Engineering Study of the Sector Magnet for the Daeδalus Experiment

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***Abstract*—The Daeδalus experiment seeks to evaluate neutrino scattering effects that go beyond the standard model. Modular accelerators are employed to produce 800 MeV proton beams at the megawatt power level directed toward a target, producing neutrinos. The Superconducting Ring Cyclotron consists of identical sectors (currently 6) of superconducting dipole magnets with iron return frames. The Daeδalus Collaboration has produced a conceptual design for the magnet, which, after several iterations, is the current best design that achieves the physics requirements of the experiment. The main purpose of the analytical effort, results of which are presented here, is to develop a viable engineering design satisfying requirements to the superconductor, as well as structural and cryogenic requirements. The work includes proposed conceptual approaches, solid modeling and analyses for the conductor and winding pack design, high-temperature superconductor and copper current leads for the magnet, structural design of the magnet cold mass, cryostat and warm-to-cold supports, cryogenic design of the magnet cooling system, and magnet power supply sizing. A description of the winding pack design, structural analysis, and cryogenic system is reported.**

***Index Terms*—Daeδalus experiment, finite element analysis, superconducting ring cyclotron (SRC), supercritical helium (SCHe).**

I. Introduction

THE engineering approach to the Superconducting Ring Cyclotron (SRC) used for the Daeδalus experiment starts with the conceptual design of the magnet, as shown in Fig. 1. It then addresses the manufacturability of the parts related to the cold mass, cryostat and support structure. The structural design includes a manufacturable concept for: (1) the coil case and warm-to-cold supports that hold the superconducting coil in place, and (2) the cryostat surrounding the cold mass.

The SRC has six sectors, each of which has two superconducting (SC) coils, electrically in series, within one cryostat surrounded by an iron return yoke. Each coil is contained in its own coil case and the two coil cases within a sector are connected (and the electromagnetic forces reacted) by columns through the midplane. The cryogenics are common at the inlet and then split to the two coils. The SRC has similarities with the RIKEN design [1] and there are several design details where the Daeδalus SRC differs from the RIKEN design, including:

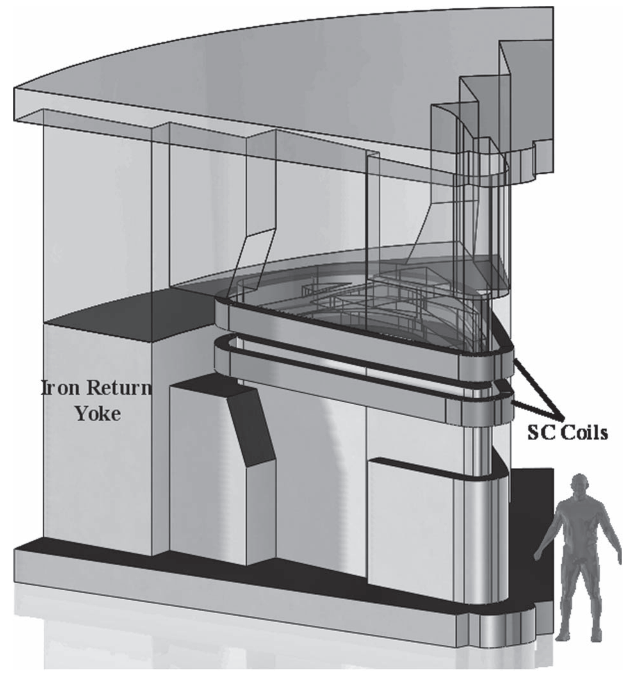

Fig. 1. Schematic of one sector of SRC showing two SC coils and the iron return yoke. The top half of the iron return yoke is transparent.

- NbTi SC cable in Cu channel;
- Double-pancake winding;
- Conduction cooled sandwich coil scheme with pairs of double pancakes (quadro pancakes) interlaced by Stainless Steel (SS) cooling plates cooled by supercritical He flow in parallel channels;
- Vacuum pressure impregnation (VPI) of the stack comprised of the quadro pancakes and the cooling plates and wrapped into the ground insulation to form a solid coil winding block;
- A special procedure of clamping and welding the walls of the SS coil case around the coil to eliminate the gaps and possible slipping at the coil to coil case interfaces;
- SS cooling and structural elements of the cold mass and copper conductor stabilizer to minimize the differential thermal contraction of the materials comprising the cold mass;

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TABLE I
SRC PARAMETERS

Coil Cross Section	16 x 31 cm^2	Current Density	35 A/mm^2
Sector Stored Energy	53.3 MJ	Sector Iron Mass	830 tons
Sector Height	6.0 m	Peak field	4.37 T
Iron Outside Diameter	14.6 m	Operating Current	4887 A
Coil Average Length	10.85 m	Operating Temp	5.0 K

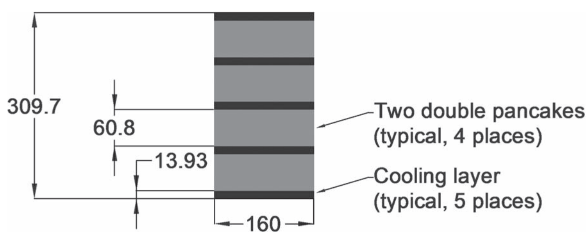

Fig. 2. Winding pack cross-section envelope consisting of four sets of two double (aka, quadro) pancakes sandwiched by five cooling layers. Dimensions are in mm.

- Structural SS Coil Case reinforced by stiffening boxes to reduce sagging over long unsupported coil spans bridging over the beam chamber space;
- Cold mass support using only SS support links.

Detailed technical discussion of the engineering approach to the Daeδalus SRC cyclotron can be found in [2] and the most important topics are highlighted here. These include the basics of the winding pack design, structural analysis and cryogenic system design. Ultimately, from this conceptual design cost estimates can be made.

II. Winding Pack Design

Table I summarizes the key parameters of the SRC. This section provides a conductor and winding pack arrangement to achieve the desired cross section (16 cm $\times$ 31 cm), current density (34.68 A/mm^2) and a per sector stored energy (53.3 MJ). The winding pack envelope is shown in Fig. 2 and consists of 4 sets of double pancake windings, interleaved with and contained at the top and bottom by a total of 5 cooling plates.

The conductor consists of 12 strands of 1.25 mm diameter NbTi superconductor with a copper to superconductor ratio of 1.3 : 1 soldered into a copper channel for stability and quench protection. With the stabilizer proposed, dump voltages during quench will be less than 600 V with a hot spot temperature less than 120 K in RRR50 copper. Achieving this performance will require quench detection using voltage taps and an active protection circuit utilizing a dump resistor of about 0.12 Ω to be switched across the terminals of the sector on detection of a normal zone. The current sharing temperature of the chosen conductor at the location of the 4.37 T peak field in the winding is 6.4 K when carrying the nominal 4887 A conceptual design current necessary to meet the ampere-turns requirement of the magnet. Thus, the superconductor temperature margin will be about 1.4 K when the conductor is operated at up to 5.0 K. This elevated operating temperature over the approximately 4.5 K temperature of the He coolant allows for steady, uniform ionizing radiation induced heat load into the winding pack of approximately 46 μW/g. A cooling arrangement is also described, which assumes a 1.33 cm thickness for helium carrying cooling plates to remove heat generated in or absorbed by the winding pack. Optimization of the cooling plate design is a task for later.

III. Structural Analysis

The goals of the structural analysis are to demonstrate that the cryostat and the coil case are not overstressed and there is less than 5 mm displacement around the beam chamber during: (1) cool-down to 4 K, (2) normal operation at 4 K, and (3) fault condition at 4 K. The fault condition simulates a short in the lower coil during fast dump in the upper coil. The flux is conserved during this event, so the current in the lower coil increases and this is accounted for by scaling Electromagnetic (EM) loads to this coil by 1.3$\times$. Accurate scaling requires a meticulous analysis and for this conceptual design our experience that such forces rarely exceed 1.2$\times$ leads us to confidently apply the conservative 1.3$\times$ scaling factor. The EM simulations include the iron yoke and superconducting coils to generate the Lorentz body forces input to the coils in the mechanical analysis. The mechanical simulations of the cold mass couple the EM loads with thermal loads to calculate the displacements and stresses as well as the forces in the warm-to-cold struts. The forces in the warm-to-cold struts are used to size the cross section of the struts. The forces in the warm-to-cold struts and atmospheric pressure are applied to the cryostat to analyze its structural integrity. Dynamic loads (e.g., earthquake) are not considered during this conceptual design phase.

The structural analyses use ANSYS to calculate the system response of the cold mass resulting from: pre-loading of the warm-to-cold support, gravity, Lorentz body forces on the coils and thermal loads [2]. The geometry input to ANSYS is shown in Fig. 3 and includes the coils, coil cases, and warm-to-cold support links. The warm-to-cold support links are modeled as linear springs with one end attached to the cryostat the other to the cold mass. The support links are numbered in Fig. 3 and the direction each constrains cold mass displacements are listed in Table III. The material properties and failure criteria used in the analyses are summarized in Table II.

A. Cold Mass

The displacements and stresses are used to evaluate the cold mass. The displacements are of interest for two reasons. First, the coil position creates the desired magnetic flux distribution and displacements should be minimized. Second, there will be tight clearances between the iron, cryostat, thermal radiation shield and coil support and we want to prevent the displacements during cool-down and coil charging from closing any initial gaps between the parts.

The analyses predict that in the region of the beam chamber, the gaps are acting to open by 1.5 mm during normal operation and 4 mm during fault condition. This is less than the 5 mm limit obtained from clearances between parts previously described. Peak axial deflections of 16 mm occur along the outside perimeter of the coils during fault condition. While these displacements are large, increased clearances can be designed

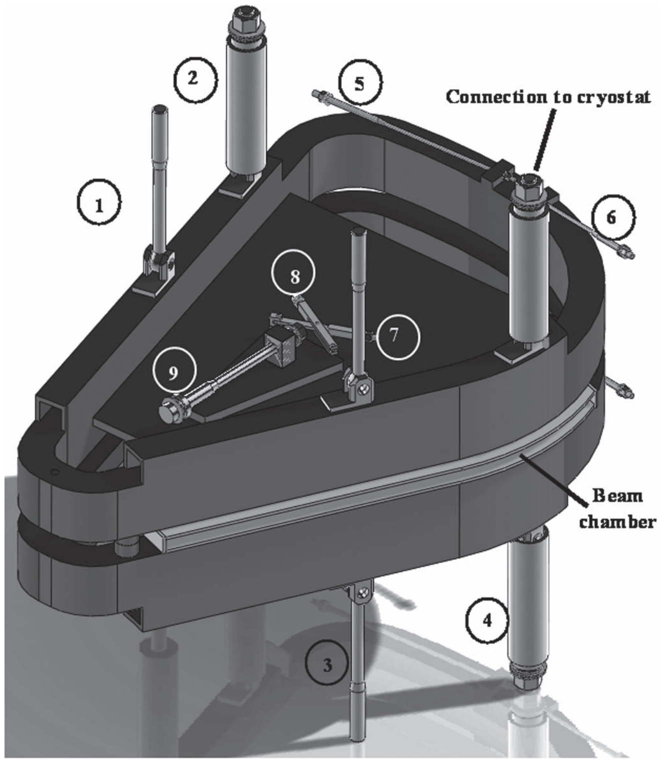

Fig. 3. Coil cases surrounding SC coils with numbered warm-to-cold support links. Supports #4 and #9 shown connection to cryostat.

TABLE II
TEMPERATURE DEPENDENT MATERIAL PROPERTIES

Material	Temp (K)	Secant CTE (10^{-6}/K)	Elastic Modulus (GPa)	Poisson's Ratio	Failure Stress, $\sigma_{UTS}/3$ (MPa)
Coil, Hoop	295	11.5 [3]	90.2 [3]	0.33	
	4	0	103 [3]		
Coil, Radial	295	13.1 [3]	18.9 [3]	0.33	
	4	0	38.6 [3]		
Coil, Axial	295	12.7 [3]	19.5 [3]	0.33	
	4	0	40 [3]		
St. Steel 316	295	10.3 [4]	193 [4]	0.27 [7]	184 [8]
	4	0	205 [4]		460 [8]
Ntronic 50	295	10.3 [5]	193 [5]	0.25	371 [6]
	77	0	205 [5]		519 [6]

at this location. Lateral deflections are small indicating the azimuthal supports sufficiently constrain the coils from rotation.

The coil is allowed to slide within the coil case and the combination of sliding with large shear can cause localized heating and/or delamination of fiberglass ground wrap leading to coil quench. Therefore, it is important to know the amount of shear between the bodies while they slide against each other. A friction coefficient of 0.1 is applied to all four sides of both coils. The analyses indicate all surface shears are < 5 MPa and that they are typically < 2.5 MPa, so such stresses are not concerning in this design.

TABLE III
MINIMUM REQUIRED DIAMETER OF WARM-TO-COLD SUPPORT LINKS TO BEAR MAXIMUM LOADS

Support Link #	Maximum Load (MN)	Minimum Diameter (cm) at 290 K	Minimum Diameter (cm) at 4 K	Link Direction
1	0.62	4.61	3.90	Axial
2	2.85	9.89	8.36	Axial
3	0.61	4.58	3.87	Axial
4	2.35	8.98	7.59	Axial
5	0.1	1.85	1.57	Azimuthal
6	0.01	1.00	1.00	Azimuthal
7	0.01	1.00	1.00	Azimuthal
8	0.15	2.27	1.92	Azimuthal
9	1.88	8.03	6.79	Radial

Stress contours on the coil case indicate $> 95\%$ of the coil case bears < 250 MPa, well below the 460 MPa failure stress. Peak stresses of 521 MPa occur during fault condition and in the location immediately surrounding the warm-to-cold supports. These locations are singularities and typically do not provide reliable data. Welds must be kept away from these locations and additional supports may need to be included in the detailed design. Therefore, the coil case design safely bears all loads and prevents too much coil displacement in the vicinity of the beam chamber.

B. Warm-to-Cold Supports

The warm-to-cold support links will carry the weight and EM forces while maintaining the position of the cold mass. The support links are arranged and designed so that they carry only tensile or zero loads. The peak load they carry during all conditions is critical to properly size each strut in order to preserve their structural integrity, while minimizing the heat load to the liquid helium. The sizing of the warm-to-cold struts uses the largest force calculated during the structural analysis in each strut among: (1) cool-down to 4 K, (2) normal operation, and (3) fault condition.

Table III summarizes the maximum load for all three operating conditions in each warm-to-cold support link. Table III also indicates the minimum diameter for both the warm and cold ends of the support links based upon the failure stress in Table II. For example, Nitronic 50 radial Strut #9 requires a minimum diameter of 6.79 cm at the cold end and 8.03 cm at the warm end. It is recommended that a minimum diameter of 1.0 cm rod be used for Struts #6 & # 7 as they typically do not carry any tensile loads, but should be included in the design for any unforeseen circumstances. It should be noted that the support struts do not necessarily need to be circular.

C. Cryostat

The cryostat is modeled using 3-D shell elements to keep the element count at a reasonable number. The loads applied include the warm-to-cold supports, atmospheric pressure, gravity and contact with the iron yoke.

Stress contours of the cryostat indicate $> 90\%$ bears stress < 184 MPa, the failure stress. The locations where the stresses exceed failure criteria are where the vertical shell elements meet the horizontal shell elements. The disadvantage of using the shell elements is that they do not carry normal stress (plane stress assumption) which prevents accurate results when high forces are applied normal to the shell. Therefore, the data in these regions are not physical. These locations should be noted and can be strengthened very easily using fillets and ribs.

The tubes surrounding the axial warm-to-cold struts bear compressive loads that can lead to buckling of the tube. This can easily be prevented using external ribs and they must be designed such that there is no interference with the iron. The buckling analysis of the tubes for both normal operation and fault condition should be performed with a more detailed design of the cryostat.

IV. Cryogenic System

The superconducting coil and associated cold mass are cooled to 4.5 K via forced flow of supercritical helium (SCHe) within a closed loop at 3.0 atm and is called the cold stage. In parallel, liquid nitrogen (LN2) at atmospheric pressure cools the warm-to-cold support links, current leads and the Multi-Layered Insulation (MLI) to 77 K and is called the warm stage.

SCHe enters each of coils at 4.5 K, 3.0 atm, and a flow rate of 15 g/s. Upon entering the coil, the flow splits into 5 parallel paths at nominally 3 g/s each and accepts a total thermal load of approximately 3.2 W. The flow is recombined at the end of the coil and exits at 4.6 K without any ionizing heat load into the coil. The SCHe then passes through a series of heat exchangers at the base of 7 of the 9 warm-to-cold supports where it accepts a load of 16.2 W, exiting slightly above 4.97 K. Flow exiting the support heat exchangers then passes through a pump where it accepts a load of 1.6 W, exiting slightly below 5.0 K. Calculation of the pump load assumes a pump efficiency of 75% and a total pressure drop per coil of 10 kPa. Finally, the SCHe enters the refrigerator heat exchanger where it exchanges heat with a 4.2 K liquid Helium bath. The SCHe enters slightly below 5.0 K and exits at 4.3 K. The heat exchanger is a simple coiled 12.7 mm inner diameter tube 1.4 m in length.

The breakdown of the 3.2 W thermal load in each coil consists of contributions from: (1) 5 kA current leads, (2) MLI insulation, and (3) heat from 9 mechanical supports. First, the current leads are binary current leads, with a warm section vapor-cooled by LN2, and a cold section composed of high temperature superconductor (HTS). The conduction heat leak through HTS is 0.6 W per coil. Second, the MLI around the cold mass consists of two stages: an LN2 intercepting layer at 77 K and a 4.5 K layer at the cold mass. The heat leak from 77 K to 4.5 K that is deposited into the SCHe inside the coil is 0.5 W. Third, the remaining heat leak to the SCHe in the coil comes from 9 warm-to-cold supports. Note that the heat exchangers accept 16.2 W and there is an additional 1.6 W heat leak past the heat exchangers and into the coil. The 2 supports without heat exchangers have a smaller diameter and only contribute 0.5 W to the SCHe in the coil, so the total thermal load to the coil from the warm-to-cold supports is 2.1 W. This assumes the conductance of the heat exchanger is 10 W/K and the thermal resistance from the bottom of the support to the SCHe flow is on the order of 1 K/W. This amounts to a 3.2 W (0.6 W + 0.5 W + 2.1 W) heat load to the SCHe flowing in the magnet coil.

The warm section heat load comes from the cryostat through the MLI, current leads and warm-to-cold supports. There is 125 W per lead, corresponding to 5.6 l/h of LN2. The heat leak from the 300 K cryostat that is intercepted at 77 K is 30 W. The LN2 load for all 9 supports is 201 W, corresponding to 190 W from 7 supports with 77 K intercepts located at 1/3 of their length and 11 W from 2 supports with 77 K intercepts only.

The overall refrigeration need per coil is 371 W at 77 K (125 W for a single current lead, 30 W for the cryostat intercept, 201 W for the supports, and 15 W for transfer line leakage) and 22 W at 4.2 K (3.2 W for the magnet coil, 16.2 W for the supports, 1.6 W for the pump, and 1.0 W for transfer line leakage). For 6 sectors, each with 2 coils, this results in a total of 4.45 kW at 77 K and 264 W at 4.2 K. The total flow rate of SCHe is 180 g/s.

V. Recommended R&D

We believe the conceptual design developed provides a manufacturable SRC; however, there are some additional R&D tasks that will further reduce manufacturing and magnet performance risk going forward. These tasks are (in no particular order):

- Study the large diameter axial support links performance,
- Coil case fabrication and fit-up,
- Helium flow arrangement,
- Tie-plate and cryostat assembly sequence,
- Magnet quench performance.

VI. Conclusion

A conceptual design is developed for the SRC for the Daeδalus experiment that demonstrates manufacturability, structural integrity, and a cryogenic system. This conceptual design is sufficient for a cost analysis and is ready for the next design stage.

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