IMCC Annual Meeting 2023 - Orsay

Carbon target, vessel & beam windows developments for the Muon Collider

International MUON Collider Collaboration

CERN

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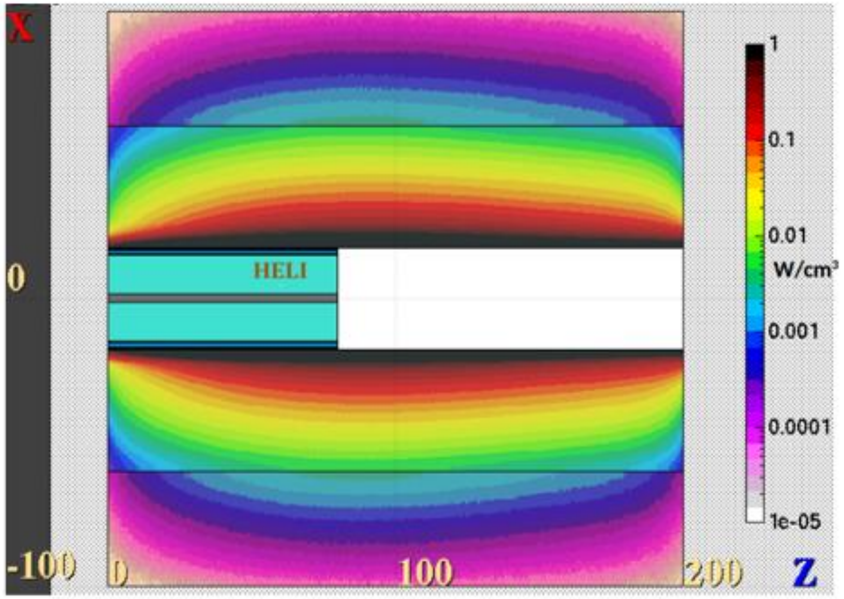
CERN – Systems Department, Sources Targets Interaction (STI), Targets Collimators Dumps (TCD)

2023/06/21

Outline

- **Beam** parameters
- **Target rod**: effect of power increase from 1.5 to 2 MW and beam tilting
- **Shielding** cooling operational point & thermo-mechanical results for 2 MW
- **Vessel** thermo-mechanical results for 2 MW
- Titanium and Berylium **window** thermo-mechanical results for 2MW

Energy Deposition & Main Parameters

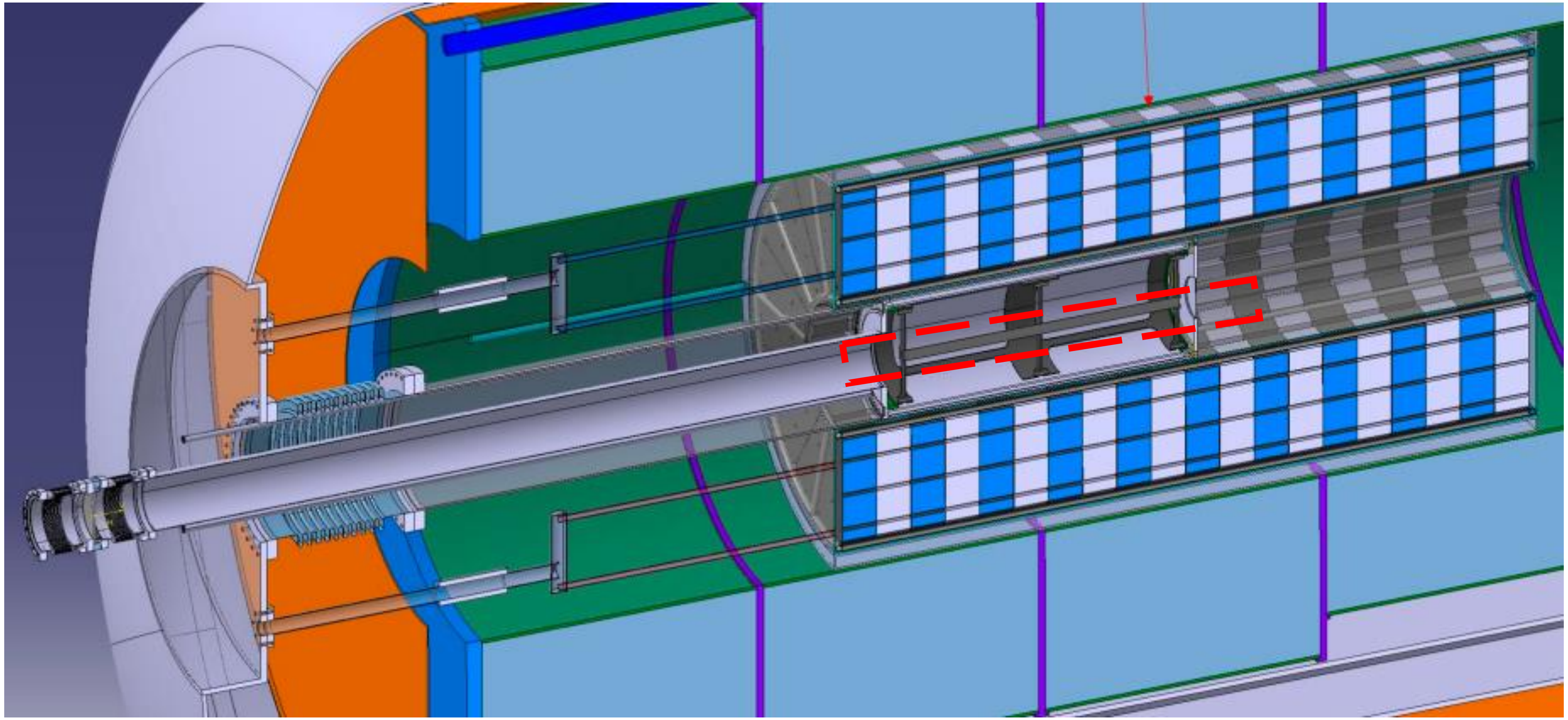


Power deposition provided by Daniele Calzolari SY-STI-BMI
https://indico.cern.ch/event/1176034/contributions/4939053

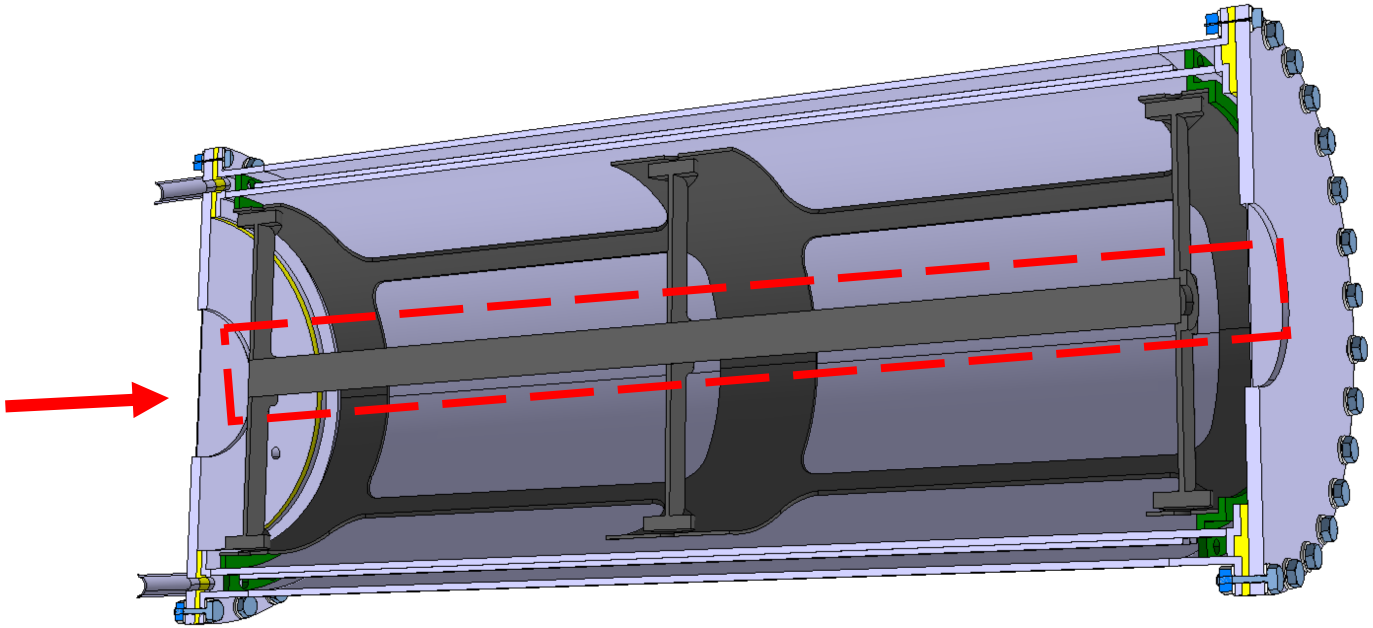
	Energy deposition (W)	Energy deposition (%)
Shielding	674 kW	33.7 %
Target	111 kW	5.6 %
Inner Vessel	13.2 kW	1.2 %
Outer Vessel	11.2	0.6%
Window (Ti)	40-637 W	~ 0%
Window (Be)	69 W	~ 0%
TOTAL	~820 kW	~ 41%

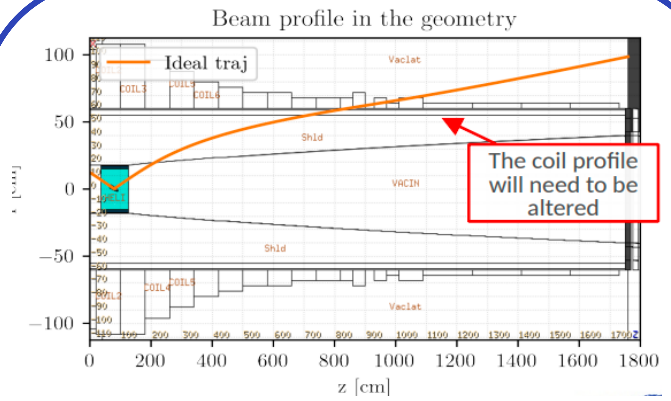
- Beam power =2 MW
- Frequency = 5 Hz
- Bunch length =2 ns
- Beam radius = 5mm

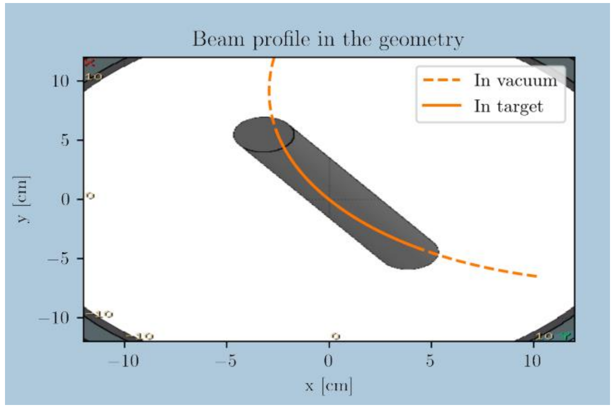
Target Rod



Target Rod







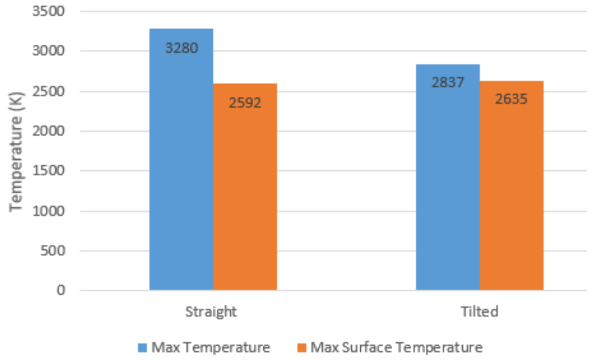
From Daniele Calzolari / Anton Lechner

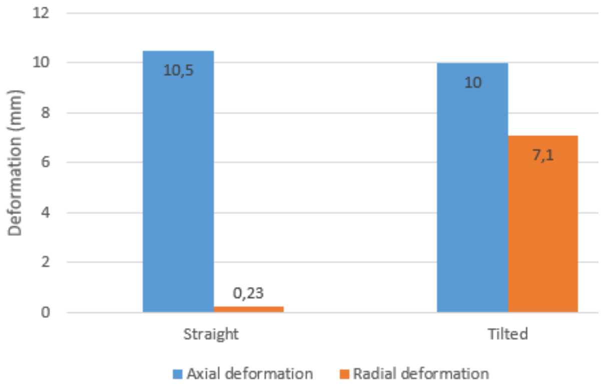
Updates:

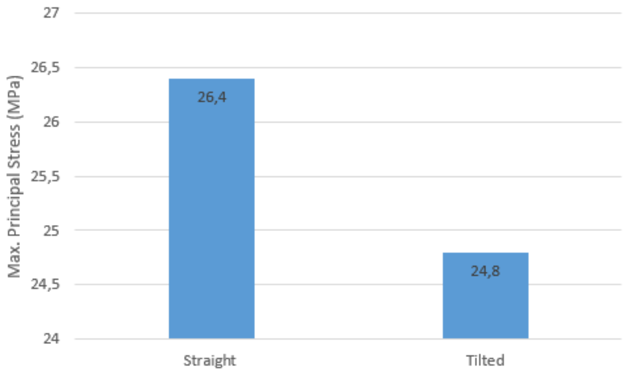
- Power increment from 1.5 MW to **2 MW**
- **Tilted beam** to direct the beam to an extraction before the chicane

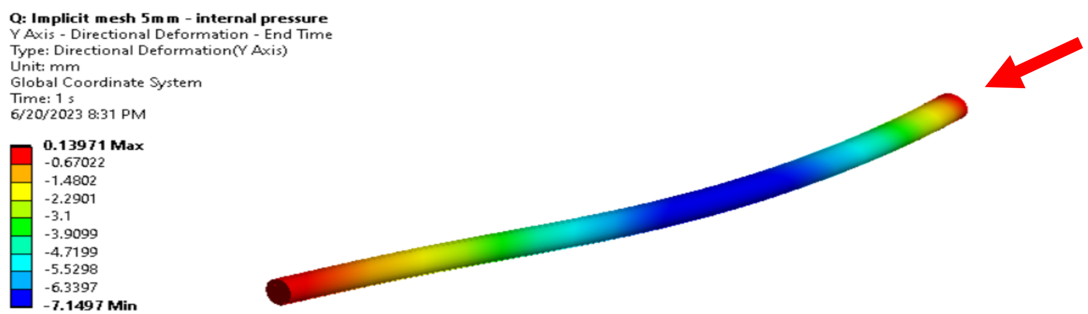
❖ Afraid of more **power** and **asymmetrical energy** deposition on the rod may affect the target **negatively**

Target Rod









Structural Analysis – radial deformation ≈ 7mm

Analysis:

- **Steady state thermo - structural** analysis
- Boundary conditions:
  - ✓ Surface **radiation** to ambient
  - ✓ Surface **convective** heat transfer coefficient (from CFD analysis)
  - ✓ Energy deposition from **FLUKA** studies

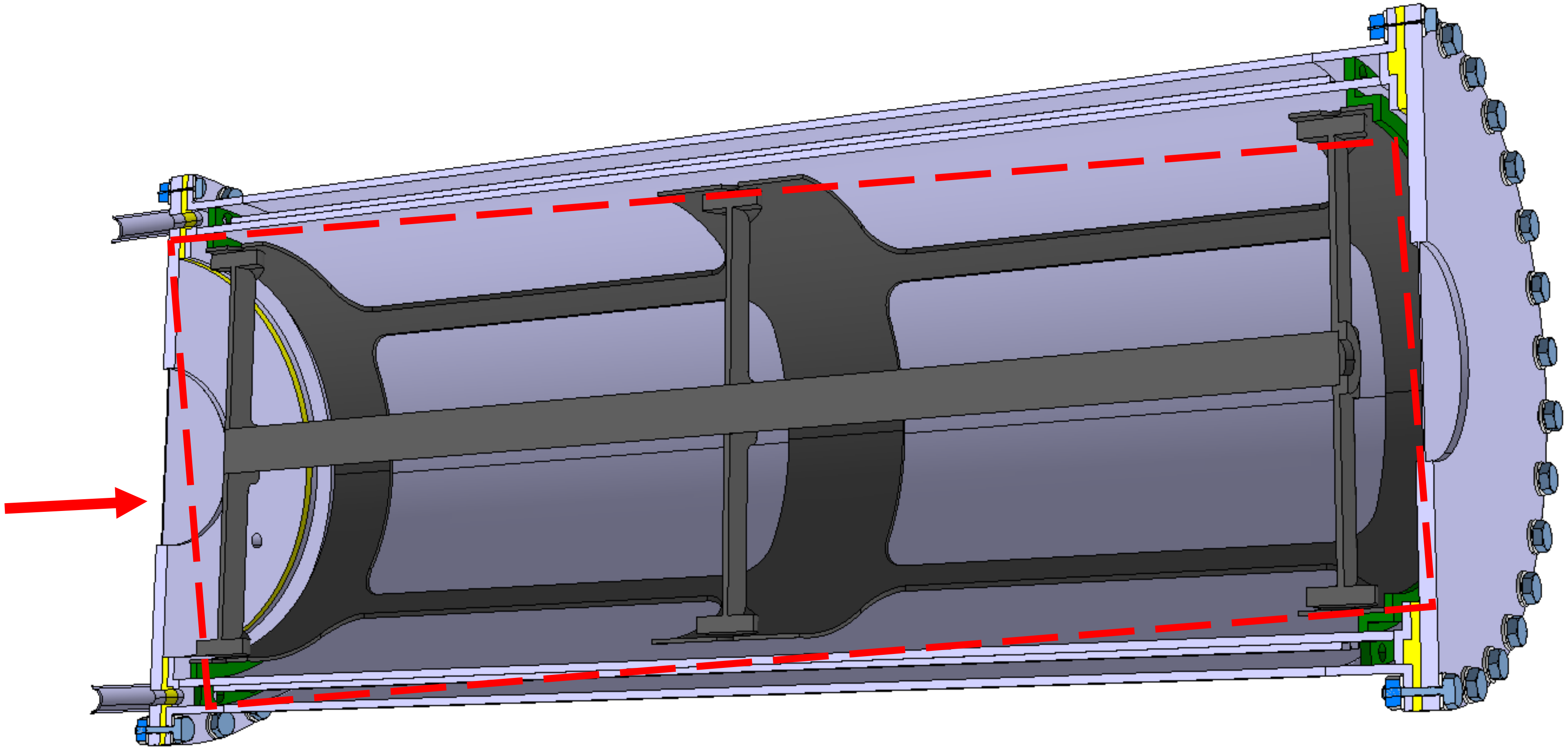
We **found**:

- **Reduction** of maximum **temperature** below 3000K
  - ➢ Lower energy deposition (keeping pion production rate)
- **Maximum principal stresses** for both cases are **acceptable** for graphite at high temperature

But tilted beam induces an important **radial deformation**

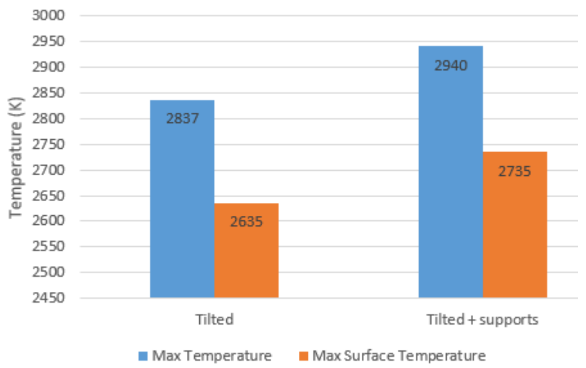
- Might be **avoided by** the inclusion of a central **support** or **splitting the target** rod(central support or splitting the target avoid this)

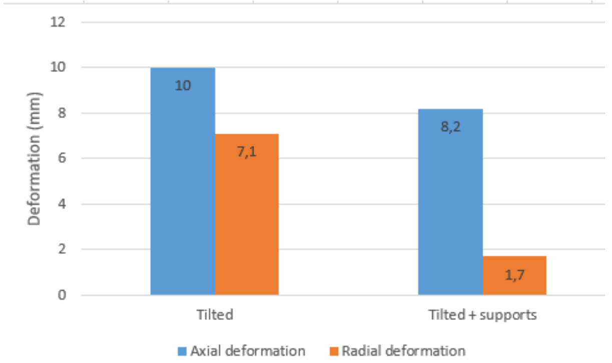
Target Rod

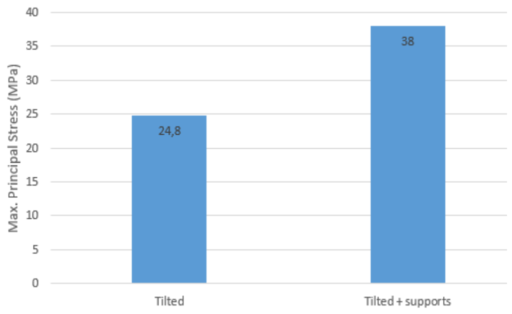


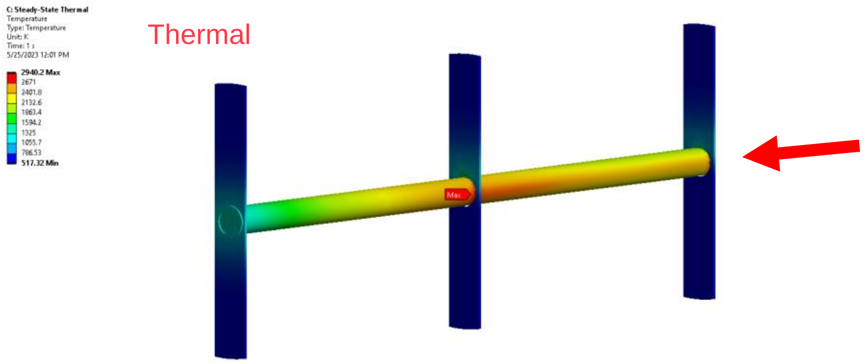
Analysis **extended** to take into consideration the effect of the **supports**
(Future work will scope the whole system)

Target Rod









Analysis:

- **Steady state thermo - structural** analysis
  - ✓ Rod in **contact** with supports
  - ✓ **Supports** dissipate heat through **radiation**
  - ✓ **Rod** surface **convective** heat transfer coefficient (from CFD analysis)
  - ✓ **Rod** surface **radiation** to ambient
  - ✓ Energy deposition from **FLUKA** studies (only on the rod)

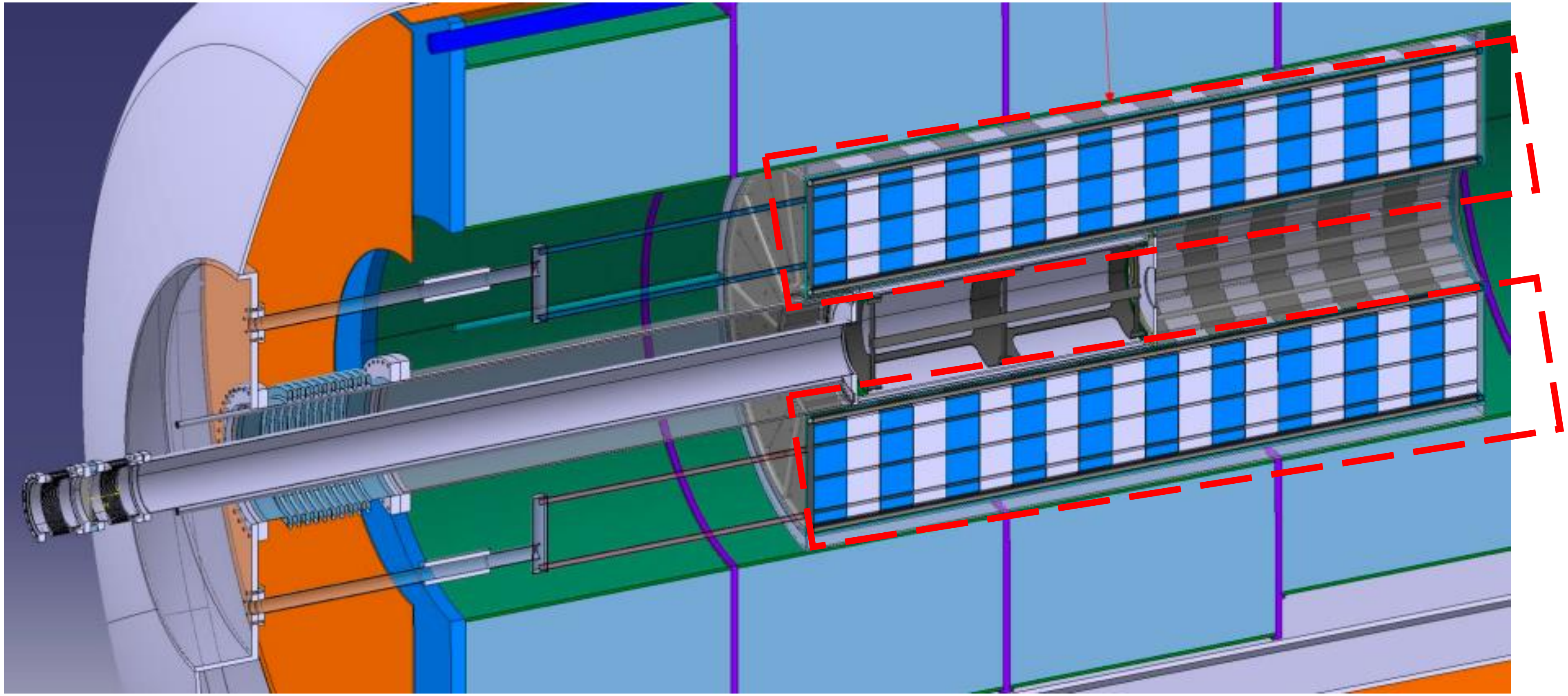
We **found**:

- **Increment** of maximum **temperature** about 100 K (wrt tilted beam case w/o supports)
- **Higher principal stresses** but still acceptable for graphite
- Reduction of **radial** deformation (wrt free tilted rod model)

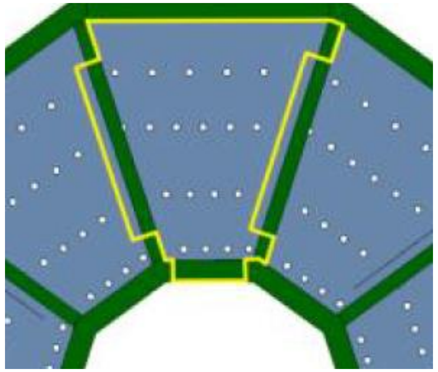
Ongoing:

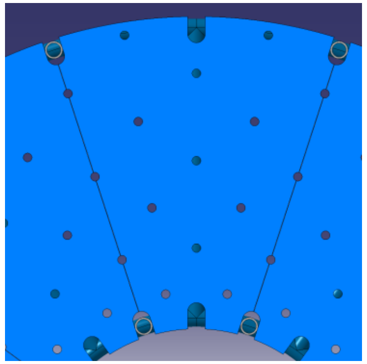
- Explicit **dynamic** simulation to assess the effect on the wave propagation
- Include energy deposition on supports and optimize the heat dissipation

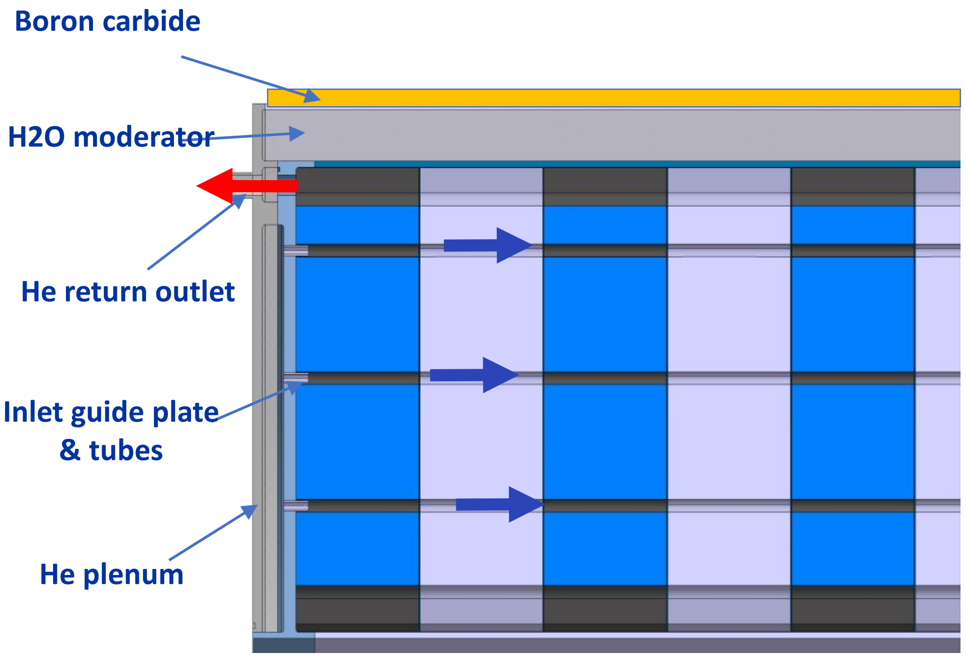
Radiation Shielding



Radiation Shielding

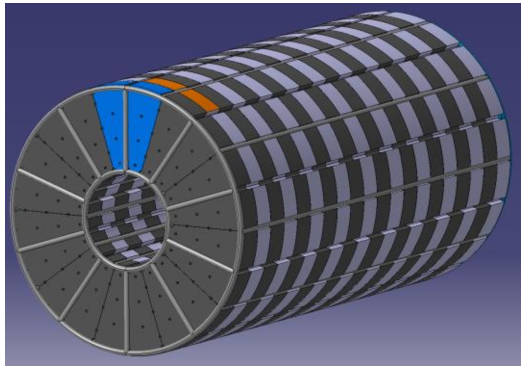






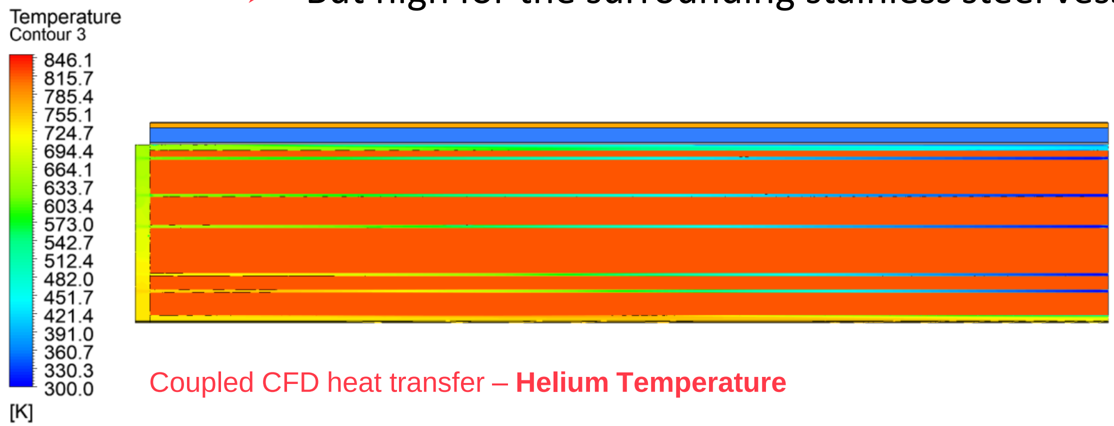
- **10 tungsten sectors (34 tons)**
  - **Self holding** e.g puzzle-like shape.
  - Alignment & structural rods
- Helium distribution
- Water moderator & neutron absorber
- **Shape** thought in order to **block direct radial radiation paths** to solenoid
- Ongoing: study of the stainless steel helium confinement (promising)

More details in Rui Franqueira yesterday´s presentation

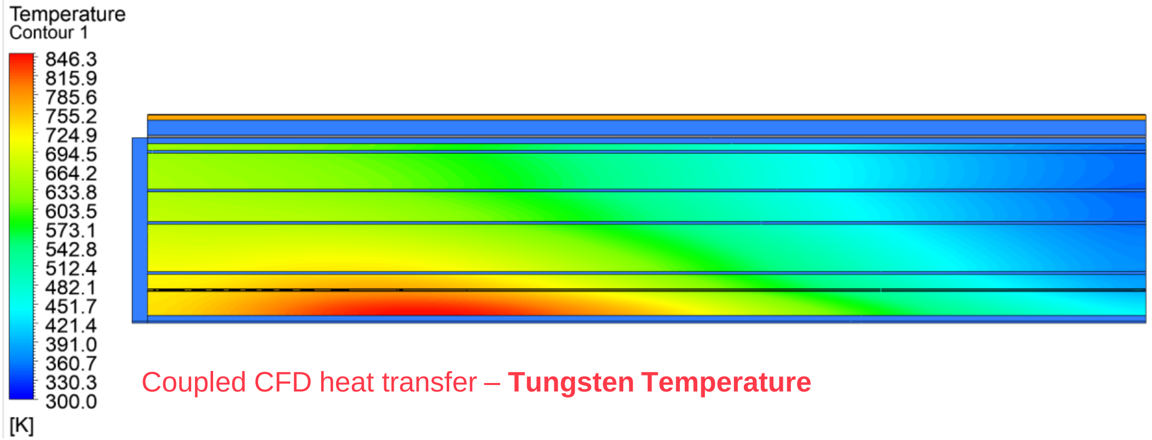


Radiation Shielding

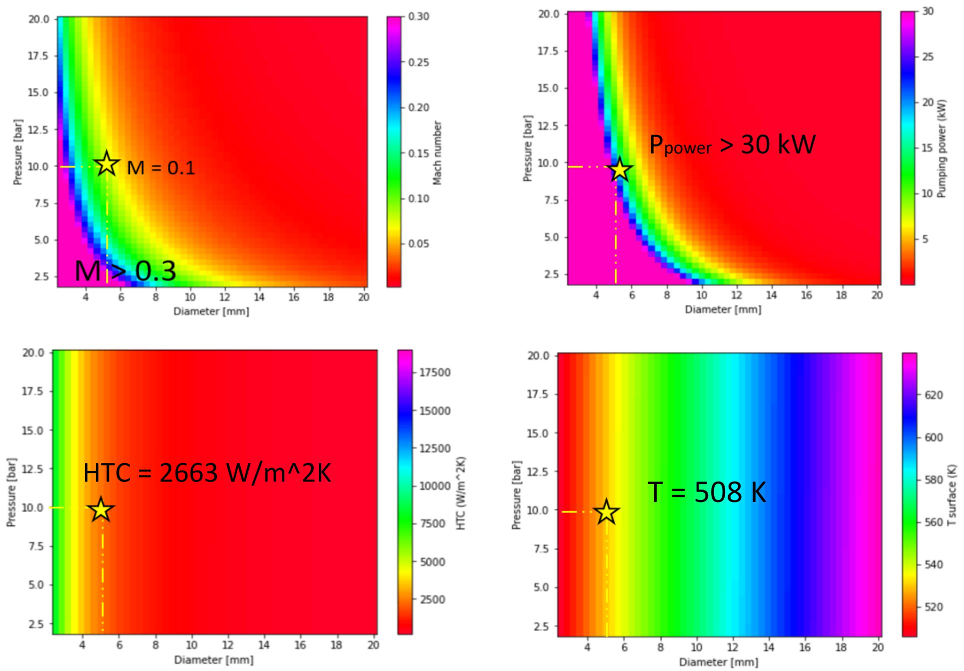
- Update for **2 MW** requirements
- Developed **numerical analytical code** to run across different mass flow/pressure/size parameters in order to choose the optimum operational point with the aim of **avoiding** unnecessary over **dimensioning**
- Temperatures acceptable for tungsten
  - But high for the surrounding stainless steel vessel (further optimization will be carried)



Coupled CFD heat transfer – **Helium Temperature**



Coupled CFD heat transfer – **Tungsten Temperature**

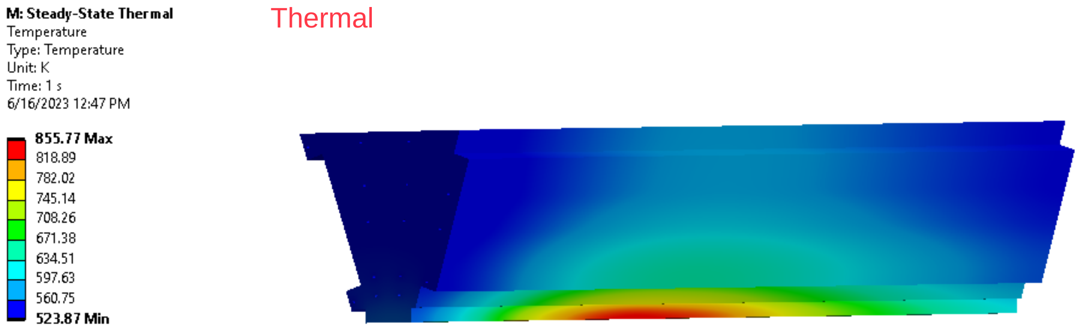


- Fluid : Helium
- Pipes diameter= 5 mm
- Number of pipes = 150

- Mass Flow = 0. 0022 kg/s per pipe
- Pressure = 10 bar

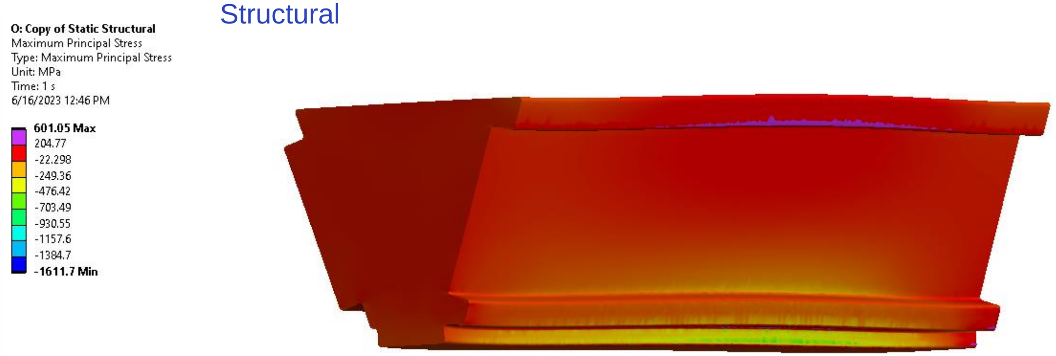
Radiation Shielding

Thermal



Max Temperature = 855 K

Structural



Max principal stress = 600 MPa @ 600 K

 # Tungsten yield @ 850 K 637 MPa
 # Tungsten yield @ 600 K 849 MPa

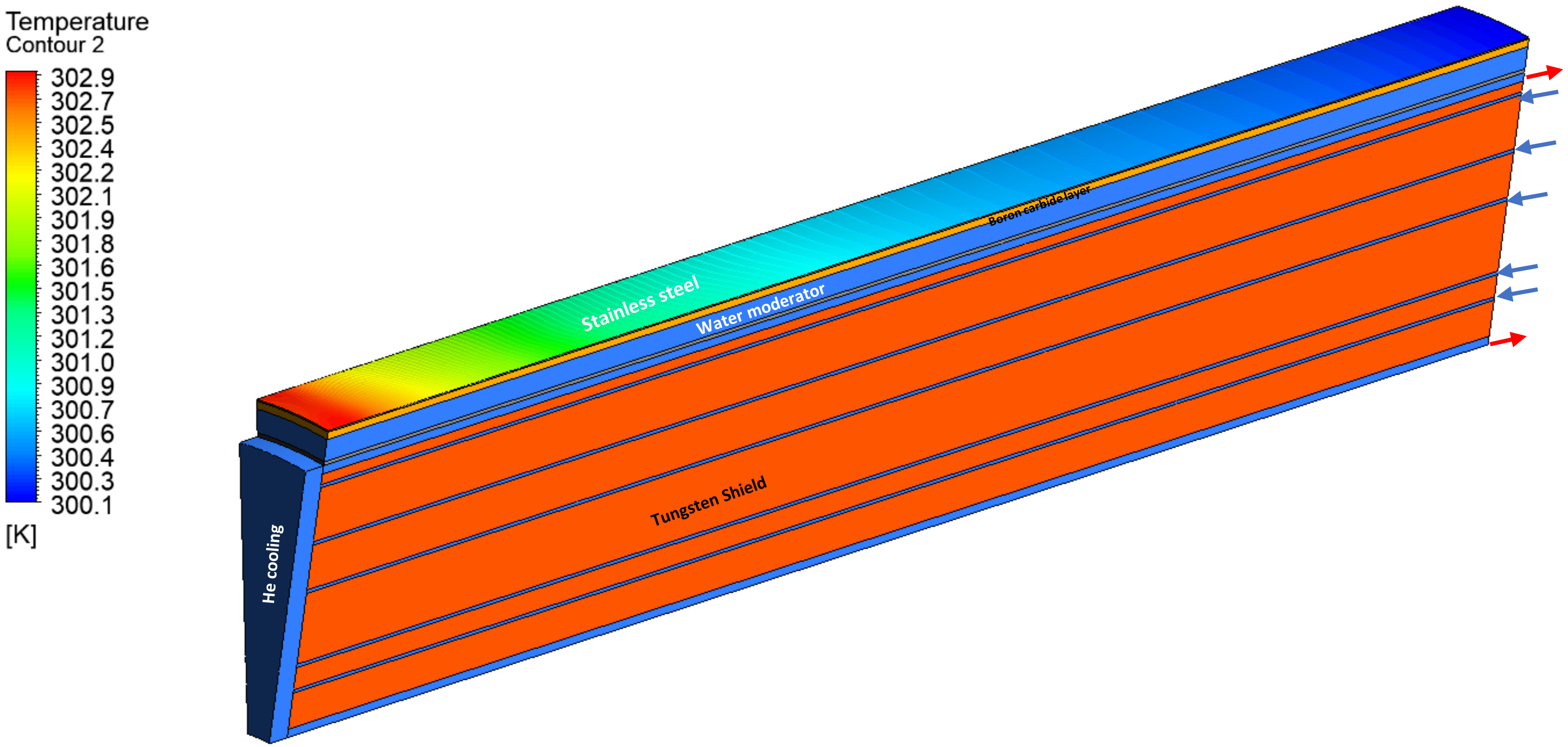
- Preliminary check to understand how the "weird" shape might affect to the tungsten slices

Analysis:
- Temperature field imported from CFD mapping
- Cooling holes omitted
- Supported by "twin" puzzle slices
- Gravity

Found:
- At T < 673 K , tungsten behaves as **brittle** (maximum principal stresses will define the survivability)
- Both temperatures and stresses are in an acceptable range
- Maximum stress on low temperature zones
- Work ongoing to assess the effect of slicing longitudinally these sectors

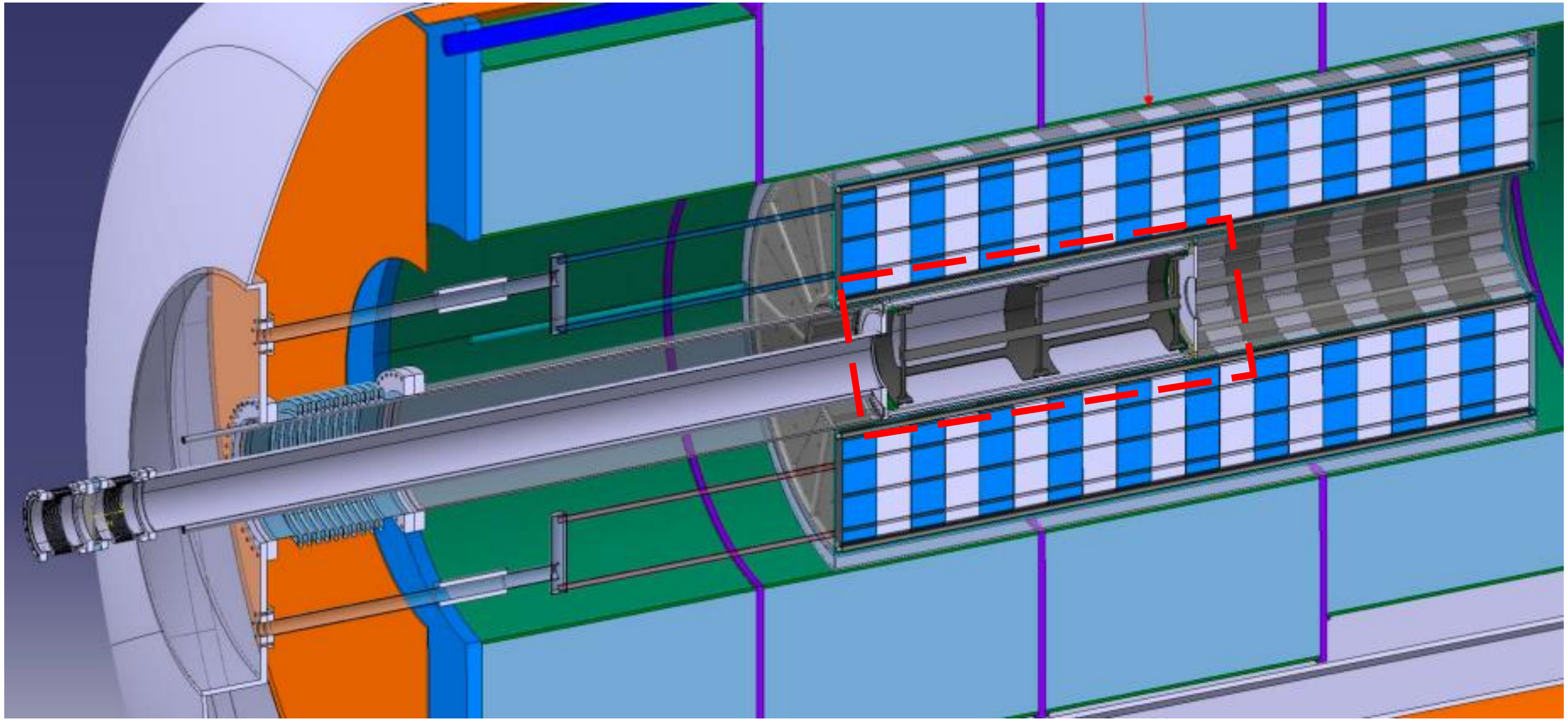
Radiation Shielding

- Agreed **interface** with magnets at **R 590 mm**
- Moderator water flowing at 0.1 m/s (0.35 kg/s)
- With the current cooling parameters the interface is mostly around **300K**



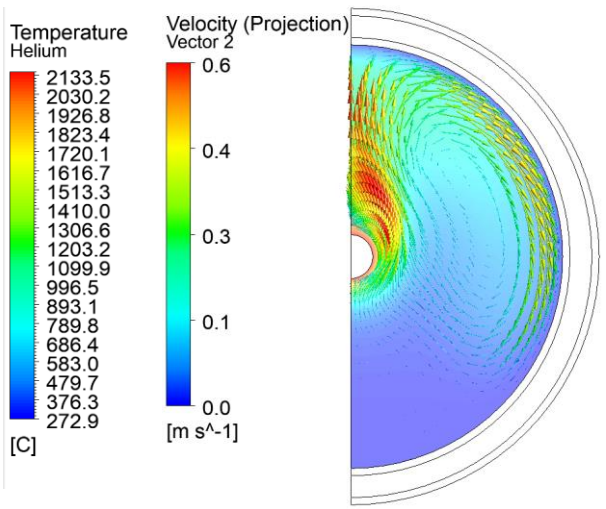
Coupled CFD heat transfer

Target Vessel

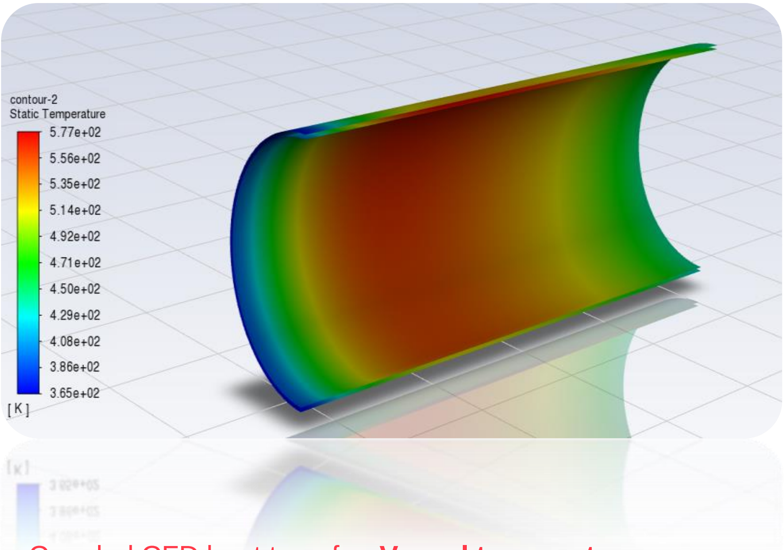


Target Vessel

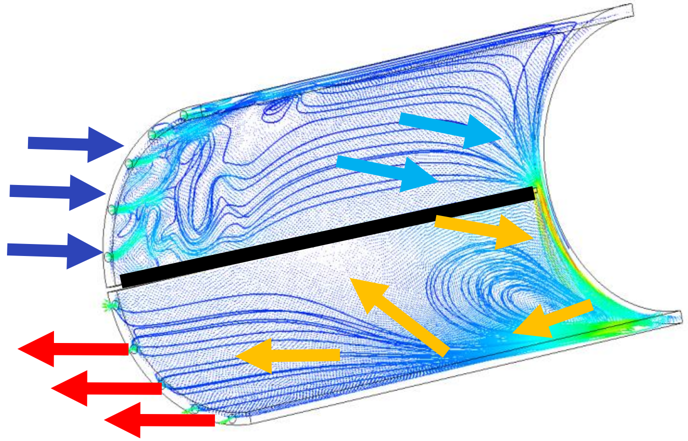
- Also updated to **2 MW**
- **Titanium** vessel - **helium** cooled
- Preliminary cooling operational point:
  - Still to optimize, but heat extraction requirements are lower than for shielding
  - Won´t affect to thermo-mechanical simulations as the needed HTC is “easily achievable”
- **CFD** validation to find out the appropriate thermal load in the vessel:
  - Inner vessel helium steady state flow: natural convection + radiation
  - First check on how a flow separator would work: recirculation found. Further optimization



Coupled CFD heat transfer: **convective cell**



Coupled CFD heat transfer: **Vessel temperature**

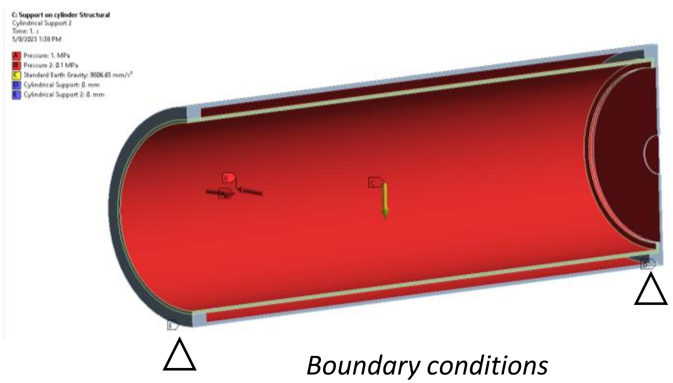


CFD: **Flow streamlines**

Target Vessel

Simply supported

Structural



Boundary conditions

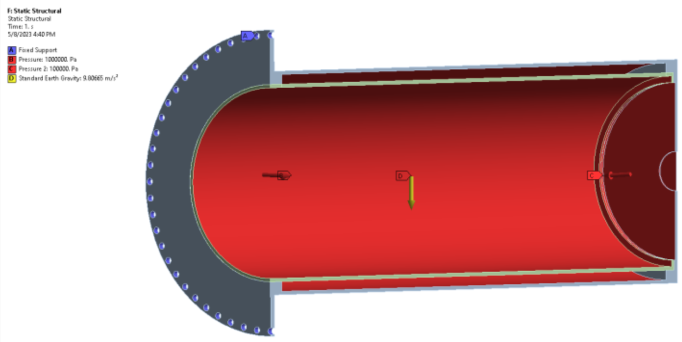
Stress field

- Max. Von Mises stress = 120 MPa
- Max deformation = 0.4 mm (radial inner vessel)
- Acceptable for Ti @ 577 K

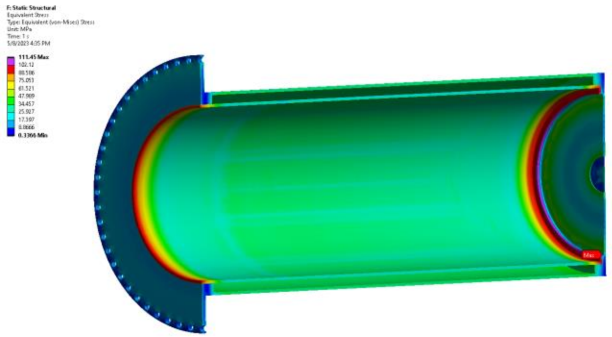
#Ti grade 5 yield @577 K = 641 MPa

Cantilever

Structural



Boundary conditions



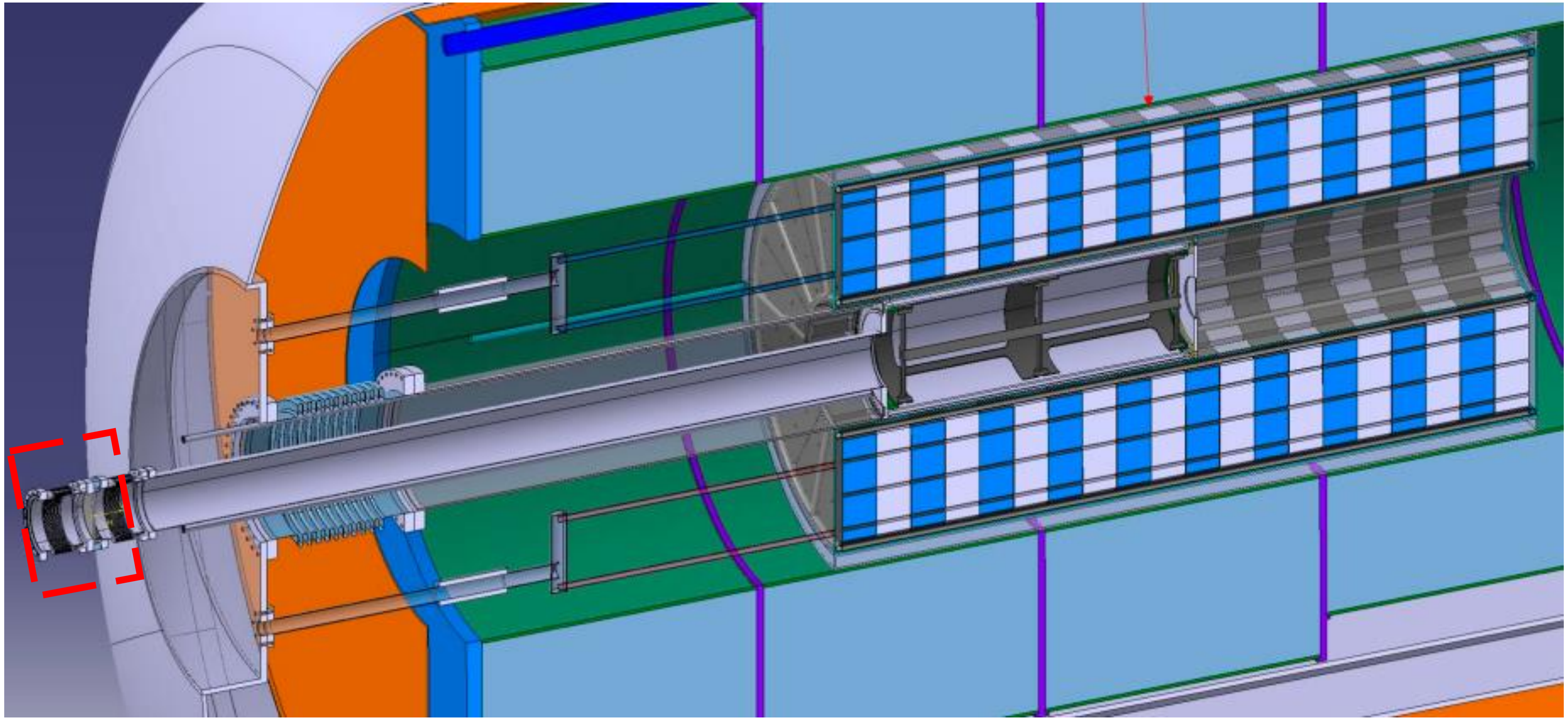
Stress field

- Max. Von Mises stress = 112 MPa
- Max deformation = 0.37 mm (radial inner vessel)
- Acceptable for Ti @ 577 K

- **2 concepts**: simply supported & cantilever
- Loads:
  - Internal & external cooling pressure (1 & 10 bar)
  - Dummy window just to ensure the correct structural behavior. (Window is dimensioned apart)
  - Gravity
  - Thermal load from direct **energy deposition** and pulsed **radiative flux** from target
    - ➢ Max T: 577 K (inner), 315 K (outer)
- No significant dynamic effects observed
  Quasi-steady state behavior

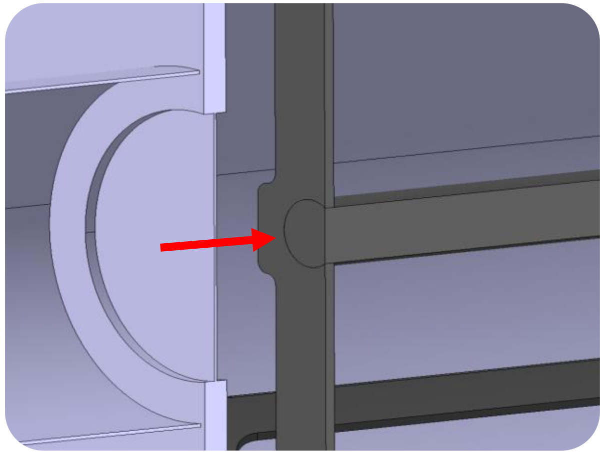
- Found that in both cases stresses and deformations are below limits
- Radiation effects on Ti grade 5 to be assessed:
  - ➢ **Thermal conductivity** can decrease and temperature might rise up too much
  - ➢ Is there a **limit** in terms of p+/cm^2?

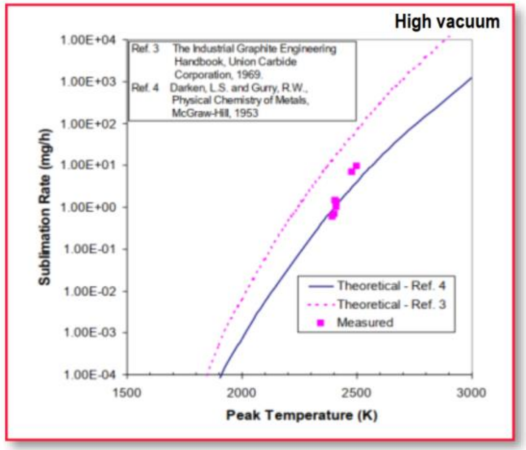
Beam Window



Beam Window

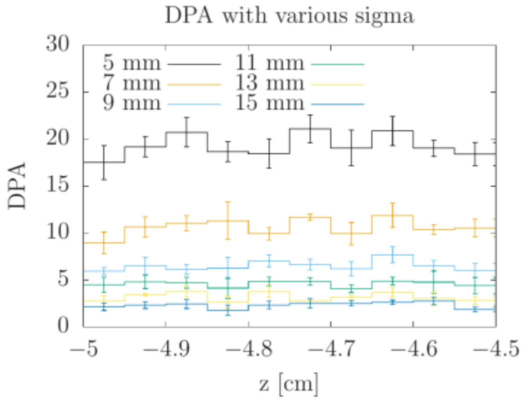
- A window is necessary to **store static helium** because:
  - In **high vacuum**, graphite may **sublimate** in a rate of around 1e-04 mg/h
  - Experiments using an atmosphere of static helium reduced the graphite sublimation rate by a factor of 30. @ 2700K *[C.C. Tsai et al.]*
- First aproximations **foresee very high temperatures , stresses and DPA** (Due mainly to the **small beam size** and high intensity)
- But there are some **ideas to dilute DPA** all over the window surface to minimize exchanges
- This fact entails the need of a **remote handling** system (such as T2K), to exchange the vessel, positioning and to align back into place



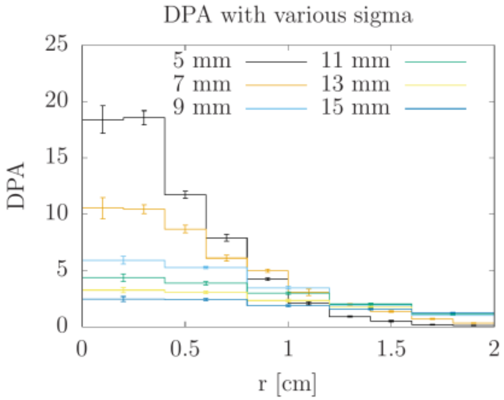


#Graphite sublimation rate - J.R. Haines & C.C. Tsai -2001

Longitudinal DPA distribution (uniform)

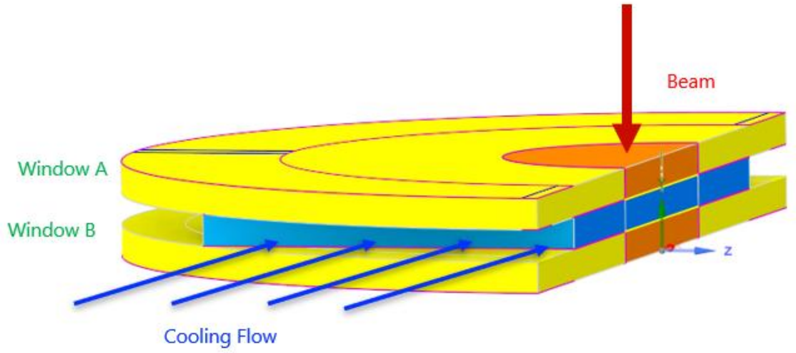


Radial DPA distribution

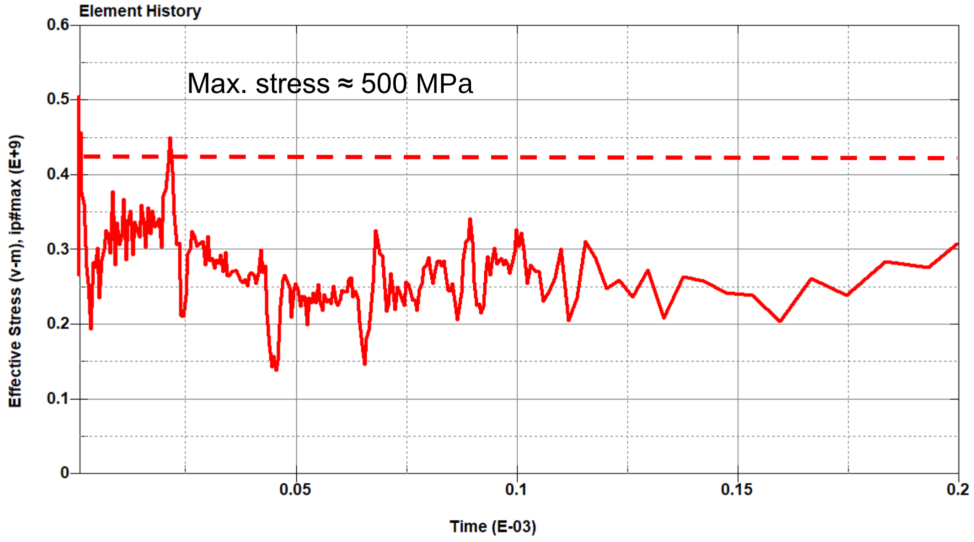


From Daniele Calzolari & Anton Lechner

Beam Window - Titanium



Window cooling concept



Dynamic stress waves after one beam shot (at centre) - Titanium

- To deal with this high requirements a first concept using a **cooled double window** has been proposed.
- Most of the energy deposition on the **inner layer**
- **Helium** at 1-2 bar would flow between the window layers

- First **parametric study** made in function of thickness for **titanium**
  - Found max HTC for every case of energy deposition
  - Solved steady state 2D axysimetric case

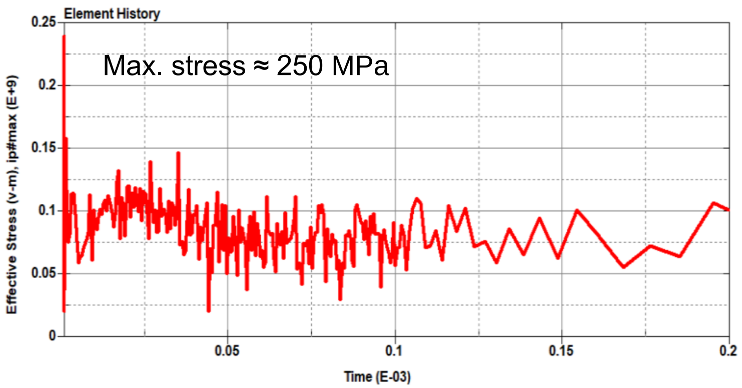
Radius (mm)	Thickness (mm)	Q (W)	HTC (W/m^2K)	Cooling pressure (bar)	Max T (K)	Stress joint (Mpa) Low T	Stress centre (Mpa) High T	Max deflection (mm)
12	1	637	2534	2	976	564	444	0,02
55	1	637	2590	2	950	867	450	1,99
55	0,25	116	1290	1	590	679	210	2,6
55	0,1	40	1283	1	394	1024	273	3,1

Thermo structural results for titanium window– steady state

 # Titanium grade 5 yield @ 300K= 890 MPa
 # Titanium grade 5 yield @ 800K = 447MPa

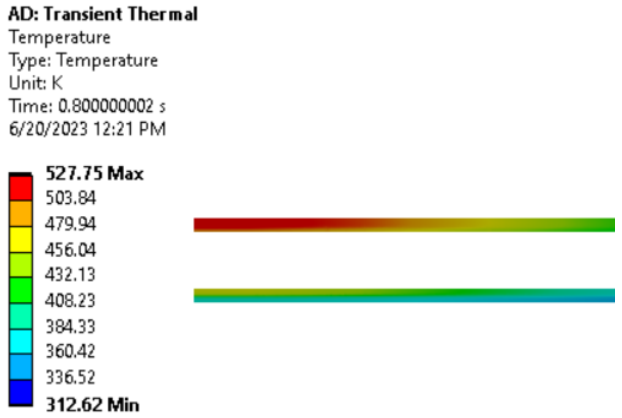
- **More thickness**, better **mechanical resistance** to pressure but higher energy deposited and therefore **higher temperature**
- Found that **250 microns** would be the “sweet spot” but titanium **fail** in the **dynamic response** after a beam shot

Beam Window - Beryllium

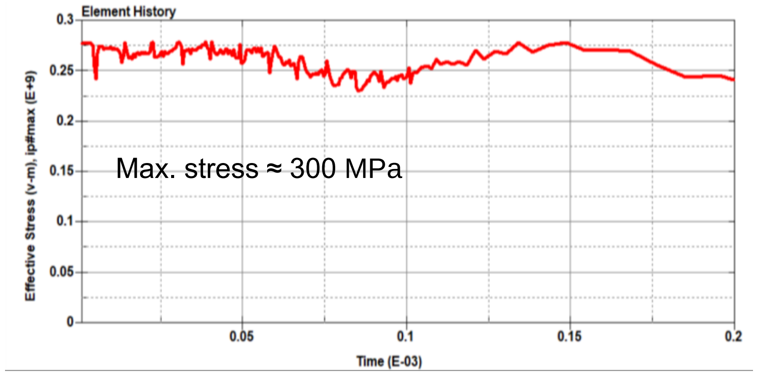


Dynamic stress waves due to one beam shot (at centre – 527K) [A]

- First essay on **250 microns beryllium**
- Preliminary results found that can **survive** a single beam **shot** far from plasticity (SF =1.2)
- Still work to be done to assess the fatigue
  - Material characterization at high temperature and irradiated
- **Radiation damage** is the biggest challenge. Some ideas to mitigate in yesterday Rui´s presentation
  - To be assessed the effect of an assymetric shot

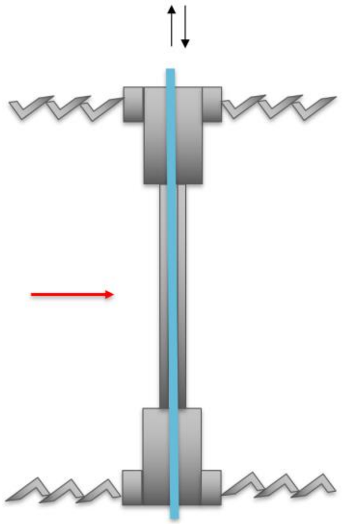


Maximum temperature on berylium = 527 K
Delta T = 83 K



Dynamic stress waves due to one beam shot (at joint - RT) [B]

 # Beryllium sheet (cross rolled) yield @ 300K= 517 MPa
 # Beryllium sheet (cross rolled) yield @ 700K= 257 MPa



Window supported on bellows to allow translation

Conclusions

- **Tilting the beam** reduces the energy deposition on target and therefore **allows to work at 2MW** keeping the muon yield
  - If the beam is straight the mechanical limit for the graphite rod is around 1.5 MW

- **Vessel and shielding** seems **no** to be a **showstopper**, but cooling requirements might be too high in terms of mass flow and pumping power if we want to go for higher power

- **Beryllium cooled window** studies are on development but looks **feasible for 2MW**. With special attention to fatigue endurance

- A **window translation** system or **beam dilution** system can be used to share the DPA along the window surface and minimize exchanges

Thank you for your attention

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Backup slides

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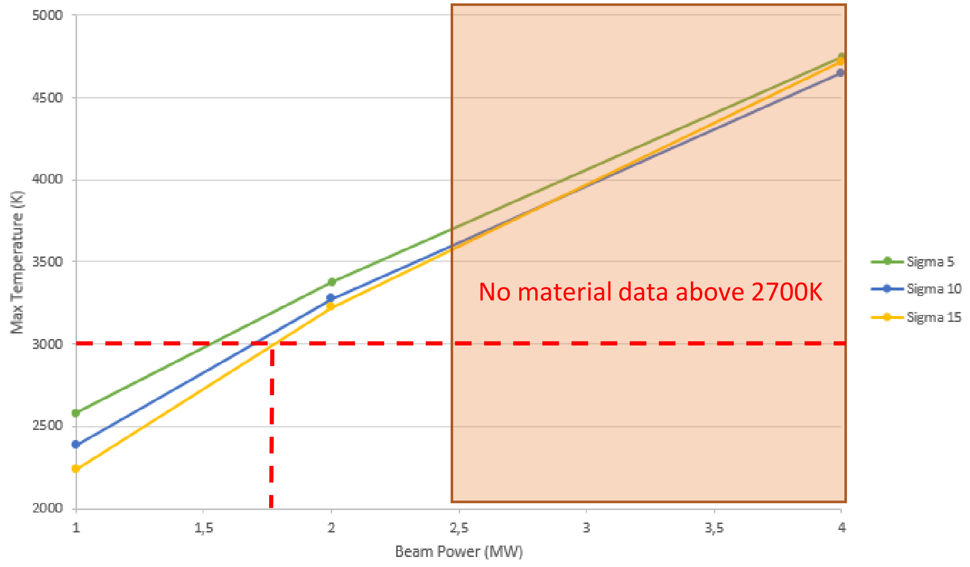
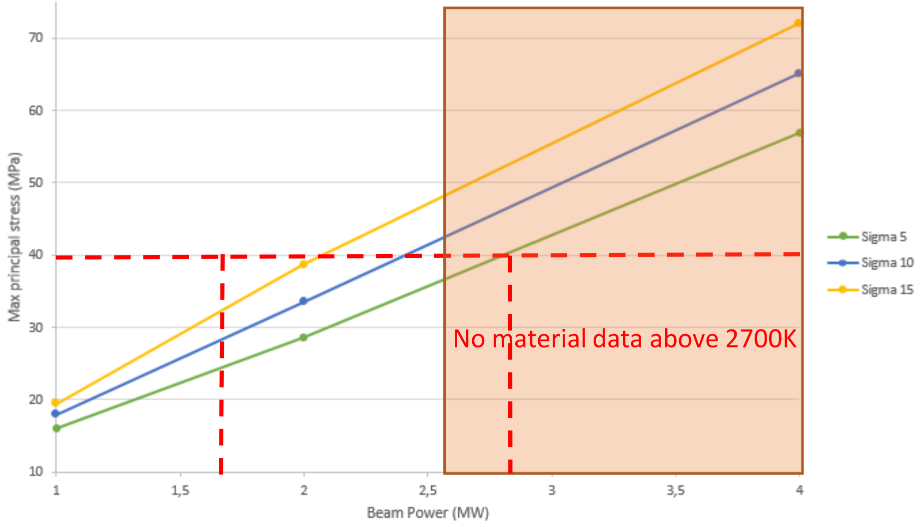
marco.calviani@cern.ch

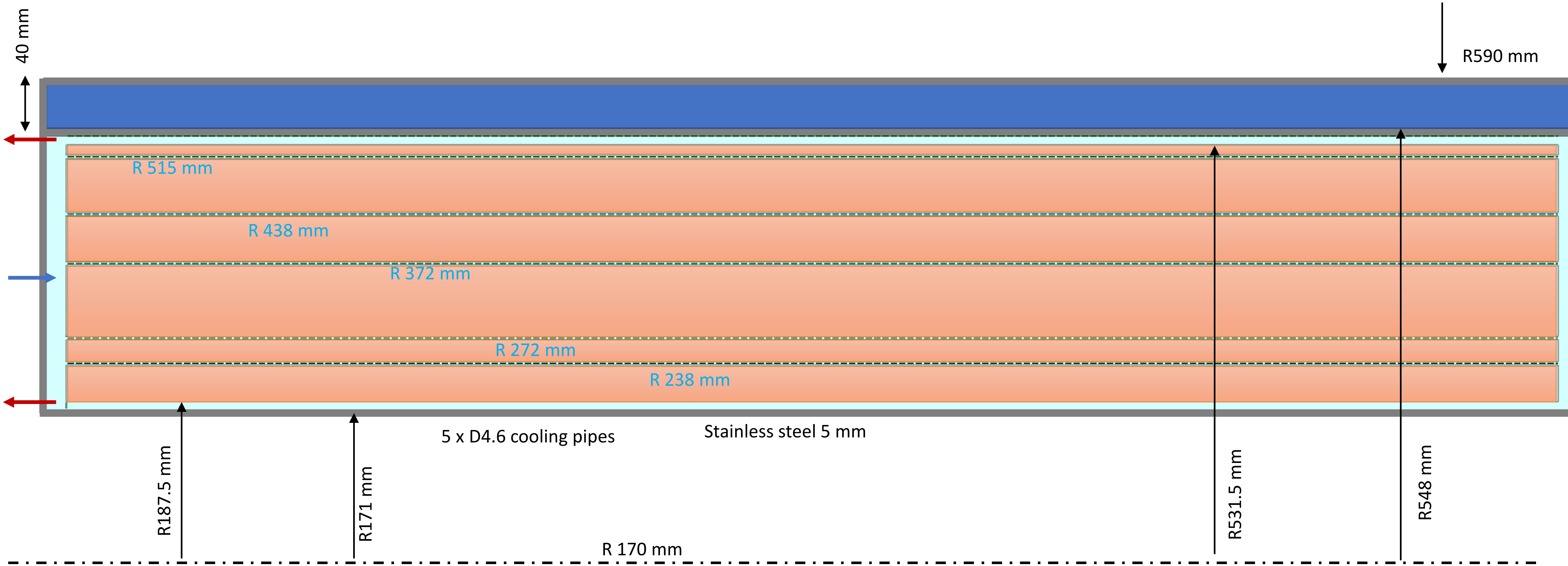
Target Rod
Power vs beam sigma





- **Parameters:**
  - **Straight** beam (no tilt)
  - 5 GeV, 2ns, 5Hz, **3σ rod radius**
  - Variable beam power, beam size and bunch intensity
- Simulation points:
  - Steady-state thermal structural for 1, 2 & 4 MW
  - Transient structural for 1.5 & 2MW
- Limits:
  - Max temperature cap @ 3000K (SF = 1,33)
  - Max acceptable principal stress of 40 Mpa (SF = 1,25)
  - Neglected limitations of the windows, vessel, shielding, cooling & graphite sublimation rate

- Found a **limit** due to max **temperature** around 1.7 MW (sigma 15)
- In general, **larger sigmas decrease temperatures,** but gain decreases with power
- **Smaller beam size** is **better** because the total power deposited is lower, so they are the static stresses.
- But **peak stresses** are larger as the smaller the beam size is



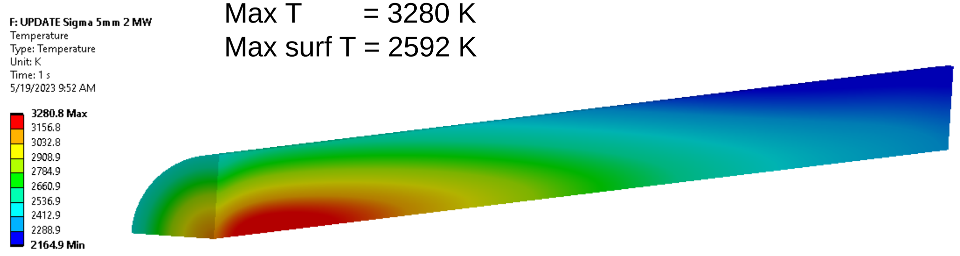
Fluka Energy Deposition = 674400 W (R178 to R600)
Max ED = 3.53 J/cm3

Target Rod

2 MW– steady state – STRAIGHT BEAM

Thermal

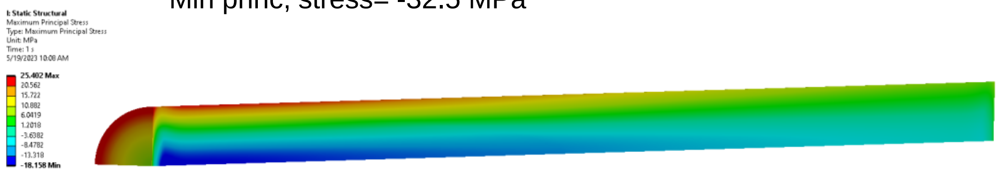
Max T = 3280 K
Max surf T = 2592 K



Structural

Max princ. stress = 26.4 MPa
Min princ, stress= -32.5 MPa

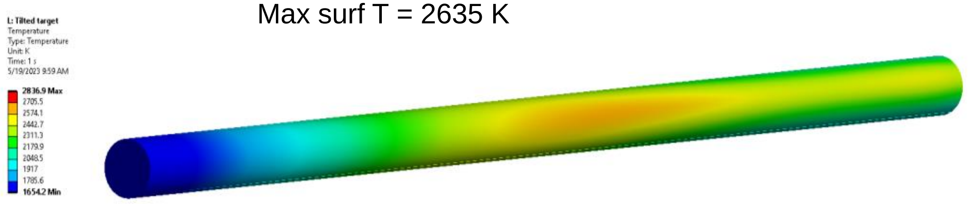
Axial def. = 10.5 mm
Radial def.= 0.23 mm



2 MW – steady state – TILTED BEAM

Thermal

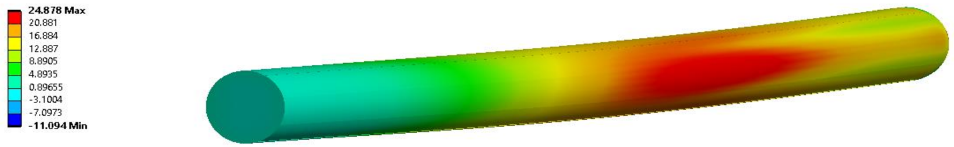
Max T = 2837 K
Max surf T = 2635 K



Structural

Max princ. stress = 24.8 MPa
Min princ. stress= -22MPa

Axial def. = 10 mm
Radial def.=7.1mm



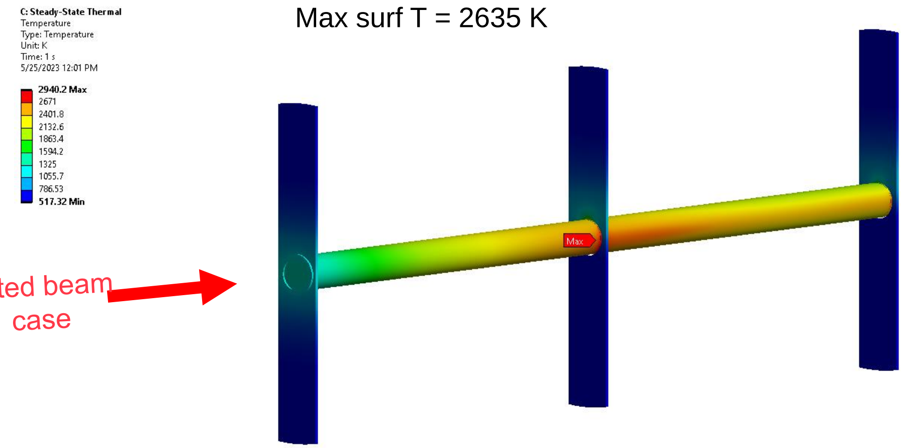
Target Rod

Influence of the supports

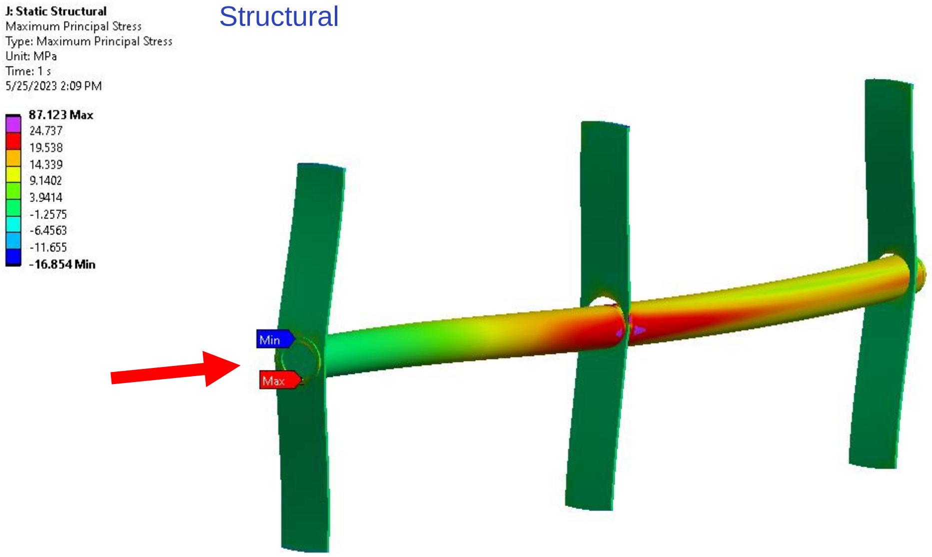
Thermal

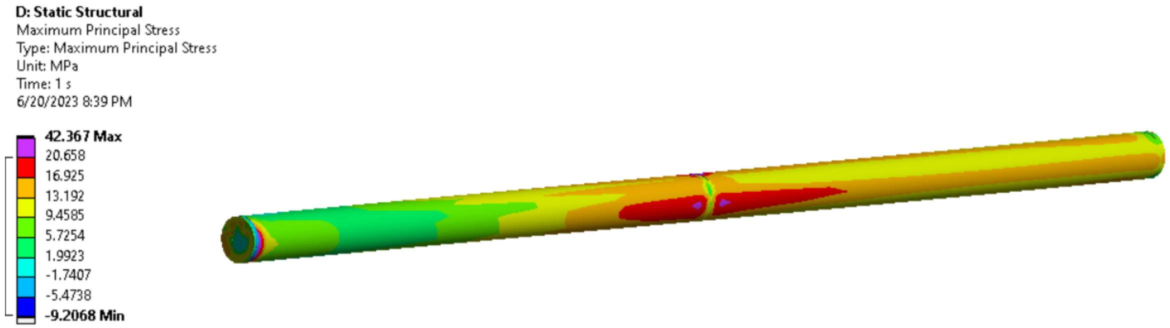
Max T = 2940 K
Max surf T = 2635 K

Tilted beam case



Structural

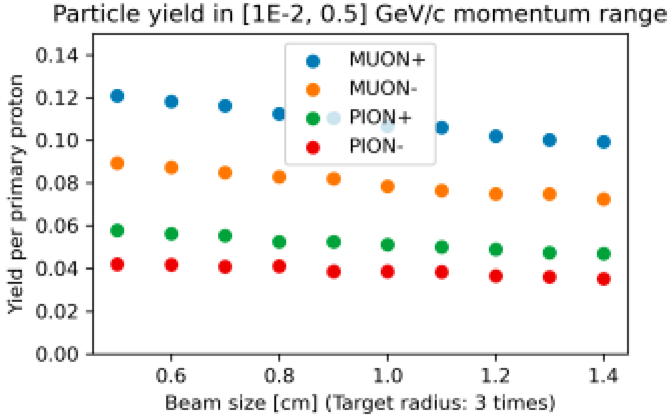


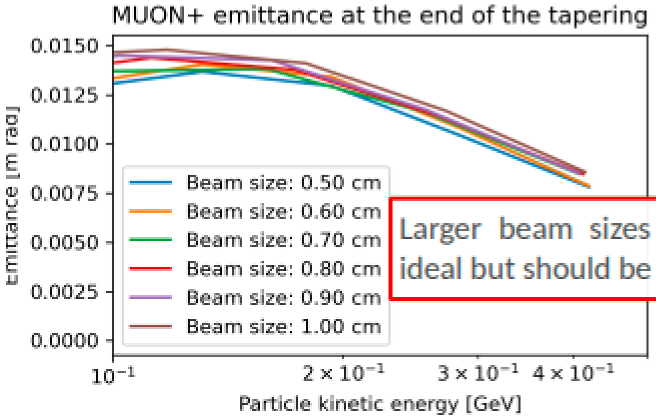


Parametric scan: beam size and transverse target size

Proton beam size:

The default case is a 5 mm beam size, and the target size is always 3 times the beam size

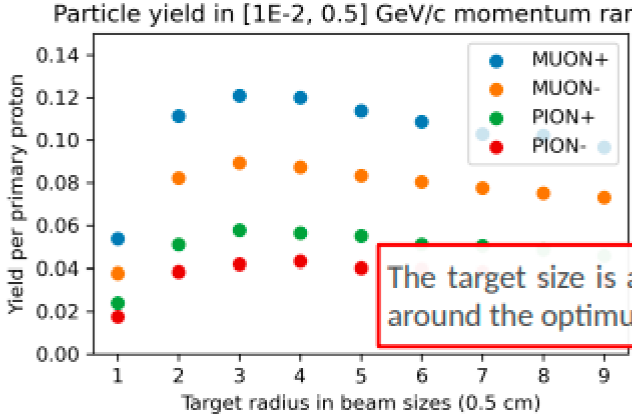




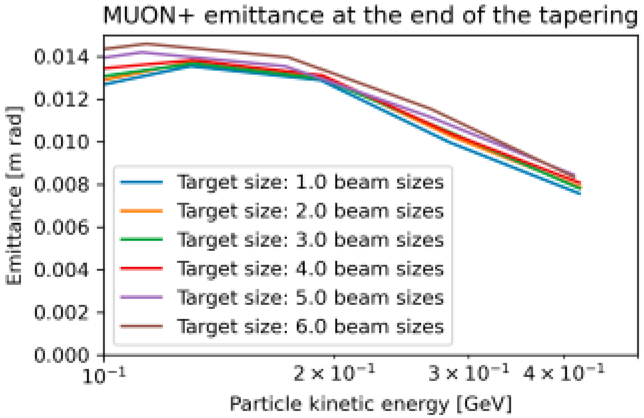
Larger beam sizes are not ideal but should be feasible

Target transverse size:

The default case is 3 times the beam size, and the beam size is always 5 mm



The target size is already around the optimum



Radiation assessment

- **Similarity with CNGS.**
  - Similar design, identical dynamic response – Plastic regime (Less power but more deposition time)
- ***Literature indicates a lifetime for graphite of 1E21-1E22 p+/cm².**

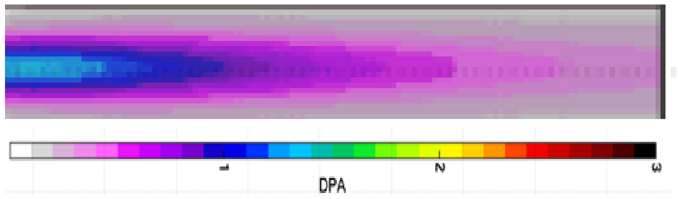
**Radiation damage study of graphite and carbon-carbon composite target materials*

- **Radiation induced creep / swelling.**
- **Thermal conductivity loss (from 0.01 DPA, but higher with increased T).**
- **Increase of stiffness and mechanical strength.**
- **High temperature may help recovering damage through annealing.**

↑ *Fatigue resistance*

Parameter	CNGS*	Muon Colider (Same p+/cm²)
Proton fluence p+/cm²	5.76E+22	=
PoT	1.27E+20	4.52E+22
Beam size (mm)	0.53	5
Extractions	5.29E+06	1.2E+08
Days	183	277
DPA	1.5	2.85

**Edda Gschwendtner NuFact'11*



MuC Target DPA for 200 days @1MW
By Daniele Calzolari SY-STI-BMI

- CNGS PIE to be done…