Design Studies of Nb_3Sn High-Gradient Quadrupole Models for LARP

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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). In 2004, the US Department of Energy established the LHC Accelerator Research Program (LARP) to develop a technology base for the upgrade. Nb_3Sn conductor is required in order to operate at high field and with sufficient temperature margin. We report here on the conceptual design studies of a series of 1 m long "High-gradient Quadrupoles" (HQ) that will explore the magnet performance limits in terms of peak fields, forces and stresses. The HQ design is expected to provide coil peak fields of more than 15 T, corresponding to gradients above 300 T/m in a 90 mm bore. Conductor requirements, magnetic, mechanical and quench protection issues for candidate HQ designs will be presented and discussed.**

***Index Terms*—Superconducting accelerator magnets, Nb_3Sn, final focus quadrupoles.**

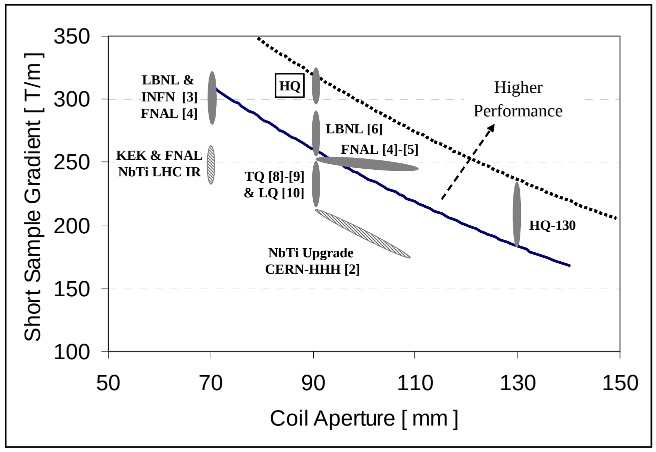

Fig. 1. Parameters of NbTi and Nb_3Sn quadrupole designs for the LHC IR.

I. 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) which are the focus of the present paper. A plot of the (aperture, gradient) parameter space comparing the HQ to other quadrupole designs for the LHC IR is shown in Fig. 1.

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II. Design Objectives

The main goal of the HQ design study is providing a basis for the development of a series of model quadrupoles exploring the performance limits in terms of peak fields, forces and stresses. In addition, the results will benefit follow-up studies (beam optics, radiation deposition, cryogenics) directed towards a self consistent IR design for the LHC luminosity upgrade.

The HQ models 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.

III. Magnetic Design

A. Coil layout

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 gradients. A cos2θ geometry was selected for optimal magnetic efficiency in large round apertures. The next step involved a comparison of coil designs using a different number of layers. Conductor design options and coil fabrication issues were investigated for each case. A 2-layer design has the smallest number of parts and assembly steps, but requires a cable with large aspect ratio to achieve the HQ performance targets, leading to difficulties in the design of the end parts and in the coil winding process. A novel 3-layer design was considered in order to reduce the cable width while maintaining a continuous winding in each quadrant. However, this option constraints the design of the third layer, requiring more longitudinal space for the coil ends. This is a disadvantage for short models such as the HQ. Finally, a 4-layer design was considered (two double-layers, each one wound continuously). This approach requires twice as many coils and fabrication steps with respect to a 2 or 3 layer design, but it can reach the required radial width (~40 mm) while limiting the cable width. This facilitates the cable design and allows increasing the keystone angle, leading to smaller/fewer wedges and a better radial alignment of the turns. It also allows grading of the outer two layers at small extra cost. Despite of the higher inductance, preliminary quench analysis indicates that the coils can be adequately protected. Based on the above considerations, it was decided to focus the design optimization on 4-layer coils.

B. Reference cross-sections

The HQ cross-section optimization targets are maximum design gradient and minimum 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. A cable width of 10.05 mm was selected to allow the use of existing TQ tooling for the inner double-layer.

A number of cross-sections were developed and compared. Two candidate designs will be discussed in some detail. The cross-section geometries are shown in Fig. 2. The cable, coil and performance parameters are listed in Tables I and II.

In the HQ1 cross-section design (Fig. 2, left) the inner double-layer is identical to that of the TQ model magnets. The cable keystone angle is relatively small (1^o) to minimize degradation and possible damage at the thin edge. A wedge in the innermost layer allows to optimize the geometric b_{10} and to recover a radial alignment of the turns near the pole. The outer double-layer has a pole angle of about 30^o, as required to independently optimize the geometric b_6. This geometry leads to a peak field comparable to that of the inner double-layer, preventing the option of grading the conductor for improved magnetic efficiency. Therefore, the same TQ strand and cable design is used in the outer double-layer, except for a small adjustment of the keystone angle to optimize the radial alignment of the turns.

The HQ2 cross-section (Fig. 2, right) features a new design for both the inner and outer double-layer, optimized for achieving the highest gradient. In order to maximize the conductor efficiency, the pole angle decreases for the coil layers further away from the bore. This geometry leads to a lower field in the outer layers, so that conductor grading can be exploited for additional gain. A larger strand diameter is used in the inner double-layer, while the copper to non-copper ratio is held constant due to practical considerations relative to the design and availability of high-performance strands. As for the previous case, in order to minimize cabling degradation and possible damage, the keystone angle in the inner double-

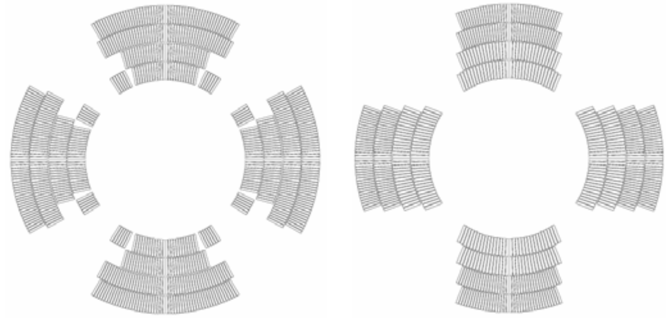

Fig. 2. HQ cross-sections. Left: HQ1 (non graded); right: HQ2 (graded).

TABLE I
Conductor, Cable and Coil Parameters

Parameter	Unit	HQ1		HQ2	
		Inner	Outer	Inner	Outer
Strand diameter	mm	0.7	0.7	0.85	0.7
Cu/non-Cu ratio		0.87	0.87	0.87	0.87
No. strands		27	27	23	27
Cable width (bare)	mm	10.05	10.05	10.05	10.05
Mid-thickness (bare)	mm	1.26	1.26	1.54	1.26
Keystone angle	deg	1.0	1.13	1.40	1.13
Insulation thickness	mm	0.125	0.125	0.125	0.125
No. turns/octant		34	52	32	38
Conductor area/octant	cm^2	35.3	54.0	41.8	39.5

TABLE II
Performance Parameters

Parameter	Symbol	Unit	HQ1	HQ2
Short sample gradient*	G_{ss}	T/m	308	317
Short sample current*	I_{ss}	kA	10.7	12.6
Coil peak field	$B_{pk}(I_{ss})$	T	15.6	15.8
Copper current density	$J_{cu}(I_{ss})$	kA/mm^2	2.2/2.2	2.1/2.6
Inductance	$L(I_{ss})$	mH/m	24.5	18.0
Stored energy	$U(I_{ss})$	MJ/m	1.3	1.4
Lorentz force/octant (r)	$F_r(I_{ss})$	MN/m	1.7	1.7
Lorentz force/octant (θ)	$F_\theta(I_{ss})$	MN/m	-6.0	-6.1
Average coil stress (θ)	$\sigma_\theta(I_{ss})$	MPa	150	152
Dodecapole (22.5 mm)	b_6		-0.2	0.0
10-pole (22.5 mm)	b_{10}		-0.05	-0.92

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

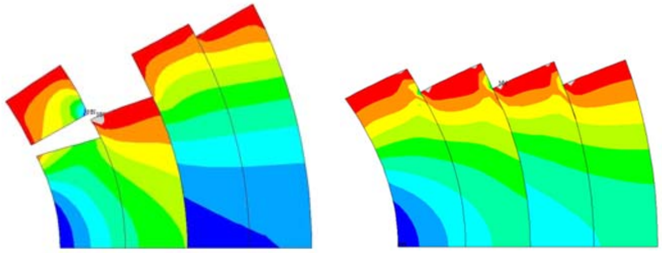

Fig. 3. Lorentz stress patterns. Peak values (dark blue) are in Table 3.

TABLE III
LORENTZ STRESS AT 300 TESLA/METER (MPA)

Coil	ANSYS (Fig 3)		Mid-plane stress: ΣF_θ/(layer width)			
Design	L1&2	L3&4	L1	L2	L3	L4
HQ1	176	167	139	98	179	150
HQ2	178	131	148	143	159	114

layer is smaller than the value required for radial alignment of the turns. Nevertheless, in order to maintain simplicity and maximize the field generation, no wedges are used in the innermost layer. This prevents from fully optimizing the field quality, and results in about -0.9 units of b_{10} at 50% of the coil radius.

Table II lists the short sample performance parameters for both designs. 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 [12] resulted in J_c above 3 kA/mm^2 at 12 T, 4.2 K for un-cabled strands. These properties justify assuming a design critical current density of 3 kA/mm^2 (12 T, 4.2 K), taking into account some degradation due to cabling. With these assumptions, the two designs achieve maximum gradients of 308 T/m and 317 T/m, respectively, with coil peak fields in the range of 15.6 T to 15.8 T.

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. 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 within a rigid boundary. The results of this analysis for the two reference designs at a gradient of 300 T/m are shown in Table III and Fig. 3. The analysis assumed that the surfaces between layer 1-2 and layer 3-4 are glued, while the surface between layer 2-3 can slide without friction. A comparison between the mid-plane stresses due to accumulated azimuthal Lorentz force in each layer, and the finite element analysis, shows that the stress at the inner coil radius significantly increases due to bending. The peak stress in the inner double-layer is comparable for both designs under consideration (176-178 MPa). However, the outer layer stress is larger in HQ1, due to contributions of the turns close to the pole. A lower preload requirement in the outer layers may facilitate the mechanical design for the HD2 case.

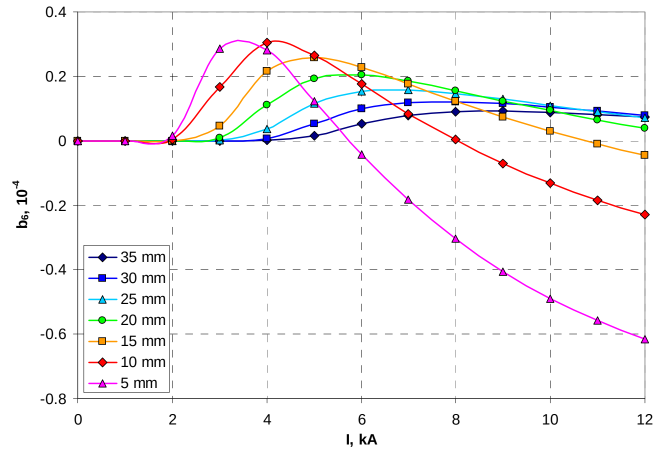

Fig. 4. Saturation b_6 as a function of the distance between coil and yoke.

C. *Iron yoke requirements*

In order to determine the optimal iron yoke parameters, the transfer function and saturation harmonics were calculated as a function of the difference between the yoke inner radius and the coil outer radius. A coil-yoke distance of 10 mm results in a saturation b_6 within ±0.3 units (Fig. 4) and a 3% increase of the high-field transfer function with respect to the 35 mm case. This distance also allows sufficient space for a thin collar surrounding the coils. The dependence of transfer function and harmonics on the yoke outer radius was also investigated. No significant improvements are observed for R_{yoke} > 250 mm. These yoke design values will be further refined based on more detailed magnetic analysis and the mechanical structure requirements.

IV. 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 the order of 3.4 MN/quadrant (Table II). 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 has not been demonstrated, and the current implementation is lacking precise coil alignment. 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 SQ program [14].

It is expected that the HQ design will combine features derived from both the TQC and the TQS structures, taking into account additional analysis and feedback from the LR and SQ magnet series. 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 [9]-[13]. The total axial Lorentz force is at the level of 1.3 MN/m in HQ, a factor of 3 increase with respect to the TQ and SQ. Feedback from TQS, TQC and SQ will again be essential for selecting the best axial support system for HQ.

V. Quench Protection

The magnet protection is based on conventional distributed composite quench heaters. The heater design consists of a 25 μm thick stainless steel strip with distributed Cu (plating or overcoat), sealed in a kapton laminate. For operation in superfluid helium, the active heater area is designed to provide a power of 45 W/cm^2 and a thin (25 μm) kapton layer is used between heater and coil to minimize the diffusion time. The adiabatic heater temperature is 100 K. The heaters are located on the inner and outer surfaces of both double-layer windings. Two independent circuits are used for redundancy, each one connecting in series heaters from both the inner and outer doublets. A preliminary analysis for adiabatic conditions shows that with a single operating circuit, and neglecting quench-back effects, the peak coil temperature at short sample conditions can be maintained below 300 K for the HQ1 design, and below 365 K for the HQ2 design. The corresponding MIITS budget is 7.1 for HQ1 (65 ms at I_{ss}=10.7 kA) and 7.8 for HQ2 (49 ms at I_{ss}=12.6 kA). In both cases, it is assumed that heaters provide 50% coverage of the winding, and are fired within 15 ms after the quench start.

VI. 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 ~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).

VII. Summary and Next Steps

Progress in the conceptual design of the LARP HQ model quadrupole series was presented. Two coil cross-sections providing maximum gradients above 300 T/m in a 90 mm aperture were selected for further optimization. Peak stresses above 180 MPa are expected. The preliminary magnetic, mechanical and quench protection analysis confirms that the proposed HQ models are feasible and consistent with the LARP objectives. Future studies will include larger aperture designs and 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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