Design of the FCC-ee positron source target: current situation and challenges

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

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Part I: Introduction

Introduction (1/4)

- **Main components of an electron-positron (e-e+) collider**

1. e-e+ production*
2. Acceleration
3. Pre-collision
4. Collision
5. Data Analysis

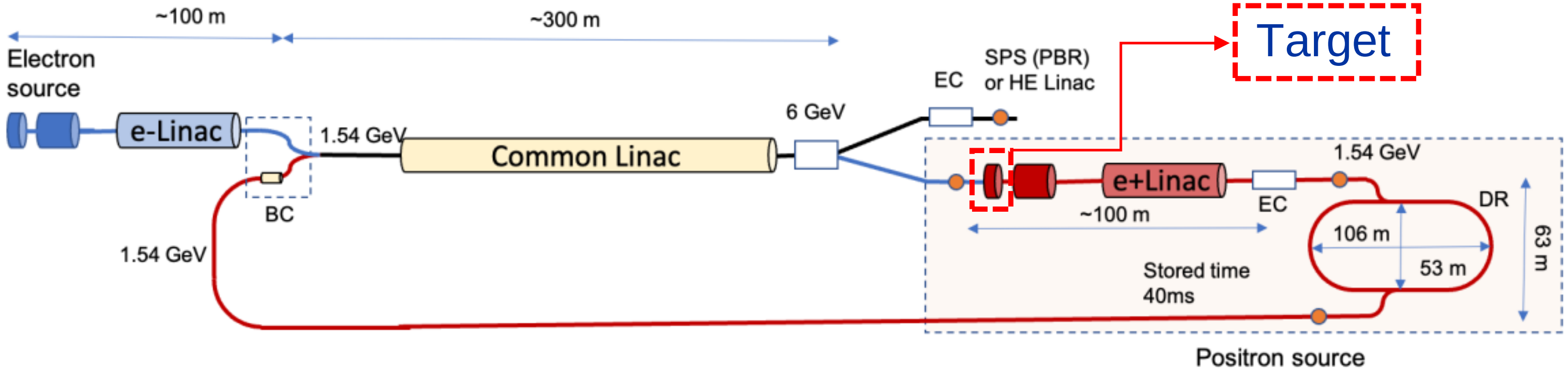
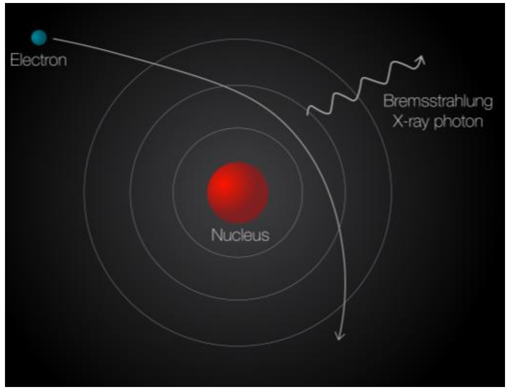
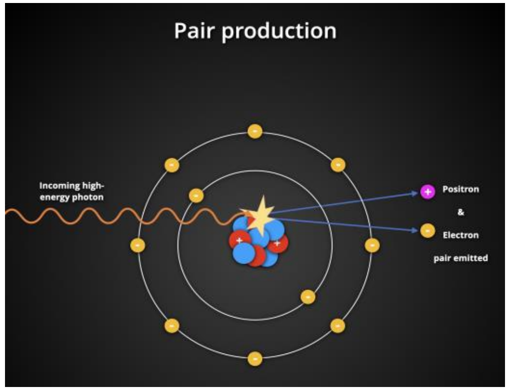


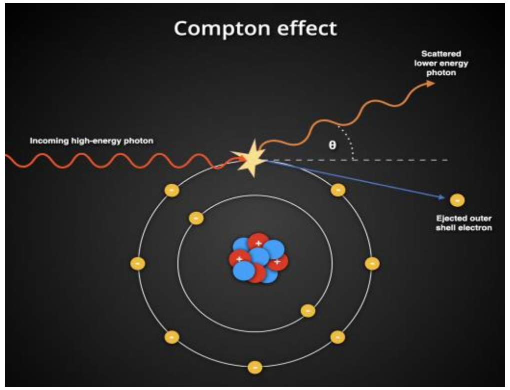
Fig. Layout of the FCC-ee injector complex. BC: bunch Compressor. EC: Energy Compressor.
[Craievich et al 2022]

Introduction (2/4)

- **How are positrons produced?**
- EN: By hitting a target made of a high Z-material with a high-energy electron beam.
- TH-EP: Involved mechanisms:
  1. Bremsstrahlung
  2. Electron-Positron pair production
  3. Compton Scattering







[radiopaedia.org]

Introduction (3/4)

- **Why the FCC-ee target is made of a high-Z material?**
- Because the electron-positron pair production cross section (σ) by gamma rays is proportional to the square of the atomic number Z.
- Possible options: Ta, W, Re
- Selected material: Tungsten W

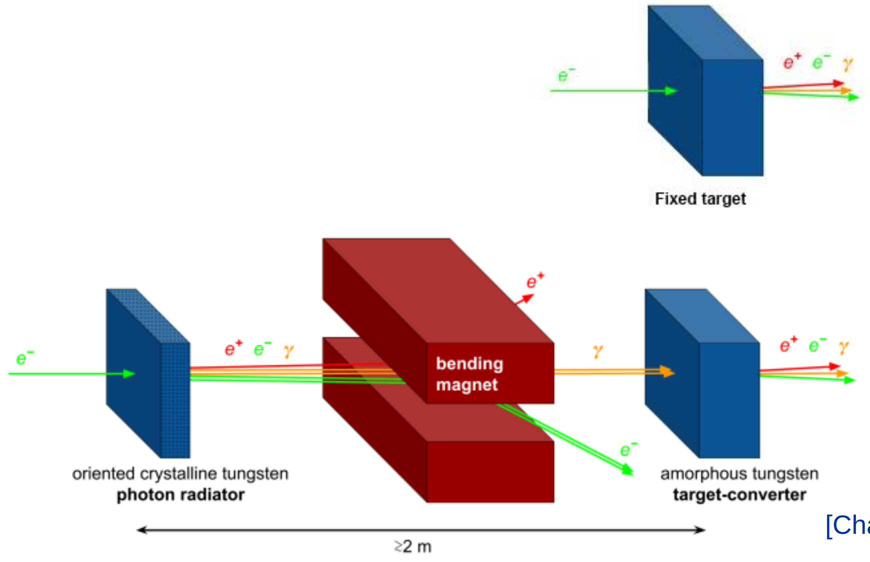
	Ta	W	Re
Atomic number	73	74	75
Melting point [K]	3258	**3695**	3459
Density [g/cm3]	16.654	19.25	21.02
Radiation length [mm]	4.09	3.50	3.18

Table. Physical properties of materials used in positron-production targets. [Enomoto et al 2021]

Introduction (4/4)

- **Which design options does the FCC-ee positron source target have?**

1. Fixed target (standard)*
2. Hybrid target (crystal + converter)
3. Moving target (trolling or rotating)



[Chaikovska et al 2022]

Part II: FCC-ee positron source target design

Target design: main parameters

Electron drive beam	6 GeV	6 GeV	6 GeV
Assumption	Max. intensity, which can be delivered by e- linac	13.5 nC e+ bunch charge at the entrance of the damping ring	
Beam size	0.5 mm RMS	0.5 mm RMS	**1.0 mm RMS**
Repetition rate	200 Hz	200 Hz	200 Hz
Bunches per pulse	2	2	2
Bunch intensity (filling)	3.47E10 (**5.56nC**)	1.205E10 (**1.93 nC**)	1.30E10 (**2.08 nC**)
Beam Power	**13.34 kW**	**4.63 kW**	**5.00 kW**

Old parameters (2022)

Current parameters (2023)

Source: [Chaikovska 2023]

Target design: P3 experiment* at PSI

- **Collaboration between CERN and PSI (FCC-ee – CHART)**
  - The goal is to have the same (or a similar) target design as for the **P3** proof-of-principle **experiment***
  - CERN (SY-STI-TCD) to design and build the P3 target (to be installed in April 2025)
- **For the moment, the FCC-ee target design studies focused exclusively on the HTS AMD**
  - As boundary condition for FCC-ee, we consider the same vacuum chamber aperture as for P3 (**72 mm**)
- **Target design vs positron yield:**
  - As a baseline, we consider a **17.5 mm** long W target, according to the e^+ yield optimization studies by Y. Zhao et al. (CERN)
  - As an alternative, we study the thin-rod design proposed by **N. Vallis et al.** (PSI)

***See details in Paolo Craievich's poster**

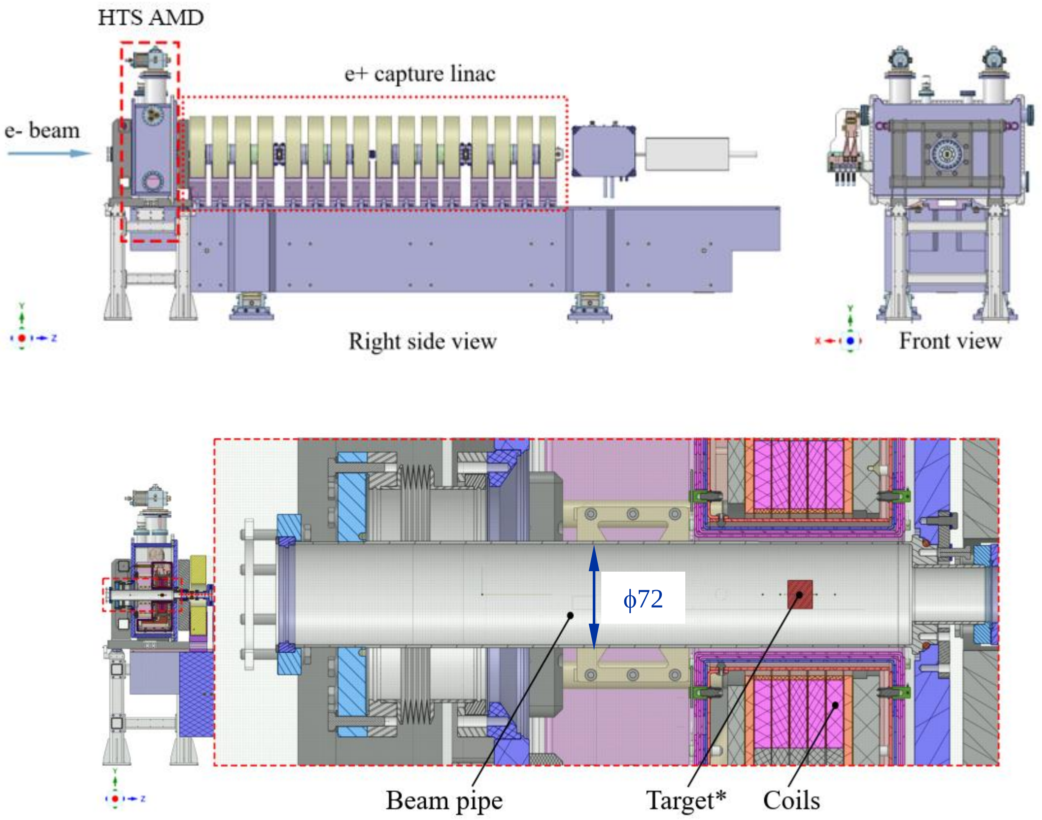


Fig. P3 experiment CAD model (top) general view and (bottom) cross section. [Courtesy of PSI]

Target design: geometry

Model properties

Effective radius r=5 mm

Thickness t=17.5 mm

Beam sigma 0.5 vs 1 mm

Material: pure W

Cooling system: Ta pipes

Cooling fluid: water (u=5m/s, P=20bar)

Estimated htc = 18 kW/m2K

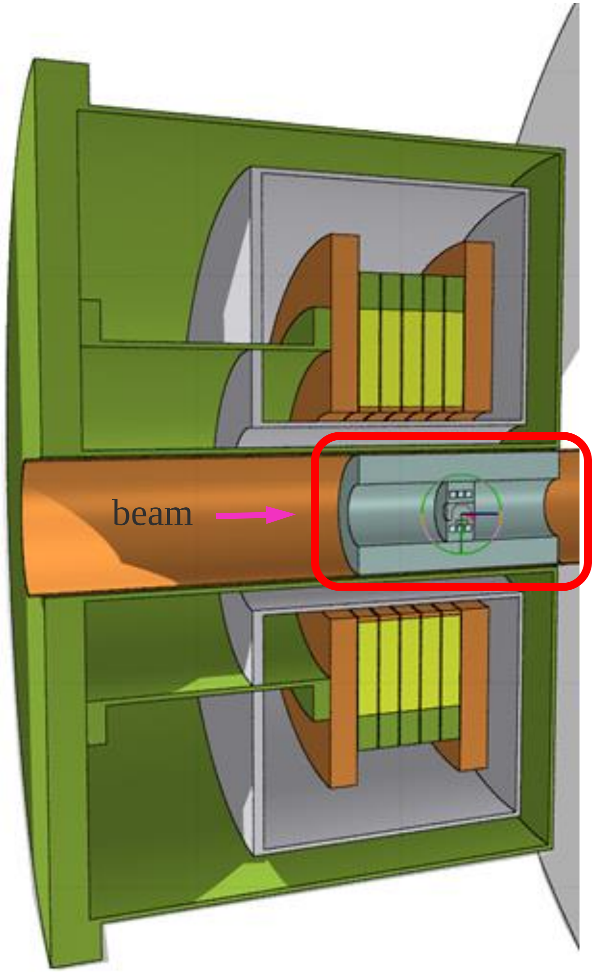


Fig. Simplified geometry of the High-Temperature Superconducting (*HTS*) solenoid Adiabatic Matching Device (AMD) and location of the target

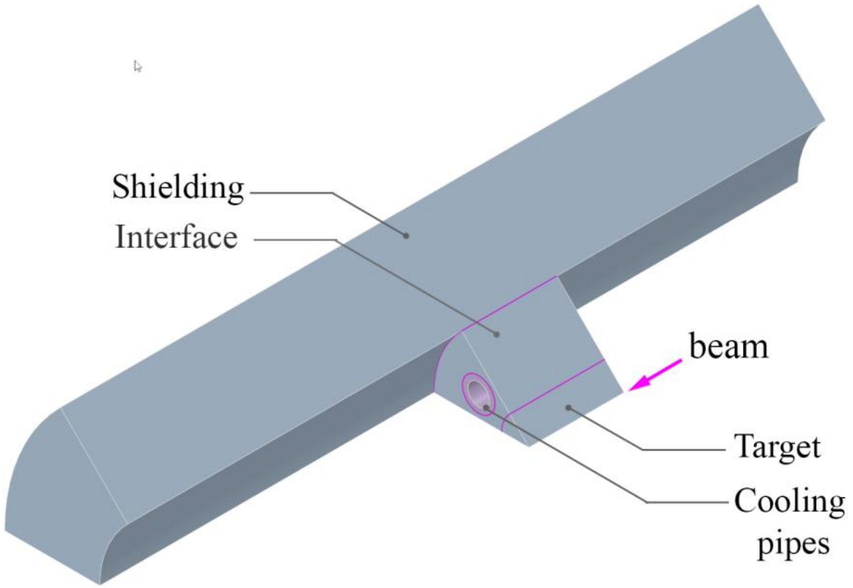


Fig. Geometry of the target (1/8 sector) model

Target design: power load distribution

Assuming e- drive beam power of 5 kW

@Z-pole

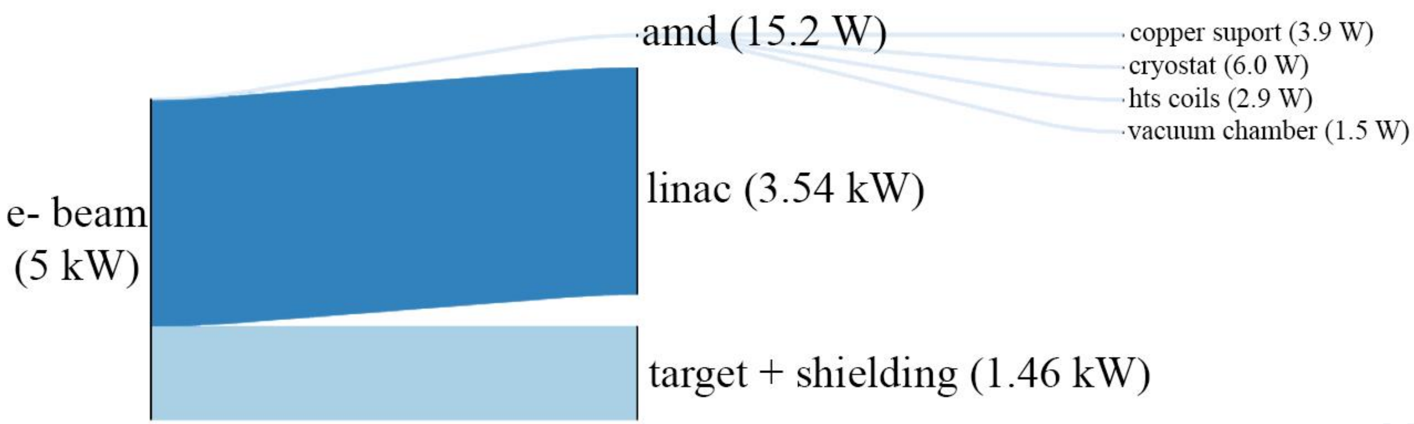


Fig. Sankey diagram of the power load distribution for sigma=1.0 mm

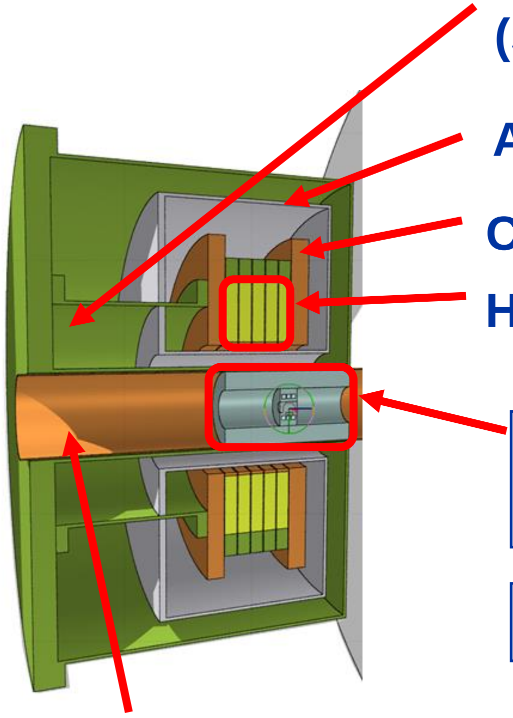


Fig. Power distribution between components for sigma=1.0 mm

Power load on AMD (in particular HTS coils) should be acceptable

Target design: power deposition maps

e- beam scenarios

a) Previous configuration: σ = 0.5 mm

- (-) power concentrated in a tinny volume fraction
- (-) challenging conditions for the material

b) Current configuration: σ = 1.0 mm

- (+) level of power density is reduced
- (+) improved condition for the material

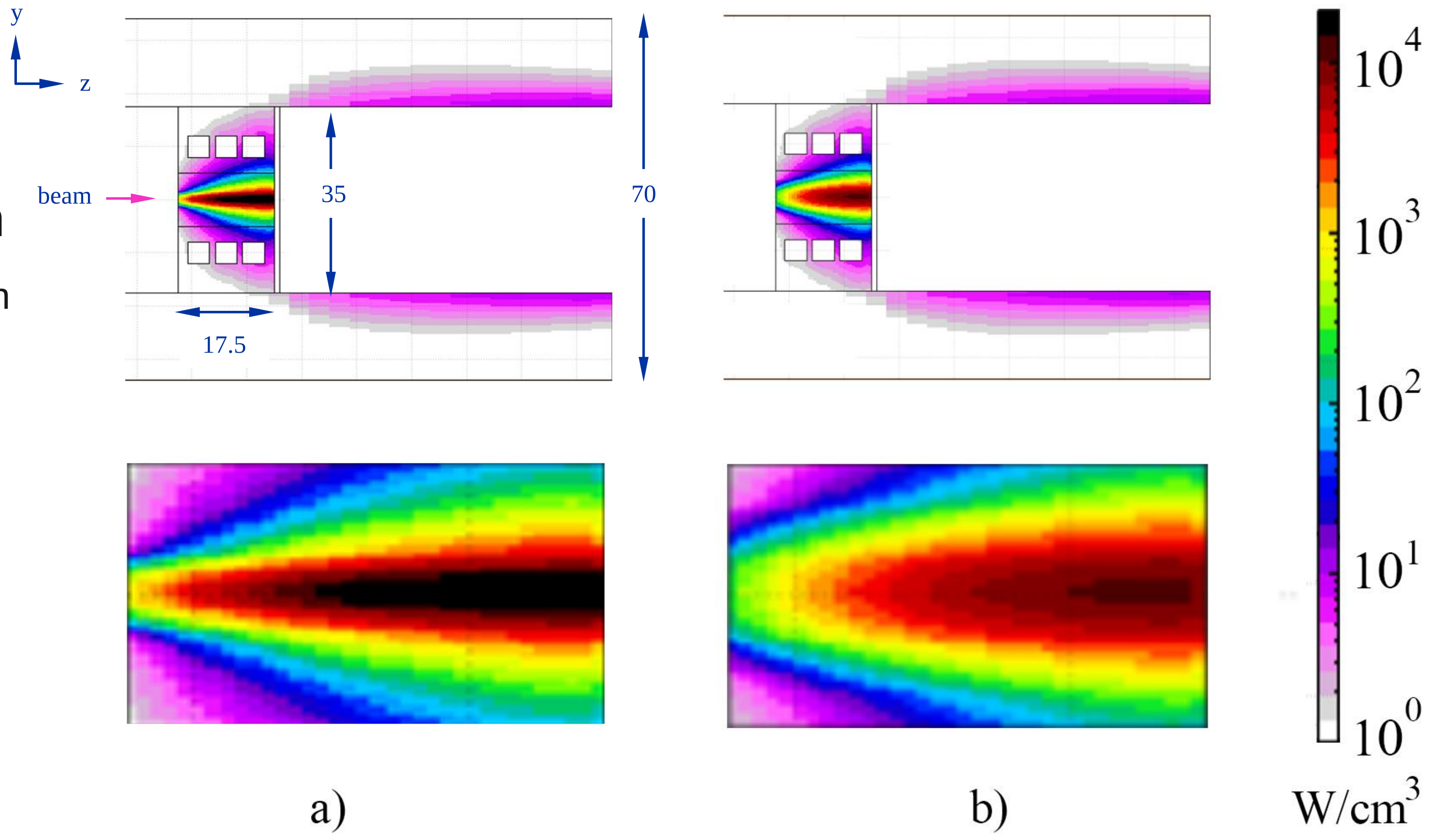


Fig. Power deposition maps for a) σ=0.5 and b) σ=1

Target design: thermo-mechanical analysis (1/3)

Steady state analysis

when moving from a beam size of 0.5 to 1.0 mm:

- there is a reduction of the peak temperature (324 °C → 305 °C). However, a bigger portion of the target is heated and as a consequence, there is an increment in the thermal stresses at the cooling pipes interface (146 → 156 MPa)
- For tungsten, its ductile-brittle transition temperature (DBTT) is 400-650 °C [Palacios et al. 2013]
- As T_{max} < DBTT, tungsten works in **brittle regime**

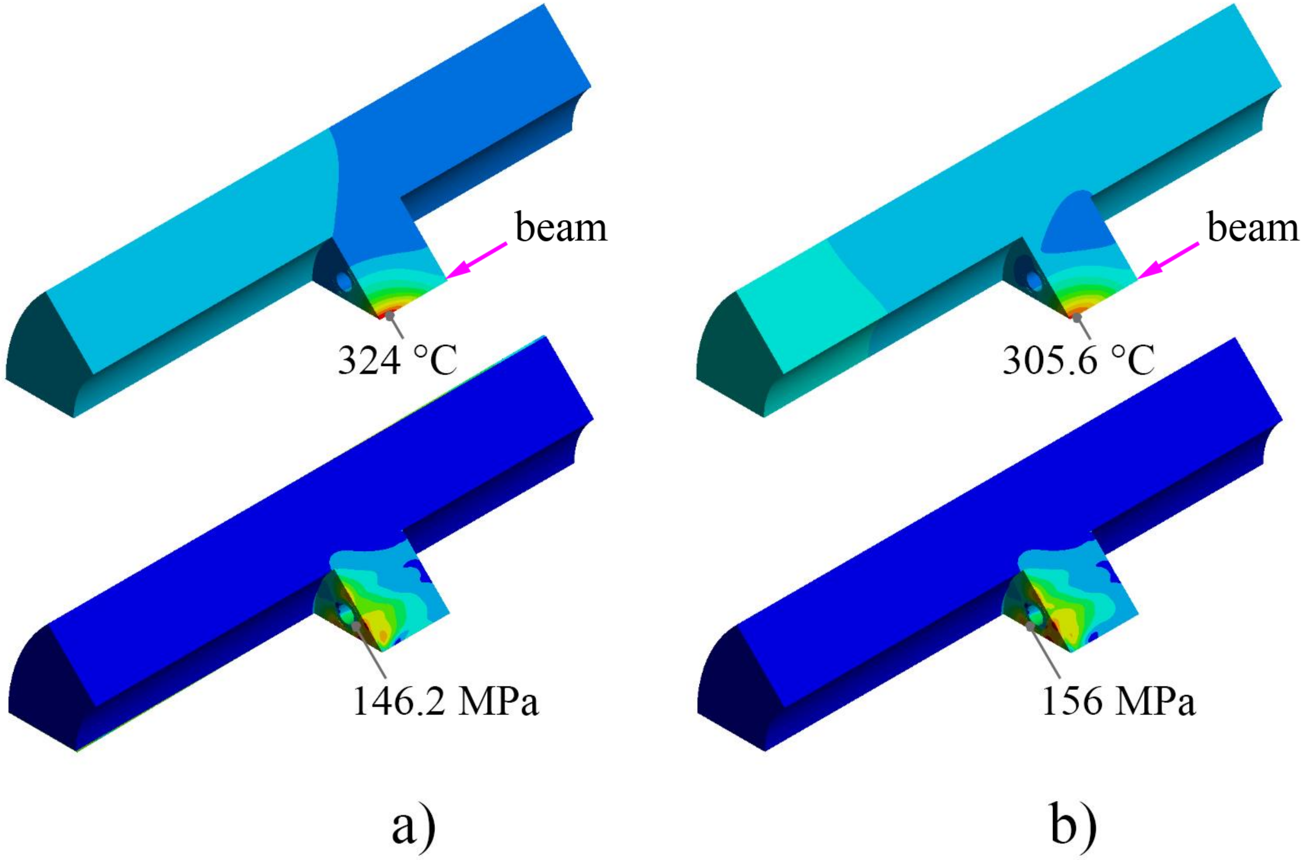
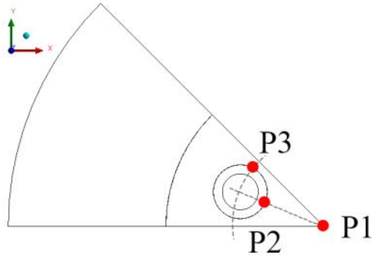


Fig. Temperature and Equivalent Von Mises stress distribution for a) sigma 0.5, b) sigma 1.0

Target design: thermo-mechanical analysis (2/3)

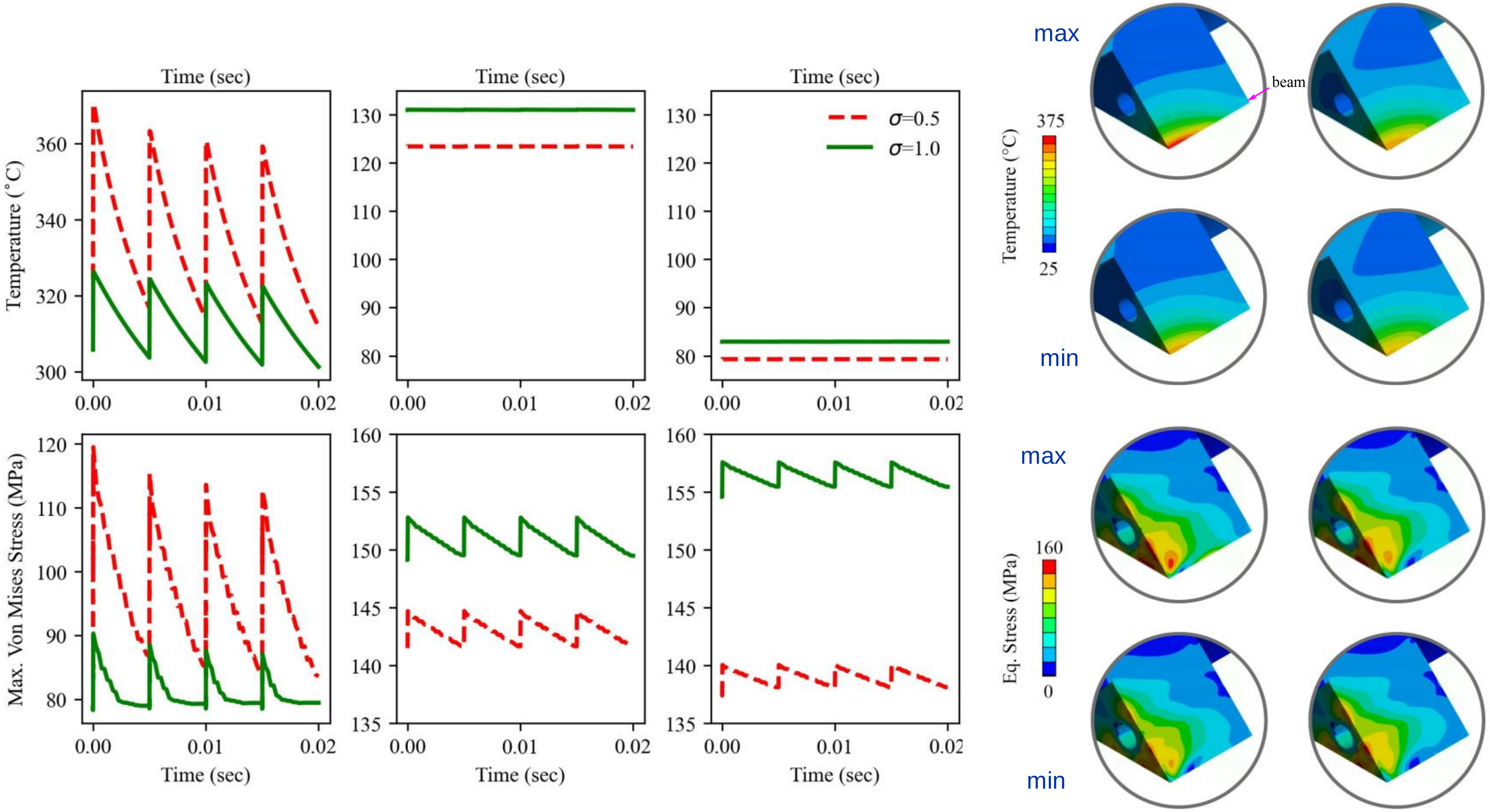
Transient state analysis

3 zones of interest: Pi, i=1,2,3



when moving from a beam size of 0.5 to 1.0 mm:

- The reduction in peak temperature at P1 (from ∆T = 58.5 °C to ∆T = 24.9 °C) is translated to a reduction in stress amplitude too during the thermal cycle of impact and cooling.
- However, although the temperature at P2 and P3 remains almost constant, there is an increment in stresses (counterintuitive)



P1 P2 P3

a) b)

Fig. Maximum temperature and Von Mises Stresses evolution in time for a) σ=0.5 and b) σ=1

Target design: thermo-mechanical analysis (3/3)

Transient analysis

- First assessment of thermal fatigue:
  - For a **brittle material**, we are mainly concerned on the variation of tensile stresses, therefore, we focus on **σ_1.**

$$\sigma_m = \frac{1}{2}(\sigma_{max} + \sigma_{min}) \; ; \; \sigma_a = \frac{1}{2}(\sigma_{max} - \sigma_{min}) \; ; \; R = \frac{\sigma_{min}}{\sigma_{max}}$$

σ = 0.5	P1	P2	P3
σ_1 max	127.7	119.9	27.9
σ_1 min	91.4	117.1	27.7
σ_m	109.6	118.5	27.8
σ_a	18.1	1.4	0.1
R	0.72	0.98	0.99

σ = 1.0	P1	P2	P3
σ_1 max	93.7	126.1	30.1
σ_1 min	76.3	122.9	29.9
σ_m	85.0	124.5	30.0
σ_a	8.7	1.6	0.1
R	0.81	0.97	0.99

Table. Mean and alternating stresses σ_m and σ_a for beam sigma 0.5 and 1 mm. Values in MPa, except for R.

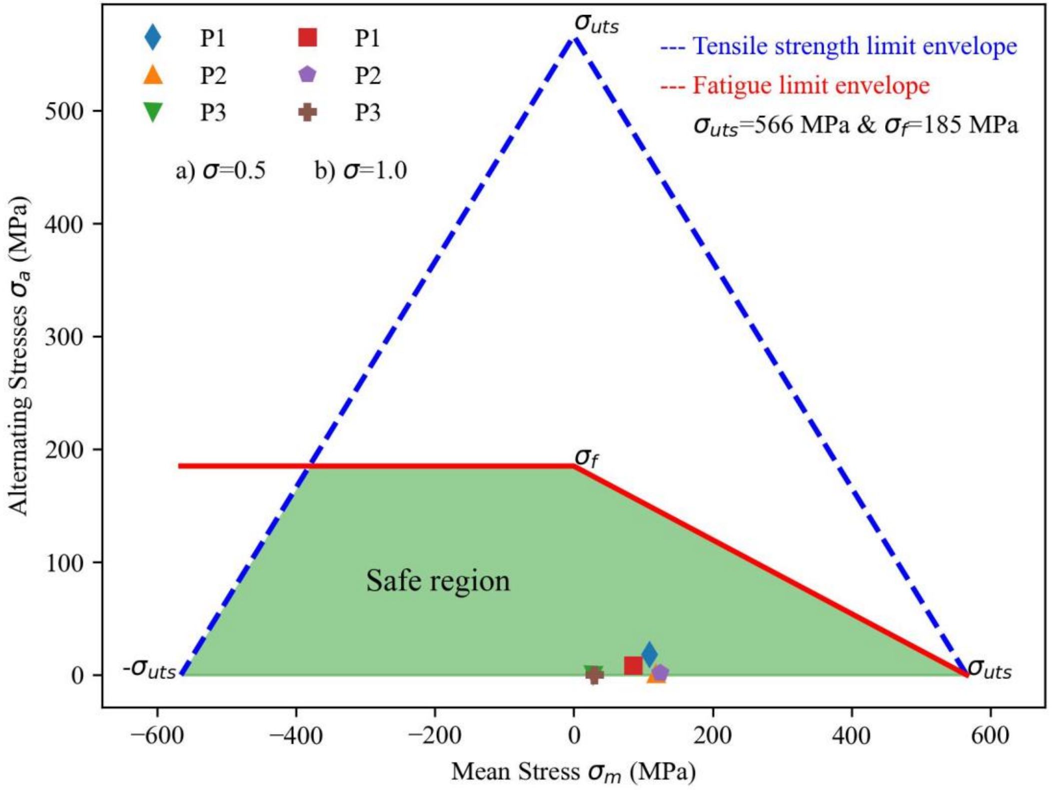
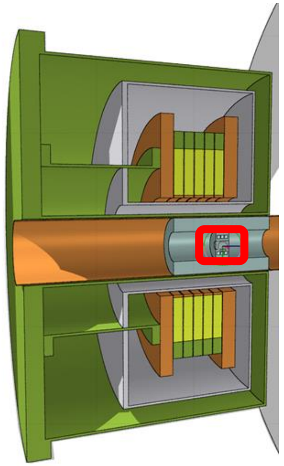


Fig. Goodman diagram for the FCC-ee target.
Note: Tungsten material properties taken from Enomoto et al 2021.

- Next step, to consider a mutiaxial fatigue criteria…

Target design: power density and DPA (vs e- beam σ)

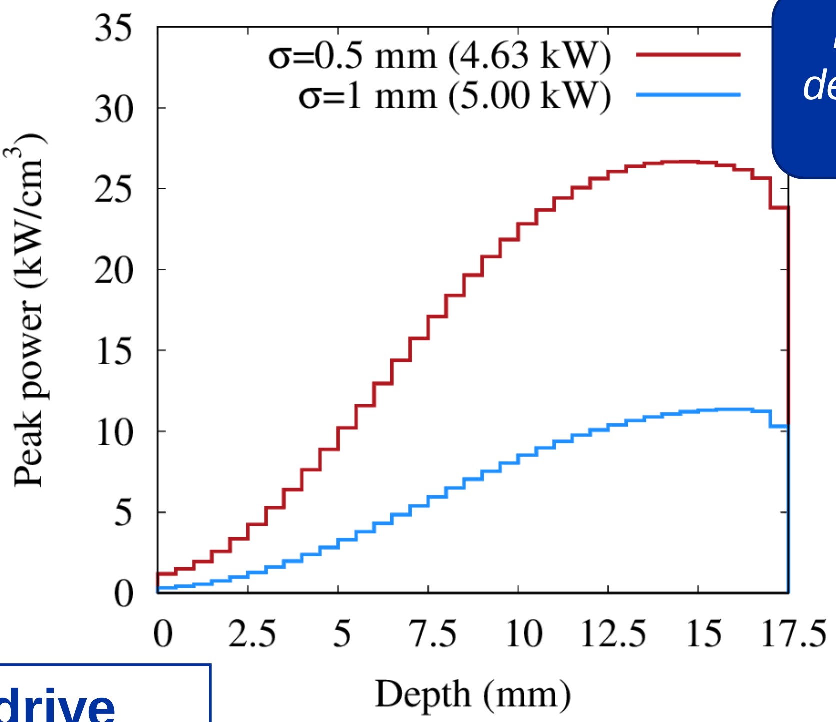


- With σ=1mm, Peak power density of **12 kW/cm³** at Z pole (**26 kW/cm³ for** σ=0.5 mm)
- With σ=1mm, about **1 DPA/yr** at Z pole (**3 DPA/yr for** σ=0.5 mm)

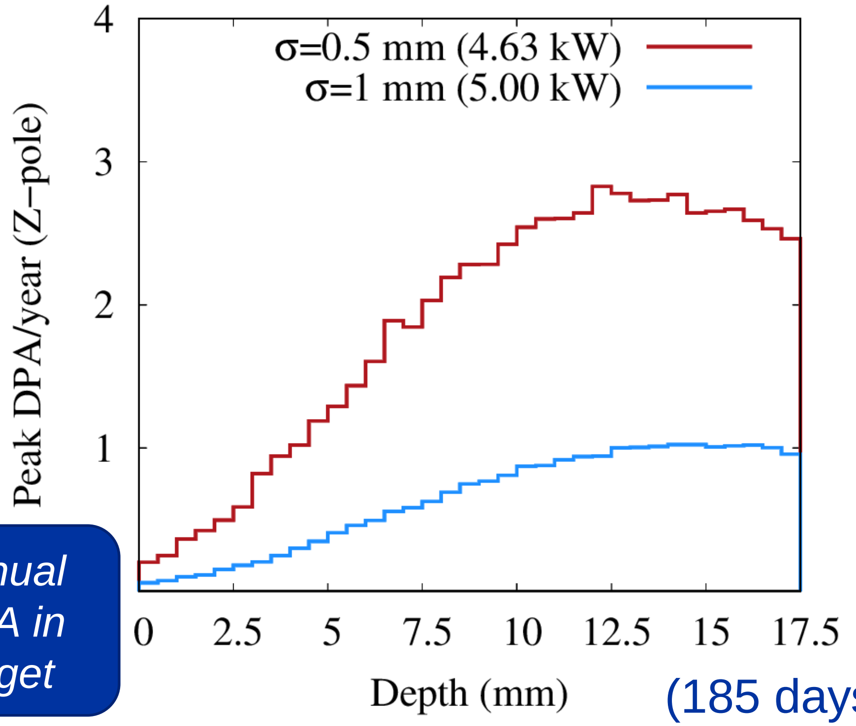
DPA → Target survival and frequency of target exchange to be assessed

@Z-pole

Power density in target



Annual DPA in target

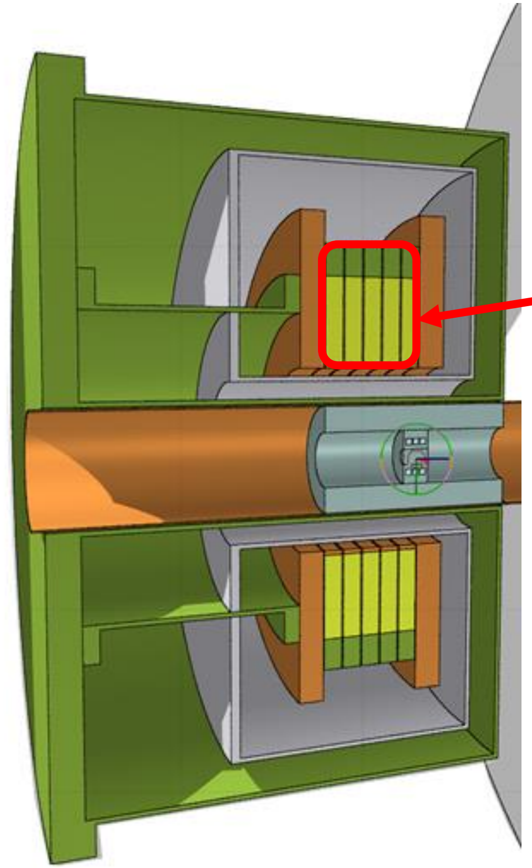


(185 days/year)

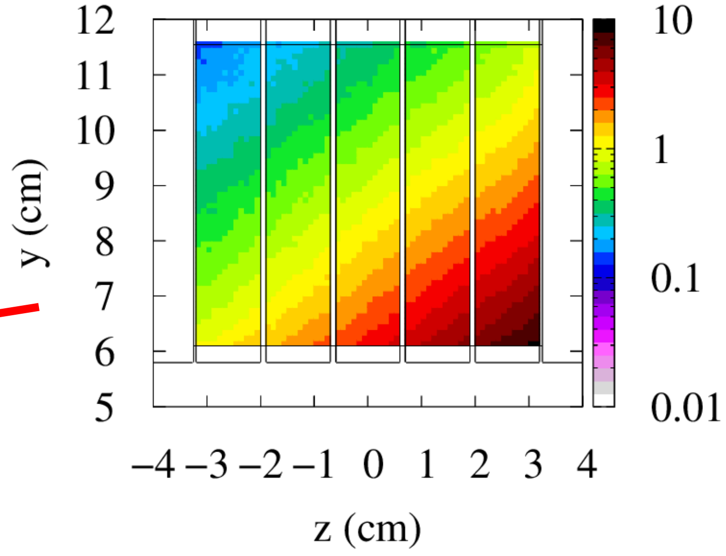
Assuming e- drive beam power of 5 kW

Target design: radiation load to HTS coils

In general, no showstopper, but
shielding design to be further optimized

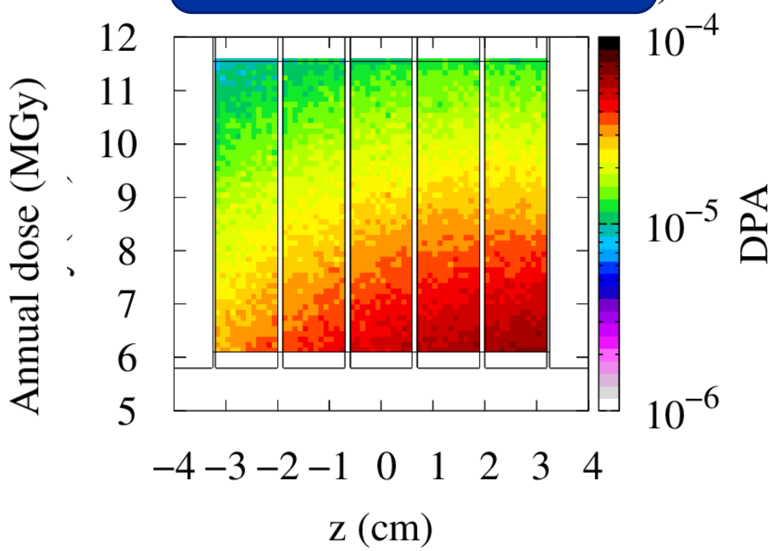


Cumulative dose in coils
(one year at Z-pole)



Up to **8MGy/year**

DPA in coils
(one year at Z-pole)



Up to **8E-5 DPA/year**

@Z-pole
(185 days/year
5 kW e- beam power)

DPA likely acceptable (with annealing cycles)
Limits for ionizing dose to be understood (if any)

Summary

- After several iterations, the current **beam parameters** provide a solid baseline for the design of the FCC-ee positron source target.
- A target made of pure tungsten now is a **feasible option.** The thermo-mechanical studies show values of temperature and stresses inside of the safety limits of tungsten.
- As a next step, a **R&D test campaign** is foreseen to evaluate different manufacturing options for the target and the hipping of the tubes for the cooling system.
- The **design of the P3 target** is ongoing and it is a key factor to study the performance in terms of positron yield inside of the P3 experiment.

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