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ULTRA STABLE HIGH FIELD SUPERCONDUCTING DIPOLES*

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SUMMARY

Tolerance of superconducting magnets to beam heating can be crucial. The magnets described produce a dipole field between parallel current sheets. Images in iron extend the sheets. The field is parallel to the current sheets so that high purity aluminum spacers can extend over the full length and height of the coil. High aluminum thermal conductivity and diffusivity results in locally produced heat being dissipated into helium over a large area. All magnets show little training with complete "memory" to ~ 100% of short sample. $\dot{B}$ induced quenching is not observed. The 2 m, 8° dipole coils do not quench at 4 T if the correcting coil is driven normal, dissipating > 1 kW. Intralayer quench propagation induced by 30 GeV protons is described. A 1 m, 6 T pulsed dipole first quenched at 5 T. Pulsing losses at 0.5 T/sec are small.

I. Introduction

The geometry of the window frame magnet and its field shape is such that a high conductivity spacer can extend over the entire surface area of each layer of conductor. To date magnets have been constructed using readily available 59's purity aluminum, with a resistance ratio at operating temperature of ~ 4000. Fig. 1 shows a plan view of a coil section. The anodized aluminum spacer extends the full length of the magnet. It is typically 10 cm high and 1.25 mm thick, with 1 mm x 6 mm x 10 cm grooves for helium heat exchange occupying 50% of the surface area. The superconducting layer is typically $\gtrsim$ 1.5 mm thick, composed of individual turns $\gtrsim$ 1.5 mm x $\gtrsim$ 3.0 mm.

With this construction a local hot spot not only heat exchanges very well with helium in its immediate vicinity, but with helium over the entire surface area of the aluminum spacer. Helium is the only significant heat sink at operating temperatures and so this mechanism inhibits quenching. In addition, once quenching is initiated, it propagates rapidly transversely and longitudinally so that high voltages and high temperatures are not generated in the coils of large magnets.

II. Beam Induced Quenching of 8° Magnet

Superconducting magnets for accelerators and primary beam lines can be accidentally quenched by beam heating. The threshold will be determined by the time structure of the beam loss and by details of the magnet application, construction, and cooling. The "8° superconducting dipole[1,2]" has operated since October 1973 as a part of the proton beam transport to the north experimental area at the AGS. Intensities of typically 8 x 10^{12} protons at 28.5 GeV/c, or ~ 40 kJ of beam energy per pulse of 3 μsec duration pass through the magnet, bending the beam through an 8° angle. Each of 2 series connected units is ~ 2 m long with a 10 cm winding bore and a 7.3 cm i.d. warm beam pipe. Because of the curved beam trajectory, the beam center is only 2.0 cm from the beam pipe at both ends and the middle of each unit.

Practical accelerator magnets require high current densities (J). The superconducting filaments must carry a large fraction of their inherent short sample critical current density (J_c), so the reserve capacity to absorb heat is very small. Temperature effects on the J_c of representative NbTi alloys have been studied.[3,4] Complete J_c, B, T surfaces have been obtained from 4.2 K up to transition temperatures (T_c) of slightly more than 9 K. For regions of interest here, at fixed T, the product, $J_c \times B_{max}$, becomes almost constant. Figure 2 illustrates that for a NbTi superconducting magnet coil, the $(J_c B_{max})^{\frac{1}{2}}$ attainable decreases linearly with rising T. In the approximation B_{max} is linear with magnet current, I, the ordinate can be expressed in units of B_{max}. Here J_c and B_{max} refer to the superconductor. The minimum and maximum curves bracket approximately the range of ultimate performance of NbTi coils. The minimum curve, using Ref. 3 data coincides with the measured short sample data of the older, coarse filament 8° conductor. The maximum curve, from Ref. 4 data, is also typical of the results obtained with high performance small strand commercial composites with adequate coldwork. For fine filamentary conductors, finite resistivity sets in below the thermal short sample limit. "Short sample" is often redefined on a resistivity basis, which places the magnet performance near the minimum curve. However, the thermal reserve i.e. the thermal runaway short sample limit is defined by the maximum curve.

The 8° magnet operates with primary protons traversing at 70% of its $(J_c B_{max})^{\frac{1}{2}}$ i.e. ~ 70% of its peak possible field. It is operating at its thermal limit if the NbTi is heated to 6.0 K, i.e. the normal temperature reserve is 1.5 K denoted by $\Delta T_1 = 1.5$ K in Fig. 2. This is relatively high performance. It is usually considered prudent to plan on $B/B_{max} \sim 80\%$, i.e., a magnet theoretically capable of 5 T is defined as operational at ~ 4 T, which gives reserve ΔT of 1 to 1.5 K. (The dotted line $\Delta T_2 = 1.5$ K shows the 8° magnet adjusted to a more modern conductor, giving $B/B_{max} \simeq 80\%$ with the same ΔT.) During quench studies the magnet survives 3 μsec thermal impulses delivering up to ~ 1 kJ into the entire cold mass at repetition periods as short as 1.3 sec. Its reserve ($\Delta T = 1.5$ K) is considerably less during a succession of beam heating pulses. Computations indicate portions of the coil receive much more heat than the enthalpy limit.[2,5] Portions of the coil must recover from the normal state with high transient heat transfer. This has been confirmed with heater experiments on small models. What about continuous heat input? With the dipole field at 4 T, the correcting coil of an 8° unit was once driven normal and was maintained for more than a minute, completely normal and stable in the cold condition with a resistance ratio of 90 and J = 26 kA/cm^2 in the Cu. The power input was > 1 kW. While the dewar pressure rose steadily, the dipole coil did not quench. Also, the 8° magnets or similarly constructed models have never quenched due to $\dot{B}$ even under extreme testing conditions. No energy removal system is used. Either of the 8° units can be quenched by the beam, and will absorb internally the energy of both units without difficulty. Analysis of quench propagation shows that entire coil layers change rapidly to the normal cold state.

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III. "Model T", 6 T Model Results

This improvised model was constructed with remnants of conductor from the 8^o magnet construction. The dipole coil has 3 splices, the correcting coil 5. Parameters and the magnet cross section are given in a companion paper.[6] Even with the limited design options, the coil thickness is only ~ 2.6 cm overall, i.e. including both structure and helium space.

Run 1 involved extensive testing of field quality up to 4.5 T, with rise rates limited to 0.5 T/sec. It was terminated without quenching pending materials testing. The outward coil pressure on the iron of ~ 3000 psi at 6 T results in 4200 psi of cyclic shear stress on the T-shaped iron inserts. This large shear stress would not occur in a conventionally constructed core.

Run 2 took place following successful tests of the cold iron shear strengths to > 4200 psi. The first quench occurred after extended pulsing to 5 T, initiated by the correcting coil. After a few quenches, all initiated by the correcting coil which was known to have some mechanical difficulties, 5.8 T fully corrected was reached. The dipole coil was taken to 6 T without quenching prior to ending the run. The field shape at 0.5 T/sec is identical to dc excitation. With repetition rates of ~ one minute, pulsing had no observable effect on the 20 watt refrigeration load. The magnet recovered following quenches, dumping most of its energy outside, even though its terminals were "short circuited" by a 20 m Ω cable.

Run 3 was primarily an instrumentation test. Fast pulsing was now possible using a 125 V power supply. At 5.5 T rise times as short as 2.5 sec were tested without quenching, and again without obvious effect on the ~ 20 watt refrigeration load with repetition periods of the order of one minute. At the end of the run the magnet was raised to 6.25 T, which corresponds to 100% of thermal runaway short sample. This gives $\Delta T \simeq 0$ on Fig. 2. As an operational device, the "model T" would be defined as a 5 T magnet. This corresponds to $\sqrt{JB}$ = 80% of maximum, and coincides on Fig. 2 with the 8^o operating point extrapolated upwards to a more advanced conductor, i.e. it follows the ΔT_2 line, but only as far as to the minimum curve.

The newer 4.5 T and 6 T conceptual designs indicated on Fig. 2 and described in a companion paper[6] are more conservative. Assuming newer conductors, the designs have larger ΔT reserve at their operating fields than the "model T" does at 5 T. They therefore should be capable of absorbing a significant level of beam heating.

IV. Heater Studies

Quench thresholds and propagation have been studied using small (.08 cm^2) "button" heaters immersed in the coil of a small model. Power is applied for Δt varying from ~ 0.1 ms up to seconds. In brief, results definitely show large transient heat transfer, with quench thresholds determined very reproducibly both by peak power and total energy deposited. There is a long delay, fractions of a second, before the magnet quench occurs. It appears that the heater imput energy, plus resulting I^2R losses in the layer being heated, must be ~ large enough to vaporize or vapor lock all helium on the layer surface to prevent recovery. For power levels below that corresponding to steady state heat transfer to helium for the entire layer cooled surface (~ 0.3 watts/cm^2) heat can be maintained indefinitely without a quench. Frozen oil was used to block the cooling channels. The model (which had been previously pulsed to 4 T with $\dot{B}$ > 10 T/sec) then showed $\dot{B}$ sensitivity several orders of magnitude worse. While not yet studied in detail, it was evident that the mechanism of heat transfer is accordingly altered.

References

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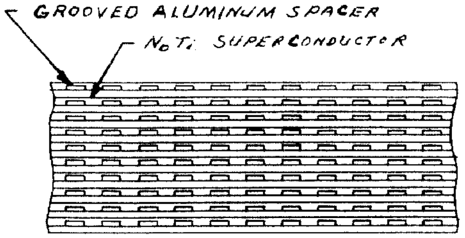
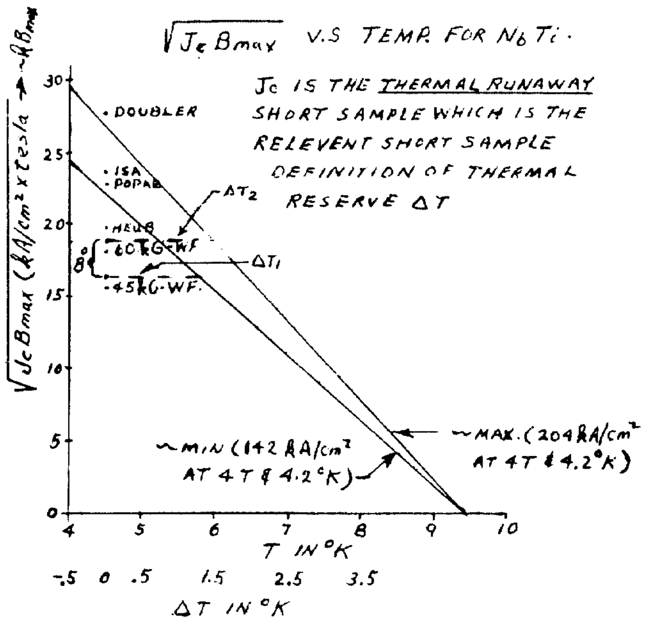


PLAN VIEW OF DIPOLE COIL SECTION

Figure 1.



1. Superimposed on Fig. 2 are the operating points of several magnet designs adjusted to 4.5°K. For each case the thermal reserve will be given by the horizontal distance from the operating point to each individual load line curve.
2. The points marked 45 kG W.F. and 60 kG W.F. are the design operating points for conceptual designs in Ref. 6. The operating line for these magnets was placed midway in the range.

Figure 2.