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NUCLEATE COOLING STABILITY CRITERIA FOR SUPERCONDUCTING COILS

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Whenever possible designers of superconducting coils choose the conductor size, operating current and coil packing factor so that the coil is "fully stable". A "fully stable" coil is one cooled by nucleate boiling of the liquid helium bath when carrying the operating current with extended regions of the coil normal, i.e., not superconducting. As seen in Fig. 1 the nucleate boiling in liquid helium persists up to a maximum heat transfer flux of 0.8 to 1.0 W/cm^2.[1]

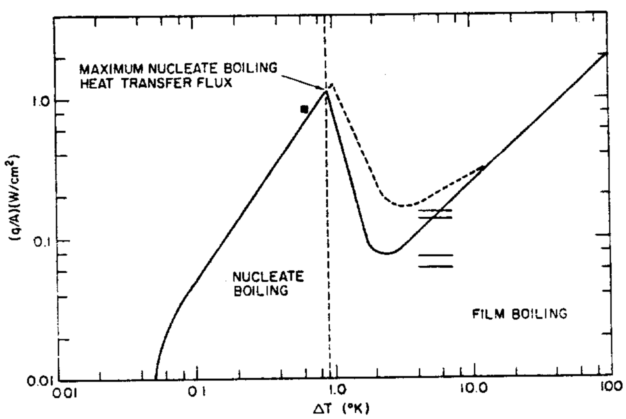

Fig. 1. Heat transfer flux *vs.* temperature difference between copper and 4.2°K liquid helium. Legend: —— clean surface; ---- surface covered with a thin coating of ice crystals. ■ = experimental maximum nucleate heat transfer flux for a totally stabilized conductor. The short horizontal lines between $\Delta T = 6°$ and 8°K are cooling values[6] corresponding to recovery currents utilizing film boiling for protection.

The basic requirement for fully stable conductor is

$$I_{max}^2 R = (\frac{q}{A})_{max} S \quad (1)$$

where, I_{max} = maximum stable operating current.

R = resistance of coil at 4.2°K

$(\frac{q}{A})_{max}$ = maximum heat transfer flux

S = surface area of conductor

This can be reduced for a round conductor to

$$I_{max}^2 = \frac{(\frac{q}{A})_{max} A \pi D}{\rho} \quad (2)$$

where, ρ = resistivity of conductor at 4.2°K

A = cross section area of conductor

D = diameter of conductor

When the basic conductor is wound into a coil, only a fraction ε of the conductor surface area is in contact with the liquid helium bath. The fully stable requirement for a coil becomes

$$I_{max}^2 = \frac{(\frac{q}{A})_{max} \varepsilon A \pi D}{\rho} \quad (3)$$

The most commonly used conductors today are Nb-Ti composites with many superconducting strands metallurgically bonded in a matrix of OFHC copper. Since the resistivity of copper at 4.2°K is much less than the normal resistivity of Nb-Ti at 4.2°K, the copper carries the current when the coil is normal at 4.2°K. In Equation 3, A is then the cross section area of the copper and ρ is the copper resistivity. The conductor is usually described, and sometimes specified, by the ratio of copper to superconductor cross section areas.

Let α = copper area/conductor area then,

$$I_{max}^2 = \frac{(\frac{q}{A})_{max}\ \varepsilon\ \left[\alpha\left(\frac{1}{4}\pi D^2\right)\right]\ \pi D}{\rho}$$

$$I_{max}^2 = \frac{\pi^2\ (\frac{q}{A})_{max}\ \varepsilon\ \alpha\ D^3}{4\rho} \qquad (4)$$

Also of interest may be the current density in the conductor corresponding to the maximum fully stable operating current.

$$J\text{cond}_{max} = \frac{I_{max}}{A}$$

$$= 2\left[\frac{(\frac{q}{A})_{max}\ \varepsilon\ \alpha}{\rho}\right]^{\frac{1}{2}} D^{-\frac{1}{2}} \qquad (5)$$

Rewriting (4) we see the heat transfer, conductor parameter and coil winding terms separated

$$I_{max}^2 = \frac{\pi^2}{4}\ (\frac{q}{A})_{max}\ \left(\frac{\alpha\ D^3}{\rho}\right)\ \varepsilon \qquad (6)$$

Whetstone and Boom[2] have shown that the maximum heat transfer flux for superconducting coils is ~ 0.4 W/cm^2. We shall use

$$(\frac{q}{A})_{max} = 0.5\ \text{W/cm}^2.$$

The resistivity, ρ, must take into account the considerable magneto-resistance effect in copper. We shall use the value of ρ at 20 kG, and 4.2°K,

$$\rho = 1.5 \times 10^{-8}\ \Omega\text{-cm}$$

Inserting these values into Equation 4, we get

$$I_{max}^2 = 0.822 \times 10^8 \, \alpha D^3 \varepsilon \qquad \text{(cgs units)}$$

Table I shows the maximum fully stable current and the operating current for two recently tested NAL magnets, and for a third now under construction. With conservative values used throughout the analysis should give the minimum value of I_{max} to be expected.

TABLE I

Magnet	α	D cm	ε	I_{max} A	J^{cond}_{max} kA/cm^2	Iop A	J^{cond}_{op} kA/cm^2
Cold-iron quadrupole	.81	.127	.625	292	23.0	250	19.7
Analysis dipole (prototype)	.67	.127	.625	265	20.9	350	27.6
Analysis dipole (production)	.75	.100	.667	203	25.8	185	23.6

REFERENCES

[1] R. D. Cummings, ScD Dissertation, MIT (1965), quoted in Reference 2.

[2] Whetstone and Boom, Advances in Cryogenic Engineering, Vol. 13, p. 68, (1967).