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High Field Magnet Development for HEP in Europe – A Proposal

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Abstract

The Large Hadron Collider (LHC) at CERN, now in operation for ten years, can be regarded as the *ultimate* collider built with Nb-Ti magnets. Its main dipoles reach a field of approximately 8 T, which is very likely close to the highest practical field for this superconductor in accelerators built on a large scale. The next project of CERN is the High Luminosity upgrade of the LHC, which 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 and the first sets of HL-LHC dipole magnets are being readied for tunnel installation, marking an historical milestone in accelerator technology and the culmination of 20 years of worldwide R&D. In this paper we recall briefly the critical challenges and main achievements of high-field magnets programs, which provide evidence that Nb_3Sn technology can be used for a large particle accelerator. Capitalizing on these results, we describe here the roadmap established for high field accelerator magnet R&D beyond HL-LHC, consisting of three complementary axes: (1) development of Nb_3Sn technology to the maturity and robustness levels required for industrialization and large-scale production, (2) research what is the ultimate field range achievable with Nb_3Sn accelerator magnets and (3) exploring the potentials of high temperature superconductors for accelerator magnet applications.

Motivation for a High Field Magnet Research and Development Program

High Field Magnets (HFM) are among the key technologies that shall enable the search for new physics at the energy frontier. Starting from the Tevatron in 1983 [Tevatron], through HERA in 1991 [HERA], RHIC in 2000 [RHIC] and finally the LHC in 2008 [LHC], 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 [NbTi], 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.

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. This is the case of the High-Luminosity LHC upgrade (HL-LHC) [HL-LHC], which is currently under construction at CERN and collaborating laboratories, and the Future Circular Collider design study (FCC) [FCC-CDR], structured as a worldwide collaboration coordinated by CERN. Similar studies and programs are on-going outside Europe, such as the Super proton-proton Collider of China's (SppC) [SppC]. Significant advances in SC accelerator magnets were driven by past studies such as the Very Large Hadron Collider at Fermilab [VLHC] and the US-DOE Muon Accelerator Program [US-MAP]. Finally, new accelerator concepts such as muon colliders presently considered at CERN and collaborators [mu-coll] 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 HFM for accelerators. The largest effort over the past 30 years was dedicated to the development of Nb_3Sn conductor and magnet technology for accelerator applications. 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 [US-CDP] [US-LARP]. 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 [US-MDP]. On the EU side the first targeted EU-wide activities were initiated under the EU-FP6 CARE (Coordinated Accelerator Research in Europe) [CARE] initiative, and in particular the Next European Dipole Joint Research Activity (NED-JRA) [NED-JRA]. NED-JRA ran from 2004 to 2008, and was followed by the EU-FP7 EuCARD [EuCARD]. The main fruit of these collaborations is FRESCA2 [FRESCA2], the magnet that still detains with 14.6 T the highest dipole field ever produced in a clear bore.

Nb_3Sn is the baseline for the high field magnets of HL-LHC, and is the material poised to take the place of Nb-Ti as the next step in SC accelerator magnet technology. At the same time, great interest and significant progress was achieved recently in HTS accelerator magnet technology. 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 initially coordinated by the US-DOE sponsored Very High Field Superconducting Magnet Collaboration [VHFSMC], which targeted Bi-2212 as HTS high-field conductor. This activity has now flown into the scope of US-MDP [US-MDP]. In the EU the first seeds initiated already with the EU-FP7 EuCARD collaboration[EuCARD], and were pursued intensely with the follow-up EU-FP7 EuCARD2 [EuCARD2] and EU-H2020 ARIES [ARIES] programs. Much of the conductor effort in Europe was directed to REBCO [EuCARD2-WP10.2]. 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. The next step, presently in preparation, is to use these small-size demonstrators as inserts in large bore, LTS background magnets to boost the central field and break the barrier of LTS magnet performance achieving fields in excess of 20 T. In parallel, the design of next generation inserts and standalone HTS demonstrators has started. This is the beginning of the path that will hopefully lead to results comparable to Nb_3Sn.

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

- 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 of the order of ten years. 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.
- The magnet programs and achievements described above are mainly the result of laboratory activities. So far industry only had a modest participation, limited to the HL-LHC Nb_3Sn magnet engineering and the production of the 11T collared coils at CERN. None of the high-field technologies (Nb_3Sn or HTS) is ripe for industrial production on a large scale.

These considerations point to the need of a strong, sustained and inclusive R&D program for high-field superconducting accelerator magnets, as a crucial element for the future of HEP, compatible with the strong recommendation emitted by the ESPP in June 2020 [ESPP]. 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. The timeline should be compatible with the expected deadlines for decision, and in particular the ESPP process which has a cycle of 5 to 7 years. Given the ambitious scope, one such program will be of collaborative nature, with strong partnership among national laboratories, universities and industry. Last not least, a particular effort shall be devoted to promoting and measuring the societal impact of the R&D program.

It is intended that the R&D program capitalizes on what was done so far, and remain in a line of continuity with the work outline presented earlier, which is still largely on-going. Finally, we remark that an R&D program with the characteristics outlined above is consistent with the plans of other organizations in research fields relevant to our discussion [US-MDP, China-HFM, DEMO, COHMAG, HFMSCI, EFML, HMF] and fits in the overarching collaboration efforts launched in the past [FuSuMaTech] and on-going [AMICI].

Objectives of the High Field Magnets Research and Development Program

Based on the previous considerations, on the anticipated needs of HEP, and on the state-of-the-art in this field, a program that responds to long-term needs of HFM for accelerators shall extend the range of application of Nb_3Sn beyond the performance (field) and scale (production) of HL-LHC, and explore the capabilities of HTS materials for accelerator magnet applications. The *mission statement* of the program proposed can be written explicitly as follows:

- Push Nb_3Sn magnet technology to its practical limit, both in terms of maximum performance as well as large scale production. The drivers of this first objective are to exploit Nb_3Sn to its full potential, which we think is not yet unfolded, and to develop the design, material and industrial process solutions that would be required for the construction of a new accelerator. The present benchmark for Nb_3Sn accelerator magnets is HL-LHC, with a field in the range of 12 T (ultimate field) and a production of the order of ten accelerator cryo-magnets. Magnets of this class should be made *robust*, and the processes adapted to an industrial production on the scale of thousand magnets. This effort should run in parallel with the development of conductor and magnet technology towards ultimate Nb_3Sn performance. The projected upper limit of performance is 16 T dipole field (the reference for FCC-hh), and equivalent performance in quadrupoles. This field should be intended as a target, to be proven and quantified;
- Provide a proof-of-principle for HTS magnet technology beyond the reach of Nb_3Sn, and sufficient field quality for accelerator application. 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 20 T. Besides answering the basic question on suitability for accelerator applications, HTS should be considered for specific applications where not only high field and field gradient are necessary, but also large operating margin and radiation tolerance are of importance.

It is possible to represent graphically the main objectives in the form reported in Fig. 1, where we plot the length of dipole magnets produced (i.e. magnet length times the number of magnets) vs. the bore field. The blue line represents the state-of-the-art, bounded on one side by the nearly 20 km of Nb-Ti LHC magnets in the range of 9 T ultimate field, and at the high-field end by single model magnets with approximately 1 m length and in the range of 14.5 T maximum field. The HL-LHC point marks the production of 6 dipoles of 5.5m length with 12 T ultimate field 11T. The program proposed plans to extend the field reach by moving both along the field axis (Nb_3Sn and HTS), and the production capability by moving along the length axis. This parallelism in the development is an important element of the program. We believe this is necessary to provide significant advancement within a 7 years time frame (i.e. the next iteration of the European Particle Physics Strategy), and is justified by the present understanding of the issues and the capacity in place.

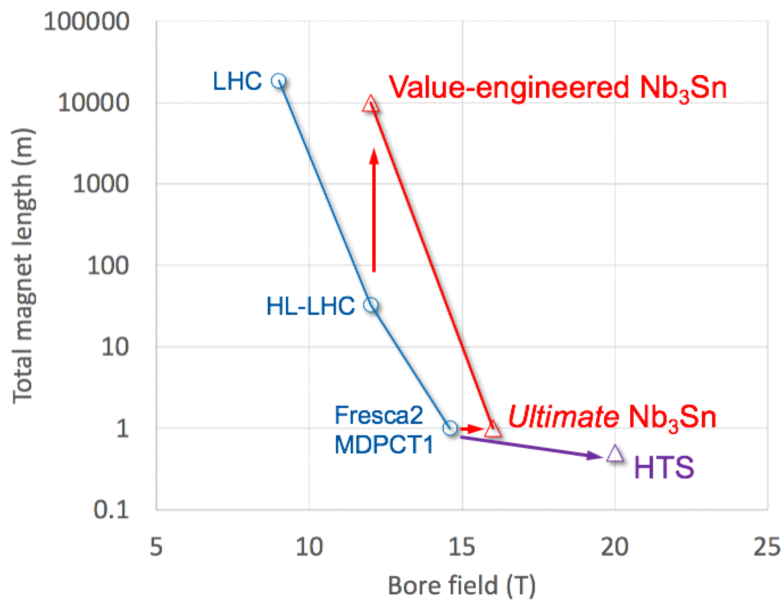

Figure 1. Graphical representation of the objective of the HFM R&D program. Both fronts of maximum field and large-scale production are intended to be advanced at the same time.

As it should be clear from the introduction, the objectives of the R&D program proposed here extend and continue the direction of the initiatives that have led to the present achievements. The on-going efforts, initiated by CERN and collaborators in the past years, are to be continued with the necessary adjustment to address the outstanding issues and take stock from the results obtained so far. For Nb_3Sn the main references are the construction of the HL-LHC magnets and the magnet R&D driven by FCC-hh. For HTS, efforts in Europe have been mainly driven by the collaborative EU programs quoted earlier, i.e. EuCARD, EuCARD2 and ARIES. The proposed R&D program is intended to remain a collaborative effort, requiring good coordination among the partners and worldwide integration, from industry to academic organizations.

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