LBL-11579

CONF-8009SC--21

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Engineering & Technical Services Division

To be presented at the 1980 Applied Superconductivity Conference, Santa Fe, NM, September 29 - October 2, 1980

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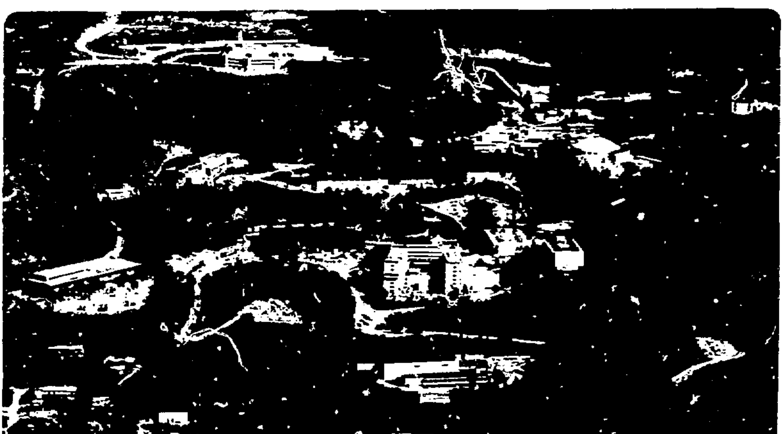
September 1980



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

A LARGE SUPERCONDUCTING DIPOLE MAGNET FOR THE HEAVY ION SPECTROMETER SYSTEM (HISS)*

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ABSTRACT

The magnet is the central element of the spectrometer system, where it will be used to momentum-analyze secondary heavy-ion fragments at relativistic energies. High bending power and large acceptance apertures are necessary for simultaneous multiple fragment measurements. Free access over large angles to the magnetic volume is recessary to accommodate a variety of experiments and particle detection systems. The magnet has pole tips two meters in diameter, a one meter gap, and a maximum central field of three tesla. The coils are designed to be cryostable, with a helical winding pattern. A window-frame steel yoke limits the stray field and augments the central field. In terms of its magnetic energy of 55 MJ it will be one of the twelve or so largest magnets in the world. Unusual engineering features of the magnet are the large magnetic forces (one million kg) between the coils at liquid helium temperature and the yoke at room temperature, and the large diameter (7 m) hydraulic cylinder base to provide rotation for the magnet. The magnet will be installed at the BEVALAC heavy-ion facility at Lawrence Berkeley Laboratory.

GENERAL DESCRIPTION

The magnet steel from the University of Michigan 83 inch cyclotron became available to the HISS project before engineering work on the Conceptual Design Report commenced. Along with the requirements of experimenters, this 300 tons of steel determined the general configuration of the magnet. Steel spacers were added to the return legs to enlarge the gap to 1 m (40 in.) to meet the physics requirement for a large vertical aperture. The 2.1 m (83 in.) dia. poles were used without modification. To carry the return flux associated with the increased central field of 3 tesla, 265 tons of steel were added to the sides and ends of the yoke, limiting the mid-plane stray field to about 0.1 tesla at a distance of 3 m from the magnet centerline. By space conserving design effort, the coil, cryostat and support structure were kept from intruding into the aperture space. The need for free space in this region also precludes the use of structurrs to tie the two coils together mechanically.

Figure 1 shows the overall layout of the magnet, and Table I lists the major parameters of the magnet.

The basic mode of experimentation with the magnet in the large aperture configuration will use ray-tracing methods. Thus the requirement on field distribution is that it be sufficiently smooth to be reconstructable

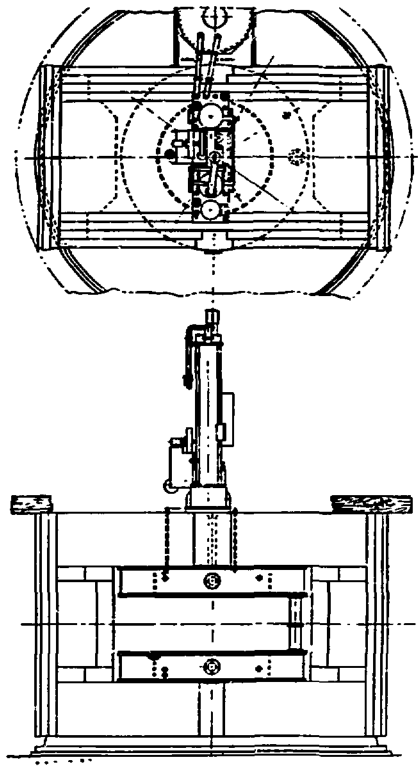


Fig. 1 - Overall layout of the magnet.

TABLE 1. HISS Magnet Parameters

Central field	3 tesla max. DC	Conductor current density	5000 A/cm^2
Field on conductor	4.55 tesla max.	Magnetic energy	55.2 MJ
Coil, superconducting	Nb-ti in copper matrix, in liquid helium at 4.6°	Yoke: window frame type, weight	5.13 x 10^5 kg (565 s.t.)
Conductor cross section	1.19 cm x .4 cm	Pole diameter	2.1 m (83 inches)
Copper/superconductor ratio	19:1	Magnet gap	1.0 m (40 inches)
Ampere turns	5.12 x 10^6	Unobstructed azimuthal angle	110° at front and back
Current	2200 A	Mounting	Rotatable base
		Magnet total weight	5.67 x 10^5 kg (625 s.t.)

* This work was supported by the U. S. Department of Energy under Contract No. W7405-Eng-48.

in the data processing computer from data obtained by a reasonable number of field monitoring sensors. Future use as a focussing spectrometer can be accomplished by the addition of shaped pole tips with some sacrifice of magnet aperture.

Figure 5 shows the POISSON computer program plot of the field lines. Figure 8 shows the mid-plane field distribution.

CRYOSTABILITY PARAMETERS

Selections of the conductor size and current level were made using the analyses of Hay and Tarrh[3] and Maddock, et al[4]. The calculations assumed a rectangular conductor with a width to thickness ratio of 4:1, with a cooling area in contact with liquid helium equal to one-half of each of the long faces of the conductor. The calculations indicated a relatively broad optimum near 2000 A, with a current density in the conductor of about 5600 A/cm^2. A current level of 2300 A was chosen because the larger conductor would require fewer turns and would stack better on the large diameter coil. The current later dropped to 2200 A with a more compact design. The conductor size was increased slightly to provide a more conservative current density of about 5000 A/cm^2. The cross section of the conductor is shown in Figure 4.

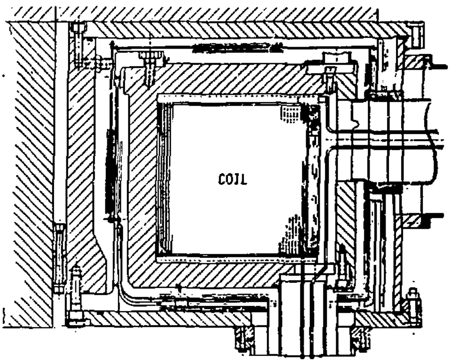


Figure 2. Cryostat cross section.

The conductor operates in a maximum field in the coil of 4.55 tesla at a temperature of 4.6 K. The critical current test value specified to the conductor manufacturer was 3400 A in a field of 5 tesla at 4.2 K. The copper to superconductor ratio as delivered was about 19:1. The Residual Resistivity Ratio of the substrate was quoted to be 180:1 in the form of 1.27 cm dia. rod, after starting with ingot material with RRR better than 220:1.

The coil winding matrix is shown in Fig. 3. The final design provided more wetted area of the conductor than was assumed in the above optimization. The cross section of the coil, support and cryostat is shown in Figure 2.

The operating hoop stress in the conductor is 66.2 MPa (9600 psi). Some work hardening was left in the conductor in order to keep the proportional limit above this value. The substrate resistivity including magneto-resistance was estimated to be 3.5 x 10^{-8} ohm cm. The cross-section area of copper in the conductor is .464 cm^2. The wetted surface area per unit length is 1.67 cm. The heat transfer rate to liquid helium required for stability is then .22 w/cm^2 (ignoring heat transfer along the length of the conductor and turn-to-turn.

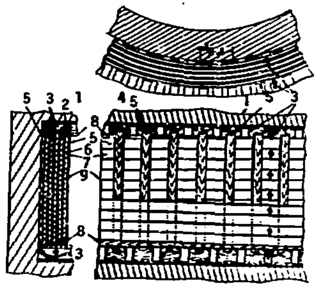


Figure 3. Coil matrix. 1) Bobbin, stainless steel, type 304. 2) Bobbin flange insulator, NEMA G-10. Alternate grooves for helium admission and layer-to-layer insulators are provided in these pieces. 3) Helium passages, including those in item 2 and item 5. 4) Groove; positions insulator (item 5) at a center-to-center dimension of 3 cm at the coil inside diameter. 5) Layer-to-layer insulator, 12 mm thick x 95 mm wide, made of NEMA G-10. It also creates a channel between conductor layers for helium flow. 6) Superconductor, Ti-Nb. 7) Conductor (stabilizer) Cu OFHC grade. 8) Helix angle wedge, NEMA G-10. 9) Turn-to-turn insulator, NOMEX type 410, .25 mm thick, is glued to one edge of the conductor. NOMEX is an aramid paper made by DuPont.

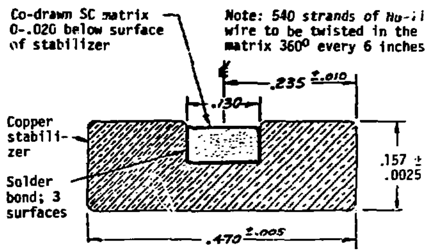


Figure 4. Coil conductor cross section.

QUENCH PROTECTION PARAMETERS

Appearance of resistive voltage in the coil will be detected by bucking one coil against the other. The quench detector will switch out the power supply and the magnet will discharge through a dump resistor, hardwired to the coil.

Assuming only a small length of conductor goes normal, the following condition must be met[5] to keep the hot spot temperature less than 300°K:

$$C_u^{-2} \int_{4^oK}^{300^oK} I^2(t)\, dt \le \int_{4^oK}^{300^oK} C_p/\rho \; dT$$

For high conductivity copper the right hand integral equals $1.4 \times 10^{17}\ A^2\ s\ m^{-4}$. C_u is the cross-sectional area in the conductor ($= .464 \times 10^{-4}\ m^2$), and I is the time variable coil current during discharge.

$$\text{Then:} \quad \int_{4^\circ K}^{300^\circ K} I\,(t)\ dt \ \leq\ 3.01 \times 10^8 \ .$$

Assuming exponential decay of the current (a constant inductance, L, of the coil; and a constant resistance, R, of the dump resistor) the last integral can be shown to be equal to $E\ I_0/V_0$, where:

E = stored energy in the magnet = 55.2 MJ.

I_0 = maximum operating current = 2200 A.

V_0 = initial and maximum voltage during discharge, calculated from the above relation to be 404 V .

$R = V_0/I_0 = .183$ ohms .

Calculating L from $E = \frac{1}{2} L\ I_0^2$,

L = 22.8 henry.

The exponential decay time = $L\ I_0/V_0$ = 124 sec.

COIL STRESSES

The magnetic characterization of the magnet was determined using a computer program called POISSON.[6] POISSON was used in the variable mu, axisymmetric two dimensional configuration. Figure 5 shows a contour map of the vector potentials in the plane of the return leg. The cutout in the upper right of the model provides for the magnetic reluctance in the non-axisymmetric portion of the return leg. The greatest field in the conductor, 4.55 tesla, is at the mid-point of the inner layer of the coil. The maximum field in the iron, 4.56 tesla, is directly adjacent in the pole tip.

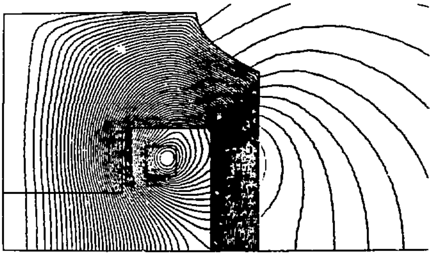


Figure 5. POISSON computer program plot of field lines.

The coil winding scheme was determined using a program called STANSOL-II.[7] This program uses thick-cylinder equations to determine the deflections and stresses of a radial section of the coil due to the effects of winding preload, thermal contraction and magnetic loading. Due to the azimuthal interruptions of the G-10 spacers (cooling channels), the orthotropic material capability of the program was used to prevent hoop stress being modeled in the spacers. Fields in the coil were taken directly from POISSON as input for this program.

Limiting requirements for the proper operation of the coils are: that no separation of the inner layers of conductor occur during operation; the conductor is stressed less than the proportional limit of 68.95 MPa (10 kpsi); and that the bobbin does not buckle due to the integrated winding preload plus differential thermal contraction. A maximum tension of 2.21 kN (475 lbs.) was available to wind the conductor. Further control of the coil is provided by an additional 8 layers of aluminum 5056-H32 of a smaller section (3.18 mm x 12.70 mm) wound at 2.21 kN (475 lbs.) tension.

Figures 6 and 7 show the radial pressure and hoop stress distribution of a mid-coil radial section. This section has a maximum force magnitude and gradient, and thus shows the limiting constraints. Al 5056-H32 was chosen for its high yield strength and high electrical resistivity, to minimize inductive heating during a quench. The aluminum is wound without spacers for cooling. This provides a longer thermal time constant for the aluminum, thus reducing the stress on the bobbin during cooldown.

HISS dipole magnet horizontal section.
Pre-tension = 475 lbs.
8 layers of aluminum .125 x .5 inches.

Figure 6.
Hoop stress.

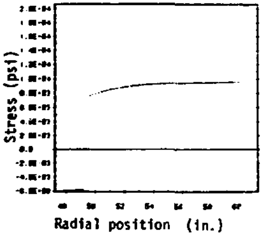
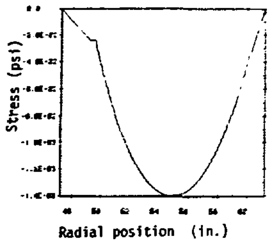


Figure 7.
Radial stress.



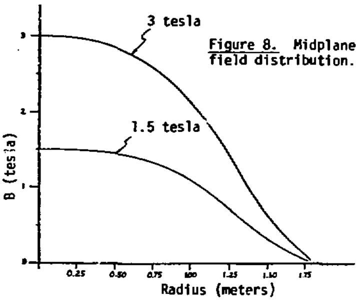


Figure 8. Midplane field distribution.

COIL SUPPORT STRUCTURE

A number of coil support systems were studied to carry the vertical electromagnetic force of 1.10 x 10^7 N, attracting the coil to the yoke, and the lateral force. The design chosen was based on a single cylinder of titanium alloy (Ti-6Al-4V) carrying the vertical load in axial tension, with a liquid nitrogen cooled thermal intercept at about one-quarter of the length from the flange at room temperature.

At the time of fabrication, the delivery time for Ti alloy plate was more than 9 months, and stainless steel 304 LN was substituted. The cylinder wall thickness was tapered according to the variation of the steel yield point with temperature. This design is shown in Figure 2.

The lateral magnetic forces were found to be a non-linear function of the displacement of the coil axis from the pole and yoke center-line. The maximum gradient was much less than the lateral stiffness of the support cylinder. At a displacement of .6 cm the lateral force is about 45 kN.

ROTATABLE BASE

The base is composed of a piston and a cylinder. The base diameter is 6.58 m (21 ft. 8 in.) selected to protect the building floors against loads of more than 167 kPa (3500 lbs./sq.ft.)

Normally, the piston rests at the bottom of the shallow cylinder. When the magnet must be rotated, oil is pumped under the piston until it, with the magnet, floats free of the cylinder bottom plate. Rotation is accomplished using a circular gear rack and pinion.

Only 1.49 m (58.75 in.) of the base piston projects from under the magnet yoke (front and back); therefore, parallel beams 2.54 cm x 22.86 cm (1 in. x 9 in.) properly spaced and welded to a flat 3.8 cm (1½ in.) circular plate, will raise and support the rotating weight, 559 metric tons (616 short tons), when hydraulic fluid at 1.6 x 10^5 pascals (23.35 psi) is pumped under the piston.

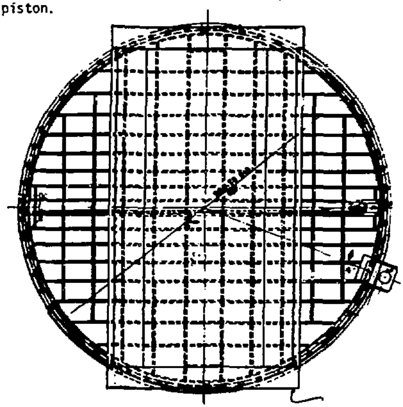


Figure 10. HISS magnet rotatable base plan view. For edge view detail see Figure 11.

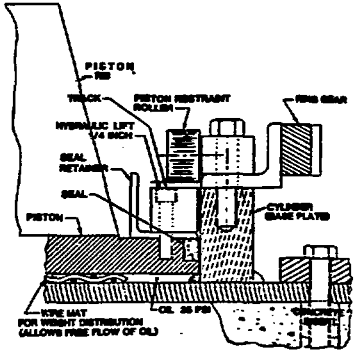


Figure 11. Rotatable base partial cross section.

CONSTRUCTION STATUS ON SEPTEMBER 15, 1980

The magnet yoke and rotatable base assembly is 75% complete.

The coil bobbin assemblies are 45% complete. The first coil bobbin is 90% complete.

The site is being prepared for the assembly of the cryostats. All shop work orders for materials required in the assemblies have been issued.

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