SSC DETECTOR SOLENOID DESIGN NOTE #11

TITLE: Hot Spot Temperature during Quench from Heat Balance

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I. Computation Method*

A. General

The maximum temperature in a superconducting coil that has quenched can be estimated by the heat balance equation

$$\int_0^{\infty} J^2(T)\,dT = J_0^2 T_d = \int_{\theta_0}^{\theta_m} \frac{\gamma\, C(\theta)}{\rho(\theta)}\, d\theta = U(\theta_m)$$

where: J = current density in normal metal
T = time
J_0 = current density at start of quench
T_d = quench decay time
θ = absolute temperature
γ = density of conductor (metal)
C = specific heat
ρ = electrical resistivity
θ_m = "hot spot" temperature

This equation ignores heat transfer to the LHe bath and for a coil which is permeable to LHe therefore gives a "worst case" temperature.

The RHS of the equation is a function of the material properties of the conductor only. The attached figure (from Wilson, page 202) shows typical curves of $U(\theta_m)$.

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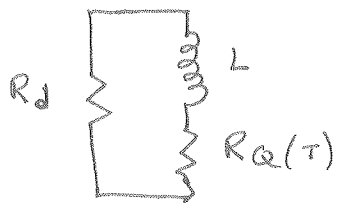
* Martin N. Wilson, "Superconducting Magnets," Clarendon Press, Oxford (1983).

B. Protection by a dump resistor*



For $R_d > R_Q(T)$

$$I(T) = I_0 e^{-\frac{R_d T}{L}} = I_0 e^{-T/T_d}$$

and $J = J_0 e^{-T/T_d}$.

The LHS of the heat balance equation becomes

$$\int_0^\infty J^2(T)\, dT = \frac{J_0^2 T_d}{2} = \frac{J_0^2}{2}\frac{L}{R_d} = U(\theta_m)$$

Therefore θ_m is a function of J_0, L and R_d, which are all in turn determined by I_0.

C. θ_m vs I_0

$$L = \frac{2E_0}{I_0^2}, \qquad E_0 = \text{stored energy at } I_0$$

$$R_d = V_d / I_0, \qquad V_d = \text{terminal dump voltage}$$

$$J \propto I^{-1/3}$$ for a simple conductor geometry, if the stability criterion is maintained (q_ℓ = constant)

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* Wilson, page 219.

II. Results Calculated for 10-m Solenoid

A. For a 16-m long, 2 T, 1.5 GJ coil

$L = 120\,H$ with $I_0 = 5\,kA$

For $V_d = 1\,kV$, $R_d = 0.2\,\Omega$

and

$$T_d = 120\,H / 0.2\,\Omega = 600 \text{ sec}$$

Taking $J_0 = 3813\ A/cm^2 = 3.813 \times 10^7\ A/m^2$ (Design Note #3)

$$U(\theta_m) = (0.5)(3.813 \times 10^7)^2 (600) \quad A^2\text{-}s/m^4$$
$$= 43.6 \times 10^{16} \quad A^2\text{-}s/m^4$$

For a copper-stabilized conductor with RRR ~ 100, this corresponds to

$$\theta_m \gg 500\,K$$

which is completely unsatisfactory, being about equal to the melting point of soft solder. We must either reduce L (by increasing the operating current or by subdividing), increase R_d (not desirable because of high voltage), decrease J, or a combination of these.

B. For a 16-m long coil and other currents keeping J_0 constant, which is not strictly true, and with $V_d = 1\,kV$

I_0	L	R	$U(\theta_m)$	θ_m
5 kA	120 H	0.2 Ω	44×10^{16}	$\gg 500\,K$
10	30	0.1	22	> 500
20	7.5	0.05	11	~160 K

C. Crude estimate for a subdivided coil*

For each 8-m long, 750 MJ coil, with $V_d = 1kV$

I_o	L	R	$U(\theta_m)$	θ_m
5kA	60 H	0.2 Ω	22×10^{16}	> 500K
10	15	0.1	11	~160K

For each 4-m long, 375 MJ coil, $V_d = 1kV$

5kA	30H	0.2 Ω	11×10^{16}	~160K

III. Summary

Subdivision is required in order to operate in the 5 to 10 kA range.

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* "Crude" because it ignores mutual inductance effects, see Wilson, page 227, for more complete analysis.