OPERATING EXPERIENCE WITH A SUPERCONDUCTING MAGNET IN A PRIMARY PROTON BEAM*

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ABSTRACT

Two superconducting dipole magnet modules have been operated successfully at BNL since October 1973 to bend 30 GeV/c protons from the AGS by 8° in the new North Area beam to the 7-ft. Bubble Chamber. The magnets have been energized for over 1000 hours, and, of that time, have been traversed by the proton beam with beam intensities up to 5×10^{12} protons per pulse, for about 750 hours. Operation of these series connected magnet units, each 2 meters long at 35kG has been routine even when they were intermittently subjected to beam heating of several hundred joules per pulse due to other operational beam difficulties. Experiments were also performed where copper blocks were inserted 2 meters upstream, resulting in very large interaction rates in the beam tube inside the units. A magnet quench occurred with target thicknesses such that energy approaching 1kJ per pulse was being absorbed in the system. These are the first superconducting magnets in operation in a primary beam on which extensive radiation heating tests have been performed.

I. INTRODUCTION

A superconducting magnet system consisting of two superconducting dipole magnet modules, a closed loop helium refrigeration system, a helium gas supply and recovery system, and an interlocked instrumentation control system with provisions for remote control was installed in October 1973 and is operating successfully in the new North Area beam at the Brookhaven National Laboratory AGS (Fig. 1) for neutrino physics.

TABLE I

Magnet Parameters (Fig. 2)

Aperture diameter(I.D. warm)	7.3 cm
Core length	1.83 m/module
Magnet design field	4 T
Dipole amp turns	408,000
Dipole current	1200 amps
Dipole current density	30.5 k A/cm ²
Sextupole amp turns	18,000
Sextupole current	300 amps
Stored energy	150 kJ/module
Inductance	0.2 h/module

The magnet system generating a magnetic field intensity of 35kG bends the 28.5 GeV/c protons from the AGS by 8°. The intensity of the proton beam traversing the superconducting magnets varies from 1×10^{12} to 5×10^{12} protons per pulse. Since these magnets are operated in a high radiation area, the refrigerator and its controls are separated from the magnets by approximately 30-ft. of shielding. The shortest direct access route to the magnets from the instrumentation control trailer is about 1000-ft. long.

A C.T.I. model 1400 refrigerator with a capacity of 74 watts operating on two compressors supplies the refrigeration for the system. A third compressor is installed into the system for redundancy (Fig. 3).

Interlocks are connected to the power lead voltage taps, insulation vacuum, helium dewar pressure, helium liquid level, and other components operating in the

beam to protect the system. If operating value of any of these parameters exceed the preset limits, the magnet power is automatically shut off and the proton beam is dumped.

The 8° magnets were installed without prior tests of the complete system, and was immediately operated successfully as part of the beam line to produce neutrinos for counter experiments and the 7-ft. Bubble Chamber (Fig. 4). These magnets have been operated routinely whenever required by the high energy physics program for ~ 750 hours. Several experimental runs have also been made with the magnet system which has raised the total time the magnets have been energized to over 1000 hours. Until late September 1974 this magnet system has been operated whenever required with no cause for delay to the experimental program. Unfortunately during the last week in September, contamination symptoms appeared in the refrigeration system necessitating a warmup and purge of the refrigerator. At the same time a checkout of the system indicated several leaks had developed in the helium line on the suction side of the compressors. These leaks were repaired, and the total down time caused by this difficulty was less than one week. This difficulty has been the only cause for delay by this system since its "maiden voyage" last year, which gives some indication of its reliability.

When the first magnet core was tested we encountered some power lead problems which were in part due to the location of the internal magnet connections. In order to maintain our very tight construction schedule, we took the calculated risk of operating the magnet immersed in liquid helium with the refrigerator shut down (Fig. 5). Protectors were scheduled for installation on the final magnet assemblies, but were not in place during the preliminary test. During this test the power lead voltage went abnormally high and the magnet coil leads went into film boiling resulting in a vaporized lead and an open circuit in the magnet. Needless to say, the ~ 150 kJ of energy stored in the magnet caused a voltage buildup of sufficient capacity to arc from the coil to the magnet core. The resulting arc vaporized some of the superconductor (Fig. 6) and made the magnet inoperative. Although the failure seemed to be a catastrophe when it occurred, the versatility of the magnet design was clearly demonstrated when the magnet core was disassembled; four layers of damaged superconductor were removed from the dipole winding; a splice was made in the superconductor and the four damaged layers were replaced. The magnet was then reassembled and tested satisfactorily to 44kG. To date this magnet, after ~ 1000 hours of service and many thermal cycles, still operates routinely. To the best of our knowledge this is the only superconducting magnet that has endured a failure of this type, and after a relatively simple repair procedure involving approximately two weeks of work for two technicians, has been put back in operable condition.

II. REFRIGERATION SYSTEM

The magnet cores are provided with a liquid nitrogen closed loop cool down system, and nichrome heater cables are also attached to the magnet core to accelerate the warmup cycle. The magnets have been thermally cycled from ambient to operating temperature many times with no difficulty. The cooldown cycle requires ~ 8 hours for the two 4500-lb. iron cores to reach about 90°K with the LN₂ precool cycle, and an additional 18 hours for the refrigerator to cool the system from 90°K to ~ 6°K. The magnet system can be

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24

warmed up from 4.5°K to 300°K in less than 24 hours, so the total time to warm up and cool down the system, when required, is relatively modest.

The helium storage system consists of a clean gas supply and recovered "dirty" gas. A 1000 liter storage dewar of LHe is also connected in parallel with the refrigerator and load so that if refrigerator difficulties are encountered the 8° magnet system can operate for about 20 hours on the stored liquid, and additional LHe can be transferred to the system if required. The primary source of clean gas for the refrigerator is furnished by a helium tube trailer adjacent to the refrigerator room. A surplus vertical storage tank with ~1000-ft.³ volume and 350 psi storage capacity is also connected to the system (Fig. 7). Eventually, the vertical storage tank will be the primary source of supply since the clean gas system will be a closed loop from the vertical tank to the refrigerator with additional gas supplied to the system only when required by a sensing device.

The dirty gas recovery system is composed of two 1500-ft.³ rubberized fabric bags which are interlocked to a compressor system. When the bags are filled to a preset limit, the compressors are actuated and transfer the helium from the gas bags to several "whales", which are Navy surplus gas tubes, connected in parallel. A pressure transducer and relief valve are installed in the helium piping to the "whales". The relief valve is set for 350 psi and an audio alarm is triggered by the pressure transducer which is set at 325 psi. When the "whales" are filled to capacity the gas is transferred to a tube trailer by equalization of pressure and the dirty gas is then transferred to our dirty gas storage area in the Cryogenic Facility (~100,000-ft.³ capacity) where the gas is purified and stored in the clean gas storage system (~40,000-ft.³ capacity) to be used in the laboratory either as clean gas or to be liquefied in the Facility refrigerator-liquefier when the need arises.

All of the LN₂ required for the operation of the system is fed from a common manifold in the refrigerator room, and supplies LN₂ to the following circuits:

1. The LN₂ precooling loops on the magnet cores.
2. The LN₂ trace lines on the LHe transfer lines.
3. The helium purifiers in the refrigerator room.
4. The heat exchanger in the refrigerator.

The LN₂ manifold is supplied by a 2500-gal. trailer which is located ~25-ft. from the refrigerator room, and is filled periodically as the need arises. Experience to date indicates a LN₂ cost of ~\$1.50 per hour of operation, but this cost has been for short runs of the system and is, therefore, adversely affected by the volume of LN₂ required to precool the cores. For running periods of several weeks or more, the average cost of LN₂ to operate the system should be less than \$1.50 per hour.

III. CONTROL SYSTEM

Until late September of this year all controls of the 8° magnet system except the refrigeration were made manually in the instrumentation control trailer which is adjacent to the refrigerator house and ~1000-ft. from the magnet dewars. In late September, the instrumentation control system was connected to the computer interface so that remote control of the magnet system can be performed directly from the main control room. Other components in the beam line were also interlocked into the system so that the beam will automatically shut down in case of a beam component malfunction. The system is connected so that in case of a computer failure the magnet control system can be switched to local control and still be operated manually.

This mode of operation will essentially eliminate the need for a technician at the instrumentation trailer whenever the 8° magnet system is in operation. The refrigerator system will need only periodic checks by the watch group to make sure the equipment is operating satisfactorily. In case of an emergency such as a magnet quench, the watch will be notified and can be on site within a few minutes. The total time for the watch to travel, monitor, and tabulate the refrigeration system parameters is about fifteen minutes, and this function will be performed once every hour. The total technician time required therefore, for normal operation of the 8° system will be 1/4 of a man hour for every hour of operation.

IV. RADIATION EXPERIMENTS

During two different periods when no experimental physics was scheduled, the fully powered magnets were exposed to intentional doses of radiation. During the first test copper blocks varying in thickness from 1/8-in. to 1/2-in. thick were inserted into the beam about 2 m upstream from the magnets, and the beam was traversed on its regular duty cycle through the magnets with intensities varying from 1.8×10^{12} to 4.6×10^{12} particles per pulse. The duration of the radiation exposure to the magnets varied from 3 to 6 minutes. The helium dewar pressure was monitored continuously during the run and the beam was shut down if the pressure exceeded 9 psig. This test was terminated when the magnets suffered a modest quench after ~30 beam pulses striking a 1/2-in. thick copper block at 3.3×10^{12} beam intensity.

A second radiation exposure test was performed in late May 1974. This test was composed of single beam pulses through copper blocks again inserted into the beam ~2 m upstream from the magnets. Six different exposures were made on the magnets with the following results:

1. Two pulses through 1/2-in. thick copper with a beam intensity of 1.36×10^{12} had no effect on the magnets.
2. One pulse through 3/4-in. thick copper with a beam intensity of 1.32×10^{12} had no effect on the magnets.
3. One pulse through 1-in. thick copper with a beam intensity of 1.34×10^{12} had no effect on the magnets.
4. One pulse through 2-in. thick copper with a beam intensity of 1.284×10^{12} quenched the magnets.
5. The dewars were then refilled and one pulse was traversed through 1/2-in. thick copper with a beam intensity of 2.5×10^{12} and had no effect on the magnets.
6. One pulse through 3/4-in. thick copper with a beam intensity of 3.2×10^{12} quenched the magnets. The radiation exposure test was terminated at this point.

A brief look at the preceding data indicates that ~ 1×10^{12} particles of 28.5 GeV protons impinging on a 2-in. thick copper block located 2 m upstream from the magnets will drive them normal. Calorimetric measurements indicate this results in ~1 kJ of energy being absorbed by the magnet which is an order of magnitude greater than the heat capacity of the superconductor itself. One should also keep in mind that the beam centerline in following its trajectory through the magnets is only ~1.5 cm from the warm bore tube wall at both ends and center of the two magnets (Fig. 8). Therefore, even a small scattering angle results in large beam losses in the warm bore tube. For 1×10^{12} protons, the beam power is 5kJ. It appears, therefore, that the superconducting coils are being exposed to high levels of radiation. The radiation tests performed to date demonstrate that the 8° magnets can survive

relatively large exposures to radiation heating without quenching which indicates a very high degree of thermodynamic stability in the magnets.

V. CONCLUSION

The results obtained from operating this system during the past year indicate that the use of superconducting magnets for beam transport and in areas of relatively high radiation heating is practical and reliable. The few difficulties we have encountered to date have been primarily related to the integrity of the helium piping system and refrigerator. In a large-scale application of such magnets employing a refrigerator plant with greater capacity regenerative purifiers in the helium stream would certainly be employed and greatly reduce the chance of contamination.

Since its inception the 8° magnet system has been operated only periodically and has been undergoing modifications to the instrumentation and cryogenic system. In the future, as more operating experience is obtained, additional information concerning technical and operational questions will become available. The effect of this information on other larger scale cryogenic systems will be evaluated.

REFERENCES

1. J. Allinger et al., Proc. IXth Intern. Conf. on High Energy Accelerators, 1974 (in press).

Fig. 1. North Area Beam Layout

Fig. 2. 8° Superconducting Magnet Module

Fig. 3. C.T.I. Model 1400 Refrigerator

Fig. 4. 8° Magnets in Beam Line.

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Fig. 5. Magnet Test Setup in Cryogenic Facility

Fig. 7. Helium Gas Supply System

Fig. 6. Fused Section in Dipole Coil

Fig. 8. 8° Dewar Cross-Section