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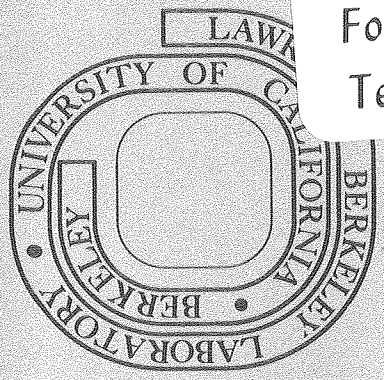

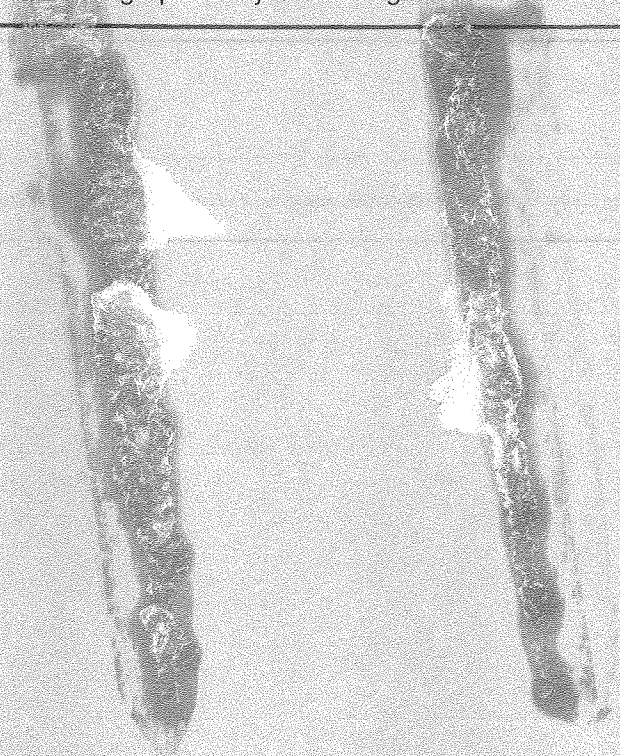

150-kV, 80-A SOLID STATE POWER SUPPLY FOR NEUTRAL BEAM INJECTION

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A 150-kV, 80-A power supply and neutral beam test facility is now operational at the Lawrence Berkeley Laboratory, Berkeley, California. This supply uses banks of 450-V electrolytic capacitors for over 10^6 joules of energy storage. SCR switches control the power flow to the neutral beam accelerator. Turn on and off times of a few microseconds are possible. An auxiliary capacitor bank also uses SCR switches to provide regulation ("flat-topping") of the main bank output by switching in additional capacitors as the main bank discharges. Air-operated switches are used to connect the main-bank sections in parallel for charging and series or parallel for discharge, depending on the operating voltage desired. A single digital switch sets the desired operating voltage. Filament and arc power supplies are also solid state. With the exception of the suppressor supply which has one vacuum tube the complete neutral beam system uses all solid state components.

1.0 Introduction

This paper describes an all solid state power supply designed for an output of 80 amperes at 150 kV. The present supply has operated at 120 kV - 100 amperes and will be upgraded to 150 kV soon. The supply consists of 3 banks of capacitors which are charged in parallel and discharged in series. A fourth capacitor bank is switched in as needed to provide regulation. The novel features of this supply are as follows:

(a) The use of electrolytic capacitors for large energy storage systems.
(b) The use of SCR's for high voltage high current switches.
(c) The use of multiple SCR switched capacitors to provide regulation.

2.0 Energy Storage System

The energy storage system consists of 8160 electrolytic capacitors arranged in a series parallel circuit. The total stored energy is 1.3×10^{6} joules. Each capacitor has a rating of 2000×10^{-6} forads at 450 volts DC working. We limit the voltage on each capacitor to 400 volts with clamping zener diodes. A 30 ohm resistor is installed in series with every 8 units to limit the current from any one string to approximately 100 amp. Two series strings of capacitors consisting of 17 rows with 8 capacitors in each row are connected in parallel to form a module.[1] 10 modules are connected in parallel to form one bank. Three banks are connected in parallel for charging and in parallel or series for discharging depending on the output voltage required. This switching is done between pulses with air operated switches. The normal pulse rate is one pulse every 60 seconds. This switching keeps the maximum voltage to ground to 54.4 kV except during the actural pulse. It also permits using three units in parallel or in single banks to limit maximum energy available to the experiment. A single digital switch selects the proper charge voltage and switching arrangment. A selector switch selects the number of banks to be used when the output voltage is less than 50 kV - Figure 1 is a picture of a typical module. This design has been used in a number of installations with very reliable operation. Figure 2 shows the modules installed in the high voltage room.

3.0 SCR Switching Networks

Figure 3 is a schematic diagram of the system. C1, C2, and C3 are the three banks of capacitors. The single pole switches shown are the air operated disconnects which automatically operate in the proper sequence for charging and discharging. SCR 2 is the series electronic switch which connects the capacitor banks to the load. SCR 1 is the commutating electronic switch and is used to terminate the output pulse. It also provides a shunt path to divert the current from the load when a fault occurs.

Each SCR switch consists of 400 SCR's connected in series. Each SCR gate is connected to one of 33 secondaries of a transformer. Two strings of 6 transformers with primaries connected in cascade provide the necessary voltage insulation to ground. L2 and C4 provide the commutating current for SCR_1. The "ring around" time is 50×10^{-6} seconds. The $\frac{di}{dt}$ through SCR_1 is limited by a small inductor to 200 amperes per 10^{-6} seconds. The current is diverted from the load in approximately 10^{-6} seconds. The commutating current flows through SCR_1 for 25 plus microseconds and then the reverse current flows in the diode D3. This action turns off SCR_1 and SCR_2 until another trigger is supplied.

L_1 limits the di/dt from the bank into the load or cummutating SCR during a fault or commutating cycle. This inductor also limits the rate of rise of current to the load. To permit a higher di/dt to the load, the current in L_1 in "pumped up" by repeated triggers applied to the commutating SCR (SCR_1)

The current is trapped by diode D1. The L/R time constant of this circuit is approximately 60×10^{-3} seconds. To "pump up" the current, the commutating SCR is triggered every 5×10^{-3} seconds until the circulating current in the the circuit exceeds the expected load current. When the series switch (SCR^{2}) is triggered this circulating current is available for the load. L_3 is used to adjust the rise time of the output pulse to the desired value.

4.0 Voltage Regulator

The regulator bank uses the same type of electrolytic capacitors as the main banks. They are connected in series parallel circuit to provide 68 - 12,000 $\times 10^{-6}$ farad units. All 68 units are charged in parallel to 800 volts maximum. 68 SCR's of the same type used in the series and shunt switches are used to switch in the regulator units as the output voltage drops. The output voltage to the load is monitored and a digital logic circuit triggers the appropriate SCR's as needed. This regulator system is described in more detail in a separate report 3. With this system the accel voltage supplied to the neutral beam injection is held to within 1% of the set value.

5.0 Conclusions

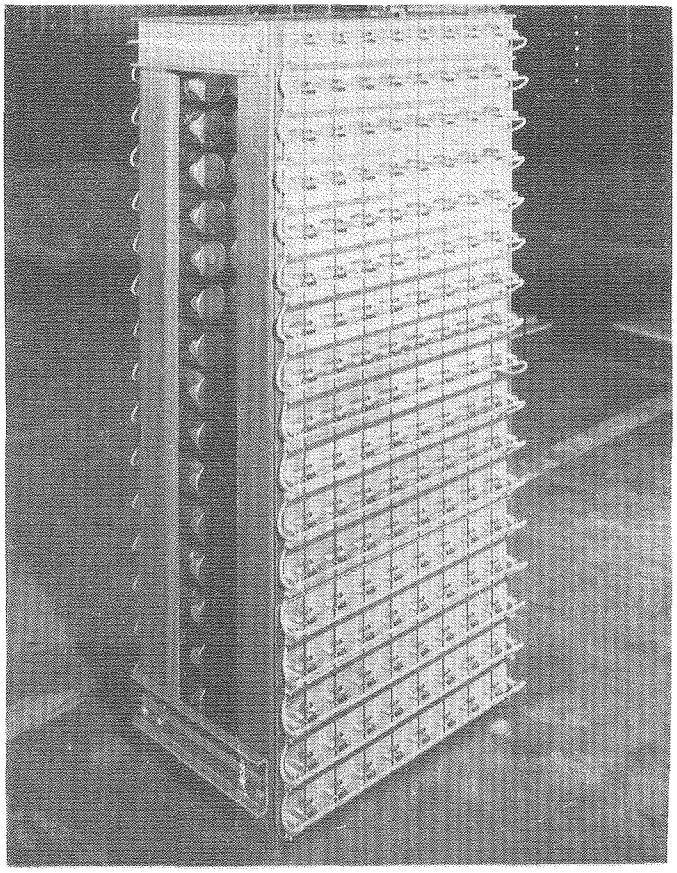
This system has been operating for 12 months. The LBL 10cm x 40cm source has been tested at 120×10^{3} volts accel and 92 amperes current[4]. This represents approximately 100 amperers out of the power supply which also supplies approximately 8 amperes of auxiliary drain. We have demonstrated the following:

1. That electrolytic capacitors may be connected in series parallel to provide economical and reliable energy storage systems. We have operated many banks of this type for several years with a zero failure rate.

2. That SCR's may be connected in series to provide reliable switch elements for 120 kV operating systems.

3. That a SCR switched capacitor bank regulating system provides a simple and reliable method of regulating the output voltage of capacitor energy storage systems.

FIGURE I



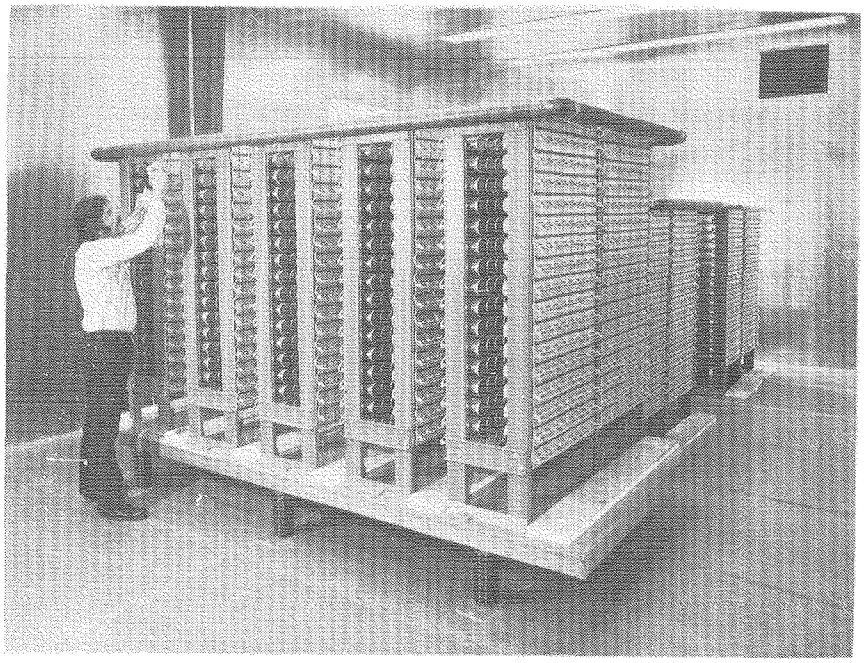
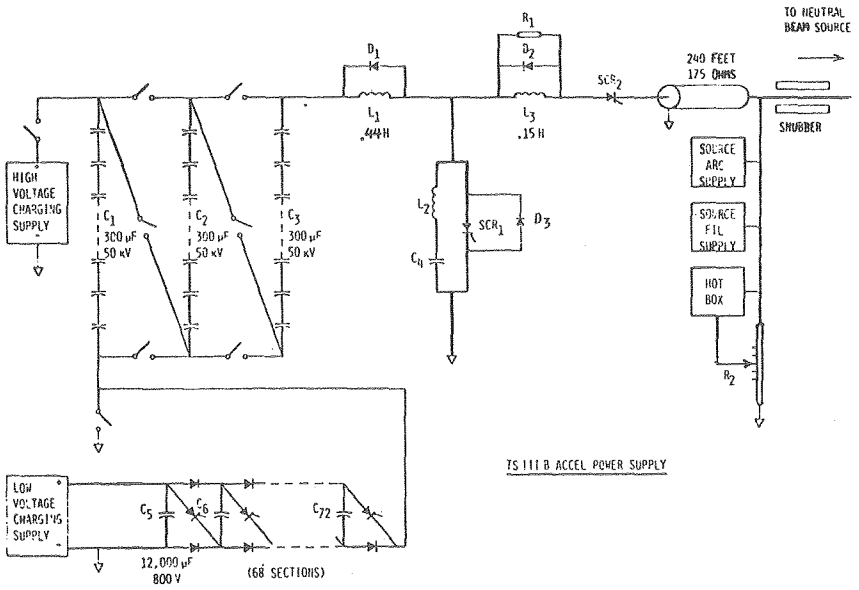


FIGURE II

FIGURE III



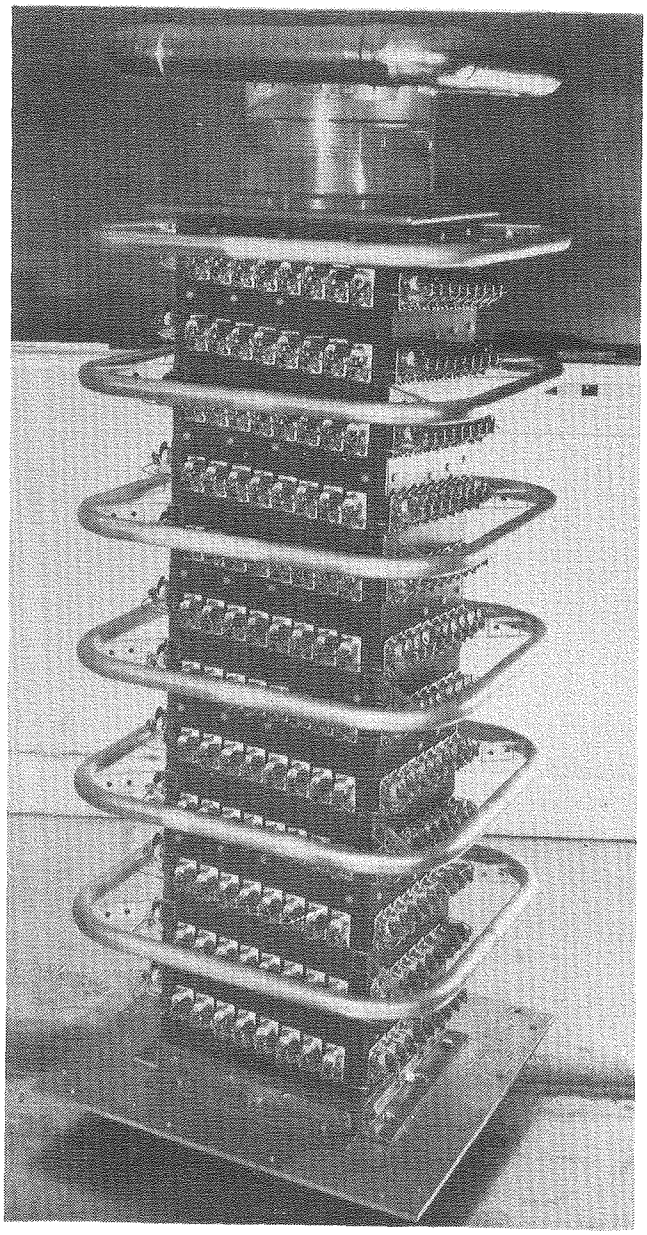


FIGURE IV

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