NB_3SN QUADRUPOLES DESIGNS FOR THE LHC UPGRADES

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Abstract

In preparation for the LHC luminosity upgrades, high field and large aperture Nb_3Sn quadrupoles are being studied. This development has to incorporate all the relevant features for an accelerator magnet like alignment and cooling channels.

The LARP HQ model is a high field and large bore quadrupole that will meet these requirements. The 2-layer coils are surrounded by a structure based on key and bladder technology with supporting iron yoke and aluminum shell. This structure is aimed at pre-stress control, alignment and field quality. We present here the magnetic and mechanical design of HQ, along with recent progress on the development of the first 1-meter model.

INTRODUCTION

The main objective of LARP is to demonstrate the feasibility of the Nb_3Sn technology for the LHC upgrades. The increase of the baseline luminosity requires IR quadrupoles with high performing gradients. Although NbTi solutions are considered, Nb_3Sn remains the best candidate to achieve the performance required for the LHC Upgrade Phase 2. In this context, LARP has developed several series of Nb_3Sn magnets:

- The SQ series (Subscale Quadrupole) provided a gradient of 90 T/m in 110 mm aperture using subscale Nb_3Sn racetrack coils and included alignment [1,2].
- The TQ series (Technologic Quadrupole) consists of 1-meter long, 90 mm aperture cosine theta quadrupole magnets with a peak field of the order of 12 T and a measured gradient between 200 and 220 T/m [3,4].
- The LR magnet (Long Racetrack in a common coil arrangement) relied on two 3.6 m Nb_3Sn racetrack coils assembled in a shell-based structure to demonstrate the scalability of Nb_3Sn racetracks [5].
- The LQ series (Long Quadrupole) is a scale up of the TQ series aiming at demonstrating the scalability of Nb_3Sn cosine theta quadrupole [6].

In order to meet the requirements for Phase 2, the next series of magnet will have to reach 14-15 T at 1.9 K in a large aperture (above 110 mm) with alignment features (to provide field quality), cooling channels and LHe containment. The objective of the HQ series (High gradient, high field Quadrupole) is to address these requirements [7].

This leads to technical challenges: in terms of coil design and mechanical structure design. The magnetic efficiency will have to be combined with mechanical efficiency. The mechanical structure will have to withstand large Lorentz forces while remaining compact enough to fit within the LHC tunnel. The cable design is also a very important step for the design: to reach high field and to manage mechanical stress in the coil, the use of a 15 mm wide cable is necessary. The windability and the cabling degradation have to be watched closely. HQ aperture is not yet determined but apertures ranging between 114 and 134 mm have been considered. We summarize here the results for a 114 mm aperture.

MAGNETIC DESIGN

Conductor

The strand is 0.8 mm in diameter with a copper/non copper ratio of 0.87. The cable is made of 35 strands. The keystone of the cable is of the order of 0.75. Some cable optimization is in progress in order to reduce current degradation due to cabling. The cable dimensions used to design the magnetic cross-section are summarized in Table 1:

Table 1: Conductor parameters

Dimensions	**Units**	**Values**
Width	mm	15
Mid thickness	mm	1.405
Insulation	mm	0.11

Magnetic Cross-section

For the same aperture, several magnetic cross-sections have been studied and compared in terms of:

- gradient
- peak field
- field quality
- pole angle in order to facilitate the windability
- maximum mechanical stress in the coil for a given mechanical structure.

This study brought to light the importance of combining the magnetic design with the mechanical design. Two different 134 mm aperture cross-sections are presented in Figure 1. The mechanical stresses induced by the Lorentz forces are compared for a gradient of 200 T/m. In both cases, the mechanical structure is infinitely rigid and the coil layers can slide one with respect to the other.

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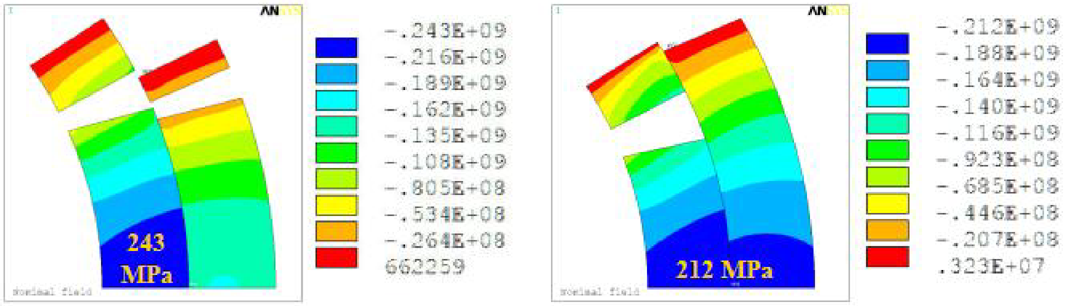

Figure 2: Azimuthal stress distribution due to Lorentz forces at 200 T/m in an infinitely stiff structure with sliding between layers for two 134 mm aperture cross-sections. Left: F_θ L_1 = -3.58 MN/m F_θ L_2 = -2.46 MN/m – Right: F_θ L_1 = -2.7 MN/m F_θ L_2 = -3.4 MN/m

In the first case (Fig. 1 left), the azimuthal force is much higher in the inner layer L_1 inducing high compressive stress on the mid-plane. In the second case (Fig. 1 right), the outer layer L_2 exhibits a greater Lorentz force than the inner layer L_1 leading to a more homogeneous stress distribution in the coil. We clearly see here that the mechanical stresses induced in the coil depend strongly on the azimuthal Lorentz forces distribution between layer 1 and layer 2.

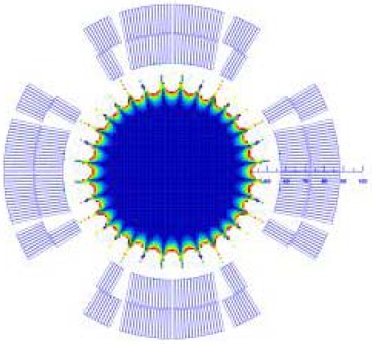

Figure 2: HQ 114 mm aperture cross-section designed by Vadim Kashinkhin, FNAL

Based on these considerations, a magnetic cross-section has been designed (Fig. 2) using the conductor described in Table 1.

The magnet short sample limit parameters at the operating operation T_{op} = 1.9 K are presented in Table 2. The critical current density taken into account in the computation is 3000 A/mm^2 at 12 T and 4.2 K.

Table 2: Magnet parameters at T_{op} = 1.9 K

Dimensions	Units	Values
G_{SS}	T/m	234
B_{SS}	T	15.39
I_{SS}	kA	19.18
F_θ L_1/L_2 at I_{SS}	MN/m	2.5 / 2.99
Stored energy	MJ/m	1.31

The iron yoke is located at 10 mm from the coil. For the magnetic computation, the outer radius is equal to 260 mm.

MECHANICAL DESIGN

The mechanical structure relies on an aluminum shell surrounding an iron yoke and four support pads.

The coils are wound around a Titanium pole. For a 114 mm aperture, the aluminum shell is 25 mm thick and the overall diameter of the magnet is 550 mm. The axial preload is provided by axial rods, which are pre-tensioned at room temperature and shrink during cool-down. The main objectives of this structure are to provide mechanical support up to the short-sample limit of the magnet and to implement alignment. The different components of the mechanical structure are shown in Figure 3. At 200 T/m, the ANYS 2D simulation shows a maximum azimuthal stress in the coil of the order of –135 MPa. At the short sample limit, that is to say for a gradient of 234 T/m, this maximum stress is equal to –177 MPa.

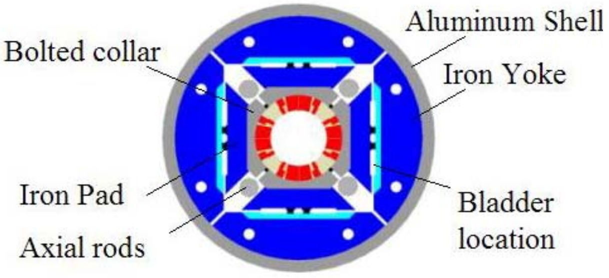

Figure 3: HQ mechanical structure

The optimization of this mechanical structure is in progress in order to incorporate all the accelerator quality features required for a LHC upgrade (cooling channel, alignment, LHe containement).

NEXT STEPS

In parallel to the mechanical analysis, the tooling is being designed. Magnetic 3D computations have also started in order to optimize the ends design and the iron shape.

REFERENCES

[1] P. Ferracin et al., “Development of a large aperture Nb_3Sn Racetrack Quadrupole Magnet,” IEEE Trans. Appl. Supercond., Vol. 15, Issue 2, June 2005.

[2] P. Ferracin et al., “Assembly and Tests of SQ02, a Nb_3Sn Racetrack Quadrupole Magnet for LARP,” IEEE Trans. Appl. Supercond., Vol. 17, Issue 2, June 2007.

[3] S. Caspi et al., “Fabrication and Test of TQS01 – A 90 mm Nb_3Sn Quadrupole Magnet for LARP,” IEEE Trans. Appl. Supercond., Vol. 17, Issue 2, June 2007.

[4] S. Caspi et al., “Test and Analysis of Technology Quadrupole Shell (TQS) Magnet Models for LARP,” IEEE Trans. Appl. Supercond., Vol. 18, No 2, June 2008.

[5] P. Wanderer et al., “Construction and Test of 3.6 m Nb_3Sn Racetrack Coils for LARP,” IEEE Trans. Appl. Supercond., Vol. 18, No 2, June 2008.

[6] G. Ambrosio et al., “LARP Long Nb_3Sn Quadrupole Design,” IEEE Trans. Appl. Supercond., Vol. 18, No 2, June 2008.

[7] H. Felice et al., “Magnetic and Mechanical Analysis of the HQ Model Quadrupole Designs for LARP,” IEEE Trans. Appl. Supercond., Vol. 18, No 2, June 2008