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CALCULATION OF FORCES ON THE ALUMINUM HEAT SHIELD PRODUCED BY EDDY CURRENTS DURING DISCHARGE OF A SUPERCONDUCTING CYCLOTRON MAGNET*

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Summary

The superconducting magnet in our 500 MeV cyclotron contains a (liquid nitrogen cooled) aluminum heat shield within the cryostat, and when, after more than two years of operation, the cryostat was disassembled, it was discovered that the outer surface of the heat shield had collapsed inward, thereby compressing the underlying super-insulation tightly against the can containing the liquid helium and coil. Consideration of the resultant geometry of the heat shield indicated that the collapsing force was produced by eddy currents generated in the aluminum either during discharge of the magnet or else when one of the radial support links happened to break. These forces have been calculated under both conditions, and the procedures used for these calculations are presented here together with the results. We conclude that the collapse of the heat shield was most probably caused when, on one occasion, the dump resistor accidentally burned out thereby producing an exceptionally fast discharge of the magnet.

Introduction

After more than two years of operation, the cryostat of the superconducting magnet in our 500 MeV cyclotron was disassembled in early 1980. The coil can is kept in a helium bath at 4°K. It is loosely wrapped in several layers of aluminized mylar (superinsulation) and enclosed in an aluminum container. This container consists of two concentric circular cylinders of radii 28.6 and 38.8 inches, with top and bottom ring-shaped covers; the height of the cylinders is 48 inches (see Figure 1). The container is kept in contact with liquid nitrogen, and works as a heat shield to decrease the radiant flow of heat toward the coil can.

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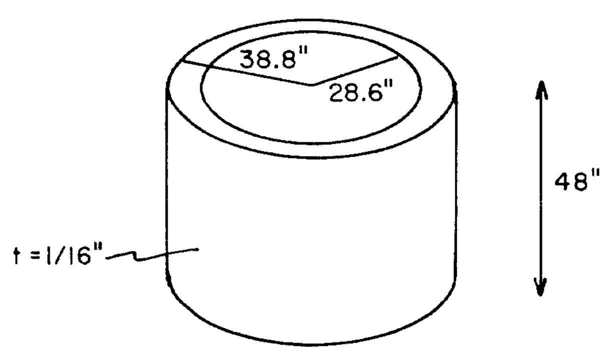

FIG. 1. Dimensions of the nitrogen cooled aluminum shield for the K500 superconducting coil.

After the cryostat was opened, it was observed that the exterior cylinder in the heat shield had collapsed toward the axis, resulting in the flattening of the outer lateral surface into an almost regular polygon, whose faces were tightly compressing the superinsulation against the helium can. This is an undesirable situation from the heat transmission point of view, reducing the path for conduction losses.

It was decided to study the different situations that could have produced the buckling of the outer cylinder. The inner cylinder did not show any sign of deformation.

Eddy currents are generated in the aluminum heat shield whenever the magnetic field changes. During a fast discharge of the magnet, the eddy currents interact with the strong axial field, applying a radial force that compresses the outer cylinder of the heat shield. The first possibility considered was that the buckling was caused by the eddy currents generated during a normal dump exercise. Second, the coil can is partially supported by three horizontal links, and in October 1977 one of these links broke, suddenly displacing the coil. This must have generated strong eddy currents similar to those produced during a dump. The third possibility analyzed was the accident which occurred in September 1977 when the dump resistor accidentally burned out and arcing was observed during what started as a normal dump.

Normal Dump

In case of an emergency, e.g., quench of one of the coils, the energy stored in the superconducting magnets is dumped into a 0.3Ω resistor submerged in water. The current in the magnet discharges then as

$$I(t) = I_o e^{-\lambda t} \ , \text{ with } \lambda = \frac{1}{150}\ s^{-1} \quad . \qquad (1)$$

The magnetic flux ϕ enclosed by any closed curve will decrease according to

$$\frac{d\phi}{dt} = -\lambda\phi \quad . \qquad (2)$$

Considering a cross section perpendicular to the axis of the heat shield, and selecting an integration path C contained in the shield, we have, by Faraday's law,

$$\oint_C \vec{E}\cdot d\vec{\ell} = -\frac{d\phi}{dt} = -\frac{d}{dt}\int_S \vec{B}\cdot\vec{n}\ ds$$

$$= -\frac{d}{dt}\int_S \nabla\times\vec{A}\cdot\vec{n}\ ds = -\frac{d}{dt}\oint_C \vec{A}\cdot d\vec{\ell} \qquad (3)$$

where $\vec{E}$ is the electric field, $\vec{B}$ the magnetic field and $\vec{A}$ its vector potential. $\vec{n}$ is the unit vector normal to a surface S with boundary on the curve C. Given the axial symmetry that our system has, we can write:

$$E_\theta = -\frac{\partial A_\theta}{\partial t} = \lambda A_\theta \qquad (4)$$

The force per unit volume is

$$\frac{dF}{dv} = \vec{J} \times \vec{B} \ , \qquad (5)$$

where

$$\vec{J} = \sigma\vec{E} \quad , \qquad (6)$$

and σ is the conductivity of the aluminum sheet. The pressure on the lateral face is

$$p_L = \frac{dF}{dS} = |\vec{J} \times \vec{B}|t = \sigma E_\theta B_z t \qquad (7)$$

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where t is the thickness of the aluminum sheet. The pressure on the horizontal faces is

$$p_H = \sigma E_\theta B_r t \quad . \tag{8}$$

It must be noted that, by Lenz's law, the eddy currents induced in the aluminum tend to counteract the decrease in field, and therefore have the same direction as the coil current. The forces between both currents are attractive, indicating that the pressures on the different faces are toward the interior of the heat shield. That means that the exterior cylinder tends to collapse, while the inner one tends to expand. Once the collapse starts, the flux decreases even more due to the smaller area, increasing the pressure toward the center so that the equilibrium is unstable. On the contrary, the equilibrium of the inner cylinder is stable, since the pressure tends to increase its radius.

The top and bottom ring-shaped covers of the heat shield are perforated to allow for penetrations corresponding to the current leads and and supporting links. These holes increase enormously the resistance of the circuit, limiting the eddy currents and consequently the force on the covers. Figures 2a, 2b show the electric field E_θ in V/m, and the pressure in psi for the inner cylinder (r=28.6 in) and the outer cylinder (r=38.8 in).

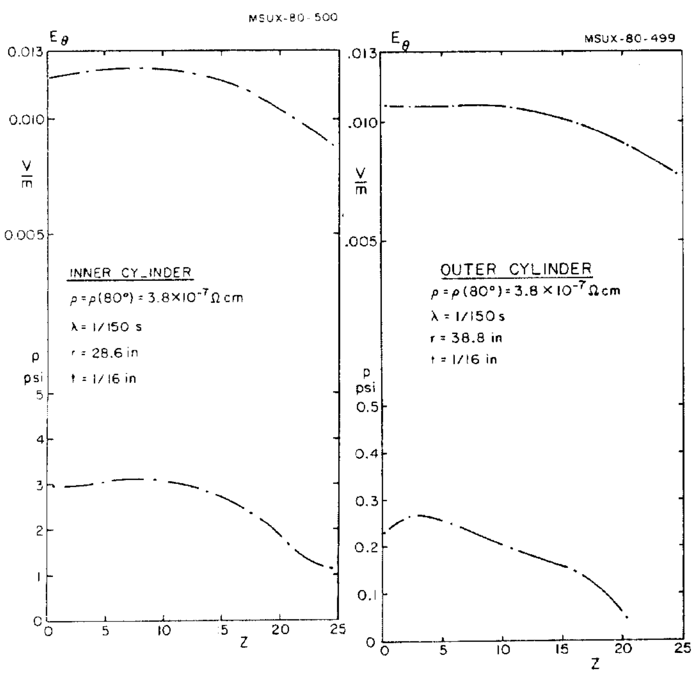

FIG. 2. Electric field in V/m and pressure in psi (a) for the inner cylinder in the heat shield during a normal dump; (b) for the outer cylinder.

The magnetic field data necessary for our computations were obtained from a special run of the TRIM[1] code. The current was 700A in both coils and there was a center plug. We must note that besides giving the $B_r B_z$ components and its derivatives, the TRIM code also prints the values of rA, that is, the quantity needed to compute the flux.

The critical collapsing pressure is given by:[2]

$$P_c = KE\left(\frac{t}{D}\right)^3 \text{ psi.} \tag{9}$$

In our case L/R=1.26, D/t=1240 giving:

a) Radial external pressure with simply supported edges

$$K = 200,\ P_c = 1 \text{ psi.} \tag{10}$$

b) Radial and end external pressure with simply supported edges

$$K = 120,\ P_c = 0.6 \text{ psi .} \tag{11}$$

We note the according to the graphs given in Mark's Handbook the number of faces a cylinder with the dimensions of ours would collapse into is about 11 or 12. This number agrees well with the observed number of faces.

As we can see from Fig. 2b, the maximum pressure on the outer cylinder in a normal dump with λ = 1/150s is only 0.27 psi.

There is also a vertical force on the lateral faces produced by the interaction of the eddy currents with the radial component of the magnetic field. This force is small compared to the axial load capable of producing buckling by itself that we estimated as[3]

$$F_c = 9\times2\pi E t^2\left(\frac{t}{R}\right)^{0.6} = 4.66\times10^4 \text{ lb} \tag{12}$$

The force per square inch in our exterior cylinder is given in the following table. The plus sign indicates force toward the median plane (z=0); minus, away from it.

z	0	5	10	15	20	25
F_z(psi)	0	−0.06	0.193	0.62	0.98	0.74

Broken Link Accident

The horizontal position of the coil is controlled by three adjustable links that penetrate through the heat shield at 120° from each other. During the accident referred to in the introduction one of the links broke, leaving the coil can unsupported from one side. The coil then suddenly moved in the opposite direction of the broken link. The total displacement was estimated to be approximately 1 cm. Since it occurred in a very short time, the rapid flux decrease could have produced strong eddy currents. If we neglect the self inductance of the aluminum cylinder, we can estimate in what time the displacement must have occurred to produce the critical pressure on the cylinder wall. The equation of the heat shield outer cylinder with respect to the center of the coil can is

$$\rho = -\delta\cos\theta + (r_1^2 - \delta^2\sin^2\theta)^{1/2} , \tag{13}$$

where δ is the relative displacement of the centers, and r_1 is the radius of the shield. The change in flux is:

$$\Delta\phi = \int_0^{2\pi} d\theta \int_{r_0}^{\rho(\theta)} B(r)\,dr - \int_0^{2\pi} d\theta \int_{r_0}^{r_1} B(r)\,r\,dr , \tag{14}$$

where r_0 is the outer radius of the coil can. We can then write:

$$\frac{d(\Delta\phi)}{d\,\theta} = \int_{r_1}^{\rho(\theta)} B(r)\,r\,dr = \int_{r_1}^{\rho(\theta)} d(rA)$$

$$= \Psi(\rho(\theta)) - \Psi(r_1) , \tag{15}$$

where $\Psi(r) = rA(r)$. Expanding $\rho(\theta)$ in powers of δ,

$$\Delta\phi = \frac{\pi}{2}\delta^2\left(\frac{d^2\Psi}{dr^2}\bigg|_{r=r_1} - \frac{1}{r_1}\frac{d\Psi}{dr}\bigg|_{r=r_1}\right) . \tag{16}$$

Taking $\delta \approx 1$ cm and $\Delta t=1$ second, we obtain for the median plane electric field $E_\theta=7.4 \times 10^{-5}$ V/m. Comparing with the value we had for E in a normal dump, E=0.011, we see that this new electric field is much smaller. We estimate the Δt that would produce a pressure of 1 psi (the critical collapsing pressure) in the median plane to be $\Delta t = 1.8 \times 10^{-3}$ seconds. If we assume that the coil of mass M(8000 kg) is displaced by a constant force F during that time Δt and moved a distance δ we have

$$F = \frac{2M\delta}{(\Delta t)^2} \sim 5 \times 10^6 \text{ kg}. \qquad (17)$$

This is an extremely short time and the force necessary to produce this sudden displacement is impossibly high. If we consider the self inductance, the result makes it even more unlikely that this accident produced the collapse of the heat shield.

Dump Resistor Accident

As mentioned earlier, the dump resistor is water cooled. In September 1977 the resistor was inadvertently left with only a shallow layer of water on top of it. When the dump started, enough water boiled off to uncover the resistor, thereby causing it to burn out.

As arcing was observed during this accident, we know that the voltage in the coil was higher than normal, indicating a rapidly changing current. Recalling the results obtained in the study of the normal dump, we observe that a transient with a time constant of 40 seconds or smaller would be enough to produce the critical pressure necessary for buckling the can. We do not have any accurate data on this accident, but as we have discarded the other two events as possible causes of the buckling, we conclude that the buckling probably occurred during the dump resistor failure.

Conclusion

Our study showed that:

(1) The pressure produced in a normal dump is not large enough to buckle the can. The time constant of current decay should be at least four times smaller than the observed one for the pressure to reach the critical buckling value.

(2) In the broken link accident, our estimate of the force on the coil necessary to produce a change in position fast enough to generate eddy currents capable of buckling the can is 5000 tons. This value looks excessively high.

(3) We conclude that the flattening probably occurred during the accident that burned the dump resistor.

The introduction of a vertical cut in the outer surface was one of the possible modifications to the original design that was considered. This cut would impede the eddy currents from completing the loop around the shield, decreasing the intensity of the currents. As the median plane of the shield had to be cut to insert the extraction elements for the cyclotron, it was finally decided to reinforce the median plane structure with two 1/16 inch aluminum strips.

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