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Chapter 31

High Field Accelerator Magnets for Next Generation Colliders – Motivation, Goals, Challenges and R&D Drivers

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The Hadron Collider (LHC) at CERN can be regarded as the *ultimate* collider built with Nb_3Ti magnets. Its main dipoles have reached a field of approximately 8 T, which is very likely close to the highest practical field for this superconductor in accelerators. The next major step is the High Luminosity upgrade of the LHC at CERN, which among the many upgrades of the accelerator, calls for a few tens of Nb_3Sn dipole and quadrupole magnets, operated at 1.9 K and at conductor peak fields up to about 12 T. HL-LHC magnets are in the production phase, marking an historical milestone in accelerator technology and the culmination of 20 years of worldwide R&D. Here we describe the rationale for high field accelerator magnet R&D beyond HL-LHC, consisting of two complementary axes: (i) development of an ultimate Nb_3Sn technology, increasing the field reach and achieving maturity and robustness level required for deployment on a large scale and (ii) demonstrating suitability of high-temperature superconductors for accelerator magnet applications. We start with a review of the state-of-the-art, review the main goals, and identify the drivers for an R&D program responding to the declared priorities of the European Strategy Upgrade. This chapter is intended as the starting point in the formation of a structured High Field Accelerator Magnet R&D Program.

1. Introduction

High Field Magnets (HFM) are among the key technologies that will enable the search for new physics at the energy frontier. Starting from the Tevatron

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in 1983 [1], through HERA in 1991 [2], RHIC in 2000 [3] and finally the LHC in 2008 [4], all frontier hadron colliders were built using superconducting (SC) magnets. All colliders listed above made use of the highly optimized superconducting alloy of Nb and Ti [5], and it is a well-accepted fact that the LHC dipoles, with a nominal operating field of 8.33 T when cooled by superfluid helium at 1.9 K, represent the *end-of-the-line* in terms of performance of accelerator magnets based on this material* [6].

At the same time approved projects and studies for future circular machines call for the development of superconducting magnets that produce fields beyond those attained in the LHC [7]. This is the case of the High-Luminosity LHC upgrade (HL-LHC) [8], which is currently under construction at CERN and collaborating laboratories, and the Future Circular Collider design study (FCC) [9], structured as a worldwide collaboration coordinated by CERN. Similar studies and programs are on-going outside Europe, such as China's Super proton-proton Collider (SppC) [10]. Significant advances in SC accelerator magnets were driven by past studies such as the Very Large Hadron Collider at Fermilab [11] and the US-DOE Muon Accelerator Program [12]. Similarly, first considerations on ultra-high-field (20 T) HTS dipoles were fostered by the High-Energy Large Hadron Collider study at CERN [13]. Finally, new accelerator concepts such as muon colliders presently considered at CERN and collaborators [14] will pose significant challenges on the magnetic system. These High Energy Physics (HEP) initiatives provide a strong and sustained pull to the development of SC accelerator magnet technology beyond the LHC benchmark, towards higher fields.

Having reached the upper limit of Nb-Ti performance, all above projects and studies are turning towards other superconducting materials and novel magnet technology. On-going activities encompass both *Low-Temperature and High-Temperature Superconductors* (LTS and HTS respectively). Besides the R&D driven directly by the projects and studies listed above, it is important to recall the coordinated efforts that have led to the present state-of-the-art in

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* Nb-Ti can produce field well in excess of the LHC nominal field of 8.33 T, as recently demonstrated by the spectacular achievement of ISEULT, a record full-body MRI solenoid operating at 11.7 T (see https://www.cea.fr/english/Pages/News/Iseult-MRI-Magnet-Record.aspx). However this is done at winding current densities that are typically one order of magnitude smaller than what is needed to build the compact windings of an accelerator magnet, and in a solenoid configuration which is magnetically twice as effective when compared to a dipole.

HFM for accelerators. The largest effort over the past 30 years was dedicated to the development of Nb_3Sn [15] conductor and magnet technology. A strong focus was given in the end of the 1990's by the US-DOE programs devoted to Nb_3Sn conductor and magnet development [16,17,18]. These programs enfolded as a collaboration among the US-DOE accelerator Laboratories and associated Institutions, and are now continuing in consolidated form under the US Magnet Development Program [19]. On the EU side the first targeted EU-wide activities were initiated under the EU-FP6 CARE (Coordinated Accelerator Research in Europe) [20] initiative, and in particular the Next European Dipole Joint Research Activity (NED-JRA) [21]. NED-JRA ran from 2004 to 2009, and was followed by the EU-FP7 EuCARD [22]. The main fruit of these collaborations is FRESCA2, the magnet that still detains with 14.6 T the highest dipole field ever produced in a clear bore of significant aperture.

As described elsewhere in detail [8], HL-LHC is presently the forefront of accelerator magnet technology and construction at the highest field ever attained. The results achieved with the nominal performance of the 11T dipoles [23] and QXF quadrupoles [24] demonstrate that Nb_3Sn has the ability to surpass the state-of-the-art Nb-Ti mentioned earlier. At the same time, it is clear that the solutions successfully implemented for the design and manufacturing of the HL-LHC Nb_3Sn magnets will need to evolve to improve robustness, industrial yield and cost before the full potential of the material can be realised.

Finally, the interest in the exceptional high-field potential of High-Temperature Superconductors (HTS) for many domains of applied superconductivity has not spared accelerator magnets. Copper oxide compounds containing rare-earths (REBCO [25]) and bismuth (BSCCO [26]) are in a stage of early technical maturity, and their application to the generation of ultra-high magnetic fields has been proven recently. Laboratories and industry have shown that HTS are capable of producing fields in the range of 28 T in commercial NMR solenoids [27] to 45.5 T in small experimental solenoids in background field [28]. As discussed later in more detail, HTS technology for accelerator magnets is only at its promising beginning [29]. This is an area where we expect to see fast progress, along the path initiated in various laboratories, and fostered in Europe by the EuCARD [22], EuCARD2 [30], ARIES [31] and the on-going I-FAST [32] EU projects.

In this chapter we start with a review of the state-of-the-art of high-field dipole demonstrators, models and long magnets relevant to accelerator technology, derive the main goals and identify the drivers of an R&D program responding to the declared priorities of the European Strategy Upgrade. This chapter is intended as the starting point in the formation of a structured High Field Accelerator Magnet R&D Program.

2. Historical Perspective

2.1. *Highest Field Attained*

The result of the efforts briefly outlined above can be appreciated graphically in Figure 1, which reports the steady increase of field produced by dipole magnets built with LTS Nb_3Sn over the past forty years. The data is a loose collection of results obtained with short demonstrator magnets (simple configurations that lack an aperture for the beam and are not built with other constraints such as field quality), short model magnets (short version of magnets that are representative of the full-size accelerator magnets), and full-size accelerator magnets.

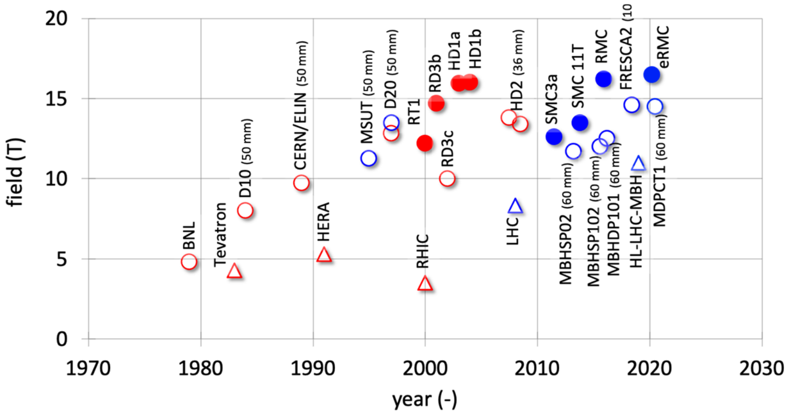

Fig. 1. Record fields attained with Nb_3Sn dipole magnets of various configurations and dimensions, and either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature. Solid symbols are short demonstrator, i.e. “racetracks” with no bore, while open symbols are short models and long magnets with bore. For comparison, superconducting collider dipole magnets past and present are shown as triangles.

We can trace first significant attempts back to the 1980's, at BNL [33] and LBNL [34]. This work eventually led to the achievements of D20 [35], in the 1990's, and the 16 T field attained with the demonstrator HD1 at LBNL [36], in the 2000's. Fields in the 16 T range were obtained at CERN [37] in 2015, and surpassed in 2020 [38] as a result of the push provided by FCC-hh. It is interesting to note here how the work in the 1900's and 2000's described above [39] has laid the foundations for the construction of the HL-LHC Nb_3Sn magnets. And yet, the R&D program itself was largely funded by HEP in the US, as well as EU initiatives in Europe, i.e. essentially independent of a specific HEP project.

We also see in Figure 1 that the timeline for progress in Nb_3Sn magnet technology is relatively slow. It took about ten years for CERN and associated laboratories [20,21,22], to reproduce the results obtained in the US, from conductor R&D, i.e. highest performance of PIT conductor achieved in 2008 [40], to the field level of 16.2 T in RMC03, achieved in September 2015 [37]. This gives a good benchmark for the time scale necessary to enter into this field of technology, including the procurement of the required infrastructure (e.g. heat treatment furnaces, impregnation tanks) and the development of the necessary skills. The end result of this work is the record magnet FRESCA2, built in collaboration between CERN and CEA, and generating a field of 14.6 T in an aperture of 100 mm diameter [41]. This field level has been reproduced recently by a high-field model dipole built within the scope of the US-MDP program [42] as a step towards the highest field that can be attained with a cos-theta coil configuration (4 layers).

Finally, the plot shows the remarkable achievement in the development of Nb_3Sn accelerator magnets, and in particular the MBH 11T dipole for HL-LHC built at CERN in collaboration with industry (GE-Alstom) [23]. Initiated in 2010, and profiting from the previous developments outlined above, it took a decade to produce the first magnet unit that met all stringent requirements for accelerator operation. The first such magnet, MBHB002, was tested in July 2019 and also retains the record within its class [43]. Though successful in achieving the specified performance, the 11T program has also pointed out that there are still problems to be resolved, on the long-term reliability of the specific design as well as the robustness of the manufacturing solutions, which will need to be addressed and resolved before this class of magnets can be used in an operating accelerator.

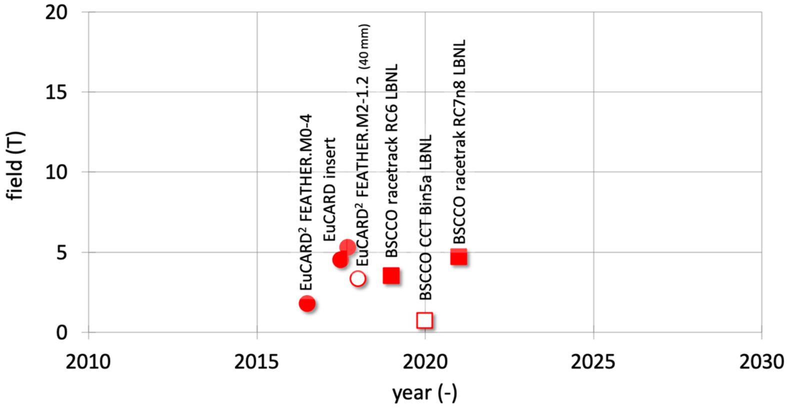

Fig. 2. Record fields attained with HTS short demonstrator magnets producing a dipole field. All tests performed in liquid helium (4.2 K). Solid symbols are magnets with no bore (e.g. racetracks), while open symbols are magnets with bore. Round symbols are magnets built with REBCO, square symbols with BSCCO-2212.

While Nb_3Sn is baseline for the high field magnets of HL-LHC, as well as the next step in SC accelerator magnet technology, great interest and significant progress was achieved recently in HTS accelerator magnet technology, reported graphically in Figure 2. The general interest in the potential of this class of material with spectacular performance coagulated at about the same time in the EU and US, i.e. in the mid of the 2000's. On the US side, efforts were coordinated by the US-DOE sponsored Very High Field Superconducting Magnet Collaboration [44], which targeted Bi-2212 as HTS high-field conductor. This activity has now flown into the scope of US-MDP [19] now addressing both BSCCO-2212 and REBCO in various cables (Rutherford and CORC) and magnet (racetracks and canted cos-theta) configurations [45-47]. As anticipated, in the EU the first seeds initiated already with the EU-FP7 EuCARD collaboration [22], and were pursued intensely with the follow-up EU-FP7 EuCARD2 [30] and EU-H2020 ARIES [31] programs. Much of the conductor effort in Europe was directed to REBCO, with a conscious choice mainly driven by the perceived potential and simpler magnet technology [29]. The result of these activities are small demonstrator magnets that have reached bore field in the range of 3 to 5 T in stand-alone mode. Figure 2 shows clearly that this is the beginning of the path that will hopefully lead to results comparable to Nb_3Sn. The next step beyond the further development of the technology is to use these small-size demonstrators as inserts in large bore, LTS background magnets to boost the central field and quantify the ability to break the barrier of LTS magnet performance, while at the same time exploring this new range of field.

2.2. *Discussion*

We can draw a number of conclusions from this rather simplified but interesting review of achievements:

- Lead times for the development of high-field magnets are long, the cycle to master new technology and bring novel ideas into application has typical duration in excess of a decade. It is hence important to pursue R&D in parallel with scoping studies of new accelerators, to anticipate demands and guarantee that specific technology is available for a new HEP realization at the moment when the decision of construction is taken.
- The development of novel SC magnet technology at the high field frontier requires specific infrastructure, often of large size. The necessary investment is considerable. Continuity is hence important in a program that requires such infrastructure and the associated investment.
- The development of high field magnets naturally spans over many fields of science and requires a broad mix of competencies, implying a research team assembled as a collaboration ranging from academia to industry. As for the infrastructure, one such research team needs considerable investment for its constitution and operates most effectively with continuity.

These considerations point to the need of a sustained and inclusive R&D program for high-field superconducting accelerator magnets as a crucial element for the future of HEP, as underlined by the strong recommendation emitted by the European Strategy Group 2020 [48]. Not only should such program respond to the demands driven by specific projects and studies, it should also unfold as a continuous line of structured R&D, ready to respond to future HEP requests, and capable of feeding HEP with opportunities. The program should include both LTS and HTS materials in a synergic manner and encompass the whole spectrum from conductor to accelerator magnets, including the key technologies that are necessary for the realization of its goals. Though we have stressed how such an R&D has long lead time, with cycles of the order of ten years, the timeline should strive to match the upcoming deadlines for critical decision, and in particular the ESPP process which has a cycle of about 7 years.

An important matter underlying the above considerations is: cost. In this respect we have to consider not only the construction cost of magnets (a very significant challenge for future accelerators, which will be explicitly covered later in this chapter), but also the cost of the R&D itself, which may limit the scope and stretch the timeline, against the wish for a fast turn-around. This is especially true for HTS materials, which explains why the scale of the demonstrators described earlier, as well as the future ones, shall be kept intentionally small (i.e. *inserts* in background field). An effective R&D program will hence include practical consideration of cost and will need to rely on a high degree of synergy.

Given the ambitious scope, the long-term engagement, and the cost, one such program will have to be of collaborative nature, with strong partnership among national laboratories, universities and industry. The R&D program should capitalize on the state-of-the-art and achievements obtained so far, remaining in a line of continuity with the work outline presented earlier, which is largely still on-going. Indeed, an R&D program with the characteristics outlined is consistent with the plans of other organizations in HEP already mentioned earlier [19,49], as well as other research fields relevant to our discussion [50-53]. Last but not least, it will be important to measure the impact of the R&D program against its relevance and impact towards other applications in science and society.

3. Goals of the High Field Magnets R&D Program

The above elements, in the context of present and future demands from HEP, were included in the process of upgrade of the European Strategy for Particle Physics (ESPP). The ESPP consultation and synthesis process started with the Open Symposium of Granada, in May 2019 [Granada], and was completed in June 2020 with the endorsement of the ESPP update by the CERN Council [48,54]. The references quoted contain strong and precise statements relevant to R&D activities on high field accelerator magnets, namely:

> […] the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;” [48]

and

> "The accelerator community, led in Europe by CERN with partners in the United States and Japan, is investing efforts in the design of high-field magnets based on Nb_3Sn superconductor. […] A focused, mission-style approach should be launched for R&D on high-field magnets (16 T and beyond); this is essential for a future hadron collider, to maximise the energy and to minimise the development time and cost. Development and industrialisation of such magnets based on Nb_3Sn technology, together with the high-temperature superconductor (HTS) option to reach 20 T, are expected to take around 20 years and will require an intense global effort." [54]

It is important to put the R&D mentioned above in the context of the request that:

> "Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage." [48]

The above statements have been translated in the following two long-term technical goals of the HFM R&D:

(1) Demonstrate Nb_3Sn magnet technology for large scale deployment, pushing it to its practical limits, both in terms of maximum field as well as production scale. The drivers of this first objective are to exploit Nb_3Sn to its full potential, which we think is not yet unfolded, developing design, material and industrial process solutions that are required for the construction of a new accelerator. We separate the search for maximum field from the development of accelerator technology by defining the following two dependent and linked sub-goals:

   (a) Quantify and demonstrate Nb_3Sn ultimate field. This effort consists of the development of conductor and magnet technology towards the ultimate Nb_3Sn performance. The projected upper limit is presently 16 T dipole field (the reference for FCC-hh). This field should be intended as a target, to be quantified and measured against the performance of a series of short demonstration and model magnets.

   (b) Develop Nb_3Sn magnet technology for collider-scale production, through robust design, industrial manufacturing processes and cost reduction. The present benchmark for Nb_3Sn accelerator magnets is the HL-LHC, with an ultimate field in the range of 12 T, and a production of the order of a few tens of magnets. Nb_3Sn magnets of this class should be made more *robust*, considering the full spectrum of electro-thermo-mechanical efforts, and the processes adapted to an industrial production on the scale of thousand magnets. The success of this development should be measured against the construction and performance of long demonstrator and prototype magnets, initially targeting the 12 T range.

(2) Demonstrate suitability of HTS for accelerator magnet applications, providing a proof-of-principle for HTS magnet technology beyond the reach of Nb_3Sn. The *Leitmotiv* of this program is to break the evolutionary changes of LTS magnet technology, from Nb-Ti to Nb_3Sn, by initiating a revolution that will require a number of significant innovations in material science and engineering. A suitable target dipole field for this development is set for 20 T, significantly above the projected reach of Nb_3Sn (see above). Besides answering the basic question on field reach and suitability for accelerator applications, HTS should be considered for specific applications where not only high field and field gradient are sought, but also higher operating temperature, large operating margin and radiation tolerance are premium.

In addition, it is also important to underline that the HFM R&D program is intended as a focused, innovative, mission-style R&D in a collaborative and global effort, signified at multiple instances in the documents already quoted, such as:

> "Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders […] The technologies under consideration include high-field magnets, high-temperature superconductors […]" [48]
>
> "The particle physics community must further strengthen the unique ecosystem of research centres in Europe. In particular, cooperative programmes between CERN and these research centres should be expanded and sustained with adequate resources in order to address the objectives set out in the Strategy update." [48]
>
> "Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes." [48]
>
> "The implementation of the Strategy should proceed in strong collaboration with global partners and neighboring fields." [48]

It is possible to represent graphically the main objectives in the form reported in Figure 3, where we plot a length of dipole magnets produced (i.e. magnet length times the number of magnets) vs. the *bore field*. The blue line gives an idea of the state-of-the-art, bounded on one side by the nearly 20 km

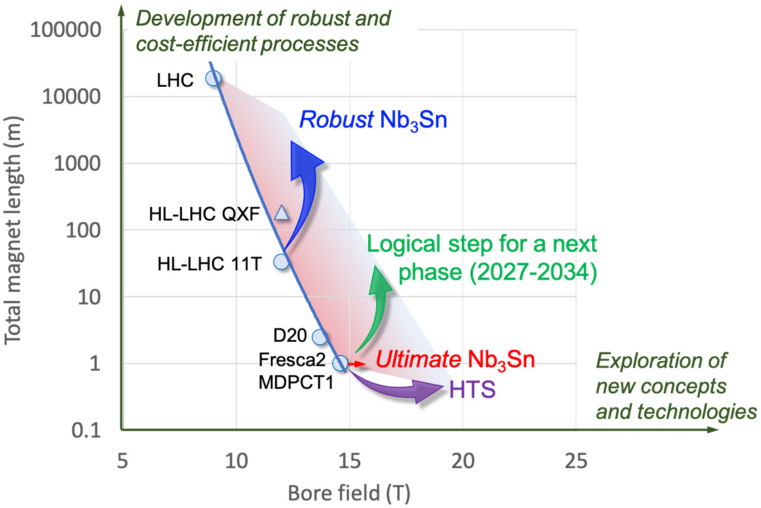

Fig. 3. Graphical representation of the objective of the HFM R&D program in this phase, 2021-2027. Both fronts of maximum field (red for Nb_3Sn, purple for HTS) and large-scale production (blue) are intended to be advanced at the same time. Also represented, in green, a possible evolution for the longer term, 2027-2034.

of Nb-Ti LHC double-aperture magnets in the range of 9 T ultimate field, and at the high-field end by single model magnets approximately 1m in length and in the range of 14.5 T maximum field. The HL-LHC point marks the production of 6 dipoles of 5.5 m length with 12 T ultimate field. The objectives listed above can be represented in this plot as an extension of the field reach by moving along the horizontal axis (magnetic field) thanks to advances in Nb_3Sn and HTS magnet technology, as well as an extension of the production capability by moving along the vertical axis (magnet length) thanks to the development of robust and efficient design and manufacturing processes. Note for clarity that the symbols at higher field (Nb_3Sn at 16 T, HTS at 20 T) and longer magnet length (5 km) represent targets, providing the desired R&D direction, and they should not be read as specified performance.

The *parallelism* in the development is an important element of the program. We believe this is necessary to provide the requested significant advances within a time frame of five to seven years, i.e. responding to the notion of a mission-style R&D that needs to feed the discussion for the next iteration of the European Strategy for Particle Physics with crucial deliverables.

The graphical representation of Figure 3 discussed above only defines the first step in the R&D, which should enfold in the 2021-2027 period. Naturally, once it is proven that the field reach can be extended, and the actual level is demonstrated, we can foresee the need of a follow-up phase. This should enfold in the period 2027-2034, being dedicated to proving the new generation of high field magnets on a scale of magnet prototype, i.e. several meters of cumulated magnet length. This is represented by the green arrow in Figure 3, whereby the choice of the field level, and the actual magnet length to be realized, are again, only indicative, and will depend on the results of the R&D in the coming few years.

A further element in support to the R&D targets formulated above, is that they respond directly to the demands coming from principal stakeholders. As evident from the quotations of the reference ESPP documents, the HFM R&D targets formulated for Nb_3Sn magnets stems directly from the demands of an FCC-hh [9]. In the staged approach described here, they are also compatible with the allotted development time of the integrated FCC program [55]. Indeed, the parallelism proposed has the advantage that it will provide options for an earlier decision on magnet technology towards the construction of the next hadron collider.

At the same time, while we recognize that the development of capture, cooling, acceleration and collider magnets for a muon collider [14] remains a formidable task, to be addressed by dedicated and targeted studies, an R&D on high-field Nb_3Sn and HTS magnets along the lines outlined above will be highly relevant to develop suitable design and technology solutions.

Examples that will become clearer in the following discussion are: (i) HTS conductor and coil winding technology towards the 20 T target, including partial- and no-insulation windings, whose results could be applied to the ultra-high field solenoids of the capture and cooling section, or to the high-field collider magnets; (ii) the study of stress management in Nb_3Sn magnets towards their ultimate performance, directly applicable to large aperture dipole and quadrupoles for the high-energy collider main ring and IR magnets; or (iii) considering HTS magnet operation at temperature above liquid helium, not mentioned explicitly above but relevant to understanding operating margin in the high heat load and radiation environment of the high-energy collider ring.

4. Challenges of High Field Magnets

A number of challenges will need to be mastered to progress towards the goals stated above [56]. Below we give a short description of the main ones, quantifying them by providing relevant orders of magnitude.

4.1. *Superconductor*

The prime rime challenge to achieve high magnetic fields of interest to HEP is to have a conductor that has, and retains, a high engineering current density J_E in operating conditions. A target of $J_E \approx 600$ A/mm2 is appropriate to yield a compact and efficient coil design [57,58]. The J_E target should be reached with limited training, well retaining the training *memory*, and making use of the highest possible fraction of the current carrying capacity of the specific superconductor. Most importantly, all known high field superconductors (Nb_3Sn and HTS) are brittle and exhibit sensitivity to stress and strain in accordance with the specific material and conductor architecture. Though the failure mechanisms and levels can be very different among them, e.g. in the very brittle multi-filamentary Nb_3Sn and BSCCO vs. more robust REBCO tape, it is of paramount importance that the state of stress and strain state in the various constituents of a coil is mastered and controlled throughout all magnet fabrication and operation conditions. This is a major change of paradigm in the design and construction of high field magnets beyond Nb-Ti technology.

The above J_E target translates to specifications for the performance of LTS and HTS materials that have commonalities and differences. In the case of Nb_3Sn the target of J_E requires a minimum critical current density in the superconductor, J_C, of the order of 1500 A/mm2 at the reference design conditions of the magnet (set to 16 T and 4.2 K) [59]. This target is at the upper end of the state-of-the-art Nb_3Sn, and still requires pursuing the on-going work on basic material and wire fabrication [60]. For HTS, the target J_E is actually already largely exceeded by the present production standards of REBCO and BSCCO materials [61,29]. The main challenge in this case is, instead, finding configurations and processes suitable to assemble single tapes and wires in high-current cables, and making sure that the extraordinary current density is retained in the magnet, avoiding the degradation induced by electro- or thermo-mechanical stress and strain.

Besides J_E, and in common to both LTS and HTS, other performance parameters need to be met. These requirements range from the high mechanical strength and good tolerance to stress and strain indicated earlier (see also next section), magnetization and the equivalent filament size (to limit flux jumps, persistent currents and AC losses), internal resistance (to promote current sharing and facilitate joints), including production quality (homogeneous long lengths are needed for magnet fabrication), and last but not least, cost [62].

The two tables below report the targets for Nb_3Sn and HTS wires and tapes performance as they were set a few years ago within the scope of the FCC conductor development program [60] and the EuCARD2 [61], followed by the ARIES [31] HTS development programs. The target values in the table include considerations of magnetization, strength, internal resistance and cost beyond engineering current density. These targets are in some instances

Table 1. Performance targets for Nb_3Sn conductor for large scale HEP applications, from [58].

Strand diameter	(mm)	0.5 … 1
Non-Cu J_C (16 T, 4.2 K)$^{(1)}$	(A/mm^2)	$\geq$ 1500
$\mu_0\Delta$M (1 T, 4.2 K)$^{(2)}$	(mT)	$\leq$ 150
$D_{eff}$$^{(3)}$	(μm)	$\leq$ 20
$RRR$$^{(4)}$	(-)	$\geq$ 150
Allowable $\sigma_{\text{transverse}}$$^{(5)}$	(MPa)	$\geq$ 150
Allowable range of $\varepsilon_{\text{longitudinal}}$$^{(6)}$	(%)	$\geq$ ±0.3
Unit Length	(km)	$\geq$ 5
Cost (16 T, 4.2 K)$^{(7)}$	(EUR/kAm)	$\leq$ 5

NOTES

(1) Critical current density referred to the non-Copper cross section of the wire

(2) Width of the persistent current magnetization loop

(3) Effective filament diameter derived from magnetization target and assumed JC scaling matching the target

(4) Residual Resistivity Ratio, customarily defined as the ratio of resistance at 293 K to resistance just above the superconductors transition but below 25 K

(5) Intended as the average stress applied transversally that the wire can withstand with no degradation of current carrying capacity

(6) Intended as the range of longitudinal strain that the wire can withstand with no degradation of current carrying capacity

(7) Computed based on a Cu:non-Cu ratio of 1.

Table 2. Performance targets for HTS REBCO conductors for demonstration to HEP applications, modified from [30] and [31] and complemented with peeling strength and internal resistance targets.

J_E (20 T, 4.2 K)$^{(1)}$	(A/mm^2)	≥ 1200
$\sigma(Ic)^{(2)}$	(%)	≤ 10
$\mu_0\Delta$M (1.5 T, 10 mT/s)$^{(3)}$	(mT)	≤ 300
Minimum $\sigma_{\text{peel}}{}^{(4)}$	(MPa)	≥ 25
Allowable $\sigma_{\text{transverse}}{}^{(5)}$	(MPa)	≥ 200
Allowable range of $\varepsilon_{\text{longitudinal}}{}^{(6)}$	(%)	$\geq \pm 0.3$
Internal $\rho_{\text{specific}}{}^{(7)}$	(nΩ/cm^2)	≤ 10
Unit Length	(m)	≥ 100

NOTES

(1) Engineering current density referred to the cross section of the whole tape
(2) Spread (1-sigma) of the engineering current density over production batches
(3) Width of the persistent current magnetization loop
(4) Intended as peeling strength of the layers in the tape, derived from an estimate of the internal stress in a tape operated at 20 T
(5) Intended as the average stress applied transversally on the broad face of the tape with no degradation of current carrying capacity
(6) Intended as the range of longitudinal strain that the tape can withstand with no degradation of current carrying capacity
(7) Intended as specific transverse resistivity among the layers of the tape, based on lowest range of measurements in industrial tapes.

challenging, but for most of them it has been shown that they can be achieved if taken one by one. The true challenge will be to reach them in combination and translate them into conductor engineered for production in large series.

4.2. *Forces and stresses*

Electromagnetic forces in dipoles scale with the square of the bore field [57,58,63], as shown schematically in Figure 4 where we have reported the horizontal and vertical electromagnetic force that are applied to a coil quadrant of dipole magnets built and designed in the past 30 years. Dipoles with bore field in the range of 16 to 20 T will therefore experience an electromagnetic force larger by a factor four to six with respect to the one experienced by the LHC dipoles, approaching the level of 10 MN/m per coil quadrant. The corresponding electromagnetic stress in the coil also increases with the field. While this value is in the range of 80 MPa for the HL-LHC 11…12 T Nb_3Sn

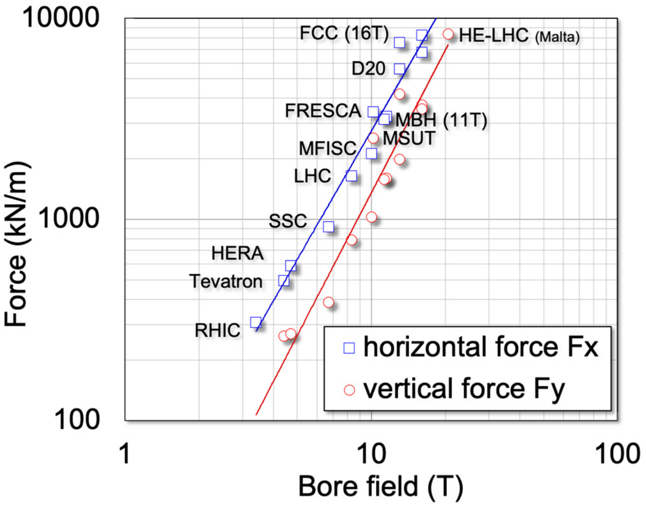

Fig. 4. Scaling of horizontal and vertical force applied on a coil quadrant of accelerator dipoles (Tevatron, HERA, RHIC, LHC, HL-LHC MBH (11T)), prototypes (SSC), models (MFISC, MFReSCa, MSUT, D20) and designs (FCC, HE-LHC). The scaling plot is an improved and augmented version of initial work reported in [57,58].

magnets, it will reach design values in the range of 150 to 200 MPa for 16 T magnet with the desired $J_E \approx 600$ A/mm^2. This poses significant challenges in the mechanical design and the resulting stress on coil and structures, to the point that mechanics of a high-current density coil becomes the first true limiting factor to magnet performance. In fact, this is not new, being a common feature across all types of high-field magnets, solenoids [64] and fusion magnets [65].

This has driven the development of new mechanical solutions and stress management concepts for high field accelerator magnets, deviating from the cos-theta collared coils paradigm already successfully implemented in Nb-Ti accelerator magnets. Notably, recent years have witnessed a progression from collared/cos-theta coils to block- or common-coils [66,67] which mitigate the issue of azimuthal stress by moving the regions of high-stress away from the region of peak field, bladder-and-key loading [68] that avoids over-stressing the coil during assembly and pre-loading at warm, and stress-managed cos-theta [69] and canted-cos-theta [70] that provide means to avoid the accumulation of electro-magnetic stress in the coil.

The new concepts mentioned above need to integrate the demands stemming from the brittle superconducting phases discussed earlier, taking into account fracture mechanisms and material limits, the fact that the coil itself is a complex composite structure with highly non-linear properties, its interfaces, and ensuring that under no condition stress and strain exceed materials allowable limits. The difficulty is exacerbated by the fact that the coils for high field magnets, as they are presently built, are stiff and significantly less accommodating towards geometric errors, manufacturing and assembly tolerances. The new concepts will hence have to respond to the need for mechanical precision, naturally increasing as interfaces become highly stressed. Indeed, tolerances have already been reached with the HL-LHC magnets practical limits for manufacturing in large series, of the order of 20 μm.

Finally, in order to achieve the required confidence in mechanical design and construction, it is likely that new material models and corresponding constitutive equations will have to be developed. These will provide the realistic material description needed for the advanced multi-physics modeling capable to resolve the stress and strain fields with the required accuracy along the whole life span of the magnet, from manufacturing, through thermal cycles, to cyclic powering and quenches.

4.3. *Stored energy*

The energy stored in the magnetic field of a dipole also increases approximately with the square of the bore field [57,58,63], shown schematically in Figure 5. We have collected in there the values measured or computed for the same set of magnets considered for the scaling of forces. Aiming at the range of 16 to 20 T, the increase in stored energy with respect to the LHC will also be a factor of 4 to 6, ranging from 1 to 3 MJ/m per aperture. This in itself may result in severe limitations on the powering of strings, both from the point of view of their inductance (voltage required to ramp the string of dipoles), as well as magnet protection (energy density and dump time). In addition, the energy per unit volume, that drives the peak (hot-spot) temperature during a quench, also increases. The HL-LHC Nb_3Sn magnets, with a design hot-spot limited to 350 K, have values in the range of 80 to 100 MJ/m^3. This value reaches 200 MJ/m^3 for the most compact 16 T FCC designs. As for magnet mechanics, this is in fact the second true limitation to magnet performance.

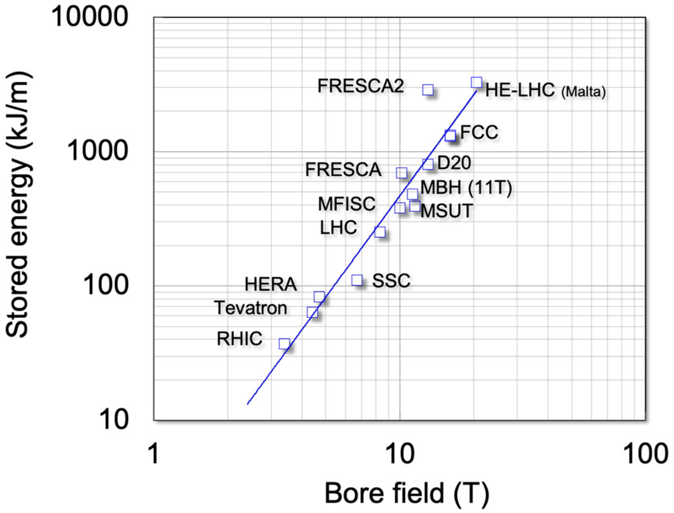

Fig. 5. Scaling of stored energy per unit length for the dipole magnets considered in Figure 4 (values refer to one aperture in case of the LHC, 11T, FCC and HE-LHC). The scaling plot is an improved and augmented version of initial work reported in [57,58].

To power magnets with larger stored energy, electrical engineering considerations would favor large voltage or current, or a combination of both. However, increasing terminal voltage significantly above the range of 1 to 2 kV or cable current significantly above the range of 10 to 20 kA is not a trivial matter, so that a future accelerator of the size of FCC may need to rely on a high level of circuit segmentation to reduce circuit inductance. This implies additional system complexity, but was successfully demonstrated and operated at the LHC. In essence, the range of magnet operating voltage and current is not expected to change significantly.

A direct consequence is that in order to keep the hot-spot temperature in the coil after a quench below reasonable values (around 300 K to 400 K, but actual damage limits are not well assessed), the quench detection and protection will need to act at least three to five times faster than in the LHC. This is already challenging for Nb_3Sn, but becomes a tantalizing task for HTS, whose quench propagation speed is one order of magnitude slower than in LTS, and quench detection based on established instrumentation would take an order of magnitude longer. Besides, quench initiation and evolution in the case of HTS is a much different process than the well characterized behavior of LTS. In fact, though relatively unexplored, the large difference in quench initiation and propagation in HTS vs. LTS may actually be an opportunity to develop alternative schemes, e.g. profiting from early low voltage quench initiation to anticipate the evolution, or the relatively long time scales of voltage development to improve measurement sensitivity.

The challenges posed by magnet powering and protection have multiple facets, and they will need to be addressed in an integrated manner. There is a remarkable parallel between the magnet protection and magnet mechanics challenges. Firstly, detection and protection in the regime of stored energy and energy density described above will require new magnet concepts, especially for HTS (e.g. non-insulated or partially-insulated windings [71]) as well as novel detection and protection techniques (two selected examples are fiber optics for quench detection [72], and alternative active quench protection methods [73]). Secondly, measurement and characterization of the thermo-mechanical and dielectric properties and limits of coils and structures will be a mandatory step to ensure that the design are safely within allowable's. Finally, comprehensive multi-physics models with augmented accuracy will be the main tool guiding design and analysis in the extended regime of field, stored energy, temperature and voltages.

4.4. *Cost*

Considering the size of a new collider for the search of physics beyond the LHC, and the quantum increase in the requested magnet performance, cost is the third limit to the new technology. For this reason, it is important to include challenging and yet realistic cost targets in the study and development of new magnet concepts and materials.

An indication of a suitable cost target can be taken from the analysis of Ph. Lebrun [74] on the ratio of the cost of the technical systems to the center-of-mass beam energy, reported in Figure 6. The analysis is based on the accelerators built at CERN, excludes civil engineering, and we can roughly assume that for hadron accelerators the cost of the magnet system is half of the total accelerator cost. The result achieved with the LHC, with a specific cost of 250 kCHF/GeV, is the present benchmark, and a rather arbitrary extrapolation to the projected energy of an FCC at 100 TeV center-of-mass gives an expectation of 70…80 kCHF/GeV. At this early stage, a tentative value of

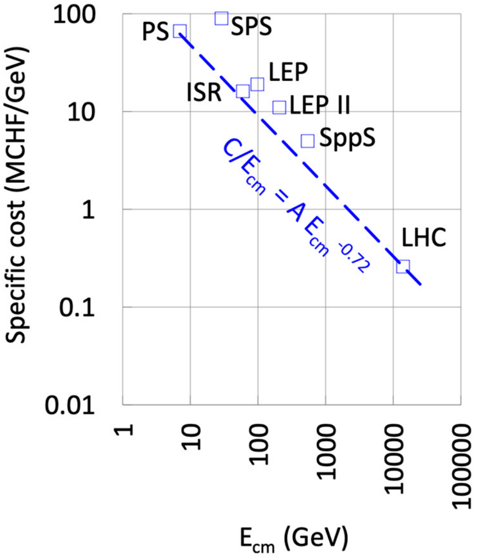

Fig. 6. Scaling of accelerator cost (excluding civil engineering) to the center-of-mass beam energy of accelerators built at CERN. Note that the data include accelerators of different magnet technology (e.g. resistive vs. superconducting) and with large disparity among the relative cost of the various accelerator systems (e.g. magnets vs. RF).

100 kCHF/GeV can be taken as a challenging but suitable benchmark. The scaling of magnet cost with beam energy may be somewhat surprising, so it is interesting to verify it by other means. The analysis in [75] provides a scaling of magnet cost purely based on the magnetic energy of the system. Projecting the cost of the LHC magnet system to an FCC, assuming a two-fold increase of the field and three-fold increase in the magnet quantity, we obtain an approximate cost of 10 BCHF, i.e. coherent with the figure of the order of 100 kCHF/GeV.

To put the cost target value in perspective, and understand the challenge, we recall that the superconductor itself is the single most expensive cost position in a high-field magnet. Normalizing to 1 AU/kg the cost of Nb-Ti, the present cost of Nb_3Sn is of about 10 AU/kg, and that of HTS is 100 AU/kg. It is clear that a substantial effort will be required to achieve feasible cost figures, starting at the level of the superconducting material.

Still, though it is clear that the construction of a large-scale machine like an FCC-hh will only be possible if targets in this range are achieved, a successful R&D program should not be hindered by considerations of final cost. Indeed, experience has shown in many fields of science and engineering that optimal technical solutions invariably make use of the best technology available at the moment of project commitment.

5. High Field Magnets R&D Program Drivers

Driven by the challenges outlined above, we can formulate practical questions that should be addressed in priority by a High Field Magnet R&D Program. These questions are the R&D *program drivers*, and they can be broadly divided into questions of relevance for Nb_3Sn, HTS, and common to both lines of development.

For Nb_3Sn high-field accelerator magnets the following leading questions can be drawn from the earlier discussion, and will need to be addressed largely looking at the pioneering Nb_3Sn development that has led to the milestone HL-LHC magnets, the present reference technology:

- Q1: What is the practical magnetic field reach of Nb_3Sn accelerator magnets, driven by conductor performance, but bounded by mechanical and protection limits, and in particular is the target of 16 T for the ultimate performance of Nb_3Sn accelerator magnets realistic?
- Q2: Can we improve robustness of Nb_3Sn magnets, reduce training, guarantee performance retention, and prevent degradation, considering the complete life cycle of the magnet, from manufacturing to operation?
- Q3: Which mechanical design and manufacturing solutions, from basic materials, composites, structures and interfaces need to be put in place to manage forces and stresses in a high-field Nb_3Sn accelerator magnet?
- Q4: What are the design and material limits of a quenching high-field Nb_3Sn magnet, and which detection and protection methods need to be put in place to remain within these limits?
- Q5: How can we improve design and manufacturing processes of a high-field Nb_3Sn accelerator magnet to reduce risk, increase efficiency and decrease cost as required by an industrial production on large scale?

For HTS high-field accelerator magnets, the leading questions are more essential to the potential and suitability for accelerators, with the awareness that the body of work in progress is not yet at the point where a reference technology can be defined:

- Q6: What is the potential of HTS materials to extend the magnetic field reach of high-field accelerator magnets beyond the present and projected limits of Nb_3Sn, and in particular is the target of 20 T for HTS accelerator magnets realistic?
- Q7: Besides magnetic field reach, is HTS a suitable conductor for accelerator magnets, considering all aspects from conductor to magnet and from design to operation?
- Q8: What engineering solutions, existing or to be developed and demonstrated, will be required to build and operate such magnets, also taking into account material availability and manufacturing cost?

Finally, common to Nb_3Sn and HTS:

- Q9: What is the specific diagnostics, instrumentation and infrastructure required for a successful HFM R&D, taking into account present and projected needs, and aspects ranging from applied material science to production and test of superconductors, cables, models and prototype magnets?
- Q10: What is the quantified potential of the materials and technologies that will be developed within the scope of the HFM R&D program towards other applications to science and society (medical, energy, high magnetic field science), and by which means could this potential be exploited at best?

6. Conclusions and Perspectives

The LHC is in the preparation phase before it enters another period of physics production, possibly reaching its nominal energy, and the next step magnets for accelerators, the Nb_3Sn 11T and QXF of HL-LHC, are in production and test. It is time to build on these developments to prepare for the evolution beyond these two technical milestones. The material presented and discussed in this chapter is a solid starting point and provides clear indications of the direction that a High Field Magnet R&D should take to respond to the technical challenges of the next step in accelerator magnets, along the following two principles:

- Nb_3Sn: demonstrate technology for large-scale accelerator deployment
- HTS: demonstrate suitability for accelerator magnet applications.

As discussed extensively, the goals pronounced here are also intimately bound to the demands stemming from the 2020 update of the European Strategy for Particle Physics, making direct reference to the needs deriving from the agreed accelerator strategy of the coming years.

R&D drivers have been identified, translating the general direction into practical questions that need to be explicitly addressed by *R&D Lines of Work*. As they have been formulated and discussed, it becomes natural to group the program drivers in R&D lines dedicated to: (i) conductor R&D (Nb_3Sn and HTS), (ii) magnet R&D (Nb_3Sn and HTS), and (iii) cross-cutting technology developments such as magnet protection, materials and models, instrumentation and diagnostics, and infrastructures for test and production. Finally, a dedicated line of work should be envisaged to probe and quantify the benefits of the technical development for other fields of research, industry and society.

These R&D Lines provide the framework of the upcoming HFM R&D Program which will move along the program drivers in a collaborative and global effort, strengthening the unique *ecosystem* of research centers in Europe, with strong focus on promoting the innovation required to extend the physics reach of future colliders.

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