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ELECTRICAL SAFETY OF A THIN SUPERCONDUCTING SOLENOID IN AN IRON YOKE*

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ABSTRACT

Fabrication of a thin superconducting solenoid[1,2] for the Upgrade Tracking System[3] for the DØ Detector[4] at the Fermilab Proton-Antiproton Collider has begun. The 2.0 T magnet is 2.75 m long, 1.2 m in diameter and stores 5.6 MJ magnetic energy at full excitation. The magnet is novel in that no thin superconducting solenoid magnet for a particle detector has yet been fabricated which operates at this field level.

The magnet is to be installed in the existing DØ detector which has a thick magnetized steel muon absorber which surrounds the superconducting solenoid. In the event of an unexpected electrical short in the magnet is is desireable that the resulting asymmetric forces generated between the magnet and the muon steel not cause collateral damage to the detector.

Although the magnet is designed to sustain a quench without a protection resistor such a resistor is provided to extract a portion of the stored energy from the magnet during a quench to permit faster recool after the quench. This resistor cannot be used for routine discharging of the magnet as its use at full current would in fact cause a quench. To enable timely routine discharge it can be switched into the circuit at some lower current to speed the discharge without causing a quench. It is necessary to estimate the current at which the protection resistor can be used to safely speed discharge.

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INTRODUCTION

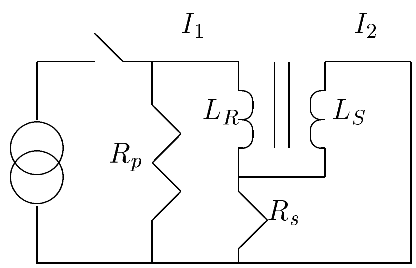
An unexpected electrical short in a solenoid magnet which is near steel can cause the appearance of unanticipated forces between the coil and the steel. The probability of such a short occurring in a superconducting detector magnet is evidently low as no such accident has been reported to date. This is especially noteworthy as the typical thin superconducting magnet has been one-of-a-kind and has pioneered new design concepts. The only known failure of this type in a detector magnet occurred with a conventional (i.e. water cooled) coil[5] .

The occurrence of a short from the conductor to the winding bobbin in a superconducting magnet can be more or less benign depending on how the bobbin is grounded to the magnet cryostat and how the magnet energization circuit is designed. If there is only one shorted path to ground one can in principle ensure that no current can flow via this path by properly isolating the magnet cryostat from the power supply ground.

The occurrence of a turn-to-turn short is vastly less benign. Provided the short has sufficently small resistance current flow can be induced through it every time the magnet is charged or discharged. This current flow can be destructive in the event of a too-rapid charge or discharge; a quench is likely to generate just such a discharge. In what follows we concern ourselves with turn-to-turn shorts.

ANALYSIS OF A SHORTED TURN

The equivalent circuit for a turn-to-turn short in a coil is:



Here R_P is the protection resistor of the magnet and R_S is the resistance of the interturn short. The turns in the shorted section of the coil are taken to be perfectly coupled to those in the remainder of the coil.

For the circuit shown:

$$L_R \frac{dI_1}{dt} + M \frac{dI_2}{dt} + (R_P + R_S)\, I_1 \;=\; 0 \tag{1}$$

$$L_S \frac{dI_2}{dt} + M \frac{dI_1}{dt} + R_S\, I_2 \;=\; 0 \tag{2}$$

where $M = \sqrt{L_R L_S}$ (i.e. perfect coupling) and L_R is the portion of the original inductance L_o not contained in L_S. It is conservative to assume perfect coupling between the two sections of the coil since imperfect coupling would reduce the current I_2. It is also conservative to ignore the presence of the outer support cylinder of the DØ magnet which acts as another "shorted secondary" because the support cylinder also reduces the current I_2 induced by rapid current change in the coil.

In any case the current induced in the support cylinder is uniformly distributed axially and does not generate decentering forces on the magnet.

Because we seek the conditions which maximize I_2, we solve the equations for the discharge of the primary circuit (which is much faster than charge of the primary circuit) to yield:

$$I_1 = I_o e^{-\lambda t} \tag{3}$$

$$I_2 = I_0 \left[\frac{M\lambda}{L_S(\lambda_S - \lambda)} exp(-\lambda t) + \left\{ 1 - \frac{M\lambda}{L_S(\lambda_S - \lambda)} \right\} exp(-\lambda_S t) \right], \tag{4}$$

where

$$\lambda = \frac{\lambda_R \lambda_S}{\lambda_R + \lambda_S}. \tag{5}$$

In fact a short in a superconducting magnet[6,7] can generate ohmic heating at the short, which can in turn cause the magnet to quench (or even lead to the destruction of the coil), depending on the resistance of the short, its location in the coil, the rapidity of the charge or discharge, the total stored energy of the coil and the current density in the windings. We are not concerned with the consequences of such heating.

For simplicity we assume R_P and R_S are constant during the discharge, although they would in fact increase somewhat during a quench. Quench studies of the DØ coil do not show a great dependence of the time constant of the decay on these effects.

Now $L_i \sim n_i^2$, so that for n turns in the entire coil and m turns in the shorted section, $L_S = m^2 L_0/n^2$, *and* $L_R = (n-m)^2 L_0/n^2$. Thus the current in the secondary can be written

$$I_2 = I_0 \frac{n-m}{m} \frac{\lambda}{(\lambda_S - \lambda)} \left[exp(-\lambda t) - exp(-\lambda_S t) \right] + I_0 exp(-\lambda_S t). \tag{6}$$

For a single-layer magnet a turn-to-turn short generally links only one turn of the coil. The DØ magnet requires two winding layers to achieve 2 T so a layer-to-layer short can cause any fraction of the magnet to be included in the secondary circuit. For any choice m of the number of turns in the short we can calculate the maximum current I_2 in the shorted section during a discharge using this result. Care must be taken to avoid numerical imprecision when λ_S and λ are nearly equal.

For $\lambda_R \ll \lambda_S$, we have

$$I_2 = I_0 \frac{m}{n-m} \frac{R_P + R_S}{R_S} \left[exp(-\lambda_R t) - exp(-\lambda_S t) \right] + I_0 exp(-\lambda_S t). \tag{7}$$

This current rises rapidly (governed by λ_S) from I_0 at t = 0 to some intermediate larger value then it decays less rapidly (governed by λ_R). In the limit of very small R_S this current has the simpler form

$$I_2 = I_0 \frac{m}{n-m} \frac{R_P + R_S}{R_S} \left[exp(-\lambda_R t) \right] \leq I_0 \frac{m}{n-m} \frac{R_P + R_S}{R_S}. \tag{8}$$

Because $\lambda_R \ll \lambda_S$,

$$\frac{R_P + R_S}{R_S} \ll \frac{(n-m)^2}{m^2}. \tag{9}$$

Thus

$$I_2 \ll I_0 \frac{n-m}{m}. \tag{10}$$

In fact we can locate the maximum value of I_2 as a function of time either analytically or numerically so that this pessimistic limit ("the transformer limit") can be avoided by use of the actual maximum.

Similar inspection shows that for $\lambda_R \simeq \lambda_S$, and for $\lambda_R \gg \lambda_S$, the current $I_2 \leq I_0$.

Decentering Forces

For any particular m the resulting shorted segment of the coil is not centered in the steel of the DØ muon system and so will experience a net axial force. By assuming the image currents in the iron are instantaneous (i.e. by neglecting the time constant of the iron) and by assuming the iron is far from saturation, an upper limit to the decentering force is obtained when the current in the shorted segment reaches its peak value during the magnet discharge.

By considerations of the interactions between the coil segment and its images mirrored in the steel one can show that the net force on the off-centered segment is

$$F = \frac{3\mu_0 M^2}{32\pi}\left[\frac{1}{(D-\Delta)^4} - \frac{1}{(D+\Delta)^4}\right], \tag{11}$$

where D is the distance from the center of the coil to the steel and Δ is the distance the shorted segment is from the center of the system. M is the dipole moment of the shorted segment, $M = \pi R^2 I_2$.

Numerical Results

Using the values of the magnet parameters pertaining to the DØ solenoid, these formulas can be evaluated to yield numerical results. In Figure 1 is shown the force on a shorted segment when the resistance of the short $R_S = 0.05$ Ohms, the same as R_P, the protection resistor of the DØ magnet. It is seen that the worst case force is not severe. The cold mass support system has been designed to support this force.

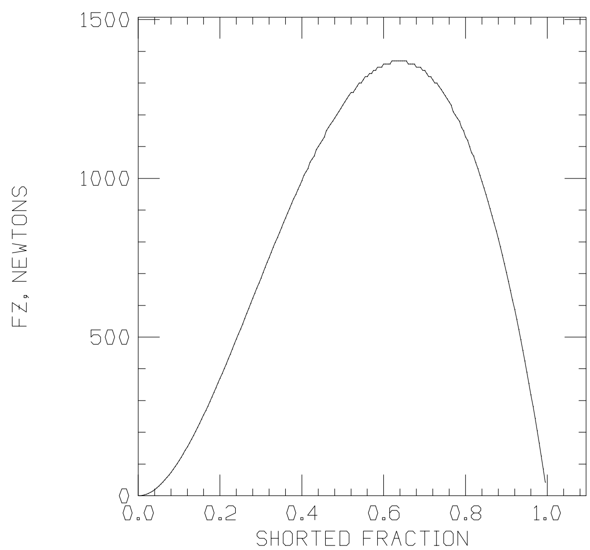


Fig. 1. Force on shorted segment with short resistance 0.050 Ohms.

In Figure 2 is shown the force for the case of $R_S = 0.5 \times 10^{-4}$ Ohms. This case reflects a short typical of contact resistance between two metal surfaces[6] . The decentering force remains readily manageable.

As the short resistance is reduced to increasingly smaller values the peak in the force for small shorted fractions increases (as does the numerical sensitivity of the calculation to small values of the

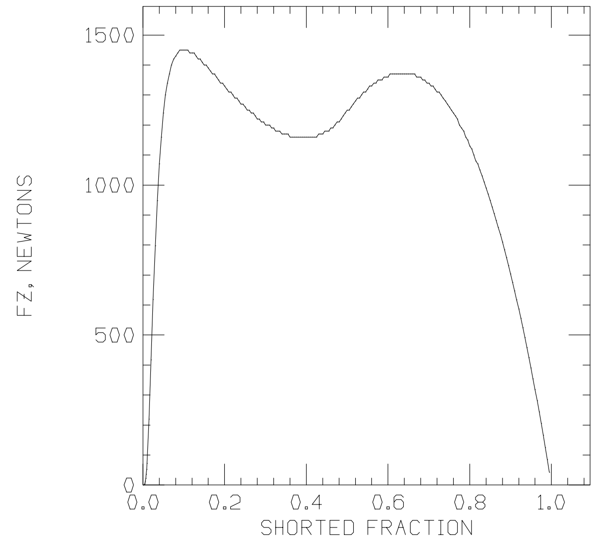


Fig. 2. Force on shorted segment with short resistance 0.0005 Ohms.

difference between λ and λ_S) toward the "transformer limit". But even for the unphysically small value for R_S of 0.5×10^{-10} Ohms the peak force remains less than 1900 N (with one turn in the shorted segment) when the exact expression is evaluated.

FACILITATING THE ROUTINE DISCHARGE

As noted previously the magnet would quench if it were discharged from full current into the protection resistor. This happens because the rapid discharge generates sufficient heating in the support cylinder to overwhelm the cooling system and drive the coil temperature above the superconductor transition temperture. To ensure that the coil can be routinely discharged without quenching, the resistance of the discharge circuit must be limited at the outset and the resulting time constant of this decay (the "slow discharge") for the DØ magnet is more than 5 minutes.

Coupled equations similar to Eq. (1) and Eq. (2) (where the second circuit is that of the support cylinder instead of a shorted turn) can be solved for the current induced in the support cylinder by the discharge of the primary circuit (the coil itself):

$$I_2 = \frac{I_0 M \lambda}{L_2(\lambda_2 - \lambda)} \left[exp(-\lambda t) - exp(-\lambda_2 t)\right]. \tag{12}$$

Here $M = \sqrt{L_1 L_2}$, $\lambda_i = R_i / L_i$, and the power in the support cylinder is just $P(t) = I_2^2 R_2$. The time at which this power is maximum can be found by differentiating Eq. (12), equating the result to zero and solving for the time. This time can be used to find the peak power generation, and the result is(where N is the number of turns in the magnet):

$$P(t_{peak}) = \frac{I_0^2 R_1^2}{R_2 N^2}. \tag{13}$$

To this discharge power is added eddy current losses in the conductor stabilizer, and magnetization and AC coupling losses in the superconductor.

Since the discharge heating rate peaks at the beginning of the discharge and decreases as the current decays and since the superconductor stability margin increases as the current and field decay, at some current less than maximum it is possible to switch in the protection resistor and speed the discharge substantially without quenching the magnet.

A finite-element heat conduction calculation was made[2] of the temperature elevation of the magnet conductor above the helium coolant in the cooling tubing on the support cylinder as a function of the heating power in the support cylinder and the cooling power of the helium in the cooling tubes. This curve is shown in Figure 3 and the conductor operating margin at full current is expected to be about 1.5 K with proper cryogenic operating conditions.

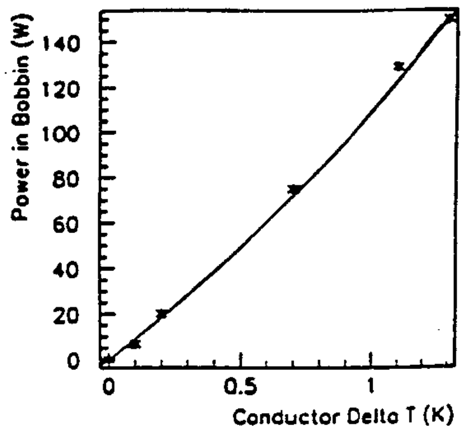


Fig. 3. Heating power in the coil support cylinder vs. temperature elevation of the conductor

For the slow discharge described above for the DØ magnet the heating power in the coil is about 15 W at the beginning of the discharge. The conductor does not approach the current sharing region.

The power corresponding to a fast discharge from only about 500 amperes however is about 180 W, sufficient to elevate the conductor temperature about 1.5 K. Because the conductor current sharing margin is greater than 1.5 K at such a low current this is a pessimistic result. Be integrating the discharge power $P(t)$ throughout the time of discharge and equating this to the enthalpy of the support cylinder and one layer of conductor, it is found that for initial currents below about 1800 amperes the coil does not rise above the current sharing temperature of the conductor.

CONCLUSIONS

Although the DØ magnet itself would in all probability be damaged internally as a result of a turn-to-turn short, from a consideration of the upset forces that might appear due to such a short it is seen that it is practical to design it so that it might not damage other components of the detector in such an event.

From a consideration of the heating induced in the coil support cylinder by a discharge we conclude that for routine discharge of the magnet the protection resistor must be omitted from the circuit at the outset of the discharge. Once the current has decayed to about one third its initial value the protection resistor can be switched into the circuit and the discharge speeded substantially without quenching the magnet.

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