Design of a 300kW proton Beam Dump for ESS-Bilbao

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Abstract. The ESS-Bilbao Neutron Applications Lab will require a proton Beam Dump to stop the proton beam during certain test and operational phases. The DTL accelerator will produce a 60 MeV proton beam with an average current of 5mA and 1.5 ms pulses at a frequency of 20 Hz. Hence, based on existing concepts, a 300 kW Beam Dump is being designed according to these beam parameters. It will have to with the impact of the beam in continuous operation. The selected concept consists of a hollow copper-made cylindrical body, with a conical cavity inside. The large surface area of the cavity allows a low heat deposition per unit area. Cooling is performed by water along helical channels embedded in the copper body. Given the coupled effects of particle transport, thermal hydraulics and thermal mechanics in this type of component, different coupling codes have been developed in order to perform multidisciplinary analyses that simulate these phenomena. A review of the mechanical design of the Neutron Applications Lab Beam Dump is presented on this paper, along with a description of the tools and codes that have allowed the designers to perform parametric analyses and to couple the different codes involved in the design process.

1. Introduction

1.1. Beam parameters

Beam parameters represent the main input data to the process of designing the Beam Dump, as they determine the total amount of energy absorbed by the Beam Dump, as well as its time and spatial distribution. The expected values of the pulsed proton beam parameters are listed on Table 1.

It can be observed that a precise value of some of these parameters is not available at this stage of the accelerator design yet. In order to produce a conservative design, it will be based on the the most demanding combination of the parameters within their range of uncertainty. Taking this into account, the Beam Dump has been designed for a **total power of 300 kW**.

The proton beam is completely defined with its geometrical profile. Regarding this, the beam is assumed to have a circular cross section of radius $R = 5\ cm$ and a two-dimensional Gaussian profile, with a standard deviation of $\sigma = 2.5\ cm$. However, for cases where it is more conservative, the beam will considered parabolic.

Table 1. Main beam parameters.

Proton energy	$50 - 60\ MeV$
Pulse length	$0.3 - 1.5\ ms$
Pulse frequency	$20 - 50\ Hz$
Peak current	$75\ mA$
Time-averaged current	$\leq 5\ mA$

1.2. Conceptual design

The design of this Beam Dump consists of a series of hollow copper-made cylinders with conical cavities of decreasing radius in their interior. The beam is spread over large surface area of this conical cavities, which have varying conical angles in order to adapt to the different intensities of the beam along its radius. Helical cooling channels are manufactured in each section to remove the heat deposited by the beam. In particular, two channels are manufactured in each section, allowing for double mass flow rate for a constant coolant velocity. Each section is manufactured in two pieces, one where the channels are carved outside a cylinder, and a hollow cover welded around the first one. This design for a Beam Dump is based on SAFARI, the Beam Dump for SPIRAL2 [1].

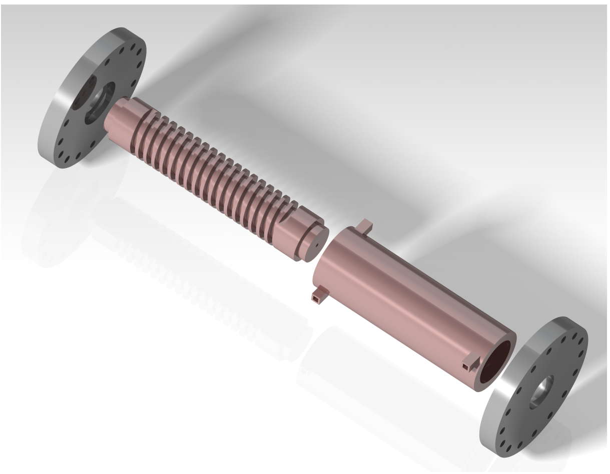

Figure 1. Example of Beam Dump section.

1.3. Design criteria and parameters

Different criteria are evaluated to decide whether a design is acceptable or not. First, the design must be easy to manufacture. This, for instance, involves that each section cannot exceed 40 *cm* in length. Then, two cooling criteria must be met: a certain maximum temperature cannot be exceeded in the copper body and, more important, there must be a safety margin of at least 20^oC from boiling temperature on the channel surface. Finally, a mechanical criteria is applied: maximum *von Mises* stress must be low enough to avoid fatigue conditions.

Trying to meet the previous criteria, the designers perform parametric analyses to determine the optimal configuration of the Beam Dump. Among others, the following **design parameters** are to be optimized:

- Number of sections.
- Length and radii (outer, inner upstream and inner downstream) of each section.
- Cooling channels dimensions and aspect ratios.
- Helical pitch.

2. Geometry

The definition of the geometry is influenced by the designers criterion that the Beam Dump should *see* a constant heat flux on its conical surface. This is the criterion to calculate the conical angle of each section, and it has an important influence in other geometrical features.

2.1. Theoretical approach

A theoretical cooling analysis has been the first step towards determining the geometry of the Beam Dump. The idea is to obtain a rough estimate of what the constant heat flux, while guaranteeing that appropriate cooling is achieved. It is at this stage of the design that a double helix was introduced instead of a single helical channel, providing improved cooling conditions. Hand-made calculations were performed for different values of heat flux on a hypothetical section. It could be observed that a heat flux of $2MW/m^2$ would lead to wall temperature around 120^oC, while $1MW/m^2$ leads to 80^oC. With the required margins from boiling temperature, it was decided to proceed with the analysis with a constant heat flux of $1MW/m^2$.

The next step was to obtain an analytical expression that would describe the conical profile of the Beam Dump along its axis, while forcing this surface to see a constant heat flux of $1MW/m^2$. It was necessary to make certain assumptions to simplify this problem:

- Protons travel in a horizontal straight line inside the Beam Dump.
- Protons deposit all of their energy in their first and only interaction with the copper surface.
- A steady-state scenario is analysed, considering the beam is not pulsed but an averaged continuous beam.

Under these assumptions, the following relationship between axial (x) and radial (r) position was found:

$$x(r) = \frac{Q_0 \cdot \sigma\sqrt{2\pi}}{2q''} \cdot errf(\frac{r}{\sigma\sqrt{2}})$$

A graphical image of this equation is shown in Figure 2.

It can be observed that the total length of the Beam Dump will be around $2.6m$. The slope is small and fairly constant at the center of the beam, while it is larger and varies sharply in the outer region.

2.2. Section dimensions

According the the profile describe in the previous section, the geometry has been divided into 8 sections. The dimensions of these sections are listed in Table 2.

3. Numerical Analysis

The general aspects of the Beam Dump have already been defined. Then, it remains to simulate the working conditions of each Beam Dump section, in order to find results for heat deposition, temperature fields, coolant flow maps, pressure drop and mechanical stress.

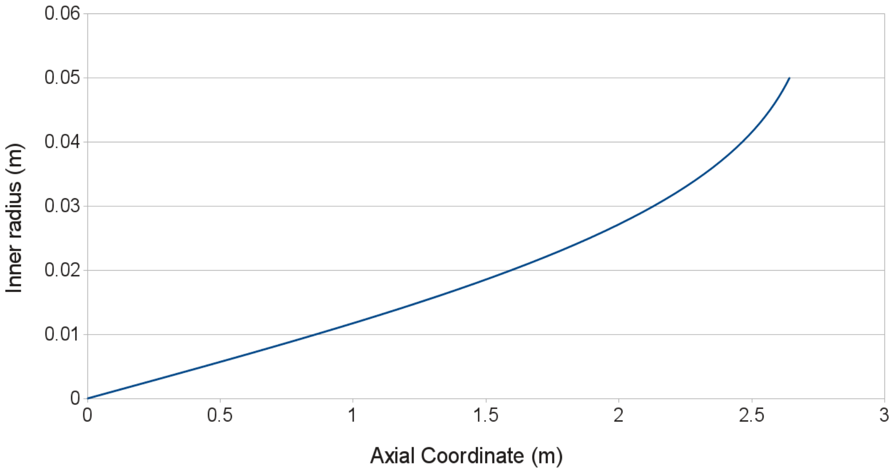

Figure 2. Beam Dump theoretical profile for a constant heat flux of $1 MW/m^2$.

Table 2. Beam Dump sections.

Section	Length [m]	Down Radius [mm]	Up Radius [mm]	Power [kW]
I	0.55	0	2	1.1
II	0.25	2	4	3.3
III	0.35	4	8	12.9
IV	0.40	8	13	26.6
V	0.40	13	18	35.3
VI	0.40	18	24	48.9
VII	0.40	24	33	73.7
VIII	0.40	33	50	98.2

3.1. Methodology and codes

While designing this Beam Dump, a procedure and a set of codes have been developed to deal with design problems where particle transport, fluid mechanics and thermal mechanics are all present. Figure 3 shows a schematic of this procedure that has been created for the simulations.

This procedure consists of the following steps.

(i) Geometry definition. The geometry is defined from the main code and it is passed to MCNPX[2] and to the FEM module. The equivalence of both geometries is guaranteed because they are generated from the same set of parameters.

(ii) MCNPX. The geometry is created in MCNPX, the beam is defined and heat deposition is measured on a mesh tally after enough particles have been launched. A heat deposition file is passed to the CFD code.

(iii) FEM Geometry. Using the parameters defined in the main code, the FEM geometry is created and passed to the CFD mesher.

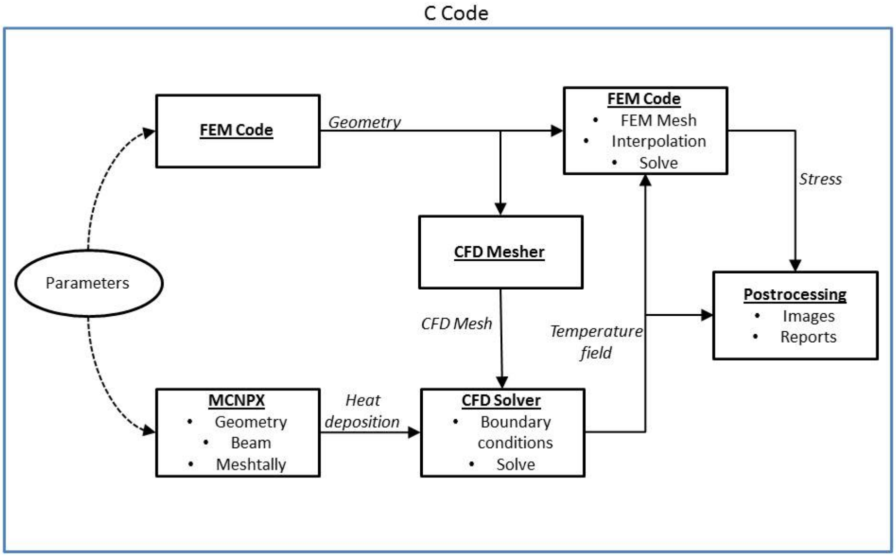

Figure 3. Schematic of applied methodology.

(iv) CFD meshing. A CFD is used to mesh the geometry for the fluid mechanics problem. The geometry is imported from the FEM code and meshing parameters are governed from the main code. A mesh file is passed to the CFD package.

(v) CFD problem. A CFD code imports the mesh from the CFD mesher, and it applies the heat deposition obtained in MCNPX via User-Defined Functions. Boundary conditions are applied and a solution is obtained for the thermal problem. The resulting temperature field is passed back to the FEM code.

(vi) FEM stress analysis. The FEM code meshes the geometry and interpolates the temperature field from the CFD mesh into its own mesh. Boundary conditions are applied and a solution is obtained. The resulting stress field is stored for postprocessing.

(vii) Postprocessing. The main code includes the required tools to postprocess the results and assess results quality. Reports and figures are automatically generated, allowing a quick review of the results.

3.2. Preliminary results

One of the first conclusions after simulating some of the sections is that the assumption that protons deposit their energy where they first interact with the copper surface is wrong. This effect is illustrated in Figure 4. This was concluded after observing heat deposition in regions with no direct view from the beam. These regions were the transition between consecutive sections, and flanges did not allow for cooling channels to reach them. Consequently, these regions were not designed to be properly cooled and unacceptable stress and temperature results were obtained.

In order to solve this issue, the original design of the transition regions was compared to three alternatives. The geometry of this alternatives is shown in Figure 5. After analysing the advantages and disadvantages of these designs, it was decided to change to alternative C, where the transition region is eliminated.

In addition to removing the perpendicular wall that was receiving a very high heat flux, the adopted alternative allows for cooling channels to reach closer to the limits of each sections, greatly reducing the stress and temperature problems that appeared in this area.

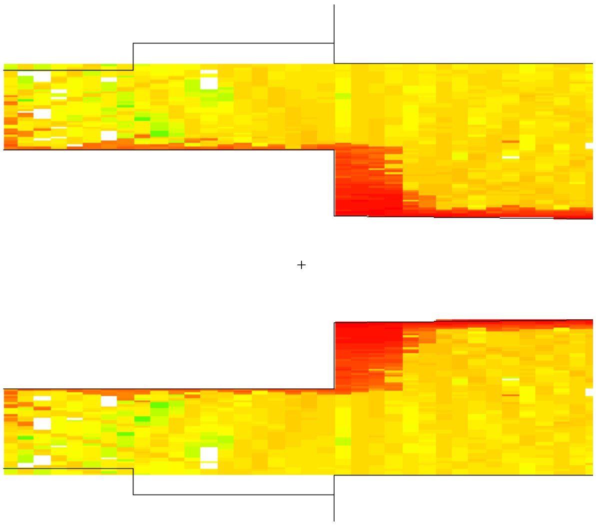

Figure 4. Heat deposition on perpendicular wall of transition region.

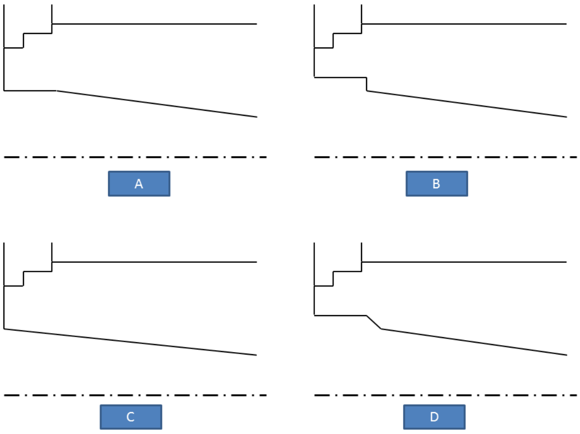

Figure 5. Different geometries studied for the transition between sections.

Although the issue with transition between sections is solved, the fact that protons do not deposit their energy where they first interact with the copper body leads to the final sections being more loaded than originally planned, while the entry regions will be less loaded than it was expected.

3.3. Optimised section results

After the modifications described in the previous section, the geometry of each section can be described by the parameters shown in Figure 6. Different series of simulations are run to optimise the value of these parameters, searching to minimise stresses and channel surface temperatures.

For instance, optimisation on parameter N, number of turns per helical channel, shows that a higher density of channel improves cooling conditions up to the limit where consecutive channels are too close and stresses increase very sharply. This effect can be observed in Figure 7, where stress increases significantly for $N = 9$ and higher. Regarding temperature, it can be observed how both maximum channel and global temperatures decrease as N increases. With these trends

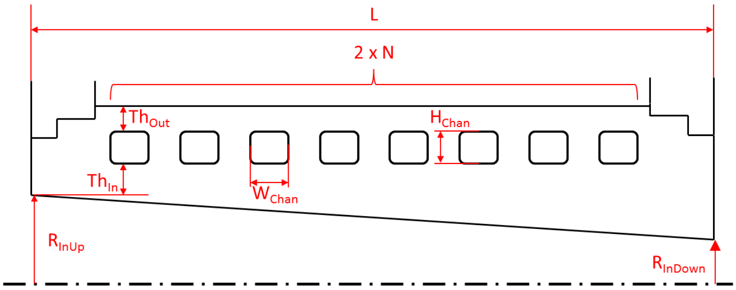

Figure 6. Parameters that define a Beam Dump section.

in mind, the optimal value of N for this particular case would be $N = 8$.

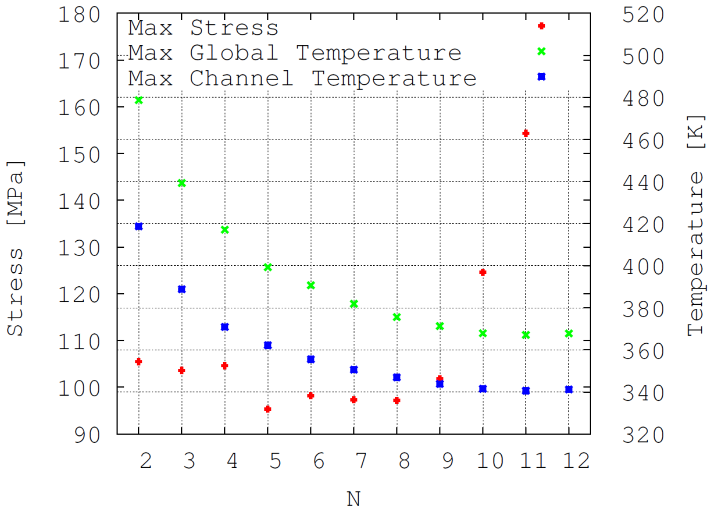

Figure 7. Example of optimisation of N.

Similar opmisation series have been run for other parameters, until a combination of them is found that satisfies the design criteria with the largest possible margins. This process has already been performed for Sections II and III, and will soon be finished for the remaining sections. Results obtained so far are listed on Table 3, while the aspect of temperature and stress fields are shown in Figures 8 and 9 respectively.

Table 3. Sections II and III results.

Section	Maximum stress [MPa]	Maximum temperature [K]	Maximum channel temperature [K]
II	100.0	375.4	343.5
III	113.0	400.5	356.2

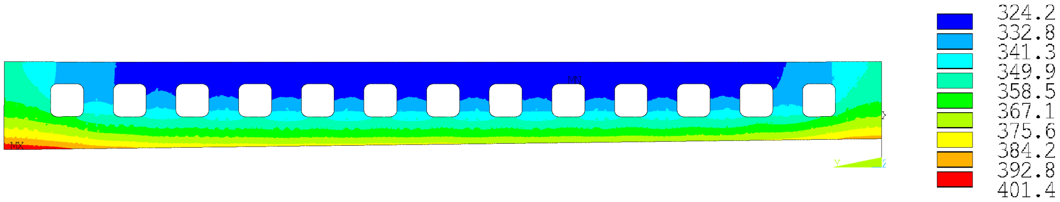

Figure 8. Example of temperature field on a Beam Dump section [K].

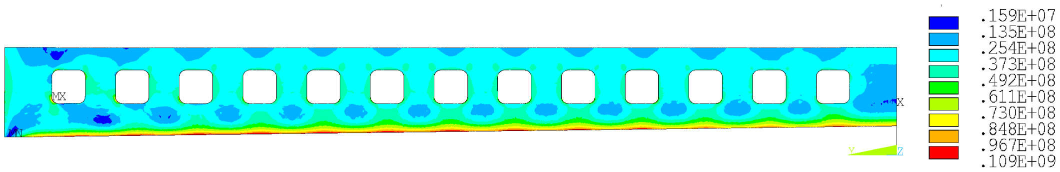

Figure 9. Example of stress field on a Beam Dump section [Pa].

4. Conclusions

Regarding the ongoing work on the Beam Dump for the Neutron Applications lab at ESS-Bilbao, it can be concluded that:

- A 300 kW proton Beam Dump is being designed to operate continuously during test of the accelerator and some operational states of the facility.
- A procedure to approach this kind of designs has been developed in parallel to this Beam Dump. It includes to codes to analyze problems with coupled particle transport, fluid dynamics and thermal mechanics.
- Optimization of the Beam Dump geometry is being performed, looking for minimum values of stress, temperature and maximum margins from boiling temperature.

Acknowledgments

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