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March 18, 1981

ACCELERATOR DEPARTMENT

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973

under contract no. DE-AC02-76CH00016 with the
UNITED STATES DEPARTMENT OF ENERGY

BNL 51387
EP&S 81-1
UC-28
(Particle Accelerators and High-Voltage Machines - TID-4500)

FINAL REPORT OF THE RADIATION-HEATING TASK FORCE

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ABSTRACT

This report discusses the ISABELLE Mark 6 radiation heating experiment and summarizes the work done by others. It concludes with recommendations for further work.

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A study of the quench sensitivity of the Mark 6 cosine Θ magnet to beam heating was recently completed and the results are published in Ref. 1, attached to this report. This experiment was conceived as an initial test of the repeatability of such an experiment under less than ideal conditions. One compromise was that the magnet was cooled by pool boiling liquid helium instead of the forced-flow technique which will be used in ISABELLE. This was done because a suitable refrigerator for forced-flow was not available. However, the experiment, although flawed, did reach several conclusions. This report summarizes these conclusions and assesses the need for further work.

Goals of the Task Force

We wanted to make reliable estimates of radiation heating effects on ISA magnets in ISA situations--injection, acceleration, beam cleanup, ejection.[2] Our philosophy was to design simple experiments which could (1) give an immediate result for the order of magnitude of the tolerance and (2) be easily interpreted by computer models of the heating process. By testing models at both 30 GeV (here) and at 400 GeV (at FNAL), we could determine the reliability of the models over the energy range important for ISABELLE. Then, one could predict radiation tolerances for any ISA situation.

Discussion of Mark 6 Study Using Beam Heating

In the Mark 6 experiment, the full 28 GeV/c beam was steered into the magnet coil by the field of the magnet. By varying the beam intensity for a given magnetic field and beam position, the intensity level was found which caused the magnet to quench. This was done for different magnetic fields below 3 Tesla and for different beam positions. The study found the magnet to be surprisingly resilient at low currents. For magnetic fields below 0.8 Tesla, the intensity necessary to cause a quench rose sharply.

G. Bozoki[3] converted the observed quench thresholds to deposited energy per volume, using a computer program which simulated the interaction of the beam in the magnet called CASIM[4] (CAscade SIMulation). As a function of the magnet currents, the energy per volume which caused the quench was compared to the enthalpy reserve, the expected energy per volume required to locally raise the temperature of the coil above the critical temperature for superconductivity. The observed quench thresholds were typically several times (5x) higher than the enthalpy reserve. Now, this difference could be due to several factors which will be discussed: heat transfer to the helium, differences between the experimental geometry and the simulation, problems with CASIM.

The effect of cooling is very uncertain. To first order, we attempted to avoid cooling questions by using a very short energy pulse to quench the magnet, the 2 μsecond AGS fast spill. Estimates and measurements of cooling time constants are tens of milliseconds. Although the energy was introduced quickly, the quench propagation velocities are slow (~ m/second)[5], so that the time required to heat a region large enough such that the magnet cannot recover may be long enough for there to be significant heat transferred to the helium. Furthermore, there is indirect experimental evidence which supports the importance of cooling, even when energy is dumped into the magnet quickly. The AGS 8° magnet[6] was able to absorb over ten times more energy than Mark 6 at a 2.5 Tesla field, where the heater for each experiment was the 2 μsecond AGS fast beam. The 8° coil has considerably more exposure to helium than the Mark 6 magnet.

Differences between the experimental geometry and the simulation contribute a 50% uncertainty to the simulation. Most parameters of the input program do not affect the result if varied within reasonable limits. The dominant uncertainty is the precise beam cross section, which was monitored by a SWIC with a storage scope display. A factor of 2 error in beam area would contribute a 40% error in the simulated energy/volume. The simulated energy deposit in a given volume is not proportional to the beam area because the width of the cascade of particles at the coil from the beam interaction is comparable to the beam size.

Bozoki has assessed the accuracy of the simulation program CASIM.[4] CASIM is based on the thermodynamical model of Hagedorn and Ranft[7] and, thus, it is normalized to available particle production data at and below 30 GeV incident proton beam energies. Calorimeter studies at 200 and 400 GeV tested CASIM at the new energies. The simulation agreed with results within a factor of 2, for the energy deposition in aluminum and copper calorimeters caused by a dumped 2.5 mm radius (σ) proton beam, as a function of radius from the beam from about 1 cm to 12 cm, and as a function of depth from a minimum of 2/3 of an absorption length (2.5 radiation lengths of aluminum) to a maximum of 4.6 absorption lengths (49 radiation lengths of copper). CASIM consistently overestimated the energy deposition at moderate radii, with better agreement at larger radii. The program has not been tested for energy depositions within a beam diameter.

Mark 6 Conclusions

If the confidence factor in CASIM is a factor of 2, then we can attribute any of the excess tolerance above this uncertainty in CASIM to cooling. Thus, Mark 6 may show excess tolerance at half maximum field as well as below 0.8 Tesla. However, one solid conclusion we have drawn from the experiment is this: If one uses CASIM now, without an uncertainty factor, then this magnet, in the test geometry and with pool-boiling, tolerates a factor 3-10 more specific heating than would have been predicted from braid enthalpy calculations anywhere between injection and half field.

Other Beam-Heating Experiments

There have been a number of other beam heating experiments on superconducting magnets. Several types of heating have been studied: a direct beam interaction in the coil, beam halo interactions with the coil, and heating from secondaries after a target with the magnet either unprotected or protected by a collimator. These experiments have been done at BNL with the 8° magnets[6], at Argonne with a ZGS magnet[8], and at FNAL with several different models of Doubler dipoles.[9,10,11] All the experiments show a characteristic rapid rise in tolerance to heating at low current (except that for the 8° magnet, this rise occurs at half of maximum field). All the magnets show remarkably similar quench thresholds at high current on a plot (see Figure*) where incident protons were converted to energy per volume in the coil, either using a calorimeter to determine the conversion, or using CASIM and the particular experimental geometry. (No conversion was made for the ZGS magnet.)

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*Notes on Figure. In several cases, the energy conversion from the measured beam intensity was done using the Monte Carlo program CASIM. For Edwards, et al.,[9] a calorimeter was used which was designed to simulate the test magnet. Allinger, et al.[6] used the magnet as a calorimeter and also used the program CYLKA. A number of approximations were necessary to convert the data of Cox, et al.[10]: the data that were taken as a function of current used a slow beam spill and had a geometry which differed from a fast beam point for which they had used CASIM to convert to an energy density. The figure shows their fast beam point at $I/I_{max} = 0.9$, and the lower current points on the figure were calculated from the slow beam points by normalizing to the (fast beam)/(slow beam) ratio at $I/I_{max} = 0.9$. When densities were reported in the units mJ/gm, the conversion factor used was 1 mJ/gm = 8.7 mJ/cm^3. The value for I_{max} was arbitrarily set: for Mark 6, a value of 5000 amperes was used; 1450 amperes for Edwards, et al.; 4000 amperes for Cox, et al.; 5000 amperes for Dixon, et al.; and 50 kilogauss for Allinger, et al. In general, the quoted I_{max} for each reference was used, even though in two cases (Edwards, Cox), this was an operating maximum rather than a calculated one. The operating temperature of all the magnets was in the range 4.5°-4.8°K.

Heater Experiments

Although it is attractive to measure the tolerance of magnets to beam heating directly, the problem divides conveniently into two - understanding initial energy deposition and understanding magnet recovery. Beam heating studies are best done with calorimeters - a superconducting magnet is a poorly-understood calorimeter.* Magnet tolerance of heat is best studied with heaters buried in the magnet - although a proton beam may be a well understood heater, it is an expensive one.

Several tests with heaters embedded near braid cooled by liquid helium support the conclusion that the magnets become quite stable at low current. The tolerance of the braid to 7 msecond pulses of heat was measured by M. Garber, as a function of current in the braid, and as a function of external magnetic field.[3] For each field value, the braid became quite stable at low current, although at somewhat higher currents than in the Mark 6 experiment.

There have also been heater tests in a simulated magnet winding[5] and heater tests in ISABELLE magnet 21.[3] These tests all verify the increased tolerance to heat at low current observed in the beam experiments. The normalization of the heater experiments from heater to heater varies by a factor of 10 (i.e., the geometrical conditions and the fraction of heater power transferred to the conductor are not reproducible for different experiments), but the relative heat tolerance for a given heater/geometry have errors of only 10%.[5] These experiments have also been done at high current and field. There is a roughly linear decrease in the response to heat as the current increases, which follows the predicted enthalpy limit of the conductor. These tests have all been done with pool-boiled liquid helium coolant.

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*Although, ultimately, superconducting magnets are the only relevant calorimeter.

Conclusions and Recommendations

Where tested, the computer model CASIM describes beam heating well, within a factor of 2 - CASIM typically overestimates the heat deposited by beams of protons in calorimeters. CASIM has not been tested for its prediction of heat deposition close to the dumped beam. All superconducting magnets tested at various laboratories have been cryostable at low ($\lesssim$ 50% of maximum) field. Mark 6 is more tolerant of heat, roughly a factor of ten, below 8 kilogauss than would be expected from enthalpy calculations. At higher currents, the heat tolerance of Mark 6 appears to follow the enthalpy limit, as a function of current.

We recommend:

1. Experimental studies should be made of forced-flow cooling, compared to liquid. All the tests described above were done with pool-boiling liquid. These studies would be most efficiently carried out with heaters buried in a magnet near the coil.
2. CASIM should be tested with a small calorimeter near the beam dump, preferably at 400 GeV, i.e. preferably at FNAL.
3. Heed the existing studies of energy deposition densities for ISA situations which have used CASIM: Bozoki studied uncontrolled beam losses for dipoles[12] and for quadrupole-dipole sequences[13], and Stevens studied the controlled losses from collimators[14] and at ejection.[15] Bozoki found, for example, that 2×10^8 400 GeV protons instantaneously scraping the vacuum chamber of a dipole on the inside of the ring would quench that dipole. Stevens discusses the

significance of such results, compared to ISR experience, and recommends limiting-aperture collimators. In his discussion of ejection, Stevens observes that, "It may be difficult not to quench one or more ISA magnets during extraction at 400 GeV assuming a dc mode of operation".

We do not recommend more studies with the AGS beam at this time.

Finally, we have filed at the ISABELLE project office, a complete set of the papers referred to in this report, under "Radiation Heating Task Force".

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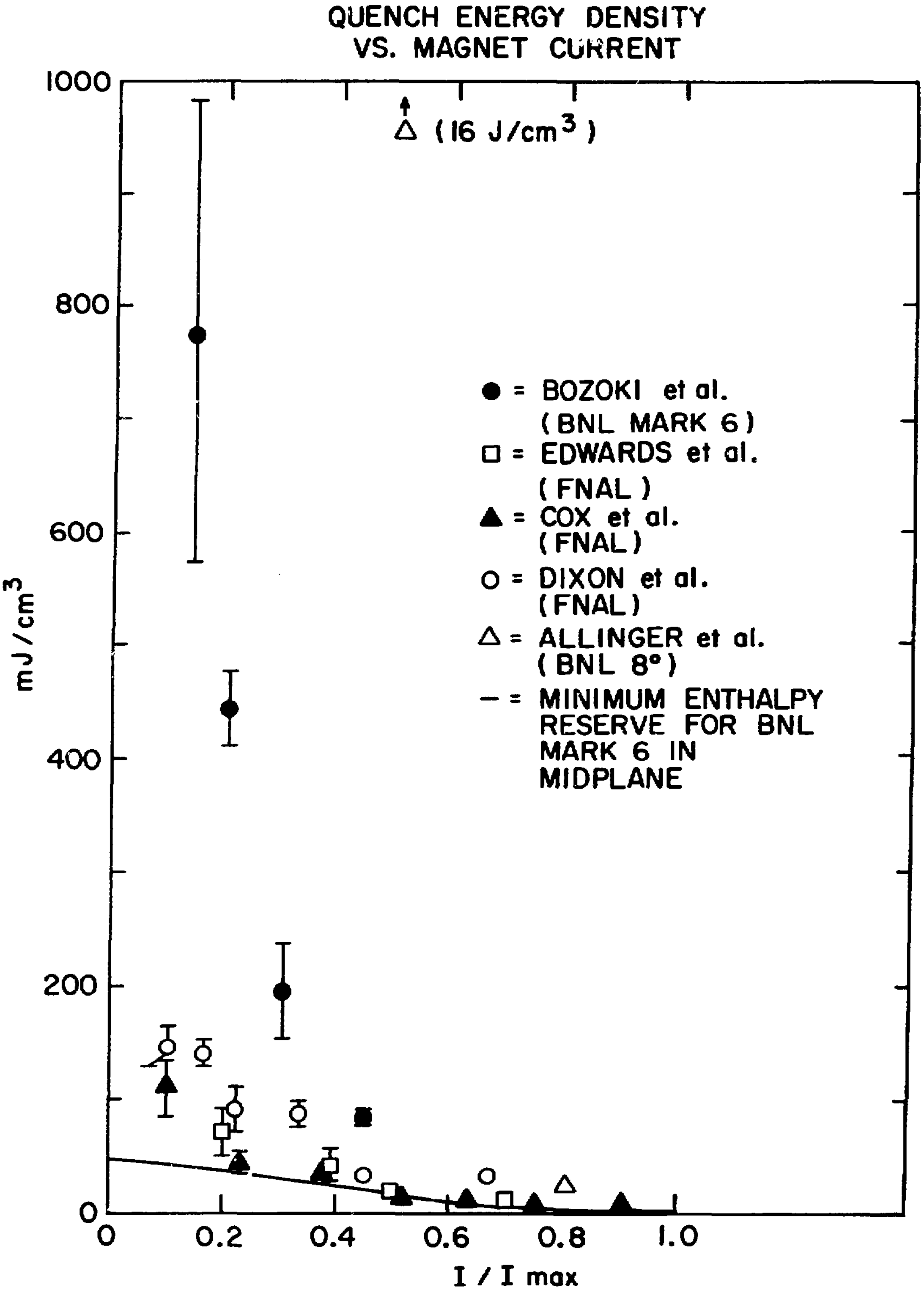

Figure. Quench energy density observed for short ($\leq$ 10 μsecond) pulses of energy deposited in a magnet coil, for several different types of magnets. The conversion from the quoted values in the references to points on this plot was not at all straight-forward - please see the text for details. The enthalpy limit shown, a calculated minimum for the Mark 6 magnet for the midplane, is similar for all the magnets. Presumably, the increased tolerance to heat above this enthalpy limit, observed for all the magnets, is due to an unknown combination of cooling and current-sharing in the conductor. A final note: the Mark 6 data were taken with pool-boiling liquid helium cooling. ISABELLE plans call for cooling with forced-flow helium gas.

To be presented at the 1980 Applied Superconductivity Conference, Santa Fe, NM, Sept. 29 - Oct. 2, 1980

BEAM HEATING STUDIES ON AN EARLY MODEL ISA SUPERCONDUCTING COSINE θ MAGNET*

BNL 28376

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ABSTRACT

Superconducting magnets for accelerators can be accidentally quenched by heat resulting from beam losses in the magnet. The threshold for such quenches is determined by the time structure of the beam loss and by details of the magnet application, construction and cooling. A 4.25 m long superconducting cosine θ dipole magnet, MARK VI, constructed during the research and development phase of the ISABELLE Project at BNL was installed in the 28.5 GeV/c primary proton beam line from the AGS. By energizing the magnet, the proton beam could be deflected into the magnet. The beam intensity required to quench the magnet was observed for different beam sizes and at several values of magnet current up to 2400 A or approximately 70% of the highest magnet operating current. The maximum current was limited by the gas-cooled power lead flow available using pool-boiling helium rather than single phase forced-flow helium at 5 atm for which the magnet system was designed. Details of the experimental setup including the magnet and cryogenic system, the beam-monitoring equipment and instrumentation are described. The measurements are discussed and compared with beam heating measurements made on another superconducting magnet and interpreted using the Cascade Simulation Program, CASIM.

I. Experimental Arrangement

Superconducting magnets in high energy physics applications may be exposed to intense particle beams which can deposit relatively large amounts of heat in the magnet in short periods of time. To investigate the effects of this radiation heating on a magnet designed for an high energy storage ring accelerator, MARK VI, an ISABELLE rad cosine θ dipole magnet was installed in the fast external 28.5 GeV/c primary proton beam in the North Area of the AGS. Figure 1 shows schematically the magnet installation in the Fast External Beam (FEB) relative to the AGS. The AGS circulating beam intensity is measured by a current transformer (CBM) located at L15 and the FEB intensity by current transformers (CT) located at U15 and U303 along the beam transport line as indicated in Fig. 1.

The experimental setup in the area of the magnet installation is shown schematically in Fig. 2. The magnet, MARK VI, is shown positioned in the beam. The magnet was mounted on rails so that it could be rolled out of the beam line when radiation heating studies were not scheduled to permit utilization of the beam for neutrino physics in detectors downstream in the U-line.

The magnet was precooled by circulating helium from the BNL 7-ft. Bubble Chamber helium refrigerator compressors through a liquid nitrogen heat exchanger and then through the magnet and returning the gas to the compressor system. The magnet was further cooled and filled with liquid helium from storage dewars supplies from the Bubble Chamber helium refrigerator/liquefier. Helium gas to pressurize the storage dewars was taken from the Bubble Chamber compressor system and helium boil-off gas from the magnet cryostat and gas flow from the magnet gas-cooled power leads were returned to the compressor system completing a closed loop system. The liquid nitrogen heat exchanger and helium storage dewars were located outside the beam line shielding berm and connected to the magnet cryostat with 48-ft. long supply and return transfer lines installed through a small conduit. The magnet and gas-cooled power leads had been designed for forced-flow cooling at 5 atm. Because the only mode of cooling available for these experiments involved pool boiling helium from storage dewars, the maximum pressure that could be attained was determined by relief valve settings on the storage dewars. This constraint limited the power lead gas flow which in turn limited the maximum magnet current that could be used safely to 2400 A or about 70% of the highest operating current for the magnet. The temperature of the magnet was monitored by sensors at the numbered locations indicated in Fig. 3.

The power supply for the magnet was installed in the same area as the helium dewars and controlled from the instrumentation trailer shown in Fig. 2. The power supply system was a standard AGS 450 kilowatt SCR type set for a maximum current of 3600 A at an output voltage of approximately 15 V d.c. Comparators were used to trip the power supply on power lead and magnet overvoltages.

The FEB at the AGS can be operated so that the entire beam in the AGS consisting of 10^{13} protons in 12 bunches spaced 200 nanoseconds apart is extracted in 2.4 microseconds with a pulse repetition rate of 2 seconds. Because the existing FEB CT monitors were suited to measure intensities 2 to 3 orders of magnitude higher than those required for the radiation heating tests, a Secondary Emission Chamber (SEC) and an Ionization Chamber (IC) for intensity measurements and a Segmented Wire Ionization Chamber (SWIC) for beam profile and position measurement, designed for lower intensities, were installed just upstream of the magnet. To track the beam intensity over a large range of values, intercomparisons were made between various measuring instruments over their overlapping ranges. The FEB CT's were useful for intensities above 0.4×10^{12} protons per pulse (ppp), the SEC measured intensities above 10^{10} ppp and the IC had a linear response below 10^{11} ppp.

The AGS was first detuned to run at its lowest stable intensity of approximately 1.5 to 2×10^{12} ppp. A gain change was then made in the rf system radial loop to permit operation down to about 5×10^{11} ppp. Lower intensities were obtained by spoiling the extraction efficiency from the typical value of 95%. A final absolute cross-calibration of the intensity was made by using foil activiation at two different intensities. These calibration measurements agreed very well with results obtained from the SEC and IC.

The SWIC, having a resolution of 2 mm/step, was used to measure relative beam profiles and to obtain

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*Work performed under auspices of U.S. Dept. of Energy.

the relative position of the beam entering the magnet. Figure 4a shows a typical SWIC display at high beam intensity, 4b, at low intensity and 4c, the beam displaced horizontally by approximately 1.5 cm. The beam was also moved vertically to investigate the effects of radiation heating off the midplane of the magnet.

A shunt was hardwired in the magnet circuit to measure current and an H-coil device, which essentially monitors the flux in an air core solenoid, was installed to measure dI/dt and, hence, $I = \int dI/dt\ dt$ also. An Hall probe was placed in the bore of the magnet to monitor directly the field at that position, and an array of search coils mounted at various angles on a 2-ft. long plastic tube, whose outer diameter equalled the bore size of the magnet, was used to measure the several multipoles present in the field. The sextupole and decapole correction windings of the MARK VI magnet were also used as search coils. The behavior of the magnet after quenching was monitored by these devices. However, this paper describes only measurements leading to the determination of quench thresholds.

II. Experimental Results

Figure 5 is a schematic of the experiments showing how the field of the magnet bent the full particle beam pulse into the magnet coil. Starting at low beam intensity with the magnet current at some constant value, a pulse of beam was deflected into the magnet. If the magnet did not quench, a second higher intensity beam pulse was sent into the magnet several minutes later. Successively higher intensity pulses were delivered in this way until a magnet quench occurred. A magnet quench was detected by observing a voltage developing across the magnet and a rapid rise of the helium pressure in the magnet dewar system. The window between the intensity of the pulse which caused a quench and the highest beam intensity which did not defined the quench threshold. The quench thresholds were determined as a function of magnet current for different beam conditions.

The initial tests with the magnet were made to determine if, indeed, the proposed experiment could be carried out. These tests were designed to respond to such questions as: Are measured quench thresholds reproducible? How carefully should the magnet temperature be controlled? What time intervals are required between quenches or pulses to achieve temperature equilibrium? How important is it to hit the magnet in the same spot with the beam?

The reproducibility of the quench thresholds was tested by making 5 runs under the same conditions with the magnet current at 1000 A which generates a field of about 1.2 T. Thresholds were obtained which were consistent to better than 10%. The possibility of residual heat building up in the magnet during a succession of pulses which could affect the observed threshold was investigated by holding the intensity near 80% of the measured threshold for a sequence of 20 pulses, 2 secs. apart. No quenches occurred under these conditions indicating that a heating effect on a 2 sec. time scale could not be observed.

The horizontal position of the beam whose cross-section was 4 mm horizontally by 3 mm vertically was also changed in 1 cm steps as shown schematically in Fig. 6. This horizontal movement changed both the location where the beam energy was deposited in the magnet coil and the angle of incidence of the beam to the magnet. A gradual increase of 10-20% in the quench threshold was observed as the location was moved from upstream to downstream until at position 4 on Fig. 6 the beam missed the coil. Cross changes in beam position change the quench thresholds by less than 20%. The apparent systematic increase in threshold as the location where beam energy was deposited was moved downstream is not yet understood.

The beam position was varied vertically by ± 1 cm with less than a 10% change in threshold. Finally, the quench threshold was observed to increase by 30% when the beam was defocused to double its cross-section. A Monte Carlo simulation of the development of the energy shower, using the appropriate beam sizes and geometries, gave a 40% increase in the threshold when the beam cross-section was doubled. The expected increase in threshold is not proportional to the beam cross-section because the energy shower develops over a considerably greater area than the beam cross-sections used in this experiment.

Figure 7 shows the measured quench thresholds for the cosine θ dipole magnet, MARK VI, as a function of magnet current. For each experimental point, the beam full width was approximately 4 mm horizontally by 3 mm vertically before entering the magnetic field. The area of the magnet coil illuminated by the beam decreased and the angle of incidence of the beam to the magnet coil increased as the magnetic field was increased, complicating the interpretation of the measurements. The non-linear increase in quench threshold below 600 A indicates that the magnet is very stable to beam heating at low currents (the injection current for ISABELLE is 300 A). At the low current values the beam was scanned horizontally as in Fig. 6 to assure that it was not being steered through the magnet without striking the magnet coil. These results were obtained using liquid helium to cool the magnet rather than forced-flow helium gas for which the magnet was designed. No attempt has been made to compensate for differences in heat capacity and transfer between these two methods of cooling.

In order to obtain a physically more meaningful interpretation of these experimental results, the MACSIM variant of the Monte-Carlo code CASIM[1] to simulate beam and cascade propagation in the presence of a magnetic field was used. Taking into account the geometry of the experiment and a detailed description of the coil region near the horizontal midplane of the magnet, the maximum overall energy densities deposited in the magnet by the beam were determined as a function of the magnet current with the MACSIM model.[2] These energies densities expressed in units of mJ/cm^3 per proton are plotted as a function of magnet current in Fig. 8. This curve is quite flat indicating that the maximum energy deposition density per proton has only a very weak dependency on the current. The breakdown of the curve at small magnet currents occurs because the cascade and the beam only partly cross the coil. Using the curve from Fig. 8 as a "calibration curve" to convert beam intensities into absorbed energy densities, the measured beam intensities from Fig. 7 were transformed to maximum absorbed energy densities and plotted as a function of current in Fig. 9. These plots of quench and recovery heat tolerance functions of the magnet are shown as dashed curves in Fig. 9 together with a full line representing a shifted ideal "short sample" heat tolerance curve as described by Sozoki.[2]

Curves representing the average and minimum enthalpy of a midplane magnet conductor are also displayed on Fig. 9. A comparison of the enthalpy curves with the heat tolerance curves shows that the BNL cosine θ magnet has excellent stability at low currents, the quench threshold at 0.5 kA and 0.6 T, for example, being a factor of approximately 20 greater than the enthalpy reserve of the midplane conductor at that current. The curves also show that this factor decreases rapidly with increasing current.

The result of an earlier published experiment[3] on radiation heating with the BNL 8° window-frame bending magnet at 2.5 T is plotted on Fig. 9 normalized with the MARK VI results as a function of $(jxB\ kA - T/cm^2)^{1/2}$. The 8° magnet, with grooved high purity aluminum spacer strips and more liquid helium in the magnet windings, has a quench tolerance larger by a factor of 40 than the MARK VI magnet at $(jxB\ kA\text{-}T/cm^2)^{1/2} = 8.5$ For magnetic fields up to 2.5 T, the 8° magnet is essentially cryostable.

III. Conclusions

The MARK VI cosine θ magnet cooled with liquid helium is quite stable to beam radiation heating at low magnet currents. A Monte Carlo program, CASIM, provides an accurate interpretation of the results of beam radiation heating experiments and may be used to predict energy densities deposited in magnets by such heating. The effects of cooling, in particular the forced-flow technique proposed for ISABELLE, have not yet been determined experimentally.

Acknowledgments

We wish to acknowledge the help and cooperation of the following people who also participated in variious stages of this effort: W. Casswell, R. Dagradi, F. Dusek, H. Gassner, E. Gill, J.W. Glenn, C. Harbach, H. Hildebrand, M. Iarocci, J. Kaugerts, R. Kehl, W. Kollner, J. Mazzeo, A. McInturff, D. Meany, C. Pearson, K. Robins, D. Salimando, M. Santos, J. Schirmer, G. Stenby, D. Wilson, D. Zantopp, and the 7-Ft. Bubble Chamber crew.

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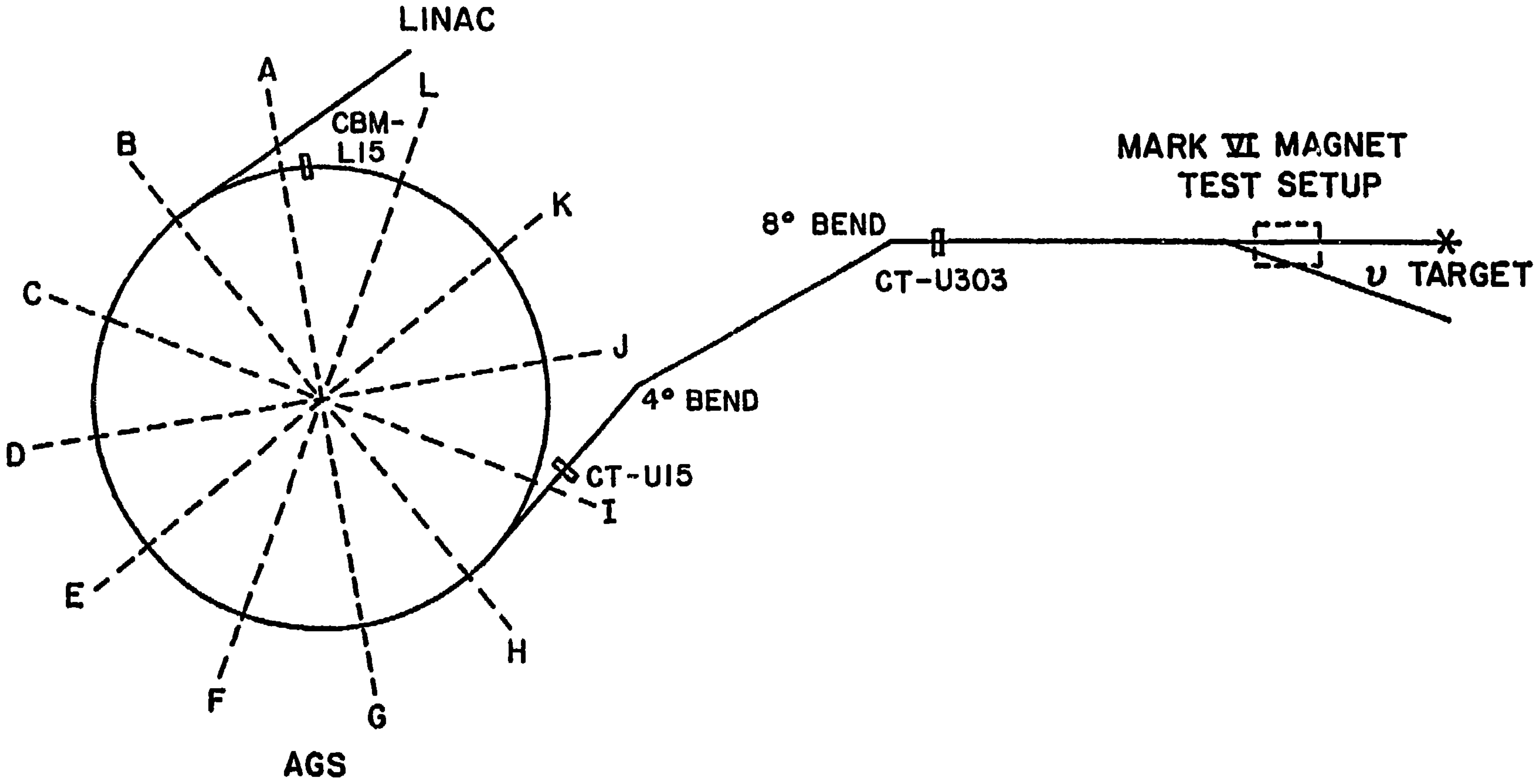
Figure Captions

Fig. 1	Schematic showing magnet installation relative to the ACS.
Fig. 2	Schematic of experimental setup in magnet installation area.
Fig. 3	Schematic showing location of magnet temperature sensors.
Fig. 4	Segmented Wire Ionization Chamber profiles.
Fig. 5	Top view schematic of radiation heating tests showing the magnetic field bending the particle beam into the magnet coil.
Fig. 6	Top view showing schematically the change in location and angle of incidence of the beam to the magnet as the beam was moved horizontally.
Fig. 7	Quench thresholds for MARK VI in terms of beam intensity of 28.5 GeV/c protons versus magnet current.
Fig. 8	Overall energy deposition density maximums per proton as a function of magnet current.
Fig. 9	Quench thresholds for the cosine θ magnet, MARK VI, in terms of energy densities deposited versus magnet current. Lower curves mark the average (A) and the minimum (M) enthalpy reserve for a conductor at the horizontal midplane. Right vertical scale: maximum temperature of normal zone with bath temperature, $T_0 = 4.5K$.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AGS

FIGURE 1

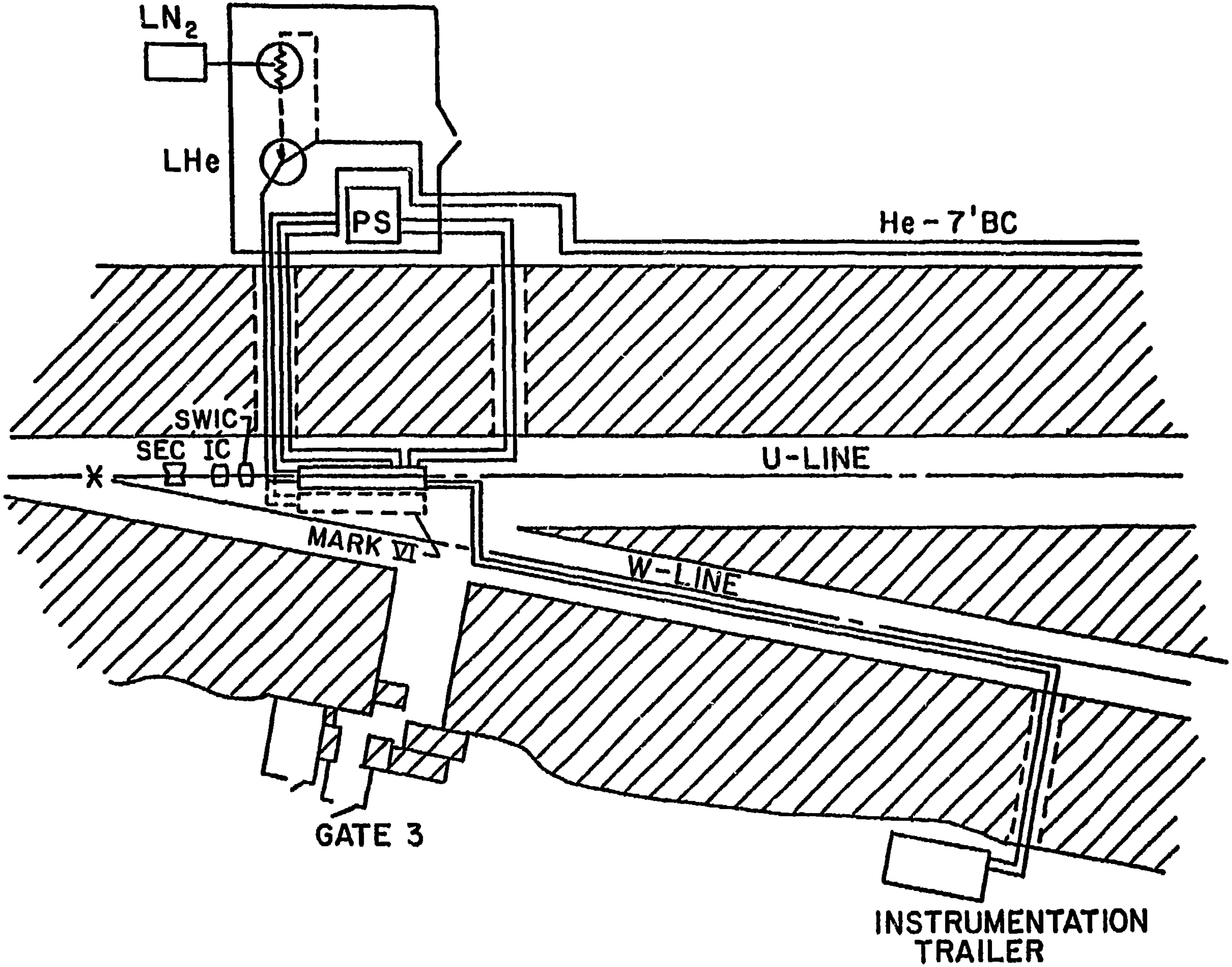

LN$_2$
LHe
PS
He - 7'BC
SWIC
SEC
IC
U-LINE
MARK VI
W-LINE
GATE 3
INSTRUMENTATION
TRAILER

FIGURE 2

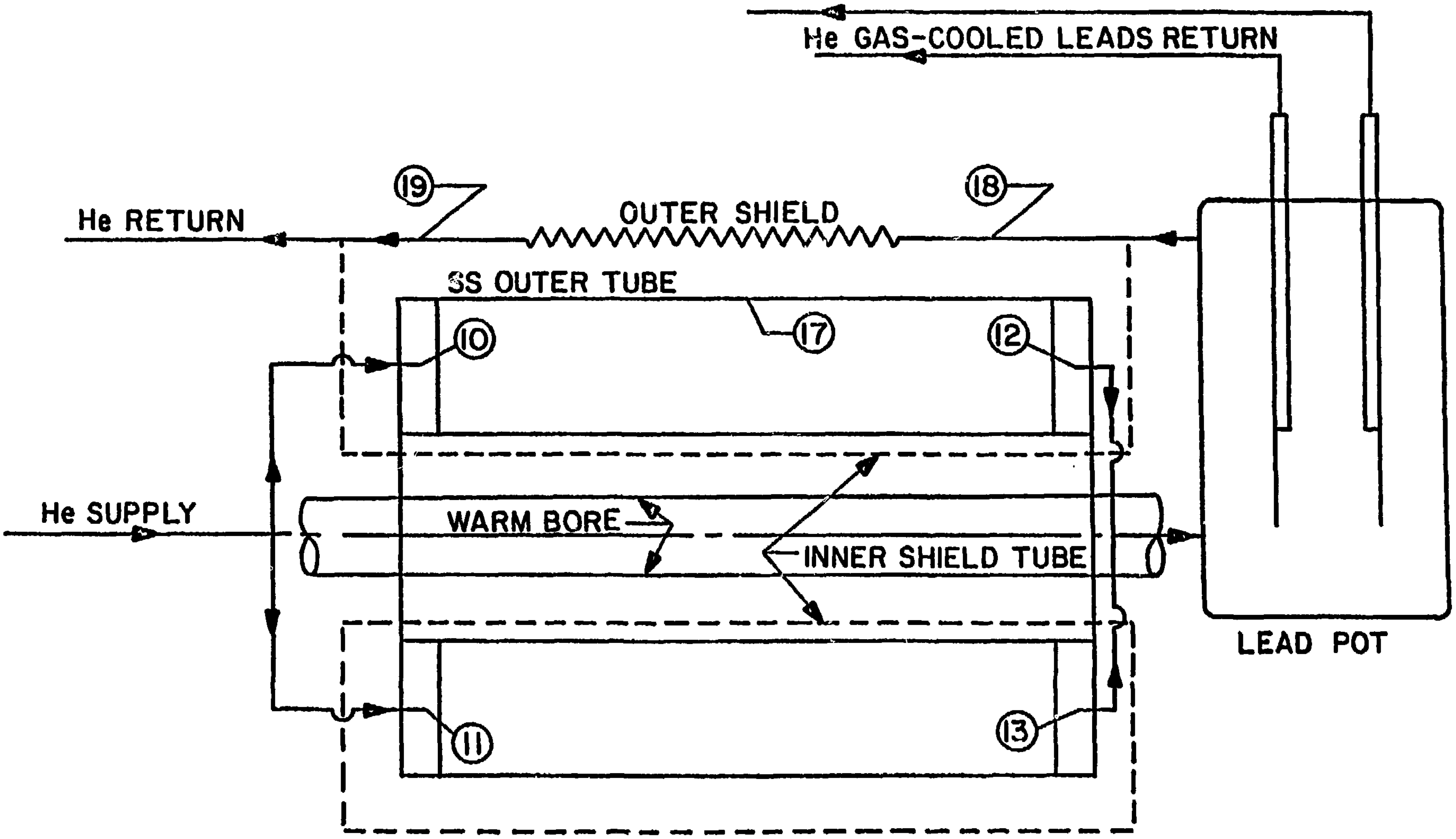
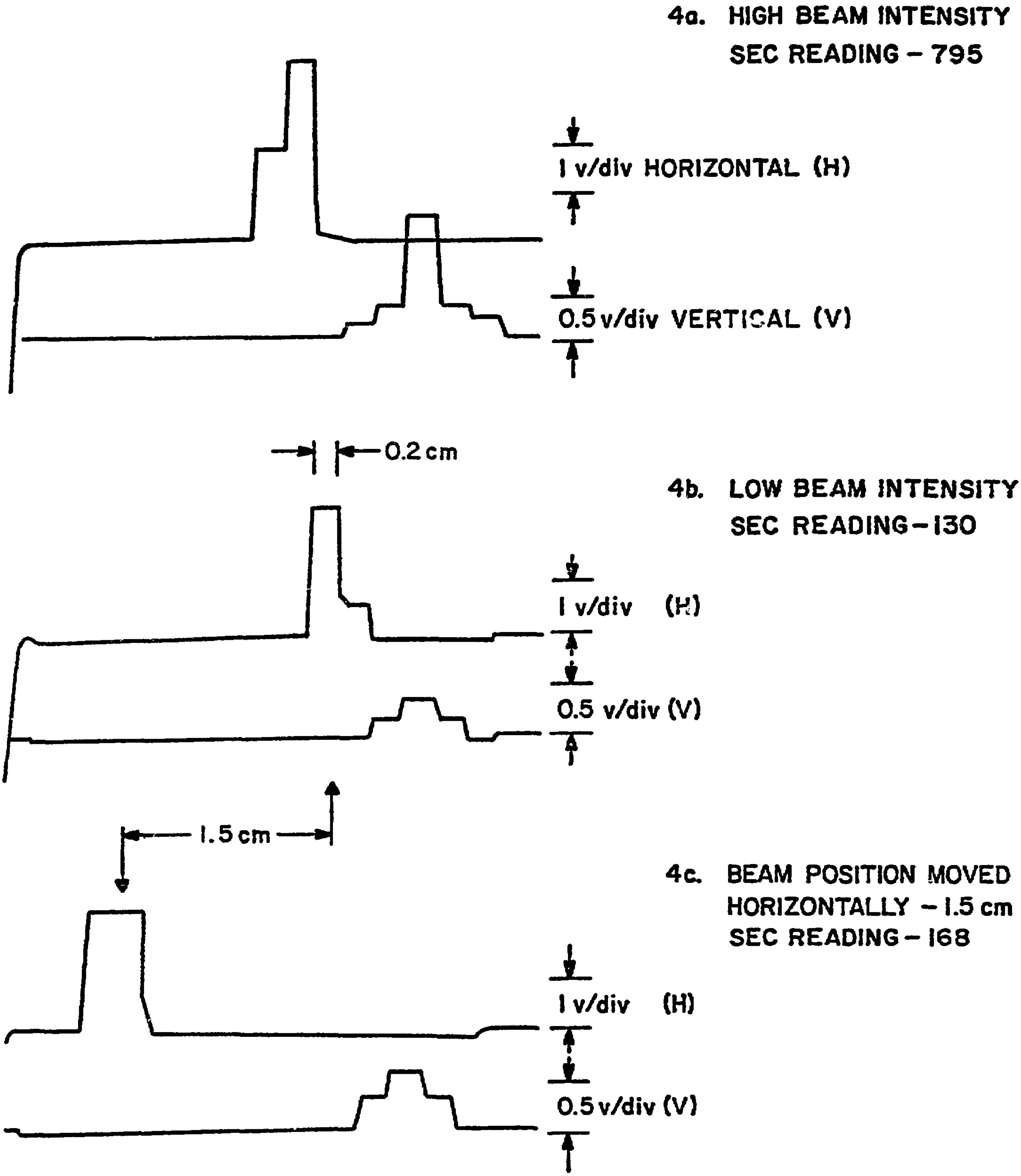

He GAS-COOLED LEADS RETURN
He RETURN
⑲
OUTER SHIELD
⑱
SS OUTER TUBE
⑰
⑩
⑫
He SUPPLY
WARM BORE
INNER SHIELD TUBE
LEAD POT
⑪
⑬

FIGURE 3


4a. HIGH BEAM INTENSITY
SEC READING – 795

4b. LOW BEAM INTENSITY
SEC READING–130

4c. BEAM POSITION MOVED
HORIZONTALLY – 1.5 cm
SEC READING – 168

FIGURE 4

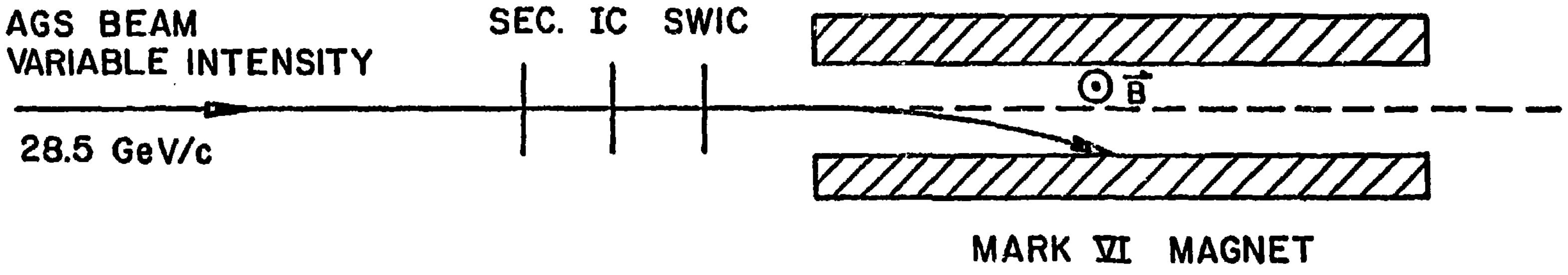

AGS BEAM
VARIABLE INTENSITY
28.5 GeV/c
SEC.
IC
SWIC
$\vec{B}$
MARK VI MAGNET

FIGURE 5

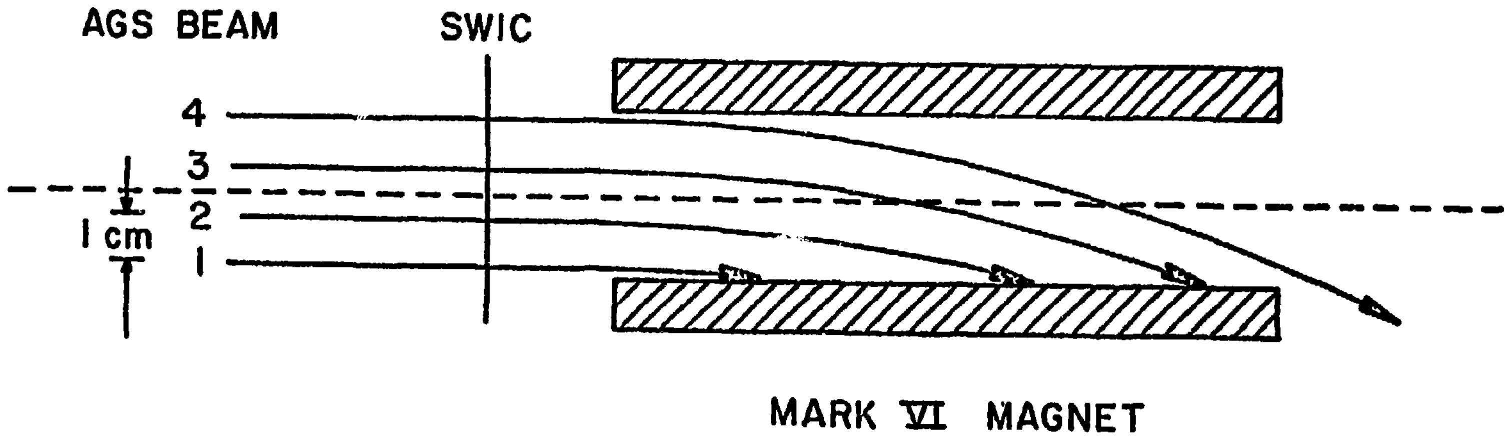


FIGURE 6

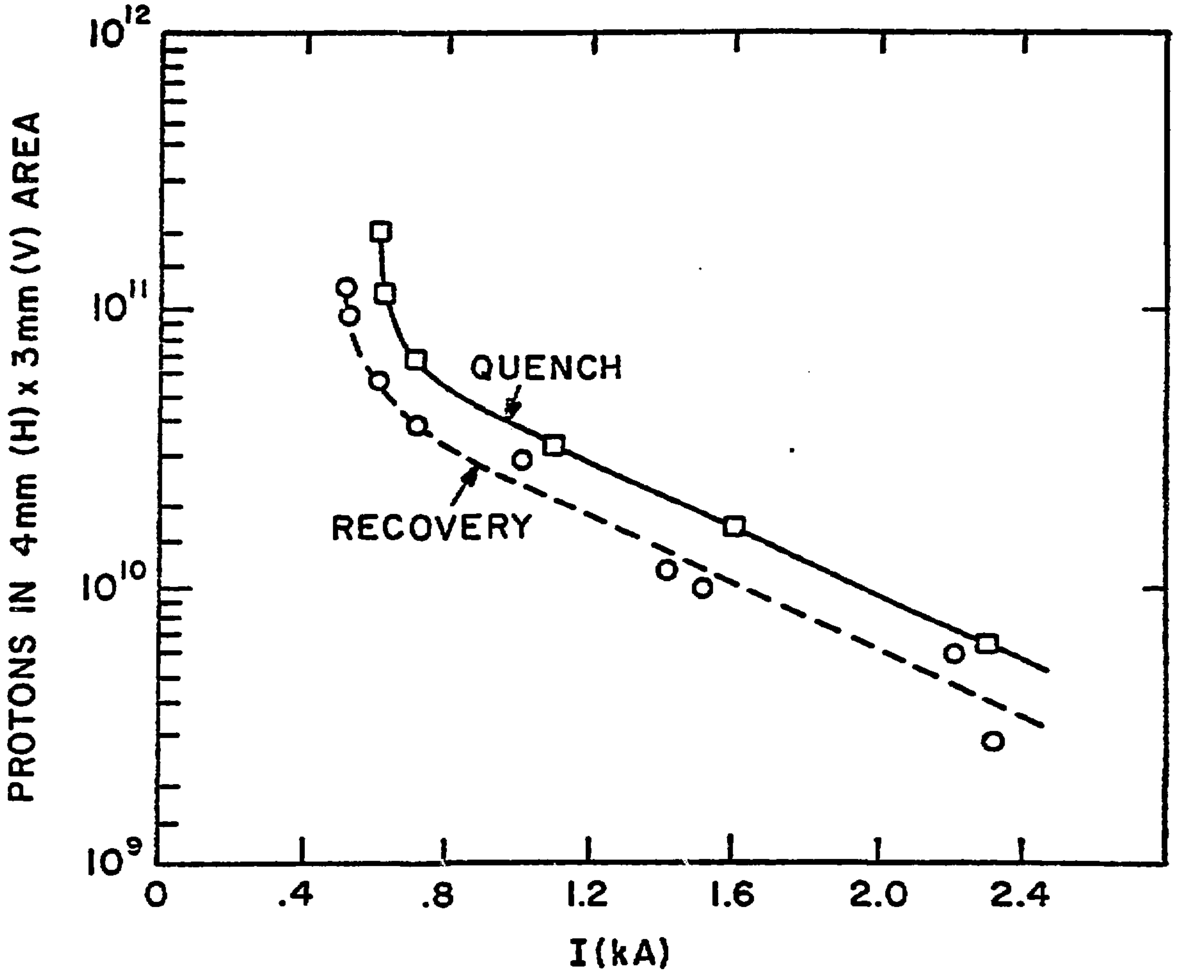

PROTONS IN 4mm (H) x 3mm (V) AREA
10^{12}
10^{11}
10^{10}
10^{9}
0
.4
.8
1.2
1.6
2.0
2.4
I(kA)
QUENCH
RECOVERY

FIGURE 7

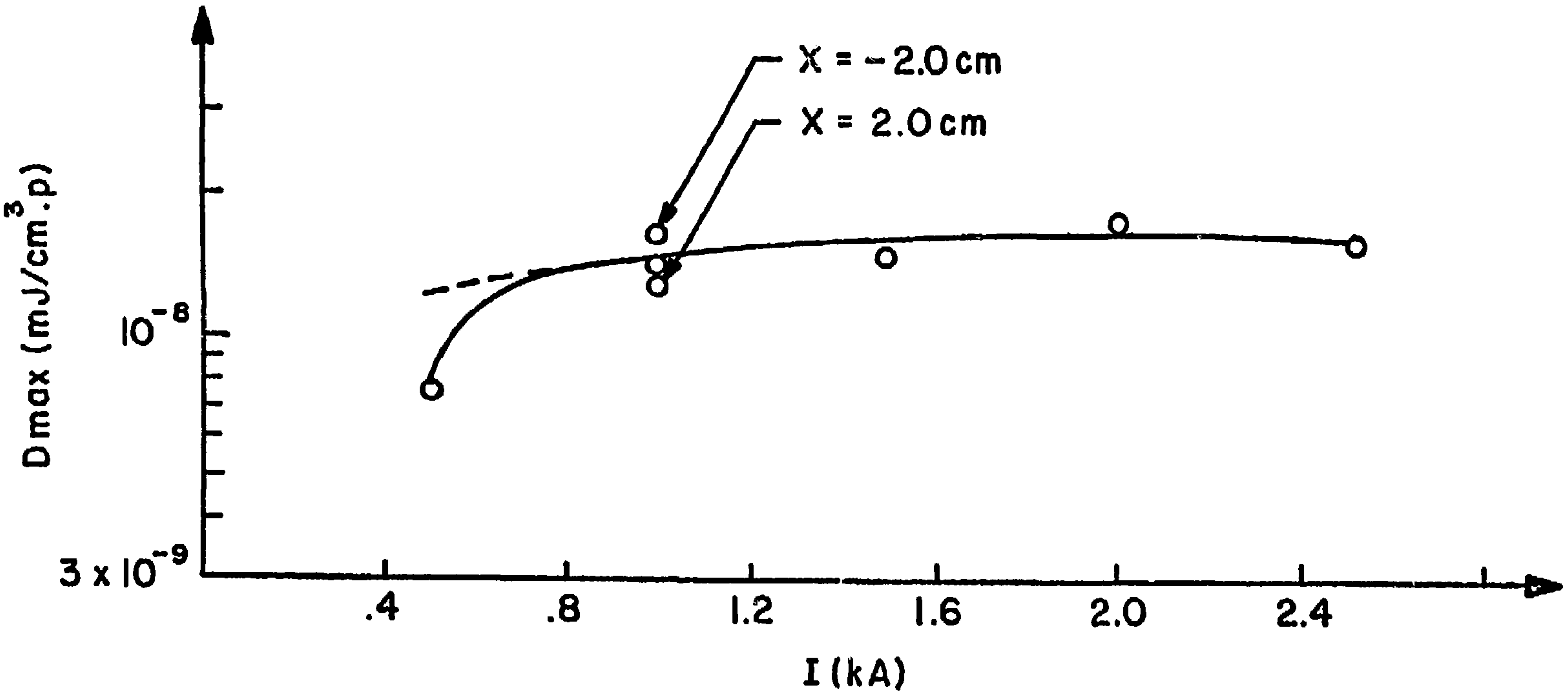
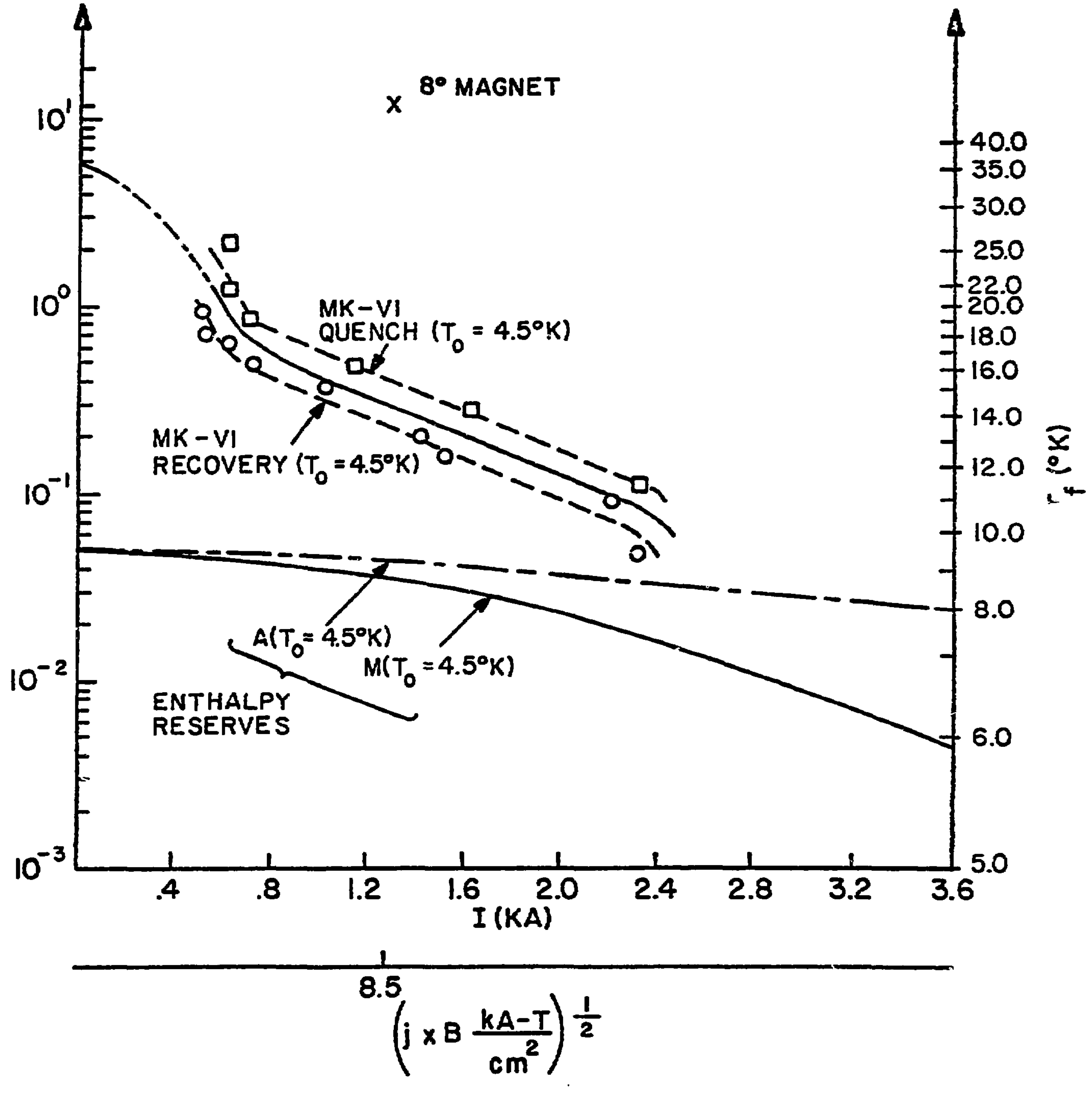


FIGURE 8



x 8° MAGNET
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Q(J/cm³)
MK-VI QUENCH (T_0 = 4.5°K)
MK-VI RECOVERY (T_0 = 4.5°K)
A(T_0 = 4.5°K)
M(T_0 = 4.5°K)
ENTHALPY RESERVES
40.0
35.0
30.0
25.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
5.0
T_f (°K)
.4
.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
I (KA)
8.5
$\left(j \times B \frac{kA-T}{cm^2}\right)^{\frac{1}{2}}$

FIGURE 9