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ISABEL

– Improving the sustainability of the European Magnetic Field Laboratory

D 3.6: Metrology strategy report

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Contents

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Introduction

Material processing and characterization under magnetic field is highly relevant for the fabrication, alignment and orientation of magnetic materials and devices used for example in magnetic resonance imaging (MRI) and spintronic devices. Characterization and specification of magnetic properties is also substantial for materials and set-ups including sensors as well as electric and electronic devices used in MRI and other industrial applications involving strong magnetic fields (ITER, superconducting transformers and energy storage devices).

The application of highest available magnetic fields is highly interesting, as most of the effects scale with the square of the magnetic field B and hence become easily visible under these conditions. In addition to static and homogeneous B including large volumes, the European Magnetic Field Laboratory (EMFL) also offers inhomogeneous B (strong magnetic gradients and levitation conditions for diamagnetic materials) and fast time varying B to study transient effects (eddy currents). All these conditions can additionally be combined with low temperatures.

Since the usage of the EMFL facilities for industry-related research and development requires application of quality management processes, aspects of metrology become highly relevant, in particular procurement of measurement standards for magnetic field and temperature under magnetic field as well as aspects of traceability within the national and international measurement systems.

In consequence and according to the specific needs of industry, EMFL explores and establishes strategies for a metrology service for magnetic field and temperature in presence of a magnetic field including prototype experimental setups.

In this report, the results of this activity are presented. It is structured as follows. After some fundamental considerations of metrology in magnetic fields, we will focus on metrology activities at the EMFL that are relevant in the context of an industry-oriented metrology for magnetic field and temperature. We will demonstrate the potential by presenting prototype experimental setups. We also identify challenges and provide suggestions for further developments, such as metrology for deformation studies of materials.

Context

Magnetic fields and metrology

With the use of electricity in the second half of the 19th century, the measurement of electric and magnetic fields became relevant. The challenge for metrology was to link the new electrical units to the existing mechanical units. This was achieved by the definition of the Ampère in 1948 [1], which paved the way to today's international system of units (SI) in 1960 [2] and its redefinition in 2018 [3], [4].

The discovery of quantum effects in the 20th century is a highlight of metrology in high magnetic fields, since the effect was first discovered in high field magnets [5]. Together with other quantum standards this allowed the redefinition of the SI system in 2018 without material artefacts (kilogram) and the quirky definition of the Ampère.

Current challenges of metrology involving magnetic fields are found in the sectors of health (field exposure in MRI, magnetotherapy), energy environment (current and power measurement using magnetic sensors) and new technologies (nanotechnologies, spintronics, sensors, lab on a chip, graphene). In addition, the fundamental metrology remains still an active research area, e.g., closing of the metrology triangle [6], [7].

The most important research and development institutions for magnetic-field metrology are the National Metrology Institutes (NMI). Recently, the have intensified their collaboration within regional metrology organizations (RMOs). In Europe, EURAMET (https://www.euramet.org/) is the RMO. It has 37 NMIs as members plus more than 70 designated institutes as associates. The missions of EURAMET are (i) the development of a measurement infrastructure for Europe responding to the needs of industry, business and government, (ii) maintaining the quality and competitiveness of the European measurement infrastructure, and (iii) supporting the members in their national mission through collaboration and balancing the European measurement infrastructure [1]. EURAMET is also regularly developing strategies for metrology in view of the needs of research and development, industry and society [8].

Although high magnetic fields are less present in everyday life and industry, there are many future technologies where they can play an important role. Examples are nuclear fusion involving strong magnetic fields, next generation superconducting magnets for nuclear magnetic resonance spectroscopy (NMR) operating above 30 T, magnetic resonance imaging (MRI) operating at 14 T as well as devices for magnetotherapy using time varying fields. Therefore, it is important for high magnetic field laboratories such as the EMFL to explore metrology strategies.

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Metrology at EMFL

Scientific research and technical development involving high magnetic fields do not only require the generation of such fields, but also the knowledge of their accurate values, spatial distributions and dynamics. For high-field electromagnets a precise knowledge of the current generating the magnetic field is not sufficient for its precise determination. This is due to effects of magnetic forces as well as thermal effects. Both can change the geometry of the magnet. An example can be found in [9].
Therefore, magnetic field metrology is an essential prerequisite for basic and applied science in high magnetic fields as well as industrial applications [10]. The metrology activities can be categorized in the following way:

- Basic and applied science
  - Fundamental research under magnetic field – precise value of *B*:
    Various experimental techniques require different precisions of the magnetic field ranging from 10^{-3} for transport, optical or thermodynamic experiments, $10^{-4}/10^{-5}$ for study of quantum oscillation and up to 10^{-6} for high resolution NMR experiments.
  - Spatial magnetic field distribution – precise distribution of *B*:
    For a second class of experimental techniques the spatial distribution of the magnetic field is also an important parameter. It defines the resolution in NMR experiments. For magnetic force magnetometers, the knowledge of the linear gradient at the sample position is essential for the determination of absolute values of the magnetization. Finally, for levitation studies of diamagnetic compounds (water, hydrogen, helium) the spatial profile of the magnet defines the size and location of the zero-gravity area.
  - Time variation of magnetic field: shape, drift and spectrum of $B(t)$:
    In many cases a precise determination of the time dependence of the magnetic field is required. For pulsed magnetic fields, the synchronous in-situ recording of the pulse shape, i.e., $B(t)$, and the experimental data is a standard technique. In the case of steady magnetic fields temporal drifts and fluctuations of magnetic fields affect the resolution of NMR experiments and can be a source of noise for many other techniques.
- Development of high-field magnets and power installation:
  Apart from the requirements for scientific experiments, the development of high field magnets also requires precise magnetic field metrology.
  - Safety and centering of magnets:
    High-field magnets are very often composed of different sub-magnets. Examples are hybrid magnets with a resistive and superconducting part and pulsed magnets driven by several capacitor banks (mono, dual, triple…). In order to avoid the occurrence of huge magnetic forces between the different sections of such magnets, they require a precise axial and horizontal alignment in the sub-mm range.
    Moreover, the knowledge of the stray field around high-field magnets is important for the safe operation according to the field limits defined by the European directive 2013/35/EU and their national implementations [11].
  - Validation of field calculations and improvement of field quality:

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During the design phase of high-field magnets, magnetic field calculations play an important role. These calculations involve finite element methods in order to solve the complex non-linear equations. Very often approximations are used in order to reduce the complexity of the problem. For their validation magnetic-field metrology is an essential prerequisite. Examples can be found in [9] and [12].

- Although there are well-established methods for magnetic-field metrology and there exist accredited companies, the high magnetic field environment imposes particular constraints. Amongst them are strong fields, small volumes, strong gradients, and low temperatures. With pulsed magnetic fields, short measurement times and fast magnetic field dynamics are additional challenges. Therefore, tailored non-standard solutions are the method of choice for high magnetic field metrology. Scientists and engineers at EMFL constantly develop innovative methods for magnetic-field metrology. Although the main interest is a precise knowledge of the magnetic field for fundamental research, the expertise of the EMFL staff is also of interest for industrial applications.

From the creation of the EMFL, metrology issues played an important role. In the following, past and ongoing activities in metrology at EMFL laboratories are listed

- During the creation phase of the EMFL, a strategy report on harmonization of instruments and standards was produced. It also included magnetic field and temperature environment as well as information about accuracy and resolution of the various experimental techniques. It collected, for the first time, information relevant for magnetic field and temperature metrology at the level of the EMFL.
- In 2016, an EMFL working group on metrology was created. This working group organized discussion session at EMFL days and organized an exchange secondment on temperature metrology at high magnetic field between LNCMI Grenoble and HFML Nijmegen.
- In 2020, a book chapter on magnetic field generation and measurement was published as part of the "Handbook of Magnetism and Materials". This book chapter was written by authors from HLD Dresden, LNCMI Grenoble and LNCMI Toulouse. It provides a comprehensive overview of magnetic-field measurement techniques with special focus on high magnetic fields including many references [13].
- In 2020, a meeting of the LNCMI with the French national metrology laboratory (Laboratoire National des Essais, LNE) was organized. During the presentations, the interest of metrology in high magnetic fields and questions of accreditation and certification were discussed. LNE scientists confirmed that the use of NMR as a primary field standard provides sufficient accuracy and is generally accepted as a trustworthy method.
- In the ongoing EU-ISABEL project and apart from this deliverable, the metrology activity at EMFL was actively promoted. First, the EMFL participated twice with a stand at the International Metrology Congress (CIM) in 2023 and 2025. For 2025, the EMFL contribution "Metrology in high magnetic fields: Challenges and opportunities for science and industry" was selected as a talk in the Electromagnetism session [14]. Second, a metrology section was included in the EMFL skill map [15].

Strategies for a metrology service at EMFL

General considerations

In order to comply with the scope of this work package, which is dedicated to the fostering of links with industry, we will restrict ourselves in the following to metrology in the context of industry.

An almost indispensable prerequisite for industry related metrology services is the accreditation according to ISO/EN 17025 [16]. Laboratories and companies with accreditation in magnetic field measurement can be found on the websites of international (https://ilac.org/), European (https://european-accreditation.org/) and national accreditation organizations. Table 1 lists selected European institutions and companies that are accredited for calibration of magnetic fields above 1 T.

Country	*Company*	*Accreditation*	*Source*
France	*Laboratoire National de Métrologie et d'Essais*	*B up to 2 T*	*https://www.cofrac.fr/en/*
Germany	*Innovent*	*B up to 2.1 T*	*https://www.dakks.de/en/home-en.html*
	Magnet-Physik Steingroever	*B up to 3 T*	
U.K.	*NPL Management*	*B up to 13 T*	*https://www.ukas.com/*
Serbia	*Senis*	*B up to 1.5 T*	*https://www.ats.rs/en*
Switzerland	*Metrolab*	*B up to 30 T at fixed fields*	*https://www.sas.admin.ch/sas/en/home.html*

Table 1 : Overview of European institutions and companies with accredition in magnetic field calibration above 1 T.

It's worth to notice that only two laboratories (Metrolab, Switzerland, and NPL management, UK) have an accreditation for magnetic fields above 10 T.

None of the EMFL facilities currently has an accreditation for magnetic field calibration. We will discuss this issue in one of the following sections of this report.

Metrology service for magnetic fields

Considering the magnetic field metrology in Europe, there is clearly a potential for magnetic field calibration opportunities at higher magnetic fields. In order to be complementary and competitive in comparison with existing and accredited facilities, such a metrology service should rather focus on special cases, which are not covered by existing magnetic field metrology laboratories and where the application of high magnetic fields is relevant. Very often such cases are at the forefront of research and development. They involve innovative methods. Furthermore, EMFL facilities with their variable fields, including strong gradients and fast field rates, provide an interesting environment for industry-related metrology projects. In such a context, the problem of missing accreditation of EMFL laboratories can become less important and might be replaced by tailored procedures that generate trustworthy results.

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Potential industrial interest

In the following, we present various industry-related metrology topics at EMFL

- *Next generation superconducting magnets above 30 T:*
  The development of next generation superconducting magnets involving high-temperature superconductors is very interesting for industry. The first commercial system are 1.2 GHz NMR magnets operating at 28.2 T. There are many activities for developing superconducting magnets beyond 30 T or special magnets that involve industrial and academic partners. Apart from NMR, such magnets are planned to be used for health (magnetic resonance imaging) and energy applications (nuclear fusion reactors).
  EMFL is strongly involved in this activity by the European Horizon 2020 project “SuperEMFL” [17] and there are also national activities, e.g., the French ANR project FASUM at the LNCMI Grenoble [18].
  The EMFL facilities provide an ideal environment for the performance test of conductors, magnets and related problems as heat transfer under strong magnetic field gradients that can cause the formation of helium gas bubbles due to the diamagnetic properties of helium.
  The related metrology activities involve both, magnetic field metrology [19] (magnetic field calibration, drift, fluctuations, study of screening currents) and accurate temperature measurements for quantitative heat-transfer studies in presence of strong magnetic fields [20].
  EMFL laboratories are already collaborating with industrial partners. Therefore, it is very promising to enlarge and promote the metrology capabilities of EMFL laboratories in this field.
- *Operation of objects in strong magnetic fields including MRI compatibility:*
  Another interesting subject with application potential in industry is the validation of the operation of mechanical, electromechanical and electronic devices in strong magnetic fields or magnetic-field gradients. Since high-field laboratories operate such devices themselves, they have a good expertise that could be of benefit for industry. Possible application fields are in the energy sector the operation of devices (pumps, automatic valves, or leak testers) in fusion reactors such as ITER, in the field of health the perturbation of magnetic resonance imaging signals by magnetic objects as well as the magnetic-field sensitivity of objects used in every-day life. Magnetic-field metrology issues play here an important role, since the test procedures require quantitative information about magnetic-field values and magnetic-field homogeneities. EMFL laboratories have provided service to industry in that field and one published example is the operation of mechanical watches of a Swiss company in strong magnetic fields up to 16 T [21]. It is, therefore, important to maintain this capability in complement to existing laboratories and for special cases where particular experimental conditions are requested.
- *Calibration of magnetic-field sensors including quantum sensing:*
  The usage of precise magnetic field sensors is an indispensable prerequisite for EMFL's research and development activity. Due to the non-standard magnetic-field environment combined with extreme conditions (very high field combined with low temperatures, small sample volumes, short durations, …), high magnetic field laboratories adapt their magnetometry methods to these constraints and develop original measurement setups. In

combination with the unique high magnetic field environment, the EMFL facilities are of interest for companies in that field. There is already one company (Paragraf) that tested their graphene-based Hall sensors in a high magnetic field environment at HFML Nijmegen [22]. Another company, Metrolab from Switzerland, expressed their interest in using EMFL facilities. Moreover, magnetic-field laboratories continue to investigate quantum effects in high magnetic fields, such as the quantum Hall effect or quantum phase transitions in strongly correlated electron systems, the properties of single spin systems or optical spectroscopy of gas of alkali atoms. Although still part of EMFL's fundamental research activity, the results could be relevant for industrial applications, as quantum standards are a central part of the actual metrology activity [2].

- *Calibration of devices generating magnetic field:*
  Apart from research in magnetic fields, EMFL also develops innovative magnets and the power electronics necessary to generate and control the current for the magnetic fields. Magnetic-field metrology accompanies these developments and the instruments and methods could be of interest for industrial application. Apart from the already mentioned development of all superconducting magnets operating above 30 T, the domain of fast varying fields is of interest. One recent example with application potential in health are fast time varying fields for magnetotherapy developed at HLD Dresden [23] and Toulouse.

Key challenges and strategies to overcome them

Although metrology-related activities are part of the expertise of the EMFL laboratories and there are interesting examples of metrology projects with industry, the development of a regular metrology service at EMFL faces various key challenges. They are basically due to the fact that the current metrology activity at EMFL falls in the category of *scientific* metrology. Its methods are very close to those used for fundamental research, which is one of the core activities at EMFL. In contrast, *industrial* metrology adds further constraints concerning standardization, which are less developed at EMFL [24]

In the following, we identify the most important challenges and describe strategies to overcome them

- *Personnel and time expenditure of metrology projects*
  Metrology projects involving industry very often require additional efforts. Amongst them are administrative procedures, such as non-disclosure agreements and contracts, extensive discussions with industrial partners, which are less aware of the operation mode of a research laboratory and adaptation of instruments and methods. In the past, this additional work was undertaken by existing EMFL staff.
  To facilitate the implementation of these complex projects, the EU ISABEL project has begun to establish structures and processes. These include the employment of an Industry Liaison Officer, who acts as a contact between scientists and industry and the standardization of processes and access for industry inquiries (WP 5).
- *Lack of accreditation of EMFL laboratories*
  Accreditation of metrology projects according to ISO/EN 17025 has become a common standard for the generation of trustworthy results and is often required. However, the EMFL laboratories are not accredited and this fact hampered in the past some requests from industry. One may, therefore, ask whether accreditation can provide a remedy.

At first glance, this certainly seems to be the method of choice. The laboratories are recognized and registered, and the results of metrology studies are accepted by the industry without further review.
However, there are serious counterarguments that make accreditation seem less appropriate. The accreditation process is time-consuming and costly. It also requires additional permanent personnel. Currently, EMFL laboratories lack the necessary financial resources, and the return on investment from industrial metrology projects is insufficient.
Furthermore, and more seriously, the question arises as to whether accreditation is the appropriate solution. Metrology projects in high magnetic fields are very often innovative and ahead of well-established standards. In addition, the magnets and experimental technologies continuously change and evolve due to improvement of methods and materials. Any standardization would deprive industrial projects of these improvements.
Finally, it was outlined in a recent publication that the open environment of scientific laboratories can cause problems for an accreditation [25].
In order to overcome this hampering issue, one has to keep in mind that trust in results of measurements is the prerequisite for metrology studies. Therefore, other methods can be used to establish this trust. Amongst them, the peer-review process is explicitly mentioned for industrial metrology [24]. Since this is the standard process used for the scientific publications of the EMFL, the staff in the laboratories is familiar with it. In addition, this procedure is better adapted to non-standard projects, since the persons and institutions involved can be adapted to the special case. However, one still has to agree in this case with the industrial partner on the peer-review procedure, the persons involved and to ensure non-disclosure and confidentiality.
Finally, one should always keep in mind and communicate to industry that the EMFL laboratories have all the necessary competences to create trustworthy metrology results: The EMFL personnel is highly qualified and worldwide recognized in state-of-art experimental techniques in high magnet fields including metrology using primary standards. Past and ongoing data management activities ensure the traceability of experimental studies.

- *Lack of awareness of the EMFL for metrological industrial applications*
  Since EMFL is not listed as an accredited metrology laboratory, there is a lack of awareness that its installations can be used for metrology studies. Moreover, the confidentially of industrial metrology projects prevents their publication and promotion.
  To remedy this lack of publicity, a number of activities were initiated in the EU ISABEL project, which were already mentioned before, but shortly listed again here: (i) participation at booth in the 2023 and 2025 International Metrology Congress with a oral presentation in 2025. Participant to Rendez-Vous Carnot each year since 2021 and to BSBF (Big Business Science Forum) in 2022 and 2024 (ii) active promotion of metrology in EMFL skill map [15].

Experimental metrology setups and benchmark experiments

In the following part we list the available experimental set-ups for magnetic field metrology at EMFL and their characteristics as well as selected benchmark experiments.

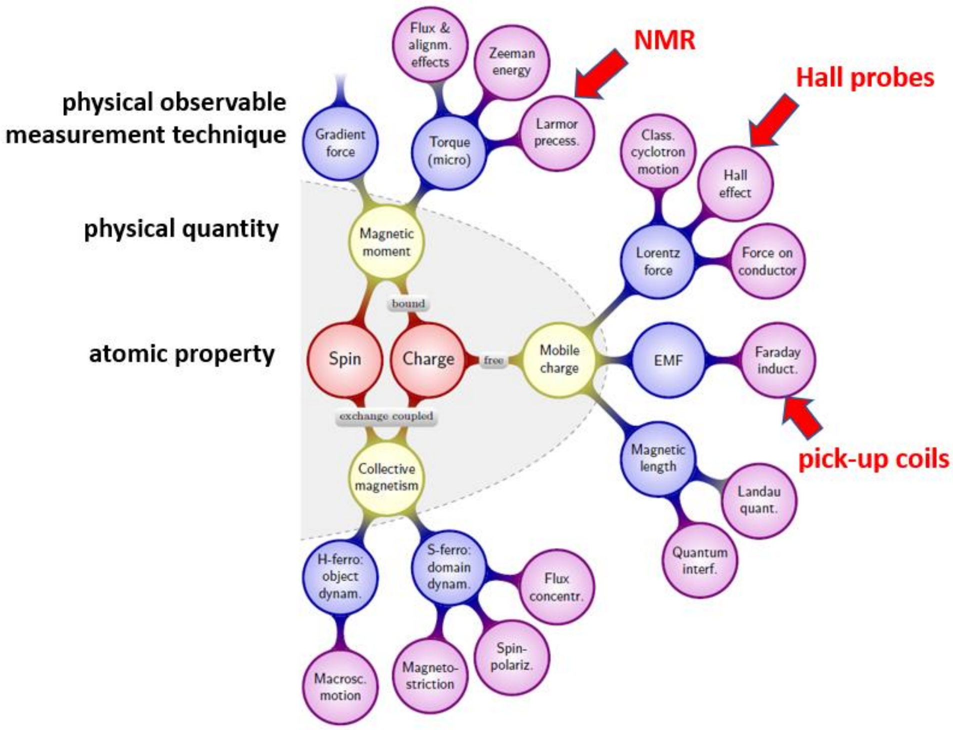

Figure 1 : Overview of magnetic field metrology methods. At EMFL laboratories NMR, Hall probes and pick up coils are used. NMR serves as a primary standard [13.]

Figure 1 provides an overview of the magnetic-field metrology methods and their underlying principles [13]. At EMFL laboratories the following techniques are used.

- *NMR as calibration standard (10^{-5}):*
  NMR is calibration standard for magnetic field: 10 ppm accuracy (1 ppm = 10^{-6}). The gyromagnetic ratio γ of ^1H in H_2O at 25°C is CODATA listed: γ = 42.57638507 MHz/T. At 35 T, the Larmor frequency of protons is 1.5 GHz. NMR can be used in steady and pulsed magnetic fields. It provides the absolute value of the magnetic field as well as the field geometry and field dynamics. All EMFL laboratories can provide this standard.
- *Pick-up coils (10^{-3}):*
  It can be used in steady and pulsed magnetic fields. Calibration against NMR is possible (ex-situ). Pick-up coils are used in steady fields for field profiles (100 µm resolution) and field factor (B/I ratio). In pulsed fields they are the method of choice for in-situ field calibration.
- *Hall probes (10^{-3}):*
  Mostly used in steady magnetic field. They provide information about the three spatial components of the magnetic field. Hall probes are the method of choice for stray field measurements.

Benchmark 1: Pick-up experiment for precise recording of magnetic-field profiles

As mentioned before, pick-up experiments are the standard tools for measuring steady and pulsed magnetic fields. They are based on the induction law and can be adapted to small bore sizes, low temperatures and fast varying fields. However, since they measure the flux variation, a calibration

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is necessary. This is usually obtained by recording the pick-up response in a magnet with known field factor and geometry.

In Figure 2, we show the experimental set-up used at LNMCI Grenoble together with a raw and integrated signal that illustrates the homogeneity and centering of the two resistive sub-magnets. Pick-up coils work in strong magnetic field gradients. In addition, they are also used for determination of the field factors of the magnets, i.e., the current over field ratios. The field values and field variations used in most experimental studies at LNCMI Grenoble are based on pick-up data. They are recorded during the installation of the magnet and stored in a database to ensure traceability. They are also made available to scientists and users by a web interface.

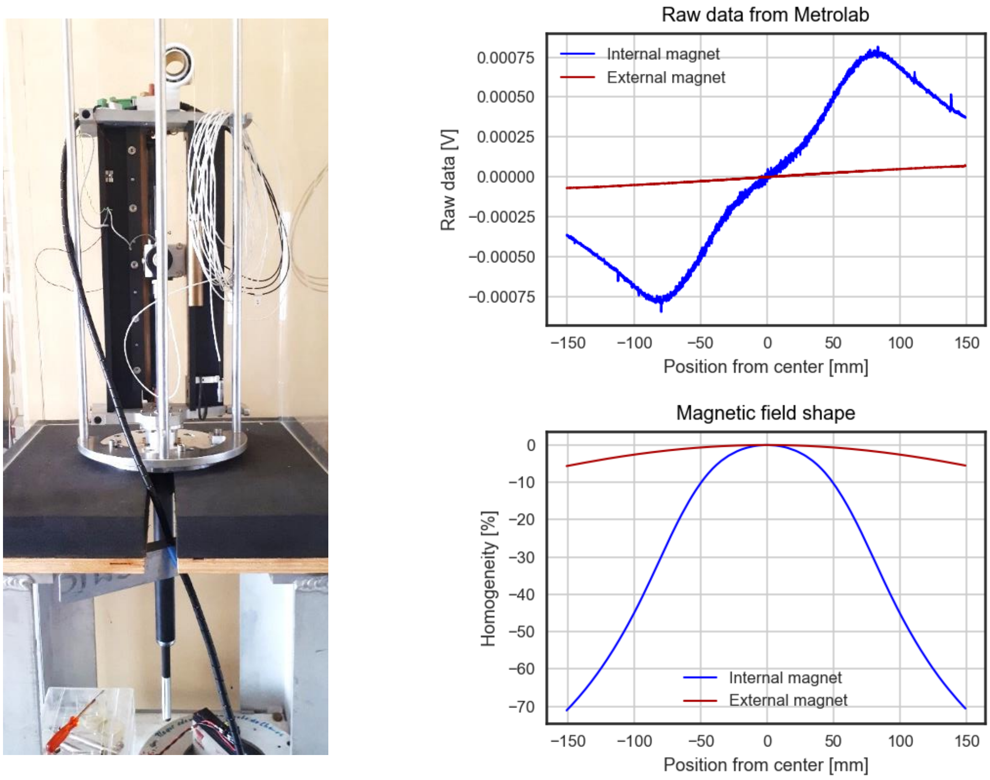

Figure 2 : Left: pick-up setup used for magnetic field profiles at LNCMI Grenoble. Right: raw and integrated data of a 30 MW high field resistive magnet. Quantitative information about the centering magnet and the field profiles can be extracted.

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Benchmark 2: NMR probes and methods for magnetic-field calibration

Magnetic-field calibration by NMR is currently the most precise way to measure magnetic-field properties, i.e., field values as well as spatial field distributions and field variations with time (drift and fluctuations). The NMR sensors can be combined for in-situ operation with other sensors, e.g., Hall probes.

As an example, we show in Figure 3 two NMR probes used at the LNCMI Grenoble. Their characteristics are

- Broadband operation: ^1H or ^2D NMR of water for high-resolution liquid state NMR or any other nucleus for solid-state NMR at low temperatures covering magnetic field up to 42 T.
- 1 mm^3 volume, 3D-positioning, sub-mm resolution

At the bottom of the figure, we show two applications: a field factor correction of the resistive magnet for high-resolution NMR and drift measurement for next generation SC magnets [19].

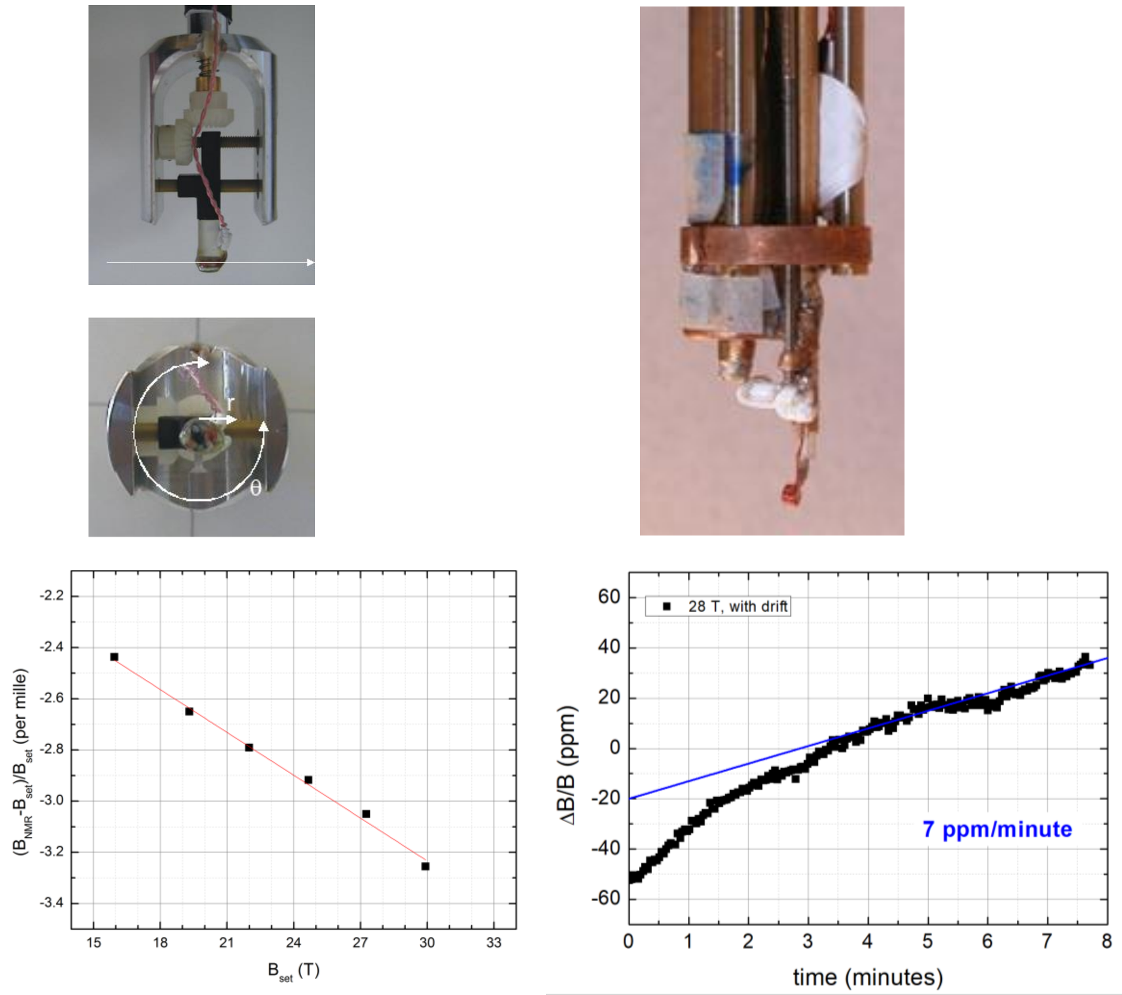
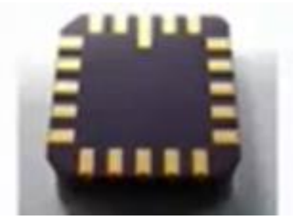


Figure 3 : Top left: side view and bottom view of NMR probe used for spatial field mapping at room temperature. Field profiles are recorded in cylindrical coordinates: axial displacement and turning of probe with NMR sample in off-center position. Top right: Low temperature NMR probe with NMR field calibration coil (small red coil at the bottom) and NMR sample (white horizontal cylinder). These setups allow to identify of field factors of resistive magnets (bottom left) and drift studies of superconducting magnets in resistive background fields [19].

Benchmark 3: Characterization of cryogenic Hall probes

Characterization of magnetic field by Hall probes is widely used in science and industry. For standard field environments up to 20 T, many models exist that are able to simultaneously measure the three components of the magnetic field in a mm volume. However, the combination of high magnetic fields and low temperatures is a challenging environment for Hall probes, since non-linear and quantum effects strongly perturb the sensor. Moreover, question of temperature dependence and reproducibility play a role.

Therefore, it is interesting to use the available experimental setups and low-temperature environments for characterization and calibration of innovative materials for Hall sensors, e.g. graphene. An example is shown in figure 4, which displays the Hall voltage of a commercial Paragraf sensor recorded at 4 K in a variable magnetic field up to 30 at HFML Nijmegen. The data are taken from [22].



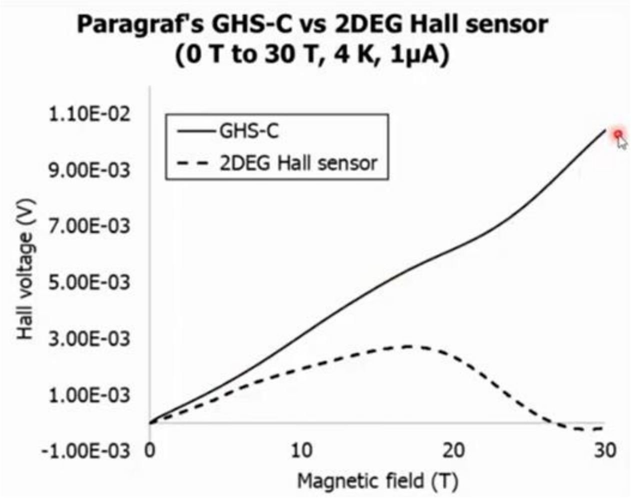


Figure 4 : Left: Commercial Paragraf Graphene based Hall sensor and field dependence of its Hall voltage at 4 K in comparison to a 2-dimensional electron gas Hall sensor. Despite the non-linearity, the Graphene based sensor has an application potential for high field magnetometry in cryogenic environments [22].

Benchmark 4: ^{87}Rb vapor magnetic field sensor in pulsed magnetic fields.

For pulsed magnetic field calibration, the recording of a pick-up signal is the standard method. For this method the accuracy is reported to 10^{-3}. The use of optical methods and alkali metals such as rubidium (^{87}Rb) in the gas phase offers an alternative metrological standard with better accuracy. The measurement principle is based on the magnetic field induced Zeeman frequency shift that can be detected in the fluorescence spectrum of ^{87}Rb vapor after laser excitation.

An experimental set-up developed at LNCMI Toulouse and a calibration example of a magnetic field pulse are shown in Figure 5. Fluorescence peaks occur, when the resonance condition is fulfilled. This allows the extraction of the magnetic field at that time. These data can then be used to scale the entire magnetic field time profile provided by the pick-up coil. The detailed analysis provides an accuracy of

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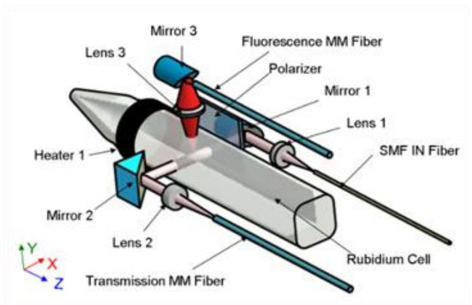
the optical measurement of 2 x 10^{-4} which allows the improvement of the pick-up signal by more than a factor 10 [26].



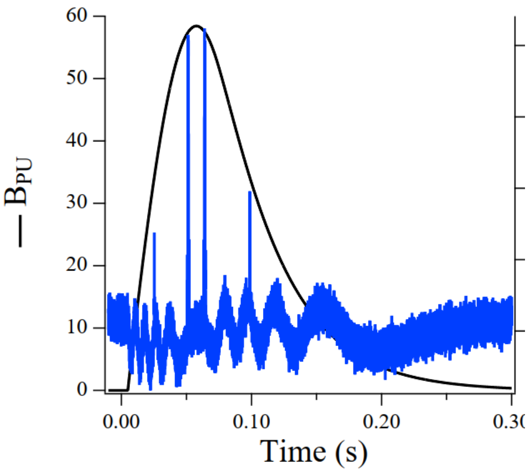


Figure 5 : Optical method for pulsed magnetic field metrology. Left: Sensor set-up for a 60 T pulsed field magnet showing the cell with the ^{87}Rb gas and the optical fibers used for excitation and fluorescence Right: Rb fluorescence signal during a field pulse (blue line). The black line is the simultaneously recorded integrated pick-up signal [26].

Benchmark 5: ^{1}H NMR in pulsed magnetic fields

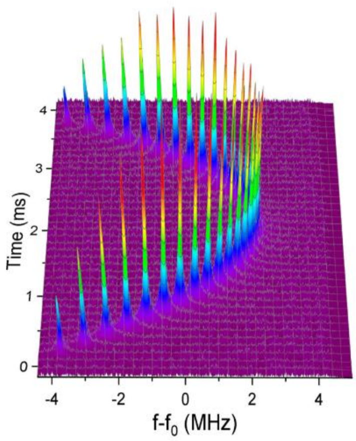


Figure 6 : 1H NMR spectra of water with dissolved GdCl3 near the maximum of a 51.2 T field pulse. The center frequency was 2180 MHz. The spectra show that magnetic field metrology with ppm accuracy is possible in such magnets [27].

For high precision, magnetic-field magnetometry in pulsed magnet field, NMR is the method of choice. Despite the short magnetic field pulse duration, the recording of an NMR spectrum is feasible with ppm accuracy using special NMR methods, such as small tip-angles, reference deconvolution and stepwise recording of broad spectra [27]. NMR field measurements can be combined with pick-up coils and enhance the precision of the latter as in the previous benchmark experiment. Moreover, it can be used as an in-situ method for precise NMR-shift measurements [28], [29]. Moreover, it has been used for technical studies providing precise information of the coil deformation during a magnetic field pulse [9].

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Metrology service for temperature

Potential industrial interest

Apart from magnetic-field metrology, there is also an interest to provide a service for temperature calibration in intense magnetic fields. Potential industrial applications are precise heat-transfer studies in high-field superconducting magnets [20].

Experimental setups and benchmark experiments

Resistive thermometers (Cernox, RuO_2) are based on the temperature dependence of their electrical resistance: R = f(T). The temperature is then obtained by the inverse relation: $T = f^{-1}(R)$. Calibration curves for zero magnetic field are supplied by the manufacturers of thermometers. However, in presence of a magnetic field a magnetoresistance occurs and the relation becomes R = f(T,B). Therefore, the zero-field calibration curve is no longer valid. This effect becomes strong at low temperatures (<4 K) and high magnetic fields. The calibration in magnetic field is obtained by field insensitive temperature measurement such as [30]

- Capacitance (4.2 K – 300 K)
- ^{4}He or ^{3}He vapor pressure (ITS90, 300 mK – 4 K)
- Coulomb Blockade (> 10 mK)
- NMR intensity (> 10 mK)
- Nuclear Orientation Thermometer (> 10 mK)

This effect is very important for experiments in steady magnetic fields. For pulsed field it is less important due to the inertia of the set-up during the short field pulse, i.e., heating occurs only after the experiment.

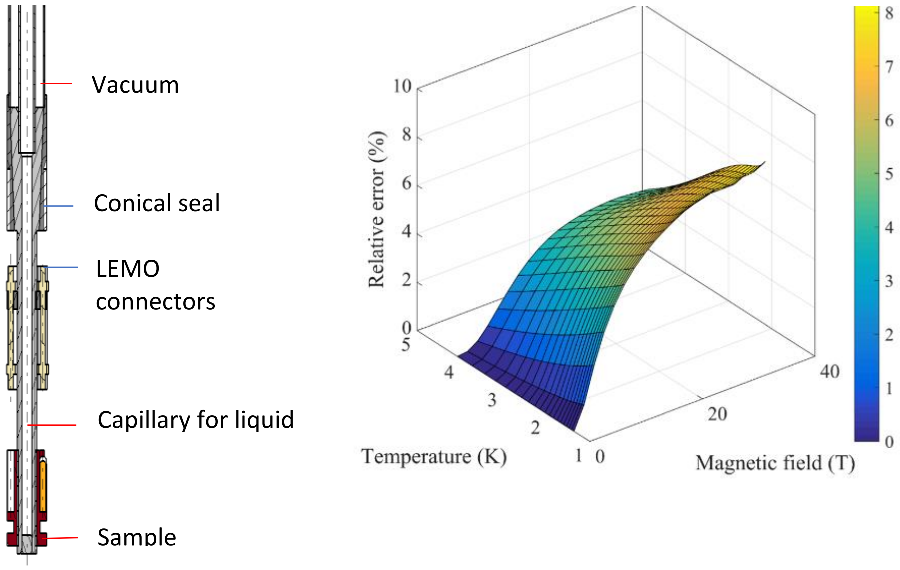

Figure 7 : Left : Bottom part of the thermometry probe operating at LNCMI Grenoble using capacitors or He vapor pressure as field independent reference. Right: Relative temperature error due to magnetoresistance of commercial Lakeshore RuO_2

At LNCMI Grenoble a thermometry benchmark experiment is operational for magnetic fields up to 37 T and temperatures down to 1.2 K. The field-independent calibration is obtained by a capacitance (above 4 K) 4He vapor pressure (1.2 K – 4K). Calibrated thermometers have been provided to projects with industry relevance studying the cooling of next-generation superconducting magnets [20].

At the HLD Dresden, two methods of low-temperature thermometry insensitive to the effects of magnetic fields are available. Coulomb Blockade Thermometry operates in the so-called weak Coulomb blockade regime and exploits single-electron tunneling effects. Field independence between 0.2 and 14 Tesla has been shown. As a primary thermometer, it can be used for calibration purposes. In addition, capacitance thermometry using sandwiched Ag- and Kapton foils on an Ag rod is less complex and yields robust, secondary thermometers. They can cover a wide temperature range, being insensitive to fields up to 45 T.

Metrology for deformation studies

The calibration of devices for measuring strain, i.e., the deformation of matter, opens up a new measurement activity to which the EMFL can potentially make an important contribution. In industry, deformation experiments are essential in the development of products subject to deformation induced by mechanical or electromagnetic forces as well as temperature variation. The objective of the studies is the determination of elastic and non-elastic deformation curves as well as failure studies. Calibrated sensors are required for these studies. In special cases, it is necessary to determine external influences such as temperature or magnetic fields on sensor accuracy.

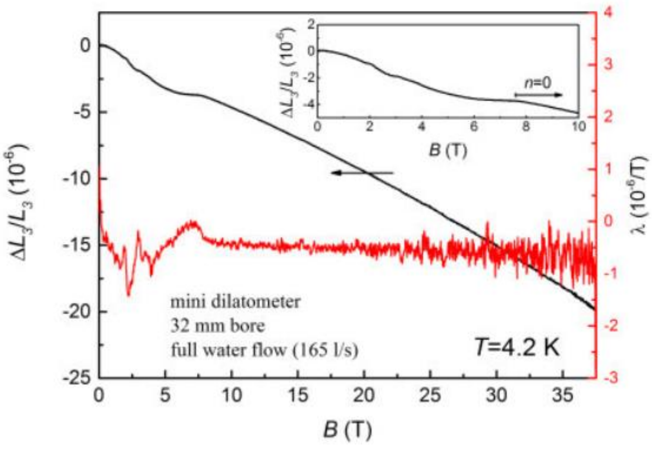

Figure 8: Left: Miniature dilatometer used for thermal expansion and magnetostriction studies at high magnetic fields. Right: Magnetostriction (left axis) and magnetostriction coefficient (red axis) of graphite sample (HOPG) at 4.2 K up to 37.5 T. An analysis of the data provides a resolution less than 0.2 nm [31].

For fundamental research, EMFL laboratories have developed innovative strain devices operating under extreme conditions, such as high magnetic fields up to 37.5 T and low temperatures down to 300 mK. In Figure 8, we show the world's smallest dilatometer for sub-nm high resolution thermal expansion and magnetostriction in high magnetic fields operating at HFML Nijmegen [31]. The expertise in the development of such instruments could be of benefit for industry and some companies have already expressed their interest.

Conclusions and perspectives

In this report, we have shown that the EMFL is an attractive and suitable infrastructure for industrial metrology projects. The regularly used methods for magnetic field and temperature calibration as well as the accurate measurement of other physical properties under magnetic field are state-of-art, recognized worldwide and continuously developed. The advantages of the EMFL for metrology are the unique magnetic-field environment that can be adapted to the needs of the project, in particular very high and variable fields, big bore sizes, fast field rates, strong gradients that can be combined with low temperatures. Moreover, EMFL has a highly qualified staff for scientific and technical aspects of metrology projects. They are able to develop metrology set-ups according to needs of scientific and technical projects.

Various fields of great interest have been identified for industry related metrology. The most promising activity is the ongoing development of all-superconducting magnets operating beyond 30 T. In this field magnetic field metrology as well as precise temperature measurement is regularly used for the characterization of prototype magnets with industrial components. Other well-developed fields are the calibration of innovative field sensors including quantum devices, magnets as well as the performance of devices under magnetic field. Industrial applications are fusion reactors for industry (ITER), next generation magnets and health applications using magnets for therapy. Apart from magnetic field and temperature metrology, we identified the measurement of deformation in extreme conditions as an interesting extension of the existing metrology activity. Given current limited resources, it seems appropriate to focus on these well-developed fields and seek more industrial partners. Furthermore, the EMFL is unique in this area, as there are very few laboratories offering such high magnetic fields.

The main challenges for further progress in this activity are the staff and time expenditure of metrology projects, the lack of awareness of the EMFL's capabilities among the metrology institutions and companies looking for metrology service as well as the lack of accreditation of EMFL laboratories. Measures taken by the EU ISABEL project have helped to improve the first two points. An access procedure for industry demands has been established and an industry liaison officer acts as contact person for industry request. In addition, EMFL presents its metrology activity to the academic and industrial actors by booths at expositions, conferences participations and by an industrial skill map. However, there remains work to be done for the third point. Not only because of the costs and effort involved, a metrology accreditation of the EMFL does not seem appropriate at this time. Metrology in high magnetic fields is subject to constant changes and innovations that contradict standardization. It is suggested to explore whether alternative procedures for validation of metrology results, such as peer-reviews, are more suitable. To make progress on this issue, it is useful to get in contact with the key actors of metrology in Europe, such as EURAMET as well as the national metrology laboratories.

Various benchmark experiments illustrate the potential of the EMFL laboratories for magnetic field and temperature metrology. They use widely accepted field-measurement techniques, including NMR as primary standard, that are adapted to the high field environment. All these measurement standards are available for industry-related metrology studies. In addition, innovative concepts such as ^{87}Rb vapor magnetometry in pulsed magnetic fields have been explored and it is interesting to pursue and improve them. Future developments could use quantum oscillations (de Haas van Alphen) for precise field measurements in the 100 Tesla range.

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