

TARGET AND HORN COOLING FOR THE VERY LONG BASELINE NEUTRINO EXPERIMENT*

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Abstract

Thermodynamic studies have been performed for the beam target and focusing horn system to be used in a very long baseline neutrino oscillation experiment [1]. A 2mm rms beam spot with power deposition of over 18 KW presents challenging material and engineering solutions to this project. Given that the amount of heat transferred by radiation alone from the target to the horn is quite small, the primary mechanism is heat removal by forced convection in the annular space between the target and the horn. The key elements are the operating temperature of the target, the temperature of the cooling fluid and the heat generation rate in the volume of the target that needs to be removed. These working parameters establish the mass flow rate and velocity of the coolant necessary to remove the generated heat. Several cooling options were explored using a carbon-carbon target and aluminum horn. Detailed analysis, trade studies and simulations were performed for cooling the horn and target with gaseous helium as well as water.

INTRODUCTION

Figure 1 is a conceptual description of the target and horn integrated system. The 1.2cm diameter, 80 cm long carbon-carbon composite target is fully inserted into the inner horn conductor allowing a 3mm annular gap between the target and horn surfaces for the coolant. Forced helium is used in the annular space for removing the heat generated in the target as well as a portion of the heat generated in the horn inner conductor.

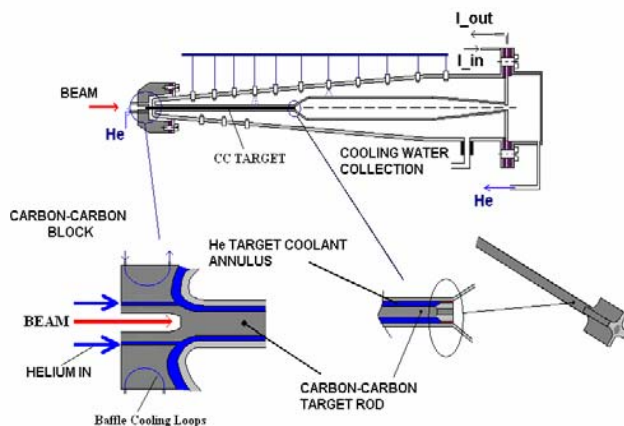


Figure 1: Conceptual arrangement of horn/target system.

The magnetic focusing horn has electric current supply and return at the downstream end. The baseline design calls for a 250 kA peak current to be achieved with a half-sine wave shape that has a base of 600μs with a repetition rate of 2.5 Hz. While heat generated in the narrowest section of the horn will be partly removed by the fluid

flowing in the annular space, the bulk of the heat generated in the conductor by the electric current is to be removed by the spraying of water through a set of optimally positioned jets.

TARGET HEAT LOAD & REMOVAL

The energy deposited by a 28 GeV proton beam with intensity of 8.9×10^{13} protons per pulse and 2mm rms on the 80cm-long, 1.2cm-diameter cylindrical target rod was estimated with the hadronic codes MARS [2] and GEANT [3]. The integrated energy deposition per pulse is estimated to be about 7.3 kJ resulting in 18 kW for the 2.5 Hz operation. Figure 2 depicts the energy distribution.

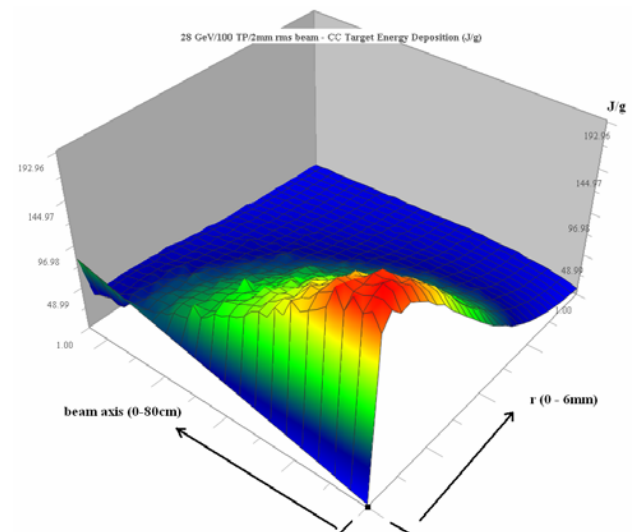


Figure 2: Energy deposition (J/g) in CC composite target from a 10^4 proton-intensity beam, 2mm rms.

The primary mechanism for removing heat deposited into the target by the beam is forced convection of gaseous helium in the annular space between the target and the horn. Due to the complex geometry and various heat transfer mechanisms from convection (via helium and water spray), conduction and radiation, a detailed FEA and CFD model will be utilized to evaluate the final cooling requirements. As a first step, however, a set of proof-of-principle estimates are presented that will indicate that the adopted scheme is feasible. The key parameters are the operating temperature of the target, the temperature of the cooling fluid and the heat generation rate in the volume of the target. These parameters establish, the mass flow rate and velocity of the coolant.

Heat via mass transport:

$$Q_m = m C_p dT_f$$

where m = mass flow rate

C_p = specific heat of fluid at constant pressure
 dT_f = change in temperature of fluid

Figure 3 shows heat removed as a function of mass flow rate, fluid pressure, and fluid temperature change. So, for approximately 18 KW of heat at 5 atmospheres operating pressure and a fluid delta T of 200 deg C, approximately 20 grams/second of Helium flow is required.

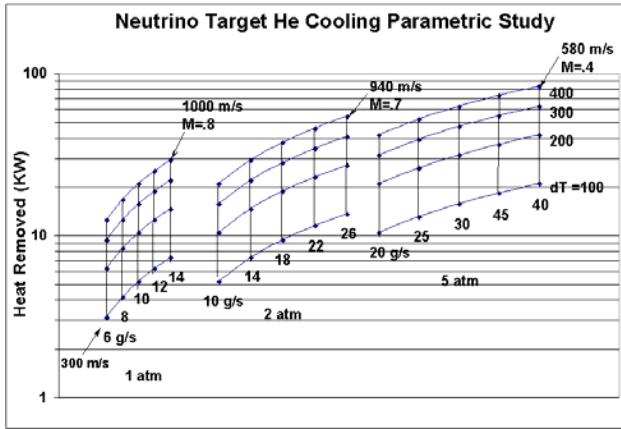


Figure 3: Heat removal via mass transport of He gas.

This heat removed by mass transport must be exactly equal to the heat removed via forced convection,

$$Q_c = h_f A dT$$

where h_f = film coefficient
 A = surface area
 dT = difference between the bulk fluid and the hot surface temperature.

The heat transfer coefficient associated with the annular space with hydraulic diameter,

$$d_h = 4A/P_w = D_o - D_i = 0.006m$$

is estimated based on turbulent flow in smooth tubes using the Dittus-Boelter relation [4]

$$Nu = 0.023 (Re)^{0.8} (Pr)^{0.3}$$

where:

- $Re = \rho V d_h / \mu$
- ρ = density
- V = Velocity
- μ = dynamic viscosity
- $Pr = Prandtl \text{ number} = C_p \mu / K$
- K = thermal conductivity

and Nu is the Nusselt number that relates to the heat transfer coefficient via the relation

$$Nu = h_f d_h / k$$

Where the average $k = 0.16 \text{ W/m-K}$, $Pr = 0.71$, and h_f is the convection heat transfer coefficient.

Thus, for the 20 gram/second flow rate, an average density of $.7 \text{ kg/m}^3$ (at 5 atmospheres pressure) and the annular flow area of $1.4 \times 10^{-4} \text{ m}^2$, the velocity of the fluid is $v = 200 \text{ m/sec}$. The average dynamic viscosity is $2.3 \times 10^{-5} \text{ kg/m-sec}$, so that $Re = 3.6 \times 10^4$ and the Nusselt number is calculated to be

$$Nu = 92$$

Thus the convection film coefficient

$$h_f = 2450 \text{ W/m}^2\text{-}^\circ\text{C}$$

Thus for the energy balance to be maintained,

$$m C_p dT_f = Q_m = Q_c = h_f A dT = 18 \text{ KW}$$

The target surface temperature can be calculated based on the target surface area of $.030 \text{ m}^2$

$$dT = 245 \text{ deg C}$$

Thus, the average temperature of the target surface is 245 deg C higher than the bulk fluid temperature.

Detailed FEA Analysis

A more detailed finite element analysis using ANSYS [5] was performed to determine the thermal-hydraulic behavior of the helium gas in the target-horn annular region and the target surface temperature profile. A helium gas coolant flow of 22 grams/second at 10 atmospheres was used, (typical value for a commercially available helium compressor, slightly above the hand calculated value). Figure 4 shows the temperature profile from this FEA model. Figure 5 shows the gas properties.

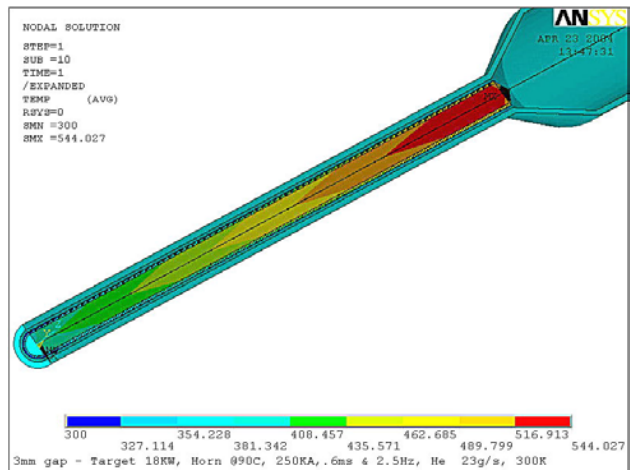


Figure 4: Target-Horn temperature profile.

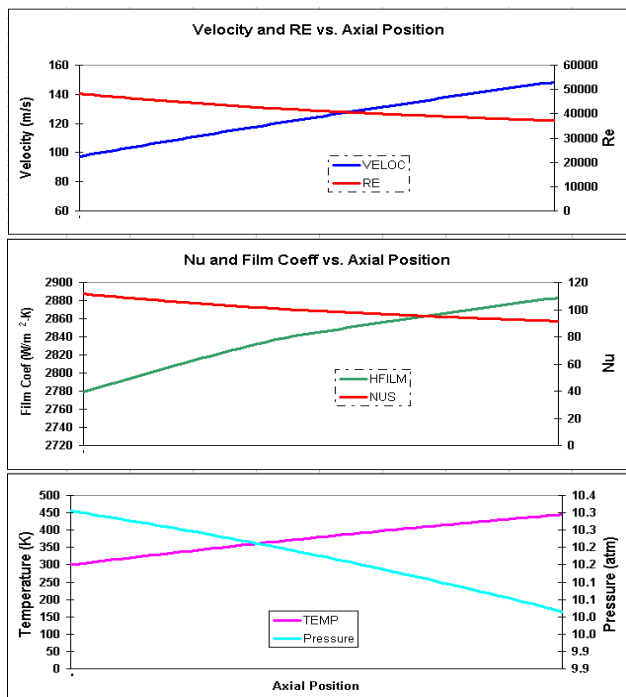


Figure 5: Helium thermal-hydraulic properties in annulus.

HORN HEAT LOAD & REMOVAL

The heat load in the horn comes from three different sources: joule heating from electric current; energy deposition due to proton beam interaction with the target, and heat by radiation from the surface of the target.

Horn Gamma-Ray Heating

The energy deposited on the inner horn conductor from gamma rays and secondary particles that are generated from the proton beam interaction with the target has been estimated using the codes MARS [2] and MCNPX [6]. The total energy has been estimated to be of the order of 10 KW.

Joule Heating Estimate in the Horn

Joule heating from the electron flow is the primary heat load in the horn. The peak current is I = 250 kA and is achieved with a half-sine wave that has a base of 600µs with a repetition rate of 2.5 Hz. This is equivalent to 830HZ. The thickness of the inner conductor (2.5mm) is smaller than the calculated skin depth for this frequency, so that the current will flow throughout the cross-sectional area. With the resistivity of aluminum ρ = 4.2 e-6 Ohm-cm, and the inner conductor geometry, it is estimated that approximately 29 KW will be deposited into the horn.

Horn Heat Load from Target Radiation

The target will be operating at approximately 270 °C. A small amount of heat will radiate from the target surface to the surface of the horn. Assuming that the surface temperature of the aluminum is maintained at ~90°C with the help of the coolant spray on the outside of the inner conductor, then the radiating heat flux can be estimated from the relation:

$$\frac{q_{CC \rightarrow Al}}{A_{CC}} = \frac{\sigma [T_{CC}^4 - T_{Al}^4]}{\frac{1}{\epsilon_{CC}} + \frac{A_{CC}}{A_{Al}} \left(\frac{1}{\epsilon_{Al}} - 1 \right)}$$

$\sigma = 5.669 \times 10^{-8} \text{ W/m}^2\text{-K}^4$, $\epsilon_{CC} = 0.98$ and $\epsilon_{Al} = 0.09$.
 Thus for the inner horn geometry, the heat flux is:

$$q/A = 500 \text{ W/m}^2$$

and the total heat transfer from the target to the horn inner conductor is only 15 Watts.

Heat Removal Using Spray on Inner Horn

Assuming that the spraying jets are positioned in such a way that the entire inner surface experiences forced flow, resembling a cylinder in cross-flow, the following relation applies:

$$Nu_D = 0.3 + \frac{0.62 Re_D^{1/2} Pr^{1/3}}{\left[1 + (0.4/Pr)^{2/3} \right]^{1/4}} \left[1 + \left(\frac{Re_D}{282000} \right)^{5/8} \right]^{4/5}$$

Assuming a free velocity of V = 2.5 m/s, T_{water} = 20° C and T_{wall} = 90° C, the following fluid properties apply: Reynolds number $Re_D = \rho V_f D_h / \mu = 87963$, Pr=3.6, $\mu = 4.7 \times 10^{-4} \text{ Kg/m-s}$, K=0.645 W/m-K:

$$Nu_D = h_f D_h / k = 367$$

$$h_f = 12485 \text{ W/m}^2\text{-K}.$$

By relating the heat flux from the conductor surface to the convective heat transfer, the heat transferred through the surface area A is:

$$q = 39 \text{ kW}.$$

SUMMARY

There are extremely large heat loads from the powerful proton beam on the target and the large electric current flow in the magnetic horn. These loads can be adequately addressed with a combination of compressed helium gas and water spray.

REFERENCES

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