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A Stationary Target for the CERN-Neutrino-Factory

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Abstract

As production target for Neutrino Factories, free mercury jets with high-axial velocity of about 20 m/s are being studied. For the CERN-Neutrino-Factory proposal with a 4 MW beam power, but with a relatively large beam size at 2.2 GeV/c and pulsed at 50 Hz, maximum energy deposition densities of below 20 J/g and average power densities of about 1 kW/g are expected in the target. Therefore a study has been made which discusses the feasibility and limits of a stationary target. It is proposed to use densely-packed solid spheres of heavy material with diameters in the millimeter range. These spheres are confined inside a Titanium container and cooled by an efficient water circuit or possibly by He-gas. Dynamic response, as pressure pulses and vibrations are greatly reduced in the small target granules due to relatively long beam bursts, each with a duration of 3.3 µs .The encouraging results achieved in this assessment justify to pursue further experimental tests, in particular of the cooling of the target, its lifetime under repetitive thermal cycles (4.3 Mio/day) and of radiation damage, to validate this proposal. It is expected that the lifetime of this target will be adequate for the operation of the CERN-Neutrino-Factory, at least over its initial phase below 4 MW beam power.

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A Stationary Target for the CERN-Neutrino-Factory

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1 Introduction

The pion-production target for the CERN-Neutrino-Factory [1] is driven by a proton beam with a momentum of 2.2 GeV/c and a beam width with an r.m.s. radius of about 10 mm. The average beam power of 4 MW is contained in a train of bursts with a frequency of 50 Hz and with an energy/burst of 80 kJ.

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This leads to a peak energy deposition in heavy targets, like mercury to about 20 J/g, burst [2]. Each burst, containing 140 short bunches, has a duration of 3.3 μs, much longer than for Neutrino Factories studied elsewhere with nano-second bunch durations [3]. The large beam size at 2.2 GeV/c and the long proton bursts lead to relatively low temperature spikes and small, thermally induced shocks respectively. This opens the path for using a stationary, solid target fitted with a cooling system capable of evacuating the average power of 800 kW deposited by the 4 MW beam [4]. A solution for such a target is proposed and its performance and design values are assessed below.

2 Dynamic response of the target material

As actual target core it is proposed to use densely packed spheres made of Tantalum (density $\rho = 16.8$ g/cm^3). With a diameter of 2 mm of each sphere and a packing factor of 60% an average density of $\bar{\rho} = 10$ g/cm^3, 30% less than mercury, is achieved. With a maximum energy density of about $\Delta E = 15$ J/g, burst, deposited by the proton beam along the target axis [2] an adiabatic temperature rise ΔT of at most $\Delta T = \Delta E/c_V = 100$ K (c_V: Specific heat of Tantalum, $c_V = 0.151$ J/g) will result. Since for each sphere the adiabatic temperature rise will be close to uniform over its small volume, thermal stresses will occur only during cooling between the proton bursts when small radial temperature gradients arise [4].

Thermal shocks induced by proton bunches with nano-second duration in liquids and solids [5] have been investigated previously. However, the driving heat pulse from each proton burst with a duration of $\Delta t = 3.3$ μs in the CERN-scheme is much longer than the characteristic response time τ in the small Tantalum spheres which is

$$\tau = R/c = 0.26\ \mu\text{s}$$

R: Radius of a sphere, $R = 1$ mm
c: Velocity of sound in Tantalum, $c = 3.8 \times 10^3$ m/s.

As compared to heating with nano-second bursts with equivalent energy, the dynamic shock is reduced by the factor $\Delta t/\tau \approx 13$, leading again to stress values well below the yield strength of Tantalum [5]. Thus, owing to the granular structure of the target material, in which only small static and dynamic stresses can build up, a sufficient lifetime of the spheres may be expected.

3 Cooling of the target

As stated above, the temperature of the 'mostly heated' spheres along the target axis rises adiabatically over a duration of 3.3 μs by at most 100 K. In the steady state the heat deposited by each burst in a sphere has to be evacuated through its surface into the cooling medium. As the heat transfer rate is proportional to the temperature difference between the sphere and the cooling water, which at sufficient high velocity can be assumed as constant, an exponential temperature decrease of each sphere after the proton bursts will occur. The time constant t_0 of this decay in temperature is given by:

$$t_0 = \frac{c_V \cdot m}{\gamma \cdot F} = \frac{c_V \cdot \rho \cdot R}{3 \cdot \gamma} = 38 \text{ ms}$$

c_V: Specific heat of Tantalum, $c_V = 0.151$ J/g
ρ: Density of Tantalum, $\rho = 16.8$ g/cm^3
m: Mass of each sphere, $m = 70$ mg
R: Radius of each sphere, $R = 1$ mm
F: Surface of each sphere, $F = 12.6$ mm^2
γ: Heat transfer coefficient, $\gamma = 22$ kW/m^2 K

To reach such elevated heat transfer coefficients γ, highly turbulent water flow with an average velocity through the voids between the spheres of 6 m/s (Reynolds number Re $= 6 \times 10^5$) is required. Thus a time constant t_0 is achieved which is of the same order as the time $t_1 = 20$ ms between the proton bursts.

In the steady state the minimum temperature T_1 just before a burst is related to the peak temperature $T_1 + \Delta T$, reached just after each burst, by $T_1 = (T_1 + \Delta T)\, e^{-t_1/t_0}$. With $\Delta T = 100$ K it results $T_1 = 144$ K and as a sum 244 K for the most heated sphere. To this temperature rise the absolute offset temperature of the cooling water of 20°C has still to be added to arrive finally at a maximum absolute peak temperature of 264°C. This clearly demonstrates the precarious limits of the cooling with water.

Although substantial formation of vapour bubbles will hardly set in over the short time of about 2 ms which the water takes to cross the most heated part of the target, it may be necessary to reduce the radius of the spheres to 0.5 mm, which would reduce the time constant t_0 to 16 ms. This would lead to a peak temperature in the spheres of 160 °C. Moreover, the boiling point of water can be raised to about 150 °C when the water circuit is pressurized to 5 atm. Finally, the maximum energy deposited by the beam may be reduced by adapting the beam power and/or beam size accordingly. Evidently, the required performance of the envisaged water cooling circuit needs experimental verification which is being prepared.

As an alternative, Helium gas cooling circuits may be considered. Operated at an absolute pressure of 20 atm. and passing at a velocity of 100 m/s between the spheres (Re $\approx 3 \times 10^4$) a heat transfer coefficient of $\gamma = 10$ kW/m^2 K, half of that for water, may be reached. This would lead to peak temperatures of 430 °C and 240 °C for radii of the spheres of 1 mm and 0.5 mm respectively.

Cooling with liquid metals, like Lithium and Sodium-Potassium has also been considered [4] but seems less attractive at this stage.

A multi-target scheme has been proposed in [6]. This would share out the beam bursts evenly over four targets, thus reducing the average power in each target by the same factor and would evidently relax considerably the constraints on the water or He-gas cooling systems.

4 Target layout

The principal structure of the granular target core confined in a Titanium cylinder and fitted with end windows and a water cooling circuit is shown in Fig. 1. Similar design principles are at present considered for Neutron Spallation Sources [7]. The target diameter, matched to the proton beam is about 40 mm and its length about 200 mm. Preliminary computations indicate that a reduction of about 20% in pion yield at this diameter is expected as compared to cm-thick Hg-targets [2]. The water inlets and outlets have to be shaped to minimise re-absorption of laterally escaping pions. At a packing factor of about 60% of the spheres and a water velocity of 6 m/s in the voids a total lateral flow through the target of about 0.011 m^3/s with a pressure drop of about 4 atm. is required. The average temperature rise in the cooling water is about 18 K, while locally levels twice as high may occur in the water stream passing through the center of the target.

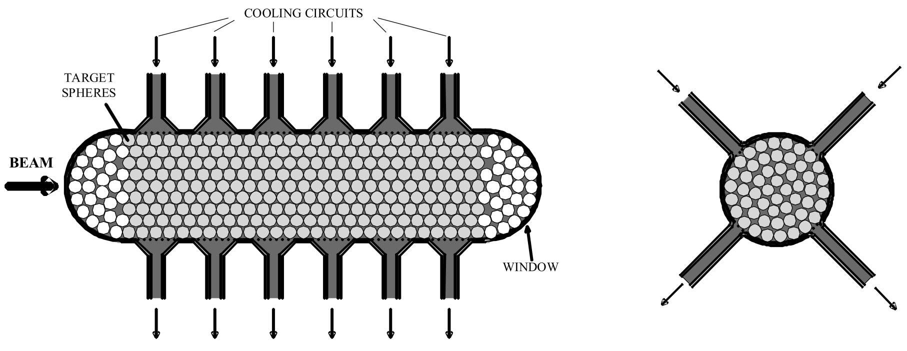

Fig. 1. Principle lay-out of a granular target. Tantalum spheres with a diameter of about 2 mm are confined in a Titanium container and cooled by water or possibly He-gas traversing the voids between the spheres.

As the shock energy in the total of all spheres is of the order of some Joules the Ti-cylinder is mainly solicited by static and beam induced pressure pulses transmitted from the cooling water which should stay well below 100 atm. Thus a wall thickness of this Ti-cylinder of 2.5 mm is more than adequate.

The windows are solicited, in addition to the cooling water, by the pulsed impact of protons and cascade particles. This leads to temperature rises per burst of 14.3 K and 4.5 K for Ti- and Be-windows respectively. The resulting thermal stresses are of the order of 10 MPa, still well below the yield strength of these materials.

To resist to the pulsed pressures transmitted from the water to the windows, spherically shaped foils [see Fig. 1] with a thickness of at most 1 mm will be required. This leads to a maximum local power density of 220 W/cm^2 to be evacuated through the inside surface of a Ti-window and thus to an average local temperature rise of nearly 160 K.

This illustrates again that He-gas cooling at a much lower pressure of 20 atm. may very well be a valid alternative, since thinner windows can be used which leads to proportionally less power deposited in the window material.

Clearly, fatigue, erosion and radiation damage in these windows are the most important issues to be addressed, along the same lines as presently done for Spallation Sources [8].

5 Conclusion

Calculated design values and estimated performance of a stationary, granular target, cooled by either water or He-gas could present a valid solution for the CERN-Neutrino Factory, at least initially, adopting a pragmatic and staged approach towards the final design goals. The main issue of such a target is not its short-term, pulse by pulse performance but rather its lifetime, being limited by fatigue, corrosion and radiation damage. These items, difficult to assess, must be checked by off-beam or, for some issues, in-beam tests. This will be tackled in the near future. Finally, substantial input can be expected from R&D, presently under way for the development of similar targets of pulsed Spallation Sources.

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