Design and study of the 8kW Diagnostic Box for the SPES proton beam line

Alberto Monetti

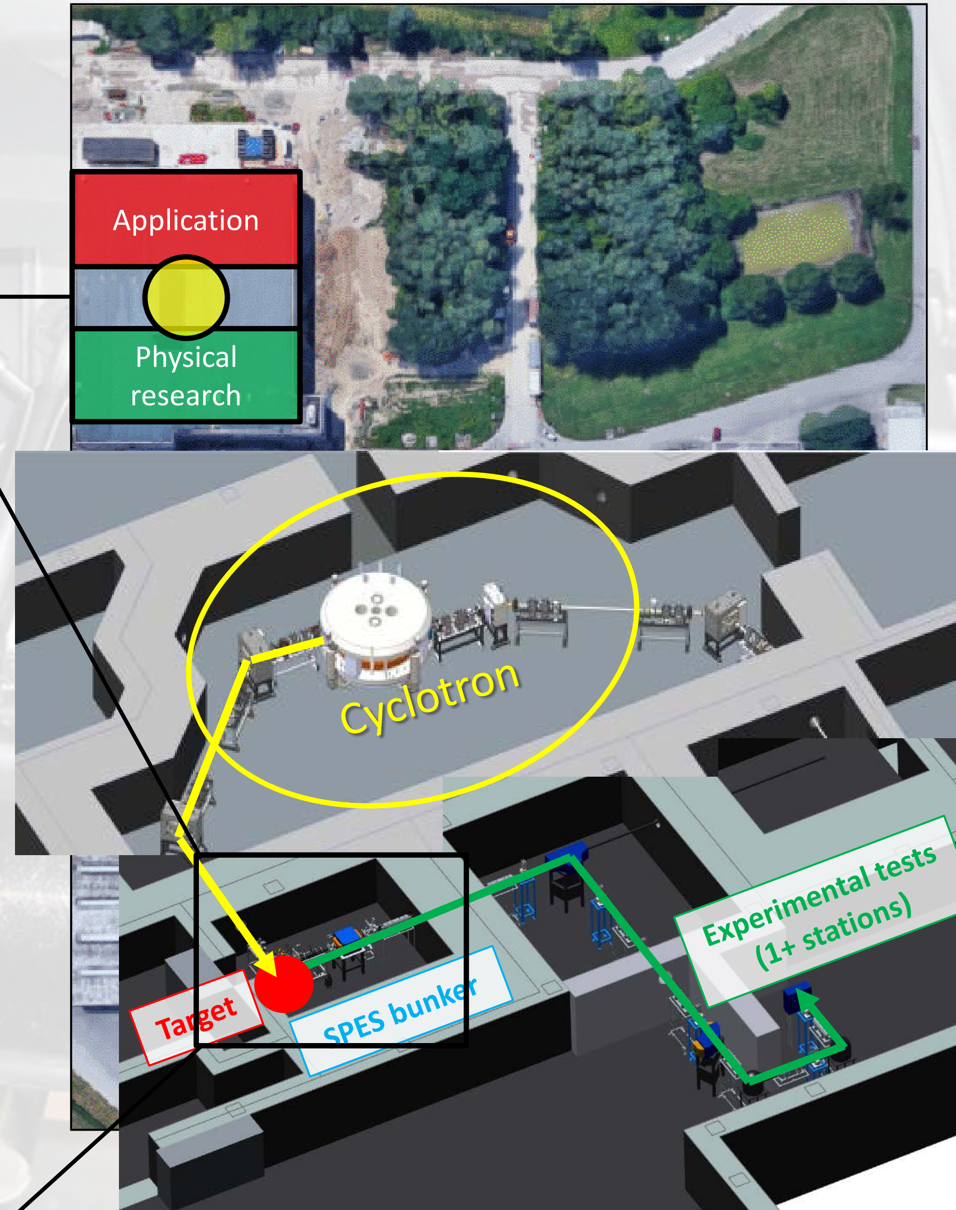
for the SPES target group

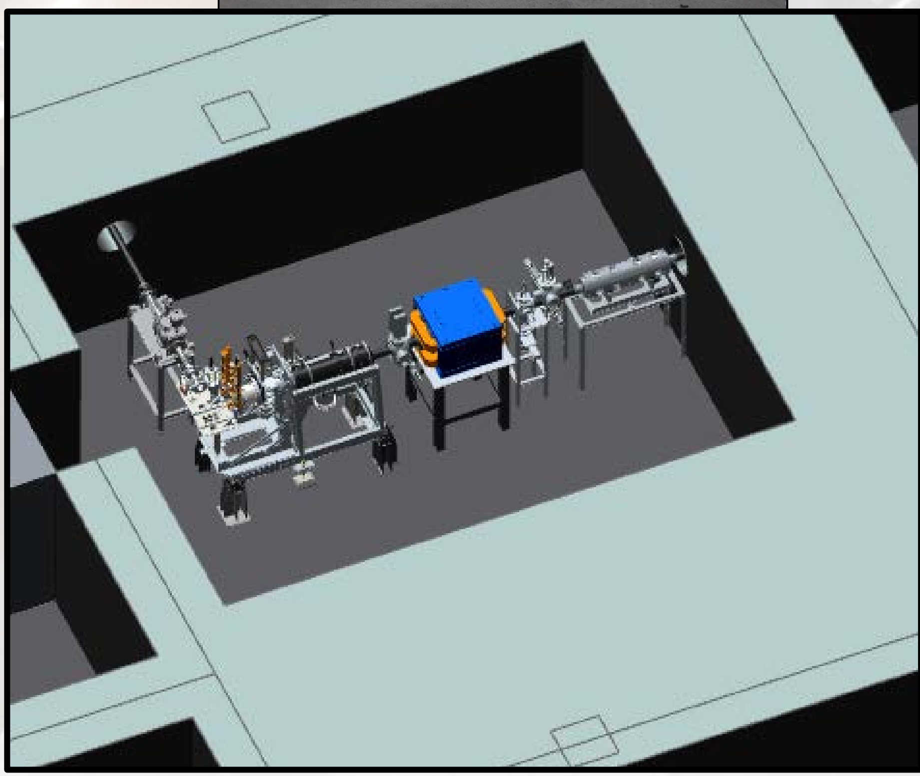
Friday, September 22, 2017

Outline

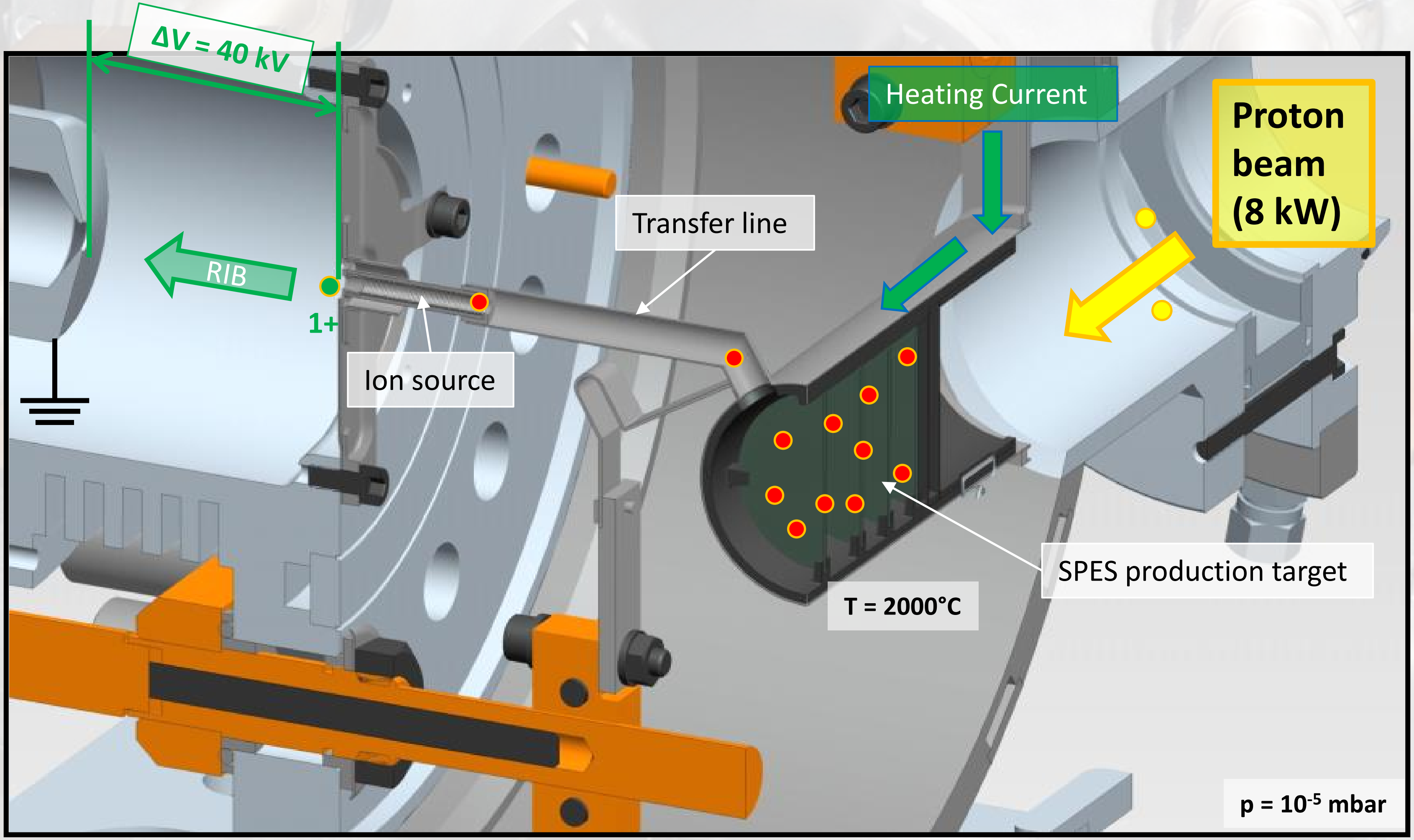
- Introduction – SPES project
- The SPES target requisites to operate
- The proton beam diagnostic inside the production bunker
  - Collimators
  - Proton Beam Faraday Cup
  - Proton Beam Profiler
  - Nuclearization steps undergoing
- Conclusions

The SPES project





The core of the facility: the Target



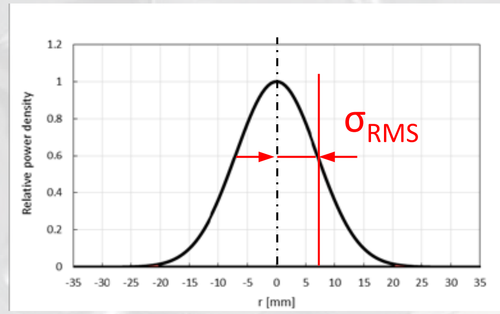
The new study on the SPES target

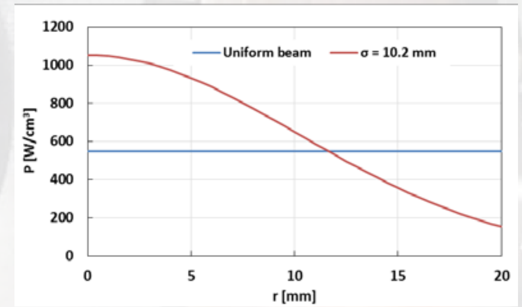
Few rules to respect:

1. The proton beam current has to be as high as possible
2. The temperatures and stresses have to be lower than the limits

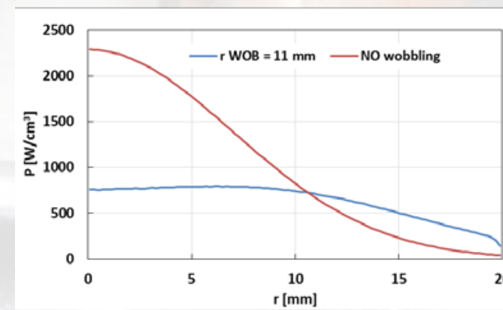
Sharp & powerful proton beam → High power density → High temperatures and stresses

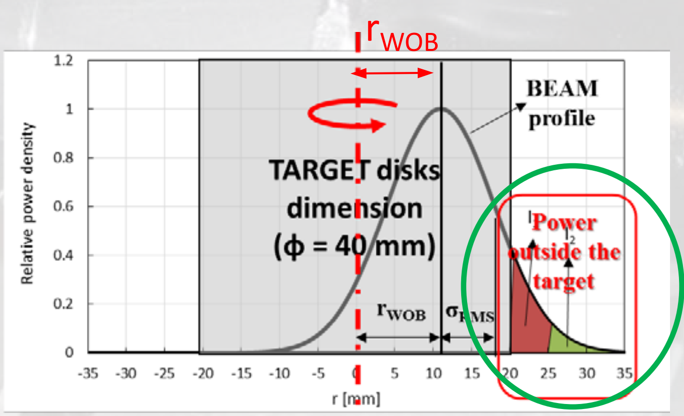
The beam can be assumed with a Gaussian profile →





To get lower temperature & lower stresses → Rotation of the beam along its axis (“**wobbled**” beam)



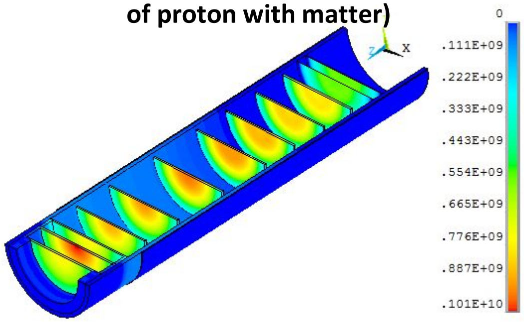


Preliminary evaluations fix the amount of power out the target to **15%**

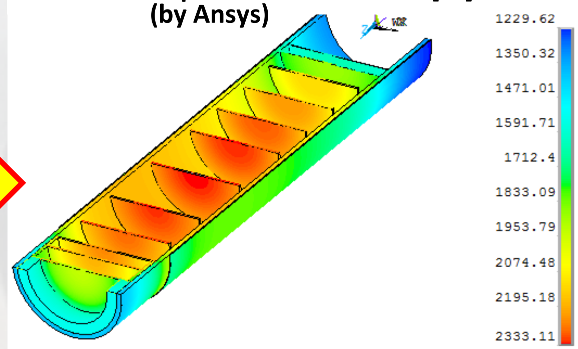
The SPES target: the beam profile effects

Procedure implemented to evaluate temperature and stresses in the target

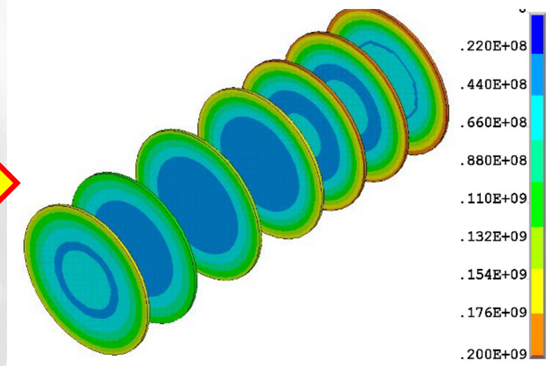
Heat generation [W/m³] by FLUKA (code to simulate the interaction of proton with matter)

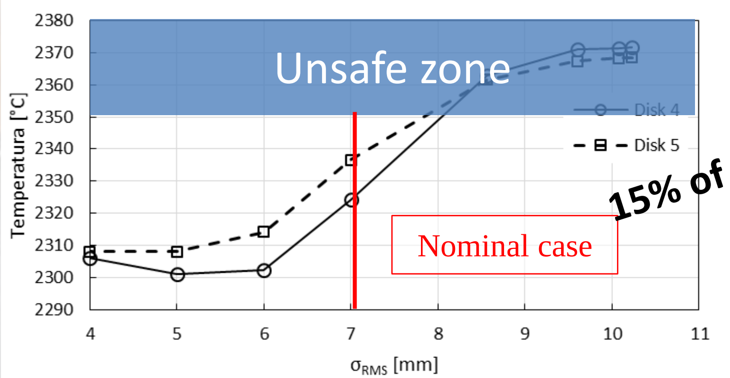


Temperature distribution [°C] (by Ansys)

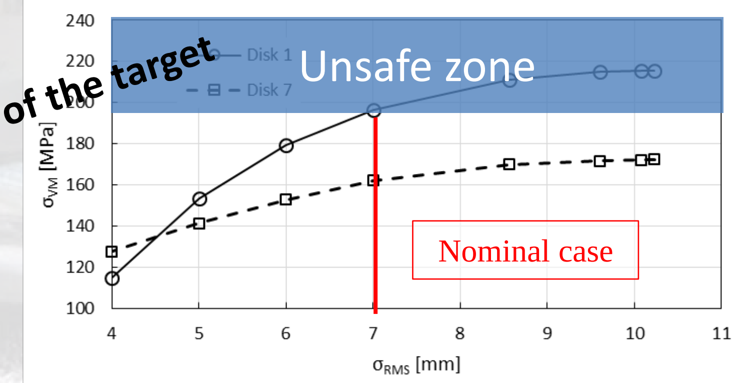


Von Mises stress distribution [Pa]





15% of power out of the target



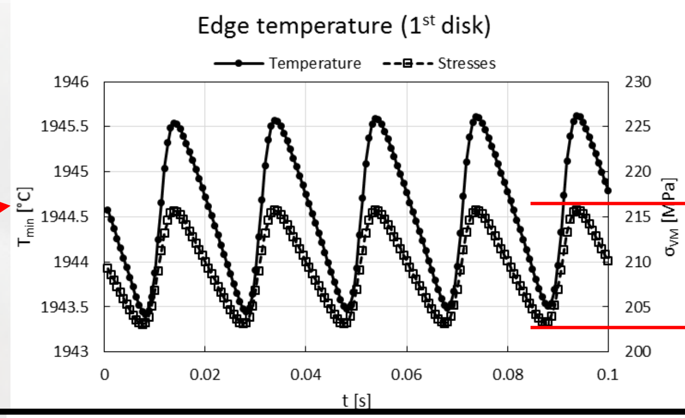
N° disk	P [W]	T_{mean} [°C]	Δt_{max} [°C]	σ [MPa]
1	553	2060	174	198
2	572	2169	158	186
3	589	2238	151	181
4	604	2274	139	169
5	597	2288	122	139
6	573	2276	120	125
7	568	2226	160	164

The nominal conditions are fixed to a beam with a **RMS radius of 7 mm** (not wobbled) and a **wobbling radius of 11 mm**

The SPES target: case studies

Effect of the wobbling (50 Hz)

Proton beam onto the disk



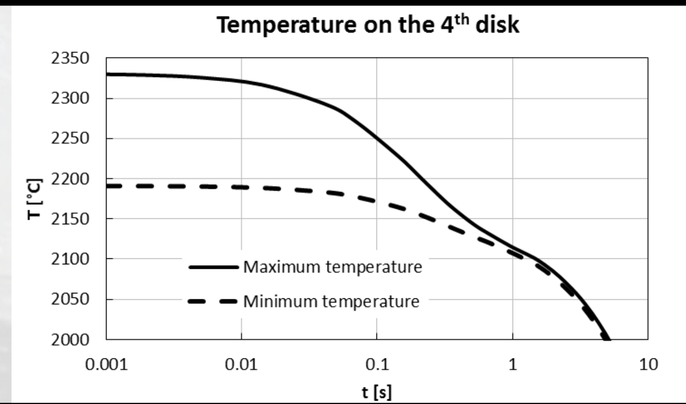
Request for an higher wobbling frequency

$\Delta T_{MAX} \approx 2.5°C$
$\sigma_{VM\_MAX} = 198$ MPa

$\Delta\sigma = 14$ MPa

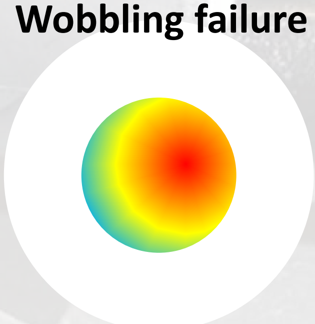
Stop of the proton beam

Proton beam onto the disk

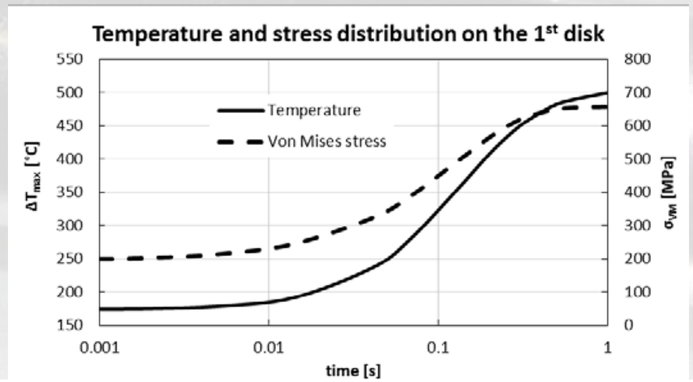


After 1 s $\Delta T_{MAX} \approx 350°C$
σ only decreases
<u>Warning on the sudden increase of the proton beam power!</u>

Wobbling failure



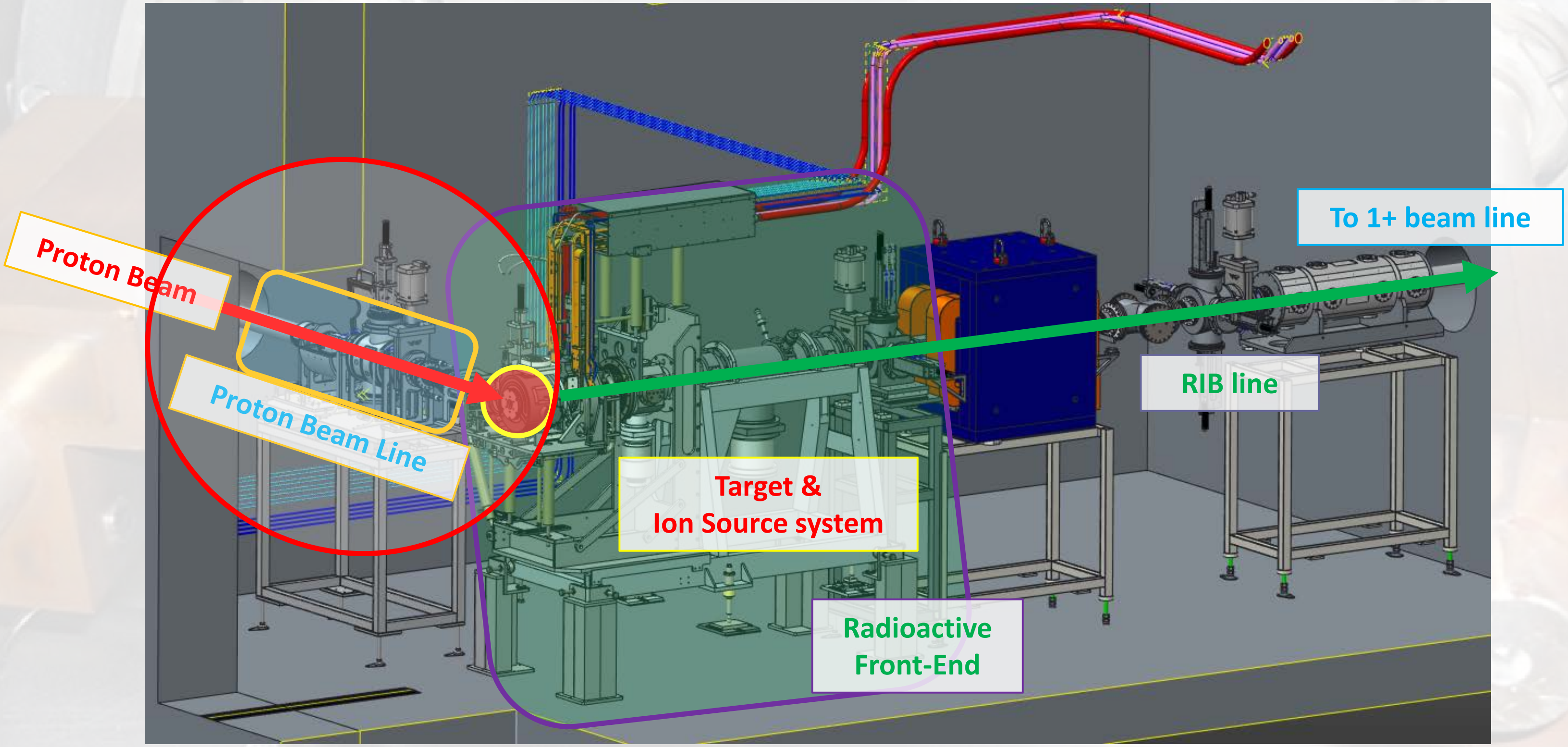
Proton beam onto the disk



t_{MAX} to stop the beam = 0.1 s
T_{MAX} @ 0.1 s = 2500°C
(evaporation of target begins)
σ_{MAX} @ 0.1 s = 450 MPa
(probable disk rupture)
Best intervention time: 10 ms

A. Monetti et al., “The RIB production target for the SPES project”, Eur. Phys. J. A **51**, 128 (2015)

The Front-End & the RIB line in the bunker



1. **The Proton Beam Line**.
   It has to accept, shape the Proton Beam and characterize it in terms of:
   - Proton Beam intensity
   - Proton Beam profile

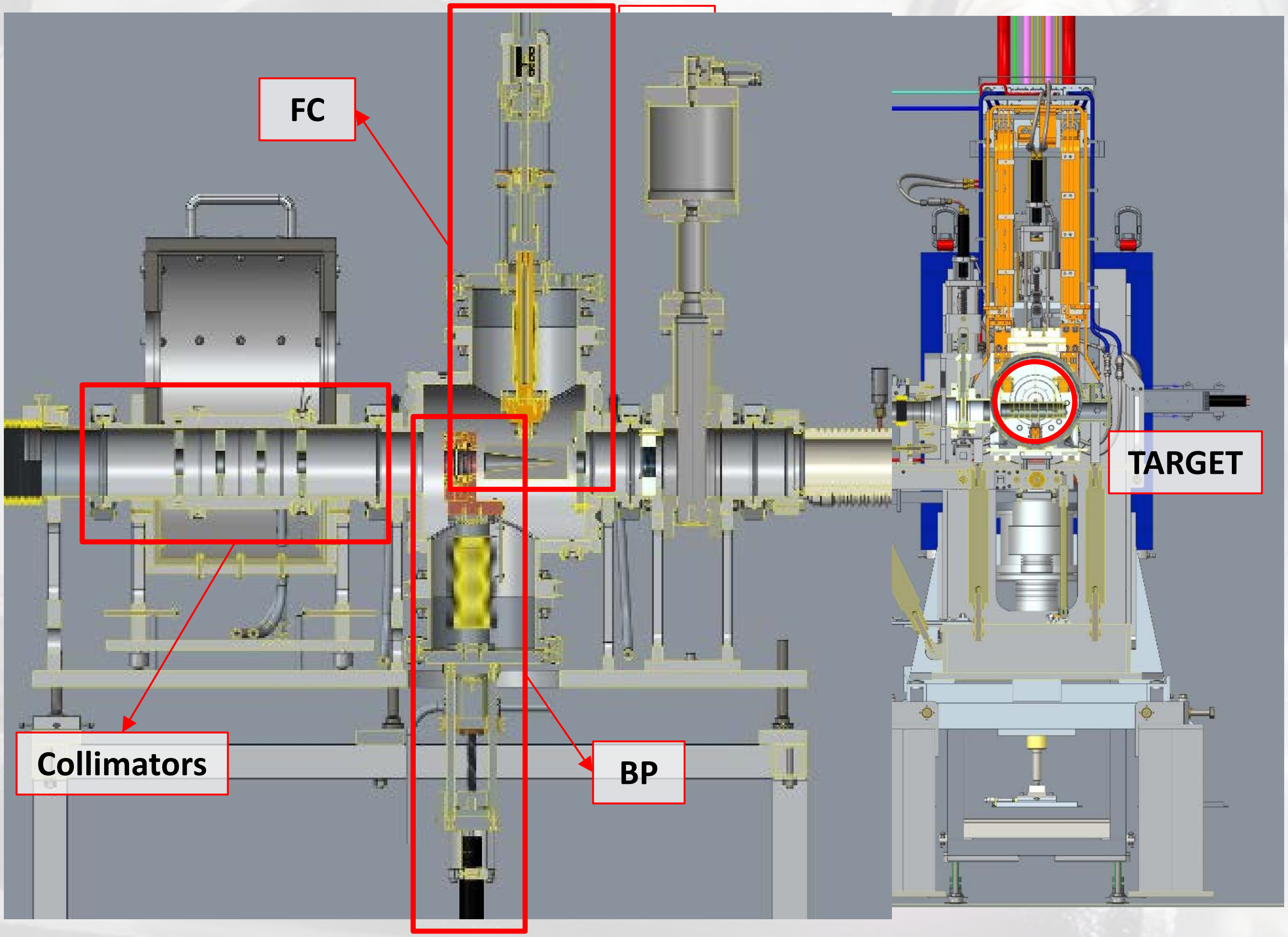
   The stainless steel has to be avoided as much as possible, especially from the zone where protons can impinged directly the components

The 8 kW diagnostic box

It has to shape the proton beam and characterize the beam in terms of intensity and profile

It has been equipped by:

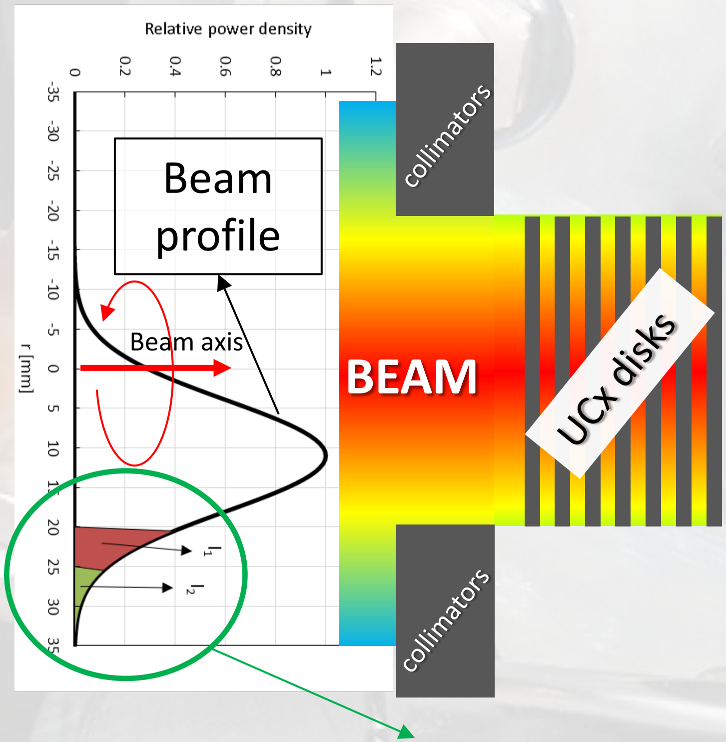
- A *collimator*
- A *Beam Profiler* (BP)
- A *Faraday Cup* (FC)



Auxiliary systems are:

- A turbomolecular pump
- A gate valve to let the target being uncouple without loosing the vacuum along the proton beam channel
- Alumina insulator with a bellow on the target side
- Bellow for the uncouple

Why collimators?



Tales of the beam not impinging the target that **has** *to be absorbed*

The collimator is the fundamental device for the operation of the target

The nominal beam is a wobbled Gaussian with:
σ_{RMS} = 7 mm, $r_{WOBBLING}$ = 11 mm, diameter = 40 mm

About **15% of the power** has to be collected by the collimators: *why not using this current*?
Current = **information**!

"Active collimator": detector

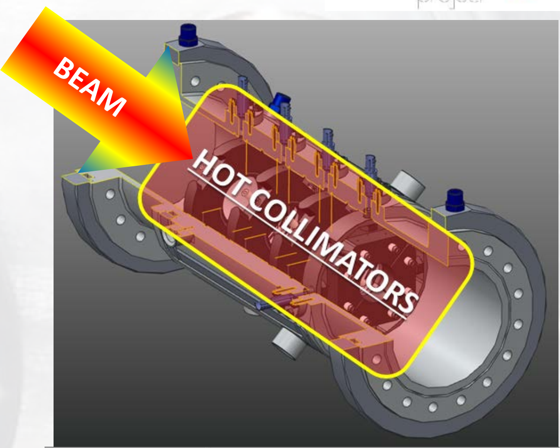
The idea was to collect the big amount of current to:

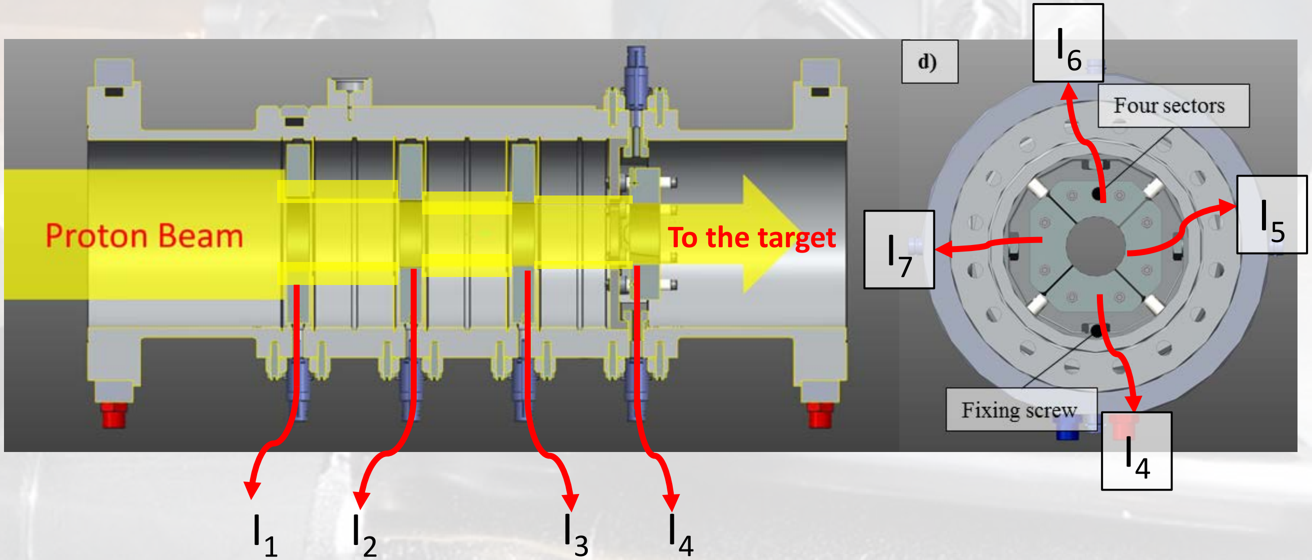
- Characterize beam shape
- Characterize beam alignment
- Monitor the beam properties & **stability** during target irradiation

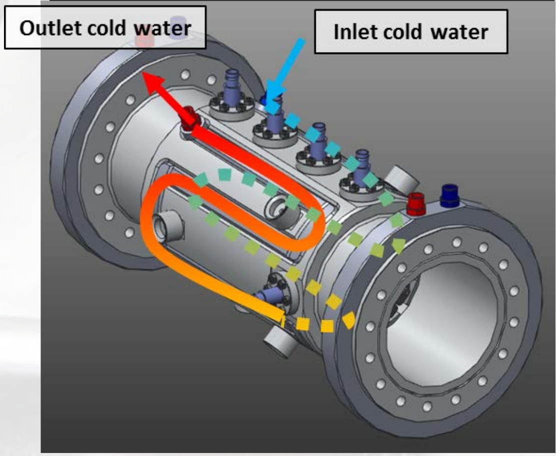
Collimators description (1)

Basic idea: radiation method exchange used to cool the collimators

- No presence of welding for the cooling circuit in the vacuum side
- Collimator temperature insensitive to wall temperature
- Collimator at high temperature







N°4 segments have been chosen to:

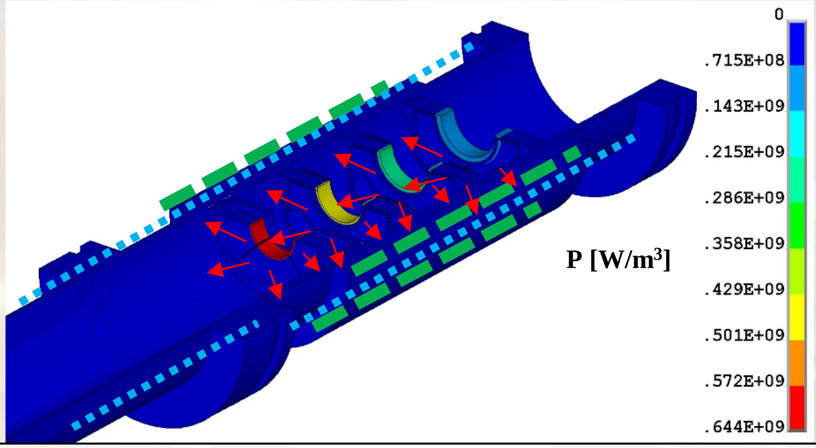
- Ability to get a good resolution on the power at the beam tales
- Do not increase too much the complexity of the system

Power to dissipate: **1.4 kW**

Power limit assumed in the design: **3 kW**

Collimators: FEM simulation

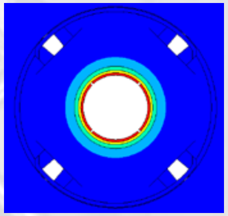
Boundary conditions



Cooling circuit (T_{WATER} = 35°C)

Radiation method exchange

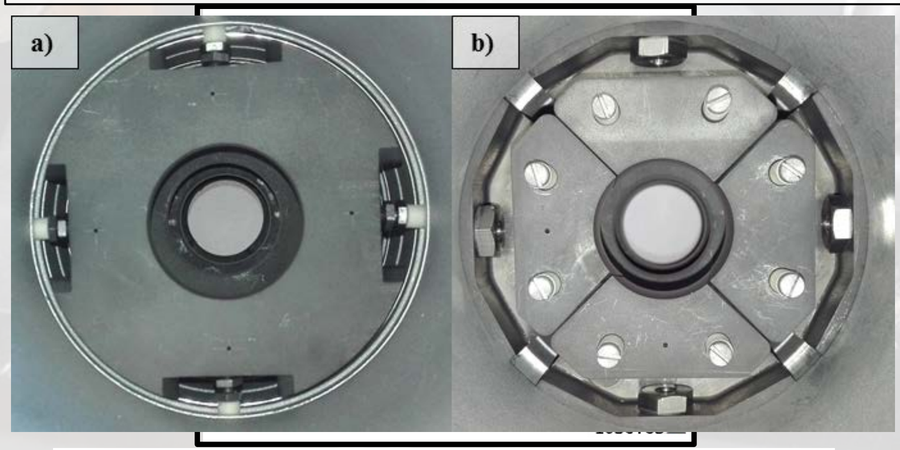
Air convection



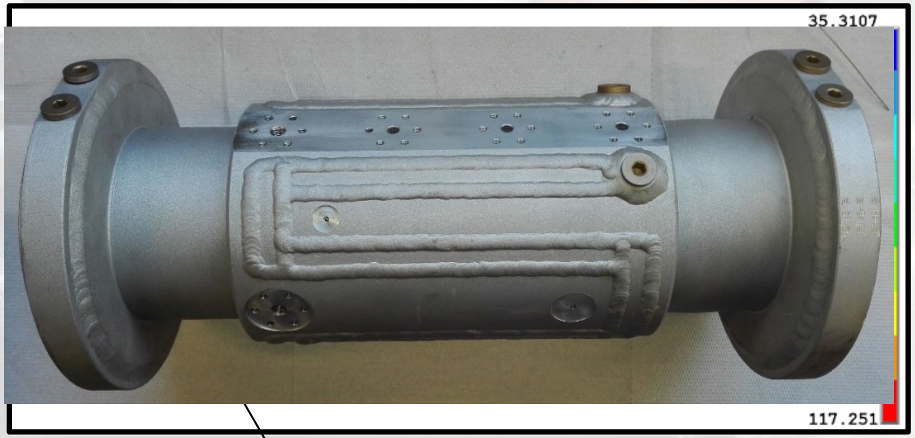
Power deposition

Total power: 3 kW

Main results



Segment N°	P [W]	I [μA]	T_{MAX} [°C]
1	1020	25.5	1050
2	790	19.8	1072
3	640	16.0	983
4	550	13.8	857

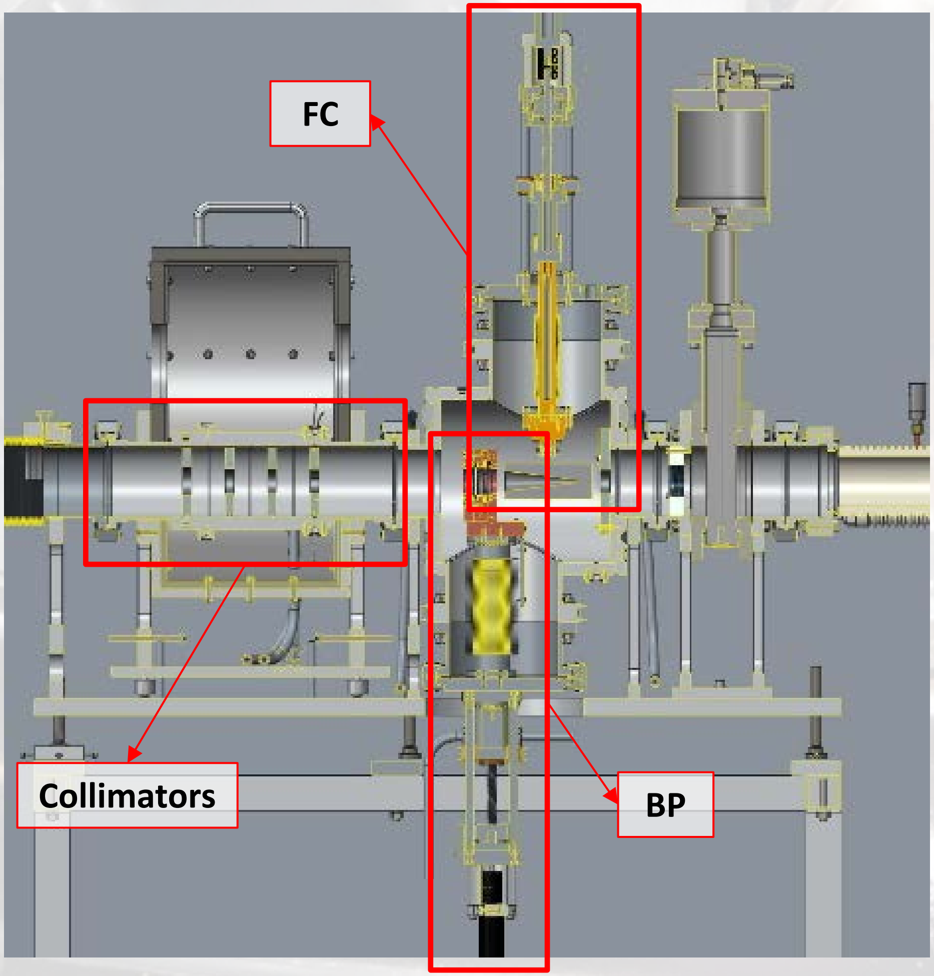


Maximum temperature flange: 115°C (**not** water-cooled)

The 8 kW diagnostic box

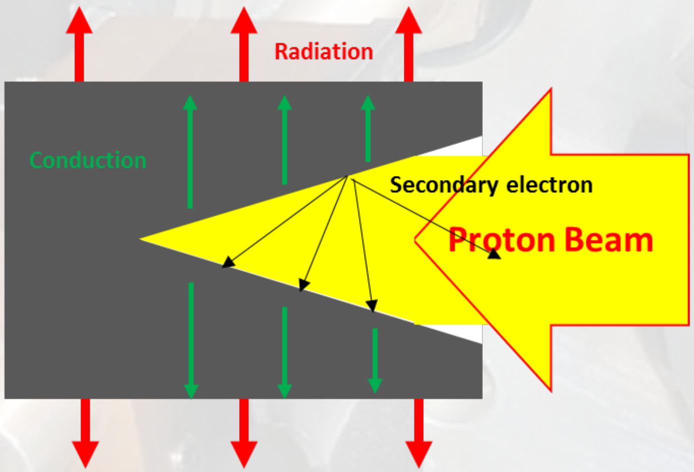
It has been equipped by:

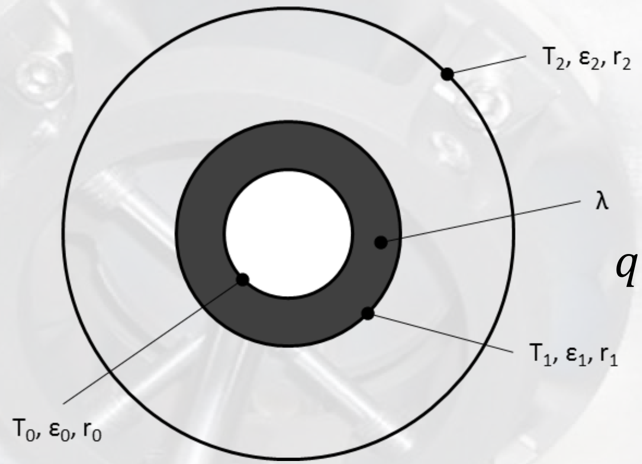
- A *collimator*
- A *Beam Profiler* (BP)
- A *Faraday Cup* (FC)



The Proton Beam Faraday Cup: first description

Working principle: as collimators, the heat is dispose only by radiation

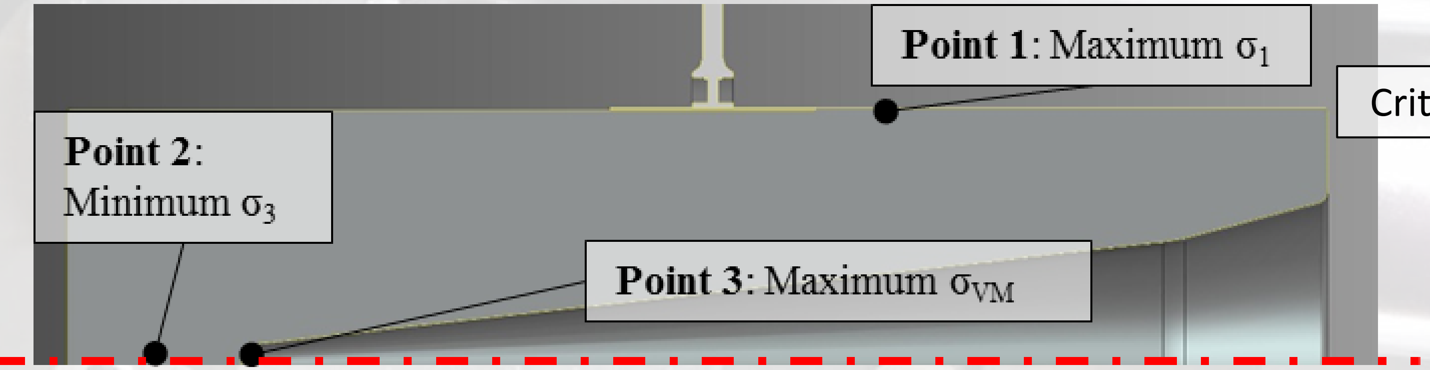




Faraday Cup temperature

$$q = \frac{2\pi r_1 L\, \sigma \cdot (T_1{}^4 - T_2{}^4)}{\frac{1}{\varepsilon_1} + \frac{r_1{}^2}{r_2{}^2}\left(\frac{1}{\varepsilon_2} - 1\right)}$$

For a 8 kW of proton beam power, a temperature of maximum 1700°C is expected
The design is focused on finding the *minimum* optimum **stresses**

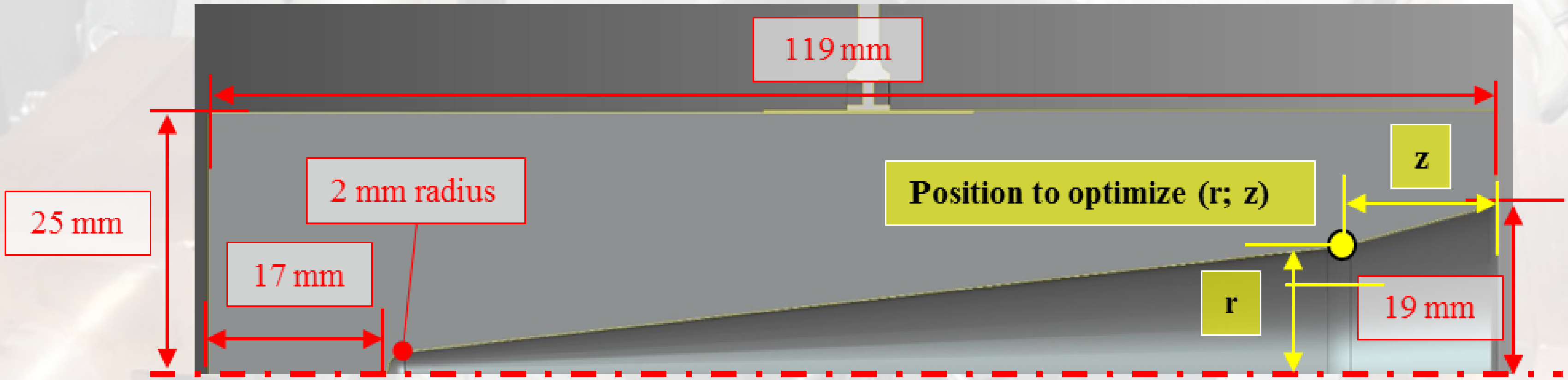


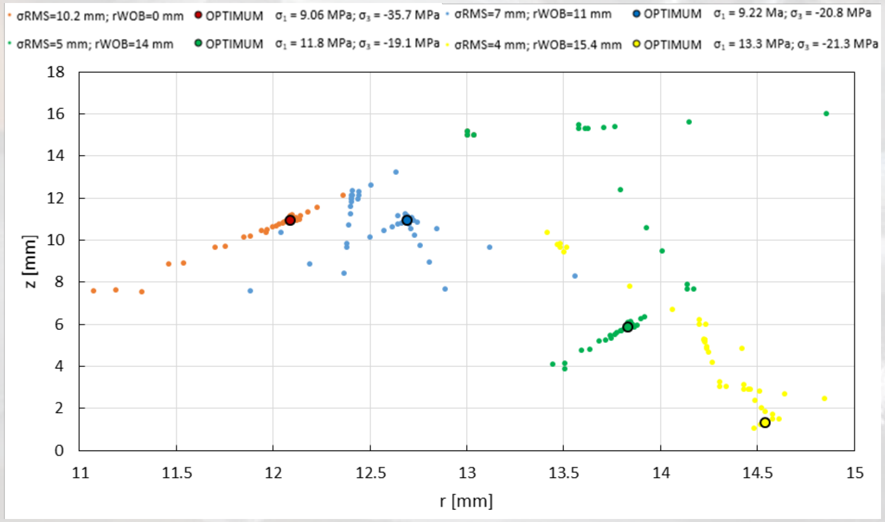
Criterion to find the optimum

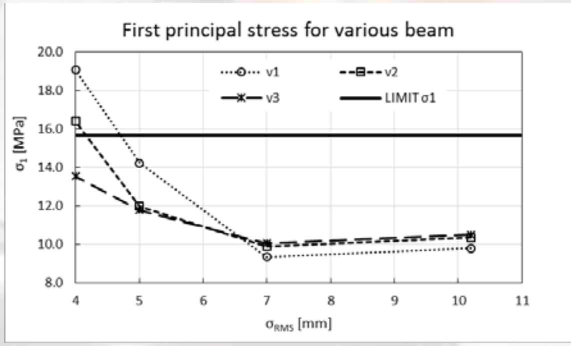
$$\frac{\boldsymbol{\sigma_1}}{\boldsymbol{2\sigma_{1\,LIM}}} \cdot \frac{\boldsymbol{\sigma_3}}{\boldsymbol{2\sigma_{3\,LIM}}}$$

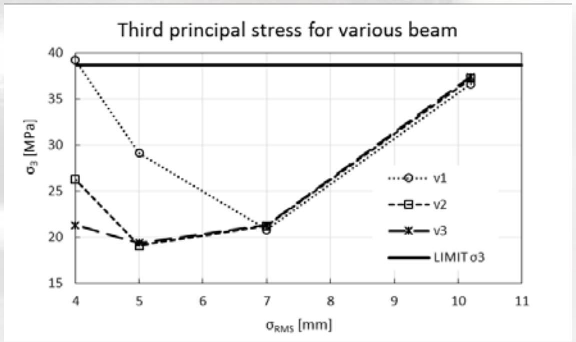
The Proton Beam Faraday Cup: FEM simulations (1)

To define the Faraday Cup shape, 2 variables has to be defined: ***z* & *r***





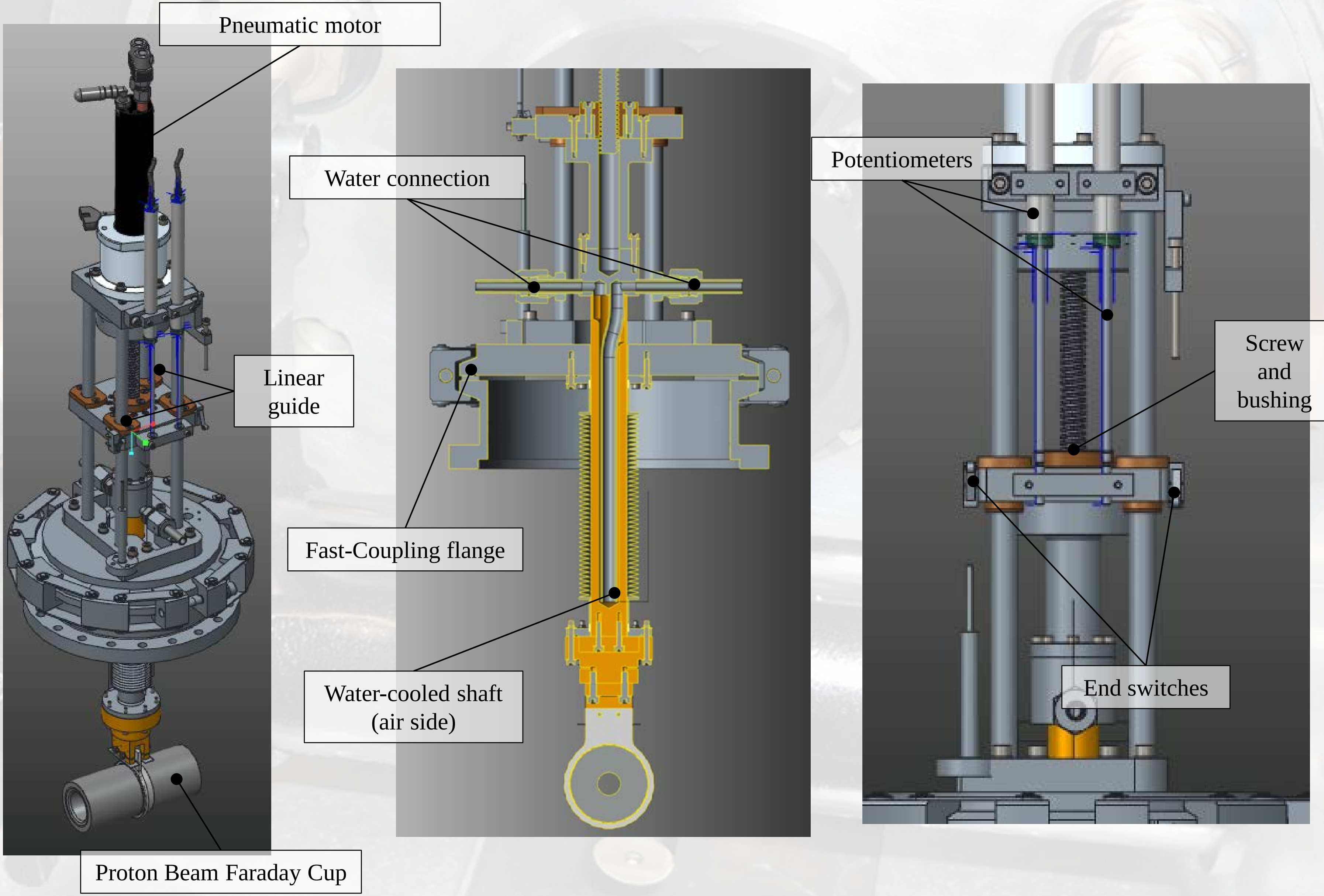




The **optimum** values depend on the proton beam profile

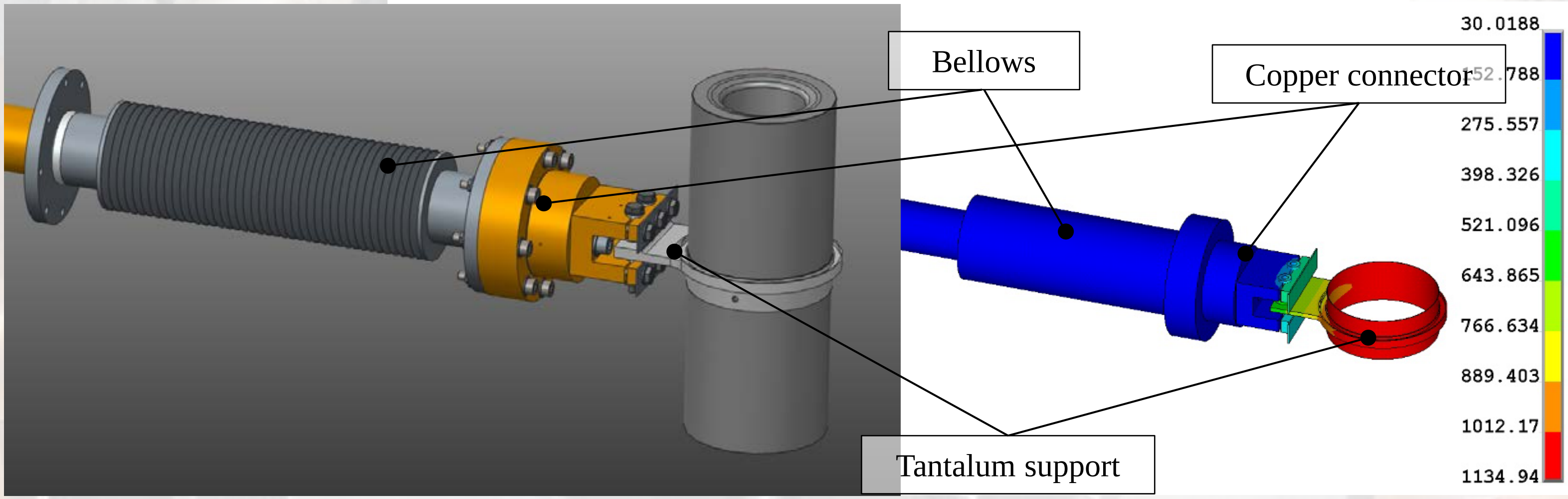
The final version supports all of the beam profile (σ_{RMS}>4 mm) for **8 kW** of beam in the **target** and **1.4 kW** on the **collimator** (nominal conditions)

The Proton Beam Faraday Cup: mechanical design



The Proton Beam Faraday Cup: FEM simulations (2)

Temperature distribution of the shaft and vacuum components



Temperature distribution of Faraday Cup for different proton beam profile

Axial-symmetric section of the Proton Beam Faraday Cup

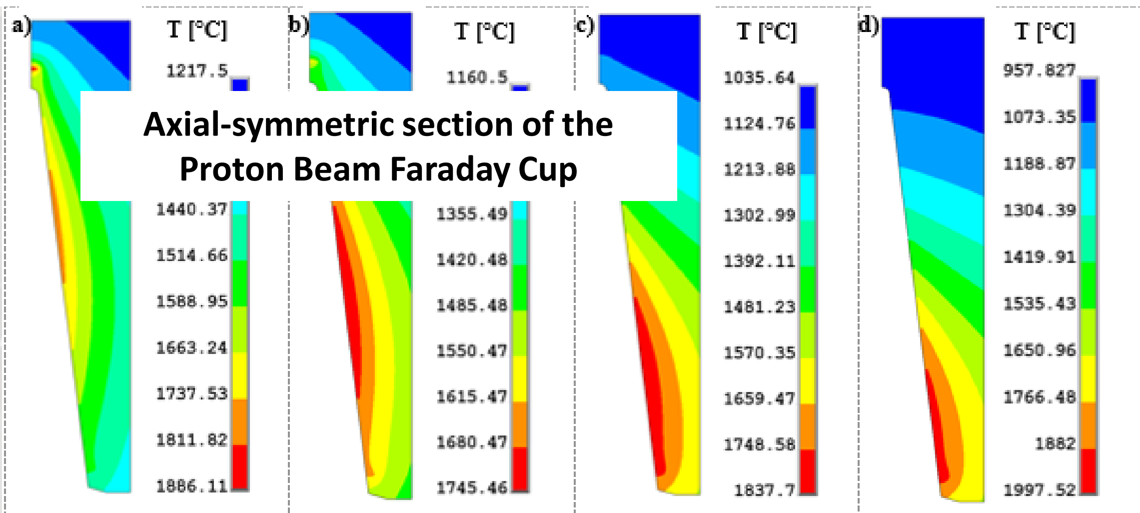
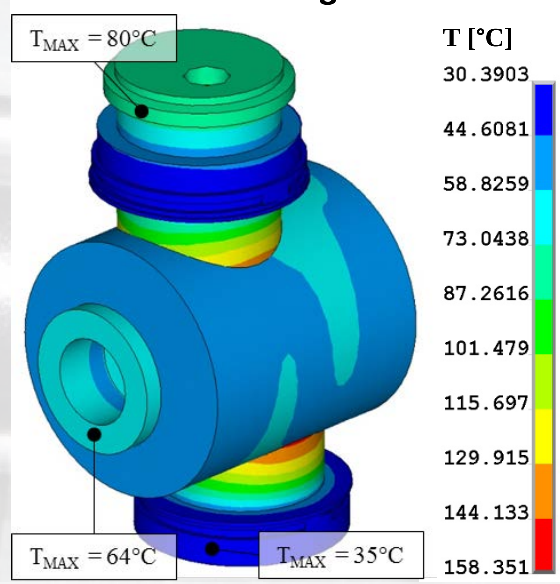


Fig. 3.26. Thermal distribution on the last geometry adopted for different beam characteristics to the target: a) σ_{RMS}=10.2 mm; r_{WOB}=0 mm; b) σ_{RMS}=7 mm; r_{WOB}=11 mm; c) σ_{RMS}=5 mm; r_{WOB}=14 mm; d) σ_{RMS}=4 mm; r_{WOB}=15.4 mm;

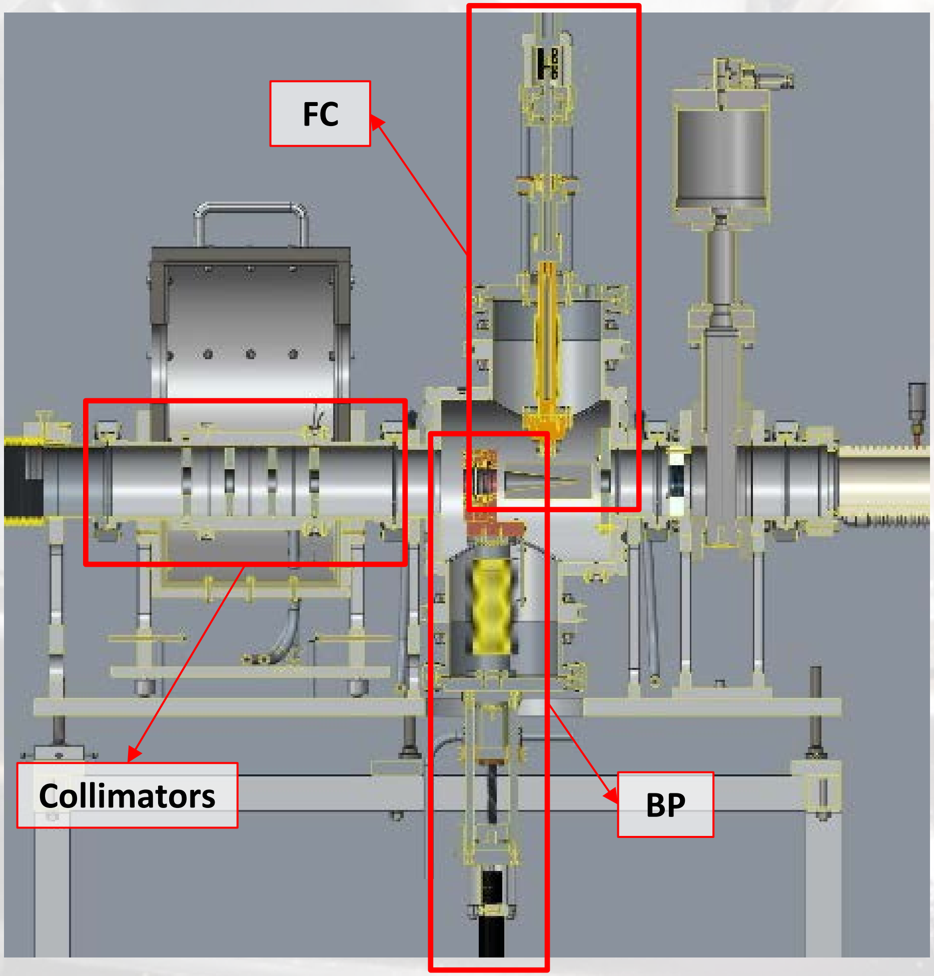
Temperature distribution of water cooled diagnostic cross



The 8 kW diagnostic box

It has been equipped by:

- A *collimator*
- A *Beam Profiler* (BP)
- A *Faraday Cup* (FC)

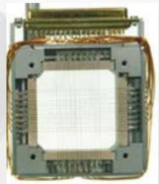


The Proton Beam Profiler: first discussions

Harp type Beam Profiler

VS

Rotatin Wire Beam Profiler?



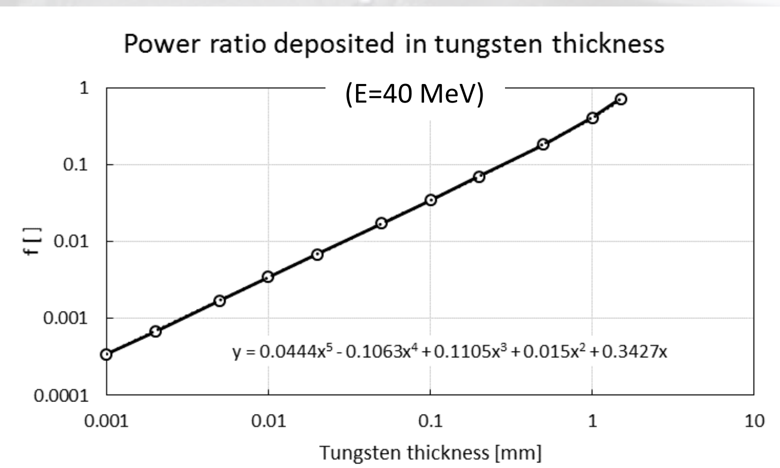
Harp type Beam Profiler was chosen:

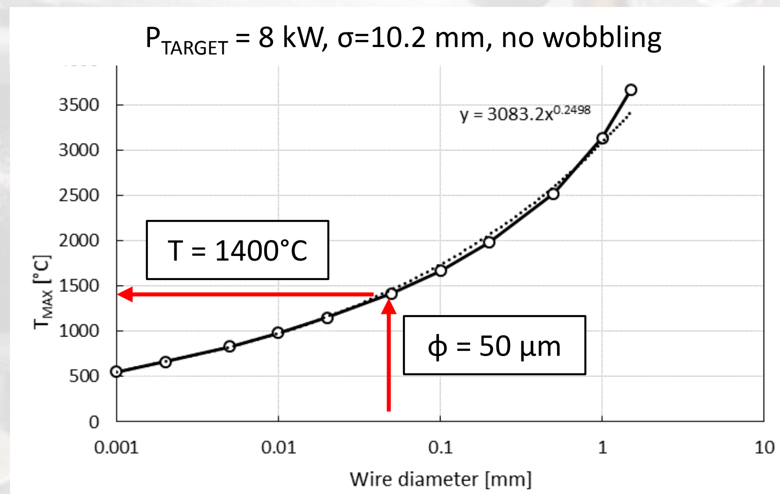
- More complex from the mechanical point of view
- No distorbtion on the beam centre
- Control system already available

Analytical expression

$$T_{MAX} = \sqrt[4]{\frac{P_{TOT}}{8\pi\sigma^2\sigma_B\varepsilon}\cdot f}$$

P_{TOT} = Beam power (without collimation)
σ = beam radius (RMS)
ε = wire emissivity
f = factor dependent on wire material, beam energy, wire diameter

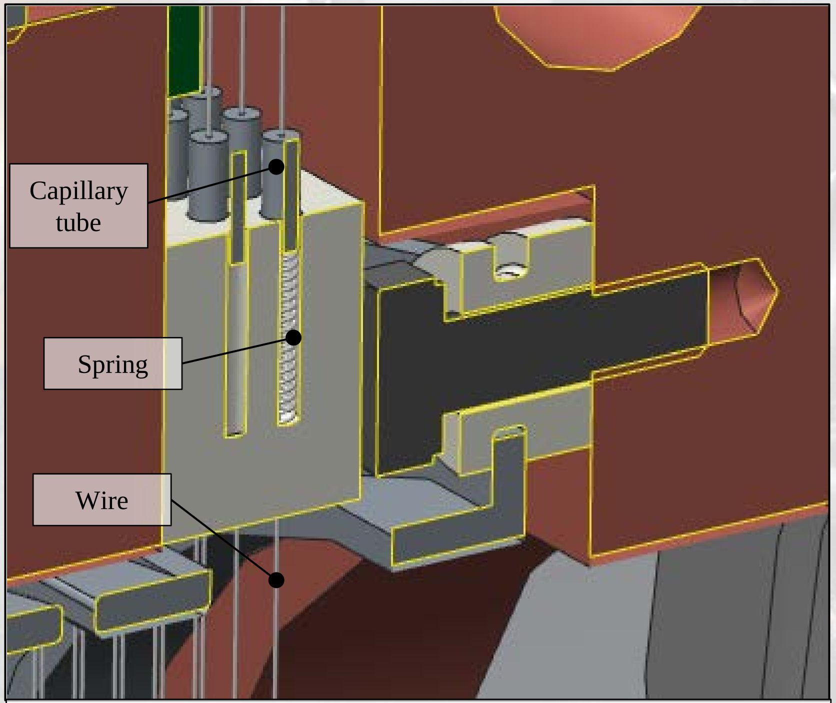




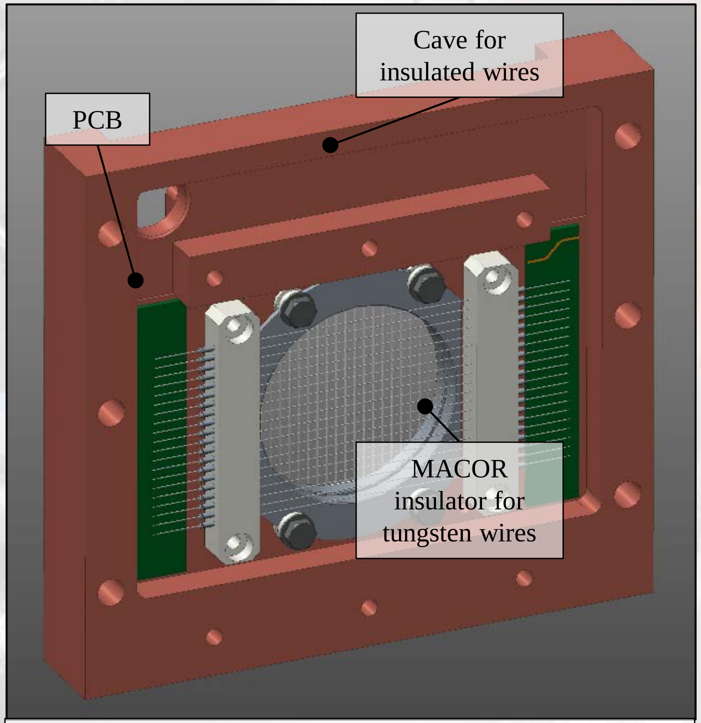
The Proton Beam Profiler: the mechanical design (1)

Increase of temperature → Wire elongation (0.2 mm) → Wire bend of 3 mm (if not compensated)

In both the wire side a spring is foreseen to maintain the wire tension



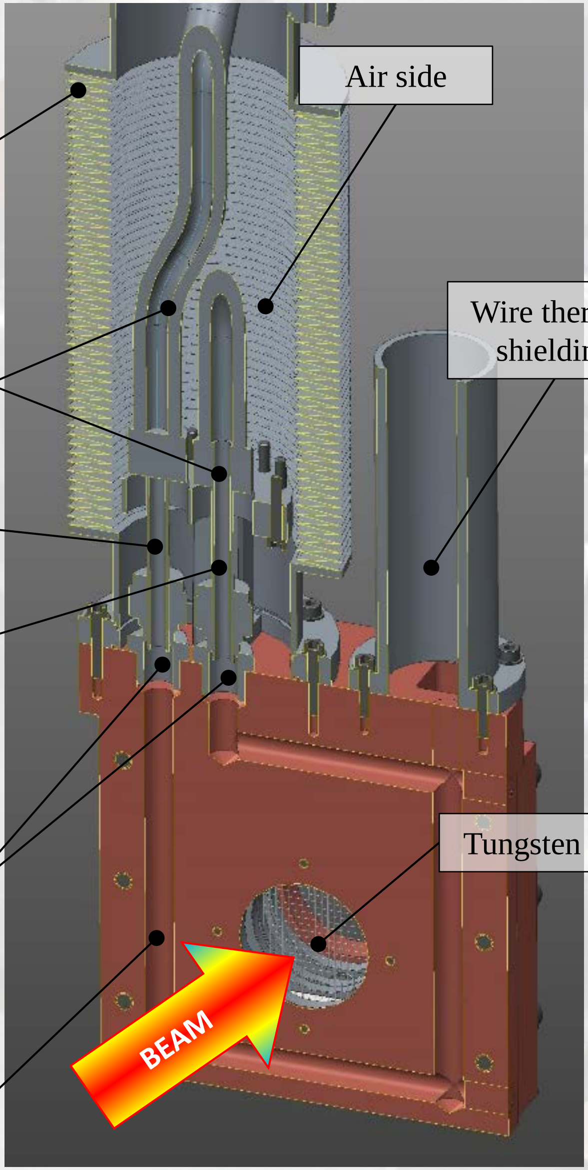
Wire tensioning system

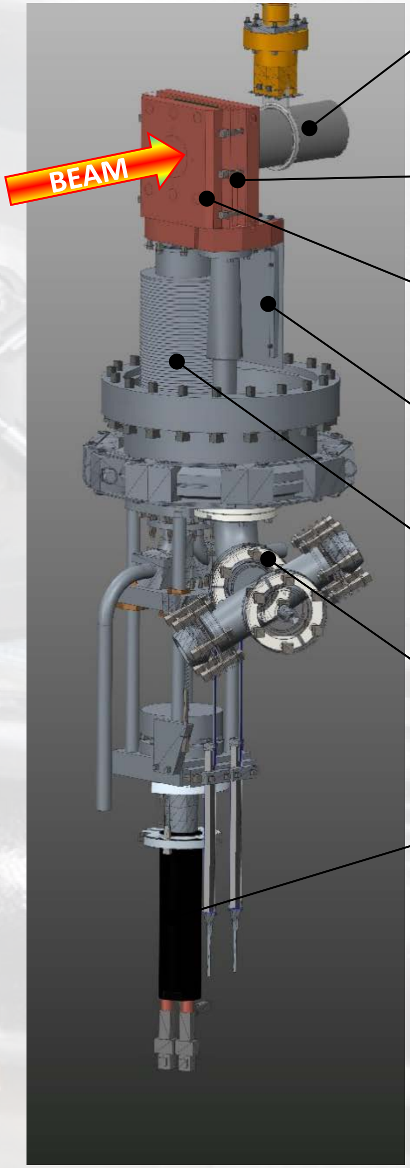


Wire assembly

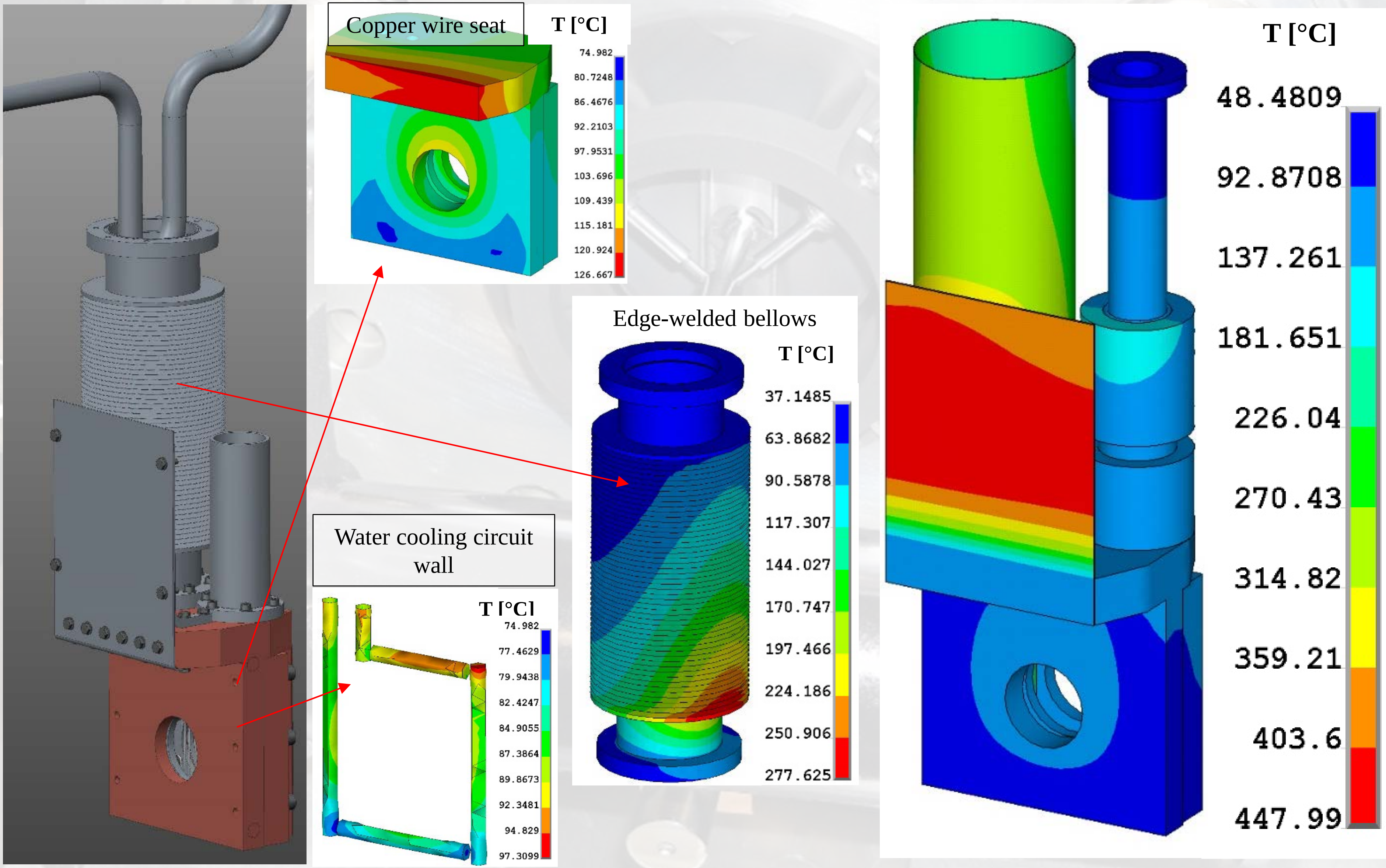
Thanks to Luca Martin (UNIPD & LNL)

The Proton Beam Profiler: the mechanical design (2)





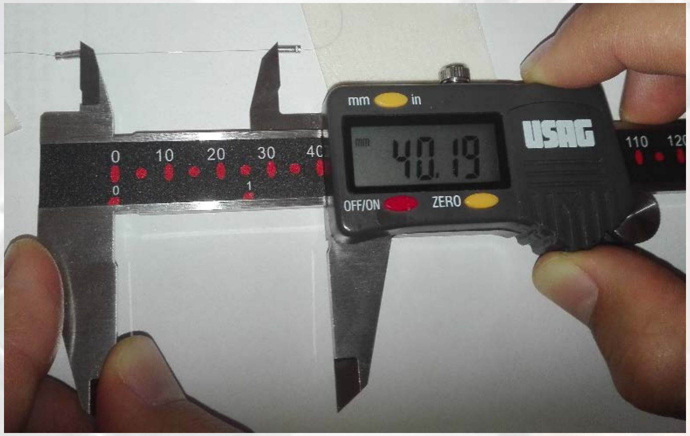
The Proton Beam Profiler: FEM simulations

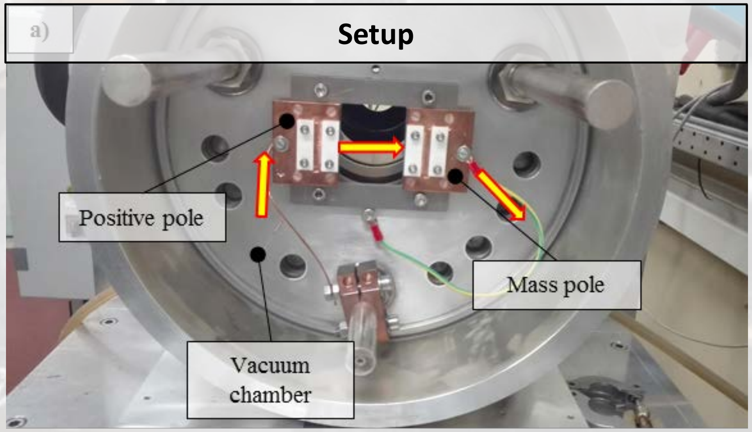


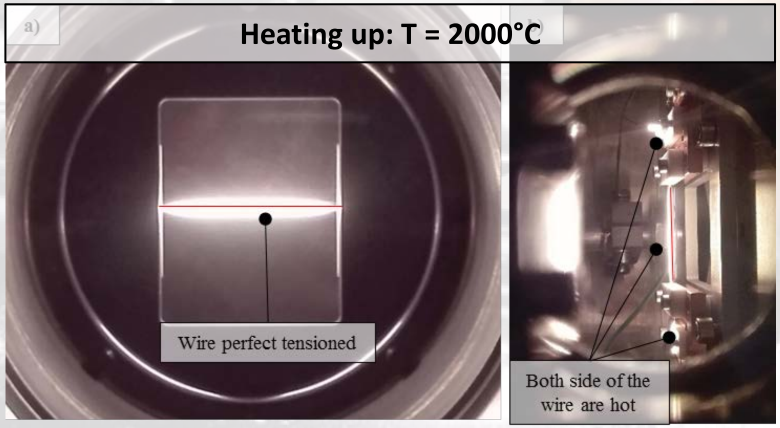
The Proton Beam Profiler: experimental tests

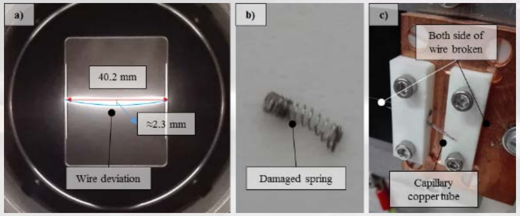
Available 50 µm Molybdenum diameter wire

Mounting precision (nominal 40 mm)





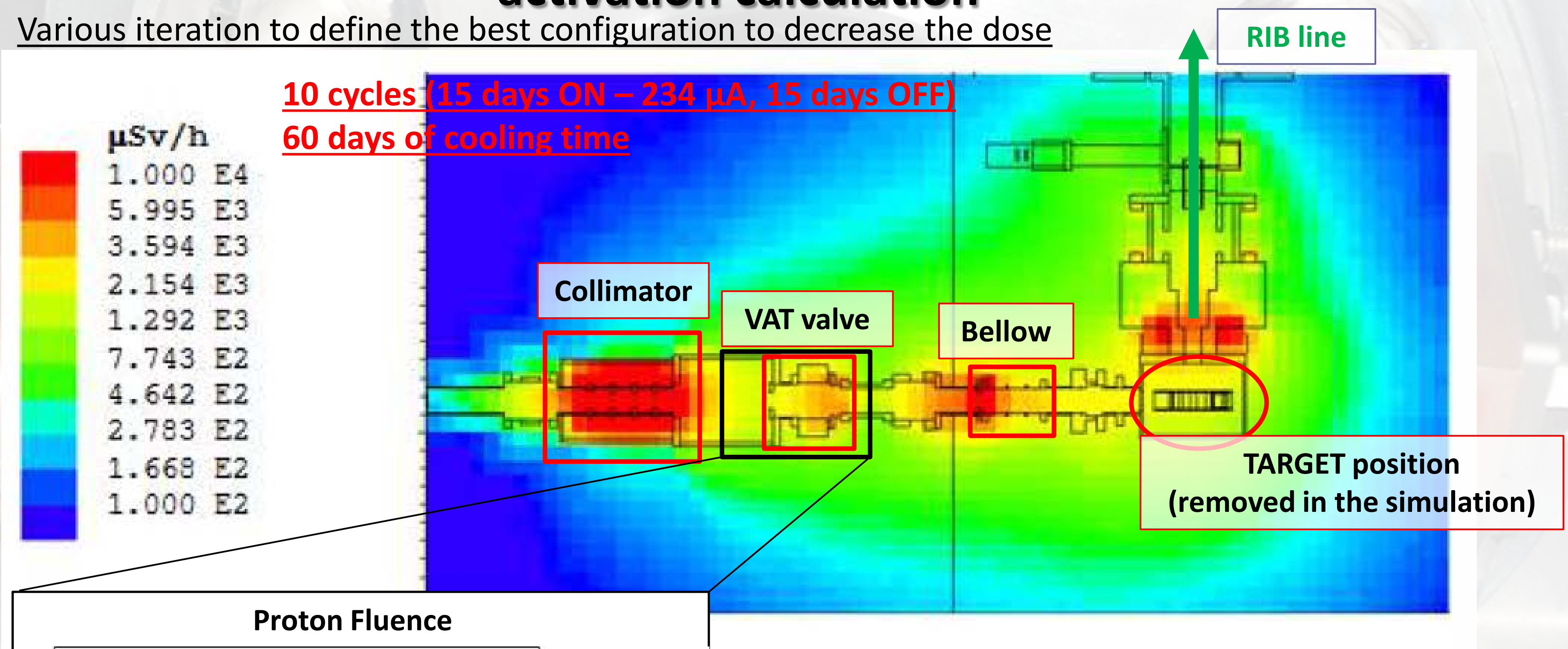


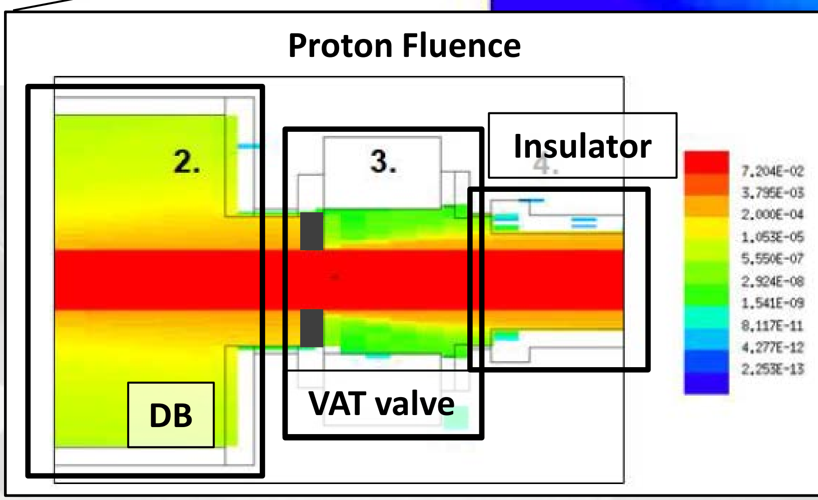


<u>Safe after 7000 cycles, 18 hours</u>

Nuclearization of the Proton Beam Front-End: activation calculation

Various iteration to define the best configuration to decrease the dose





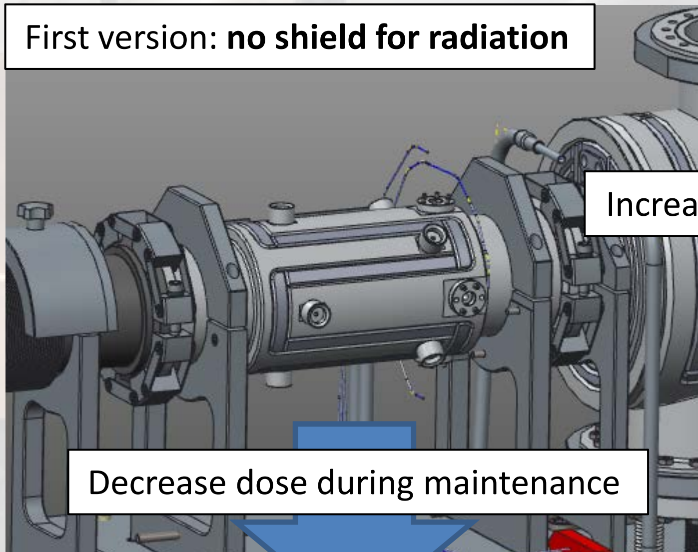
Rules to respect to decrease activation:

- Vacuum pipe in aluminum alloy (typically Al6082T6)
- Bellows in the Proton Beam Line after the collimators in **Titanium**
- Graphite annuli foreseen before components in stainless steel (vacuum valve, bellows)

Thanks to Matteo Ferrari (UNIBS)

Nuclearization of the Proton Beam Front-End: actual solution

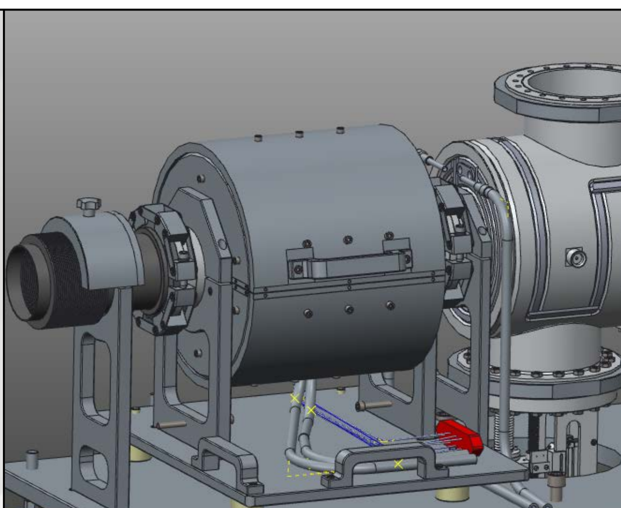
First version: **no shield for radiation**



Increase speed of intervention

Decrease dose during maintenance

Second version: **1 cm lead**. Left: *close*. Right: *open* (for alignment purposes)



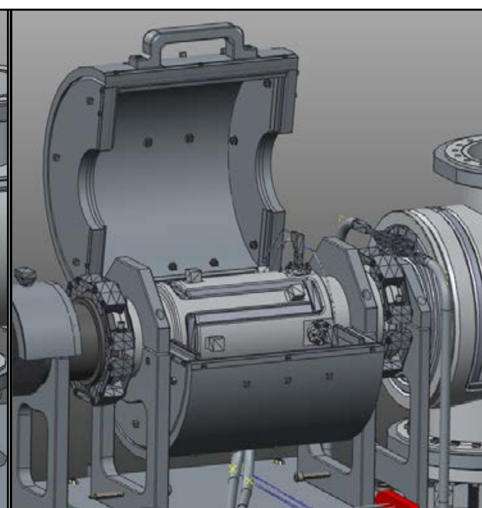
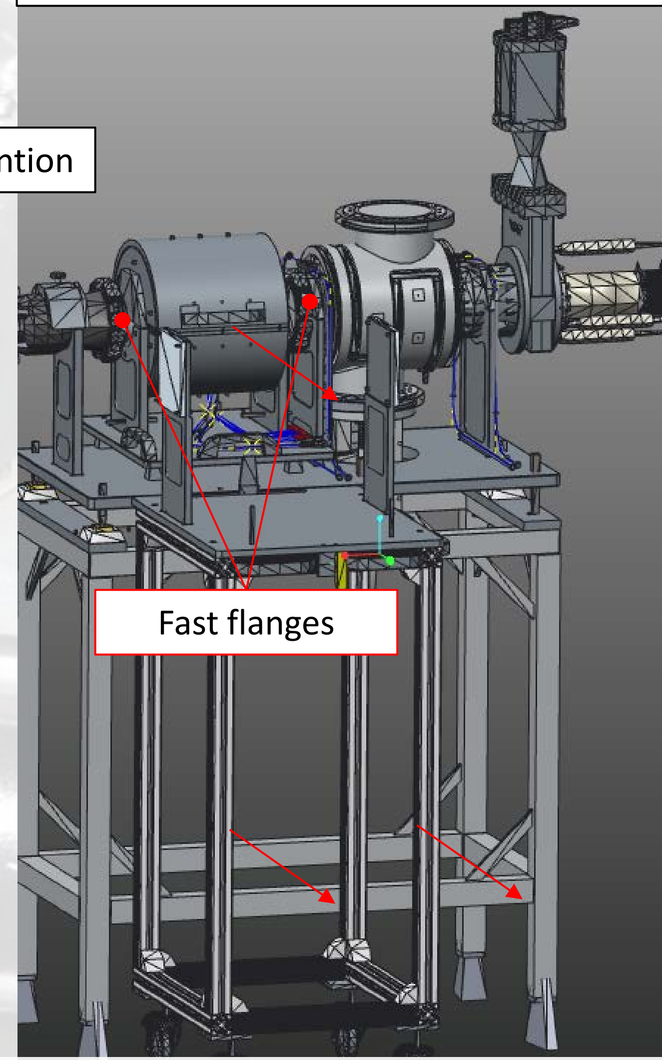


Table for fast replace of collimators



Fast flanges

Thanks to Alberto Raccanello (UNIPD & LNL)

Conclusions

During this talk:

- Analized the target requisites to operate

The design of:

- 3 kW collimator
- 8 kW graphite Faraday Cup
- 8 kW Beam Profiler

BUT

A lot has still to be done!

- Manufacture the last components of the Proton Beam Line
- Installation and test the various components
- Continue to optimize the apparatus to reduce the maintenance time
- ….

Questions?