Solid Target Cooling for High Power Neutrino Super Beam

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Abstract

In this note the feasibility of the cooling of a solid target is investigated. This target fills the hole of the magnetic horn which acts as a magnetic lense for the secondary hadrons and is integral part of it's inner conductor. Low atomic number materials Beryllium, Aluminium and the compound AlBeMet have been chosen as target materials and are compared to Carbon. The beam parameters are assumed to be Super conducting Proton Linac-Super Beam like with about 5 GeV kinetic energy of the primary proton beam and a beam power of 1 MW and 4 MW, respectively. The final temperatures of the target are obtained in steady state cooling regime assuming a range of values for the average heat transfer coefficient $\bar{h} = \{5, 10, 15, 20\}$ kW/(m^{2}K) taking into account as heat sources the interaction of the primary beam with the target and the Joule losses due to the horn electric current.

1 Introduction

Neutrino accelerator experiments are based on the generation of a ν_μ beam from secondary particle decays of $\{\pi^+, K^+\} \to \mu^+ + \nu_\mu$ and the corresponding CP conjugated decays for $\bar{\nu}_\mu$, which are produced by a primary proton beam on a target. In order to improve the neutrino flux towards the detectors, the focusing of charged secondary particles is achieved with a strong toroidal magnetic field which is produced by a so-called magnetic horn [1].

The next-generation accelerator experiments are foreseen to work with primary beam powers of the order of few MW leading to huge energy depositions inside the target-horn station from the interaction with the beam.

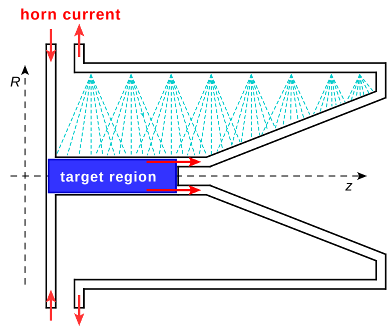


Figure 1: Schematic cut of the target being integrated as the inner conductor of the horn and cooled by water jets. The current circulates in the r-z plan, a toroidal magnetic field B_ϕ is produced inside the horn conductors.

The low kinetic energy of the primary beam requires the target to be placed inside the inner conductor of the horn [3], which offers the possibility to use the target itself as the inner conductor of the horn (Fig. 1). Consequently, the target material should be solid and conducting but also compatible with the material of the horn. The main heat source will be the primary beam, however for the integrated target the pulsed horn current will act as an additional heat source in form of resistive (Joule) losses. The purpose of this note is to investigate the impact of the two heat sources and to study the general feasibility of such a design.

2 Beam and target parameters

The current design studies [4] foresee a beam power of 4 MW at 50 Hz repetition frequency with protons of about 5 GeV kinetic energy. The pulse duration of the proton beam delivered on the SPL-Super Beam target-horn station, however, should be $\lesssim 5$ μs [2, 5] in order to limit the energy stored in the magnetic field generated by the pulsed current of the horn.

The primary beam consists of protons with kinetic energy with $E_{\mathrm{kin}}^{\mathrm{bm}} = 4.5$ GeV, chosen along the $+z$-direction. The beam spot is assumed to have a gaussian profile with a width of $\sigma^{\mathrm{bm}} = \{2, 4, 6\}$ mm in x- and y- directions when hitting the target and the preferred value of 4 mm [2]. The beam power is $P^{\mathrm{bm}} = 4$ MW which reduces to 1 MW per target in the case of operating with 4 target-horn stations and assuming an equal temporal distribution of the load.

Finally, the considered target is a cylinder centered around the z-axis and starting at $z_0^{\mathrm{tg}} = 0$ cm (for definiteness). It has the length $L^{\mathrm{tg}} = 78$ cm (about 2 radiation lengths) and the radius $R^{\mathrm{tg}} = 1.5$ cm. In this study the low atomic number materials Beryllium, Aluminium and the compound AlBeMet will be used and compared to Carbon (Graphite).

Properties at 300 K [9]	Be	C	AlBM	Al
Specification		IG 43	Be 61%, Al 38%, O 1%	alloy 2024-T6
Density ρ [g/cm^3]	1.85	1.85	2.10	2.7
Elect resistivity $\rho_{el} \times 10^{-8}$ [Ω m]	4.2	900	3.5	4.8
Thermal conductivity k [W/(m K)]	90 to 200	140	210	170
Specific heat C [J/(kg K)]	1752	710	1560	875

Table 1: Thermal and electrical properties of Beryllium (300 to 1000 K), Carbon, AlBeMet and Aluminium alloy at 300 K.

3 Energy deposition

The simulation of the energy deposition is done with FLUKA version 2008.3c [6, 7] scoring the deposited energy density per primary proton on target using a $r - \phi - z$ mesh in units of [GeV/cm^3/proton]. The target materials are modeled according to the density and composition in terms of mass fraction in the case of compounds as given in Tab. 1.

Figure 2 shows the typical energy distribution deposited from the beam in the longitudinal direction of the target and with a beam power of 4 MW. The distributions of the energy deposition serve as input of the numerical calculation of heat flux and temperature distributions in Sec. 6 and are referred to as heat source due to the beam-target interaction $\dot{q}_{\mathrm{Beam}}(r, z)$.

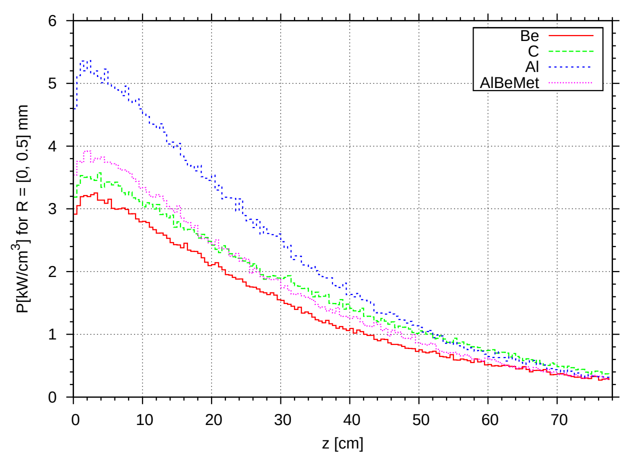


Figure 2: Distribution of deposited power in [kW/cm^3] from the beam in the z direction at $r \in [0, 0.5]$ mm in the targets for $P^{\mathrm{bm}} = 4$ MW and $\sigma^{\mathrm{bm}} = 4$ mm.

4 Joule losses

In the case of an integrated target as the inner horn conductor, the horn current which has to pass the target will lead to significant energy deposition caused by resistive (Joule) losses. They act as a second heat source besides the one due to the interaction of the target with the primary beam.

In order to estimate the power loss P over a certain length l:

$$\frac{P}{l} = \frac{R}{l} I_{rms}^2 \tag{1}$$

the assumption is made that all the current flows in the cylindrical surface layer of thickness δ of the target with the radius R^{tg}. The corresponding cross section is $S = \pi\delta(2\,R^{\text{tg}} - \delta)$ and the resistivity $R = \rho_{el}\, l/S$. It follows $I_{rms} = I_0\sqrt{\frac{\tau}{2T}} =$ 15 kA for a horn peak current of $I_0 = 300$ kA with a half sinusoidal pulse shape of $\tau = 100\,\mu$s duration, 20 ms time period, Aluminium material and:

$$\frac{P}{l} = \{108,\, 78,\, 64\}\frac{\text{kW}}{\text{m}} \tag{2}$$

for $R^{tg} = \{1.1,\, 1.5,\, 1.8\}$ cm as an estimate.

5 Model

The heat source coming from the joule effect is calculated with AC/DC module in COMSOL 3.3 with the meridional induction current mode, vector potential formulation for a 2D axisymmetric rectangle of dimensions $R^{\text{tg}} = 1.5$ cm and length $L^{\text{tg}} = 78$ cm. The temperature and heat flux are obtained by solving the heat conduction equation for the rectangle domain and using the resistive heating term calculated from the AC simulation and the source therm coming from the proton beam. A data file with power density $\dot{q}_{\text{Beam}}(r, z)$ function of the spatial location r-z is read by COMSOL to assign power density value every 0.5 mm in the radial position and 5 mm in the longitudinal z direction. Constant convection cooling coefficient is applied on the surface of the target cylinder, i.e on the line $r = 1.5$ cm.

5.1 AC/DC model for joule loss

The resistive losses denoted as $\dot{q}_{\text{Joule}}(r, z)$ are calculated with the help of COMSOL 3.3 [8] solving numerically Maxwell's equations in the quasi-static approximation for magnetic fields in conductors. Assuming media of uniform and frequency-independent permeability μ and permittivity $\varepsilon = \varepsilon_0\varepsilon_r$, the corresponding equations are:

$$\nabla \cdot \mathbf{E} = 0, \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{3}$$

$$\nabla \cdot \mathbf{B} = 0, \qquad \nabla \times \mathbf{H} = \sigma\mathbf{E} + \frac{\partial \mathbf{D}}{\partial t} \tag{4}$$

where the conductivity of the material is denoted by $\sigma = 1/\rho_{el}$. There are no external currents due to the absence of free charges. The electric and vector potentials V and $\mathbf{A}$ are defined as usual:

$$\mathbf{B} = \nabla \times \mathbf{A}, \qquad \mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t} \tag{5}$$

such that $\mathbf{E} = -\partial\mathbf{A}/\partial t = \frac{\mathbf{J}}{\sigma}$ in the absence of free charges ($V = 0$). Finally, the vector potential obeys:

$$\nabla^2\mathbf{A} = \mu\left[\sigma\frac{\partial}{\partial t} + \varepsilon\frac{\partial^2}{\partial t^2}\right]\mathbf{A} \overset{\varepsilon/\sigma\ll 1}{\approx} \mu\sigma\frac{\partial \mathbf{A}}{\partial t}. \tag{6}$$

The current density $\mathbf{J}$ has only a non zero component in the z direction and since $\mathbf{J}$, $\mathbf{E}$ and $\mathbf{A}$ are collinear, the magnetic potential is a scalar for the z component. For time harmonic fields, the corresponding equation used in the COMSOL model is:

$$-\frac{1}{\mu}\nabla^2 A_z + \omega(i\sigma - \omega\varepsilon)A_z = 0 \tag{7}$$

where the axial symmetry has been exploited.

The boundary conditions are implemented in COMSOL by specifying the the tangential magnetic field at the boundary (Neumann type) in terms of the total current using Ampere law. $H_\phi = \sqrt{2}I_{rms}/2\pi R^{\text{tg}}$.

Finally the volume energy losses from the electrical current are given by:

$$\dot{q}_{\text{Joule}} = \frac{1}{2}\sigma\mathbf{E}\cdot\mathbf{E}^* = \frac{1}{2}\sigma\omega^2\mathbf{A}\cdot\mathbf{A}^*. \tag{8}$$

with $\mathbf{A}^*$ the complex conjugate phasor of $\mathbf{A}$.

material	conductivity [W/mK]	σ^{bm} [mm]	Q_{Beam} [kW]	Q_{Joule} [kW]
Al	170	4	278	60
		6	256	60
Be	90 to 200	4	165	56.3
		6	153	56.3
AlBeMet	210	4	200	51
		6	185	51
Carbon IG 43	140	4	196	-
		6	182	-

Table 2: Summary of total power deposition inside the Al-, Be-, AlBeMet- and C-target for $\sigma = \{4, 6\}$ mm and $P^{\mathrm{bm}} = 4$ MW due to beam interaction and Joule losses.

5.2 Heat conduction equation

In steady state regime the axial-symmetric model is described by the following static heat conduction equation:

$$\nabla \cdot [k \, \nabla T(r, z)] + \dot{q}(r, z) = 0. \tag{9}$$

The heat source density distribution is composed of:

$$\dot{q}(r, z) = \dot{q}_{\mathrm{Beam}}(r, z) + \dot{q}_{\mathrm{Joule}}(r, z) \tag{10}$$

which have been discussed in the previous sections Sec. 3 and Sec. 5.1, respectively. $\dot{q}_{\mathrm{Beam}}(r, z)$ was calculated with FLUKA for this geometry for the Be-, C-, Al- and AlBeMet-targets and three different beam widths. Throughout the results for the beam widths of $\sigma^{\mathrm{bm}} = \{4, 6\}$ mm are used. The thermal conductivity is denoted by k and given in Tab. 1. The temperature dependence of k has been neglected for the moment as well as heat transfer by radiation. We further neglect potential influences due to radiation damages caused by the primary beam particles.

The heat conduction equation is solved with COMSOL to obtain the heat flux and temperature distribution inside the target for the domain $\Omega : r \in [0, 1.5]$ cm $\times\, z \in [0, 78.0]$ cm.

The boundary conditions are applied as follows. Thermal insulation is specified for $z = 0$ cm, and $z = 78.0$ cm. On the surface of $r = R^{\mathrm{tg}} = 1.5$ cm uniform heat convection is applied to simulate the cooling characterised by an average heat transfer coefficient $\bar{h} = \{5, 10, 15, 20\}$ kW/(m^{2}K) and the temperature of an external heath bath $T_\infty = 20\,^\circ$C. The surface temperature $T(r = R^{\mathrm{tg}}, z)$ is then fixed via the surface heat flux as:

$$k \left.\frac{\partial T}{\partial r}\right|_{r=R^{\mathrm{tg}}} = \bar{h}\,[T(r = R^{\mathrm{tg}}, z) - T_\infty]. \tag{11}$$

6 Results

This section presents the details and results of the calculation of the heat flux and the maximal value of the core and surface temperature of the target assuming a continuous incoming primary beam, i.e. neglecting the envisaged pulsed operation, and taking into account Joule losses. The cooling is simulated with a constant (z-independent) heat transfer convection coefficient $\bar{h}$ on the surface of the target.

6.1 Power distribution

The combined power distributions are shown in Fig. 3 for Be when adding the two heat sources of beam interaction $\dot{q}_{\mathrm{Beam}}$ and Joule losses $\dot{q}_{\mathrm{Joule}}$. The integrated powers Q_{Beam} and Q_{Joule} are summarised in Tab. 2.

The beam provide the main heat source term, the joule effect is visible near the surface of the cylinder as shown in Fig. 3.

6.2 Surface heat flux

In order to maintain the target surface and core temperatures below a certain limit, for example 200 °C and 300 °C, respectively, it is necessary to design a cooling system with sufficient high heat flux removal. The heat flux is a function of the deposited power in the target and the radius and length. It is calculated with the model described in Sec. 5.2 for each material for $\sigma^{\mathrm{bm}} = \{4, 6\}$ mm and $P^{\mathrm{bm}} = \{1, 4\}$ MW. Note, that for Carbon the heat source due the Joule effect is not taken into account because it can not be used as an electrical conductor.

Fig. 4 shows that the maximum surface heat flux is located around $z = 5$ cm with a magnitude of $\{2.5, 1.8, 1.7, 1.2\}$ MW/m^2 for Al, AlBeMet, Be and C at $P^{\mathrm{bm}} = 1$ MW.

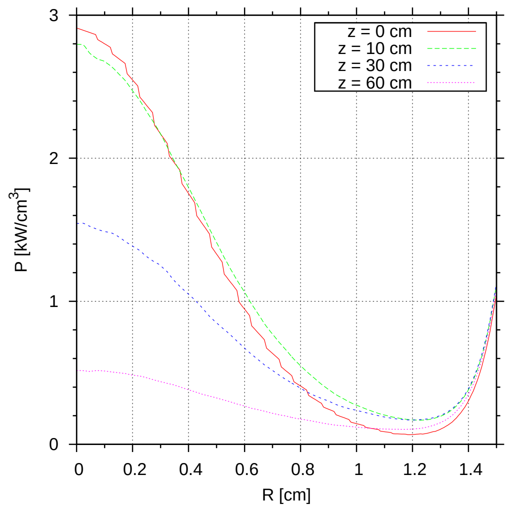


Figure 3: Power distribution in [kW/cm^3] along r for $z = \{0, 10, 30, 60\}$ cm, $P^{\text{bm}} = 4$ MW and beam width $\sigma^{\text{bm}} = 4$ mm in the Be-target from beam and joule losses.

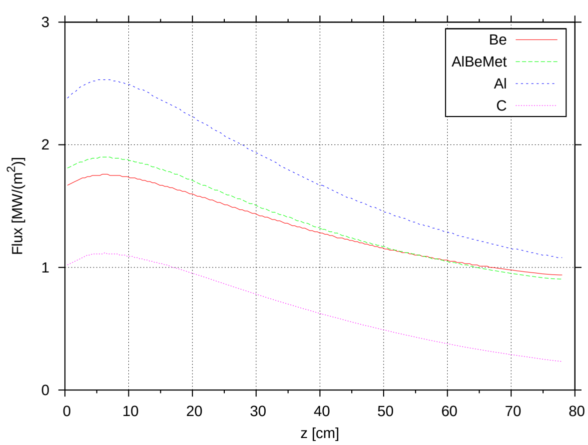


Figure 4: Heat flux at the target surface for Al, Be, C, AlBeMet and $P^{\text{bm}} = 1$ MW.

6.3 Core and surface temperature

In Fig. 5 and Fig. 6, the maximal temperatures at the core and surface of the target are plotted for the four materials at different heat transfer coefficients. These plots are used to determine the minimum $\bar{h}$ coefficient required to keep the target temperature below a safety limit.

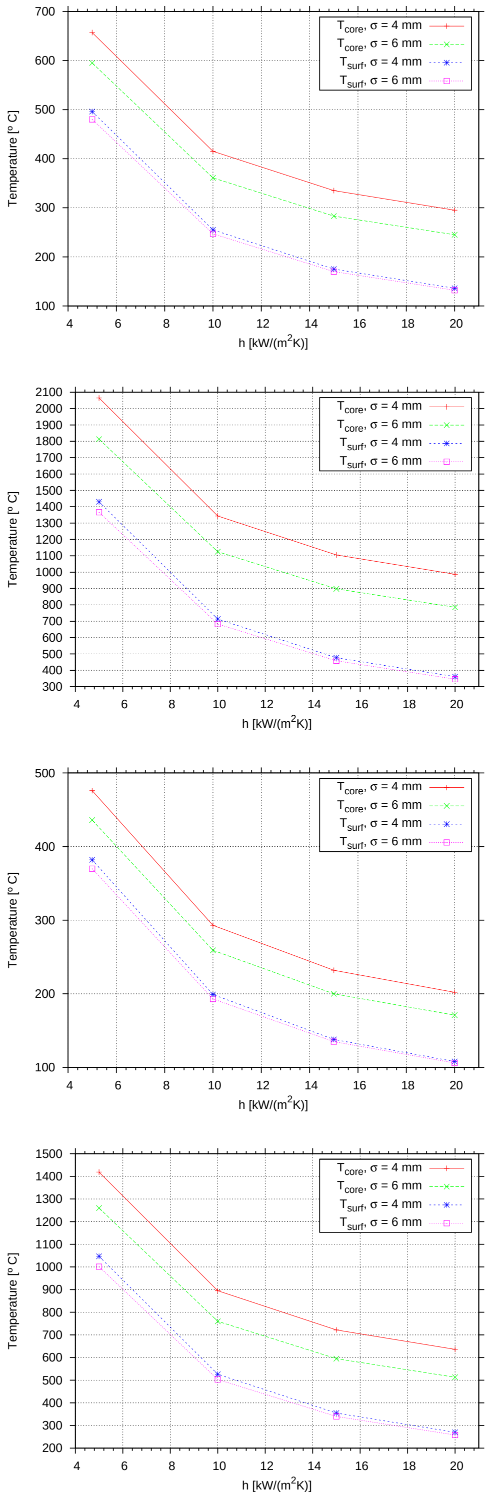
At $P^{\text{bm}} = 4$ MW, the lowest temperatures are obtained at $\bar{h} = 20$ kW/(m^{2}K) and $\sigma^{\text{bm}} = 6$ mm with $T_{\text{core}} = \{800, 600, 560, 520\}\,^{\circ}$C for Aluminium, Beryllium, Carbon and AlBeMet, respectively.

The respective melting points are $\{502, 644, 1277\}\,^{\circ}$C for Al, AlBeMet and Be and the disintegration temperature of $\gtrsim 3500\,^{\circ}$C for Carbon. The use of Be, AlBeMet and C would be possible but only with $\bar{h} > 20$ kW/(m^{2}K) which is difficult to obtain. It does not seem feasible to use Al at 4 MW

At $P^{\text{bm}} = 1$ MW Fig. 5 and Fig. 6 show that the maximal core temperature of the target could be maintained below $300\,^{\circ}$C with $\bar{h} \geq \{13, 20\}, \{8, 10\}, \{8, 10\}, \{5, 7\}$ kW/(m^2K) for Al, Be, AlBeMet and C with $\sigma^{\text{bm}} = \{6, 4\}$ mm.

7 Summary

A study of the cooling of a pion production target is provided in view of application to the high power muon neutrino SPL-Super Beam from CERN to Fréjus. The materials Beryllium, Carbon, Aluminium and the compound AlBeMet with low atomic numbers were considered. The corresponding energy distribution at proton beam energy of 4.5 GeV was determined with the help of FLUKA in a cylindrical geometry of length $L^{\text{tg}} = 78$ cm and radius $R^{\text{tg}} = 1.5$ cm, at different beam width (gaussian in transverse plane) $\sigma^{\text{bm}} = \{4, 6\}$ mm. Additionally, the resistive (Joule) losses due to a pulsed horn electric current of 300 kA have been taken into account with COMSOl 3.3 for the conducting materials Beryllium, Aluminium and AlBeMet as a second heat source, in anticipation of the integration of the target as integral part of the inner horn conductor.



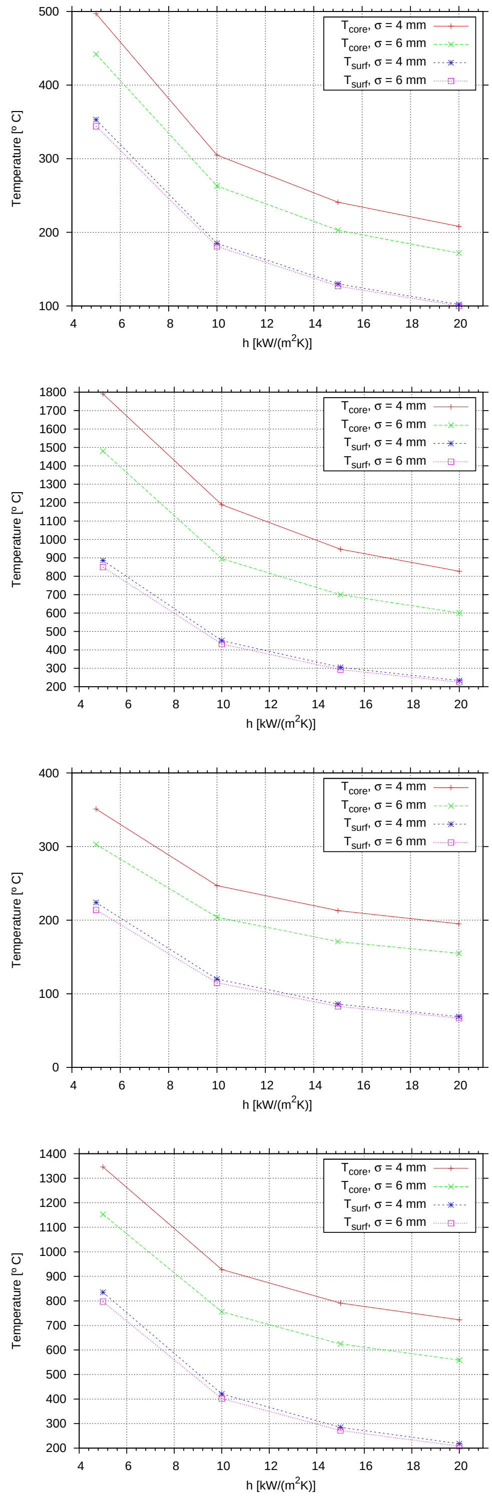


Figure 5: Core and surface temperature versus $\bar{h}$ for beam width $\sigma^{\text{bm}} = \{4, 6\}$, from top to bottom Al with $P^{\text{bm}} = 1$ MW, Al with $P^{\text{bm}} = 4$ MW, AlBeMet with $P^{\text{bm}} = 1$ MW, AlBeMet with $P^{\text{bm}} = 4$ MW

Figure 6: Core and surface temperature versus $\bar{h}$ for beam width $\sigma^{\text{bm}} = \{4, 6\}$, from top to bottom Be with $P^{\text{bm}} = 1$ MW, Be with $P^{\text{bm}} = 4$ MW, C with $P^{\text{bm}} = 1$ MW, C with $P^{\text{bm}} = 4$ MW

The corresponding distribution of the surface heat flux and the core and surface temperatures have been calculated in steady state regime with COMSOL, assuming a constant average heat transfer coefficient $\bar{h} = \{5, 10, 15, 20\}$ kW/(m^{2}K) at the target surface for a beam power of $P^{\rm bm} = \{1, 4\}$ MW.

When distributing the 4 MW on 4 target-horn stations at a power of 1 MW core temperatures around or below 300 °C can be achieved for Beryllium, AlBeMet and Carbon already with $\bar{h} = 10$ kW/(m^{2}K) and $\sigma^{\rm bm} = 4$ mm, the case of Aluminium requires $\bar{h} = 20$ kW/(m^{2}K).

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