# THE NEUTRINO HORN 300 KILOAMPERE PULSED POWER SUPPLY AT BROOKHAVEN NATIONAL LABORATORY*

J. Sandberg, G.A. Smith, A.S. Carroll, W. Leonhardt, R. Monaghan, C. Pearson, A. Pendzick, G. Ryan,
W.P. Sims, P. Stillman, J.C. Walker
AGS Department, Brookhaven National Laboratory,
Upton, Long Island, New York 11973

## Abstract

A 300 Kiloampere pulsed power system used to energize the Brookhaven focusing neutrino horn is described. The constant current switching section, coaxial power feed and low level control system are presented. Calculations determining system performance are compared with measured values. Plans for future systems are discussed.

## I. Introduction

Since the early 1960's pulsed power supplies have been used at Brookhaven National Laboratory (BNL) to provide the high currents required to focus intense beams of pions for neutrino experiments. The focusing devices, called horns, consist of aluminum cones in a coaxial arrangement. The basic power supply described here is not new, but has been rebuilt, moved, and improved many times since its initial installation.[1] Each version of the supply has incorporated improvements based on operational experience and updated technology. What we have attempted to do here is to present the current state of the neutrino horn power supply "art" as it is applied at BNL.

## II. General

The Horn power supply is located in the northwest experimental area of the Alternating Gradient Synchrotron (AGS). It is housed in a trailer 12' wide by 48' long, approximately 25' above the neutrino beam line decay tunnel. The trailer is divided into two sections, one containing the charging power supplies and one containing the energy discharge modules. The grounds of the two sections are isolated from one another, and the entire section containing the discharge modules is enclosed in an earthed metallic cage.

The "load" consists of two magnetic focusing horns which are located in the beam tunnel about 100' upstream of the trailer location. The horns are connected to the power supply via a coaxial transmission line made of several sections. Thirty-six flexible coax cables (Belden type YR-10914) run from a common junction in the power supply trailer, through three 14" diameter penetrations, to a common movable junction in the beam tunnel directly below the power supply. This floating junction, in part, allows for thermal expansion of the power feeds in the tunnel and is called the transition header. The transition header is connected to the horns with four runs of rigid coaxial cable connected in parallel. This coaxial line was fabricated at BNL from 4" aluminum pipe and Kapton insulation. Each coax line is 16' to 24' long and is extended to 98' by joining together individual segments with special flexible couplings.

In its simplest form, the discharge circuit may be modeled as shown in Fig. 1. Capacitor bank C is initially charged to from 12 to 14 kV. The discharge starts when switch S1 closes, and the horn current may be approximated by:

$$I(t) = V(C/L)^{1/2}[\sin t/(LC)^{1/2}]\exp(-r/2L)t \quad (1)$$

Current in the horns rises nearly sinusoidally to a maximum value of $I(T_r)$ at time $T_r$ where

$$T_r = (\pi/2)(LC)^{1/2} \quad (2)$$

Voltage reversal at capacitor C automatically causes S2 to close, and the remainder of the discharge becomes:

$$I(t) = I(t_r)\exp(-r(t-t_r)/L), \text{ for } t \geq t_r \quad (3)$$

The horns require a current of up to 300 kiloamperes. Since the geometry of the horns and therefore their inductance is dictated by physics considerations, one must maximize the system capacitance in order to minimize the system voltage. The basic limiting constraints on capacitance is the maximum charging current available, which determines the system charge time and ultimately determines the repetition rate of the device. During Fast Extracted Beam running, the repetition rate of the AGS is around 1.4 seconds. A sensible choice of system capacitance, given a maximum charging current of 11 amperes and taking into account available capacitor values, is 850 uf. During later runs, this value was increased to 1116 uf. These values, coupled with a system inductance of about 1.1 uh, dictate an operating voltage of from 10 to 14 kilovolts, depending on the required current and the specific horns involved.

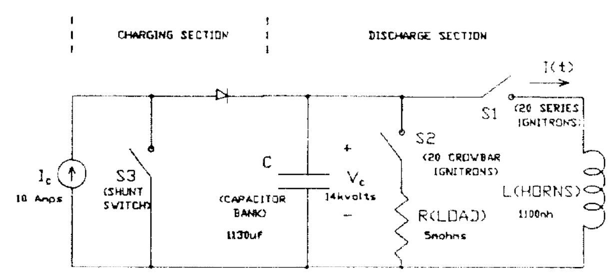


Fig. 1 - Simplified system schematic

## III. Charging Power Supply

The capacitor bank in the discharge section is charged to the required voltage by two 5.5 ampere constant current power supplies. These two charging supplies are each comprised of a monocyclic constant current network, a step-up power transformer, a three-phase rectifier bridge, a current shunt, and an isolation rectifier stack. As the bank charges, a precision voltage divider feeds back the bank voltage to a comparitor located in the control circuits. When the bank reaches the required setpoint, a 4CX15000A tetrode used as a switch is put into conduction, and the D.C. charging current is diverted to ground. Each charging supply is isolated from the other charging supply and from the capacitor bank by a series rectifier stack.

---

*Work performed under the auspices of the U.S. Dept. of Energy.



CH2387-9/87/0000-1743 $1.00 © IEEE

For the most part, monocyclic network power supply design has been amply covered in the literature and need not be belabored here.[2]

The two charging units, one a copy of the other, have been in existence for quite some time and have been rebuilt several times to incorporate advances in technology. These supplies have, over the last 20 years, given many thousands of hours of relatively trouble-free operation.

## IV. Capacitor Bank Modules

The capacitor bank or discharge section of the supply is constructed in a modular fashion along two rows of shelves 15' long by 5' high by 2' deep. Each row contains ten "modules" giving a total of 20 modules for the entire bank. The shelves are located within the caged-in section of the power supply building. Access to this area is controlled and interlocked.

A schematic of one module is shown in Fig. 2. All 20 modules are electrically connected in parallel by individual runs of coaxial pulse cable (BICC type 100P2), which go from the top of each module to a common junction header 5 to 20 feet away.

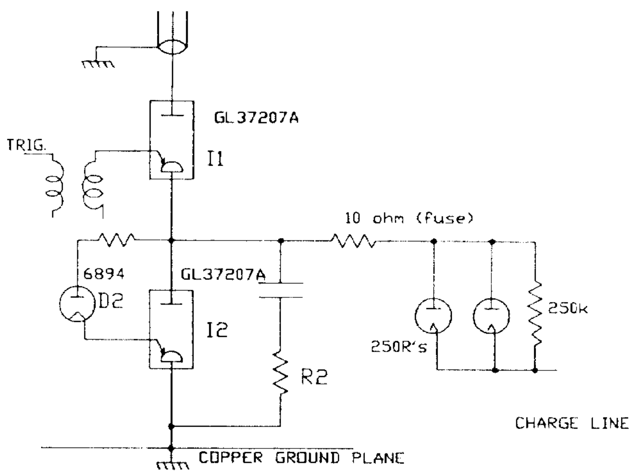


Fig. 2 - Single module schematic

During the charging cycle, current from the charging supplies divides into each module by flowing through a pair of 250R vacuum diodes and a 10 ohm resistor. The diodes serve to isolate the modules from one another in the event of a spontaneous discharge, called a prefire, in one or more of the ignitrons. A 250 kilohm resistor shunts each of the 250R's and acts as a spoiler, allowing for the eventual redistribution of charge along the bank. The 10 ohm resistor is put in mechanical tension by a spring and together with the spring acts as a high voltage fuse assembly. If an ignitron malfunctions by shorting repeatedly, the increased current drawn through the series resistor causes it to fracture. The spring then retracts the broken resistor opening the charge line to the malfunctioning module.

The discharge begins when a high energy trigger pulse is applied to the ignitor of series ignitron, I1. As the discharge proceeds, voltage across the capacitors reverses and crowbar ignitron I2 is triggered automatically by current flowing through diode D2. This action causes the capacitor to be effectively removed from the circuit. The lifetime of a pulsed discharged capacitor is greatly reduced by the amount of voltage reversal which is allowed to occur. Since the lifetime of this power supply is expected to be many tens of millions of pulses, the operation of the crowbar circuit is very important. Resistor R2 is a water cooled length of stainless steel tubing, specifically bent, wound, and potted for low inductance and a resistance of 20 milliohms. This resistor, in parallel with the other 19, forms a "load" of 5 milliohms, which ultimately dissipates most of the stored energy. In an earlier version of this system, R2 did not exist. Instead the load was a large coaxial barrel with stainless steel tubes chosen to have a total resistance of 5 mohm and placed in series with the total current. Replacing this barrel with the parallel combination of R2 greatly improved the reliability of the supply for several reasons. First, structurally the barrel often broke due to the high forces it had to sustain. Secondly, the new resistors act as current limiters in the event of a prefire in a crowbar ignitron when the bank is fully charged. Without this limiting resistance, the huge currents generated often caused significant damage to the ignitrons and the interconnecting cabling.

The ignitrons used are General Electric GL-37207A's. These water cooled devices are rated specifically for capacitor discharge service at 300,000 amperes peak, 25,000 volts peak. They are mounted in specially designed fixtures that provide easy access for removal but are still nearly coaxial to keep inductance to a minimum and to promote tube life. A coaxial structure creates a magnetic field, which compresses the plasma within the conducting tube and keeps it away from the walls of the tube. This increases the expected lifetime of the device.

## V. Power Feeds

The horn power supply is located approximately 100' away from the horns themselves. In order to minimize the system inductance and produce a radiation hard device, a special low inductance coaxial power feed was designed and built. This line is made of 4" aluminum pipe wrapped with 12 layers of 5 mil Kapton and then covered with a piece of split 4.5" aluminum pipe. The outer conductor is clamped with hose clamps every 2.5". The inductance of this coax is approximately 1.8 nanohenerys per foot. These pipes were then placed 4 in parallel and run to the horn. Special flexible couplings were inserted in the coax about every 16-21' to allow for thermal expansion of the system during pulsing. To facilitate the wrapping of the coaxial conductor a machine was built which slowly rotated the pipes as sheets of Kapton were taped and wrapped around them. The inner pipe was first prepared by sanding with 600 grade paper. After wrapping, the outer conductor was installed and secured in place with multiple hose clamps. After assembly, each piece of coax was hipotted to 26 kV for 5 minutes. The peak system voltages during pulsing are on the order of 18 kV.

During the initial running period, only 6 wraps of Kapton were used. There also were inadequate provisions for the thermal expansion of the coax. During this period, there were at least a half dozen serious failures of these power feeds. These failures were stopped by increasing the number of wraps of Kapton from 6 to 12 and by increasing the amount of flex in the lines by adding more flexible couplings and the movable junction header.

## VI. Instrumentation

The system voltage is monitored in three different ways. Each charging power supply has an internal voltage divider which is monitored in the neutrino horn control trailer. The output of these dividers show the power supply voltages ramping to their final value and then quickly dropping to several hundred volts when the current shunt is fired. There is also an independent voltage divider located after the power supplies series rectifier strings which is an indication of capacitor bank voltage. The output of this divider ramps up with the dividers on each of the power supplies but holds its voltage until the series ignitrons in the discharge modules are triggered. It is the output of this divider that controls the current shunt. Finally, each individual discharge module has its own voltage divider which is displayed on a panel consisting of 20 meters located within the discharge enclosure and monitored in the control trailer via a television hookup, thus maintaining isolation between the discharge modules and the control trailer. These individual dividers provide a means of determining faulty modules.

In addition to the voltage monitoring, the total charge time of the capacitor bank is displayed and can be used to interlock the power supplies if this parameter falls outside of a prescribed window. The charge time is a sensitive indicator of module trouble.

The discharge pulse from each of the twenty modules is also monitored by individual current transformers. The output of each of these transformers is available to the experimenter as is the sum of all the signals, which is an accurate indication of total horn current. This composite signal is also used to determine the timing of the discharge current pulse vis a vis the proton beam. A signal is provided to the horn control trailer when the extraction process begins in the AGS. This signal is then used to start a clock which controls the timing of the discharge trigger pulse. A scintillator paddle and photo multiplier tube are located within the beam tunnel just downstream of the horn. The signal from this detector is displayed on a digital storage oscilliscope along with the total horn current signal. With this setup it is fairly easy to adjust the correct timing for the horn trigger.

Since the horn is generally run unmanned and since any failure such as a shorted transmission line can produce catastrophic effects at such high current levels, special monitoring systems have been implemented. An additional circuit monitors the output of the summing amplifier representing total horn current and is set to trip the horn power supply off if the horn current exceeds a preset value for several pulses. Another circuit consists of a microphone monitoring the sound made by the horns as they pulse. The signal from this microphone goes to an integrator, which is reset before every pulse, and the output of the integrator is compared to a preset voltage level. If this level is exceeded, a warning is sounded in the AGS Main Control Room, and the horn power supply is turned off. Generally during a fault, either the sound of the horns or the peak current value changes drastically. These interlocks have proven invaluable during several horn faults and have limited component damage to repairable levels.

## VII. Comparisons of Measured and Calculated Values

The calculated system inductances for the narrow band horn are as follows:

1. Coaxial Cable = 50 nh
2. Horn Coax = 125 nh
3. Horn #1 = 462 nh
4. Horn #2 = 567 nh
5. Keys = 350 nh
6. Links = 35 nh
7. Modules (measured) = 75 nh

The total calculated inductance is, therefore, 1664 nh. The measured rise time of the current pulse with an 850 microfarad capacitor bank is 58 ms. Putting this value into Eq. (2) yields an inductance of 1.604 microhenries, which is in close agreement with the calculated value.

The measured voltage which produces 240 kiloamperes with the above system, is 12.44 kilovolts. Using this value and the above values for L and C in Eq. (1) yields a value of 9.6 milliohms for the total system resistance.

In an effort to reduce system voltage for the board band horn run, we added capacitance to the discharge bank bringing the total capacitance to 1.116 millifarads, and we reduced the series R to 4.5 milliohms (calculated) by removing a damping resistance which had been introduced into the system in the past and was no longer necessary. With these modifications it was possible to run the system at 285 kiloamps.

The system inductance for the broad band horn, based on the calculated horn inductance and measured values of component inductance found from the narrow band horn run, was 1.198 microhenries. The calculated rise time and capacitor voltage for this mode of running were 10.4 kilovolts and 57.4 microseconds. These values compare favorably with the measured values of 58 microseconds and 10.98 kV. If we assume that the inductance calculation is correct, based on the rise time calculation, then the error in voltage is probably due to an error in the resistance calculation. Using the measured values for V, L, and C, the resistance should be 7.5 milliohms instead of 4.5 milliohms.

## VIII. Future Improvements

The monocyclic constant current power supply will be replaced with a higher current (20 ampere) primary SCR controlled charging power supply, which is now undergoing tests at BNL. This supply should prove to be more reliable than the monocyclic supply and due to its higher current capacity will allow for an expansion of the capacitor bank. This expansion will allow the supply to run at higher currents with similar voltages and should greatly increase the reliability of the system in general. One of the primary sources of downtime for the existing system is the vacuum tube series rectifiers, 250Rs, which isolate the individual capacitor modules. These rectifiers are marginal at best and will be replaced with solid state devices. Although the solid state devices will have a much higher initial cost than the vacuum tubes, their much longer projected lifetime will prove economical after their first few runs.

To contain the new power supply, a new house will be built. This house will be significantly larger than the existing building and will, therefore, lend itself to a redesigned discharge module with more ample spacings and easier assembly and repair logistics. The new house will be situated closer to the horn itself and will, consequently, minimize the system inductance and resistance. The new system should be ready for testing some time in 1988.

## References


1. E.B. Forsythe, "A General Purpose Hundred Kilojoule Pulser," BNL Internal Report, Circa 1965.

2. L.C. Green and J.B.H. Kuper, "Constant Current Sources," Rev. Sci. Instr., August 1940 Vol. 2.