Structural Analysis of the SHMS Cosine Theta Superconducting Dipole Force Collar

Steven Lassiter, Paul Brindza, Mike Fowler, Eric Sun and Greg Markham

Abstract—Jefferson Laboratory is developing a set of innovative superconducting magnets for the 12 GeV upgrade in JLAB Hall C. We will report on the finite element analysis (FEA) of the force collar for the Super High Momentum Spectrometer Cosine Theta Dipole magnet. The force collar is designed with an interference fit and intended to provide enough pressure after cool down to operating temperature to counteract Lorentz forces acting on the dipole coil during operation. By counteracting the Lorentz forces and keeping the coil pack in overall compression, movement of the coils is expected to be minimized. The dimensional geometry of the cold mass is maintained in the commercial solid modeling code UG/I-DEAS while the magnetic field design is maintained in the commercial TOSCA code from Vector Fields. The three dimensional FEA was conducted in the commercial codes ANSYS and IDEAS. The method for converting the models and calculating the loads transferred to the structure is discussed. The results show the cold mass response to: force collar assembly preload, differential thermal contraction, and operational Lorentz loads. Evaluations are made for two candidate force collar materials and two candidate force collar designs.

***Index Terms*—Dipole, FEA Analysis, Force Collar, Superconducting Magnet.**

I. INTRODUCTION

THE 12 Gev upgrade at JLAB calls for a small horizontal bender magnet followed by a triplet of focusing quadrupole magnets and a vertical bend, momentum selector dipole, $dQ_1Q_2Q_3D$ spectrometer to be housed within the experimental area of Hall C [1],[2]. The maximum energy to be delivered to Hall C will be 11 GeV. All magnetic elements of the SHMS will be superconducting, utilizing surplus SSC outer strand NbTi cable, either in a copper stabilizer or just Rutherford cable. The large dipole magnet will bend 11 GeV electrons 18.4° using a nominal 4.5 T bend field and having an acceptance of 4.5 mSr.

The reference design of the dipole is a cryostable (Stekely Parameter < 1) cosine theta coil, 2 sectors with 6 winding layers, arranged as double cylindrical pancake coils with constant perimeter ends [3]. The two sectors are separated by keys that define the critical cosine theta angles. The coil system is then surrounded by a thick aluminum cylinder, herein called the force collar, under a compressive load used to constrain the coils from any motion due to magnetic energization. This cold mass assembly is then encased in a helium containment vessel and surrounded by a cryostat. The magnet uses a warm steel yoke that surrounds the cryostat. The magnet has a warm bore diameter of 0.6 m, height of 3.2 m, width of 2.3 m, iron yoke length of 3.1 m and an overall length of 4.1 m. The overall size of the magnet is limited by the physics requirement of the SHMS being able to reach small forward angles relative to the beam line and the overall length restriction of the SHMS within Hall C. Fig. 1 shows a cross sectional view of the SHMS Dipole with its non-circular warm iron.

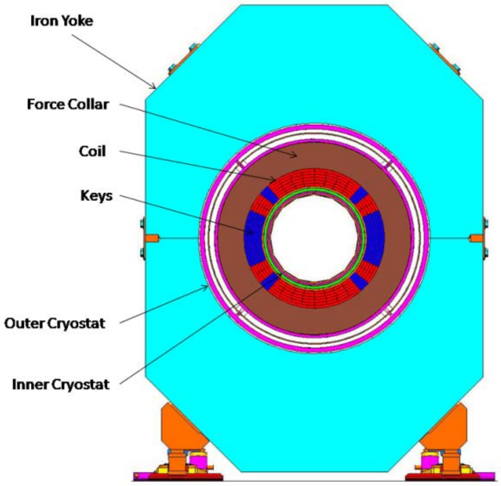

Fig. 1. Cross Section view of the SHMS Dipole.

The structural finite element analysis, (FEA) of the force collar will be described beginning with the preliminary design, continuing with the most recent FEA done at JLAB, to the current work in progress.

II. DESIGN CONCEPT

The basic design concept calls for the shrink fitted force collar to preload the keys and coils against the Lorentz forces of the energized magnet. Fig. 2 shows a sectional view of the SHMS Dipole magnet. The cold mass assembly is developed with room temperature interference between the force collar

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and the coil/keys substructure. This room temperature interference is enhanced upon further cooling down of the cold mass to liquid helium temperatures. The shape of the keys along with the difference in thermal contraction between the coils/keys and the force collar produces azimuthal and radial preloads upon the coils. Lorentz forces tend to compress the coils in the azimuthal direction, with the tendency of the coils to separate from the keys, and it also produces large outward radial forces at the midplanes. It is the intent that the force collar provides sufficient precompression and stiffness to maintain complete compressive stresses in the coil across the range of magnet operation. Isotropic material properties were derived from commercial available data sources [4]-[6] or from the result of 2D FEA studies of the composite coil build up. The physical properties of the coil stack will be measured, both at room temperature and at liquid helium temperature, to confirm the 2D FEA.

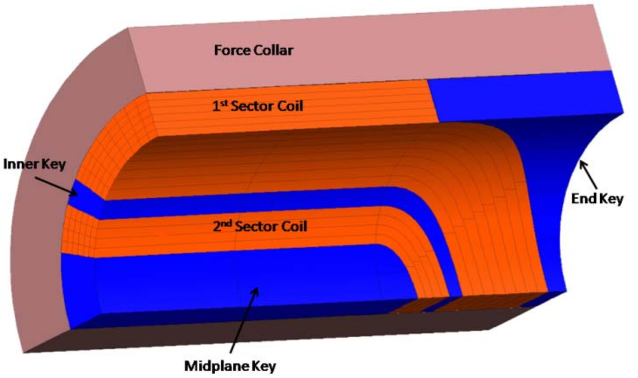

Fig. 2. 3D view of the cold mass of the SHMS Dipole. 1/8 of the geometry used in the FEA. Shown is the Force collar, coils and keys

III. PRELIMINARY FEA WORK

Several parallel engineering studies were done on preliminary designs to investigate the mechanical performance of the SHMS Dipole force collar [7]-[9]. Studies included different material choices for the force collar and keys, different thickness for the force collar, the amount of room temperature thermal interference, and solid vs. bolted clam shell force collar. Both 2D and 3D finite element models were employed to calculate the magnetic fields and Lorentz forces, to simulate material properties, and to calculate stresses due to assembly, cool down and energizing of the magnet. FEA analyses were performed using the following software: TOSCA®, ANSYS®, and IDEAS®. The force collar/key material combinations ranged from aluminum or stainless steel for the force collar and titanium, C51000 phosphor bronze or stainless steel for the keys. None of the FEA models took into account the helium containment vessel to help contain coil movement, thus decoupling any mechanical loading from the pressure vessel requirements. Consensuses among the studies were: the larger the thickness of the force collar, the less room temperature preload is needed; a bolted clamshell force collar would be difficult to achieve with preference being a solid shell, either welded or cast; measured physical properties of the coil stack should be undertaken as well as the insulation scheme developed and modeled. It was also noted that to reduce bending stresses in the force collar at the ends where the end key forms a solid, continuous stiffer ring, clearances between the force collar and the end key should be added. Based upon the findings and suggestions of these early models, considerations for cost and overall size, it was decided to concentrate on a solid 18 cm thick aluminum force collar with stainless steel keys utilizing a shrink-fit technique by warming the aluminum ring to 100° C before assembly.

IV. ANALYSIS STEPS

A. Coil Forces

By using symmetry and boundary conditions the model geometry was reduced to its simplest size, 1/8 of the magnet. Forces acting upon the coil were obtained from the software code TOSCA®. The coil geometry was partitioned into several segments to obtain greater density of coil forces. Meshing differences between the TOSCA model and the FEA model required use of an in-house translator program to match the forces to the FEA nodal locations.

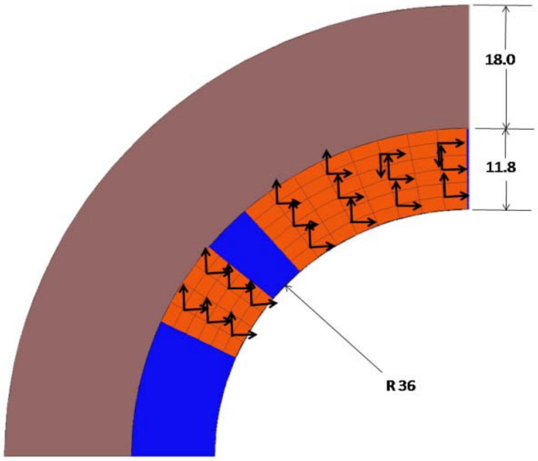

Fig. 3. Nodal forces applied to coils. Note the force vectors lengths are not indicative of the magnitude of the forces, only of their direction in the Cartesian coordinate system. Dimension units are cm in the figure.

The Lorentz forces are extracted from the TOSCA files using its standard Cartesian coordinates. Post analysis within IDEAS is done using the more suitable cylindrical coordinate system. The labels on the graphs are still marked X, Y and Z but these correspond to the R, Theta, and Z coordinates. Table 1 gives the magnitude of the force components for the 1/8 geometry at the two excitation currents.

TABLE I LORENTZ FORCES

Magnet Setting	*Current Density A-Turns/cm^2*	Fx MN	Fy MN	Fz MN
11 Gev	*4736.7*	5.293	-2.318	-1.193
Max Excitation	*5300.0*	8.031	-3.398	-1.793

B. Model Preparation

The FEA model in IDEAS uses the CAD 3D model that defines JLAB's reference design. The coil pack, composed of Rutherford superconductor cable, solder, copper stabilizer, Kapton insulating film, B-stage tape and G-10 sheets, was modeled as a solid material. Its physical properties were derived using a 2D FEA model of a ten turn stack build up. In the 2D model, each component of the coil stack was modeled at room temperature with its own physical properties. The results indicate that the physical properties are nearly equal in the two planes of the cross section. Only homogenous, isotropic properties were used in the 3D FEA model. Table 2 lists the physical properties at both room temperature and 4.5 K for the main components of the cold mass assembly.

Separate volumes for the force collar, the first and second coil sectors, the midplane key, the inner key and the end key were used to generate the mesh. Using a mesh size of 2 cm resulted in the generation of 252,041 solid tetrahedron elements. Global contact elements were applied for any gaps between 0 and 1.5 mm. No friction coefficient was applied between any mating surfaces. The end key was constrained in the axial direction, to track the movement of the force collar. This is to mimic the attachment of the end key to the force collar and results in a small amount of axial preloading to the coils after cooldown. Without this attachment of the end key to the force collar, a gap between the end key and the coils would appear upon cooling down from room temperature to 4K. Movements of the nodes along each boundary surface were restrained accordingly to match the relevant boundary condition.

The room temperature heat shrink of the force collar to the coil/key package was simulated by adjusting the Coefficient of Thermal Expansion (CTE) of the aluminum force collar. The force collar was modeled with its inner diameter just touching the outer diameter of the coil/key package and the aluminum's CTE was adjusted to match the contraction from 393 K to 4.5 K. The reference temperature for the rest of the materials was 293 K.

TABLE II PHYSICAL PROPERTIES

Property	Coil[1]	Aluminum 6061-T6	SS 304L
Young's Modulus GPa	56.5	72.2/78.5	198/208
Possion Ratio	0.175	0.32	0.29/0.28
Shear Modules GPA	24.1	27.3	75.6/80.2
Density $x10^{-3}$ *kg/m*^{3}	7.587	2.70/2.73	7.86/7.93
CTE $x10^{6}$ */K*	16.3	17.6[3]	10.35
Tensile Strength MPa	TBD	311/510	727/1,725
Yield strength MPa	TBD	283/365	250/700
Allowable peak stress MPa	150[4]	255/330	225/630

1. Values from 2D FEA model.
2. Room Temperature/4.5 K values.
3. See Text for explanation of Al's CTE ($14.53x10^{-6}$ at 293 K).
4. Reference 3, Working stress for azimuthal compression from FERMILAB LARP program.

A gap of 1.37 mm was introduced between the force collar and the end key. This amount allows the force collar to just touch the end key when at 4.5 K, thus eliminating the bending stress in the softer aluminum collar.

C. Model Solution

The model was solved for three load cases; cool down from 293 K to 4.5 K, the 11 GeV setting and the maximum current excitation of the magnet. The solutions were solved as linear models, with no plastic flow or stress hardening taken into account. The allowable peak stress was set to be 90% of yield or as determined by experience, as for the case of the superconductor. A good solution was one that had stress levels less than the allowable within the materials, maintains compressive loading of the coil and ensures the coil-to-key and coil to collar contact. The development of a gap along any of the coil surfaces is to be minimized, thus lowering the possibility of coil motion and likewise, unwanted coil quenches. Typical solutions took 3 days to solve on a Dell Precision 690 workstation with 3GB RAM.

V. RESULTS

Fig. 4 shows the stress in the cold mass due to the room temperature and final cool down to 4.5 K, taken at the mid section of the magnet. The amount of hoop stress in the force collar at 4.5 K is 38 MPa. The amount of thermal contraction in the axial direction is 18.4 mm (end to end). The outer radius of the force collar contracted by 3.2 mm and the collar/coil interface contracted by 2.2 mm radially. The azimuthal stresses and the radial stress at the maximum magnet excitation setting are shown in Fig. 5.

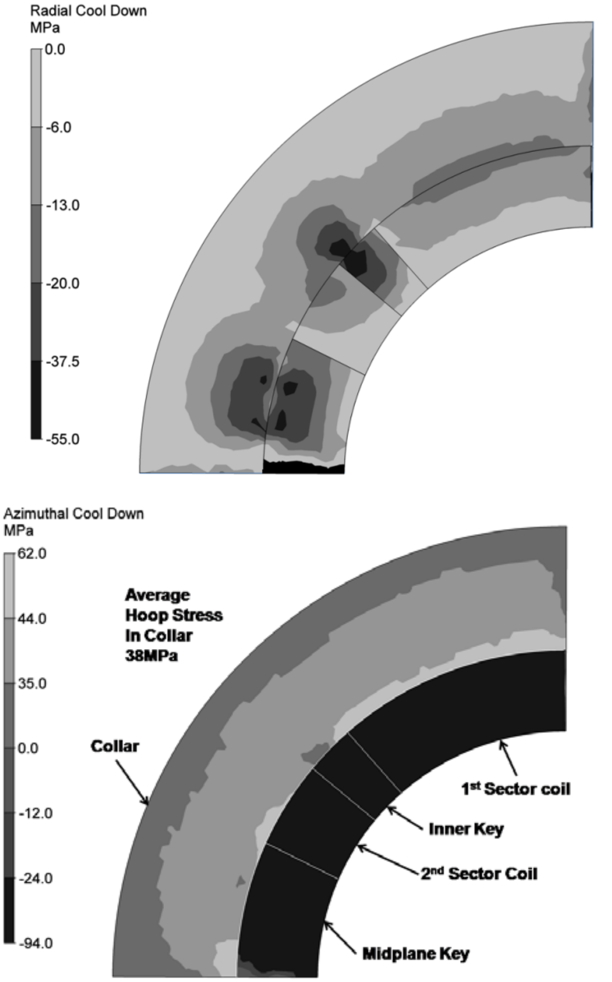

Fig. 4. Stresses at the midplane cut of the SHMS Dipole due to cooldown from room temperature to 4.5 K. Top: Radial Stresses, Bottom: Azimuthal Stresses.

Fig. 6 shows the compressive loadings on at a few nodal locations along the coil/key boundary. The first points are after cool down to 4.5 K, the second points are at 11 GeV and the last points are at the maximum excitation. The coil remains under compressive loading up to the highest current excitation, which is ~18% above the 11 GeV setting.

The maximum current excitation of 5300 A.Turns/cm^2 yielded a von Mises stress of 170 MPa in the force collar. The inner and midplane stainless steel keys experience maximum von Mises stress of 300 MPa, while the end key had a peak stress, at the end, along the inner diameter, and along the median plane of 590 MPa. The coil's maximum principal stress were 135 MPa (tensile) along the hard bend of the 2nd sector coil and -64 MPa (compressive) at the outer edge of the hard bend of the 1st sector coil where it reacts against the end key. The maximum shear stress in the coils was 149 MPa in the area of the maximum tensile stress. The largest amount of coil movement due to Lorentz forces, after cooling down, was 1.43 mm occurring along the straight section of the vertical midplane.

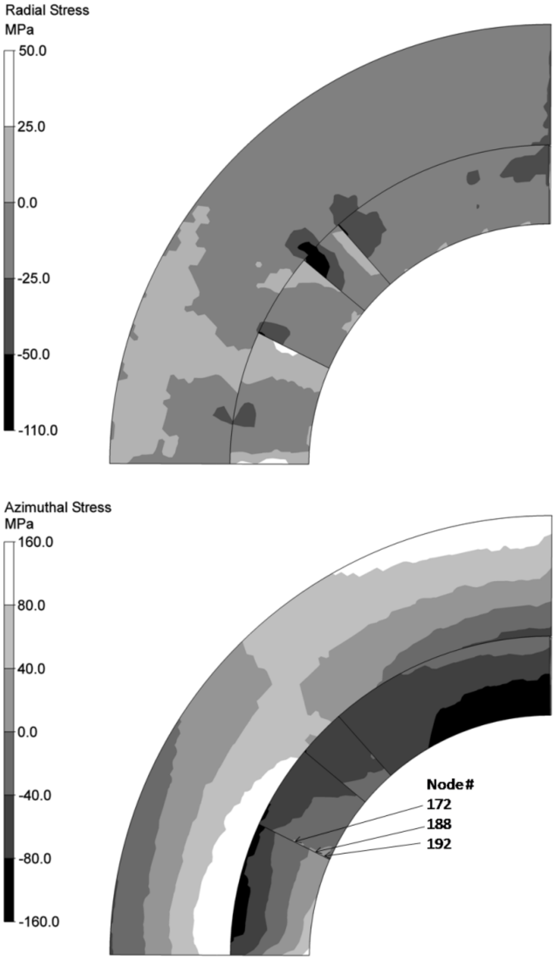

Fig. 5. Stresses at the midplane cut of the SHMS Dipole for the 5300 A.T/cm^2 excitation. Top: Radial Stresses, Bottom: Azimuthal Stresses.

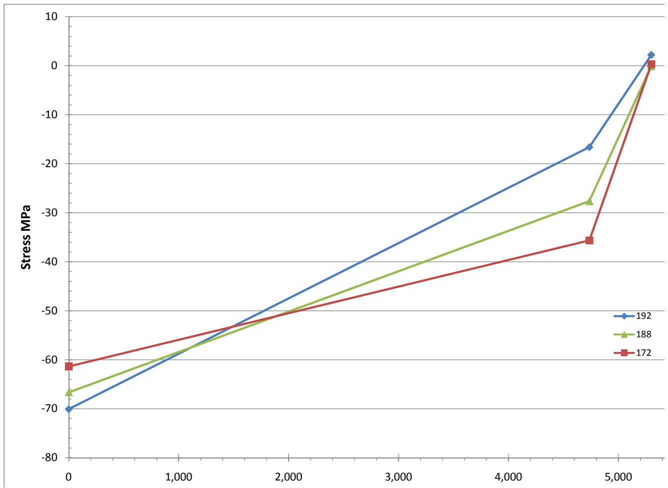

Fig. 6. Chart showing compressive loading of the 2nd sector coil against the midplane key for the three load cases.

VI. CURRENT WORK

Results from the FEA analysis of the force collar are guiding the design of mechanical details such as incorporating helium cooling channels, the locations and details of the conductor splices between pancakes and coils, current lead and signal wire extraction, and attachment of the cold mass components. Due to a portion of the magnet's 19.8 MJ stored energy being deposited into the aluminum force collar as the result of eddy currents during a fast discharge of the magnet, the force collar will need to be partitioned and its segments electrical isolated from each other. The amount of energy deposited into the force collar ranges from 1.54 MJ for a single, continuous solid cast collar, down to 0.0122 MJ for a collar composed of 24 insulated segments of 6" thick plates. These designs will be evaluated for their mechanical reliability, enhancement to the successful operation of the magnet, as well as their cost impact. The JLAB reference design is expected to be completed in time for a call for proposals by the end of this calendar year.

VII. CONCLUSION

A finite element analysis of the force collar for the SHMS Dipole magnet of Hall C is presented. The design, evolving over several FEA studies, satisfies the requirements of maintaining coil compression, preventing unwanted gaps from developing, maintaining an acceptable of level of stress and meets the spatial requirements set forth by the layout of the SHMS within Hall C. The mechanically clamped, cryostable coil will greatly decrease the occurrence of unintended quenches in the magnet, and will result in a successful superconducting dipole magnet for JLAB's 12 GeV experimental program within Hall C.

VIII. ACKNOWLEDGMENT

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