Analysis of the Magnet Lead Failure

Spectrometer Solenoid Review

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An Explanation of What Happened

- The highest current density part of the coil M2 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 lead copper melted. The solder in the soldered sections of the lead system at the ends of the high current density lead didn’t melt. This is explained later.
- The cause of the quench in the high current density leads isn’t known. A likely 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.
- The fact that the high current density section of the lead was not in liquid helium may have been a factor in the failure.

Calculation of MPZ length and Quench Energy

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

L_{MPZ} = minimum quench propagation zone length (m)
L_o = Lorenz Number (L_o = 2.45 x 10^{-8} W Ω K^{-2})
T_C = superconductor critical temperature (T_c = 7.2 K)
T_o = magnet operating temperature (T_o = 4.2 K)
J_M = conductor current density (A m^{-2})
ρ_{Cu} = copper electrical resistivity (ρ_{Cu} = 2.2 x 10^{-10} ohm-m)
r = conductor copper to superconductor ratio

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

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 A and ΔH = 1.08 x 10^4 to 2.04 x 10^4 J m^{-3} depending on case

Lead Section Current Density, Cu to S/C Ratio, MPZ Length, and Quench Energy

Case 1 1.32 mm Φ wire inside of the vacuum tight feed-though 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)

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	3.74	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}

Energy of a pin (10^{-4} kg) dropping about 250 mm

Cu and Solder Melting Time, Cryogenic Stability

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

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^2dt to melt (for Copper F* = 2.2×10^{17} A^2 m^{-4} s)

(for solder F* = 1.7×10^{17} A^2 m^{-4} s)

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

r = conductor copper to superconductor ratio

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

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

$Q/A < 1000$ 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)

Time to Melt and Cryogenic Stability

Time to melt the 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

Cryogenic Stability for Various Cases

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

Quench Propagation Velocities for the Cases

Adiabatic Quench Propagation Equation for Nb-Ti in Copper

$$V_Q = (5.7x10^{-14})(1+B)^{0.62} J_M^{1.65}$$

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}.

Calculated Adiabatic Quench Propagation and Reality

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

Results of the Analysis

- A quench in the highest current density wire will propagate until the quench hits 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.
- The high current density wire burns out before the solder in conductors attached to the wire can 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 and can start a quench.
- The high current density wire burns out before the magnet 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. Good cooling may prevent quenching.

Expected Effect of the Proposed Fix

- The fix surrounds the high current density wire with 18.5 mm^2 of copper. Any high current density wire that is not covered is much less than a minimum quench propagation length.
- The conductor connected to the feed-through is cryogenically stable in liquid helium. It is probably stable in helium gas too.
- The fix improves the stiffness of the conductor going into the feed-through. This makes motion far less likely. What motion there is won't cause a quench because of 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. Unsupported conductor is less than an MPZ in length.