Internal Structures: Cassette

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

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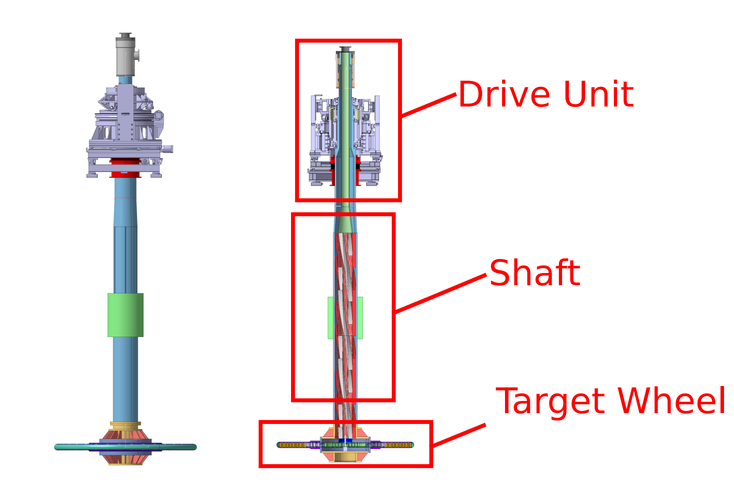
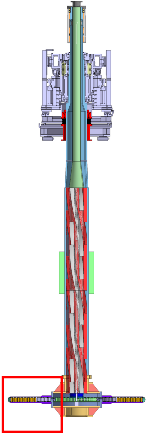
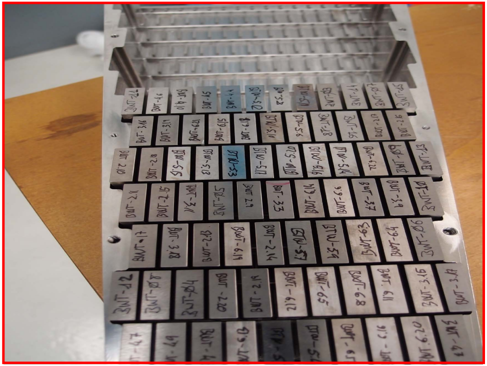
Target, shaft and Drive Unit



Introduction: ESS-Bilbao (Internal structure)

Target, shaft and Drive Unit

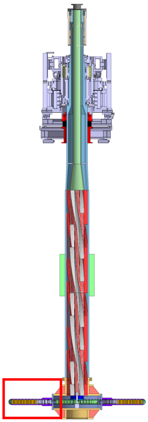


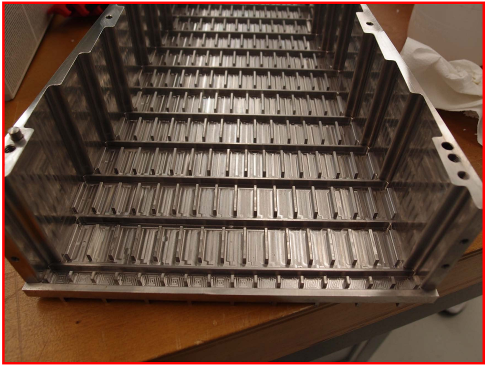


Spallation Material

Introduction: ESS-Bilbao (Internal structure)

Target, shaft and Drive Unit

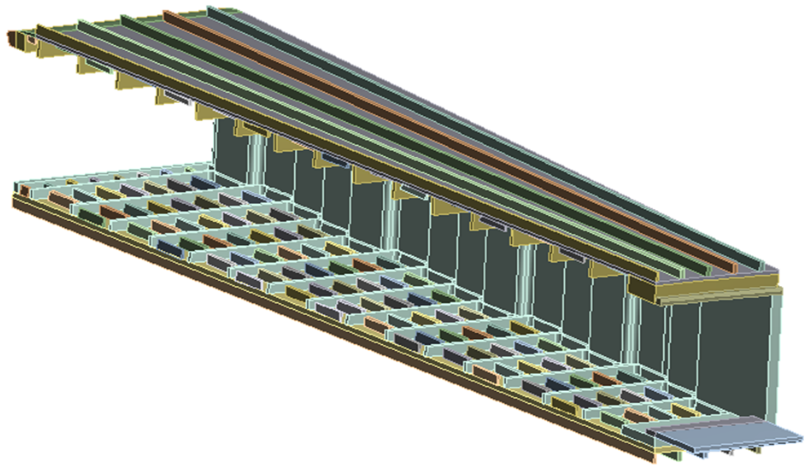




Internal structures (SS-316L)

Introduction: ESS-Bilbao (FE geometry)

Internal structure



General design rules

Source: RCC-MRx-2012 EDITION with 2013 1^{st} Addendum, Section III, Tome 1, subsection C: Class $N2_{Rx}$ reactor components its auxiliary systems and supports

RCC-MRx

RCC-MRx design rules **(ranges)**

*** Analysis considered:**

- Elastic
- Inelastic (plasticity, viscoplasticity, creep)

*** Loads considered:**

- Internal & external pressures;
- Weights, forces resulting from the weight, static & dynamic loads, thermal expansion...
- Temperature effects

RCC-MRx

RCC-MRx design rules **(classiffication)**

* **Categories:**

- 1st (SF1) and 2nd (SF2): normal operation, including normal operating incidents, start-up and operational shutdown.
- 3rd (SF3): emergency conditions (very low probability of occurrence but which must nonetheless be considered).
- 4th (SF4): highly improbable but whose consequences on component are studied among others for safety reasons.

Type of **damages considered** (Level A, SF1 & SF2)

* Damage of type P (due to constant or ramped loads), immediate damages:

- Immediate or time-dependant (creep) excessive deformation
- Immediate or time-dependant (creep) plastic instability or fracture
- Elastic or elastoplastic instability (buckling)

* Damage of type S (due to cyclic loads), cyclic damages:

- Progressive deformation (ratcheting)
- Fatigue

RCC-MRx

RCC-MRx design rules **(stresses)**

*** Categories:**

- General Primary **Membrane stress** (P_m): mean value of the primary stress tensor within the thickness of the wall.
- Primary **Bending stress** (P_b): stress distributed linearly within the thickness (same moment as the primary stress).
- **Local** primary membrane stress (P_L): that is in a small zone adjoining the discontinuity. The membrane stress associated with this stress is noted $(L_m) \rightarrow (P_L) = (P_m) + (L_m)$

RCC-MRx design rules **(Post-processing)**

*** Criterias to check:**

- $P_m \leq S_m(\theta_m)$ *Source: (RB 3251.112.1)*
- $P_L \leq 1.5 * S_m(\theta_m)$ *Source: (RB 3251.112.2)*
- $P_L + P_b \leq 1.5 * S_m(\theta_m)$ *Source: (RB 3251.112.3)*
- $P_m + Q_m \leq S^A_{em}(\theta_m, G_{tm})$ *Source: (RB 3251.2121)*
- $P_L + P_b + Q_m + F \leq S^A_{et}(\theta, G_t)$ *Source: (RB 3251.2122)*

Material: SS 316L annealed

Source: ESS Materials Handbook (ESS-0028465)

Material: SS 316L

Density

Density ρ is given as a function of temperature θ by the table A3.3S.24.

Density ρ

Temperature [°C]	ρ [kg·m^{-3}]	Temperature [°C]	ρ [kg·m^{-3}]
20	7930	450	7747
50	7919	500	7724
100	7899	550	7701
150	7879	600	7677
200	7858	650	7654
250	7837	700	7630
300	7815	750	7606
350	7793	800	7582
400	7770	-	-

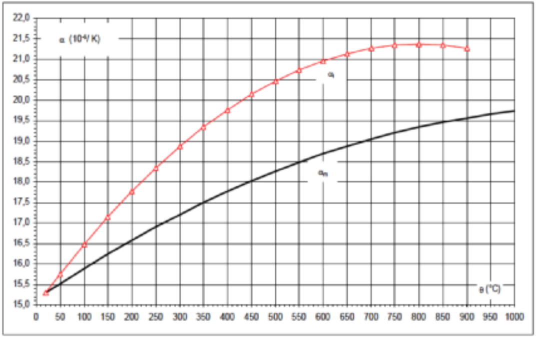
Physical properties

Coefficients of thermal expansion

The average coefficient of linear thermal expansion α_m between 20 ^oC and the temperature indicated T and the instantaneous coefficient of thermal expansion α_i are given as a function of T.

Coefficients of linear thermal expansion α_m and α_i

Temperature [°C]	α_m: Mean CTE [μm·m^{-1}·K^{-1}]	α_i: Instantaneous CTE [μm·m^{-1}·K^{-1}]
20	15.3	15.3
50	15.5	15.7
100	15.9	16.5
150	16.2	17.1
200	16.6	17.8
250	16.9	18.3
300	17.2	18.9
350	17.5	19.3
400	17.8	19.8
450	18.0	20.1
500	18.3	20.5
550	18.5	20.7
600	18.7	21.0
650	18.9	21.1
700	19.0	21.3
750	19.2	21.3
800	19.3	21.4
850	19.5	21.3
900	19.6	21.3
950	19.7	-
1000	19.7	-



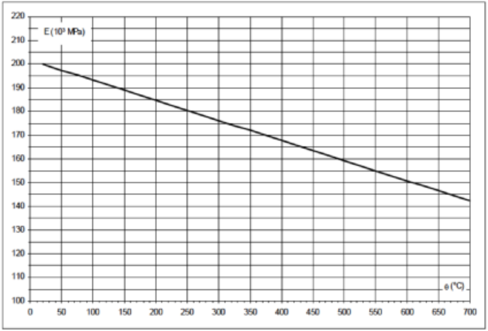
Physical properties

Young´s modulus

The Young's modulus E is given as a function of the temperature T by the formula:
E = 201660 - 84.8 T and the following figure.

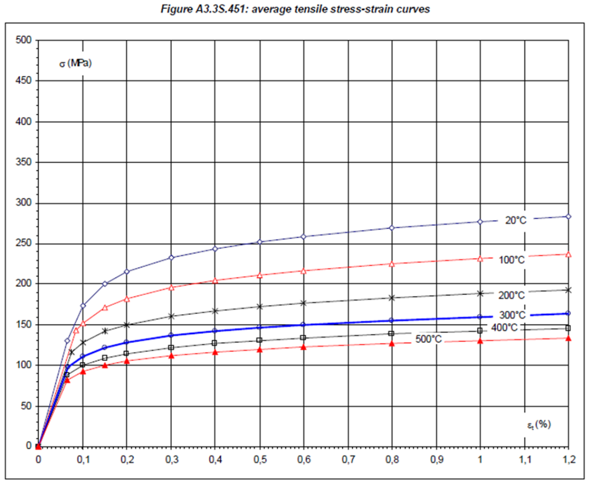
Young modulus E (MPa)

Temperature [°C]	E [GPa]	Temperature [°C]	E [GPa]
20	200	375	170
50	197	400	168
75	195	425	166
100	193	450	164
125	191	475	161
150	189	500	159
175	187	525	157
200	185	550	155
225	183	575	153
250	180	600	151
275	178	625	149
300	176	650	147
325	174	675	144
350	172	700	142



Physical properties

Tensile stress-strain curves



SS 316L annealed

Primary load values. Level A (SF1 and SF2) **(Operational limits)**

Temp (C)	**100**	150	**200**	250	300
S_m (MPa)	127	127	123	114	106
S (MPa)	119	114	108	106	106
$(R^t_{p0.2})_{min}$ (MPa)	165	150	137	127	118
$(R_m)_{min}$ (MPa)	430	–	390	–	380
Peak $1.5 * S_m = S^A_m$ (MPa)	190.5	190.5	184.5	171	159
Welding $S_m * 0.85$ (MPa) $S_m * 0.70$ (MPa)	107.95 88.9	107.95 88.9	104.55 86.1	96.9 79.8	90.1 74.2

Primary load maximum stress values for SS 316L annealed alloy under Level A. Level D criteria: minimum value between [2.4$*$ S_m] or [0.7$*$ (R_m)min]

SS 316L annealed

Secondary load values. Level A (SF1 and SF2) **(Operational limits)**

100 °C			
D (dpa)	2.75	5	10
(S^A_{em}) (MPa)	3711	2038	552
(S^A_{et}) (MPa)	6371	3680	1275
200 °C			
D (dpa)	2.75	5	10
(S^A_{em}) (MPa)	3257	1817	536
(S^A_{et}) (MPa)	5600	3295	1231
300-350 °C			
D (dpa)	2.75	5	10
(S^A_{em}) (MPa)	2827	1447	294
(S^A_{et}) (MPa)	4849	2626	472

Note: all values from 7 dpa are constant.

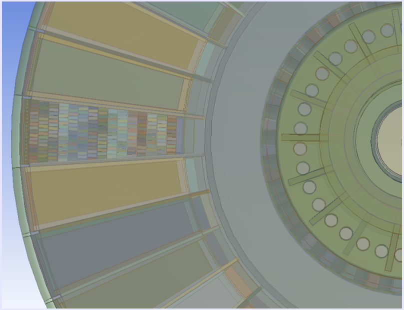
Methodology

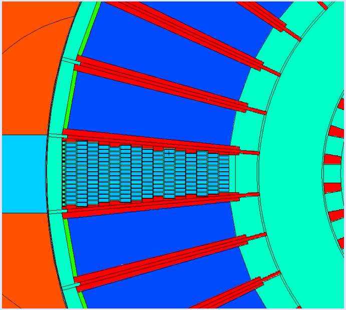
Source: Super MC/MCAM 5.2 User Manual, INEST, CAS; ACAB-2008, NEA Data Bank NEA-1839; Initial MCNP6 release overview, Nuclear Technology (2012)

Particle transport analysis

This analysis in complex geometries need several codes, software and tools to be implemented:

- SuperMCAM or MCAD → convert CAD geometries to MCNP format & other codes.
- MCNPX/6 → used for particles transport.
- ACAB 2008 → designed to perform activation and transmutation calculations.
- GIGANT → developed as neutron tool in order to implement complex geometries for activation calculations.



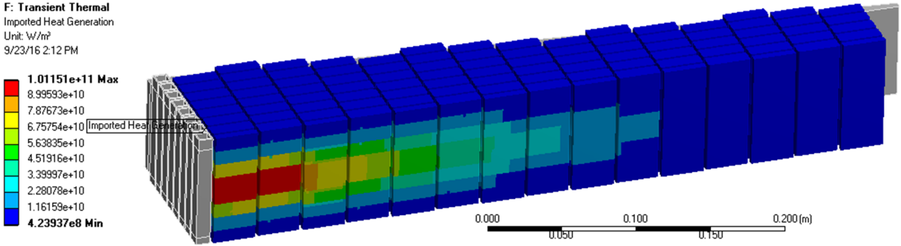


FEM-Thermal model

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)

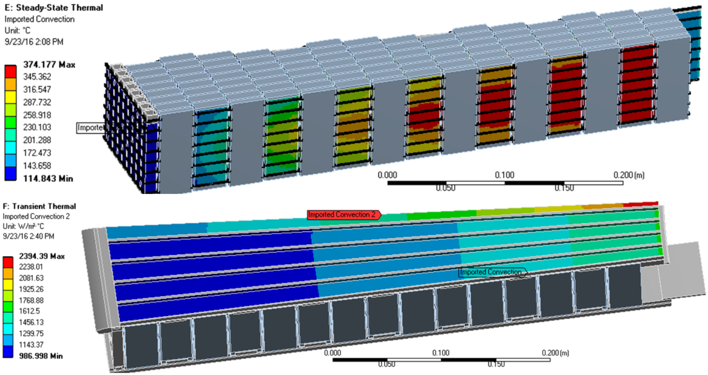


FEM-Thermal model

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:

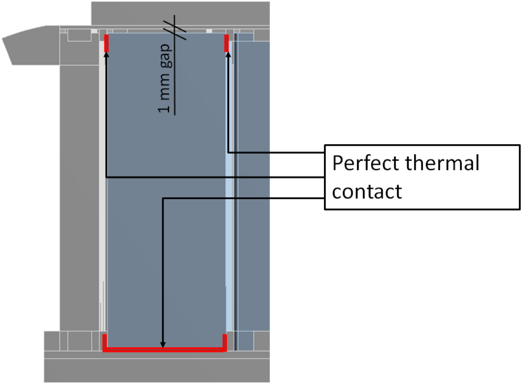
$$Nu_D = 0.023 \cdot Re_D^{0.8} \cdot Pr^{0.4}$$



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

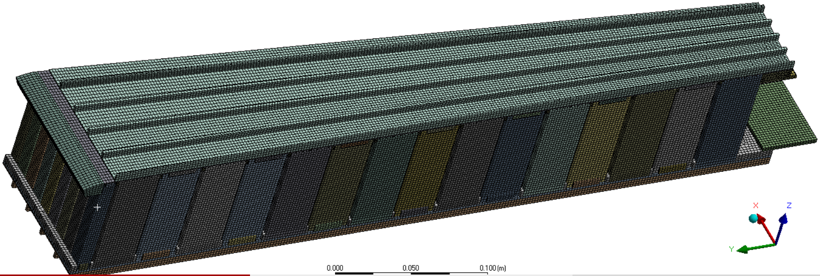


FEM-Thermal model

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

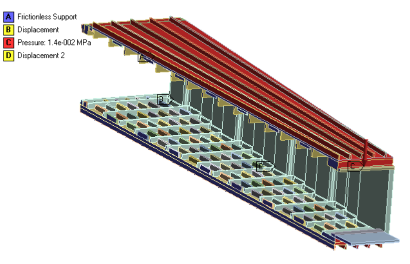


Methodology

FEM-Mechanical model

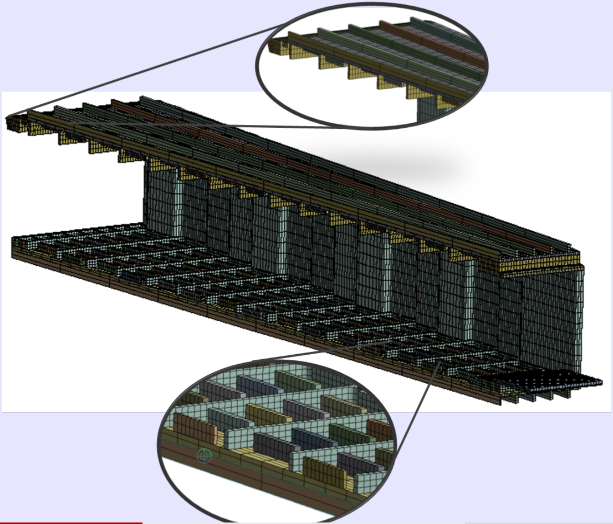
The geometry includes 219 bodies and 218 lineal bounded contacts. The following boundary conditions are considered:

- Frictionless support in the symmetry axis;
- No displacement is allowed along X and Y direction, but Z displacement is free for "B" point.
- No displacement is allowed along Z, but X and Y displacement are free for D.
- Δ Pressure between inlet and outlet helium path (0.14 Bar).



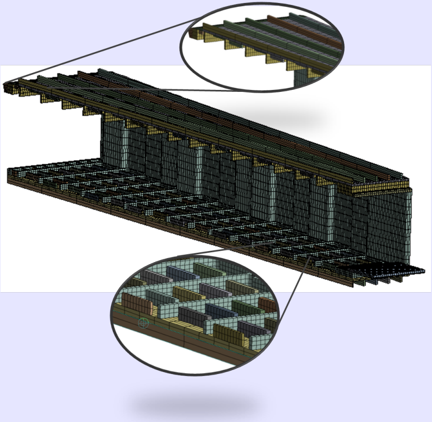
Methodology

FEM-Mechanical model. **Mesh**



Methodology

FEM-Mechanical model



Mesh parameters:

- Nodes: 217221
- Elements: 32964
- Average Skewness (indicator of the mesh quality and suitability. Into the excellent mesh quality metrics (0-0.25)) ≈ 0.13
- Average Aspect ratio (It is the ratio of longest to the shortest side in a cell. Extremely large values $>> 40$ should be closely examined to determine where they exist and whether the stress results in those areas are of interest or not.) ≈ 3.16
- Element quality (0.3 is termed as good) ≈ 0.64

Radiation damage conditions

Radiation damage conditions

Radiation damage conditions

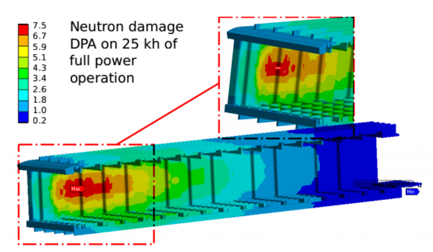
Neutrons have enough energy to produce displacements in the metallic meshes of the elements, degrading the mechanical properties. The damage produced by neutrons play a role in mechanical behavior. Several conclusions based on previous analysis are remarkable:

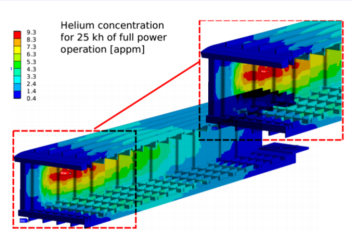
- High energy neutrons will produce nuclear cascades similar to neutrons considered on $RCC - MR_x$ damage analysis methodology.
- Ratio Helio/DPA in the elements not in contact with the proton beam are comparable with fission reactors.
- Helium and hydrogen production are far below values that can produce mechanical effects (swelling).
- The faction of disperse protons that produces damage in the cassette is negligible compared with neutron damage on nominal operational conditions.

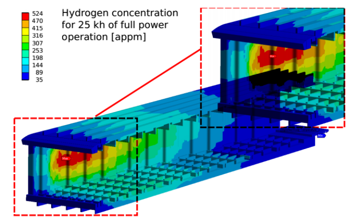
Radiation damage conditions

Radiation damage conditions

In the lateral of the cassette with stresses, in the range of 7 dpa after 5 years of operation (but low stress values). The material is far from the mechanical limits.







Load scenarios thermomechanical analysis

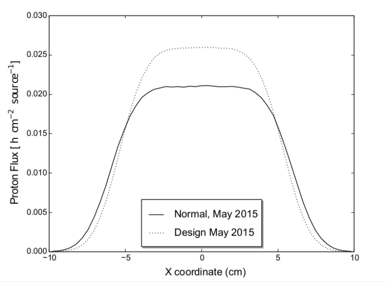
SF1: Design beam

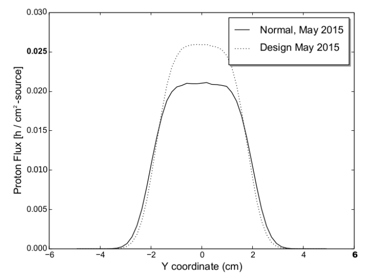
SF1: Design beam

SF1: Normal operation conditions. Beam profiles

The beam is considered synchronized with the wheel and hitting in the center of the cassette.

- He mass flow: 3 kg/s → 0.0833 kg/s per cassette.
- Beam Energy: 2.0 GeV (Max. Beam Energy: 2.2 GeV)
- Pulse repetition rate: 14 Hz
- Beam energy per pulse: 357 kJ (Max. Energy per pulse: 371 kJ)



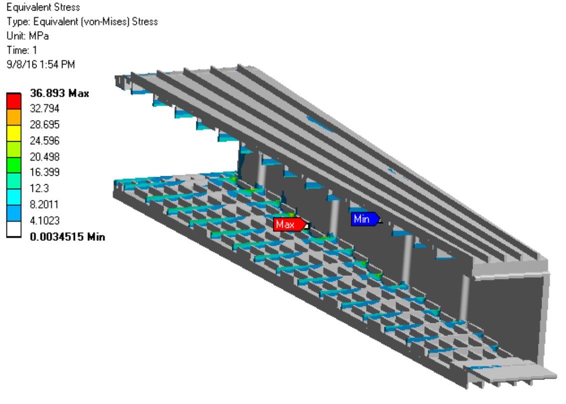


SF1: Design beam

P damage analysis. Primary loads

Loads: death weight and the ΔP (inlet and outlet helium flow $\rightarrow$ 0.14 bar)

Equivalent Von-Mises stress *Primary load Limit at 300º C is* $S_m = 106$ *MPa*

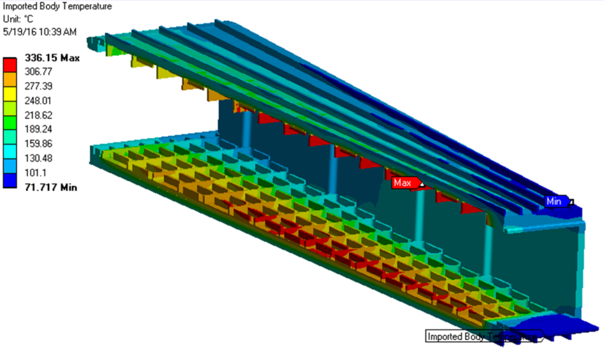


SF1: Design beam

P damage analysis. Secondary loads

Loads: death weight, ΔP (inlet and outlet helium flow $\rightarrow$ 0.14 bar) and temperature distribution.

Temperature profile

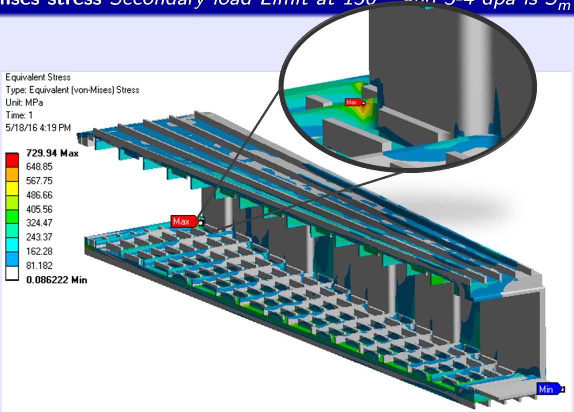


SF1: Design beam

P damage analysis. Secondary loads

Loads: death weight, ΔP (inlet and outlet helium flow $\rightarrow$ 0.14 bar) and temperature distribution. Peak value $\approx$ 730 MPa, normal values between 324-480 MPa.

Equivalent Von-Mises stress *Secondary load Limit at 150 ° and 3-4 dpa is* $S_m^{et} = 1817 MPa$

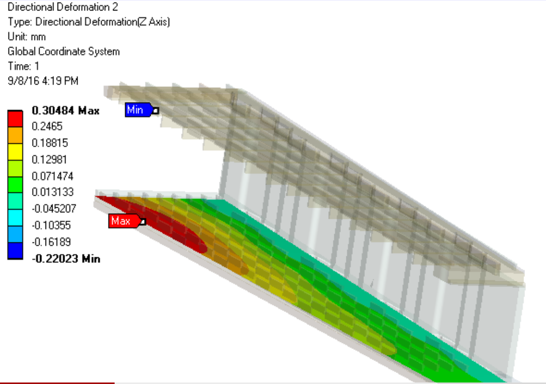


SF1: Design beam

P damage analysis. Secondary loads

Loads: death weight, ΔP (inlet and outlet helium flow $\rightarrow$ 0.14 bar) and temperature distribution.

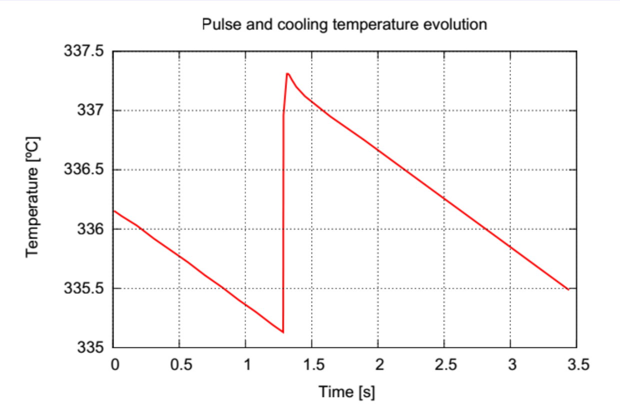
Directional Z deformation *Less than 1 mm*



SF1: Design beam

S damage analysis. Cyclic loads

Time dependence load: temperature distribution.
$\Delta T < 2.5^o$ C (not produce significant stresses)



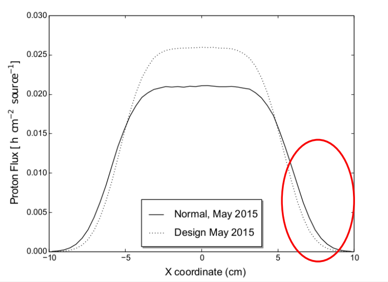
SF1: Nominal beam

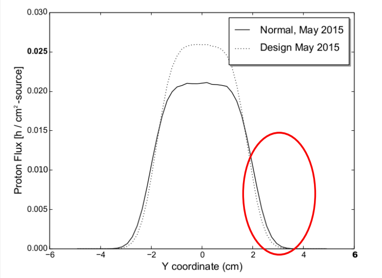
SF1: Nominal beam

SF1: Nominal beam. Beam profiles

The beam is considered synchronized with the wheel and hitting in the center of the cassette.

- He mass flow: 3 kg/s $\rightarrow$ 0.0833 kg/s per cassette.
- Beam Energy: 2.0 GeV (Max. Beam Energy: 2.2 GeV)
- Pulse repetition rate: 14 Hz
- Beam energy per pulse: 357 kJ (Max. Energy per pulse: 371 kJ)



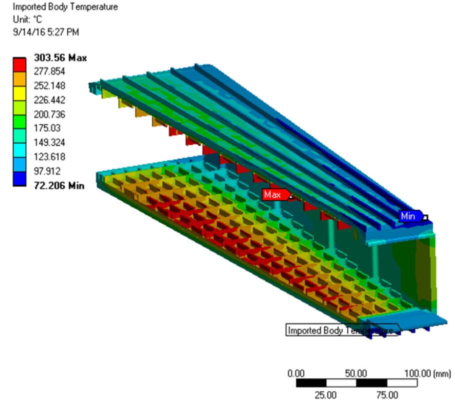


SF1: Nominal beam

P damage analysis. Secondary loads. Temperature profile

Comparing with design beam temperature, the profile is quite similar but T_{nom} is 33 ^{o} C less than T_{design}

Temperature profile

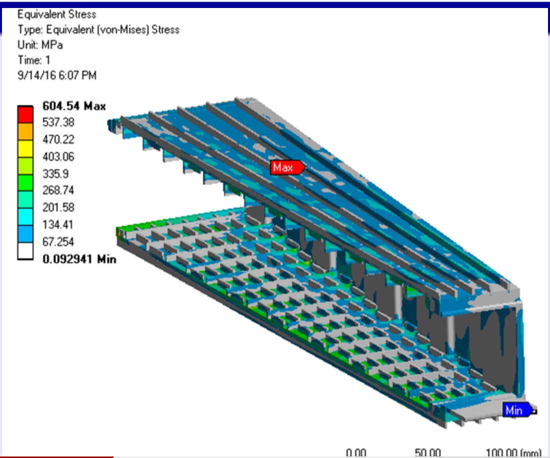


SF1: Nominal beam

P damage analysis. Secondary loads. Equivalent Von Mises stress

Comparing with design beam stress, σ_{nom} is 125 MPa less than σ_{design}, but in any case, both are far from $S_m^{et} = 1817 MPa$

Secondary loads



Accidental conditions

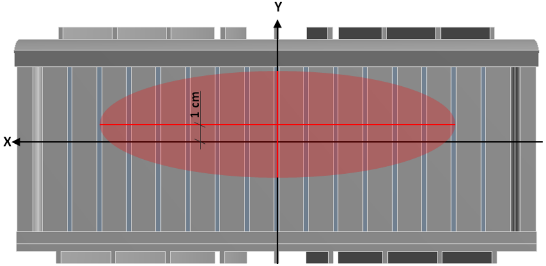
SF2: Vertical displacement beam

Accidental conditions

SF2: Vertical displacement beam

Same design beam, with a positive vertical displacement of 10 mm from the center of the cassette.

- He mass flow: 3 kg/s $\rightarrow$ 0.0833 kg/s per cassette.
- Beam Energy: 2.0 GeV (Max. Beam Energy: 2.2 GeV)
- Pulse repetition rate: 14 Hz
- Beam energy per pulse: 357 kJ (Max. Energy per pulse: 371 kJ)

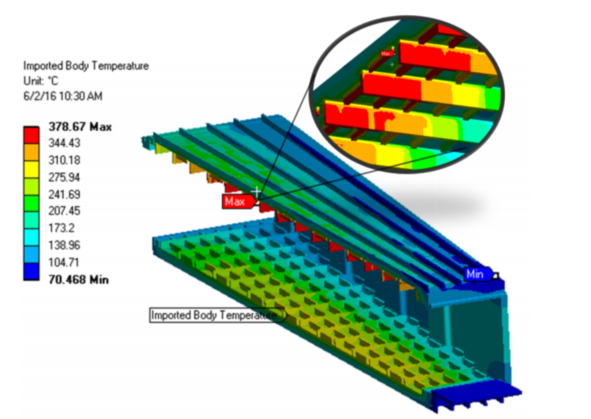


Accidental conditions

SF2: Vertical displacement beam. Temperature profile

Increase of 42 ^{o} C compared with the design beam case. Only secondary loads have been considered, due to primary loads do not change (Pressure, weight...).

Temperature profile

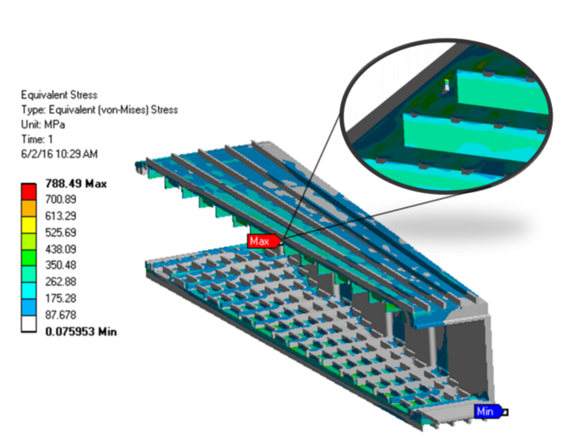


Accidental conditions

SF2: Vertical displacement beam. Equivalent Von-Mises stress

The maximum stress level far below the S_m^{et} limit so the component clearly fulfill the Level A requirements. Peak value ≈ 790 MPa, normal values between 350-525 MPa.

Secondary loads



SF3: Shutdown

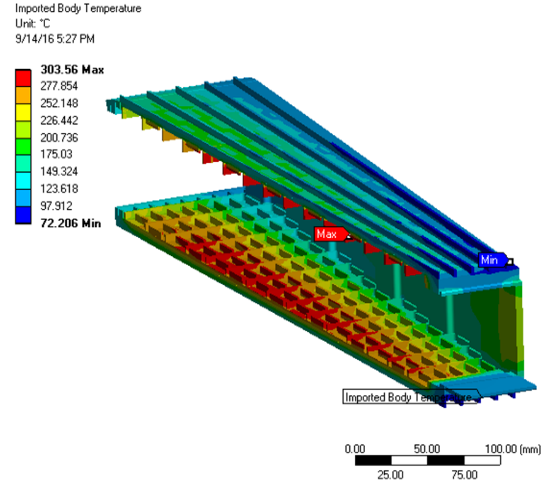
Accidental conditions

SF3: Shutdown

- Helium flow and beam are stop. On this conditions, the target remove the heat by radiation from its external surfaces so, the temperature evolves slowly up to the equilibrium value after 10^4 s.
- The profile is relative smooth due to the low decay heat generation ($\sim$ 30 kW).
- Primary loads are not considered because the helium is not flowing (all the faces are under the same pressure)
- Maximum value is far below the S_m^{et} limit for the material.

Accidental conditions

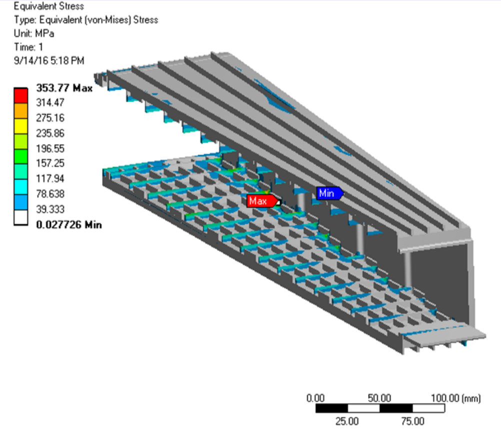
SF3: Shutdown. Temperature profile in the maximum of temperature (1E+4 s after shutdown)



Accidental conditions

SF3: Shutdown. Von-Mises stress in the maximum of temperature (1E+4 s after shutdown)

The maximum stress level far below the S_m^{et} limit so the component clearly fulfill the Level A requirements.



Conclusions

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The analysis described in the previous sections can be summarized in the following points:

- The complete analysis of the component (radiation damage, temperature distribution and mechanical stress analysis) has been completed.
- The radiation damage for the component is in an acceptable level for 5 year operation.
- Temperature distributions will not produce significant deformations that change its functionality.
- In all the scenarios considered in the design process fulfill RCC-MRx requirement with significant safety margin.