PROGRESS IN HIGH FIELD SUPERCONDUCTING MAGNET TECHNOLOGY FOR ACCELERATORS*

G. Sabbi, LBNL, Berkeley, CA 94704, USA

Abstract

High-field magnets are the enabling technology for the highest energy colliders. During the next 10 years, a series of LHC upgrades will be implemented aiming at a 10-fold increase of the integrated luminosity with respect to the original design. Future colliders significantly expanding the energy reach of LHC are also under study. New magnet technologies are required to support the objectives of these projects. High-field models with increasing performance and complexity are being developed, with particular emphasis on addressing accelerator quality and length scale-up issues. A review of progress to date and future challenges is presented.

INTRODUCTION

Excellent mechanical and electrical properties make Niobium-Titanium (NbTi) the preferred conductor for accelerator magnets with operating fields up to 8 T. In order to surpass this threshold, materials with higher critical field are required. Among these, Niobium-Tin (Nb_3Sn) is in the most advanced state of development. Nb_3Sn wires carry sufficient current densities to sustain coil windings operating in the 15 T range, and can be produced in multi-km lengths with uniform properties. Nb_3Al offers lower strain sensitivity with respect to Nb_3Sn, but its manufacturing process is not sufficiently well developed for application in magnets. The use of High Temperature Superconductors such as YBCO and Bi-2212 is also being actively explored to surpass the intrinsic limits of Nb_3Sn. While these materials can in principle support operating fields well above 20 T, many technological challenges need to be addressed to exploit their fundamental properties in practical magnet designs. The most significant achievements to date, remaining issues and future directions are discussed.

Table 1: Technology challenges for high-field Conductors

Material	NbTi	Nb_3Sn (Nb_3Al)	Bi-2212	YBCO
Max Field	10-11 T	16-17 T	Stress limited	Stress limited
Reaction	Ductile	~675^{0}C in Air/Vacuum	~890^{0}C in O_2 (±2^{0}C)	None
Wire axial compression	N/A	Reversible	Irreversible?	Reversible
Transverse stress	N/A	< 200 MPa	60 MPa?	≥ 150 MPa
Insulation	All	S/E Glass	Ceramic	All
Construction	G-10, stainless...	Bronze/Titanium, Stainless	Super alloy	All
Quench propagation	>20m/s	~20 m/s	~0.05 m/s? (4.2 K, 8 T)	~0.01 m/s? (4.2 K, 0 field)

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Nb_3Sn MAGNET TECHNOLOGY

The development of Nb_3Sn accelerator magnets focused on designs suitable for arc dipoles with apertures in the range of 40-60 mm [1-7]. To date, dipole fields of up to 13.8 T have been achieved and work is in progress to realize the full potential of this material. However, large aperture quadrupoles have recently become the main focus of the R&D effort [8], to address the near term requirements of the High Luminosity LHC [9].

Contrary to NbTi, all high field superconductors are extremely sensitive to strain. In order to prevent significant degradation due to tight bending at the ends, coils may be wound using un-reacted cable, when components are still ductile, and the superconductor is formed by high temperature heat treatment after coil winding. This technique (wind-and-react) has emerged as the leading approach for Nb_3Sn magnets. High reaction temperatures require the use of special materials such as fiberglass or ceramic insulation, and metallic coil parts. In addition, thermal expansion differentials among components could lead to excessive strain during the reaction cycle. It is therefore essential to minimize friction between coil and tooling, and to introduce gaps between components at critical locations. Finally, in order to increase the allowable pressure range during magnet assembly and operation, coils are impregnated with epoxy resin to avoid stress concentration on the superconducting wires. With this approach, the limit for permanent degradation is 150-200 MPa.

Optimization of Nb_3Sn Rutherford cables also presents significant challenges. Sufficient compaction is required to maintain mechanical integrity during winding, but may result in deformation of the sub-elements at the cable edges, leading to low-field instabilities and critical current degradation. Acceptable design solutions require lowering the compaction factor especially in the horizontal (wide) direction. Keystone cables require an additional compromise between the vertical compaction factors at the two edges. The resulting range of keystone angles in Nb_3Sn cables is about half of what would be available in NbTi cables of similar aspect ratio.

Large electromagnetic forces are generated in high-field magnets and several new design concepts are being developed to provide adequate coil support. A specific requirement for Nb_3Sn is to minimize stress on the conductor at all stages of magnet fabrication and operation. This can be accomplished using a thick outer cylinder (shell) as the main support element. The shell is typically made of Aluminum and pre-tensioned at assembly using hydraulic elements (bladders) and interference keys. During cool-down, the shell tension increases due to differential thermal contraction relative to the iron yoke. This allows to limit the peak coil stress during assembly, and to minimize the amount of structural material taking advantage of its increased strength at lower temperature. To restrain the coil against axial forces, pre-tensioned rods are used to compress thick stainless steel plates against the coil ends. Detailed 3D FEA modelling is required to accurately predict the stress levels at assembly and their evolution during cool-down and excitation [10].

Protection of Nb_3Sn magnets is complicated by high levels of stored energy, high current density and high critical temperature requiring more heater power and increasing heater delays. In addition, epoxy cracking or damage to the conductor may result from the stress generated during a quench. Extensive heater coverage is required to limit the quench temperatures and voltage within safe limits, and small margins are available to account for failure modes. Nevertheless, prototype tests show that with properly designed protection systems, quenches can be sustained without damage.

LHC IR QUADRUPOLES

Program Goals and Components

Replacing the first-generation IR quadrupoles with higher performance magnets is one of the required steps to achieve a significant increase of the LHC integrated luminosity with respect to the baseline design. The new magnets are required provide increased focusing power, operate under radiation loads corresponding to a 5-fold increase in peak luminosity, and achieve a radiation lifetime consistent with the 3000 fb^{-1} integrated luminosity goal.

Starting in 2004, the US LHC Accelerator Research Program (LARP), working in close collaboration with CERN, has led the effort to develop Nb_3Sn quadrupole magnets for the LHC luminosity upgrade. After an initial phase focusing on basic technology development with racetrack coils, the main R&D components have been two series of cos(2θ) quadrupoles using either 90 mm aperture (TQ/LQ models) or 120 mm aperture (HQ/LHQ models).

The TQ quadrupoles are 1 m long and achieved a gradient of 240 T/m, about 20% higher than the original performance target of 200 T/m. A systematic study of Nb_3Sn stress limits was performed using TQ, up to 200 MPa average. A fatigue test involving 1000 cycles from low to high current was also completed [11].

The LQ quadrupoles are a scale-up of the TQ design from 1 m to 4 m. They achieved their 200 T/m target gradient was achieved during the first test, and later increased to 220 T/m, about 10% higher than the original performance goal of 200 T/m [12].

The HQ quadrupoles are designed to explore the performance limits associated with larger apertures. Their two-layer coil design with a 15 mm wide cable results in a 15 T peak field and 1.2 MJ/m stored energy, about a factor of 3 higher than in TQ and LQ. For the first time, coil alignment features are included at all phases of fabrication, assembly and excitation. Based on observations from the first series of coils, several improvements were implemented to decrease conductor strain during reaction and improve the electrical integrity. In parallel, selection of the best first-generation coils through assembly and test of several models yielded an optimized assembly which achieved 184 T/m in a 1.9K test conducted by CERN [13]. This gradient is higher than the one obtained in the TQ models (240 T/m) when adjusted by the ratio of the two apertures. A scale up of the HQ coil to 4 m length is also underway in preparation for the construction of the full scale IR quadrupole prototypes. For efficiency, only single coil tests will be performed using a magnetic mirror structure.

Following the selection of 150 mm aperture quadrupoles for the new IR layout, the development and demonstration of prototypes has started and will become the dominant part of the LARP effort during the next several years. The main goal for this phase is to fabricate and test a series of four meter long prototypes (LQXF). In addition, a series of short models of the same design (SQXF) will be fabricated and tested in collaboration between LARP and CERN.

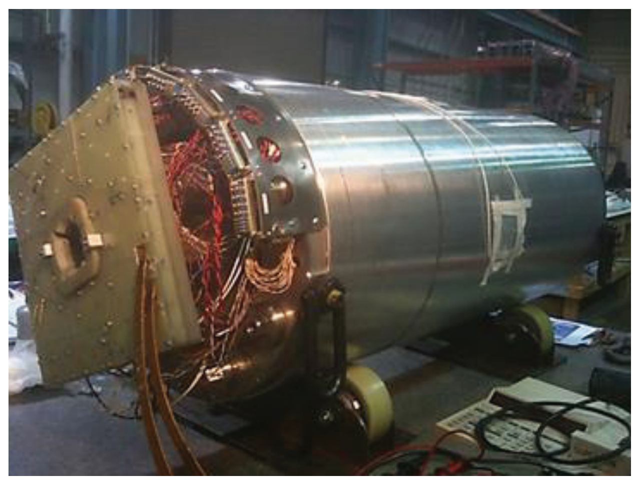

Figure 1: Assembled HQ02a quadrupole [9].

R&D Progress

Conductor The Nb_3Sn wires utilized by LARP are produced by Oxford Superconducting Technology (OST) with the Rod Restack Process (RRP). Two main designs have been used, the RRP 54/61 (61 sub-elements, 54 of which contain superconducting filaments while the remaining 7 are made of copper stabilizer) and the RRP 108/127 (127 sub-elements, 108 of which contain superconducting filaments while the remaining 19 are made of copper stabilizer). The RRP 54/61 wire allowed the LR, TQ and LQ models to reach their R&D objectives and performance goals. The RRP 108/127 has smaller filament size which benefits conductor stability and field quality. It provided solid performance in the TQS03 model, leading to its adoption as a baseline LARP wire starting in 2009. A review of conductor performance and new developments is provided in [14].

Cable Although the fabrication of Nb_3Sn cables was already well established at the start of the program, LARP provided an opportunity for larger scale manufacturing, optimization and detailed characterization. To date, more than 7 km of cable of different designs were fabricated with minimal losses. Several cored cables have been fabricated for the latest generation HQ models using stainless steel and fiberglass cores. Coils have been fabricated using cored cables and successfully tested.

Coil Fabrication Several factors contributed to a steady improvement in coil fabrication procedures throughout the program. Different experiences and methods were compared and integrated. Robust handling and shipping tools were devised to allow distributed coil production lines for the TQ, LQ and HQ models. Careful analysis was performed in relation to the scale up to 4 m length in the LR and LQ models. Nevertheless, the coil fabrication methods are still largely based on empirical knowledge and several iterations are typically needed to optimize new designs. A recent example is given by the development of the HQ models, in which excessive compaction during coil fabrication led to high rates of coil damage in the first tests [15].

Quench Performance and Training The capability to approach the conductor limit in model magnets is an important indicator of the maturity of the technology, and the capability to reach the design point with minimal training and no retraining is an essential requirement for operation in the accelerator. On both fronts, positive results were obtained. The full conductor potential (based on critical current measurements of extracted strands, without accounting for stress degradation) was obtained in the best SQ, LR, TQ and LQ models at 4.5 K, indicating that the assembly process is well controlled and optimized. The best models also showed fast training and no retraining. However, in most cases several iterations of assembly and test were needed for a new design to achieve its full potential.

Mechanical Design Providing adequate mechanical support in high-field magnets based on brittle superconductors requires structures that can generate large forces while minimizing stress on the conductor at all stages of magnet fabrication and operation. Consistent with the R&D goals of the program, the application of new concepts and advanced modeling capabilities was emphasized. In particular, a support structure originally developed at LBNL for high field dipoles [10] was applied to the LARP quadrupoles. This concept is based a thick aluminum shell, pre-tensioned at room temperature using water-pressurized bladders and interference keys. During cool-down, the stress in the shell increases due to differential thermal contraction relative to the iron yoke. This shell-based structure was evaluated against the more traditional collar-based structure in the TQ models, scaled-up to 4 m length in the LR and LQ models, and further optimized in the HQ models.

A series of tests were performed at CERN using the TQS03 models to better understand the Nb_3Sn stress limits and its tolerance to a large number of cycles. It was found that the magnet could perform satisfactorily up to 200 MPa average coil stress, which results in peak local stresses of the order of 250 MPa. This result considerably expands the engineering design space with respect to the 150 MPa level which was previously considered as the limit. In addition, a cycling test involving one thousand ramps from low to high field was performed, and no degradation was found.

Field Quality Due to large beam size in the IR quadrupoles, their field quality plays a critical role on the beam dynamics during collision. Therefore, precise coil fabrication and structure alignment are required. Although early LARP magnets had limited alignment features, steady progress has been made and the last generation of HQ models incorporates full alignment at all steps of coil fabrication, magnet assembly and operation. No negative impact on mechanical support and quench performance resulting from the introduction of these features has been observed. Recent studies [16] indicate that the conductor blocks can be positioned with an accuracy of about 30 μm, which is consistent with the best tolerances obtained in NbTi magnets (Fig. 2).

Field errors at injection are less critical, but need to be carefully analyzed since Nb_3Sn wires exhibit large magnetization due to high critical current density and large filament size. Compensation of persistent current effects by saturation of carefully designed iron inserts may provide an intermediate solution. Ultimately, wires with larger number of sub-elements should be developed to decrease the effective filament size.

Additional features will need to be incorporated in the magnet cold mass in order to successfully integrate the new IR quadrupoles in the cryogenic system of the LHC. A mechanical structure focusing on these requirements is currently under development and will be tested in future HQ models [17].

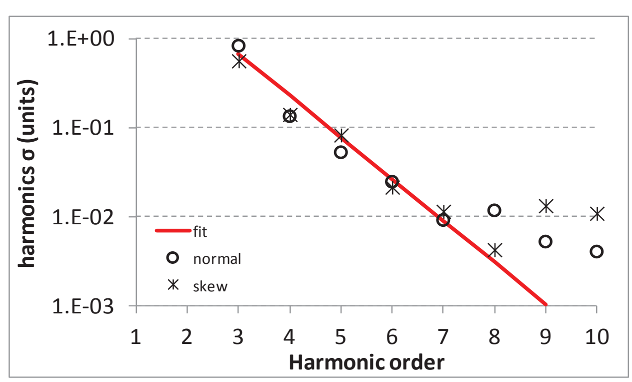

Figure 2: Fabrication tolerances in HQ01 [16]. Random error calculations are consistent with the measured harmonics assuming a coil positioning accuracy of 30 μm.

HIGH FIELD DIPOLES

The arc dipoles are a major cost driver for next-generation hadron colliders. Stored energy and size/cost considerations tend to limit the aperture to smaller values than in previous machines. While traditional shell-type (cosθ) coils can still be considered a strong candidate design, as field increases and aperture decreases the advantages of this approach are progressively diminished. Wide cables are required to minimize the number of layers and magnet inductance. Due to limitations in the keystone angles, coils need to incorporate several wedges, decreasing the magnetic efficiency. Winding issues become critical due limited mechanical stability and high aspect ratios of the cables. High mid-plane stresses due to Lorentz force accumulation can degrade the critical current and limit the magnet performance.

Conversely, block-type coil geometries use flat cables with few or no spacers, resulting in high packing factor and magnetic efficiency even for small aperture designs [18]. When the magnet is energized, physical separation between high-field and high-stress points reduces the sensitivity to stress degradation. Good alignment between cable and field orientation favours efficient grading. Simplification of end part design and coil winding procedures lowers the development time and fabrication cost. These attractive features need to be weighed against the loss of high-field magnetic aperture to provide internal coil support against pre-load. Also, deviations from the simplicity of planar racetrack coils are necessary to address issues of conductor efficiency and field quality. A qualitative comparison of the two approaches is given in Table 2. Prototype development is required to evaluate these features in realistic configurations, and demonstrate performance and cost suitable for accelerator applications.

Table 2: Comparison of *cos*(θ) and Block Coil Designs

Comparison of key features	Cos(θ)	Block
Max. dipole field achieved	13.5 T (D20)	13.8 T (HD2c)
Cable design	Keystone	Rectangular
Internal bore support	Self supporting	Required
Minimum winding radius	Small	Small
Conductor efficiency	Large aperture	Small aperture
2-in-1 arrangement	Horizontal	Horizontal
2-in-1 pre-load	1x	1x
High field/stress locations	Combined	Separated
Coil width/layer	Cable width	No. turns
Grading efficiency	Low	High
End peak field	High	High
End design/winding	Saddle	Flat or Flared
Layer transition	High field	High field

Several R&D programs to develop high field magnets using Nb3Sn have been underway in recent years. The highest dipole fields to date were obtained in the LBNL "HD" magnets using block-coils and a shell-based support structure. The first dipole in this series, HD1, focused on fundamental technology issues using a flat racetrack coil configuration. The magnet achieved a bore field of 16 T at 4.5K, under coils stresses of 180 MPa [8]. The next step in this series, HD2 (Fig. 3) incorporates key design features relevant to accelerator applications [19]. The magnet achieved a maximum dipole field of 13.8 T at 4.5K, to be compared with a short sample dipole field of 15.6 T at 4.5 K. The short sample field at 1.9K is 17.1 T. these values can be considered as a practical limit for accelerator quality designs using state of the art Nb_3Sn conductor.

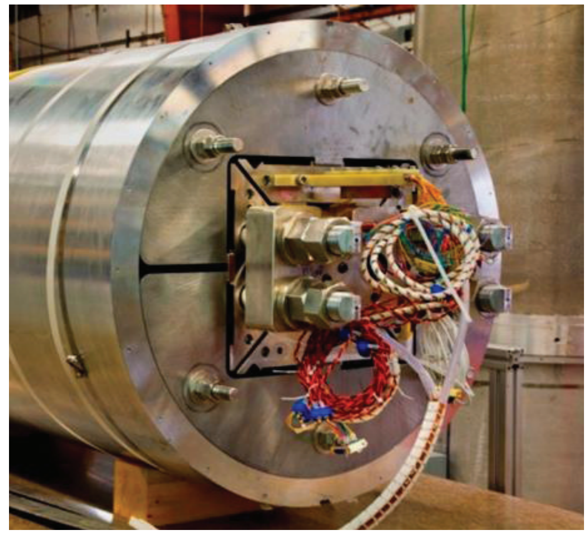

Figure 3: HD2 model [19].

BEYOND Nb_3Sn

The most promising candidate superconductors to surpass the intrinsic limits of Nb3Sn are the high-temperature superconductors Bi2Ca2CuSr2O8+x (bismuth strontium calcium copper oxide or Bi 2212) and YBa2Cu3O7 (yttrium barium copper oxide or YBCO).

Bi-2212 is available in round wires with isotropic performance and has been made in sufficient lengths for the fabrication of coils based on Rutherford-type cables. Since both Nb3Sn and Bi-2212 are brittle and require a wind-and-react approach to coil fabrication, the magnet design methods developed for Nb_3Sn provide a starting point for work on Bi-2212. However, Bi-2212 technology is significantly more challenging due to higher strain sensitivity, high formation reaction temperature in an oxygen-rich environment, and chemical compatibility of the insulation and construction materials during the reaction heat treatment.

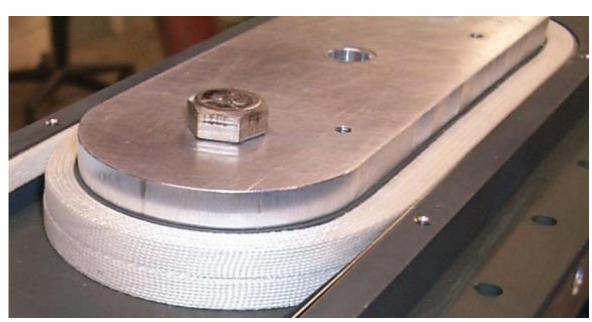

Figure 4: Bi-2212 coil winding [20].

YBCO is produced by deposition on thin tapes that include layers of metals, oxides and ceramics for crystal plane alignment, mechanical strength and electrical stability. The main challenge for application of these conductors to accelerator magnets is the development of cables capable of carrying high currents while retaining sufficient flexibility to be wound in coils with minimal degradation. Additional challenges are represented by electromagnetic anisotropy requiring good alignment of the tape to the field direction for optimal current carrying capability, and slow quench propagation velocities requiring new approaches to quench detection and protection [21].

SUMMARY

Intensive magnet R&D efforts are underway to meet the requirements of future colliders at the energy frontier. Dipole fields close to 14T have been achieved, and further progress to 15-16T can be expected with further optimization. The LARP program has fabricated and tested several series of magnets with increasing performance and complexity, leading to the choice of Nb_3Sn as the baseline technology for the LHC luminosity upgrade. A successful luminosity upgrade based on Nb_3Sn is expected to open the way to other potential applications, both within and beyond high energy physics.

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