Target Nb cladding R&D & Baseline Design Optimization

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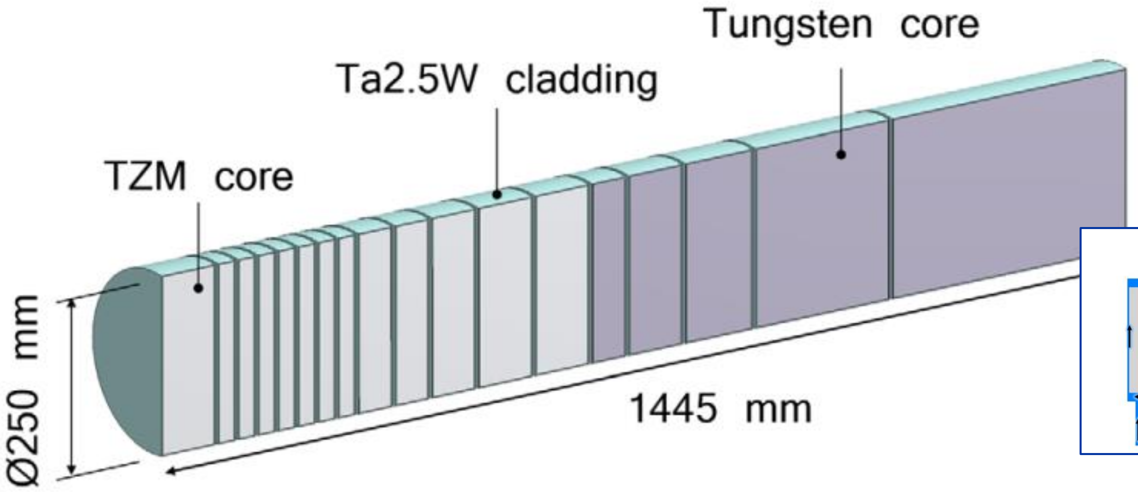
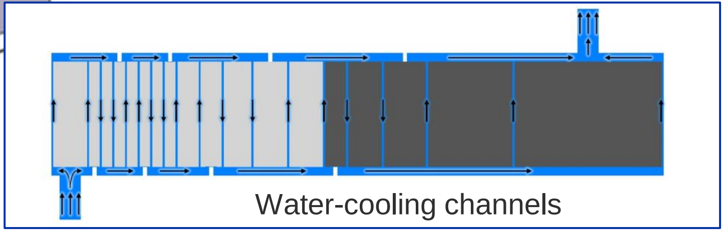
HI-ECN3 BDF target & target complex - initial review
29/04/2024

Baseline of BDF Final Target Design



18x Ta2.5W-cladded Blocks


Water-cooling channels

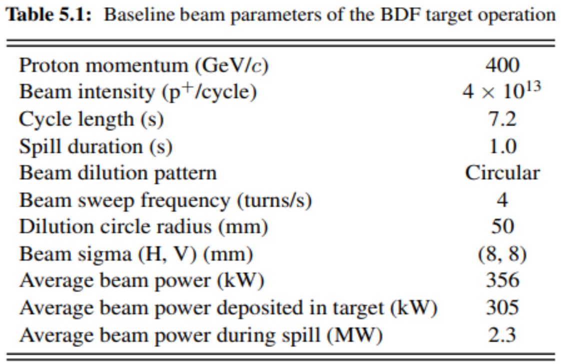
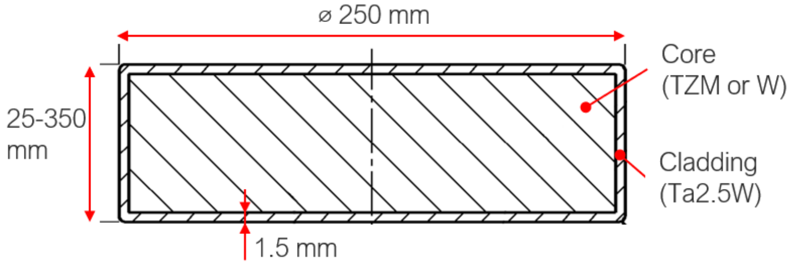


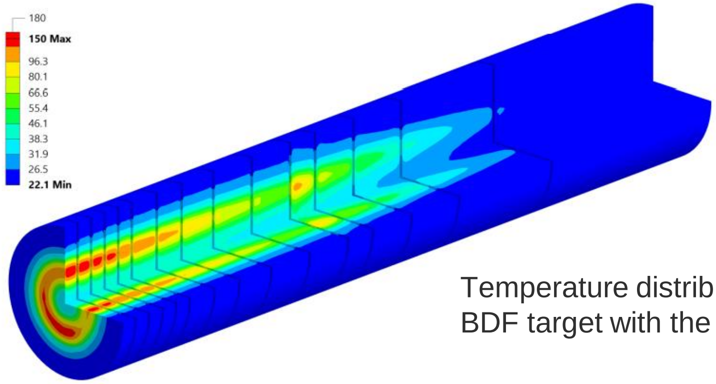
Table 5.1: Baseline beam parameters of the BDF target operation

Proton momentum (GeV/c)	400
Beam intensity (p^+/cycle)	4×10^{13}
Cycle length (s)	7.2
Spill duration (s)	1.0
Beam dilution pattern	Circular
Beam sweep frequency (turns/s)	4
Dilution circle radius (mm)	50
Beam sigma (H, V) (mm)	(8, 8)
Average beam power (kW)	356
Average beam power deposited in target (kW)	305
Average beam power during spill (MW)	2.3

CDS report: Beam parameters



BDF Block Dimensions

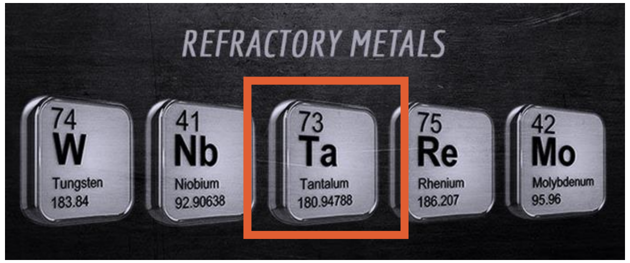


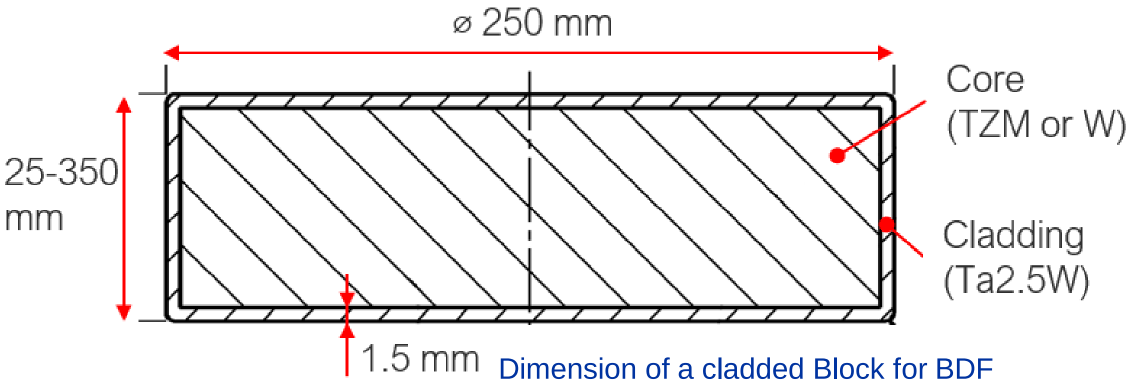
Temperature distribution (in degrees Celsius) in the BDF target with the circular beam dilution pattern

CDS report: https://cds.cern.ch/record/2703984

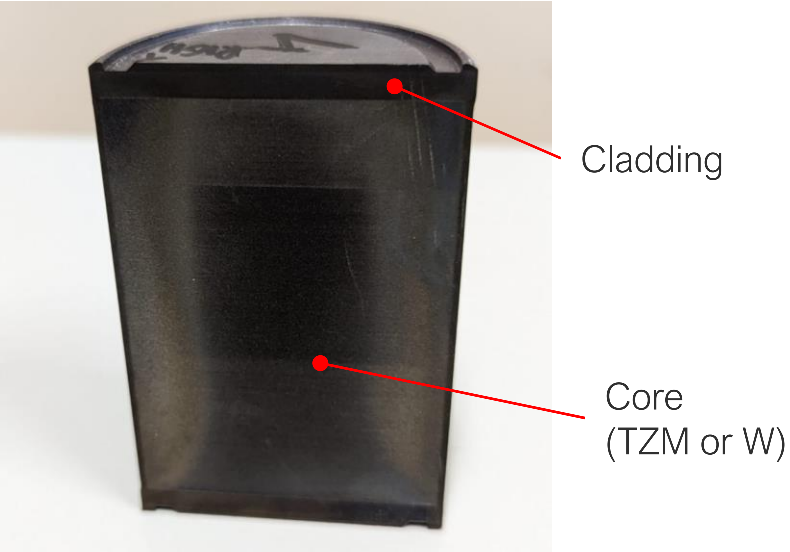
Tantalum 2.5-Tungsten as Cladding for BDF

- Refractory metal
- Very resistant to multiple chemical agents
- Good corrosion resistance
- Shows good qualities to bond with BDF core materials W and TZM
- Usage as cladding material in a variety of other research facility targets e.g., ISIS, LANSCE, and KENS





Dimension of a cladded Block for BDF



Half of a cladded Block

What is cladding?

Why is cladding needed for BDF?

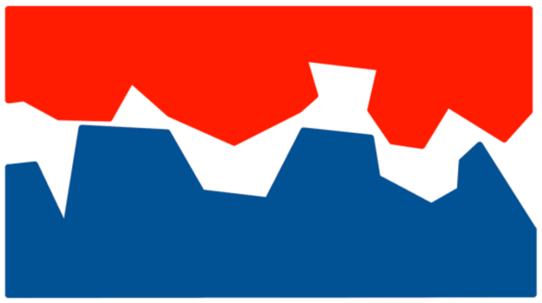
- Water-cooling can induce erosion, corrosion, and hydrogen embrittlement in TZM and W
- Layer between the water and the core material is needed to prevent direct contact with the water

How is cladding created?

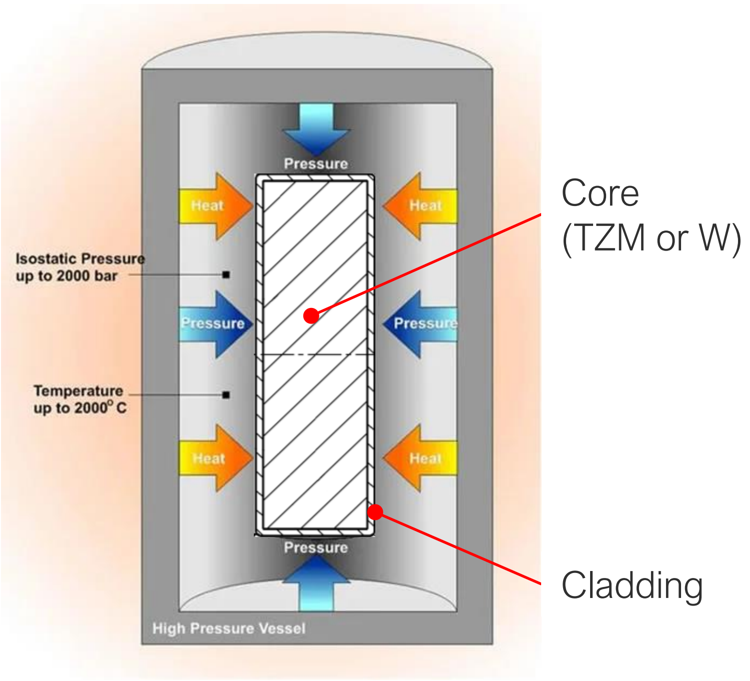
- Diffusion bonding of cladding and core materials via Hot Isostatic Pressing (HIP)
- HIPing furnaces utilize high temperatures and pressure for a defined period

Advantages

- Core materials have no direct contact with water
- Reliable heat transfer from core material to water circuit



Diffusion bonding process[1]



HIPing Furnace

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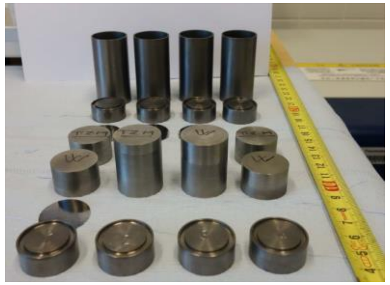
[1] LaurensvanLieshout (https://commons.wikimedia.org/wiki/File:Diffusion_welding_animation.gif)

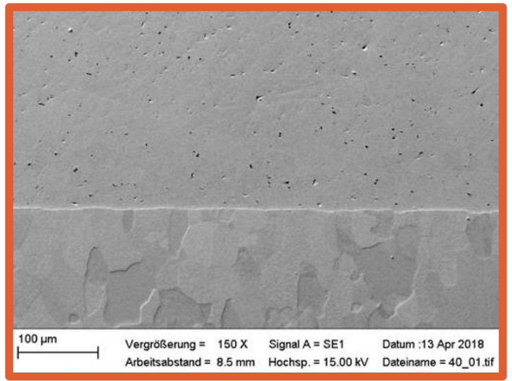
Niobium Cladding R&D studies

Prior Ta2.5W cladding Study

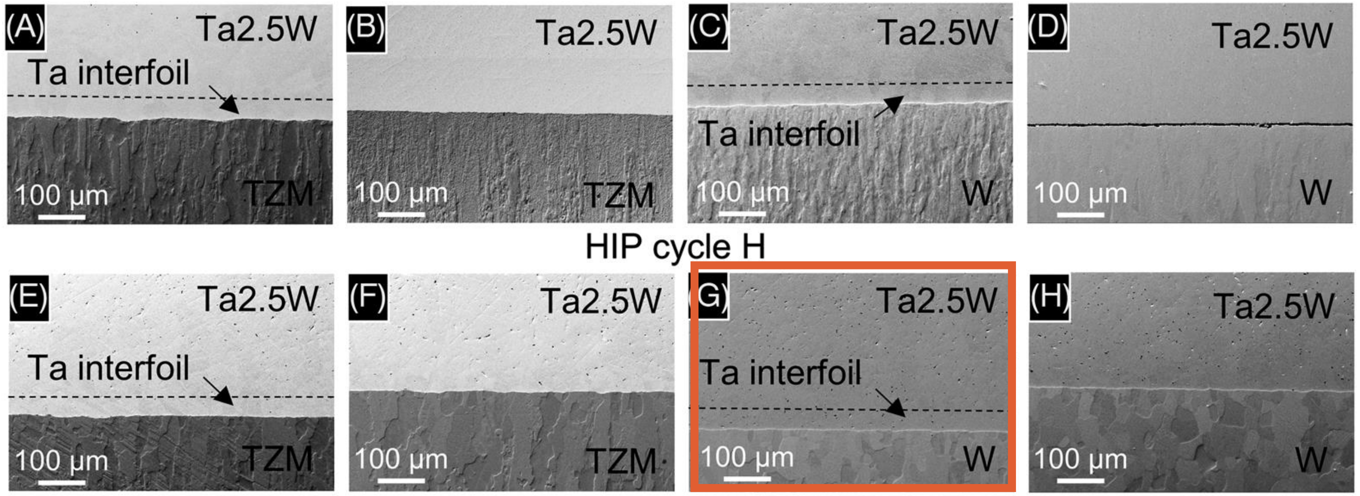
Project Scope

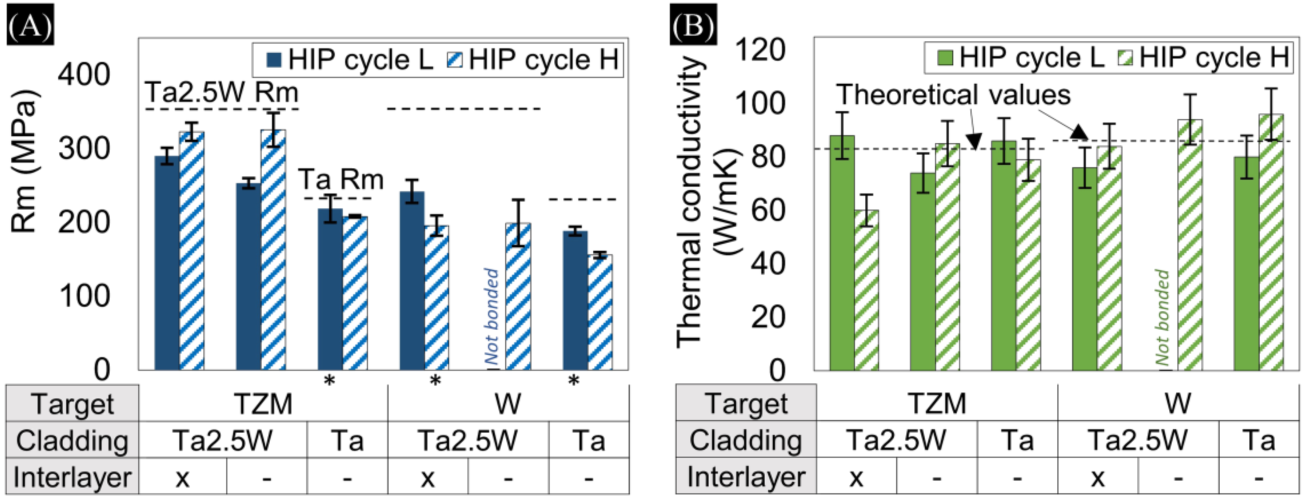
- Comparing two Heating cycles (1200°C/150MPa and 1400°C/200MPa)
- Determining bonding quality of Ta2.5W vs Ta cladded on W and TZM, w/wo interface foil





Very difficult to see any diffusion layer !

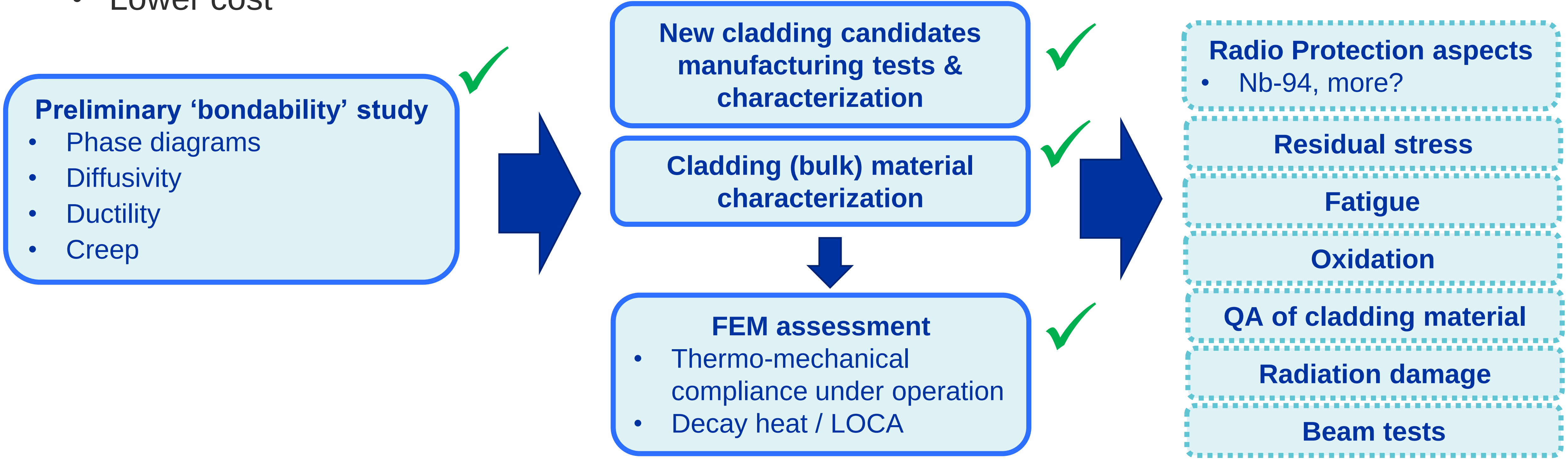




Microstructural observations, tensile strength and conductivity measurements for some of the studied interfaces (https://doi.org/10.1002/mdp2.101)

Alternative Cladding Material Selection

- **Search for alternative cladding materials (Zircaloys, Nb-alloys): Nb, Nb1Zr, Nb10Hf1Ti (C103)**
  - Less activation, less decay heat
  - Refractory. Share outstanding thermo-mechanical properties of Ta and good corrosion-erosion resistance
  - Lower cost



Preliminary 'bondability' study ✓
- Phase diagrams
- Diffusivity
- Ductility
- Creep

New cladding candidates manufacturing tests & characterization ✓

Cladding (bulk) material characterization ✓

FEM assessment ✓
- Thermo-mechanical compliance under operation
- Decay heat / LOCA

Radio Protection aspects
- Nb-94, more?

Residual stress

Fatigue

Oxidation

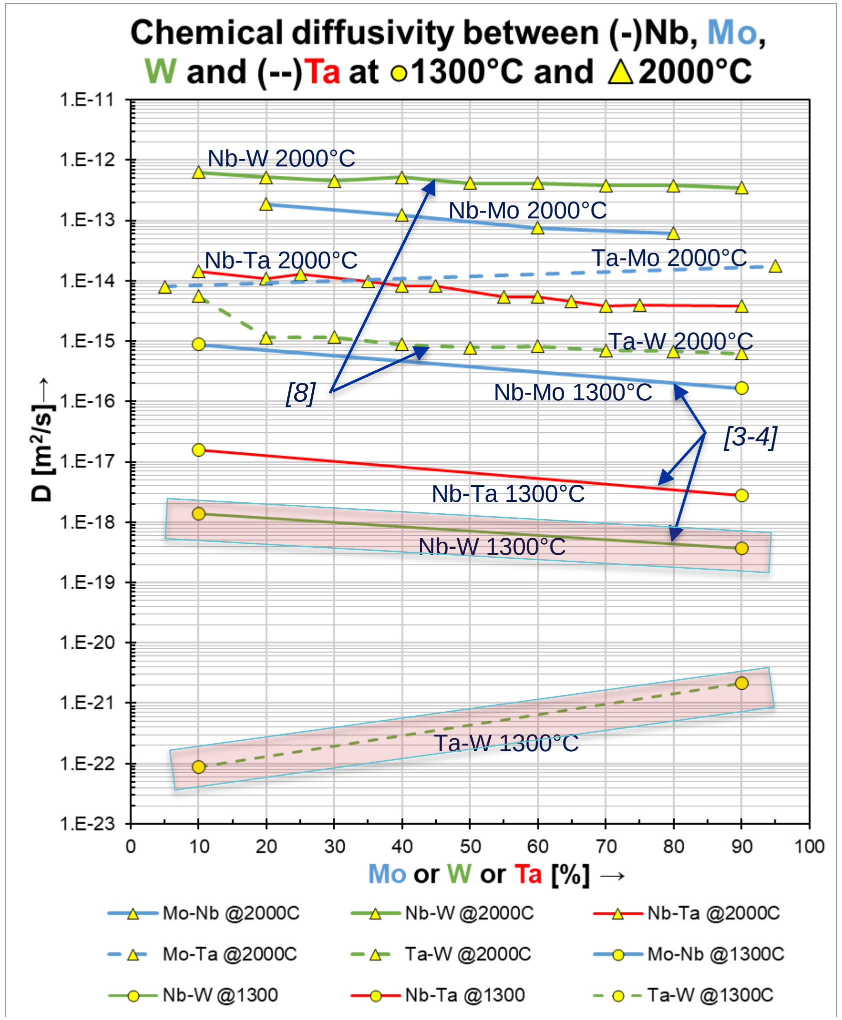
QA of cladding material

Radiation damage

Beam tests

IPreliminary ‘Bondability’ Study of Nb alloys

- **Phase diagrams:**
  - Good solubility of Nb and Ta with W and Mo
  - No major showstoppers regarding intermetallic phases
- **Diffusivity**:
  - Nb shows as much diffusivity into W and Mo as Ta.
  - However, diffusion length is very small for the HIP time scale.
    → Creep dominates bonding rather than chemical diffusion.
- **Ductility**:
  - Nb identical to Ta (ε at break >20% ASTM B393, B654)
- **Creep**

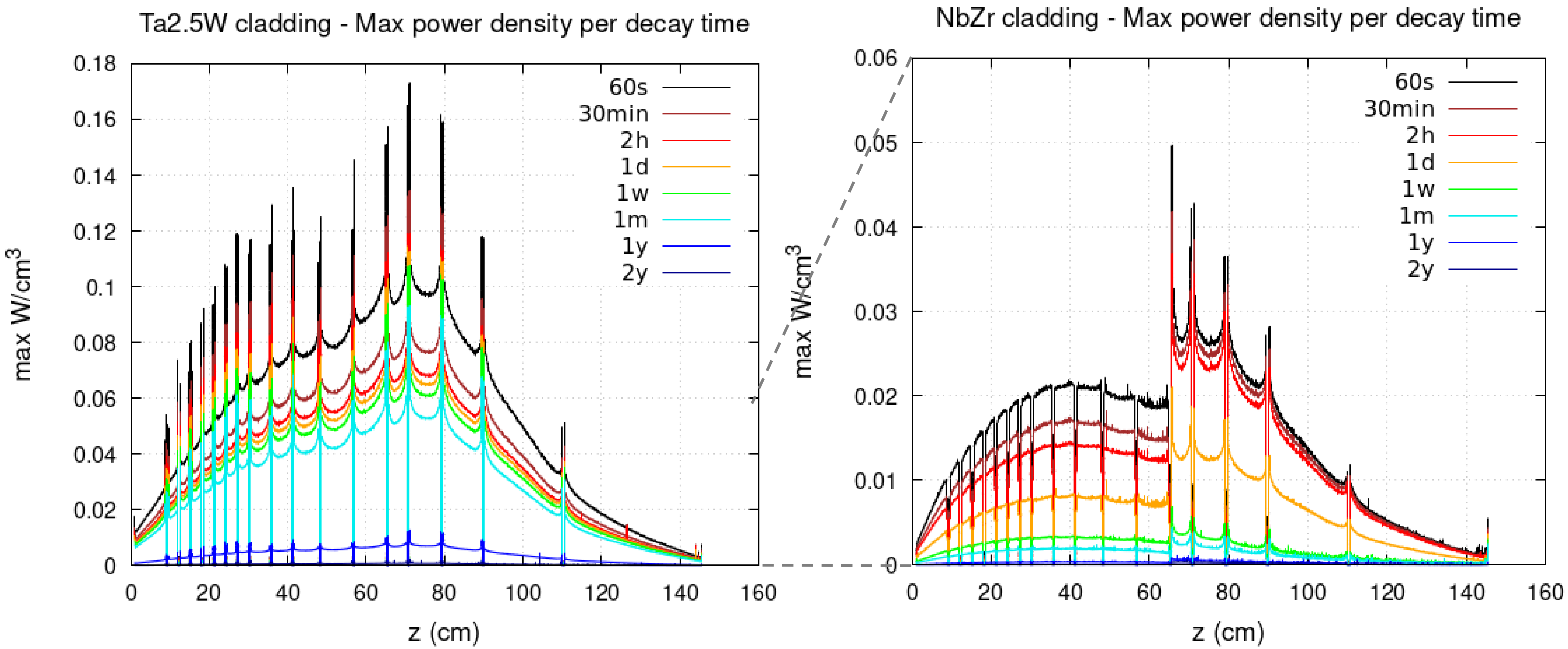


Decay heat of Nb-alloys

✓

- Decay heat calculated with FLUKA.CERN

FLUKA



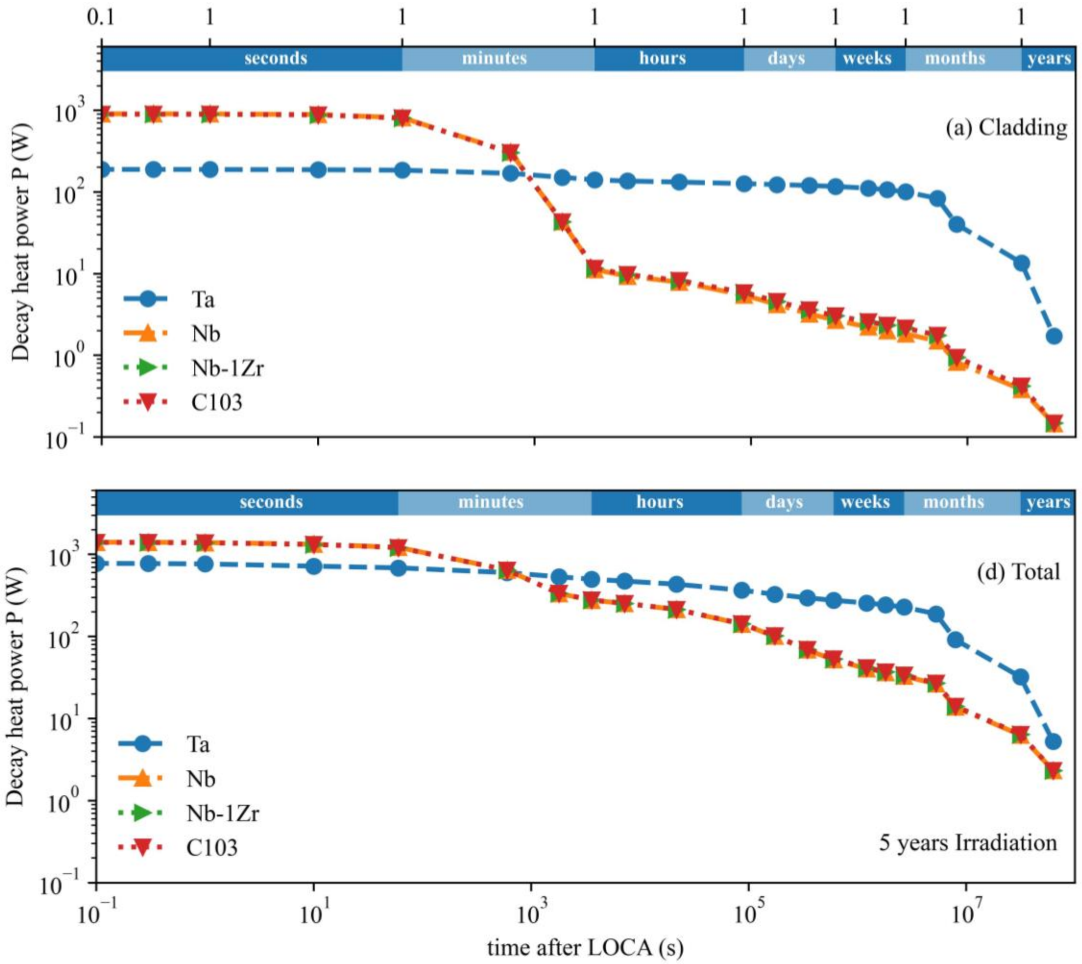
Ta2.5W cladding - Max power density per decay time

NbZr cladding - Max power density per decay time

Nb-alloys cladding R&D

✓

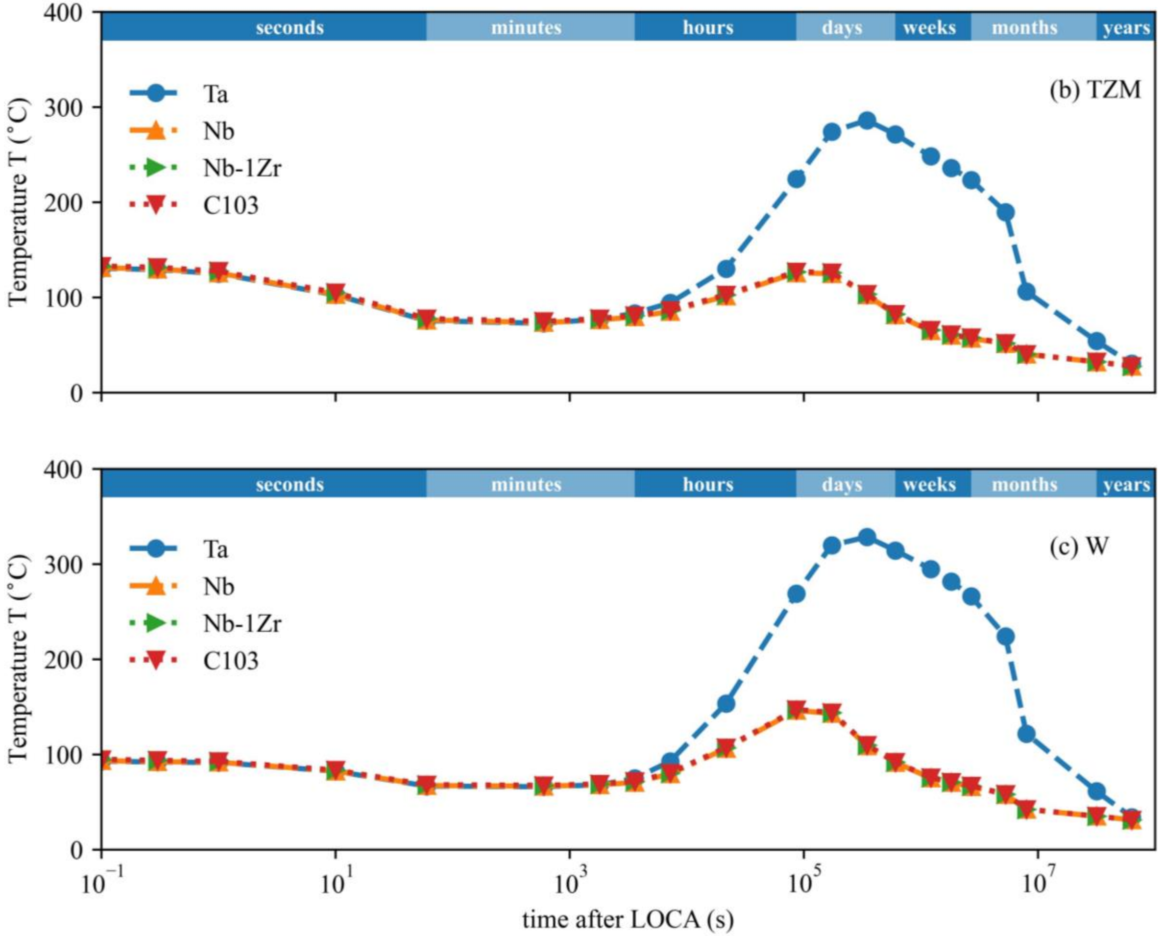
Decay heat power



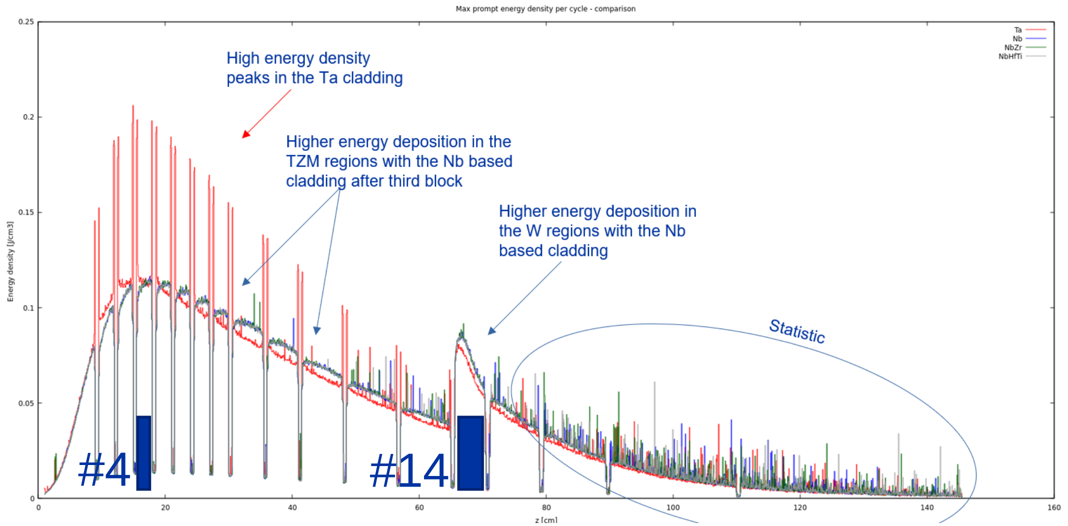
Temperature after LOCA

Assuming htc=1W/m2.K

New studies consider a more robust HTC(T) formulation*



Safety Factor under Operational Conditions

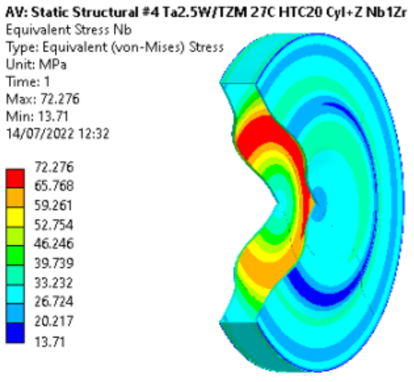


No Residual stress considered here !

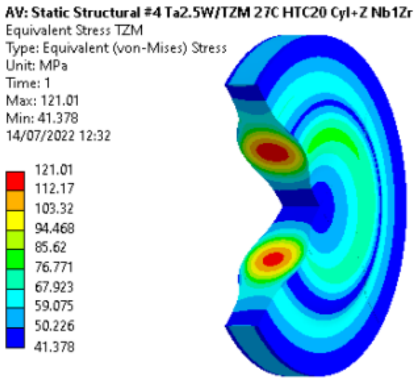
	Material	Pw [kW]	Max. T [°C]	σ_{vm} | σ_1 [MPa]	σy | UTS @ 200 °C [MPa]	Safety factor
BLOCK 4	Ta2.5W	14.4	156	127	227	2
	TZM		170	123	460	4
	Pure Nb	12.3	133	79	149	2
	TZM		165	120	460	4
	Nb1Zr	12.3	136	72	170	2.5
	TZM		166	121	460	4
	Nb C103	12.4	138	63	254	4
	TZM		167	121	460	4
BLOCK 14	Ta2.5W	19.6	111	80	227	3
	W		144	96	142	1.5
	Pure Nb	20.3	111	70	149	2
	W		155	120	142	1
	Nb1Zr	20.2	114	72	170	2.5
	W		156	117	142	1
	Nb C103	20.2	116	71	254	3.5
	W		157	116	142	1

UTS & σ_1 for W, Yield strength & von Mises stress for TZM, Ta2.5W, Nb-alloys
Material properties from BDF prototype Target batch characterization

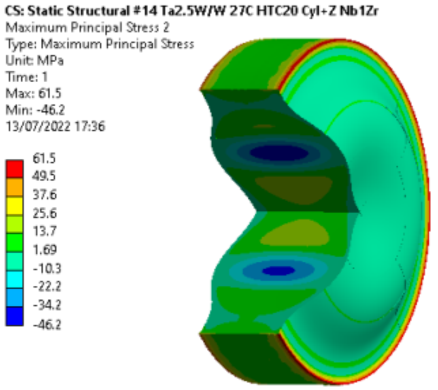
→ Same critical Blocks #4 and #14 for Nb alloy cladded blocks



Clad Block #4 TZM//Nb1Zr



Core Block #4 TZM//Nb1Zr



Core Block #14 W//Nb1Zr

Consideration of Residual Stresses under Operation

✓

- Blocks are HIPed and during cool-down process **residual stresses** build up
- Material specific **‘lock-in’ temperature** of 500 °C is considered based on [1] to simulate the residual stresses

➢ Residual stress for Nb1Zr in the same order of magnitude as Ta
→ still far from elongation at break

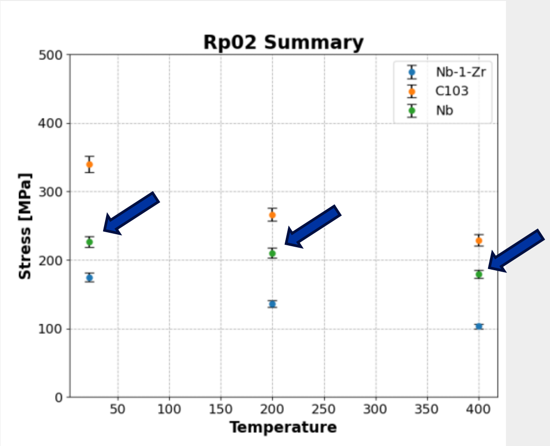
		After HIP	After HIP + 2nd beam impact		
	Material	**$\sigma_{vm} \mid \underline{\sigma_1/\sigma_3}$ [MPa]**	**$\sigma_{vm} \mid \underline{\sigma_1/\sigma_3}$ [MPa]**	**Total strain [mm/mm]**	**Eq plastic strain [mm/mm]**
BLOCK 4	Ta2.5W	123	171	-	-
	TZM	18	92	-	-
	Nb1Zr	130	154	-	-
	TZM	19	94	-	-
BLOCK 14	Ta2.5W	248	269	1.8e-3	3.7e-4
	W	0/-18	73/-134	-	-
	Nb1Zr	191	200	2.2e-3	3.6e-4
	W	0/-14	106/-157	-	-

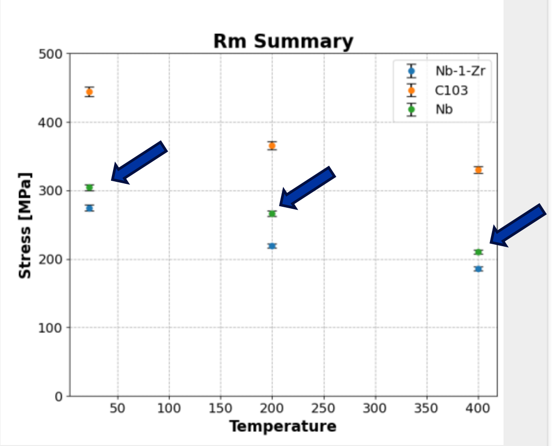
Residual stresses after HIPing (lock-in temperature 500 °C) and beam impact of Block #14; without residual stress is presented in parentheses

[1] D. Wilcox et al. “Stress levels and failure modes of tantalum-clad tungsten targets at ISIS”. In: J. Nucl. Mater. 506 (Nov. 2017), pp. 76–82.

Material characterization (Nb, Nb1Zr, C103)

Tensile Testing – Rp02 & Rm

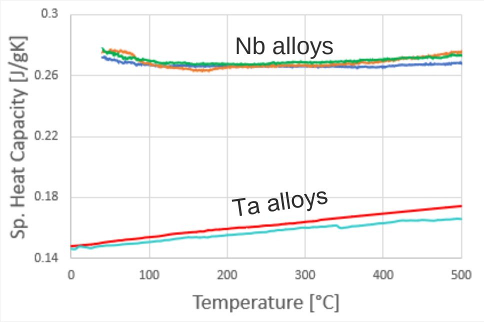




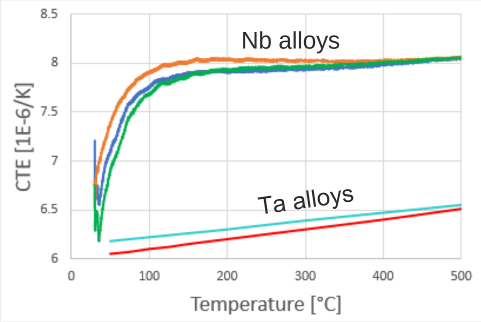
- Investigations showed that pure Nb was not fully annealed
- Difficulties procuring Nb alloys from CERN member states
- In general, multiple issues occurred from Nb alloys which were procured from Chinese suppliers

→ Importance of **Material Certificate 3.1** and knowledge about the manufacturing process / parameters

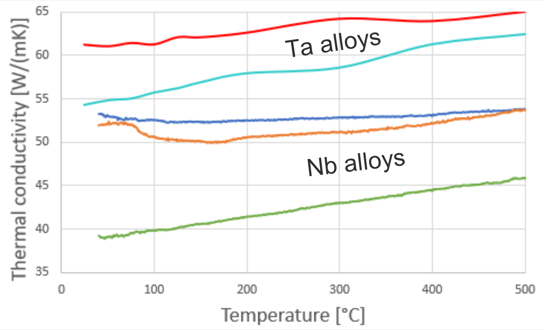
Sp. Heat Capacity



CTE



Thermal Conductivity



—pure Nb
—Nb1Zr
—C103
—Ta
—Ta2.5W

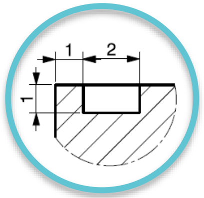
EDMS 2752630

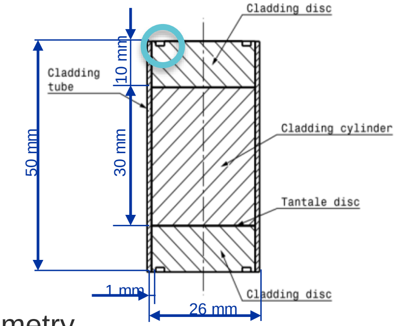
Nb alloy cladding R&D - Prototype Capsules

- I. EBW of Capsules
- II. Helium Penetrant Test
- III. 1st HIPing Cycle (1200 °C)
- IV. 2nd HIPing Cycle (1400 °C)
- V. Ultrasonic Testing
- VI. Cutting & OM at interface
- VII. Thermal Characterization
- VIII. Mechanical Characterization

→ Validation of **manufacturing and bondability**

Welding lip





Capsule Geometry

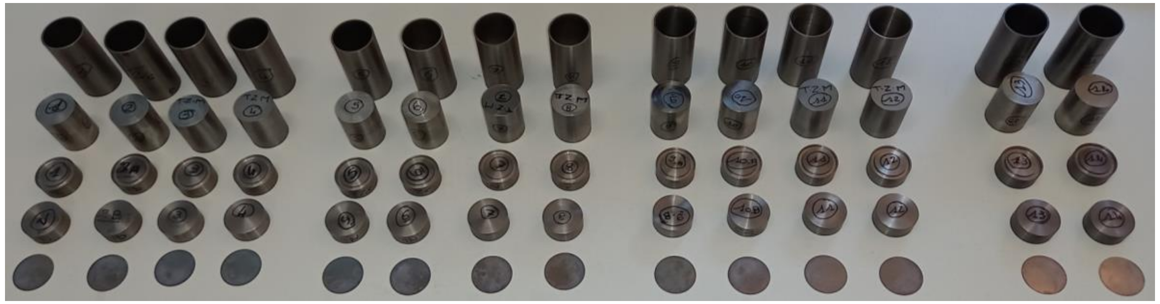
Capsules after EB welding

1st batch after HIPing

HIPing Furnace at Nuclear AMRC

Successfully bonded capsule

Single failed UT capsule fell apart when cut open

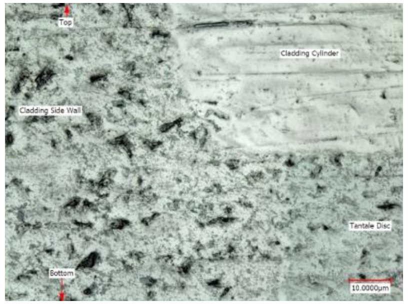


W | TZM
Nb

W | TZM
Nb1Zr

W | TZM
C103 (Nb10Hf1Ti)

W
Ta



OM of Nb//W

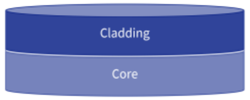
OM to visually check the bonding interface
→ **Bonding visually ok**

Thermo-mechanical Testing at the Interface

I. EBW of Capsules
II. Helium Penetrant Test
III. 1st HIPing Cycle (1200 °C)
IV. 2nd HIPing Cycle (1400 °C)
V. Ultrasonic Testing
VI. Cutting & OM at interface
VII. Thermal Characterization
VIII. Mechanical Characterization

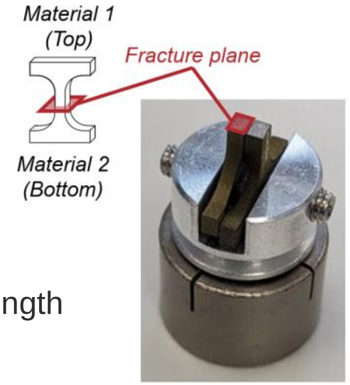
Thermal diffusivity specimens

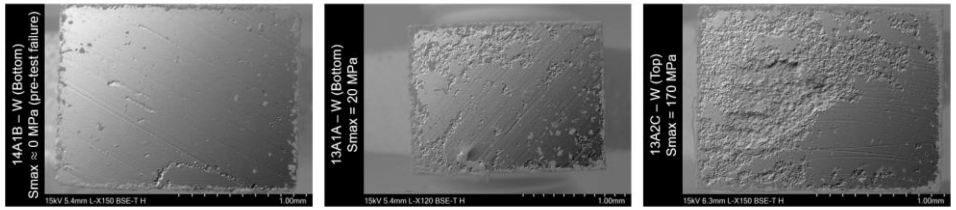
- Excellent thermal contact has been confirmed for all Niobium alloys (Nb, Nb1Zr, C103)
  - ➢ Contact resistance < 8e-6 [$m^2 K W^{-1}$]
  - ➢ TCC > 125 000 [$W m^{-2} K^{-1}$]
- No dependency visible for Ta foil or HIPing temperatures and differences of Nb alloys are not notable



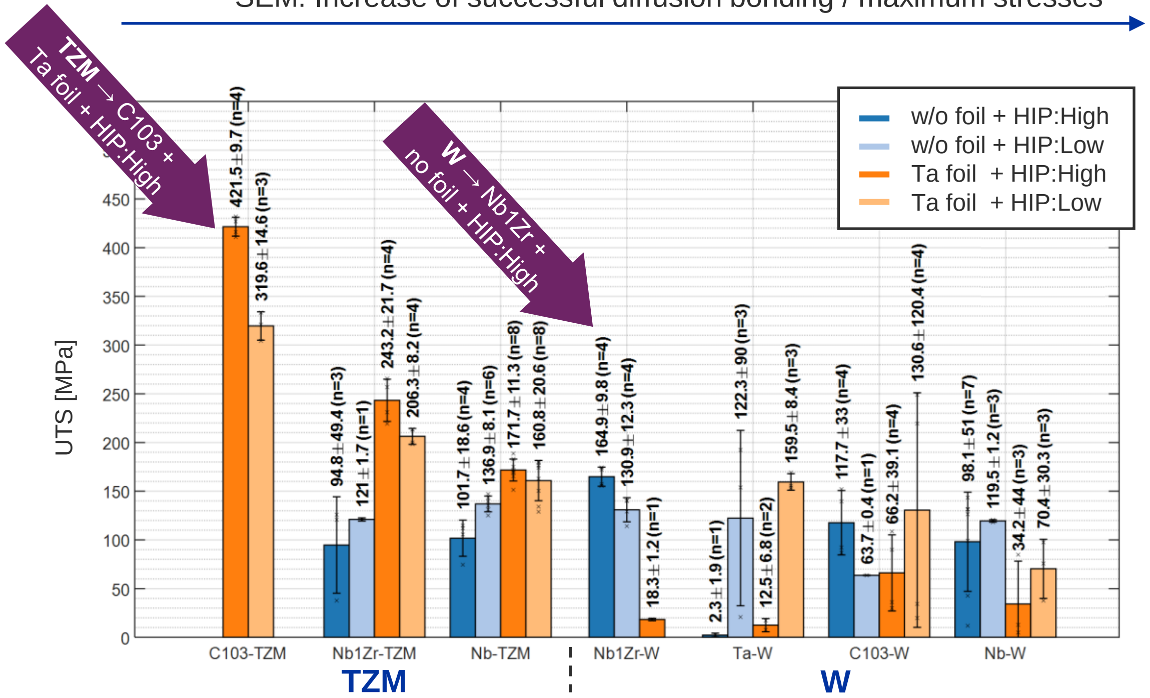
Tensile specimens

- Tested at Bangor University in the UK
- Out of 144 specimens 92 were successfully tested
- Interface strength for Nb alloys higher for TZM than W
- TZM core
  - For all cases, Ta foil + HIP:High increased the strength
  - Only C103 did not bond without the foil
- W core
  - Higher variation, but it seems no foil increases interface strength





SEM: Increase of successful diffusion bonding / maximum stresses

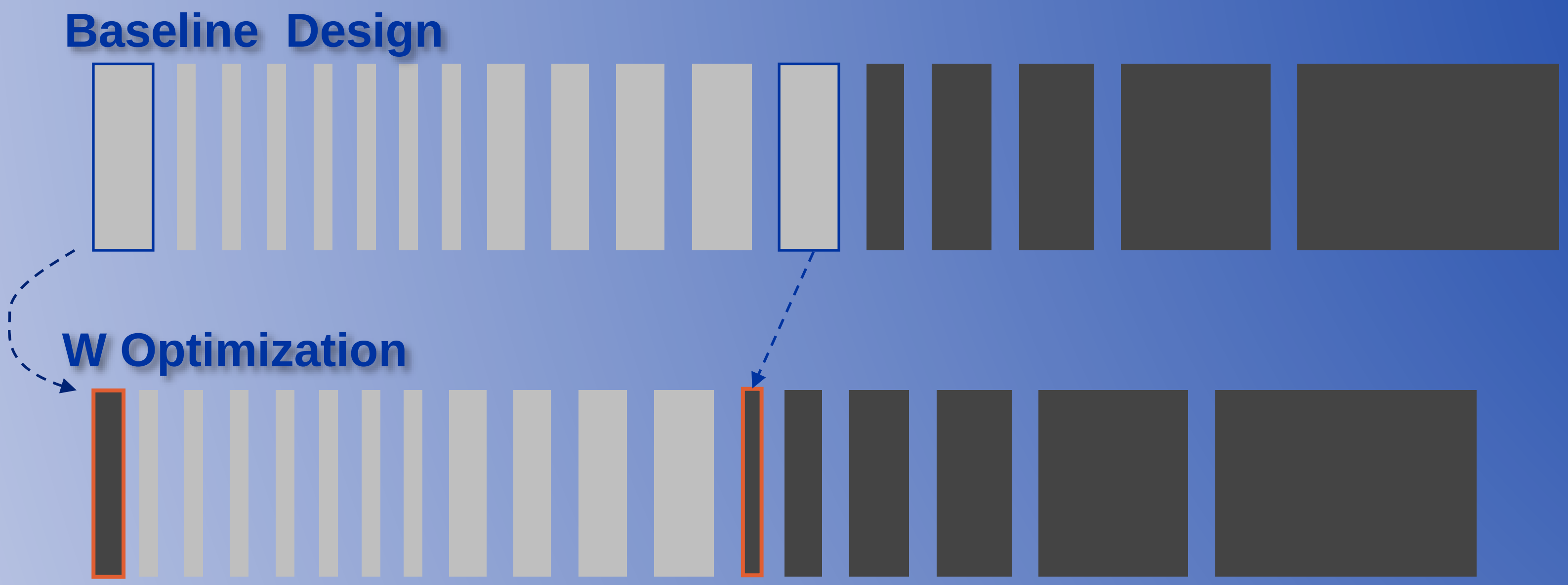


Nb R&D Study Conclusions

✓ Better
✓ Similar than Ta2.5W
✗ Worse

- ✓ Decay Heat
- ✗ Radio Protection
  → Nb-94 (Half-life of 2000 years) → Long-term storage / dismantling
- ✗ Thermal and mechanical properties (Nb1Zr)
- ✗ Strength of bonding interfaces (Nb1Zr)
- ✓ Thermal contact resistance of bonding interface
- ✓ Safety factor under operational conditions (simulations)
- ✓ Residual stresses under operational conditions (simulations)
- ✓ Bondability and manufacturing (prototype capsules)

→ LOCA of tantalum-cladded BDF not as critical as expected
→ Lower cost Nb alloys may have **higher dismantling/waste disposal cost** after irradiation due to long-lived isotopes



W Optimization Study of the Baseline Design (in 2023)

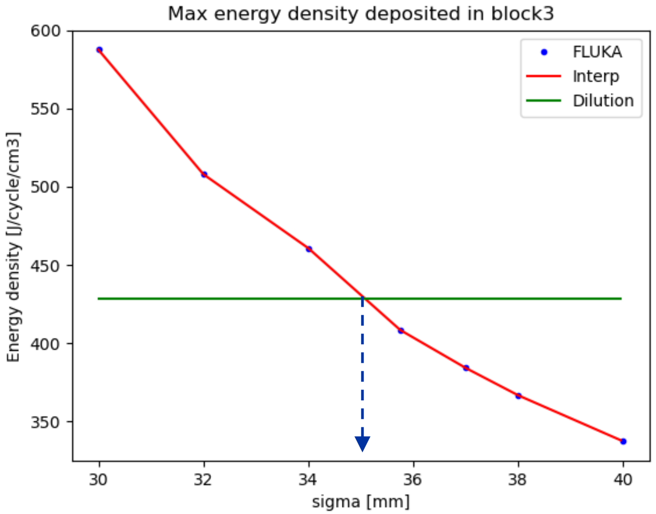
Idea: Non-diluted Beam

- BDF sweep is using a beam sigma of (x,y) = (8 mm, 8 mm)
- Idea for a no-sweep beam came as a mean to simplify the optics and eventually reduce the number of fatigue cycles in the target → 75 % less per pulse

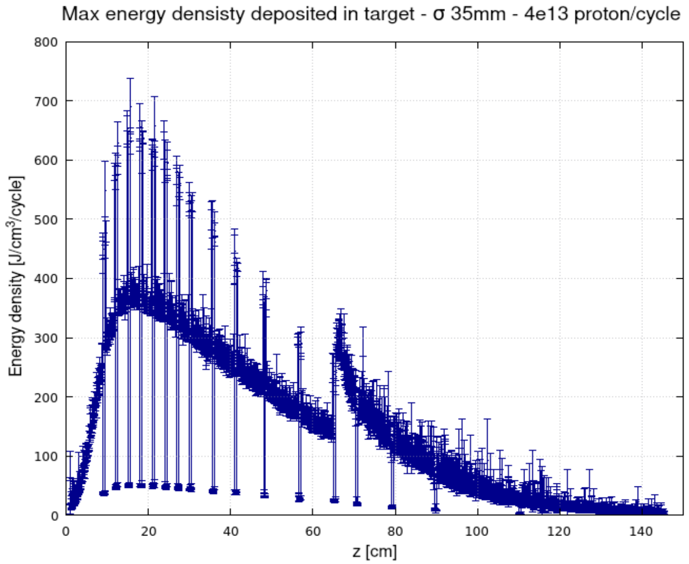
- **First investigation by Giuseppe M. & Luigi E. (SY-STI)**
  - Ta2.5W-cladded target, same spill length and ppp parameters as CDS report
  - Non-diluted beam impact on the center with different spot sizes

- **Investigation by Rebecca R. & Mathew F. (BE-ABT)**
  - Using the current optics in ECN3
  - Concluded non-diluted beam for the ECN3 beam line of

    (x,y) = (~34.9mm, 33.7mm)



Beam sigma study for same energy density of BDF Baseline



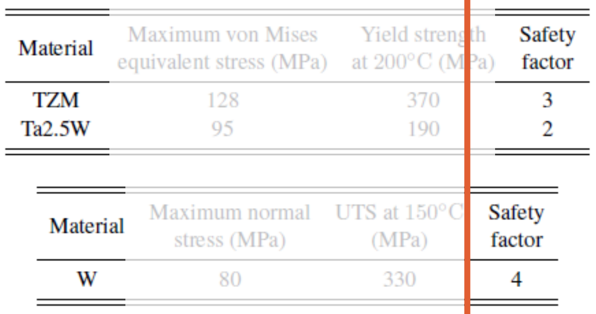
Energy deposition along the beam impact axis

Material Safety Margins
Beam Sweep vs. Non-diluted Beam

Beam Sweep

No-sweep Beam

Material properties from literature



Material	Maximum von Mises equivalent stress (MPa)	Yield strength at 200°C (MPa)	Safety factor
TZM	128	370	3
Ta2.5W	95	190	2

Material	Maximum normal stress (MPa)	UTS at 150°C (MPa)	Safety factor
W	80	330	4

CDS report

Material properties from characterization campaigns

Beam Sweep

Material	**Max. Temperature**	**Max. von Mises Stress (MPa)**	**Yield Strength at 200 °C (MPa)**	**Safety Factor**
TZM	170 °C	123	460	4
Ta2.5W	156 °C	127	227	2

Material	**Max. Temperature**	**Max. Principal Stress (MPa)**	**UTS at 150 °C (MPa)**	**Safety Factor**
W	144 °C	96	330	3.5

No-sweep Beam

Material	**Max. Temperature**	**Max. von Mises Stress (MPa)**	**Yield Strength at 200 °C (MPa)**	**Safety Factor**
TZM	167 °C	117	460	**4**
Ta2.5W	137 °C	102	227	**2.5**

Material	**Max. Temperature**	**Max. Principal Stress (MPa)**	**UTS at 150 °C (MPa)**	**Safety Factor**
W	155 °C	69	330	**5**

More conservative model constraints +
new material properties and limits

No-sweep Beam Impact

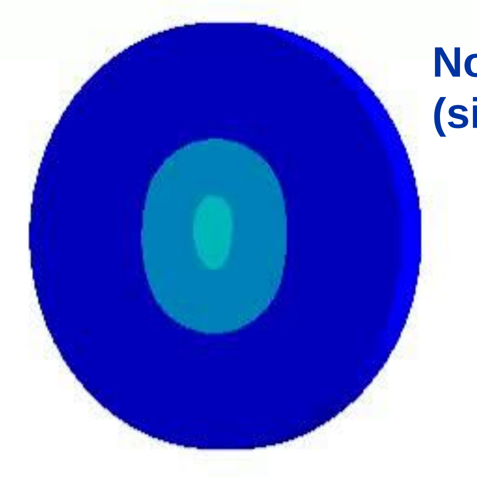
Non-diluted Beam vs. Sweep Beam

Advantages of non-diluted Beam Impact

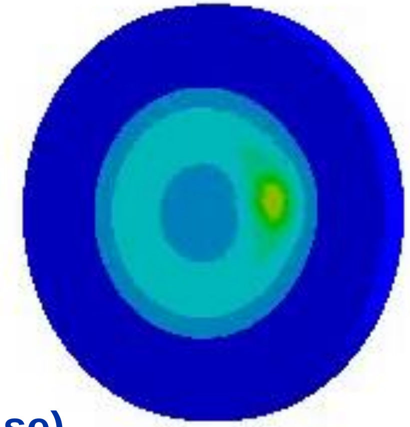
- Lower stresses in the critical blocks

  ⟶ Higher safety factors
- Longer lifetime due to **less material fatigue**

  (4 sweep turns vs. 1 impact during in one pulse)



Non-diluted Beam Impact
(single impact)



Beam Sweep
(4 turns per pulse)

➢ From thermo-mechanical point of view:
  → Only positive effects

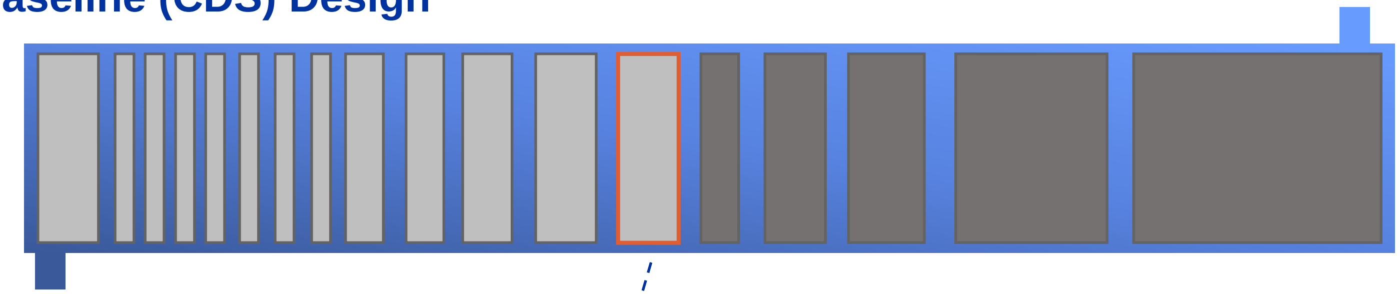
➢ **Potential to utilize more tungsten?**

Replacing the last TZM Block(s) with W

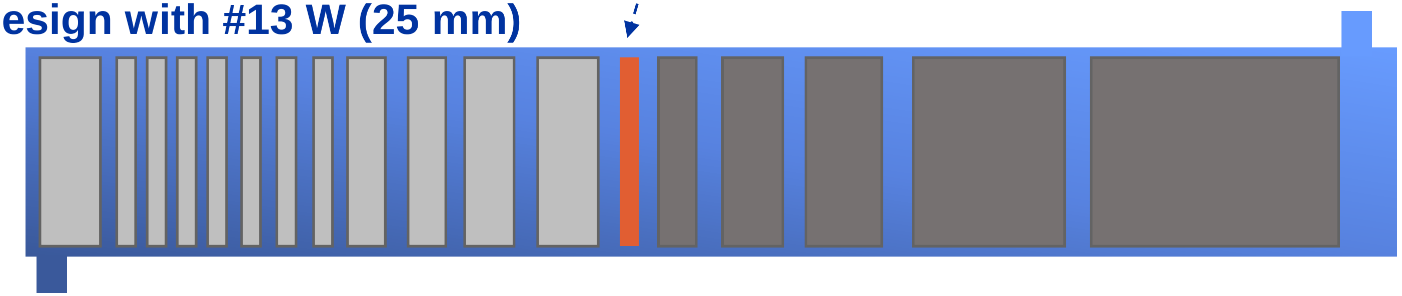
- Can we replace the last TZM Blocks #13 or #12 with W?
- Purpose: Increase the amount of W by replacing TZM to get a denser target
- Simulations performed with non-diluted Beam (35 mm) + Ta2.5W cladding

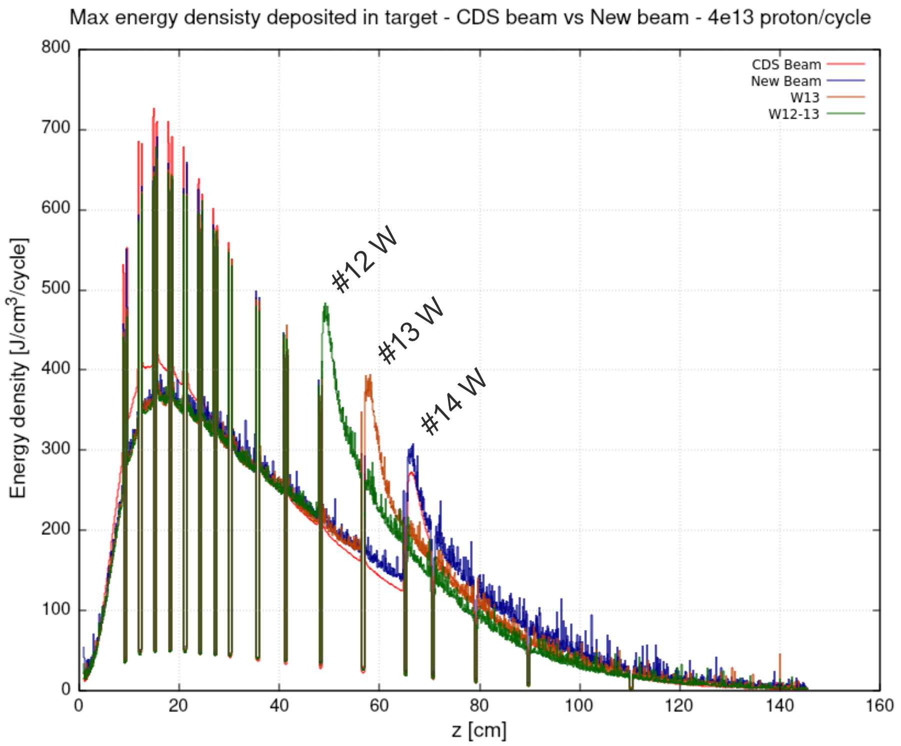
➢ **#13 W with 25 mm thickness**

Baseline (CDS) Design



Design with #13 W (25 mm)

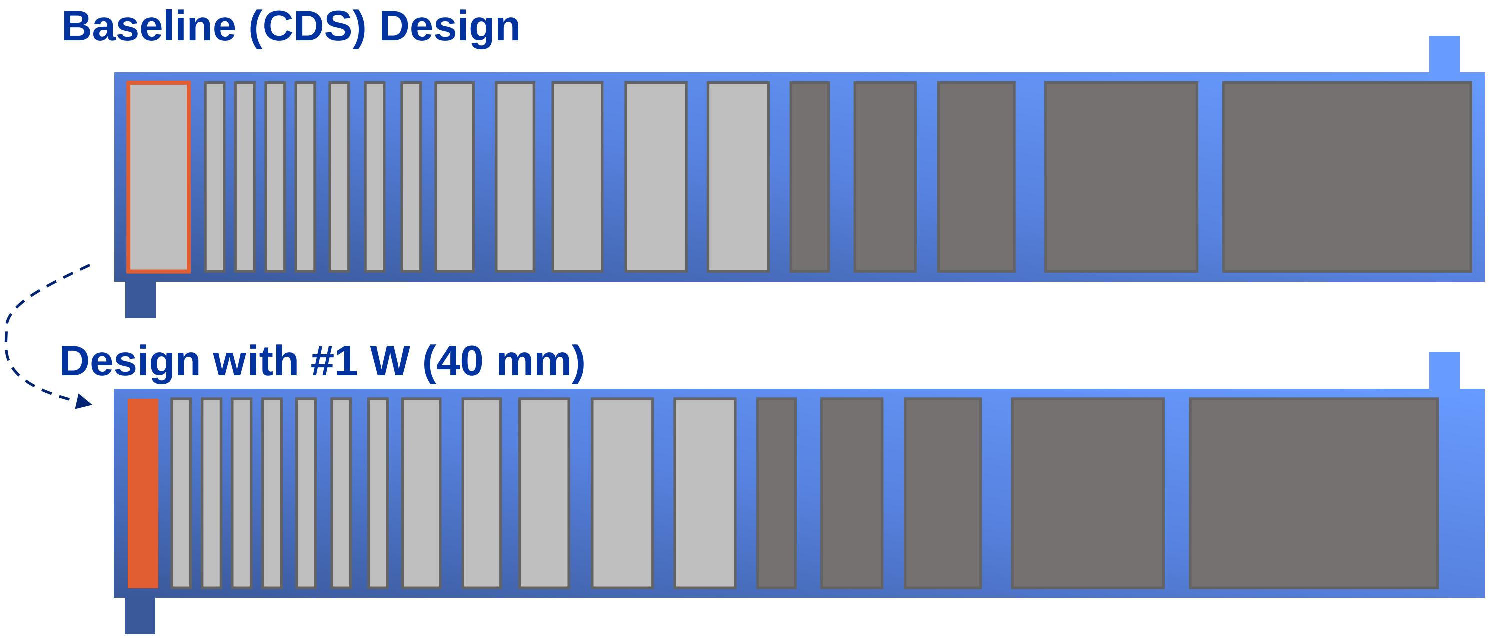


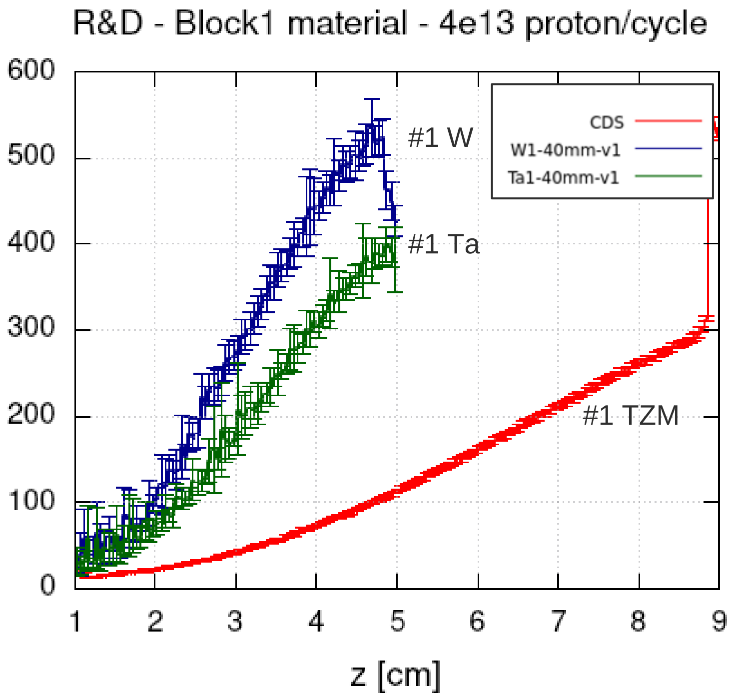


Replacing the first TZM Block with W

- Can we replace the first TZM Block #1 with W?
- Simulations performed with non-diluted Beam (35 mm) + Ta2.5W cladding

➢ **#1 W with 40 mm thickness**

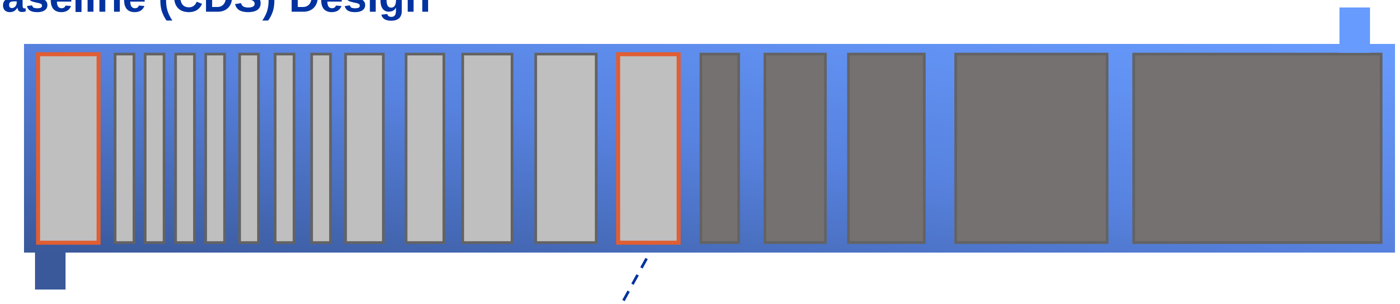




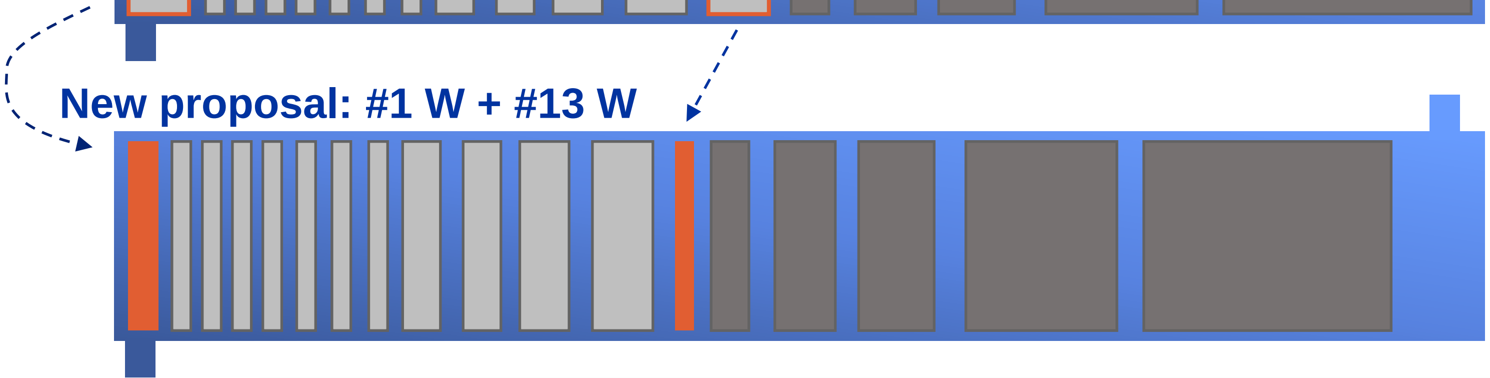
Combining Block #1 W and Block #13 W

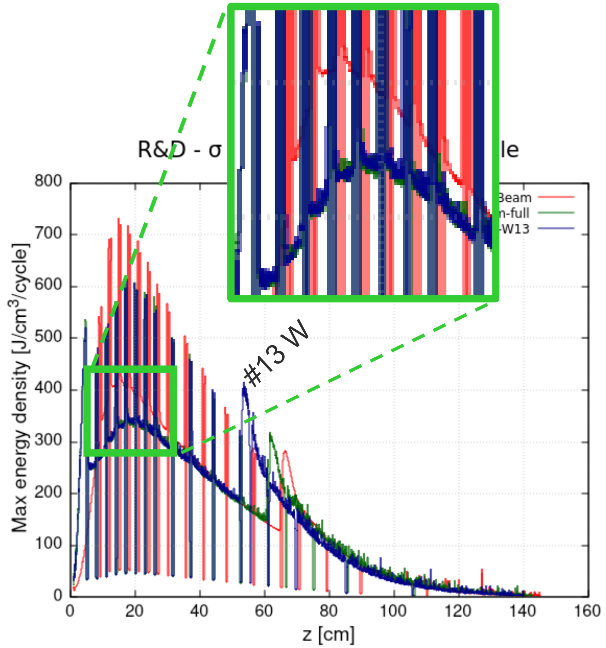
- **Safety margin is high enough** when replacing the TZM Blocks #1 and #13 with W
- Same nuclear interaction length as baseline (12) with more W interaction length 780mm → 885 mm
- Improves the physic performance of the target

Baseline (CDS) Design



New proposal: #1 W + #13 W





Energy deposition lower in TZM Blocks #2 - #8 with using Block #1 W (40 mm)

→ Denser and shorter target is feasible when using Block #1 W (40 mm) & Block #13 W (25 mm)

Conclusion & Outlook

- Robust BDF baseline design with Ta2.5W-cladded Blocks
- Niobium alloys also show good results → But are Nb-isotopes a showstopper?

- Non-diluted beam shows sufficient safety factor and causes lower material fatigue
- Possibilities to optimize the current baseline design by replacing TZM Blocks with W and create a denser and shorter target with the same nuclear interaction length

- More room for optimization?
- Possible to remove the water channels in direct contact with the blocks?
  → Eliminating the need of cladding the blocks
  → Allowing **less conservative material failure criteria**

home.cern

BDF Materials vs. Common Metals

Refractory Metals

Tungsten W

- Density [g/cm3]: 19.3
- Melting point [°C]: 3422
- T. Conductivity [W/(m·K)]: 165
- Young Modulus [GPa]: 400

Molybdenum alloy TZM

- Density [g/cm3]: 10.2
- Melting point [°C]: 2623
- T. Conductivity [W/(m·K)]: 125
- Young Modulus [GPa]: 210

Tantalum Ta

- Density [g/cm3]: 16.6
- Melting point [°C]: 3017
- T. Conductivity [W/(m·K)]: 60
- Young Modulus [GPa]: 160

Common Metals

Stainless Steel (316L)

- Density [g/cm3]: 7.9
- Melting point [°C]: ~1390
- T. Conductivity [W/(m·K)]: 15
- Young Modulus [GPa]: 197

Copper (OFE-Cu C10200)

- Density [g/cm3]: 8.9
- Melting point [°C]: 1080
- T. Conductivity [W/(m·K)]: 395
- Young Modulus [GPa]: 122

Aluminium (Al AW-5083)

- Density [g/cm3]: 2.7
- Melting point [°C]: ~600
- T. Conductivity [W/(m·K)]: 123
- Young Modulus [GPa]: 72

[1] Thermal Conductivity and Youngs Modulus at RT

Source: Rui Franqueira Ximenes (TCD Extended Section Meeting, March 2022)