SHELL-BASED SUPPORT STRUCTURES FOR NB$_3$SN ACCELERATOR QUADRUPOLE MAGNETS*

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Abstract

Shell-based support structures are being fabricated and tested as part of the development of large-aperture Nb$_3$Sn superconducting quadrupoles for future upgrades of the LHC Interaction Regions. These structures utilize water pressurized bladders for room-temperature pre-load control, and rely on a pre-tensioned aluminum shell to deliver a substantial part of the coil pre-stress during cool-down. The coil final pre-load is therefore monotonically approached from below, without overstressing the strain-sensitive conductor. This method has been adopted by the US LARP collaboration to test subscale racetrack coils (SQ series), 1 m long cos-theta coils (TQS series), and 4 m long magnets (LRS and LQS series). We present recent progress in the development of shell-based support structures, with a description of the principles of operations and the future plans.

INTRODUCTION

As part of the LHC Accelerator Research Program (LARP [1]), three US national laboratories (BNL, FNAL, and LBNL) are currently engaged in the development of Nb$_3$Sn superconducting magnets for a future upgrade of the LHC Interaction Regions (IR). In order to contain the superconducting coils during magnet excitation and minimize conductor motion induced by electro-magnetic forces, LBNL has developed shell-based support structures for quadrupole magnets. The main components and features of these structures are the following:

- An external aluminum segmented shell (solid tube).
- A 4-piece iron yoke with gaps open during all magnet operations.
- Assembly performed through two sub-assemblies.
- Pre-loading obtained with water pressurized bladders.
- Maximum coil stress reached after cool-down.
- Axial coil support provided by end-plate and axial rods.

These support structures have been originally adopted by the LBNL Superconducting Magnet Program to cope with the needs of high field Nb$_3$Sn magnets, which, because of large e.m. forces acting on a brittle superconducting material, require a precise control of the coil pre-load [2-3]. In this paper with give an overview of how these structures have been applied to quadrupole magnets, we describe their main principles of operation and finally we present how, through LARP, accelerator quality features are in the process of being included in the design.

OVERVIEW OF LARP SHELL-BASED STRUCTURES

Four different structures have been adopted for the following LARP quadrupole magnets (Fig. 1).

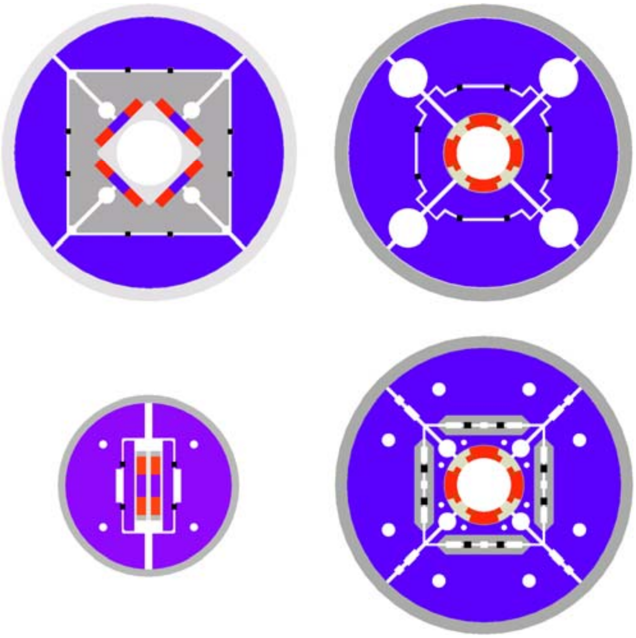

Figure 1: Cross-sections of LARP magnets with shell-based support structures (in scale): SQ (top left), TQ (top right), LR (bottom left), and LQ (bottom right).

SQ (Subscale Quadrupole)

The subscale quadrupole magnet SQ [4-7] was the first magnet where the shell-base structure concept was applied to a quadrupole configuration. The cross-section is shown in Fig. 1 (top left). The 300 mm long magnet features four racetrack coils and an aperture of 110 mm. The coils and the structure were fabricated and assembled at LBNL and a total of 5 tests (first test in 2005) were performed at LBNL and FNAL. The design includes alignment features for the structure components and the coils. The maximum conductor peak field of 11.8 T (98% of the expected magnet limits), corresponding to a gradient of 89 T/m, was reached during the SQ02b test at 1.9 K.

TQ (Technology Quadrupole)

The technology quadrupole magnet TQ [8-13] was the first magnet where the shell-base structure concept was applied to a cosθ-type quadrupole magnet. The cross-section is shown in Fig. 1 (top right). The 1 m long magnet features four cosθ coils and an aperture of 90 mm.

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The coils were fabricated at FNAL and LBNL, and assembly and loading were carried out at LBNL and CERN. A total of 5 tests (first test in 2006) were performed at LBNL, FNAL, and CERN. The design does not include alignment features for the structure components and the coils. The maximum conductor peak field of 11.2 T (90% of the expected magnet limits), corresponding to a gradient of 220 T/m, was reached during the TQS02a test at 4.5 K.

LR (Long Racetrack)

The long racetrack magnet LR [14-17] was the first magnet where the shell-base structure concept was applied to long racetrack coils. The cross-section is shown in Fig. 1 (bottom left). The 3.6 mm long magnet features two racetrack coils in common coil configuration and no bore. The coils were fabricated at BNL, while LBNL was responsible for the fabrication of the structure, as well as the assembly and loading of the magnet. A total of 2 tests (first test in 2007) were performed at BNL. The design does not include alignment features for the structure components and the coils. The maximum conductor peak field of 11.5 T (96% of the expected magnet limits) was reached during the LRS02 test at 4.5 K.

LQ (Long Quadrupole)

The long quadrupole magnet LQ [18-19] is going to be the first magnet where the shell-base structure concept will be applied to a long cosθ-type quadrupole magnet. The cross-section is shown in Fig. 1 (bottom right). The 3.5 m long magnet features four cosθ coils and an aperture of 90 mm. The coils are fabricated at FNAL and BNL while LBNL is responsible for the fabrication of the structure, as well as the assembly and loading of the magnet. The first test is expected in 2009. The design includes alignment features only for the structure components. The maximum expected conductor peak field at 1.9 K is 12.3 T, corresponding to a gradient of 240 T/m.

PRINCIPLES OF OPERATION

Coil azimuthal and radial support

The shell-based support structure comprises several components: pads surrounding the coils, iron yokes, and an aluminum outer shell. As a first step in the assembly, the four pads are bolted around the coils. The coil-pad sub-assembly is then inserted into a structure composed by the four-piece iron yoke and the aluminum shell. A 5 mm gap between pads and yokes provided room for inserting four pressurized bladders.

The pre-loading operation is depicted in Fig. 2 using deformed shapes computed by a 2 D finite element model with displacements enhanced by a factor 20. The contact pressure between coil and pole during assembly, cool-down, and excitation is plotted in Fig. 3 assuming different bladder pressures. Both figures refer to the LQ case. The bladders generate the primary force needed to spread the yoke apart, apply tension to the shell and pre-compress the coil-pads subassembly (Fig 2, top left). Once the structure is locked by interference keys, the bladders are deflated and removed (Fig 2, top right). During cool-down, the shell generates further pre-load on the coils, due to the different thermal contractions of aluminum and iron (Fig 2, bottom left).

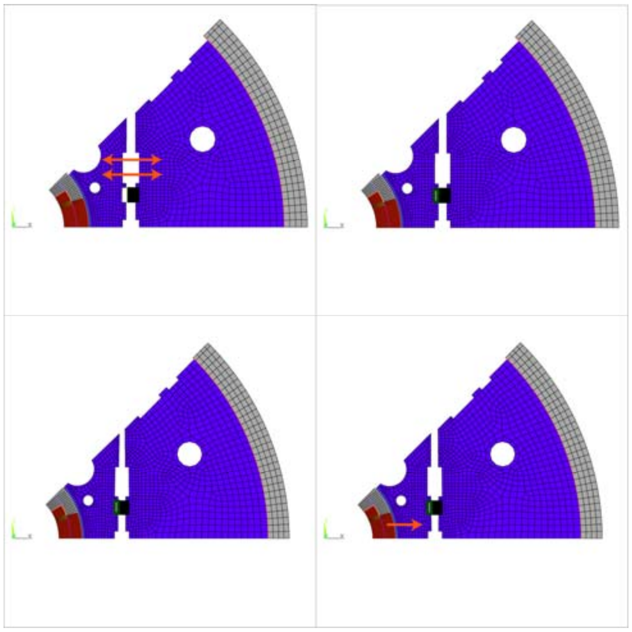

Figure 2: Principles of operation (deformed shape of a 2D finite element model with displacements enhanced by a factor 20): insertion-pressurization of bladders (top left), insertion of interference key and deflation-removal of bladders (top right), cool-down (bottom left), and excitation (bottom right).

The e.m forces push the coil against the structure (Fig 2, bottom right), at the same time unloading the pole: the bladder pressure is chosen in order to guarantee full contact between coil and pole when the magnet is energized (Fig. 3)

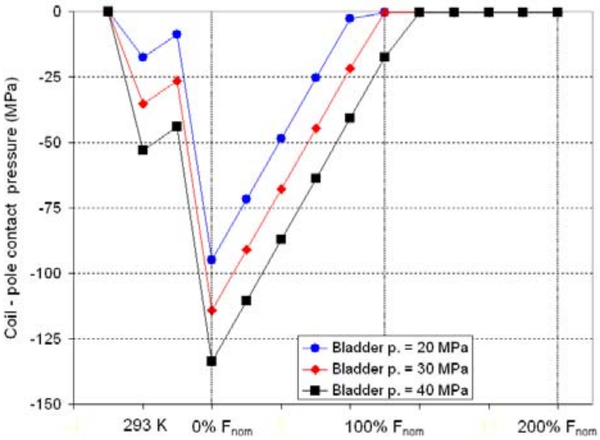

Figure 3: Contact pressure between coil and pole (MPa) during assembly, cool-down, and excitation (as a function of the fraction of nominal electro-magnetic force). Data

are plotted assuming three different bladder pressures.

Coil axial support

In order to reduce the conductor motion in the end region resulting from axial e.m forces, a longitudinal support system is included in the design (Fig. 4 left). Four aluminum rods are inserted in the four holes of the pads, and bolted to two stainless steel end plates. The rods are pre-tensioned with an axial piston at room temperature (Fig. 4 right) and, similarly to the outer shell, they significantly increased their stress during cool-down.

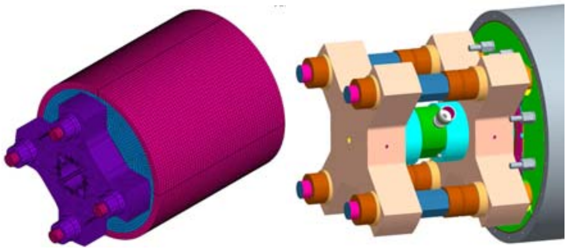

Figure 4: Coil axial support: end-plate (left) and pre-load system composed by an additional plate and a piston (right).

NEXT STEP: HQ

Following the experience gained with the SQ, TQ, and LQ programs, LARP is now designing HQ, whose goals are to explore the performance limits in terms of peak fields (≥ 15 T), forces and stresses, and to include in the design accelerator quality features as alignment and LHe containment. A preliminary cross-section of HQ is shown in Fig. 5. The structure components are aligned through round pins between shell and yokes and keys between pads and yokes. The coil is surrounded by aluminum bolted collars which align the coil poles to the pads. An external stainless steel tube is currently considered as a possible LHe containment.

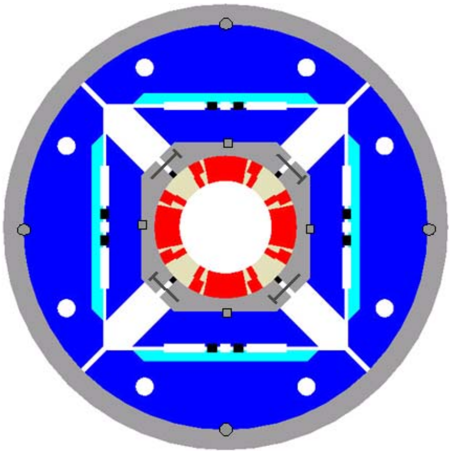

Figure 5: Cross-section of HQ.

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