HIGH FIELD NIOBIUM-TIN QUADRUPOLES

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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). Nb_3Sn conductor is required in order to operate at high field and with sufficient temperature margin. We report here on the development of a "High-performance Quadrupole" (HQ) that will demonstrate the technology required for achieving the target luminosity. Conductor requirements, magnetic, mechanical and quench protection issues are presented and discussed. The HQ design is also suitable for an intermediate "Phase 1" upgrade, operating with large engineering margin.

INTRODUCTION

Superconducting accelerator magnets have supported advanced programs in experimental high-energy physics for the past 20 years. The ductile Niobium-Titanium alloy (NbTi) allows simple fabrication methods for cable and coils. However, NbTi performance is ultimately limited by its upper critical field Bc2=10.5 Tesla at 4.2K. A 3 Tesla increase of Bc2 can be obtained by lowering the temperature to 1.9K. This technique allows approaching a peak coil field of about 10 T in practical dipole and quadrupole magnets. However, several next-generation facilities demand significantly higher fields. In particular, 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 are being considered as an intermediate solution (Phase 1 upgrade), 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 (Fig. 1). 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 [1]. A series of 1-meter long "Technology Quadrupoles" (TQ) have been fabricated and tested, achieving a gradient well above 200 T/m in a 90 mm aperture. The TQ models are the basis for a series of 4-meter long quadrupoles (LQ) with same aperture and gradient, and for a series of 1 m long "High-gradient Quadrupoles" (HQ) which are the focus of the present paper.

MAGNETIC DESIGN

It is expected that the optimal coil aperture for the "Phase 2" upgrade quadrupoles will be in the range of

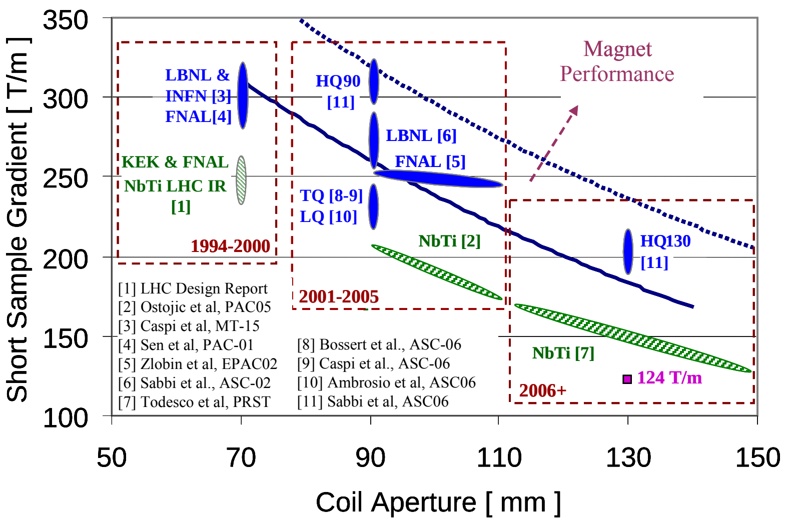

TABLE I
PERFORMANCE PARAMETERS

Parameter	Symbol	Unit	HQa	HQb
Short sample gradient*	G_{ss}	T/m	205	204
Short sample current*	I_{ss}	kA	17.0	16.5
Coil peak field	B_{pk} (I_{ss})	T	15.4	15.6
Inductance	L (I_{ss})	mH/m	11.4	12.0
Stored energy	U (I_{ss})	MJ/m	1.6	1.6
Lorentz force/octant (x)	F_x (I_{ss})	MN/m	3.9	3.6
Lorentz force/octant (y)	F_y (I_{ss})	MN/m	-5.1	-4.8
Cable width		mm	15.1	15.1
Aperture		mm	130	130

(*) Assuming J_c(12 T, 4.2 K) = 3.0 kA/mm^2; operating temperature T_{op}=1.9K

100-130 mm [2]. Recent studies show that quadrupoles with 130 mm aperture are suitable for the "Phase 1" upgrade [3]. Therefore, the development of Nb_3Sn quadrupoles with a 130 mm aperture addresses both near-term and long-term needs. From an R&D standpoint, the 130 mm aperture is also suitable for exploring the technological limits related to very high fields (15 T) and stresses (200 MPa). In addition, a 130 mm aperture coil can be combined with a 90 mm aperture TQ coil to produce a 4-layer configuration. The test of models with both 90 mm and 130 mm aperture allows covering the entire range of apertures being considered for the upgrade (Fig. 1).

Although minimizing the superconductor volume is not a critical design consideration for the IR quadrupoles, efficient field generation is essential in order to achieve high focusing power. A cos2θ geometry was selected for optimal magnetic efficiency in large round apertures. A 2-layer design has been the smallest number of parts and assembly steps, and was successfully used in several Nb_3Sn dipoles and quadrupoles. In order to limit the coil stresses and quench temperatures, a cable with large aspect ratio needs to be developed for this application. The HQ conductor needs to provide high critical current density at high field, with consistent properties and reliable delivery over a series of model magnets. Heat treatment optimization of recent OST 54/61 billets [4] resulted in Jc above 3 kA/mm2 at 12 T, 4.2 K for un-cabled strands. These properties justify assuming a design critical current density of 3 kA/mm2 (12 T, 4.2 K), taking into account some degradation due to cabling.

The HQ cross-section optimization targets are maximum design gradient and minimum coil stress. Conductor degradation due to high stress represents a major factor potentially limiting the HQ performance. Therefore, stress considerations need to be taken into account in selecting the coil cross-section. Comparison of different designs shows differences in the accumulated Lorentz forces that may be exploited to minimize the peak coil stress. Several fabrication constraints and cost-performance trade-offs also need to be taken into account, such as limits on cable compaction and winding radii, incorporation of wedges and conductor grading. A consistent set of assumptions (conductor parameters, iron properties, etc.) were defined for comparing different options. Table I lists the short sample performance parameters for two candidate designs.

MECHANICAL DESIGN

The HQ mechanical structure needs to provide an average azimuthal pre-load at the 150 MPa level over a 4 cm coil radial width, and support the coils against radial Lorentz forces of 3-4 MN/quadrant. Due to the increased force and stress levels for the HQ case, the coil support will be mainly provided by an outer shell or welded skin through the iron yoke. The use of a TQS-type approach for increasing the pre-load at cool-down is particularly attractive in view of the very high coil stress. A thin collar will facilitate coil pre-assembly and alignment.

The use of axial pre-load to support the coils against axial forces generated at the coil ends is also being investigated as part of the TQS and SQ model magnet series. The total axial Lorentz force is at the level of 1 MN/m in HQ, a factor of 2-3 larger with respect to the TQ and SQ. Therefore, it is expected that axial pre-load will be required to obtain satisfactory performance.

CONCLUSIONS

Progress in the conceptual design of the LARP HQ model quadrupole series was presented. Peak stresses of 150-200 MPa are expected. The preliminary magnetic, mechanical and quench protection analysis confirms that the proposed HQ models are feasible and consistent with the upgrade objectives. Future studies will include a detailed analysis and selection of the mechanical support structure, taking into account feedback from the ongoing model magnet and supporting R&D.

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