15 T AND BEYOND – DIPOLES AND QUADRUPOLES*

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Abstract

Starting with the invention of the cyclotron by Lawrence, accelerator-based experiments have been the primary source of new discoveries in particle physics. In order to progress toward higher energy and luminosity, higher field magnets are required. R&D programs are underway to take advantage of new developments in superconducting materials, achieve better efficiency and simplify magnet fabrication while preserving accelerator-class field quality. A review of recent progress on high field dipole and quadrupole magnets is presented.

INTRODUCTION

The Large Hadron Collider (LHC) will soon replace Fermilab's Tevatron as the world's most powerful accelerator. LHC will collide proton beams with 14 TeV center-of-mass energy and 10^{34} $cm^{-2}s^{-1}$ luminosity. The maximum dipole field is 8.3 T, obtained using Niobium-Titanium (NbTi) conductor at 1.9 K. After several years of LHC operation, performance upgrades will be required to maintain its potential for new discoveries. Current plans involve a series of luminosity upgrades followed by an energy upgrade aiming at doubling the center of mass energy [1]. Both the luminosity and energy upgrades require very high field magnets, operating well beyond the fundamental limits of NbTi.

Superconductors suitable for high field applications are brittle and strain sensitive, requiring new design concepts and fabrication methods to complement or replace the ones established for NbTi. Niobium-Tin (Nb_3Sn) is currently the most advanced material for practical applications [2]. It carries current densities similar to NbTi at more than twice the field, and is available in long lengths with uniform properties. Nb_3Al offers lower strain sensitivity with respect to Nb_3Sn, but requires further improvements in the manufacturing process. The low-temperature properties of HTS materials such as Bi-2212 are far superior to both Nb_3Sn and Nb_3Al. However, many fundamental technology issues need to be addressed before practical magnet designs can be developed and implemented in prototypes.

Because of their brittleness, high field superconductors cannot be drawn to thin filaments like NbTi, but have to be formed in the final geometry by high-temperature heat treatment. In the fully reacted state, the filaments are extremely sensitive to strain. Therefore, attempting to wind reacted cable in coils may result in unacceptable critical current degradation at the ends. A first approach (wind-and-react) is to wind coils using un-reacted cable, when components are still ductile, and perform the heat treatment after coil winding. This technique requires the use of special insulation and coil structural components that can withstand the high reaction temperatures. A second approach (react-and-wind) is to modify the coil design to avoid sharp bending, allowing the use of pre-reacted cable.

During the last 15 years, LBNL has been developing accelerator magnet technology towards progressively higher fields, using Nb_3Sn conductor in different coil configurations. Since each configuration has specific advantages and drawbacks, the available design options should be evaluated in the context of specific applications as part of an optimization process involving both the magnet and the accelerator. This paper presents prototype test results and design studies of dipoles and quadrupole magnets aiming at coil peak fields above 15 Tesla.

HIGH FIELD DIPOLES

Coil layouts

Shell-type (cosθ) coils using keystone Rutherford cable have been adopted in most superconducting accelerator magnets due to their self-supporting Roman-arch structure and optimal use of superconductor in the design range of interest. Wind-and-react technology allows extending this approach to Nb_3Sn. In the mid-90s, the University of Twente dipole MSUT and the Berkeley dipole D20 were built using a costθ layout, reaching fields of 11T and 13T, respectively [3]-[4]. However, several considerations have prompted designers to explore alternative schemes based on block-type coil geometry with flat cables.

The arc dipoles are a major cost driver for next-generation colliders. Large stored energy, magnetic forces and conductor requirements tend to limit the bore size to smaller values than in previous machines. As the field increases and the aperture decreases, the advantages of shell-type coils are progressively diminished. Wide cables are desired in high field magnets to limit the number of layers and magnet inductance. At the same time, keystone angles are limited by degradation at the narrow edge. Under these conditions, cosθ coils need to allocate a larger fraction of the coil volume to wedges, decreasing the magnetic efficiency. Winding issues also become critical due to tight bending radii at the ends. Azimuthal force accumulation results in high stress levels at the mid-plane.

Conversely, block-type coil geometries offer several potential advantages: high packing factors with no wedges; use of flat cables with minimal degradation; simplification of end part design and coil winding procedures; good alignment of the conductor to the field

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lines, allowing efficient grading; physical separation between high-field and high-stress points, leading to reduced sensitivity to stress degradation. These attractive features need to be weighted against the loss of high-field magnetic aperture to provide internal coil support against pre-load, and generation of large horizontal forces. Also, deviations from the simplicity of planar racetrack coils are necessary to address issues of conductor efficiency and field quality. The design, fabrication and test of prototypes is therefore required to evaluate the properties of block-coil dipoles under realistic conditions, and demonstrate performance and cost suitable for future accelerator applications.

The HD Prototype Series

The "HD" magnet series was conceived as a vehicle for developing Nb_3Sn technology at the maximum attainable fields using single-bore block-coils [5]. The first magnet in this series, HD1, was based on a flat racetrack coil configuration and had a 10 mm bore. These features were consistent with the HD1 goals: exploring the Nb_3Sn conductor performance limits at the maximum fields and under high stress.

Providing adequate coil support in high-field magnets based on brittle superconductors requires new mechanical designs that can generate large forces while minimizing stress on the conductor at all stages of magnet fabrication and operation. A special support structure was developed at LBNL for high field dipoles and applied to HD1 [6]-[7]. This concept is based on the use of water-pressurized bladders to compress the coil pack while tensioning a thick aluminum shell. When the shell reaches the required tension, interference keys are inserted and the bladders deflated and removed. During cool-down, the stress in the shell almost doubles due to differential thermal contraction relative to the iron yoke. This allows limiting the peak coil stress during assembly, and reducing the shell thickness taking advantage of its increased strength at lower temperature. The pre-load is controlled in both the horizontal and vertical direction. To restrain the coil against axial forces, pre-tensioned aluminum rods are used to compress thick stainless steel plates against the coil ends [8].

Fig. 1: HD1 Dipole

HD1 was tested in 2003 and achieved a maximum bore field of 16 T under coil stresses approaching 180 MPa [9]. This result demonstrated that Nb_3Sn block-coils have the potential to achieve very high fields. However, in order to further develop this concept for future high-field accelerators, larger aperture and improved field quality are needed. The first technical challenge to be confronted is a loss of magnetic aperture to provide structural support against the pre-load forces in the magnet bore. In addition, conductor placement in the vicinity of the magnetic mid-plane is desirable for magnetic efficiency and field quality, but leads to deviations from a flat geometry in the coil ends, where the conductors have to clear the magnet bore. The second prototype in the series (HD2) addresses these issues aiming at a central dipole field above 15 T, a clear bore diameter above 36 mm, and nominal field harmonics within a fraction of one unit. The cross-section combines two double-layer coil modules in a block configuration. A stainless steel tube, inserted between the winding poles, provides the bore support. The coil ends are still of the racetrack type, but a ramp is included to avoid obstructing the beam path [10].

The HD2 mechanical structure, similar to the one used for HD1, is composed of horizontal and vertical load pads, bridges, yoke and aluminum shell. Interference keys located between pads and yokes tension the shell and compress the coil-pack in both the vertical and the horizontal direction. Hydraulic bladders are used to provide clearance for inserting the keys. Horizontal and vertical pushers transfer the load from the pads to the coils. Four aluminum rods provide axial pre-stress, to minimize displacements in the coil end regions [11].

Each coil is a double-layer wound around an aluminum-bronze pole, with a minimum winding radius of 12.5 mm. A 0.8 mm wire diameter is chosen due to practical considerations relating to strand availability. However, this design concept would be easily scalable to larger diameter wires, resulting in a better aspect ratio for the cable, lower cost of fabrication and lower inductance. The coil aperture is approximately square, 45 mm on each side. A mid-plane spacer separates the coils. The winding poles have a round cutout on the side facing the magnetic mid-plane. This cutout is used to assemble the coil modules around a stainless steel tube, providing a 36 mm diameter clear bore.

TABLE I

CONDUCTOR PARAMETERS FOR HD2 AND HD1

Parameter	Unit	HD2	HD1
Strand diameter	mm	0.8	0.8
Design Ic (16 T, 4.2K)	A	322	322
Cu/Sc ratio		0.94	0.94
No. strands		51	36
Cable height	mm	22.0	15.75
Cable thickness	mm	1.36	1.36
Insulation thickness (h/v)	μm	93/130	93/130
No. turns/quadrant		54	69

TABLE II

DESIGN PARAMETERS FOR HD2 AND HD1

Parameter	Unit	HD2	HD1
Bore size	mm	36	8
Short sample current*	kA	15.2	11.4
Central dipole field	T	15.1	16.7
Coil peak field	T	16.1	16.1
Copper current density	kA/mm^2	1.3	1.3
Inductance	mH/m	7.7	10.2
Stored energy	MJ/m	0.89	0.66
Fx (quadrant)	MN/m	5.9	4.75
Fy (quadrant)	MN/m	-2.7	-1.55
Ave. Lorentz stress (x)	MPa	140	150

The HD2 coil peak field at short sample is about 16 T, similar to HD1. The higher bore field in HD1 due in part to the smaller aperture and in part to the contribution of the iron pole to the field. A non-magnetic (Titanium) pole is used in HD2, to avoid generating a saturation effect. The conductor volume and Lorentz forces show relatively modest increases from HD1 to HD2. The inductance is lower in HD2, due to the use of a wider cable and fewer turns. As it was previously noted, the HD2 coil cross-section is suitable for a further increase of the wire (and cable) size. The resulting reduction of the inductance would be beneficial for protection of long magnets in a large accelerator

At high field, all HD2 design harmonics are below 0.1 units at 10 mm radius (R_{ref}). Despite the absence of inter-turn spacers in this coil, it is possible to optimize the geometric harmonics to low values by tuning the thickness of the mid-plane spacer, the number of turns in each layer, and the relative position of the two conductor blocks. In this design, the geometric harmonics b_3 and b_5 are very small and would be likely dominated by magnetization effects, iron saturation and random errors. The yoke was optimized for saturation effects. And a thin magnetic insert in the bore compensates for persistent current effects.

Three HD2 test were performed to date, achieving a maximum dipole field of 13.8 T, and a coil peak field of 14.5 T. Details of the test results are provided in another paper presented at this workshop [12].

LARGE APERTURE QUADRUPOLES

A staged upgrade of the LHC and its injectors is under study to achieve a luminosity of 10^{35} cm^{-2}s^{-1}, a 10-fold increase with respect to the baseline design. Replacing the first-generation NbTi IR quadrupoles with higher performance magnets is one of the required steps in this direction. Although improved designs based on NbTi will be used as an intermediate solution (Phase 1 upgrade), Nb_3Sn conductor is required to meet the ultimate performance goals for operating field and temperature margin. The new IR magnets need to provide increased focusing power and at the same time be able to operate under radiation loads corresponding to the 10^{35} cm^{-2} s^{-1} luminosity target.

Minimizing the superconductor volume is not a critical design consideration for the IR quadrupoles, since their number is limited. However, efficient field generation is essential in order to achieve high gradients. Several design studies have shown that in the parameter range of interest, cos2θ coils provide optimal magnetic efficiency.

Starting in 2004, the LHC Accelerator Research Program (LARP) has been coordinating the US effort to develop prototype magnets for the luminosity upgrade [13]. Following a series of "Technology Quadrupoles" (TQ) with 90 mm aperture and 220-250 T/m gradient, larger aperture and higher field designs were developed, aiming at coil fields above 15 T. These studies allowed to investigate the main technical issues (magnetic, mechanical, quench etc) and to explore the aperture design space in the range of 90-140 mm. Coil stresses above 180 MPa are expected and conductor degradation due to high stress represents a major factor potentially limiting the magnet performance. Comparison of different layouts shows differences in the accumulated Lorentz

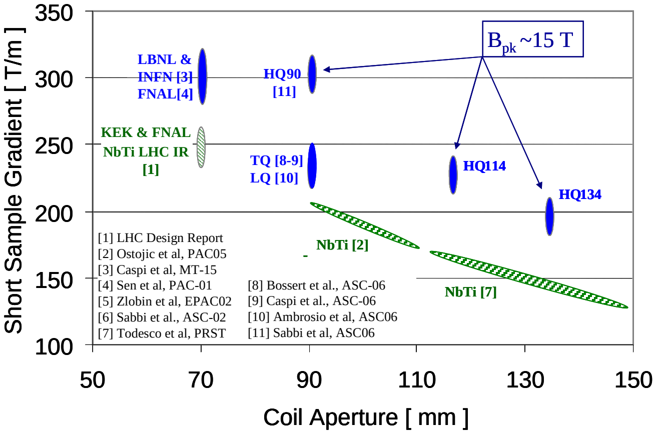

Fig. 2: Quadrupole designs for the LHQ IR.

forces that may be exploited to minimize the peak coil stress. Therefore, stress considerations need to be taken into account already when selecting the coil cross-section. In order to include the effect of deflections and friction among layers, the stress patterns for each candidate cross-section were evaluated using a 2D mechanical analysis. As for the high field dipoles, the mechanical structure is based on a thick Aluminum shell over iron yoke, assembled using water-pressurized bladders and interference keys [14].

The IR quadrupoles need to provide high field quality, in particular during collision. Therefore, precise coil fabrication and structure alignment are required. In addition, field errors due to persistent current effects are a concern. 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 is being actively explored as an intermediate solution. Ultimately, wires with larger number of sub-elements are being developed to decrease the effective filament size [15]-[16].

The upgrade quadrupole design will be developed through a series of 1 meter models (HQ) and then implemented in a series of 4 meter models (QA). The magnets will initially use the parameters and accelerator quality specifications of the “Phase 1” NbTi quads to facilitate their evaluation for use in the LHC. Goal of both HQ and QA is to demonstrate large performance margins with respect to the NbTi quads, on the timescale of the Phase-1 upgrade. The full set of features needed for an accelerator magnet will be gradually incorporated into successive HQ magnets and used in QA.

In the last months, considerable progress was made toward the start of HQ model fabrication. Prototype cables were evaluated from both the mechanical and electrical standpoint. Several cross-sections were optimized, and detailed analyses of the coil stresses were carried out for different variants of the supporting structure geometry. End parts were fabricated and used for winding experiments. After a final iteration of the coil and tooling design, component procurements will start, followed by winding of the first practice coil. Test of the first HQ model is expected in November 2009.

HTS COILS

Our studies indicate that the ultimate magnetic field in a practical dipole configuration using Nb_3Sn technology is limited to 17-18 T by the material’s maximum $\mu_0 H_{c2}$ of about 29 T. In order to develop dipoles approaching 20 T and higher, a material with a higher H_{c2} is required. The most promising candidate for this purpose is $Bi_2Ca_2CuSr_2O_{8+x}$ (Bi-2212), which is available in round wires and has been made in sufficient lengths for the fabrication of coils based on Rutherford-type cables.

Since both Nb_3Sn 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, constructing a magnet using Bi-2212 is significantly more complicated than using Nb_3Sn. The new technological challenges are related to cabling of the wires, 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.

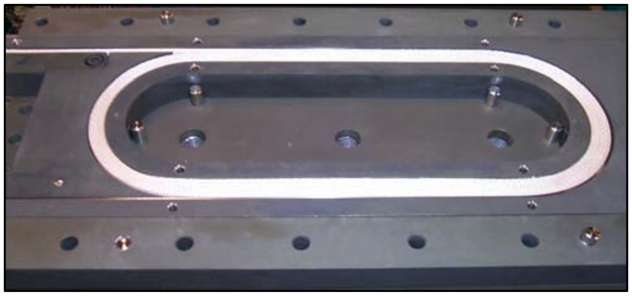

Fig. 3: Bi-2212 sub-scale coil fabrication.

The implementation of HTS for high-field magnets requires a development program that addresses the novel characteristics of the superconductor and its implementation in real magnets. Issues that are readily apparent include: (a) developing and selecting insulation, tooling, fabrication procedures and structural materials suitable for a wind and react approach; (b) detailed analysis of the stress/strain state of the magnet throughout fabrication and operation; (c) design of support structures for their control; (d) protection of the magnet during a quench [17].

Despite these challenges, several factors are contributing to an efficient program start. Previous development of Bi-2212 cables at LBNL, in close collaboration with wire manufacturers, has resulted in sufficient experience to design a cable suitable for sub-scale coils. The available structures and tooling from the Nb_3Sn program can be adapted to the HTS coils with relatively small modifications. A modified tooling for sub-scale coil winding and reaction was designed, and several coils were fabricated and tested. The thermal characteristics of these mechanical coils will be suitable for optimization of the reaction schedule. Nevertheless, it is recognized that Nb_3Sn technology, particularly related to fabrication processes and magnet protection, is not directly applicable to HTS-based magnets.

Taking into consideration the high cost of Bi-2212, and its relatively low current carrying capability at fields below 15 T, a hybrid Nb_3Sn-Bi2212 coil represent an optimal approach in terms of efficiency and cost. The Bi-2212 insert is wound from a high current Rutherford-type cable, resulting in high packing factor, high magnetic efficiency and low inductance. Specific R&D issues that need to be addressed are: protecting the Bi2212 insert from excessive stress during pre-load and excitation; current matching and high-field splicing between sub-coils (for a series-connected hybrid) or independent powering of the sub-coils.

SUMMARY

Intensive magnet R&D efforts are needed to meet the requirements of future colliders at the energy frontier. In recent years, new design approaches and technology developments have resulted in cost-effective designs that include accelerator quality features. Record dipole fields have been achieved, and further progress is enabled by improvements in high field superconducting materials. The LHC luminosity and energy upgrades provide the opportunity to apply the results obtained in proof-of-principle models to full-size production magnets suitable for operation in the challenging accelerator environment.

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