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SENSITIVITY OF AN ENERGY DOUBLER DIPOLE TO BEAM INDUCED QUENCHES

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ABSTRACT

In a series of tests in the Fermilab P-West proton beam an Energy Doubler dipole, model E22-12, was exposed to various intensity 400 GeV/c beams with several types of spills. Results are presented for the sensitivity of this magnet to beam induced quenches. A Monte Carlo beam shower calculation was performed to predict the energy deposition in the coil by the beam and these predictions are compared with quench data. In one case (4.75°K, 3500 A, 15 x 18 mm beam spot), the beam required to induce quenching for microsecond spill was 0.5 to 0.7 x 10^8 protons per pulse. The Monte Carlo prediction for these conditions is 0.8 x 10^8 protons per pulse, corresponding to an energy density in the superconductor of 10 mJ cm^{-3}.

INTRODUCTION

The question of the amount of beam loss which will quench a superconducting magnet has taken on special importance at this time because of the plans for the 1000 GeV Energy Doubler. Previous studies have been performed on dissimilar[1] magnets and on a very early prototype Doubler magnet[2]. For a period of three months an Energy Doubler dipole[3], model E22-12, was operated in the P-West beam line with proton beams in the range 10^7-10^{12} per spill passing through it. During this time a special series of tests was conducted to determine the amounts of micro-second, 1 millisecond, and 0.5 second slow spill beam loss that would induce quenches in this magnet.

EXPERIMENTAL ARRANGEMENT

The installation was situated in the P-West line and the Doubler dipole in normal operation performed the function of bending the incident 400 GeV proton beam 10.375 mrad onto the High Intensity Laboratory target. The nominal current required for this standard operation was approximately 2300 A. The schematic of the helium refrigeration system used to cool this magnet is shown in Fig. 1. The helium refrigeration for this magnet was provided by a CTI 1400 refrigerator which produced 30-40 liter/hour into a 450 liter dewar pressurized to 4.5 psig. The dewar pressure was then raised to 8 psig and liquid was transported from this dewar via a 100 foot transfer line to a counterflow heat exchanger (subcooler) before entering the dipole coil region as a single phase fluid. In standard operation the pressure of this region was 23 psia corresponding to a saturation temperature of 4.73°K. The helium was subcooled by ∿ 0.05°K. The single phase liquid then passed through the magnet to a Joule-Thompson valve into the two phase region, which is in thermal contact with the single phase region. The helium, at this point a boiling two phase mixture, passed back through the subcooler and to the refrigerator cold return. The Joule-Thompson valve was operated in both manual and automatic modes. In automatic mode, the valve was controlled using the temperature difference between the gas returning from the subcooler to the refrigerator and its saturation

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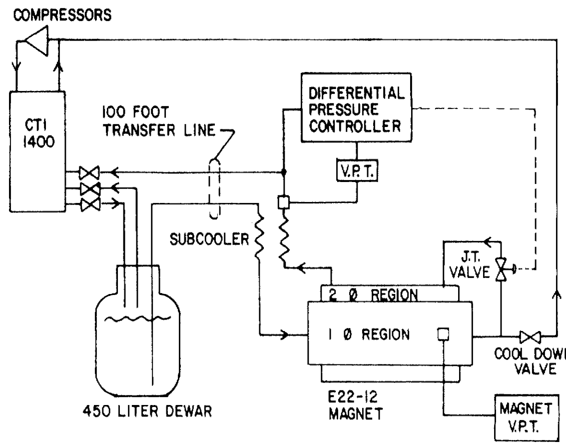

Fig. 1. Schematic of the Helium Refrigeration System.

temperature. This was accomplished by measuring the pressure difference between the returning gas and a vapor pressure bulb in the gas stream. A pressure difference of 1-2 psi, corresponding to a temperature of 0.05-0.1°K above saturation was used. It was found that, due to the long response times of the system to changes in flow (of order 5 minutes), more stable operation could be obtained by setting the J-T valve manually. A 1-2 psi pressure drop across the valve resulted in stable operation with a constant dewar pressure of about 8 psig and a refrigerator return pressure of about 6 psig. Heat transfer in this early version of the Doubler magnet was insufficient to maintain subcooling, and the vapor pressure thermometer just before the J-T valve indicated the helium there was boiling.

To explicity measure the quench properties of this Doubler dipole it was exposed to slow, millisecond and microsecond spills of varying intensities. In these tests we attempted the following measurements:

1. Protons required to induce a quench using slow, millisecond, and microsecond spills with the 400 GeV beam striking the coil region in a grazing trajectory (Geometry I, Fig. 2).
2. Protons required to induce a quench with the beam striking the upstream end of the magnet in an island region (Geometry II, Fig. 2).
3. Protons required in Geometry II to induce a quench with the beam as a function of magnet current.
4. Protons required in Geometry II to quench the magnet for different beam spot sizes.

Figure 3 shows the relative position of the coils and the bore tube. The impact angle of the beam on the coil region in the grazing configuration of Geometry I is 10.75 milliradians and the impact region starts approximately 60 inches from the downstream end of the magnet when the magnet is run at 3500 A. A crude measure of the relative energy dump at various intensities was proved by a pair of coupled ion chambers (loss monitors) positioned on the downstream end of the magnet. The temperature of the magnet was monitored by a vapor pressure thermometer situated in the single phase helium volume at the upstream (beam reference system) end of the magnet (cryogenically, the downstream end). Incident beam intensity was measured by a

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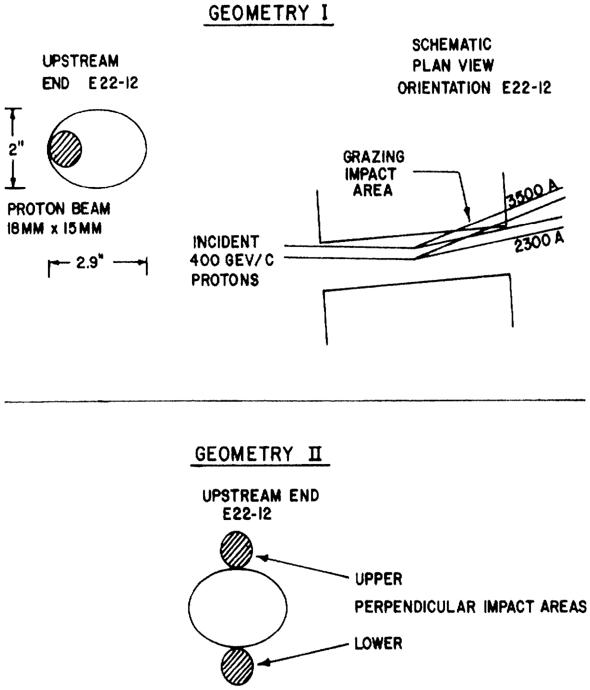

Fig. 2. Beam Impact Geometry. In Geometry I the beam enters the coil from the bore tube at an angle of 10.75 milliradians. In Geometry II the beam strikes the coil directly in the end turn region.

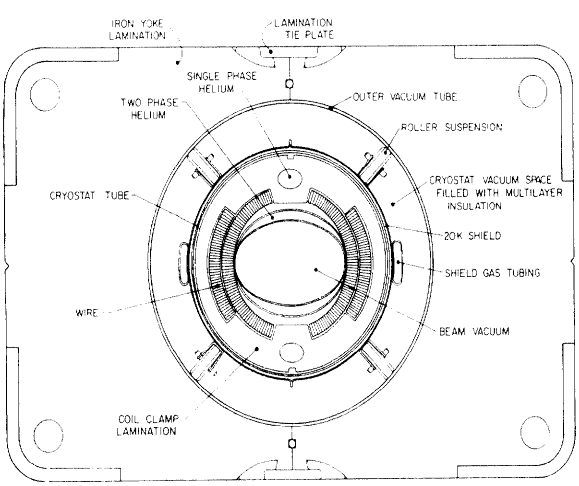

Fig. 3. Cross section of Energy Doubler magnet E22-12.

battery of ion chambers and secondary emission monitors upstream of the dipole for slow spill. A calibration of the loss monitors was made for the slow spill and the loss monitors were then used to provide beam intensity information for the fast spill data.

MEASUREMENTS

Figure 4 shows the response in Geometry I of the loss monitor vs. the 400 GeV proton beam intensity. As shown in Fig. 4, the quench points of E22-12 were measured a number of times for our different types of spill; 0.5 s slow spill, 1 ms fast spill, 20 microsecond spill with four 1.6 μs booster bunches spread uniformly around the main ring and 4 microsecond spill with two 1.6 μs booster bunches adjacent to one another. A Monte Carlo shower calculation was per-

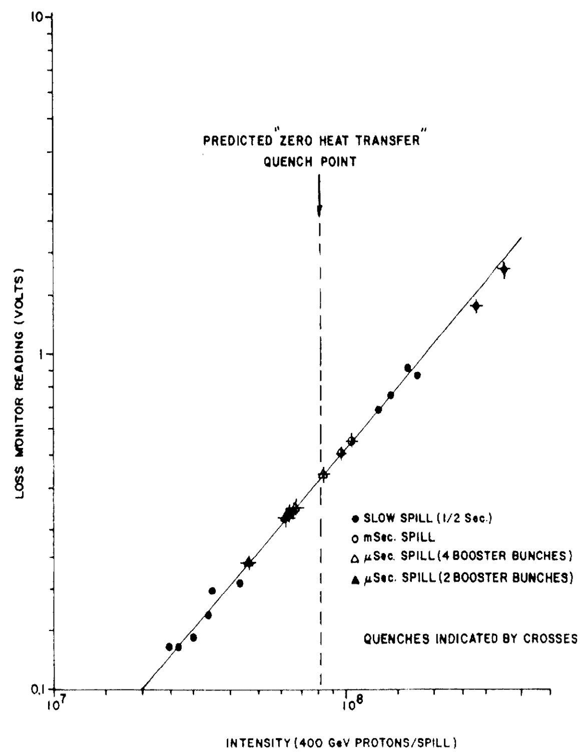

Fig. 4. Beam intensity required to induce quenching in Geometry I.

formed to estimate the energy densities of the hadronic and electromagnetic showers caused by the impact of the beam in both Geometry I and II. An elliptical beam spot of 18 x 15 mm with a gaussian distribution along the principal axis was used in the calculation. Approximately 95% of the beam was contained within this ellipse. This profile was consistent with the beam profiles measured on the beam monitors during all phases of the tests. For Geometry I the largest energy density is predicted to occur in the inner turns of the coil at the midplane and is approximately .75 GeV/cm^3 per incident proton. It is estimated that the energy density is accurate to approximately 25%. The temperature of the single phase (coil) region was monitored to be $4.78 \pm .05^{o}K$ before beam impact for all the quenches. The magnetic field in the region of maximum energy density at 3500 amps is estimated to be 3.5 T. The variation of short sample limit with temperature for the superconductor is such that at $6.2^{o}K$ the critical current will be exceeded for this magnet at 3500 amps. This corresponds to an allowable ΔT of $1.4^{o}K$ which in turn corresponds to an allowable energy density[4] of 9.8 mjoules/cm^3. From the results of the shower calculations the maximum beam that could strike the coil without quenching (in the absense of heat transfer mechanisms) would be approximately 8×10^7 protons. As shown in Fig. 4, slow spill quenches occur at approximately 4 times this level at 3×10^8 protons per 0.5 seconds. When the millisecond fast spill was measured we saw a marked increase in the sensitivity of the magnet with the quenches occuring at 10^8 protons. Finally for the microsecond spills we saw a slight increase in sensitivity with the quenches occuring typically at 5-8 x 10^7 protons. As shown in Fig. 4 there was a small increase in sensitivity when the microsecond spill structure was changed from four 1.6 μs bunches spread evenly over 20 μs to a "faster" microsecond spill with two 1.6 μs bunches adjacent to one another. While this change is probably not significant there still may be some heat transfer effects present at this level. The dashed line shows the upper limit on acceptable targeted beam in this geometry which is predicted by our simple calculation.

A second measurement of the sensitivity of E22-12 was done in the beam impact geometry shown as Geometry II in Fig. 2 with the .5 second slow spill. The results of this "perpendicular" impact measurement are shown in Fig. 5. The major observation is that the quench point occurs at a factor of 10 higher intensity ($\sim$ 2-3 x 10^9 protons at 3500 A). This is because the beam is initially striking an island and not a coil region in the dipole. This interpretation is approximately supported by the result of a shower calculation for Geometry II which predicts a maximum energy density roughly a factor of 10 less than the maximum density calculated for Geometry I. This shower calculation is analogous to that performed for Geometry I. The maximum energy density in the coil region is calculated to be 30-40 cm into the magnet and was .078 GeV/cm^3 per incident proton. This energy density was roughly independent of the magnetic field for 3.5 T and 0.4 T. In Geometry II we tried two other measurements. In order to determine whether the magnet was at a uniform temperature and to try to detect the possible existence of gas pockets in the coil region the beam was targeted both above and below the gap. As Fig. 5 shows, there is no change in sensitivity when the beam is targeted in the upper position. The second type of measurement was made by increasing the spot size to lower the energy density of the shower. A slight decrease in sensitivity is seen for this larger spot. The change is slight but seems to go in the proper direction.

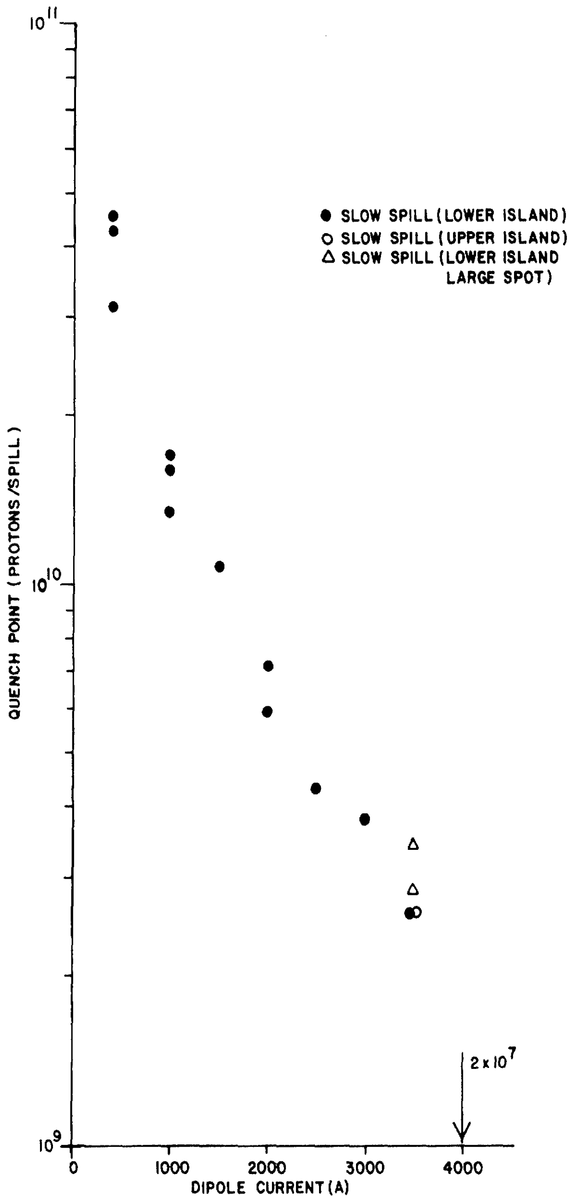

Fig. 5. Beam intensity required to induce quenching in Geometry II for 0.5 second spill vs. magnet current.

As a final measurement of the sensitivity of this dipole to beam, the variation of the slow spill quench point with magnet current was measured. The results are also shown in Fig. 5. Between 420 A and 3500 A there is an increase of an order of magnitude in the sensitivity of E22-12. In exercising this magnet without beam we found that spontaneous or training type quenches began to occur between 3900 and 4000 A (the magnet had been trained to 4800 A but a lower temperature). When we set the magnet at 4000 A we found a marked increased in sensitivity with the magnet quenching at the 10^7 proton level. This phenomenon was reproducible.

In conclusion, we have measured the beam initiated quench behavior of an Energy Doubler dipole. The results of our measurements appear (at the level thus far studied) to indicate that the quench behavior of this magnet can be predicted by a shower calculation and the assumption is approximately correct that no heat transfer mechanism is rapid enough in carry off an appreciable amount of beam energy in the case of the microsecond spill. In the case of 0.5 second slow spill nearly an order of magnitude more beam can be tolerated than in the case of microsecond spill. There is also a systematic variation of the quench point of the Doubler dipole with field which allows an order of magnitude more slow spill beam to be scraped at 420 amps (Energy Doubler injection current) than at 3500 A.

Finally, a number can be quoted for the sensitivity of the Doubler magnet to beam. The instantaneous energy density must be kept below 9.8 mj/cm^3 for 3500 A at 4.8°K or 5.2 mj/cm^3 for 4250 A at 4.3°K (nominal Doubler operating parameters). The power density must be kept below 72 mw/cm^3 at 3500 A and 4.8°K.

ACKNOWLEDGEMENT

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