Status of Target and Magnetic Horn Studies for the CERN to Fréjus Super Beam

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Abstract.
In the framework of the EUROnu design study, a new design for the CERN to Fréjus neutrino beam based on the SPL is under development by the WP2 group. The main challenge of this project lies with the design of a multi-MW neutrino beam facility. The horn and the decay tunnel parameters have been optimized to maximize any potential discovery. The target design, thermo-mechanical analysis, and power supply design of the horn system as well as any safety issues are being studied to meet the MW power requirements for the proton-beam.

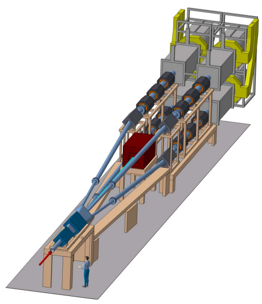


FIGURE 1. 4 MW beam into 4×1 MW splitting apparatus

INTRODUCTION

The summary of the recent horn studies for the CERN to Fréjus neutrino beam is presented in this paper. Emphasis is given to the multi-physics simulation to investigate heat transfer, cooling and mechanical stress for the horn, and furthermore for the support module of the four horns. Also, a target design able to withstand a multi-MW proton-beam power, the optimization procedure for the horn shape and layout-geometry to achieve optimum physics, and safety aspects are discussed. The design and the physics reach of the Super Beam project are described in [1].

THE PROTON-BEAM AND FOUR-HORN/TARGET STATION

A 4-MW proton-beam from CERN's SPL is foreseen to be separated by a series of kicker magnets into four beam lines. Then each beam will be focused by a series of quadruples and correctors to a four horn/target assembly as shown in Figure 1 [2, 3]. In that way each horn/target assembly is able to accommodate better the multi-MW power and thus increasing its lifetime, the target in particular. The four-horn target system will be placed within a single large helium vessel. The downstream of the neutrino beam-line consists of several collimators, the steal decay tunnel for the mesons to decay and the graphite beam-absorber at the end.

A 0.25 mm thick beryllium beam window has been studied as the interface between each 1 MW proton-beam line and each horn/target assembly in the vessel [1]. Maximum temperatures as high as 180 °C and (109 °C) and Von Mises stresses as high as 50 MPa and (39 MPa) are developed respectively for water and helium cooling: these are well below the beryllium strength limit.

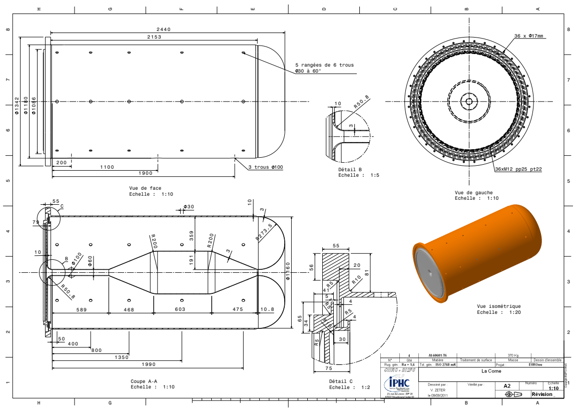


FIGURE 2. Horn detailed design

TARGET STUDIES

A packed-bed target with Ti6Al4V-spheres and helium transverse cooling has been chosen as the baseline target option [1]. It is placed inside the upstream part of horn's inner conductor. The advantages of the packed-bed target are among others a large surface area for heat transfer with coolant able to access areas with highest energy deposition, minimal thermo-mechanical and inertial stresses, and potential heat removal rates at the hundreds kilowatt level with high helium flow rate. Advantages of the helium transverse cooling are an almost beam neutral, no generation of stress wave in coolant and low activation of coolant with no corrosion problems. Because of the small 3-4 mm diameter of each sphere, the gradient of its temperature field is very small resulting in minimal thermal, and inertial dynamic stress.

Alternatively, a pencil-like geometry of solid beryllium has been studied [4]. This pencil-like geometry gives steady-state thermal stress within acceptable range for beryllium. Pressurized helium cooling appears feasible but center proton-beam effects could be problematic because of the stress induced: this point needs further thermo-mechanical studies.

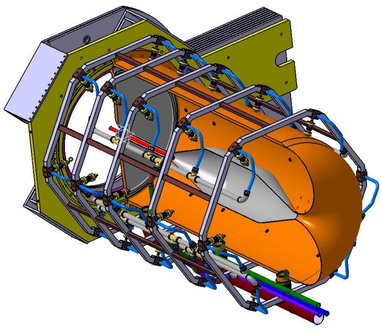


FIGURE 3. Horn drawning with cooling system. The target and the inner conductor's shape are shown as well

HORN STUDIES

Horn shape and layout-geometry optimization

The end-design consists of an inner conductor with a cylindrically shaped upstream part to decrease the transverse momentum of the low-energy charged mesons, followed by a trapezoidal shaped middle part to select a special particle energy spectrum (for optimum physics) and finally a convex downstream plate to de-focus wrong-sign mesons that contribute to the background neutrino spectra. This configuration has been selected as the best compromise between physics performance and reliability under 1 to 1.3 MW proton-beam power [1]. The detailed design and drawning for the horn are shown in Figures 2 and 3.

The horn and the geometrical parameters of the decay tunnel (length and radii) are optimized for the best achievable sensitivity limit on $\sin^2 2\theta_{13}$. The beam parameters are initially scanned broadly and then restrictly in three iterations in order to minimize the CP-violation averaged 99% C.L. sensitivity limit on $\sin^2 2\theta_{13}$ [5, 6].

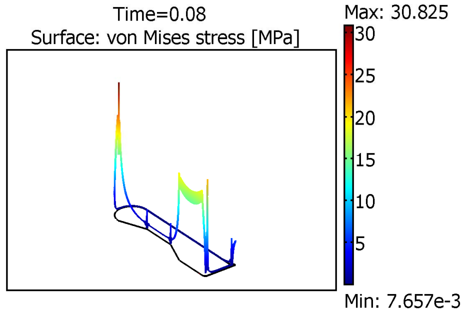


FIGURE 4. Horn stress s_{max} = 30 MPa

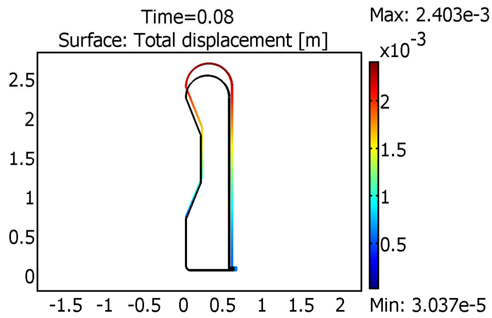


FIGURE 5. Horn deformation u_{max} = 2.4 mm

Horn thermo-mechanical and dynamical stress studies

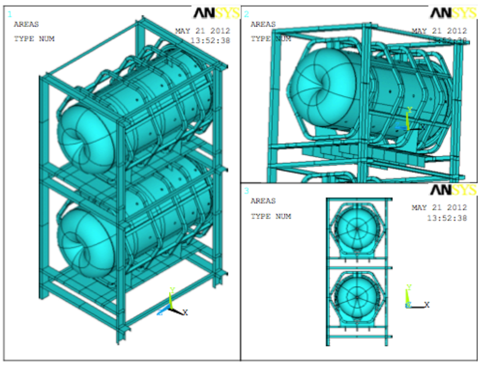
The Al-6061T6 alloy is the chosen material for the horn because it represents a good trade off between mechanical strength, resistance to corrosion, electrical conductivity and cost. Each horn is subject to a peak 350 kA current at 12.5 Hz frequency. As a result, the aluminum alloy is subjected to cyclic deformation due to a pulsed magnetic pressure load. In addition, the temperature field creates a thermal static stress due to joule effect and secondary particle crossing the conductors. The maximal static thermal stress is calculated about 60 MPa for a non uniform cooling with maximal temperature of 60 °C and is located in the upstream corner and downstream top part of the horn [7]. If a uniform temperature is achieved everywhere, the horn is expanding, and the maximum thermal static stress is 6 MPa. The stress in the upstream part of the inner conductor due to magnetic pulses and thermal expansion is around 20 MPa for a uniform achieved temperature of 60 °C. The stress and the deformation of the horn are shown in Figures 4 and 5, and the detailed studies are written in [7].

Fatigue

There is no fatigue limit available for Aluminum alloy so the fatigue data can only give a probability of failure for a determined level of stress and number of cycles. According to [8], the fatigue strength limit is 20 MPa for 10^9 pulses with a mean static stress due to thermal dilatation. For the weld junction a limit of 10 MPa should be respected to maximize horn lifetime. For the inner conductor horn, the magnetic pressure pulse creates a peak on the von Mises stress value of about 16 MPa. This value is below the 20 MPa limit strength for 10^8 cycles and with mean stress due to thermal dilatation [7, 9].

Cooling system

To remove a total power of about 60 kW and maintain a temperature of about 60° C a water-jet cooling system is being studied. This system will be made of 5 rows of 6 nozzles (Figure 3) and to spray water toward the inner conductor of the horn. The estimated water flow rate is calculated between 60 to 120 l/min per horn depending on the design. To minimize the thermal static stress, the nozzle size and disposition should be properly located in order to achieve the most uniform temperature everywhere inside the horn [10].



Source: [1]

FIGURE 6. Horn support half-frame design

Four-horn system support

The horns and collimators will be held in place by support modules which can be lowered vertically into the helium vessel by crane. One support module will hold the four horns and the strip-lines, and a second will hold the four collimators. The support modules rest on kinematic mounts at the top of the helium vessel. Removable shield blocks will fit inside the support modules, and rest on the sides of the vessel. The sides of the shield blocks will be stepped to create a labyrinth, preventing direct shine of radiation to the top of the vessel. The support for the four horns (Figure 6) has been designed and a complete static and dynamic analyses have been performed [1].

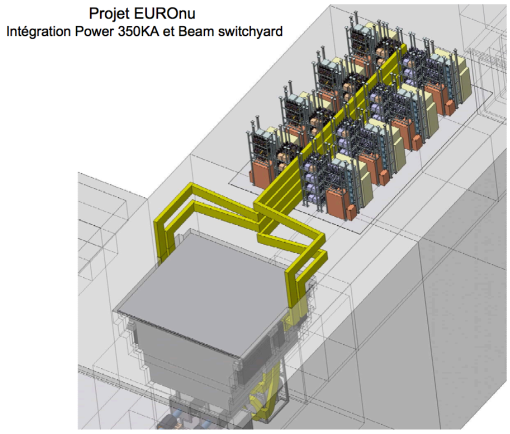


FIGURE 7. Power supply modules with strip-lines

Power supply

A one-half sinusoid current waveform with a 350 kA maximum current and pulse-length of 100 μs at 12.5 Hz frequency is needed for each horn. A capacitor charged at +12 kV reference voltage will be discharged through a large switch in a horn via a direct coupled design. A recovery stage allows to invert rapidly the negative voltage of capacitor after the discharge, and to limit the charge capacitor current. In order for the system to be feasible, a modular architecture has been adopted with 8 units: 2 modules are interconnected on a same transmission line based on 2 strip-lines. The recovery energy efficiency of that system is very high at 97 % [11]. Schematics of the power supply apparatus and details of one module are show in Figures 7 and 8 respectively.

SAFETY

The future design of Multi-Mega Watt sources facility has to take to account the significant amount of radi-

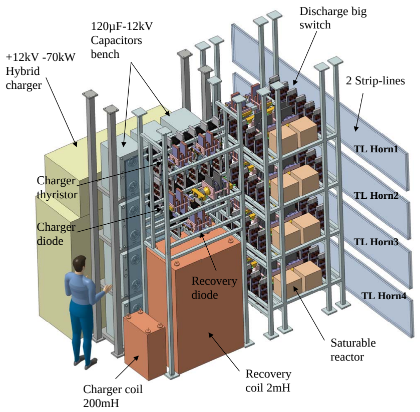


FIGURE 8. Schematics of one power supply module

ation produced during beam operation and the radio-activation of the surrounding environment. The design of the shielding should reduce the dose equivalent rate to a minimal level. In order to reach these dosimetry objectives the ALARA (As Low As Reasonably Achievable) approach will be used in the design of the facility. ALARA consists of an iterative process between three phases: a) Preparation, design of the facility, dose equivalent rate map, study the intervention procedures for workers b) execution, engineering phase check/improve the dosimetry objectives and c) analyse and feedback on safety from previous experiments.

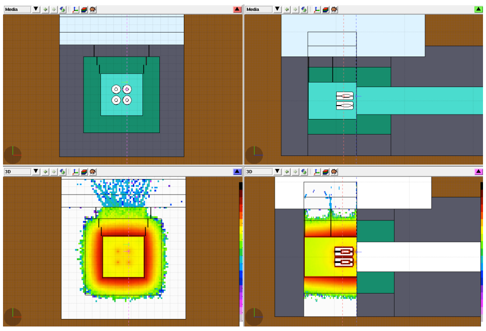


FIGURE 9. Power density distribution on the target/horn station (green for iron, grey for concrete, and brown for molasse rock at CERN)

The Super Beam infrastructure consists of: a) Proton Driver line, b) Experimental Hall (Target Station, Decay Tunnel, Beam Dump), c) Spare Area Room, d) Hot Cell, e) Service Galleries (Power supply, Cooling system) f) Air-Ventilation system and g) Waste Area. Energy deposition (Figure 9 for the horn/target station) and activation studies have been performed for that apparatus in order to design the cooling systems and appropriate shielding taking into account ALARA [1, 12].

CONCLUSION

Monte-Carlo, thermo-mechanical and dynamical stress finite-elements analysis studies show that the four-horn/Target system can be feasible under the extreme 4 MW proton-beam power conditions. Furthermore, R&D is needed for the target and the horn in order to study the fatigue, cooling, power supply designs and radiation degradation.

ACKNOWLEDGMENTS

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