HIGH ENERGY PULSED POWER SYSTEM FOR AGS SUPER NEUTRINO FOCUSING HORN *

W. Zhang, J. Sandberg, W-T Weng, BNL, Upton, NY 11973, U.S.A.

Abstract

This paper present a preliminary design of a 300 kA, 2.5 Hz pulsed power system. This system will drive the focusing horn of proposed Brookhaven AGS Neutrino Super Beam Facility for Very Long Baseline Neutrino Oscillation Experiment. The peak output power of the horn pulsed power system will reach Giga-watts, and the upgraded AGS will be capable of delivering 1 MW in beam power.

INTRODUCTION

An upgraded AGS will be able to provide a 1MW "Super Neutrino Beam" covering 1.0 GeV to 7.0 GeV wideband. It will be the proton driver for the Very Long Baseline Neutrino Program.

The physics goal of the program is to observe the oscillation pattern as a function of neutrino beam energy, covering three full oscillations yielding precise resolution of all interested parameters. A unique aspect of the BNL proposal is the ability to measure CP parameters with ν_μ beam alone.

The main facility upgrade will include a new addition of 1.2 GeV Super-conducting LINAC, or FFAG, a higher repetition rate of 2.5 Hz in AGS, and a 1.0 MW target station and neutrino channel.

A target and the beam focusing horn system are essential components of the accelerator based neutrino facility. The 28 GeV proton beam from AGS will be transported to a graphite based carbon-carbon composite target, and large number of pions will be generated and decay into muons and neutrinos. Pulsed horns are required to focus the pion beam.

The basic requirement of horn is a 250 kA pulsed system, and is desirable to have a system capable of 300 kA. Hence, the design is aimed at 300 kA. Table I lists Horn/Target design parameters.

Table 1: Horn/Target design parameters

Proton Beam Energy	28 GeV
Protons per Pulse	8.9×10^{13}
Average Beam Current	35.7 μA
Repetition Rate	2.5 Hz
Pulse Length	2.58 μs
Number of Bunches	23
Number of Protons per Bunch	3.87×10^{12}
AGS Circumference	807.1 m
Bunch Length	40 ns
Bunch Spacing	60 ns
Normalized Emittance - X	100 π mm-mrad
Normalized Emittance - Y	100 π mm-mrad
Longitudinal Emittance	5.0 eV-sec
Target Material	carbon-carbon composite
Target Diameter	1.2 cm
Target Length	80 cm
Horn Small Radius	7 mm
Beam Size (Radius) on Target	2 mm (rms)
Horn Smallest Radius	6 mm
Horn Large Radius	61 mm
Horn Inner Conductor Thickness	2.5 mm
Horn Minimum Thickness	1 mm
Horn Length	217 mm
Horn Peak Current	250 kA
Current Repetition Rate	2.5 Hz
Power Supply Waveform	Sinusoidal, Base Width 1.2 ms

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AREA AND SYSTEM LAYOUT

The present plan for AGS Super Neutrino Beam Facility is to use two horns at approximately 8 meters apart. The power supply will be housed in a service building 50 ft away from the target/horn area, as shown in Figure 1.

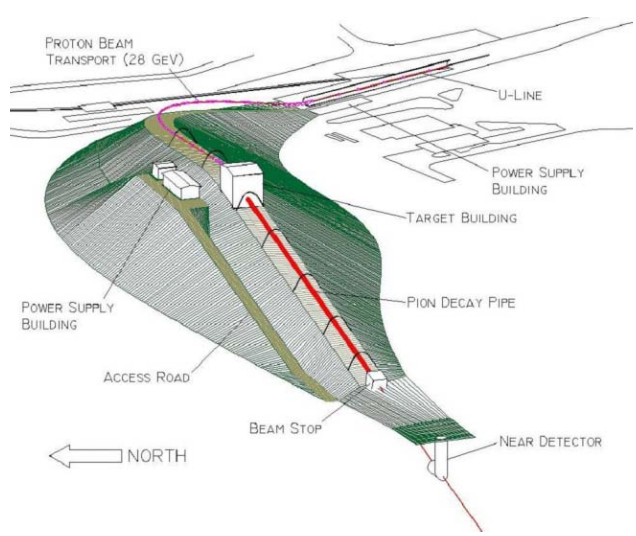

Figure 1: Target/Horn area map.

A preliminary study is being conducted to explore the key issues associated with the power supply system design. Advanced technologies used in similar systems as well as new ideas are being examined, simulated and evaluated. This power supply will be a very high stored energy, high average power, and high peak power system.

Most commonly used scheme is the capacitor discharge circuit. In this type of circuit, a capacitor bank stores the

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energy, and a main discharge switch releases the energy to the load through transmission lines. For very long distant transmission, pulsed transformers have been added into the KEK design and CNGS horn system. Figure 2 shows a simplified block diagram of a horn system.

The technical challenge is often the realization of this simple circuitry. Major technical issues include:

- ✓ High voltage design;
- ✓ High current transmission;
- ✓ High energy storage;
- ✓ High radiation environment;
- ✓ Device availability;
- ✓ Electrical, mechanical, and radiation safeties;
- ✓ High noise immunity of control system, etc.

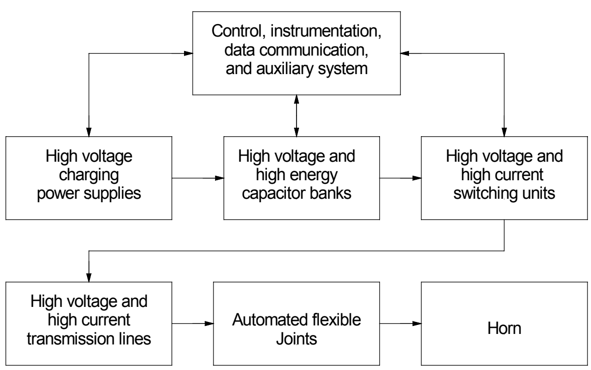

Figure 2: Simplified block diagram of horn system.

CRITICAL ISSUES

The horn as an electrical load is usually being described as an inductor in series with a resistor. Discrete parameters of inductance and resistance are also used to formulate the short length, low impedance transmission lines when associated with low bandwidth pulse. Hence, the circuit can be simplified as a RLC discharge circuit.

In the high current path, the resistance caused voltage drop and energy dissipation are critical factors to be considered. The cooling system for heat removal from the effective resistor, and the additional charging power required to make up the resistive dissipation can be very costly. Hence, the low resistance design is preferred.

Resistance and Skin Effect

The load and transmission line resistance varies with frequency due to skin effect. For any given material, the skin depth δ_s is inverse proportional to the square root of the frequency f, and the effective resistance R_{eff} is proportional to the oscillating frequency. Here $\delta_s = 1/\sqrt{\pi f \mu_R \mu_o \sigma}$, and $R_{eff} = l/\sigma b \delta_s$, where l is the conductor length and b is the conductor width. The material's conductivity, relative permeability, and the free space permeability are described by σ, μ_R, and μ_o , respectively.

One can see that lower frequency leads to lower effective resistance. The other factors associated with effective resistance are the length, width, and permeability and material conductivity. For non-magnetic material, the relative permeability is close to unit. The switching device on-state resistance and hardware connection joints resistance also contribute to the total resistance.

In summary, the lower effective resistance can be achieved by using lower frequency, higher skin depth, wider conductor width, shorter conductor length, higher conductivity material, lower switch on-state resistance, and lower connection joint resistance.

For the 300-series aluminum being considered in the horn mechanical design, the material skin depth is 3.574 mm at 833 Hz.

Inductance Issue

The total inductance includes the horn inductance, transmission line inductance, series inductance of the capacitor, switch inductance, and circuit loop stray inductance. The external inductance depends on the inductor geometry and material permeability. The internal inductance has frequency dependence.

The voltage across the inductor is $V_L(t) = LdI(t)/dt$. Hence, the larger inductor and faster current rate of change requires higher voltage.

The current going through the inductor is the inductively stored energy. Therefore, we have that the higher the inductance and current, the higher the capacitance and its initial voltage. For a reasonable design, the total inductance shall be kept as low as possible, and the current rise time shall be chosen to accommodate the device operating voltage.

Electromigration Issue

The electromigration phenomena are associated with very high current densities [2]. The horn system is a high current system. Horn tip, target pipe, switch connections, capacitor leads, and transmission line joints are places of potential electromigration damage. With a peak current of 300 kA, the current flow through the metallic pathway is a major concern. The transmission lines can be designed with large metal plates or large quantity of coaxial cables in parallel. All joints need to be designed with low resistance material, large conducting area, high contact pressure, and smooth conducting surface.

SIMULATION RESULTS

Let us consider a basic system, with overall inductance of 2.5 μH, a horn and line resistance of 2 mΩ, and a capacitor bank of 16 mF. If the initial capacitor voltage is 4200 Volts, the peak output current amplitude is above 300 kA with 314 μs rise time.

In this design, a diode is used to protect capacitor from excessive reverse voltage. Since the main switch is at on state during conversion, the current will continue flow through the output circuit and the stored energy is fully dissipate in each operating cycle. The reverse damping resistor is chosen to critically damp the current. The capacitor voltage waveform and the horn current waveform simulations are shown in Figure 3.

The stored energy in the capacitor is 141 kJ, and the peak output power is above one Giga-watt. For 2.5 Hz pulse repetition rate, the minimum charging power supply is 352 kW. The resistance used in the example is tight for the chosen frequency. If higher resistance has to be used, then the voltage and capacitance have to be increased accordingly.

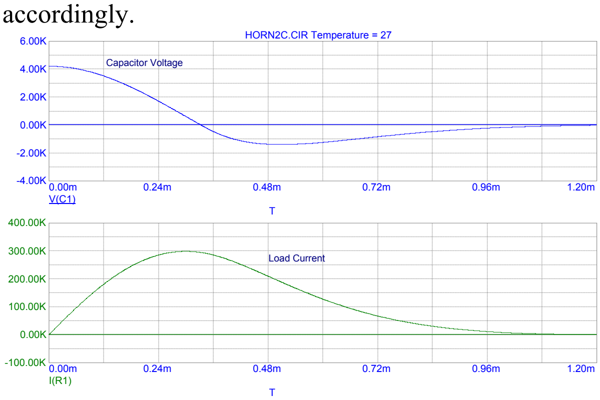

Figure 3: Capacitor voltage and horn current waveform simulations.

To minimize the resistive heat dissipation on horn, two factors may be considered. One is to reduce the horn resistance by mechanical design; another is to recover the electrical energy, as shown in Figures 4.

In this particular example, the energy recovered is about 50%. However, additional active components will make the circuit more complicate and the reverse voltage on the capacitor is higher.

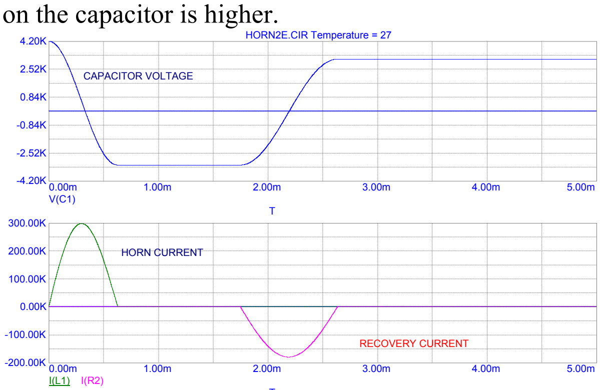

Figure 4: Horn system with recovery circuit: Capacitor voltage, horn current, and recovery current waveform simulations.

The design options of high voltage, high current pulsed system are often limited by the industry development and available components. In this case, the preferred operating voltage is less than 5 kV. The total resistance shall be kept to less than or around 2 mΩ.

HARDWARE CONSIDERATIONS

A typical horn power supply system occupies several tens of standard racks and weights tens of tons.

The large storage capacitance and very high stored energy, a few hundred kilo joules, make it necessary to divide the capacitors into individual cells and isolate them from each other to avoid catastrophic failure. In new and proposed designs, self-healing capacitors are being used for the fault tolerance, and increased reliability. This type of capacitor is usually rated under a few kilo-volts.

The very high current switching has to be accomplished by using multiple switches in parallel. The discharge switch in favor is the light triggered SCR. The trend of new designs is to use solid-state switch, which has much longer lifetime compared to gas discharge switches.

The low inductance and low resistance transmission line has to be made by multiple coaxial cables or planar transmission lines. Both planar and coaxial transmission lines are being considered. Planar transmission line has the advantage of ultra low resistance. Nevertheless, the open structure of the planar line is more sensitive to the condensation and ionized air at horn. Brookhaven developed rigid coaxial cables is better for higher voltage holding. Robotic arms will be used to remotely connect and disconnect transmission lines from the horn. The mechanical structure of the flexible joint of the transmission line will be a major concern.

The high voltage power supply, several hundred kilo Watts, is often multiple units in parallel sharing common control and combined as a single power source. In our situation, it makes sense to built the system with modularized approach. This topology shall provide a better output inductive isolation, higher operability and maintainability, and more flexible charging system.

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