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Alternative Mechanical Structure for LARP Nb_3Sn Quadrupoles

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***Abstract*—An alternative structure for the 120 mm Nb3Sn quadrupole magnet presently under development for use in the upgrade for LHC at CERN is presented. The goals of this structure are to build on the existing technology developed in LARP with the LQ and HQ series magnets and to further optimize the features required for operation in the accelerator. These features include mechanical alignment needed for field quality and provisions for cold mass cooling with 1.9 K helium in a helium pressure vessel. The structure will also optimize coil azimuthal and axial pre-load for high gradient operation, and will incorporate features intended to improve manufacturability, thereby improving reliability and reducing cost.**

***Index Terms*—Collar, Lorentz forces, magnet, niobium tin, quadrupole, structure, superconducting accelerator magnet.**

I. INTRODUCTION

LARP is presently building 120 mm aperture (HQ) [1] and 90 mm aperture (LQ) [2] R&D niobium tin quadrupole cold masses in support of the upgrade to the LHC [3] at CERN. These cold masses utilize aluminum shell support systems with "bladder and key" technology [4]–[9] instead of traditional collar and stainless steel support shells, in order to reduce and more accurately control the required coil prestress during assembly and still provide sufficient restraint against Lorentz forces during operation. This alternate structure attempts to employ all the benefits of the existing 90 mm and 120 mm structures while making important improvements. Specifically the structure will contain sufficient provisions for 1.9 K helium cooling in the form of heat exchanger holes in the yoke. The structure replaces the bolted collars (used in LQ and HQ as handling aids) with more traditional low prestress aluminum collars in conjunction with the support shell and "bladder and key" assembly for reliable coil loading. In addition the structure shifts the boundary of the inner and outer yoke outward radially to provide more uniform loading at the collar interface and to permit more surface area and corresponding low working pressure of the bladders. The structure also shifts the parting planes of the yoke to coincide with the coil midplanes to permit continuous alignment of the coils to the exterior survey locations in the helium vessel. Finally the structure utilizes the stainless steel helium vessel for support of axial Lorentz forces, eliminating tie rods and permitting the maximum area for helium cooling.

II. DESIGN

The 2-D cross-section of the cold mass structure can be seen in Fig. 1. Standard 120 mm HQ LARP quadrupole coils with integral titanium poles are supported by 7000 series aluminum collars of 24 mm annular thickness providing full radial support to the coil outer surface. Each collar has keyways for two tapered keys to efficiently distribute the collaring forces. Collar details can be seen in Fig. 2. Collars are planned to be made as a single part with features for interlocking opposing collars machined as a secondary operation. This method of fabrication permits the greatest alignment accuracy, eliminates the need for accurate pinning or spot welding and reduces the number of stampings by half. Tapers in the keys permit an optimized assembly process, first utilized at LBNL for SSC, where inward radial pressure is applied to the collars to enable the key to be started in the keyways. Incrementally pressure is then increased to the keys while being reduced to the collars so as to eliminate or minimize the amount of over-pressure needed to be applied to the coils during assembly (known as eliminating "springback" losses). Collars employ keys which engage keyways in the coil poles and the inner yoke for alignment. Inner yokes contact the collar outer radii providing continuous line to line radial support. Laminated carbon steel inner yokes are four way symmetric with parting planes coincident with the coil midplanes. Radial geometry provides the maximum amount of iron for magnetic flux return. 80 mm helium heat exchanger holes are located at the coil pole for optimized magnetic saturation of the yoke. The outer yoke to inner yoke interface is located at the most radial outward position possible to permit the use of four 50 mm wide bladders per quadrant, resulting in a relatively low bladder working pressure of 35 MPa. Keys in line with collar keys at the coil poles align the inner and outer yokes. The keys are shimmed radially to provide loading along with four additional loading keys per quadrant. Laminated outer yokes are aligned through access holes (later fiducials) in the aluminum support shell and stainless steel helium vessel to permit alignment during all phases of assembly and magnet installation. A 25 mm thick 570 mm O.D. 6000 series aluminum support shell provides the final restraint against Lorentz forces. The support shell is inserted with radial

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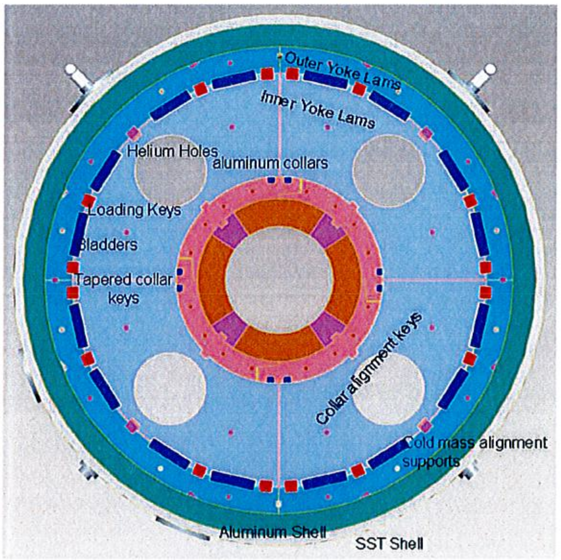

Fig. 1. 2-D view of the 120 mm LARP quadrupole cold mass structure.

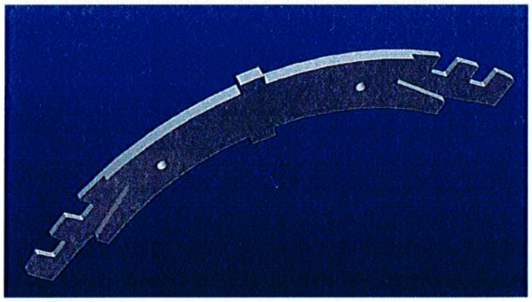

Fig. 2. Collar lamination detail.

clearance into the 12.7 mm stainless steel helium vessel (clearance facilitates assembly and ensures decoupling of the radial and axial coil support), and then aligned and supported using supports welded at the access holes.

The 3-D cutaway view of the cold mass structure can be seen in Fig. 3. Axial Lorentz forces are restrained by set screws that load against the coil end pressure plates. The set screws are located in the 127 mm thick stainless steel end plate which is welded to the 12.7 mm thick stainless steel helium vessel. The end plate is subsequently welded to the end dome and to the inner helium vessel/beam tube to complete the helium containment.

III. ANALYSIS

ANSYS finite element modeling was performed for the 2-D mechanical structure. 2-D 6-node or 8-node structural solid elements were used as well as contact elements at interfaces. A sliding friction coefficient of 0.2 was assumed. All materials are assumed to be isotropic except the coil which is orthotropic (see Table I for values). Loading was performed in five steps; collaring, full bladder pressure at assembly, yoke shims installed with no bladder pressure, cool down to 4 K and powered to 220 T/m flux gradient. Fig. 4 shows the FEM mesh.

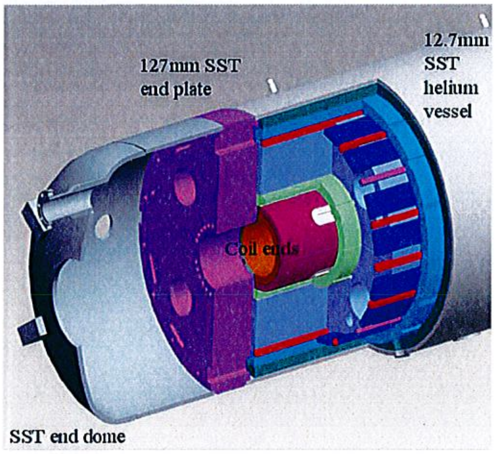

Fig. 3. 3-D cutaway view of the 120 mm LARP quadrupole cold mass structure.

TABLE I
MATERIAL PROPERTIES

	Young's mod (GPa) 4.3 K	Young's mod (GPa) 293 K	Poisson ratio	Thermal contraction (m/m) 293 K to 4.3 K
Coil azimuthal	44	44	0.30	3.36E-03
Coil radial	52	52	0.30	3.08E-03
Stainless steel	210	193	0.28	2.84E-03
Iron	224	213	0.28	1.97E-03
Aluminum	79	70	0.34	4.20E-03
Titanium	130	130	0.30	1.74E-03

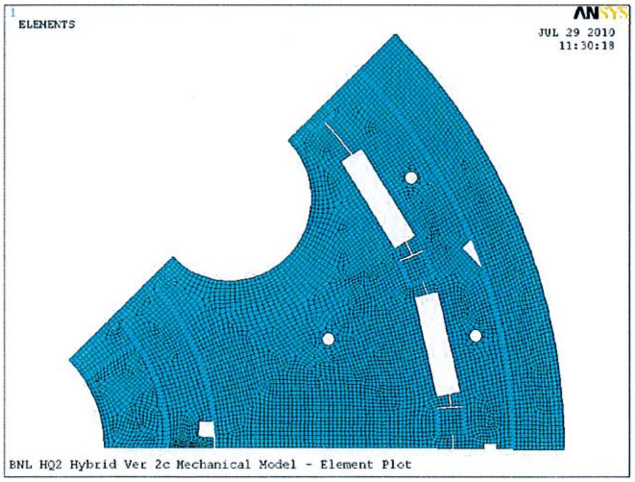

Fig. 4. 2-D cold mass FEM mesh.

A. Collar Analysis

Collars are designed to apply a modest coil prestress at assembly of 20 MPa. Series 7000 aluminum is used to withstand the resulting local stress in the keyway of ∼400 MPa. Collars have a mechanical stop at the midplane which is deliberately open by 0.1 mm after collaring. This midplane gap closes during

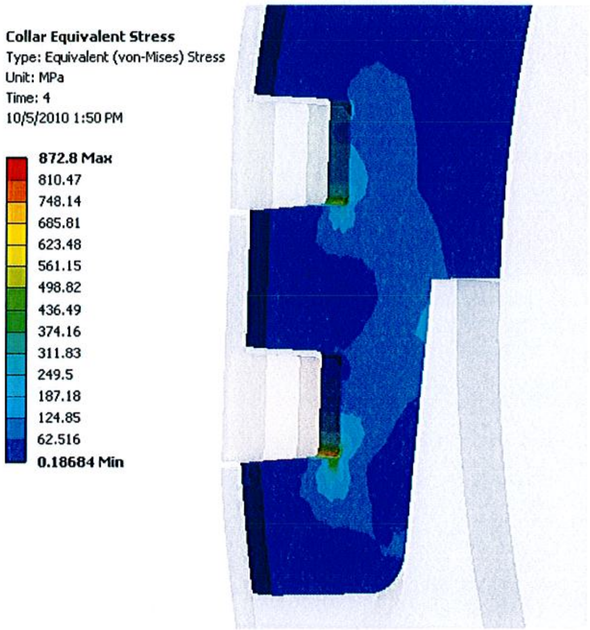

Fig. 5. Equivalent stress in collar keyway at key insertion.

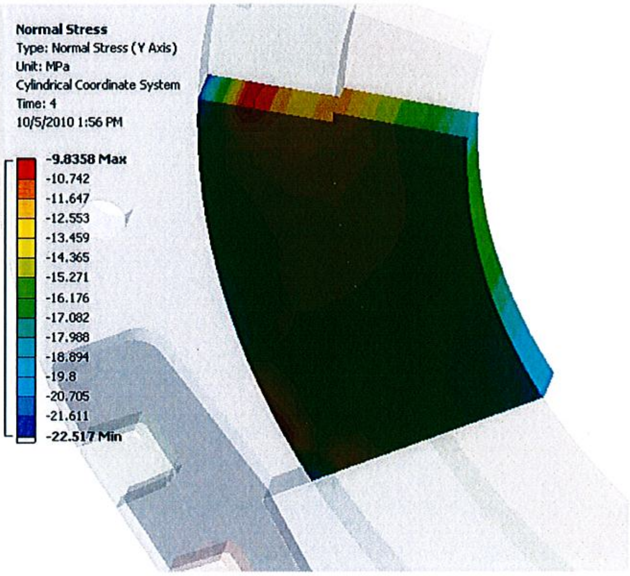

Fig. 6. Coil stress after collar assembly.

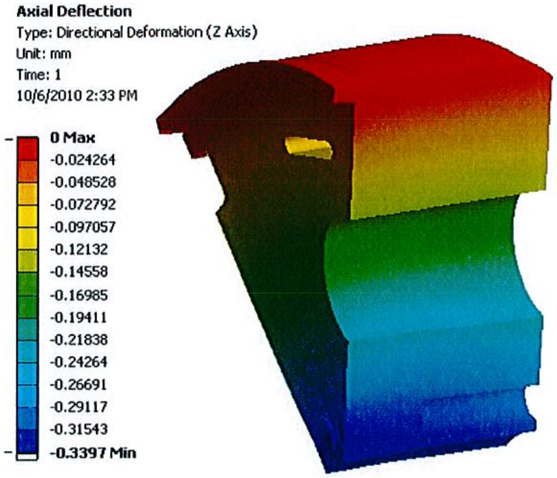

Fig. 7. End plate deflection at 1.4 MN.

TABLE II
2-D MECHANICAL ANALYSIS SUMMARY

Parameters	MPa
AVERAGE COIL POLE	
$\sigma_{\theta\,\max}$ with bladder pressure	-110
$\sigma_{\theta\,\max}$ with yoke keys installed	-83
$\sigma_{\theta\,\max}$ at cool down	-159
$\sigma_{\theta\,\min}$ at 220 T/m, 1.9 K	+19
SHELL	
σ_{eq} with bladder pressure	190
σ_{eq} at cool down	220
σ_{eq} at 220 T/m, 1.9 K	224

bladder and key insertion during support shell assembly to prevent over-stressing of the coils at room temperature. Figs. 5 and 6 show the stress in the collar during assembly and resulting coil stress at collar assembly, respectively.

B. 2-D Cold Mass Analysis

The analysis assumes that a sliding clearance of 0.25 mm is needed to install loading keys. A maximum bladder pressure of 35 MPa is applied to achieve this clearance which results in an average coil pole stress of 110 MPa and a peak coil stress at the inner edge of the coil inner layer midplane of 150 MPa. After keys are installed and bladder pressure is removed the coil pole stress reduces to an average of 83 MPa and a peak at the inner layer inner midplane edge of 116 MPa. Yoke and support shell stresses are all within acceptable limits during all stages of assembly.

During cooldown the shrinkage of the aluminum support shell increases the loading of the coils to the extent allowed by the mechanical stops of the collars. Since the magnetic yoke steel shrinks less radially than the aluminum support shell and collars, and since the yoke quadrants do not contact each other at the midplane parting planes they therefore assist with the increasing of load on the coils during cooldown. Coil stress after cooldown reaches an average value of 159 MPa at the pole. Due to support shell loading and thermal contraction as a result of cooldown the coil midplane at the layer 2 outer radius is reduced by 350 microns.

Lorentz forces are applied using coil nodal force vectors from the 2-D magnetic analysis. After applying magnetic forces the coil at the pole reaches a minimum of 19 MPa in tension which is within the allowable limit to prevent separation. As a result of the Lorentz forces the coil midplane at the layer 2 outer radius deflects 86 microns outward radially with respect to the position of the coil after cooldown.

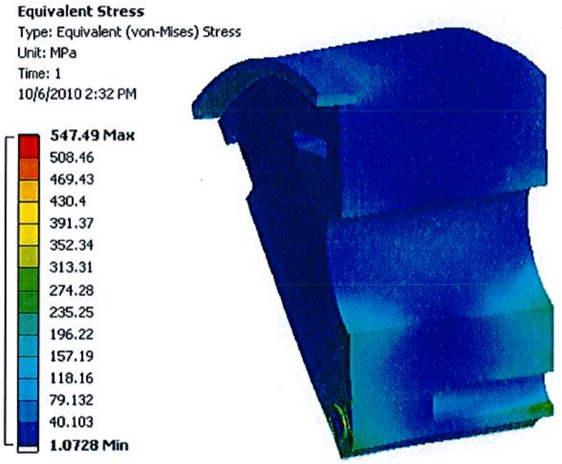

Fig. 8. Shell and end plate stress at 1.4 MN.

A summary of the 2-D mechanical analyses of the azimuthal coil stresses and Von Mises stresses in the support shell structure from assembly through test is provided in Table II below.

C. 3-D Cold Mass Analysis

ANSYS finite element modeling was performed for the 3-D mechanical structure. 3-D 10 and 20-node structural solid elements were used as well as contact elements at interfaces. A maximum axial Lorentz force of 1.4 MN was assumed [1]. End plate deflection under full Lorentz force was seen to be 0.3 mm as can be seen in Fig. 7. Shell elongation under full load was determined to be 0.15 mm. From these results overall coil strain can be determined to be less than 0.2%. Equivalent stresses in the shell and end plate as a result of this loading are within 270 MPa as is seen in Fig. 8.

IV. CONCLUSION

An alternate mechanical structure for 120 mm aperture Nb3Sn quadrupole magnets designed to operate in LHC is proposed. The mechanical analyses show that structure can properly support the coils during assembly and operation to 220 T/m and as such is an equivalent structural support system to the shell and key assembly presently used for the 1 m HQ LARP quadrupoles. The structure has been designed to provide reliable alignment of coils needed to achieve field quality. A provision for helium cooling of the coils is incorporated into the structure. More analysis is planned to optimize the applied loads at various stages of assembly in parallel with testing of the structure in a 15 cm mockup and in 1 m magnet tests.

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