DEVELOPMENT OF LHC-IR MODEL QUADRUPOLES IN THE US

G. Sabbi (LBNL, Berkeley, California) for the LARP Collaboration

Abstract

Insertion quadrupoles with large aperture and high gradient are required to achieve the luminosity upgrade goal of 10^{35} cm^{-2} s^{-1} at the Large Hadron Collider (LHC). In 2004, the US Department of Energy established the LHC Accelerator Research Program (LARP) to develop a technology base for the upgrade. The focus of the magnet program, which is a collaboration of three US laboratories, BNL, FNAL and LBNL, is on development of high gradient quadrupoles using Nb_3Sn in order to operate at high field and with sufficient temperature margin. Other program components address issues regarding magnet design, radiation-hard materials, long magnet scale-up, quench protection, fabrication techniques and conductor and cable R&D. This paper reports on the development od model quadrupoles and outlines the long-term goals of the program.

INTRODUCTION

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 [1]. 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 are being considered as an intermediate solution [2], Nb_3Sn conductor is required to meet the ultimate performance goals for both operating field and temperature margin. Several design studies of Nb_3Sn IR quadrupoles for this application have been performed in the past several years [3-6]. Under typical upgrade scenarios, the new magnets will provide increased focusing power to double or triple the luminosity, and at the same time will be able to operate under radiation loads corresponding to the 10^{35} cm^{-2} s^{-1} luminosity target.

Starting in 2004, the LHC Accelerator Research Program (LARP) has been coordinating the US effort to develop prototype magnets for the luminosity upgrade [7]. At present, a series of 1-meter long "Technology Quadrupoles" (TQ) with 90 mm aperture and 220-250 T/m gradient are being fabricated and tested [8-9]. The TQ models are intended to serve as basis for a series of 4-meter long quadrupoles (LQ) with same aperture and gradient [10], and for a series of 1 m long "High-gradient Quadrupoles" (HQ). A plot of the (aperture, gradient) parameter space comparing the HQ to other quadrupole designs for the LHC IR is shown in Fig. 1.

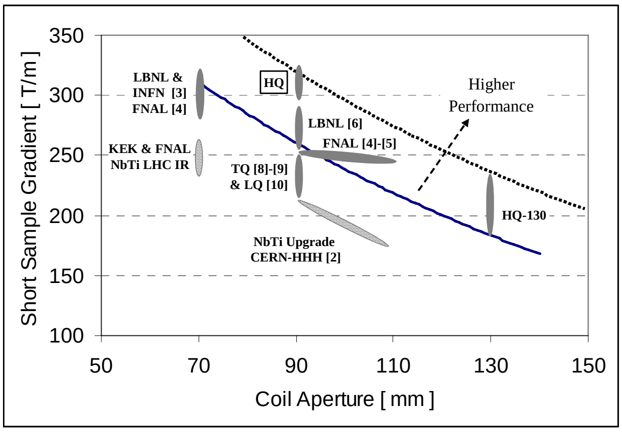

Fig. 1. Parameters of NbTi and Nb_3Sn LHC-IR quadrupole designs.

MAGNET DESIGN

The program goals are structured around the numerous issues related to development of a technological base necessary to meet performance and operational requirements. Some are generic to Nb_3Sn accelerator magnet technology and others are specific to LARP applications.

Conductor and Cable

The demanding operational parameters of the upgrade magnets require the use of superconducting materials substantially beyond NbTi. Recent progress in the development of Nb_3Sn magnets has encouraged the prospects for its use in LHC upgrades. However Nb_3Sn technology, as applied to accelerator magnets, is still far from fully developed. While conductor current density properties have improved dramatically since the start of the DOE sponsored Conductor Development Program (CDP), there are still several important issues remaining, such as reducing effective filament diameter, increasing RRR and piece length, while maintaining a high critical current density. These properties relate more to the conductor's stability and manufacturability. At this time, Nb_3Sn is the leading choice because of manufacturability, cost potential, critical current density and mechanical properties. A conductor development program, initiated by the U.S. Department of Energy, has resulted in readily available conductor with critical current densities over 3 kA/mm2 @ 12 Tesla and 4.2 K [12].

Coil Layout

There are several possible limitations to achieving higher luminosity and a number of upgrade options have been proposed. The actual configuration for an IR upgrade will not be known until after significant experience is gained with operating the existing IR's. However, in all cases, large bore quadrupoles are required and as an initial target, the program will focus on development of a quadrupole with 90 mm bore and a gradient equal to or greater than the current design. A staged approach will be used, beginning with a simple two-layer coil design providing field gradients in the range of 220-250 T/m and moving to more complex coil designs to increase the gradient and/or operating margin. The latter part of the program may consider increasing the aperture depending on early results of the program and ongoing studies.

Mechanical Structure and Assembly

Nb_3Sn is a brittle compound and requires careful control of stress throughout assembly, cool-down and excitation. The current accepted working limit is 150 MPa. The LARP program is currently evaluating the performance of two mechanical design concepts on virtually identical sets of coils (TQ model magnet series). The first structure (TQC) is based on stainless steel collars supported by an iron yoke and a welded stainless steel skin [8]. It is readily extendable to long magnet lengths and provides precise positioning of the coils. The second structure (TQS) is based on an aluminum shell over iron yoke and support pads, without collars [9]. It features low assembly pre-stress using an hydraulic system, with large stress increase during cool-down. However, the applicability to long magnets and the accuracy of the coil alignment need to be demonstrated. The extension to long lengths is being investigated by LARP under the LR program [13], while basic alignment features have been implemented as part of the sub-scale quadrupole (SQ) program [14].

Magnet Fabrication

The fabrication process is based on the Wind and React approach. The Rutherford cable is insulated with either an S-2 glass sleeve or wrapped with ceramic fiber tape. The coil is wound and then treated with a ceramic binder, cured to size in a press to facilitate handling and inserted into a reaction fixture. After reaction the coil is impregnated with CTD-101®, an epoxy produced by Composite Technology Development. This general fabrication process has been used successfully for short models but has not been scaled to coils longer than 1 meter. Length scale-up, in terms of reacting, impregnating and handling long coils, is considered to be a critical issue and is one of the three main goals of the first phase of the program.

MODEL QUADRUPOLE DEVELOPMENT

The above issues and others that emerge during the course of the R&D program are addressed by the general goal of the program to "demonstrate by 2009 that Nb3Sn magnets are a viable choice for an LHC IR upgrade." This goal has three components that are implemented by a combination of model magnets with specific targets.

<u>Predictable and reproducible performance</u>

The viability of any new technology application is judged on the consistent reproducibility of performance and operating parameters. This component of the program is expressed through the construction of a series of "Technology Quadrupoles" (TQ). The TQ's are based on a two-layer, cos-theta geometry with a 90 mm bore. The first series uses Modified Jelly Roll (MJR) conductor with a Jc of approximately 2,000 A/mm2 at 12 T and 4.2 K. The expected maximum gradient is 220 T/m at 4.2 K (240 T/m at 1.9 K). The TQ's are also used to compare two support structure designs; TQC01, based on stainless steel collars supported by an iron yoke and thick stainless steel skin and TQS01, a shell-based structure using bladders for pre-stress control and interference keys to retain the pre-stress. A tensioned aluminum shell compresses internal iron and coil components developing substantial pre-stress on cool-down.

<u>Long magnet fabrication</u>

Development of fabrication, handling and assembly techniques required for the construction of long magnets will begin with scale-up of simple racetrack coils. A nominal length of 4 meter was chosen for the "long racetrack" (LR) coils, and later adjusted to 3.6 m so that the magnet would fit in available vertical test dewars at both BNL and Fermilab. The Long Racetrack coils (LR) are based on a well-developed 2-layer design, contained in a simple aluminum shell-type structure similar to that used for TQS01 [13]. Successful completion of this program will be followed by construction of a 3.6 m long cos-2θ quadrupole (LQ) based on the TQ cross section.

<u>High gradient in a large aperture</u>

The HQ models will explore the ultimate performance limits in terms of peak fields, forces and stresses. They are expected to demonstrate peak fields in the coils of 15 T or higher. A coil aperture of 90 mm, corresponding to gradients above 300 T/m, was chosen as the baseline. This aperture choice has practical advantages in the context of the LARP program, due to the possibility of sharing tooling and parts with the TQ series, decreasing the development time and cost. However, a 90 mm aperture is at the lower boundary of the range being considered for the LHC luminosity upgrade [11]. At present, the 90 mm case is used as a reference for comparing different design approaches. In parallel, a detailed analysis of the benefits and costs of moving to larger apertures is underway. We expect that the results of the conceptual design analysis and optimization will still be applicable to model magnets with apertures in the range being considered.

VERY LARGE APERTURE DESIGNS

It is presently expected that the optimal coil aperture for the LHC upgrade quadrupoles will be in the range of 100-130 mm [11]. Using an HQ aperture larger than 90 mm would therefore increase its relevance to the upgrade. This option is currently being evaluated against several cost, schedule and risk factors. A change of the aperture precludes the possibility of sharing tooling and parts with the TQ and LQ model series, as well as the use of existing TQ coils for the inner double-layer of HQ. In addition, the TQ magnet development shows that the length of the true magnetic straight section which can be obtained in a 1 m long model with 90 mm aperture is quite limited. This limitation is a consequence of the longitudinal space required for the termination of the windings, both from the magnetic standpoint (decreasing the peak field using end spacers, iron design etc) and from the mechanical standpoint (to incorporate ramps, splices, end shoes). Therefore, an aperture increase not only requires an increase of the overall transverse size (coil, volume, tooling, structure etc) but also an increase of length, with additional impact on cost and the infrastructure (reaction oven, test cryostat etc). Finally, larger aperture will result in higher stresses and stored energy.

A staged approach may be envisioned for investigating very large aperture designs. Following the fabrication and test of 90 mm bore HQ models, the outer double-layer coils would be tested in standalone configuration with 130 mm aperture and about 190 T/m gradient. As a next step, the quadrupole gradient in the 130 mm aperture would be increased by adding a second double-layer. The development of models with both 90 mm and 130 mm apertures would cover the entire range of apertures being considered for the upgrade (Fig. 1).

SUMMARY

The US LHC Accelerator Research Program has launched an aggressive program to develop accelerator magnet technology for upgrades that will enhance the physics potential of the LHC. LARP is an excellent opportunity to extend high field accelerator magnet technology, and to create and strengthen national and international collaboration that will continue into future projects.

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