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A 110 kA RAPID-PULSING POWER SUPPLY

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INTRODUCTION

The multi-turn injection[1] of 200-MeV protons into the Fermilab. 8-GeV Booster Synchrotron requires the shifting of the closed orbit towards the inflector septum. This local orbit bump is produced by a symetrical arrangement of two double-bend magnets; one increasing the radius of the beam, the second decreasing the radius. The load for the power supply consists of these two identical magnets, one located at the upstream end of the booster injection girder and the other at the downstream end of the injection girder. Each magnet assembly consists of two magnets connected in parallel in such a manner as to provide equal but opposite magnetic fields. The amplitude of the closed orbit shift is required to decrease as each successive turn is injected. For optimum efficiency, the rate of decay of the magnetic field should be linear. A good approximation can be achieved from a sine curve in the region from $5/6\ \pi$ to π. The power supply which is used to furnish excitation currents to the orbit bump magnets is designed as a series resonant, capacitive discharge system with thyristor switches. The orbit bump power supply is located in the equipment gallery of the booster synchrotron and the injection girder is located about 5 m below the power supply. Connections between the supply and the magnets are made with multiple coaxial cable conductors.

The required peak magnetic field is 5500 gauss in each half of the magnet and with a gap of 6.25 cm, a peak current of 55000 amperes per magnet is required. To optimize the rate of decay for a varying number of injected turns, the resonant frequency of the discharge circuit is varied from 2.98 kHz to 6.95 kHz. This give a reverse $\dot{B}$ corresponding to the peak magnetic field of -240 G/μs at the highest discharge frequency and -103 G/μs at the lowest discharge frequency. The currents i the two magnets are required to track each other during the injection period of the cycle to at least 0.1% of the peak current. This is achieved by dividing the power supply into two sections in which the network impedance can be independently adjusted. The power suppl is designed to operate at a network impedance ($\sqrt{L/C}$) ranging from 18 mΩ to 44 mΩ (per section). Rated current is achieved at the maximum network impedance with a capacitor voltage of 2400 Vdc. The power supply operates at a pulse repetion rate of 15 pps and is designed to operate at a 50% repetition rate duty factor.

CIRCUIT

An L-R-C series resonant network was chosen becaus of its simplicity and its ability to make large current at modest voltages. Energy is initially stored in the capacitor bank and upon command from an external timing signal, the capacitor bank is connected to the inductive load. The power supply is divided into two identical sections. One section is connected to the upstream magnet and the other connected to the downstream magnet (Figure 1). The capacitance in each section is made equal by selection of the individual capacitors that

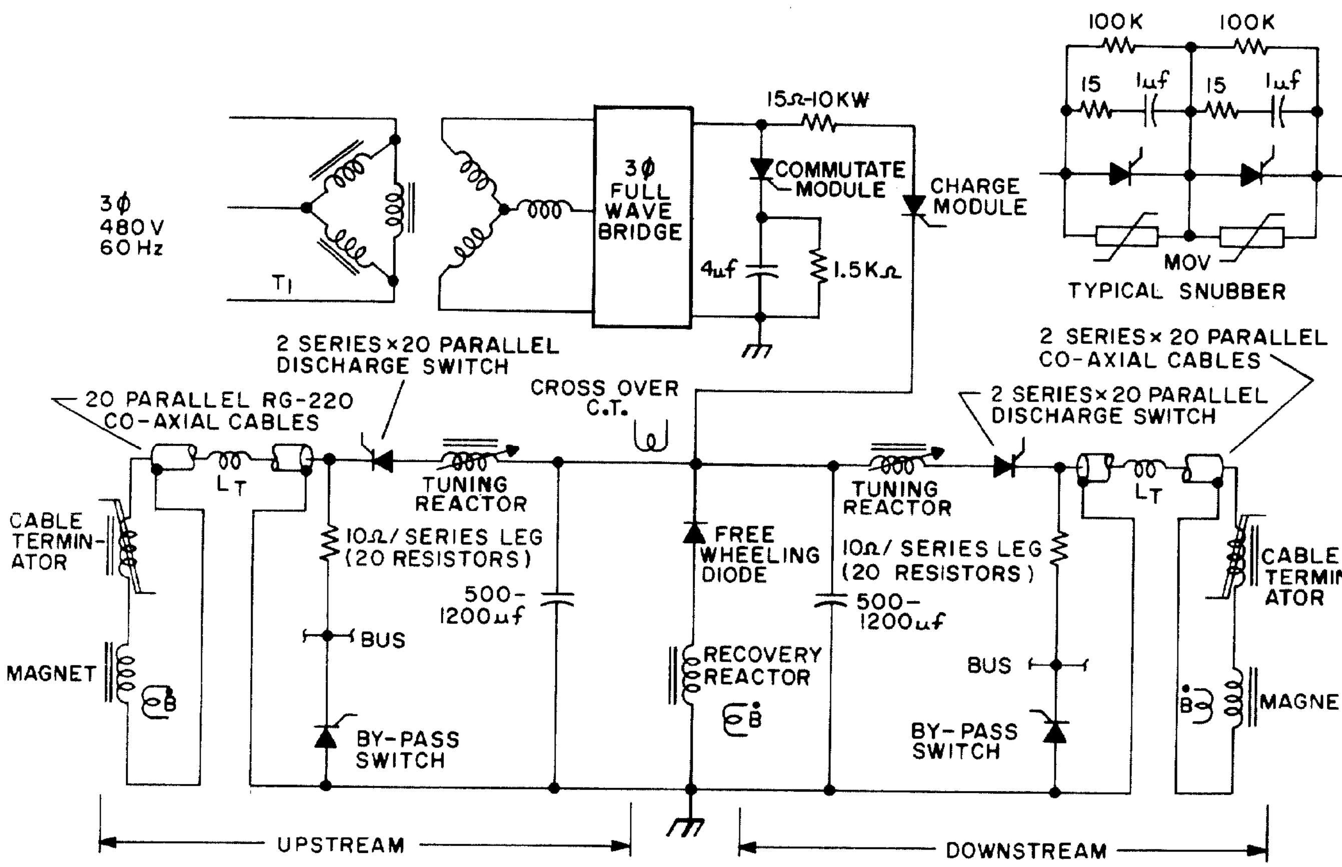

Fig. 1. Functional Schematic Diagram

*Operated by URA, Inc., Under Contract With the U. S. Energy Research and Development Administration make up the total bank. These capacitors are of the energy discharge type and are rated at 100 microfarads (nominal) at 3000 Vdc. The capacitors are connected in parallel to form a network capacitance ranging in value from 500 microfarads to 1200 microfarads. The capacitor bank of both sections are charged from a common power source to achieve equal bank voltages.

The discharge switch used in the power supply consists of a series-parallel array of thyristors. Each thyristor assembly is connected from the capacitor bank to the magnet load through matched Type RG-220 coaxial cable (7.9 m nominal length) to provide for current sharing in the discharge switch. There is a total of 40 parallel connected switch assemblies, 20 to the upstream magnet and 20 to the downstream magnet. The current rating for each switch assembly is 3300 amperes, peak, 85 amperes, rms. The circuit limited turn-on di/dt for the thyristors is 140 amperes/microsecond.

Thyristors which were considered for application in this power supply were evaluated in a test set that could provide the maximum current and a turn-on di/dt of 160 amps per microsecond which is about 15% greater than the rating of the switch assembly. The thyristors were selected on the basis of the magnitude of the forward anode to cathode voltage drop at the peak of the sinusoidal current waveform. It was found that those devices whose forward drop exceeded 15 volts at 3300 amperes were subject to an early failure in that the forward blocking characteristics were degraded. Devices were found whose forward drop ranged from 4 volts to 6 volts. Operation experience has shown that these devices are satisfactory for this application as several million operations have been recorded with no failures. The power supply is presently loaded with Westinghouse T72C devices which have a 30 mm diameter junction and the International Rectifier 450 PQ has been tested and they exhibit similar voltage drop characteristics.

The discharge switch assembly is rated for a working voltage of 2400 Vdc. This was achieved with a safety margin of about 50% by series connecting two thyristors whose forward and reverse blocking voltage is 1800 volts or greater. Voltage sharing between the two devices is achieved by an RC network placed across each thyristor. This network is shown in Figure 1.

At the end of the discharge cycle the capacitor bank has been charged to a reverse voltage of about 90% of the original voltage. The energy stored is recovered by discharging the capacitor bank through the recovery reactor and recovery diodes. The reactor is a high Q inductor and has an inductance of about 350 microhenries. The parameters of the recovery reactor are shown in Table I.

TABLE I

RECOVERY REACTOR PARAMETERS

L, μhy	351
Q	11.3
I Peak, kA	7.3
I rms, kA	1.1
Turns	12
Gap Height, cm	12.86
Core Material	.305 mm, Selectron, (3% Si 97% Fe)
Core Weight, kg	844

The resonant frequency of the recovery circuit varies from 167 hertz to 258 hertz depending upon configuration of the capacitor banks. Approximately 90% of the reverse voltage is recovered (Figure 2).

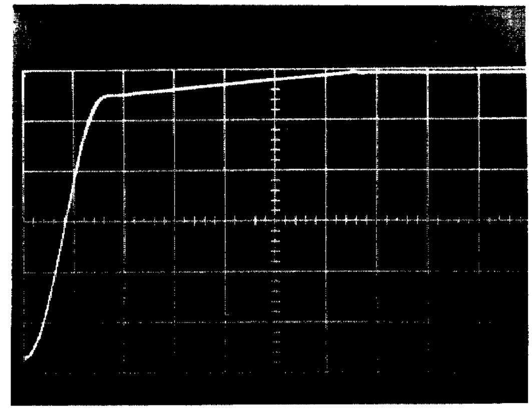

Fig. 2. Recovery Voltage
Vertical: 500V/div
Horizontal: 2 ms/div

Following the recovery cycle, the capacitor bank is recharged by a 2800 volt, 3-phase fullwave bridge rectifier power supply connected through a 16 Ω, 10 kW current limiting resistor. The power transformer (T_1) is rated at 87.5 kVA and is located external to the power supply cabinet. The power supply is connected to the capacitor bank when the charge module is pulsed. The power supply is disconnected by firing the commutate module. A series resonant circuit is formed with the 4 microfarad capacitor at the cathode of the commutate module and the leakage reactance of the power transformer. At the time the commutate module is fired, the 4 microfarad capacitor begins a resonant charge from the rectifier. In addition reverse current flows through the charge module thyristors, causing them to block. The cycle is completed at the end of the resonant charge of the 4 microfarad capacitor. The power transformer has a series leakage reactance of about 8.5 millihenries, which gives a resonant frequency of 864 hertz.

The commutate and charge modules have a dc voltage rating of 8000 volts and 12000 volts, respectively. They are made up of a series string of thyristors each whose voltage rating is 1000 volts. The series string is protected from transient and static voltages in the same manner that the discharge switch assemblies are protected. The thyristors in the charge module were chosen for a 20 microsecond turn-off time in order to obtain a large operating voltage range for the power supply. These modules are loaded with Westinghouse T627 thyristors.

Gate drive and circuit isolation for all thyristor switches is provided by a gate amplifier and transformer arrangement (Figure 3). Up to four thyristors are triggered off of each transformer. The transformer is wound with 6 turns on the secondary and with 1 turn on the primary. This circuit can achieve a 1½ ampere short circuit gate drive current and an open circuit voltage of 16 volts. The rise time of the current pulse is less than 500 nanoseconds.

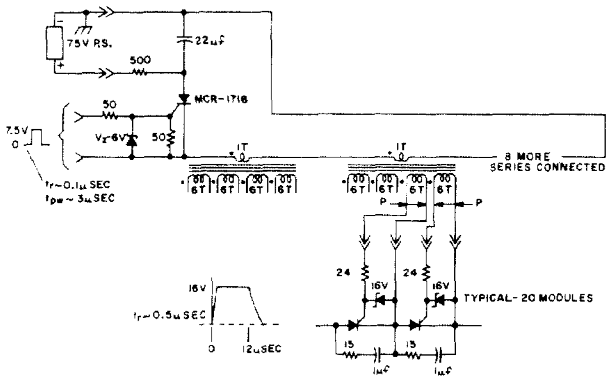

Fig. 3. Firing Circuit Schematic Diagram (Typical)

Alteration of the Resonant Frequency

The reverse $\dot{B}$ of the magnet field is altered by changing the resonant frequency of the discharge circuit. The only restriction on chosing the resonant frequency is that the impedance of the resonant circuit must be within the impedance range of the power supply. Step changes in the resonant frequency are achieved by adding units of 100 microfarad capacitors to the two capacitor banks. Continuous alteration of the resonant frequency is achieved by the variable tuning reactors included in each of the discharge circuits. The inductance of the tuning reactor can be varied from a minimum of 0.28 microhenry to a maximum of 1.58 microhenry. The tuning reactor is a single-turn loop which is open at one end. A non-contacting shorted turn, magnetically coupled to the single-turn loop, is introduced into the open end. By means of a mechanical lead screw the position of the short can be changed within the reactor, thus changing the magnetic stored energy and hence the terminal inductance. The parameters of the tuning reactor are shown in Table II.

TABLE II

TUNING REACTOR PARAMETERS

L, Maximum, μhy	0.28
L, Minimum, μhy	1.58
Q, 3 kHz	75
I peak, kA	66
I rms, kA	2
Gap Height, cm	8.25
Gap Width, cm	10.16
Gap Length, cm	91.4
Core Material	0.1 mm, Selectron, (3% Si 97% Fe)
Core Weight, kg	244

Load Current Quenching

One of the more interesting aspects of the power supply is the requirement for near zero current at the end of the discharge cycle. Typically, the discharge switch thyristors have a reverse current on the order of 10-15% of the forward current they were conducting. Carriers were formed in the junction during the forward conduction period and the reverse current is needed to sweep the carriers from the junction. Normally this reverse current would flow in the load and thus give an unacceptably large reverse current bump at the end of the cycle. This problem was solved in the power supply by adding a saturating reactor in series with each magnet and a bypass circuit to the discharge thyristors. The reactor is located within the coaxial cable termination assembly and consists of a single conductor around which a tape wound Deltamax magnetic core has been placed (Figure 4). The parameters of the saturating core are given in Table III.

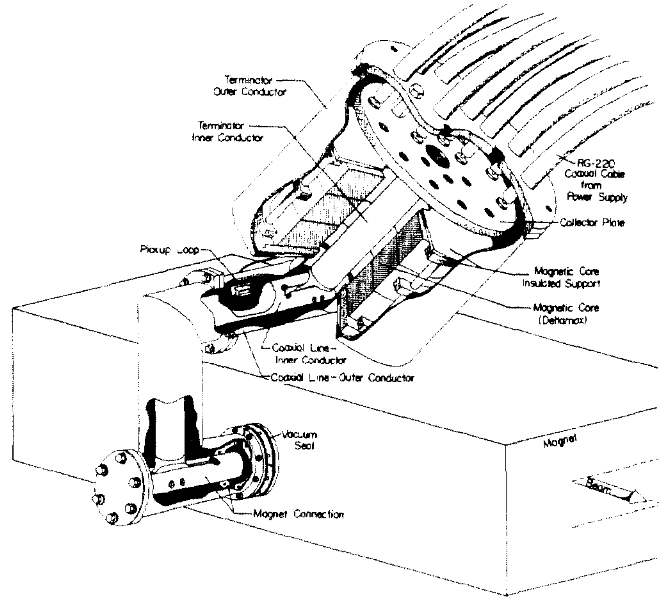

Fig. 4. Cable Termination, Cutaway View

TABLE III

SATURATING CORE

Material	0.025 mm Deltamax, (50% Ni, 50% Fe)
Core Area, cm^2	111.3
Core Height, cm	15.24
Core Diameter (Mean) cm	18.73
Core Weight, kg	54
B (Saturation), kG	16
H_c, amperes	$\sim$ 40

The volume of core required is determined largely by the recovery time of the discharge thyristors. Referring to Figure 5, the action of the saturating reactor

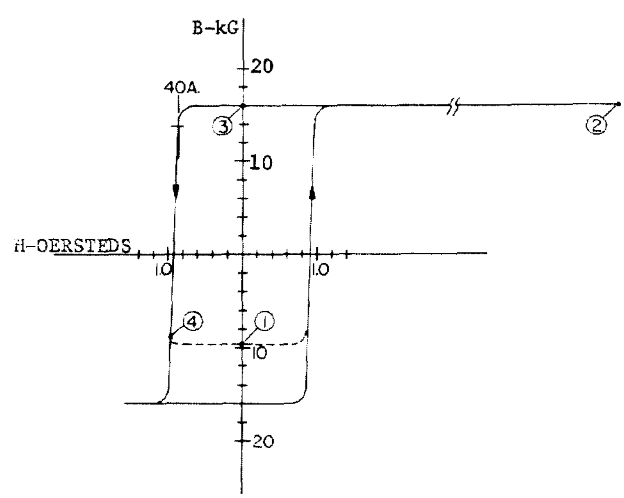

Fig. 5. B-H Curve for Saturating Reactor

can be explained. At Point 1 on the B-H curve, the discharge thyristors have just been triggered and the current is limited to the magnetization force of the saturated reactor. A very short time later, on the order of 10 microseconds, the reactor saturates and the current is limited only by the constraints of the network. The reactor remains in a saturated condition (Point 2) throughout the duration of the discharge current pulse and only begins to come out of saturation when Point 3 is reached. During the time required to go from Point 3 to Point 4, the load current is limited to the coercive force of the magnetic material. The inclusion of the saturating reactor in the load circuit now requires that an alternate means be provided to commutate the discharge switch thyristors. At Point 3 in the cycle the capacitor bank will be reversed charged. The bypass switches are triggered and a current of a magnitude determined by the reverse capacitor voltage and the series current limiting resistors then flows through the discharge thyristors, causing them to commutate. Failure to provide sufficient current through the bypass circuit to commutate the thyristors before the reactor reaches the reverse saturation induction will allow the load current to increase in the reverse direction as the reactor saturates. The thyristors will then be commutated in the normal way. Normal operation of the bypass circuit limits the load reverse current to about 40 amperes.

Each power supply section has two sets of bypass switches because of the high turn-on di/dt requirements. With 1600 volts reverse on the capacitor bank, the peak current in each discharge thyristor will be limited to 160 A by the 10 Ω current limiting resistor. The rate of rise of the current is limited only by the tuning reactor inductance and the stray circuit inductance. At the worst case, the bypass thyristor turn-on di/dt is 80A/μs per discharge thyristor. To keep the total di/dt for the bypass thyristor to less than 1000A/μs, only ten of the discharge thyristors are connected to one switch. A series connection of three G. E. Type 509, 1200 volt thyristors gives the bypass switch a 50% voltage margin.

System Load and Performance

The total system inductance has a maximum value of 2.27 microhenries and a minimum value of .969 microhenries. The contributions of individual elements is shown in Table IV.

TABLE IV

SYSTEM INDUCTANCE

Magnet, μhy	0.4
Cable Termination (Saturated), μhy	0.15
Coaxial Cable (20), μhy	0.118
Stray, μH	.02
Tuning Reactor	
Maximum, μhy	1.58
Minimum, μhy	.28

Network losses are principally in the magnet and coaxial cable. The measured value of Q was 15.5, from which the calculated network resistance was determined to be 2.49×10^{-3} ohms. A composite oscilloscope display showing the typical operating features of the power supply is shown in Figure 6. The resonant discharge frequency is 3.2 kHz which gives a reverse $\dot{B}$ of 74.4 G/μsec.

CONTROLS

The power supply is interlocked for both personnel and equipment safety. The interlocks include power supply cabinet and accelerator enclosure areas, charging power supply overcurrent, coolant failure, overvoltage and discharge current unbalance. The capacitor bank voltage is regulated by means of an analog comparator in the control section. The charge module is triggered shortly after the end of the recovery cycle, beginning the recharging cycle. The output of a voltage divider on the capacitor bank is compared to an externally supplied reference voltage and when the bank voltage has reached the reference level, the comparator triggers the commutate module, ending the charge cycle. The discharge switches are triggered through the pulse logic. The pulse interlocks prevent the switches from being triggered if the capacitor bank voltage has not achieved its proper value.

ASSEMBLY

The major components of the power supply are housed in a metal-clad cabinet (Figure 7) located in the booster equipment gallery. To facilitate servicing, the cabinet panels are designed for easy removal. The capacitor banks are located in the lower central section of the cabinet with the upstream and downstream discharge switch assemblies (Figure 8) being located to the right and left sides of the power supply. The large tuning reactors are located also at either end of the cabinet. The recovery choke is mounted on structural box beam supports directly above the capacitor bank. Cooling of the critical heat generating components is done both with water and forced air. All thyristor assemblies, both tuning reactors, and the recovery reactor are water cooled while forced air is used to cool the 3-phase bridge assembly and the 10 kW current limiting resistor.

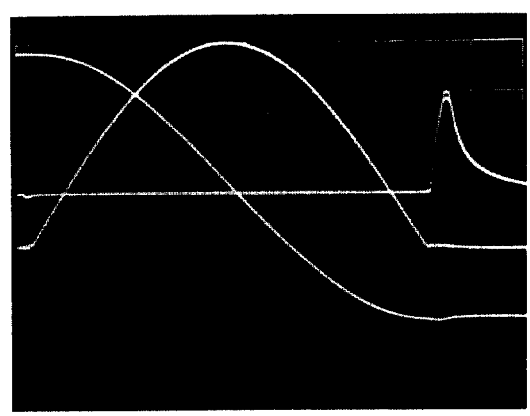

Fig. 6. System Operation for a Reverse $\dot{B}$ of 74.4 G/microsecond

Bottom: Sinusoid Discharge Current, 10 kA/div
Center: Bank Voltage: 500V/div
Top: Commutating current for 10 discharge thyristors in the bypass circuit: 500A/div
Horizontal: 20 microseconds/div.

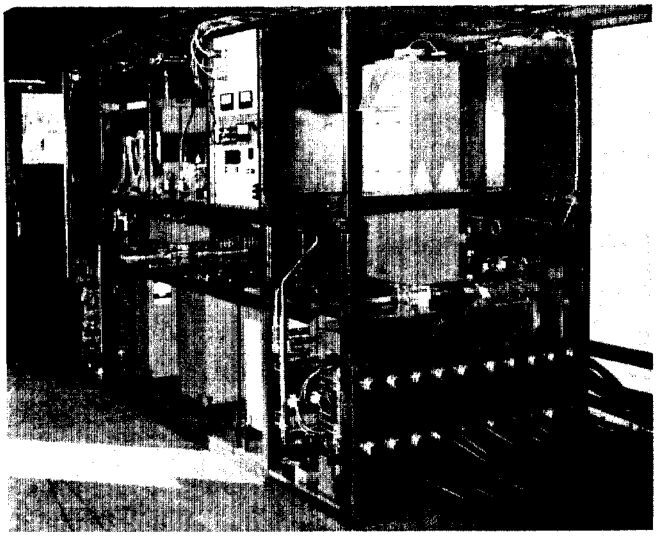

Fig. 7. Orbit Bump Power Supply With Panels Removed

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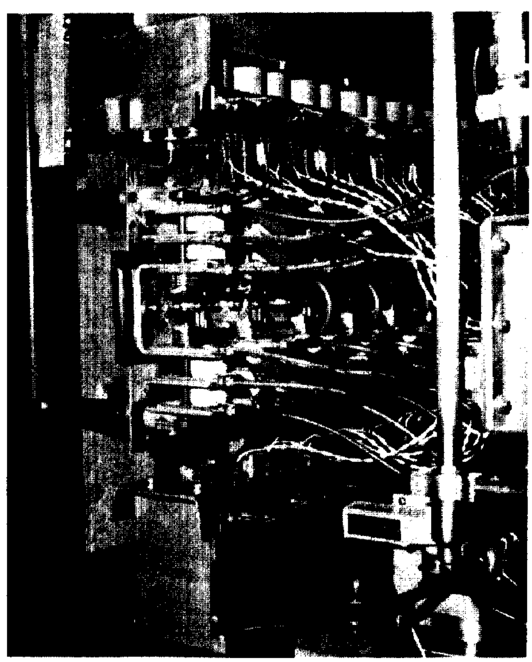

Fig. 8. Interior View Showing the Discharge Switch and Snubber Assembly