Experimental set-up for thermal resistance at interface measurements

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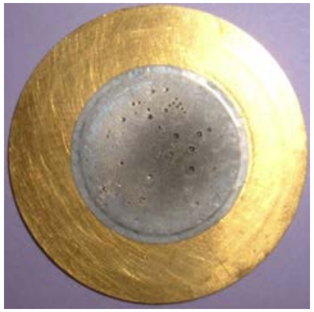
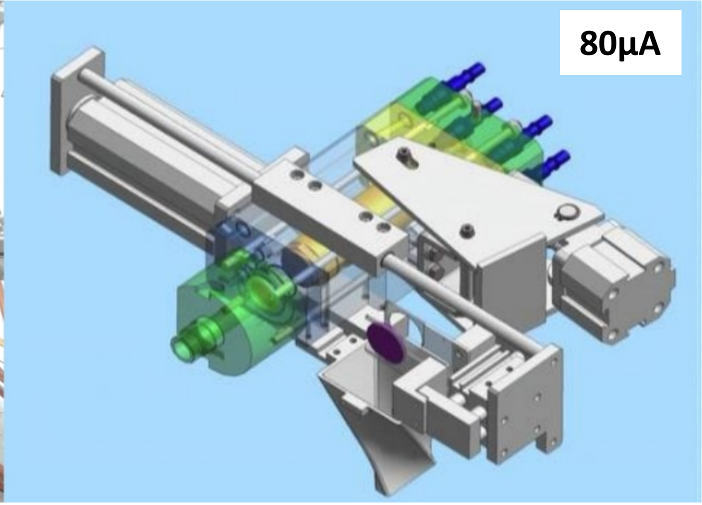
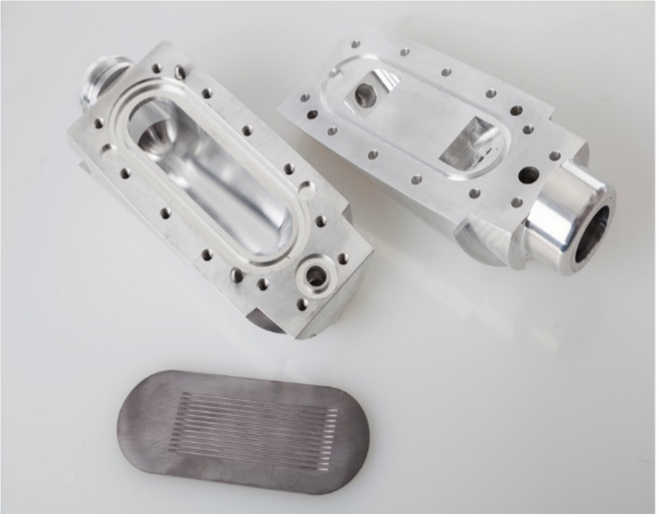
Cyclotron solid target station

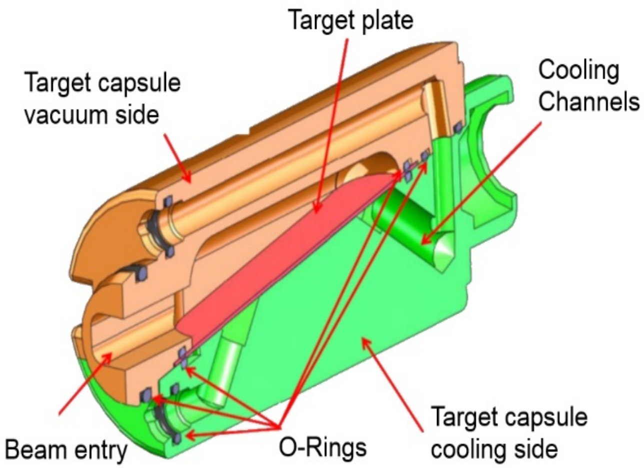
TEMA target prototype
St.Orsola Hospital, Bologna





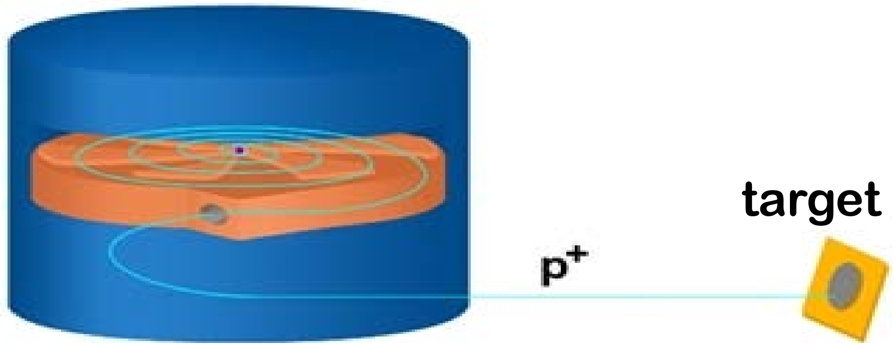
TR19 target of Advanced Cyclotron Systems Inc.





300µA

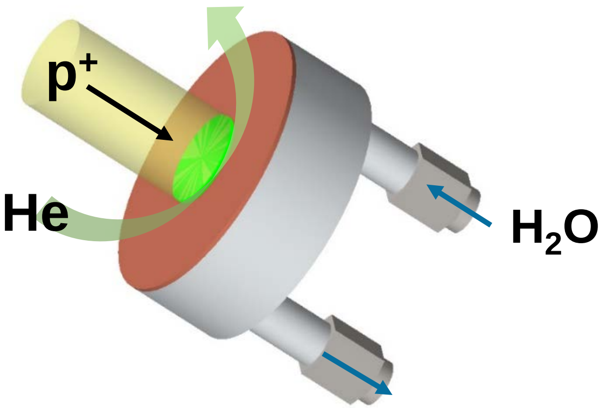
Solid target station: a technical design challenge



New high performance cyclotrons -> High radioisotopes yields -> heat power removal eng. issues

High heat power density hitting the target

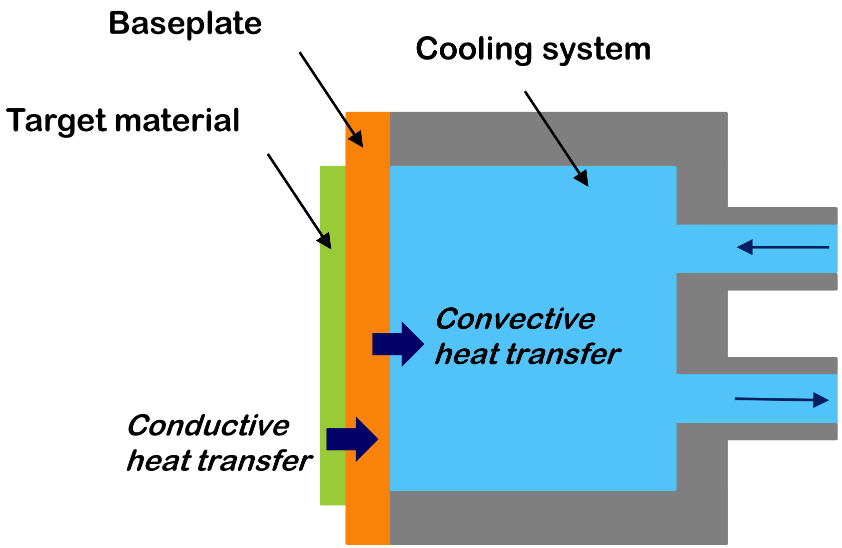
Heat dissipation system



How to dissipate the heat power?
State of art: radioisotope solid target system

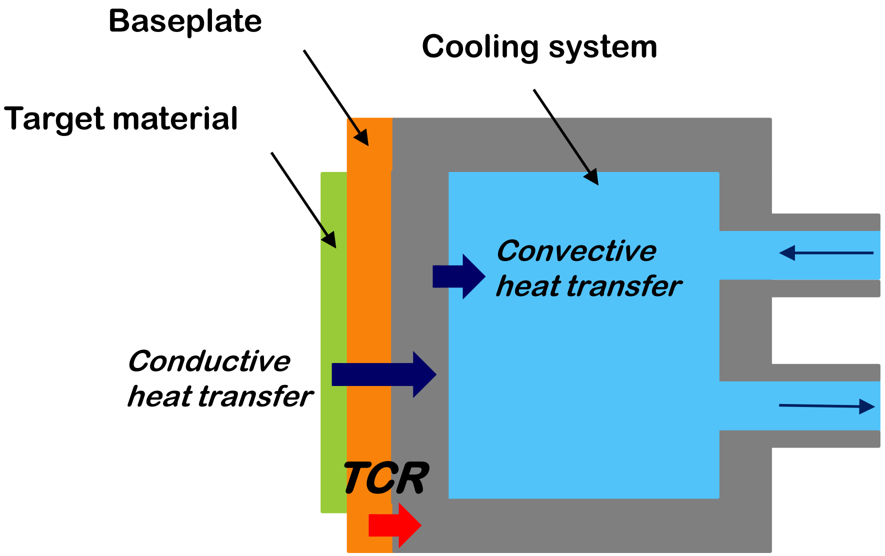
Open cooling system conf.

- ✓ Direct more efficient cooling
- X Potential loss of coolant accident (LOCA)



Closed cooling system conf.

- ✓ No water losses → higher safety
- ✓ Possible different cooling sink geometry
- X Target temperatures affected by **Thermal Contact Resistance** at interface



LARAMED target system : main design goal

Main target station design input :

- **Heat power removal : 30 kW**
- **Possible beam hitting configurations:**
- **E_{max} =70 MeV, I_{min}= 100 μA**
- **E_{min} =40 MeV, I_{max} =750 μA**

Average beam power density of 1 kW/cm^2 on the target

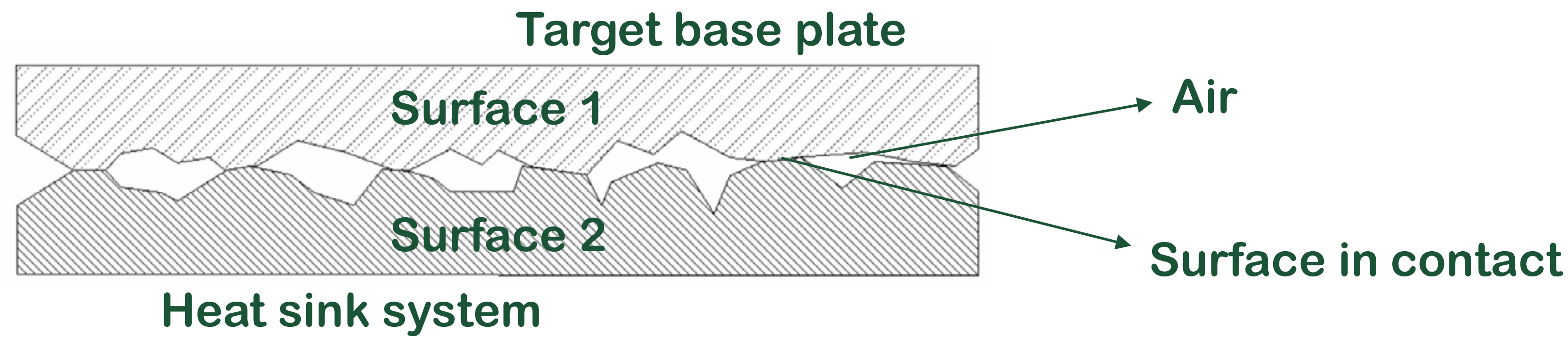
(reference target area spot size: 30 cm^2)

High power cyclotron solid target station

<u>Preferred configuration: closed cooling system</u>

Thermal Contact Resistance at interface

The main problem to work out: Thermal Contact Resistance (TCR) at interface



Thermal Contact Resistance (TCR) depends on:

- materials
- surface roughness
- contact pressure
- oxidation level

Thermal Contact Resistance at interface
Analytical model*

$$TCC = 1{,}55\, k_s \left(\frac{m}{\sigma}\right)\left(\frac{\sqrt{2}p}{mE'}\right)^{0{,}94}$$

TCC: Thermal contact conductance [W m^{-2} K^{-1}]

k_s: harmonic average of thermal conductivity of the materials [W m^{-1} K^{-1}]

σ: RMS surface contact roughness [m]

m: slope of material asperity f(σ)

p: contact pressure [Pa]

E': Young Modulus of the materials [Pa]

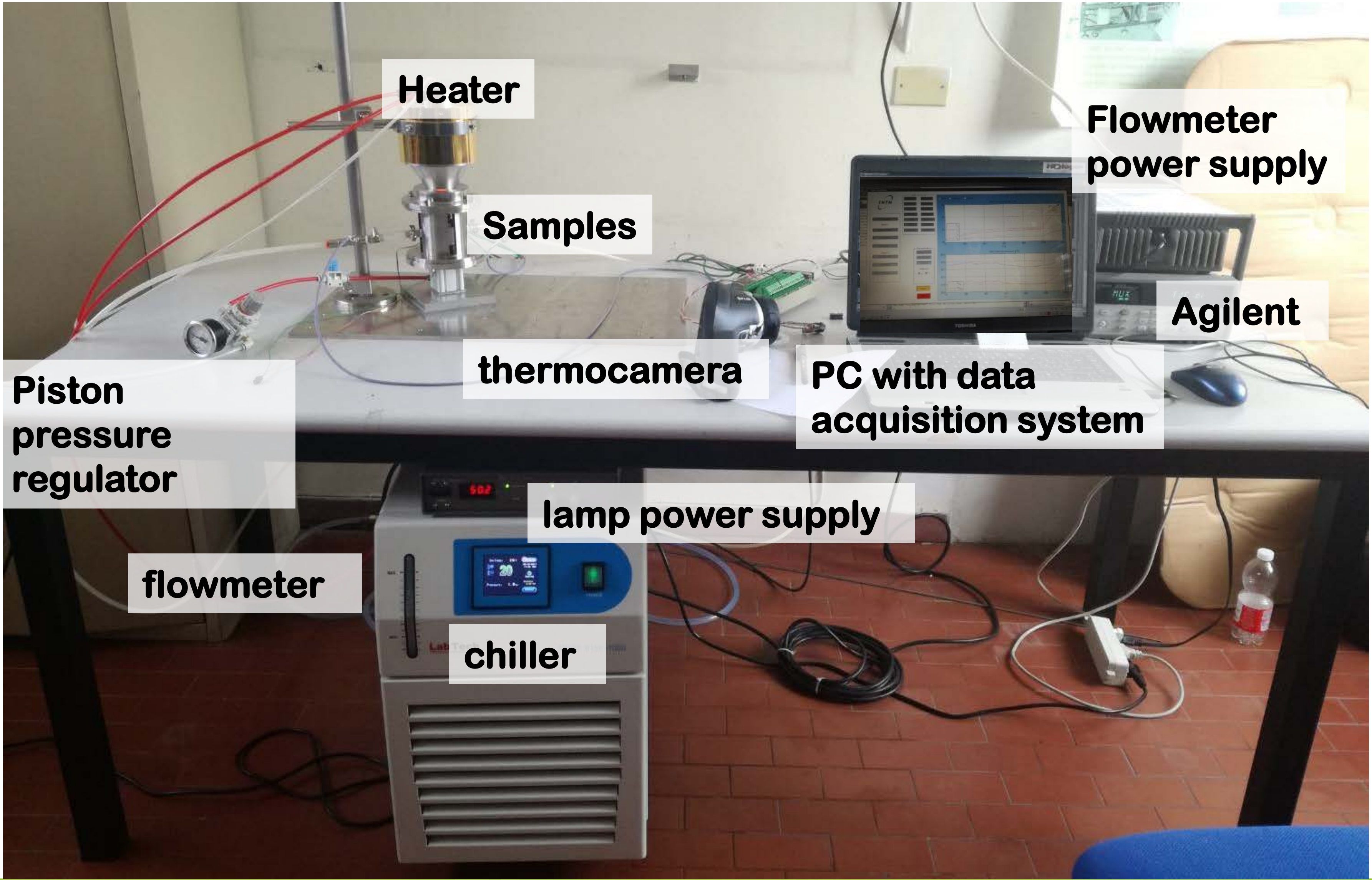
* A. Dall'Occhio, A. Bertarelli et al., "LHC Collimators: un modello agli elementi finiti per l'analisi termostrutturale", Associazione italiana per l'analisi delle sollecitazioni (AIAS), XXXVI Convegno Nazionale

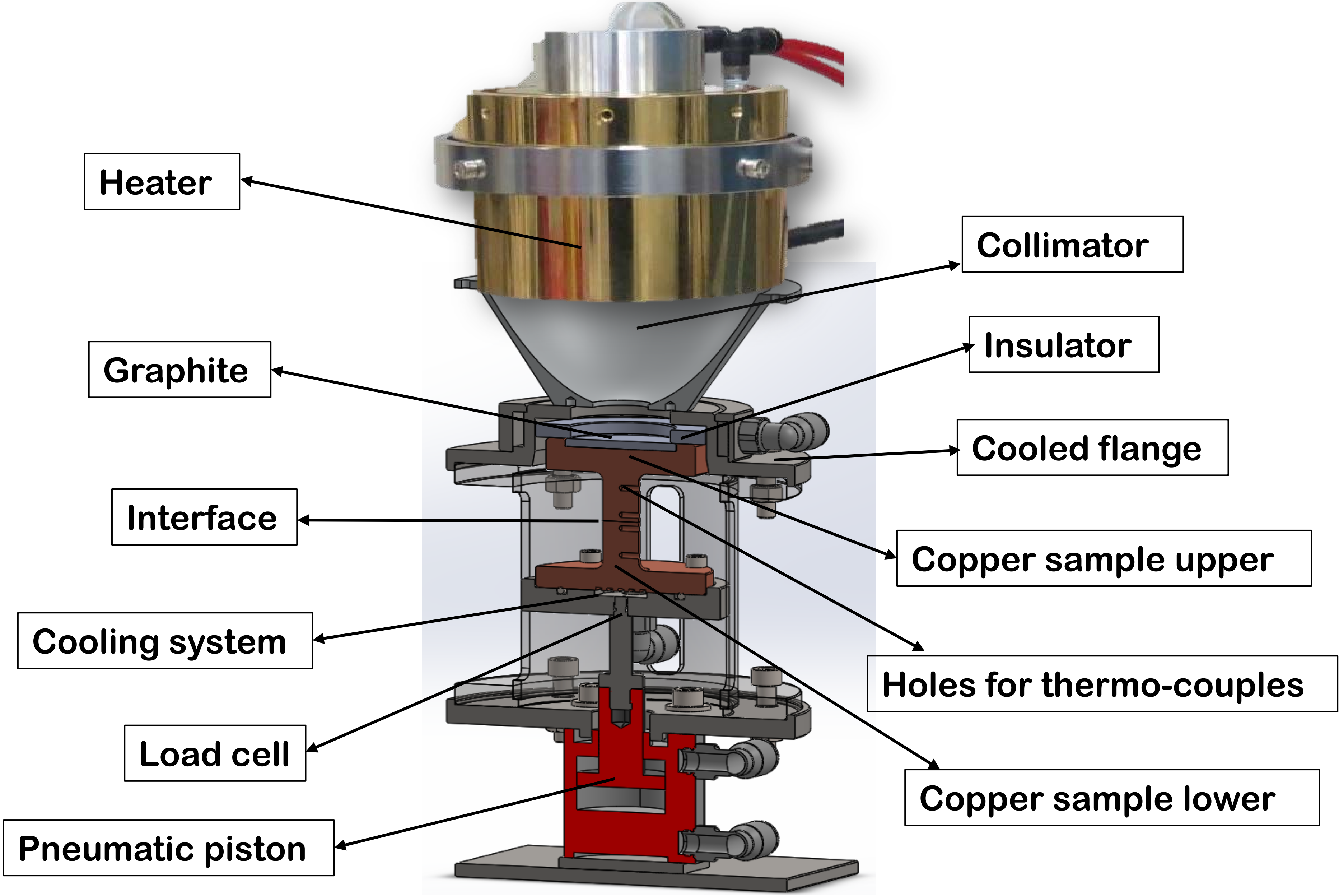
Experimental set-up for TCR measurement

Experimental set-up designed in order to measure Thermal Contact Resistance (TCR) for **real systems**

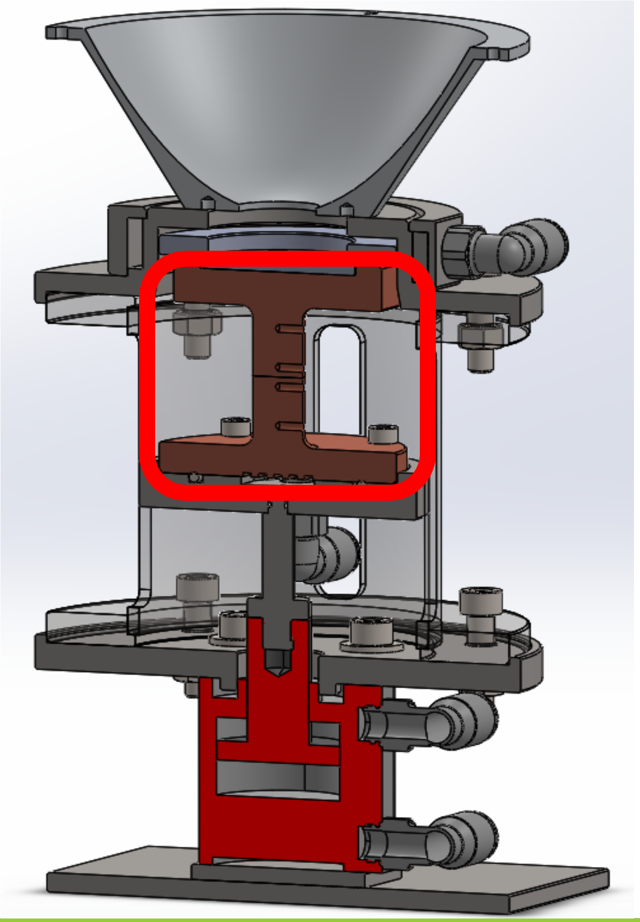
- **different target/heat sink materials**
  (Cu-OFE /Al alloys, other materials)
- **different surface finishing**
  (turning, grinding, lapping)
- **different contact pressures**
  (1.3 – 4.2 MPa)
- **different surface oxidation level**

Experimental set-up for TCR measurement

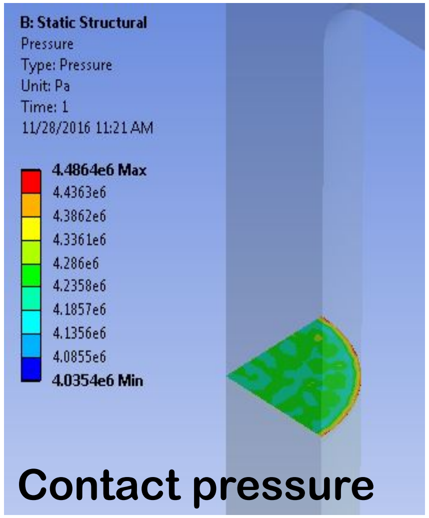


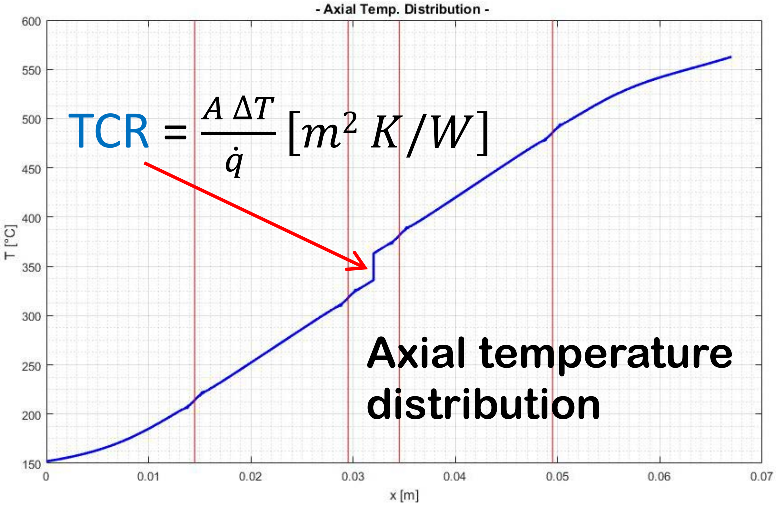

Heater
Collimator
Insulator
Graphite
Cooled flange
Interface
Copper sample upper
Cooling system
Holes for thermo-couples
Load cell
Copper sample lower
Pneumatic piston

Samples geometry chosen



- ANSYS thermal and structural FEM to get:
  - a uniform contact pressure at interface
  - a linear temperature distribution along the axis

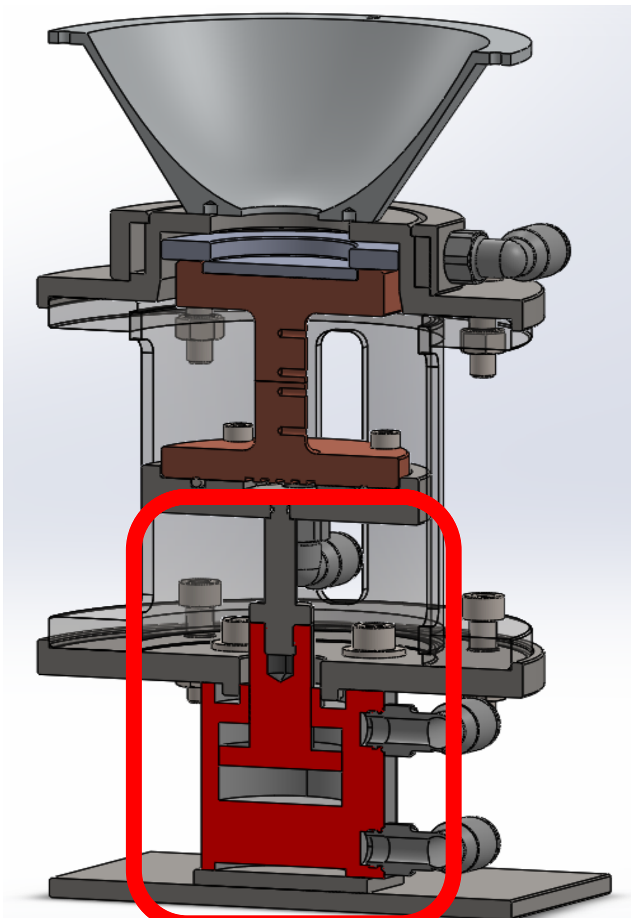


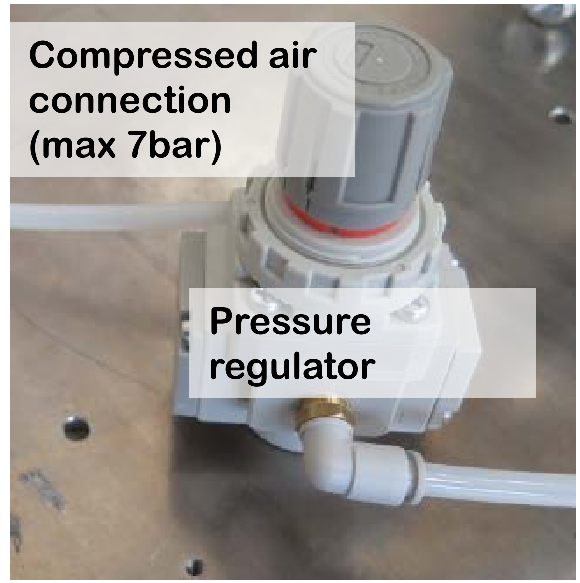


- 4 K-Thermocouples
- Different surface treatments at interface

Pressure load system

- Compressed air driven pneumatic piston to tune the samples contact pressure

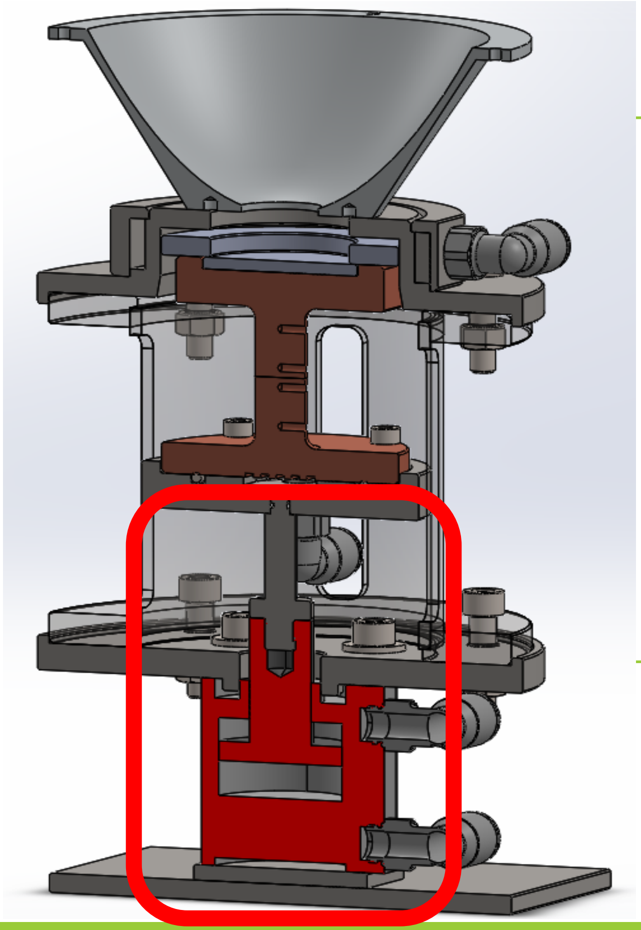




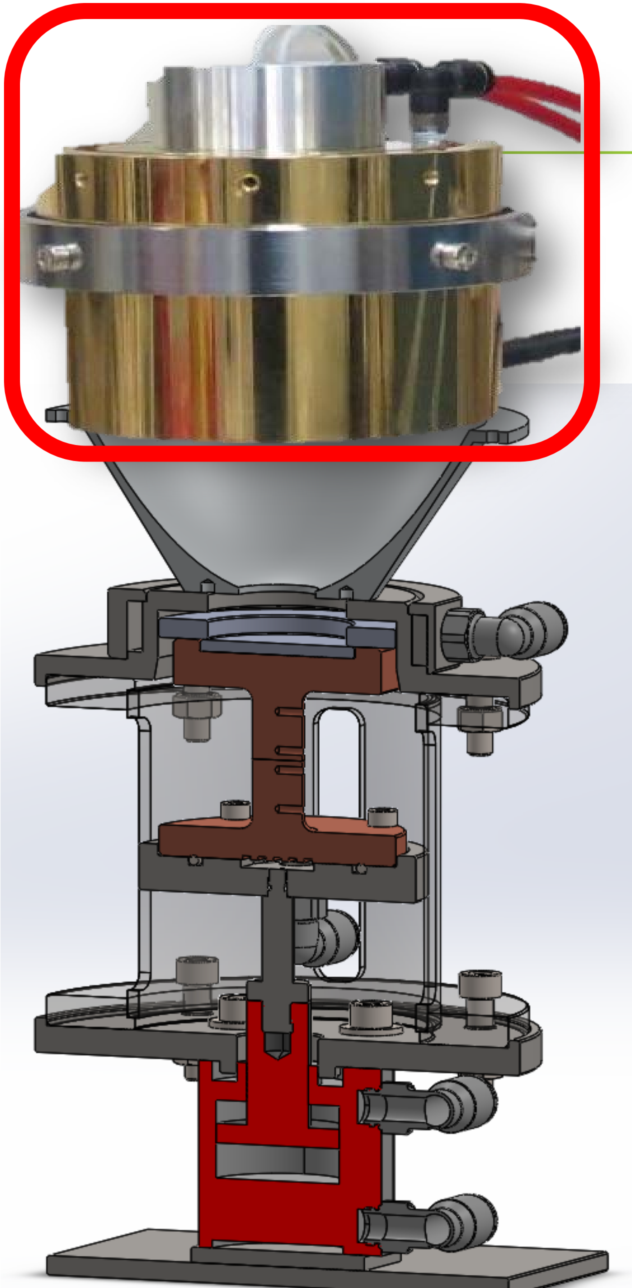
- Load cell to measure the force used to keep the samples pressed

FX1901 Compression Load Cell

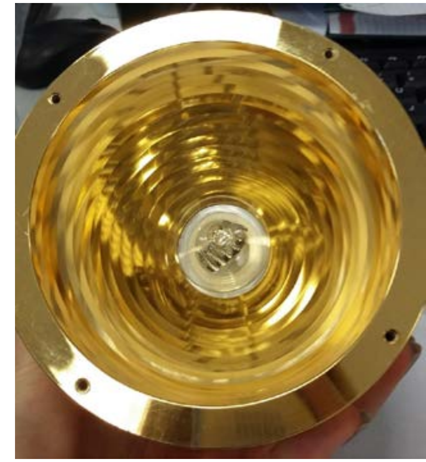
Air pressure – Contact pressure loads ranges



Air pressure [bar]	Contact pressure [Mpa]
2	1,3
3	1,9
4	2,5
5	3,1
6	3,6
7	4,2



Heat source - IR lamp main data



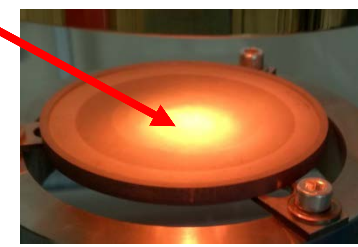
Main Electric parameters

- Power supply voltage: 0-100 V
- Absorbed Power: 1 kW

IR output range

- Beam spot Ø15 mm

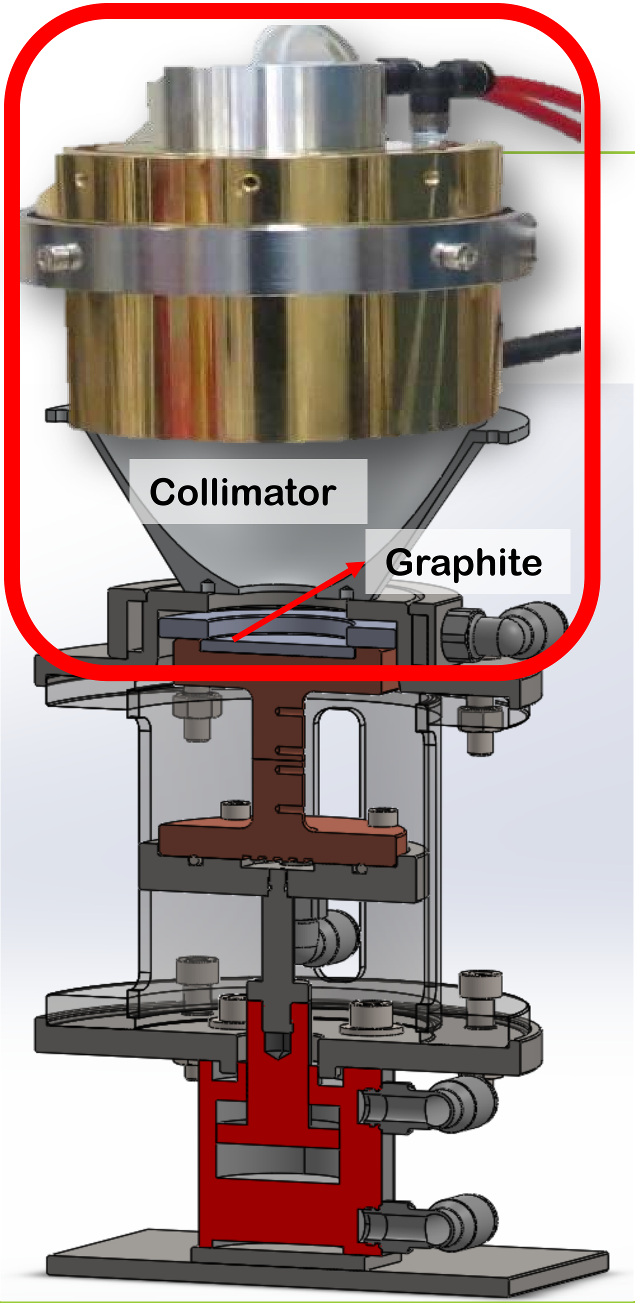
Declared beam power density



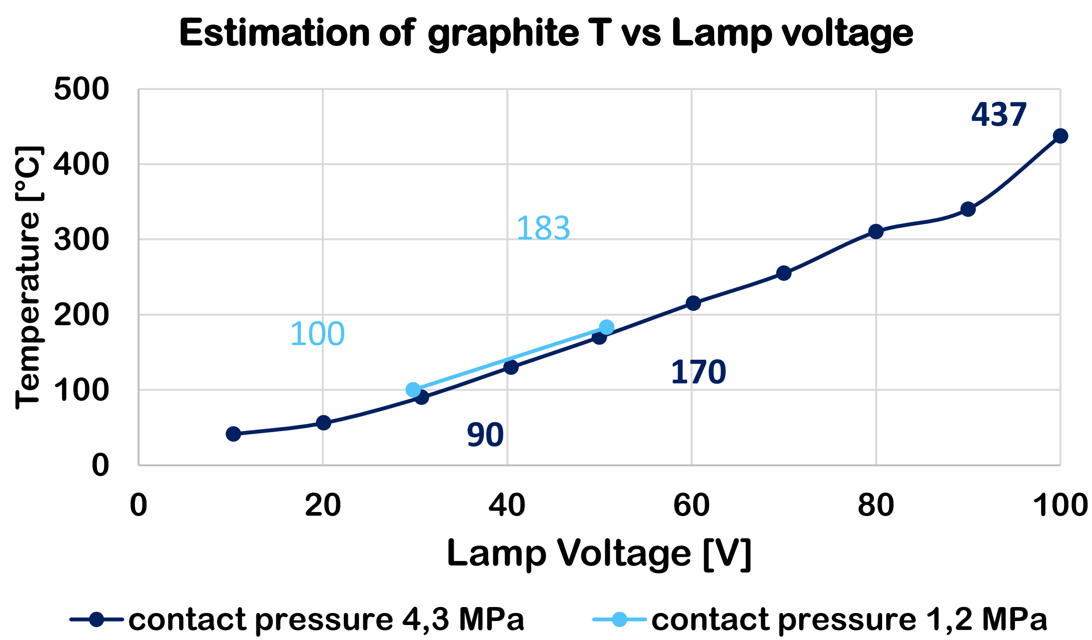
- approximately 124 W/cm^2

Max. heating temperature: 1000 °C

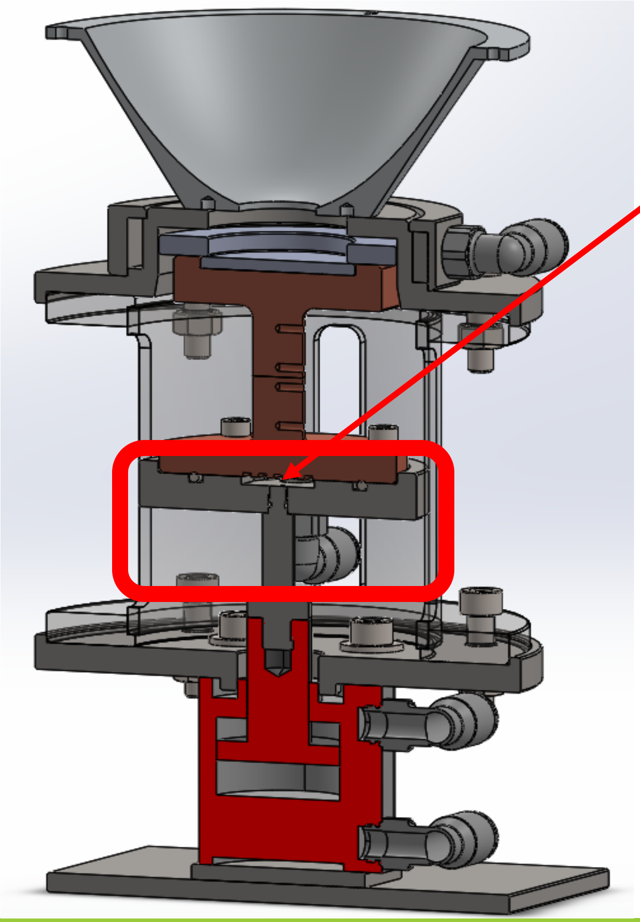
Heat source- IR lamp



- Use of collimator to focus the spot and protect the eyes
- Use of graphite disk to absorb better IR (Cu and Al reflect IR light)



Water cooling

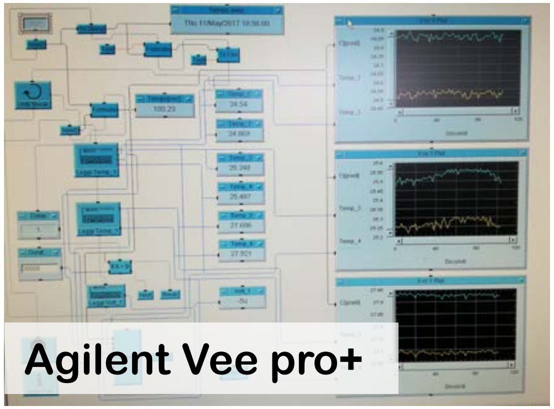


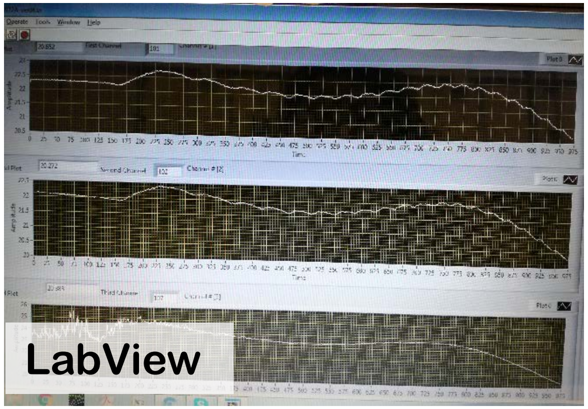
- Chiller
- Cooling chamber in contact with the lower sample
- RTD sensors to acquire water Inlet and Outlet temperature
- Ultrasonic flowmeter to control the water flow rate

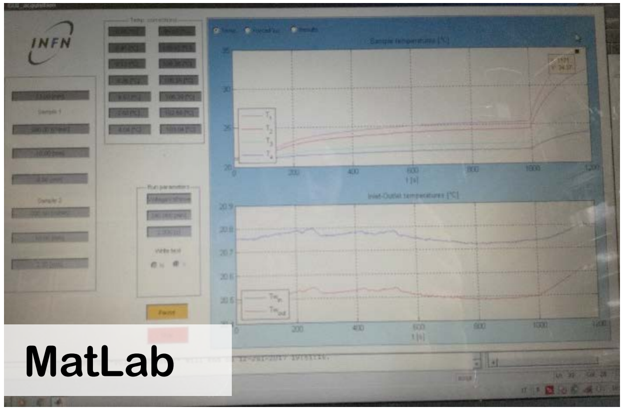
Data acquisition system

- Agilent for board sensors connection

- Program to record the data
  - Agilent Vee pro+
  - Labview
  - MatLab

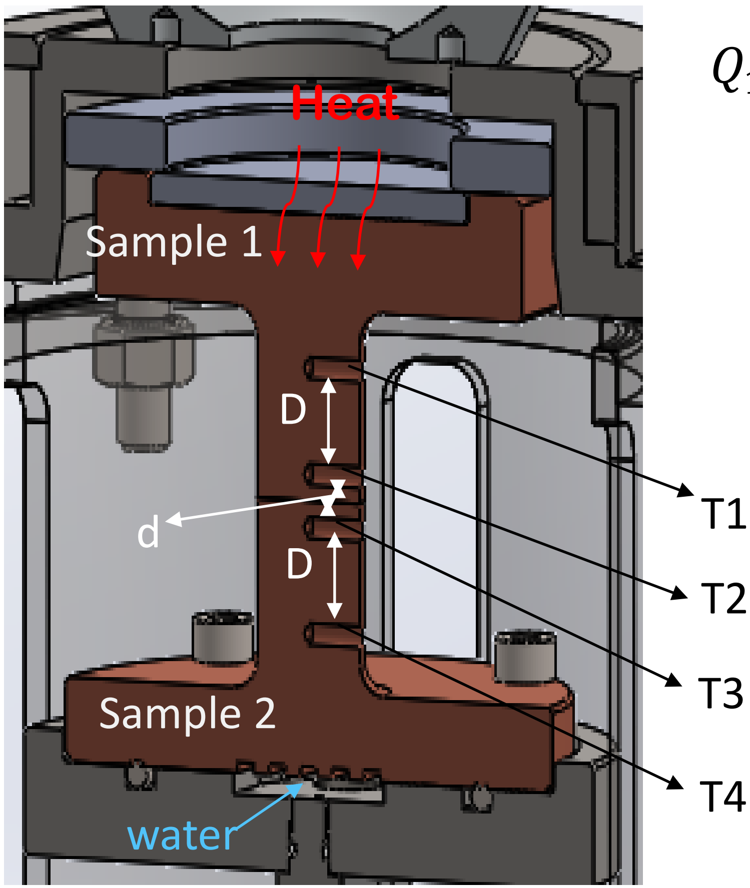






- Calibration of T sensors in respect to calibrated TC
  - Error in Tc reading with Agilent vs channel

TCR estimation based on measured parameters



$$Q_1 = \frac{k \cdot A \cdot (T_1 - T_2)}{D} \qquad Q_2 = \frac{k \cdot A \cdot (T_3 - T_4)}{D}$$

$$Q_{water} = h_c \cdot A \cdot (T_{w\,out} - T_{\mathrm{w\,in}})$$

$$\text{Power density} = \text{mean}\,\{\frac{Q1}{A} \ldots \frac{Q2}{A}\}$$

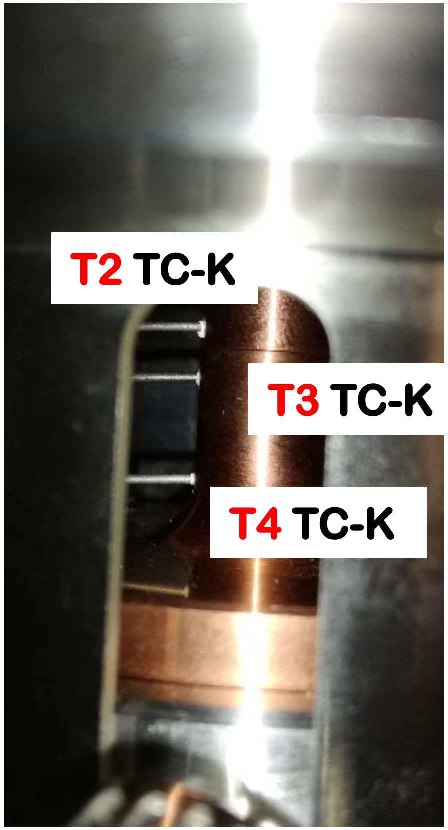
$$T_{cont\,1} = T_2 - [\frac{(T_1 - T_2)}{D} \cdot d]$$

$$T_{cont\,2} = T_3 + [\frac{(T_3 - T_4)}{D} \cdot d]$$

$$\mathrm{TCR} = \frac{T_{cont\,1} - T_{cont\,2}}{Power\ density}$$

First experimental test
Samples and water cooling system assembling

First experimental test
Temperature sensors and assembled system

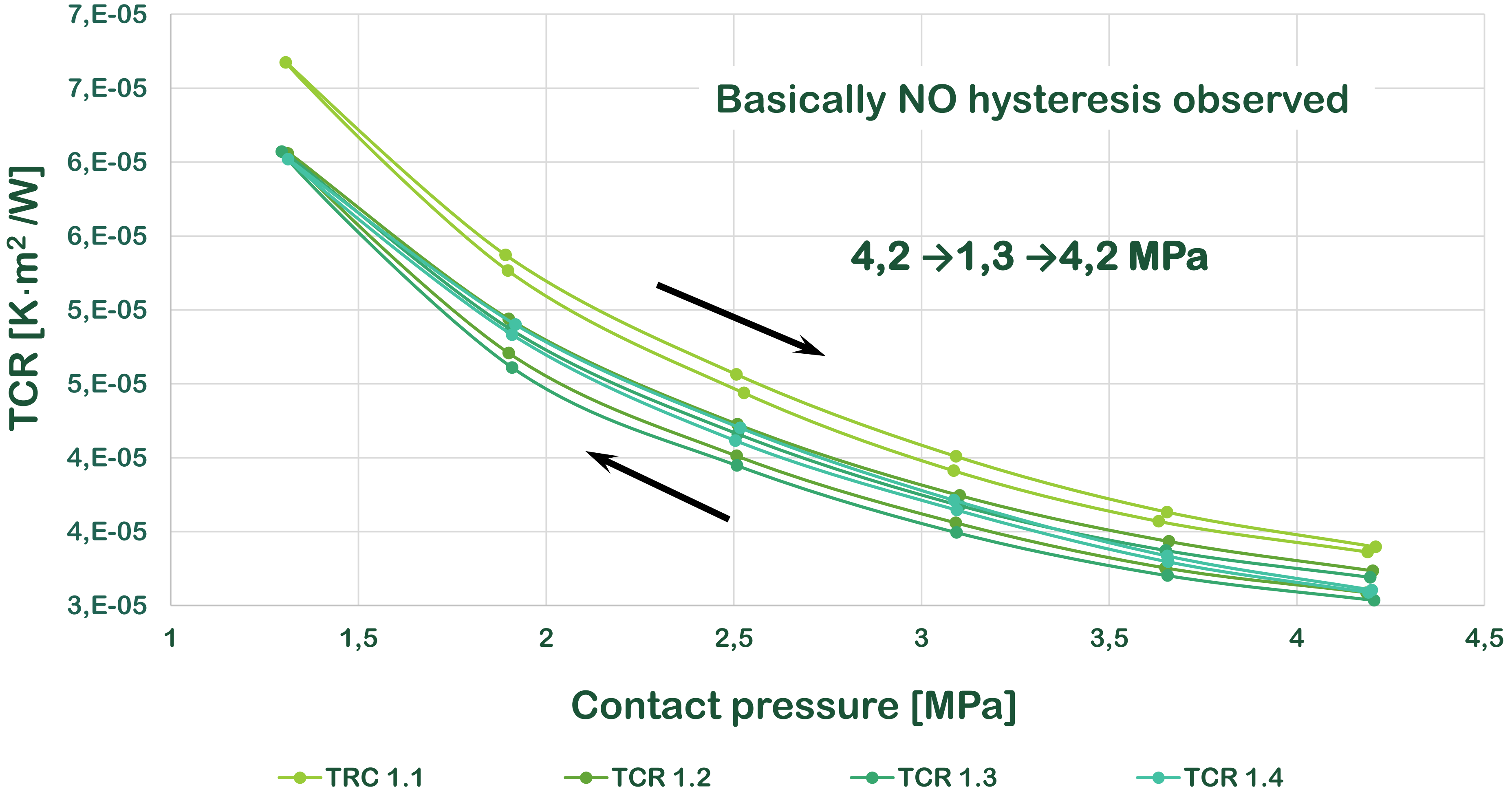


First experimental test
TCR vs Contact pressure

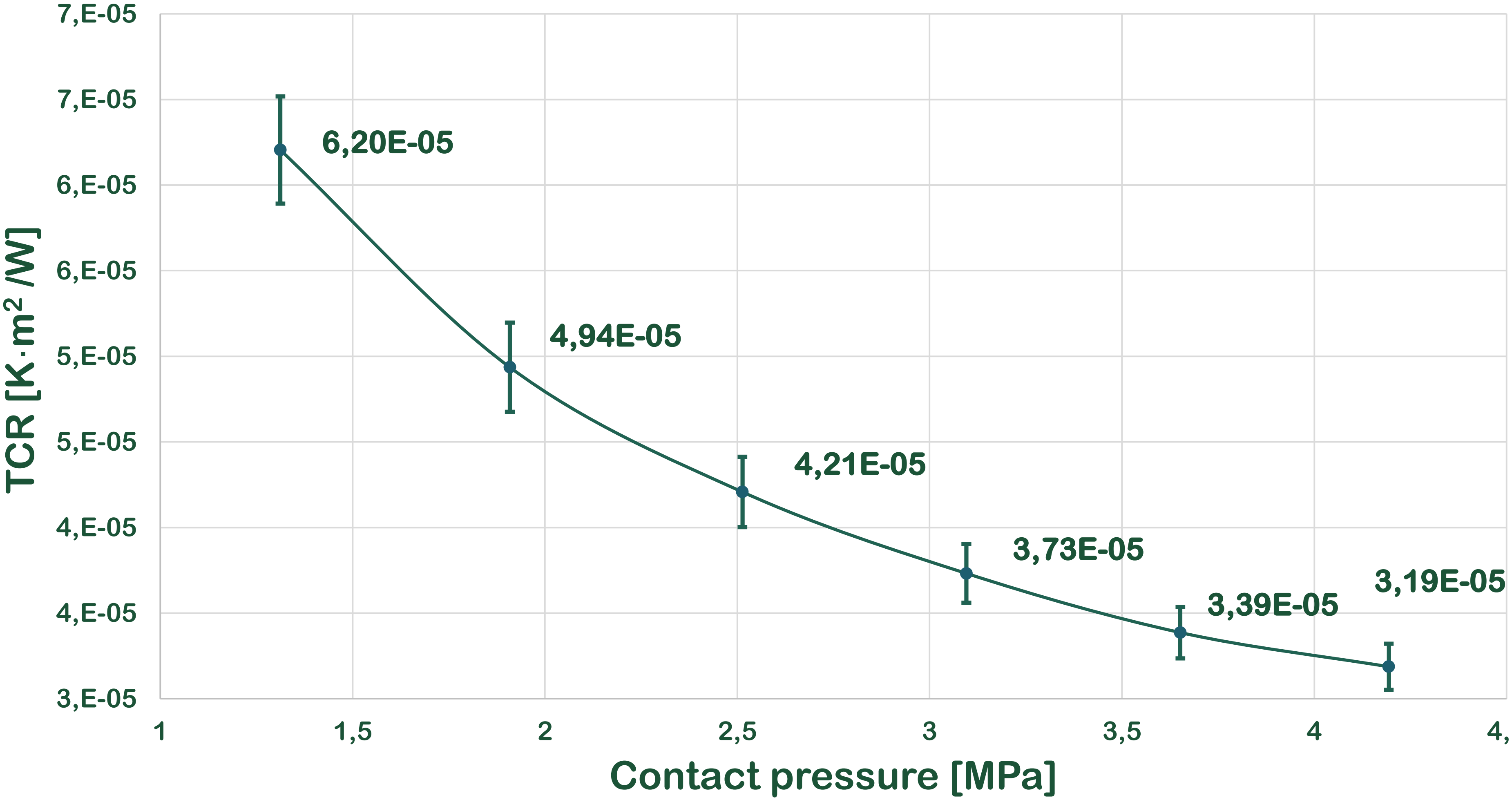
Conditions

Cooling of upper flange	NO
Collimator	YES
Lamp Voltage	50 V
Contact pressure [MPa]	4,2 → 1,3 → 4,2
Samples	Cu (standard turning R_{a}~3-5μm)
Water flow rate	2.4 l/min
Water inlet temperature	20 °C
Repetition	4 runs

First experimental test
TCR vs Contact pressure trend



First experimental test
TCR vs Contact pressure trend



First experimental test
Comparison with analytical model

$$TCC = 1{,}55\, k_s \left(\frac{m}{\sigma}\right)\left(\frac{\sqrt{2}p}{mE'}\right)^{0{,}94}$$

Working	Roughness R_a (µm)
Turning	0.2-6

TCC: thermal contact conductance [W m^{-2} K^{-1}]

k_s: 390 [W m^{-1} K^{-1}]

σ: 3 · 10^{-6} [m] (standard turning surface finishing)

m: 0,19

p: 4,2 · 10^{6} [Pa]

E’: 117 · 10^{9} [Pa]

TCC = 1,7 · 10^{4} W m^{-2} K^{-1}

↓

TCR_{model} = 5,8 · 10^{-5} m^2 K W^{-1}

TCR_{exp} = 3..4 · 10^{-5} m^2 K W^{-1}

Good matching between theoretical and experimental values

Thermal contact resistance at interface
Expected values at fixed surface roughness

Estimation of TCR vs Concact pressure

Cu-Cu, **0.1 µm**, 1kW/cm^2		
Pressure [MPa]	**TCR [K m^2 W^{-1}]**	**ΔT expected [K]**
4	2,0e-6	20
3	2,6e-6	26
2	3,8e-6	38
1	7,2e-6	72
0.5	1,4e-5	139

Taking into account a standard lapping surface finishing (R_a ~0.1 µm) the design specs may be achieved → minimal interface temperature drop.

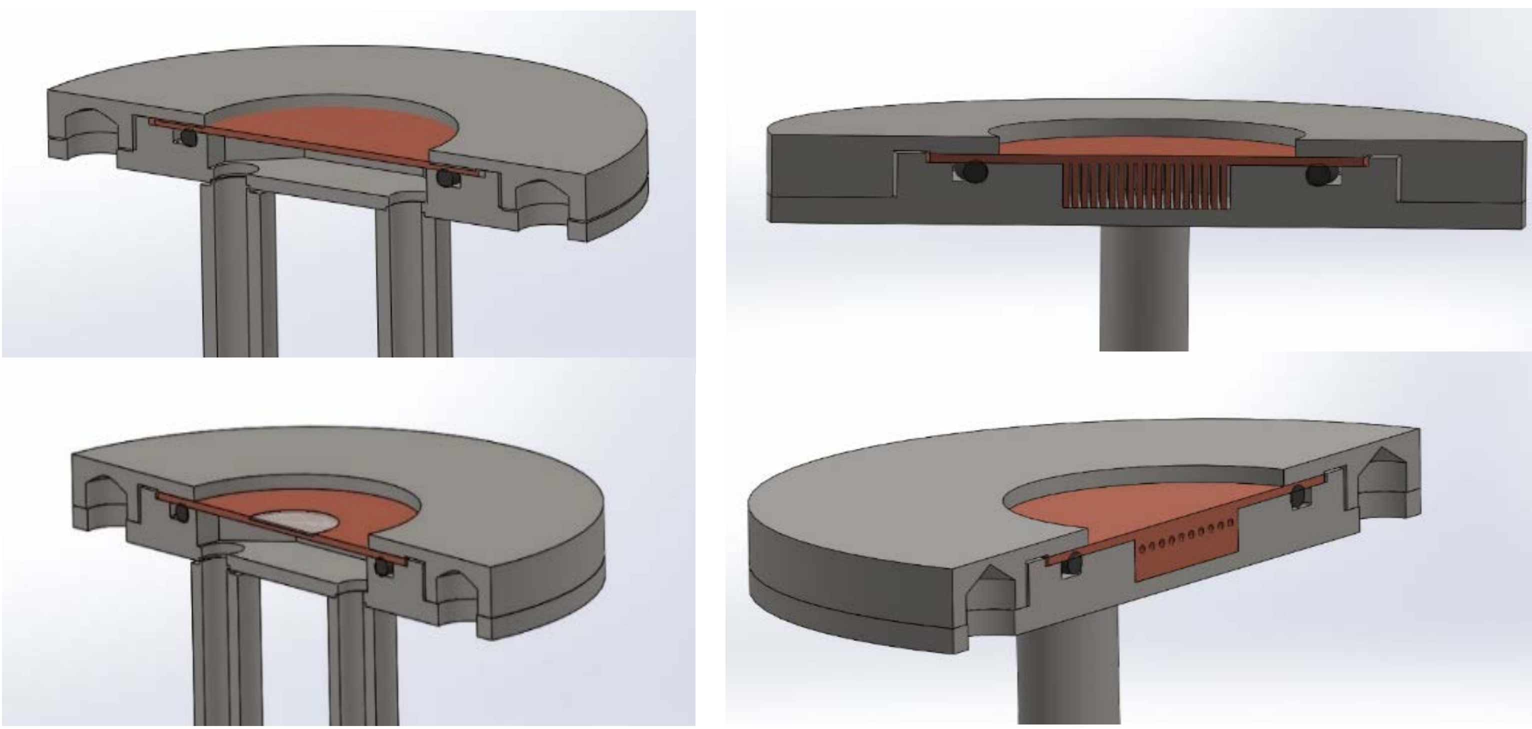
Future plan

- TCR vs roughness (lapped, standard turning, mirror-like)
- + Al samples
- Oxidized surfaces
- Use of protective coating (Au)

Future plan

Additional prospective

➢ Test particular cooling chamber system geometry (lamella, microchannel, non-standard geometries prepared with Additional Manufacturing)



Thank you for your kind attention!