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Superconducting Super Collider Laboratory

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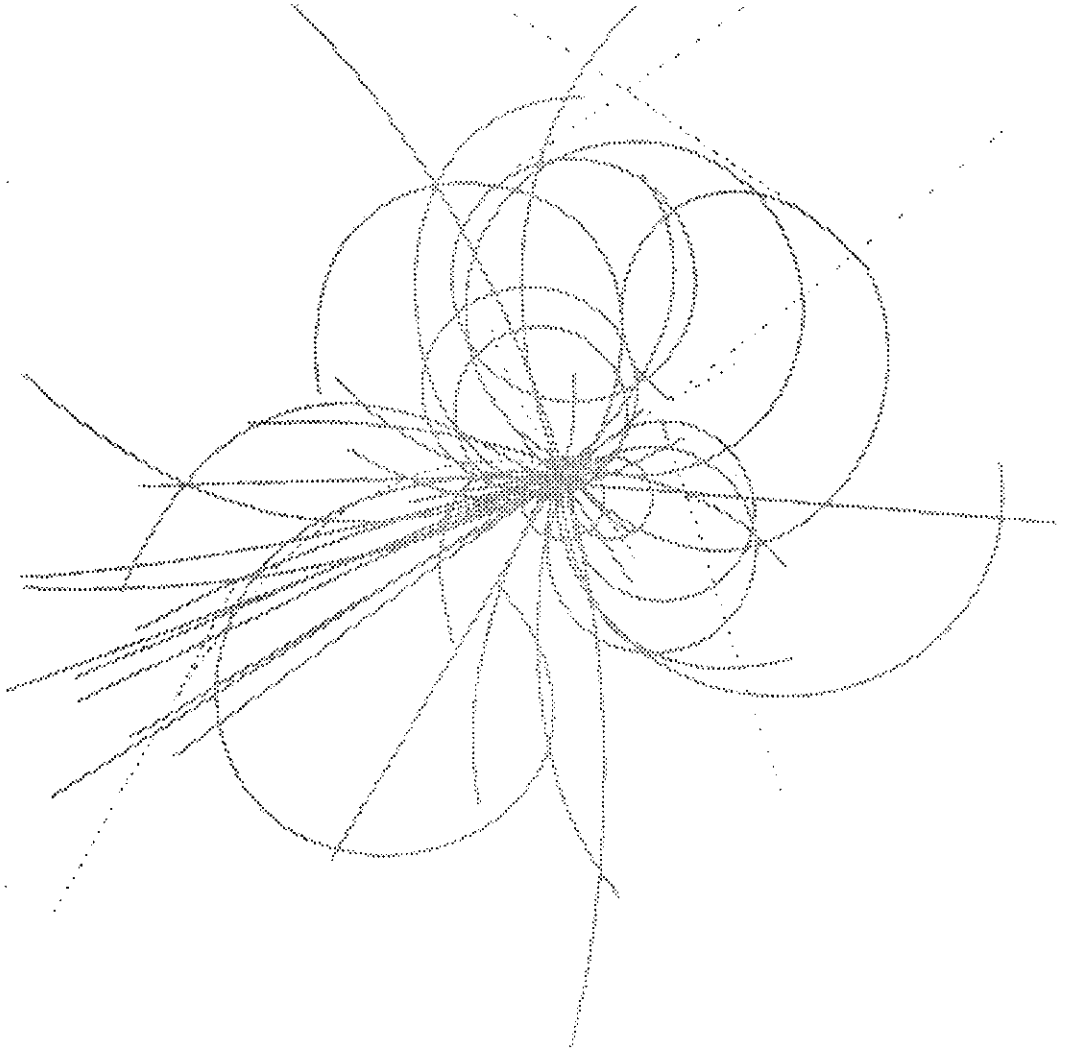

Ramp Rate Dependence of Dipole Magnet Quenching

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I will discuss a model for the quenching of magnets subjected to distributed transient heating. Distributed means that the energy deposition occurs over a volume of the winding large compared to a minimum propagating zone. Such heating can occur due to various AC-loss mechanisms as the magnet current is changed, or due to nuclear interactions if particles are lost from the beam. Transient means that the time is short enough that the temperature rise is determined by energy deposition and heat capacity. At long times, by contrast, the temperature rise depends upon the rate of energy deposition and the effective heat conductance to a reservoir of helium. For the present SSC Collider dipole, with steel collars, the diffusion time to transfer heat from windings to helium passages is about 40 sec. Emergency ramp-down takes 20 sec to accomplish and, therefore, can be considered a transient. I wish to discuss the conditions under which a magnet can quench during ramp-down.

A quantitative calculation of magnet heating due to AC loss is appallingly difficult and, I believe, unnecessary. Rather, I present a simpler discussion based partly on experimental data and partly on quite general arguments. Figure 1 shows curves of various energy quantities, on a log scale, as a function of magnet current. The solid curves marked A_1 and A_2 show, qualitatively, the amount of energy required to raise two "typical" windings from bath temperature to critical temperature. For a 4-cm collider dipole at operating conditions, the temperature margin at the high field point is 0.35K, assuming "standard" SSC conductor. The operating current is about 95% of critical current, so that a temperature rise of 0.35K will cause a decrease of 5% in plateau current. When the magnet is at zero current and field, the temperature margin is 5.0K. The variation in enthalpy with temperature margin depends upon the materials included in the calculation. For the moment let us consider only curve A_1, which illustrates the case for a mixture of NbTi and copper and is modeled on Figure 5.7 of Wilson[1]. The enthalpy margin at operating current is less than 1000 j/m^3 and, because the enthalpy is a strong function of temperature, the enthalpy margin varies rapidly with magnet current, increasing by a factor of 100 as current decreases to zero.

Curve B_1 illustrates the energy deposition due to AC losses during ramp up. I have made no attempt to depict the correct functional form of this curve. The only thing that matters is that it is monotonically increasing, so I have simply drawn a straight line. The magnet will quench at the current where curves B_1 and A_1 intersect. Curve B_2 illustrates the case for a faster ramp rate, chosen such that the magnet quenches at the operating current. Curve C_1 illustrates the case in which the magnet is ramped down at the same rate as was used in B_2, so that the total energy deposition is the same for the two cases. It is clear that C_1 lies well below A_1 and, therefore, cannot cause a quench. If the magnet is ramped down at the higher

rate represented by curve C_2 it will just quench at zero current; even higher ramp rates would be required to quench the magnet at a current greater than zero.

LBL has measured the dependence of quench current on ramp rate for various short magnets over the past years. In detail, the results depend upon the parameters of the strand and cable in the magnets. The most relevant measurement is for the 5-cm bore Cable Test Magnet[2], which uses "standard" SSC wire in a 28-strand inner cable and 36-strand outer cable. This magnet shows a 5% decrease in quench current at a charging rate of 200 A/sec, corresponding to curve B_2 during charging or C_1 during discharge. As already pointed out, the enthalpy along curve A_1 increases by a factor of 100 as the current decreases from operating to zero and the magnet seems to be safe with plenty of margin for error. The specified emergency dump rate is 330 A/sec, rather than 200 A/sec. Even if all the AC loss is due to eddy currents, the energy deposition would increase only a factor of 1.65 and there would still be plenty of margin.

In the above discussion, a large part of the energy margin at zero current resulted from the strong temperature dependence of the enthalpy of solid materials. Curve A_2 illustrates a "worst case", in which energy absorption capability is dominated by liquid helium, which fills the 15% void space that is estimated to occur in the present dipole winding. It is assumed that the helium is immobile and, therefore, absorbs energy at constant density. The energy absorption capacity at all currents is increased but the variation with temperature is less dramatic because C_v for helium is almost independent of temperature. Even so, the ratio of energy margin at zero current to that at operating current is at least as large as the ratio of temperature margins, which is 14.

One can complicate this model at will, adding the heat capacities of the helium that surrounds the bore tube and of the portion of collar and yoke to which heat can diffuse during the transient heating. None of this appears to change the above conclusion: for the present strand, and for the "wide cable" projected for use in a 5-cm-bore dipole, there is plenty of margin against quenching during charge or discharge at specified rates.

Without a model for the complex thermal processes occurring within the magnet, a measurement of quench current vs ramp rate does not yield a value for energy dissipation. Despite the fact that charge or discharge will not produce quenching during accelerator operation, it would still be useful to have experimental results on energy loss vs. ramp rate for a magnet of "baseline" design, using standard strand and cable. It is important to check that AC losses will not have an impact on the cryogenic system for the collider. Further, the results can be scaled to produce a better estimate for losses in the HEB; the present estimate[3] was made by scaling from the Tevatron. The requisite measurements are best made by determining the temperature rise as a magnet is cycled in a bath of Helium II. The Supercon group at LBL was, as of several years ago, able to perform such experiments on a routine basis.

What benefit would be gained by separating the inner and outer coil layers by "fishbone", providing an additional volume of helium in contact with the coil?. The time constant for heat to diffuse from the windings to this helium will be a few tens of milliseconds, because of the low thermal diffusivity of the Kapton ground

wrap. The helium enthalpy will thus not help in the event of rapid transient heating, such as caused by a sudden shower of particles. For steady state power dissipation it seems unlikely that the addition of a small amount of helium in narrow channels will add to the overall heat removal capability of the system Finally, as already argued, the available enthalpy is already more than sufficient to accommodate AC loss during ramping. I thus see no evident gain by adding "fishbones"; on the downside, there is additional expense and some concern about changing the mechanical structure of the magnets.

References

1. "Superconducting Magnets", M.Wilson, p.75. Oxford, 1982.
2. R.Althaus, et al, LBL-28086. (2/90).
3. Site-specific Conceptual Design for the SSC, Vol.I, p.345. (1989)

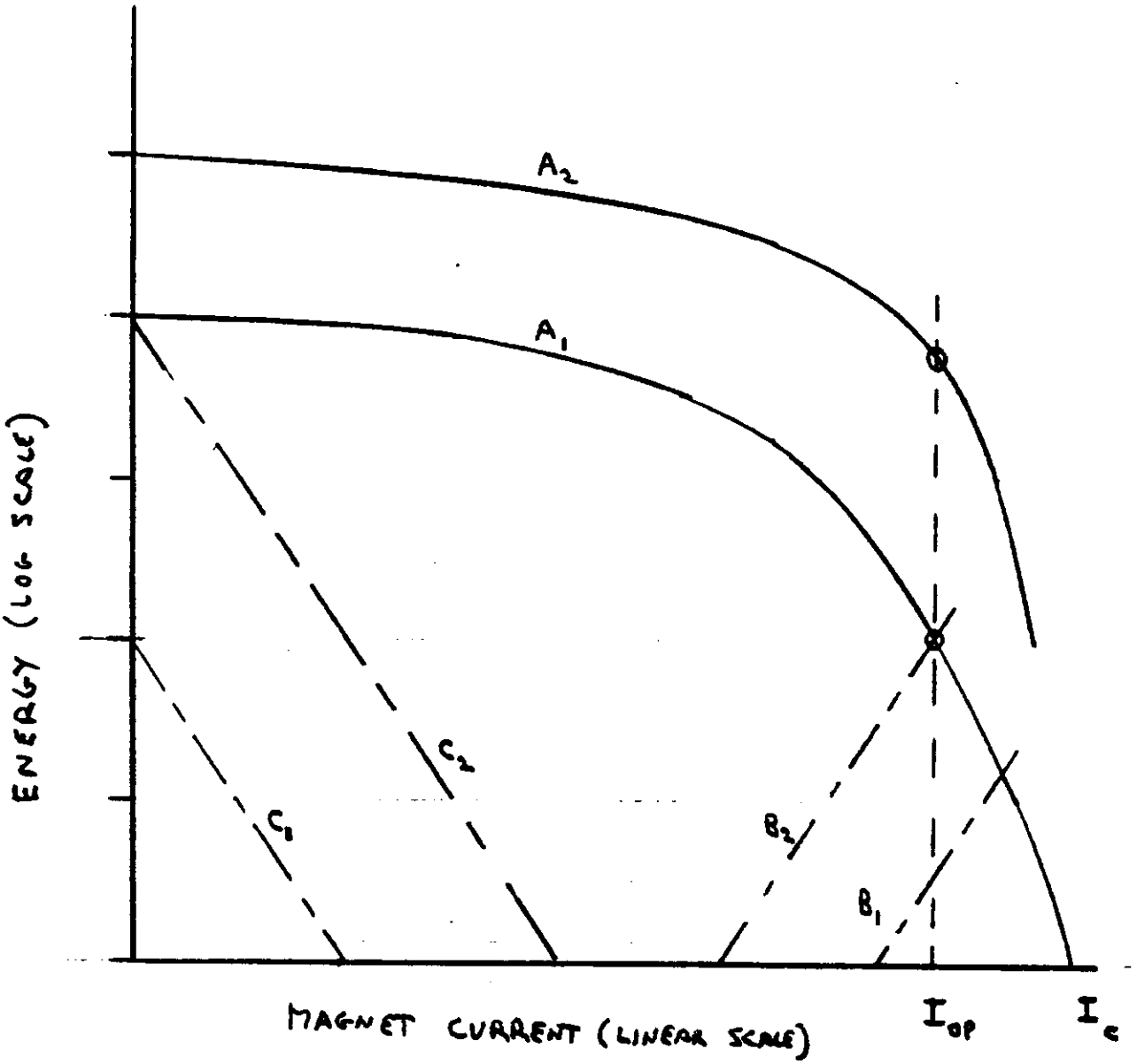

Figure 1. Energy margin and energy release as a function of magnet current. On the horizontal axis, I_c is the critical current and I_{op} is the operating current. The vertical axis has a log scale; tic marks represent factors of ten in energy. Curves A_1 and A_2 illustrate the variation in energy margin- that is, the amount of energy per unit volume needed to raise the superconductor to its critical temperature. Curve A_1 is typical of a winding containing only superconductor and other solid materials, while the winding in Curve A_2 has liquid helium trapped in voids totalling 15% of the volume. Curve B_1 shows the energy deposition during ramp up at a low ramp rate; for curve B_2 , the ramp rate is fast enough to cause the magnet to quench at the operating current. Curve C_1 shows the energy deposition during ramp-down, with the ramp rate the same as in B_2 . Curve C_2 shows the energy deposition during ramp-down at a much higher rate, in which the magnet is heated to its critical temperature at zero current and field.