# DESIGN AND CONSTRUCTION OF A 15 T, 120 MM BORE IR QUADRUPOLE MAGNET FOR LARP*

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*Abstract*

Pushing accelerator magnets beyond 10 T holds a promise of future upgrades to machines like the Large Hadron Collider (LHC) at CERN. $Nb_3Sn$ conductor is at the present time the only practical superconductor capable of generating fields beyond 10 T. In support of the LHC Phase-II upgrade, the US LHC Accelerator Research Program (LARP) is developing a large bore (120 mm) IR quadrupole (HQ) capable of reaching 15 T at its conductor peak field and a peak gradient of 219 T/m at 1.9 K. While exploring the magnet performance limits in terms of gradient, forces and stresses the 1 m long two-layer coil will demonstrate additional features such as alignment and accelerator field quality. In this paper we summarize the design and report on the magnet construction progress.

## INTRODUCTION

$Nb_3Sn$ magnets have a relatively short history. In comparison to the thousands of NbTi magnets built in the past 40 years only several dozen $Nb_3Sn$ accelerator magnets were built. This statement reflects the complexity of $Nb_3Sn$ technology as well as the potential and attractiveness of reaching higher fields and gradients. In the US three laboratories (BNL, FNAL, and LBNL) are collaborating in a development that demonstrates such technology as an option towards the fabrication of a full scale Interaction Region (IR) quadrupole magnet for the LHC Phase-II upgrade [1],[2]. Four years ago LARP started developing an IR quadrupole (TQ) that could reach 200 T/m in a 1m long, 90 mm aperture [3],[4]. Over a dozen tests demonstrated that 200 T/m can be consistently exceeded. Although the current plateau never went beyond 90-92 % of its "short-sample" prediction, a peak gradient of 231 T/m was reached at 2.5 K. In order to demonstrating that the technology of 1 m long $Nb_3Sn$ magnets can be extended to 3.6 m, a subscale racetrack coil was built and tested successfully reaching 98 % of its "short-sample" limit [5]. LARP is now progressing towards a similar demonstration expanding the TQ magnet program by extending it from a 1 m to 3.6 m long. That program, called LQ [6],[7] will test its first magnet later this year.

To meet CERN's Phase-II needs, LARP is also developing an IR quadrupole (HQ) that extends the bore size from 90 mm to 120 mm and pushes the field at the conductor just over 15 T. This magnet will include accelerator features such as alignment and field quality. The HQ magnet Phase-II upgrade will operate at a gradient (yet to be determined) above CERN's Phase-I upgrade of 120 T/m. This paper covers the design parameters and the status of the HQ magnet.

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## MAGNET DESIGN

### *HQ - Conceptual Design and Parameters*

The cross-section of the HQ quadrupole magnet is shown in Figure 1. The magnet components include *cos2θ* coils, collars, pads, yokes and an outer shell. The functionality of most structural components was previously tested as part of the LARP $Nb_3Sn$ program with the exception of the collars [8],[9]. Aluminum collars were added to provide alignment and assembly control and not for pre-stress.

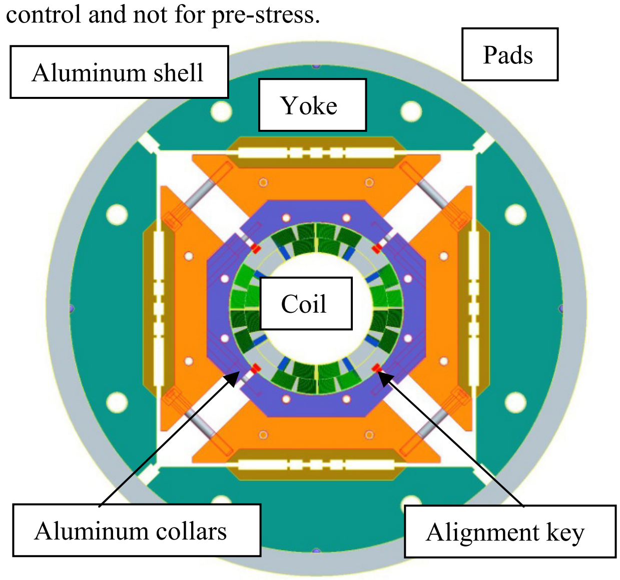


Figure 1: HQ cross-section – 120 mm high gradient $Nb_3Sn$ quadrupole.

The two layer coil uses a 35 strand Rutherford cable insulated with a S2 glass sleeve. Each layer of the double layer coil is wound around a Titanium pole (island) and includes stainless steel end shoes and spacers. The stainless steel end pieces replaced previously used Bronze parts as a cost saving measure. A single Bronze wedge within each octant separates each layer into two blocks. The overall design parameters are listed in Table 1.

Table 1: HQ design parameters.

| | | | |
|---|---|---|---|
| Coil aperture | | mm | 120 |
| Yoke OR | | mm | 260 |
| Outer Shell thickness | | mm | 25 |
| Overall magnet diameter | | mm | 570 |
| Bare cable width | | mm | 15.15 |
| Bare cable mid-thickness | | mm | 1.437 |
| Cable keystone angle | | deg | 0.75 |
| Cable insulation thickness | | mm | 0.10 |
| Turns per quadrant IL/OL | | | 20/26 |
| Mid-plane shim per octant | | mm | 0.14 |
| Maximum gradient 1.9 K | | T/m | 219 |
| Maximum current 1.9 K | | kA | 19.5 |
| Peak field 1.9 K | | T | 15.2 |
| Maximum gradient 4.4 K | | T/m | 199 |
| Maximum current 4.4 K | | kA | 17.7 |
| Peak field 4.4 K | | T | 13.9 |
| Jc 12T, 4.2 K | | $A/mm^2$ | 3000 |
| Inductance (at quench) | | mH/m | 7.71 |
| Max. stored energy 1.9 K | | MJ/m | 1.4 |
| Max octant forces 1.9 K | Fx total | MN/m | 3.38 |
| | Fy total | MN/m | -5.03 |
| | $F_\theta$ IL/OL | MN/m | -1.92/-3.2 |
| Maximum axial force per end | | MN | 1.4 |

Table 2: Calculated harmonics of HQ.

| **Field reference radius** | | **40mm** |
|---|---|---|
| Harmonics @ 10 T/m | $b_6$ | -1.6317 |
| | $b_{10}$ | -0.0156 |
| | $b_{14}$ | -0.0106 |
| | $b_{18}$ | -0.3910 |
| Harmonics @ 120 T/m | $b_6$ | 0.0 |
| | $b_{10}$ | -0.0021 |
| | $b_{14}$ | -0.0118 |
| | $b_{18}$ | -0.4059 |

### *Magnetic design*

The magnet was designed to reach a "short-sample" field, gradient and current of 15.2 T, 219 T/m and 19.5 kA respectively at 1.9 K. Taking into account saturation, the good field quality at 2/3 of the bore radius was set at a gradient of 120 T/m. Table 2 lists the first 4 allowed harmonics at low and intermediate field.

The iron yoke near the end regions was replaced with stainless steel to reduce the conductor end peak field to same level as in the straight section.

### *Quench protection*

A quench analysis has been performed using the program QuenchPro [10]. The analysis evaluated the expected peak temperature in the coil (hot spot temperature) after a spontaneous quench. With a stored energy of 1.2 MJ, wide protection heaters are needed for both layers. The protection heaters are part of a trace: an instrumentation technique adopted in all LARP magnets relying on printed–circuit technology and based on a Kapton sheet and a 25.4 microns thick stainless steel foil [11]. A 65 % heater coverage and a conservative approach (low quench propagation velocity and no quench-back) result in a hot spot temperature of around 300 K for a short sample quench at 4.4 K but reaches ~400 K at a short sample current at 1.9 K. Some additional protection heaters optimizations will be needed to reduce this peak temperature.

### *Assembly and Cool-down*

Four aluminum collars placed over the coils align them by pressing the collars against four keys. The collars are used for assembly and alignment only and not as "self supporting collars" commonly used in NbTi magnets. Surrounding the collars and maintaining their alignment are four stainless-steel pads. The pads are lightly bolted to each other completing the coils subassembly. A structure subassembly consisting of an iron yoke and an aluminum shell is held together following a bladder operation that stretches the outer shell and compressing the inner iron yoke (interference "gap-keys" are placed between the yokes to provide azimuthal continuity). During the final assembly both subassemblies are nested and with the help of pressurized bladders gaps are created into which thin interference shims are slipped (Fig. 3). As the "gap-keys" between the yokes are removed the tension in the outer aluminum shell is balance by the azimuthal compressive stress in the coils. The process is monitored and controlled with strain gauges mounted on the shell and coil islands. Most of the coil pre-stress is obtained during cool-down as the aluminum shrinks over the yoke and pads taking advantage of thermal expansion differences between the two.

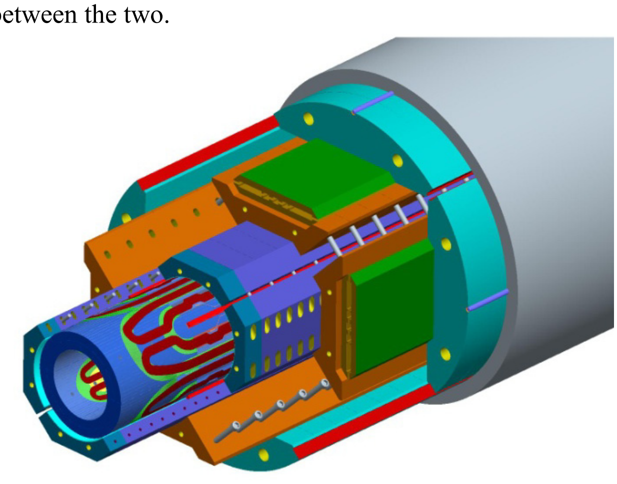

Figure 3: Final assembly of coils and structure.

### *Mechanical Analysis*

A 2D and 3D Finite Element Analysis was carried out with ANSYS to determine the stresses in the windings and structure. The analysis was done in 3 steps a) during room temperature loading (bladder operation BO), b) cool-down (CD) and c) excitation (LF). Table 3 summarizes the average azimuthal stress in the coil pole turn and in the aluminum shell during each step.

Table 3: Azimuthal stress during assembly, cool-down and under Lorentz force.

| Gradient (T/m) | σθ BO (MPa) | σθ CD (MPa) | σθ LF (MPa) |
|---|---|---|---|
| **Layer 1** | | | |
| 180 | -28 | -109 | -5 |
| 219 | -91 | -142 | +8 |
| **Layer 2** | | | |
| 180 | -16 | -72 | -4 |
| 219 | -35 | -92 | +7 |
| **Outer Shell** | | | |
| 180 | +43 | +142 | +146 |
| 219 | +96 | +211 | +217 |

## HQ MODEL

### *Coil Fabrication*

The process of winding the coils included an intermediate curing step. Winding the first layer (inner) the coil is placed inside a curing cavity, pre-sized and cured at 150°C. The curing process bonds the turns together, shapes the overall coil size and creates a smooth outer surface on to which the outer layer can then be wound. Winding the second layer the coil is placed once again into the curing cavity cured and aligned using a key. The coil is then placed into a reaction cavity and reacted at 650°C with an intermediate temperature hold at 210°C and 400°C. The time from the moment reaction starts until the coil is removed from the oven is approximately 10 days.

Following reaction, voltage taps and strain gauges are added. The gauges and voltage taps are attached to a trace that also includes the coil protection heaters. The $Nb_3Sn$ to NbTi splice is done along the end-shoes and the coil is vacuum impregnated with CTD101k epoxy.

### *Practice Coil – Winding Test*

Three winding tests were carried out to determine the cable lay around ends. The first two tests placed several turns around the pole using bare cable in order to better examine the possibility of popped strands. The third test was done with insulated cable and completed all turns of layer one. The three tests used islands, spacers, end-shoe and wedges made from plastic rapid-prototype (RP) parts. Manufacturing the RP parts directly from CAD models that included various holes and the layer-to-layer transition was proven to be very useful and cost effective in testing the new tooling and the cable lay around the "ends" (Fig. 4).

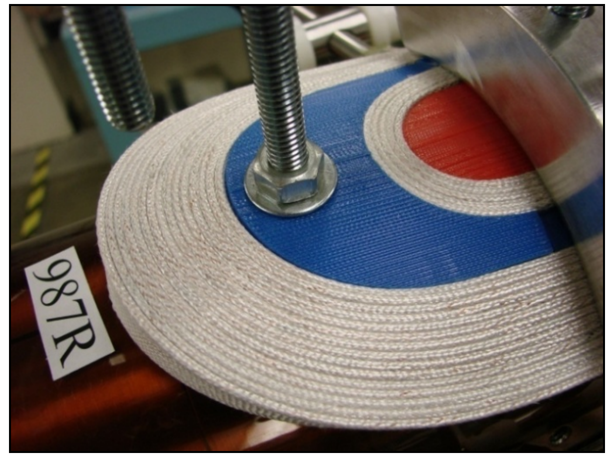


Figure 4: A practice coil using rapid-prototyping parts.

## CONCLUSION

All parts for winding 4 coils (islands, end spacers and wedges) as well as the cable have been made. The manufacturing of the curing, reaction and impregnation tooling is near completion and winding the first practice coil has started. The plan is to assemble the magnet by the end of the calendar year and test at the beginning of 2010.

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