ESS-Bilbao Beam Stoppers criteria

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Introduction

Objectives

The Beam Stoppers on the MEBT have to resist the impact of the proton beam. The material chosen will have to ensure the physical integrity of these elements. In order to fulfill the thermo-mechanical limits, some criteria have to be define related to the proton beam parameters.

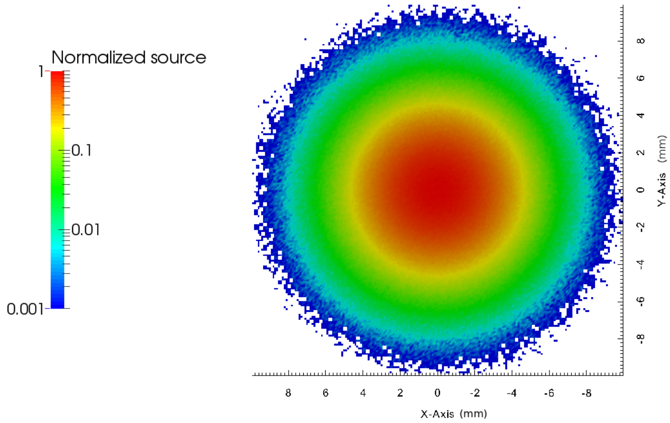
The pulse length and the frequency will be the two variables to analyze. Each variable affects in different way to the thermo-mechanic steady state and the transient state. For that reason, two criteria have to be analyzed and the proton beam has to fulfill both at the same time.

- Transient state that depends on the pulse length, $\boldsymbol{\mu}\mathbf{C}/(\mathbf{cm^2}\cdot\mathbf{pulse})$
- Steady state that depends on the pulse length and frequency, $\boldsymbol{\mu}\mathbf{C}/(\mathbf{cm^2}\cdot\mathbf{s})$

Beam parameters fixed

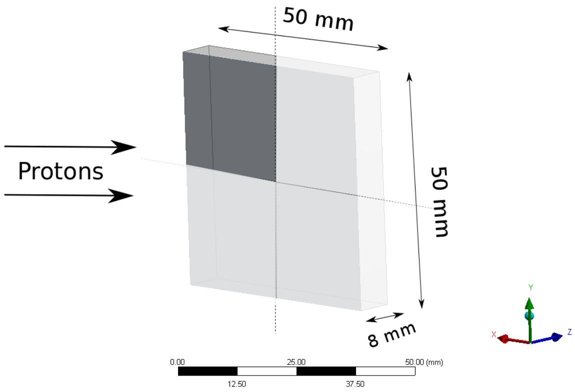
The proton beam has an energy of 3,62 MeV and the current peak is 65 mA. The beam travels in the direction of the Z axis to collide into the Beam Stoppers (BS). Its distribution corresponds to a Gaussian function in the X and Y axis, which are determined by the parameter FWHM (Full Width at Half Maximum). In order to create the criteria, the beam parameters have been fixed for this analysis .

- FWHM axis X: 5.8875 mm $\rightarrow \sigma_x = 2.5\ mm$
- FWHM axis Y: 5.8875 mm $\rightarrow \sigma_y = 2.5\ mm$



Geometry

The model used in the simulations is a straight plate with a volume of 20 cm^3. This plate has 8 mm of thickness, that 1 mm corresponds to coating material (Tungsten or Graphite) and 7 mm corresponds to Copper. The model studied is the quarter of its geometry, due to its symmetry.



The straight plate is the model simulated because it is the worst case for the BS in nominal conditions. This allows to normalize the limits and adapt them to other geometries with different footprints.

Current normalization

The criteria are normalized in area units, so the current beam footprint in the Beam Stoppers has to be normalized. It is important to remark that the area normalized is the footprint in the BS, so if the BS increase the impact surface (for example inclining the plate) this area is going to increase.

$$I''(x,y) = \frac{I_{peak}(\mu A)}{2\pi\sigma_x\sigma_y \cdot factor} = 1.65521 \cdot 10^5 \ \mu A/cm^2 \tag{1}$$

$I_{peak}= 65 \cdot 10^3 \ \mu A$
$\sigma_x= 0.25 \ cm$
$\sigma_y= 0.25 \ cm$
$factor= 1/sin\alpha$
[proportional increment of area in the BS, related with the straight plate case 90 $(factor = 1)$]

Criteria estimation

Limits are calculated with the next two expressions related with the pulse length, t_{pulse} (μs) and the frequency, f (Hz).

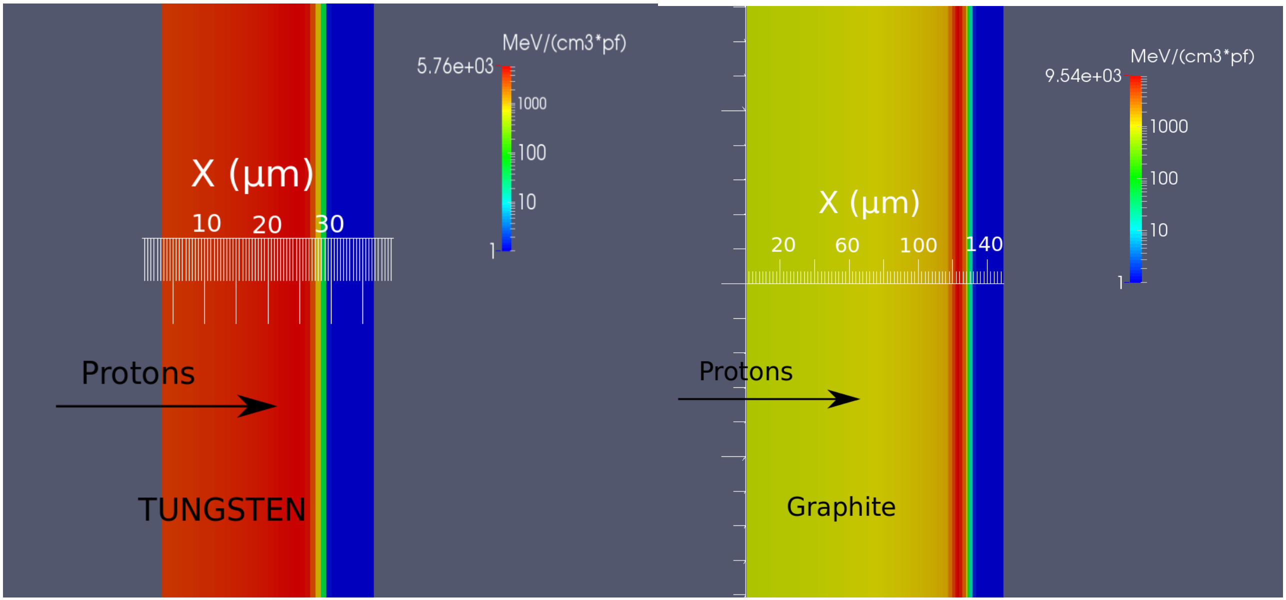
$$\textit{Transient state} \quad \mathbf{I_1 = [\int_0^{t_{pulse}} I''(\mu A/cm^2)dt]\ /pulse} \quad \longrightarrow \mu C/(cm^2 \cdot pulse)$$

$$\textit{Steady state} \quad \mathbf{I_2 = [\int_0^{t_{pulse}} I''(\mu A/cm^2)dt]\ \cdot f} \quad \longrightarrow \mu C/(cm^2 \cdot s)$$

Analysis considerations

Proton penetration

Due to the activation results and thermo-mechanical properties, the two materials chosen for the analysis are tungsten and graphite. The maximum penetration of protons reaches 30 μm and 135 μm in tungsten and graphite, respectively.



Simulations conditions

Two materials have been analyzed for these BS criteria: Tungsten and Graphite. Their thermo-mechanical properties are described in the Appendix.

The heat deposition in each material have been simulated with the Montecarlo code MCNPX, using a mesh to detect the Bragg peak.

The thermal analysis has been done with four boundary conditions and the calculations have been done with ANSYS.

- Natural convection on the outer surface of the BS, whose heat transfer coefficient is 10 $W/(m^2\ C)$ *(Fundamentals of Heat and Mass Transfer; Frank P. Incropera)*.
- Ambient temperature: 22 C.
- Adiabatic conditions on the inner surface of the BS.
- No radiation effects.

The mechanical analysis in ANSYS has been done with a boundary condition of fixed support in the face back of the BS.

Thermal analysis

One of the specifications is not to reach a limit temperature of the material during normal operation. Due to that, a temperature factor has to be defined: $\mathbf{T}^* = \frac{\mathbf{T_{max}(K)}}{\mathbf{T_{limit}(K)}}$

The maximum temperature is related with the steady state and the transient state thermal:

$$T_{max} = T_{steady} + \mathbf{\Delta} T$$

Steady State Thermal

The steady state thermal is dependent on the cooling conditions, so it can change with the considerations of the problem. In the equation, no cooling system has been added ($\dot{q}_{cooling} = 0$) to the convection conditions. An equation for the steady state temperature dependent on the current per area $I''(\mu A/cm^2)$ can be defined:

$$\begin{cases} \dot{Q} = E(MeV) \cdot I_{peak}(\mu A) \cdot t_{pulse}(s) \cdot f(Hz) \\ \dot{Q} = h \cdot A_{conv} \cdot (T_{steady} - T_0) \\ I_{peak} = 2\pi\sigma_x\sigma_y \cdot factor \cdot I'' \end{cases}$$

$$\mathbf{T_{steady}} = \mathbf{T_0} + \frac{(\mathbf{E} \cdot \mathbf{2}\pi\sigma_\mathbf{x}\sigma_\mathbf{y} \cdot \mathbf{factor} \cdot \mathbf{I}'' \cdot \mathbf{t_{pulse}} \cdot \mathbf{f})}{\mathbf{h} \cdot \mathbf{A_{conv}}}$$

Steady State Thermal

In the case of these simulations, the parameters used are:

$h = 10^{-3}\ W/(cm^2\ C)$, $A_{conv} = 41\ cm^2$, $\sigma_x = \sigma_y = 0.25cm$, $E = 3.62\ MeV$, $T_0 = 22C$.

$$\left.\begin{aligned} T_{steady}(C) &= 22(C) + 34.7 \cdot I'' \cdot t_{pulse} \cdot f \\ I_2 &= I'' \cdot t_{pulse} \cdot f \end{aligned}\right\} \rightarrow \mathbf{T_{steady}(C) = 34.7 \cdot I_2 + 22}$$

The simulations will check this steady state equation.

Transient State Thermal

The transient state thermal is more difficult to define by an equation. For that reason, different simulations have been done modifying the parameters of the proton beam. Then, with the results of the simulations, an approximated equation can be determined.

Mechanical analysis

Another specification is not to reach a limit stress produced by the impact of the proton beam in normal operations. Due to that, a stress factor has to be defined: $\boldsymbol{\sigma}^* = \frac{\boldsymbol{\sigma}_{max}}{\boldsymbol{\sigma}_{limit}}$

The Mechanical analysis has been done taking into account the elastic and plastic deformation for the tungsten and elastic deformation for the graphite.

The stress is dependent on the increment of the temperature in the materials on the elastic zone:

$Y = Young\ Modulus\ (MPa)$
$\alpha = coefficient\ thermal\ expansion\ (C^{-1})$

$$\boldsymbol{\sigma}_{\mathbf{max}} = \mathbf{Y} \cdot \boldsymbol{\alpha} \cdot \boldsymbol{\Delta}\mathbf{T}$$

Tungsten analysis

In case of tungsten, the plastic deformation can appear. When this happens, the model of Johnson-Cook for plastic deformation has been used (see Appendix).

Tungsten is a ductile material, for that reason the Von Mises criterion has been used to analyse the maximum stress in the tungsten.

Graphite analysis

Graphite has not the same resistance in tension and in compression. In this case, Von Mises criterion does not consider the higher resistance of graphite under a compressive load, which is the most important stress produced by a temperature load.

The Rankine criterion has been used to analyse the maximum stress in graphite. This criterion consists on select the maximum principal stress, that can be tension or compression.

Beam parameters for the simulations

In order to study the peak temperature evolution, some calculations have been done changing the pulse length and fixing the frequency at 1 Hz.

This table shows the data used in the calculations with the conversion to $\mu C/(cm^2 \cdot pulse)$ units.

Frequency (Hz)	**pulse length (μs)**	$\mathbf{I_1}$ **[μC/(cm^2 · pulse)]**	$\mathbf{I_2}$ **[μC/(cm^2 · s)]**
1	50	8, 276	8, 276
1	25	4, 138	4, 138
1	10	1, 6552	1, 6552
1	5	0, 8276	0, 8276
1	2, 5	0, 4138	0, 4138
1	1	0, 1655	0, 1655

Final Thermal considerations

- Only convection has been simulated as cooling system. These conditions affect to the steady state final temperature. The steady temperature is very dependent with the cooling system, doing very difficult to establish a precise criterion for $\mathbf{I_2}$ $[\mu\mathbf{C}/(\mathbf{cm^2}\cdot\mathbf{s})]$.
- The cooling system does not affect to $\Delta T(C)$, because the heat footprint does not penetrate more than 150 μm into the materials studied. For that reason, the criterion $\mathbf{I_1}$ $[\mu\mathbf{C}/(\mathbf{cm^2}\cdot\mathbf{pulse})]$ can be established properly.

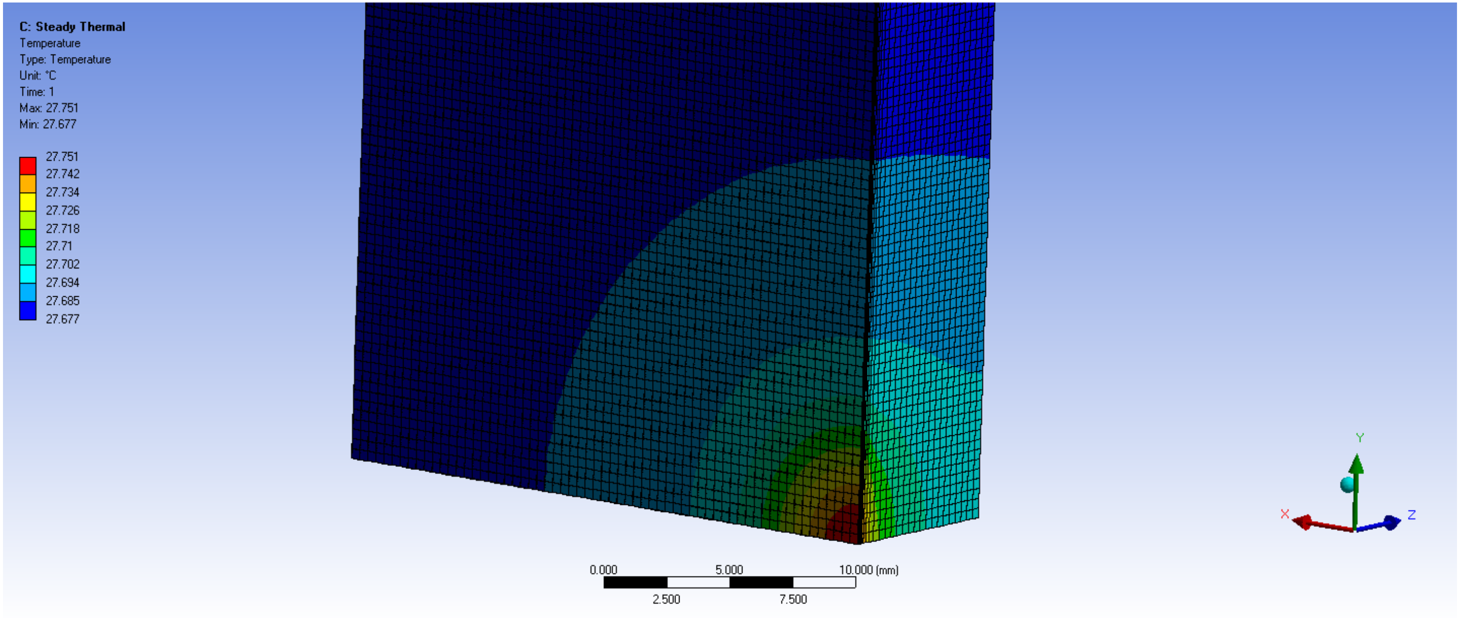
Final Mechanical considerations

- The support restrictions of the Beam Stoppers affect to the global maximum stress. The stress analyzed in the simulations corresponds to the local maximum stress generated by the proton beam footprint.
- The possible maximum stress produced in other parts of the Beam Stoppers haven't been taken into considerations for the conclusions, only the local stress in the temperature footprint area.
- This analysis is an ideal scenario which can not ensure the same limits for a real configuration of the elements.

Thermo-mechanical Results

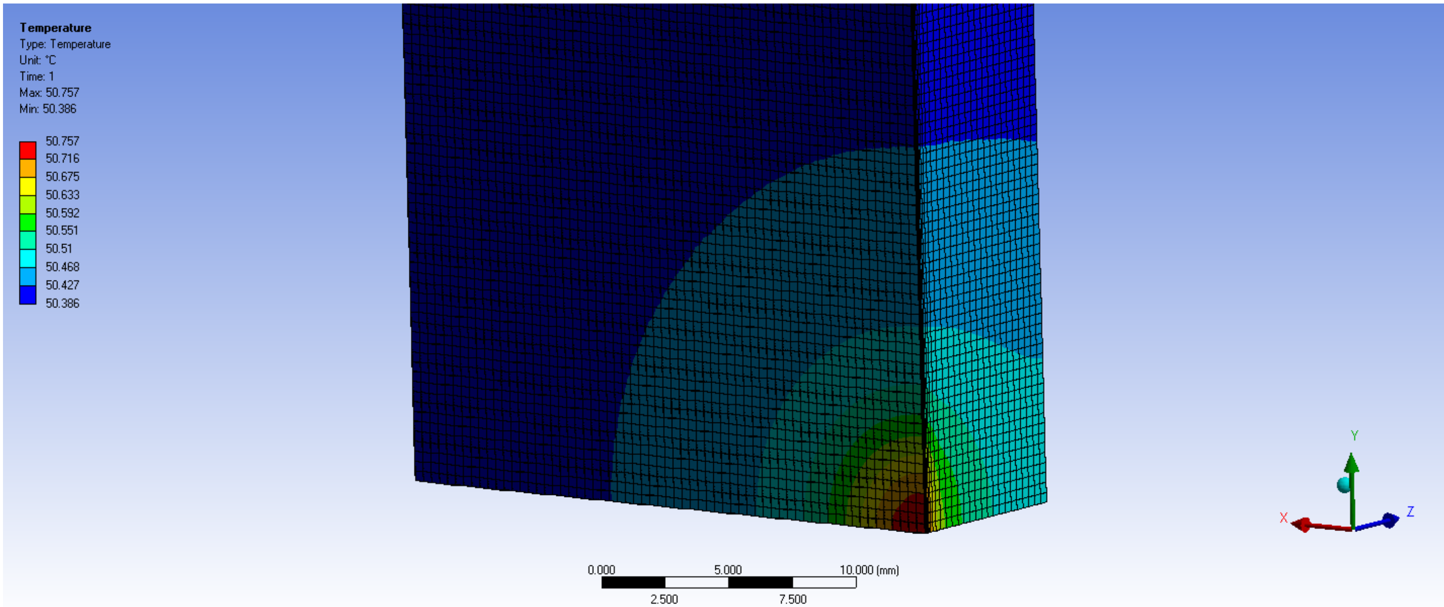
Steady State Thermal

These results are from the case of 1 μs and 1 Hz, reaching 27 C in the steady state.



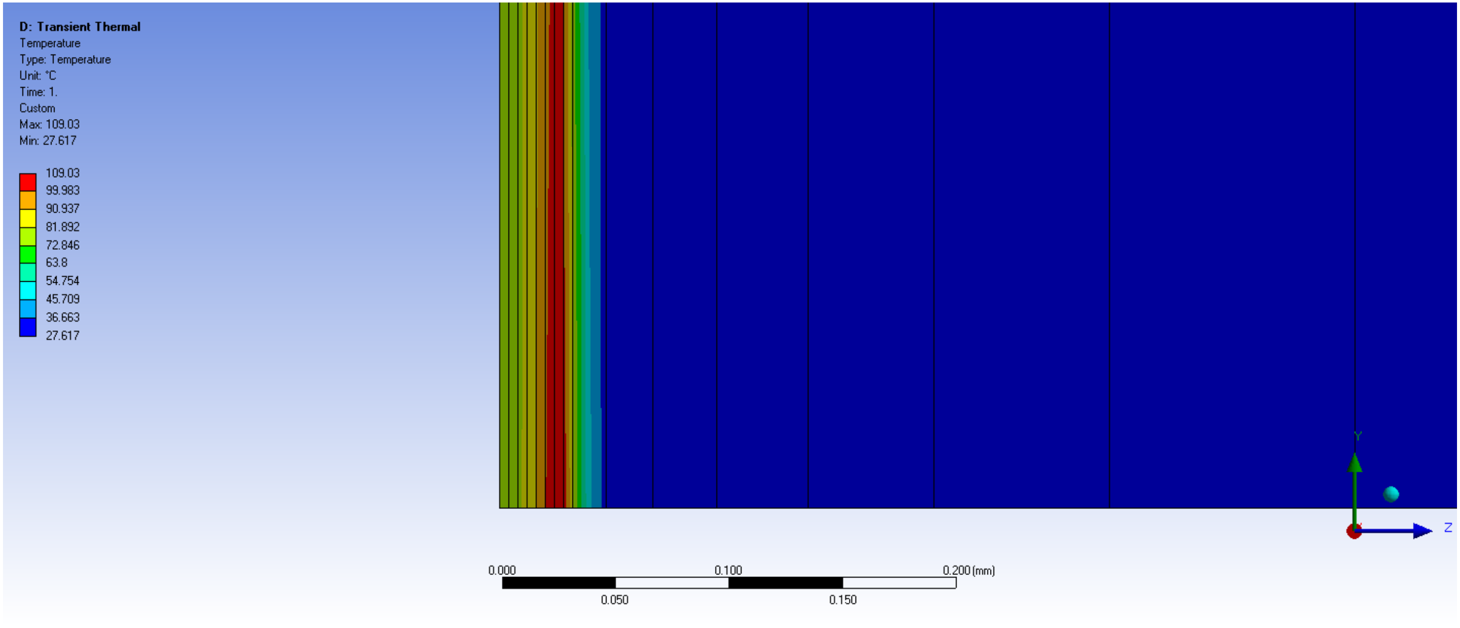
Steady State Thermal

These results are from the case of 5 μs and 1 Hz, reaching 50 C in the steady state.

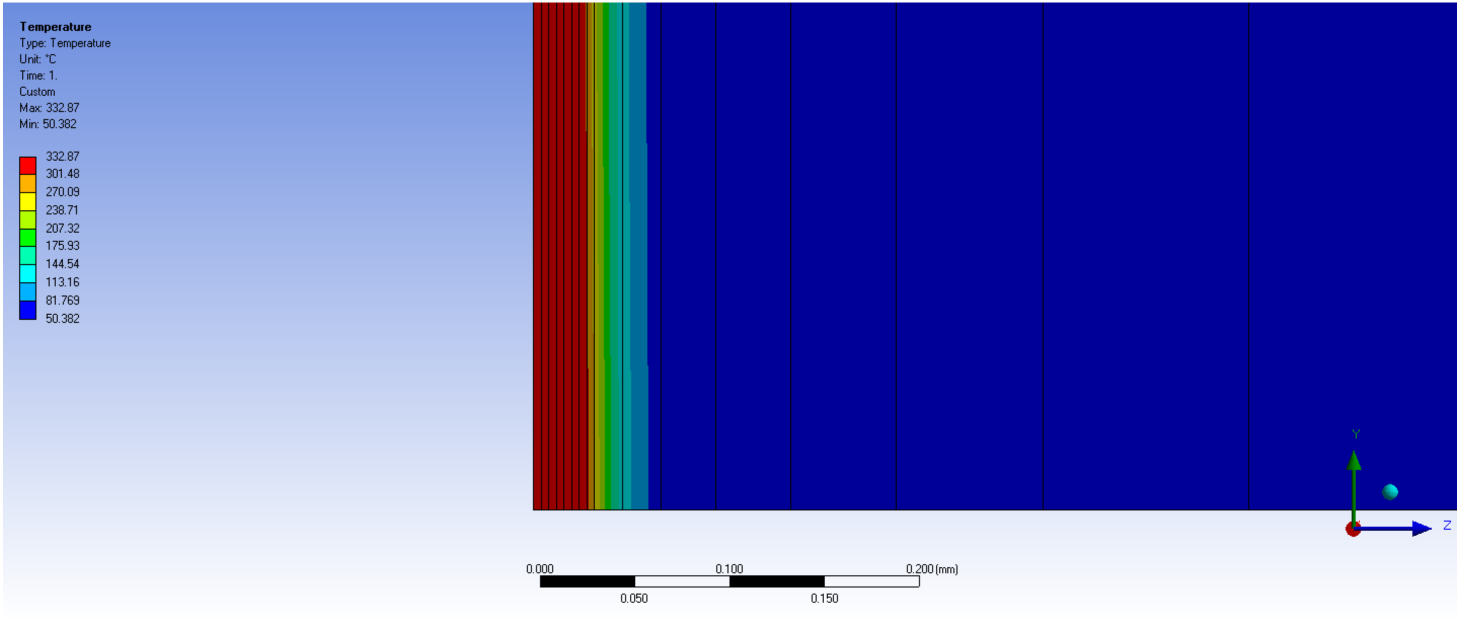


Transient State Thermal

These results are from the case of 1 μs and 1 Hz, reaching 109 C and with an increment of temperature 82 C in the transient state.

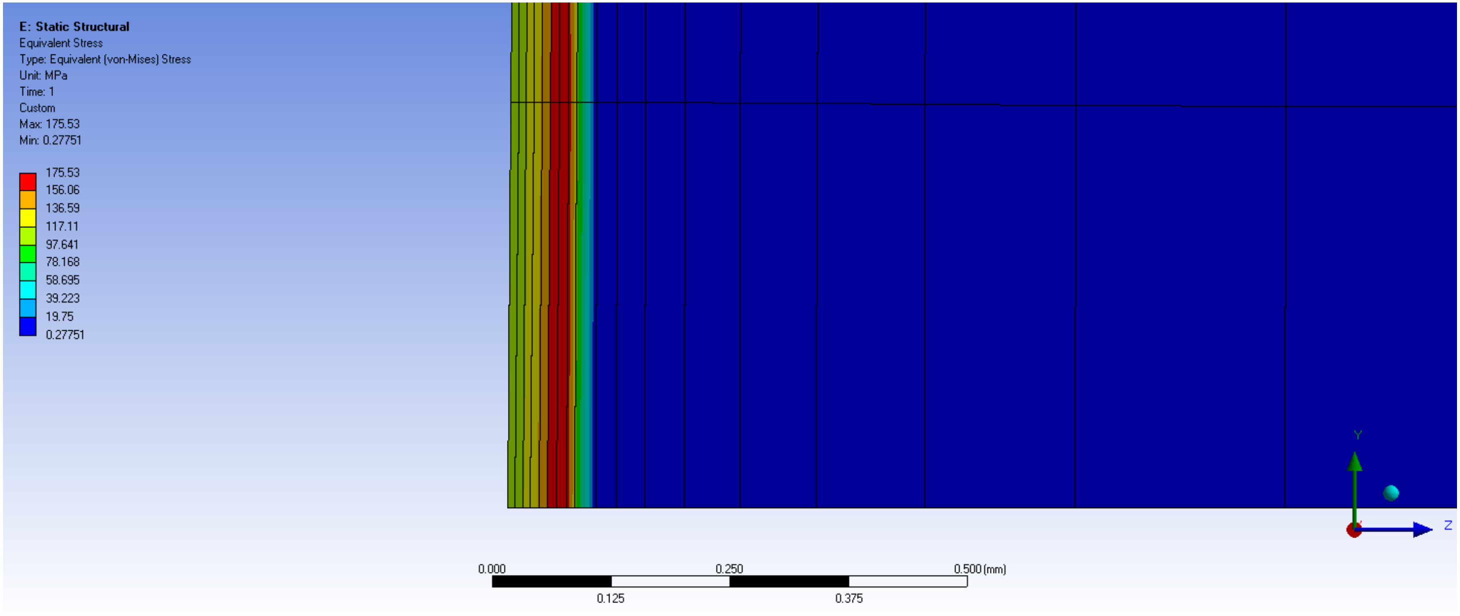


Transient State Thermal
These results are from the case of 5 μs and 1 Hz, reaching 332 C and with an increment of temperature 282 C in the transient state.



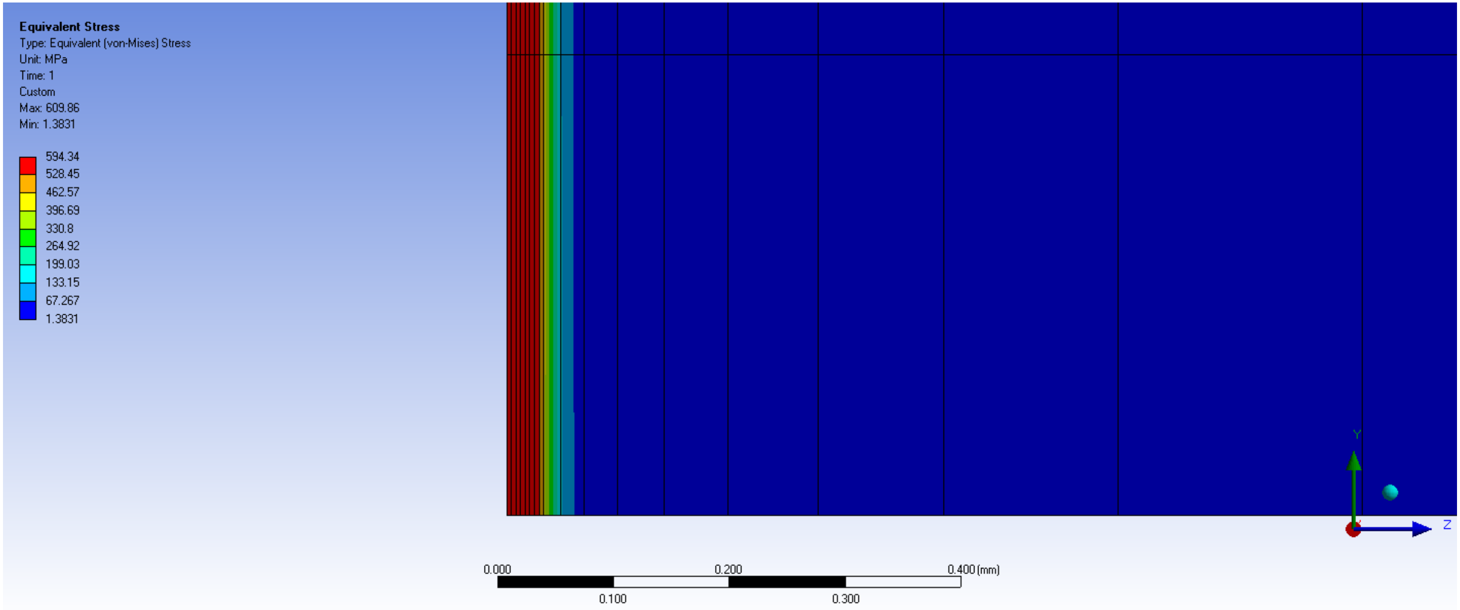
Mechanical Analysis in footprint area

These results are from the case of 1 μs and 1 Hz, reaching 175 MPa.



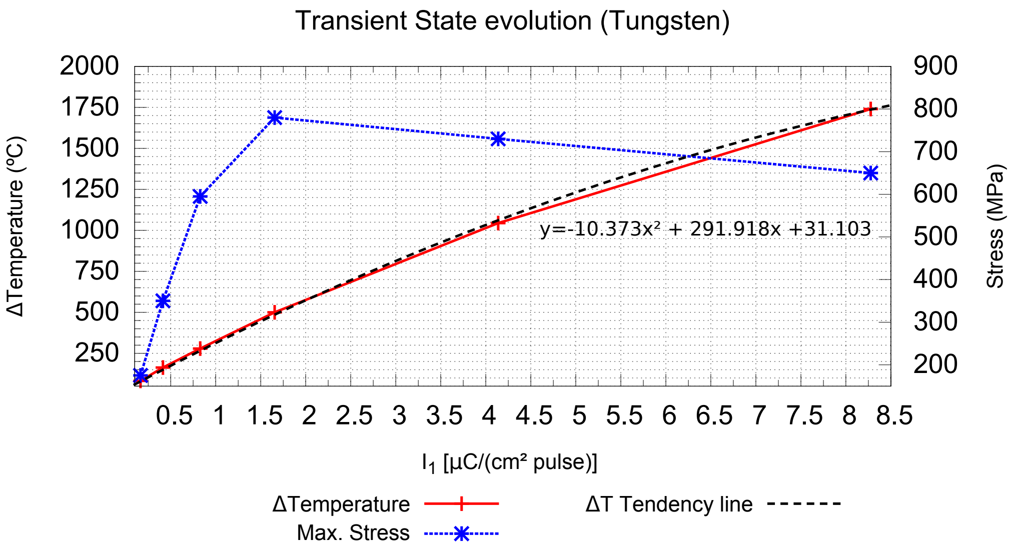
Mechanical Analysis in footprint area

These results are from the case of 5 μs and 1 Hz, reaching 594 MPa.



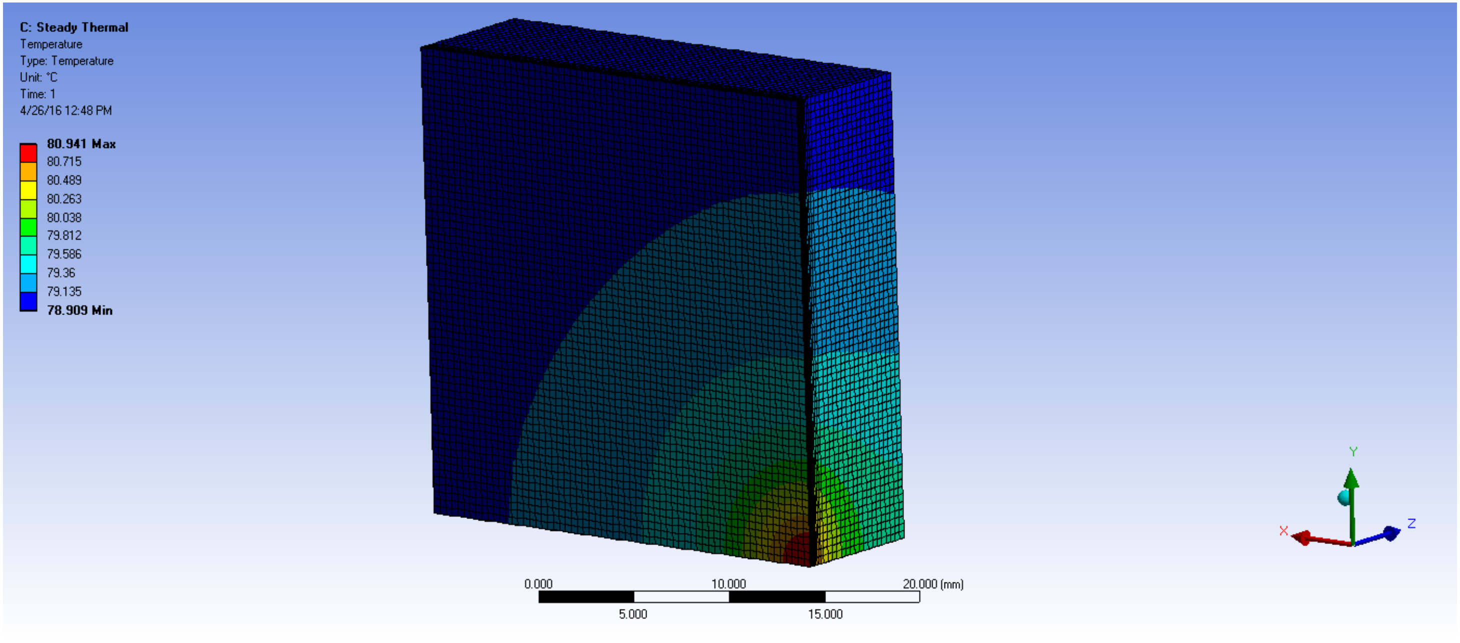
Results evolution

The results show the increment of temperature (ΔTC) and maximum stress (MPa) increasing the variable $I_1[\mu C/(cm^2 pulse)]$. The temperature evolution has a tendency line that can be approximated by the equation: $\mathbf{\Delta T = -10.37 \cdot I_1^2 + 291.9 \cdot I_1 + 31.1}$. The maximum stress evolution corresponds to the elastic deformation in the first part, and then the plastic deformation appears.



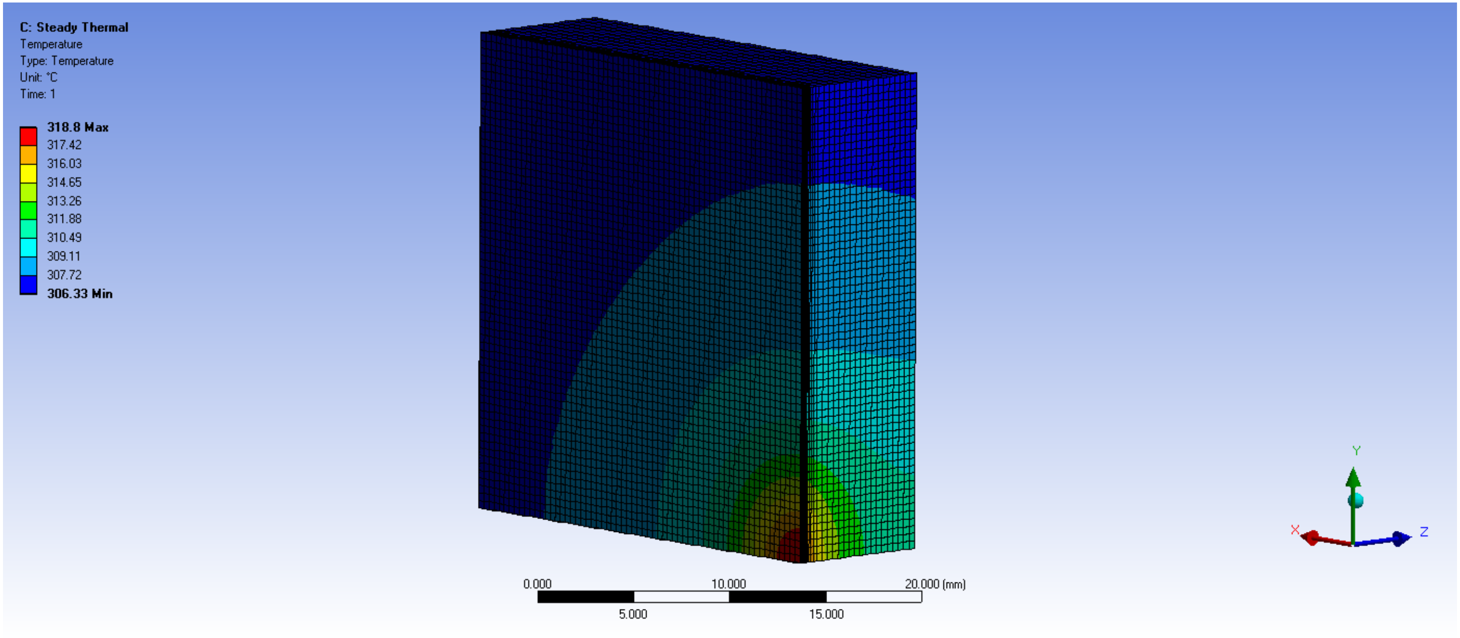
Steady State Thermal

These results are from the case of 10 μs and 1 Hz, reaching 81 C in the steady state.



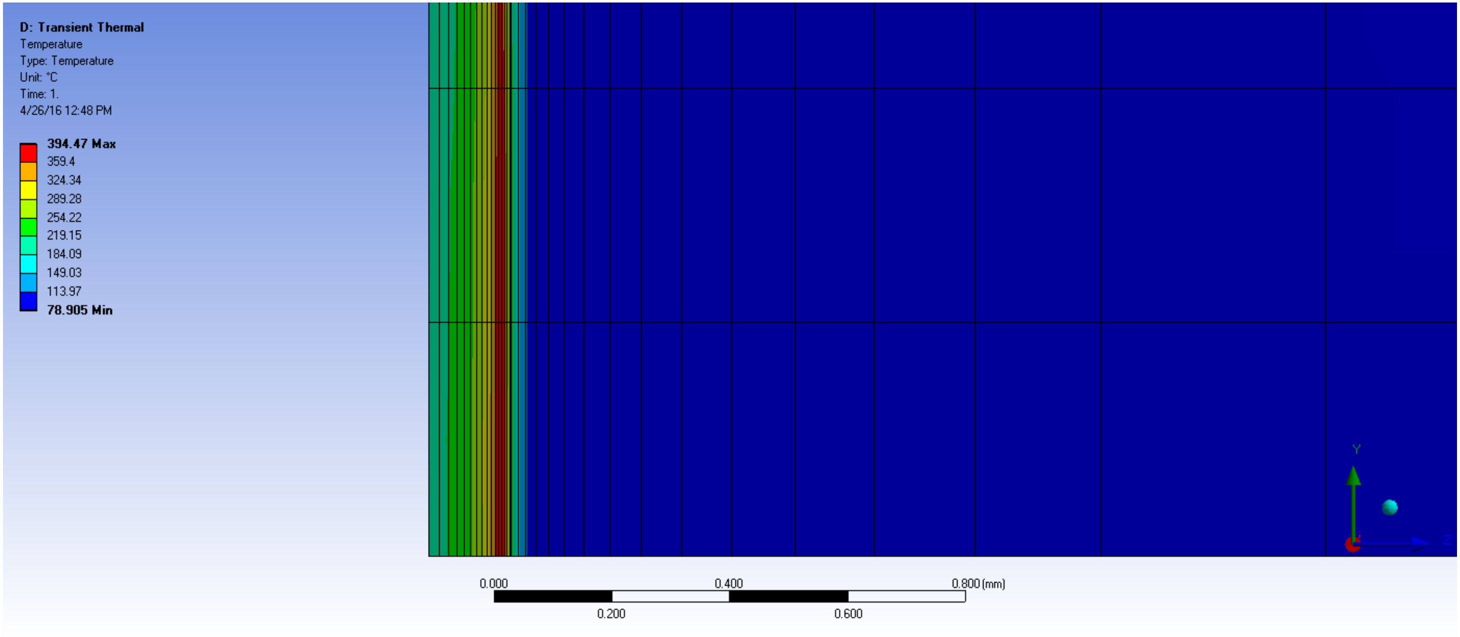
Steady State Thermal

These results are from the case of 50 μs and 1 Hz, reaching 318 C in the steady state.



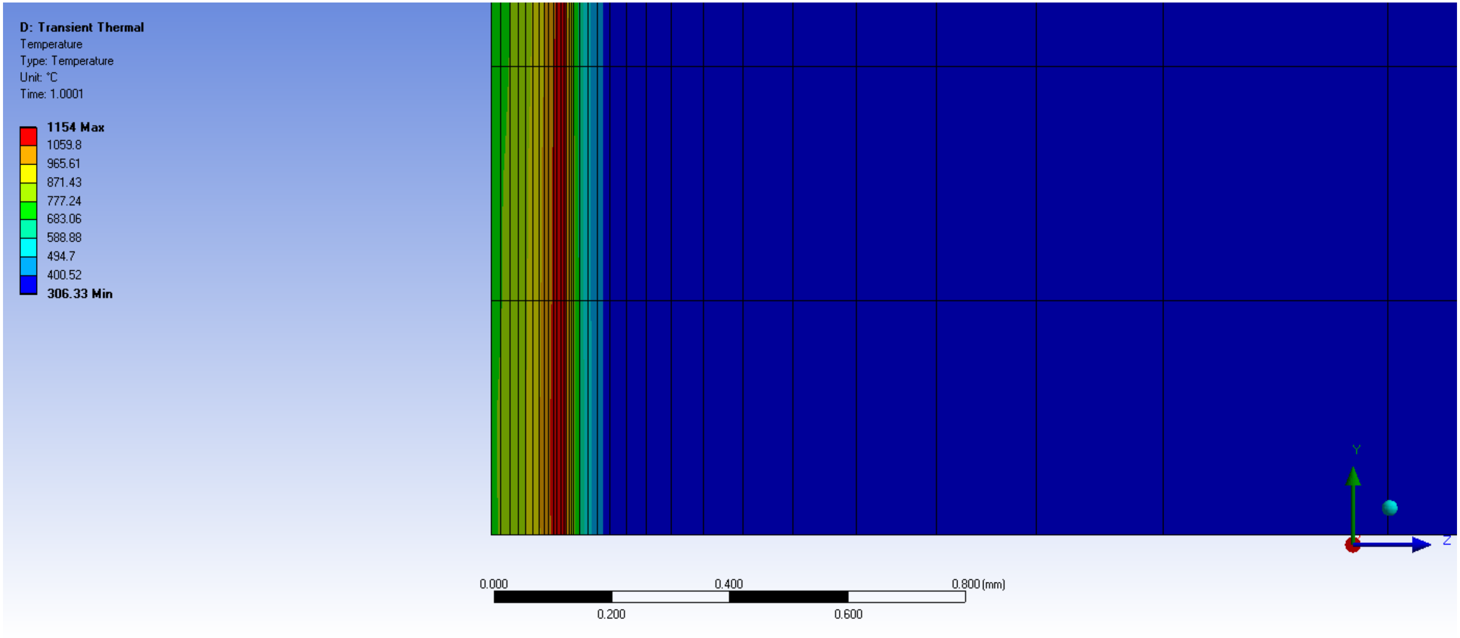
Transient State Thermal

These results are from the case of 10 μs and 1 Hz, reaching 394 C and with an increment of temperature 315 C in the transient state.



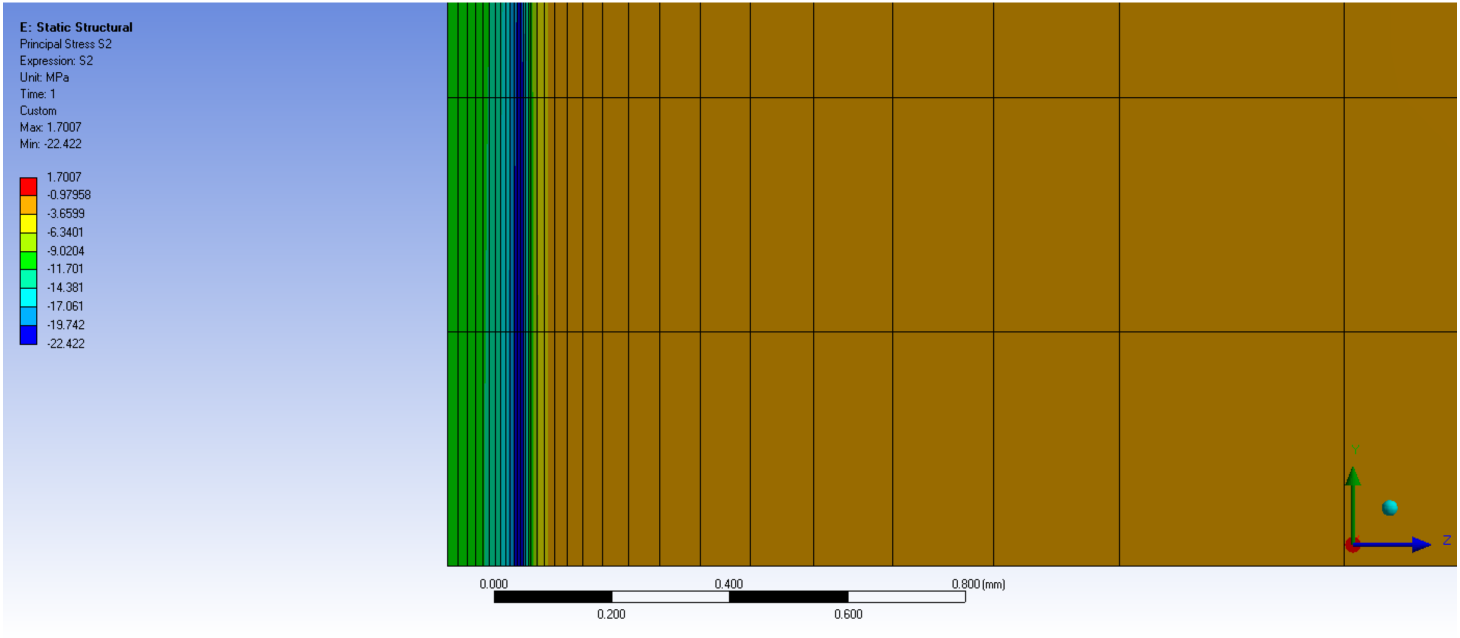
Transient State Thermal

These results are from the case of 50 μs and 1 Hz, reaching 1154 C and with an increment of temperature 848 C in the transient state.



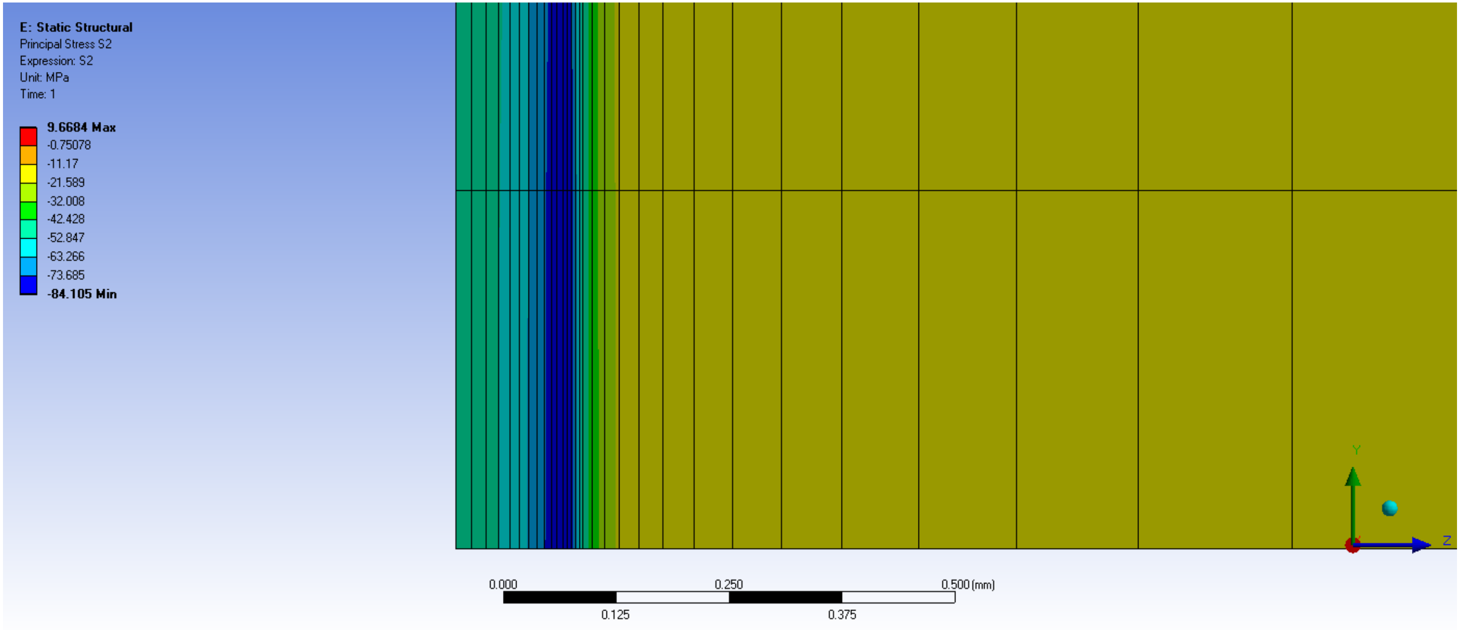
Mechanical Analysis in footprint area

These results are from the case of 10 μs and 1 Hz, reaching $22,4$ MPa in compressive stress and $1,7$ MPa in tensile stress.



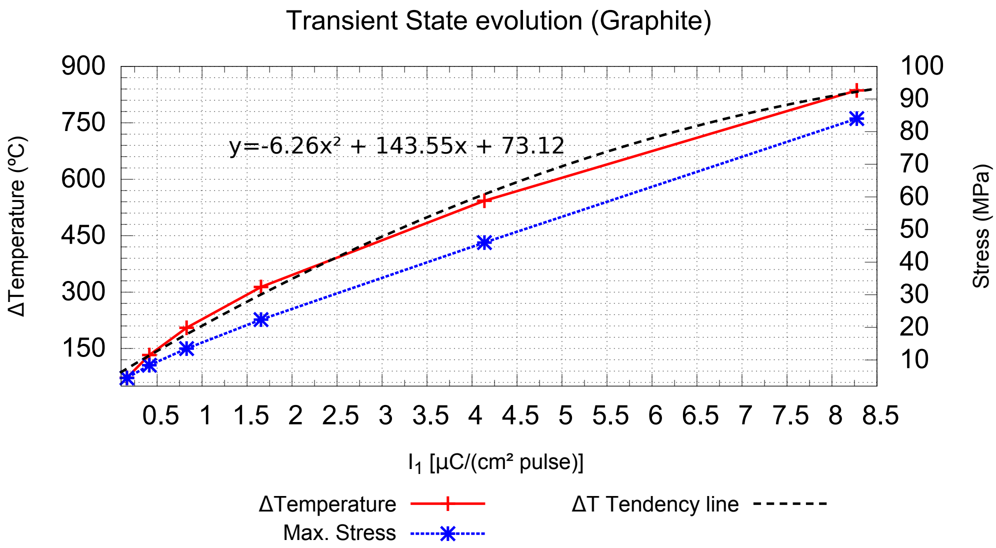
Mechanical Analysis in footprint area

These results are from the case of 50 μs and 1 Hz, reaching 84 MPa in compressive stress and 9,6 MPa in tensile stress.



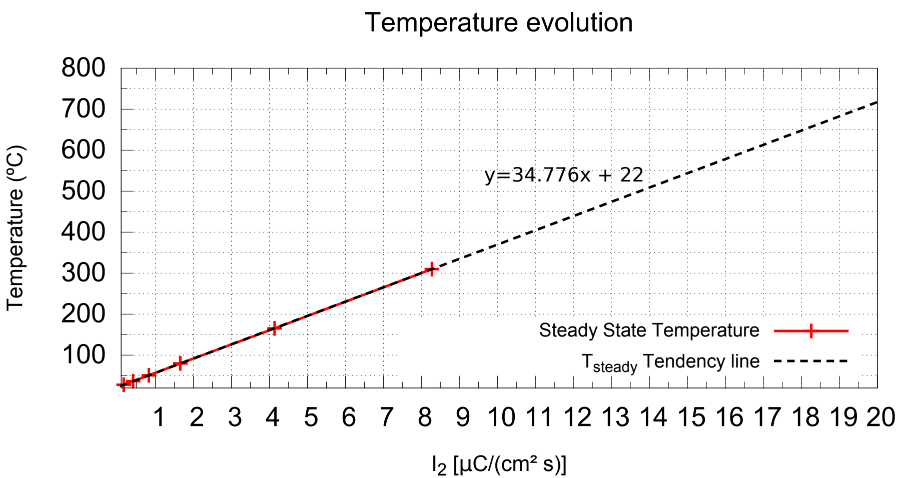
Results evolution

The results show the increment of temperature ($\Delta T C$) and maximum stress (MPa) increasing the variable $I_1[\mu C/(cm^2 pulse)]$. The temperature evolution has a tendency line that can be approximated by the equation: $\mathbf{\Delta T = -6.26 \cdot I_1^2 + 143.55 \cdot I_1 + 73.12}$. The maximum stress has the same tendency as the increment of temperature, due to the elastic behavior of the graphite.



Results evolution

The Steady State has the same behavior in both materials and checks the theoretical equation for the parameters of our case. The steady state equation is $\mathbf{T_{steady}(C) = 34.77 \cdot I_2 + 22}$. This equation depends on the cooling conditions, so it is only for this particular case.



Criteria definition

Temperature criteria

First specification is not to reach a limit temperature of the material during normal operation, using a temperature factor: $T^* = \frac{T_{max}(K)}{T_{limit}(K)}$

The temperature limit for tungsten and graphite can be defined as $T_{limit} = 1/3\ T_{melting}(K)$

Tungsten: $T_{limit} = 1/3 \cdot 3673K = \mathbf{1220K}$
Graphite: $T_{limit} = 1/3 \cdot 3773K = \mathbf{1250K}$

Stress criteria Graphite

Second specification is not to reach a stress limit of the material during normal operation, using a stress factor: $\sigma^* = \frac{\sigma_{max}}{\sigma_{limit}}$

Graphite is a ceramic material with no plastic deformation and a Strength of 40 MPa and 125 MPa tensile and compressive stress, respectively.

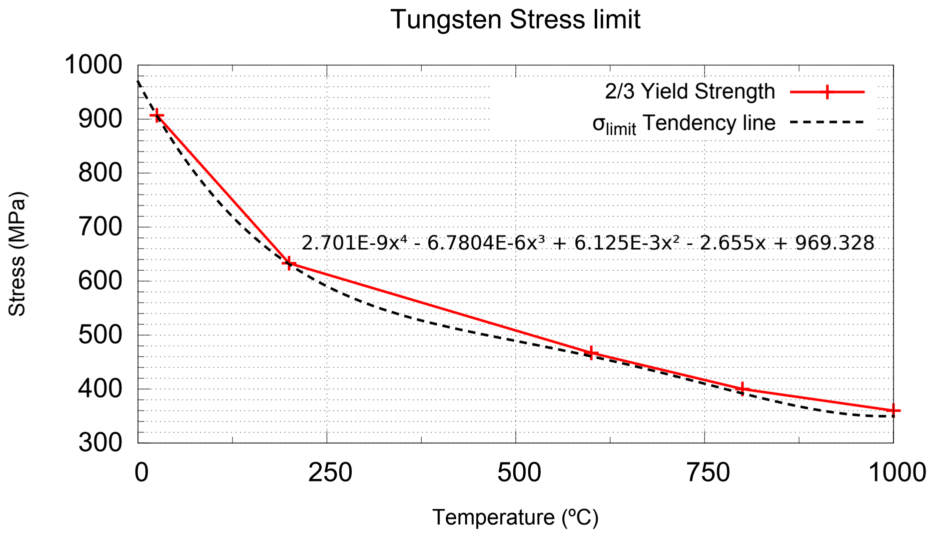
Conservative Criterion:
$\sigma_{limit1} = 1/3\ Tensile\ Strength = \mathbf{13\ MPa}$
$\sigma_{limit2} = 1/3\ Compressive\ Strength = \mathbf{41\ MPa}$

Linac4 Criterion:
$\sigma_{limit1} = 2/3\ Tensile\ Strength = \mathbf{26\ MPa}$
$\sigma_{limit2} = 2/3\ Compressive\ Strength = \mathbf{83\ MPa}$

Stress criteria Tungsten

Tungsten is a metallic material with plastic deformation, which Yield Strength is dependent on the temperature. The Yield Strength has been calculated with the Johnson-Cook model and the limit stress can be defined as:
$\sigma_{limit} = 2/3$ *Yield Strength*.

$$\boldsymbol{\sigma_{limit} = 2.7 \cdot 10^{-9} T^4 - 6.78 \cdot 10^{-6} T^3 + 6.1 \cdot 10^{-3} T^2 - 2.65 T + 969.3}$$



Conservative Criteria analysis: parameters simulated

With the parameters simulated, the criteria ranges can be set:

First criterion $\mathbf{I_1}$ can be set between $\mathbf{0.414}$ and $\mathbf{0.828}$ $\mu\mathbf{C}/(\mathbf{cm^2 pulse})$ for tungsten and $\mathbf{1.65}$ and $\mathbf{4.14}$ $\mu\mathbf{C}/(\mathbf{cm^2 pulse})$ for graphite. It will be refined using the extrapolation with the equations previously defined.

Second criterion $\mathbf{I_2}$ can be analyzed with the equations, fixing the maximum $\mathbf{I_1}$ $[\mu\mathbf{C}/(\mathbf{cm^2 pulse})]$. As it was said before, it will depend on the cooling parameters.

Tungsten									
Frequency (Hz)	Pulse Length (μs)	I2 (μC/cm2 s)	I1 (μC/cm2 pulse)	T_steady(ºC)	ΔT (ºC)	T_peak (ºC)	Stress_max (MPa)	T*	σ*
1	50	8,276	8,276	309,8	1740,0	2050,0	650	1,55	2,53
1	25	4,138	4,138	165,9	1044,6	1210,0	730	0,99	1,45
1	10	1,655	1,655	79,6	500,1	580,0	780	0,57	1,65
1	5	0,828	0,828	50,8	279,3	330,0	595	0,40	1,08
1	2,5	0,414	0,414	36,4	163,6	200,0	350	0,32	0,55
1	1	0,166	0,166	27,8	82,2	110,0	175	0,26	0,24

Graphite									
Frequency (Hz)	Pulse Length (μs)	I2 (μC/cm2 s)	I1 (μC/cm2 pulse)	T_steady (ºC)	ΔT (ºC)	T_peak (ºC)	Stress_max (MPa)	T*	σ*
1	50	8,276	8,276	318	836	1154	84	0,93	2,02
1	25	4,138	4,138	169,7	542,7	712,4	46	0,64	1,10
1	10	1,655	1,655	81	313,5	394,5	22,4	0,44	0,54
1	5	0,828	0,828	51	205	256	13,5	0,35	0,32
1	2,5	0,414	0,414	36,7	132,6	169,3	8,4	0,29	0,20
1	1	0,166	0,166	27,8	72,2	100	4,5	0,24	0,11

Conservative Criteria analysis: parameters extrapolated

Once the range has been set, the criteria can be established using the equations previously estimated. These final criteria have been calculated with the extrapolation of the equations.

A security factor of a 20% has been applied to the results. The tungsten criterion $\mathbf{I_1}$ can be at **0.6** μ**C**/(**cm^{2}pulse**). The graphite can be set at **3** μ**C**/(**cm^{2}pulse**). Moreover, the frequency 14 *Hz* exceeds the temperature limit for the graphite, being necessary a cooling system.

Tungsten									
Frequency (Hz)	Pulse Length (µs)	I2 (µC/cm2 s)	I1 (µC/cm2 pulse)	**T_steady(ºC)**	**ΔT (ºC)**	**T_peak (ºC)**	**Stress_max (MPa)**	**T***	**σ***
1	5	0,828	0,828	50,8	265,6	316,4	591,2	0,39	1,07
1	4,5	0,745	0,745	47,9	242,8	290,7	551,8	0,38	0,97
1	4	0,662	0,662	45,0	219,8	264,9	508,6	0,36	0,87
1	3,5	0,579	0,579	42,1	196,7	238,9	461,7	0,34	0,77
1	3	0,497	0,497	39,3	173,5	212,8	411,1	0,32	0,66
1	2,5	0,414	0,414	36,4	150,1	186,5	356,8	0,31	0,55
14	4	9,269	0,662	344,3	219,8	564,2	508,6	0,56	1,07
1	4	0,662	0,662	45,0	219,8	264,9	508,6	0,36	0,87
14	3	6,952	0,497	263,8	173,5	437,3	411,1	0,47	0,80
1	3	0,497	0,497	39,3	173,5	212,8	411,1	0,32	0,66

Graphite									
Frequency (Hz)	Pulse Length (µs)	I2 (µC/cm2 s)	I1 (µC/cm2 pulse)	**T_steady (ºC)**	**ΔT (ºC)**	**T_peak (ºC)**	**Stress_max (MPa)**	**T***	**σ***
1	25	4,138	4,138	165,9	560,1	726,0	46,7	0,65	1,12
1	22	3,641	3,641	148,6	513,0	661,6	41,9	0,61	1,01
1	20	3,310	3,310	137,1	479,8	617,0	38,6	0,58	0,93
1	15	2,483	2,483	108,3	391,0	499,3	30,2	0,50	0,73
1	12	1,986	1,986	91,1	333,6	424,7	25,1	0,46	0,60
1	10	1,655	1,655	79,6	293,6	373,2	21,6	0,42	0,52
14	22	50,981	3,641	1794,9	513,0	2307,9	41,9	1,69	1,01
1	22	3,641	3,641	148,6	513,0	661,6	41,9	0,61	1,01
14	20	46,346	3,310	1633,7	479,8	2113,6	38,6	1,56	0,93
1	20	3,310	3,310	137,1	479,8	617,0	38,6	0,58	0,93

Linac4 Criteria analysis: parameters simulated

With the parameters simulated, the criteria ranges can be set:

First criterion $\mathbf{I_1}$ can be set between $\mathbf{0.414}$ and $\mathbf{0.828}$ $\boldsymbol{\mu}\mathbf{C/(cm^2 pulse)}$ for tungsten and $\mathbf{4.14}$ and $\mathbf{8.28}$ $\boldsymbol{\mu}\mathbf{C/(cm^2 pulse)}$ for graphite. It will be refined using the extrapolation with the equations previously defined.

Second criterion $\mathbf{I_2}$ can be analyzed with the equations, fixing the maximum $\mathbf{I_1}$ $[\boldsymbol{\mu}\mathbf{C/(cm^2 pulse)}]$. As it was said before, it will depend on the cooling parameters.

Tungsten									
Frequency (Hz)	Pulse Length (μs)	I2 (μC/cm2 s)	I1 (μC/cm2 pulse)	T_steady(ºC)	ΔT (ºC)	T_peak (ºC)	Stress_max (MPa)	T*	σ*
1	50	8,276	8,276	309,8	1740,0	2050,0	650	1,55	2,53
1	25	4,138	4,138	165,9	1044,6	1210,0	730	0,99	1,45
1	10	1,655	1,655	79,6	500,1	580,0	780	0,57	1,65
1	5	0,828	0,828	50,8	279,3	330,0	595	0,40	1,08
1	2,5	0,414	0,414	36,4	163,6	200,0	350	0,32	0,55
1	1	0,166	0,166	27,8	82,2	110,0	175	0,26	0,24

Graphite									
Frequency (Hz)	Pulse Length (μs)	I2 (μC/cm2 s)	I1 (μC/cm2 pulse)	T_steady (ºC)	ΔT (ºC)	T_peak (ºC)	Stress_max (MPa)	T*	σ*
1	50	8,276	8,276	318	836	1154	84	0,93	1,01
1	25	4,138	4,138	169,7	542,7	712,4	46	0,64	0,55
1	10	1,655	1,655	81	313,5	394,5	22,4	0,44	0,27
1	5	0,828	0,828	51	205	256	13,5	0,35	0,16
1	2,5	0,414	0,414	36,7	132,6	169,3	8,4	0,29	0,10
1	1	0,166	0,166	27,8	72,2	100	4,5	0,24	0,05

Linac4 Criteria analysis: parameters extrapolated

Once the range has been set, the criteria can be established using the equations previously estimated. These final criteria have been calculated with the extrapolation of the equations.

A security factor of a 20% has been applied to the results. The tungsten criterion $\mathbf{I_1}$ can be at **0.6** μ**C**/(**cm^{2}pulse**). The graphite can be set at **6** μ**C**/(**cm^{2}pulse**). Moreover, the frequency 14 *Hz* exceeds the temperature limit for the graphite, being necessary a cooling system.

Tungsten									
Frequency (Hz)	Pulse Length (µs)	I2 (µC/cm2 s)	I1 (µC/cm2 pulse)	**T_steady(ºC)**	**ΔT (ºC)**	**T_peak (ºC)**	**Stress_max (MPa)**	**T***	**σ***
1	5	0,828	0,828	50,8	265,6	316,4	591,2	0,39	1,07
1	4,5	0,745	0,745	47,9	242,8	290,7	551,8	0,38	0,97
1	4	0,662	0,662	45,0	219,8	264,9	508,6	0,36	0,87
1	3,5	0,579	0,579	42,1	196,7	238,9	461,7	0,34	0,77
1	3	0,497	0,497	39,3	173,5	212,8	411,1	0,32	0,66
1	2,5	0,414	0,414	36,4	150,1	186,5	356,8	0,31	0,55
14	4	9,269	0,662	344,3	219,8	564,2	508,6	0,56	1,07
1	4	0,662	0,662	45,0	219,8	264,9	508,6	0,36	0,87
14	3	6,952	0,497	263,8	173,5	437,3	411,1	0,47	0,80
1	3	0,497	0,497	39,3	173,5	212,8	411,1	0,32	0,66

Graphite									
Frequency (Hz)	Pulse Length (µs)	I2 (µC/cm2 s)	I1 (µC/cm2 pulse)	**T_steady (ºC)**	**ΔT (ºC)**	**T_peak (ºC)**	**Stress_max (MPa)**	**T***	**σ***
1	50	8,276	8,276	309,8	833,1	1142,9	83,9	0,93	1,01
1	45	7,448	7,448	281,0	795,6	1076,6	77,0	0,88	0,92
1	40	6,621	6,621	252,2	749,6	1001,8	69,8	0,83	0,84
1	35	5,793	5,793	223,5	695,0	918,4	62,3	0,78	0,75
1	30	4,966	4,966	194,7	631,8	826,5	54,6	0,72	0,66
1	25	4,138	4,138	165,9	560,1	726,0	46,7	0,65	0,56
14	50	115,865	8,276	4051,3	833,1	4884,4	83,9	3,37	1,01
1	50	8,276	8,276	309,8	833,1	1142,9	83,9	0,93	1,01
14	45	104,278	7,448	3648,4	795,6	4444,0	77,0	3,08	0,92
1	45	7,448	7,448	281,0	795,6	1076,6	77,0	0,88	0,92

Conclusions

Conclusions

Main conclusions

The proton beam has to fulfill the two criteria simultaneously to ensure the thermo-mechanic integrity of the Beam Stoppers.

- Tungsten has a limit of $\mathbf{0.6\ \mu C/(cm^2 pulse)}$ and could work with 14 *Hz*, depending on the cooling conditions.
- Using the conservative criterion, Graphite has a limit of $\mathbf{3\ \mu C/(cm^2 pulse)}$ and could work with 14 *Hz*, depending on the cooling conditions.
- Using the Linac4 criterion, Graphite has a limit of $\mathbf{6\ \mu C/(cm^2 pulse)}$ and could work with 14 *Hz*, depending on the cooling conditions.

From a thermo-mechanical point of view, Graphite is the best option as Beam Stopper material. The decision of choosing one material will also depend on other aspects:

- Vacuum conditions and possible problems with the materials in a vacuum environment.
- Fatigue process resistance.
- Fabrication process, machining and assembly, etc.

Limitations of the criterion: simulations

The simulations done to estimate this criterion are limited by the simulation conditions and parameters:

- Parameters of the model: proton energy, materials, cooling conditions, supports, etc.
- Properties estimated: temperature ranges, properties evolution, criteria limits, etc.

Limitations of the criterion: ideal geometry model

The results have been calculated for an **ideal case**, which have been analysed in the beam footprint area. The maximum stress obtained for the criterion corresponds to the maximum compressive stress generated by the thermal expansion.

A **real case** with a complex geometry and stress concentrators could produce higher tensile stress, doing more restrictive this criterion.

Possible configurations: conservative criterion

Fixing the limit on 3 $\mu C/(cm^2 pulse)$ for the graphite, some maximum pulse length have been estimated depending on the beam parameters.

Peak current (mA)	Angle (º)	Beam size		I'' (µA/cm2)	Pulse Length MAX (µs)
		σ_x (mm)	σ_y (mm)		
65	90	2,5	1	4,14E+05	7,2
65	45	2,5	1	2,93E+05	10,3
65	30	2,5	1	2,07E+05	14,5
65	90	2,5	2,5	1,66E+05	18,1
65	45	2,5	2,5	1,17E+05	25,6
65	30	2,5	2,5	8,28E+04	36,2
65	90	5	2,5	8,28E+04	36,2
65	45	5	2,5	5,85E+04	51,3
65	30	5	2,5	4,14E+04	72,5
65	90	7,5	5	2,76E+04	108,7
65	45	7,5	5	1,95E+04	153,8
65	30	7,5	5	1,38E+04	217,5
65	90	7,5	7,5	1,84E+04	163,1
65	45	7,5	7,5	1,30E+04	230,7
65	30	7,5	7,5	9,20E+03	326,2

Faraday cup					
65	90	2,488	2,624	1,58E+05	18,9
65	45	2,488	2,624	1,12E+05	26,8

Chopper Dump					
65	10	3,804	1,563	3,02E+04	99,3
65	5	3,804	1,563	1,52E+04	197,8

WS3/Slit					
65	90	3,157	3,835	8,54E+04	35,1
65	45	3,157	3,835	6,04E+04	49,7

Possible configurations: Linac4 criterion

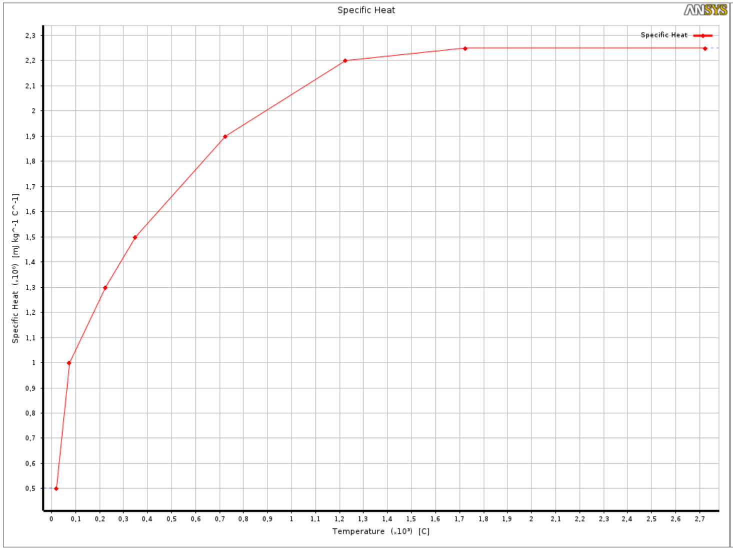
Fixing the limit on 6 $\mu C/(cm^2 pulse)$ for the graphite, some maximum pulse length have been estimated depending on the beam parameters.

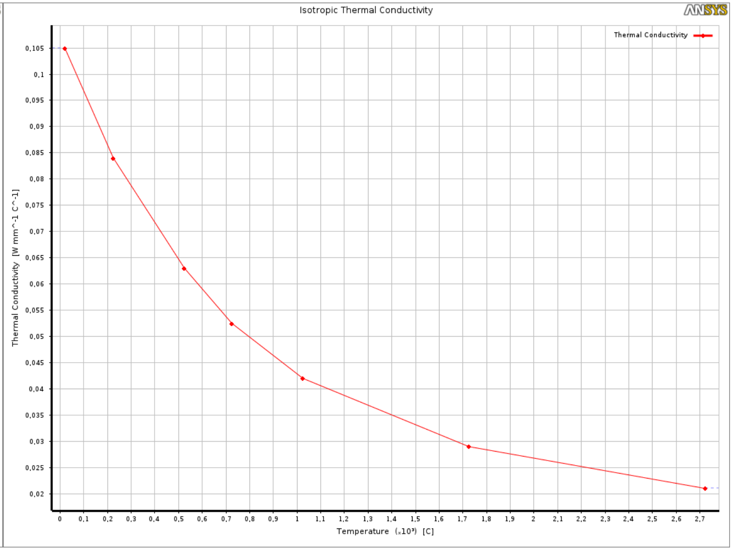
Peak current (mA)	Angle (º)	Beam size σ_x (mm)	Beam size σ_y (mm)	I'' (µA/cm2)	Pulse Length MAX (µs)
65	90	2,5	1	4,14E+05	14,5
65	45	2,5	1	2,93E+05	20,5
65	30	2,5	1	2,07E+05	29,0
65	90	2,5	2,5	1,66E+05	36,2
65	45	2,5	2,5	1,17E+05	51,3
65	30	2,5	2,5	8,28E+04	72,5
65	90	5	2,5	8,28E+04	72,5
65	45	5	2,5	5,85E+04	102,5
65	30	5	2,5	4,14E+04	145,0
65	90	7,5	5	2,76E+04	217,5
65	45	7,5	5	1,95E+04	307,6
65	30	7,5	5	1,38E+04	435,0
65	90	7,5	7,5	1,84E+04	326,2
65	45	7,5	7,5	1,30E+04	461,4
65	30	7,5	7,5	9,20E+03	652,5
Faraday cup					
65	90	2,488	2,624	1,58E+05	37,9
65	45	2,488	2,624	1,12E+05	53,5
Chopper Dump					
65	10	3,804	1,563	3,02E+04	198,6
65	5	3,804	1,563	1,52E+04	395,7
WS3/Slit					
65	90	3,157	3,835	8,54E+04	70,2
65	45	3,157	3,835	6,04E+04	99,3

Appendix

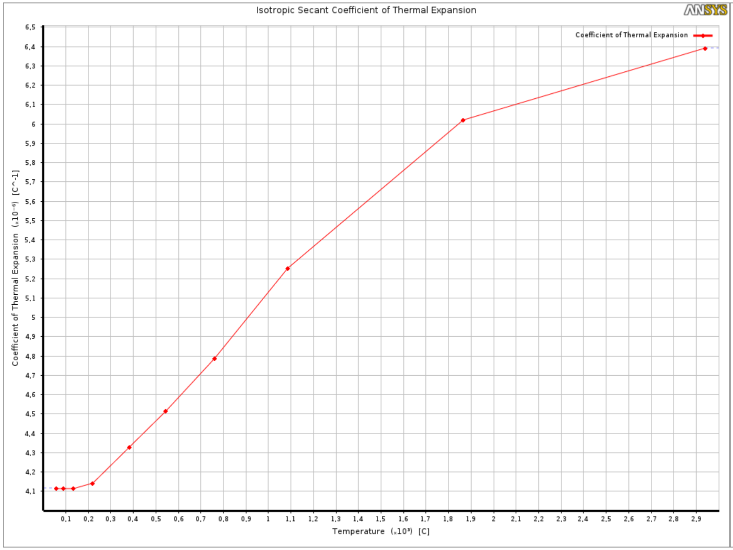
Material properties: Graphite

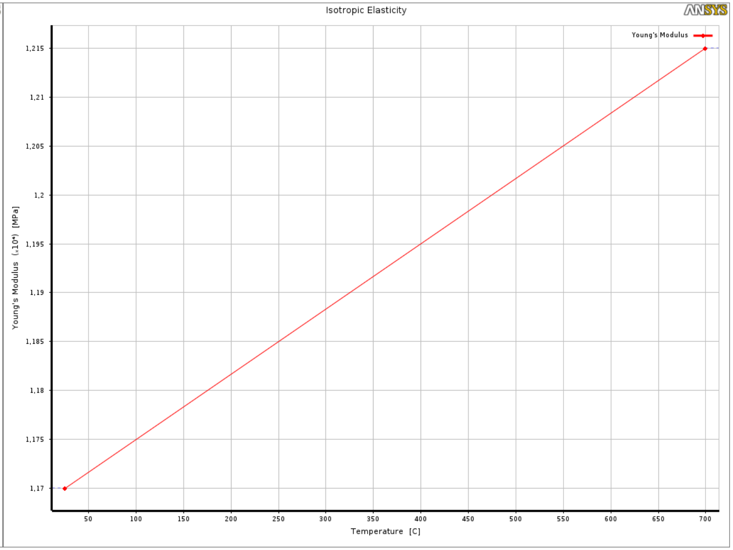
Graphite R4550 with a density of 1.8 g/cm^3.



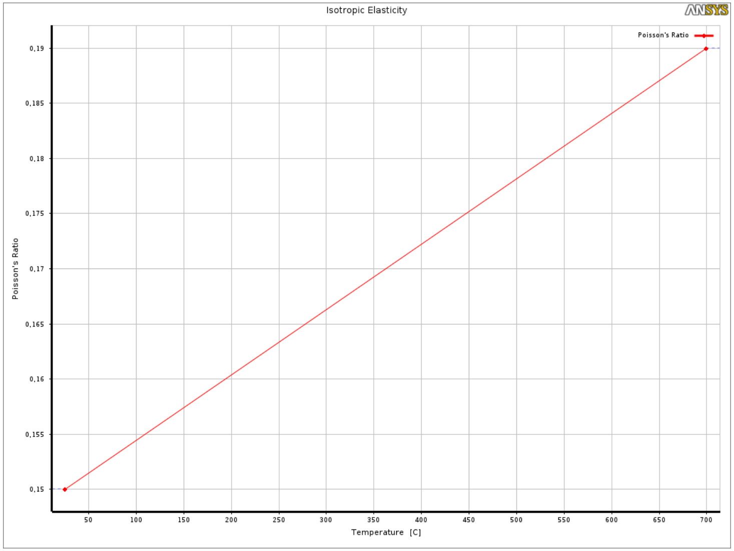


Material properties: Graphite





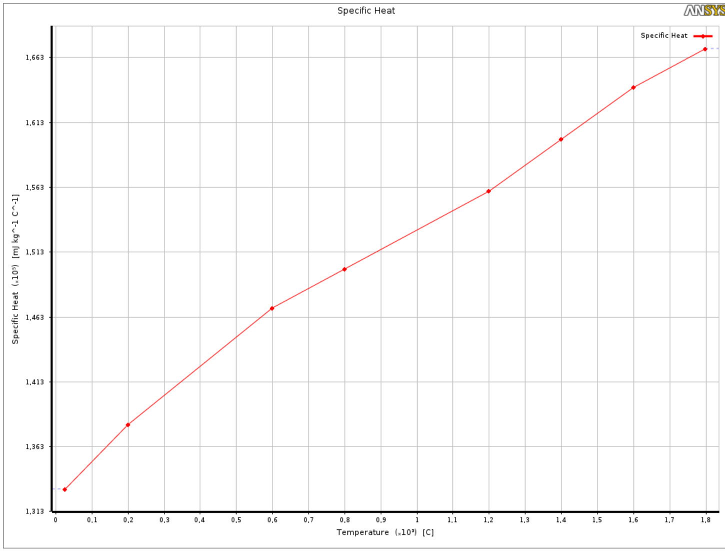
Material properties: Graphite

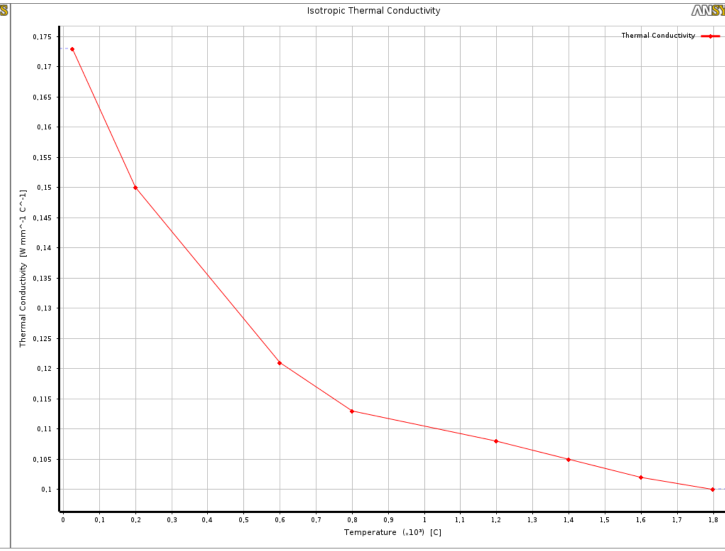


- Tensile Strength: 40 MPa
- Compressive Strength: 125 MPa

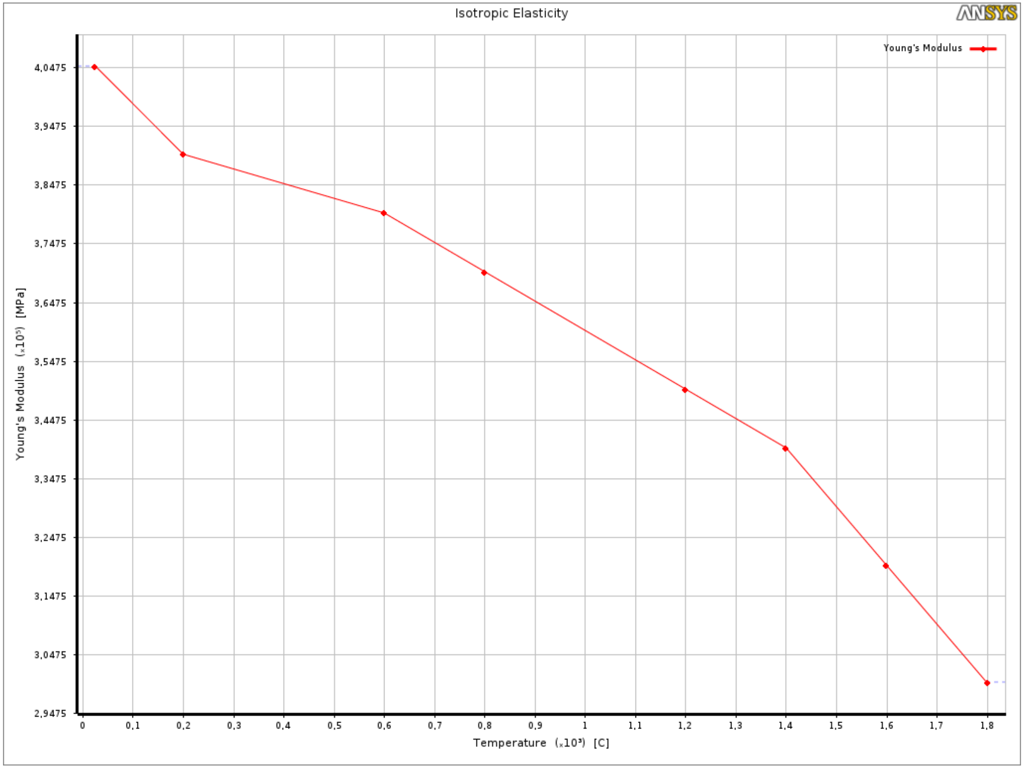
Material properties: Tungsten

Tungsten with a density of 19 g/cm^3.





Material properties: Tungsten



Material properties: Tungsten

Johnson-Cook model