B12 Doubler Magnet Operating Experience

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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.

More recently, the emphasis at B12 has shifted toward duplicating the anticipated operating environment of the Tevatron 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 with and without current.

4. Check the magnet power supply interlocks, energy dump circuit, quench heaters, voltage taps and microprocessor used for quench detection.

5. Ramp at full power (>4000A) and measure the 1ϕ and 2ϕ pressure rise during a quench with the energy dump. Repeat the pressure measurements with the magnet string shorted during the quench.

II. Magnet Installation

The installation of superconducting magnets at the B12 facility proved routine. One dipole was completely replaced by an experienced four 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 can be expected to be somewhat longer due to the cramped work space.

III. Vacuum and Leak Detection

The insulating vacuum of the cryostats was evacuated by 260 ℓ/sec turbo molecular pumps coupled at the start and end of the magnet string. Vacuum instrumentation consisted of a thermocouple and cold cathode gauge pair mounted on the downstream cryostat end box of each dipole. In the absence of leaks, this pumping geometry required 24 hours to reach 10^{-3} torr and 48 hours to reach 5 x 10^{-4} torr. During magnet cool down, the cold fronts of liquid nitrogen and liquid helium were readily observed on the cold cathode gauges by the local sequential pressure drop to 10^{-5} torr and 10^{-7} torr respectively.

The leak checking technique consisted of monitoring the insulating vacuum of the cryostat with a helium sensitive leak detector as the 1ϕ, 2ϕ, LN and bore tube volumes are sequentially pressurized to 2 atm with helium. This readily localized a leak to a region between two magnets. Little can be done to further localize small leaks aside from replacing the magnet or the conoseals. Both options are time consuming. Conventional leak checking techniques could be applied if the leak detector could be connected to the leaking volume via the vents located in the quadrupoles. In the case of the 1ϕ and 2ϕ volumes, some means would be required to defeat the check valves.

More than a week was required to obtain a leak tight system. One magnet had to be replaced because of a persistent leak in a weld near the 2ϕ bellow. A second magnet required the replacement of its liquid nitrogen bellow. Particular difficulty was experienced with the 2ϕ and liquid nitrogen conoseals. Two had to be coated with indium to achieve a proper seal. The conoseal leak problem was aggravated by our inability to torque the seal without squirming the adjacent bellow. A fixture has been developed to overcome this problem.

Instrumentation has been installed which allows us to measure cold helium leaks into the bore tube. This measurement is scheduled to be performed during the next cool down.

IV. Refrigeration

The refrigeration system presently at B12 is depicted in Fig. 1. Most of the heat capacity of the magnets and end boxes is absorbed during cool down by the one way flow of liquid nitrogen through the nitrogen shield. Two CTI 1400 refrigerators fed by six compressors for a combined refrigeration capability of 180 watts at 4.6^{o}K further cool the magnet coils to 4.6^{o}K. Approximately 96 hours were required to cool the system from room temperature to LHe temperature. No supplemental cooling from LHe storage dewars was used. The cool down elapsed time is longer than the times previously recorded, in part due to the increased mass of the type 5 collar (factor of 2) compared to the type 4 collar.

An average static heat load (zero magnet current) of 8 watts/dipole was measured for these magnets. An attempt to measure the heat load during ramping failed due to inadequate refrigeration and instrumentation. Both problems are presently being corrected.

A critical concern prior to this test was the lack of convective cooling between the inner and outer 1ϕ helium flow in the type 5 collar. This removes the 1ϕ to 2ϕ heat transfer for the 1ϕ helium in contact with the coil except at the cryostat ends where the two 1ϕ helium streams recombine. Insufficient heat transfer to the 2ϕ could result in a cumulative 1ϕ temperature rise until a downstream magnet quenches.

The four magnet string was ramped for 1.5 hours with an estimated 10 watt/magnet AC load. The 1ϕ temperature at the power lead connection of the last magnet rose 0.2^{O}K within six ramp cycles and remained stable at this temperature for the duration of the run.

Each power lead was operated with approximately 24 watts of LHe cooling while the magnet string was ramped. At this cooling level, the voltage across the power leads was 1 mv per 250 A of magnet current and appeared linear up to 4000 A. No evidence of thermal instability was observed at this cooling rate. Each safety lead was cooled with 1.5 watts of LHe flow. No damage was sustained during a 4100 A quench.

The recovery time of the refrigeration system following a quench ranged from 0.5 to 24 hours depending on the quench current and mode of quench protection. When the magnet string was quenched without firing the heaters and with the energy dump active, the fraction of the magnetic energy absorbed by the magnets in the form of heat scales as the ratio of the magnets normal zone resistance relative to the resistance of the external dump resistor. Typically, this means that approximately 10% of the stored magnetic energy goes into heat and at low quench currents, the refrigeration recovery is fast.

However, a magnet half cell that is protected with heaters and a shunting "bypass" SCR will absorb all of its magnetic energy (maximum of 1.8 MJ/half cell at 4250 A). A test of this quench mode at 1000 A required 24 hours to recover. In the future, an auxiliary 500 ℓ LHe dewar will be used for fast cooldown.

V. Cryostat Single Phase Pressure Rise

The rapid deposition of energy into the 1ϕ 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 1ϕ bellows unless an adequate venting system is provided. Independent pressure measurements on the bore tube and 1ϕ bellow have shown that the pressure has to be limited to 125 PSIA, the squirm threshold of the bellow, to insure reliable survival of the cryostat. This pressure occurred at a 2500 A quench current in an earlier type 4 magnet string test (Fig. 2).

The pressure test was repeated at 1000 A with the present type 5 magnet string and a larger 1.5" diameter triggered Ross relief valve system. No reduction in the peak pressure was obtained. Concurrently, a sequence of single magnet pressure tests were performed at the production magnet test facility. By increasing the 1ϕ vent tube diameter from 1.0" to 1.25", replacing miter joints with smooth elbows and replacing the internal ball check valve (required to dampen thermal oscillations for reduced heat leak) with a flapper valve design, a type 5 magnet has been repeatedly quenched at 4600 A with a 1ϕ pressure peak of 125 PSIA (Fig. 2). At present, eight type 5 magnets are in various stages of retrofitting to this MOD 3 vent geometry and full powered heater protected string quench tests will resume as these magnets become available.

VI. Magnet Power Supplies and Quench Protection

Aside from the number of series magnets powered, a facsimile of the proposed Tevatron magnet power supply system and quench protection scheme was tested (Fig. 3). The power supply for the dipole string test was a converted main ring power supply located in the B1 main ring service building. The 0.5Ω "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 Tevatron magnet lattice. Therefore, heaters and "bypass" thyristors are not required to protect the magnets. However, the peak current and voltages present during a Tevatron quench were reproduced in miniature in the magnet string and power supply circuit.

The conditions of a heater protected half cell were approximated by not switching in the 0.5Ω dump resistor. In this case, the shunt SCR performs the function of the "bypass" SCR, shorting the magnets and all the magnetic energy goes into heating the magnets. A more realistic test of this quench protection mode requires a longer magnet string with the correct mix of dipoles and quadrupoles. This test will be delayed until a full satellite refrigerator is installed at B1.

The magnet string trained to 4098 A (260 A/sec, 4.8°K) in two quenches. The first quench occurred at 3813 A. All quenches during the tests occurred in the first magnet downstream of the power leads.

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. An indication of failure in any of the circuits initiated an "energy fountain" dump. The power supplies were also interlocked to the 1ϕ and 2ϕ helium temperatures.

Too numerous to mention trips 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. During future tests, these circuits will be interlocked with the main ring control system.

VII. Quench Trip Levels

In the case of the power lead monitors, the trip levels into the microprocessor were set as low as 5 mv without spurious triggers. However, the magnet quench trip voltage had to be set to 5 volts because of nonlinearities in the prototype MADC and the nature of the magnet voltage tap. The voltage tap was a 1:200 resistive divider to ground.

A 5 volt quench detection level is marginal from the standpoint of maximum temperature in the superconductor. At 4500 A, the magnet in the half cell experiencing a quench will have seen 4 Miits (Miits $\equiv \int I^2 dt/10^6$) by the time a quench is detected (Fig. 4). At this point, the heaters of the half cell dipoles are fired and another 4.5 Miits (Fig. 5) are accumulated until the current is transferred to the bypass SCR. This totals 8.5 Miits for the magnet that initiated the quench and results in a maximum local temperature of 650°K (Fig. 6). At this temperature, the soldered splices of the coil will melt.

An effort has been made to reduce the Miits accumulated after the heaters are fired. This included simultaneously firing two heaters per dipole, changing the power and energy levels applied to the heater and changing the location and size of the heater. No single or combination of the above changes reduced the Miits more than one Miit. As a result, a differential quench voltage monitoring system is under construction that will allow us to set the quench detection threshold as low as 100 mv. Such a system will limit the total Miits to 5.5 (approximately 250^{o}K) without requiring a change of the heater design at the expense of slightly more complicated electronics.

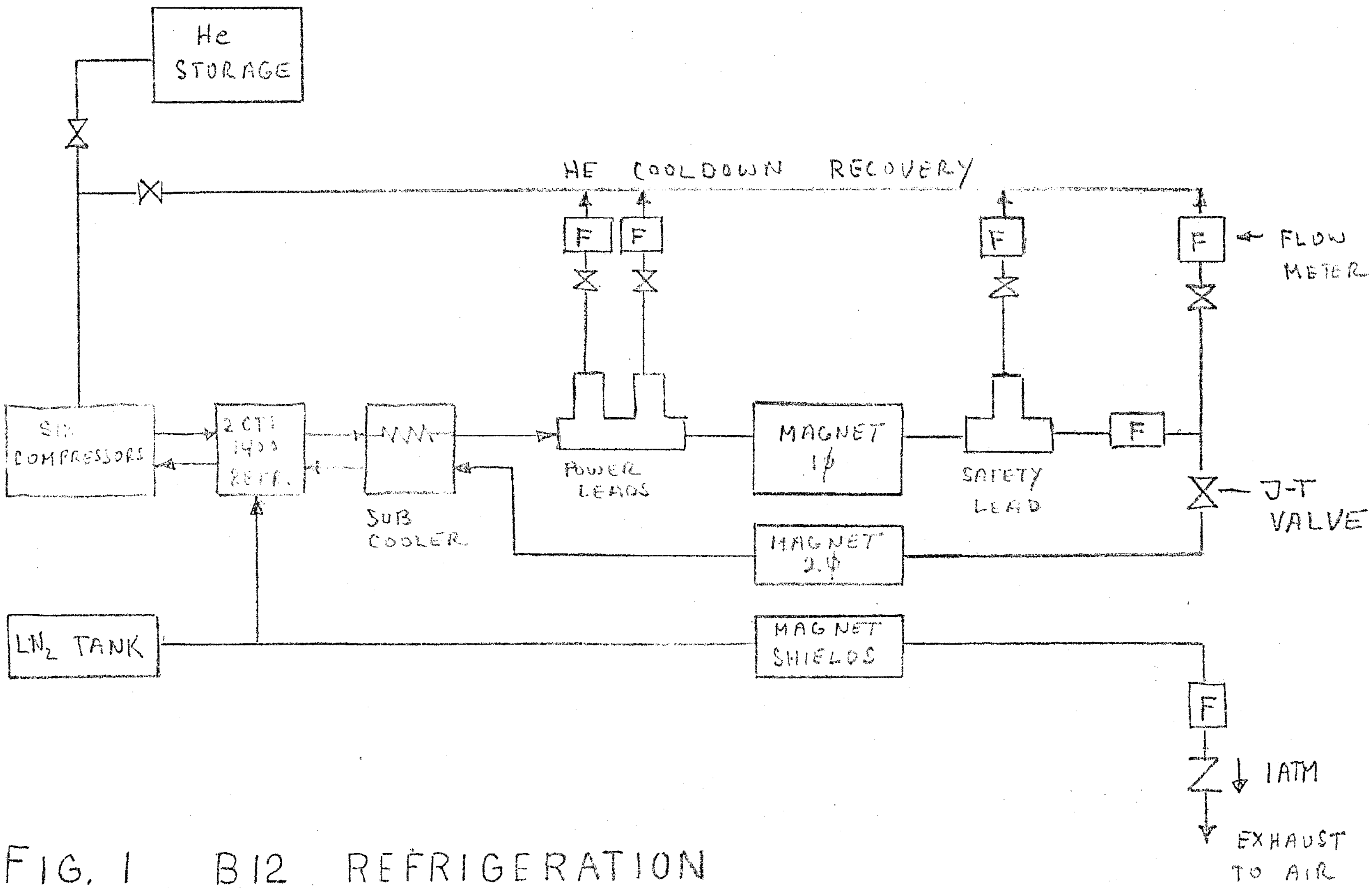

FIG. 1 B12 REFRIGERATION

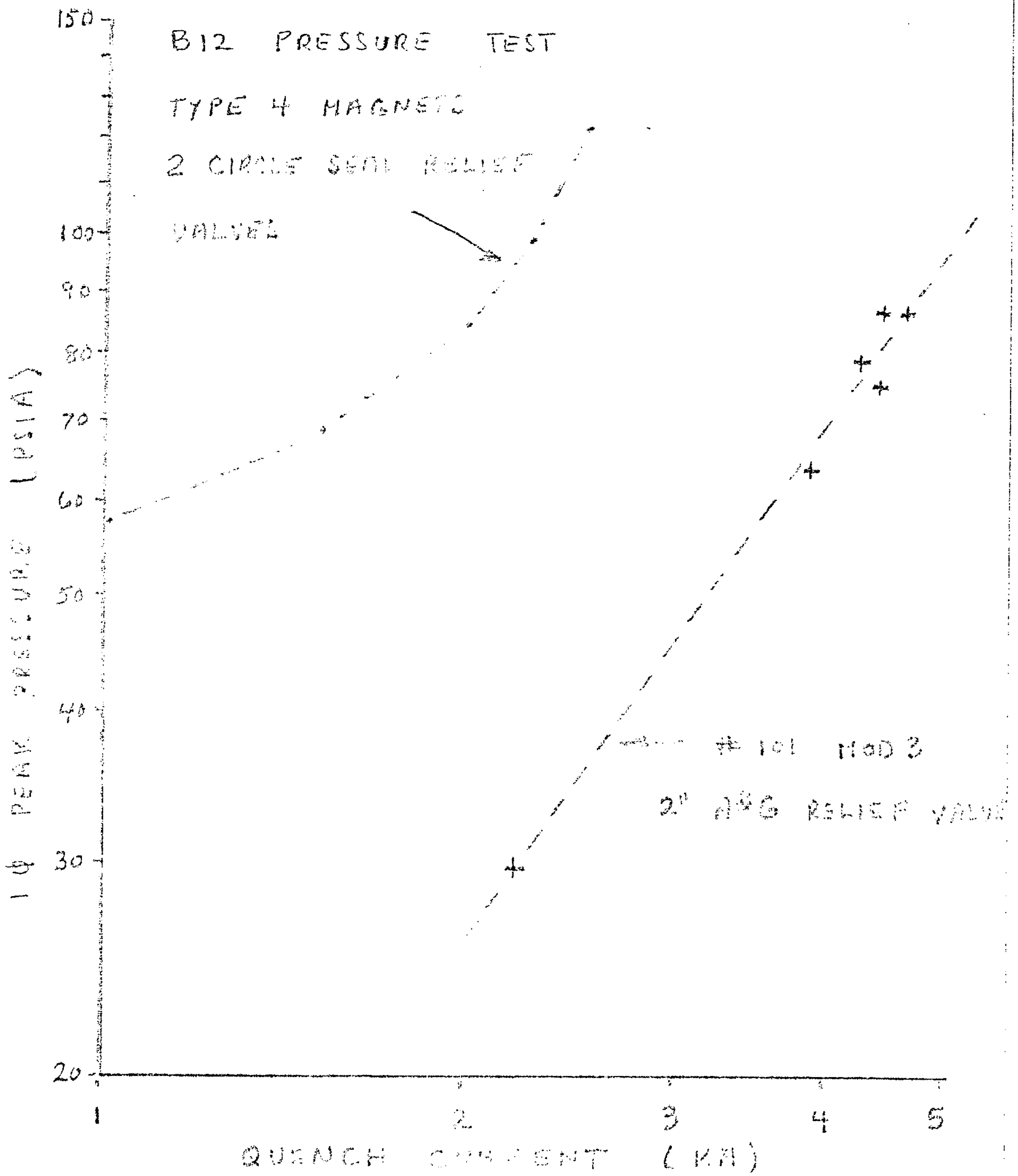
B12 PRESSURE TEST
150
100
90
80
70
60
50
40
30
20
PEAK PRESSURE (PSIA)
101 MOD 3
1
2
3
4
5
QUENCH CURRENT (KA)

FIG. 2

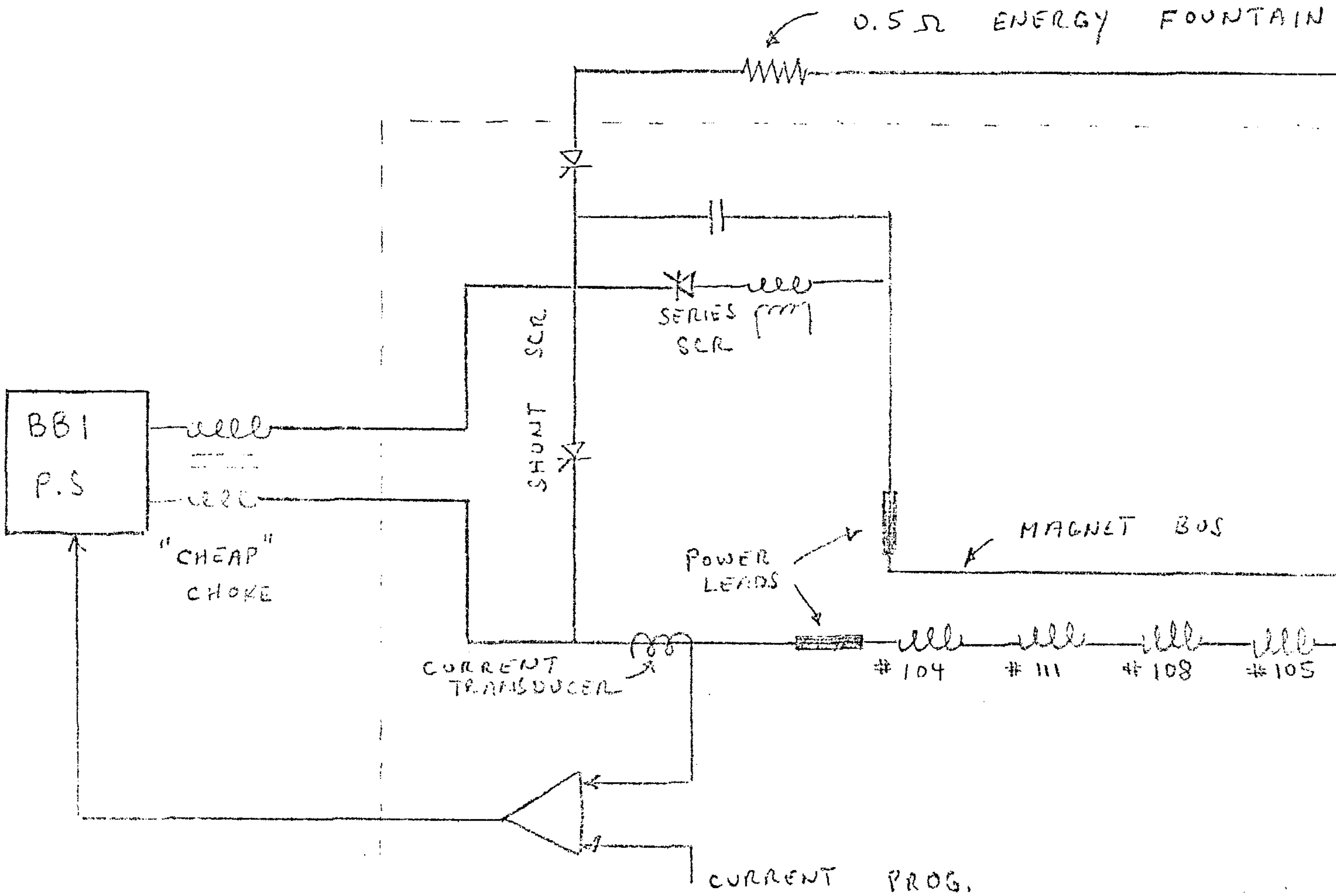

FIG. 3 MAGNET POWER CONNECTIONS

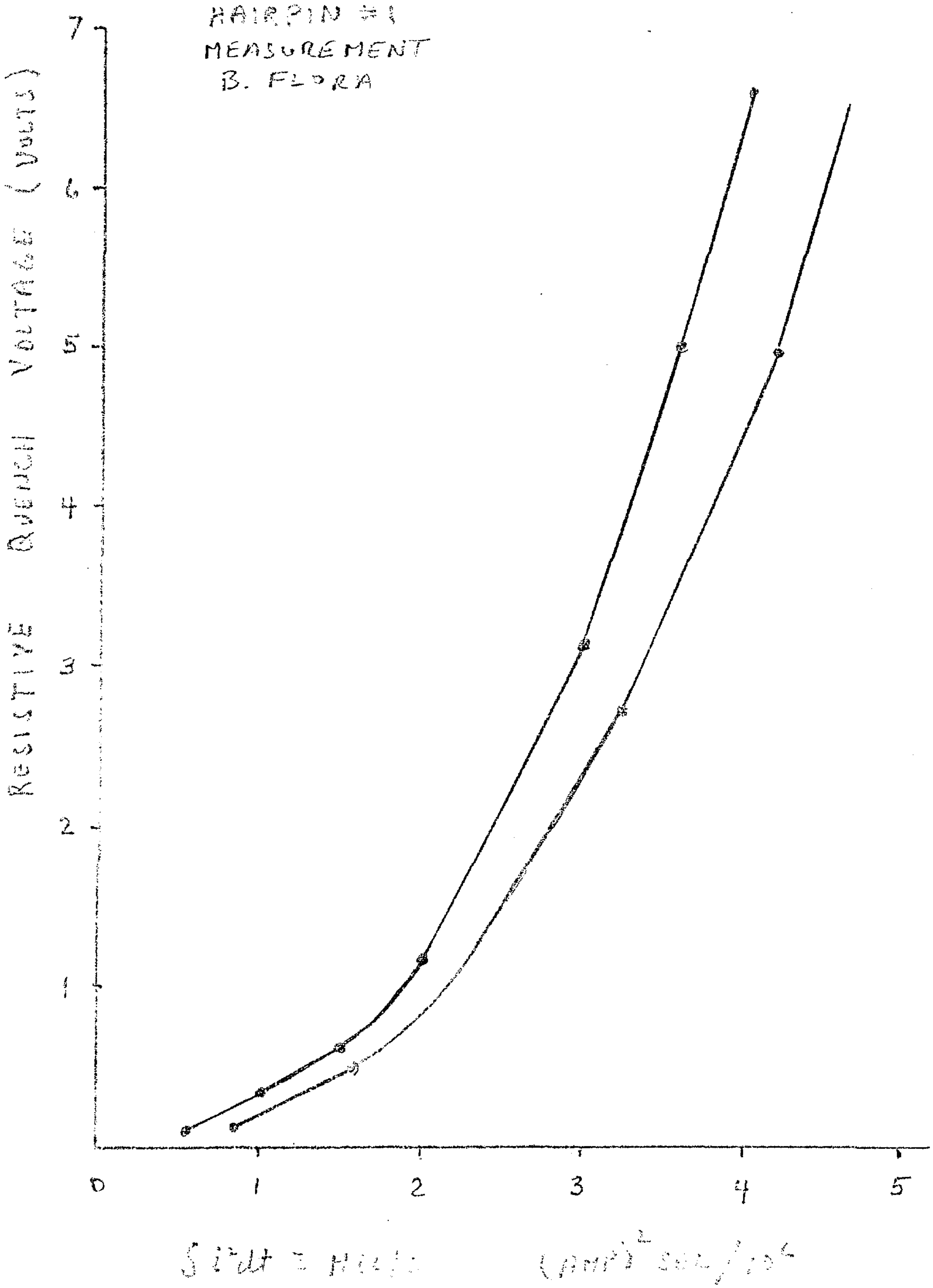
HAIRPIN #1
MEASUREMENT
B. FLORA
RESISTIVE QUENCH VOLTAGE (VOLTS)
1
2
3
4
5
6
7
0
1
2
3
4
5

Figure 4

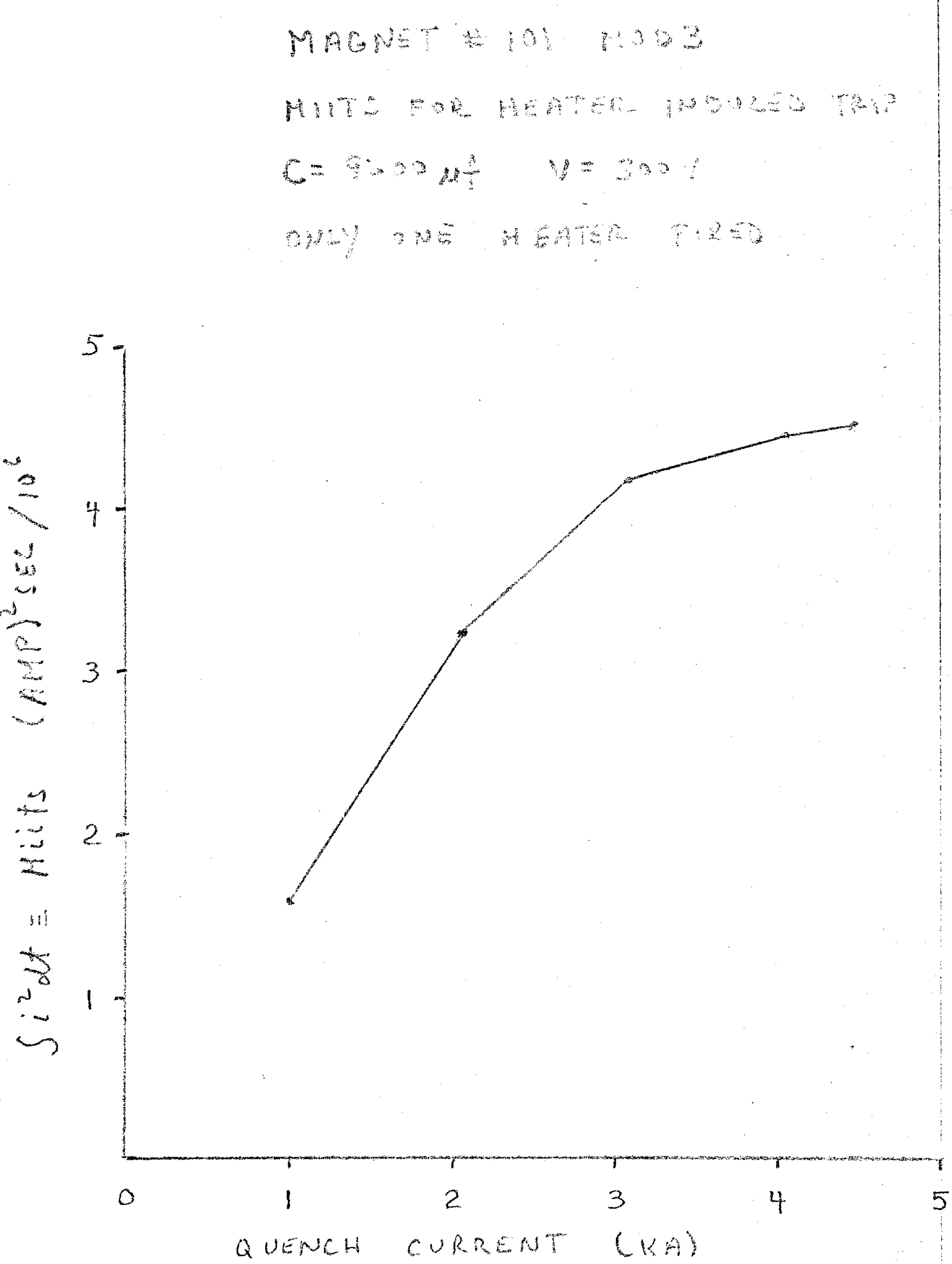
MAGNET # 101
MIITS FOR HEATER INDUCED TRIP
ONLY ONE HEATER FIRED
$\int i^2 dt$ = Miits (AMP)^{2}SEC / 10^6
0
1
2
3
4
5
QUENCH CURRENT (KA)

Figure 5

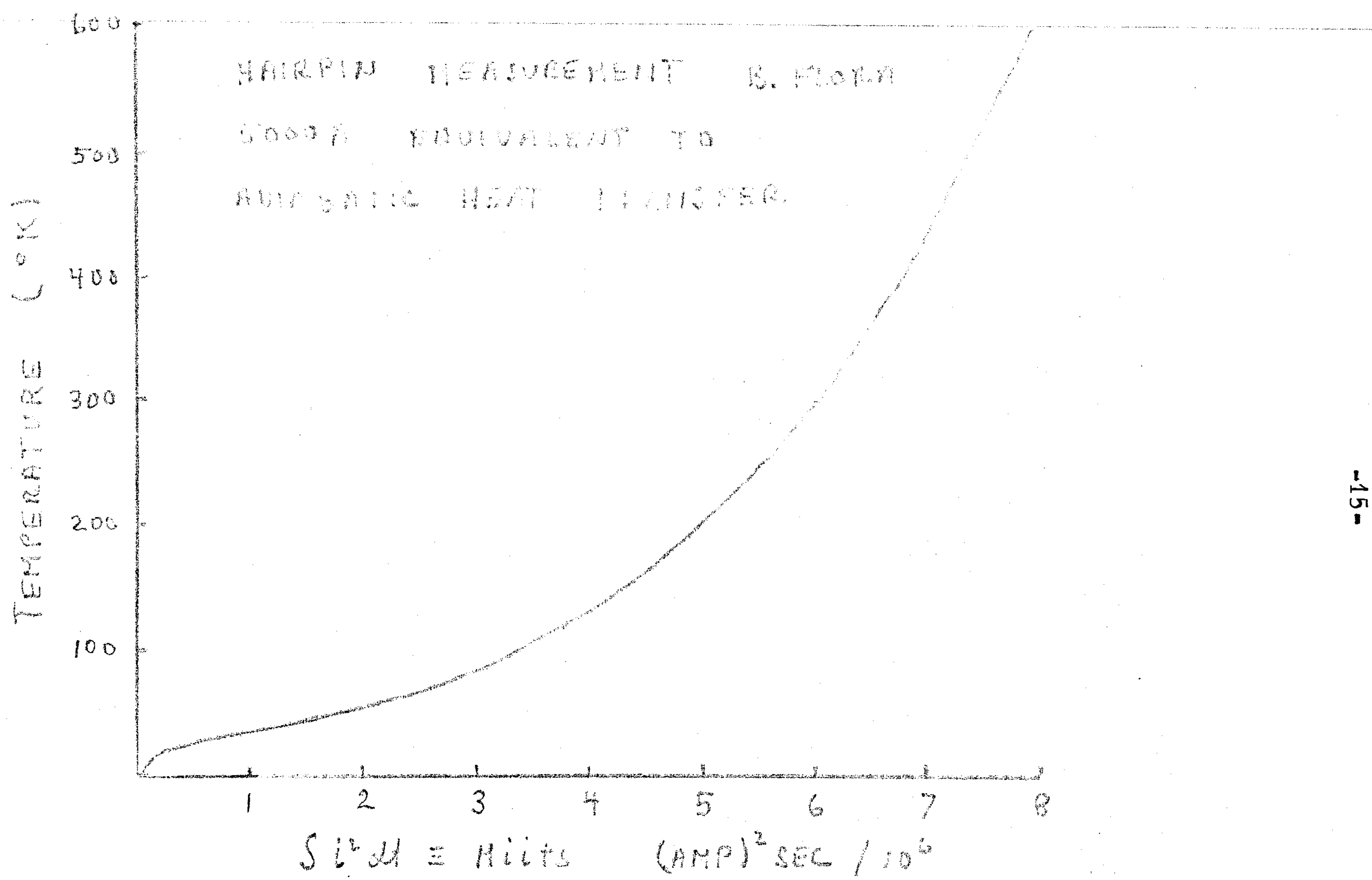
HAIRPIN
EQUIVALENT TO
HEAT
600
500
400
300
200
100
TEMPERATURE (°K)
1
2
3
4
5
6
7
8
(AMP)^2 SEC / 10^6

FIG. 6

R. Orr
1/6/79

B12 AWNING PROGRAM - PHASE IV

The next series of tests to be conducted in the B12 test area will require the operation of as much of the actual Energy Doubler system as possible.

We propose to install the following test setup:

Two complete Energy Doubler cells (see Fig. 1). Each cell consists of eight dipoles and two quadrupole packages. Because of space limitations one cell will be installed above the other, although they will be connected electrically and cryogenically.

In addition to the quadrupole itself, each quadrupole package will contain a complete set of correction magnets, safety leads, a beam position monitor, temperature monitoring resistors and diodes, a beam tube vacuum sniffer, and an insulating vacuum barrier.

VACUUM

Each cell will have one roughing pump station for the insulating vacuum. A pump station consists of one 120 ℓ/sec turbo-molecular pump backed by a matching direct-drive rotary vane pump, two electro-pneumatic 4" gate valves, two hand operated valves, two Pirani gauges, a cold cathode gauge, and a complete set of interlocks. At each of the quadrupole beam tube sniffers a Bayard-Alpert gauge will be installed in order to measure the cold beam tube vacuum. The beam tube will be rough pumped by one 120 ℓ/sec turbo pump backed by a rotary vane pump. This system is described in the Energy Doubler Vacuum System by P. Limon - October 20, 1978.

All pump controllers and gauge readout devices will be located in the Awning control room and connected to the pumps and gauges by the same lengths of cable that will be required between the tunnel magnets and the service buildings.

POWER

The modified main ring power supply that is now in use for testing four magnet strings will power the extended string. The dump switch electronics rack will be moved from the Awning into its final location in the B1 service building. The main power supply, dump circuitry, and quench protection system will be monitored by the microprocessor based system ("I.B.M.") located in the Awning control room.

A no-break power source (M.G. set) will be installed in B1 to power the dump switch, controls, and safety circuitry in the event of a power failure.

REFRIGERATION

The string will be cooled by a full satellite refrigerator located in the B1 refrigerator building. The two-stage screw compressor for the refrigerator will be in the B0 service building. An s-shaped He transfer line will be constructed to run from the roof of the refrigerator building to the cryogenic and power feed box in the awning.

CONTROLS

A full set of controls will be installed. The main control system will interface with the power supply and quench protection monitoring system, the satellite refrigeration system, the vacuum controllers and gauge readouts, interlocks, etc. Displays will be available showing interlock status, power supply voltage and current, helium pressures and temperatures, expansion engine waveforms and speeds, etc. Limits and alarms will be available. Graphic displays will be developed.

TESTS AND EXPERIMENTS - Partial List

INSTALLATION

1) The magnets will be aligned as if they were being installed in the tunnel. Records will be kept of the mismatch (if any) among the magnet-to-magnet connections.

2) Records will be kept of the failure rate for conoseal connections, and procedures will be modified if necessary.

3) Records will be kept on bellows leaks. Tooling and/or procedures will be modified if necessary.

4) The temperature will be monitored at the solder joints while connecting the superconducting cables. Too high a temperature for too long will result in the degradation of the superconductor. (See memo - Biallas to Hanson dated November 17, 1978.) Procedures will be developed based on these data for the tunnel installation job.

5) We will measure how far we can twist a string of four dipoles (cold) while keeping the ends of the four magnet string fixed.

VACUUM

1) A comparison will be made of the pump down rate of the insulating vacuum using a 120 ℓ/sec turbo pump with that using a 350 ℓ/sec turbo pump. This measurement will determine if the system is conductance limited and if the smaller pump will do the job as well as the larger.

2) A pressure burst (of N_2) injected into the insulating vacuum will test the protection circuitry and whether the speed

of closure of the automatic valves is sufficient to protect the pumps.

3) A power failure will be simulated to insure that the interlock system behaves properly.

4) A measurement will be made of the amount of He diffusing (or leaking) into the beam vacuum chamber.

REFRIGERATION

1) Experiments will be made with the valve settings, compressor pressures, and expansion engine speeds to minimize the cool-down time.

2) We will determine whether the fast cool-down of a long string damages the magnets.

3) We will find out whether the magnet string can be warmed up quickly without damage to the magnets.

4) Measurements will be made of the time of recovery from a quench as a function of magnet current, number of magnets quenched, etc.

5) Heat load measurements will be made under d.c. and ramping conditions.

6) Measurements will be made of the pressure rise in the 8" He collection header as a function of the number of magnets quenched at full energy.

7) Measurements will be made of the pressure rise as a function of pipe I.D. in the pipe connecting the single phase relief valve to the relief header when the magnet is quenched at full energy.

8) Relief valves of various types will be evaluated.

9) A measurement will be made of the return He temperature as a function of time under sustained ramping. If, for example, the temperature drops, this could be an indication of the formation of a vapor lock in the inner single phase chamber.

10) We will test the double turn-around box. This box turns around the He at the ends of two cryogenic loops. The magnet current passes through the eddy between the loop ends (see Fig. 2). This test will be made using two CTI 1400 refrigerators cooling one half of an eight magnet string and the B1 satellite cooling the other half. The double turn-around box will connect the two halves. Sustained full power ramping of this system will test whether or not the cooling of the superconducting power lead in the transition between the two loops is adequate. The beam pipe sector valve (which is part of this box) and its interlock system will also be tested.

POWER SUPPLY AND QUENCH PROTECTION SYSTEM

1) A short to ground will be created to test the performance of the protection system.

2) An open condition in the power bus will be created to test the protection system.

3) A power failure will be simulated to test the protective system and the no-break power supply.

4) A quench will be caused in one half-cell (at full energy). We will observe whether or not this quench propagates to the adjacent half-cells.

5) Measurements will be made of the current regulation at injection and flat-top.

6) Ripple measurements will be made leading to the development of a better filter if necessary.

7) We will test the quench heater firing system to insure fail-safe operation without false firing.

8) The trim magnets will be run with the primary magnets ramping at full field in order to see if quenches are induced.

CONTROLS

1) Tests will be made to insure that we have the best mix between local and central monitoring and control.

2) A series of tests (not yet defined) will be made of the microprocessor power supply monitor to see if it can orchestrate a system crash under most conditions.

1/11/79 LDS

FIG 1

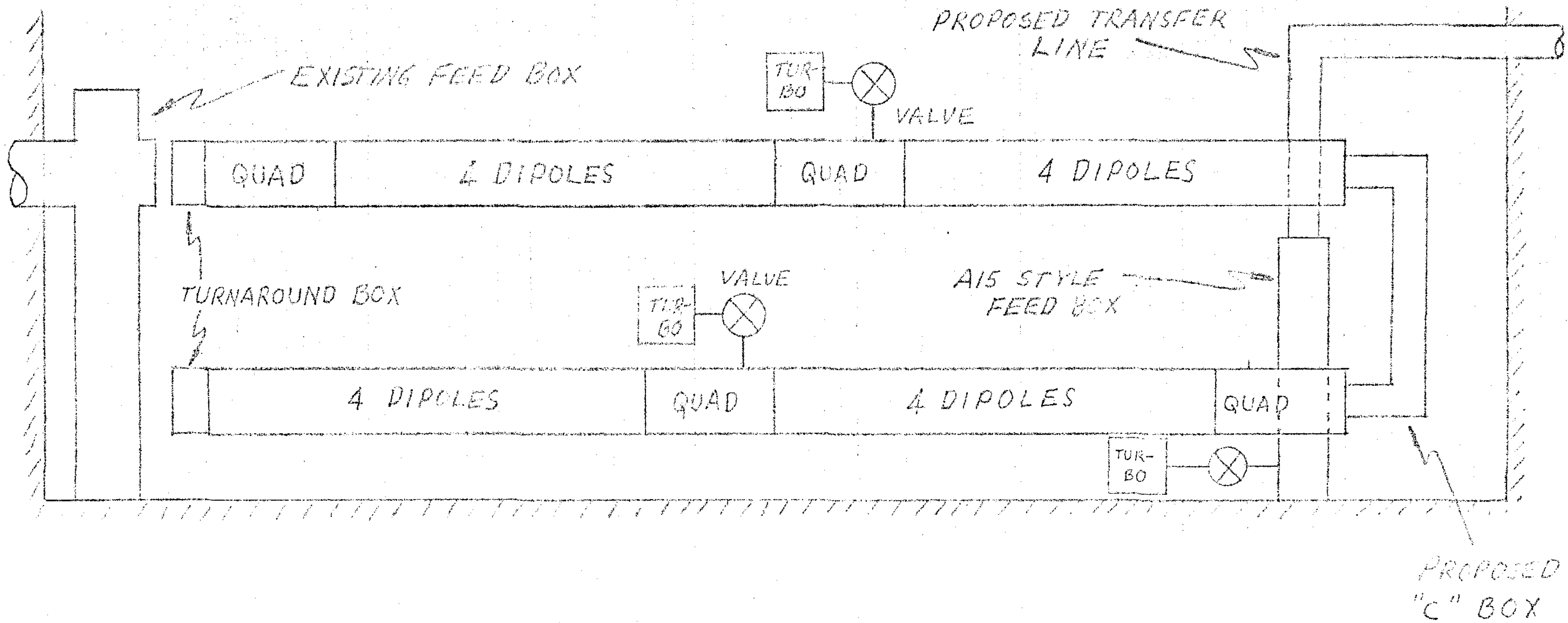

FIG. 2