

Optimisation of the thermal characteristics of an oxide high power target for radioactive ion beam production

E. Noah, F. Ames, E. Bouquerel, P. Bricault,
R. Catherall, M. Dombisky, S. Fernandes, P.
Kasprowicz, P. Kunz, J. Lettry, S. Marzari, S.
Mathot, T. Stora

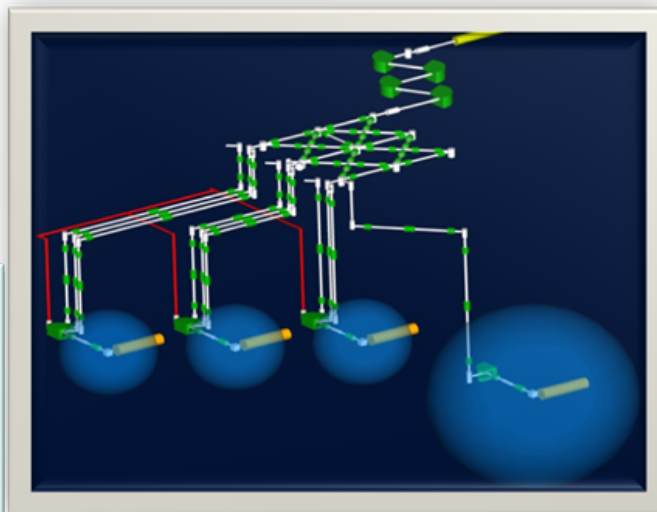
10th International Workshop on Spallation
Materials Technology
Beijing, 18-22nd October 2010

Optimisation of the thermal characteristics of an oxide high power
target for radioactive ion beam production
E. Noah, 10th IWSMT, 18-22nd October 2010

Outline

- >The EURISOL Design Study
- >Oxide targets
- >Thermal contact conductance studies
- >Optimisation
- >Summary

The EURISOL Design Study



100 kW direct targets

RIB production:

- Spallation-evaporation
 - Main: P-rich
(10 to 15 elements below target material)
 - Residues: N-rich
(A few elements below target material)

Target materials:

- Oxides
- Carbides
- Metal foils
- Liquid metals

Participants:
~20 institutions

Duration:
2005-2009

Contributors:
~20 institutions

12 Tasks

EU support (~30%):
~9.2 MEuros

mMW fission target

RIB production:

- Fission
- N-rich
- Wide range
 $Z = 10$ to $Z = 60$

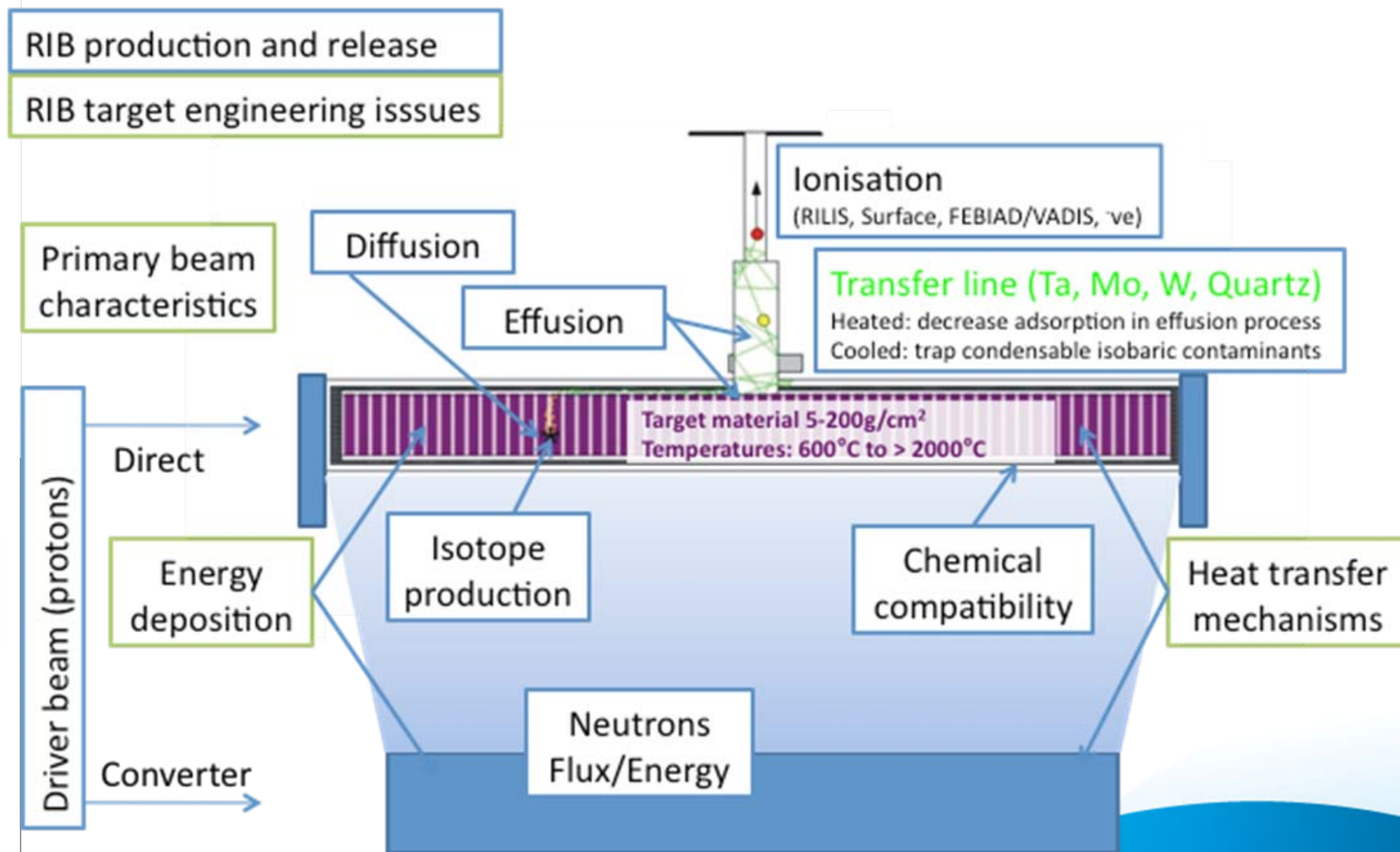
Target material:

- U (baseline)
- Th

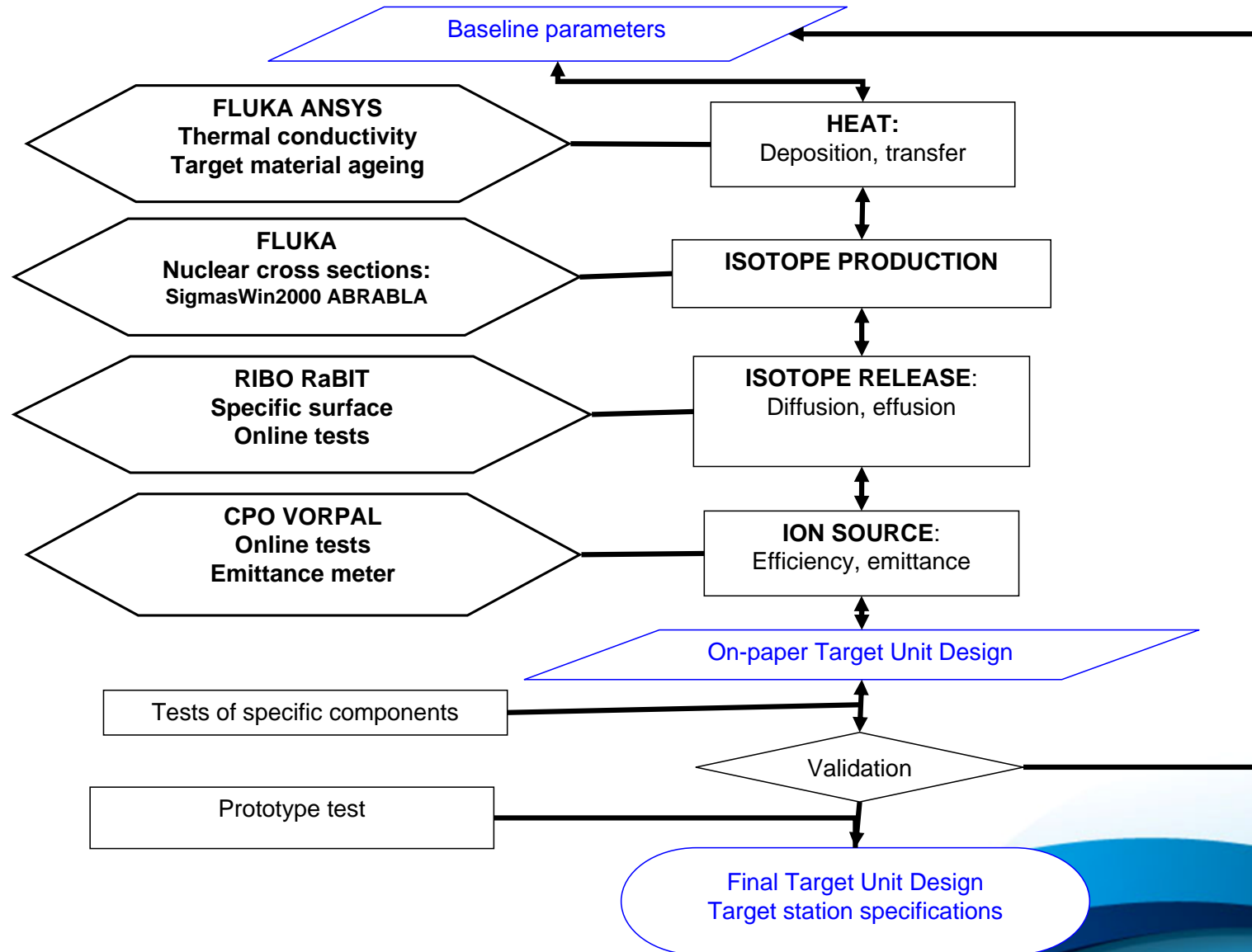
Converter:

- Hg

Radioactive Ion Beam Target



EURISOL 100 kW Target Design

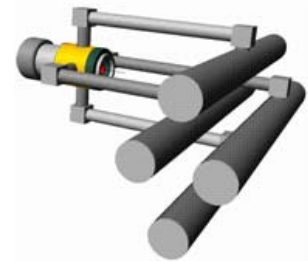


EURISOL 100 kW Baseline Parameters

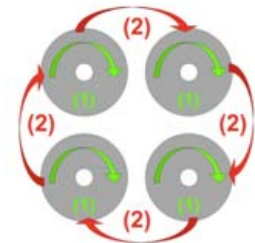
Parameter	Symbol	Units	Nval	Range
Target material	Z_{targ}	-	SiC, Ta, BeO, Pb (molten)	Be-U
Beam particles	Z_{beam}	-	Proton	Deuterium – ^{12}C
Beam particle energy	E_{beam}	GeV	1	0.5 – 3
Beam current	I_{beam}	μA	100	100 – 1000
Beam time structure	-	-	dc	ac 50Hz 1ms pulse
Gaussian beam geometry	σ_{beam}	mm	7	3 – 20
Beam power	P_{beam}	kW	100	100-1000
Target thickness	X	g/cm^2	200	10 – 250
Target radius (cylinder)	r_{targ}	mm	$3 \sigma_{\text{beam}}$	$3 \sigma_{\text{beam}} - 5 \sigma_{\text{beam}}$
Target temperature	T_{targ}	$^{\circ}\text{C}$	2000	500-2500
Number of target containers	j_{targ}	-	4	1 – 10
Plasma ionization outlet diameter	\varnothing_{out}	mm	3	2 – 6

100 kW Direct Target Issues

- Heat dissipation + target temperature profile optimisation are main drivers of 100 kW direct target design:
 - Uniform high temperature for fast diffusion and effusion
 - Avoid cold spots where isotopes could condense
 - Heat dissipation by conduction/thermal radiation T^4
 - Compact target geometries to minimise effusion losses
- Solid targets: Oxides and Carbides
 - Oxides: thermal insulators (e.g. ThO_2 0.4 W/mK @1673 K)
 - Relatively low operation temperature (e.g. CaO 1673 K)
 - Composite target pills
 - Multibody target concept + neutral beam merging
- Solid targets: Metal foils
 - Foil thickness optimisation for mechanical properties/diffusion
- Liquid metal targets:
 - Loop required to dissipate factor x20 more heat than can be accommodated classically
 - Diffusion chamber required to optimise release efficiency of short-lived isotopes

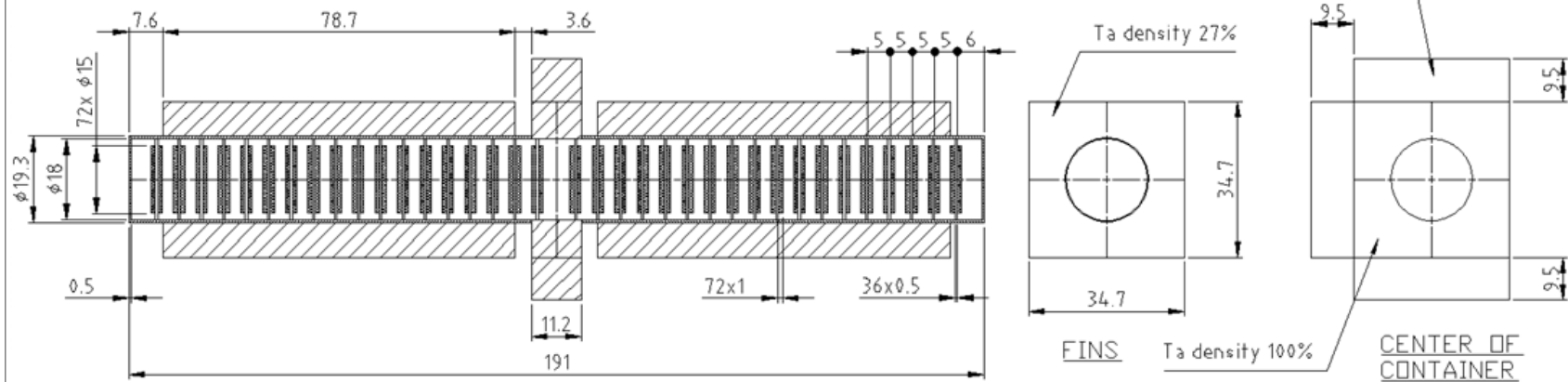
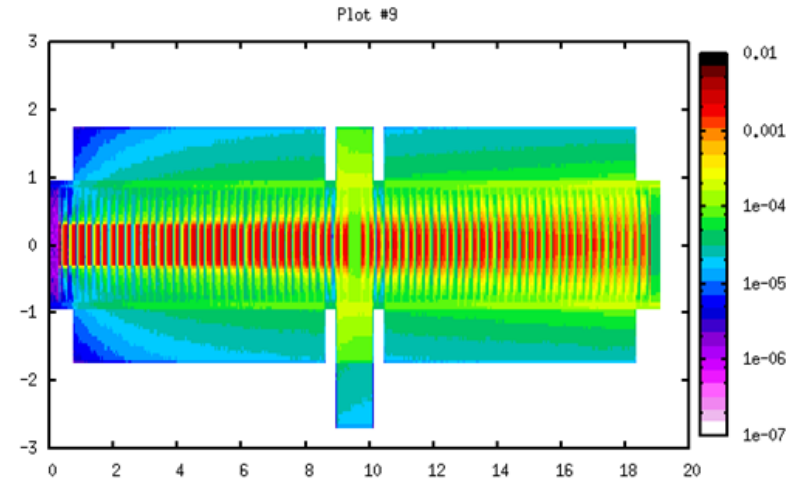
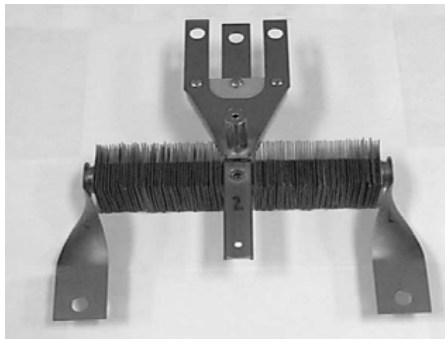


Multi-body target



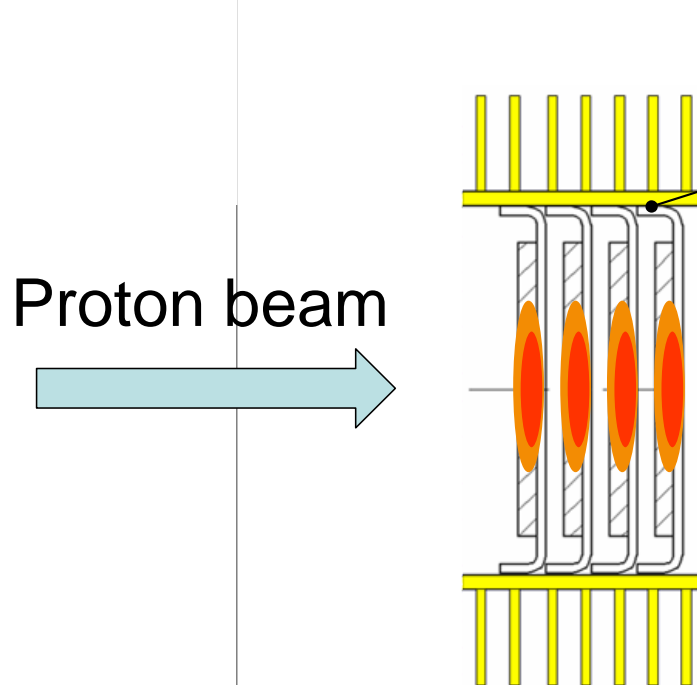
Beam sharing
between sub-units
of one target station

High Power Oxide Target Prototype



Thermal Design Principle

1. The proton beam deposit the power on the Al_2O_3 pills and Nb sheets
2. This generated heat is dissipated by **radiation and conduction** to the Ta container
3. Then the power is dissipated by **radiation** to the surrounding environment



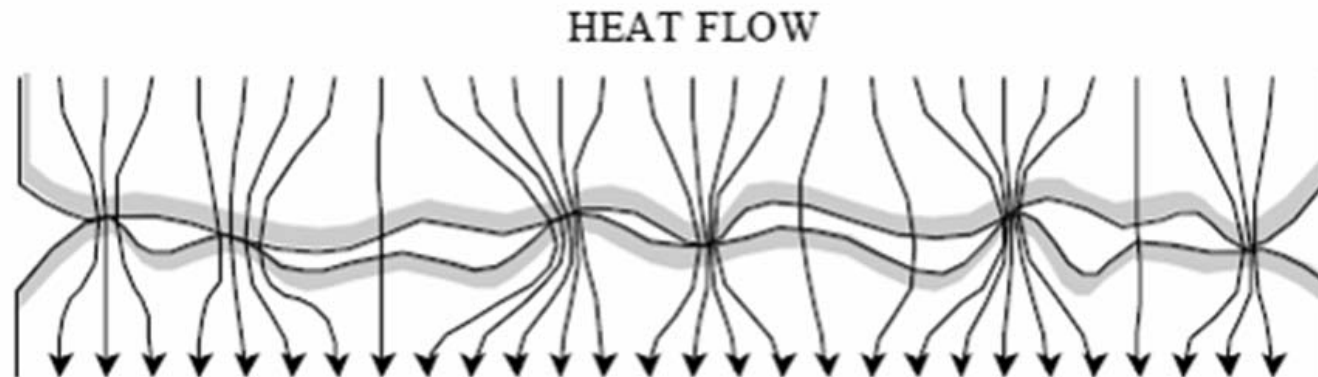
Thermal contact between Nb sheet
and Ta container area

Challenges:

- **imperfect geometry of the Ta container** (diameter and shape tolerances)
- **Imperfect geometry on the Nb support**
- **fragility** of the pills and brazing during mounting
- no defined value of the **thermal conductance** between Nb support and container

Thermal Design Principle

- The thermal **contact conductance** is the main unknown parameter for the simulations.
- This value depend on geometry, surface finish, pressure, materials choice, temperature range.
- For our working ranges of 1000...1500° C it's very difficult to find reliable values in the literature.
- Hence decision to do thermal measurements on an electron beam setup.
- The conductance value [W/m²K] is an average value for a covered contact area, this value includes exchanges by **conduction** and by **radiation** between the 2 surfaces.



Initial Nb Geometry Configurations

- The Nb support shape is given by stamping on a pre cut sheet (of 0.5mm thickness)
- 3 Nb sheets geometry:
 1. stamped and lathed to a normalized exterior diameter (slightly forced mounting)
 2. stamped on a 8 x 1mm groove sheet (contact work on elasticity)
 3. stamped on a 16 x 1mm groove sheet (contact work on elasticity)



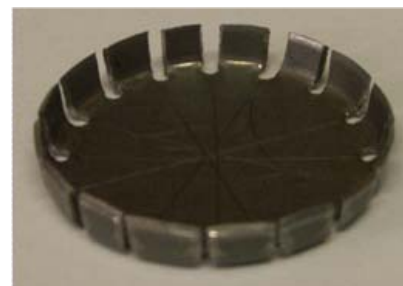
Sample 1: rigid & asymmetric

Theoretical contact surface= 130mm²



Sample 2: elasticity 0.2mm

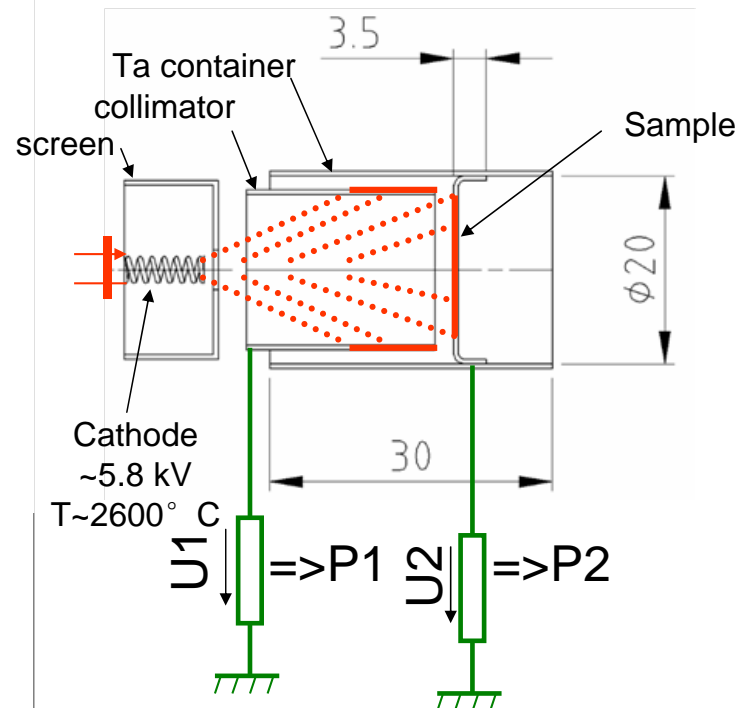
Theoretical contact surface= 137mm²



Sample 3: elasticity 0.2mm

Theoretical contact surface= 117mm²

Thermal Contact Conductance



2 heating effects on sample :

1. By electron beam deposition
2. By cathode radiation

First Trials

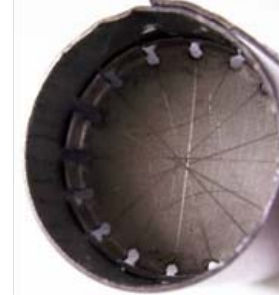
Mounting



Sample 1:
 (only 3 or 4
 contacts points)

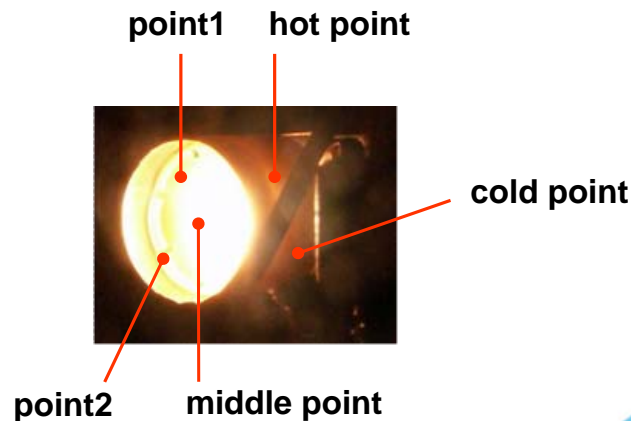


Sample 2:
 (forced mounting, 8
 contacts points)



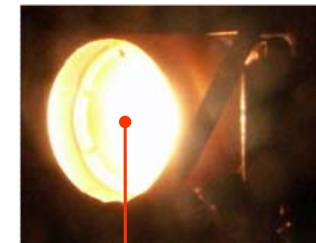
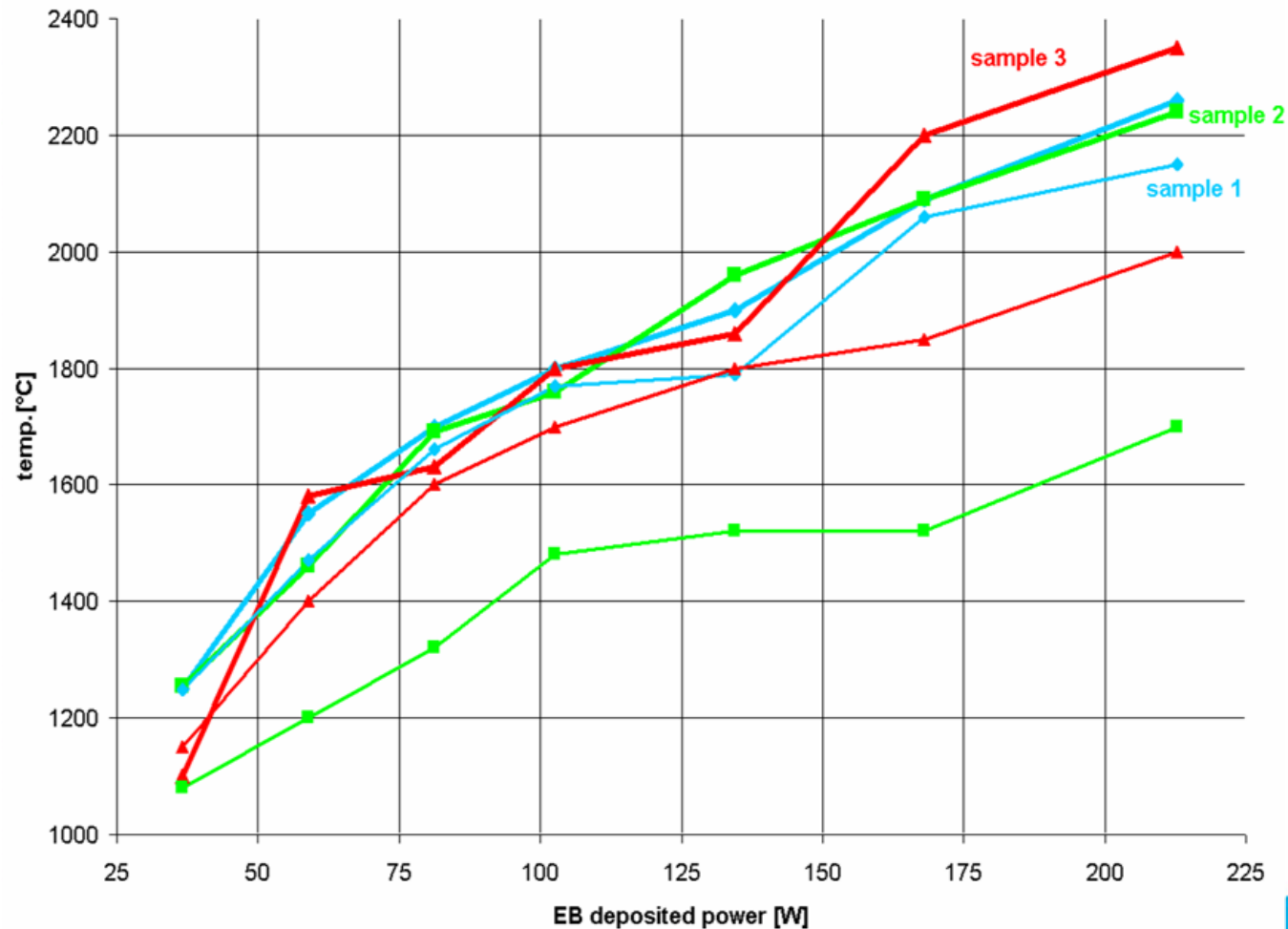
Sample 3:
 (forced mounting, 16
 contact points)

Thermal measurements



Thermal Measurements

Max./Min. temp. on Nb support = $f(P)$



Max./Min. temp.



sample1



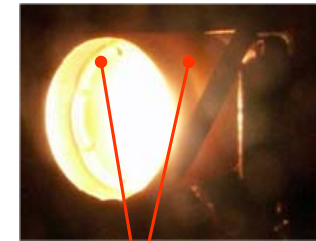
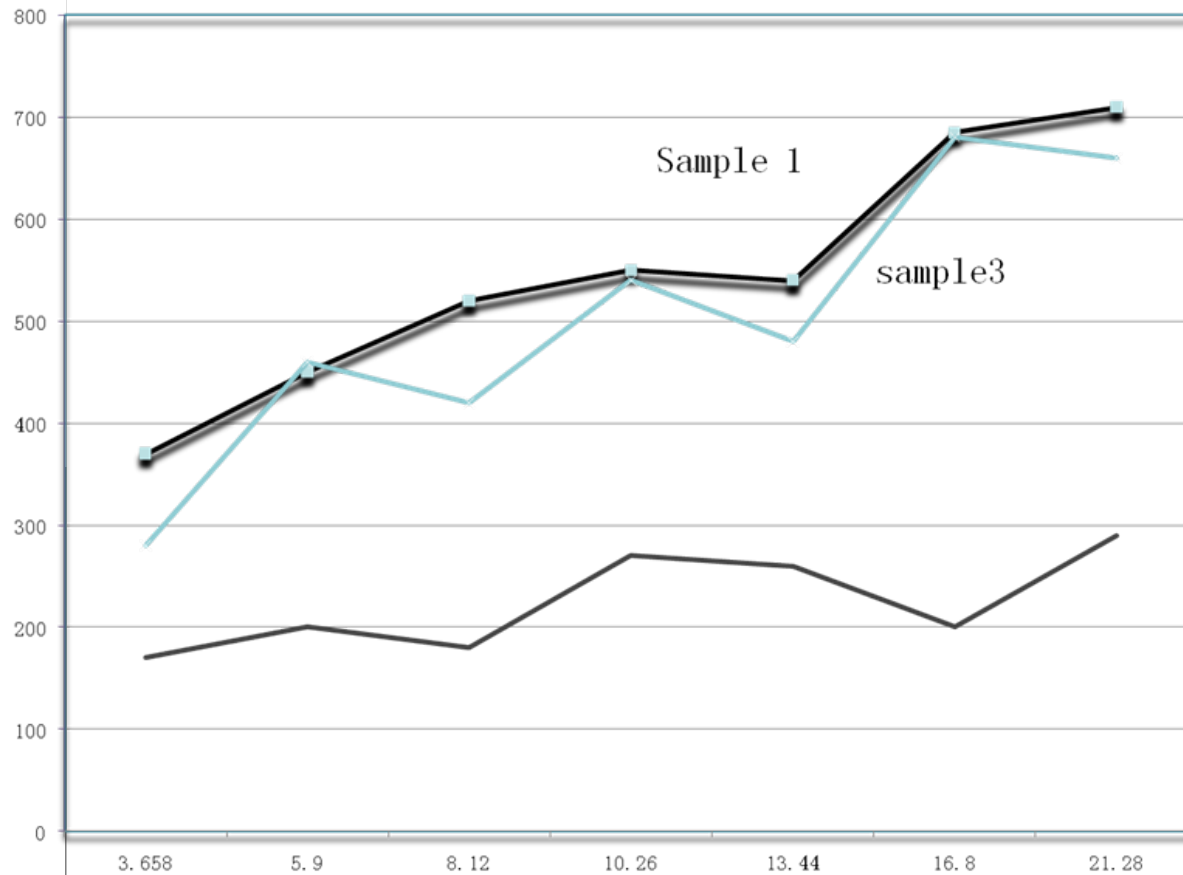
sample2



sample3

Thermal Measurements

Delta T on contact region [$^{\circ}\text{C}$]



Delta T



sample1



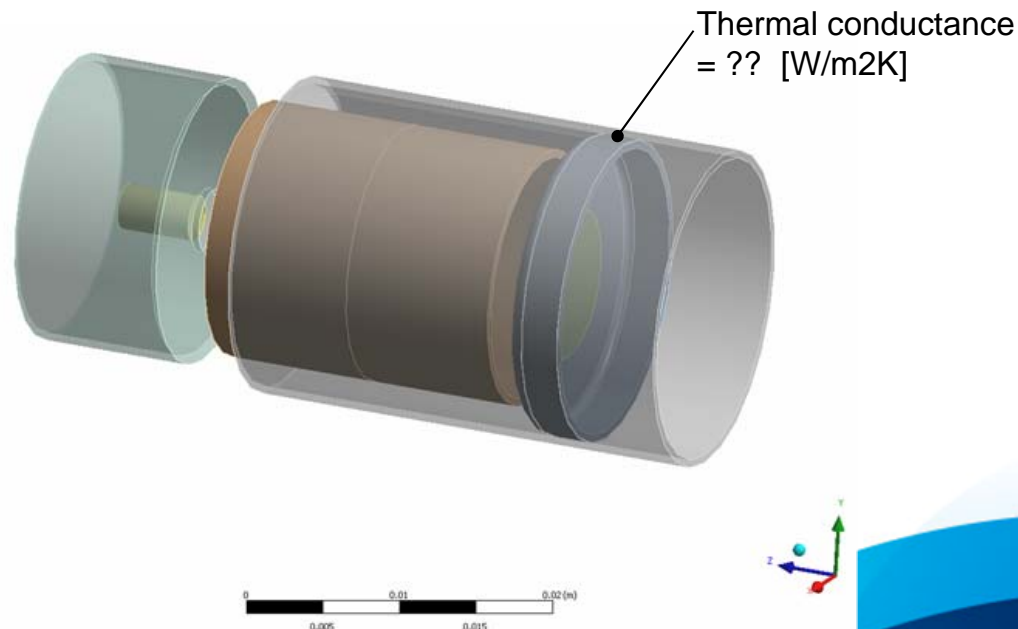
sample2



sample3

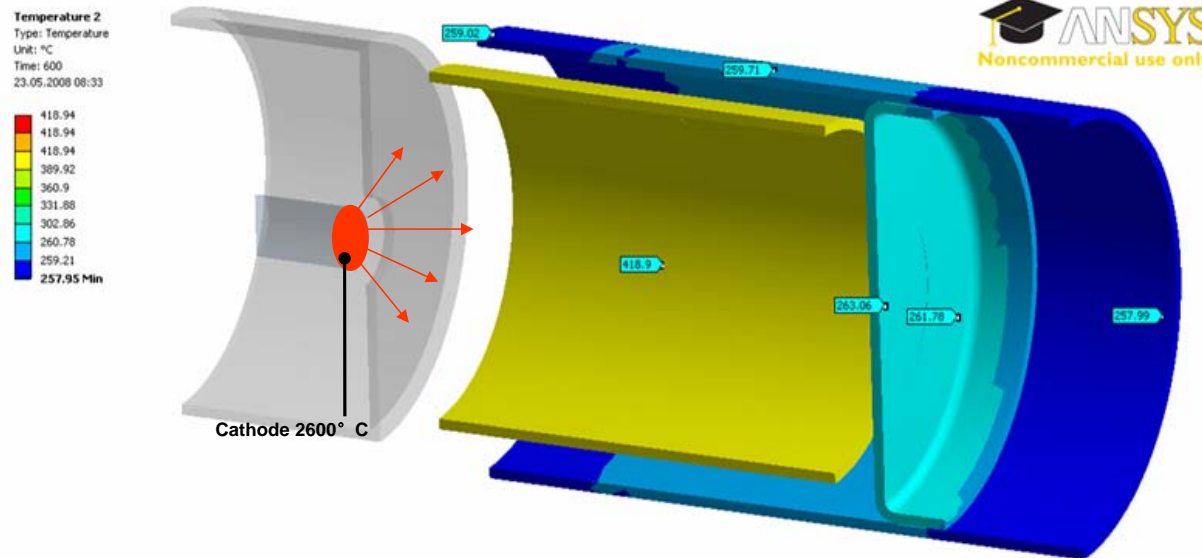
Simulating Thermal Contact Cond.

- To understand the thermal contact behavior: simulate the full setup with Ansys Workbench 11.0.
- The goal is to introduce the real loads and boundary conditions in the model (deposited power, temperatures, material emissivity...).
- Then vary the thermal conductance as a parameter to obtain a good fit between model and measurements
- Simplified geometry:



Cathode Heating

- Verify whether the **effect of the cathode radiation** is negligible ?
- The cathode is heated to 2600°C and a transient analysis of 600 s is run
- **Simulation results:**



=> The radiation effect of the cathode is not negligible !!!

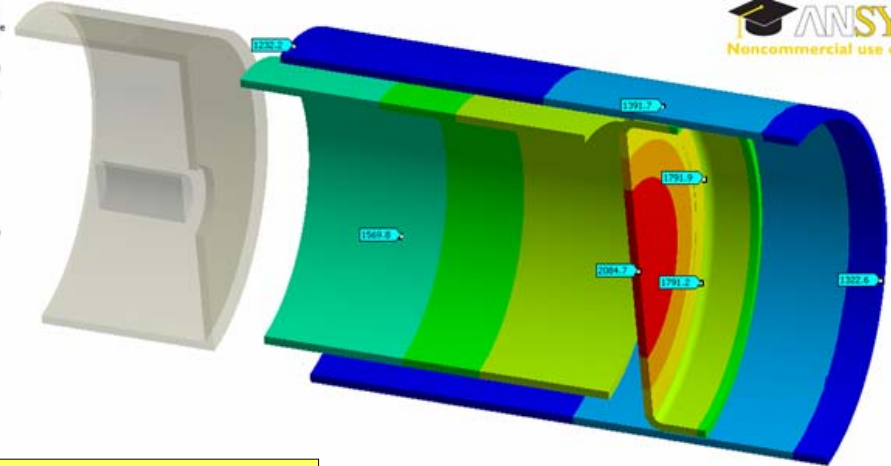
Simulating Thermal Contact Cond.

- **The second step** is to add the EB deposition on Nb support + collimator (59+28W) & (213+84W) and vary the thermal conductance of the contact (250...2000W/m²K)
- The cathode is heated to 2600° C and a transient analysis of 600 s is run
- **Simulation results:**



sample2

Temperature Z
Type: Temperature
Unit: °C
Time: 600
22.05.2008 10:23



ANSYS
Noncommercial use of

Collimator POWER [W]	Nb_support + container		Nb_support						container			
	POWER		point2		middle point		point3		hot point		cold point	
	[W]		em	temp	em	temp	em	temp	em	temp	em	temp
SAMPLE 2	17.7	36.58	0.15	1180	0.2	1155	0.2	1248	0.1	1110	0.1	840
	28.32	59	0.15	1200	0.2	1460	0.2	470	0.1	1000	0.1	900
	40.6	81.2	0.2	1320	0.2	1690	0.2	1660	0.15	1140	0.15	1060
	47.88	102.6	0.2	1480	0.2	1760	0.2	1770	0.15	1210	0.15	1120
	56	134.4	0.2	1520	0.2	1960	0.2	1790	0.15	1260	0.15	1200
	61.6	168	0.2	1520	0.2	2090	0.2	2060	0.15	1320	0.15	1310
	84	212.8	0.2	1700	0.2	2240	0.2	2150	0.15	1410	0.15	1430

Ansysis results for thermal
conductance = 1000
[W/m²K]

Ansysis results for
thermal conductance =
1500 [W/m²K]

Simulating Thermal Contact Cond.

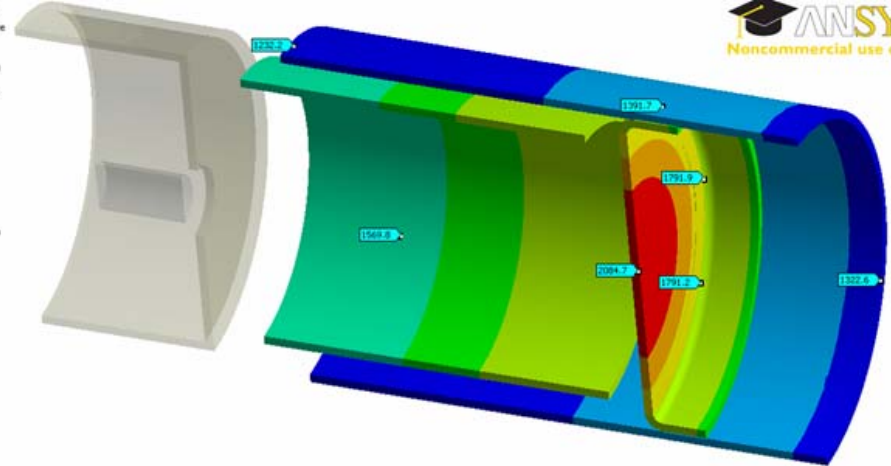
- **The second step** is to add the EB deposition on Nb support + collimator (59+28W) & (213+84W) and vary the thermal conductance of the contact (250...2000W/m²K)
- The cathode is heated to 2600° C and a transient analysis of 600 s is run
- **Simulation results:**



sample1

Temperature Z
Type: Temperature
Unit: °C
Time: 600
22.05.2008 18:23

2085 Max
1990.2
1895.4
1800.6
1705.8
1611.1
1516.3
1421.5
1326.7
1231.9 Min



Collimator	Nb_support+container	Nb_support						container			
POWER	POWER	point2		middle point		point3		hot point		cold point	
[W]	[W]	em	temp	em	temp	em	temp	em	temp	em	temp
			~1345° C		~1410° C				~890° C		
SAMPLE 1											
17.7	36.58	0.15	1200	0.2	1350	0.2	1248	0.1	830	0.1	810
28.32	59	0.2	1500	0.2	1550	0.2	470	0.15	1050	0.1	905
40.6	81.2	0.2	1700	0.2	1700	0.2	1660	0.15	1180	0.15	1080
47.88	102.6	0.2	1750	0.2	1800	0.2	1770	0.15	1200	0.15	1190
56	134.4	0.2	1810	0.2	1900	0.2	1790	0.15	1270	0.15	1240
61.6	168	0.2	2100	0.2	2090	0.2	2060	0.15	1415	0.15	1255
84	212.8	0.2	2200	0.2	2260	0.2	2150	0.15	1490	0.15	1405

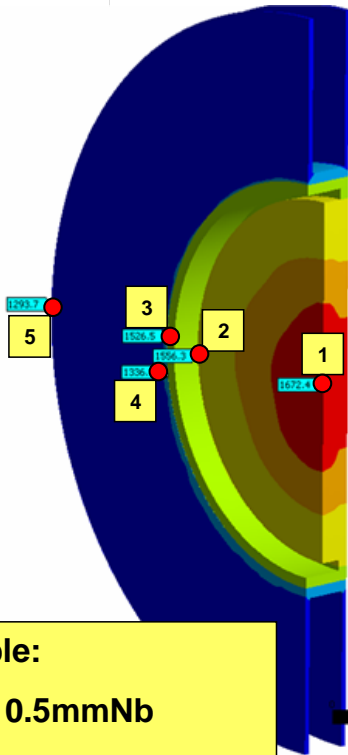
Ansysis results for
thermal conductance
= 250 [W/m²K]

Ansysis results for
thermal conductance
= 250 [W/m²K]

Optimisation of Nb Thickness 1/3

Temperature
Type: Temperature
Unit: °C
Time: 300
27.05.2008 09:55

1672.6 Max
1630.5
1588.3
1546.2
1504
1461.8
1419.7
1377.5
1335.3
1293.2 Min

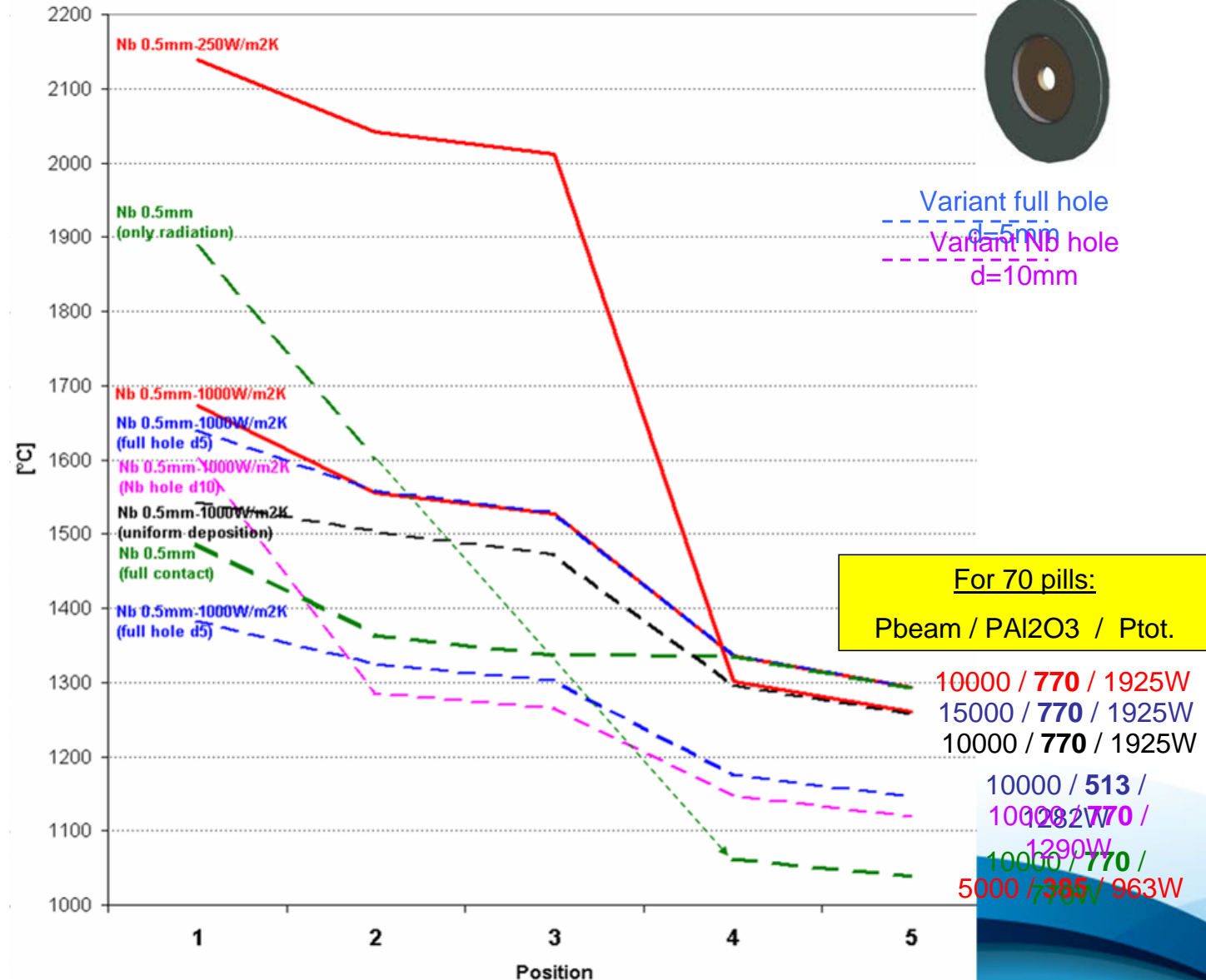


Example:

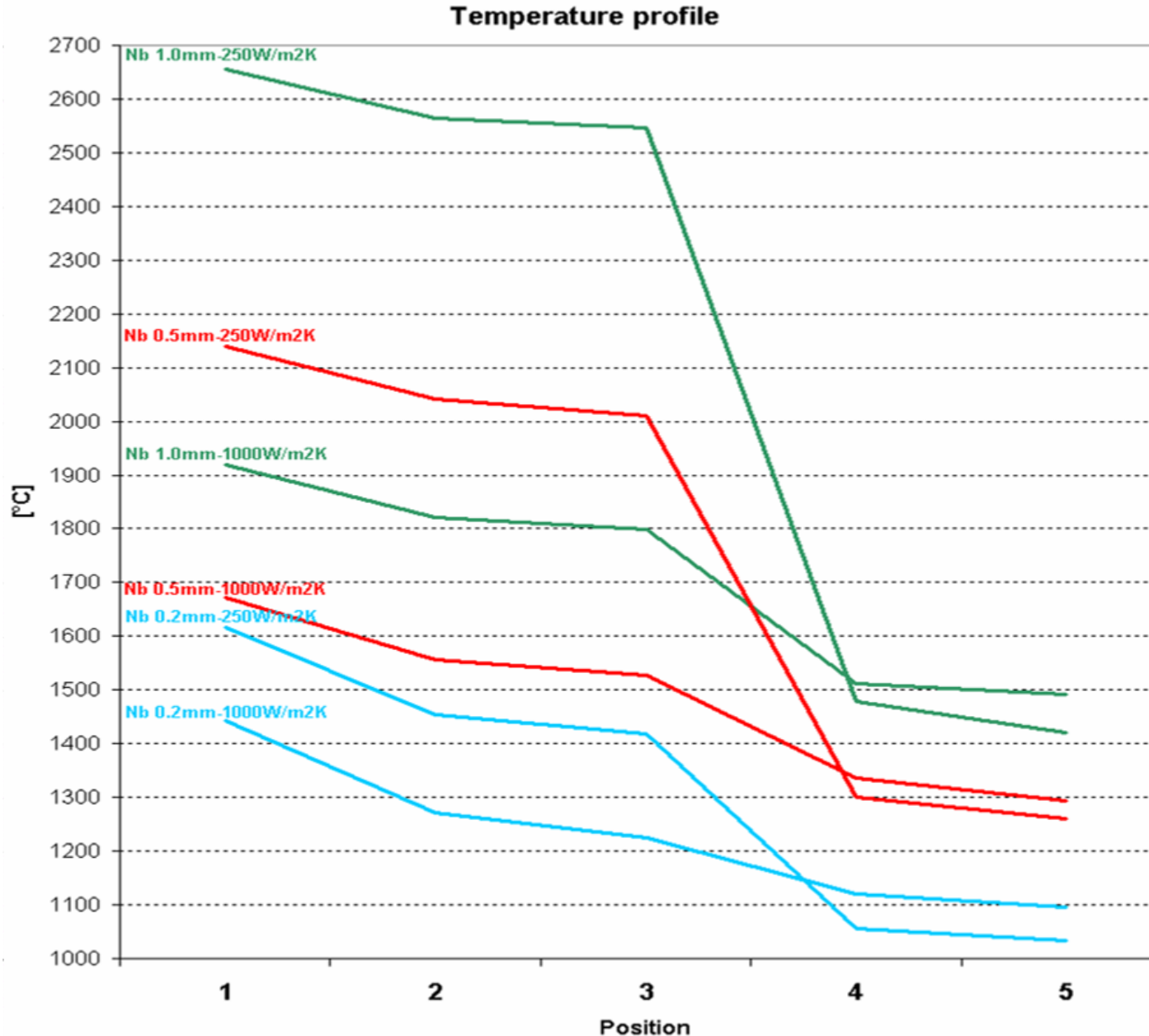
10kw - 0.5mmNb

Th. contact 1000W/m²K

Temperature profile Nb 0.5mm



Optimisation of Nb Thickness 2/3



For 70 pills and 10kW:
Pbeam / PAI2O3 / Ptot.

10000 / 784 / 3150W

10000 / 770 / 1925W

10000 / 756 / 1201W

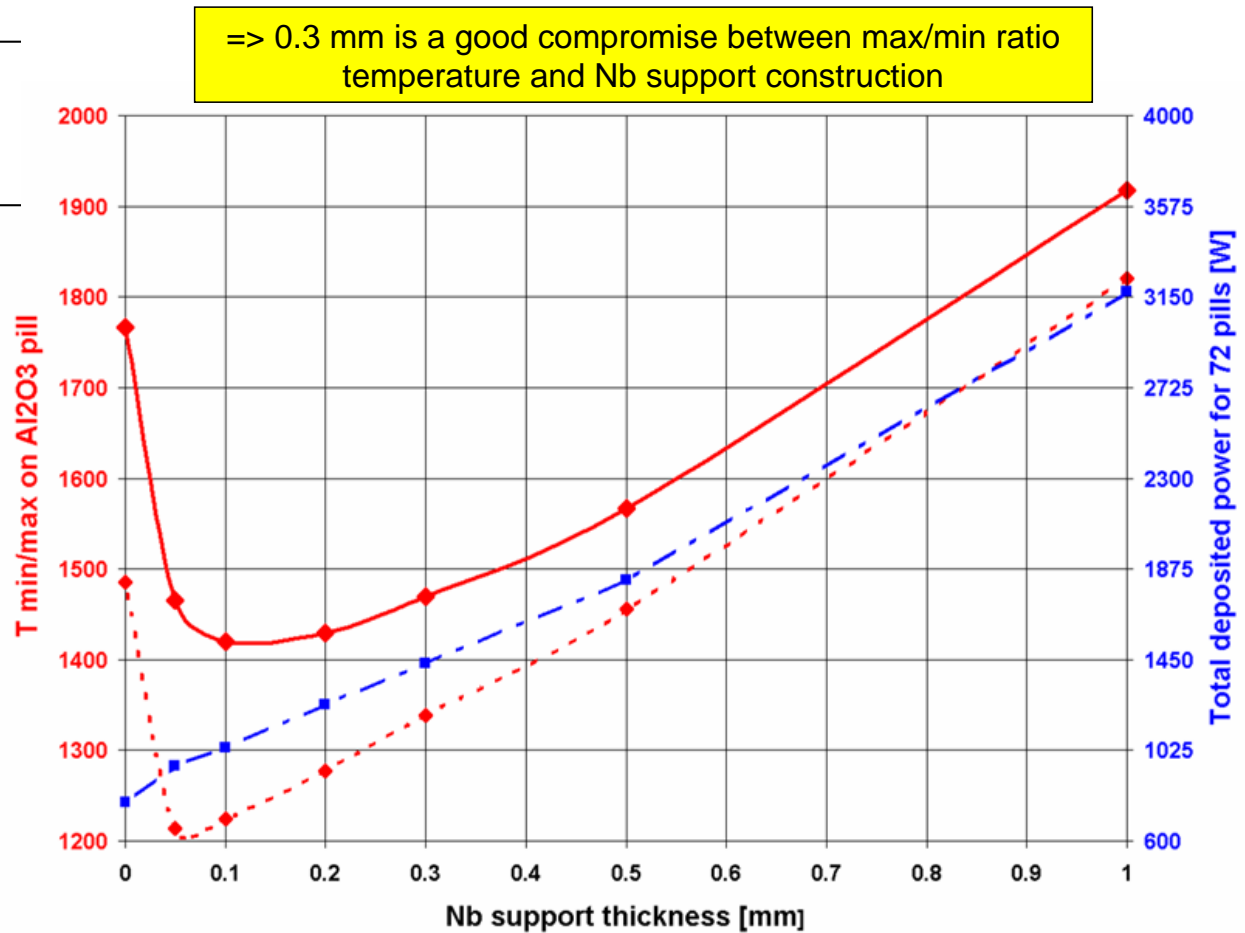
Optimisation of Nb Thickness 3/3

Power deposited by 10 kW beam in 1 composite pill, 1.0 mm thick Al_2O_3 brazed onto Nb, as a function of Nb thickness.

	Nb Thickness		
	0.2 mm	0.5 mm	1.0 mm
Nb [W]	6.36	16.5	33.8
Al_2O_3 [W]	10.8	11	11.2
Total [W]	17.16	27.5	45

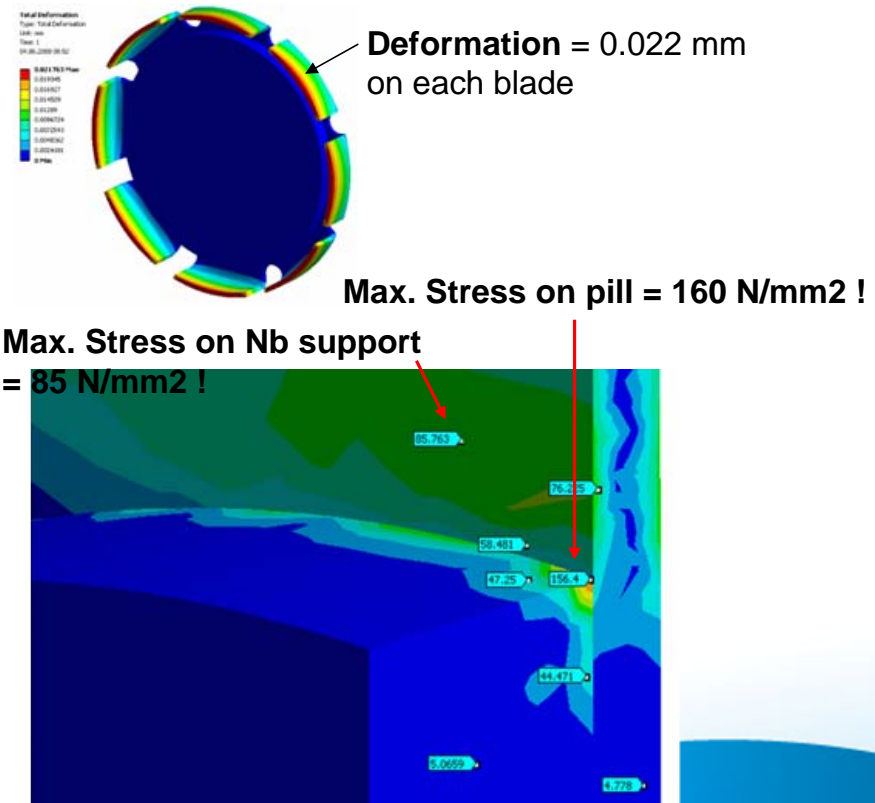
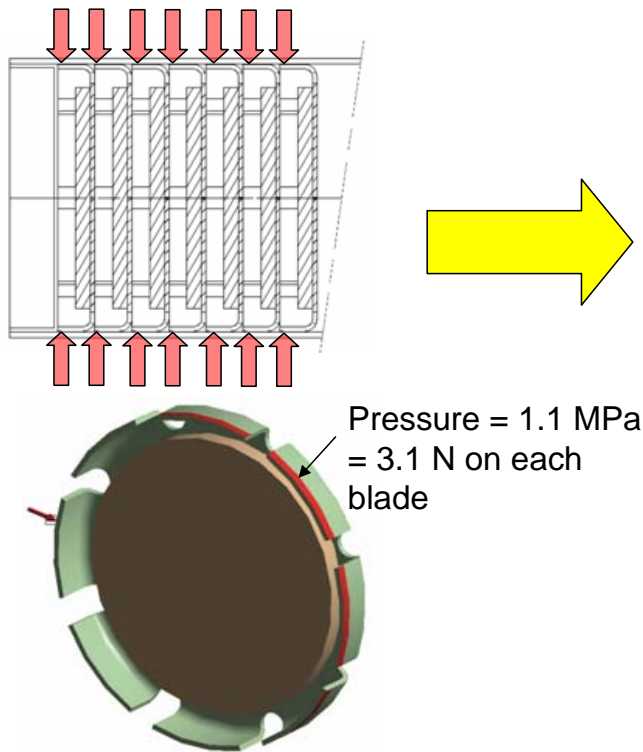
FLUKA

ANSYS WB



First Design Variant 1/2

- During the **mounting** we introduce an elastic force on the blades
- This force generate the contact pressure but has to be safe for the Al_2O_3 pill...
- **Structural simulation at 20° C:**

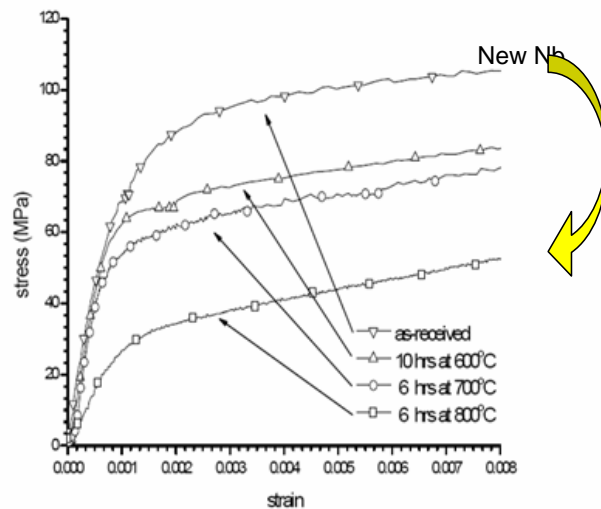


First Design Variant 2/2

- The mounting stresses are high and could give cracks on the ceramic !
⇒ Has to be tested...

⇒ Thermal behavior of Nb:

Apparent YM Issue

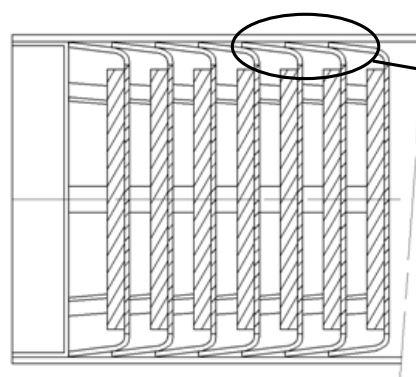
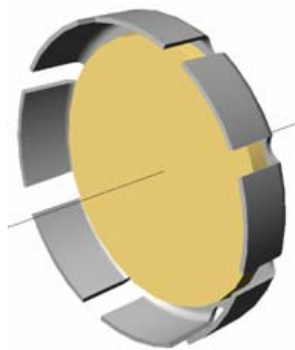
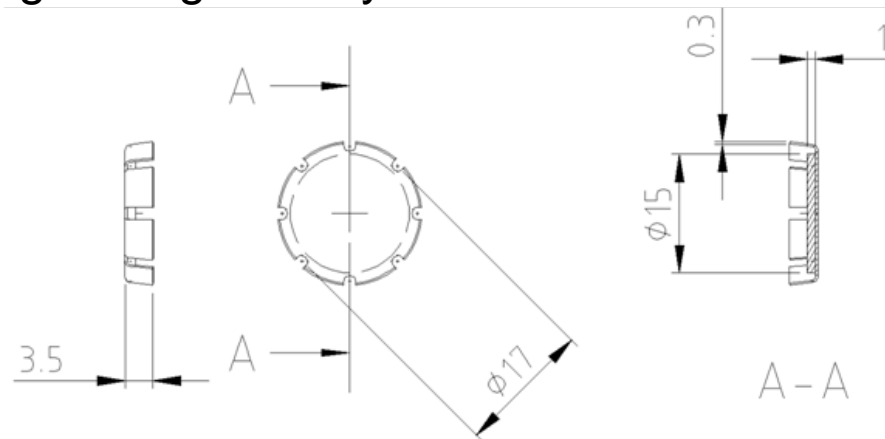


With temperature and time, observe a drastic reduction of the elastic module and the plastic limit with probable consequences:

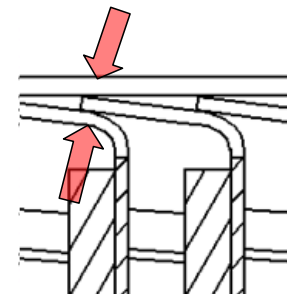
- ⇒ Permanent deformation on the Nb support
- ⇒ Reduction of the mounting stresses
- ⇒ Reduction of contact pressure
- ⇒ Reduction of the thermal contact conductance
- ⇒ Increase of gradient temperatures

Second Design Variant 1/2

- To avoid the inconvenience of mounting stresses and give a **high contact pressure** we design this geometry:

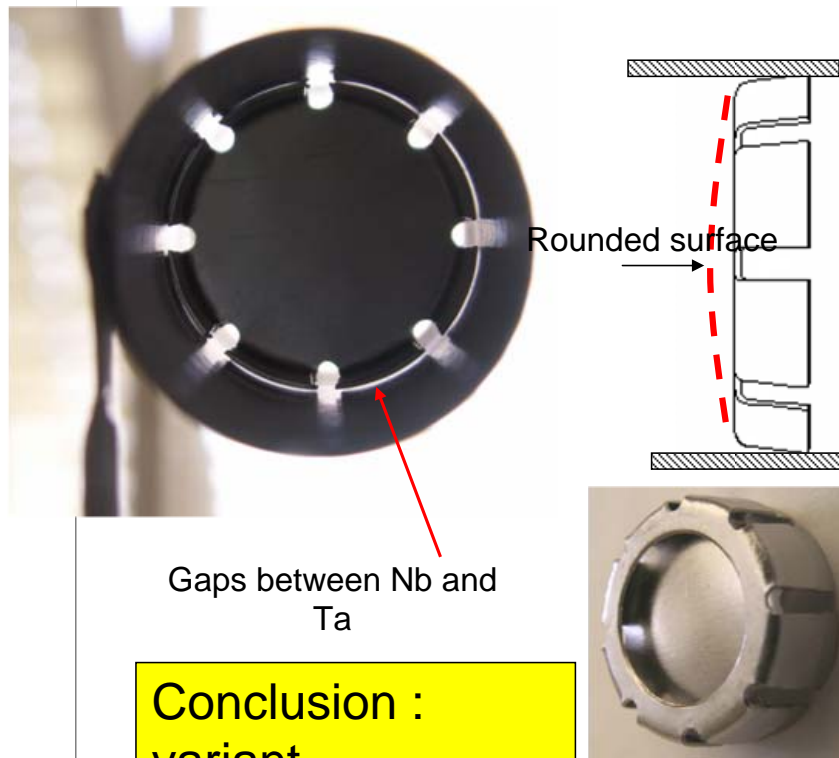


zoom



Second Design Variant 2/2

- After heating the sample shows a new problem:
 - The blades are no more in contact with the container surface
 - The Nb support is like “rounded”



Conclusion :
variant
abandoned



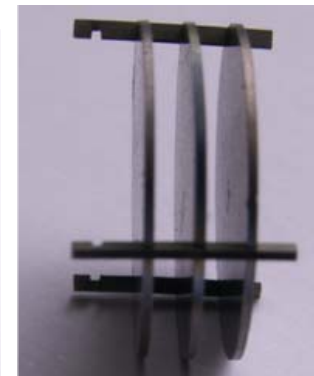
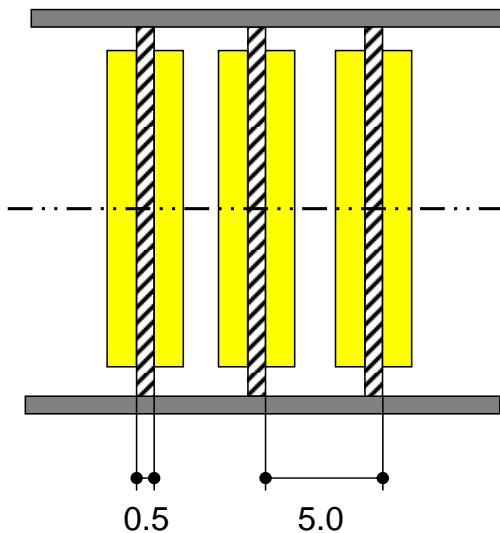
New sample mounted



New sample heated

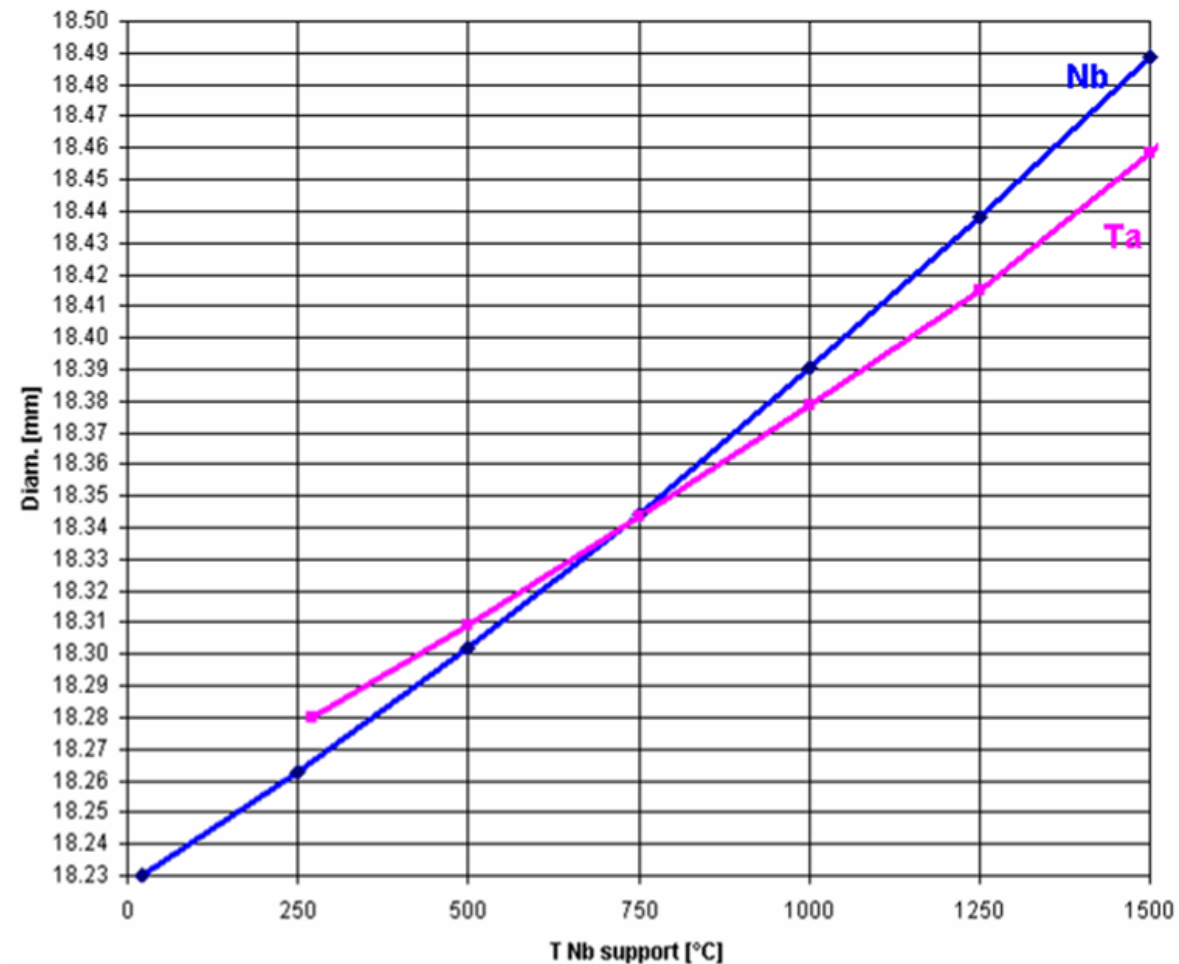
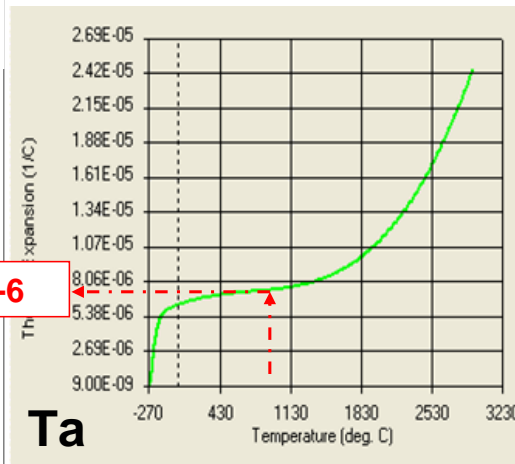
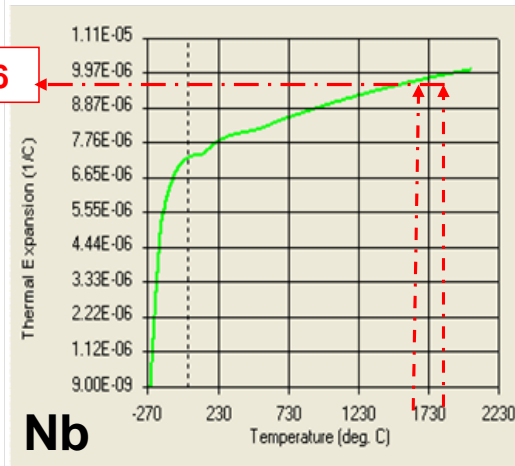
Third Design Variant 1/3

- To give more mechanical stability we modify the geometry as a simple disc machined to a precise diameter ($\pm 0.01\text{mm}$) with controlled dilatation
- The cold inner diameter of the Ta container is **18.28mm** (as received)
- We machine the Nb support to diam. **18.23mm** for an “easy mounting”
- To give a good symmetry we braze the pills each side and double the thickness of Nb support
- For the same density we increase the step from 2.5mm to 5mm
- We can use Nb “comb” as spacer (laser cut or electro erosion)



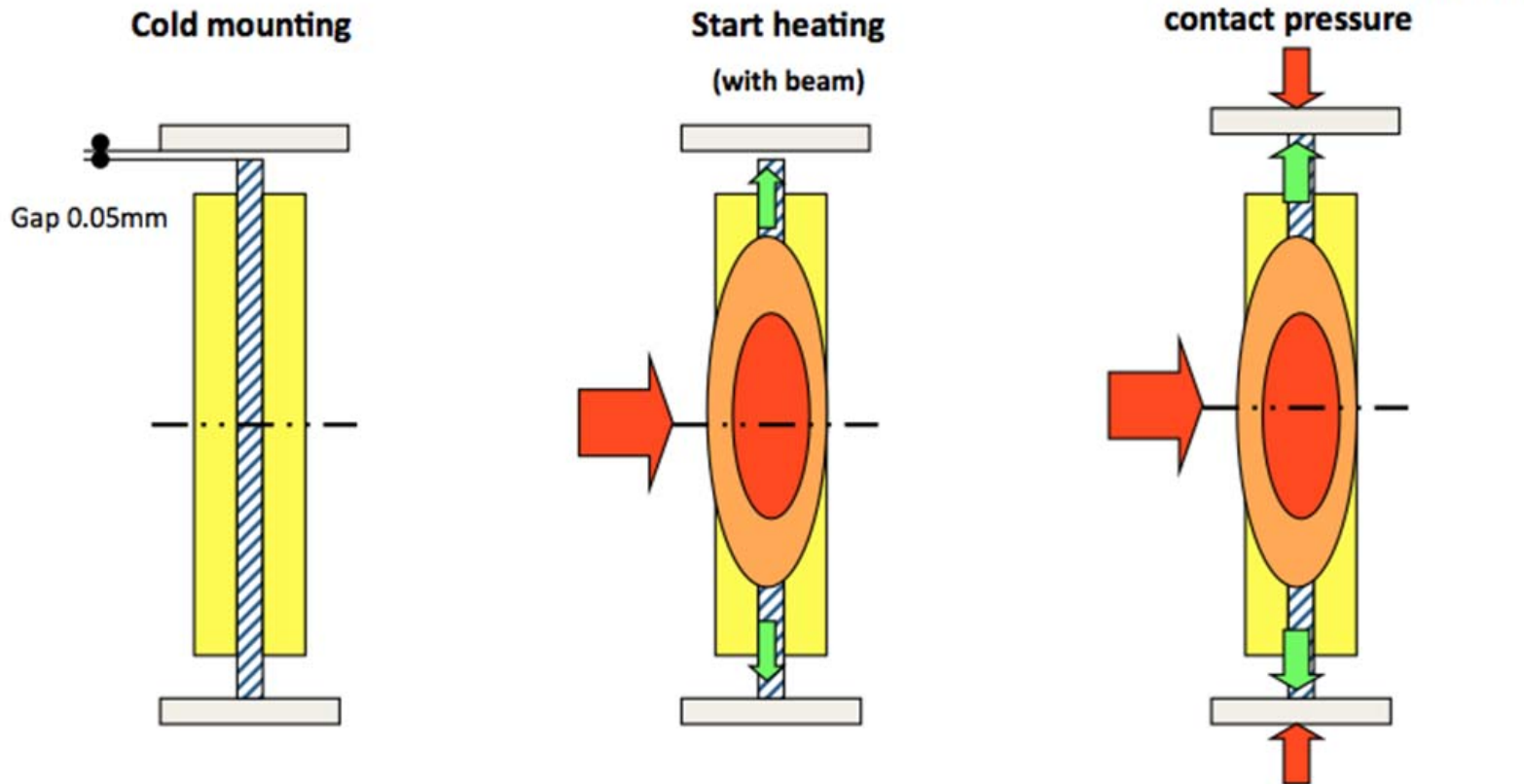
Third Design Variant 2/3

- This variant works on the differential dilatation effect between Nb and Ta :
Dilatation = $f(T)$ [mm]
for $T_{Ta} = T_{Nb} - 250^\circ\text{C}$



Third Design Variant 3/3

- After beam heating, the mounting gap (+0.05mm) becomes negative and give a contact pressure between Nb support and Ta container :



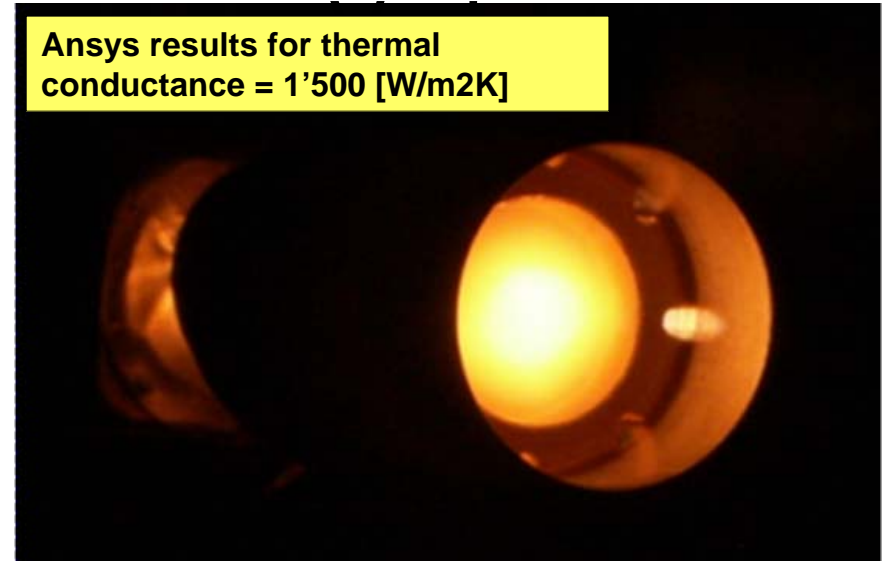
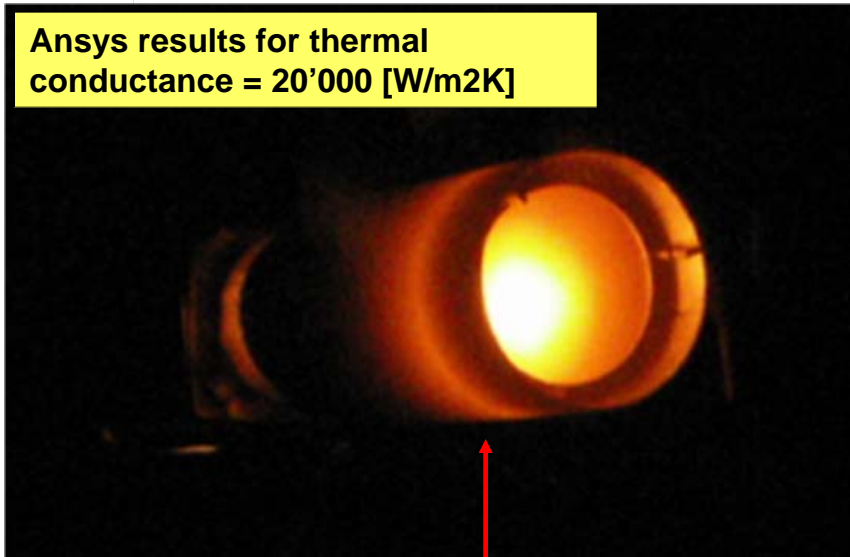
Comparing Contact Conductance

Third Variant

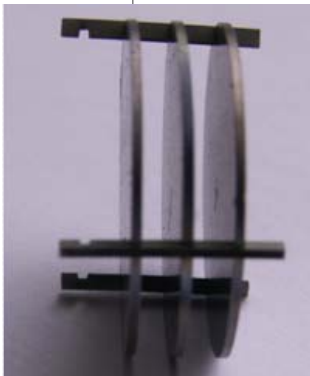
Second

Ansys results for thermal
conductance = 20'000 [W/m2K]

Ansys results for thermal
conductance = 1'500 [W/m2K]

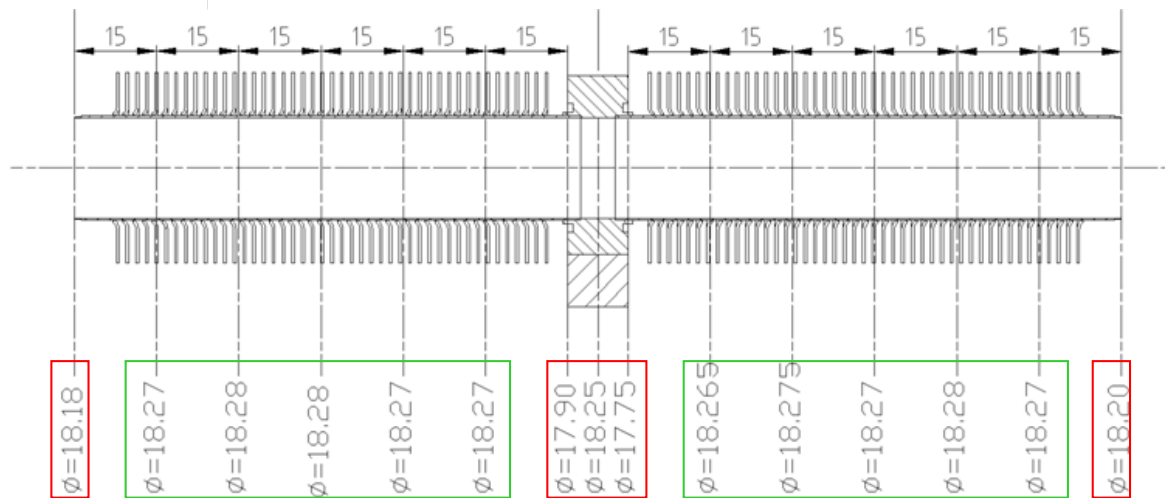


Contact region

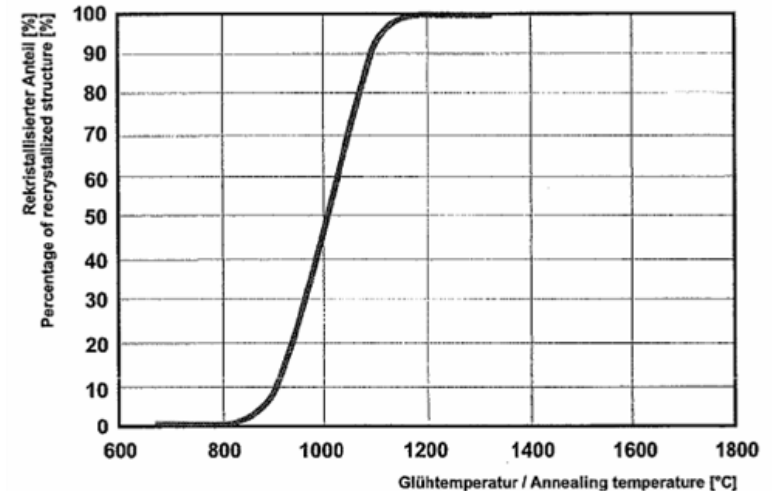


Tantalum Container Conditioning

- To stabilize the mechanical properties and dimensions of the Ta container we annealed it 1400° C during 2 hours
- Measure of the inner diameter before/after annealing:



From Plansee



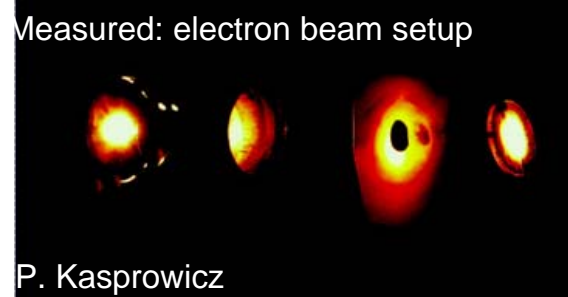
Rekristallisierter Anteil von TaS-Blechmaterial (Blechdicke 1 mm)
in Abhängigkeit der Glühtemperatur (Glühdauer 1h)
Percentage of recrystallization of TaS sheet (1 mm thickness)
as a function of annealing temperature (for 1 hour)

⇒ The annealing was held in the pump stand at 950° C during 16 hours (limitation due to the over heating of the container connections ~1400° C)

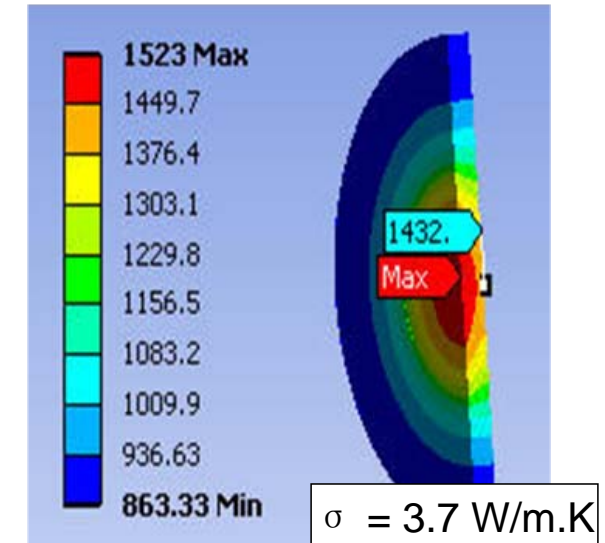
⇒ The measured variations after annealing are negligible +/- 0.005mm

⇒ **Correction of the diameter along z axis to 18.30mm**

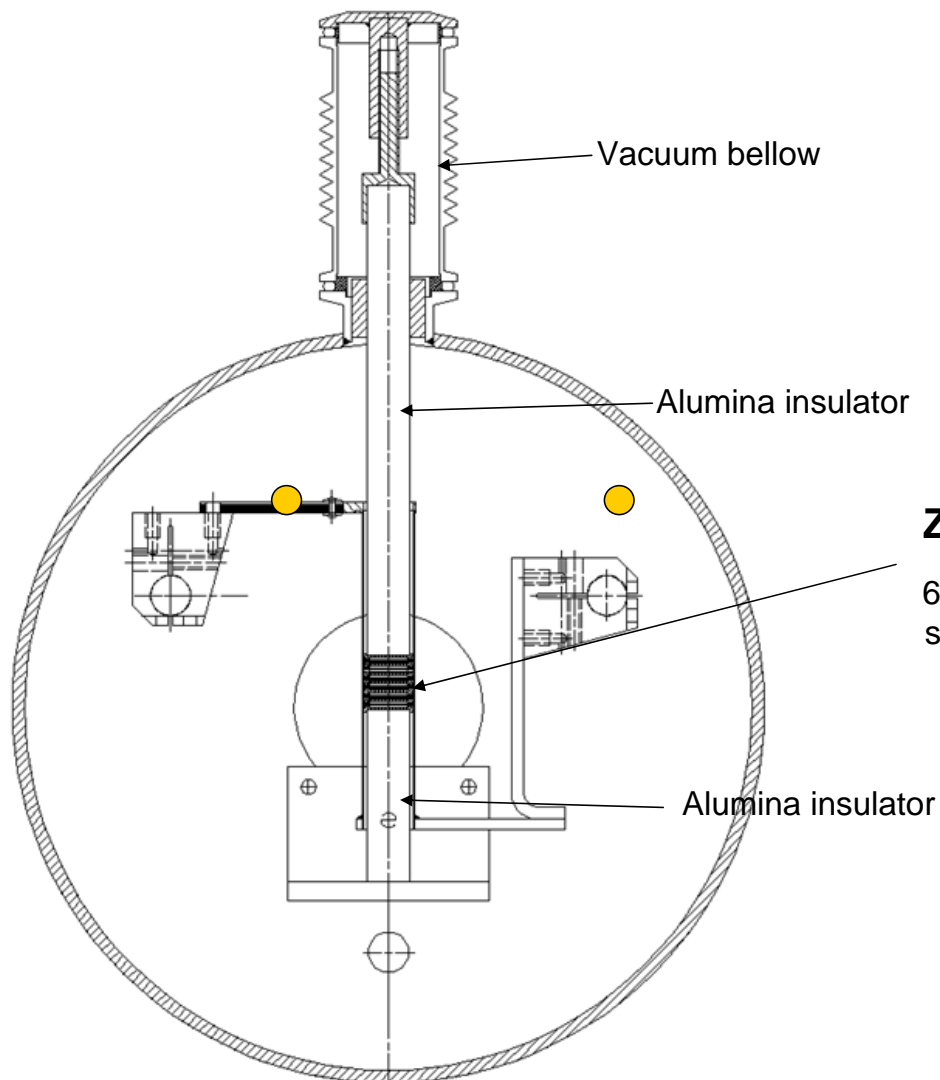
Al_2O_3 Thermal Conductivity



Power on sample = 28 W
Beam spot < 8 mm
Front = 1524 °C
Back = 1432 °C



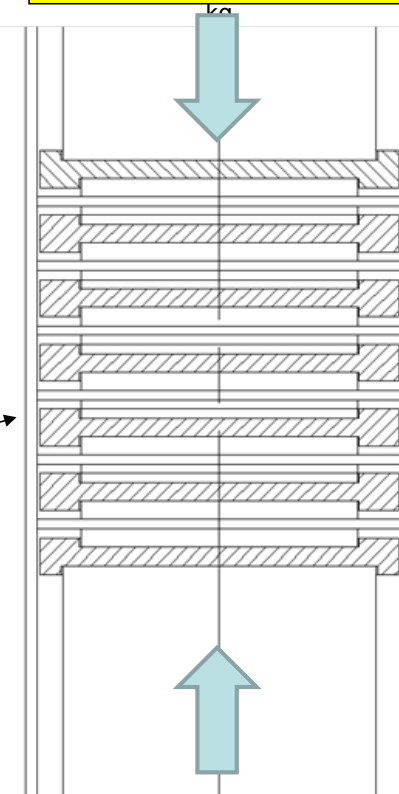
Al₂O₃/TA6V/Nb Brazing 1/2



=> The pressure applied due to the vacuum on the bellow > 10

Zoom

6x pills+
spacers

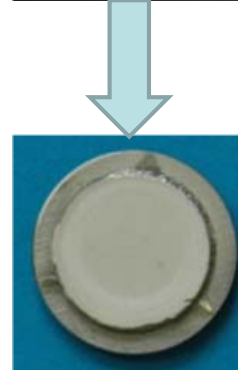
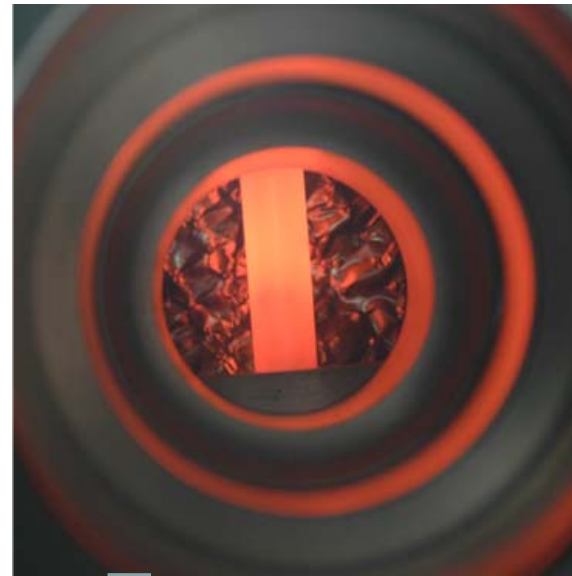
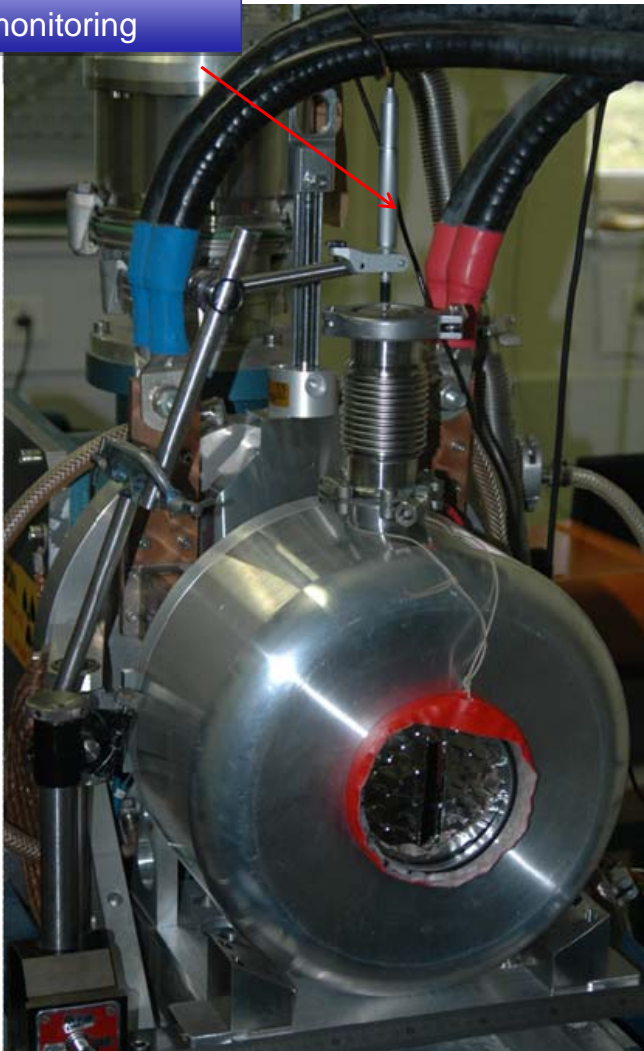


Al₂O₃:
1 mm thick
 $\rho = 2.7 \text{ g.cm}^{-3}$
30 % open porosity

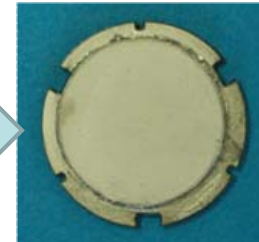
TA6V:
100 μm thick
86.2%Ti, 10.2%Al, 3.6%V

Al₂O₃/TA6V/Nb Brazing 2/2

Gauge for dilatation
monitoring



Brazed pills after
final laser cutting

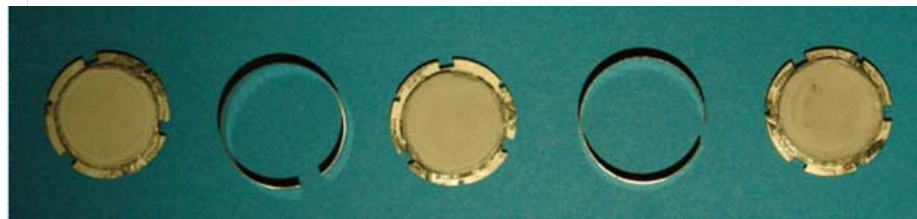
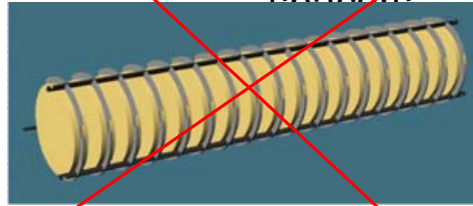


Contact Conductance $\text{Al}_2\text{O}_3/\text{Nb}$

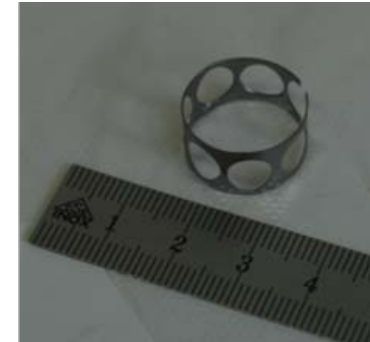


Al₂O₃ Target Final Assembly

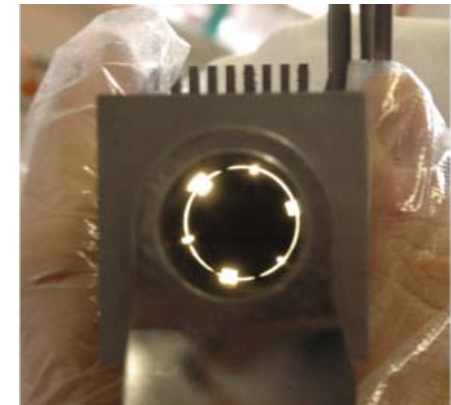
- During mounting it was decided to replace the gap spacers for ring



Central spacer



Average gap ~0.03 mm



Target Tests at TRIUMF: 12 kW



Experiment S1149
22nd-31st March 2009
First FEBIAD-type ion source

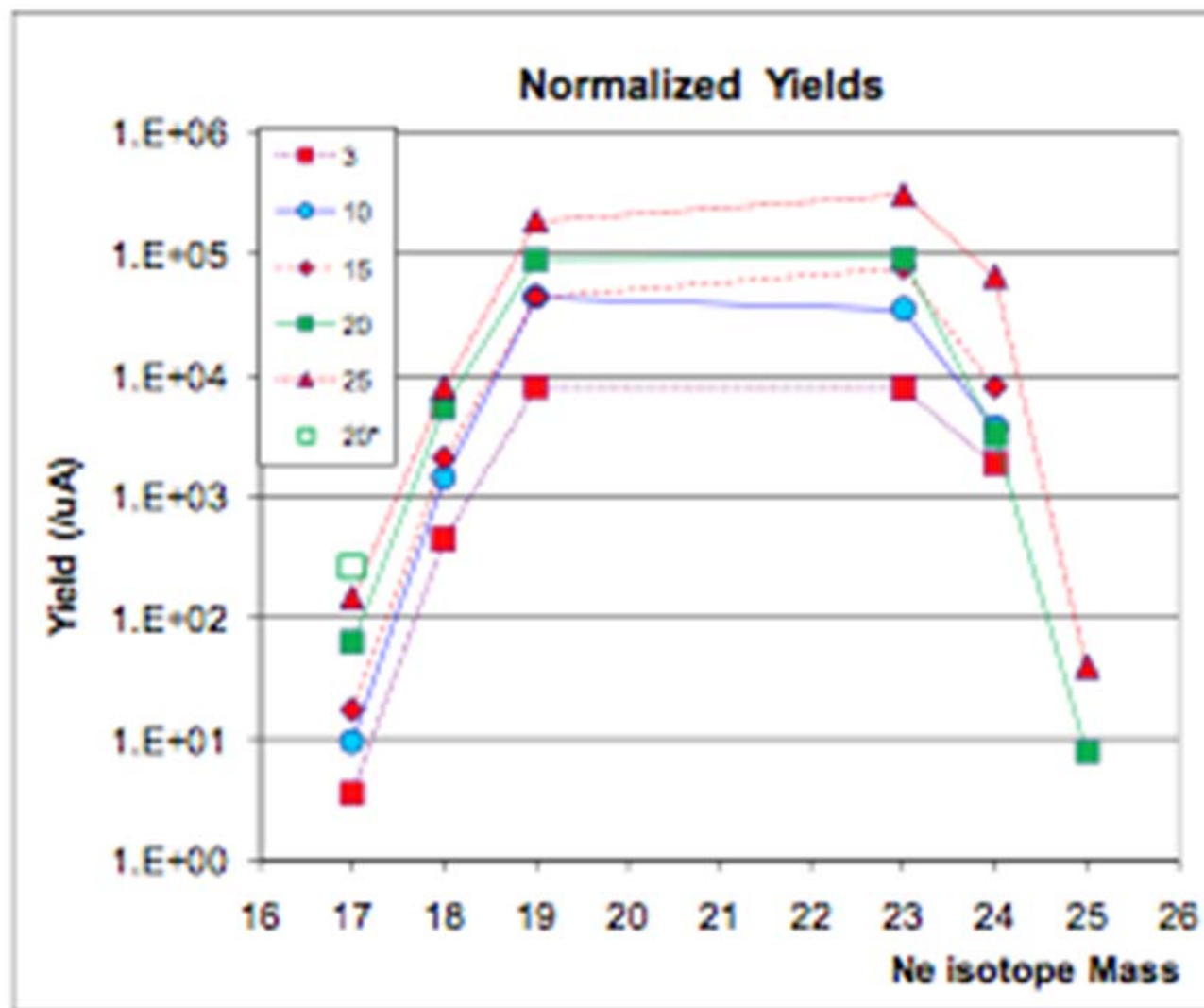


> Previous record for oxides was 1 kW, CaZrO_3

[M. Dombisky et al. Nuclear Physics A 746 (2004) 32c-39c]

Optimisation of the thermal characteristics of an oxide high power target for radioactive ion beam production
E. Noah, 10th IWSMT, 18-22nd October 2010

Neon Yields



Outlook

- > **Al₂O₃ target** tested at TRIUMF can be extended to **100 kW** at **EURISOL** with **4 target units**.

	TRIUMF	EURISOL
Proton energy [GeV]	0.5	1
Beam current [μ A]	20	20
Target elements [W]	1334	1136
Container [W]	51	60.6
Cooling fins [W]	202	212
Total [W]	1587	1409

- > **TRIUMF target** operated for **3174 μ A.hrs**, **25%** of the 12600 μ A.hrs required for 3 weeks at **EURISOL**.
- > **Thermal design principles** can be applied to **other targets** but must be carefully studied on a **case-by-case basis**.

Summary

- > Oxide targets for RIB production:
 - Brazing to metallic substrate for thermal/mechanical properties.
- > Thermal design principle:
 - Study all thermal paths conduction/radiation.
 - Combine measurements and simulations.
 - Thermal contact conductance Nb foil/Ta container.
 - Thermal contact conductance across brazing interface.
 - Thermal conductivity of Al_2O_3 .
- > EURISOL 100 kW oxide targets:
 - Feasible.
 - 4 sub-units required.