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A preliminary design of a dump for 2.2 GeV, 4 MW proton beam

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Abstract

This note provides a first conceptual design of a dump to absorb the 4MW proton beam emerging from the pion production target of a future CERN Neutrino Factory. This device has to be specially designed to cope with the enormous heating power density of the beam. The note deals with the design of the device from a thermal point of view only, without taking into account radiation issues.

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1. Introduction

The conceptual design of a CERN neutrino factory [1] is based on a superconducting H^- linear accelerator as an intense proton source for pion production [2]. The linac, which pulses at 50 Hz, produces a proton beam of 2.2 GeV energy and 4 MW mean power. This beam is sent onto a target in order to generate an intense pion beam. These pions decay into muons, which are then accelerated to 50 GeV before being injected into a storage ring where they in turn decay giving rise to an intense neutrino flux. The target and pion capture system will be one of the most challenging components of the entire facility. The present CERN design foresees a liquid metal target, with horn focussing preferred over solenoid focussing.

The target will receive approximately 10^{16} protons per second and will not be large enough to contain the 2.2 GeV beam. Only about 25% of the primary particles are here assumed to undergo a hadronic interaction with the target material. The remaining primary protons and the secondaries emerging from the target have to be stopped in a dump. This note provides a first conceptual design for this high-power dump under the conservative assumption that the whole proton beam is sent directly to the dump. The note deals with the design of the device from a thermal point of view only, disregarding radiation issues such as induced radioactivity.

2. Conceptual design of the dump

2.1 Material Choice

Material choice is fundamental in order to reasonably meet the requirements set for the absorber. The conceptual design proposed here is based on the use of low-density graphitic carbon foam surrounded by high density carbon to manage effectively the heat load deposited by the proton beam. This choice of material also allows the use of helium to cool the core of the dump. Another advantage of a low mass material is that the cascade is shifted further towards the inner part of the dump, which reduces the probability that secondary particles escape the absorber.

The carbon foam is a light-weight (ρ=0.6 g cm^{-3}), porous rigid material which can be cut, shaped and cleaned using a variety of conventional machining techniques. It has a graphitic nature, with the graphitic planes forming the walls of open cells in a honeycomb-like structure. The continuous network of carbon ligaments provides dimensional stability, a low coefficient of linear thermal expansion (2 μm m^{-1} °C^{-1}) and a relatively high compressive strength (3.4 MPa).

The graphitic structure retains the thermal properties of standard high-density graphite: it allows an isotropic thermal transfer with a high thermal conductivity k (100 W m^{-1} °C^{-1}) and a high specific heat c_p (700 J kg^{-1} °C^{-1}) at 300 K, which increases considerably with temperature (reaching 1900 J kg^{-1} °C^{-1} at 1000 °C). These properties, together with the low density ρ, give the carbon foam an extremely high thermal diffusivity $\lambda = k / r \, c_p$ (2.31 cm^2 s^{-1} at room temperature), which leads to a very rapid and uniform heat distribution.

The foam porosity (total porosity is 73%, with an average pore diameter of 350 μm) is of an open nature: more than 96% of the pores are interconnected. This provides a

huge internal surface area (larger than 4 m^2 g^{-1}) and allows a large amount of heat to be transferred to any coolant passing through the porosity.

The chemical properties of the foam allow brazing to realize thermally conductive attachments, purification, very low outgassing and oxidation resistance up to 400 °C in air and up to 3400°C under vacuum or inert atmosphere.

Based on these properties, the use of graphitic carbon foam is deemed suitable for the inner upstream part of the absorber (the "inner" core), where the highest thermal power density is deposited. Standard high-density (2.0 g cm^{-3}) polycrystalline graphite may be used for the remaining part of the core (the "outer" core), while the whole structure could be surrounded by a cast iron shielding to absorb the remaining secondary particles (see Figure 1).
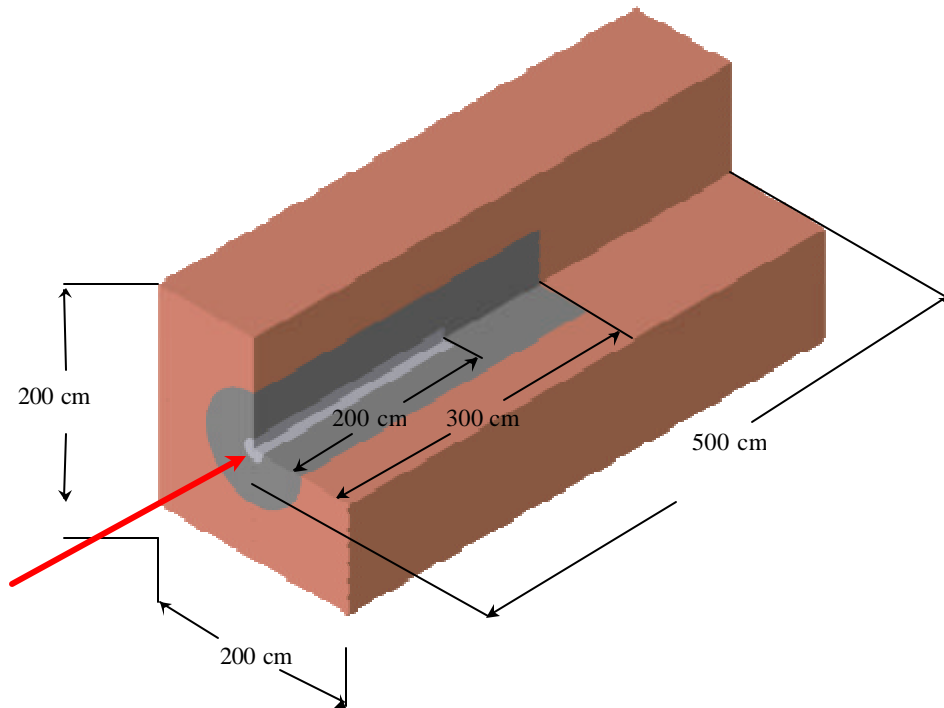

Figure 1. Conceptual design of the 4 MW neutrino factory dump. The top right quarter of the dump is removed in order to show the inner structure. The inner cylinder (Ø20x200 cm) is made of low-density graphitic foam ($\rho = 0.6$ g cm^{-3}). The outer cylinder (Ø100x300 cm) consists of high-density polycrystalline graphite ($\rho = 2.0$ g cm^{-3}). The whole structure is embedded in an iron shielding. The structure has been dimensioned according to the Monte Carlo calculations and the thermal study discussed in sections 2.2 and 2.3.

2.2 Monte Carlo simulations

In order to dimension the absorber core and estimate its temperature distribution, the energy deposition inside the materials must be known. To this purpose a number of calculations were performed with the FLUKA Monte Carlo code [3, 4], simulating the whole electromagnetic and hadronic cascades. All relevant physical effects (FLUKA default card: PRECISION) were taken into account. The lower transport threshold for electrons and positrons was set to 200 keV. Photons produced in the simulation were tracked until they reached an energy of 100 keV, whereas neutrons were followed down to thermal energies. The histories of all other charged particles were simulated until the secondaries reached 100 keV.

In the simulations the beam hits the centre of the low-density carbon core, as shown in Figure 1. The parameters of the proton beam are the following:

- Energy = 2.2 GeV
- Beam intensity = $1.1 \cdot 10^{16}$ protons per second
- Beam power on the dump = ~4 MW
- Beam radius = 2 cm

For this preliminary calculation, the particles were assumed to be uniformly distributed within the beam diameter of 4 cm.

Figure 2 shows the energy deposition in the whole dump structure caused by the beam absorption. The detector used consists of a concentric cylindrical substructure, which is arranged around the beam impact point. The length of the single detectors is 5cm. The radial extension of this binning structure is also 5cm. As expected, the highest energy deposition density in the dump is found around the beam axis. If the secondary particles cross the boundary from the low-density carbon to the high-density carbon, a sudden increase in the energy deposition per unit volume is observed. This is explainable by the higher density of the outer core and by the fact that the interaction probability of particles traversing matter rises exponentially with the density of the material. The same effect can be observed at the interface between carbon and iron. The effect of different stopping powers of carbon ($\Delta E/(g/cm^2)$) and iron has a minor influence on this behaviour.

The binning structure used in Figure 2 is larger than the beam size. Therefore an accurate assessment of the energy deposition around the beam axis is not possible. In order to investigate the situation around this "hot line" more closely, the same kind of detector providing a bin size of 1 cm in both radius and length was used. In the hot spot of the beam an energy deposition larger than 1.0×10^4 GeV/cm^3 per primary proton is found. This correlates with a heating power of more than 176 W cm^{-3}.
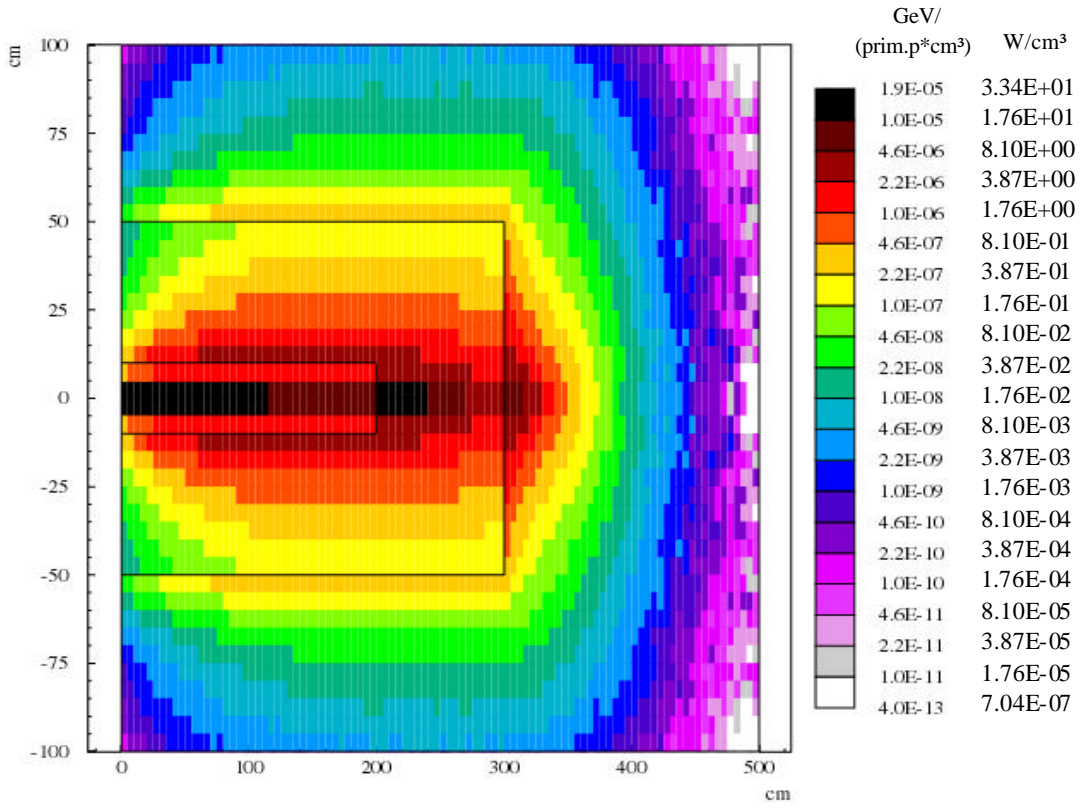
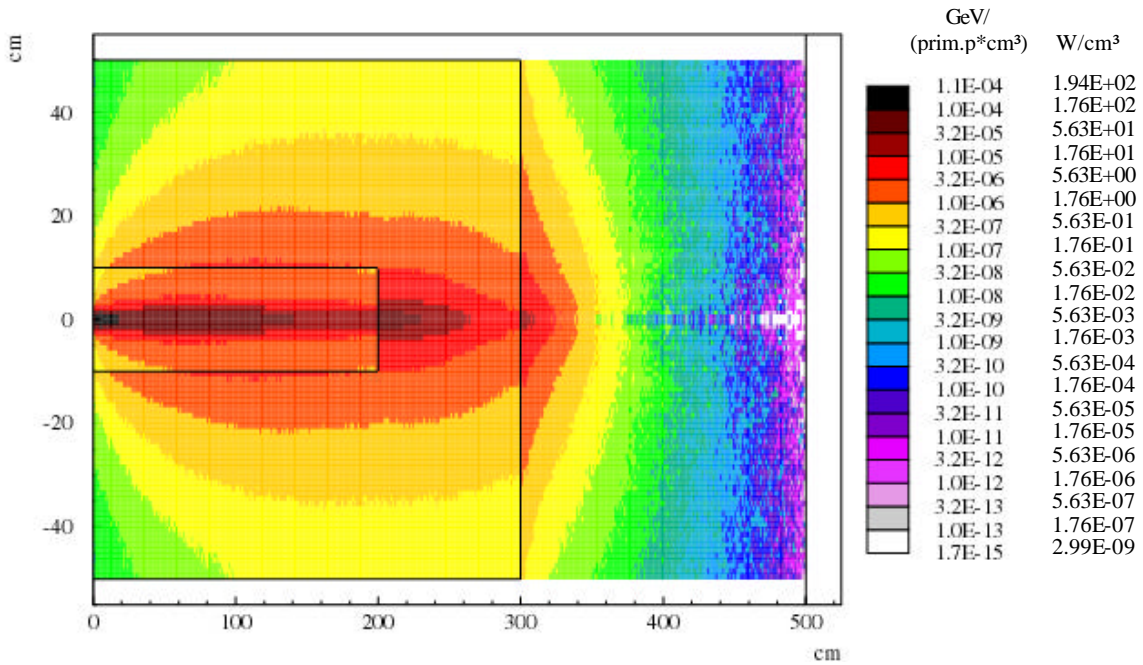**Figure 2.** Coarse energy deposition in the beam dump.

Figure 3. Accurate energy deposition in the inner part of the beam dump.

The integrated radial and axial profiles of the thermal power density are shown in Figure 4. With the present material choice, the effectiveness of the beam dump in absorbing the 2.2 GeV protons apparently saturates at a radius of 1.0 m and a length of 3.5 m. In both cases we find the saturation of the integrated value of the energy at 1.89 GeV. Since the nuclear reactions in our materials are endothermic, most of the remaining primary beam energy (0.31 GeV) is needed to separate nucleons from nuclei (about 8 MeV per nucleon), to perform fission or to produce neutrinos which are discarded in the simulation. In the present setup only 0.8% of the incident energy (2.2 GeV) is escaping the dump structure. Further analysis showed that 13.1% of the heating power (1.89 GeV) is deposited in the innermost core, 51.8% in the outer carbon structure and 35.1% in the iron shielding of the dump.

Within this cylindrical volume, the material density is functionally graded so that the absorbed energy density per unit volume is kept everywhere at acceptable levels. Figure 5 shows the radial and axial profiles of the absorbed energy density at $z = 120$ cm and on the beam axis respectively.
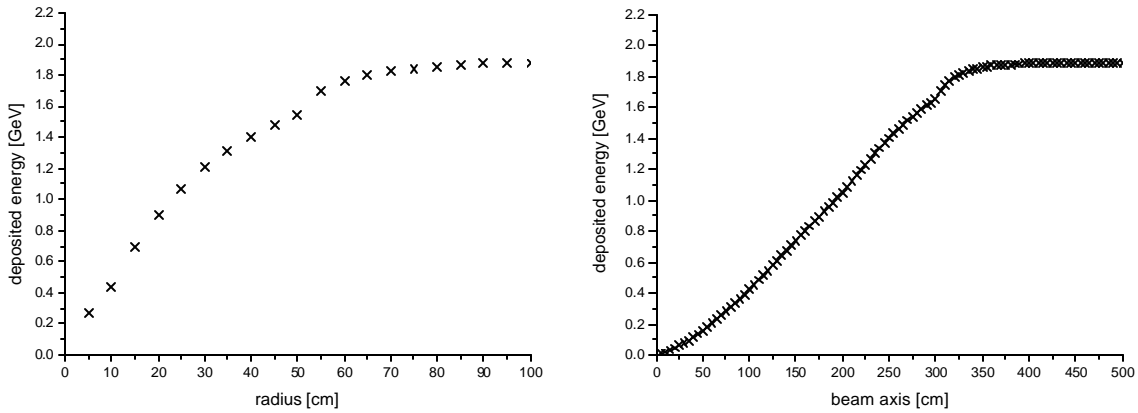

Figure 4. Integrated radial and axial profiles of the thermal power density per incident proton within the 4 MW beam dump.
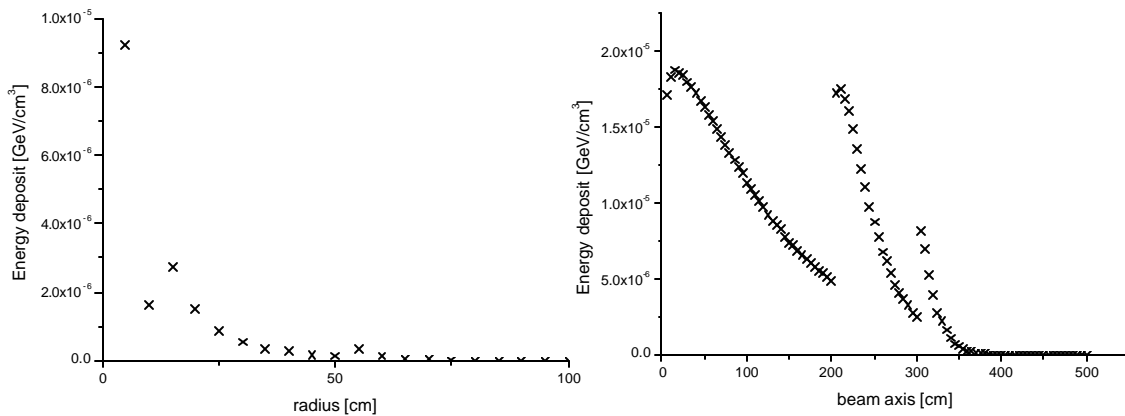

Figure 5. Radial and axial profiles of the absorbed energy density per incident proton at $z = 120$ cm and on the beam axis, respectively (bin size = 5 cm).

2.3 Thermal design

Based on the Monte Carlo simulations, the core has been subdivided into an inner and an outer part, to be built in graphitic foam and polycrystalline graphite, respectively. The former, where the peak of the thermal power density is located, can be directly cooled by a gas flowing through the porosities, while the latter could be refrigerated by conduction towards its free surfaces which are cooled by forced convection. The thermal design of the outer core is estimated of standard technological complexity and is not discussed here.

Direct gas cooling of the inner core is, together with the suitable material choice, a key idea of the present conceptual design. Cooling directly the most heated part of the core avoids in fact high temperatures, thermal gradients and stresses which could otherwise be prohibitive for reasonably simple engineering solutions.

The inner core acts as a once-through heat exchanger, with the carbon foam contained in a leak tight tube of heat resistant alloy closed at both ends by titanium beam windows. The coolant flows axially along the beam direction, the coolant inlet being located upstream to better cool both the window and the most critical section of the dump. The outer core is shrink-fitted into an actively-cooled jacket to refrigerate its outer surface. The cast iron shielding could be built in two halves and provided with cooling channels, similarly to those already in use at CERN.

The thermal transient at the start-up of the beam dump is smooth: based on the temperature-dependant specific heat of graphite, a maximum adiabatic ΔT of ~280 °C is estimated to occur during the first second of beam absorption. Later on, the adiabatic rise is slower, as the specific heat of graphite increases with temperature. This value is low enough to prevent dangerous dynamic effects (stress waves), which are therefore not of concern in the present conceptual design.

The huge internal surface of the carbon foam (2.4 $m^2 cm^{-3}$) allows to evacuate the peak power density of 176 W cm^{-3} estimated in the previous section. Heat transfer coefficients as low as 7.3 W $m^{-2}°C^{-1}$ are sufficient to cool effectively the inner core by a temperature difference between the foam and the cooling gas of only ~10 °C.

The use of a gas as a cooling medium implies inevitably a high temperature difference of the coolant between the core inlet and outlet in order to have reasonably low mass flow rates. In this respect, a high-temperature cooling system is envisaged which is based on a closed circuit Brayton cycle, coupling the advantages of high thermal efficiency and direct heat rejection into the atmosphere by means of a gas-gas heat exchanger.

The choice of the cooling medium must consider the issues of activation, required pressure levels, cost, as well as the properties of the gas as they affect the cooling performance. In this respect, carbon dioxide, nitrogen and helium represent possible choices which have been investigated in nuclear engineering.

Carbon dioxide has been considered since long time because of its availability at low cost, inertness in contact with materials and lack of serious activation problems (chemical reaction with the graphitic foam can be avoided by addition of CH_4).

However, at temperatures higher than 400 °C, dissociation becomes somewhat a problem. Helium, being inert and monatomic, is attractive at high temperatures. Nitrogen can be chosen as a inert diatomic gas with properties intermediate between the other two.

Despite chemical inertness, it is impossible to avoid reactions between the coolant impurities and graphite or the metal surfaces of the cooling circuit (for instance, typical He impurities in ppm are 0.1 H_2O, 10 H_2, 2 CO_2, 25 CO). The oxide layers protecting the high-temperature alloys normally become ineffective above 600 °C, so that particular care should be taken in choosing the right materials. However, for temperatures as high as 700 °C proven engineering solutions exist. Leak tightness of the cooling circuit is also not an issue, as a loss of 0.1% of coolant per day is achievable even when He is used, which is usually safe and economically acceptable.

In the case of helium, typical temperatures at the inlet and outlet of the dump core could be T_{in} = 50 °C and T_{out} = 700 °C, while limit pressures could be p_{min} = 35 bar and p_{max} = 85 bar. The pressure loss factor of the dump core and of the gas-gas heat exchanger can be estimated at 4%, while the compression and expansion efficiency would be typically 85%.

Under these conditions, the amount of heat evacuated by the cooling medium would be 2536 kJ kg^{-1}, while 842 kJ kg^{-1} would be required by the compressor. In the present design, ~13% of the beam power (~500 kW) is absorbed by the inner core. This would require a He mass flow rate of ~200 g s^{-1} with an apparent gas speed of 74 cm s^{-1} (the He density would be 8.4 kg m^{-3}), and a pressure drop through the foam porosity less than 4% (3.4 bar), in agreement with the hypothesis.

Part of the thermal power could be recuperated by a gas turbine, in which case a regeneration stage should be implemented in the Brayton cycle to increase thermal efficiency. If a regenerator efficiency of 80% is assumed, this would allow to recuperate ~17% of the energy deposited by the beam in the inner core. However, regeneration would reduce to 1372 kJ kg^{-1} the amount of heat per unit mass evacuated by the coolant, thus increasing its mass flow rate. Though higher thermal efficiencies (up to >30%) can be achieved by increasing the temperature in the dump core, it is not clear whether the net gain would justify the added complexity.

3. Conclusions

The present note was just intended to provide a first idea on how a dump for a 4MW proton beam may look like. No considerations were here given to several factors, such as radiation damage, which will have to be taken into account in a real design of a dump surrounded by many other components installed both upstream and downstream of it. For example, it is entirely possible that the dump and the horn (or solenoid) downstream of the pion production target will have to be of an integrated design.

Further issues which will have to be considered in the next stage of the design are the stray radiation emerging from the dump as well as activation of the materials and of the coolant. The choice of graphite for the core has the clear advantage that only two long living radioactive products (^{7}Be and ^{3}H) can be produced by nuclear reaction processes. In this respect graphite may thus prove much better than materials of

higher atomic number. The present conceptual design only focused on the energy deposition and thermal properties of the device, in order to evaluate whether a relatively simple solution was possible. Hence, the present design should be regarded as a sort of minimum configuration; a real device might be bigger simply because more material will be needed around the core to keep the secondary radiation escaping from the outer shielding to an acceptable level.

References

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