Fermilab

SDC SOLENOID DESIGN NOTE #119

TITLE: Transient Heat Load to Outer Support Cylinder from Eddy Currents

AUTHOR: Ron Fast Ron Fast

DATE: November 7, 1990

ABSTRACT: The heat load applied to the outer support cylinder during charging due to the circumferential eddy current is estimated to be about 175 W for a Type-U solenoid with magnetic end cap calorimetry and about 220 W if non-magnetic calorimetry is used. The energy which must be removed during a constant-voltage charge to 10 kA is about 260 kJ in either case.

ASSUMPTIONS: For this calculation I used the dimensions and parameters given in the Letter of Intent (LoI) for the Type-U solenoid except where noted. I calculated the power loss for both magnetic and non-magnetic calorimetry. I assumed conductor dimensions 5.6 mm x 40 mm and an outer support cylinder thickness of 28 mm, which were the values suggested by T. Kondo and Yamamoto for the 10-kA ACS (SDC Solenoid Design Note #110).

DIMENSIONS AND PARAMETERS

	Item	Magnetic Calorimetry	Nonmagnetic Calorimetry
D	Average coil diameter (m)	3.62	3.62
CL	Coil/outer support cylinder length (m)	8.94	7.7
B	Central field (T)	2.0	2.0
E	Stored energy at 2 T (MJ)	147	122
i_0	Operating current in coil (kA)	10.0	10.0
L	Self inductance of coil (H)	2.94	2.44
z	z-thickness of conductor (SDC DN#110) (mm)	5.6	5.6
r	r-width of conductor (SDC DN#110) (mm)	40	40
rc	r-width of outer support cylinder (SDC DN#110) (mm)	28	28
D'	Diameter of outer support cylinder (m)	3.688	3.688
p	Perimeter of outer support cylinder (m)	11.59	11.59

n'	Turns per unit axial length (t/m) = 1000/z	178.6	178.6
A	Cross section area of coil = $\pi D^2/4$ (m^2)	10.3	10.3
m	Turns on secondary	1	1
ρ	Resistivity of outer support material (assume 5083) at 4.2 K ($\mu\Omega$-m)	0.0305	0.0305

CALCULATIONS USING ABOVE DIMENSIONS AND PARAMETERS

M Mutual inductance between coil and outer support cylinder

$= \mu_0 n'Am$ (Ref: W.R. Smythe, Static and Dynamic Electricity, p.335)

$= (4\pi \times 10^{-7}$ H/m)(178.6 t/m)(10.3 m^2)(1 t) = 2.31 mH

R Circumferential resistance of outer support cylinder

$= \rho p$/circumferential cross sectional area of outer support cylinder

$= \rho p/(rc \times CL)$

= (0.0305 $\mu\Omega$-m)(11.59 m)/(0.028 m)(CL)

= (12.6 $\mu\Omega$-m)/CL ($\mu\Omega$) 1.41 1.64

di/dt = Charge rate at constant voltage

= Terminal voltage/L = 20 V/L (A/s) 6.80 8.20

P Joule heating in outer support cylinder due to induced eddy currents

$= (M\ di/dt)^2/R = (M^2/R)\ (di/dt)^2$ (W) 175 219

t Constant-voltage charge time to i_0 (s/min) 1470/24.5 1220/20.3

U Energy dissipated in outer support cylinder during charge = Pt (kJ) 257 267

GENERAL CALCULATIONS

With a little bit of algebra I showed (details in the appendix) that, if E α CL, then P α 1/E (or 1/L) and U is independent of E (or L):

$$P = [(4\mu_0/\pi)(rc/\rho p)(Mi_0V/DB_0)^2]\ L^{-1}$$

The above values approximately follow this: E(mag)/E(nonmag) = 1.20 while P(nonmag)/P(mag) = 1.25. The difference is due to the fact that E is not quite proportional to CL, CL(mag)/CL(nonmag) = 1.16.

CONCLUSION

The power put into the outer support cylinder for the dimensions given above is 175 W for a longer coil with magnetic calorimtry and 220 W for a shorter coil with non-magnetic calorimetry. The total energy delivered during a constant-voltage charge is approximately the same for each case, about 260 kJ.

CAVEAT

The power is inversely proportional to the thickness of the outer support cylinder (rc), so this calculation should be done over when the final dimensions of the conductor and outer support cylinder are known.

APPENDIX

$$E = \frac{B_o^2}{2\mu_o} \, \text{Volume} = \frac{B_o^2}{2\mu_o} \frac{\pi D^2}{4} (CL)$$

$$= \frac{\pi B_o^2 D^2}{8\mu_o} (CL)$$

And

$$CL = \frac{8\mu_o E}{\pi B_o^2 D^2}$$

$$= \frac{8\mu_o}{\pi B_o^2 D^2} \left(\frac{1}{2} L i_o^2 \right)$$

$$= \left(\frac{4\mu_o i_o^2}{\pi B_o^2 D^2} \right) L$$

So

$$R = \frac{\rho p}{rc \, CL} = \frac{\rho p}{rc} \frac{\pi B_o^2 D^2}{4\mu_o i_o^2} \frac{1}{L}$$

$$P = \frac{M^2}{R} \left(\frac{di}{dt} \right)^2$$

$$= M^2 \left(\frac{4\mu_o i_o^2 L}{\pi B_o^2 D^2} \right) \left(\frac{\rho p}{rc} \right) \left(\frac{V}{L} \right)^2$$

$$= \left(\frac{4\mu_o}{\pi} \right) \left(\frac{rc}{\rho p} \right) \left(\frac{M i_o V}{B_o D} \right)^2 L^{-1}$$