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Date: **8/31/10**

TECHNICAL NOTE



MICE Spectrometer Solenoid: M2 Coil Lead Failure Analysis

1. Introduction

The second assembled Spectrometer Solenoid magnet had been cooled down for a second time and was undergoing a second round of training runs. The first round of training runs had been halted at 238 amps when an HTS lead failed due to insufficient cooling. The HTS lead issue was addressed with the addition of a single stage cryocooler. The magnet was then trained to a current of 258 amps (all five coils in series) when one of the cold leads on the M2 coil was found to contain an open circuit.

The cold mass was subsequently opened to locate the failed lead just inside the vacuum-to-helium feedthrough. All other internal and external leads were found to be intact. The damage to the lead was very localized, indicating that the failure occurred over a very short period of time. The lead consisted of a 1.32 mm diameter circular cross-section conductor with a copper-to-superconductor ratio of 1.4. The conductor was unsupported over a length of 3 to 4 cm on either side of the feedthrough and was not stabilized by any additional copper. The vendor has stated that this conductor is rated for up to 1000 amps when cooled to superconducting temperature.

2. Lead Failure Scenario

The highest current density part of the M2 coil lead system burned out because this lead section quenched. The quench propagated into lower current density leads but not into the magnet. The high current lead carried the full current of the magnet until the copper in the lead melted. The solder in the soldered sections of the lead system at the ends of the high current density lead didn't melt. This will be explained later but is essentially due to the fact that the lead burned out so quickly.

The specific cause of the quench in the high current density lead isn't known. A possible cause is conductor motion in the lead system that caused the high current density section to quench. One can make a case for this happening based on the level of magnetic field in this area and the fact that the conductor was unsupported in the area of the failure. The fact that the high current density section of the lead was not in liquid helium could also have been a factor in the failure.

3. Lead Failure Scenario

A series of calculations have been performed in order to assess the stability of the original cold leads at the feedthrough and compare the results to the same calculations for the proposed modified leads. These results are presented below.

a. Calculation of MPZ length and Quench Energy

Four cases have been assessed. Case 1 represents the single superconductor wire just inside the feedthrough. Case 2 is for the area inboard of the Case 1 wire where it is stabilized by an added copper wire. Case 3 represents the single superconductor wire where it passes through the hollow copper tubing of the commercial feedthrough. Case 4 is for the proposed final configuration of the cold leads adjacent to the inboard and outboard sides of the feedthroughs.

The minimum quench propagation zone length is calculated as follows:

$$L_{MPZ} = \left[\frac{L_o (T_c^2 - T_o^2) \left(\frac{r}{r+1} \right)^3}{(J_M \rho_{Cu})^2} \right]^{0.5}$$

L_{MPZ} = minimum quench propagation zone length (m)

L_o = Lorenz Number ($L_o = 2.45 \times 10^{-8} \text{ W } \Omega \text{ K}^{-2}$)

T_c = superconductor critical temperature ($T_c = 7.2 \text{ K}$)

T_o = magnet operating temperature ($T_o = 4.2 \text{ K}$)

J_M = conductor current density (A m^{-2})

ρ_{Cu} = copper electrical resistivity ($\rho_{Cu} = 2.2 \times 10^{-10} \text{ ohm-m}$)

r = conductor copper to superconductor ratio

The energy required to cause the conductor to quench is calculated as follows:

$$QE = A_c L_{MPZ} \Delta H$$

QE = energy to cause the conductor to quench (J)

A_c = conductor cross-section area used to calculate J_M (m^2)

ΔH = enthalpy change per unit volume from T_o to T_c (J m^{-3})

current $I_o = 275 \text{ A}$ and $\Delta H = 1.08 \times 10^4$ to $2.04 \times 10^4 \text{ J m}^{-3}$ depending on the case

Table 1 provides a summary of the lead current density, Cu to S/C ratio, MPZ length and quench energy for the four different cases. For comparison, the energy of a 0.1 gram pin dropping about 250 mm is approximately 2.51×10^{-4} joules.

Table 1: Minimum quench propagation zone lengths and quench energies.

CASE	J_M (A m^{-2})	Cu to S/C Ratio	L_{MPZ} (m)	E_Q (J)
1	2.02×10^8	1.4	0.0092	2.51×10^{-4}
2	6.69×10^7	3.7	0.044	2.69×10^{-3}
3	3.46×10^7	13.9	0.159	1.47×10^{-2}
4	1.39×10^7	33.8	0.420	8.94×10^{-2}

Case 1: 1.32 mm Φ wire inside of the vacuum tight feed-through at 4 K (old)

Case 2: 1.6 by 1.9 mm section plus wire for case 1 (old)

Case 3: 3.18 mm Φ vacuum tight feed-through pin (both old and new)

Case 4: 4.17 by 4.76 mm section used in the repaired solenoid (new)

b. Time to Melt Cu and Solder and Cryogenic Stability

The time required to melt the copper or the solder in the leads can be calculated as follows:

$$t_{melt} = \frac{F^*(T_{melt})}{J_M^2} \frac{r}{r+1}$$

t_{melt} = time needed to melt the copper or the solder in the conductor

T_{melt} = melt temperature (for Cu $T_{melt} = 1350$ K, for solder $T_{melt} = 570$ K)

$F^*(T_{melt})$ = integral $j^2 dt$ to melt (for Copper $F^* = 2.2 \times 10^{17} \text{ A}^2 \text{ m}^{-4} \text{ s}$)

(for solder $F^* = 1.7 \times 10^{17} \text{ A}^2 \text{ m}^{-4} \text{ s}$)

$J_M = I_o/A_c$ = conductor current density (A m^{-2}), note that $I_o = 275$ A

r = conductor copper to superconductor ratio

The cryogenic stability of the leads can be assessed by calculating the heat flux per unit area as follows:

$$\frac{Q}{A} = \frac{I_o^2 \rho_{Cu}}{A_c P_{wet}} \frac{r+1}{r}$$

$Q/A < 8000 \text{ W m}^{-2}$ for He nucleate boiling $T_c < 5$ K

$Q/A < 1000 \text{ W m}^{-2}$ for He film boiling $T_c > 5.2$ K

$Q/A < 100$ to 200 W m^{-2} for He gas cooling

Q/A = heat flux per unit area at conductor surface (W m^{-2})

I_o = magnet design current ($I_o = 275$ A)

ρ_{Cu} = conductor copper resistivity ($\rho_{Cu} = 2.2 \times 10^{-10}$ ohm m)

r = conductor copper to superconductor ratio

A_c = conductor cross-section area (m^2)

P_{wet} = conductor wetted perimeter exposed to helium (m)

Table 2 provides a summary of the time to melt the copper and solder in the leads for the four cases under consideration.

Table 2: Summary of time to melt copper and solder.

Case	J_M (A m^{-2})	$r/(r+1)$	t_{melt} Cu (s)	t_{melt} solder (s)
1	2.01×10^8	0.583	4.36	-NA-
2	6.69×10^7	0.789	38.8	30.0
3	3.46×10^7	0.932	171	132
4	1.39×10^7	0.971	1105	854

Table 3 provides a summary of the cryogenic stability for the four lead configurations.

Table 3: Cryogenic stability for the various cases.

Case	J_M (A m ⁻²)	Q/A (W m ⁻²)	Remarks about Case
1	2.01 x 10 ⁸	8740	Unstable in liquid He or He gas
2	6.69 x 10 ⁷	900	Stable in liquid He, unstable in He gas
3	3.46 x 10 ⁷	165	Stable in liquid He, He gas is ??
4	1.39 x 10 ⁷	40.4	Stable in liquid He or He gas

c. Quench Propagation Velocity

The adiabatic quench propagation velocity for Nb-Ti in copper can be calculated using the following equation:

$$V_Q = (5.7 \times 10^{-14})(1 + B)^{0.62} J_M^{1.65}$$

V_Q = quench propagation velocity along wire (m s⁻¹)

B = magnetic induction at the wire (used B = 0.5 T)

J_M = current density in the conductor cross-section (A m⁻²)

Quench propagation velocity is independent of r and ρ_{Cu} .

Table 4 provides a summary of the calculated adiabatic quench propagation velocity for the four lead configurations including comments regarding quench propagation for the various scenarios.

Table 4: Calculated adiabatic quench propagation velocity.

Case	J_M (A m ⁻²)	V_Q (m s ⁻¹)	Remarks about Case
1	2.01 x 10 ⁸	3.7	Quench will propagate in liquid or gas
2	6.69 x 10 ⁷	< 0.60	No propagation in liquid He, propagate in gas
3	3.46 x 10 ⁷	< 0.20	No propagation in liquid He, gas ?? (slow)
4	1.39 x 10 ⁷	< 0.045	No propagation in liquid He or He gas

4. Interpretation of the Analysis

A quench in the highest current density wire will propagate until the quench reaches a conductor of lower current density. In the lower current density cases, the quench doesn't propagate in liquid helium. In helium gas, the propagation is slow. Based on this analysis, the high current density wire burned out during the recent training runs before the solder in the conductors attached to the wire were able to melt. The cryogenic stability limit is governed by film boiling because the conductor T_c is greater than 5.2 K

outside of the magnet. The energy to quench the high current density wire is small despite the high value of T_c .

Forces on low current density wires attached to the high current density wire can cause it to move. As a result, a quench can be initiated by the small amount of heat generated. In this case, the high current density wire burns out before the magnet coils can quench. The lead burnout will not occur at currents less than 140 A because the minimum propagation zone is too long and the quench energy is too high.

5. Assessment of the Proposed Fix

The proposed fix surrounds the high current density wire with copper wire having a total cross section of 18.5 mm^2 . Any high current density wire that is not covered by the copper will have much less than the minimum quench propagation length. The conductor that passes through the feed-through is cryogenically stable in liquid helium and likely stable in helium gas as well.

The fix also improves the stiffness of the conductor on both sides of the feed-through, making motion far less likely. Any motion that occurs won't cause a quench because of the cryogenic stability. The conductor outside of the feed-through is well cooled by conduction to the helium tank. The conductor is constrained to prevent conductor motion that might cause a quench. Any unsupported conductor is less than a MPZ in length.