Title
Nb3Sn Quadrupoles Designs For The LHC Upgrades

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Abstract
In preparation for the LHC luminosity upgrades, high field and large aperture Nb$_3$Sn 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$_3$Sn technology for the LHC upgrades. The increase of the baseline luminosity requires IR quadrupoles with high performing gradients. Although NbTi solutions are considered, Nb$_3$Sn 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$_3$Sn magnets:

- The SQ series (Subscale Quadrupole) provided a gradient of 90 T/m in 110 mm aperture using subscale Nb$_3$Sn 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$_3$Sn racetrack coils assembled in a shell-based structure to demonstrate the scalability of Nb$_3$Sn racetracks [5].
- The LQ series (Long Quadrupole) is a scale up of the TQ series aiming at demonstrating the scalability of Nb$_3$Sn 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 15mm 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>
<thead>
<tr>
<th>Dimensions</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>mm</td>
<td>15</td>
</tr>
<tr>
<td>Mid thickness</td>
<td>mm</td>
<td>1.405</td>
</tr>
<tr>
<td>Insulation</td>
<td>mm</td>
<td>0.11</td>
</tr>
</tbody>
</table>

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.
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.

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.

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 containment).
**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**


