ESS-Bilbao Faraday Cup thermo-mechanical analysis

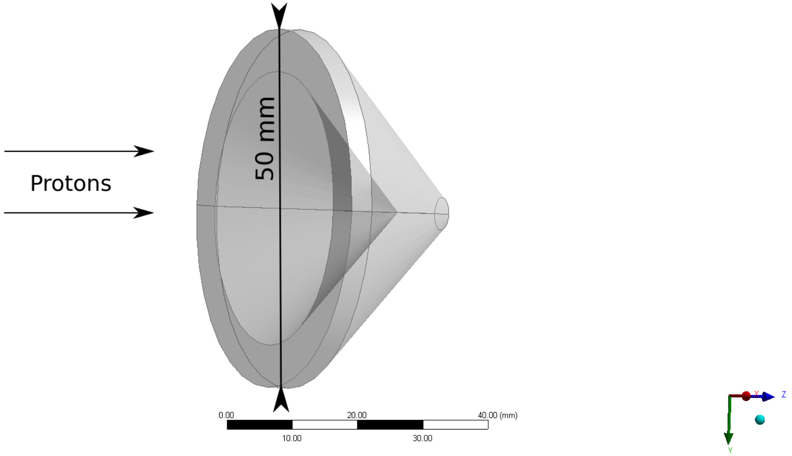
T. Mora, F. Sordo, I. Bustinduy, et al.
ESS-Bilbao
Neutronics Group
July 4, 2016
(MEBT-BI-FC03-04)

Introduction

Geometry description

The Faraday Cup is an element whose purpose is to stop a pulsed proton beam. In this study different modes of the proton beam will be analyzed in order to estimate the thermo-mechanic effects produced in the FC. The preliminary geometry corresponds to a conical element with 40 mm of inner diameter, whose material is copper. The FC volume is 20.1 cm^3.

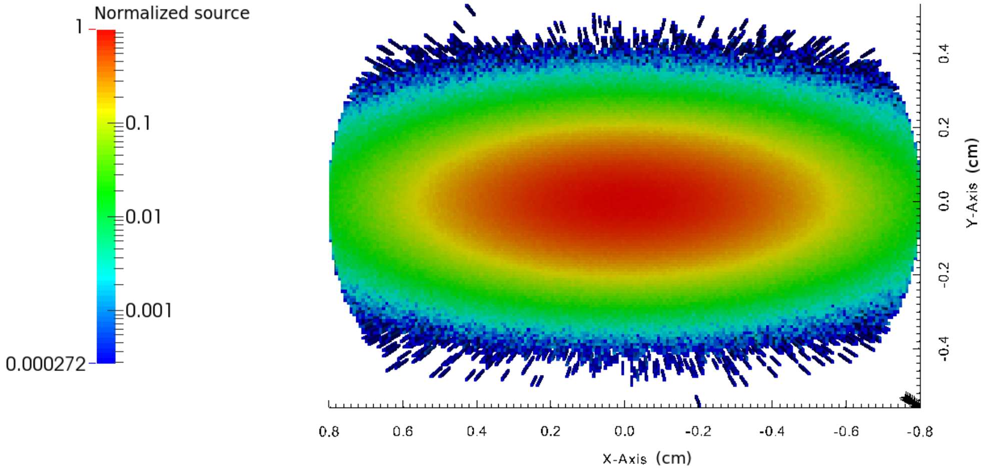
Geometry



Beam parameters

The proton beam has an energy of 3.6 MeV and travels in the direction of the Z axis to collide into the FC. Its distribution corresponds to a Gaussian function in the X and Y axis, which are determined by the parameter FWHM (Full Width at Half Maximum). For the following study and agreed beam footprint will be used based in the **2015.v0** layout, this footprint has been taken as a worst case scenario. From the thermo-mechanical calculations perspective, the beam will have symmetry to a quarter of its geometry.

- FWHM axis X: 6.6 mm $\rightarrow \sigma_x = 2.8\ mm$
- FWHM axis Y: 2.4 mm $\rightarrow \sigma_y = 1.1\ mm$



Operation modes

	Mode 1	**Mode 2**
Protons energy (MeV)	3.6	3.6
Current peak (mA)	62.5	62.5
Pulse length (μs)	5	50
Pulse frequency (Hz)	14	1
Current average (μA)	4.375	3.125
Power average (W)	15.75	11.25

Solving methodology

The objective of the analysis will be to determine the temperature evolution in the Faraday cup after proton pulse occurs.

Three steps have been followed to make the calculations:

- A MCNPX model has been done in order to determinate the heat deposition in the FC.
- Steady state thermal calculations: temperatures.
- Transient state thermal calculations: peak temperatures and its time evolution.

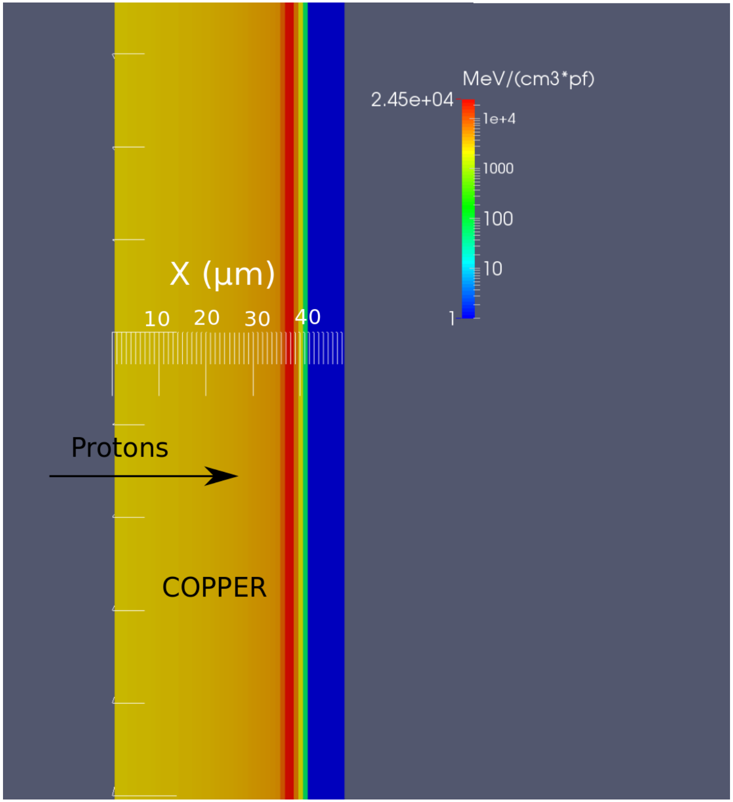
Calculation parameters

The thermal analysis has been done with four boundary conditions

- Natural convection on the outer surface of the FC, whose heat transfer coefficient is 10 $W/(m^2\ ^oC)$ *(Fundamentals of Heat and Mass Transfer; Frank P. Incropera)*.
- Ambient temperature: 30 ^oC.
- Adiabatic conditions on the inner surface of the FC.
- No radiation effects.

Bragg Peak

First of all, initial MCNPX simulations have been done to estimate the depth in which the Bragg peak occurs with a proton energy of 3.6 MeV in the copper. The Bragg peak appears at $35 - 37$ μm of length, and the maximum penetration of protons in copper reaches 40 μm.



Particularities of the problem

In order to make a postprocessing of the information, getting exactly the energy deposition of protons in the FC geometry presents several difficulties.

- The conical geometry: it is hard to adjust this shape to the MCNPX tallies coordinate systems, used to catch the energy deposition.
- Small penetration into the material: it is needed a fine mesh to achieve an accurate measure of the different energy deposition areas.

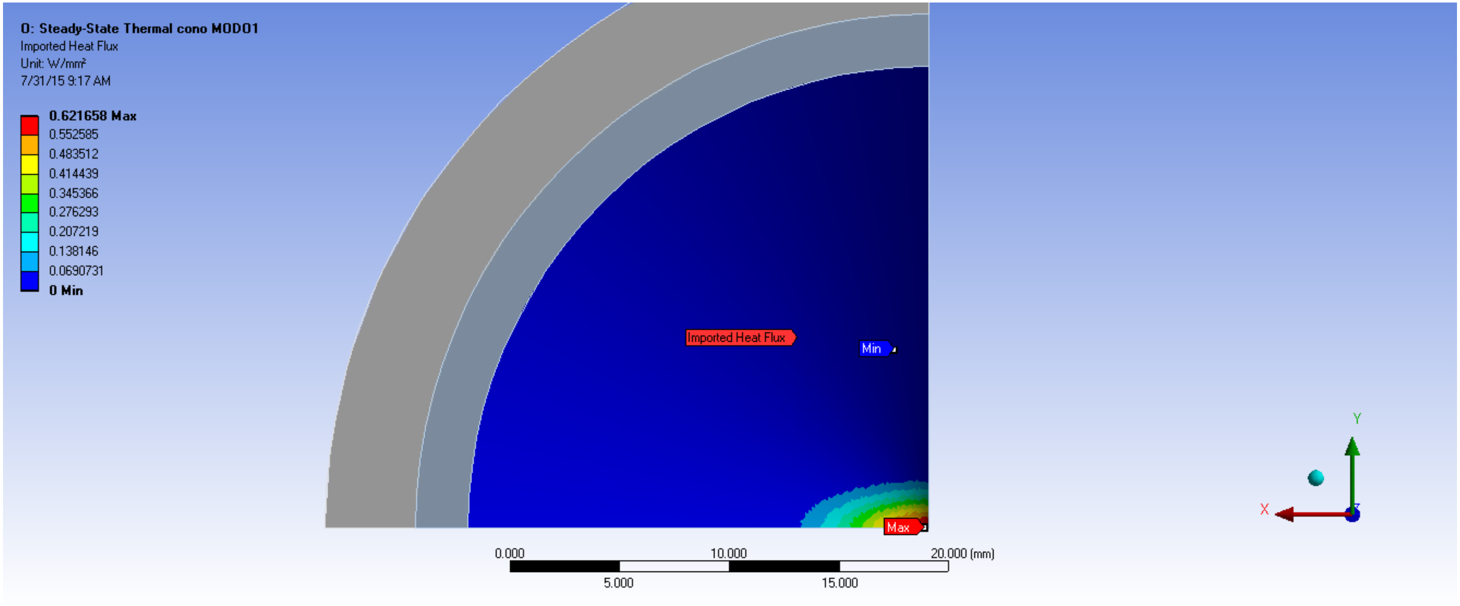
Model Approximations

- Due to the small penetration of the protons, the volumetric heat deposition has been transform into a heat flux on the inner surface of the Faraday Cup.
- The calculations have been done in a quarter of the model because the FC geometry and the proton beam have a quarter symmetry.
- The transient analysis have been done with a submodel of the steady analysis, using boundary conditions.
- No phase shifts have been taken into account. Due to this, some temperatures can be grater than the melting point of the materials.

Initial Analysis: Modes of operation

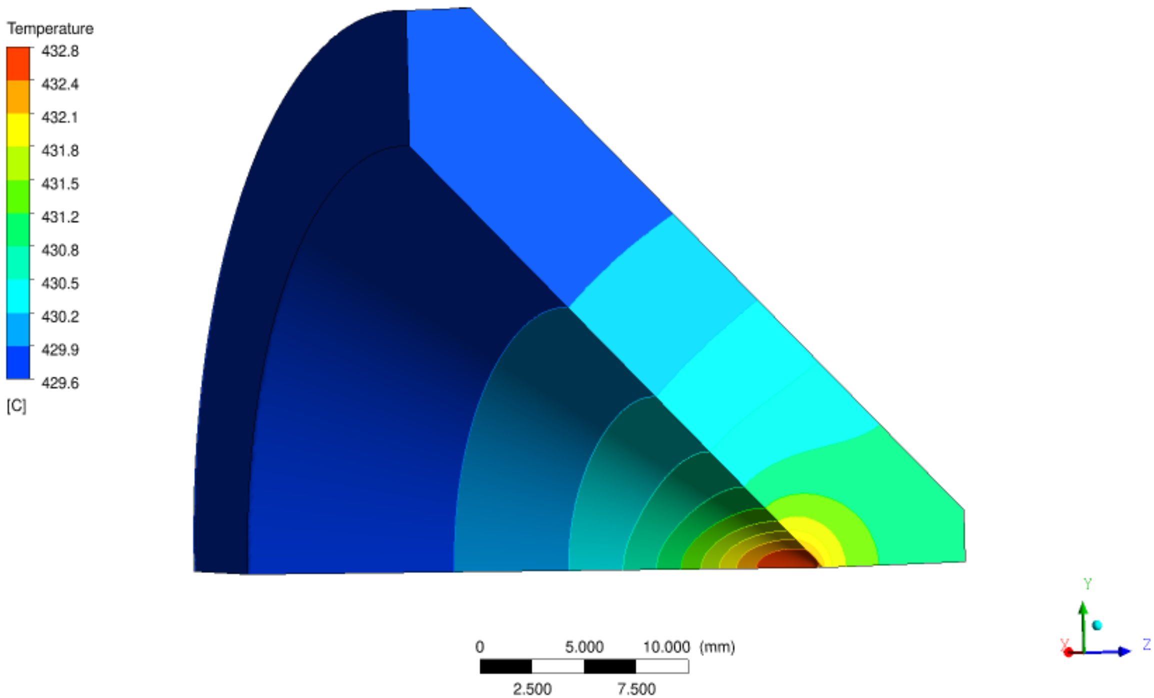
Steady State Heat deposition trace

The MCNPX results are coupled to ANSYS. This figure corresponds to the steady state heat deposition.



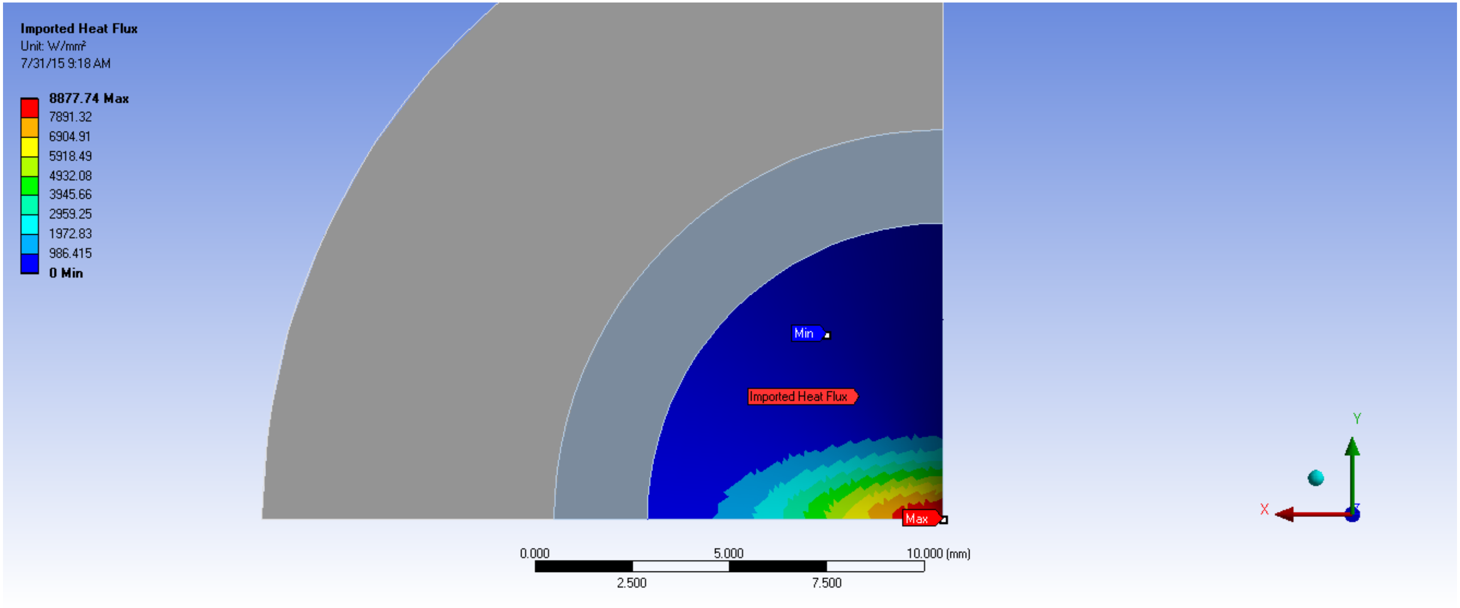
Steady calculation: Temperatures

The maximum temperature is $432^o C$ and the thermal gradient is $3^o C$.



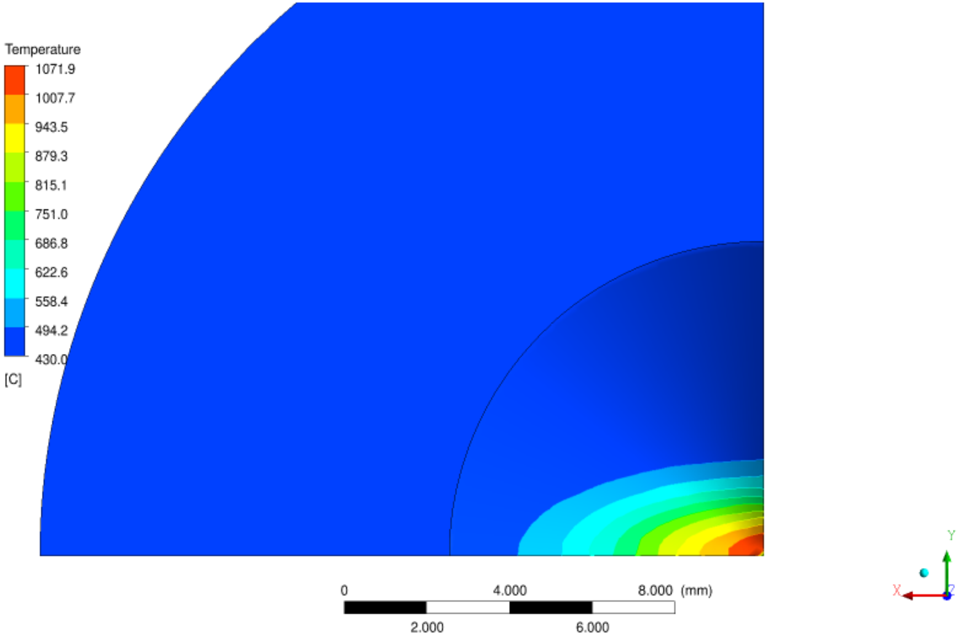
Transient State Heat deposition trace

The MCNPX results are coupled to ANSYS. This figure corresponds to the transient heat deposition in the submodeling geometry.



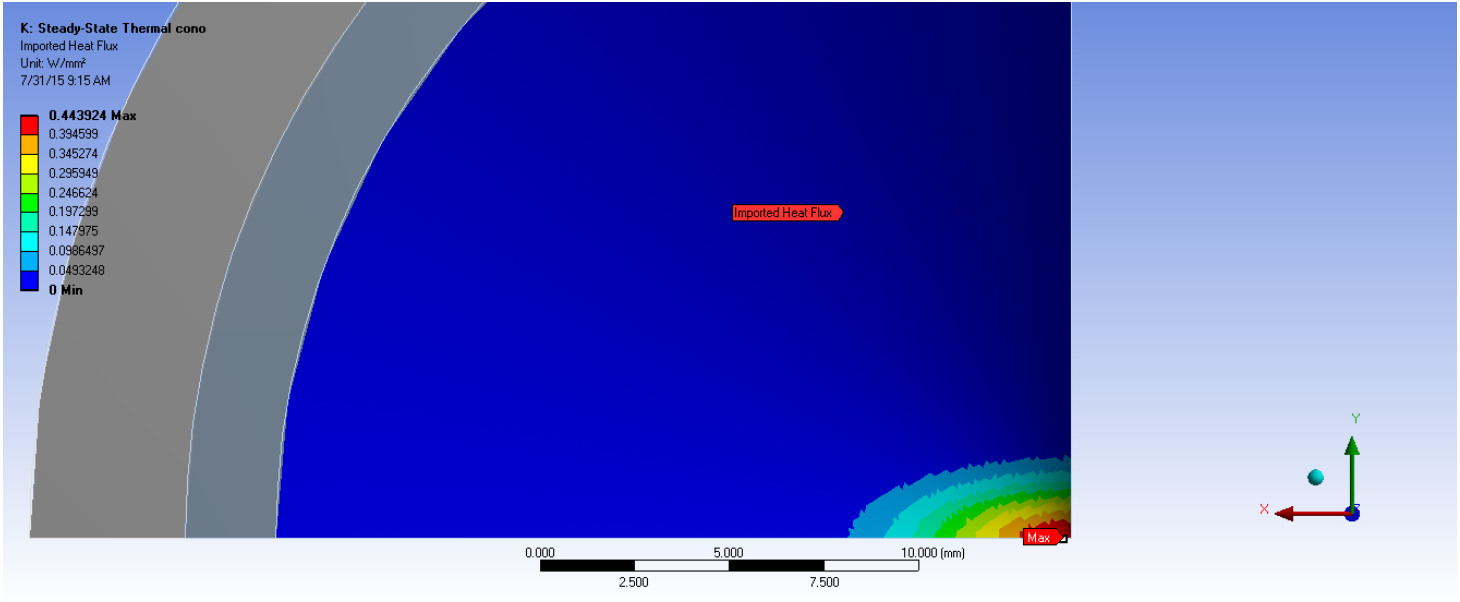
Transient calculation: peak temperatures

The steady state results have been imported into this submodel to initialize the transient calculations and to establish the boundary conditions. The maximum temperature is $1071^{o}C$ that matches with the heat deposition area. The thermal gradient is greater than $640^{o}C$.



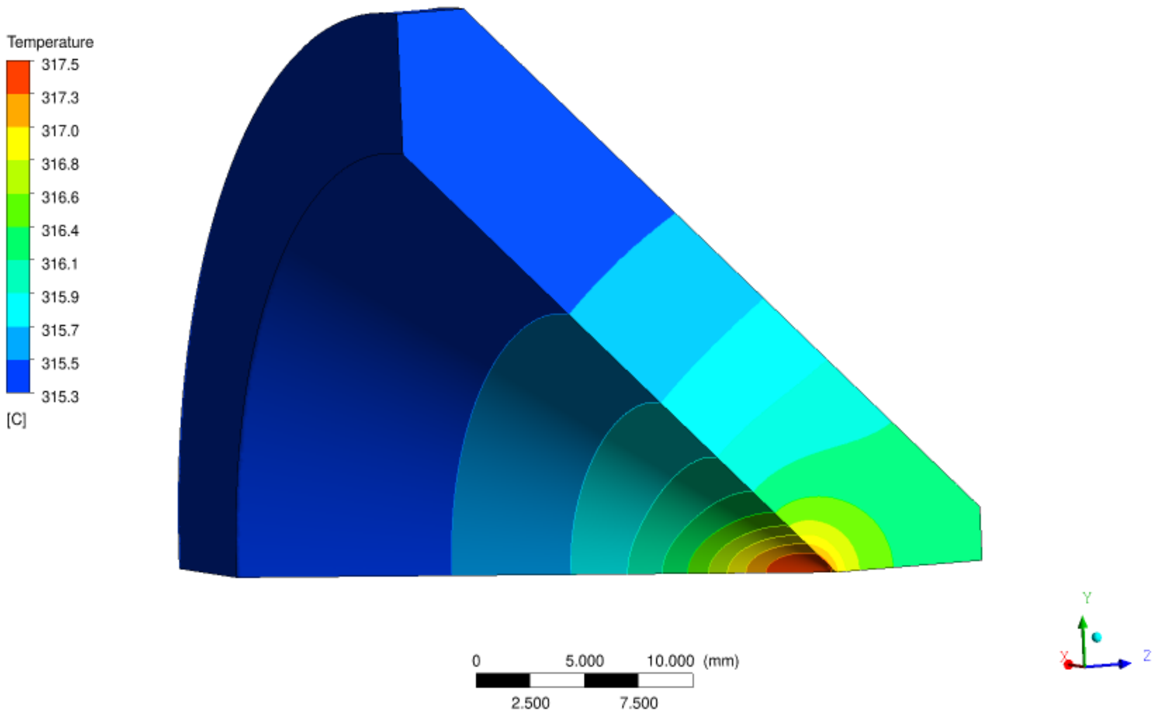
Steady State Heat deposition trace

The MCNPX results are coupled to ANSYS. This figure corresponds to the steady state heat deposition.



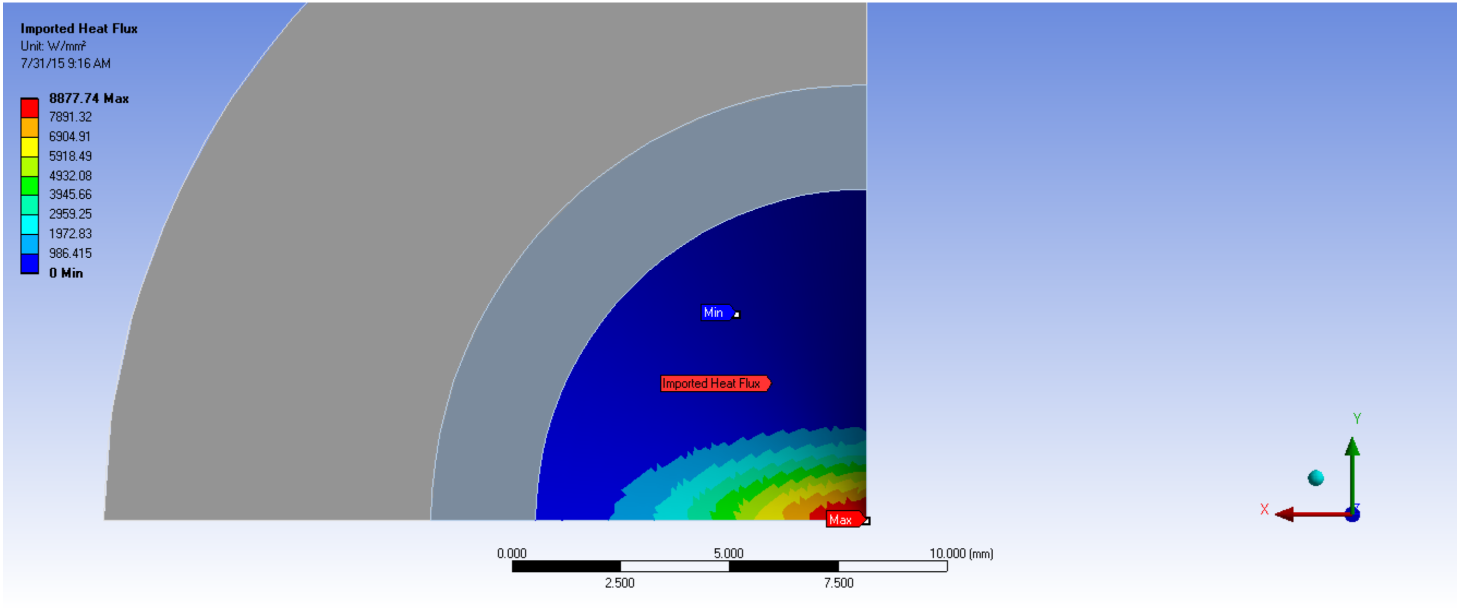
Steady calculation: Temperatures

The maximum temperature is $317^o C$ and the thermal gradient is $2^o C$.



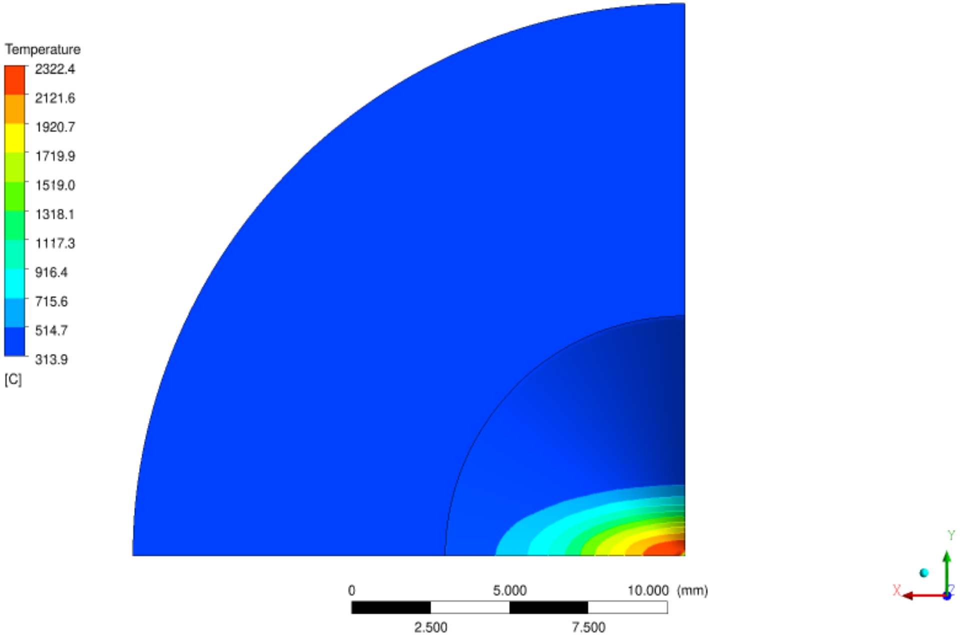
Transient State Heat deposition trace

The MCNPX results are coupled to ANSYS. This figure corresponds to the transient heat deposition in the submodeling geometry.



Transient calculation: peak temperatures

The steady state results have been imported into this submodel to initialize the transient calculations and to establish the boundary conditions. The maximum temperature is 2322$^o C$ that matches with the heat deposition area. The thermal gradient is greater than 1900$^o C$.



Mode 1: $5\mu s$; 14Hz

- The temperature reaches 432^oC on the steady state and it reaches peaks almost 1071^oC on the **transient state**. These values are very close to the copper melting point, 1100^oC.
- The copper FC reaches temperature near the melting point of the copper due to the high heat flux in the mode 1.

Mode 2: $50\mu s$; 1Hz

- The temperature reaches 317^oC on the steady state and it reaches peaks of 2322^oC on the **transient state**. These values are over the copper melting point, 1100^oC.
- The copper FC reaches very high temperature peak due to the high heat flux in the mode 2.

In this first set of calculations a standard copper conical block has been considered. From the **transient state** calculations, one can infer that this model has to be discarded given the combination of high power distributed in a very concentrated beam size and a swallow deposition surface. In the following sections variations in geometry and stopping material will be studied. Please note that current and energy combination result in a **230 kW** peak power which exceeds other MEBTs, SNS peak power 130 kW, LINAC4, RAL, JPARC (∼180 kW). If we are demanded to concentrate the beam even further than similar installations, design will become less reliable.

Alternative geometries study

Geometry and parameters

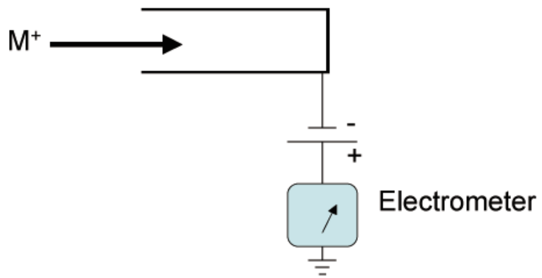
In order to study different materials, one important parameter to study beforehand is its manufacturability and welding techniques. With this in mind a simpler geometry has been done which consists on a straight plate made of copper. This geometry has two configurations to change the area in which the proton beam collides:

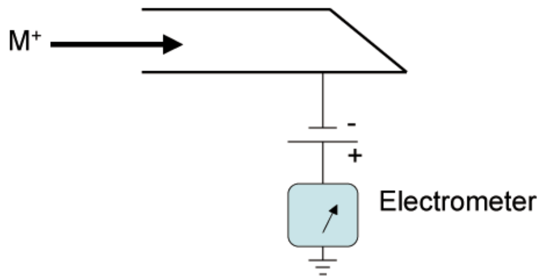
- No angle between proton beam and the FC: 0^o.
- Angle between proton beam and the FC: 45^o.

The same parameters of the proton beam have been used on this case. Only the **mode 2** ($50\mu s$; 1Hz) has been calculated because it brings the worst conditions.

The thermal analysis has been done with the same boundary conditions: natural convection and adiabatic conditions.

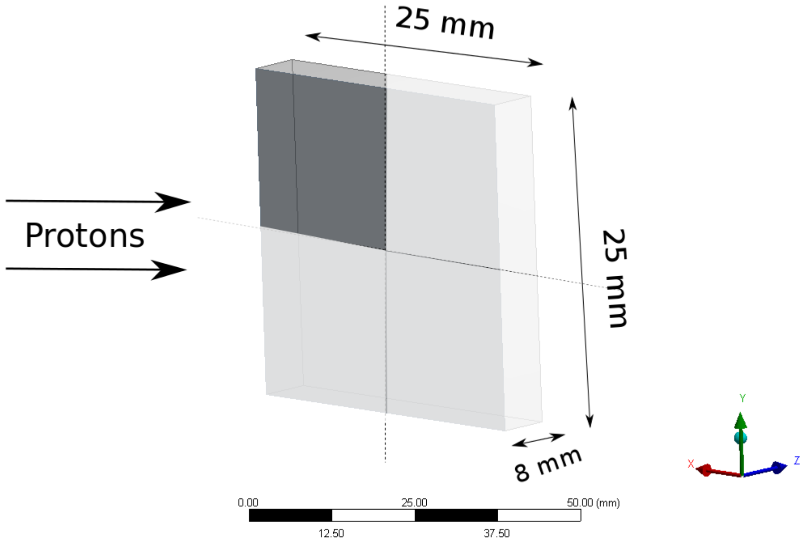
The copper plate has the same volume than the conical geometry, 20 cm^3. Also, a quarter symmetry has been applied to gain agility in the simulations.





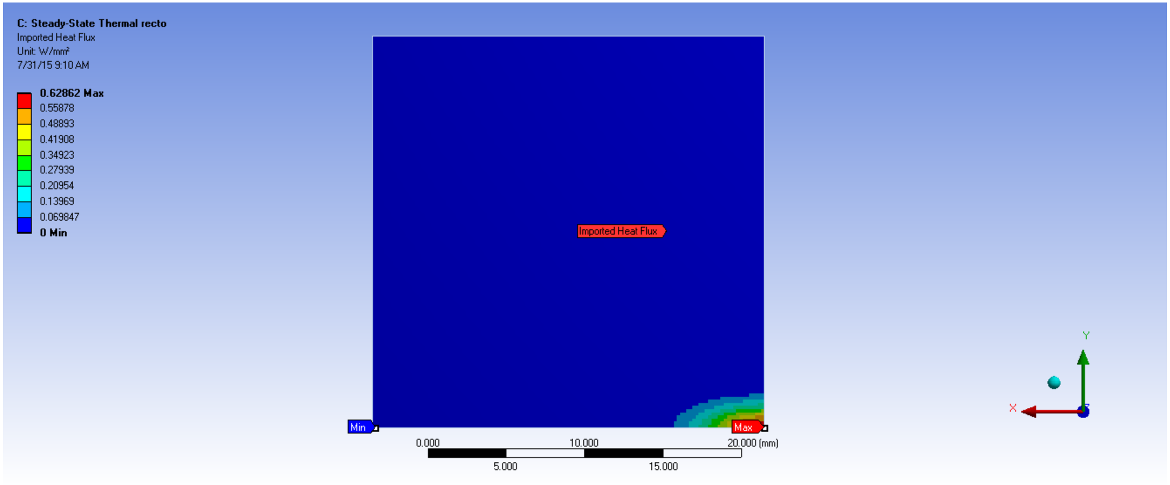
Mode 2: Geometry and Heat deposition trace

The MCNPX results are coupled to ANSYS. These figures correspond to the steady state with a quarter symmetry.



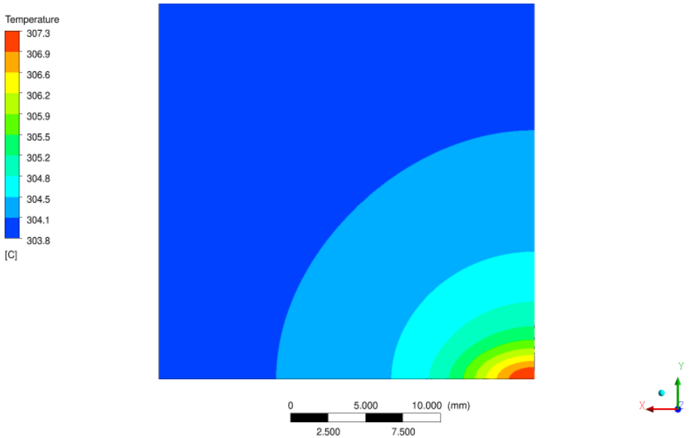
Mode 2: Geometry and Heat deposition trace

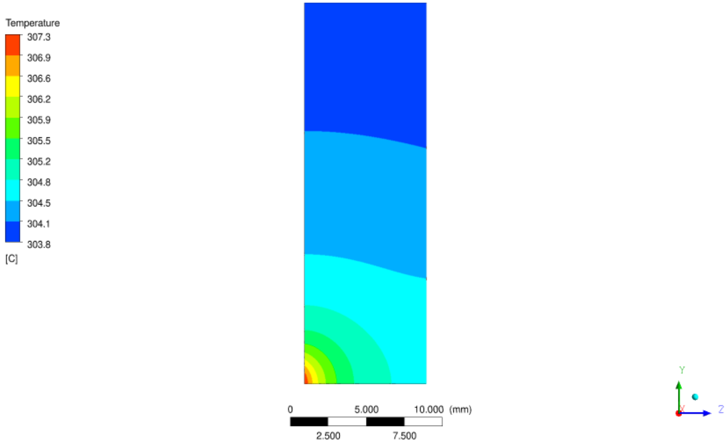
The MCNPX results are coupled to ANSYS. These figures correspond to the steady state with a quarter symmetry.



Mode 2: Steady calculation: Temperatures

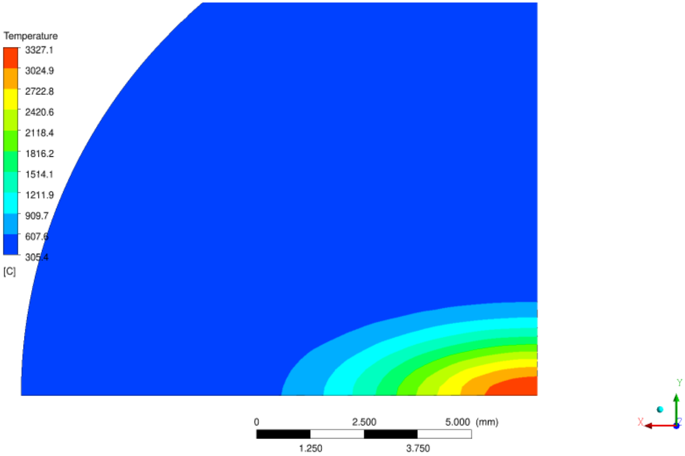
The maximum temperature is $307^{o}C$ and the thermal gradient is lower than $5^{o}C$.

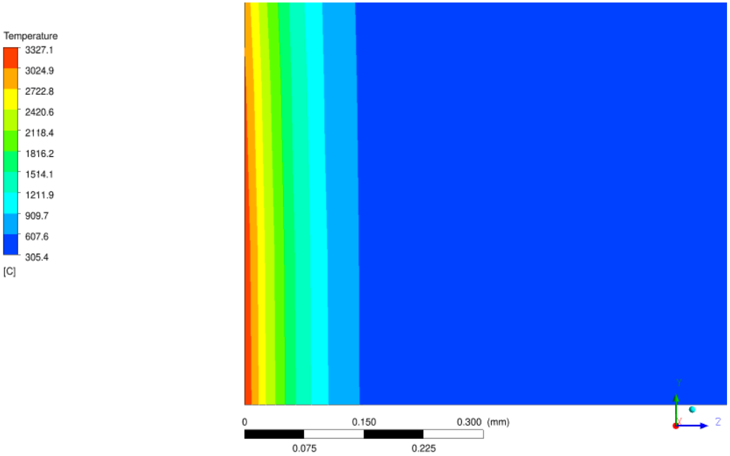




Mode 2: Transient calculation: peak temperatures

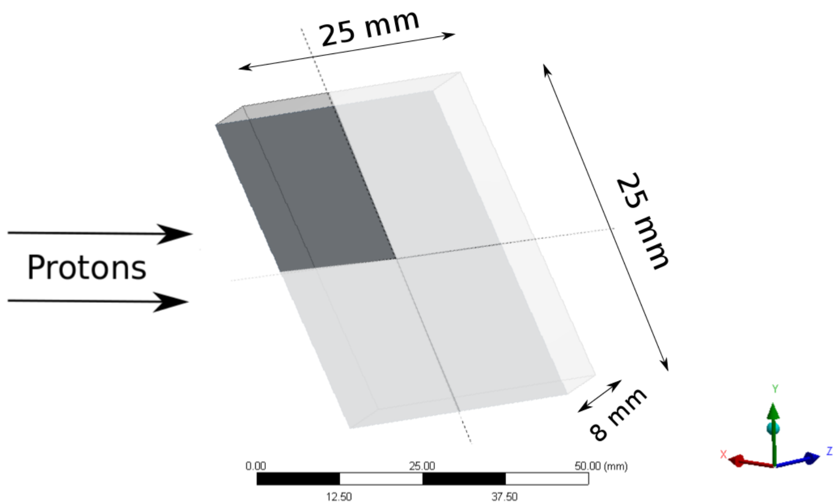
The maximum temperature is $3327^{o}C$ that matches with the heat deposition area. The thermal gradient is greater than $3000^{o}C$.





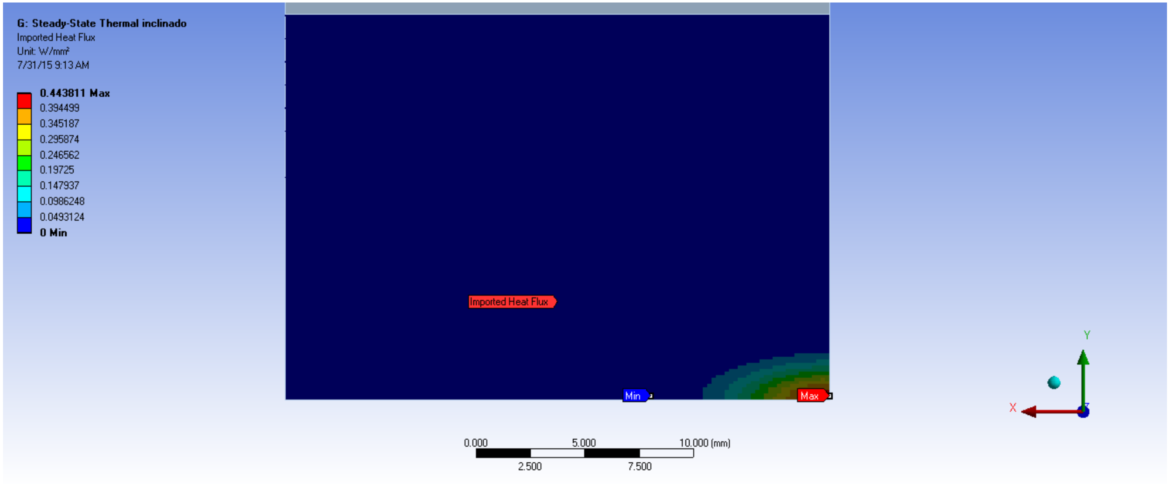
Mode 2: Geometry and Heat deposition trace

The MCNPX results are coupled to ANSYS. These figures correspond to the steady state with a quarter symmetry.



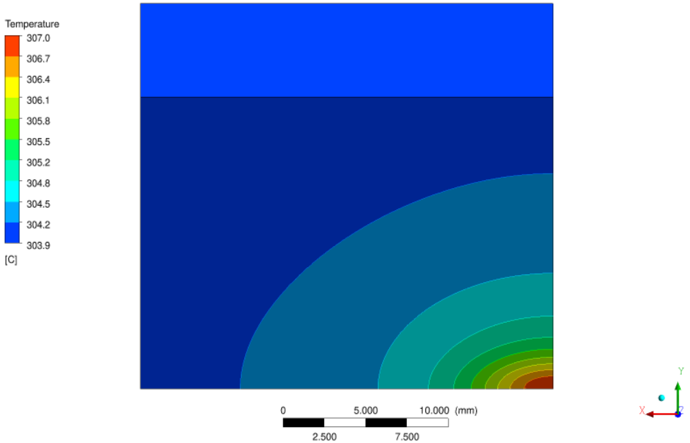
Mode 2: Geometry and Heat deposition trace

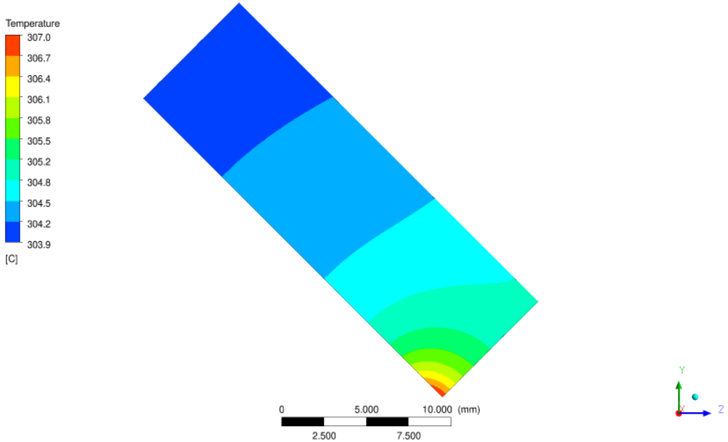
The MCNPX results are coupled to ANSYS. These figures correspond to the steady state with a quarter symmetry.



Mode 2: Steady calculation: Temperatures

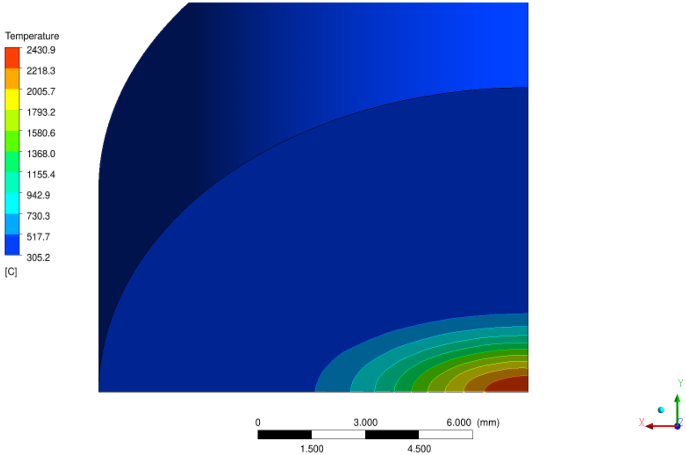
The maximum temperature is $307^o C$ and the thermal gradient is lower than $4^o C$.

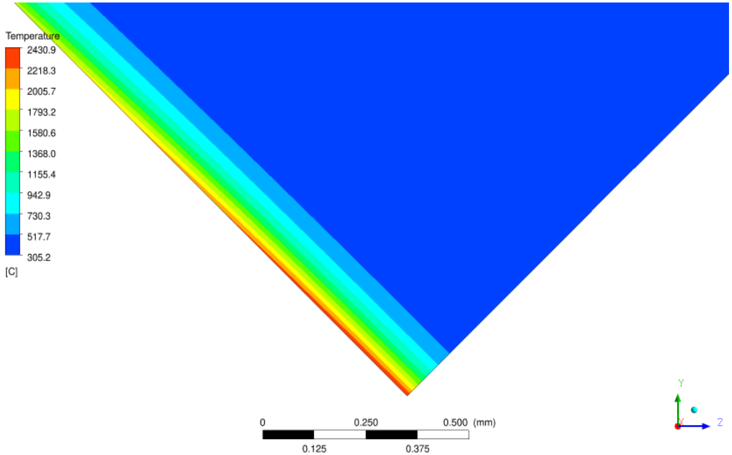




Mode 2: Transient calculation: peak temperatures

The maximum temperature is 2430$^o C$ that matches with the heat deposition area. The thermal gradient is greater than 2100$^o C$.





Results

- No inclination: the temperature reaches $307^o C$ on the steady state and it reaches peaks of $3327^o C$ on the transient state. These values are over the copper melting point, $1100^o C$.
- Inclination 45^o: the temperature reaches $307^o C$ on the steady state and it reaches peaks of $2430^o C$ on the transient state. These values are over the copper melting point, $1100^o C$.

Table : Main results for copper

Geometry	mode	max temp steady ($^o C$)	max temp transient ($^o C$)
Conical shape	1	432	1071
	2	317	2322
90^o straight plate	2	307	3327
45^o straight plate	2	307	2430

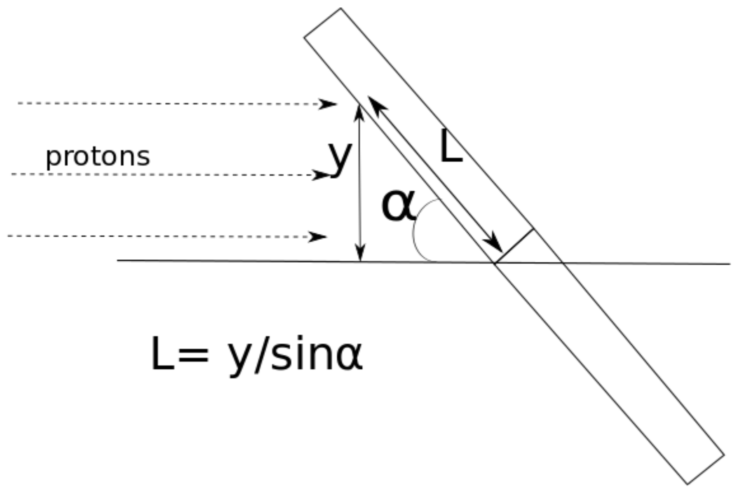
Conclusions

These new geometries confirms than the area in which the proton beam collides has an important role in the heat deposition.

The geometry with the inclination 45^o has more surface[1] to dissipate the heat generated by the proton beam, so the peak temperature reached by the plate without inclination is higher. Its temperature is the 70%, the same value than the increment of the surface ($sin(45^o) = 0.707$).

The images of the transient state revels the large thermal gradient in the direction of the FC thickness. This effect produces the concentration of the heat and temperature in the same point.

The plate with 45^o of inclination reaches the same temperature than the conical geometry, with the benefit of easy of manufacture, new materials will be studied in the following sections.



[1] a factor of $\sqrt{2}$

Activation materials

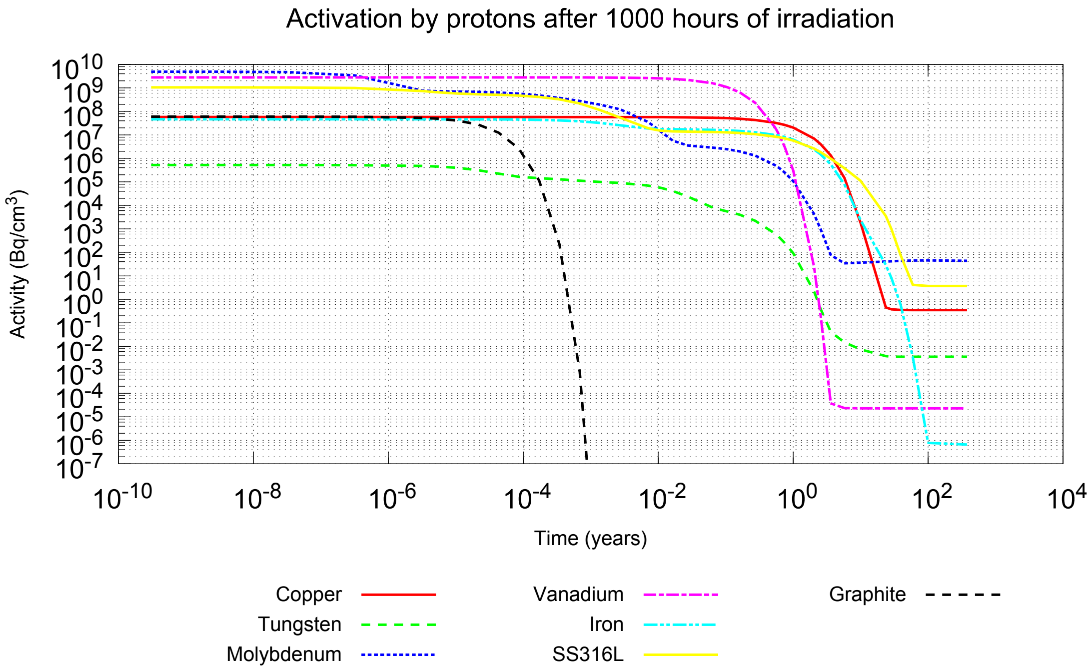
Introduction and parameters

In order to select the best coating material, an activation study has been done to compare the effect of using different materials in terms of activation. For this purpose, a straight plate has been considered as a valid reference.
The study is done for the **mode 1** (5 μs; 14 Hz) because his average current is the highest of the two modes ($4,375\ \mu A$). The irradiation time considered was 1000 hours.
In the first place, total disintegration is compared for the 7 materials analysed and in the second place, the gamma activation is calculated.

- Copper
- Tungsten
- Molybdenum
- Vanadium
- Iron
- Stainless Steel, SS316L
- Graphite

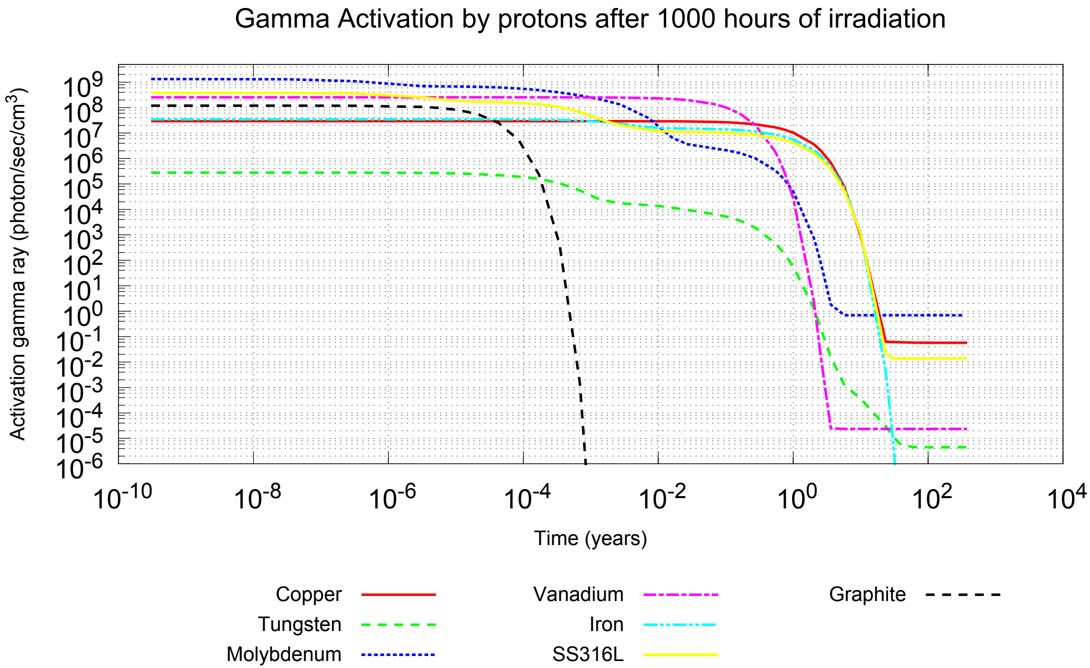
Total Activity

Total activity for the different materials ($Bq/s/cm^3$)



Gamma Activity

Gamma activity for the different materials ($photon/s/cm^3$)



Activation Conclusions

Total Activity

- The material that produces lower total initial activity is tungsten, followed by copper, iron and graphite.
- The activity produced by graphite decays quickly and it is very low after few hours.
- After $1-5$ years, the total activity produced by vanadium and tungsten are the lowest values, after graphite.

Gamma Activity

- The gamma activity has the same tendency than the total activity.
- The gamma activity in the graphite is produced by the isotope N-13. This isotope is the most important and it decays in β^{+}, with the emission of two 0.511 MeV gammas.

Conclusions
The two materials with lower levels of activity in the short therm are **Tungsten** and **Graphite**. Moreover, they have higher melting point than the copper. For those reasons, these materials could be the alternatives for coating the FC.

Conclusions

Once copper as only stopping material has been discarded, and geometrically the straight plane can be considered as a valid alternative to the traditional conical shape. In this section, the best two materials found in the activation study will be considered: **Tungsten** and **graphite**.

On top of the low activity produced by 3.6 MeV protons, they also offer higher melting point (tungsten: $3400^o C$; graphite: $3500^o C$; copper: $1100^o C$). This stage of the study has been developed considering with the 45^o inclined plate geometry, and the **beam commissioning mode 2** ($50\,\mu$ s and 1 Hz). This higher melting point has to compensate the lower isotropic thermal conductivity of this two material (tungsten: 170 $W/m -^o C$; graphite: 120 $W/m -^o C$; copper: 400 $W/m -^o C$ at ambient temperature). Please note thermal conductivity properties dependent of temperature.

Conclusions

Geometry conclusions

- The conical geometry of the Faraday Cup can be replaced for a plate geometry, from the thermal point of view.
- The main factor is the area in which the protons collide. For that reason, a tilted plate with an inclination of 45^o is a good option.

Activation conclusions

- The coating materials with less activity after irradiation with protons at 3.62 MeV are tungsten and graphite.

Parameter conclusions

- The heat flux produce by the provided proton beam footprint in the Faraday Cup is too high.
- The beam size is too small, and pulse length too long for these energy and current.

As a main conclusion, one can observe that unless *commissioning beam mode 2* pulse length is shortened down significantly and beam footprint widened, it is difficult to believe that a stopping device can be manufactured with the imposed space restrictions. Next work will be focused in determining the limits of both Stationary and Transient State charge density (μC / (cm^2 s)).