Development of FCC-ee and P3 positron source targets at CERN

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on behalf of the WP3 team (FCC-ee injector update studies)

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1. FCC-ee positron source target: design studies

2.1 Manufacturability constraints (1/3)

Motivation:

to include manufacturing constrains in the design.

Study A: Cooling pipes (CP) configurations

Commercial Ta tubes ID4.35 & OD6.35 mm

3 geometry cases:

- a) CP outside the target
- b) CP tangent to the external target face
- c) CP embedded 1mm inside

Results: Case 3 (internal pipes) provides the best performance in terms of peak temperature and lower equivalent stresses respect to the other candidates*.

*Further studies are required to evaluate its feasibility.

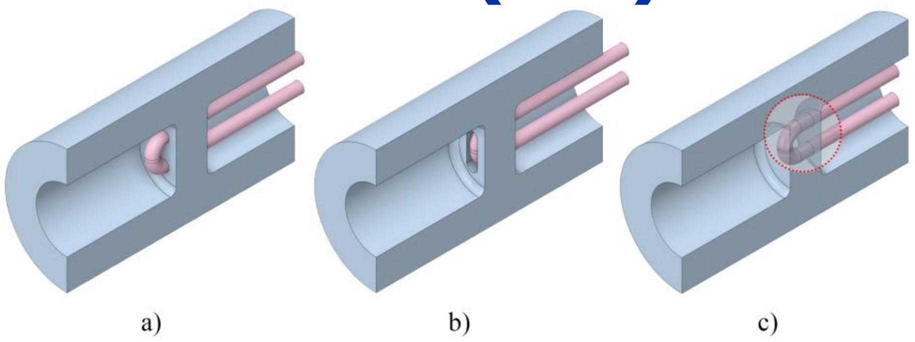


Fig. Geometry of the target (1/2 sector) model a) case 1, b) case 2 and c) case 3

e⁻ drive beam (GeV)	6.0
Beam size RMS (mm)	1.0
Repetition rate (Hz)	200
Bunches per pulse	2
Bunch intensity	1.3E10
Beam power (kW)	5.0

Table.
Beam parameters for the simulations
Source: (FCC-ee Week 2023)

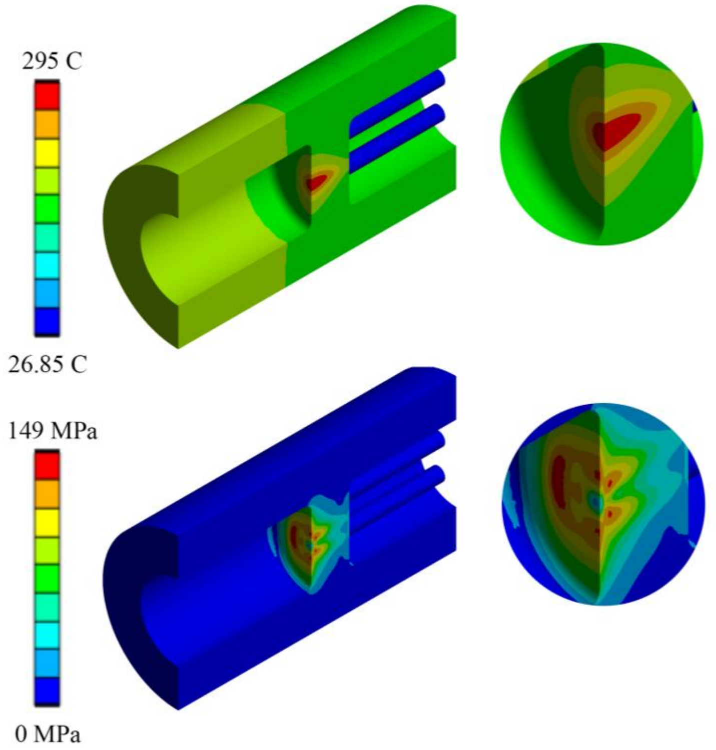


Fig. Study A results: Temperature (top) and equivalent stress (bottom) distributions for case 3

2.1 Manufacturability constraints (2/3)

Case B : Bending of cooling pipes

Motivation: To define the minimum **bending radius** to manufacture the CP elbow (180°)

Strategy: Numerical model + experiments

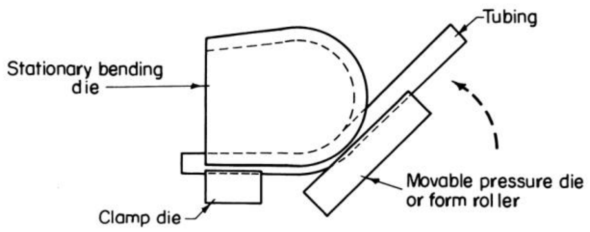


Fig. Compression bending [Olofson 1961]

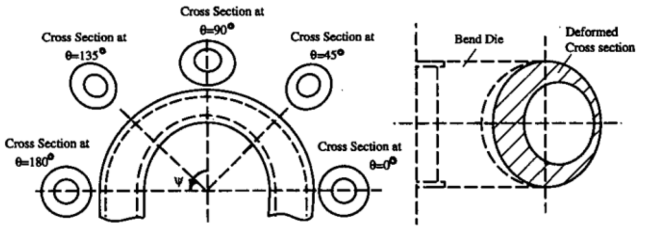


Fig. The deformation at different cross-sections caused by plastic deformation of a tube during bending [Pan and Stelson 1995]

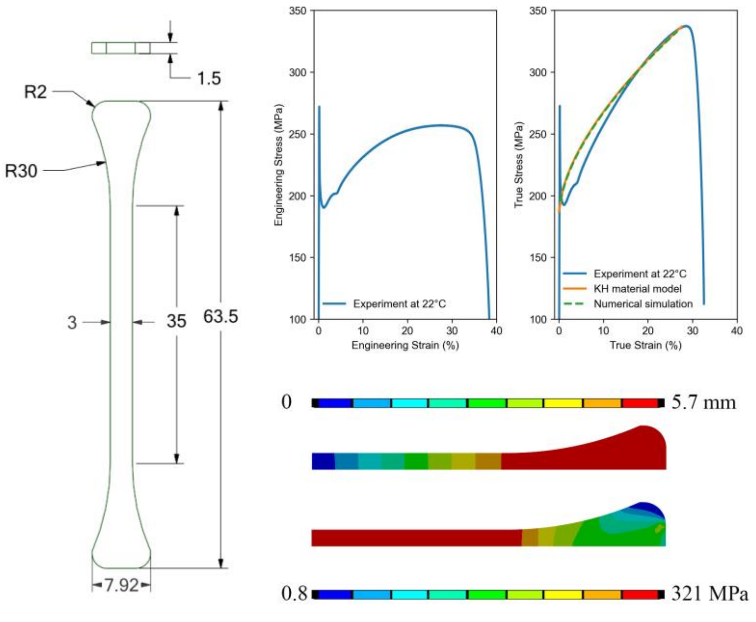


Fig. Step 1. Material calibration

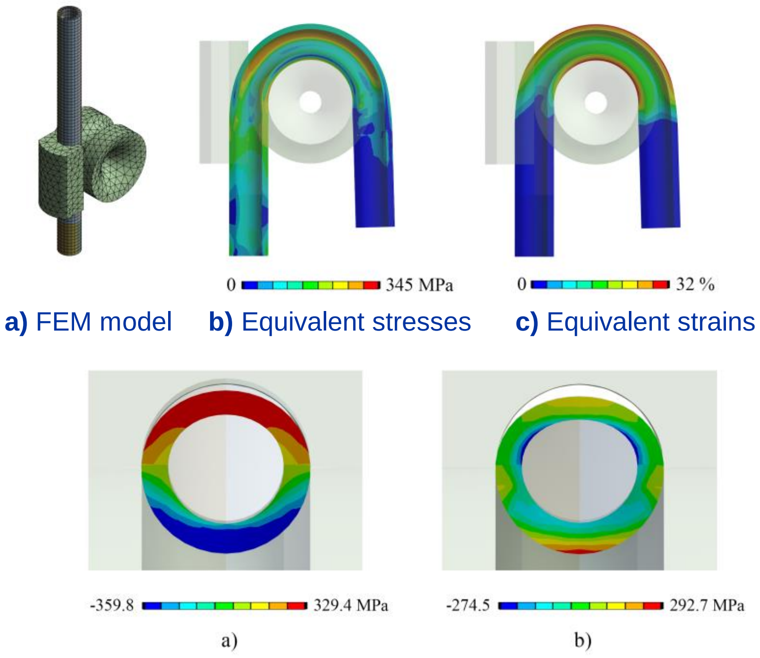


Fig. Step 2. Plastic bending simulation

Fig. Step 3. Plastic bending experiment. [T.Coiffet EN-MME CERN]

2.1 Manufacturability constraints

Model update:

a) Previous design: R_b= 6.35 at ϕ20 mm

b) Updated design: R_b=10 at ϕ28.28 mm

Comments:

- The increase on the **bending radius R_b** has a minimal impact in terms of peak temperature (+2.8%) and in equivalent stresses (+2%).

Open questions:

- The model assumes a **perfect geometry** on the elbow of the cooling pipes, but it was demonstrated before that **ovalization** occurs.

- How to include the **residual stresses** caused by bending and HIPping in the model?

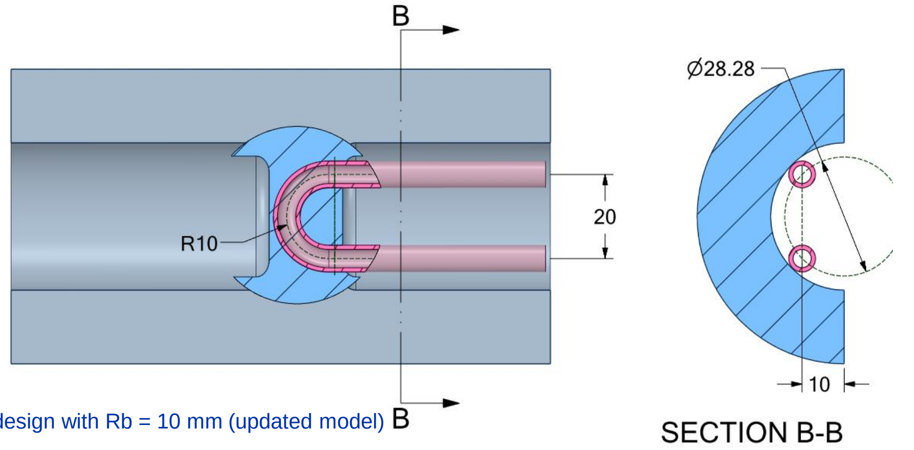


Fig. Target design with Rb = 10 mm (updated model)

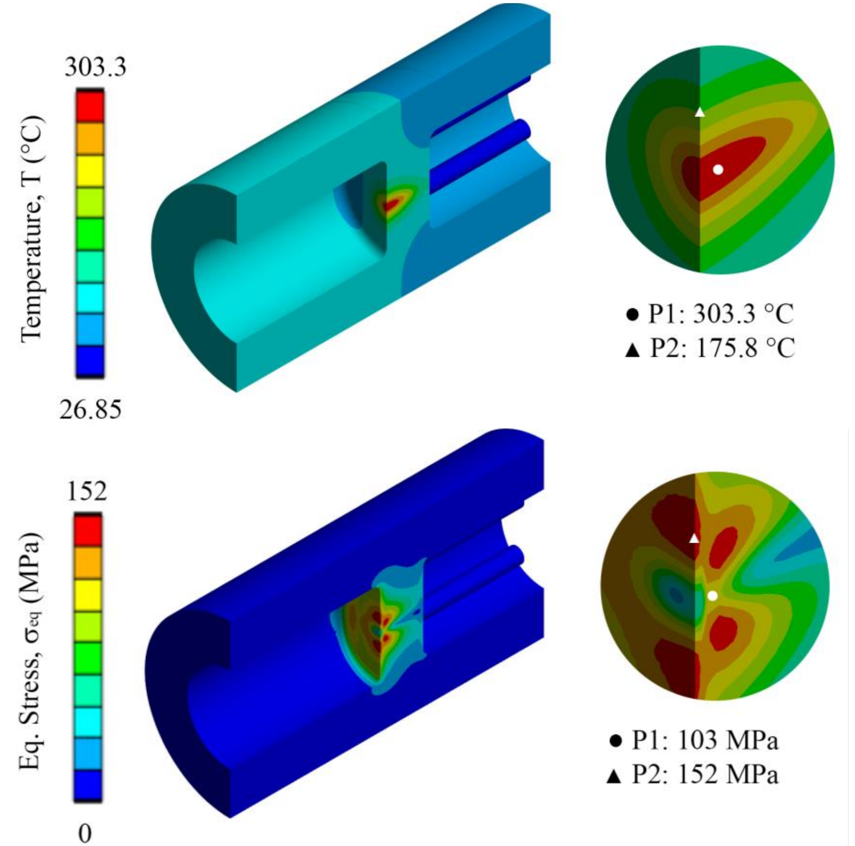


Fig. Steady state temperature (top) and equivalent stress (bottom) distributions for the updated model

2.2 Geometrical studies (1/3)

Parameter	(a) standard	(b) conical	(c) conical
Beam size RMS (mm)	1.0	0.5	1
Bunch intensity x e10 (nC)	1.3 (2.08)	0.827 (1.325)	1.11(1.775)
Beam power (kW)	4.99	3.18	4.26
Beam power on target (kW)	1.46	1.66	1.79

Table. Beam parameters for the simulations*.

*Electron drive beam, repetition rate and bunches per pulses are 6 GeV, 200 Hz and 2, respectively

Motivation:

To increase the positron yield respect to the *standard geometry*

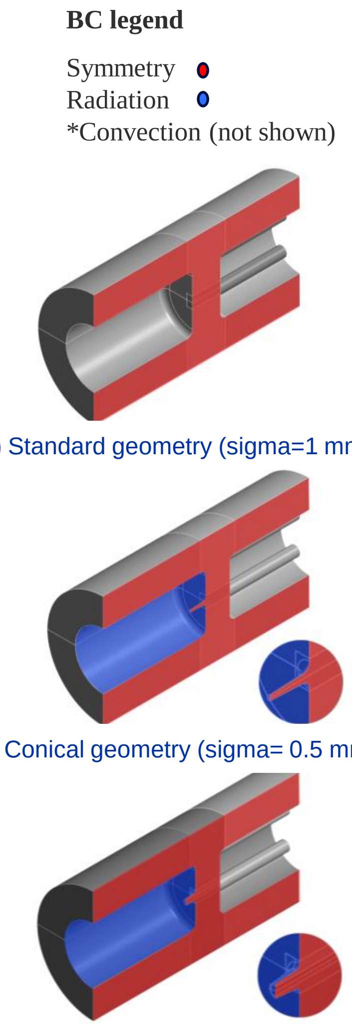
Options: [N. Vallis @PSI]

Long thin rod: discarded

Conical geometry: present study

Model setup:

Input: Energy deposition done with FLUKA [B. Humann @CERN SY-STI]



a) Standard geometry (sigma=1 mm)

b) Conical geometry (sigma= 0.5 mm)

c) Conical geometry (sigma= 1 mm)

Fig. Model geometry and boundary conditions

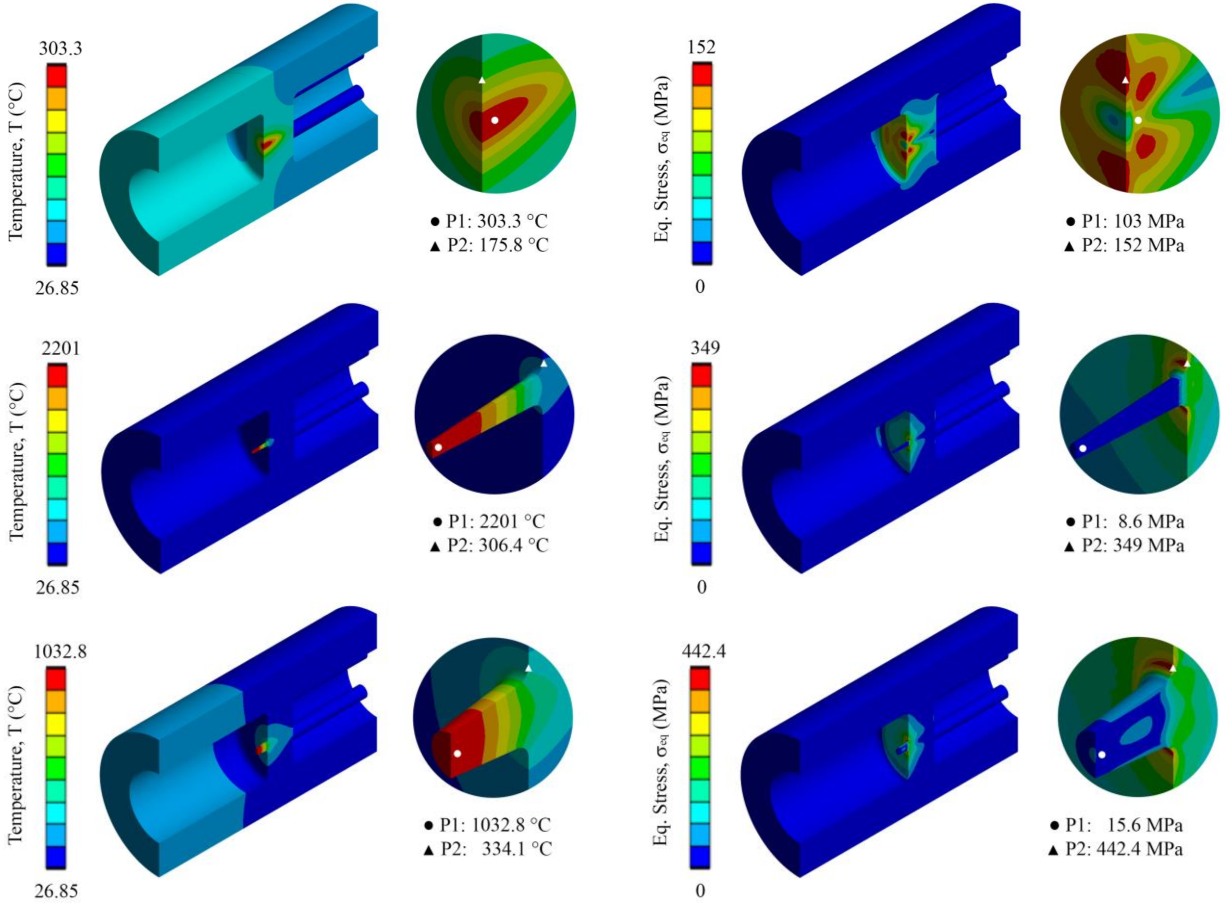


Fig. Temperature (left) and equivalent stress (right) distributions

2.2 Geometrical studies (2/3)

Discussion:

Deformation mechanism maps

- Tool to evaluate the thermo-mechanical performance between configurations [Ashby et al. 1972]

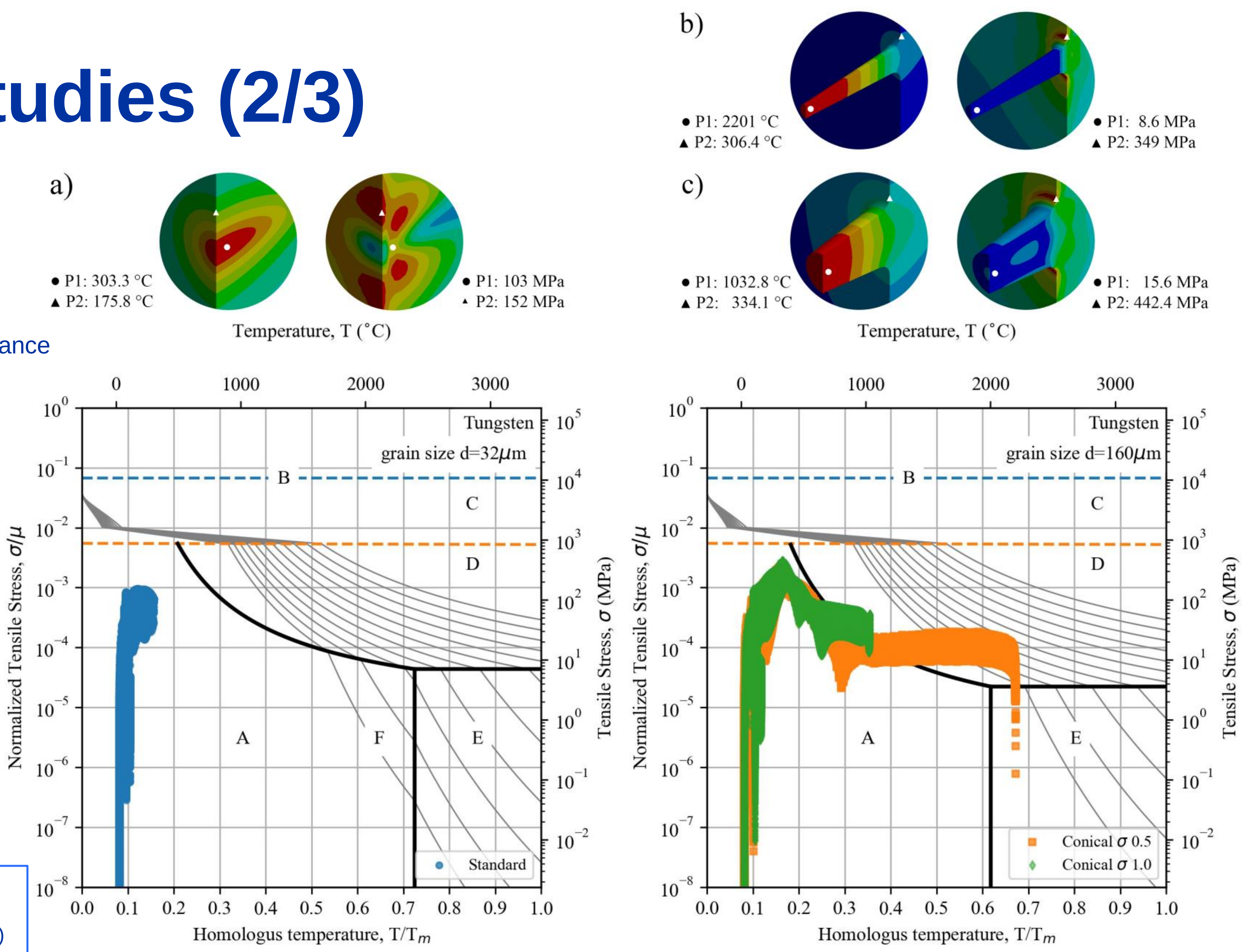
(a) Standard: Tmax < DBTT [350-400] °C

(b-c) Conical: Tmax > Tr

- W Tr [1000-1550] °C [Suslova et al.,2014]
- Pure W can be recrystallized at 1100 °C for long term exposition (time ≥ 200 hours) [Tsuchida et al. 2018]
- Grain size increment in the conical zone (with a negative impact).

DBTT: Ductile to Brittle Transition Temperature
Tr: Recrystallization Temperature

Legend:
A: Elastic regime
B: Theoretical shear stress
C: Dislocation glide
D: Dislocation creep
E: Diffusional flow (Nabarro creep)
F: Diffusional flow (Coble creep)



(a) Fig. Deformation mechanism map for W (32μm)

(b-c) Fig. Deformation mechanism map for W (160μm)

2.2 Geometrical studies (3/3)

Summary:

For both conical targets:

- **Radiation** as a heat transfer mechanism is negligible (main limitation is given by the **small area**).
- **Grain size** increment in the conical area due to a long exposition at temperatures above Tr

For the conical model with sigma 0.5:

- **Radiation damage** can be a limiting factor. FLUKA simulations estimated O(2 DPA/year) [B. Humann 2023].
- **Manufacturing** of the cantilever structure is not a showstopper.

For the conical model with sigma 1.0:

- **Radiation damage** is similar w.r.t the standard geometry O(1 DPA/year) [B. Humann 2023].
- Maximum **thermal stresses** are increased by a factor 2.73 with respect to the standard geometry.

For all geometries:

- Further assessment is needed to study the impact of **thermal fatigue** (i.e multiaxial fatigue criteria).

2.3 Alternative material (1/3)

Motivation:

To study the influence of using **different materials** for the target from the thermo-mechanical point of view.

Candidates:

W (baseline), Ta and Au [F. Alharti @IJCLab 2023]

- Standard geometry (cylindrical)
- Beam size (sigma = 1.0 mm)

ID	Z	Radiation length X_0 (mm)	Target thickness $L_t \sim 5X_0$	Production Rate [e+/e-]	Variation [%]
Ta	73	4.094	21.0	13.96	-0.993
W	74	3.504	17.5	14.1	-
Au	79	3.344	17.0	14.25	1.064

Table. Variation on the production rate for different target materials [F. Alharti]

Model setup:

Input: Energy deposition done with FLUKA
[B. Humann @CERN SY-STI]

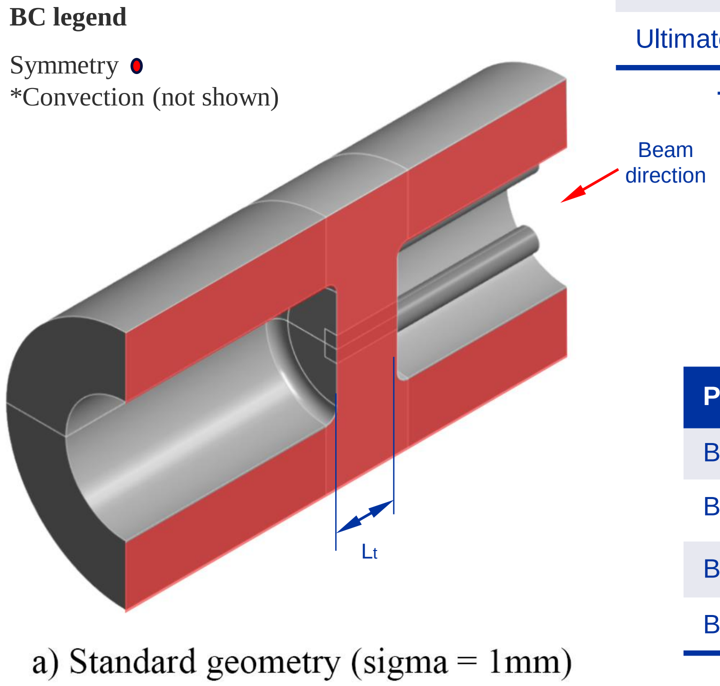


Fig. Model geometry and boundary conditions

Property	Symbol	W	Ta	Au
Density	ρ [kg/m3]	19250	16600	19320
Melting temperature	Tm [°C]	3386	2995	1062
Thermal conductivity	*k* [W/mK]	174	57.5	317
Young's Modulus	E [GPa]	340	175	76
Yield stress	σy [MPa]	n/a*	200	8.6
Ultimate strength	σUTS [MPa]	550	270	118

Table. Selected ppropperties for the candidate materials at room temperature RT

Parameter	(a) W	(b) Ta	(c) Au
Beam size RMS (mm)		1.0	
Bunch intensity x e10 (nC)		1.3 (2.08)	
Beam power (kW)		4.99	
Beam power on target (kW)	1.46	1.88	1.82

Table. Beam parameters for the simulations*.
*Electron drive beam, repetition rate and bunches per pulses are 6 GeV, 200 Hz and 2, respectively

2.3 Alternative materials (2/3)

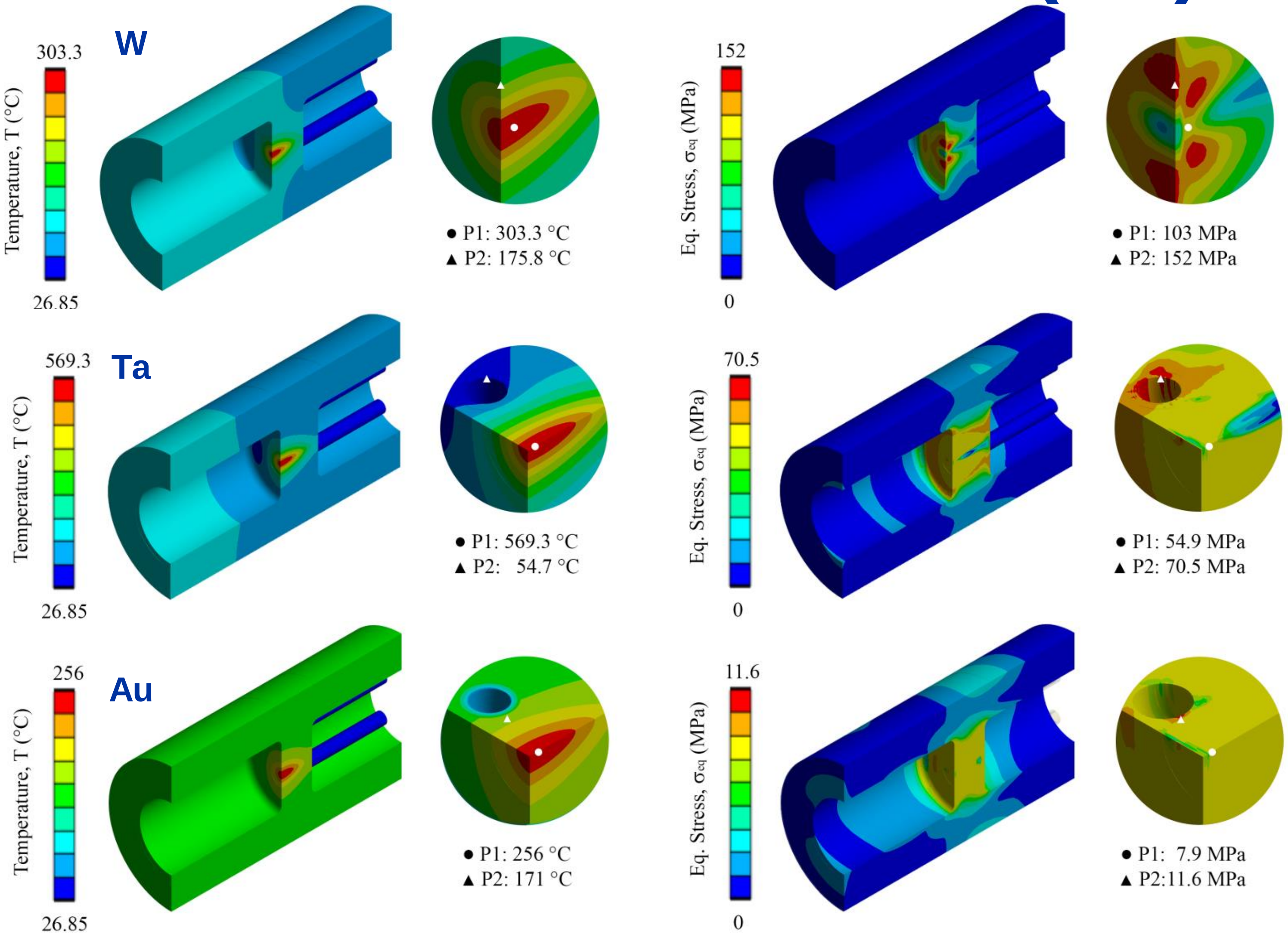
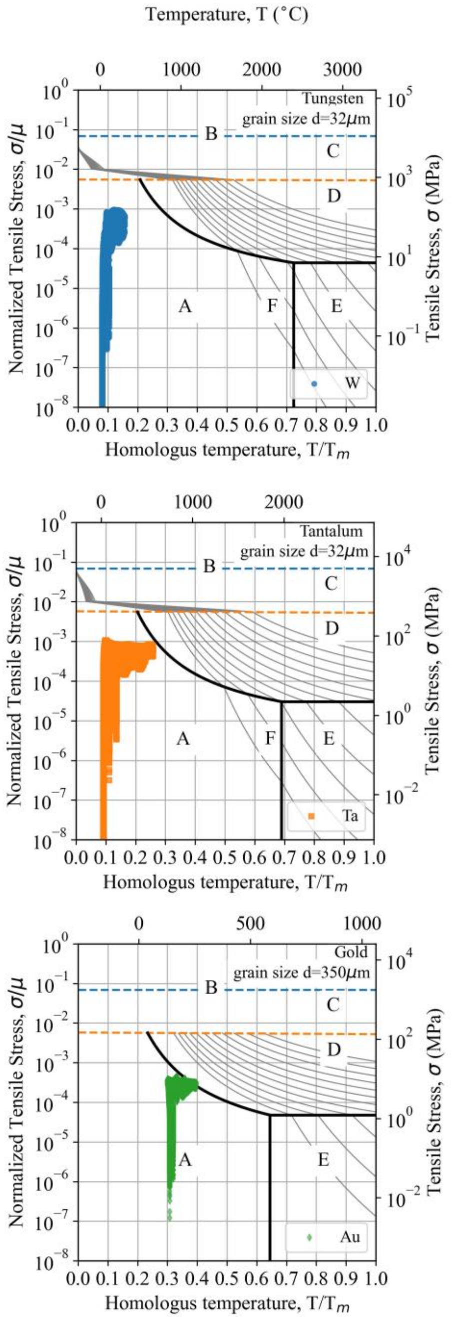


Fig. Temperature (left) and equivalent stress (right) distributions for W (top), Ta (middle) and Au (bottom) targets



Comments:

(a) W: **reference configuration**. The maximum thermal stresses are in the region above the peak temperature.

(b) Ta: **highest temperature** with **some plasticity** around the beam*.

(c) Au: **lowest temperature** with almost all the target working in plastic regime.

* This can be an artifact caused by the material model.

2.3 Alternative materials (3/3)

Summary:

- W: This option continues as the baseline design. Here, the target is expected to be working in the **elastic regime**.
- Ta: This option could potentially simplify the design as the same material for the cooling pipes and the target is used. In addition, machining Ta at room temperature is ductile.
- Au: The target is fully working in the **plastic regime**. More R&D work is needed to define the optimum parameters to join the stainless-steel pipes for cooling.
- For all models, the **thermal fatigue assessment** is required (ongoing) and the construction of prototypes are under consideration inside of the R&D program.

Fig. Selected candidate materials. Images' source: [periodictable.com]

2.4 HTS vs FC preliminary comparison (1/3)

Goal:

- To perform a comparison between the **HTS** (High Temperature Superconductive) Solenoid and the **FC** (Flux Concentrator) technologies for the target design from the thermo-mechanical point of view.

Main question:

- What is the impact on the target performance when increasing the beam parameters by a factor of **2.3***?

Model:

- HTS: baseline design
- FC: same thickness as HTS (17.5mm) and OD 37mm but without shielding and with updated parameters (see table)

Beam parameters

Parameter	HTS	FC	Ratio (FC/HTS)
Bunch charge, e-	1.3e10	3.0e10	2.3 ↑
Num. bunches	2	4	2 ↑
Frequency (Hz)	200	100	0.5 ↓
Beam power, kW	5.0	11.6	2.3 ↑

Table. Comparison between HTS and FC beam parameters

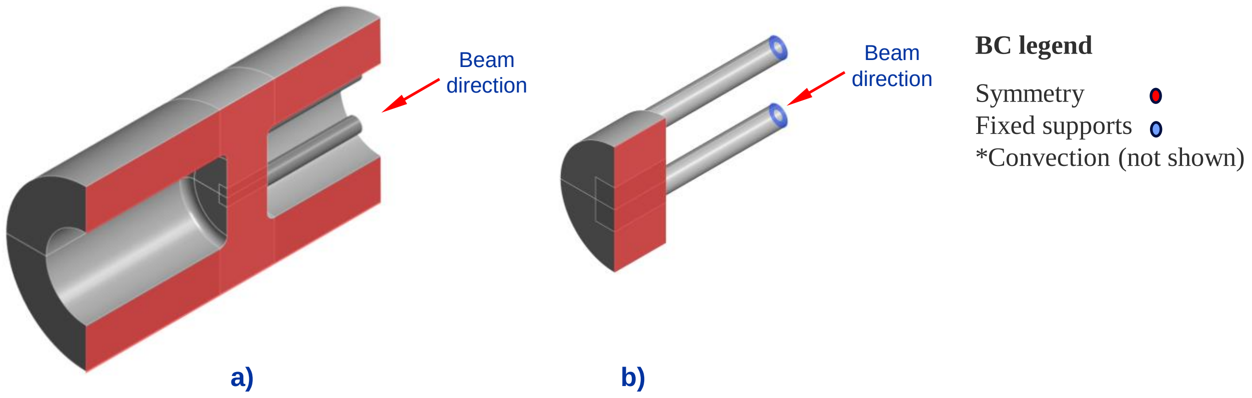


Fig. Model geometry and boundary conditions. a) For HTS and b) For FC configurations.

2.4 HTS vs FC (2/3)

Thermo-mechanical response (steady state)

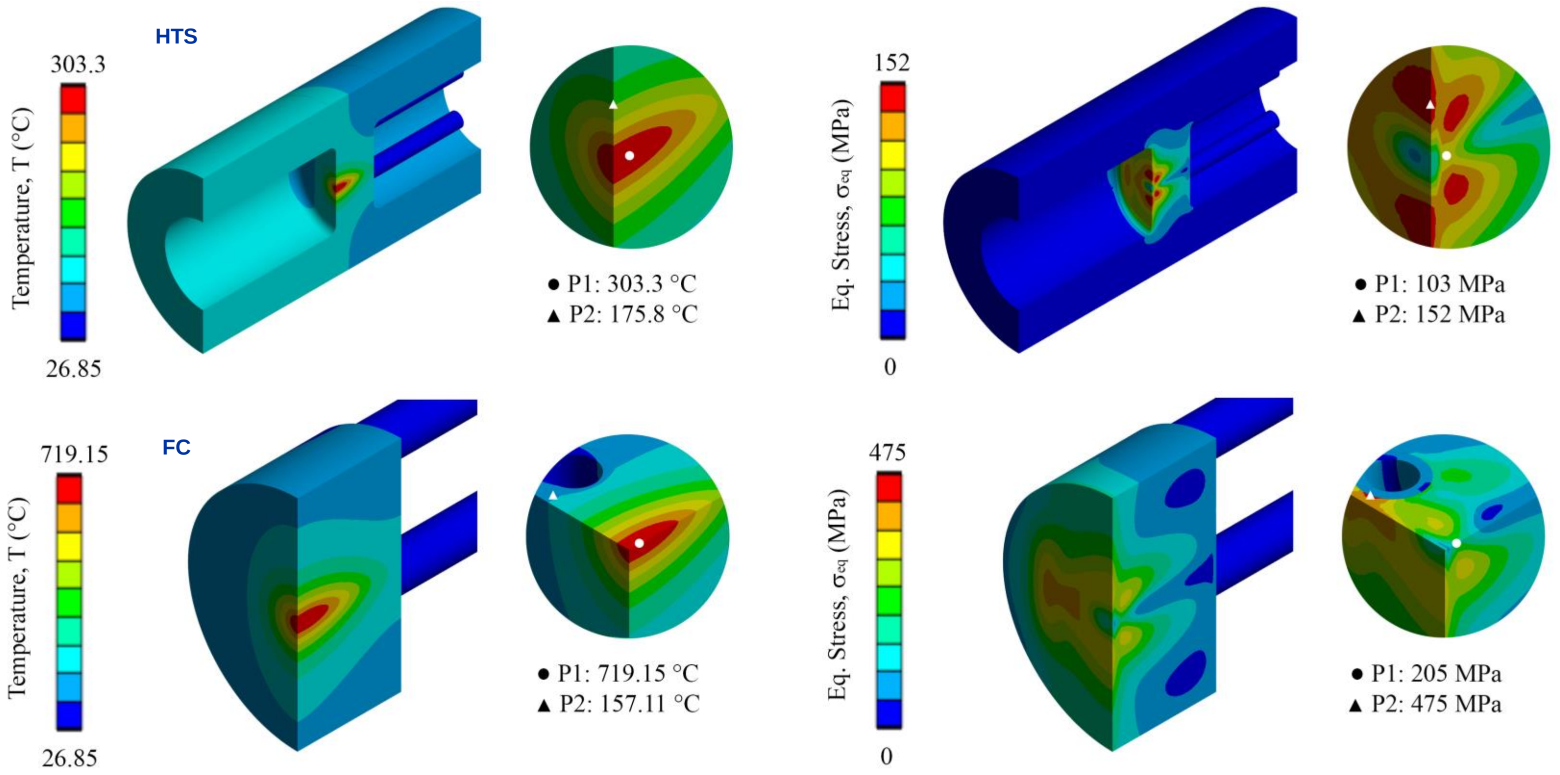


Fig. Temperature (left) and Equivalent Stresses (Right) distribution for the HTS (top) and FC (bottom) configurations

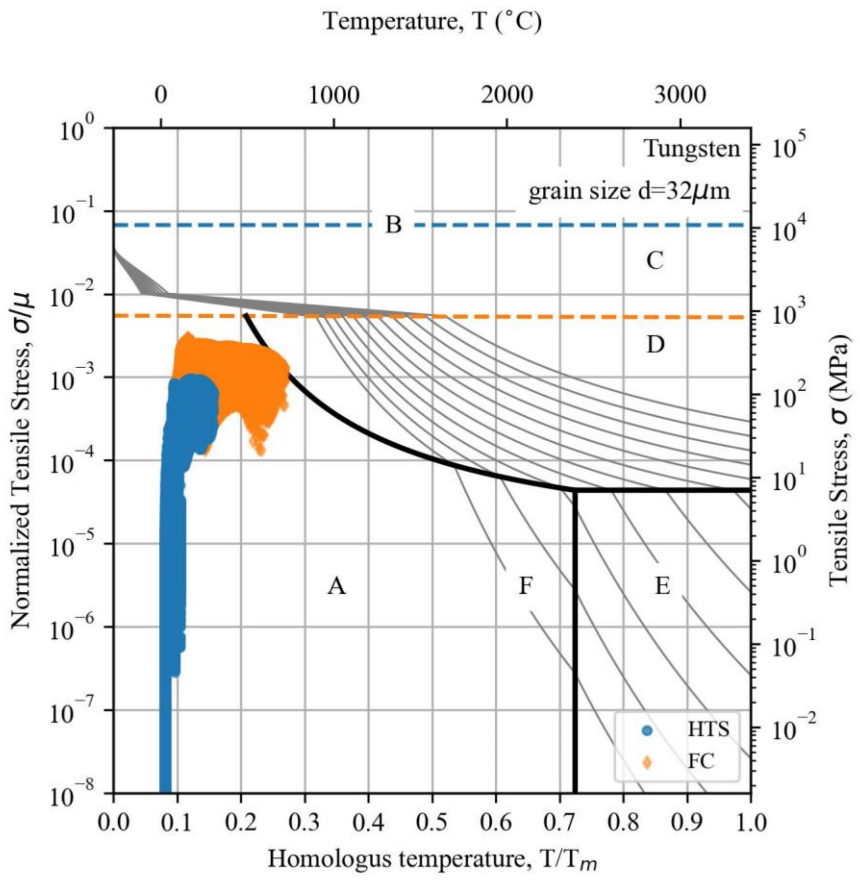


Fig. Deformation mechanism map for pure Tungsten and comparison on terms of temperature and equivalent stresses between the HTS and FC configurations.

HTS provides a feasible solution by using lower beam parameters and less demanding material conditions for the target.

5. HTS vs FC preliminary comparison (3/3)

- **Summary:**
- The **HTS** configuration reaches the **design requirements** with the use of a more **efficient beam parameters**. From the thermo-mechanical point of view, the target material works in the elastic regime below the DBTT.
- On the other hand, the **FC** configuration requires the use of a **more intensive e- beam parameters** (e.g higher number of particles and bunches with a reduction only in terms of frequency) to reach the required positron yield production. This option produces higher temperature and stresses in the target and for the 11.6 kW case, the use of a fixed target is close to its limit. In case a higher beam power is foreseen (e.g 20.2 kW for the FC KEK), the use of a movable target would be required.

2. FCC-ee positron source target: integration overview

2. Integration overview (1/2)

Goal:

To define the **integration** of the positron source target as a system w.r.t the surrounding equipment (e.g soleoind, beam pipe).

Requirements (non exhaustive list):

- Cooling system
- Positioning system
- Vacuum connection mechanisms
- Mobile shielding
- Handling system
- Installation and replacement

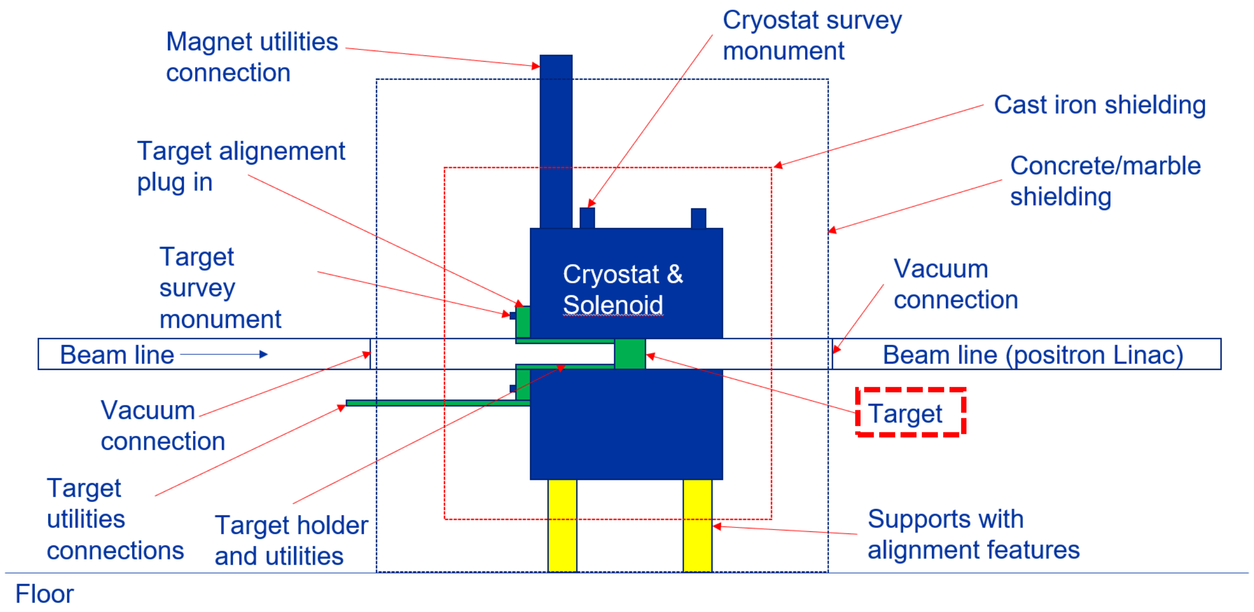


Fig. Target system integration scheme (draft)

2. Integration overview (2/2)

Some key considerations:

- **Remote handling should be part of the design and construction process**, especially when dose rate of key components will reach **tens of mSv/h** after irradiation.
- **Maintenance scenarios and unforeseen** operations shall be anticipated as much as possible.
- **Dismantling** of the overall infrastructure and **waste packaging** should be part of the initial design and **provisioned as part of the design and construction process.**
- Availability of the target systems (**downtime optimisation**) is a critical aspect which must be considered in the design of the facility.
- **Residual dose rate** in accessible areas shall be maintained within reasonable limits, as to allow technical teams to work “hands-on” (including infrastructure - not only on target systems).

3. P3 target: current status

3. P3 target: current status (1/2)

Context: The **PSI Positron Production (P3 or P-cubed) experiment** is developed inside the CHART Collaboration (PSI-CERN and others).

Goal: to design, build and test a prototype of the **positron source**.

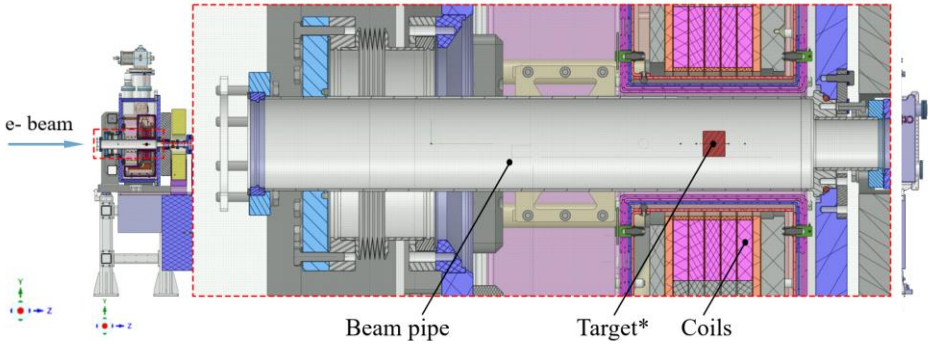


Fig. P3 experiment CAD model (without the target subsystem)

- **Requirements: P3 vs FCC-ee**
- Less demanding beam parameters*
  - Scaling factor → **1/4160**
  - Lower beam power
  - Minor thermo-mechanical loads and radiation damage
- **Design specification:**
- Cooling system is **not required**
  - However, it is an **opportunity** to carry out **manufacturing R&D** activities for FCC-ee

	FCC-ee	P3
Injection energy [GeV]	6	6
Beam size RMS [mm]	1	0.5-1
Repetition rate [Hz]	200	1
Number of bunches per pulse	2	1
Bunch intensity x e10 (nC)	1.3 (2.08)	0.125 (0.2)
Beam power (W)	5000	1.2
Average power on target (W)	1460	0.31

Table. Comparison between beam parameters for FCC-ee and P3

3. P3 target: current status (2/2)

P3 target holder design status

- Mechanical design:
  - Work done by **K. Guergar** and R. Seidenbinder
  - Bending radius Rb10 mm is included in the model.
  - Simplification of the operations of (des)installation.
- Manufacturing:
  - 4 x 2 target units without cooling available
    (W & Ta standard and W conical 0.5 and 1.0 mm)
  - 2D mechanical drawings under production
  - Expected delivering time: end of 2024
- R&D activities:
  - Manufacturing of target with cooling
  - Joining of Ta/Stainless steel
  - Testing of the target in an electron beam facility
  - Integration

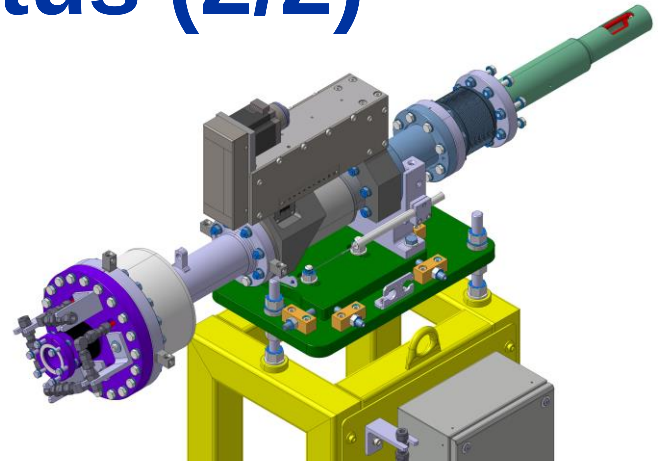


Fig. P3 target holder current status

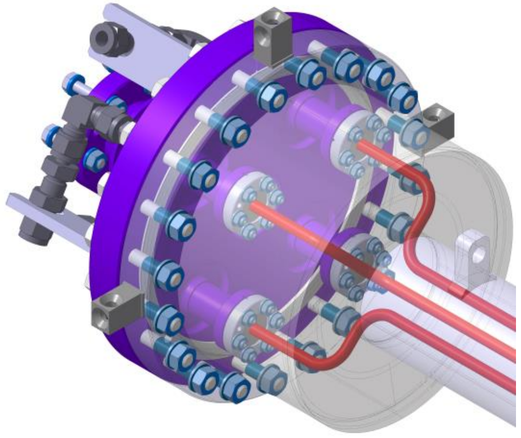


Fig. P3 target holder cooling pipes connection detail

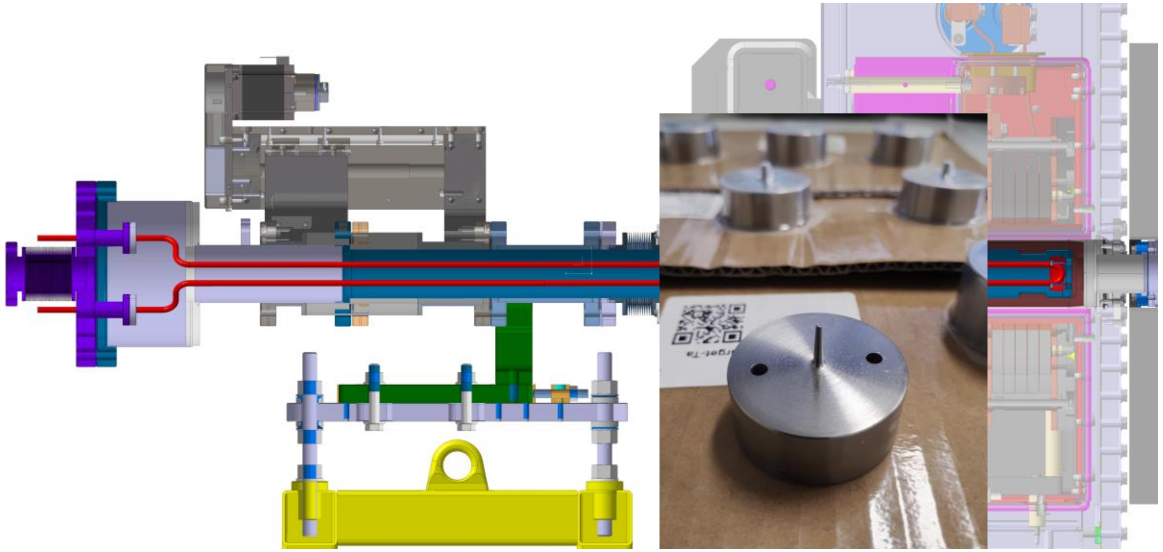


Fig. P3 target holder in and out position

4. Conclusions

4. Conclusions

- **Manufacturing considerations, non-standard geometries (x3), alternative materials (W, Ta, Au),** and **different technology configurations (HTS vs FC)** were analyzed for the FCC-ee positron source target. Their impact was evaluated in terms of temperature and stresses by using the current numerical model and with support of the deformation mechanism maps.

- A brief discussion on **integration requirements** was initiated. The message is that the interaction of the target as a system must be foreseen and included in the design loop.

- The **mechanical design of the P3 target system** was described. The P3 experiment plays a key role for FCC-ee to validate experimentally different concepts (e.g. target geometries and materials) as well as a source for valuable lessons to be extracted during its integration, operation and replacement.

5. Questions?

CHART Swiss Accelerator Research and Technology

CERN

FUTURE CIRCULAR COLLIDER

Backup slides

0. FCC Week 2023: recap (1/1)

Summary

(+) Mechanical design presented
from steady to fatigue assessment

(+) sigma 1.0 preferred instead of 0.5 mm

(-) simplified geometry (1/8)

(-) CFD based on previous iterations

(-) Cooling pipes are outside the target

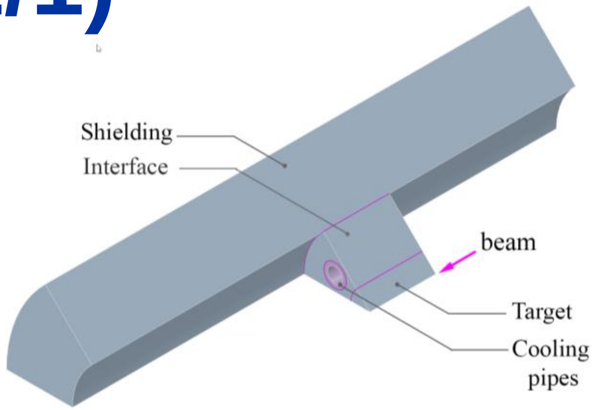


Fig. Model geometry: (1/8) sector

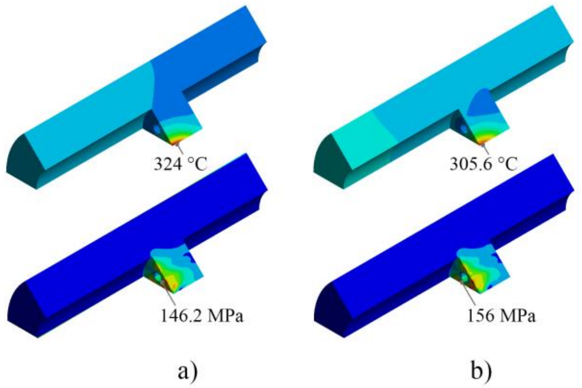
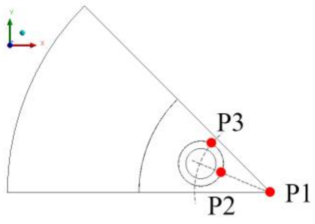


Fig. Temperature and Eq. Stresses for sigma a)0.5 and b) 1mm



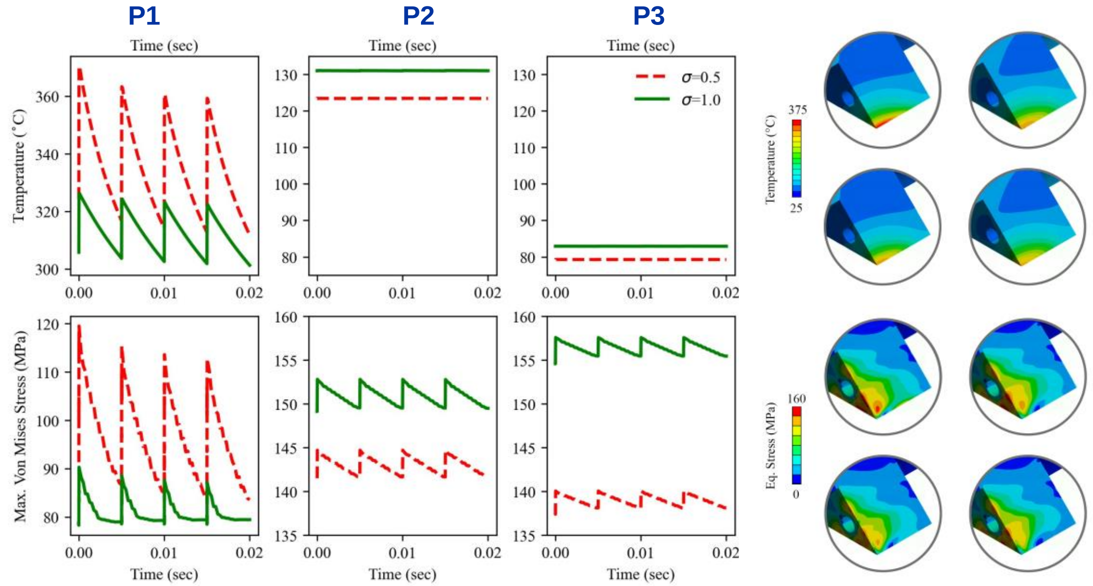


Fig. Temperature (top) and Eq. Stresses (bottom) at P1, P2 and P3 during 4 impacts

Next steps:

- Update the geometry to (1/2)
- Evaluate the impact of different positions for the cooling pipes
- Explore manufacturing options

2.4 HTS vs FC

Thermo-mechanical response (transient state)

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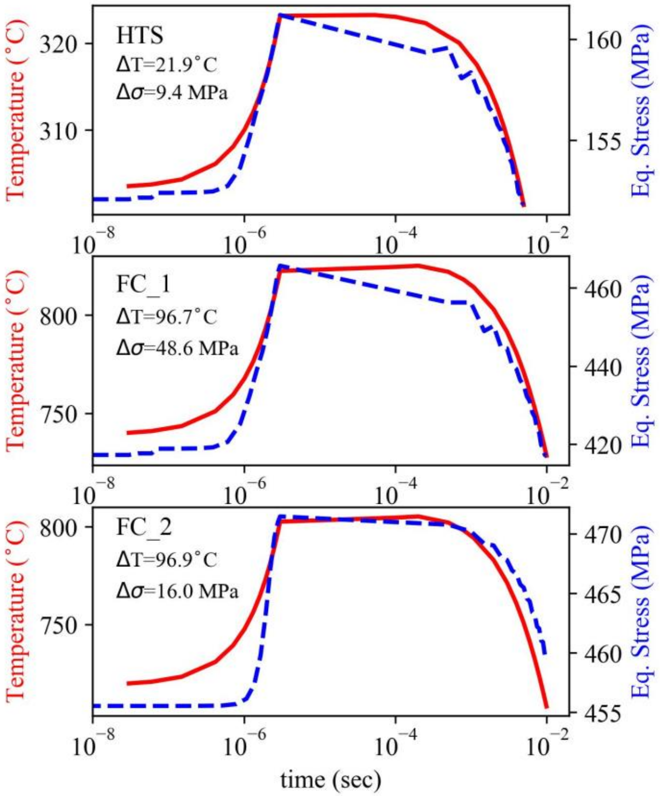

Fig. Maximum temperature and equivalent stresses during one single beam impact

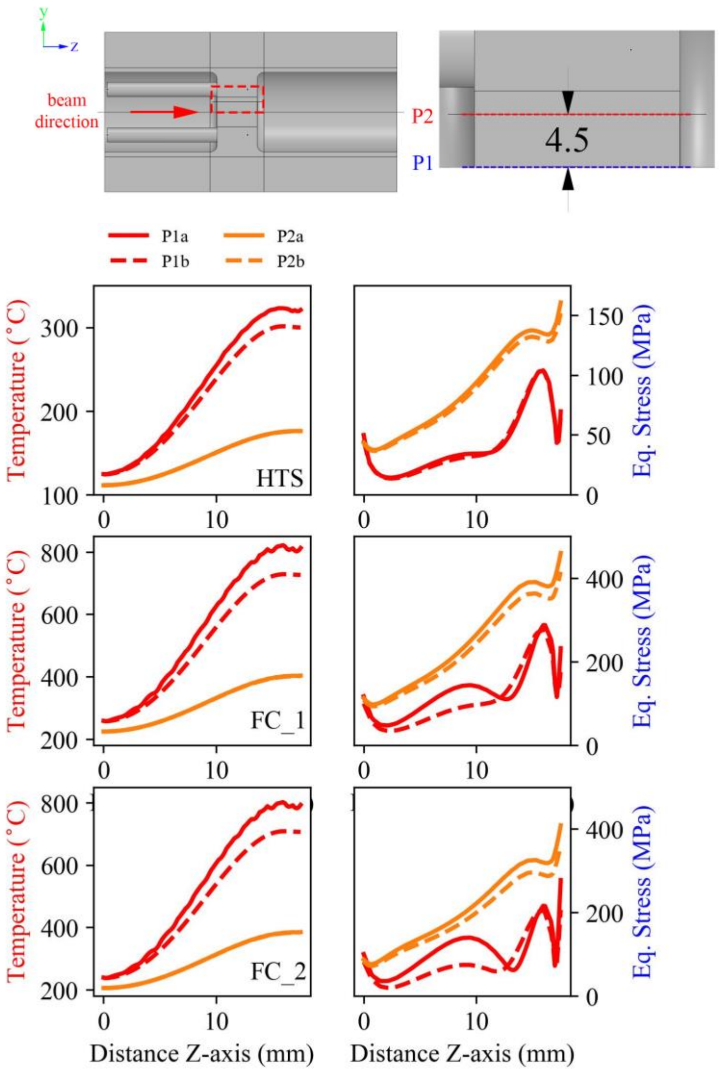

Fig. Temperature and equivalent stresses along the z-axis

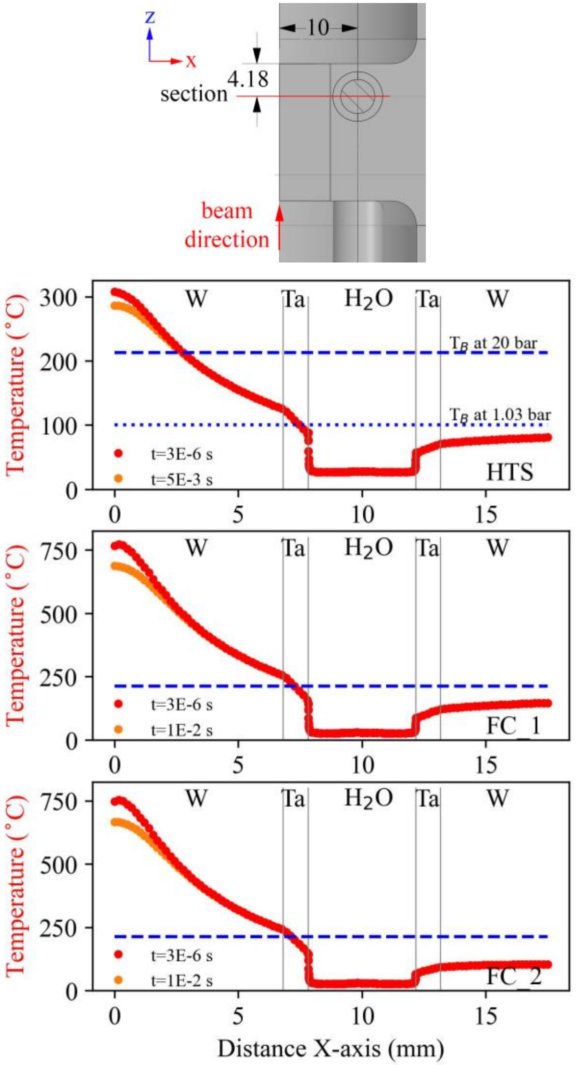

Fig. Temperature distribution along the x-axis at a fixed z location