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QUENCH THRESHOLDS IN OPERATIONAL SUPERCONDUCTING MAGNETS **

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ABSTRACT

Superconducting magnets exposed to intense primary proton beams in high energy physics applications are subject to potentially extreme heat deposition. The beam power density, its duration and spatial distribution, the current density in the superconductor and, potentially, in the normal metal substrate, as well as the construction and cooling details of the magnet, are all relevant parameters.

We will discuss an extension of some earlier work in which 28.5 GeV/c proton beams with up to 50 k joules of energy were targeted upstream from a 4 m long, 4 T dipole magnet used to deflect the protons through an angle of 8^o. Quench thresholds much greater than the enthalpy limit of the magnet materials were observed.

In the beam exposure experiment described in this paper, intense beams of 1.5 GeV/c protons have been deflected directly into the magnet coil at relatively steep angles of incidence. The magnet quench threshold was studied by varying the beam currents and beam sizes.

I. INTRODUCTION

The magnets used in this experiment are the superconducting 8^o bending magnets which have been operated since October, 1973 in the 28.5 GeV/c primary proton beam from the Alternating Gradient Synchrotron to the neutrino experimental area at Brookhaven National Laboratory. Figure 1 is a photograph showing the cryostats containing these magnets installed in the tunnel housing the primary proton beam line. These magnets

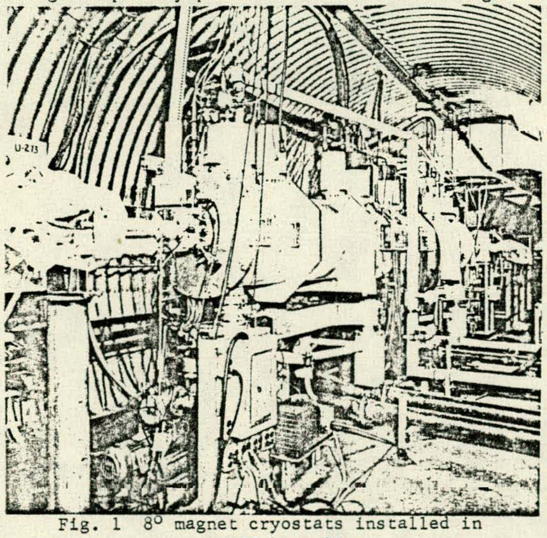

Fig. 1 8^o magnet cryostats installed in AGS beam line CN1-152-73

are of the window-frame type as shown schematically in Fig. 2 and produce a dipole field between parallel current sheets. Because images in the iron return path extend the sheets, magnetic fields comparable in precision and predictability to those of conventional magnets can be obtained at all levels of excitation by utilizing a single auxiliary correction coil in a predetermined way.

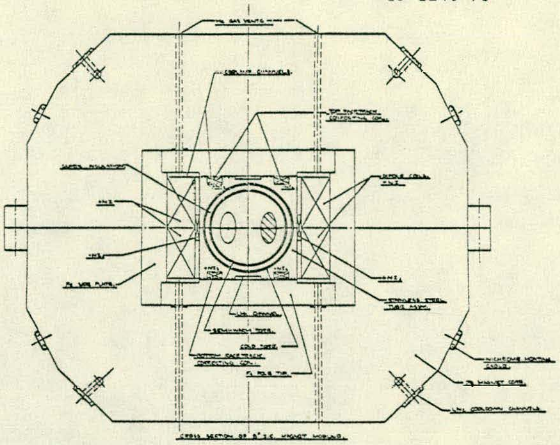

Fig. 2
Schematic showing cross section of 8^o S.C. magnet module

The main dipole coil and the correction coil are wound with high purity aluminum spacers between vertical layers of the coils which extend over the full length and height of the coils. A section of the dipole coil and correction coil are shown in Fig. 3. These aluminum spacers are grooved to allow helium to contact directly

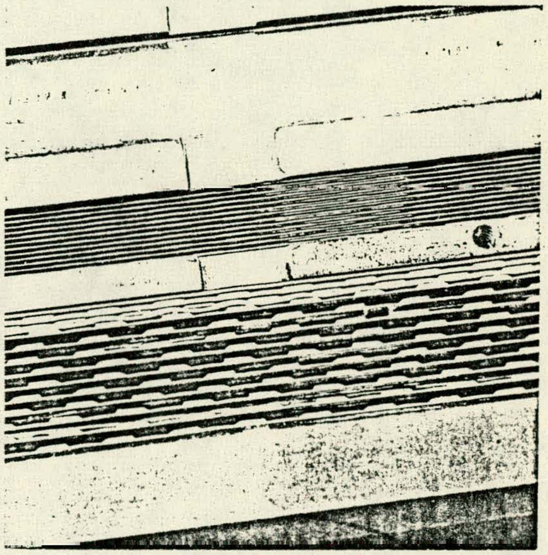

Fig. 3 Sections of main dipole coil and auxiliary correcting coil showing the high purity aluminum interlayer spacers. CN8-992-73

50 percent of the surface area of one vertical face of each coil layer. In addition to this direct contact of coil conductor with helium, the high thermal conductivity and diffusivity of the aluminum cause locally produced heat to be dissipated rapidly into helium over an extended area. This mechanism inhibits quenching since helium is the only significant heat sink at magnet operating temperatures. However, if a quench is initiated, it is propagated rapidly transversely and longitudinally so that high voltages and excessive temperatures are not developed in the coils of the magnet.

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II. RADIATION HEATING EXPERIMENTS

The 8° magnet dipole sytem had previously been exposed to radiation heating in secondary particle flux from C, Cu, and Pb targets of various thicknesses which were inserted in the 28.5 GeV/c primary proton beam at distances 2 m and 5.6 m upstream from the first magnet.[1] In the experiment described in this paper, beams of 1.5 GeV/c protons with various intensities and beam cross-sections were deflected directly into the magnet coil at angles of incidence of about 13°. To produce this deflection, the magnet was operated with a current of approximately 500 A in the dipole coil conductor, generating a magnetic field intensity of 2.5 T. Under these conditions, the current density in the NbTi superconductor of the 1.25 Cu to 1.0 NbTi composite conductor is 29 kA/cm^2.

The observations recorded during the experiment are listed in Table I.

TABLE I

OBSERVATIONS

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I (INTENSITY)	ENERGY INTO DIPOLE	MAGNET CURRENT	PRESSURE RISE	V-COIL	P IN.COIL
A. Beam Size - 1.507 cm^2 - Particle Density - 0.8 x 10^{12} $Protons/cm^2$					
1.144 x 10^{12}	153 Joules	500 A	Yes	None	-
1.247 x 10^{12}	166 Joules	500 A	Yes	None	-
1.322 x 10^{12}	176 Joules	498 A	Yes	0.18 V	89.6 W
NOTE: Pressure decreased when supply was turned down, conductor was resistive and heating in a metastable way, recovered as current was decreased.					
1.255 x 10^{12}	168 Joules	510 A	Yes Rapidly	>1.5 V	>765 W
NOTE: Quench - 61 W from increase of temperature of magnet conductor to 50° K.					
B. Beam Size - 0.7452 cm^2 - Particle Density - 0.84 x 10^{12} $Protons/cm^2$					
0.627 x 10^{12}	83.9 Joules	500 A	No	No	-
0.625 x 10^{12}	83.6 Joules	510 A	Yes	.25 V	127.5 W
NOTE: Magnet recovered when supply was turned down.					
C. Beam Size - 5.057 cm^2 - Particle Density - 0.111 x 10^{12} $Protons/cm^2$					
0.556 x 10^{12}	74.4 Joules	500 A	No	No	-
0.575 x 10^{12}	76.9 Joules	510 A	Yes,Slow	.21 V	107 W
NOTE: Magnet recovered from metastable state when power supply was turned down.					
D. Beam Size - 1.716 cm^2 - Particle Density - 0.216 x 10^{12} $Protons/cm^2$					
0.369 x 10^{12}	49.4 Joules	510 A	No	No	-
0.342 x 10^{12}	45/8 Joules	520 A	Yes,Slow	No	-

As indicated in the table, several beam-size settings were used and the beam intensity and magnet current varied within each setting. The helium pressure in the magnet cryostat and the voltage across the magnet coil were monitored. The Energy into Dipole represents the amount of energy deposited by the proton beam in the dipole coil structure including conductor, aluminum sheets, formvar insulation, and helium, based on preliminary calculations. P in Coil represents the power being dissipated in the magnet as determined by the magnet current and voltage readings.

The above observations indicate that after the initial heat impulse from the proton beam which created a normal region in the dipole coil of the magnet, the magnet could be operated in a metastable condition with approximately 100 w being dissipated in the coil. An increase in magnet current would cause the normal region to grow and decrease would be followed by coil recovery. Under one set of conditions a complete magnet quench was initiated.

For the case of the complete quench, preliminary calculations indicate that the energy deposited by the particle beam in the section of dipole coil struck by the beam is approximately 168 joules. An error of ±50% is presently assigned to this value which should also be applied to other calculated results depending on its magnitude. From considerations of beam path and cross-section, and coil structure, 125 of the 168 joules mentioned above are deposited in 68 gms of dipole conductor which is equivalent to 1.84 joules/gm.

Using Curve 4 from Fig. 4 for the temperature interval 4.5 - 10K and the curve for the specific heat of

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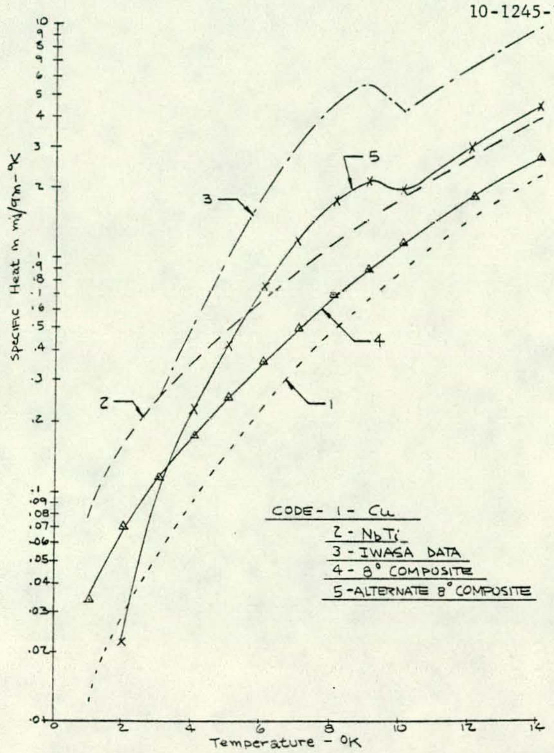

Fig. 4 Specific heat of 8° magnet conductor

copper as a function of temperature from WADD Tech. Report 60-56 [2] for the temperature interval 10-300K, it is estimated that an enthalpy change of 1.84 joules/gm will raise the temperature of the conductor struck by the beam to approximately 50 K, assuming no heat transfer occurs during the 6 μsec beam pulse. At this temperature with the magnet current fully in the Cu of the conductor, representing a current density in the Cu of 23 kA/cm^2, the resistance of the Cu is such that 61 w are being dissipated in the volume of conductor struck by the beam

A previous paper[1] has discussed the temperature reserve of superconductors, indicating that because of the dependence of the short sample critical current density (J_c) on temperature (T) the reserve capacity of practical accelerator magnets, which require high current densities, to absorb heat is very small. Plots of J_c vs T for NbTi alloys give essentially straight lines of negative slope for constant B values, and for regions of practical interest where the operating temperature, T, is 4 to 5 K and the peak field, B_{max}, is 3 to 7 T, the parametric relationship can be further simplified. At any fixed T, the product ($J_c B_{max}$) becomes almost constant.

The quantity $(J_c B_{max})^{\frac{1}{2}}$ attainable for a NbTi superconducting magnet coil decreases linearly with increasing T as shown in Fig. 5. When the ordinate is expressed as $(J_c B_{max}$ kA-Tesla/cm$^2)^{\frac{1}{2}}$ where J_c and B_{max} refer to the superconductor, a general relationship is obtained independent of design details and magnet saturation.

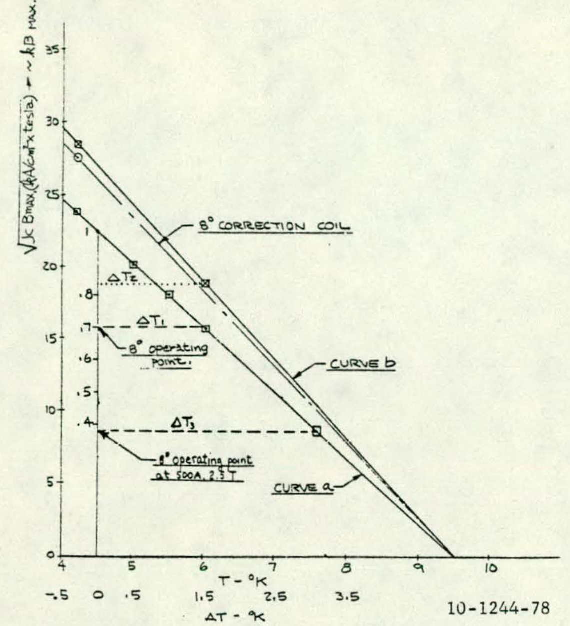

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Fig.5 $(J_c B_{max})^{\frac{1}{2}}$ versus temperature for NbTi.

Curve a of Fig. 5 has $(J_c B_{max})^{\frac{1}{2}} = 23.8$ at 4.2 K where $J_c = 142$ kA/cm^2 was measured at B = 4 T and T = 4.2 K. The data for Curve a are for a single strand of NbTi from a commercially available conductor with a large strand radius of nominally 120 μm and are taken from load line data of Hampshire, et al.[3] Curve b uses the data of Bindari [4] on a specially prepared high J_c performance NbTi filament of nominal radius, r = 100 μm, and is typical of the results obtained with high performance small strand commercial composites, i.e., $J_c \simeq 200$ kA/cm^2 at 4 T and 4.2 K. The Curves a and b of Fig. 5 thus bracket the range of ultimate performance of NbTi coils.

The 8° magnet conductor with superconducting filaments of relatively large radius is rated $J_c = 142$ kA/cm^2 in NbTi at 4.2 K and 4 T, placing the conductor on Curve a. For the same material, drawn down to one-fourth the cross-sectional area for the correcting coil, J_c increased as shown in Fig. 5 almost to Curve b due to the additional size reduction and cold work. The vertical scale drawn at 4.5 K in Fig. 5 represents the 8° dipole excitation at its typical operating temperature. Point 1 at the intercept of Curve a represents no thermal reserve, or, short sample operation at about 5.5 T. The iron yoke for the 8° magnet was designed to saturate heavily above 4 T and, because of iron saturation, a field of only about 5 T is generated with $(J_c B_{max})^{\frac{1}{2}} = 22.5$.

The usual operating mode for the 8° magnet is with a field in the aperture of 3.6 T at 4.5 K and, under these conditions, B = 4 T in portions of the coil on the horizontal midplane closest to the proton beam. This mode of operation requires J = 59 kA/cm^2 and $(JB)^{\frac{1}{2}} = 15.4$, i.e. 68% of the limiting $(J_c B_{max})^{\frac{1}{2}}$. The magnet would thus be operated at its thermal limit only if the NbTi filaments were heated to 6.0 K. The normal temperature reserve is, therefore, 1.5 K and is indicated by $\Delta T_1 = 1.5$ K in Fig. 5. For the experiment described in this paper, the magnet was operated with 500 A in the conductor at a field of about 2.5 T or about 38% of the limiting $(J_c B_{max})^{\frac{1}{2}}$. The thermal limit in this mode of operation is 7.5 K and the temperature reserve, as indicated by ΔT_3 in Fig. 5, is about 3.0 K.

From curve 4, Fig. 4, it can be found that the enthalpy change of the 8° dipole conductor for $\Delta T_3 = (7.5-4.5)$ K is about 1.12 mJ/gm. As mentioned above, the energy deposited by the 1.5 GeV/c proton beam in the dipole conductor struck by the beam is sufficient to produce an enthalpy change in the conductor of 1.84 joules/gm, a change 1600 times as great as that needed to raise the temperature of the conductor to 7.5 K and cause a quench.

The heat vaporization of helium at 4.5 K is about 20 joules/gm, and for equal volumes, at this low temperature, the helium is a heat sink approximately 10^3 times larger than that provided by the magnet coil material. If it is assumed in those cases where the magnet coil was struck by the beam but did not quench that all the energy deposited in the conductor was dissipated by vaporizing liquid helium contained in the dipole coil structure, then the amount of liquid helium vaporized is about 50 cm^3. From details of the coil structure, the length of a complete dipole coil section containing this quantity of liquid helium is about 140 cm. Table II is a summary of the calculated results.

TABLE II

CALCULATED RESULTS

Energy in Beam of 1.3×10^{12} Protons at 1.5 GeV	312 Joules
Beam Cross-Section	1.5 cm^2
Beam Pulse Duration	6 μsec
Energy Deposited by Particle Beam in Section of Dipole Coil Struck by Beam (This result is presently assigned an error of ± 50% which should be applied to the calculated results listed below.)	168 Joules
Energy Deposited in the Dipole Coil Conductor	125 Joules
Enthalpy Change (Δh_B) of the Dipole Conductor	1.84 Joules/gm
Final Temperature of the Dipole Conductor for Enthalpy Change of 1.84 Joules/gm	>50 K
Thermal Reserve (ΔT_3) of Dipole Conductor Operating at 4.5 K and 25 kG	(7.5 -4.5)K
Enthalpy Change (Δh_3) of Dipole Conductor for ΔT_3	1.12 mJ/gm
Ratio $\Delta h_B/\Delta h_3$	~1600
Assume all Energy Deposited in the Conductor Dissipated by Vaporizing Liquid Helium in the Dipole Coil — Volume of Liquid Helium Vaporized	~50 cm^3
Length of Dipole Coil Containing 50 cm^3 He	~140 cm
Current Density in NbTi of $\frac{1.25\ Cu}{1\ NbTi}$ Conductor at 25 kG Before Heating	29 kA/cm^2
Current Density in Cu After Heating	23 kA/cm^2

The Magnet at 25 kG Recovers from Beam Heating Impulses Depositing Energy of About 1600 x Enthalphy in the Coil Section Struck by the Beam.

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Although these results have been obtained using simple assumptions which do not include, for example, detailed heat transfer considerations, they do give strong indication of the remarkable stability and tolerance to radiation heating that have been incorporated in the 8° magnet design by the use of the high purity aluminum interlayer spacers. The behavior observed is similar to that of cryogenically stable conductors and is attributed to ample cooling with liquid helium and the high thermal conductivity and diffusivity of the aluminum spacers which serve to rapidly distribute heat from thermal disturbances over large areas.