6. MAGNET POWER SUPPLY AND PROTECTION

6.1 Requirements

The main magnet system is a single series circuit of 774 dipoles and 216 quadrupoles distributed around the 1-km radius ring. There are also typically ten main quadrupoles in each low-beta section and a large number of correction elements powered separately from the main circuit.

The main power supply must be capable of pulsing the entire series circuit, whose total distributed inductance is 36 H, from 500 A to 4400 A at ramp rates up to 330 A/s. It also must have invert capability so that the 350 MJ of energy stored in the magnetic field can be returned to the power line during de-excitation. The supply must also be capable of dc operation at maximum current. The current regulation needed for slow beam extraction and beam storage is extremely good, on the order of 10^{-5}, and the dc supply must be capable of this.

The cable used in the magnets has a low copper-to-superconductor ratio and is not cryogenically stable. Thus a magnet will quench if a normal region develops. Consequently, a fail-safe mechanism for removing the stored energy from the system must be provided. A reliable quench detector is necessary to trigger this protection system.

6.2 Power Supply

The main power circuit is illustrated in Fig. 6-1 on the next page and parameters of the power supply are listed in Table 6-I. All the magnet coils are connected in series on the coil bus and the current returns through the return bus, which is a superconducting winding adjacent to the main coils

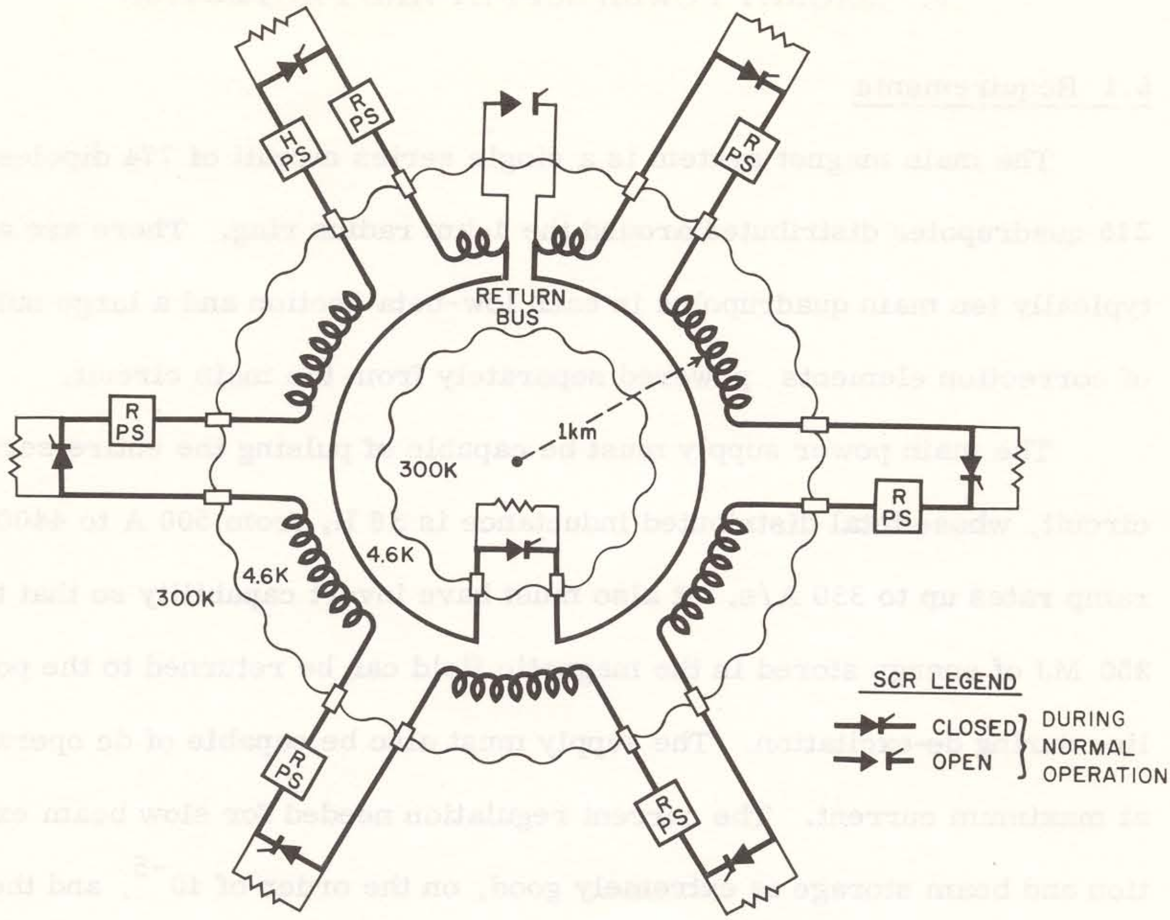

Fig. 6-1. Excitation circuit for superconducting ring.

in the magnets. The return bus contributes to the magnetic field and it is therefore necessary that it carry current at all times during magnet operation.

Six ±2-kV, 4500 A bidirectional converter-inverter energy-transfer supplies are distributed at equal spacing along the coil bus. These six power supplies will be obtained by converting twelve existing Main-Ring power supplies to this use. At each of the A1, B1, C1, D1, E1, and F1 service buildings, the two 1-kV Main-Ring bend-bus power supplies will be removed from the Main-Ring magnet system and connected in series to

Table 6-I. Magnet Power-Supply Parameters.

Power Supply		
No. of rectifier stations (ramping)	6	
No. of rectifier stations (holding)	1	
Peak current	4500	A
Maximum rms current (ramping)	2500	A
Maximum rms current (holding)	4500	A
Peak power (ramping)	54	MW
Peak power (holding)	900	kW
Peak voltage (ramping)	12	kV
Peak voltage (holding)	200	V
Peak voltage to ground	1000	V
Peak coil to bus voltage	1000	V
Current Data - Magnets		
Dipole inductance	0.045	H
Quadrupole inductance	0.006	H
Total inductance (100 cells)	36	H
Total resistance of cables and holding supply components	0.025	Ω
System L/R	1400	s
System stored energy	350	MJ
Nominal Excitation Profile		
Maximum rate of rise	330	A/s (75 GeV/s)
Injection current	660	A
Minimum operating current	500	A
Maximum flattop current	4400	A
Time to flattop (minimum)	12	s
Maximum rate of fall	-330	A/s
Ramping-station ripple	1.5	volt peak
Holding-station ripple	0.15	volt peak
Current Tolerance		
Ramping mode	N.A.	(voltage regulated)
Holding mode	±40	mA
Emergency Energy Dump		
Number of stations	6	
Resistance/station	0.5	Ω
Peak voltage to ground during dump	1000	V
Peak coil to bus voltage during dump	1000	V
Total system L/R in dump mode	12	s

provide a 2-kV energy-transfer station. These power supplies will have a local voltage-regulation loop. The Main-Ring bus will bypass these buildings with a minor modification of the bend buses in the tunnel.

In addition, there is one low-voltage holding supply that is capable of continuous operation at 4500 A. This power supply must be constructed anew and requires a special transformer providing a lower voltage than existing Main-Ring transformers, but capable of continuous operation at 4500 A. This power supply will act as the system current regulator.

The function of the ramping supplies is to change the current of the magnet. The holding supply is used to make up non-superconducting bus losses during constant-current portions of the cycle. All six of the ramping supplies will be programmed to produce equal voltage. Thus the maximum voltage between any coil and ground, or between any coil and the bus, will be one-half the peak voltage of each supply, or 1 kV.

The maximum-performance acceleration cycle is shown in Fig. 6-2. At the start of the cycle, 150-GeV protons are injected from the Main Ring while the current is at 660 A (see Section 10). Previous to injection, the current has been cycled to 500 A in order to compensate for the hysteresis behavior of the main magnets. The ramping stations then increase the magnet current as the beam is accelerated. When the peak current is reached, the ramping stations are removed from the magnet circuit and the current is held constant by the current-regulated holding supply. A current tolerance of ±40 mA is required while the beam is stored or slowly extracted from the synchrotron.

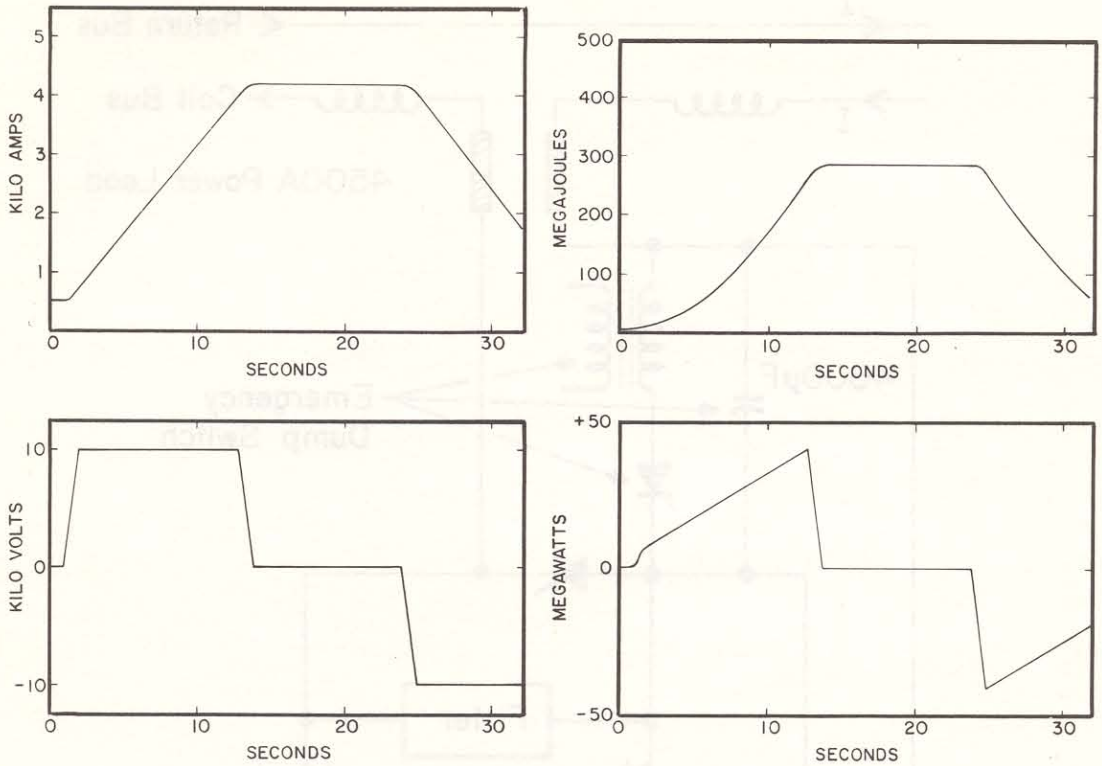

Fig. 6-2. Maximum-performance magnet cycle.

Removal of the ramping stations is accomplished by bringing the power-supply voltage to zero and shorting their outputs with bypass SCR's. A schematic of a ramping station is shown in Fig. 6-3. In order to keep the dc losses made up by the holding supply to a minimum, substantial copper buses must be provided between the tunnel and service buildings at the six power-supply locations and at the bus energy-dump location.

6.3 Filter, Regulation, and Controls

6.3.1 Filter. Each supply consists of a twelve-pulse rectifier system utilizing thyristors. The output of the power supply is variable from 0 to $\pm V_{max}$ by controlling the firing angle of the thyristors. Power supplies of

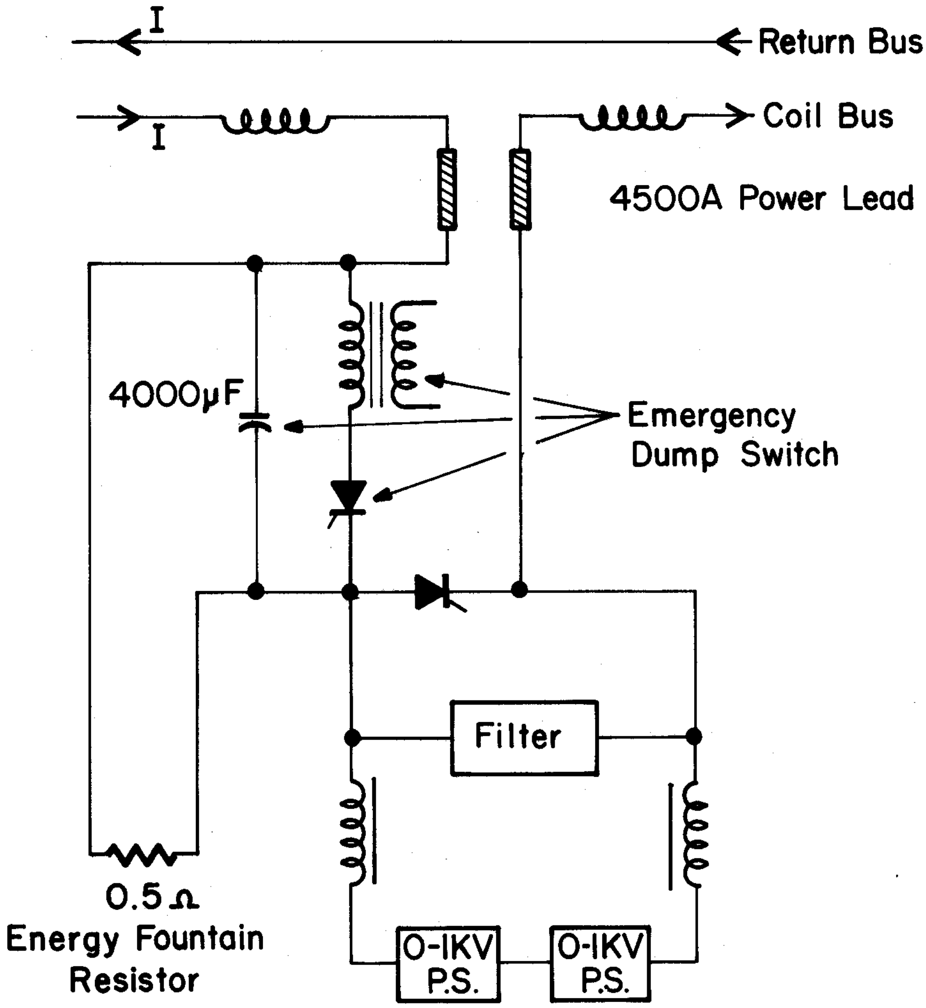

Fig. 6-3. Schematic of a ramping station.

this type produce ripple at a fundamental frequency of 720 Hz with a varying amplitude and harmonic content dependent upon the firing angle. This ripple voltage must be attenuated significantly to ensure that variations in the magnetic field are below the level required for stable operation of the beam.

A passive filter, shown in Fig. 6-4, will be provided at each power supply. It is an underdamped low-pass filter with an added 720-Hz trap to improve attenuation at the fundamental ripple frequency. The voltage attenuation of this filter is shown in the graph of Fig. 6-5 on page 111. The

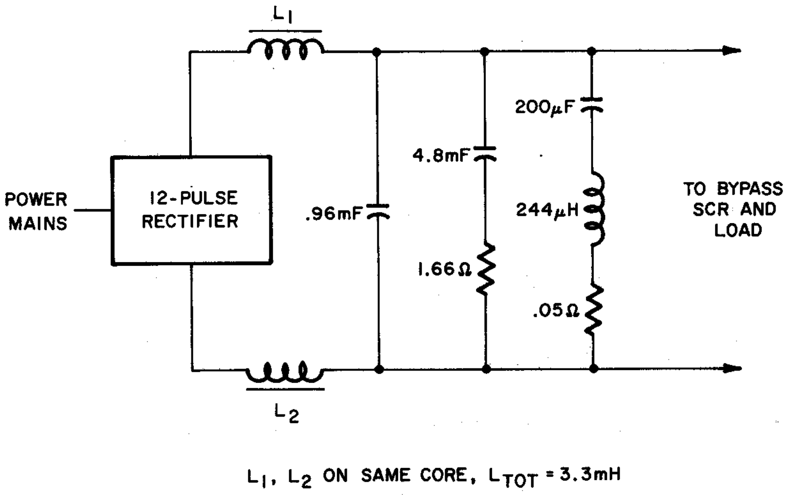

Fig. 6-4. Power supply passive filter.

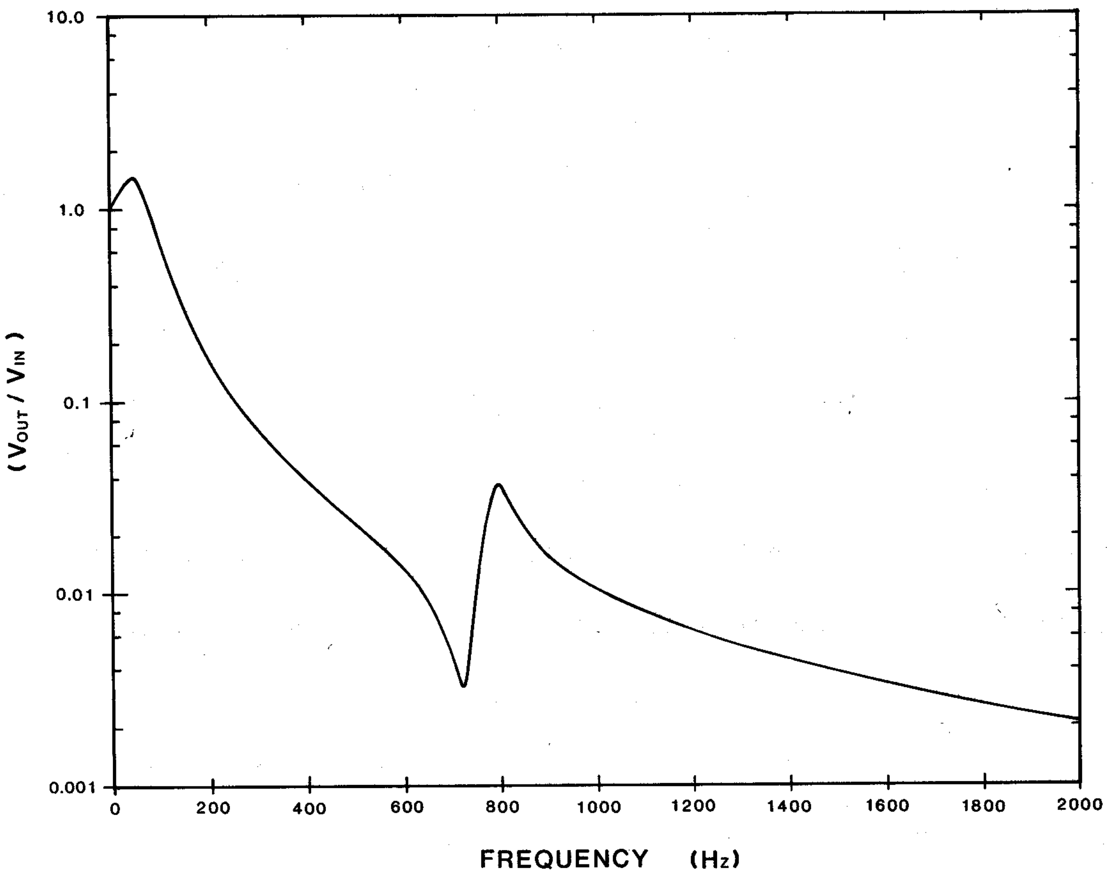

Fig. 6-5. Frequency response of passive filter.

filter provides a ramping supply worst-case ripple of 3 V peak-to-peak, and a holding-supply worst-case ripple of 0.3 V peak-to-peak, ignoring sub-harmonics caused by feeder-line unbalance.

The average ripple current of this voltage should be adequately filtered but, should the final regulation requirement exceed that now expected, the components used in the passive filter could be reconfigured with a shunt active filter of modest voltage and current rating to provide significantly greater ripple reduction. In the interest of simplicity and reliability, only the passive filter is presently planned for use.

At 720 Hz, the expected peak current is about 2 mA, based on a peak voltage at that frequency of 1 V, a damping resistor of 80 Ω per half cell, and a characteristic transmission-line impedance of 260 Ω for the dipole string. The purpose of the damping resistor is primarily to damp standing waves in the dipole string, which would otherwise occur at multiples of 12 Hz. The expected attenuation length at 720 Hz is 22 dipoles, and the phase rotation about 3.1 degrees/dipole. Although the dc transfer ratio is 10 G/A, at 720 Hz it is only 0.9 G/A as the damping resistor shunts most of the ripple current around the magnet, and the eddy currents internal to the magnet attenuate the magnetic field effects. Thus the peak fields expected at 720 Hz for a typical supply are about 2 mG, and for a holding supply about 0.2 mG. Hence $\Delta B/B = 3\times 10^{-7}$ for a normal supply (worst case) and $\Delta B/B = 3\times 10^{-8}$ for a holding supply.

The most serious subharmonic expected is the 120-Hz component (about 13 V peak), which will produce about 11 mA of ripple current. The transfer ratio is expected to be about 4 G/A and we therefore expect 5×10^{-2}

G (peak) for a normal supply, and 5×10^{-3} G (peak) for a holding supply. The attenuation length and phase rotation at this frequency are 75 dipoles and 1.3 degrees per dipole, respectively. The worst-case $\Delta B/B$ is then about 1×10^{-5} for a normal supply and 1×10^{-6} for a holding supply (at injection). Although these fields seem quite tolerable as far as orbit motion is concerned, tune-change effects on extraction must still be evaluated. Thus some active filtering of the holding supply may be required.

6.3.2 Regulation. The regulation system is shown schematically in Fig. 6-6. Operation and regulation of the power supplies is controlled by an integral microcomputer. A primary function of this microcomputer is to

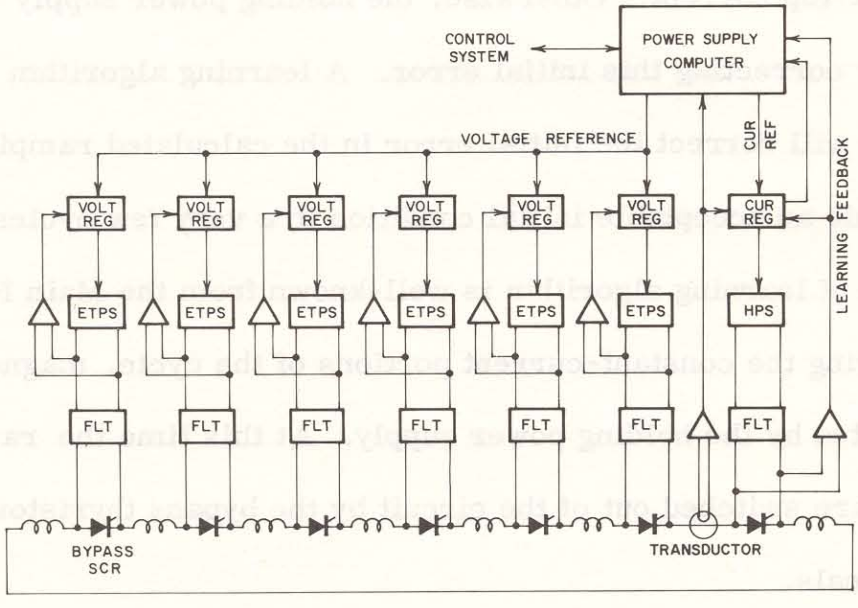

Fig. 6-6. Power-supply regulation system.

generate voltage and current waveforms that command the ramping power supplies and the holding power supply to excite the magnet in the desired manner.

During the ramping portions of the accelerator cycle, the locally voltage - regulated ramping power supplies all receive identical voltage programs from the microcomputer. The voltage capability of the holding supply is extremely small relative to these, so current regulation does not occur during ramping. Magnet-current ripple during this regime must be maintained low, but since the magnet field is the independent variable in the accelerator, lack of current regulation during ramping is acceptable. In order for the holding power supply to provide good regulation during flattop, the ramping power supplies must provide a precise initial flat-top current. Otherwise, the holding power supply will waste its capability correcting this initial error. A learning algorithm in the microcomputer will correct the initial error in the calculated ramping program and provide an acceptable initial condition in a very few cycles after startup. This kind of learning algorithm is well-known from the Main Ring.

During the constant-current portions of the cycle, magnet current will be regulated by the holding power supply. At this time the ramping supplies are switched out of the circuit by the bypass thyristors at their output terminals.

The primary current sensor will be a transductor providing a signal of 2 mV/A of magnet current. Short-term errors and noise in this device are equivalent to approximately 2 mA of magnet bus current at injection and approximately 20 mA at 1000 GeV. Achieving regulation of 1 part in 10^4 at extraction should be easy and achieving 1 part in 10^5 by extra care and sophistication appears possible.

6.3.3 Controls. The power-supply control system is integrated into the total control system discussed in Section 12 of this report. Ramp and safety parameters and commands will be transmitted from the central control room via a serial link. Local microprocessors in the six service buildings with power supplies will directly control the supplies. These microprocessors will be 8-bit Z80 and 16-bit MC68000 devices.

The central accelerator control system will also monitor key operating waveforms directly through analog channels and high-bandwidth binary data links. A B-dot clock signal will be transmitted around the ring by the power-supply system for the benefit of the quench-protection monitors. This signal will also be used for other control functions.

6.4 Quench Detection and Protection

6.4.1 Quench detection. For detection of quenches, we have developed a microprocessor system that sequentially measures the voltage across each half-cell of magnets (4 dipoles and one quadrupole). One microprocessor system, shown in Fig. 6-7, monitors 165 magnets or one-sixth of the entire accelerator.

Each system runs under the supervision of a high-level interpretive BASIC-language program. This program is responsible for setting up parameters, analyzing statistics, and reporting status to the operators.

Every 17 ms, synchronized with the power line, this supervising program is interrupted for a high-priority safety scan of all the analog signals

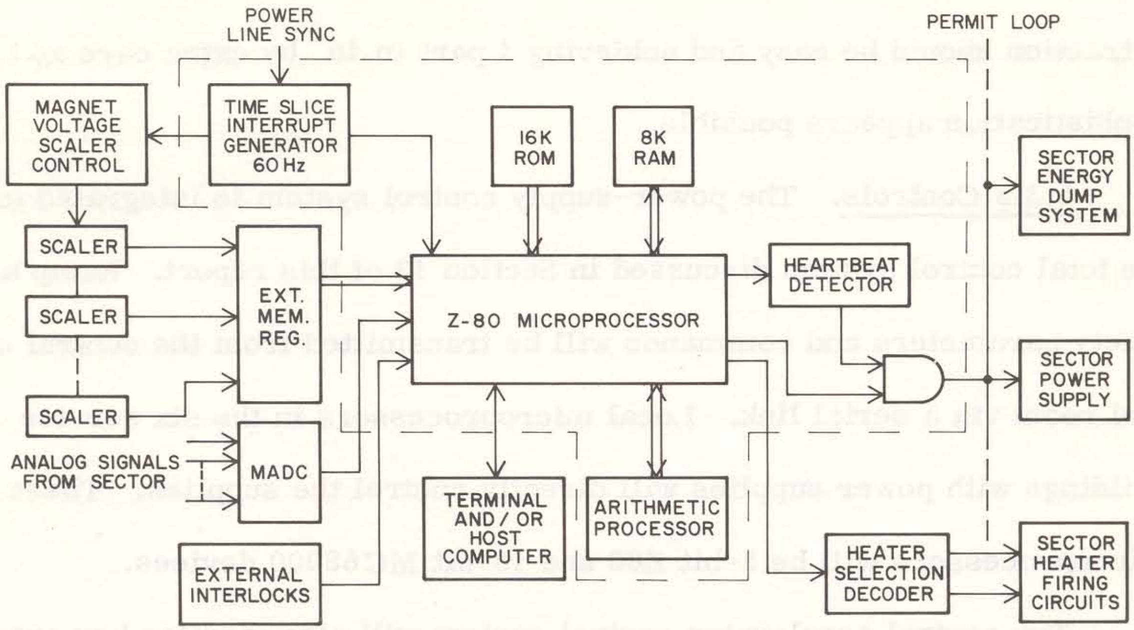

Fig. 6-7. Microprocessor system for quench protection.

from its one-sixth of the accelerator. An auxiliary arithmetic processor is used to enhance the fast on-line safety analysis. If the scan does not reveal any anomalies, the software generates a "heartbeat." If an anomalous condition--quench, overvoltage, lead runaway, overcurrent, etc.--is detected, or if the processor fails to give an indication of activity to the heartbeat detector, the emergency dump system, described below, is activated. The 17 ms between these scans is negligible in comparison with quench-development times. Good voltage-detection sensitivity is critical to insure adequate detection.

The quench-detection algorithm depends on the fact that voltages tapped from the magnets should be distributed according to known inductances. A deviation of a few tenths of a resistive volt indicates the start of a quench.

<u>6.4.2 Coil quench protection.</u> When a quench is detected, the power supply is turned off and a 0.5-Ω air-cooled "energy-fountain" resistor is switched into the coil bus at each of the ramping stations by the emergency dump switch shown in Fig. 6-3. This causes the magnet current to decay with a time constant of 12 s.

In Fig. 6-8 we show schematically the electrical connection of a protection unit containing four dipoles and one quadrupole, a half-cell of the accelerator. After the resistors have been switched into the coil bus, a

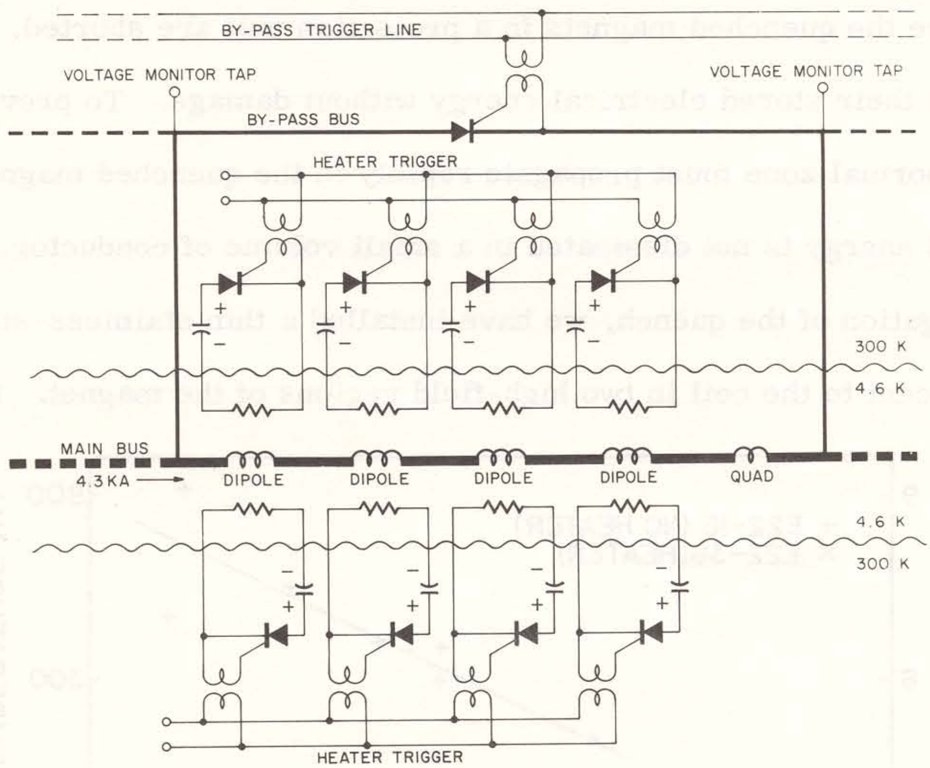

Fig. 6-8. The quench-protection system for one half-cell.

pulse train is applied to the gates of the shunt thyristors all around the magnet ring. If resistive voltage has developed across any protection unit, the associated shunt thyristor will turn on and divert the decaying current around the quenched unit, through two safety leads. These leads are 3/8-in. diameter copper rods designed to carry one pulse of decaying current without damage and to cause a negligible heat leak when passive. They will, of course, have to cool down again before re-use.

In order to protect the thyristors against damage from radiation, they are mounted in a "hole-in-the-wall" module which extends 4 ft through the wall of the tunnel. Surrounding earth provides the shielding. Nevertheless, all shunt thyristors will be regularly tested by gating them on and ramping the magnets fast enough to force current into them. The microprocessor system will scan voltage taps for any open thyristors.

Since the quenched magnets in a protection unit are shorted, they must absorb all their stored electrical energy without damage. To prevent damage, the normal zone must propagate rapidly in the quenched magnet so that the stored energy is not dissipated in a small volume of conductor. To speed the propagation of the quench, we have installed a thin stainless-steel heater strip adjacent to the coil in two high-field regions of the magnet. Results of

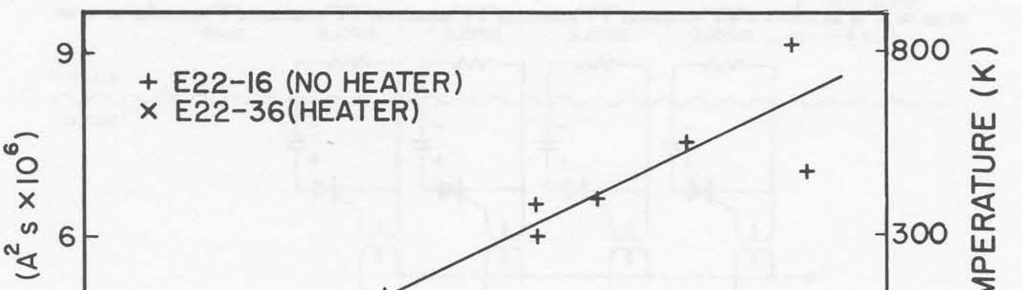

Fig. 6-9. Quench load and maximum coil temperature vs. current for shorted magnets with and without heater protection.

experimental tests of heater strips are shown in Fig. 6-9 on the preceding page. If a quench is detected, then heaters in all the dipoles of the quench unit will be fired.

6.4.3 Return-bus quench protection. The voltage across the bus in each sector (±10 V during ramping, 72 V during dumping) will be monitored via a differential-voltage channel. The total voltage of the entire bus (±60 V during ramping, -1.5 V during dumping) will also be monitored at the fold. It will be possible to detect 0.2 V of normal resistance in the bus.

When a quench is detected, all bypass thyristors will be gated on, including the one at the fold. This will enable the coil current to be bypassed around the entire bus. The bus is dumped through a 0.1-Ω resistor. The bus current falls rapidly at first with a time constant L_{bus}/R_{bus} = 0.15 s, then more slowly with a time constant L_{coil}/R_{coil} = 12 s for 13% of the coil current. The total quench load in the bus gives a maximum temperature rise of 100 K. Figure 6-1 illustrates the bus quench protection elements.

The voltage stress is approximately 200 V if the dump is located opposite the fold. Exact placement is a matter of convenience. The dump must absorb 0.34 MJ at most. It could be made of stainless steel 25 ft long and 0.087 in.^{2} in cross section. The maximum temperature rise in this design would be 350°F (194 K).

Portions of the bus through straight sections will be made of fully stabilized superconductor.