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MEASUREMENTS OF MAGNET QUENCH LEVELS INDUCED BY PROTON BEAM SPRAY

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ABSTRACT

A superconducting dipole magnet was installed in the Fermilab primary beam line. Targets were inserted in the proton beam upstream of the magnet and measurements made of the energy deposition within the magnet sufficient to cause quenching. The quench levels were 25 mW/g for 1 sec beam spill and 1 mJ/g for a spill of 1 msec or less. In comparison, the energy deposition at the extraction septum was 0.6 mJ/g.

I. INTRODUCTION

A most important consideration in the design of superconducting magnets for application in high energy physics is the energy deposition due to ionizing radiation. The resulting temperature rise in the superconducting material may cause the magnets to quench. The cryogenic system may require a higher refrigeration capability. Radiation damage to the wire composite may degrade the conductor properties. Measurements of the beam "spray" sufficient to induce quenches are reported here. A summary of previous observations is given by Danby[1].

The investigations presented here fall into three categories: (a) measurements of the beam intensity and target thickness at the quench level as a function of magnet current for a number of experimental situations, (b) calibration of the energy deposition in the magnet coils with the aid of a calorimeter and (c) comparison of the energy deposition at quench to that experienced by materials in the immediate neighborhood of the extraction septum.

II. EXPERIMENTAL ARRANGEMENT

The superconducting magnet was placed in the extracted beam line of the Fermilab main proton synchrotron. The accelerator yields up to $2x10^{13}$ protons per pulse at a repetition rate of 4 to 7 pulses per minute. Normal operation requires two types of extraction of the protons for delivery to the experimental areas. One mode, "slow spill" brings the protons out over a period of one second, with an approximately uniform time distribution. The other mode, "fast spill", extracts the protons abruptly (in 20 μsec or 1 msec depending on the technique). These two varieties of extraction are essential to the high energy physics program, so as a consequence it is important to perform measurements with both extraction modes.

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The test dipole was located some 140 ft downstream of the point at which the beam emerges from the synchrotron. In this position, it was subjected to radiation from both extraction and injection losses; nevertheless it was found that the magnet could be operated under normal accelerator conditions with the extracted beam passing within its aperture.

For these studies, a copper target of variable thickness was inserted upstream of the test magnet - initially 50 inches from the magnet and subsequently 220 inches from the magnet.

Four sets of runs with various geometries were made. The conditions are listed in Table I. For Run 1, no shielding was interposed between target and magnet. While this run was in progress, the accelerator energy was raised from 300 to 400 GeV. Fast spill data was taken only at 300 GeV. Slow spill data was obtained at both ½ and 1 sec extracted beam duration. Helium boil-off from the cryostat was measured only at 400 GeV - the 300 GeV data will be treated as if it had the same calibration.

In Run 2, an iron collimator was placed between the target and the magnet. Due to the small magnet aperture, the iron was an inadequate shield for the downstream section of the magnet. In this run, this section was driven normal, whereas in all other cases the upstream portion was observed to quench.

For Run 3 the target was moved upstream and the same collimator was used to shield the magnet. The calorimeter was installed just downstream of the magnet so that intercalibration of energy deposition could be made between the helium boil-off rate and the calorimeter. In Run 4 a larger collimator was installed and again calibration and intercalibration using the calorimeter and helium boil-off rate were done. No appreciable change from Run 3 was observed.

After the runs were completed the superconducting magnet was removed and the calorimeter installed in the magnet location. Measurements of energy deposition were again obtained.

III. THE TEST MAGNET

The magnet is an early product of the Energy Doubler/Saver design study[2]. Relevant data are given in Table II and Fig. 1. The magnet consists of two separate sections 29 inches long, mounted tandem in the same cryostat. The sections are wired in series, bucking so that no significant beam deflection is produced. This magnet is of a three shell design with the outer two shells made of a different conductor than that used in the inner shell. Banding of the shells to the bore tube is spaced so as to allow 40% of one thin edge of each conductor to be in contact with the helium bath. The magnet has warm iron and a cold

TABLE I

Running Conditions for the Experiment

Run	Date	Beam Energy Spill Length	Target Distance (Inches)	Colli-mator	Calor-imeter data	He boil off data	K mJ/g -10^{12}ppp in Cu
1	6-18,7-1-75	300 GeV-fast	50	none	No	No	43
	7-30-75	400 GeV-½sec	50	none	No	No	43
	8-7-75	400 GeV-1sec	50	none	No	Yes	43
2	8-18-75	400 GeV-1sec	50	7/8"ID, 5"OD, 48"	No	Yes	16.4
3	8-27-75	400 GeV-1sec	220	7/8"ID, 5"OD, 48"	Yes	Yes	6.7
4	9-16-75	400 GeV-1sec	220	1 1/8"ID, 15"OD, 60"	Yes	Yes	6.7
	3-11-75	400 GeV-1sec	220	1 1/8"ID, 15"OD, 60"	Yes	Yes	6.7

bore; the vacuum of the cryostat connects directly to the beam line vacuum system. Because of the warm iron design about 55% of the cold mass of the magnet is in the conductor coils.

Data analysis is complicated by the fact that two different types of conductor were used in the magnet. Not only do the conductors have very different short sample currents but they also have different NiTi/Cu ratios and different volume to cooling area ratios. No instrumentation was installed to determine which coil initiated the quench and though it is likely that the conductor with low short sample current quenches at the higher currents, this is not necessarily true at low operating currents where specific heat or conductor volume to area ratios may dominate. It will be assumed below that it is the low short sample conductor which is driven normal. The conclusions would not be appreciably different where the other choice to be made.

IV THE CALORIMETER AND HELIUM BOIL-OFF MEASUREMENTS

The calorimeter is based on that of Loe[3] and is specifically designed to approximate the geometry of the superconducting magnet, so that when the calorimeter is installed in the magnet location the energy deposition per gram is directly related to that which the magnet would receive. A cross section of the calorimeter is given in Fig. 1. The copper tube, which has about the same diameter as the magnet coils, is used as the heat detector. It is insulated from both aluminum tubes. The latter have heating coils mounted on them so that they may be kept at the same temperature as the copper and reduce the heat leak from this tube. Actually, it was not necessary to use the heaters; the heat leak from the copper to its surroundings could be determined adequately by turning off the beam and observing the rate of temperature change. The inner stainless tube is the vacuum chamber through which the primary proton beam passes.

To measure the energy deposition from the beam one need only record the temperature change in the copper caused by a given number of primary protons and target thickness. The temperature measurements were made with a platinum resistor and a bridge and amplifier circuit with a sensitivity of 0.8V/°C. Typically, changes of 0.2V over 40 beam pulses were observed; recognition of changes four times smaller was no problem.

The calorimeter was used to determine the calibration constant K given in Table I; K is defined as the energy density, in mJ/g, deposited in the calorimeter resulting from the equivalent of 10^{12} protons incident on a one-inch thick copper target. Measurements of K during Runs 3 and 4 agree to ±7%. After Run 4, the calorimeter was moved upstream to the magnet position and the calibration constant was found to increase by a factor of 1.5 due to the reduced distance between calorimeter and target. The values of K listed in the table incorporate this factor of 1.5.

A similar calibration constant for the magnet itself may be obtained by comparing the rate of helium boil off with and without beam. This is performed by closing the helium transfer valve and determining the rate at which the liquid helium level changes. Typically, measurements with beam were made at two to three times the background heat leak rate of some 6 watts. The product of the difference in helium usage and the heat of vaporization yields a lower limit to K, since no allowance is made for heat absorbed

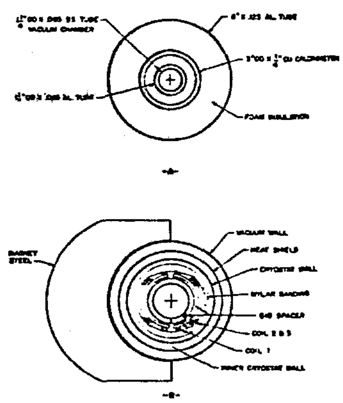


Fig. 1. Cross section of (A) the calorimeter and (B) the test magnet.

TABLE II

Test Magnet

Design short sample center field 29kG at 2000A		
Max current ever obtained		1620A
I_{max} - maximum current obtained during experiment		1450A
Conductor Characteristics		
NbTi, Cu substrate, solid conductor, formvar		
	Coil 1	Coil 2,3
Size (inches)	.150 x .075	.122 x .056
Area Sub/Area S.C.	2/1	1.25/1
Short Sample	2250A @ 5T	1250A @ 5T
Density	7.93 gm/cc 5.93Cu, 2.0 sc	7.61 gm/cc 4.94Cu, 2.67sc
Cooling Area/gm	.134 cm^2/gm	.172 cm^2/gm

by the escaping gas or by thermal capacitance of the cryostat. In Runs 3 and 4, K as determined in this fashion was 1/1.7 times that found with the calorimeter. However, reproducibility of the boil-off results was poor, with variations of ±40%. The calorimeter was not available for Runs 1 and 2; therefore the K values of Table I for these runs are the results of the boil-off measurement multiplied by the foregoing factor of 1.7.

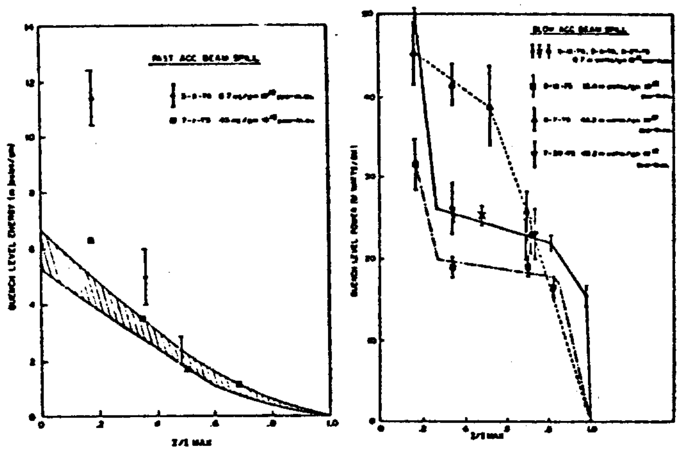
V RESULTS AND ANALYSIS

The fast beam spill measurements of quench level are shown in Figure 2a. Only two sets of data were taken, one at the very beginning of the experiment and one at the end under very different geometries as indicated by the values of K. The first set of data was taken by running the accelerator continuously and slowly increasing the target thickness until the magnet quenched. All other data were taken by having a set target thickness and running different beam intensities one pulse at a time to map the stable and unstable intensity regions. The error bars indicate the closest quench and nonquench beam pulses measured. The quench threshold level energy is a very steep function of the magnet operating current normalized to the maximum current at which the magnet will run with no beam. Only very small beam irradiation is tolerable at high currents.

The crosshatched area on Fig. 2. represents an estimate of the expected quench level if only the enthalpy of the coils between 4.2°K and a temperature T is considered. This temperature is related to the magnet current I by assuming an I vs T function similar to that obtained from short sample measurements of NbTi.[4,5] This short sample data shows that the relationship between T and I is approximately $\Delta T(^\circ K) \approx 5(1-I/I\ max)$, where ΔT is the temperature differential above 4.2 deg and I max is the short sample current at 4.2 degrees. For some load lines the data departs slightly from the above linear expression with about 10% higher temperatures in the I/I max range of ½. The width of the crosshatching not only takes into account these possible variations from the linear temperature relationship but also indicates the effect of allowing for the possibility that either type of magnet conductor might quench at low currents. Data for the enthalpy of NbTi and Cu was obtained from References 6 and 7.

Slow beam spill measurements are given in Figure 2b. The quench level is expressed in terms of mW during the beam spill and K is normalized in terms of protons per second of beam spill per pulse. The characteristic shape of the slow spill data with an apparent plateau up to 90% of the maximum current is very different from the fast spill behavior. The main difficulty in obtaining the data came from the sensitivity of the magnet to short time (<.1 sec) small increases in beam intensity. The quench power level was reproducible independent of run conditions except in Run 2 and the data of 8-7 (Run 1). It is reasonable to expect a lower quench level in Run 2 because the collimator was shielding only the first half-magnet and the second half-magnet was going normal. There is no explanation for the inconsistency of the 8-7 data.

The data of Runs 3 and 4 have been replotted in Figure 3 in terms of W/cm^2 of cooling area. The mass to cooling area factor for coils 2 and 3 has been used and also the approximate relationship between temperature and current given above. Data from Lyon[8] on heat transfer to helium is shown as the crosshatched regions for nucleate and film boiling with an indeterminate region between. The wide extent of the area shows effects from the dependance of the



a b

Fig. 2. Energy deposition at quench threshold as a function of magnet currents (a) Energy in mJ/g per beam pulse for fast spill of <1 msec. Crosshatched area is expected level from enthalpy data. (b) Power density in mW/g during slow beam spill of ½ to 1 sec.

flux on different geometrics and hysteresis paths. Film boiling heat transfer is consistent with the data and appears to give an explanation for the plateau behavior. The higher heat transfer associated with nucleate boiling is probably not attainable because samll variations in beam intensity will force the boiling to the film region.

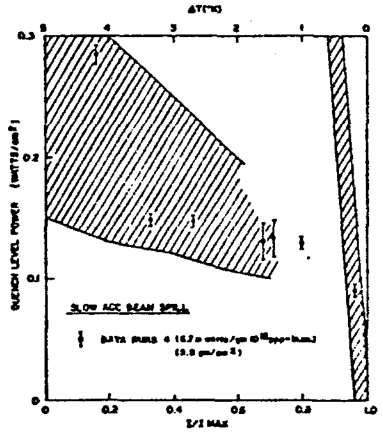


Fig. 3. Comparison of the power level per unit cooling area for quench threshold with heat transfer data.

VI IMPLICATIONS & CONCLUSIONS

What do the measured quench energy levels imply for accelerator operation? A 1 mJ/g for fast spill and a 25 mW/g for a slow spill design level is indicated from the data and how do these numbers relate to the accelerator environment? A calorimeter similar to the one described above but with wider beam aperture was installed just downstream of the electrostatic septa which initiate the extraction of the beam from the accelerator. This location should be one of the worst environments that superconducting accelerator magnets will have to work in. Energy levels of 0.4 to 0.7 mJ/g per 10^{13} particles extracted were measured for typical slow extraction efficiencies. During times of unstable operation levels of 7 mJ/g-10^{13}p were observed. The above measurements are probably an underestimate of the peak energy deposited in this region because of the size of the calorimeter. The calorimeter dimensions were 4½"x7½"x10" (h,w,l) whereas magnet coils would be on a 3 inch diameter and the shower maximum may not occur until greater thickness. In any case, it appears that fast extraction at the 10^{13} level is marginal unless single turn extraction which is four times less inefficient is used. There appears to be no difficulty with slow spill as long as refrigeration is adequate.

The slow spill data can be used to guess an upper limit on the amount of high energy beam that can be lost at a specific place in the accelerator. From the calibration constant of Run 1 when the target was 50 inches from the magnet it can be seen that 5x10^{11} particles interacting with 1 inch Cu will reach the 25 mW/g level. Presumedly any particle hitting the magnet would effectively interact for at least 5 inches reducing the allowable number of particles to 10^{11}/sec or 1%/sec of a 10^{13} beam.

The measured quench energy levels for fast and slow spill are reasonably consistent with simple models of specific heat and heat transfer. Undoubtedly the processes are not as simple as these models imply and approximate agreement must be regarded as somewhat fortuitous. Obviously the data given here should be remeasured with different magnets, geometrical conditions, and refined calibration. Further investigation into the actual beam heat loads encountered in accelerator environments and comparison with calculation is necessary.

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