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A 230 kJ PULSED POWER SUPPLY

R. Winje
Fermi National Accelerator Laboratory
Batavia, Illinois

Introduction

The Meson Focussing System (Horn), consisting of two single-turn coaxial structures, in which circular magnetic fields of varying intensity are produced, and a 230 kJ pulsed power supply has recently been built and operated at Fermilab. The development and construction of the power supply and its related control system is reported in this paper, while a companion paper published in these proceedings[1] reports on the design and development of the magnetic structures (horns) and the interconnecting transmission line.

The capacitor discharge series resonant network was chosen because of the ability to generate the required high current at a relatively modest voltage. Ignitrons are used as the switching elements. A dual set of ignitrons and their controls are connected to the capacitor bank which allows the time-shared operation of the power supply into two loads without the necessity of mechanical, high-current switching. The alternate load for the power supply is a test area where development work on new horn system components is carried out.

The power supply is located outside the Neutrino Laboratory Target Hall where the capacitor bank and ignitron switches are safely positioned in an isolated room. The associated support equipment is adjacent to the bank room.

System

The power supply was designed as three separate banks which, through the control system, can be operated as a full capacity, single power supply or as three partial capacity, independent banks. Each bank is rated for a working voltage of 14 kV and a working current of 100 kA. Simultaneous operation of the three into a common load can produce as much as 300 kA at 14 kV. Added flexibility in both the operation of the power supply and the range of loads which can be accommodated is achieved with this design. System redundancy is increased as a failure of one component can usually be absorbed by the others with only a small reduction in performance.

Each bank has an 800 μF capacitor which is charged from a 225 kW (peak) power supply. The bank has been subdivided into five electrically isolated modules to limit the capacitively stored energy to that which an individual capacitor can safely withstand. Isolation is obtained by connecting the charging power supply through a decoupling network on each module, thereby preventing energy in one module from being fed into another. The decoupling network also limits the current fed back to the charging power supply to less than 5 A during the short interval when the capacitor bank has a reverse charge.

The power supply was constrained to limit the load current to a single, unidirectional pulse for each power supply cycle. This is done to minimize the rms current in the horn load. Ignitrons are characterized by their long turn-off times (some as long as several hundred microseconds) and hence their susceptibility to arc-back when the anode-cathode voltage reverses. For this reason, a crowbar circuit is used and none of the magnetic energy stored in the load is recovered; instead, it is discharged into the crowbar circuit.

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Module Description

The five modules which make up a power supply bank are built on a common support structure. Each module consists of a 160 μF, 14 kV, capacitor assembly, two sets of ignitron switches, output coaxial cables, crowbar resistors and other auxiliary hardware. The electrical connections within a module are shown in Figure 1, although the circuit parameters listed there are for the entire horn power supply network which is described later.

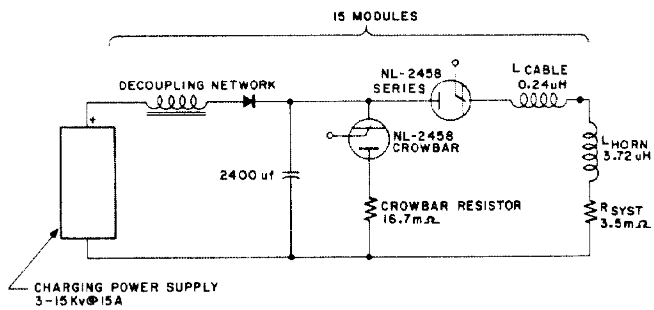

Fig. 1. Pulsed power supply circuit diagram with parameters for the two-horn installation.

A. Crowbar

The electrical placement of the crowbar received considerable attention in the design stage of the project. Three possible configurations were considered:

I. The crowbar in shunt with the load.

II. The crowbar in shunt with the discharge capacitor.

III. The crowbar in shunt with the series ignitron.

Both circuit I and II will give the required single current pulse per cycle while risking either arc-backs in circuit I or arc-throughs in circuit II. Either of the two faults can result in dangerously high currents as there is little impedance within the module to limit the current. While it does not have the risk of unlimited fault currents, circuit III produces a ringing load current, with high rms currents, which is damped only by the natural resistance of the circuit.

Circuit II, modified by adding a 0.25 ohm resistor in series with the crowbar, was chosen for the power supply. Even though more hardware is needed, two positive features result: (1) the danger of unlimited currents from a fault in either the series or crowbar tube is removed; and (2) the L/R ratio is reduced during the period of load current decay which reduces the rms load current.

The crowbar resistor was originally a 0.5 ohm, type SP Globar, rated for 1000 watts (manufactured by Carborundum). These resistors had a short lifetime brought about by arcing at the ends as it was difficult to make reliable, high-current connections to them. They have since been replaced with a 0.25 ohm resistor made from 69 inches of ¼-inch diameter, 10 mil wall, type 304 stainless steel tubing which was wound on a 4-inch diameter form. Although this resistor has more self inductance (0.14 μH) than the Globar, this does not appear to have detrimental effects on the operation of the power supply. The stainless steel resistors are water cooled.

B. Capacitor

The capacitors in the module consist of six parallel connected 26.7 μF, 14 kV energy discharge type capacitors, which were furnished by Maxwell Laboratories, San Diego, CA. The capacitors have extended aluminum foil electrodes with paper-oil insulation which is stressed to 1450 Volts/mil, test. This type of construction has an internal inductance of less than 50 nH. The capacitor is built in a mild steel case that is 35.6 cm wide, 27.9 cm high and 61 cm long. Connection to the electrode is made through a low profile, cast epoxy bushing. With the capacitors mounted on their side, similar bushings made of porcelain, have been prone to leak. However, in more than two years after they were installed, no leaks have developed in the epoxy bushings.

The total stored energy of the module is 15.7 kJ and the individual capacitors are rated to withstand 25 kJ without rupture.

There are 90 capacitors used in the power supply.

C. Switches

Two choices of switches for both the crowbar and series position existed. The obvious choice for the switches were ignitrons, but at the beginning of the project thyristors were considered.

Thyristors are attractive because of the low excitation power requirements, their high rms current ratings, and their small size. However, single devices could only switch 3000 A (peak) with blocking voltage ratings of only 1200 V commercially available. To accommodate the highest current and voltage envisioned, some 1800 devices in an 18 x 100 (33 per bank) series - parallel matrix would be needed - attaining only a 50% voltage margin. In addition to the acquisition costs being high (at that time, about $150 each), the risk was great, that through a circuit malfunction, an entire series string of devices could be lost.

The ignitron, on the other hand, was designed for capacitor discharge service. It has been used by other pulsed power supply builders and it is a well understood and reliable switch. The principle problems with ignitrons are their tendency to preignition, the low average current rating, the high excitation power and their large physical size.

The ignitron used in both the crowbar and series position is a National Electronics Type NL-2458. The ratings and characteristics of this type is shown in Table I.

TABLE I

NL-2458 RATINGS AND CHARACTERISITCS

Size	
Diameter	
(with integral water jacket)	12.7 cm
Height	50.8 cm
Maximum Peak Current	100 kA
Maximum Average Current	2 A
Maximum Anode Voltage	20 kV

This tube is similar in ratings and characteristics to the NL-1059A, except that special internal baffles have been added to obtain a 5:1 reduction in the deionization time.

D. Assembly

The module components are mounted on a grounded metal frame which is 3 m high and 1.2 m deep. The bank of five modules is 3.6 m long. A side view of the module assembly is shown in Figure 2. Six capacitors are mounted vertically on the frame, with their cases electrically isolated from the frame to avoid multiple grounds. Two sets of ignitrons are mounted in front of the capacitors, although only one set is visible in Figure 2. From the circuit diagram it appears that the two ignitrons are connected in series and the capacitor bank attached at the midpoint. Such is the case in the assembly where the flexible anode cable from the series tube attaches both to the cathode of the crowbar and to the midpoint of the capacitor bank.

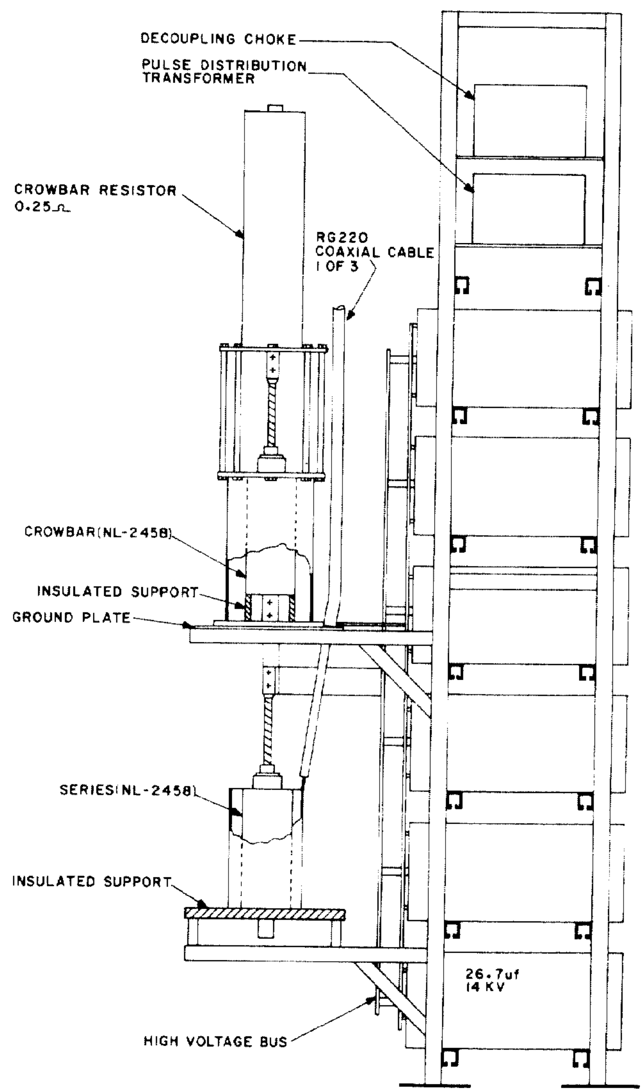

Fig. 2. Pulsed power supply module cross section.

The ignitrons are mounted in coaxial, current carrying structures to ensure that the magnetic fields generated by the load current in the tubes will be nearly circular so as to minimize the movement of the plasma arc. The output cables are located symmetrically on the rim of the series tube coaxial mount. Coaxial geometry is likewise maintained in the crowbar circuit by the coaxial crowbar resistor assembly.

The ground plate is common to all five modules and serves as the common point of the circuit. The grounds from the three banks are tied together and earthed at a single point. The metal frame is also tied to the earth ground.

The power supply is coupled to the two load areas by coaxial cable. Three Type RG-220 cables per module connect the bank to the high current termination for the horn load located at the downstream end of the Target Hall. These cables have a nominal length of 41 m. The second set of ignitrons is connected through two Type RG-17 cables, 75 m long, to the test area. Smaller cables are used because of the lighter rms current demand in that area.

The decoupling network is a series connection of a 1 H, 5 Adc choke and a 20 kV, 5 A diode array. The network is mounted at the top of the module assembly.

The ignitrons are cooled by a closed loop, deionized water system. The mercury-pool cathode of the tubes is maintained at 24°C by the water-cooled envelope that is an integral part of the tube. Pre-ignition problems are also minimized by heating the anode of the tube which is done by two 150 watt heat lamps located 20 cm from the anode seal.

Drivers

The ignitron trigger pulses are generated by a small transformer coupled, capacitor discharge power supply. The system was designed to produce a 2000 V (open circuit) pulse, 12 microseconds wide with a short circuit current capability of 200 A.

The five modules receive their trigger pulses simultaneously from a pulse distribution transformer where the primary to secondary current step-up ratio is $1:\sqrt{3}$. The transformer has five secondaries which are connected to the ignitron igniters through 10 ohm resistors to assure module-to-module isolation. There are separate transformers for each ignitron function in the bank; making a total of four per bank.

The primary of the transformer is connected to a capacitor discharge power supply. With a thyristor pulse amplifier, the timing pulse (5 V for 10 microseconds) is amplified and is applied to the control grid of an ITT Type 8354 thyratron, which is the switching component for the power supply. The power supply generally operates at 4 kV which, with a one-microfarad capacitor, produces about 1½ joules per igniter.

Charge Power Supply

Each of the three 800 μF capacitor banks are charged by a 225 kW (peak), power supply rated at 15 kV, 15 A. A three-phase fullwave bridge rectifier is connected to the secondary of a three-phase, delta/wye connected, 140 kVA power transformer. The transformer has 50% secondary taps to permit full control operation at an output voltage of 7.5 kV.

The output of the power supply is controlled by a fullwave, three-phase thyristor switch connected to the primary of the transformer. Through a feedback system, the power supply furnishes a constant charge current to the capacitor bank.

Operating at a current of 15 A, the 800 μF bank can be charged to its rated voltage in 0.75 seconds.

Control and Safety

The three banks, their charging power supplies and ignitron drivers are controlled by a central control system located just outside the capacitor bank room. The power supply is protected against component failure by a relay-type interlock chain.

Three levels exist for protection of operating and servicing personnel from the hazards of the capacitor banks. They are:

1. Key locked capacitor bank room.
2. A soft (resistive) ground system operated through the control system.
3. A manual, hard ground system.

In addition, the usual access interlocks for both the capacitor bank room and the areas where the loads are located are incorporated into the interlock system.

The timing pulses for all the various functions are generated in the sequencer unit. Through a manual system of pre-set counters, the timing pulses are generated for the charging power supplies, the ignitron drivers and all other auxillary systems requiring timing pulses. A programmed sequencer, using a microprocessor and PROM stored program,[2] now in its early development stages, will replace the manual sequencer. The full capability of the power supply will then be realized.

The regulation of the current is done indirectly by maintaining a constant voltage on the capacitor bank. The charging power supplies charge the bank at a constant rate until the voltage on the bank, measured by a voltage divider, equals the reference value. The charging power supplies are turned off at this point.

Horn Operation

The power supply has been operated into a one-horn load for well over 500,000 pulses and for a shorter time into a two-horn load with few difficulties. The bank voltage and load current are shown in Figure 3. Design operating parameters for the horn load are given in Table II. (See Figure 1 for circuit parameters).

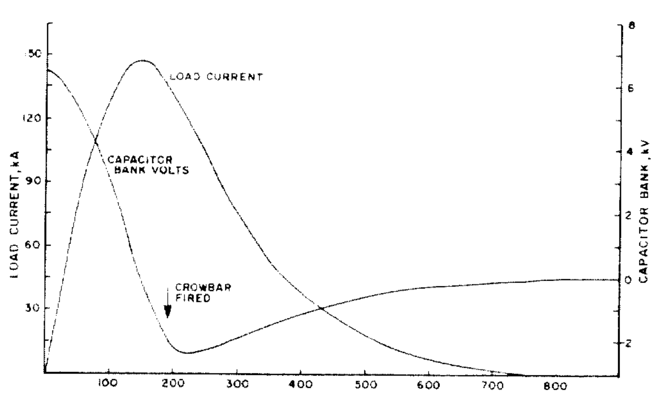

Fig. 3. Design current and voltage for the two-horn operation.

TABLE II

TWO-HORN LOAD OPERATING PARAMETERS (DESIGN)

Load Current,	
Peak, kA	150
rms, kA	1.9
Load Inductance, μH	3.96
Load Resistance, mΩ	3.5
Quarter Cycle, μsec	153
Cycle Time, second	1
Bank Voltage	
Forward, kV	6.5
Reverse, kV	2.4
Series Tube	
Peak Current, kA	10
Average Current, A	1.16
rms Current, A	129.6
Charge Transfer, Coulomb	2.32
Crowbar Tube	
Peak Current, kA	6.43
Average Current, A	.65
rms Current, A	77.2
Charge Transfer, Coulomb	1.3

Acknowledgements

The power supply project was the combined effort of many people. The first phase of the project was the construction of the capacitor bank which was done by the Fermilab 30-inch Bubble Chamber crew. The installation of the igniter drivers, the design and installation of the control system, including the sequencer was done by the Neutrino Laboratory technicians with Mr. Gene Woods and Mr. Bill Williams. Mr. Reid Rhiel and the Neutrino Laboratory mechanical technicians designed and installed the water system.

References

1. F. A. Nezrick, "Fermilab Neutrino-Horn Focussing System," to be published, proc. of this conference.

2. J. Bobbitt, "Application of Microprocessors in Accelerators," to be published, proc. of this conference.