Spallation material: thermomechanical Modeling and load cases

Consorcio ESS-BILBAO & Instituto de Fusión Nuclear & ESS-ERIC

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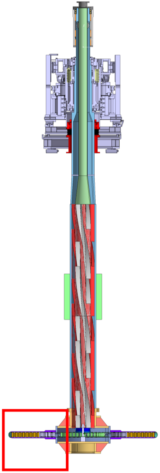
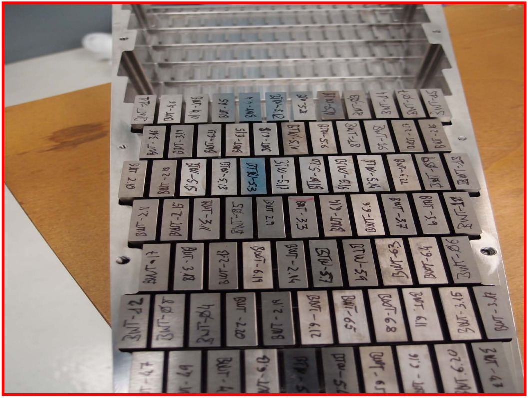
Introduction

The ESS Spallation material

Cross flow tungsten bricks configuration





Spallation Material

Material Properties

Material Properties

ESS Target Materials Handbook

Material properties according to **ESS Target Materials Handbook** have been employed for the analysis. Nonirradiated properties have been used, except for the low conductivity scenario (sensitivity analysis). **NOTE:** Temperature is in [°C] unless specified.

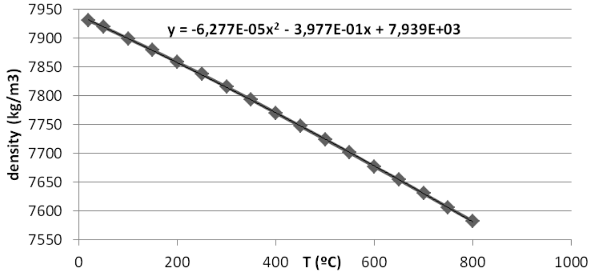
Tungsten

- **Density:** $\rho(\frac{g}{cm^3}) = 19.3027 - 2.3786 \cdot 10^{-4} T - 2.2448 \cdot 10^{-8} T^2$
- **Thermal conductivity:** $\lambda(\frac{W}{m \cdot {}^{o}C}) = 174.9724 - 0.1067 T + 5.0067 \cdot 10^{-5} T^2 - 7.8349 \cdot 10^{-9} T^3$
- **Specific heat:** $c_p(\frac{J}{kg \cdot {}^{o}C}) = 128.308 + 3.2797 \cdot 10^{-2} T - 3.4097 \cdot 10^{-6} T^2$
- **Thermal expansion**: $\alpha_m(\frac{\mu m}{m \cdot {}^{o}C}) = 4.43 + 5.50 \cdot 10^{-4} T - 1.47 \cdot 10^{-7} T^2 + 6.07 \cdot 10^{-11} T^3$
- **Young modulus**: $E(GPa) = 397.903 - 2.3066 \cdot 10^{-3} T - 2.7162 \cdot 10^{-5} T^2$
- **Poison ratio**: $\nu = 0.279 + 1.0893 \cdot 10^{-5} T$

Material Properties

Stainless Steel 316L

- **Density:** Polynomial fit was done from the values of the ESS Materials Handbook



- **Thermal conductivity:** $\lambda(\frac{W}{m\cdot{}^{o}C}) = 13.98 + 1.5202 \cdot 10^{-2} T$
- **Specific heat:** $c_p(\frac{J}{kg\cdot{}^{o}C}) = 462.69 + 5.2026 \cdot 10^{-1} T - 1.7117 \cdot 10^{-3} T^2 + 3.3658 \cdot 10^{-6} T^3 - 2.1958 \cdot 10^{-9} T^4$
- **Thermal expansion**: $\alpha_m(\frac{\mu m}{m\cdot{}^{o}C}) = 15.13 + 7.93 \cdot 10^{-3} T - 3.33 \cdot 10^{-6} T^2$
- **Young modulus**: $E(GPa) = 2.01660 \cdot 10^2 - 8.48 \cdot 10^{-2} T$
- **Poison ratio**: $\nu = 0.3$

Material Properties

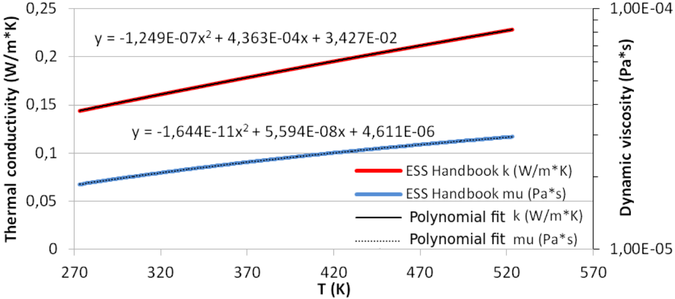
Helium

- **Density**: Ideal gas law
- **Thermal conductivity**: Polynomial fit was done from

$$\lambda(\frac{W}{m \cdot K}) = 0.144 \cdot (T[K]/T_0)^{0.71};\ T_0 = 273.16[K]$$

- **Specific heat**: $c_p(\frac{J}{kg \cdot {}^oC}) = 5193$ (T,P not dependant)
- **Dynamic viscosity**: Polynomial fit was done from

$$\mu(Pa \cdot s) = 1.865 \cdot 10{-}5(T[K]/T_0)^{0.7};\ T_0 = 273.16[K]$$

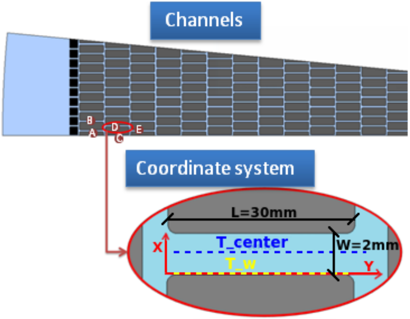


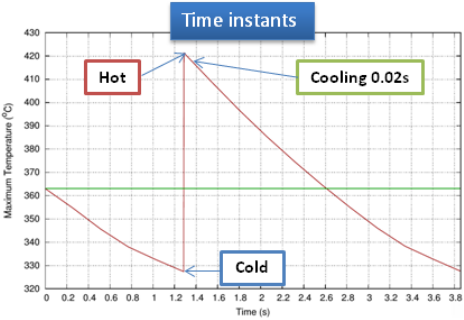
Spallation material convection cooling analysis

Description of the spallation convection analiyisis

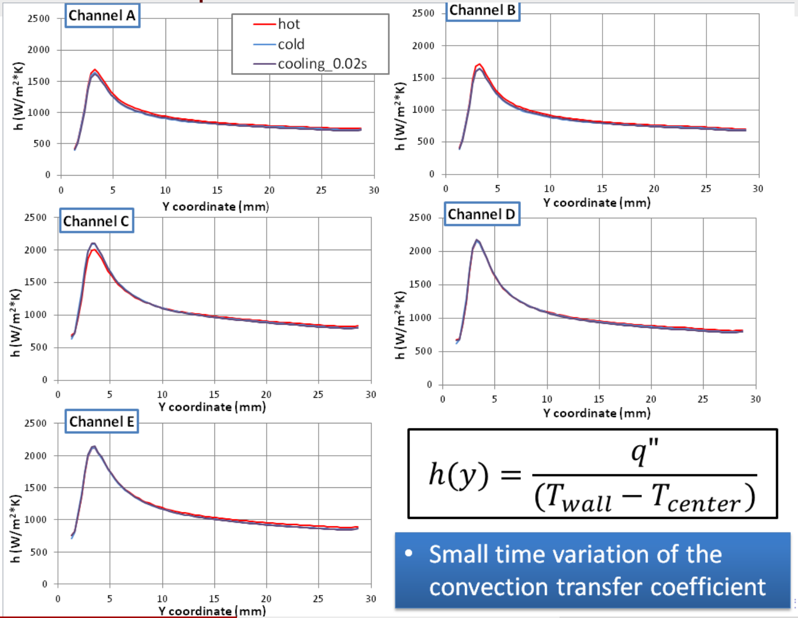
- 2D-CFD transient simulation
- ESS-TDR 2013 proton beam heat source and 33 sectors target configuration
- Local coordinate systems in five different channels (**A,B,C,D,E**)
- Variables: Wall temperature ($\mathbf{T_w}$), helium bulk temperature ($\mathbf{T_{center}}$), wall heat flux (**q**”)
- Time instants: end of cooling (Cold), pulse end (Hot), 0.02s after pulse end (Cooling 0.02s)

<u>NOTE:</u> Actual conditions are different ⇒ T profile not comparable but valid conclusions.





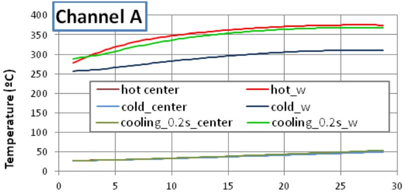
Helium bulk temperature

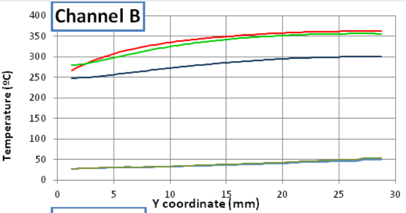


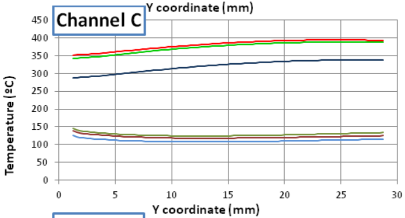
$$h(y) = \frac{q''}{(T_{wall} - T_{center})}$$

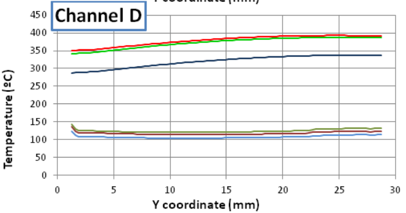
- Small time variation of the convection transfer coefficient

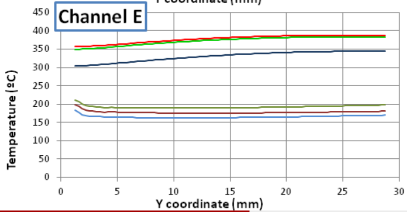
Temperature vs Y cordinate





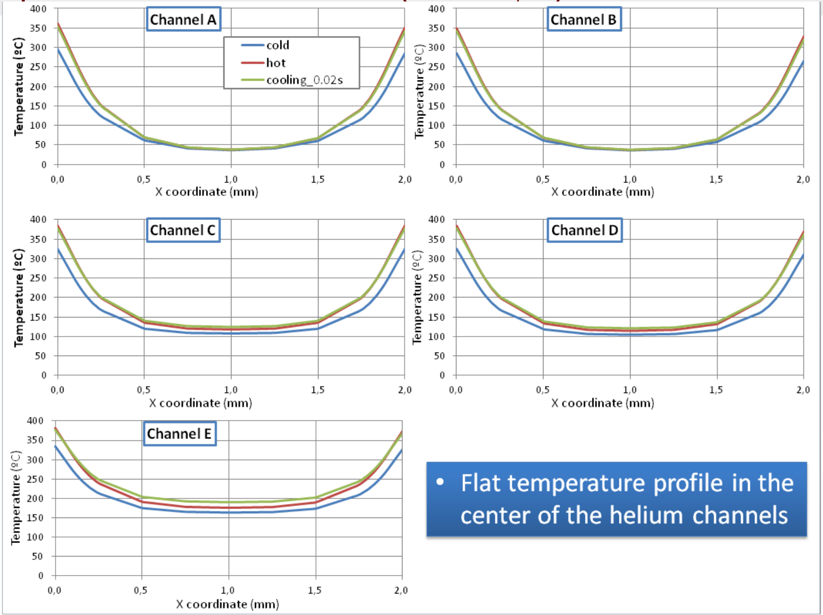






- Small time variation of the helium bulk temperatue

Temperature vs X cordinate ($Y = L/2$)



- Flat temperature profile in the center of the helium channels

Conclusions

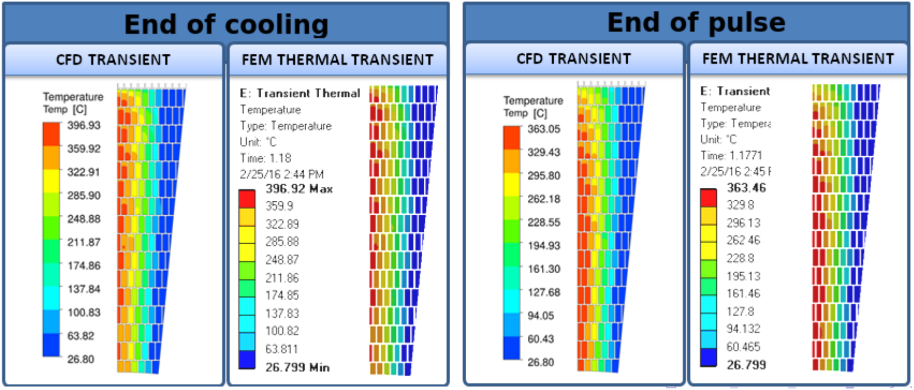
Summary

- Helium temperature near the tungsten wall ($\mathbf{T_{wall}}$) have a considerably variation over time. However the temperature in the helium close to the center of the channel ($\mathbf{T_{bulk}}$) is almost no time dependent.
- Over the width of the channel helium temperature has a sloping shape near the wall (thermal boundary layer), but in the center of the channel the profile is flat (outside the thermal boundary layer).
- Heat transfer coefficient between helium and walls the tungsten is practically invariant over the time $\mathbf{h(y) = q" \cdot (T_{wall} - T_{bulk})^{-1}}$.
- **The fluid-solid uncoupling is allowed**. Convection boundary condition ($\mathbf{h, T_{bulk}}$) on the surfaces in contact with helium could be calculated from a steady state simulation at average power and this BC will not vary over the time.

Fluid solid uncoupling validation

Transient CFD vs transient FEM

In order to validate and check the methodology BC were obtained for the 2D. After steady state CFD simulation at average power BC were imported to a 2D FEM thermal transient model. The solution was compared with the transient CFD model results. The **temperature profiles are practically identical**, but the computational time and resources required are much higher to solve the transient CFD model.



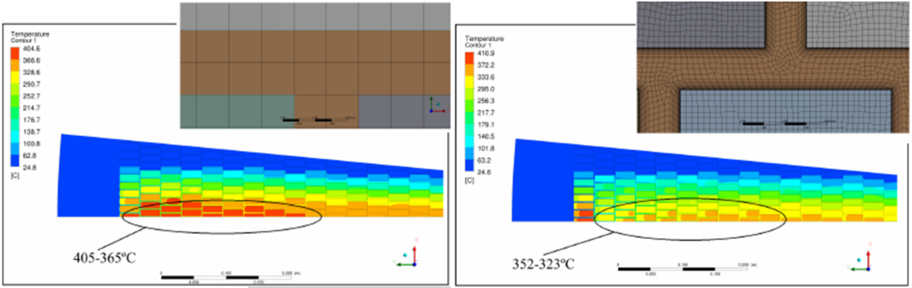
Models description

Thermomechanical simulation methodology

Turbulence role and CFD accuracy

- Turbulence play an important role ⇒ CFD solved with accuracy ($\mathbf{y}^+ \approx \mathbf{1} - \mathbf{5}$)
- Complex fluid-tungsten boundary
- 3D-CFD transient simulation ⇒ prohibitive computing time and resources

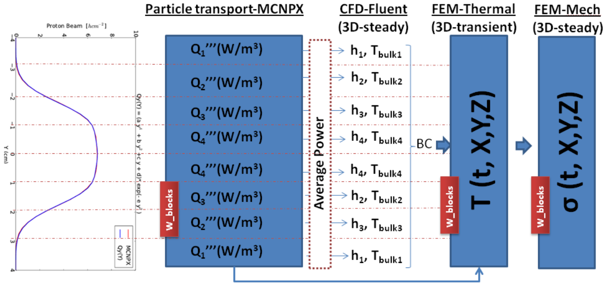
For these reasons **solid-fluid uncoupling methodology** was chosen to solve the SF1, SF2 and SF3 main load cases.

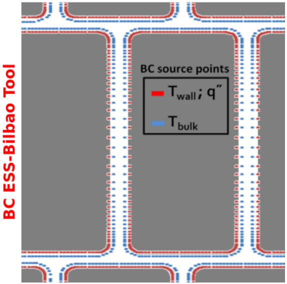


Thermomechanical simulation methodology

Steps

1. Generate the Thermal Source using MCNP.
2. Solve the CFD steady state model at average power.
3. Generate the convection BC ($\mathbf{T_{bulk}}; \mathbf{h}$) from the CFD solution (BC ESS-Bilbao Tool).
4. Solve the FEM-Thermal Transient model.
5. Solve the FEM Mechanical steady state model for the end of cooling and end of pulse.





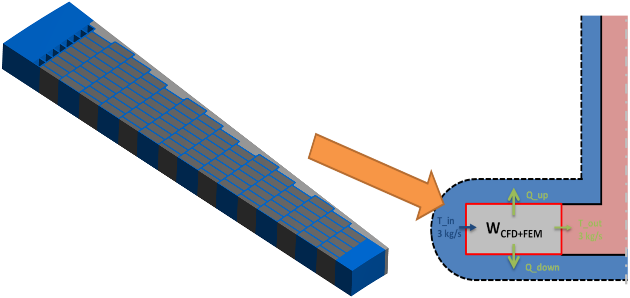
CFD-Tungsten convection BC generation

BC generation

The aim this CFD model is to generate the helium-tungsten convection boundary conditions ($\mathbf{T_{bulk}}; \mathbf{h}$), from a steady state solution, to be employed in the FEM-thermal transient model.

Boundary conditions and assumptions

- Tungsten heat source generated by average current beam
- Helium: $T_{inlet} = 115°C(conservative); P_{op} = 10bar; \dot{m} = 3kg/s$
- Conduction between Tungsten and cassette is not considered
- Symmetry is considered, 1/4 or 1/2 depending on the load case scenario

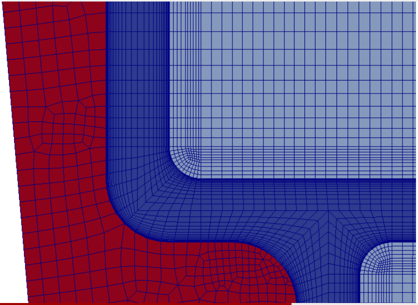


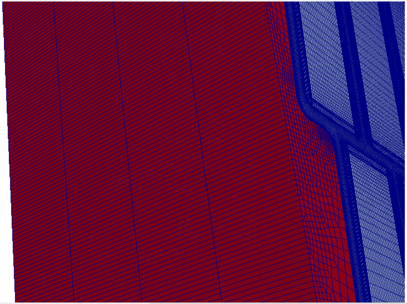
CFD-Tungsten convection BC generation

Turbulence model and mesh

- Turbulence model: $\kappa - \omega$ **SST**
- Conformal hexahedral mesh (3 zones)
- Fine boundary layer:
    - 15 elements
    - 1.24 growth rate
    - $y^+ \approx 1$
- High mesh resolution in flow directions
- Height mesh resolution: 1 element/cm*
- Mesh parameters:

Parameter	**Aver. Value**	**Worst value**
N^o Elements	2,205,420	-
Orthogonal Quality	0.992	0.29
Skewness	0.05	0.67
Aspect ratio	203.9*	244.93*



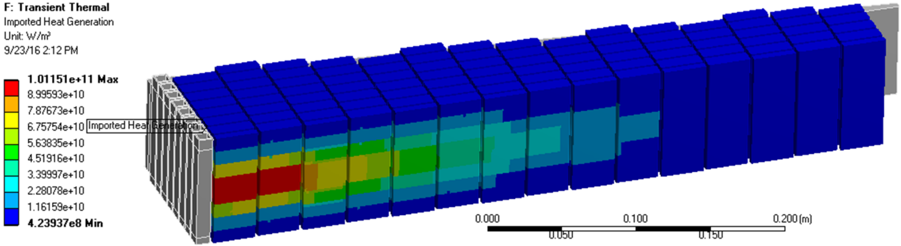


FEM-Thermal model

Boundary conditions and assumptions

The aim this FEM model is to calculate the evolution of the temperature profile in the spallation material and the cassette.

- Tungsten heat source generated by instantaneous current beam
- Heat source is activated during the pulse ($t_{pulse} = 2.86 \cdot 10^{-3}$ ms) and disabled during the cooling ($t_{cooling} = 2.56857$ s)

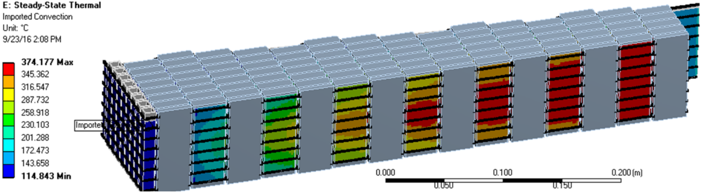


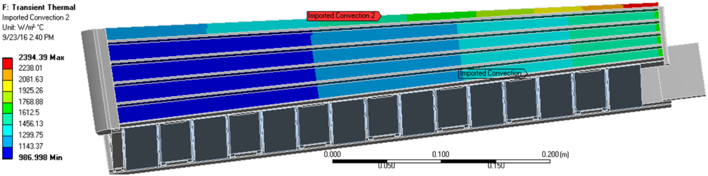
FEM-Thermal model

Boundary conditions and assumptions

- Imported convection BC on tungsten walls and cassette side from CFD steady state model
- Convection boundary condition to consider the cooling effect of the helium on the inlet channels of the cassette plates. The Dittus-Boelter equation was used:

$$Nu_D = 0.023 \cdot Re_D^{0.8} \cdot Pr^{0.4}$$

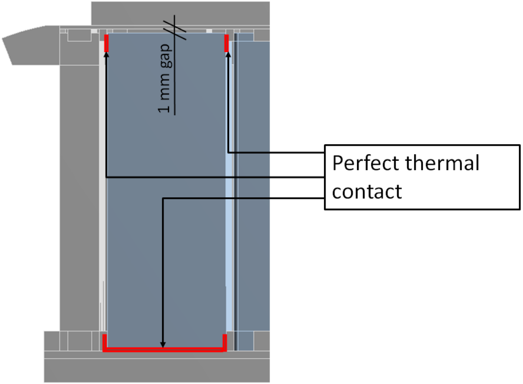




FEM-Thermal model

Boundary conditions and assumptions

- Perfect thermal between the tungsten bricks and the cassette, maintaining 1mm gap above without heat transfer
- All other surfaces are considered adiabatic
- Symmetry is considered depending on the load case scenario

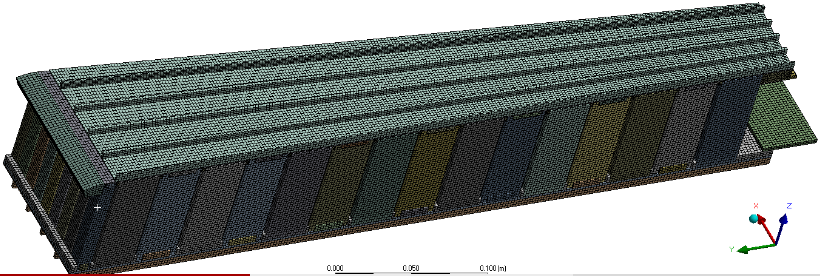


FEM-Thermal model

Mesh

Unlike the CFD problem the required mesh to accurately solve the thermo-mechanical problem is coarser. A non conformal mesh composed by 466,000 elements was employed, most are hexahedrons but some complex bodies were meshed with tetrahedrons.

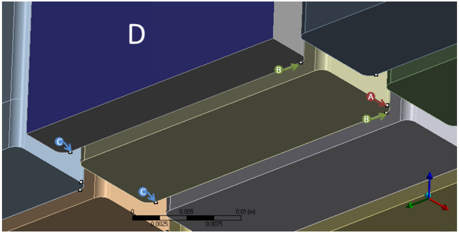
Parameter	**Aver. Value**	**Worst value**
N^o Elements	465,974	-
Element Quality	0.89	0.23
Skewness	0.19	0.9
Aspect ratio	1.47	6.7



FEM-Mechanical model

Boundary conditions and assumptions

- Temperature distribution produced by the proton beam interaction with the tungsten is the only considered load. Two temperature profiles have been imported from the FEM thermal model: the end cooling and the end pulse.
- Following mechanical BC reproduce the supports of tungsten bricks on the cassette, avoiding the simulation of the cassette:
  - **A:** No displacement is allowed for these points.
  - **B:** No displacement is allowed along Y and Z direction, but X displacement is free for these points.
  - **C:** No displacement is allowed along Z, but X and Y displacement is free for these points.
  - **D:** YZ is a symmetry plane which slices some tungsten bricks. The symmetry condition is considered applying a frictionless support to the sliced faces.

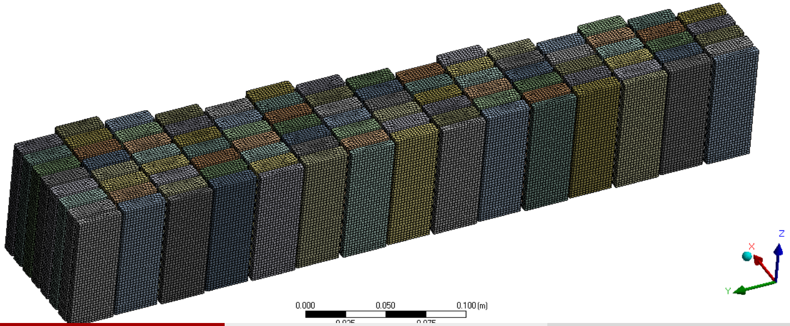


FEM-Mechanichal model

Mesh

The mesh is composed by 321,100 hexahedral elements.

Parameter	Aver. Value	Worst value
N^o Elements	321,112	-
Element Quality	0.94	0.71
Skewness	0.15	0.6
Aspect ratio	1.05	1.84



SF1: Normal operation conditions

SF1: Normal operation conditions

Introduction

- Design beam at nominal *f(Hz)*
- Non irradiated Target
- Wheel at nominal *rpm* and Beam synchronized
- Beam hitting in the cassette center
- Cooling system at nominal conditions *rpm*
- $P_{He} = 10 bar$ and $\dot{m} = 3 kg/s$

SF1 Design Beam

Design beam includes the uncertainty on beam instrumentation, which means 20% more concentrated beam than nominal one.

Parameter	**Value**
Beam Energy	2.0 GeV
Pulse Repetition Rate	14 Hz
Beam energy per pulse	357 kJ
Maximum Energy per pulse	371 kJ

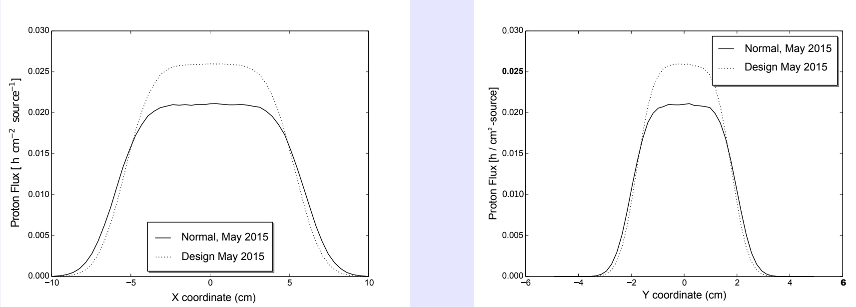
SF1: Normal operation conditions

Introduction

Loads on nominal conditions are produced by the design beam under nominal frequency for the repetition rate, with the wheel at his nominal rotation speed. Also the beam is considered synchronized with the wheel and hitting in the center of the cassette. The cooling system is working at nominal conditions, so helium mass flow trough the wheel is 3.0 kg/s which means 0.0833 kg/s in each cassette.

SF1 Design Beam

Design beam includes the uncertainty on beam instrumentation, which means 20% more concentrated beam than nominal one.

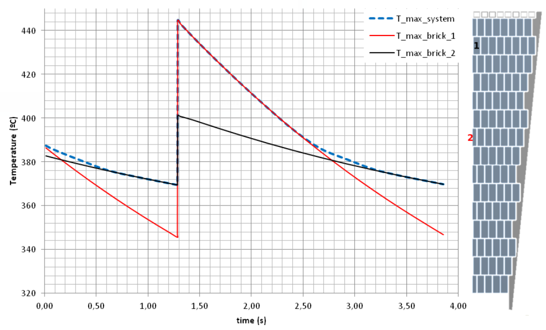


SF1: Normal operation conditions

Thermal analysis

The maximum temperature increase happens when the beam hits the tungsten, the energy deposition of the protons interacting the spallation material produces a **$\Delta T_{max} = 100$ºC**, which occurs **in the brick 1**. The front rows bricks have higher heat deposition by protons but they are better cooled, for this reason at the end of the cooling the temperature of these bricks is lower than others. The brick 2 has the maximum temperature at the end of the cooling cycle.

Temperature evolution

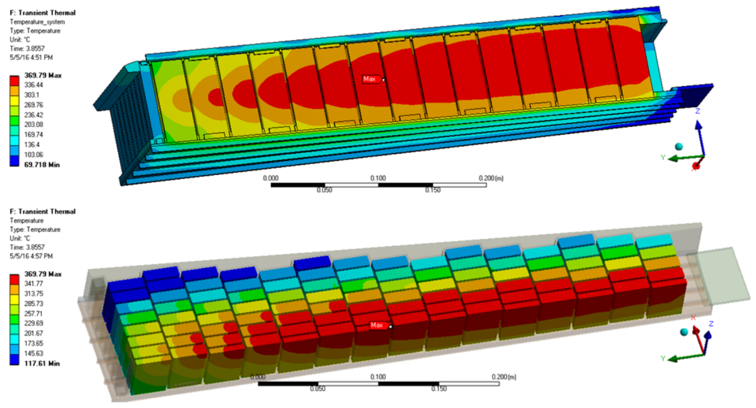


SF1: Normal operation conditions

Temperature profiles

The **maximum temperature at the end of the cooling is 370°C** and **after the pulse is 445°C**, but the hottest brick changes during the pulse and subsequent cooling process.

End of cooling

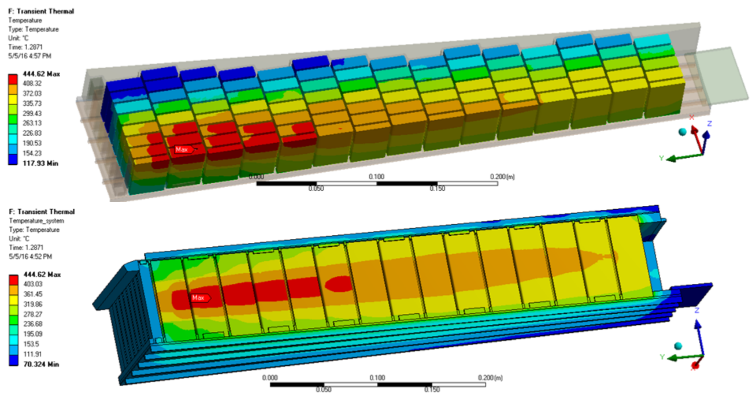


SF1: Normal operation conditions

Temperature profiles

The **maximum temperature at the end of the cooling is 370°C** and **after the pulse is 445°C**, but the hottest brick changes during the pulse and subsequent cooling process.

End of pulse

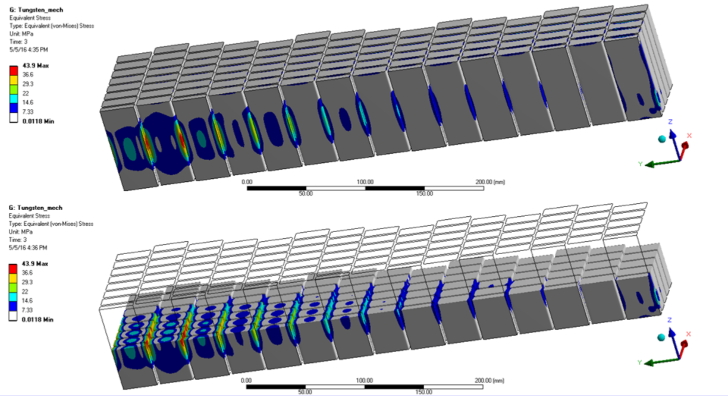


SF1: Normal operation conditions

Equivalent von-Mises stress profiles

The maximum equivalent stress at the **end of the cooling is 44 MPa** and **after the pulse is 110 MPa**.

End of cooling



SF1: Normal operation conditions

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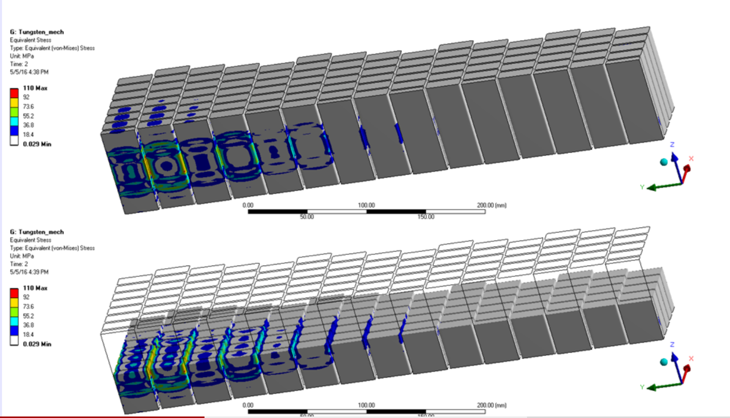
End of pulse



SF1: Normal operation conditions

Conclusions

- The maximum temperature and maximum stress values are below the limits.

	Limit	Value
Maximum W temperature	<500°C	445°C
Averaged maximum stress	100 MPa	77 MPa
Post pulse peak stress	50 MPa	44 MPa

- Requirements already include its own safety margin so it can be concluded that the design fulfill the design criteria for the SF1: normal operation conditions load case.

SF2: Vertical displacement beam

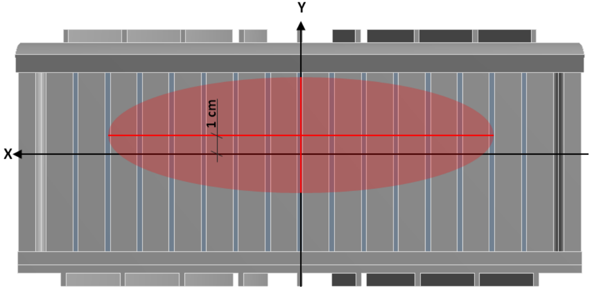
SF2: Vertical displacement beam

Introduction

- Design beam at nominal *f(Hz)*
- Non irradiated Target
- Wheel at nominal *rpm* and Beam synchronized
- **Beam vertical displacement 1cm**
- Cooling system at nominal conditions *rpm*
- $P_{He} = 10 bar$ and $\dot{m} = 3 kg/s$

SF2 Design Beam

Design beam includes the uncertainty on beam instrumentation, which means 20% more concentrated beam than nominal one.



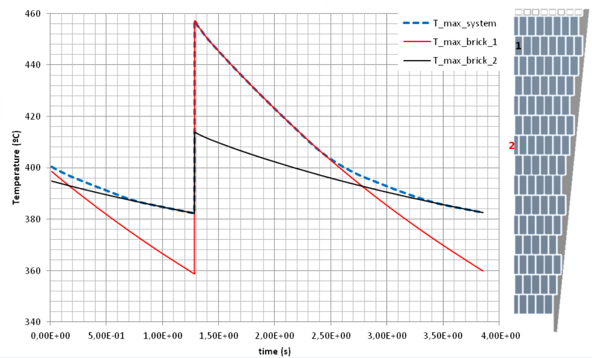
Parameter	Value
Beam Energy	2.0 GeV
Pulse Repetition Rate	14 Hz
Beam energy per pulse	357 kJ
Maximum Energy per pulse	371 kJ
Vertical displacement	+1 cm

SF2: Vertical displacement beam

Thermal analysis

The maximum temperature increase happens when the beam hits the tungsten, the energy deposition of the protons interacting the spallation material produces a $\mathbf{\Delta T_{max} = 100^{o}C}$, which occurs in the brick 1. The brick 2 has the maximum temperature at the end of the cooling. The vertical displacement of the proton beam produces **12^{o}C of maximum temperature increase comparing with SF1 load condition**.

Temperature evolution



SF2: Vertical displacement beam

Thermal analysis

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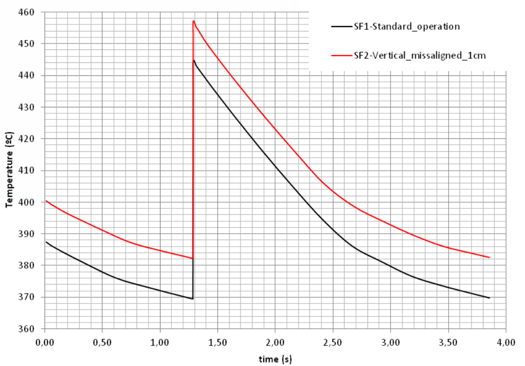
Temperature evolution

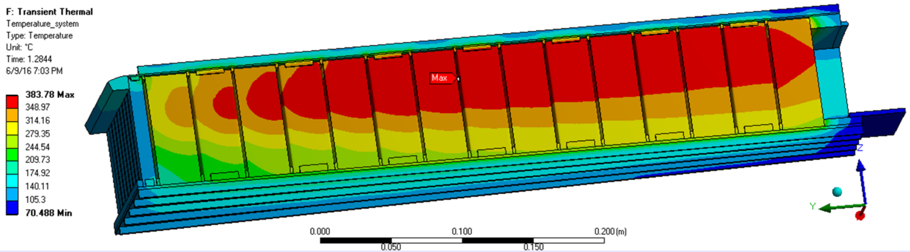


SF2: Vertical displacement beam

Temperature profiles

The **maximum temperature at the end of the cooling is 384°C** and **after the pulse is 457°C**, but the hottest brick changes during the pulse and subsequent cooling process.

End of cooling

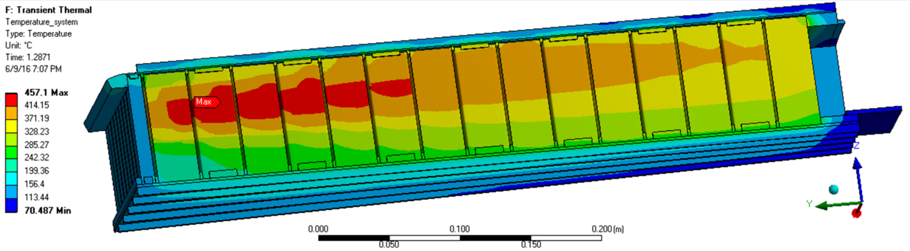


SF2: Vertical displacement beam

Temperature profiles

The **maximum temperature at the end of the cooling is 384°C** and **after the pulse is 457°C**, but the hottest brick changes during the pulse and subsequent cooling process.

End of pulse

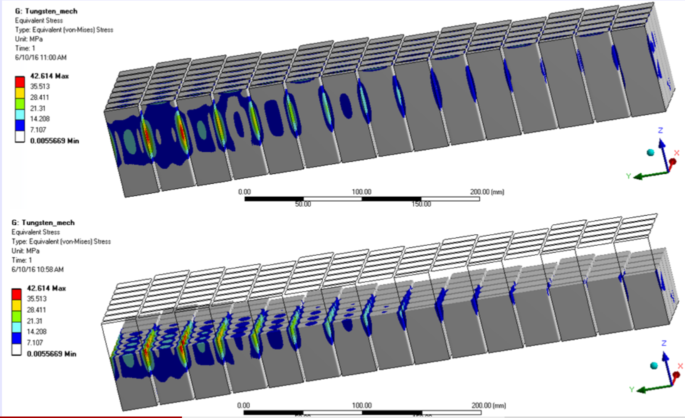


SF2: Vertical displacement beam

Equivalent von-Mises stress profiles

The maximum equivalent stress at the end of the cooling is 43 MPa and after the pulse is 111 MPa.

End of cooling

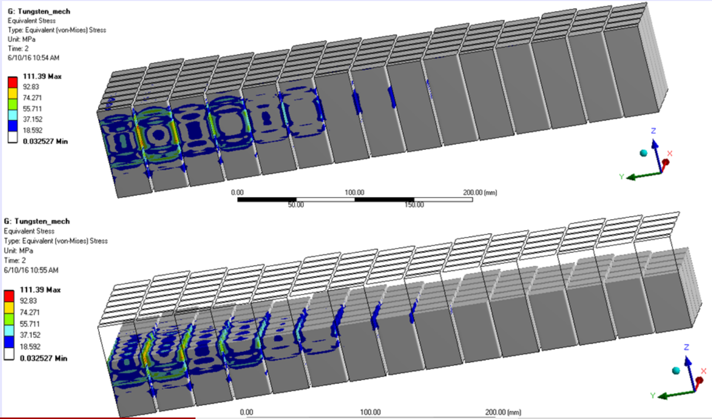


SF2: Vertical displacement beam

Equivalent von-Mises stress profiles

The maximum equivalent stress at the end of the cooling is 43 MPa and after the pulse is 111 MPa.

End of pulse



SF2: Vertical displacement beam

Conclusions

- The maximum temperature and maximum stress values are below the limits.

	Limit	**Value**
Maximum W temperature	<600°C	457°C
Averaged maximum stress	100 MPa	77 MPa
Post pulse peak stress	50 MPa	43 MPa

- Requirements already include its own safety margin so it can be concluded that the design fulfill the design criteria for the SF2: Vertical displacement beam.
- It is not clear if stress criteria limits apply to the SF2 scenarios

SF2: Unsynchronized wheel

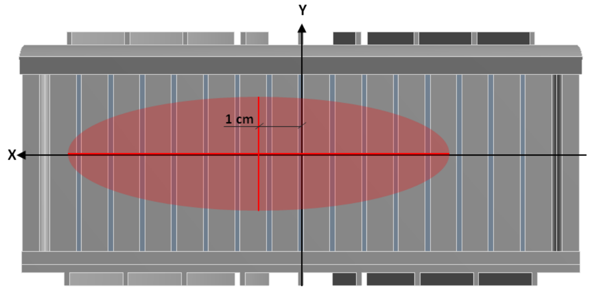
SF2: Unsynchronized wheel

Introduction

- Design beam at nominal *f(Hz)*
- Non irradiated Target
- Wheel at nominal *rpm* but **Beam unsynchronized**
- **Beam horizontal displacement 1cm**
- Cooling system at nominal conditions *rpm*
- $P_{He} = 10 bar$ and $\dot{m} = 3 kg/s$

SF2 Design Beam

Design beam includes the uncertainty on beam instrumentation, which means 20% more concentrated beam than nominal one.



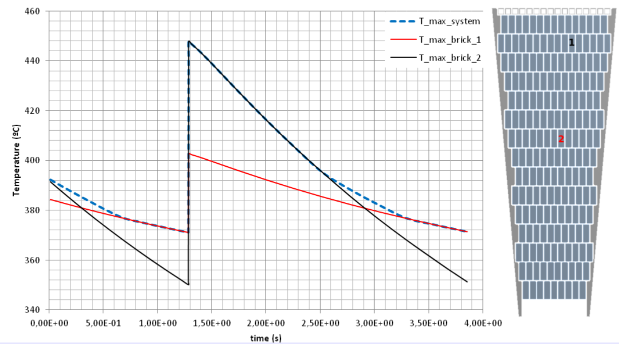
Parameter	Value
Beam Energy	2.0 GeV
Pulse Repetition Rate	14 Hz
Beam energy per pulse	357 kJ
Maximum Energy per pulse	371 kJ
Horizontal displacement	+1 cm

SF2: Unsynchronized wheel

Thermal analysis

The maximum temperature increase happens when the beam hits the tungsten, the energy deposition of the protons interacting the spallation material produces a $\mathbf{\Delta T_{max} = 100^{o}C}$, which occurs in the brick 1. The brick 2 has the maximum temperature at the end of the cooling process. The horizontal displacement of the proton beam produces **3^{o}C** of maximum temperature increase **comparing with SF1** load condition, also the **position of the hottest bricks changes**.

Temperature evolution

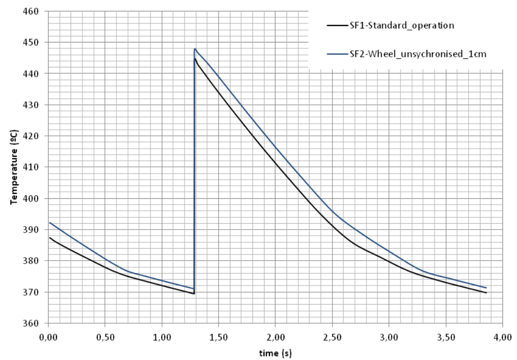


SF2: Unsynchronized wheel

Thermal analysis

The maximum temperature increase happens when the beam hits the tungsten, the energy deposition of the protons interacting the spallation material produces a $\mathbf{\Delta T_{max} = 100^oC}$, which occurs in the brick 1. The brick 2 has the maximum temperature at the end of the cooling process. The horizontal displacement of the proton beam produces $\mathbf{3^oC}$ of maximum temperature increase **comparing with SF1** load condition, also the **position of the hottest bricks changes**.

Temperature evolution

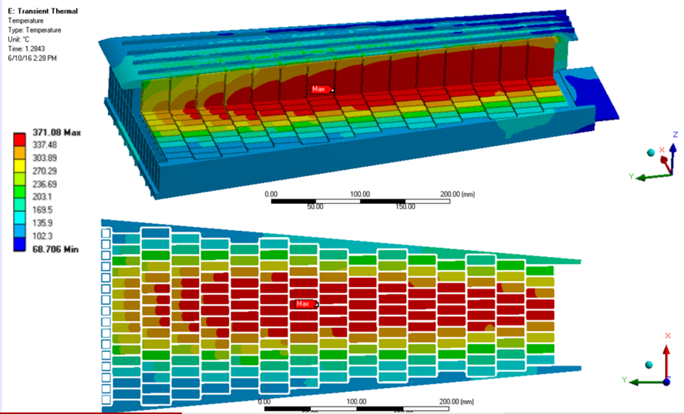


SF2: Unsynchronized wheel

Temperature profiles

The **maximum temperature at the end of the cooling is 371°C** and **after the pulse is 448°C**, but the hottest brick changes during the pulse and subsequent cooling process.

End of cooling

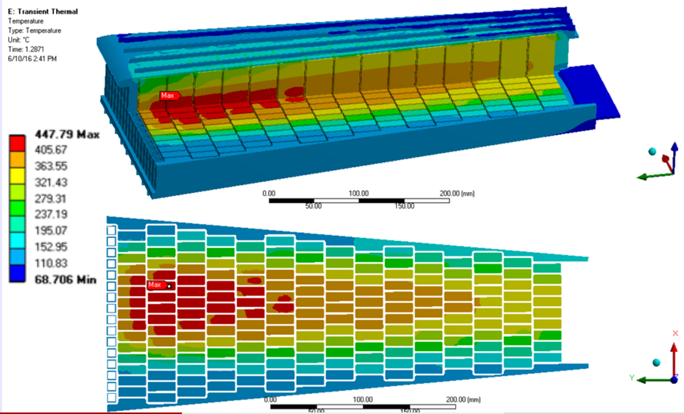


SF2: Unsynchronized wheel

Temperature profiles

The **maximum temperature at the end of the cooling is 384°C** and **after the pulse is 457°C**, but the hottest brick changes during the pulse and subsequent cooling process.

End of pulse

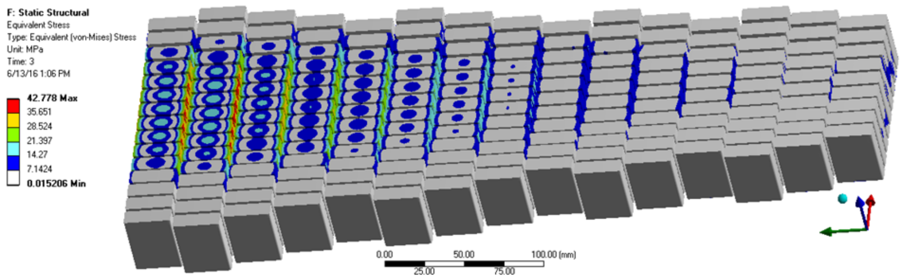


SF2: Unsynchronized wheel

Equivalent von-Mises stress profiles

The maximum equivalent stress at the end of the cooling is 43 MPa and after the pulse is 95 MPa.

End of cooling



SF2: Unsynchronized wheel

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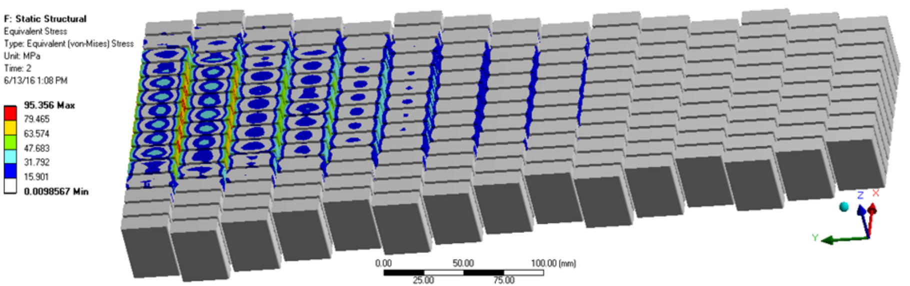
The maximum equivalent stress at the end of the cooling is 43 MPa and after the pulse is 95 MPa.

End of pulse



SF2: Unsynchronized wheel

Conclusions

- The maximum temperature and maximum stress values are below the limits.

	Limit	Value
Maximum W temperature	<600°C	448°C
Averaged maximum stress	100 MPa	69 MPa
Post pulse peak stress	50 MPa	43 MPa

- It is not clear if stress criteria limits apply to the SF2 scenarios
- Requirements already include its own safety margin so it can be concluded that the design fulfill the design criteria for the SF2: Unsynchronized wheel.

SF2: Channel blockage

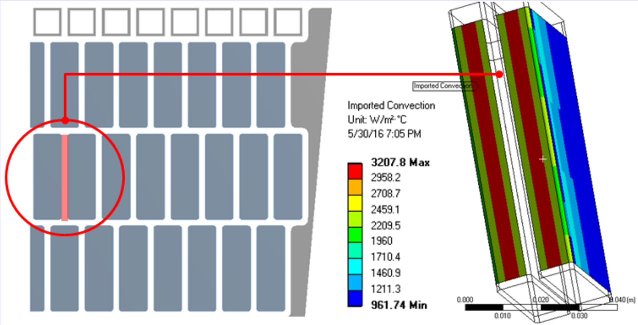
SF2: Channel blockage

Introduction

- Design beam at nominal *f(Hz)*
- Non irradiated Target
- Wheel at nominal *rpm* and Beam synchronized
- Cooling system at nominal conditions *rpm*
- $P_{He} = 10bar$ and $\dot{m} = 3kg/s$
- **Helium channel completely blocked**

SF2 Blocked channel BC

- **Adjacent walls of the channel are considered adiabatic**
- Adjacent brick to the blocked channel have the **maximum P′′′[W/m^{3}]**

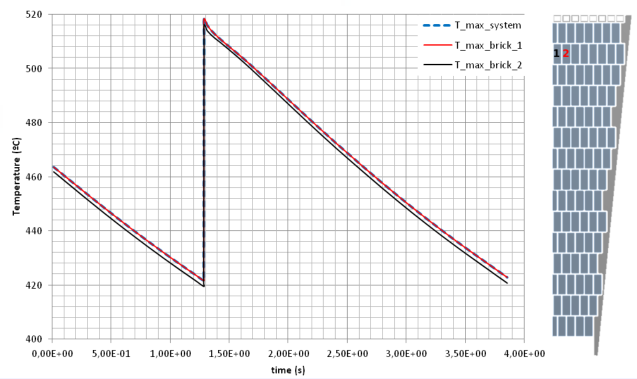


SF2: Channel blockage

Thermal analysis

The maximum temperature increase happens when the beam hits the tungsten, the energy deposition of the protons interacting the spallation material produces a $\mathbf{\Delta T_{max} = 100^{o}C}$, which occurs in **the brick 1**. The temperature in the bricks **1 and 2 is 70^{o}C, higher than the same bricks in the SF1 load scenario**.

Temperature evolution



SF2: Channel blockage

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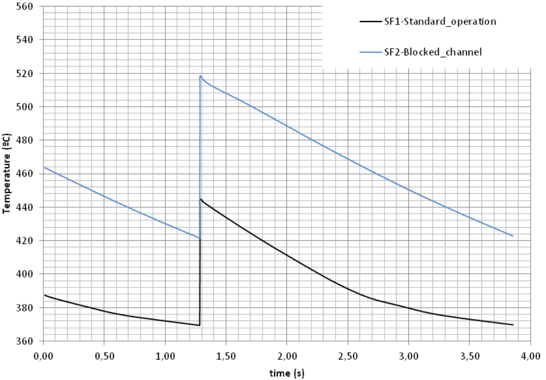
Temperature evolution

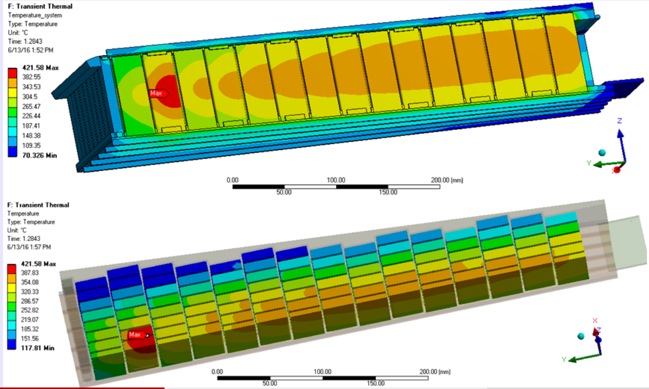


SF2: Channel blockage

Temperature profiles

The maximum temperature at the **end of the cooling is 422^{o}C** and **after the pulse is 518^{o}C**. The **maximum temperature** of the system is located in the **bricks 1 and 2** of because of the channel blockage and a worse cooling.

End of cooling



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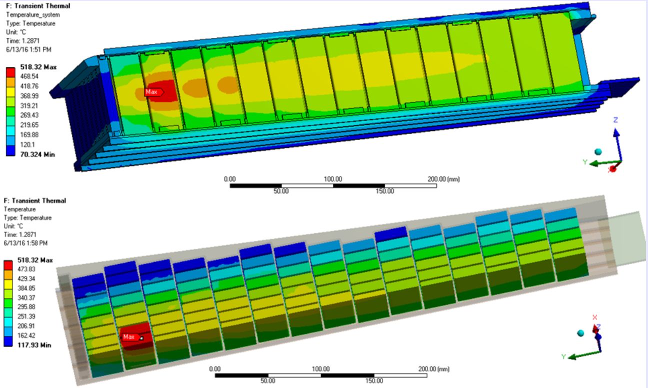
End of pulse

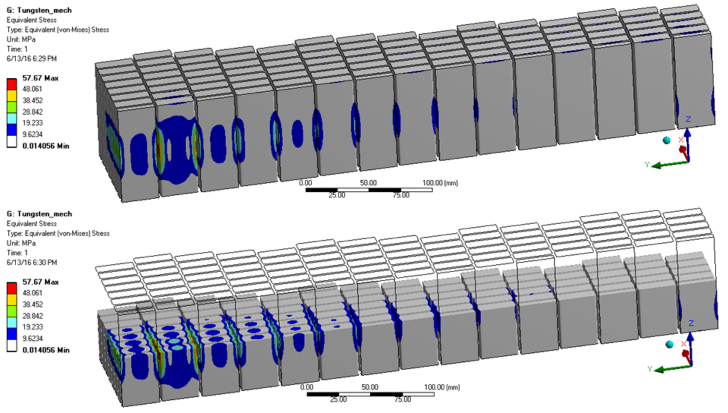


SF2: Channel blockage

Equivalent von-Mises stress profiles

The maximum equivalent stress at the end of the cooling is 58 MPa and after the pulse is 125 MPa.

End of cooling



SF2: Channel blockage

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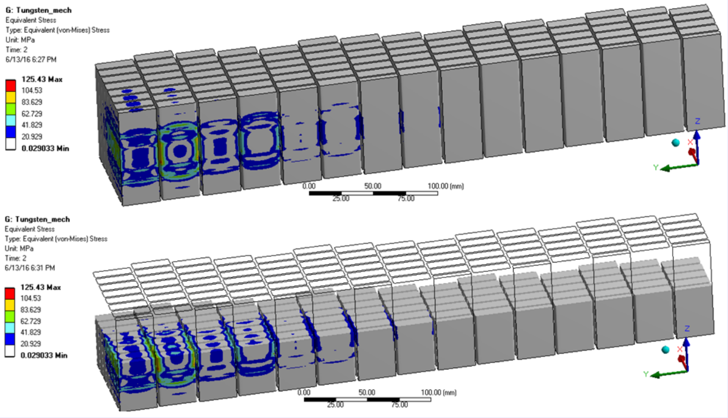
The maximum equivalent stress at the end of the cooling is 58 MPa and after the pulse is 125 MPa.

End of pulse



SF2: Channel blockage

Conclusions

- The maximum temperature and average maximum stress values are below the limits. The post pulse peak stress

	Limit	Value
Maximum W temperature	<600°C	518°C
Averaged maximum stress	100 MPa	91 MPa
Post pulse peak stress	50 MPa	58 MPa

- The post pulse peak stress criteria is not fulfilled, however it is not clear if the stress criteria limits apply to th e SF2 scenarios.

SF2: Tungsten brick break

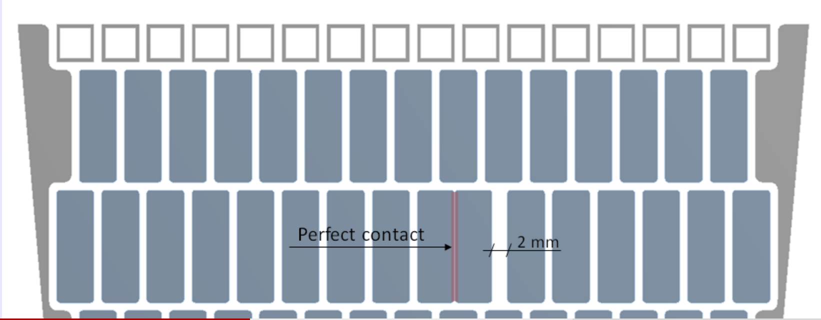
SF2: Tungsten brick break

Introduction

- Design beam at nominal *f(Hz)*
- Non irradiated Target
- Wheel at nominal *rpm* and Beam synchronized
- Cooling system at nominal conditions *rpm*
- $P_{He} = 10 bar$ and $\dot{m} = 3 kg/s$
- **Broken and displaced brick**

SF2 Broken brick position

- Broken brick displaced an in **perfect contact** with adjacent
- Broken and adjacent have the **maximum** $\mathbf{P'''[W/m^3]}$

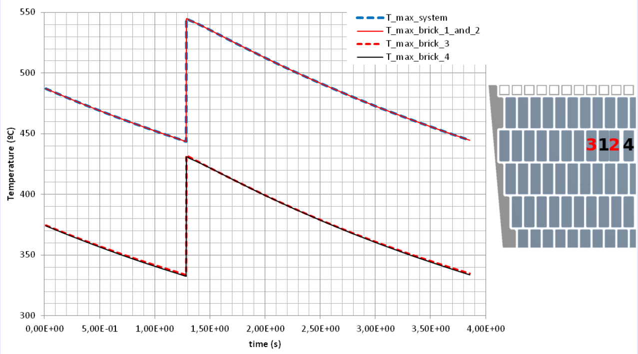


SF2: Tungsten brick break

Thermal analysis

The maximum temperature increase happens when the beam hits the tungsten, the energy deposition of the protons interacting the spallation material produces a $\mathbf{\Delta T_{max} = 100^oC}$, which occurs in the contact of the bricks 1 and 2. The temperature in these bricks 1 and 2 is 100^{o}C higher than the same bricks in the SF1 load scenario.

Temperature evolution



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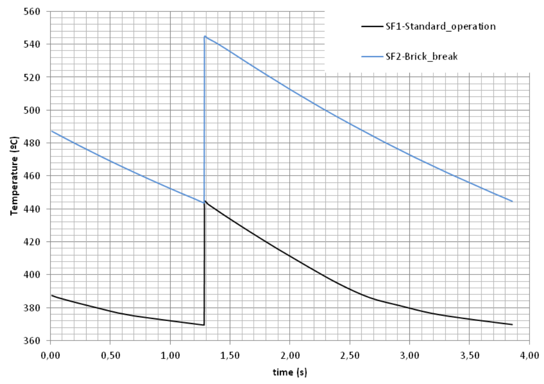
Temperature evolution

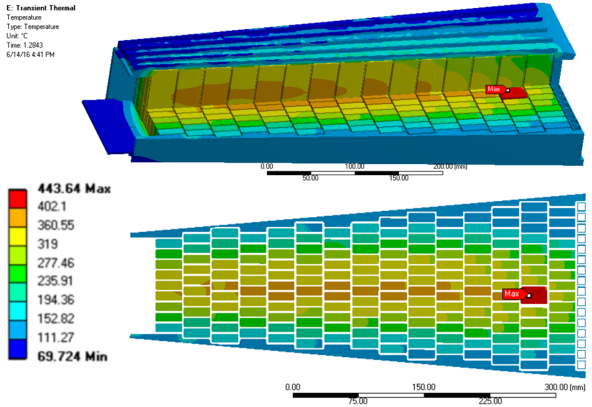


SF2: Tungsten brick break

Temperature profiles

The maximum temperature at the **end of the cooling is 444°C** and **after the pulse is 545°C**. The **maximum temperature** of the system is located in the **bricks 1 and 2** because of a worse cooling due to the faces in contact, and the coolant velocity reduction in the 2 mm channel

End of cooling



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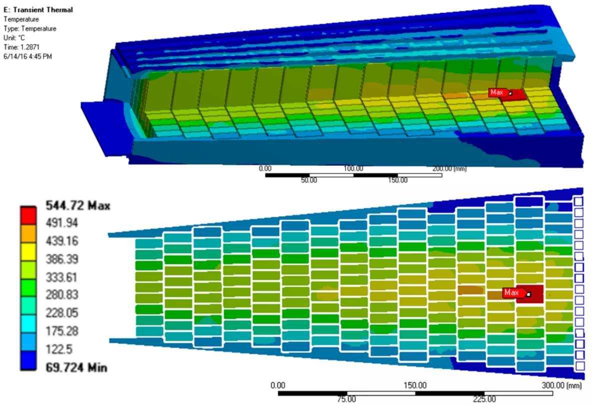
End of pulse

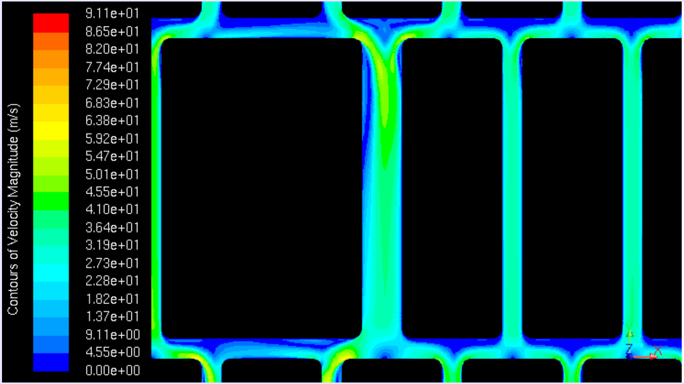


SF2: Tungsten brick break

Broken brick cooling

The low velocity of the helium in the 2mm channel leads to a worse cooling and as consequence a higher temperature. In this scenario 27°C more than the blocked channel scenario.

Velocity profile in the 2mm channel

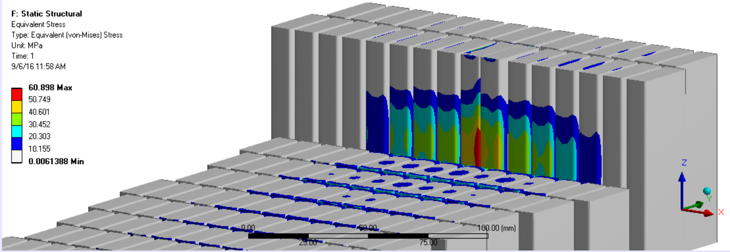


SF2: Tungsten brick break

Equivalent von-Mises stress profiles

The maximum equivalent stress at the end of the cooling is 61 MPa and after the pulse is 112 MPa.

End of cooling

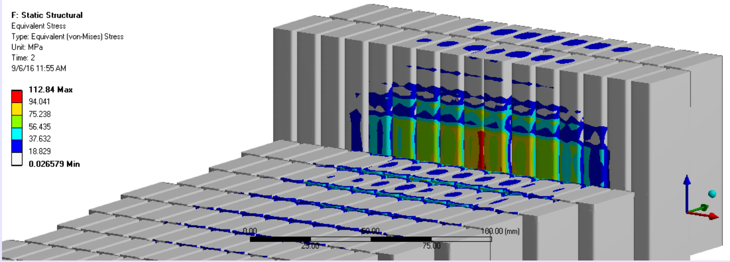


SF2: Tungsten brick break

Equivalent von-Mises stress profiles

The maximum equivalent stress at the end of the cooling is 61 MPa and after the pulse is 112 MPa.

End of pulse



SF2: Tungsten brick break

Conclusions

- The maximum temperature and average maximum stress values are below the limits. The post pulse peak stress

	Limit	**Value**
Maximum W temperature	<600°C	545°C
Averaged maximum stress	100 MPa	86 MPa
Post pulse peak stress	50 MPa	62 MPa

- The post pulse peak stress criteria is not fulfilled, however it is not clear if the stress criteria limits apply to the SF2 scenarios.

SF3:Loss of coolant flow and pressure

SF3: Loss of coolant flow and pressure

Description

The conditions described as "Loss of coolant flow and pressure" corresponds to a series of operational accidents in the helium loop that modify the cooling conditions of the spallation material.
This accidental conditions (SF3) do not have any design limit related with the stress. Hence, only thermal problem will be consider for this accidental case.

Loss of coolant flow and pressure scenarios

	Operating pressure	**Massflow**	**Shaft helium inlet temperature**
Design	10 bar	3 kg/s	40 °C
Low helium pressure	6.2 bar	3 kg/s	40 °C
Low helium massflow	10 bar	2 kg/s	40 °C
High helium inlet temperature	10 bar	3 kg/s	240 °C
Low helium pressure and massflow*	6.2 bar	2.4 kg/s	40 °C

* **Low helium pressure scenario** is an additional scenario with 2.4 kg/s of helium massflow pressurized at 0.62MPa was performed. The massflow reduction is the result of maintaining the ΔP_{max} that the blowers can handle.

SF3: Loss of coolant flow and pressure

Modeling

Only the CFD model was used to simulate the loss of coolant accidents and obtain the temperature of the spallation material for each scenario at at average power. This model considers only heat transfer between the tungsten bricks and the coolant which **leads to conservative results**.

Results

The maximum temperature at the end of a beam pulse was estimated considering adiabatic heat deposition which is a conservative approximation.

	Time average max Temp. [^{o}C]	Pulse end max Temp. [^{o}C]
Design	393	454
Low helium pressure	3936.2 bar	454
Low helium massflow	524	585
High helium inlet temperature	586	647
Low helium pressure and massflow*	467	528

*** Low helium pressure scenario** is an additional scenario with 2.4 kg/s of helium massflow pressurized at 0.62MPa was performed. The massflow reduction is the result of maintaining the ΔP_{max} that the blowers can handle.
the maximum temperatures are below .

SF3: Loss of coolant flow and pressure

Conclusions

- Even in this conservative scenario, maximum temperature values are below the 700^o degrees limit in all the scenarios.

	Limit	**Value**
Maximum W temperature	<700°C	647°C
Averaged maximum stress	-	-
Post pulse peak stress	-	-

SF3: Shut-down

SF3: Shut-down

Introduction to the accidentlal conditions

On normal conditions, when the beam is off the helium loop will continue cooling the target along several hours to remove the decay heat. The shut-down scenario is produced when the helium flow is interrupted after the shutdown of the beam. In this conditions, the residual heat is removed only by thermal radiation in the target vessel surface.

Load scenarios

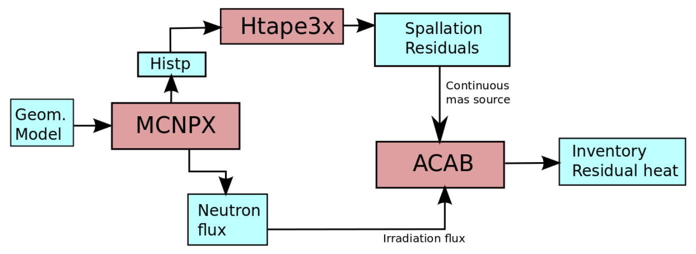
Requirement	**Loads**	**Level**	**Prot.**
Shut-down	No beam Operating pressure (10 bar) No coolant flow Wheel stopped	SF3	D $T_{max} < 700^o C$

SF3: Shut-down

Residual heat evaluation

The methodology applied for residual heat evaluation is based on neutron transport with MCNPX and activation with ACAB. Additional considerations are needed to consider the beam footprint and the rotation of the wheel: the neutron flux has been analyzed homogeneously with no angular divisions, but the spallation residuals have been analyzed for different angles.

Residual methodology



SF3: Shut-down

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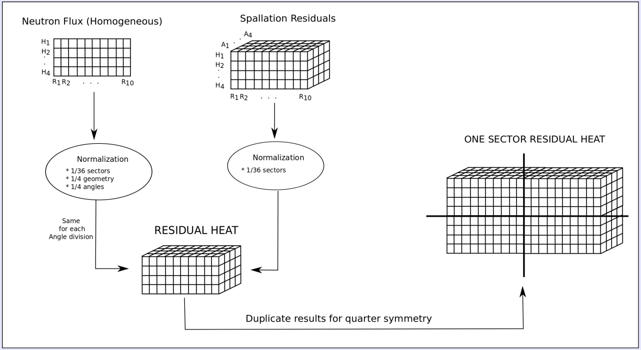

SF3: Shut-down

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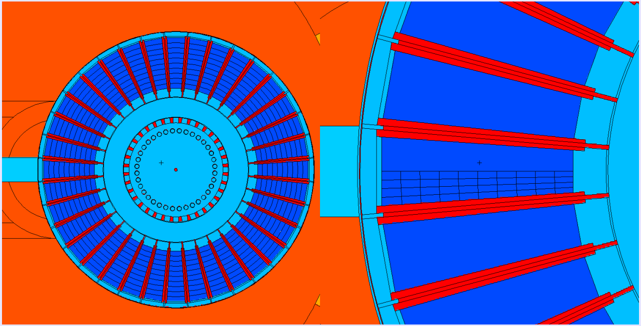
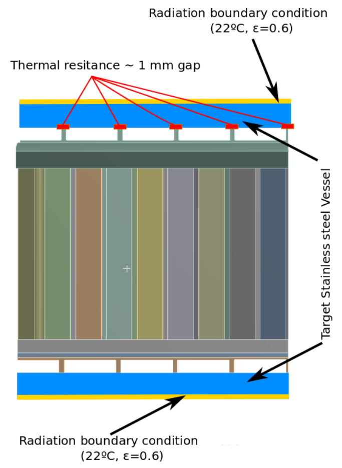


SF3: Shut-down

FEM-thermal model

The analysis model is based on the FEM-Thermal model in which we have include two stainless steel plates connected to the cassette ribs.

- The bottom plate is bounded to the cassette.
- Scenario 1: Top plate bounded to the cassette.
- Scenario 2:Between top plate an the cassette we have include a thermal resistance equivalent to 1 mm helium gab is included

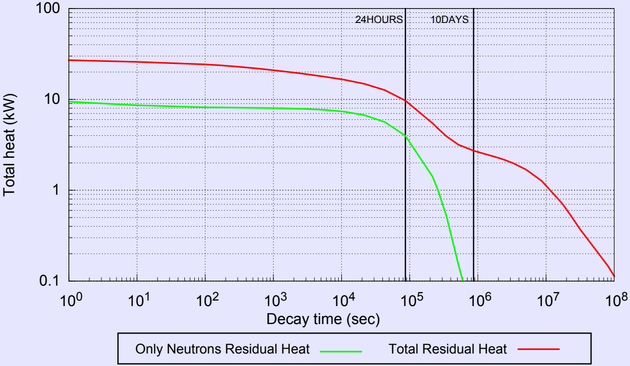


SF3: Shut-down

Residual heat

During the first 24 hours, the spallation residuals represent the 60% of the total heat. Then, its importance grows until the 99% when 10 days has passed. There is a clear effect produced by the capture reactions on thermal range close the moderator-reflector.

Residual results



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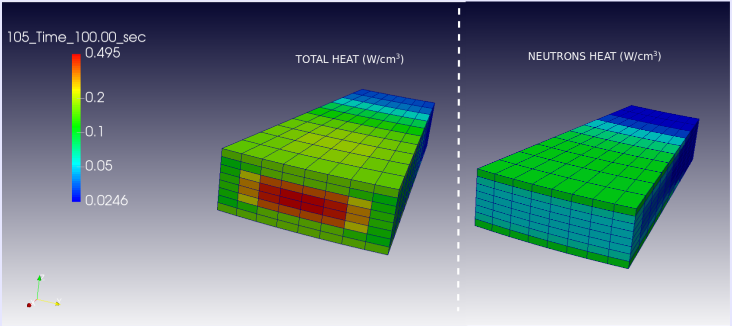

SF3: Shut-down

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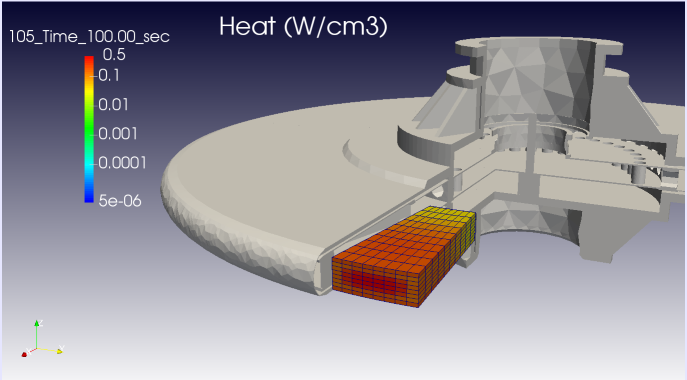
Residual results



SF3: Shut-down

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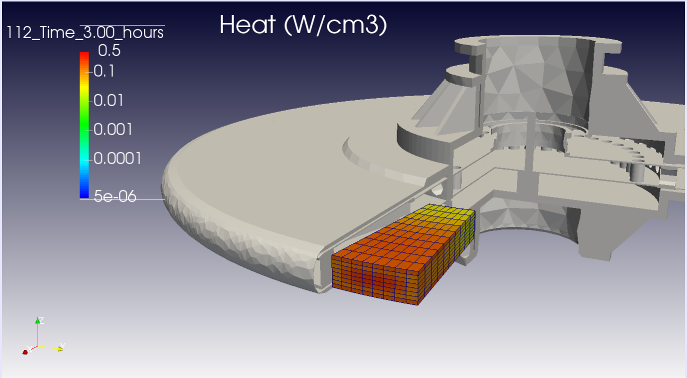
Residual results



SF3: Shut-down

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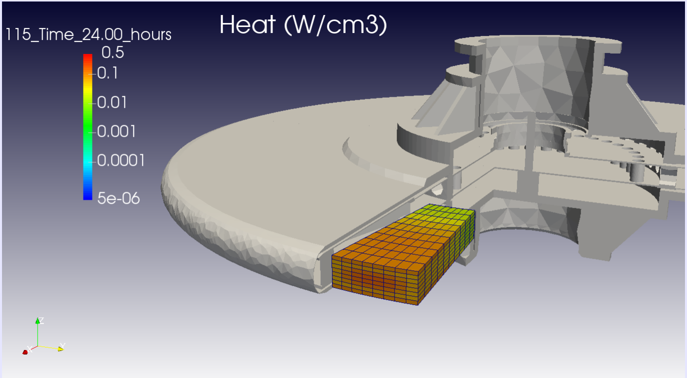
During the first 24 hours, the spallation residuals represent the 60% of the total heat. Then, its importance grows until the 99% when 10 days has passed. There is a clear effect produced by the capture reactions on thermal range close the moderator-reflector.

Residual results

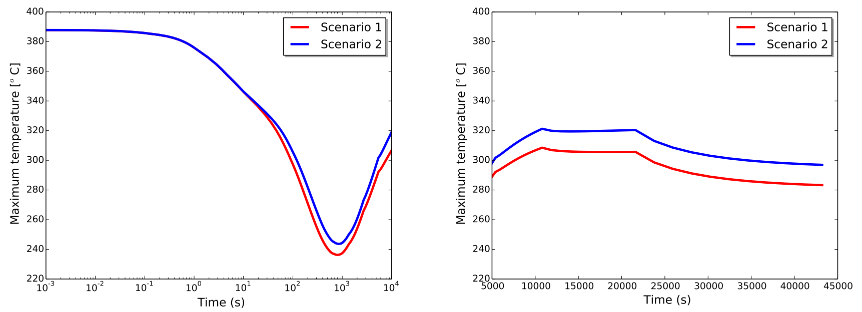


SF3: Shut-down

Thermal analysis

The temperature after the shutdown is proportional to the beam foot print. After the shutdown, the temperature is homogenized along 100 s. Finally, after this initial homogenization the heat the decay heat increases slowly the temperature up to the maximum after 10^4 s.

Maximum temperature evolution

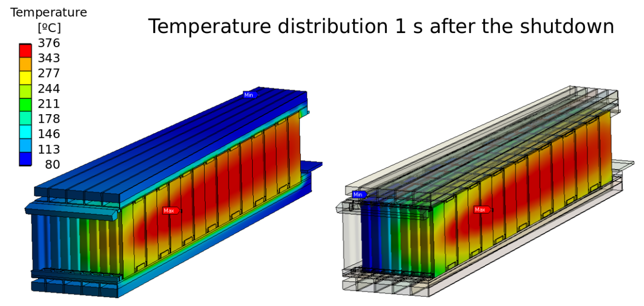


SF3: Shut-down

Thermal analysis

The temperature after the shutdown is proportional to the beam foot print. After the shutdown, the temperature is homogenized along 100 s. Finally, after this initial homogenization the heat the decay heat increases slowly the temperature up to the maximum after 10^4 s.

FEM thermal analysis (Scenario 2)



SF3: Shut-down

Thermal analysis

The temperature after the shutdown is proportional to the beam foot print. After the shutdown, the temperature is homogenized along 100 s. Finally, after this initial homogenization the heat the decay heat increases slowly the temperature up to the maximum after 10^4 s.

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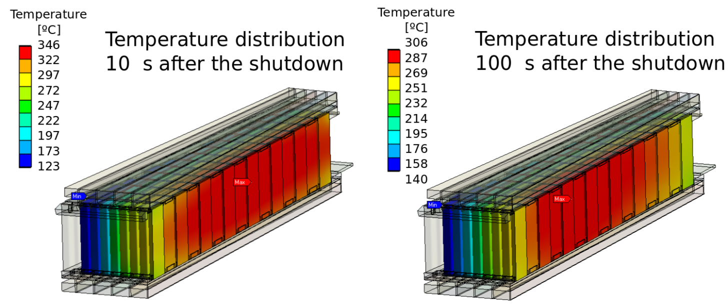
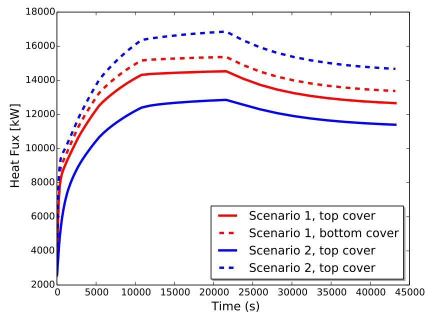


SF3: Shut-down

Thermal analysis

The radiation boundary conditions have been evaluated considering radiation to a black body at $22^o C$ and a surface emissivity of 0.6. If the black body temperature increases up to $200^o C$ the target external surface temperature will increase less that 50^o. If we consider a low emissivity factor (0.3) in the black body, the maximum temperature increases up to $\sim 450^o C$ far below the 700^o limit.

Heat flow in the Target covers



SF3: Shut-down

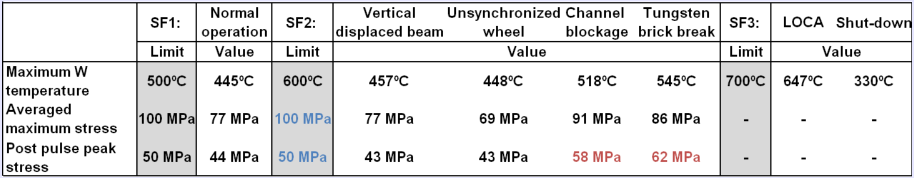
Conclusions

The main conclusion for the shut-down case is that the maximum temperature in the spallaton material for a conservative scenario is far below the $700^o C$ limit.

Conclusions for load cases

Conclusions for load cases

Ressults summary



	SF1:	Normal operation	SF2:	Vertical displaced beam	Unsynchronized wheel	Channel blockage	Tungsten brick break	SF3:	LOCA	Shut-down
	Limit	Value	Limit	Value				Limit	Value	
Maximum W temperature	500ºC	445ºC	600ºC	457ºC	448ºC	518ºC	545ºC	700ºC	647ºC	330ºC
Averaged maximum stress	100 MPa	77 MPa	100 MPa	77 MPa	69 MPa	91 MPa	86 MPa	-	-	-
Post pulse peak stress	50 MPa	44 MPa	50 MPa	43 MPa	43 MPa	58 MPa	62 MPa	-	-	-

Conclusions

- SF1 load case fulfill the temperature and stress criteria.
- All SF2 load cases fulfill the temperature criteria.
- Channel blockage and Tungsten brick break exceed the Post pulse peak stress criteria, however it is necessary to clarify if stress criteria limits apply to the SF2 scenarios. The rest of the SF2 load case fullfil the stress criteria.
- SF3 scenarios fulfill all the temperature criteria. SF3 scenarios do not have any design limit related with the stress.