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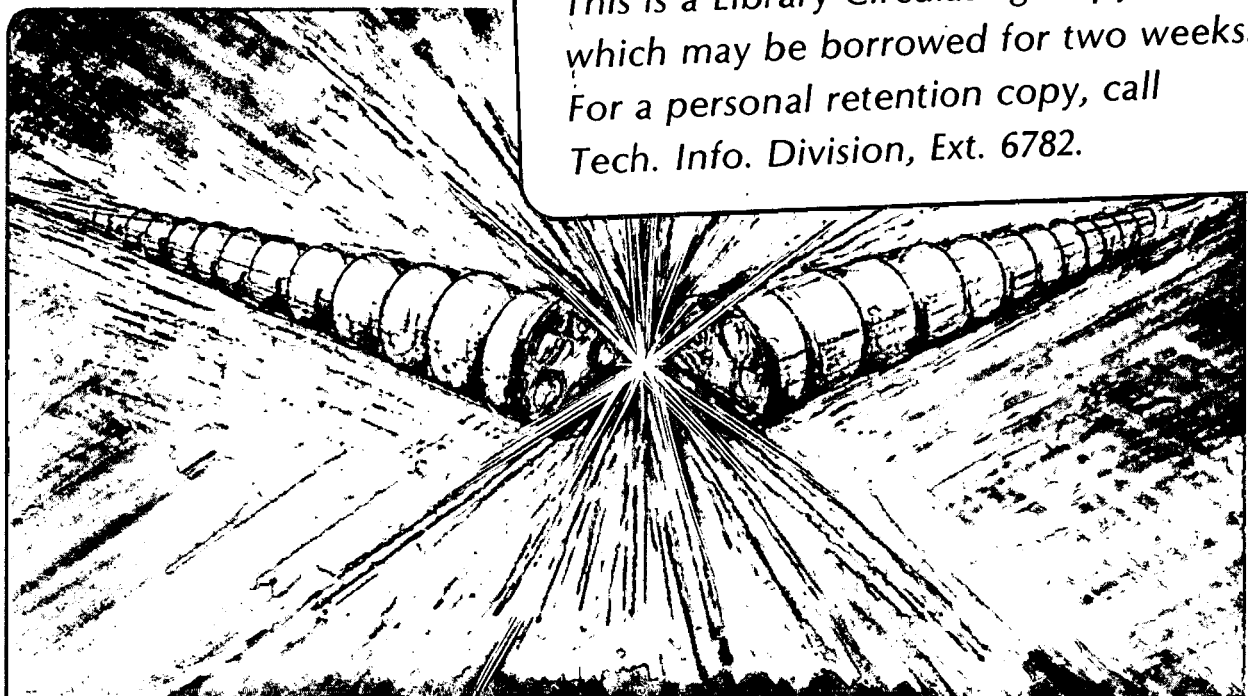
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DISCLAIMER

MAGNET COIL SYSTEM FOR A SUPERCONDUCTING SPECTROMETER (HISS)*

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Summary

The Heavy Ion Superconducting Spectrometer (HISS) facility and coils are briefly described while most of the paper discusses the support structures consisting of flanged doubly tapered stainless steel cylinders having a Z-shaped cross-section with average diameter of approximately 2.35 meters and height of approx. .49 meters. This member serves as a one piece coil support to resist gravitational, seismic, and magnetic forces with an approximate heat leak to helium of 59 watts per cylinder during operation of magnet at 4 degrees K. Maximum magnetic forces on each coil are over 11 meganewtons at 3T excitation. Magnetic forces attracting the coils to the core vary with excitation in direction as well as in magnitude. Radial magnetic forces produce stresses internal to the coil bobbin.

Introduction

The HISS facility is located in LBL's Bevalac experimental area where particle beams as heavy as uranium at energies approaching 1 GeV/nucleon are available.[3] It provides a high field large gap high volume magnetic region to momentum analyze heavy particles and fragments. A general description has been given by Wolgast.[4]

Magnet

The magnet has a 1 meter gap, a max. central field of 3 Tesla, and 2.1 m pole tip diameter. Its total weight is about 5.6×10^4 newtons (625 tons). It is capable of rotation through 180 degrees. At a 3 Tesla field the steel core saturates and stray field in the midplane 3 meters from the pole center is about 0.1T. In order to reduce particle data a field map is required because of the large non-uniformity and extent of stray field. This mapping has been done and the field data stored for use during particle data analysis.

Superconducting Coils

Fig. 1 shows a cross section through the upper coil. Both coils are electrically identical. Each coil is designed to carry 2200 amperes at full field while at 4.6° Kelvin. Each weighs 8.5×10^4 newtons (19,100 lbs) and is supported by cylinder 19F7886 as shown in Fig. 1. The cooling system has been described by Porter,[5] the power supply and quench system by Wolgast.[4] Cooldown from 90K to 4K liquid helium typically has taken eight days using a 400 HP compressor system.

Support Cylinder

The design criteria for the support cylinder were (a) support the coil without excessive elastic or plastic distortion, displacement, or cracking when acted upon by magnetic, gravitational, seismic, or thermal forces; (b) minimize the total cost of cryogenic fluid and equipment; (c) avoid freezing cryostat O-ring seals; (d) avoid condensation on cryostat exterior; and (e) provide an experimental magnetic field region as unimpeded by support as possible (the ideal support would of course have vanishingly small mass and thermal conductivity with great strength, ductility, and fracture toughness).

Various support materials were studied extensively. Fiberglass epoxy, titanium alloy, and various stainless steels were considered. Type 304LN stainless produced to an LLNL specification was chosen due to its favorable low temperature properties and availability. In particular we needed good ductility and fracture toughness coupled with higher yield strength than type 304 would give. Fortunately a piece excess to the LLNL-MFTF program was available to us as were its certifications. Titanium alloy was the preferred choice but had a very long delivery.

A number of support geometries were considered. It would have been desirable to connect the coils to one another mechanically but the connections would have impinged on the high field area and restricted the usefulness of the spectrometer.

Rods were considered but encountered lateral stability problems since both non-linear radial forces due to coil eccentricity relative to the poles and seismic forces had to be considered.

The support cylinder concept was proposed for a bubble chamber conversion by J. Heim (FNL) and developed by Wolgast. Computer stress anaylsis was done by A. Kennedy (LBL). Advantages of the cylinder are: (a) the ability to handle both axial and radial loads while remaining stable; (b) one component restrains all six degrees of freedom; (c) the coil is firmly supported and located relative to the
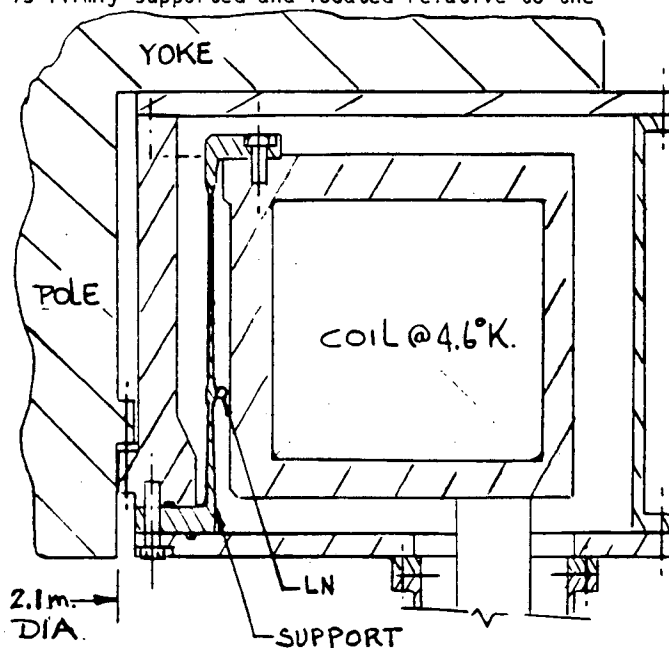
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Fig. 1: Coil System Typical Cross-section
(Upper coil shown) per LBL dwg. 19F8526

vacuum enclosure; (d) the support fits in the required space; (e) the part can be made from a material having predictable properties held to close tolerances; and finally the above design criteria are met. The parts were fabricated in Los Angeles and Oakland commercially.

Forces, Stresses, and Strains

Computer studies of the magnetic forces attracting the coil to the yoke showed that they varied in both size and direction as a function of current. The most severe magnetic axial loading of the support occurs at maximum field and is 1.1×10^7 N (2.46×10^6 lbs). Lateral magnetic forces are estimated not to exceed 45 kN (10,100 lbs).

Strain gages with digital readouts to a VAX 11/780 computer system indicate that the strains (and thus stresses) in the support cylinder are very close to prediction up to 2.4 Tesla fields.

Seismic forces are assumed not to exceed .7 g in a lateral direction thus producing 13,400 lbs per coil.

Thermal Behavior of Coil

The superconducting coil will cool much faster than the coil bobbin. To prevent yielding of the copper matrix coils during cooldown, a maximum differential cooling temperature between the coils and bobbin was calculated. Since the stainless bobbin will cool much more slowly than the superconducting coil, it's cooling rate will be the factor governing cooldown time.

let
σ = stress (support cylinder)
E = modulus of elasticity
ϵ = strain
σ = $E\epsilon$ = $E \Delta L/L$
σ/E = $\Delta L/L$ = (yield stress of coil) - (pre-stress in coil)/modulus of elasticity

$\Delta L/L$ = (8000 psi-5000 psi)/17×10^6 psi = 17.6×10^{-5} in/in

This value of $\Delta L/L$ represents the max. cooldown induced strain allowed.

A graph of thermal expansion for copper and stainless steel was plotted vs. temperature. Using the above calculated allowable strain, a maximum allowable Δ temperature between the coil and its bobbin can be found. The maximum allowable temperature difference between the coil and bobbin between room and LN_2 temperature is 20-25°K. After the bobbin reaches 90°K, there is no limitation to the cooldown temperature. Sensors are attached to the bobbin and inlet cooling gas to monitor the temperatures.[1]

Support Cylinder Analysis

Keeping heat load to a minimum while still maintaining structural strength and integrity are the main parameters used in designing the support cylinder. Because of the non-linearity of yield stress and thermal conductivity as a function of temperature, a Hewlett-Packard system 45B desktop computer was used. The temperature gradient along the support cylinder length was computed using integration techniques. By keeping the design stress throughout the support cylinder to 2/3 of the yield stress, the cross-sectional area of the support cylinder as a function of location was determined for a given temperature range. Hence the optimum design

of minimum area (i.e. minimum heat load) vs. maximum allowable material stress was achieved and the cylinder taper determined.

The mechanical properties including yield point improve as the temperature decreases so the coldest portion is thinnest. Stainless tubing to provide LN was brazed to the cylinders at a calculated point in order to provide a fixed temperature at a known location to intercept heat flux from the room temperature portion while not freezing the O-Ring seals, and to minimize total cost of helium plus LN refrigeration.

Heat Load Calculation Through Support

Q = KA dt/dx watts
K = thermal conductivity of material
A = cross-sectional area, sq. in.
dt/dx = temperature gradient in direction of heat flow, deg. K. per inch.

basic stress equations $\sigma = F/A$ for axial loading.
where σ = stress in cylinder, lb/in^2
F = force acting axially, lbs.
A = cross-sectional area of cylinder, in^2
Since both thermal conductivity and yield stress are a function of temperature, the above can be combined:

$$Q = k(t) A \frac{dt}{dx} \tag{1}$$

$$\sigma(t) = F/A \tag{2}$$

Substituting & rearranging, $Q dx = F \frac{k(t)}{\sigma(t)} dt \tag{3}$

Integrate with respect to x(length) & t(temp.),

$$Q \int_0^x dx = F \int_{t_1}^{t_2} \frac{k(t)}{\sigma(t)} dt \tag{4}$$

Letting L = cylinder length,

$$Q = \frac{F}{L} \int_{t_1}^{t_2} \frac{k(t)}{\sigma(t)} dt \tag{5}$$

This Q represents conductive heat load thru the support to the helium or LN.

The calculated heat leak of 36 watts to helium appears to be 59 watts per coil support at 4°K as determined by helium boiloff.

Temperature Distribution in Support Cylinder

Temperature distribution along the support cylinder length between L He and LN_2 temp. is:

$$Let \ x(t) = \int_0^x dx = \frac{F}{Q} \int_{t_1}^{t_2} \frac{k(t)}{\sigma(t)} dt \tag{6}$$

Then, substitute for Q from eq.(5):

$$x(t) = \frac{L \int_{4.2}^{t_2} \frac{k(t)}{\sigma(t)} dt}{\int_{4.2}^{10} \frac{k(t)}{\sigma(t)} dt} \tag{7}$$

Since L, k(t), & $\sigma(t)$ are known, the gradient may be found from dt/dx.

After the support cylinder's temperature gradient is found, the corresponding allowable stress for a given temperature can be computed. When this is

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known, the optimal cylinder cross-section is $A(t) = F/\sigma(t)$.

A similar analysis can be used between LN$_2$ temp. and room temperature to find the cross sectional area required for the part of the cylinder between 80K and ambient.

Conclusion

The coil systems and supports have functioned well as intended for two years at fields up to 2.4T. The coils have been thermally cycled from near ambient to 4.6°K several times due to necessary operating economies during shutdowns. Fields of 3T are planned.

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ACKNOWLEDGMENT