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Introduction

A potential problem with using superconducting magnets in an accelerator is that radiation from beam interactions might raise the temperature of the magnet coils high enough for the coils to revert to a "normal" state. The relatively high resistance of these normal coils, carrying a high current, would then generate sufficient heat to overwhelm the coolant, and the magnet would quench. A task force with ISABELLE and Accelerator Department members was set up at Brookhaven in the fall of 1978 to study this question. Earlier groups had studied the window-frame design magnets which are used in the beam transport to the neutrino detector area of the AGS and the ISABELLE dipoles used for beam transport in the A-line of the AGS. There have also been studies of FNAL magnets. This report describes a series of tests made with the ISABELLE dipole Mark 6. The conclusions discuss the present state of knowledge in the field, and give recommendations for future work.

In ISABELLE, there are several distinct periods during the full cycle from injection to acceleration to stored beam to ejection when beam losses may be large. J. Kaugerts described these in ISA Technical Note 20 (1976). At injection, the 28 GeV/c beam from the AGS will be scraped over a long period (up to 50 msec) before stacking in ISABELLE. There will be scraping after the beam is stacked, which can also be done slowly. Some losses are anticipated during acceleration and storage. Occasionally, the full energy beam will be scraped. At the end of the cycle, the beam will be ejected within 10 μseconds. In addition, during normal running, there will be magnet failures, etc., which will lead to unexpected beam losses. An important addition to this is the startup period for ISABELLE when, undoubtedly, the entire beam will be lost occasionally since, ultimately, the beam will be the final survey instrument, field sensor, and optics programmer.

Our tests with the Mark 6 magnet were done in the North Area of the AGS, where the beam spill time was 3 seconds. The full 28 GeV/c beam was steered into the magnet bore by the magnetic field of Mark 6. By varying the beam intensity for a given magnetic field and beam position, we found the intensity level which caused the magnet to quench. This was done for different magnetic fields and for different beam positions.

Thus, our measurements addressed directly the question of the tolerance of Mark-6-type magnets to a sudden missteering of the beam at injection. However, the magnet was cooled with pool-boiled liquid helium, instead of by the forced-flow helium gas technique planned for ISABELLE. We do not have measurements on the difference between the two cooling techniques.

The importance of these measurements is that the results can be interpreted in a straightforward way and can be compared directly to computer simulations of the energy deposition in the coils under our experimental conditions. This comparison works quite well. In addition, the same computer simulation program has been checked and works well for other magnets at a factor of ten higher energy. Thus, we feel we can use the computer program confidently to predict the effects of radiation heating at ISABELLE for the various conditions described above.

What is not well known, however, is the effect of cooling on the tolerance to radiation heating. In our experiment, we dumped the energy into the magnet in a very short time (3 μseconds), much shorter than expected cooling times, so that we hoped to ignore these effects in the interpretation of our results. There is evidence to the contrary, however. The AGS 8° magnets do not quench at 25 kilogauss for very large energy impulses. In any case, one needs to understand how the planned ISABELLE cooling for the magnets will affect their tolerance to radiation.

Test of Mark 6

A. Acknowledgments

The results described here are based on three runs of about ten hours each with the AGS dedicated to the test and we quenched the magnet 32 times. There was considerable effort involved in setting up and doing these tests. The Mark 6 magnet had to be prepared - it had not been used for over a year; several leads had been damaged in its last quench, and the lead pot had to be modified to fit the magnet in the AGS tunnel. A. McInturff and K. Robins prepared the magnet. A vacuum system which could stay with the magnet when it was rotated into the beam had to be set up in the AGS tunnel - J. Mateos and ___________ did this. Thermometers in the magnet were read out in the west shed. ______________ did this. The magnet had to be placed in the tunnel on a stand with rails built for the test, the power and water hooked up, a shed was set up for cryogenics and the power supply - C. Pearson was the liaison engineer for the test who arranged these. The electrical work was done by the EAO group at the AGS - H. Gassner, et al. Beam instrumentation (SWIC, ion chamber, SEC) was done by A. Soukas and J. Schirmer. We needed to be able to reach very low beam internsities to do the tests--E. Gill spent several shifts working on this. The cryogenics effort was considerable. Transfer lines were purchased and installed, a liquid nitrogen bath was built to take the magnet from room temperature to 100°K, a copper return line was installed to take warm helium gas from the magnet return to the 7' compressor and plumbing, gauges, etc., were installed in the west shed. During the tests, dewars had to be filled from the 7' refrigerator and carted to the west shed--typically, a dewar lasted 2 hours. There was also monitoring of the cooldown and monitoring the cryogenics during the tests. This was all done by the 7' group under R. Louttit, J. Sondericker, and A. Prodell. R. Dagradi, M. Iarocci, and R. Picinich did much of the work. R. Kiss, M. Sardzinski, ... took shifts. We had a number of current and magnetic field sensors which were read-out and

the information stored on floppy disks by an LSI-11 computer. This was done by G. Danby's group: J. Jackson, R. Stoehr, J. Weisenbloom.

B. Philosophy

A paper, attached, has been submitted to the 1980 Applied Superconductivity Conference at Santa Fe, New Mexico. This describes results of tests made at the AGS on the ISABELLE Mark 6 magnet, an early model superconducting cosine magnet. We wanted to study the sensitivity of ISA magnets to beam heating under experimental conditions chosen to allow as simple an interpretation of the results as possible. To this end, 1) the magnet was placed in the North Area where one-turn extraction of the beam from the AGS gave a 3 second beam pulse, shorter than the expected cooling times of ∿ mseconds. We would not need to include a heat-transfer calculation in the analysis. 2) We chose to use the magnetic field of Mark 6 to bury the entire beam in the magnet, rather than do experiments with targets. We would not need to understand the conversion of the beam to secondary particle and the geometry of the incident beam relative to the magnet was well understood. Of course, in order to predict the effects of scraping in ISABELLE, we will need to understand particle production caused by the scraping, but this is probably better done with calorimeters other than a superconducting magnet. Likewise, we need to be able to predict the heat-transfer caused by cooling, but there are less expensive and more easily controlled heat sources than the AGS beam.

C. Setup

The magnet was placed on rails to the side of the beam transport to the bubble chamber in the spring of 1979. (See Figure 1) By removing a piece of vacuum pipe, the magnet could be pushed into placed and various beam monitors -inserted. We used pool-boiled helium to cool the magnet instead of the forced flow helium gas which is to be used at ISABELLE--the Model 2000 refrigerator necessary for forced-flow was not available for the test. The helium was fed to the magnet from dewars located on the west side of the tunnel through transfer lines. These lines had flexible ends so that the magnet could be cooled while sitting out of the beam line. The power supply was also located in the portable house on the west side. Our instruments for detecting a quench were in a trailer on the east side. We had both telephone and bicycle connections between the east and west sides.

D. Mark 6 Magnet

The magnet we tested was an early model cosine θ design with braided conductor. Figure 3 shows the dimensions and Figure 4 shows its quench history. Its maximum current was _____ amperes. The magnet had voltage taps across the magnet, at the lead pot, and on the sextupole and decupole correction coils. There was no center voltage tap (the tap had broken during an earlier quench).

E. Cryogenics and Temperature Monitoring

To provide cooling for the magnet, dewars were filled at the 7' chamber refrigerator and fork-lifted over to the cryogenics shed. Transfer lines were purchased to take the helium from the shed through an access hole to the magnet in the tunnel. Boil-off gas returned to the shed, then through a copper line to the 7' compressor system.

Monitors for the cooling included pressure gauges at the dewar, on the return line, and on the return lines which cooled the power leads in the lead pot. Typically, the dewar pressure was 6 psi, the return pressure was 3 psi and the lead flow pressure was 4 psi. This lead flow, which we pushed as high as possible with the pool-boiling set-up, was considerably less than required for full-current running (20 psi) and limited our current to below 2400 amperes D.C. Above 2400 amperes, the magnet quenched.

Figure 2 shows a schematic of the helium system and the position of several thermometers which we used to monitor the magnet cooling. Figure 2 also shows several of the thermometer readings during a cooldown in preparation for a quench test. Cooling down to 100°K was done by flowing helium gas through the magnet which passed through a liquid nitrogen bath. From 100° down to 4.4° operating temperature, liquid helium from dewars was used.

The magnet was built for forced-flow cooling and had no liquid-level indicator. The exit line from the magnet dewar to the lead pot was above the coils, so that we believe the coils were covered with liquid during the tests.

In a typical quench with the current below 2000 amperes, temperatures in the magnet rose to about 12° and return line pressures reached 12-14 psi (a relief valve was set to open at 15 psi). Fifteen minutes after a quench, the magnet was cold and ready for another tests.

F. Power Supply

The power supply was a standard AGS 450 kilowatt supply set at a transformer tap which gave a maximum voltage of 15 volts d.c. and a maximum current of 3600 amperes. The supply, located in the west cryogenics shed, was run from the east side instrumentation trailer. A ramp generator was used to set the current, thus avoiding supply overshoot. Comparators were added which could trip the supply on either lead overvoltage or magnet overvoltage (as after a quench). Typically however, these were not used, and the supply was turned off manually a minute after a quench.

G. Beam - FEB and Intensity Monitors

The MARK VI magnet was placed in the AGS U-line, 640 feet downstream of the H13 straight section of the AGS and 200 feet upstream of the focal point for the beam at the neutrino target. This area is fed by the AGS fast extracted beam (FGEB), a one-turn extraction in 2.5 μseconds in 12 bunches 200 nseconds apart, with a pulse repetition rate of 2 seconds, although many tests involed only single pulses.

The profile of the beam was measured by a segmented wire ion chamber (SWIC) with 2 millimeter wire spacing. Horizontal and vertical beam profiles are shown in Fig. 3 for high and low intensity pulses and a pulse with the beam position changed by 1.5 centimeters horizontally. These are pictures of a storage scope trace with different sensitivities. For normal running, the full width of the beam at the SWIC was 3 mm (H) by 6mm (V). The upstream end of the magnet was 5' downstream of the SWIC, considerably closer than the focal point of the beam, so that the SWIC profiles accurately monitored the beam spot size at the magnet.

In order to determine the quench threshold of the magnet, we needed to be able to select single pulses of from 10^9 to 10^{12} protons. The normal beam intensity of the FEB is several 10^{12}. Two of the difficult technical problems we encountered were to reduce the beam intensity to 10^9 without smearing the image at the magnet and to monitor a beam intensity three orders of magnitude below normal. The beam intensity was reduced by a combination of reduced circulating beam intensity and inefficient extraction. After extraction, the beam transport to our experimental area, involving 4° and 8° bends, resulted in a clean image at the magnet. At low intensity (a few 10^9), the beam intensity was very difficult to control, with 50% pulse-to-pulse variations.

Monitoring the beam intensity from 10^9 to 10^{12} protons turned out to be very difficult. We used a number of different monitors which had different sensitivities to track the intensity over the full 3 orders of magnitude. A current transformer in the AGS (L15CBM) monitored the circulating beam intensity accurately (it integrated over many beam passes). Two current transformers along the extracted beam line (U15CT and U303CT) monitored extracted intensities above 0.4×10^{12}. A secondary emission chamber (SEC) measured intensities above 10^{10}. An ion chamber had a linear response below 10^{11}. Figure 4 shows a schematic of the positions of the monitors, with their operating ranges. The SEC ion chamber and SWIC were added to the beam line for this test. Figure 5 shows the determination of these ranges: (a) shows the extracted beam current transformer outputs plotted against the internal CBM where the extraction conditions were held constant and the intensity was varied in the AGS; (b) shows the SEC versus the internal CBM; (c) shows the ion chamber versus the SEC. To reach intensities below a few 10^{11}, it was necessary to spoil the extraction, so that the internal CBM could no longer monitor the intensity of the extracted beam. Figure 5c shows the ion chamber saturation. One can also see that two SEC counts represent 10^9 protons--thus, the ion chamber was the only sensitive intensity monitor below about 10^{10} protons.

The normalization of the readings of the monitors to real protons was done in three ways: the internal CBM had been separately normalized with foil runs by the AGS operators; foils were exposed at two intensities and were counted and compared to ion chamber readings; the SEC conversion constant can be calculated directly. These three normalizations all agreed to 10%. We feel the beam intensity for our tests was known to better than 20%.

H. Instrumentation of Magnet-Quench Detection

The primary monitors of the magnet were a series shunt giving us the current in the magnet and a voltmeter attached across the magnet measuring total magnet voltage. When the magnet was superconducting, no voltage registered. When the magnet quenched, up to 15 volts were generated.