# CONCEPT DESIGN OF THE TARGET/HORN SYSTEM FOR THE BNL NEUTRINO OSCILLATION EXPERIMENT♣

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*Abstract*

The design concept for the integration of the target and the focusing horn system for the proposed BNL neutrino oscillation experiment is described in this paper. Also presented are issues associated with the functionality and thermo-mechanical response of the selected target intercepting the 28 GeV protons of the 1 MW upgraded AGS beam, the loading and mechanical response of the focusing horn subjected to high currents and energy deposited due to beam/target interaction, the integration of the two systems, and the heat removal schemes. The proposed target intercepts the $8.9 \times 10^{13}$, 28 GeV protons with a 2.5 Hz cycle time over a spot that encloses the $3\sigma$ of the beam. In the baseline design the inner conductor of the aluminum horn encloses the target while allowing for an annular space for forced cooling. Approximately 250 kA pulse of current of 20μs duration will flow through the horn at 2.5 Hz repetition rate inducing high compressive forces, vibration and heat. The paper addresses these issues of horn mechanical response, heat removal scenario, and useful life estimation including radiation damage.

## 1 INTRODUCTION

To achieve the 1 MW beam power for the proton driver at BNL serious consideration must be given to both the selection of target material and the horn configuration. Assessment studies indicate that a solid target is a viable option for the proposed 1 MW beam. As a result, low- and high-Z materials have been investigated both in terms of material endurance as well as feasibility of the target/horn configuration. A carbon-carbon composite, formed by a special weaving of carbon fibers, has been selected as the target baseline. Specifically, this carbon-carbon composite exhibits very low thermal expansion between room temperature and approximately 1000$^o$C. Such property leads to small generated thermo-mechanical stresses due to beam-target interaction and will extend the useful life of the target. Experiments performed on this target material as well as other common graphite-based targets verified the advantage of the carbon-carbon composite in the way it responds to short-duration proton beam pulses. Long-term irradiation effects on the properties of this carbon composite, such as thermal expansion, thermal conductivity, strength, etc., are to be experimentally assessed. The pion-focusing horn is to be made out of an aluminum-based material. Candidate materials are the 3000-series and 6061-T6 aluminum.

Parameters controlling the horn material selection are the low resistivity, the high strength and the resistance to corrosion and micro-cracking. The pulsed nature of the machine, combined with irradiation effects that lead to material embrittlement, can potentially limit the useful life of the focusing horn if micro-cracking is allowed to develop. In order to enhance the corrosion resistance of the horn conductor, especially the surfaces exposed to water used for heat removal, special surface treatments in the form of nano-structured films are being explored.

## 2 INTEGRATED SYSTEM

Figure 1 is a conceptual description of the target and horn integrated system being considered for this experiment. The 12mm diameter, 80cm long carbon-carbon composite target considered in this study is fully inserted into the inner horn conductor while allowing for a 1mm annular gap between the target and inner horn surface for forced coolant flow. Shown in the front of the target is a beam "collimator" or baffle that has a dual role. Specifically, it provides the upstream target support and accommodates the special channels that provide coolant into the annular space. It also plays the role of beam diffuser in the event the proton beam strays off the beam axis. In addition to the above two functions, the front end of the target will be maintained at a low temperature which will help in removing heat deposited on the target by conducting into the mass of the baffle. At the downstream end of the target a special fin-like end support allows the forced coolant to leave the annular space. The horn, made out of an aluminum alloy, has a diameter in its narrowest section of 1.4cm and a thickness over that section of 2.5mm. The thickness of the inner horn conductor reduces to ~ 1mm downstream of the neck-down section where the captured pions pass through on their way to the decay pipe. The overall horn length is 217 cm.

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The baseline design requires a 250 kA peak current with a repetition rate of 2.5 Hz. One of the options being considered assumes a 20μs half-sine current pulse. Results of horn response with such current pulse structure are presented in this paper. Under such short current pulse most of the flowing current will be within one skin depth of the conductor. The magnetic pressures and joule heating generated in the conductor control the mechanical design of the horn. While heat generated in the narrowest section of the horn by both current and secondary particles is partly removed by the fluid flowing in the annular space, the balance will be removed by the spraying of coolant through a set of optimally positioned jets against the current-side of the inner conductor. Two coolant options are being considered, namely, the spraying of water and of cold helium. The schematic of Figure 1 depicts the water-cooling option.

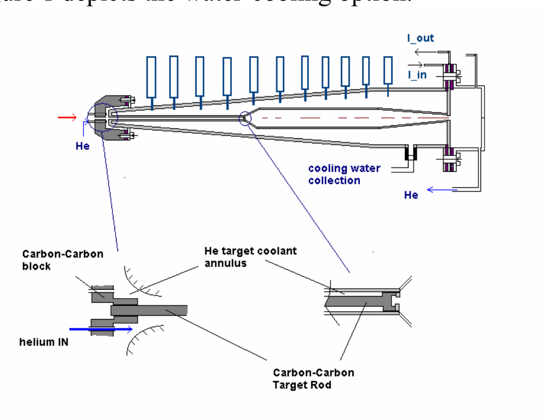


**Figure 1:** Horn/Target Configuration

Also under consideration is a downstream thin window whose role is to hold the target coolant in a closed system. The coolant is thus collected, cooled and returned to the target upstream to be re-ejected into the annular space. The key issue with such window is the fact that it will see a significant portion of the incoming beam power and will be subjected to high thermo-mechanical stress conditions. Further, the presence of additional material in the flight path of pions generated and focused by the horn represents an additional impediment. However, since the only role of such window is to prevent the coolant from escaping from the closed envelope, a low-Z material (for minimal interaction with secondary particles or heat generation from intercepting the beam protons) such as carbon-carbon composite can provide the required boundary.

## *2.1 Energy Deposition and Heat Removal*

Energy generated in the target/horn system is due to the target/proton interaction and the current flowing in the horn. Energy is also deposited in the horn from secondary particles generated in the target. Different mechanisms, namely heat convection, conduction and radiation heat exchange between target and horn are responsible in removing the deposited heat. The heat balance of the overall system, as it reaches an operating temperature, is addressed by utilizing a sophisticated finite element analysis.

*Target Heat Deposition*

Energy depositions for two different beam spots on two target diameters have been estimated using hadron interaction codes. Specifically, 1mm and 2mm rms proton beams are interacting with 6mm and 12mm diameter targets respectively effectively capturing 3σ of the beam. $8.9\times10^{13}$, 28 GeV protons are delivered on target with a 2.5 Hz cycle time. The integrated energy deposited on carbon-carbon target per $8.9\times10^{13}$ protons is 5.1 kJ and 7.3 kJ respectively resulting in temperature rises of 1000 $^{o}$C and 280 $^{o}$C in the target. While the 1mm beam deposits less energy, thus easing the heat removal capacity required, the temperature rise is high making the 2mm beam more preferable.

*Horn Joule Heating*

For a 20μs half-sine current pulse (effective frequency of 0.025 MHz) the current is expected to flow over a skin depth of the inner surface of the inner conductor. The skin depth δ for a horn made out of 3000-series aluminum, for example, with resistivity $\rho$ = 4.2 mohm-cm, is calculated based on the following relations:

$$\delta = (6.61/f^{1/2})\, k_1 \quad ; \quad f = 0.025 \text{ MHz}$$

$$k_1 = [\rho/\rho_c]^{1/2} \quad ; \quad \rho_c = 1.724 \text{ mhoms-cm}$$

leading to a skin depth of $\delta_{Al} = 0.06525$ cm.

In the narrow section of the inner conductor which surrounds the target and is subject to peak joule heating, the heat generated per unit length is derived from

$$JH_{pulse\text{-}cm} = \int_0^{20\mu s} \int_A J^2(z,t)\, \boldsymbol{\rho}\; dA\, dt = 3.88 \text{ Joules}$$

where $J(z,t) = J(z)\sin(\pi t/20\mu s)$, $J(z) = J_o\, e^{-z/\delta}$ and $J_o$ = 689 kA/cm$^2$ is the current density at the conductor surface. The peak temperature rise in the horn, induced by joule heating alone is estimated to be $\Delta T = 7.4^{o}$C.

*Secondary Particle Heating*

Based on the simulation results of different hadron interaction codes, a significant amount of heat is deposited on the horn from secondary particles produced in the target. The heat deposited in the inner conductor of the horn is estimated to be ~ 8.4 kW.

*Heat Removal Scheme*

The deposited heat in both the target and horn is removed by forced flow. In this study the target and the horn have been decoupled. Specifically, forced helium is used in the 1mm annular space between the target and horn to remove the heat from the target which amounts to

18.25 kW for the 2mm rms beam. Forced convection heat transfer calculations were performed to assess the required convection capacity for removing the heat from the target. To maintain the base temperature of the carbon-carbon composite target in a safe regime, a value of 840°C was assumed with a beam induced ΔT~280 °C.

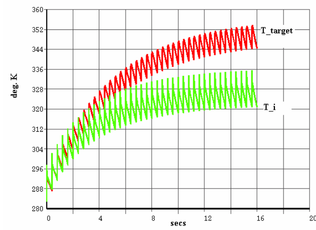


**Figure 2:** Transient temperatures in the horn conductor

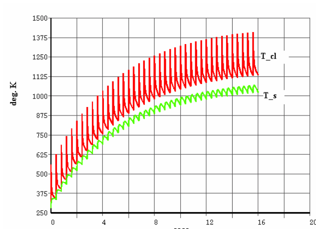


**Figure 3:** Transient temperatures in the C-C target

The inlet temperature of the helium in the annulus is assumed to be 5°C. In the integrated system the target exchanges heat with the inner conductor of the horn through radiation which, based on an allowable surface temperature of the horn of 90°C (the goal is to maintain the aluminum temperature below 100°C whenever it is in contact with water), amounts to ~1.36 kW. Heat from the target is also being removed through conduction to the baffle block upstream of the target that is maintained at a low temperature. It is estimated that helium with a bulk velocity of ~40m/s is required to remove the deposited heat from the target.

The heat deposited on the horn (current, secondary particles and radiation exchange) is being partially removed by the helium in the annulus and mainly by coolant spraying on the surface of the horn where current flows. While re-circulating water is the baseline choice, the option of forcing cold helium is being also explored. Preliminary heat transfer calculations show that there is significant margin of heat removal capacity using water and just enough capacity using helium. The use of helium will reduce corrosion issues of the horn conductor and extend its useful life. Using detailed finite element analysis [3] incorporating the entire heat transfer scheme and the transient nature of the two inputs (protons and current) the "steady-state" temperatures in the target and horn were calculated and shown in Figures 2 and 3.

### *2.2 The Thermal Stress Problem*

The rapid temperature rises induced by the beam/target interaction and the intensity of the proton beam pulse will induce very high thermal stresses in solid targets. The carbon-carbon composite was selected for its low thermal expansion that in turn leads to low thermal shock stresses. Figure 4 depicts the von Mises stresses generated in the target and their attenuation between pulses. The calculated stresses are within the mechanical strength of the material. Figure 5 is a comparison of the response of an ATJ graphite and a carbon-carbon composite target to the same proton beam intensity obtained experimentally. The results clearly show significant stress reduction. Preliminary stress calculations for the horn due to current and secondary particle heating pulses as well as magnetic pressures indicate that the horn can operate safely under the required parameters.

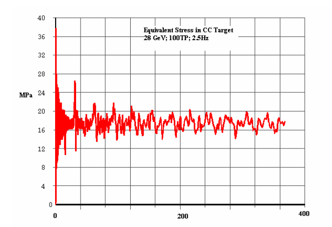


**Figure 4:** Beam-induced von Mises stresses on target

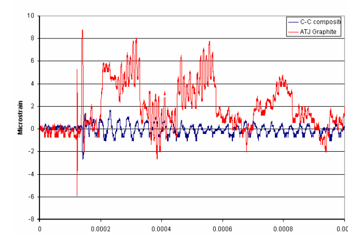


**Figure 5:** Experimental strains (CC vs. ATJ graphite)

### *2.3 Radiation Damage and Surface Treatment*

High levels of irradiation along with thermal fatigue and potential corrosion are anticipated when operating a 1 MW system. The effects of long-term irradiation on the key properties of the target material, such as thermal expansion and conductivity, are not yet known and will be assessed through irradiation studies. In addition, innovative surface treatments for the horn material, such as nano-structured films and plating, are being explored to help extend the useful life of the component.

## REFERENCES

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