

THE MULTIPLE MAGNET TEST PROGRAM

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Abstract

A test facility has been constructed at the B12 location of the Fermilab main accelerator in order to test superconducting Doubler magnet strings under conditions similar to their final operating conditions while minimizing the interference to the ongoing 400 GeV program. Tests on the cryogenic, magnet and magnet power supply systems have been performed. In addition, a quench protection system has been tested that protects the magnets from damage due to a quench up to the full operating current of the Doubler.

I. Introduction

The B12 doubler magnet test facility is located in an above ground enclosure between the B0 and B1 service buildings of the existing main ring accelerator. This location allows ready access to the existing accelerator's electrical, water and control systems without limiting its operation to the maintenance schedule of the accelerator. The enclosure is of sufficient size to accept an in-line connected doubler magnet cell (eight dipoles and two quadrupoles). Larger magnet strings are possible if vertical and/or horizontal magnet stacking is employed.

In the past, series connected dipole strings have been powered at this location for extended periods. One 8-dipole string was continuously ramped for a week's duration without interruption or failure. These tests confirmed our ability to cool and ramp series connected magnets and provided valuable initial experience in the techniques of transporting, installing, evacuating and leak checking extended magnet systems.

Recently, the emphasis at B12 has shifted toward duplicating the anticipated operating environment of the Doubler in order to test its operating philosophy and components. Much work remains to be done. However, our operating experience with the last group of dipoles disclosed no insurmountable difficulties. Four type 5 collar magnets with Ebonol coated superconducting cable were tested. The primary objectives of this test were:

1. Training and experience in the task of installing the magnets without heat or vacuum leaks.
2. Cool down of the magnet string without the use of auxiliary liquid helium dewars.
3. Measure the magnet heat load.
4. Check the magnet power supply interlocks, energy dump circuit, quench heaters and micro-processor used for quench detection.
5. Ramp at full power (> 4000A) and measure the LHe pressure rise during a quench.

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6. Investigate the system recovery after a full power quench.

The installation of superconducting magnets at the B12 facility is now routine. One dipole was completely replaced by an experienced two man crew in four hours, an elapsed time comparable to the replacement time of conventional magnets in the main ring tunnel. The superconducting magnet installation time in the tunnel is not significantly longer in spite of the cramped work space.

II. Cryogenics System

Currently there are two CTI 1400 helium refrigerators with six compressors and LN₂ precooling. The nominal system capacity is 180 watts of refrigeration (60 liters per hour liquifaction) and is capable of circulating 10 gm/sec through the magnets. Enhanced capacity can be attained by two additional on-line compressors. Dewar-supplied liquid helium can be added to the refrigerator return flow to achieve liquifaction rates as high as 160 l/hr. A pump dewar option is also available to achieve circulation rates as high as 40 gm/sec. (See Fig. 1.)

The refrigerators are coupled in parallel to the magnets via bayonets and an elaborate feed box. The feed box contains the electrical power leads for the magnets, the liquid helium subcooler and the instrumentation for monitoring pressures, temperatures, subcooler performance, and power lead voltage. It supplies the magnets with sub-cooled liquid helium, LN₂ for the radiation shield, and electrical power as well as access to the insulating vacuum for pumpdown and leak checking.

A turnaround box is attached to the end of the magnet string and contains the J-T expansion valve, cooldown vent, LN₂ vent, and additional instrumentation including a liquid helium Venturi flowmeter. The instrumentation used is a combination of electrical and pneumatic devices and measures system parameters at all key points. System control is achieved by several very simple pneumatic logic circuits in addition to the automatic controls on the refrigerators. The system on the whole is quite reliable, and has operated unattended for as long as a month. The installation of an Energy Doubler satellite refrigeration system is currently in progress. A 20 magnet testing program will start as soon as it is operational.

III. Magnet Power Supply and Quench Protection System

The proposed Doubler magnet power supply and quench protection system has been described elsewhere.¹ Aside from the number of series magnets powered, a facsimile of this system was tested. (Fig. 2).

The power supply for the dipole string test was a converted main ring power supply located in the B1 main ring service building. The 0.5 Ω "energy fountain" located at B1 and the proposed series SCR dump circuit (one required per sector) were used to extract the stored magnetic energy from the string. With four powered dipoles, the L/R time constant is 0.36 sec instead of the 11 sec time constant for the Doubler magnet lattice. Therefore, heaters and "bypass" thyristors are not required to protect the magnets. However, the peak current and voltages present during a Doubler quench were reproduced in miniature in the magnet string and power supply circuit.

The conditions of a heater protected magnet half-cell were approximated by delaying the off command to the magnet power supply and series SCR. This maintains the power supply current while the resistive voltage developed in the superconducting magnets during a quench drives the current into the bypass SCR.

As soon as a quench is detected in a magnet half-cell, heaters in the coils of the half-cell dipoles are energized. This prevents the deposition of the total half-cell magnetic energy in the magnet that initiated the quench. The lack of a quadrupole during this test only slightly decreases the stored energy of the half-cell due to the small inductance (8 mH) of the quadrupole relative to the dipoles. The conventional main ring (M.R.) magnet in the circuit served as a convenient load for the power supply after the current transfer into the quench bypass SCR was completed.

Extensive magnet protection interlocks were active during magnet ramping. Power lead and magnet voltages and magnet current were redundantly monitored by analogue circuits and a prototype microprocessor. The microprocessor detects the onset of a quench by comparing the voltage across a magnet to the average voltage per magnet of the string. Trips too numerous to mention and quenches occurred during experimentation with the refrigeration system and current regulation. In every case, the interlock and dump circuits safely reduced the magnet current to zero.

IV. Magnet Cooldown and Refrigeration

An attempt to cool down long strings of Doubler magnets in the loop flow mode is nearly impossible because the magnets are almost perfect heat exchangers and most of the refrigeration that is supplied is heat exchanged back through the return line. We therefore use single pass cooling through the single phase (1 ϕ). The cold wave front is very steep and travels through the magnet string much like a step function through a transmission line; i.e., the discharge remains at room temperature during almost the entire cooldown cycle. The cooldown rate at B12 is limited to about four hours per dipole by the refrigerator capacity. A Doubler satellite refrigerator can cut this time in half.

When the cooldown wave arrives at the end of the magnet string, a transition to loop flow is made with the cold gas returning to the refrigerator through the 2-phase channel. Liquid helium accumulates in the magnets until the 1 ϕ volume is filled at which time we subcool the helium.

Subcooled liquid helium .3° K below the boiling point has the highest heat capacity as well as the highest heat transfer coefficients and is therefore a desirable operating environment. The liquid helium is subcooled by a small heat exchanger located in the feed can. During a magnet current cycle, the heat generated by the coil located in the 1 ϕ chamber is heat exchanged to the 2 ϕ return helium flow, vaporizing the liquid in the 2 ϕ chamber. Thus a constant temperature across the magnet string is maintained. The degree of subcooling is adjusted by the J-T expansion valve.

V. Static Heat Load Measurements

We have measured the static heat load of the four magnet string at B-12 in the following manner. Helium gas at 10° K and a flow rate of 1.7 gm/sec from the refrigerator was allowed to flow through the magnets and vented through a warm return line to be recompressed. The temperature rise across the four magnets was measured as well as the temperature rise across the third and fourth magnets with commercially calibrated "glassy Carbon" resistors.

The flow was measured simultaneously by a cold Venturi, a rotameter, and a calibrated gas volume meter. After reaching 10° K the system was allowed 72 hours to come into equilibrium. The total heat leak was found to be 34 watts, consistent with a previous measurement. Based upon the measurement of the heat load of just the third magnet (6 watts) and an estimate of the radiative heat load from the ends, we conclude that the typical static heat load per dipole is of the order of 6 watts. This is consistent with an earlier measurement of 5.6 watts and calculations. More measurements of static heat load, stressing improved end-box shielding, are being planned.

VI. Quench Related LHe Pressure Rise

The bypass SCR of the quench protective system forces a magnet half-cell to absorb its stored magnetic energy, thereby transferring the burden to the cryostat and refrigeration system. The rapid deposition of energy in the 1 ϕ LHe volume of the cryostat during a heater protected quench results in a pressure rise which is sufficient to collapse the bore tube and rupture the 1 ϕ bellows unless an adequate venting system is provided. Independent pressure measurements on the bore tube and 1 ϕ bellows have shown that the pressure has to be limited to approximately 125 PSIA, the squirm threshold of the bellows, to insure reliable survival of the cryostat. This pressure occurred at a 2500 A quench current in an earlier type 4 magnet string test.

Since then, the size of the venting system has been increased sufficiently such that full power quench tests could be performed. The peak pressures listed in Table I were obtained with a 1.5" aperture Ross valve. The substitution of a lower impedance relief valve and the addition of the quadrupole vent are expected to lower the quench pressures even further.

VII. Quench Recovery

During a quench the energy is deposited in the coil and the surrounding liquid helium. The heated helium inventory (15 liters/dipole) is vented on each magnet, thus carrying away some of the quench energy. The remaining energy is distributed through the coil structure and residual helium gas. The equilibrium temperature inside the magnets occurs within five minutes after the quench and is listed in Table I as a function of quench current.

TABLE I

Current (A)	Energy (KJ)	Final Temp. (°K)	Pressure (PSIA)	Recovery Time
Initial Conditions		4.65	25	-
1000	25	4.72	25	-
1400	49	5.8	30	6 min
2000	100	8.3	37	10 min
3000	225	16.5	65	16 min
4000	400	24.3	108	27 min
4300	460	42.8	151	35 min

Quench recovery requires a return to single pass He flow. Prompt recovery from quenches has been achieved by injecting helium from a dewar into the return of the refrigerator to achieve much higher flow rates than the normal refrigerator output. This flow rate, initially limited to 80 liters/hour by the pressure drop of the hot magnet, steadily increases to about 160 liters/hour as the cold front moves through the magnets. The hot gas returns via the cooldown line at the end of the magnet string (Fig. 1). In this mode, refrigerator output is subcooled and the magnets are filled with subcooled liquid. We have recovered from maximum current quenches in 35 minutes with no resulting damage to the magnets. Lower energy quenches require shorter recovery times (Table I).

Acknowledgement

The authors wish to acknowledge the contributions and efforts of the following to the experimental effort at B12: L. Ray, S. Hayes, J. Lockwood, J. Sykes, R. Norton, D. Wendt, L. Krafczyk, W. Habrylewicz, and J. Smith.

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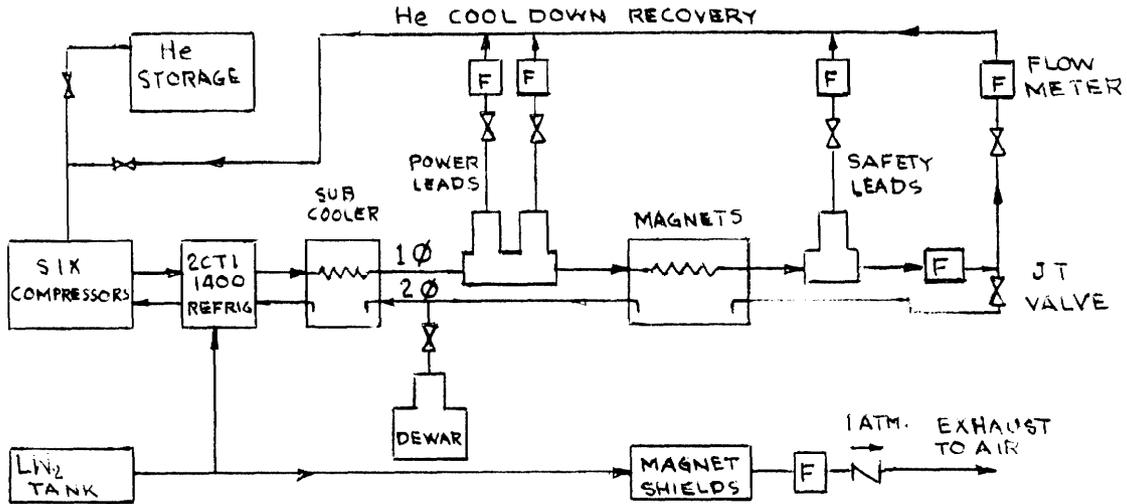


Figure 1: B12 Refrigeration System.

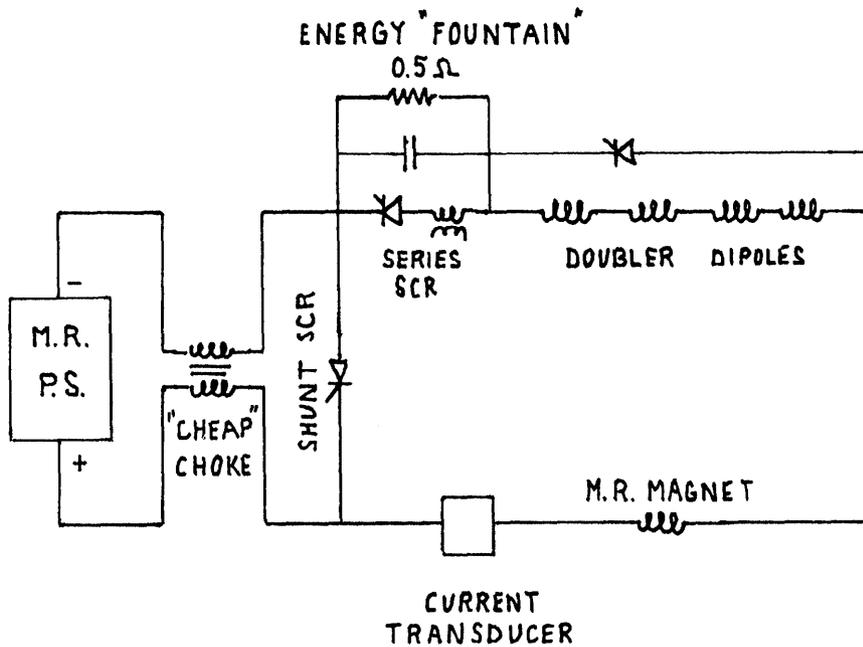


Figure 2: B12 Magnet Power Supply System.