QUENCH PROTECTION STUDIES ON CBA MAGNETS*

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Abstract

Results from quench studies on both short cable samples and prototype Colliding Beam Accelerator project magnets are presented. The quantity of paramount interest is $\int I^2 dt$ which is a monotonic function of the maximum conductor temperature obtained in a quench. Conductor damage in short samples has been observed for $\int I^2 dt \gtrsim 8.4 \times 10^6$ amp^2-sec at 50 kG and 4.2°K. Each magnet is equipped with spot heaters in various locations so that systematic studies of quench propagation under controlled conditions can be made. Values of $\int I^2 dt$ as a function of current, location, bath temperature, and cooling mode (single phase helium versus two phase helium) are presented. The magnets are able to absorb their own energy with a modest margin of safety for the type of quenches expected in an accelerator environment. In order to obtain an additional margin of safety, a quench protection scheme which employs current shunting diodes across each magnet half has been adopted.

Introduction

The original quench protection system[1-2] for the superconducting magnets in the CBA Project employed current shunting cold diodes across each magnet. This scheme is satisfactory if every magnet is able to absorb its own energy during a quench (i.e., - is "self-protecting") without degradation in performance. Although this system has been slightly modified, as discussed in the last section, the studies described herein were directed toward determining the degree of self-protection of the CBA dipoles. Neglecting cooling effects, Joule heating during a quench gives a maximum temperature (T_{max}) which is related to the quantity $\int I^2 dt$ which is a function of current, quench location, quench source size, bath temperature, and magnet-to-magnet variations. A study of self-protection then involves a measurement of $\int I^2 dt$ as a function of these variables in sufficient detail to allow extrapolation to an accelerator environment. The "allowable" $\int I^2 dt$ was determined from short sample studies which are described.

Short Sample Measurements[3]

The bare superconductor is a Rutherford type cable composed of 23 strands, each having a 2070 filament matrix superconductor with a ratio of 1.7 Cu to 1.0 NbTi. The cable cross section is wedge shaped with a nominal width of 0.307" and an average thickness of 0.0495". It is wrapped with 0.001" of kapton and 0.0040" of epoxy-impregnated fiberglass for insulation. For the damage studies described below a three layer cable section was prepared under nominally the same conditions as the magnet coils are molded: ~ 10 kpsi and 155°C for 1-1/2 hours. This cure reduces the insulation ~ 0.002"/turn and the void area to the 5% to 10% range.

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By measuring the short sample resistance as a function of temperature and also during a high current pulse, the experimental relation between conductor temperature and $\int I^2 dt$ can be established. This is shown in Fig. 1, measured at 4.22°K and in a 5.0 Tesla external field. Also shown is a calculation of $\int I^2 dt$ vs temperature for zero external field.

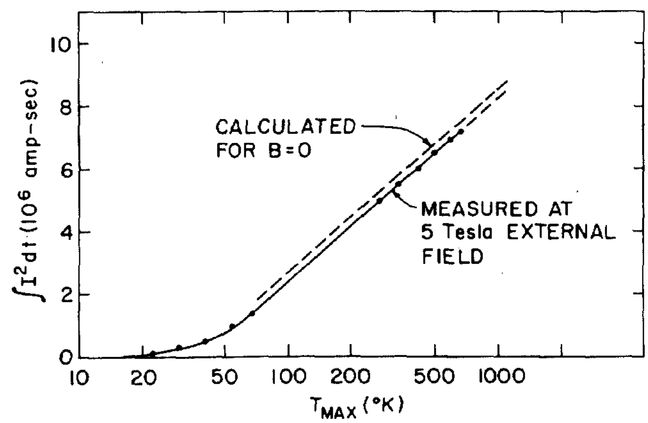

Fig. 1. $\int I^2 dt$ vs T_{max} from short sample measurements.

Damage studies were performed on a sample prepared as described above. The sample is quenched with an attached heater while carrying 4000 amps and $\int I^2 dt$ is varied by turning off the power supply after a fixed time interval. After each pulse, the quench current is measured to determine whether degradation has occurred. For convenience, t = 0 in the $\int I^2 dt$ measurement is taken to be when the (resistive) voltage is 20 mV which matches the typical noise level in magnet measurements. The results near degradation are shown in Table I.

TABLE I

$\int I^2 dt$ (10^6 amp^2-sec)	No. Pulses	ΔI_Q (Amps/Pulse)
8.30	4	0
8.38	1	0-50
8.46	5	240

A damage threshold at ~ 8.4×10^6 amp^2-sec at 50 kG is observed, or from Fig. 1, T_{max} ~ 1050°K. Visual inspection of the sample whose performance degraded at the 8.46×10^6 level revealed nothing remarkable. The kapton was still intact and the fiberglass wrap was not discolored. The strands of the cable are solder coated and the flowing of this solder whose melting point is ~ 500°K has stiffened the cable but this effect should be quite harmless.

Magnet Studies

The CBA dipole has a two layer (inner and outer) design. Each layer is divided into two blocks separated by copper wedges. A "spot" heater is installed in close proximity to the turn nearest the midplane in each of the four blocks. This is shown schematically in the inset in Fig. 2. These heaters are used to systematically study quench propagation under controlled conditions.

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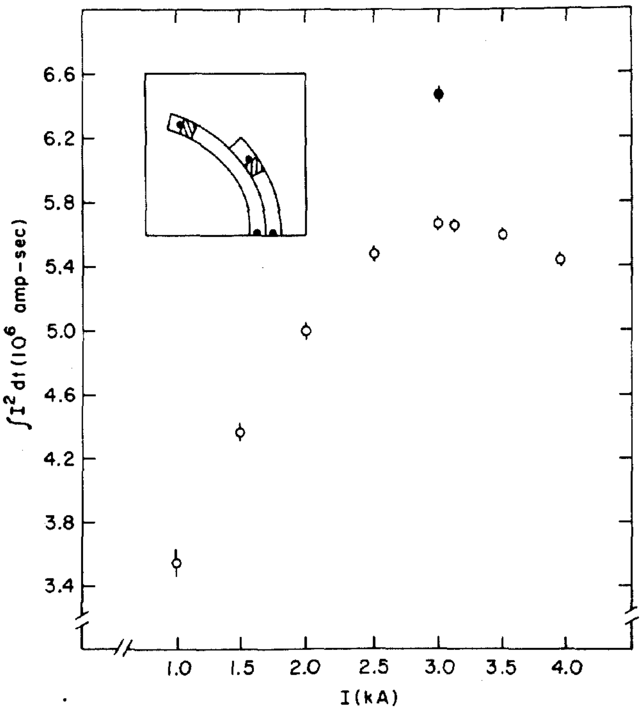

Fig. 2. $\int I^2 dt$ vs initial magnet current for inner coil midplane quenches on LM1 in liquid He. The open circles are at 4.5°K. The solid circle is at 3.62°K. The inset schematically shows the spot heater locations in a dipole quadrant.

Figure 2 shows $\int I^2 dt$ as a function of magnet current for quenches induced by the inner coil midplane heater the prototype magnet designated LM1. This location is of particular interest since quenches due to beam loss in an accelerator will occur near the midplane. No energy is extracted from the magnet in these data or any other data described in this note. The peak at 3000 amps is a consequence of the effective quench propagation velocity; when the quench velocity as a function of current (I) is rising more slowly than I^2, $\int I^2 dt$ will increase with I whereas when the reverse is true, $\int I^2 dt$ will decrease. Subsequent tests at lower bath temperature and different locations showed $\int I^2 dt$ to be essentially flat ($\pm$ 0.1 × 10^6 amp^2-sec) above I ≅ 3000 amps.[4] Note also the single quench at 3.62°K in Fig. 2 which shows the extreme sensitivity to bath temperature.

Varying amounts of data from spot heater induced quenches have been obtained for nine prototype dipoles in liquid helium at 4.5°K. The magnet-to-magnet fluctuations at 3000 amps are shown in Fig. 3 which is a population distribution of $\Delta\int I^2 dt = \int I^2 dt - \langle\int I^2 dt\rangle$ where the average is over the nine magnets for a given heater location. In fact, only the mean of the outer coil midplane location is significantly different from the other locations. This is the worst case location and will be discussed further. The rms of Fig. 3 is ~ 0.25 × 10^6 amp^2-sec. Since this is significantly larger than the current dependence above 3000 amps only data taken at this "worst case" current will be analyzed.

The magnet data presented thus far, with the exception of the single low temperature quench in Fig. 2, is in liquid He at 4.5°K but the CBA proposal plans to use forced circulation of super-critical (single phase) He in the temperature range 2.6 – 3.8°K. One magnet LM7, has been studied with spot heater quenches in both liquid and single phase. Quench velocities are slower in single phase than in liquid at the same temperature. This results in an increase in $\int I^2 dt$ of between 0.5 and 1.0 × 10^6 amp^2-sec.[5]

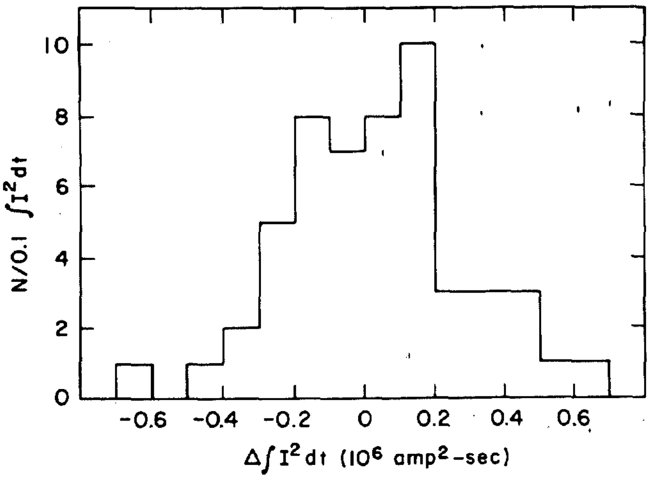

Fig. 3. Histograms of $\int I^2 dt - \langle\int I^2 dt\rangle$ for nine magnets at 3000 amps and 4.5°K in liquid He. Data from all four locations are in this distribution although the mean is computed separately. A given magnet may have more than one entry in this plot because some magnets have heaters in each half.

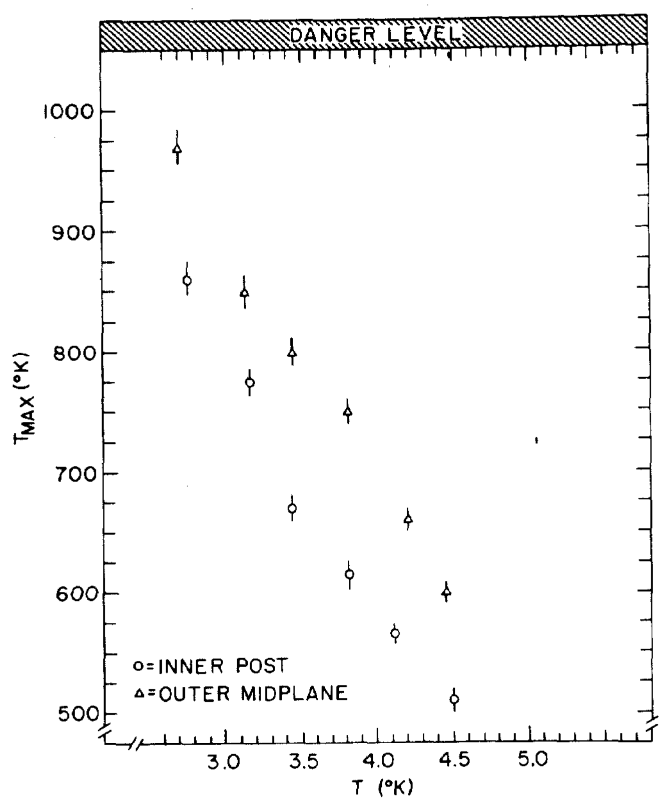

Fig. 4. Maximum conductor temperature vs bath temperature for LM7 in single phase He at 3000 amps. T_{max} was obtained from $\int I^2 dt$ measurements and the short sample T_{max} vs $\int I^2 dt$ relationship.

LM7 was also tested as a function of bath temperature in single phase helium. The results are shown in Fig. 4. As mentioned above, the outer coil midplane is the position of highest $\int I^2 dt$ and T_{max}. This is because $B \approx 0$ at this position and the quench velocities are slowest here. However, this is also the most stable (highest current capacity) point in the magnet and therefore the least likely to quench.

Of more interest are the open circles in Fig. 4 which are more representative of beam loss quenches or of spontaneous quenches near the high field point. The margin of safety shown in Fig. 4 is not large, at the lowest bath temperature, in comparison with the magnet-to-magnet variations. For this reason, an improved scheme using a "double-diode" has been adopted.

The double-diode arrangement is shown schematically in Fig. 5. The idea here is to commute current out of the quenching magnet half in less time by reducing the inductance. The mutual inductance between the magnet halves must be considered and detailed calculations compare well to an experiment performed with prototype magnet LM5.[6] This experiment indicates a reduction in $\int I^2 dt$ of between 0.5×10^6 and 2.0×10^6 amp^2-sec depending on quench location.

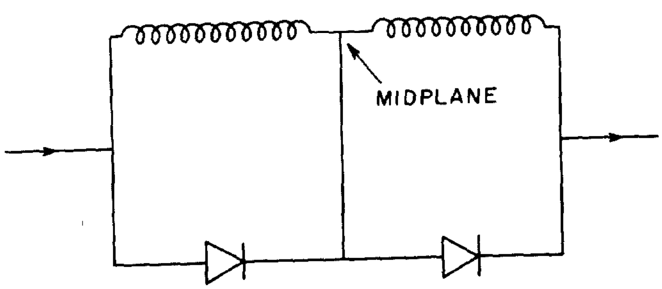

Fig. 5. Schematic representation of the double-diode protection circuit. The original scheme employed one diode and had no midplane connection.

The spot heaters used in the LM7 test (Fig. 4) are represented in the histogram in Fig. 3. $\int I^2 dt$ for other magnets can therefore be calculated assuming a constant difference in $\int I^2 dt$ relative to LM7. Combining this with the double diode calculation allows an estimate to be made of T_{max} in an accelerator environment. This result is shown in Fig. 6. For representative quenches, as discussed above, Fig. 6 shows a safety margin of between 225°K (at T_{bath} = 2.6°K) and 475°K (at T_{bath} = 3.8°K) in the worst magnets observed to date.

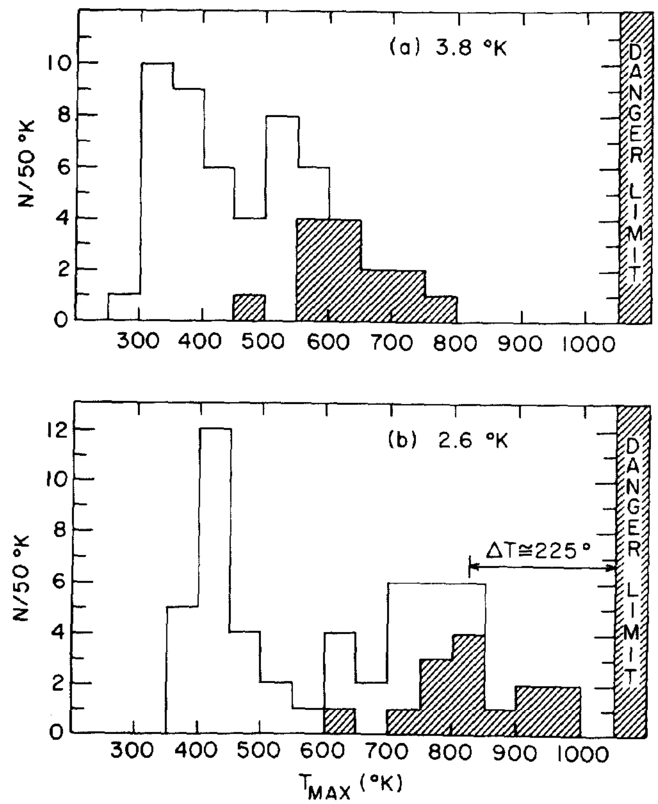

Fig. 6. Estimates of T_{max} for all induced heater quenches in an accelerator environment. The shaded entries are the outer coil midplane location.

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