling, but not any higher due to the intrinsic limitations of LTS materials. The operation of most existing LTS systems requires liquid He and is affected by volatile supply situations, limiting their regular use to facilities with a liquefier and He recovery system. Those, which can be operated cryogen free provide lower maximum fields and offer limited sample-cooling capabilities.

Recently, cryogen-free conduction-cooled HTS split-pair coils in the 12 T range have been developed using 1st generation HTS conductors based on BSCCO (bismuth strontium calcium copper oxide). They have the major benefit of higher compactness and simpler operation (no lambda plate for sub-cooling) as the operating temperature can be well above 4.2 K. The Institut Laue-Langevin (ILL) has developed unique knowledge in designing and implementing a cryostat hosting such a HTS BSCCO conduction-cooled split-pair and a variable-temperature insert fed by a liquid He bath. The bath is only used to cool the sample down to 1.5 K or ultra-low temperature with a dilution insert (40 mK). However, BSCCO-based magnets can only be an intermediate step because of their very large silver content. They are weak mechanically and, thus, inefficient for developing compact magnets in the 20 T range and beyond. The large silver content makes them also fundamentally expensive to produce, so much so that the largest and best-known producers of reinforced BSCCO tapes, Sumitomo, has announced that it will cease their production this year.

4.2 Pulsed magnets

4.2.1 At laser laboratories

A coupling between a high magnetic field, i.e., well above 30 T and high-power lasers is of major interest for high energy density physics (HEDP) in Europe. Laser laboratories able to generate high magnetic fields exist in Europe (LULI, European XFEL) [90–93]. These experiments mostly require the use of split coils in order to provide an access perpendicular to the high energy/power laser beam to probe the plasma evolution. Sometimes, conical bores will be needed to fit the lasers properties, i.e., focal length and beam diameter. Today limited to 30 T – 100 µs, nondestructively, and 70 T – 1 µs, destructively, many experiments will require higher magnetic fields.

4.2.2 At synchrotron and neutron facilities

Numerous pulsed high magnetic field setups have been implemented at synchrotron and neutron sources over the last 20 years [37,94–106]. These advancements have expanded the accessible magnetic field range from the typical 15-17 T produced by superconducting DC magnets to 30-50 T in 1-100 ms pulses, at low energy costs and moderate technical infrastructure requirements. A wide set of scattering techniques – including powder and single crystal diffraction, absorption spectroscopy, magnetic dichroism, nuclear resonant scattering, magnetic scattering and emission spectroscopy – have been successfully demonstrated in pulsed fields. However, many experiments remain exploratory, and successful campaigns at x-rays and neutron sources require careful topic selection and expert preparation. Future coil developments aimed at achieving higher fields, improved duty cycle, larger sample volume, enhanced stability, and vacuum compatibility will facilitate to transition from exploratory to precision experiments in the existing techniques. These improvements combined with lower sample temperature will also broaden the range of accessible subjects, and enable the application of new techniques, such as inelastic x-ray scattering, phase-contrast imaging and magnetic holography in pulsed high magnetic fields.

4.2.3 At FELs

HLD has developed a pulsed magnetic field setup for x-ray scattering experiments at the Helmholtz International Beamline for Extreme Fields (HIBEF) at the European XFEL (EuXFEL). The pulsed-field setup is combined with the High Energy Density (HED) instrument of the EuXFEL, covering x-ray energies from 5 to 25 keV [107]. The EuXFEL offers a unique time structure with bunch trains of up to 2700 pulses separated by 220 ns. By matching the length of the magnetic-field pulses with the length of the x-ray bunch train, 0.6 ms, the field dependence of fundamental and/or superlattice diffraction intensities can be measured in a single magnetic-field pulse. We have developed a 750 kJ/24 kV capacitor bank with a peak current of 50 kA for energizing a horizontally aligned bi-conical solenoid with a 60 and 20 degree opening. The solenoid magnet has been designed to achieve a maximum magnetic field of 60 T. This coil system integrates an eddy-current shield to minimize stray fields and vibrations due to interactions with the environment. We performed the first commissioning experiment in February 2024 and the first user experiment based on a community proposal in October 2024 up to 50 T. To access larger scattering angles, a split-pair coil is also under consideration with a maximum magnetic field of about 45 T.

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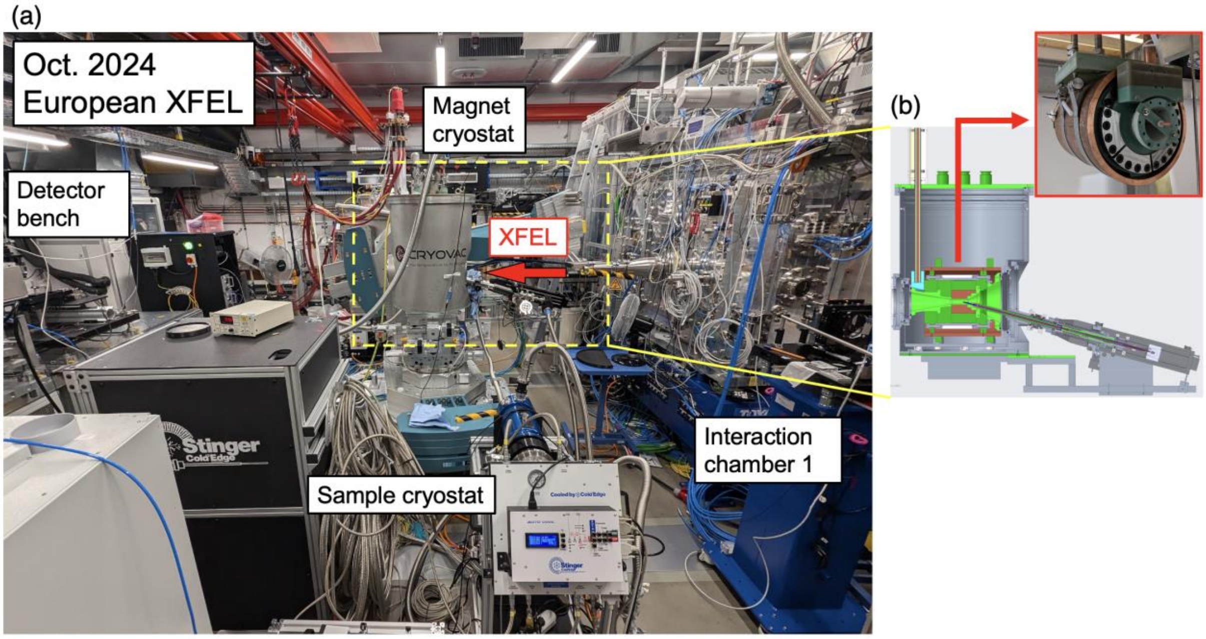

Figure 1 (a) Pulsed-field setup at the high-energy-density endstation in the European XFEL, which was developed within the HiBEF consortium (HZDR, DESY, and European XFEL). (b) Schematic diagram of the bi-conical solenoid in the magnet cryostat. The image on the top-right corner shows the coil with the eddy-current shield.

4.3 Resistive magnets

4.3.1 At FELs

One of the 33 T Nijmegen magnets is connected to three free electron lasers (FELs) providing high-intensity, widely tunable and ultra-short pulse radiation in the infrared and THz spectral range; in total they cover a wavelength range from 3 to 1500 µm (0.25 – 100 THz). Pulse duration and pulse energy vary with wavelength but range typically between 1-50 ps and 5-50 µJ. Advanced pulsing schemes are available to produce the best pulses for the experiments. In the near future the beamline of the FELs will be connected to all other magnets, including the 30 T wide bore magnet and the 45 T Hybrid magnet.

5. Expression of needs

5.1 At neutron facilities

In November 2022, the HMF4NS workshop[1] gathering scientists and technical experts of HMF and neutron facilities has been organized to identify the needs of the neutron user community, evaluate the technical challenges and prepare a roadmap for developing unprecedented capabilities. The urgency to provide neutron scattering capabilities beyond 15 T in steady-state mode at ultra-low temperature was for a short time met by a highly specialized installation using a hybrid technology combining superconducting and resistive

[1] Workshop on "Perspectives with high magnetic fields at neutron sources" organized by ILL and LNCMI in Nov. 2022.

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coils to reach static fields of 26 T down to 100 mK. It was installed permanently at the EXED instrument at the now decommissioned BER-II research reactor at the Helmholtz-Zentrum Berlin (HZB) and developed by NHMFL [108–110] . The massive magnet and power supply each required a separate building, representing an operational expenditure of 1 M€/year and showing that this approach to generating magnetic fields cannot be used flexibly at all large-scale research facilities. A much more practical answer to these needs could be now reached through the creation of a new generation of magnets built from the 2nd generation of high-T_c superconducting (HTS) tapes. These will open up many more possibilities for further scientific discoveries that may only be achievable using higher fields and neutron techniques. In addition, the operation of a HTS magnet will be much simpler and 300x cheaper. The design and **construction of such a HTS magnet** is, therefore, a priority for this community.

In parallel, several pulsed-field devices have also been used at different neutron facilities to access magnetic phases above 15 T [98,111] , like the mini-coil systems developed by the Nojiri group (Tohoku University, Japan). These experiments have clearly demonstrated the necessity to increase the pulse duration. Together, ILL and LNCMI have built a long-pulse 2 K/40 T magnet, which is used successfully by the community since 2015 on the instrument IN22 at ILL [104]. However, the time to cool down the magnet between pulses (which is still about 10 min at maximum field strength) seriously limits the beamtime at field. Discussions held at the HMF4NS workshop have converged towards the need for a **higher duty cycle**, much **lower temperatures** and **access to different instruments** to further improve data statistics and allow the investigation of a broader range of scientific topics including quantum spin systems.

5.2 At free electron laser facilities

On June 14-15, 2023, the workshop "The combination of High Magnetic Fields and Free Electron Lasers" was held at Radboud University in Nijmegen. The goal of the workshop was to present the state-of-the-art of the experimental possibilities using high power free electron laser (FEL) radiation in combination with the highest magnetic fields and to define the needs of the international research community to enhance these possibilities to address current scientific challenges (described in section 4). It became clear that the application areas of FELs at high magnetic fields 1) can be very broad, ranging from superconductivity, magnetism, over semiconductor physics to organics, material science and structural biology, and 2) are still relatively unexplored. Considering these two points, the community stressed that it is important to **further develop the combination of existing FEL features of the FELs with the highest DC magnetic fields at HFML-FELIX**.

Important examples are
1) to extend the FEL beamlines to all magnets to expand the field range to 38 T (45 T in the future)
2) to expand the possibilities towards time-resolved and/or two-color pump-probe experiments
3) to expand towards non-linear spectroscopy utilizing the high FEL power
4) to expand towards FEL-based EPR and ESR techniques in the highest magnetic fields.

Although many of those experiments can be performed in existing magnets, the community stressed the importance of developing **additional FEL access geometries**. Radial-access and split-coil magnets have been discussed, but the use of these type of magnets would significantly reduce the maximum field strength (by about 30%). Multi-purpose magnets with vertical access and a larger bore size would also give more flexibility in measurement geometries in combination with waveguides and mirrors.

Finally, the community emphasized that there is a need for a **well-defined chain of experiments towards high-field FEL experiments**, which could be established by running a sample through different levels:

- Zero-field experiments with FEL only and/or high-field experiments without FEL
- Low-field preliminary FEL experiments using superconducting magnets
- Time-resolved experiments (if desired)
- high-magnetic-field FEL experiment

The establishment of such a generalized test lab should allow the development of new experiments even before a high-field proposal is submitted.

5.3 At synchrotron and XFEL facilities

The workshop, Frontiers of Synchrotron and XFEL Research at High Magnetic Fields, held in Dresden, Germany, in November 2023, brought together experts to explore advances in the use of high magnetic fields at synchrotron radiation (SR) and XFEL facilities. Discussions focused on the recent studies of quantum materials, charge density waves, superconductivity, and magnetoelectric materials using advanced x-ray scattering and absorption measurements at high magnetic fields and low temperatures. Key highlights included recent technological advances such as a 17 T superconducting magnet and sub-kelvin sample temperature environments at synchrotron facilities and 30-40 T class pulsed magnets at both synchrotron and XFEL facilities to selectively study magnetic/electronic/lattice degrees of freedom in correlated systems. In 2023, pulsed-field installations are available at ESRF (SR in France), BESSY-II (SR in Germany), APS (SR in USA), SPring-8 (SR in Japan), SACLA (XFEL in Japan) and LCLS (XFEL in USA). Pulsed magnets have been developed by LNCMI in Toulouse and by Prof. Nojiri at Tohoku University in Japan. Moreover, participants discussed the challenges of sample-environment compatibility in high field experiments such as limited sample space and possible heating of the sample temperature by x-ray irradiation, mechanical and electrical noises from the generation of the pulsed magnetic fields, and integration of fluorescence yield detection in pulsed-field setups.

Several collaborative projects were outlined to advance this research frontier. 1) At the HED endstation of the hard x-ray beamline of the European XFEL, within the HiBEF consortium, a collaboration between HZDR, DESY and the European XFEL, a non-destructive pulsed magnet aiming at 60 T is synchronized with ultrabrilliant femtosecond x-ray pulses for x-ray scattering experiments. 2) At the Cristallina endstation of the hard x-ray beamline of the SwissFEL, a non-destructive pulsed magnet reaching up to and beyond 40 T will be combined with low-temperature sample environments to study quantum matter under extreme conditions. 3) At ID32 of the ESRF soft x-ray beamline in Grenoble, the PUMA project, which is a collaboration between the University of Duisburg-Essen, the TU Darmstadt, and the HZDR in a BMBF project, aims at developing experimental setups for x-ray magnetic circular dichroism (XMCD) and resonant inelastic x-ray scattering under pulsed magnetic fields up to 50 T to identify magnetic properties of new functional magnetic materials. 4) At the hard x-ray endstation of SACLA, a pulsed-field setup with a destructive single-turn coil is currently under development, reaching over 100 T with microsecond pulse duration. 5) At the UE46-PGM1 beamline of BESSY-II, the German synchrotron facility in Berlin, a pulsed magnet provided by Prof. Nojiri of Tohoku University, Japan, aiming at 40 T has been integrated for XMCD experiments, and, currently, resonant elastic soft x-ray scattering is being developed using that pulsed magnet to study exotic states of matter such as charge and spin density waves.

All these projects highlight the role of interdisciplinary collaboration in advancing material science and high-field applications in this community.

5.4 At laser labs

In December 2022, a workshop that took place in Paris and Palaiseau, France, gathering scientists and technical experts of high energy density physics (HEDP) experiments coupled with high magnetic fields has been organized. Beyond the presentation of worldwide state of the art, it has been proceeded to the identification of the needs of the community. Due to the specificity of such experiments, i.e., nanosecond or even shorter duration plasma interaction pulsed magnets are perfectly adapted. For experiments using plasmas generated by high power laser at least one access perpendicular to the high-power beam is required to probe the plasma spatial and temporal evolution. Due to this specificity of this kind of experiments, electromagnets for HEDP experiment must be split coils. The accessible magnetic field with this type of geometry is lower than with standard solenoids. Nondestructive split coils with 10 mm bores can be operated up to 60 T in a near future. Magnet pulse duration is not an important parameter; this type of experiment only requires a few nanoseconds for data acquisition. The repetition rate of existing laser facilities is currently from one pulse per minutes up to ten pulses per second. To fit these repetition rates and improve the duty cycle, the cooling of the magnet must be pushed and the pulse duration must be reduced and only a very low duty cycle ($< 10^{-6}$). This pulse duration is compatible with semi-destructive field generation, that would allow to go above 100 T.

Particular case of the Laser MégaJoule (LMJ)

Laser Mégajoule (LMJ) is a laser-based ICF research facility near Bordeaux, France, that can deliver over 1 MJ of laser energy to targets. One aim of the PETAL Upgrade project (PETAL stands for PETawatt Aquitaine Laser), funded by the Région Nouvelle Aquitaine, is to integrate into the LMJ-PETAL facility a device allowing carrying out experiments under high magnetic field. The required performances have been specified together with the laboratories LULI and CELIA: a magnetic field higher than 30 T on a 0.2 cm^3 volume is targeted as a first step, with a 5-10% spatial homogeneity and a temporal stability of 5% during 100 ns.

To go beyond this first step that will be reached in the midterm, the development of future pulsed magnets will benefit from the know-how of the EMFL and be integrated into the roadmap. Non-destructive magnetic fields beyond 30 T coupled with intense lasers have never been achieved anywhere in the world without collaboration with members of the EMFL. Further **envisaged developments** are defined in the table below. This project benefits from a strong support from the academic community whose scientific motivations concern the study of numerous systems in astrophysics, photon and particle generation and inertial confinement fusion. As an example, the first experiments could be about direct drive fusion or radiative shocks (cf. figure below).

B field	Magnetic intensity Magentized volume	Spatial homogeneity	Duration	Temporal stability	Direction
Primordial	B = 10 T Ø = 3 mm x h = 3 mm	10 %	10 ns	10 %	Vertical
Important	B = 30 T Ø = 6 mm x h = 6 mm	5 – 10 %	100 ns	5 %	Vertical or horizontal
Desirable	B = 50 T Ø = 6 mm x h = 30 mm	< 5 %	1 µs	2 %	Adjustable

Figure 2 Summary of the required performances specified for magnets to be installed at LMJ.

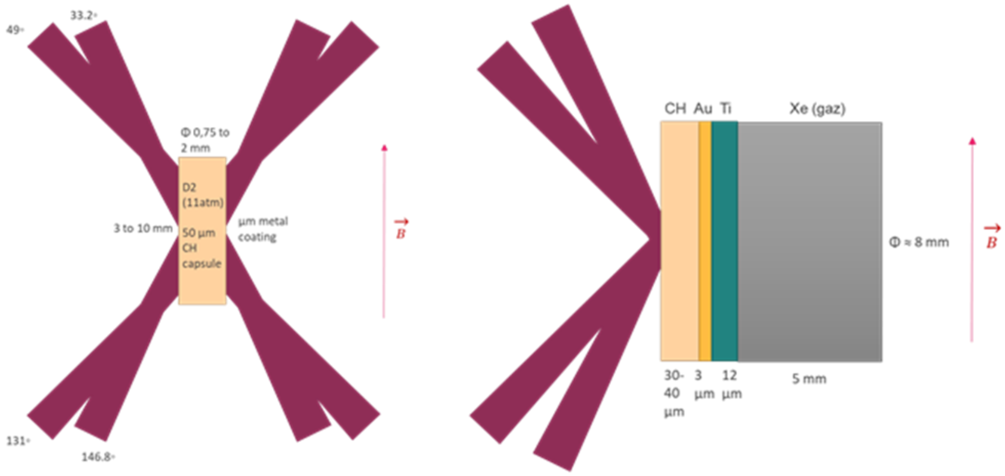

Figure 3 Examples of experimental configurations at LMJ. On the left, a direct drive fusion target is presented, on the right, a solid target for laboratory astrophysics experiments. Outer laser beams are represented in red to show the minimal aperture required inside the magnet bore.

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6. Roadmap proposition

Based on the needs identified in the four workshops, the global state of the art and feasibility considerations, five magnets have been included on the EMFL roadmap for the development of high magnetic fields at advanced sources. The properties of these magnets are summarized in the table below.

Magnet	1		2		2'		3		4
Maximum field (T)	**25**		**45**		**45**		**60**		**38**
DC or pulsed	DC HTS		Pulsed		Pulsed		Pulsed		DC resistive
Type	Split coil		Split coil		Solenoid with conical bore		Split coil		Solenoid
Duration (if pulsed)	n/a		~ 100 ms		~ 100 ms		< 1 ms		n/a
Repetition rate (if pulsed)	n/a		> 1 pulse / 15 minutes		> 1 pulse / 2 minutes		Few pulses / minute		n/a
Duty cycle	100 %		~ 0.01 %		~ 0.01 %		~ 0.01 % (*)		100 %
Magnet bore diameter and temperature	50 mm 298 K		20 mm 77 K		20 mm 77 K		15 mm 77 K		50 mm 298 K
Perpendicular aperture at the center	30 mm		20 mm		20 mm		15 mm		n/a
Angular perpendicular aperture	> 90° horizontal ~ +/- 5° vertical		> 90° horizontal ~ +/- 5° vertical		> 90° horizontal ~ +/- 5° vertical		~ 2x30° horizontal ~ +/- 15° vertical		n/a
Advanced source	Synchrotron	Neutron sources	Synchrotron	Neutron sources	Synchrotron	Neutron sources	XFELs	High power lasers	FELIX
Bore diameter for experiments/ min temperature (**)	20 mm 0.1 K		10 mm 1.5 K	20 mm 1.5 K	10 mm 1.5 K	20 mm 0.1 K	10 mm 1.5 K	15 mm n/a (***)	50 mm (300 K) 34 mm (1.5 K)

Figure 4 Summary of the magnets considered in the roadmap and some of their most important properties

(*) repetition rate of such a high power pulsed laser facility can be up to 10 Hz (i.e., 600 laser pulses per minute) .

(**) for pulsed magnets, these values strongly dependent of samples types and sizes (metallic samples will heat during a pulse)

(***) targets are in vacuum and not thermally connected to the magnet

6.1 Magnet type #1

Split 25 T high-Tc cryomagnet

The objective is to build a mobile and compact high-field cryomagnet from 2nd generation HTS tapes, expanding the fields of research tackled at EU neutron facilities from the range 13.5-15 T to 25 T at temperatures between 40 mK and 300 K (max. field estimated from simulations presented at the HMF4NS workshop). The coils of the magnet will be cooled by a cold-head operating in the 8 - 16 K range, and a second cold-head will be used to reduce by a factor 2 the boil-off in the helium bath

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feeding a double-heat-exchanger ensuring 3x faster sample cool-downs/warm-ups and compatibility with ULT equipment. With a 40 mm diameter sample bore and a diameter of less than 300 mm for HTS coils, the cryostat will host 2x larger sample volumes (e.g., for pressure cells) and be 2x smaller than the existing 13.5 T - 15 T cryomagnet at beam height, allowing for a tighter radial beam collimation and a better signal-to-background ratio.

A design study will take some years, since many new developments are needed in terms of construction of such magnets, as well as in the search of tapes to be able to realize such magnets.

The construction cost and operation cost are also unknown at this stage.

This magnet design will enable EU research infrastructures and companies to initiate a new generation of ambitious split-pair magnets for neutron and x-ray scattering as well as other lab applications.

6.2 Magnet type #2

General description of pulsed split magnets

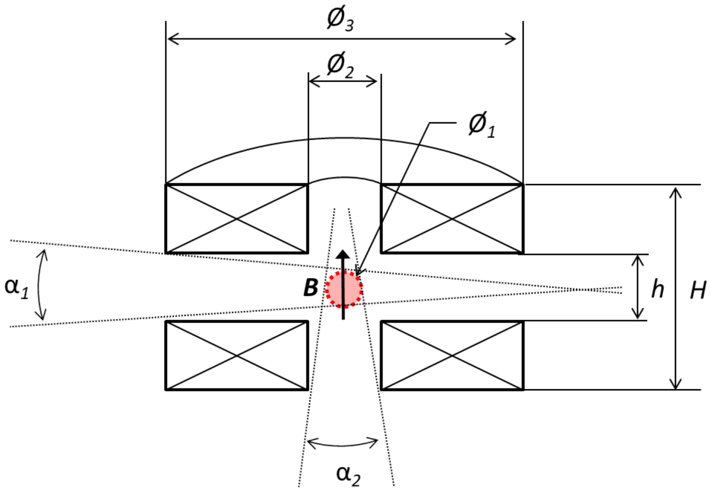

Figure 5 Cut view of a split coil with some important dimensions. The zone of interest for the experiment is the red sphere of diameter $Ø_1$. In this sphere, the experimental constraints beyond the magnetic field strength could be, for example and depending on the experiment, the temperature and the homogeneity of the magnetic field. h is the available space in the midplane.

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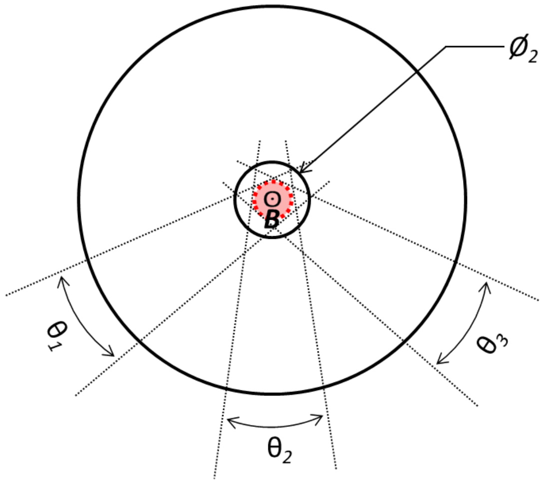

Figure 6 Cut view along B in the midplane of a split coil. θ_i are the opening angles in the midplane for one access, for example for an incoming light beam. A number 'i' of "windows" that allows optical access perpendicular to the magnetic field can be used to collect diffracted light or insert targets/sample holders or diagnostic laser beams. $Ø_2$ is the free bore diameter, where the cryogenics equipment must fit in, if required.

The first limitation to produce high magnetic fields is the Lorentz force. The magnet must be large enough for a given field to sustain the magnetic forces for a given field. This means that $Ø_3$ and B must have minimum values to keep the magnetic energy density, i.e., the mechanical stress, below the strength limits of the materials used in the magnet. The second limitation is Joule heating. For a given pulse duration, the magnet must have sufficient mass to prevent the temperature rise from exceeding a reasonable limit. In that case, $Ø_3$ and H will determine the total energy required to generate the magnetic field. If a capacitor bank is not available in the facility and needs to be developed and built, the total investment for the experiment must be adjusted accordingly.

In this roadmap, different types of experiments require pulsed split magnets but with very different properties. Neutron scattering, for example, demands the longest possible acquisition duration, that is, the length of the pulse multiply by the number of pulses per experiment. In contrast, plasma-physics experiments with intense lasers allow for the shortest possible magnetic field pulses, as plasma evolution occurs on a timescale of tens of nanoseconds. On the other hand, producing magnetic pulses shorter than tens of microseconds is difficult. Between those two limits, experiments involving synchrotrons and XFELs require pulse durations adjusted to fit the cryogenic requirements and achieve the highest possible repetition rate.

Beyond the magnetic-field strength and bore diameter, many other parameters must be considered. For example, the duty-cycle, the optical apertures and the lowest temperature for the sample will significantly influence the design of the magnet, the cryogenics and the energy supply. The total investment required for an experiment includes not only the cost of the magnet and the manpower to build it, but also the design and construction or purchase of the associated energy supply and cryogenic system, if needed.

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6.3 Magnet #2'

Magnet **#2'** is a solenoid with large conical openings in the bore, specifically designed for synchrotron or neutron experiments. Based on the experience gained during the construction and operation of the 2 K / 40 T pulsed-field magnet, which is currently available at ILL [104], the EMFL has the capability to develop a new version of this unique mobile cryomagnet, offering higher fields and/or an enhanced duty cycle for experiments at European Neutron Sources. Thanks to the state-of-the-art of rapid-cooling methods, a duty cycle multiplied by a factor 4 can be expected. Equally significant is the development of a sample changer allowing to insert/rotate samples without breaking the vacuum of the cryostat. This sample mounting system will avoid the warm up of the cryostat and will significantly reduce beamtime losses and workload from a day to a few hours.

Since cryogenic systems are an integral part of the magnetic apparatus, plans to go below the current temperature limit must be considered. For example, combining dilution refrigerators with pulsed fields to achieve 100 mK in a 40 – 50 T cryomagnet could facilitate investigations of samples at lower temperatures, particularly in quantum spin systems.

The cost of magnets #2 and #2' is several hundreds of k€ for the magnet in its cryostat, while the associated capacitor bank, which stores about 1 MJ, can cost up to 1 M€. To reduce investment costs across various neutron sources in Europe, one possible solution is to share a mobile capacitor bank. EMFL labs have the experience in designing and building mobile capacitor banks and magnets that can be used throughout Europe.

The development of a conical access bore with a high duty cycle, along with the required cryogenics down to 2 K, will take approximately 2 years for the design study, 2 years for the construction phase, and 3 years for the exploitation phase. A split coil, such as magnet **#2**, will require an additional year due to the complexity of its design.

The primary operational costs are cryogenic fluids, especially liquid nitrogen, as well as the potential need to replace the magnet in case of a failure. With high duty cycle, the consumption of liquid nitrogen will be around 10000 L per week of experiment. Regarding the lifetime of such a pulsed magnet, we can expect comparable performance to the existing magnet installed at ILL, which achieved more than 20.000 pulses without failure. Given this minimum lifetime value, the magnet would need to be replaced after several weeks of experiments, resulting in an additional cost of tens of thousands of euros per year.

6.4 Magnet type #3

This type of magnet is relatively compact, with magnetic energy typically in the 100 kJ range, and designed for HEDP or XFEL experiments.
The total cost, including manpower for definition, modeling, mechanical design, and integration into the laser facility, is several hundred k€. This process takes approximately one year. If an energy supply needs to be built or purchased, an additional cost of a few hundred k€ must be considered, along with about two years for realization.
At XFEL facilities, access to low temperatures requires the development of specialized cryogenic equipment. Based on the EMFL expertise [94, 101, 103], temperatures below 2 K are achievable, and the development of such a device would take approximately 2 years at a

total cost of around 100 k€. The operating cost of such a magnet depends heavily on its repetition rate, with the primary expense being cryogenic fluids.
For HEDP applications, avoiding the use of cryogenics or cooling fluids significantly reduces operating costs, though these costs are strongly influenced by the magnet's lifetime. Pulsed magnets have a limited lifetime, typically of a few hundred pulses at high fields, and must be replaced regularly. However, magnets designed for advanced sources generally incorporate higher safety margins. Some have successfully completed tens of thousands of pulses without failure at neutrons sources or synchrotrons. Replacing a pulsed magnet for HEDP or XFELs experiments is estimated to cost a few tens of k€.

6.5 Magnet type #4

Magnet #4 is a multi-purpose 35-38 T resistive magnet with vertical access and a room temperature bore size of 50 mm. It will be part of a to be constructure modular high-field magnet platform at HFML-FELIX, which will give optimal flexibility in measurements that require a large sample volume, such as reaching ultra-low temperatures, high pressures and strain. It will also expand the possibilities using the FELIX free electron lasers, i.e., with varying geometries in combination with waveguides and mirrors, as well as sufficient volume for imaging. The design is based on the Florida-Bitter technology used at NHMFL (Tallahassee) and HFML-FELIX (Nijmegen). The total cost, including manpower for definition, modeling, mechanical design, and integration into the facility is about 2.5 M€. This process takes approximately one year. HFML-FELIX has ample experience in operating this type of user magnets also in connection with the free-electron facilities.

35 T in a 50 mm bore is feasible with the currently existing 22 MW power supply. Higher fields are only possible with an upgrade of the power supply at HFML-FELIX towards 30 MW. This implies, amongst others, new transformers and is estimated to cost about 3-4 M€. As described in WP9, such a power supply will also allow reaching higher field strengths in 32 mm bore magnets (> 38 T) and eventually other special magnets such as split-coil or conical-bore magnets for use with free-electron lasers.

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7. Implementation plans at EMFL

<u>**Magnet 1 (DC 25 T HTS split-coil):**</u> Although the development of high-field HTS magnets is actively progressing within EMFL, the implementation of a split-coil design remains particularly challenging, demanding extensive research into advanced materials. Realizing such a magnet would require a dedicated request from a large-scale research facility, supported by a coordinated effort to secure both funding and specialized expertise.

<u>**Magnet 2 (45 T pulsed split coil):**</u> The operation of such a magnet would, in principle, be feasible using the existing power infrastructure at facilities like the European XFEL and ESRF. However, the technical specifications—such as a pulse duration of approximately 10 ms, a 77 K bore diameter of around 20 mm, and a cooling time of roughly 30 minutes resulting in a duty cycle of ~1×10^{-5}—pose significant engineering challenges. While the concept is viable, its construction is not currently planned for the near future. It is worth noting that a 40 T conical pulsed magnet, developed by LNCMI-Toulouse and equipped with a cryostat specially engineered by ILL-Grenoble to reach temperatures as low as 2 K, is already in operation.

<u>**Magnet 2' (45 T pulsed solenoid):**</u> A solenoid magnet exceeding 50 T with conical bores is already in operation at the European XFEL. It features a pulse duration of approximately 10 ms, a 77 K bore with a diameter of around 20 mm, and a cooling time of roughly 30 minutes. For lower field strengths—up to 45 T—shorter cooling cycles in the range of 5 to 10 minutes may be achievable, offering improved experimental throughput.

<u>**Magnet 3 (60 T pulsed split coil, 1 ms):**</u> At present, this concept appears largely infeasible. Its realization would require two independents ~80 T coils powered by significantly larger energy supplies, posing substantial risks for deployment within large-scale research environments such as beamlines. Achieving the targeted 1 ms pulse duration would necessitate specialized designs operating at extremely high voltages and currents—conditions that are considered too hazardous for use in the open-access spaces typical of user facilities.

<u>**Magnet 4 (35-38 T DC resistive solenoid for HFML-FELIX):**</u> This concept is considered viable, because it exploits proven technology using the Florida-Bitter coil design. 35 T is feasible with the existing power supply (22 MW) and higher fields can be realized with an upgrade of the power supply towards 30 MW. A large part of the different ingredients (housing, most coils) of the 35 T wide-bore magnet have been purchased.

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