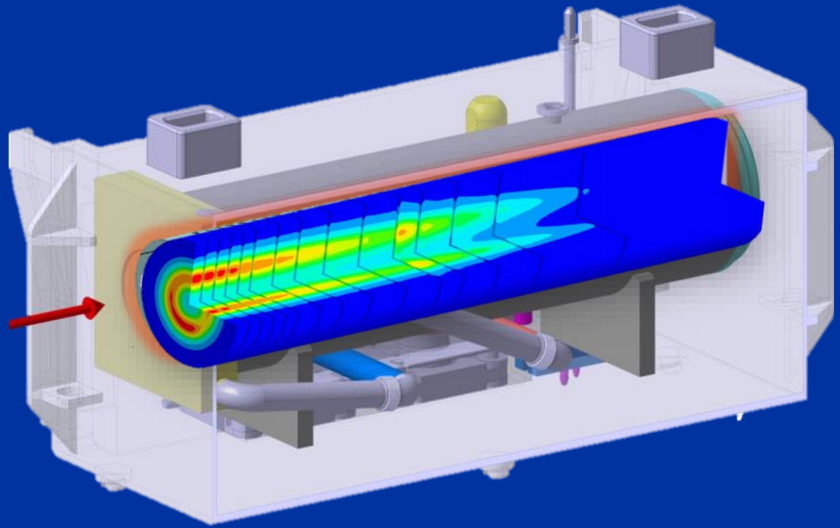


Target design baseline and challenges
WP3 BDF/HI-ECN3
Target & Target Complex Initial Concept Review (ICR)

Rui Franqueira Ximenes, M.Calviani, T.Griesemer, A.Francia, M.Parkin, Jean-Louis Grenard, D.Grenier, C.Mucher, L.Esposito, G.Mazzola (SY-STI), L. Gentini, S.Sgobba, A.Fontenla (EN-MME), M. di Castro, J.Lendaro (BE-CEM), R.Jacobsson (EP), M. Fraser (SY-ABT), C. Ahdida (HSE-RP), + HI-ECN3 team et al.

29/04/2024

Target presentations - Goal of today

- Outline the current design, the studies and rational from CDR times until today
- Highlight key challenges that need to be addressed
- Set the plans for TDR
- Show the recent developments/ideas
- Identify missing threads

Target Agenda (morning): From CDR to today

09:30 → 09:40	**Beam delivery for HI-ECN3** Speakers: Aleksandr Gorn, Francesco Maria Velotti (CERN)	10m	774/R-013
09:40 → 10:05	**Target design baseline and challenges** Speaker: Rui Franqueira Ximenes (CERN)	25m	774/R-013
10:05 → 10:25	**2018 Target prototype & lessons learnt from PIE** Speaker: Tina Griesemer (CERN)	20m	774/R-013
10:25 → 10:45	**Coffee break**	20m	774/R-013
10:45 → 11:00	**LOCA, oxidation and residual stress past studies** Speaker: Ramiro Francisco Mena Andrade	15m	774/R-013
11:00 → 11:20	**Target Nb cladding R&D & baseline design optimization** Speaker: Tina Griesemer (CERN)	20m	774/R-013
11:20 → 11:35	**Looking ahead - Target alterative designs** Speakers: Alvaro Romero Francia (CERN), Mike Parkin, Rui Franqueira Ximenes (CERN)	15m	774/R-013
15:55 → 16:10	**TDR threads & project timeline for the Target WP** Speaker: Rui Franqueira Ximenes (CERN)		

- Beam delivery for HI-ECN3 → From the SPS to the Target
- Target design baseline and challenges → Looking in detail at the baseline design and CDR studies & some points left to be addressed
- 2018 Target prototype & lessons learnt from PIE → Lessons learnt from the 2018 Prototype post-irradiation examination
- LOCA, oxidation and residual stress past studies → Quantifying critical items
- Target Nb cladding R&D & baseline design optimization → Pre 2024 studies in view of addressing concerns
- Looking ahead - Target alterative designs → Looking ahead to an optimized and validated Target design
- TDR threads & project timeline for the Target WP → TDR Plans

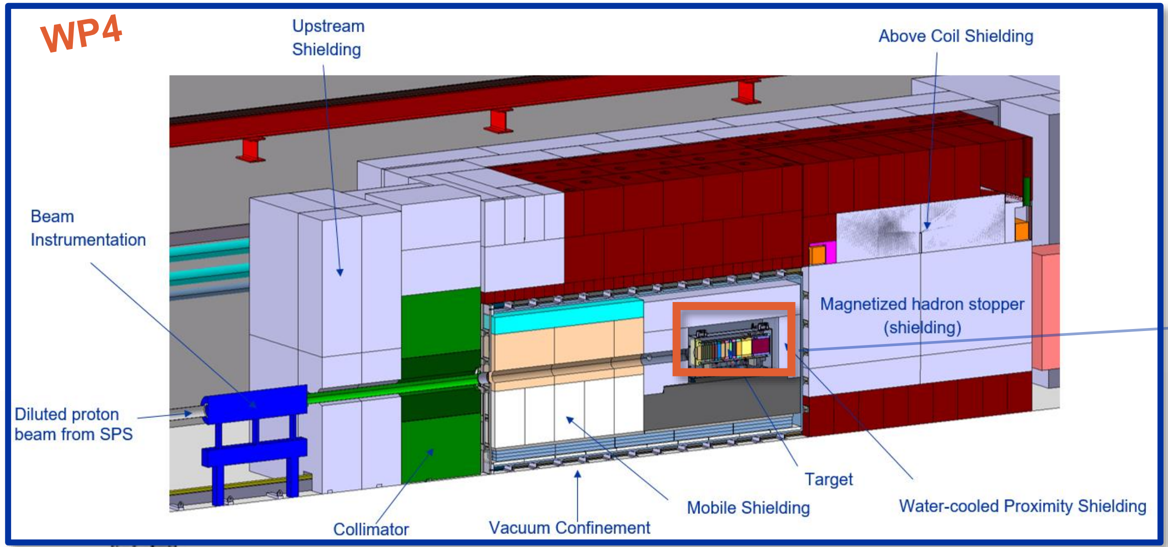
Content

- Intro Target talks & goal
- Target function & requirements
- Baseline design
- Thermo-mechanical behaviour
- Ta2.5W cladding
- Target Radiation dose & damage
- 2018 Prototype
- Conclusions

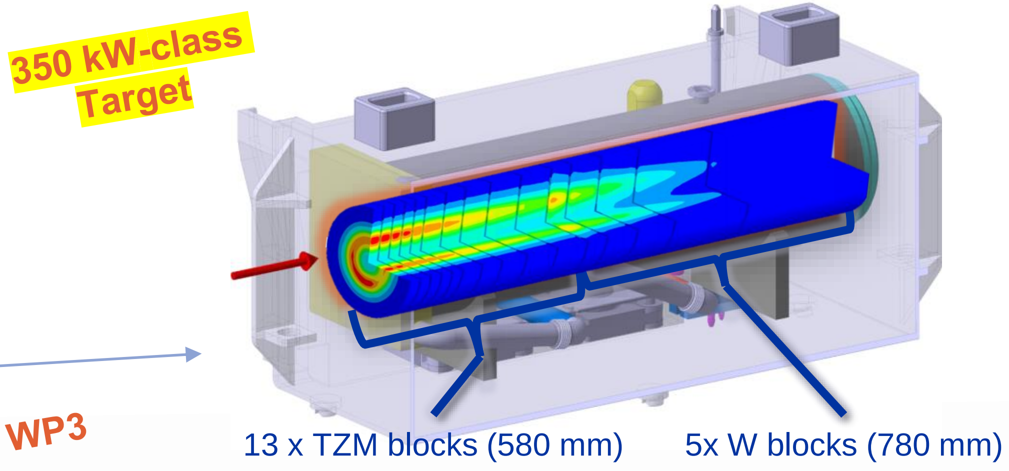
+ Missing threads

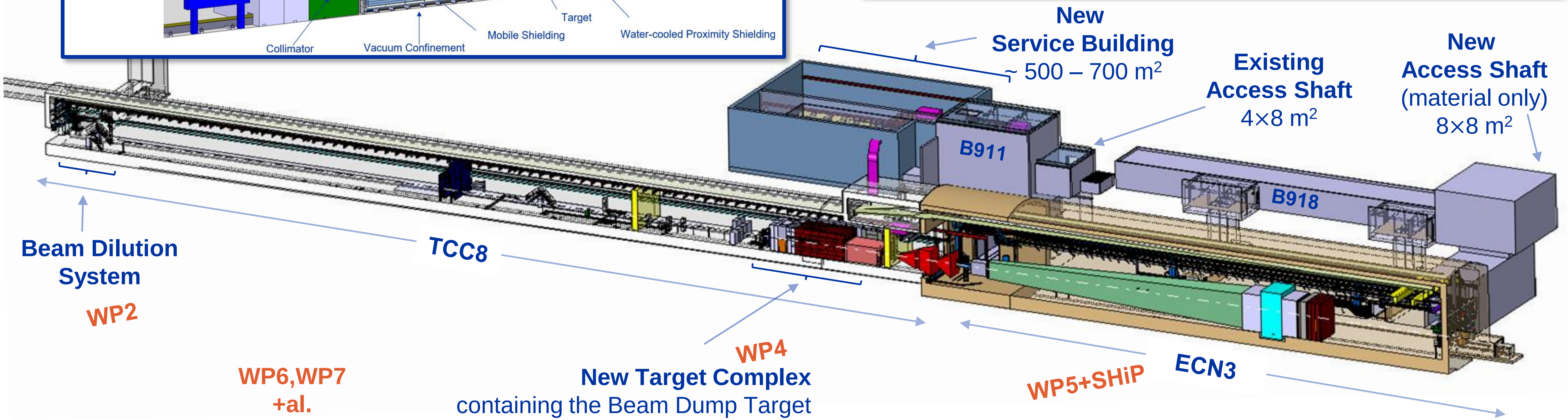
Target function & requirements

BDF/SHiP Target & Complex



Baseline Design → To be improved during TDR





BDF/SHiP Target

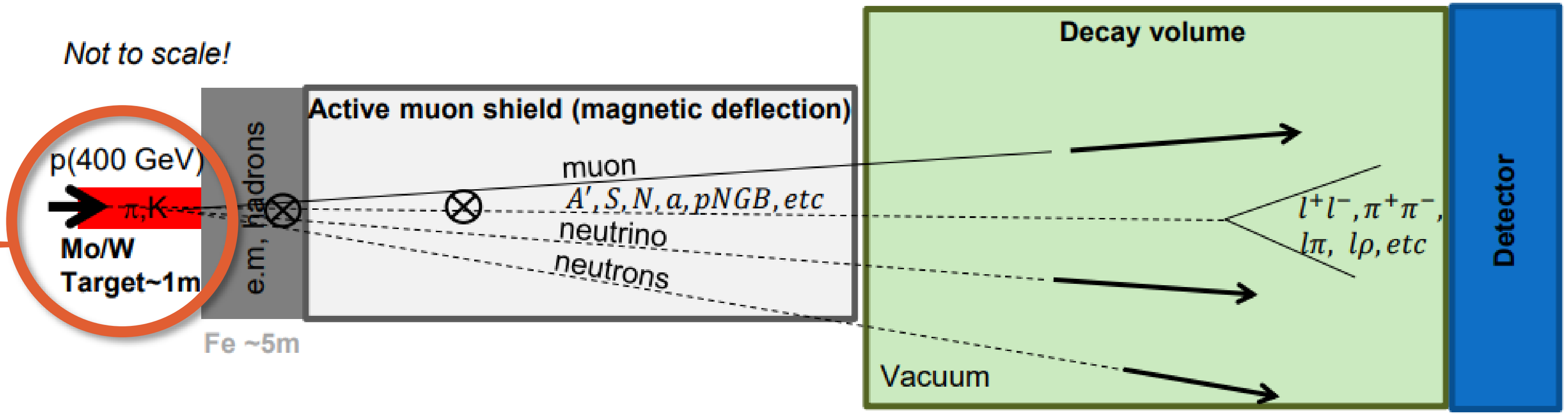
- **Beam Dump Target** / SHiP Target
  - ➢ Fully absorbe all p+, maximize production of charm and beauty hadrons & re-absorption of pions, muons and kaons

High energy → production of charmed and beauty mesons

High ppp & POT → overcome small prod cross-section of extra rare events of hidden particles

High ρ, Z & A → Maximize p+ interaction

Shortest λ → Force absorption of K & π to reduce muon & neutrino background



R. Jacobsson

SPS Beam Dump Facility: Comprehensive Design Study, https://doi.org/10.23731/CYRM-2020-002
SHiP Experiment - Comprehensive Design Study report, https://cds.cern.ch/record/2704147

BDF Target

Target requirements

- **Physics**:
  - high-Z material & with short interaction length
  - Fully absorb SPS p+ beam
- **Engineering**:
  - 305kW power → cooling needs
  - 305kW power → temperature & thermal-induced stresses
  - High nr of spills & POT → mechanical fatigue & radiation damage
- **Safety:**
  - High activation → Remote handling, waste disposal considerations, spallation/contamination products…

Baseline beam parameters of the BDF Target operation. https://doi.org/10.23731/CYRM-2020-002

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

~ 4.0×10^{19} p^{+}/y

Very similar requirements to a neutron spallation target

Synergies with other labs are being pursued

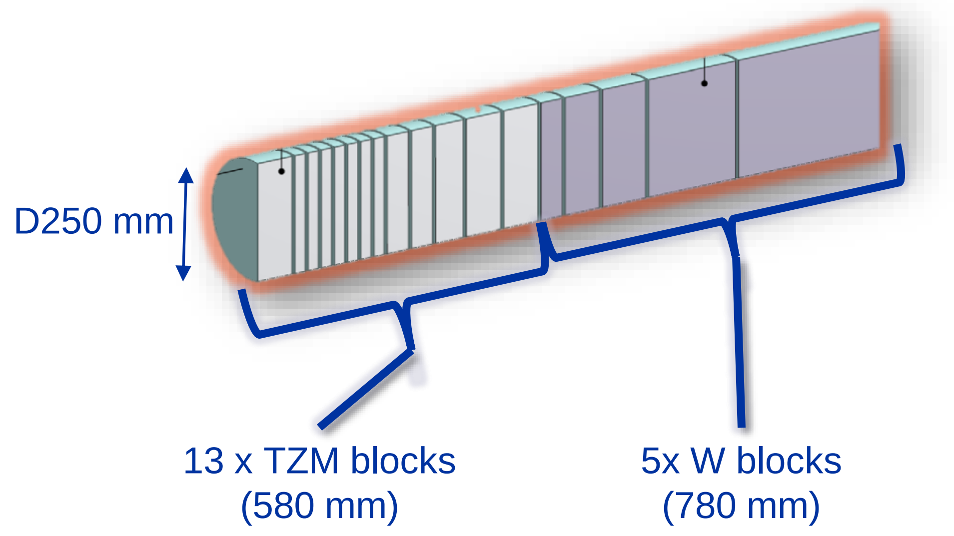
Baseline Design

https://doi.org/10.1103/PhysRevAccelBeams.22.113001

BDF Target baseline design

Core geometry & materials

- **250 mm Diameter Target**
- **580 mm of TZM (13 blocks)**
  - Reasonable high density & Z (Z=42, ρ=10.2g/cm^3)
  - Higher strength, better creep resistance, higher recrystallisation temp wrt Mo.
  - Absorbs most of the beam power.
- **780 mm of W (5 blocks)**
  - High Z and density (Z=74, ρ=19.3g/cm^3)
  - Good radiation damage resistance
- **95 mm of water (5 mm * 19 channels)**
  - Required to cool the blocks
- **54 mm of Ta2.5W cladding (1.5 mm * 2 * 18 blocks)**
  - To avoid corrosion-erosion of the core materials



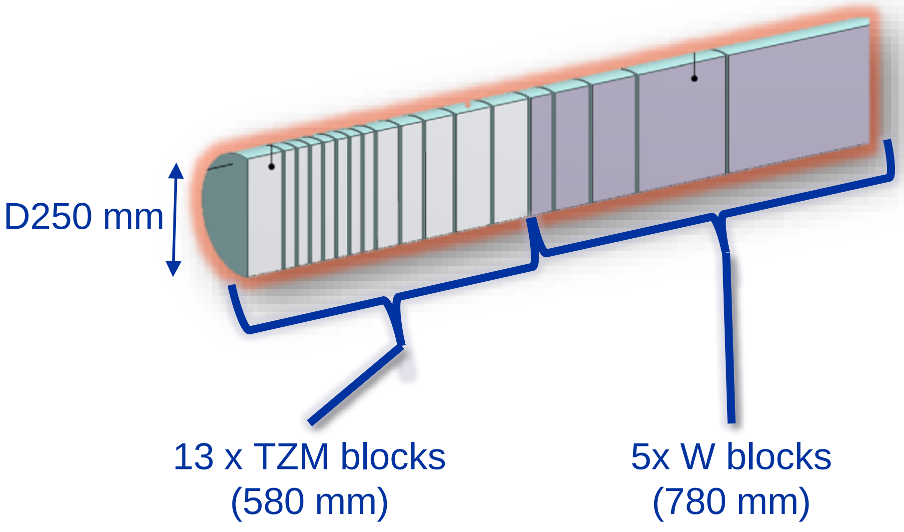
Target Core with reasonable physics performance & that allows diluting (longitudinally) the energy deposition

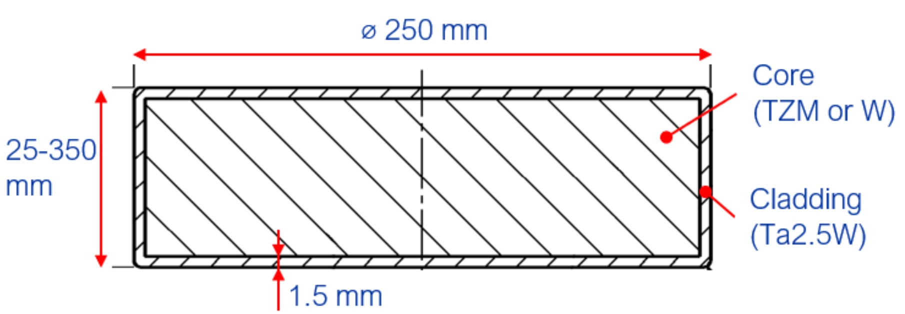
https://doi.org/10.1103/PhysRevAccelBeams.22.113001

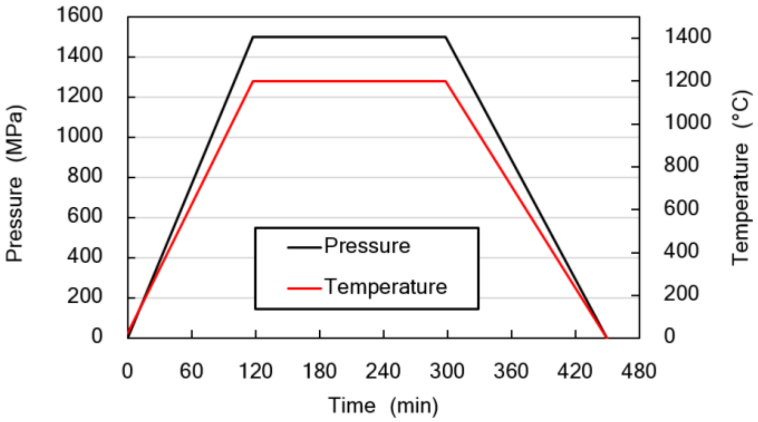
BDF Target baseline design

Manufacturing technology

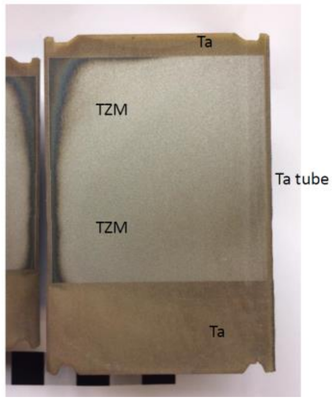
- Water-cooling circuit → Corrosion-erosion → Core cladded with Ta2.5W (1-1.5 mm thickness) by means of Hot Isostatic Pressing (HIP)
- HIP (Hot Isostatic Pressing)
- Diffusion bonded at High pressure and high temperature
- Key manufacturing feature. Essential for good heat transfer to the water circuit (cooling)







TZM containing capsule (electro eroded)

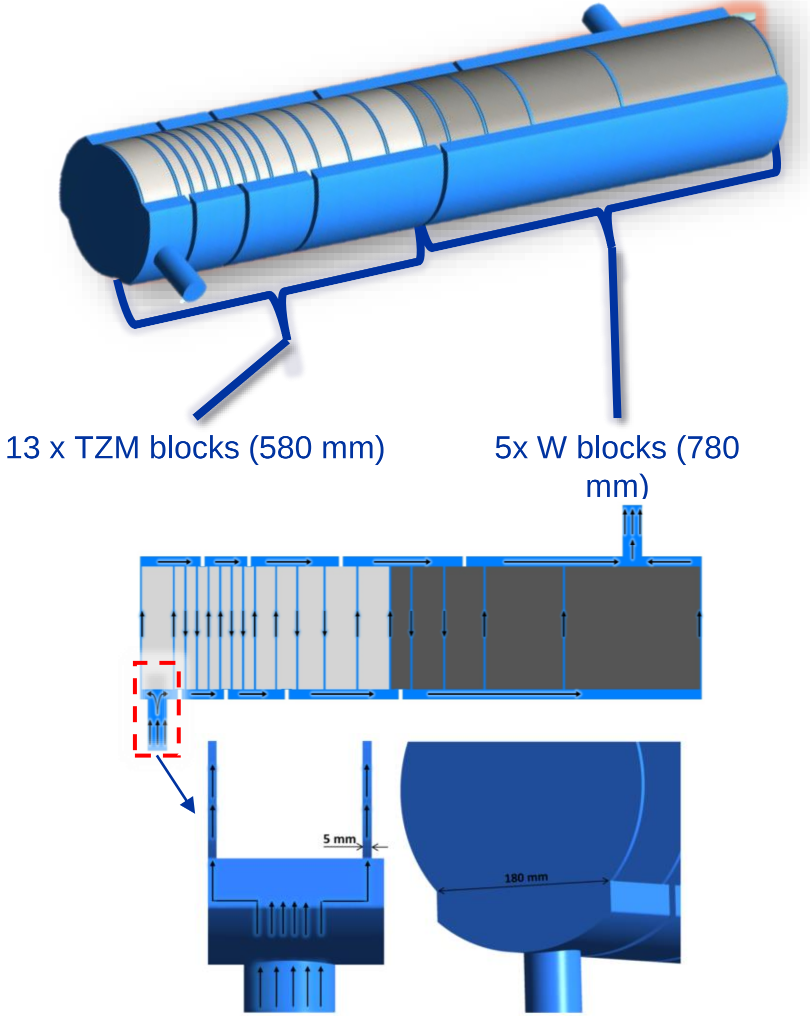


https://doi.org/10.1103/PhysRevAccelBeams.22.113001

BDF Target baseline design

Cooling

- **95 mm of water (5 mm * 19 channels)**
  - Water → better cooling for identical flow rate wrt He, Air.
  - 22 bar → higher boiling threshold
  - 5 m/s → high heat convection coefficient and limited erosion
  - ~660l/min → To extract ~305kW of heat.
  - Circuit Serpentine configuration with 2 parallel channels
    - Serpentine → high speed at moderate flow rate
    - 2 parallel channels → pressure drop reduction & reduce failure in case 1 channel is blocked.



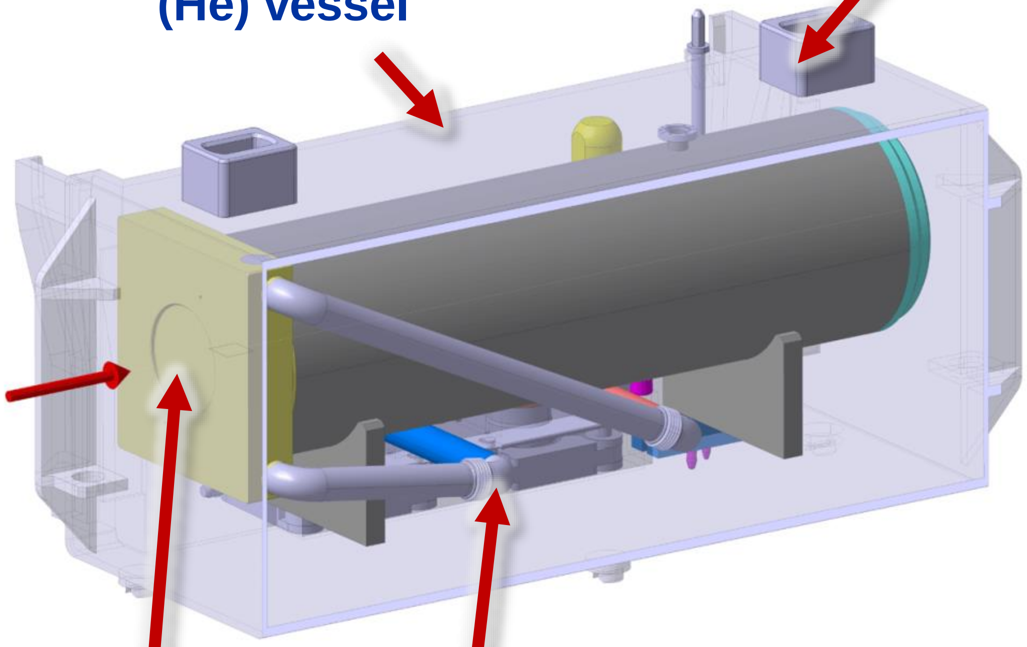
Key components

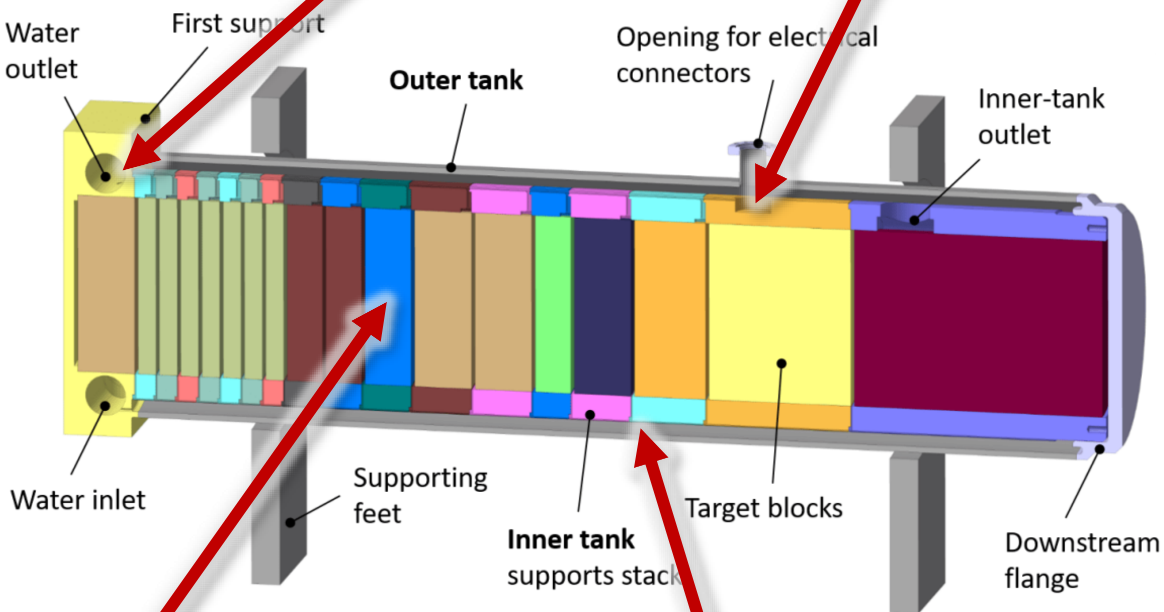
Remote handling & waste disposal features

Cooling

Instrumentation & integration

2nd outer Target (He) vessel





Beam windows

Services connections

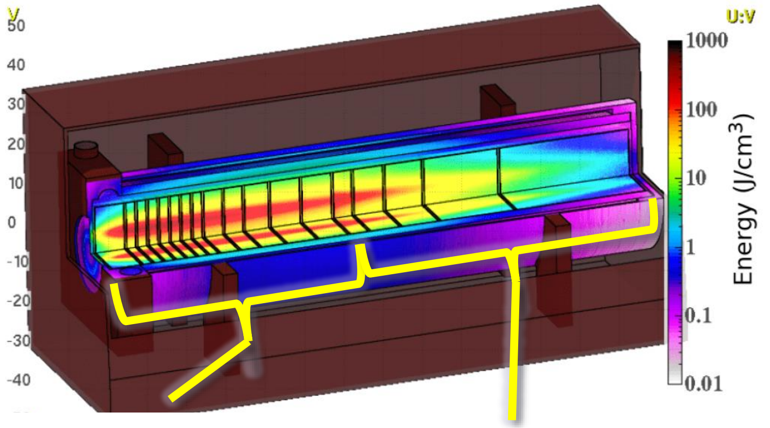
Target core

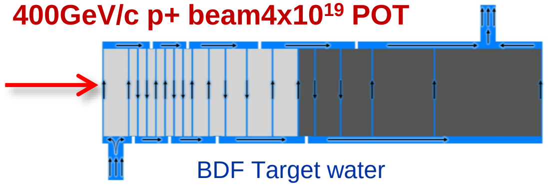
Target inner vessel

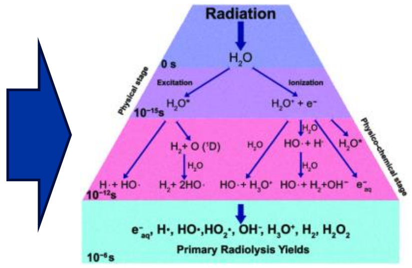
Missing threads → TDR studies (1/5)

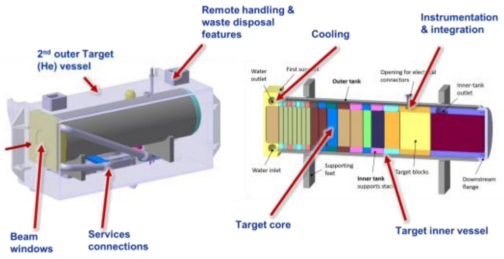
- Most of the shower develops on TZM and not on W → core could be further optimized for physics
- Water in-beam promotes formation of radicals → safety concerns should be addressed
- Target system missing full definition & design → detailed system design & engineering to be done

→ Mike, Alvaro & Tina's presentations ←









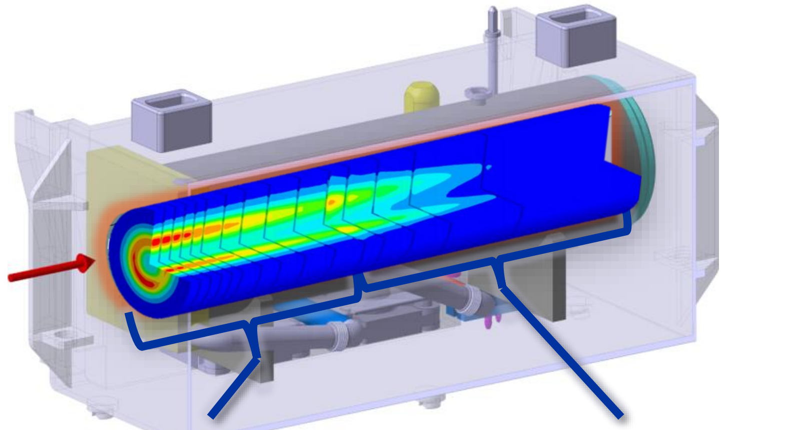
Themo-mechanical behavior

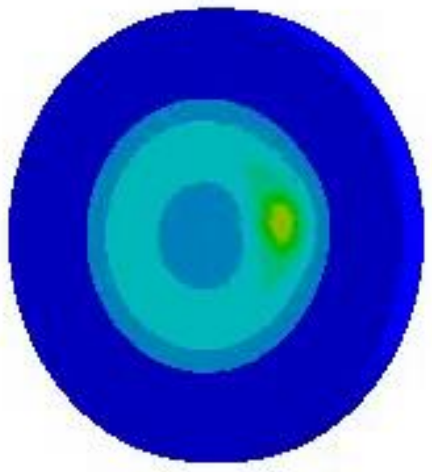
Baseline design

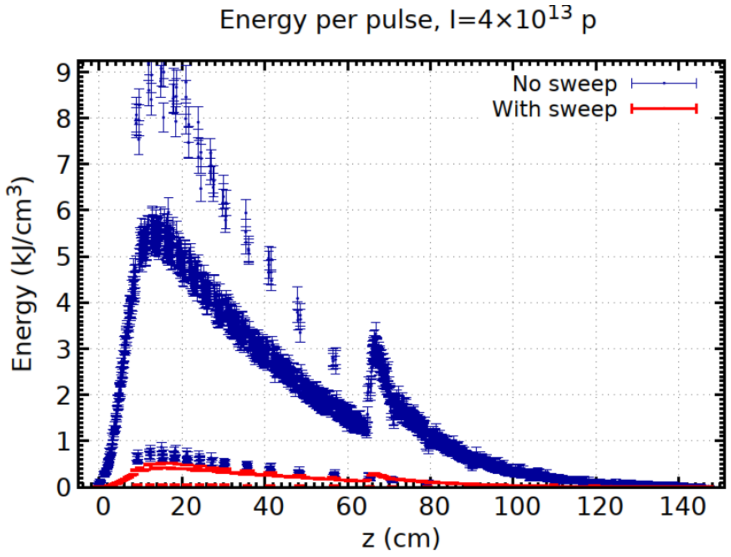
Thermo-mechanical behavior

Dilution system

- **2.3MW during the 1 s spill**
- → Beam must be somehow diluted (blown-up and/or swept)



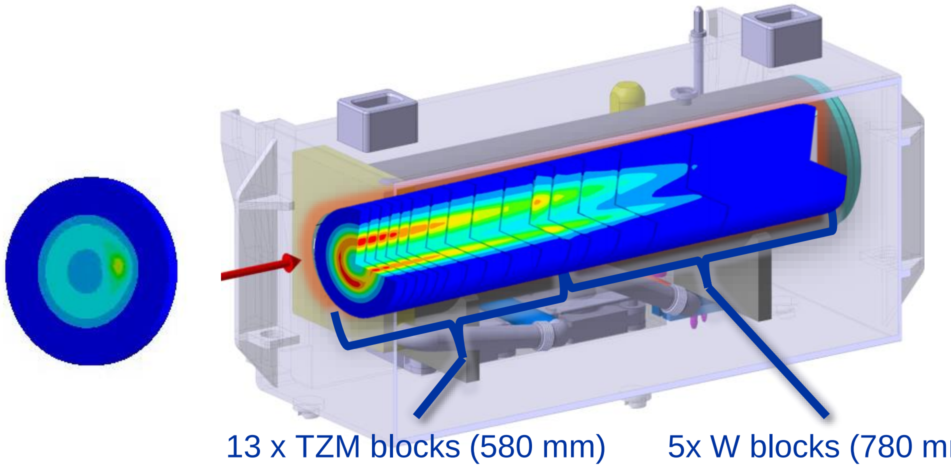


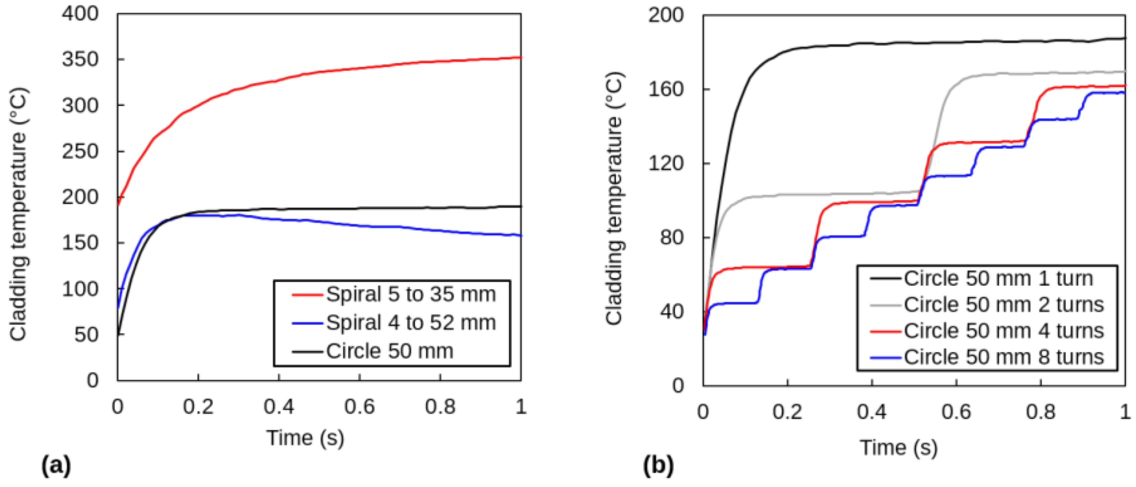


Thermo-mechanical behavior

Dilution system

- Spiral, circular and elliptical sweep patterns explored.
- Spiral discarded due to added complexity of the dilution magnets
- **Circular pattern using 4 dilution kickers**
  - Circular with 4 turns sweep
  - π/2 scheme best in case of failure (33%p. target failure if 2 kickers fail)
  - Beam size of 8mm 1σ. Limited by upstream magnets

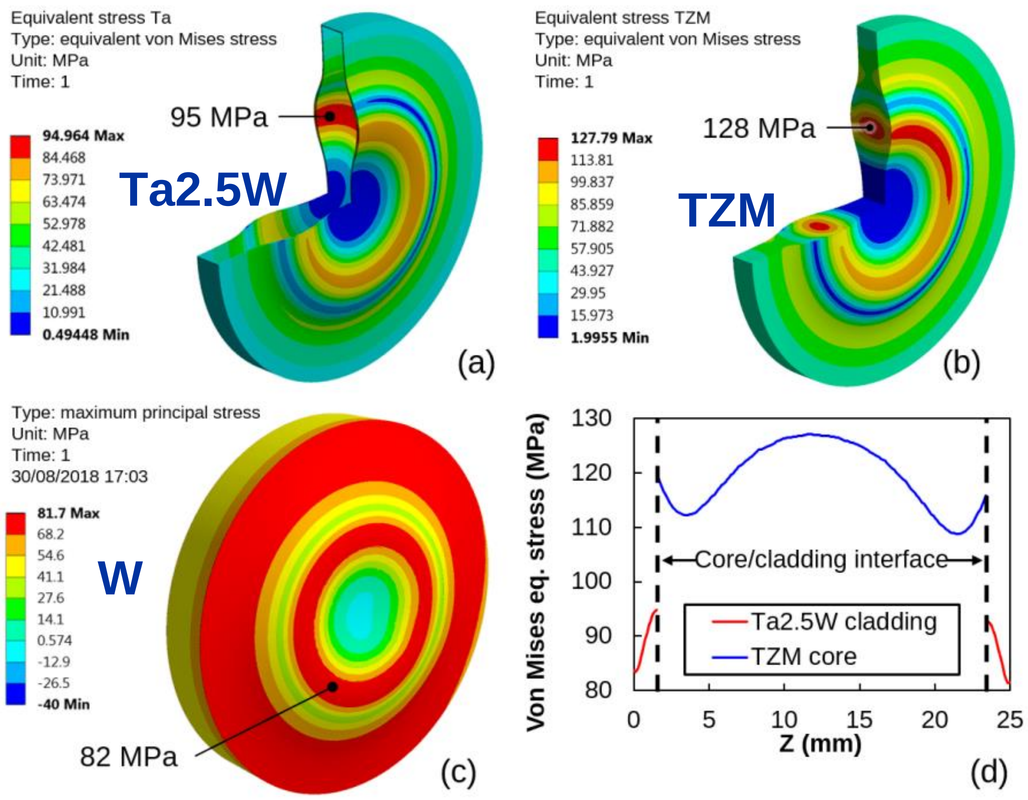


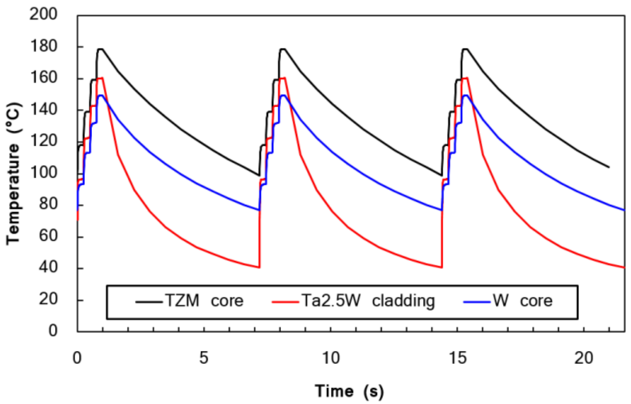


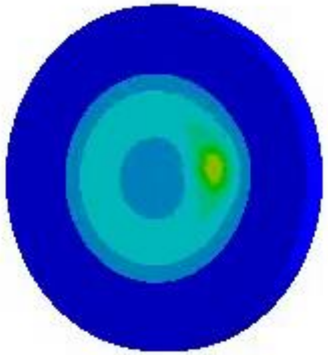
Thermo-mechanical behavior

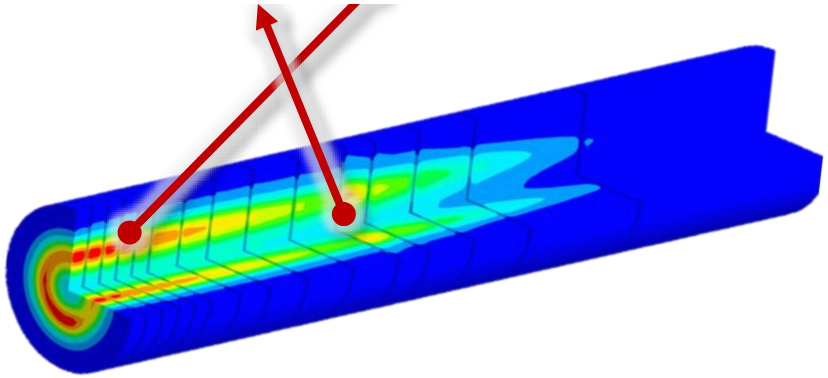
Thermo-mechanical conditions of the core

- High temperature (high average power)
- Thermal-induced stresses (SS + pulse)
- Residual stresses from manufacturing
- Fatigue (10^6 cycles / year)
- Radiation damage / loss of mechanical properties
- Erosion/corrosion









#4 TZM & #14 W

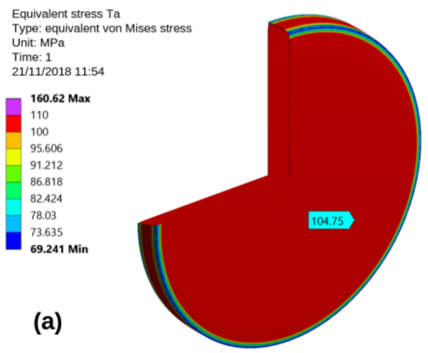
Thermo-mechanical behavior

Residual stress (RS) TZM blocks

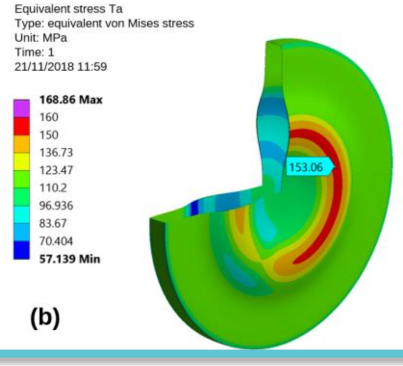
➢ **HIPing creates RS → driven by CTE difference between core material & cladding**

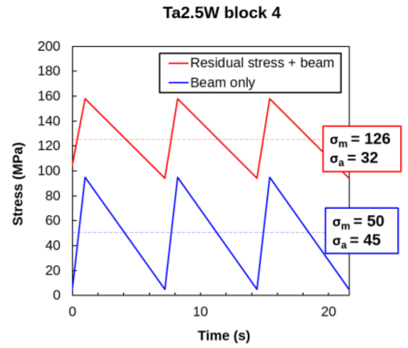
- **RS is high in Ta2.5W cladding of TZM block** (Purely tensile, radial direction).
  - With beam, stresses are added.
  - Stress amplitude is smaller, despite higher mean stress. No negative impact on fatigue.
- **RS is low in TZM itself** (purely compressive).
  - With beam, increases the circumferential radial stress by a small fraction.
  - Slight impact on fatigue (increased mean stress)

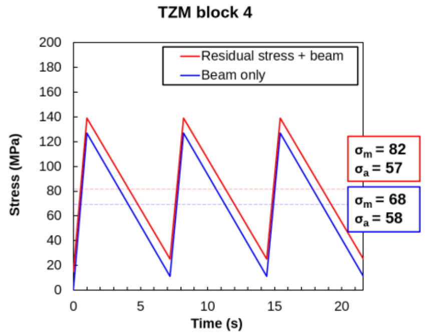
Ta2.5W after HIP



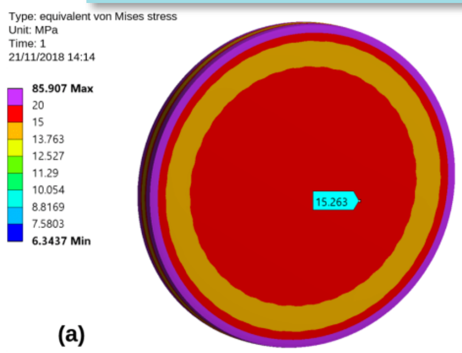
HIPed Ta2.5W after spill



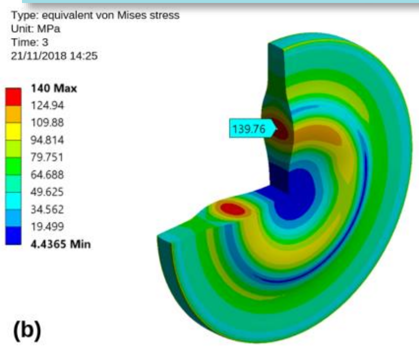




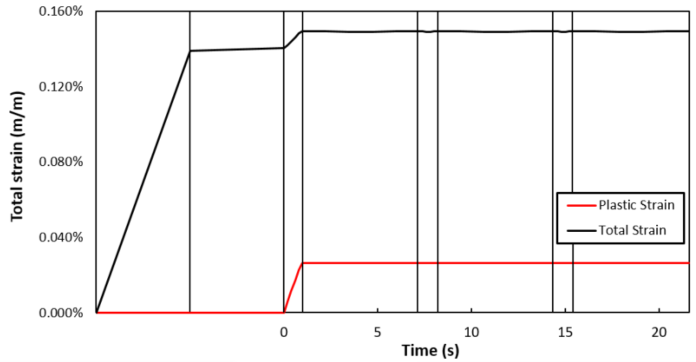
TZM after HIP



HIPed TZM after spill



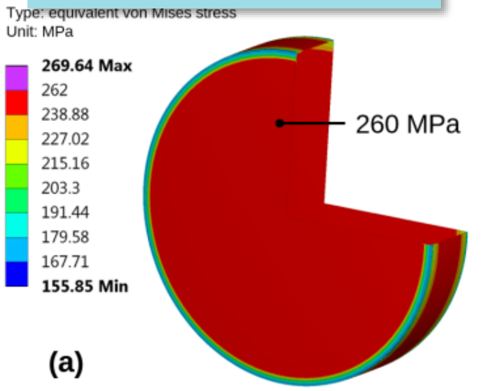
Thermo-mechanical behavior



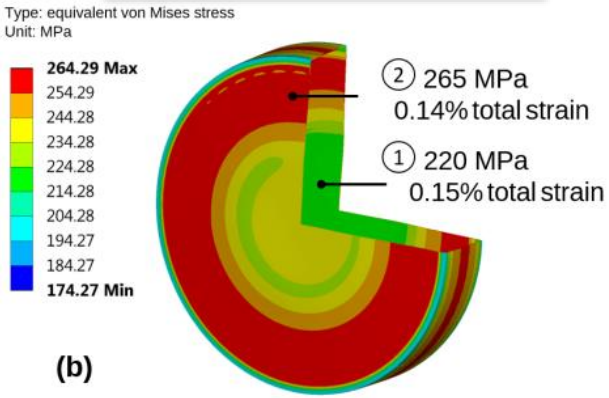
Residual stress (RS) W blocks

- **With W, CTE difference is higher**
- **RS is very high in Ta2.5W cladding of W block** (Purely tensile, radial direction).
  - With beam, circumferential compressive stresses from beam relieve the RS in the centre & tensile in the external part.
  - Stress amplitude is smaller, despite higher mean stress. No negative impact on fatigue.
  - → elastic shakedown
- **RS is low in W itself** (purely compressive).
  - Max principal stress decreases. Compressive increase by a small fraction.
  - No impact on fatigue (increased mean stress)

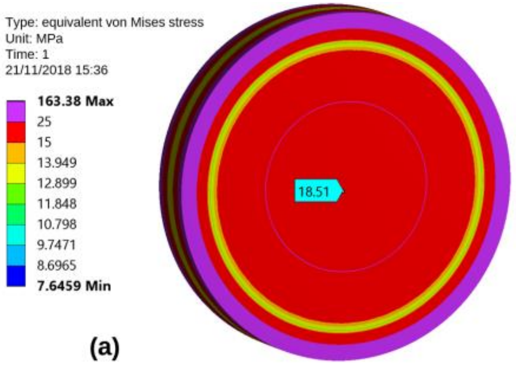
Ta2.5W after HIP



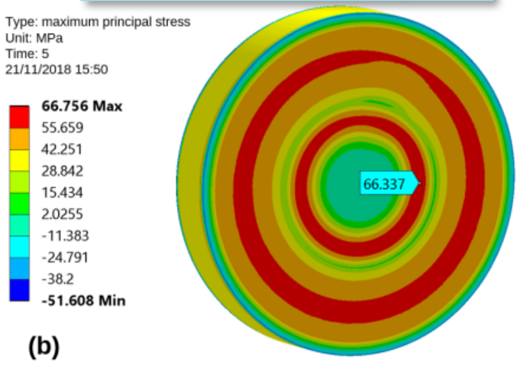
HIPed Ta2.5W after spill



W after HIP

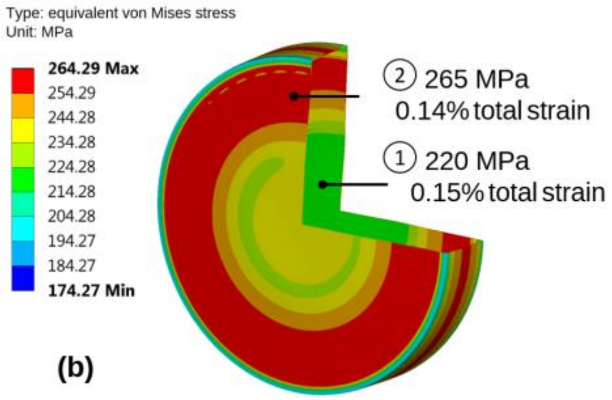


HIPed W after spill



Thermo-mechanical behavior conclusions & Missing threads → TDR studies (2/5)

- No cumulative yielding or failure expected with baseline during normal operation.
- However, stress relaxation of the cladding is expected with first pulses. → Residual stress shall be fully understood & quantified
- Large safety margin on W (even if operating at low temperature (brittle)) → Margin for Target core optimization
- Critical element/material is Ta2.5W cladding.
  → Need for QA plan



Ta2.5W cladding

Manufacturing know-how

Ta2.5W cladding

Tantalum

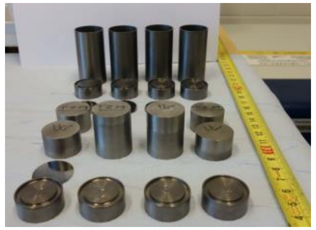
- ✓ Refractory with high melting point, conductivity, strength and ductility
- ✓ High density
- ✓ Low CTE
- ✓ Full solubility with Molybdenum and Tungsten
- ✓ Very good corrosion-erosion resistance in water medium
- ✓ Sound experience in other Targetry applications (ISIS, LANSCE, KENS…)

Ta-2.5W: Solution strengthened Ta alloy with W

- Higher strength yet still ductile
- Enhanced hydrogen embrittlement resistance

- **Preliminary HIP and SPS Cladding trials w/ Ta2.5W & core materials**
- **Prototype manufacturing**
- **Extensive material & HIPed cladding characterization**
- **Prototype beam tests**
- **Post Irradiation Examination**

Ta2.5W cladding



Preliminary HIP and SPS Cladding trials w/ Ta2.5W

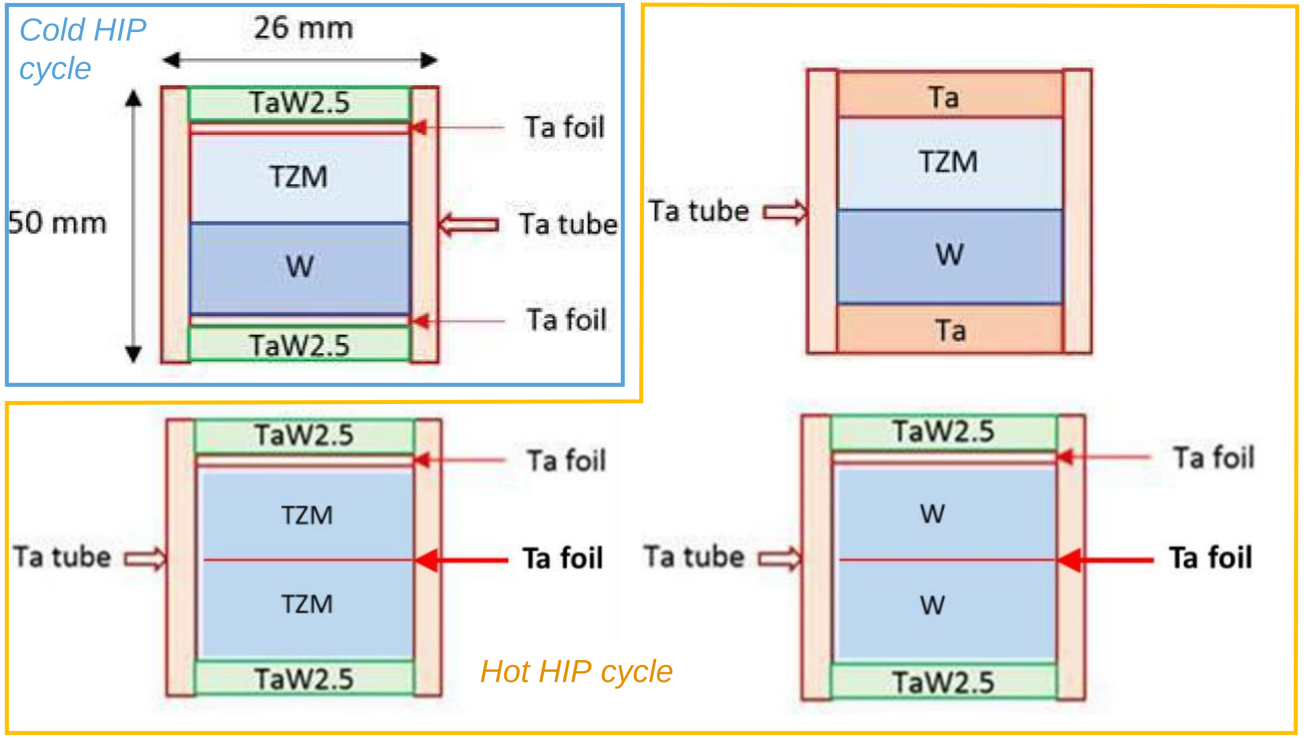
- Assembly with EBW & joining via hot isostatic pressing (HIP)

<u>Scope</u>

- Comparing two Heating cycles (1200°C/150MPa 1400°C/200MPa)
- TZM//TZM & W//W via HIP w/wo interface Ta Foil
- Ta2.5W vs Ta cladded on W and TZM, w/wo interface foil

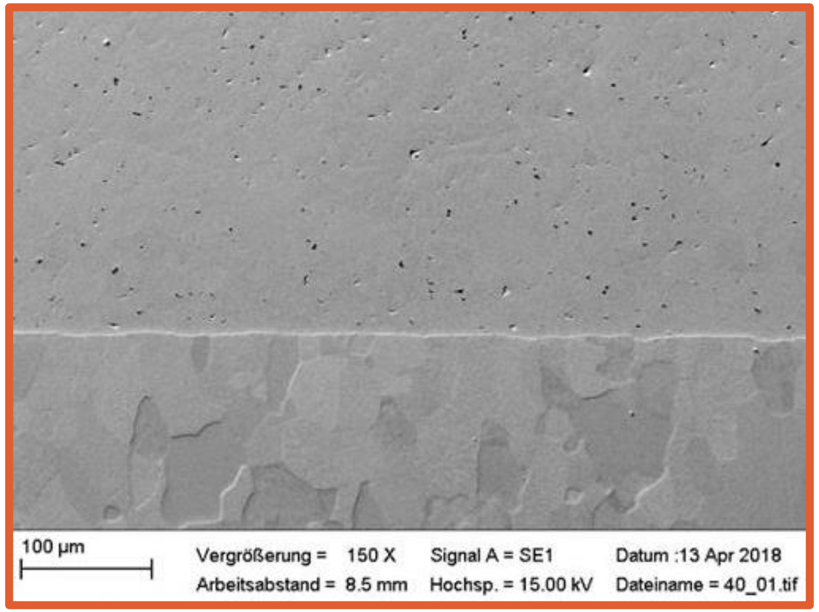
<u>Methodology</u>

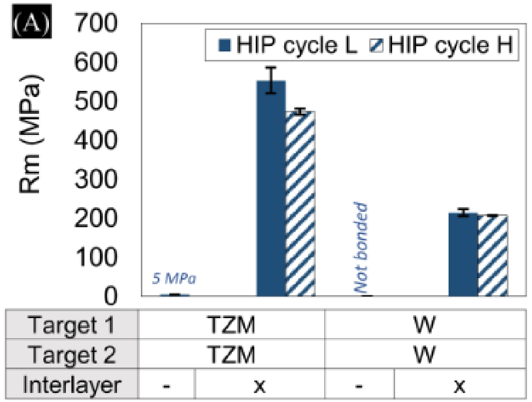
- Microstructure w/ optical and electron microscopy
- k (RT-300°C) and ρ measurements
- Mechanical characterization of interfaces

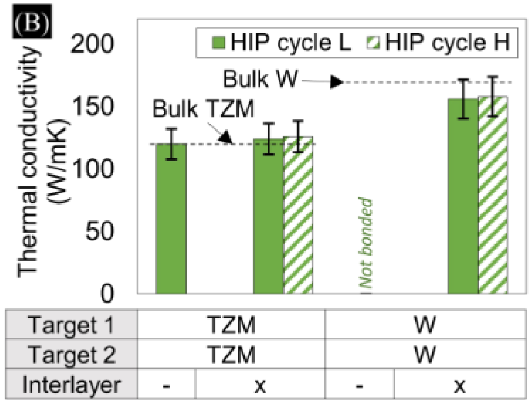


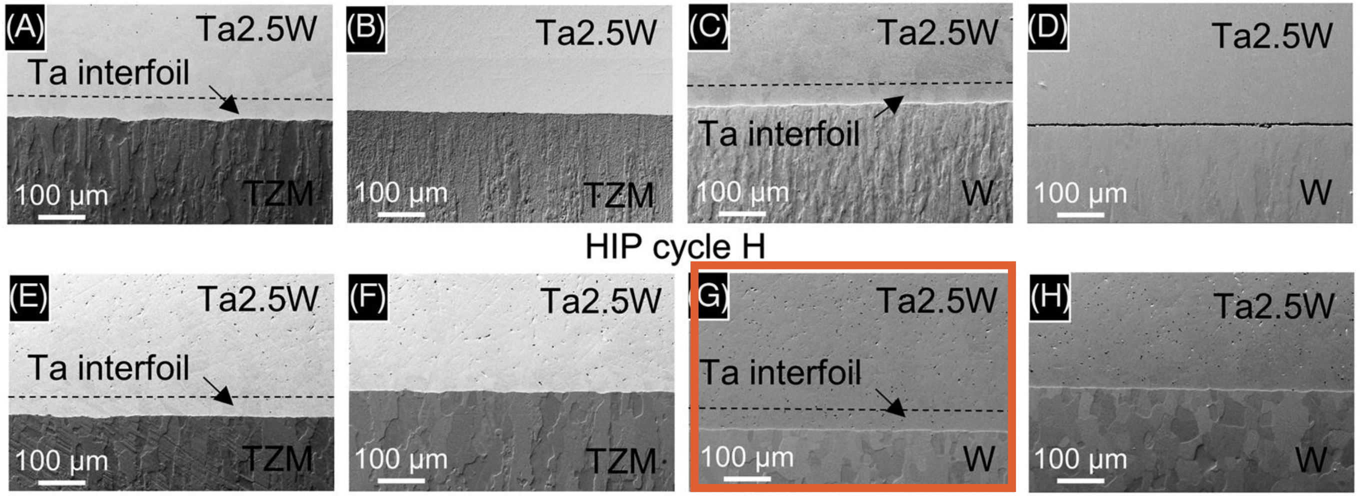
Ta2.5W cladding

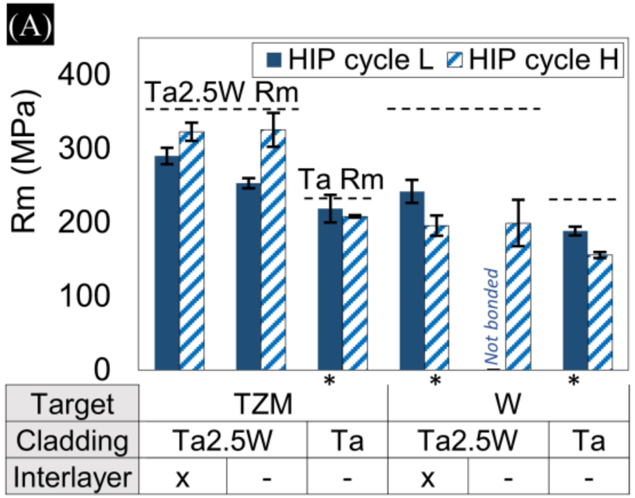
Very difficult to see any diffusion layer !

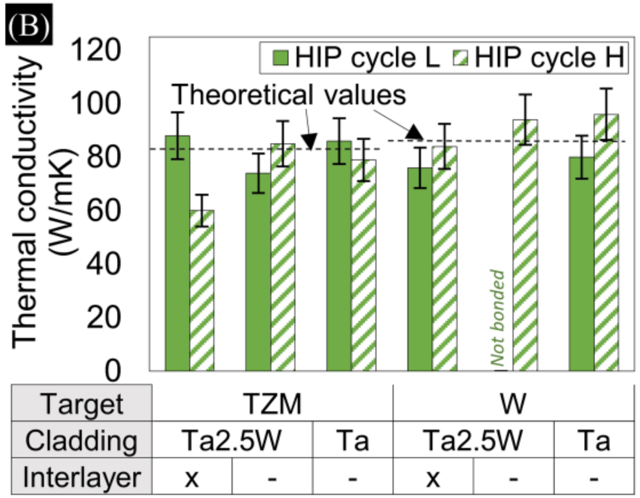












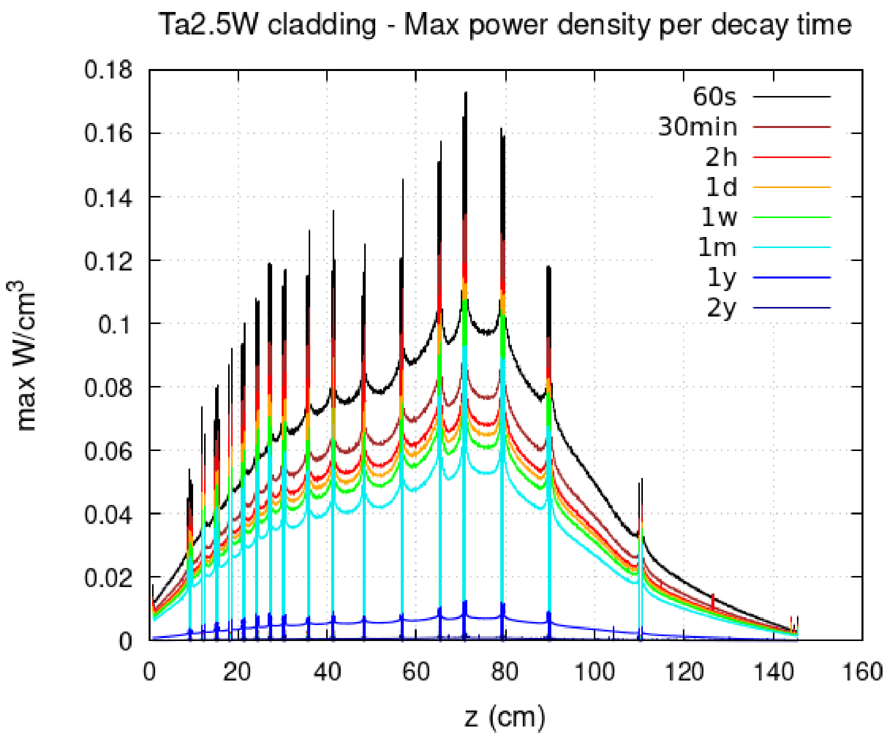
Microstructural observations, tensile strength and conductivity measurements for some of the studied interfaces (https://doi.org/10.1002/mdp2.101)

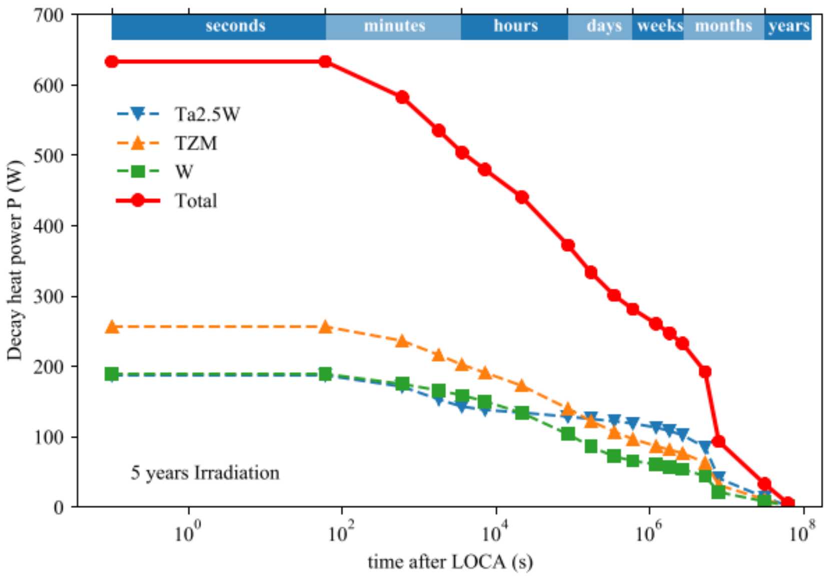
Ta2.5W cladding – the caveat

Ta2.5W cladding – LOCA

LOCA: Loss-of-Coolant Accident scenario

- Hypothetical scenario used as a criterion for assessing the safety of a nuclear installation during its design phase.
- Thermo-mechanical assessment in CDR
  - Determine the temperature evolution of the target in a 2 years scenario after the accident.
  - Depending on the assumptions, T > 300 C may be reached for prolonged periods ((O)weeks)
  - & we already know the cladding is the most critical element of the target core on a thermo-mechanical point of view



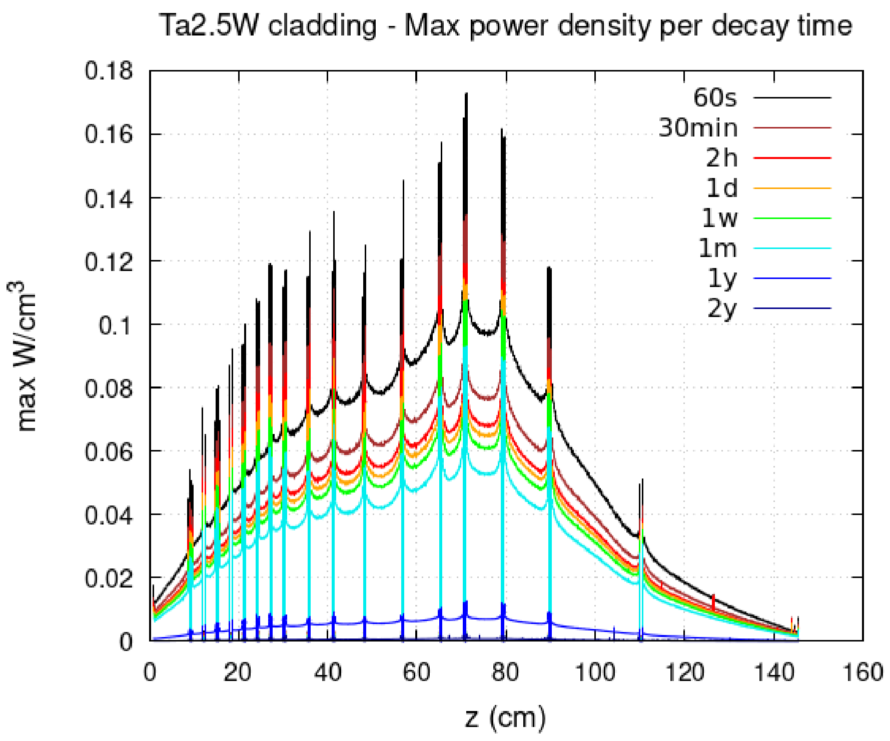


- *Mena R., Ximenes R.F. and Calviani M. (2022), Loss-of-Coolant-Accident study for the Beam Dump Facility at CERN, NURETH-19 Conference*

Cladding conclusions & Missing threads → TDR studies (3/5)

- Decay heat on baseline target is considerable & driven by cladding.
- Possibility of LOCA poses a critical safety risk
  - → Address LOCA in detail
  - → look for alternative claddings

→ Ramiro & Tina's presentations ←



Target radiation dose & damage

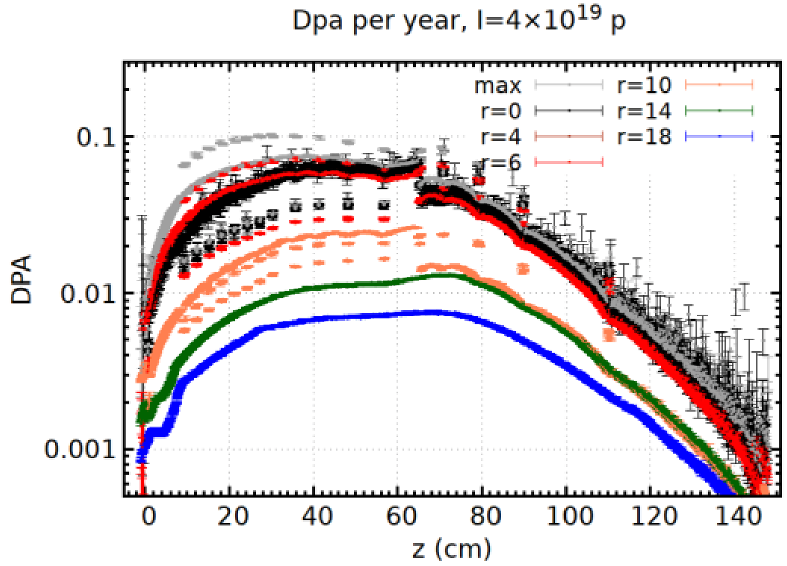
Target Radiation dose & damage

Radiation dose

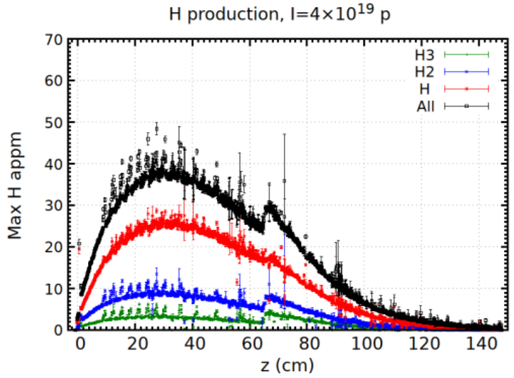
- ~100 Sv/h after 4h cooldown

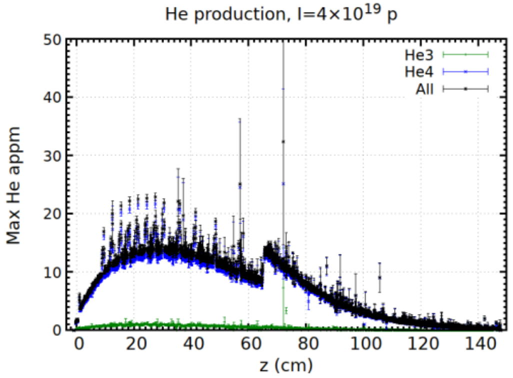
Radiation damage

- **Radiation damage (dpa)**
  - Dpa up to 0.1 per year (1dpa without sweep)
- **H & He gas production → swelling, grain boundary embrittlement**
  - 40 ppm H & 15 ppm He per year



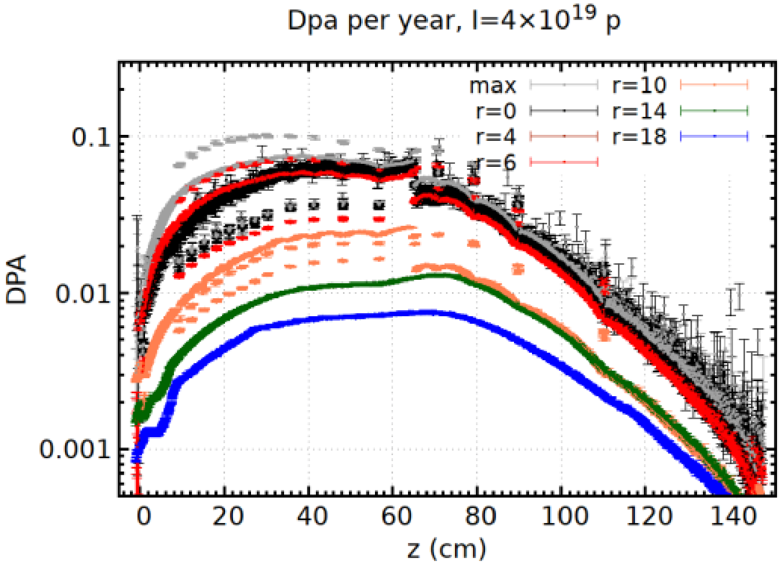
Material/ position	Dose (GGy)	p fluence (1/cm^2)	n fluence (1/cm^2)	HeHad (1/cm^2)	dpa	H (appm)	He (appm)	H/dpa	He/dpa
TZM/	~40	2.9×10^{18}	1.7×10^{20}	2.7×10^{19}	0.074	37.9	15	~650	~275
block no.	4	9	13	9	10	8	8	1	1
W/	~14	1.8×10^{18}	2.5×10^{20}	2.3×10^{19}	0.053	30	13	~560	~300
block no.	14	14	15	14	14	14	14	14	18
Ta2.5W/	~54	2.9×10^{18}	2.5×10^{20}	2.7×10^{19}	0.053	51	30	~900	~280
block no.	3–4	8 and 9	15	9	9	9–10	9–10	1	1 and 2



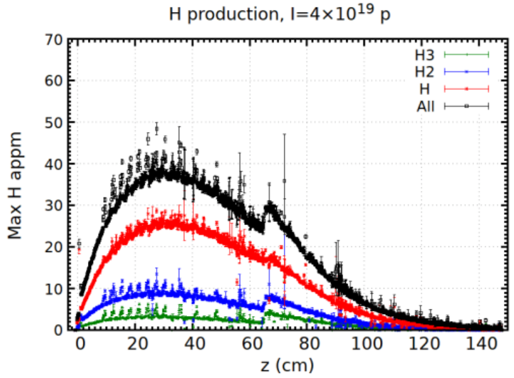


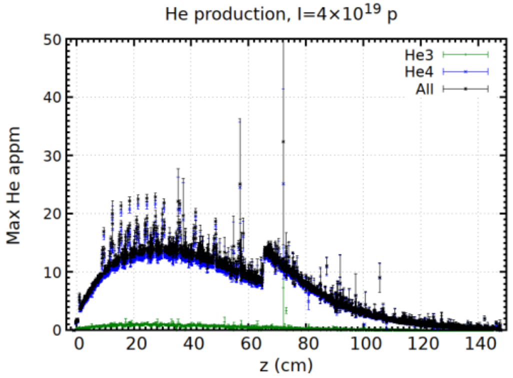
Target Radiation dose & damage & Missing threads → TDR studies (4/5)

- Very high radiation doses → ALARA driven design and detailed waste disposal considerations to be analysed



- Radiation damage & gas production → effect on target materials mechanical properties to be well understood and quantified

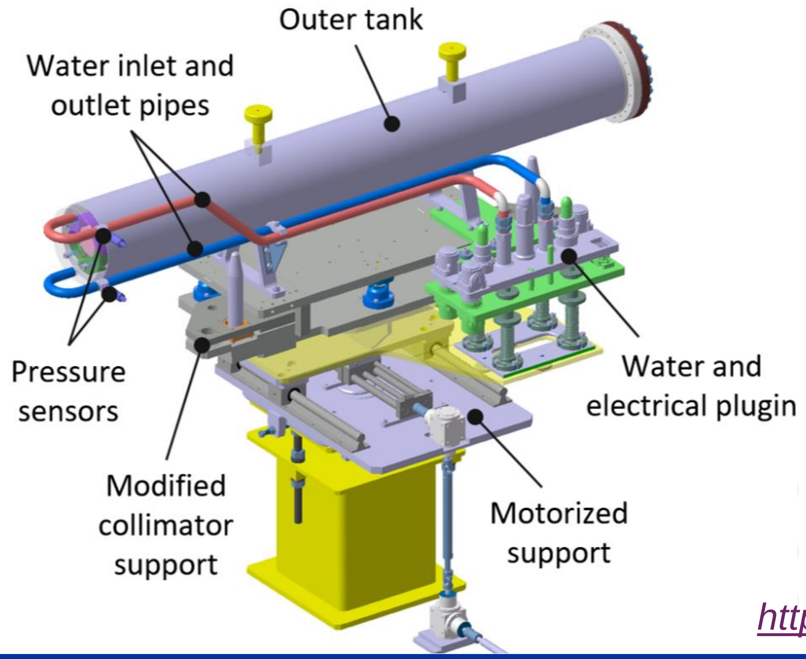


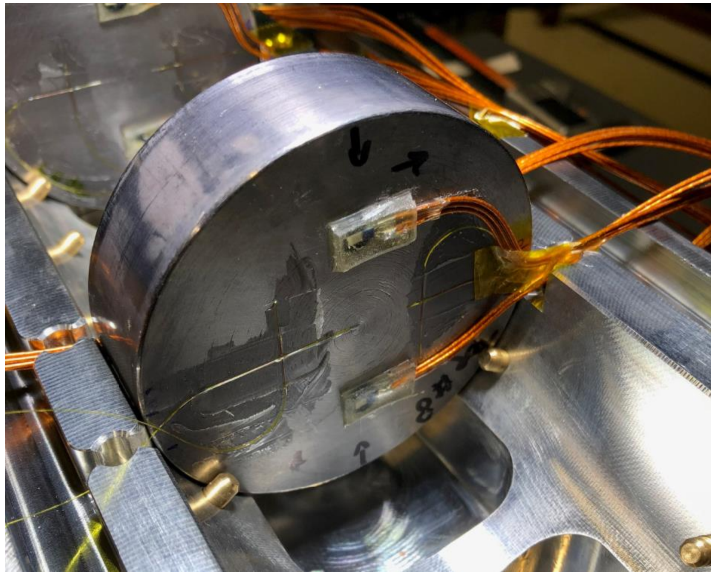


2018 Prototype

BDF Target Prototype

- **Purpose:** to validate manufacturing and test operation at identical temperatures & mechanical stresses.
- Reduced diameter (80 mm) prototype.
- Tested in 2018 on a **dedicated slow extraction (SX) testbench** in the T6 primary beam line in TCC2 at CERN. Total of 2.4×10^{16} p^+

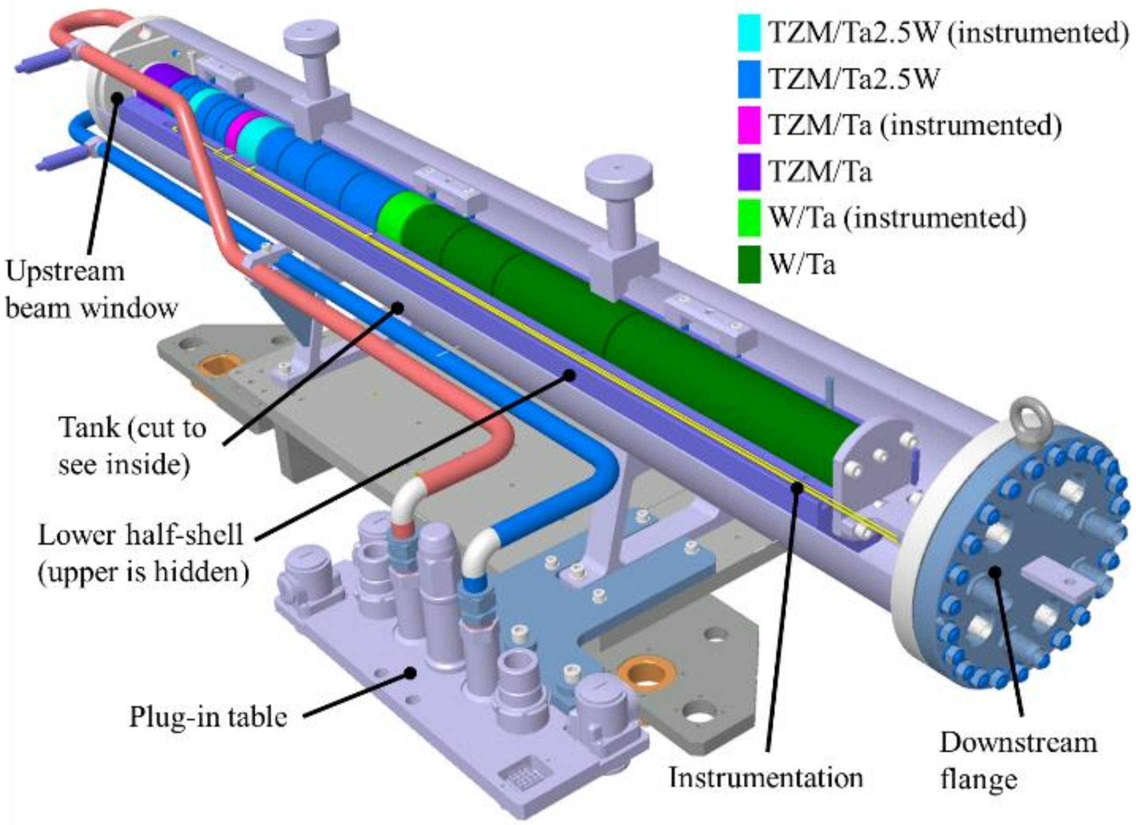


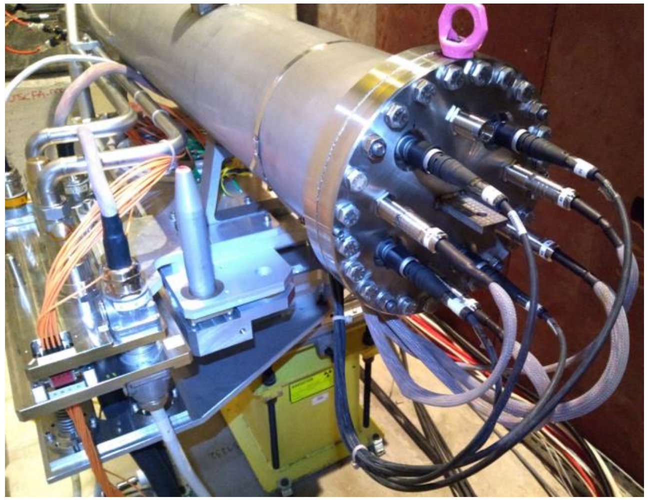


https://doi.org/10.1103/PhysRevAccelBeams.22.123001

BDF Target Prototype

Design summary:





- 4 blocks instrumented with strain gauges and temperature sensors
- Target blocks two half-shell parts which allow free expansion while guiding the 20-bar cooling water.
- Shells inserted in a cylindrical SS tank. Water connections on the upstream side of the tank. Instrumentation on the downstream.
- Collimator-like plug-in table, allowing fully remote handling. The prototype was designed to be the first complete remotely dismountable device of its type at CERN

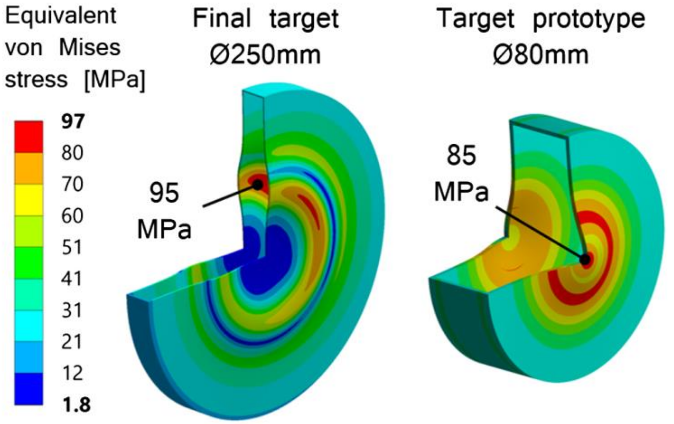
BDF Target Prototype beam tests (2018)

Final target (at 4 × *10^13 p+/cycle)* :

- Expected (FEM) Max von Mises stress of 95 MPa & max T of 160 °C on Ta2.5W. (180 & 150 °C on TZM & W respectively)

	Final target	Target prototype
Proton momentum [GeV/c]	400	
Beam intensity [p+/cycle]	4×10^{13}	$3\text{-}4\times10^{12}$
Beam dilution	four circular sweeps	no
Beam extraction	7.2 s cycle with 1s of beam extraction	
Average beam power [kW]	355	27-35
Average power on target [kW]	300	18-23

FEM calculation (with 3×10^{12} p+/cycle on the prototype)



Prototype (at *3.75 × 10^12 p+/cycle)* :

- Expected (FEA) max stress amplitude(σ_a) of 50 Mpa (105 MPa von Mises equivalent) and max temperature of 250 °C on the Ta2.5W
- **σ_a @r=20mm: 37 MPa (FEA) vs 43 MPa (SG) on the Ta2.5W**
- **T@r=20mm: 40 °C (FEA) vs 38.8 °C (Pt100) on the Ta2.5W**

Maximum[1] temperatures, strains measured (Transverse & Radial) and equivalent stress amplitudes vs calculated via FEA for 3.75×10^{12} p+/cycle

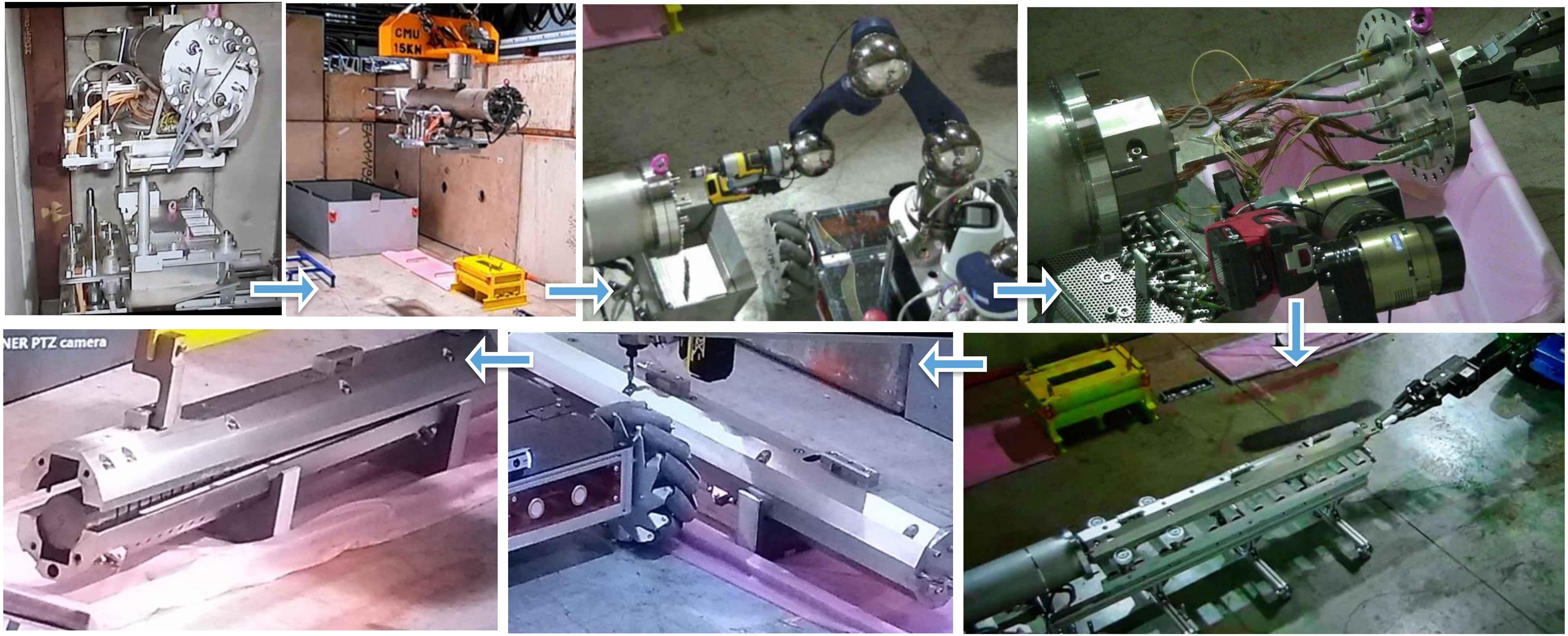
Cladding Material (block)	T_{Pt100} [°C]	T_{FEA} [°C]
Ta2.5W (4)	38.8±0.5	40
Ta (8)	46±0.5	43.8

Cladding Material (block)	$\Delta\varepsilon_{SG}$ [μm/m]	$\sigma_{a,SG}$ [MPa]	$\Delta\varepsilon_{FEA}$ [μm/m]	$\sigma_{a,FEA}$ [MPa]
Ta2.5W (4)	190 |-450	43	170 | 390	37
Ta (8)	100 |-230	22	87 |-250	23

[1] Maximum within all the measured values by the instrumentation. The FEA values are at the same location of the PT100 and SG. The actual maximum temperatures in the blocks are higher but were not directly measured.

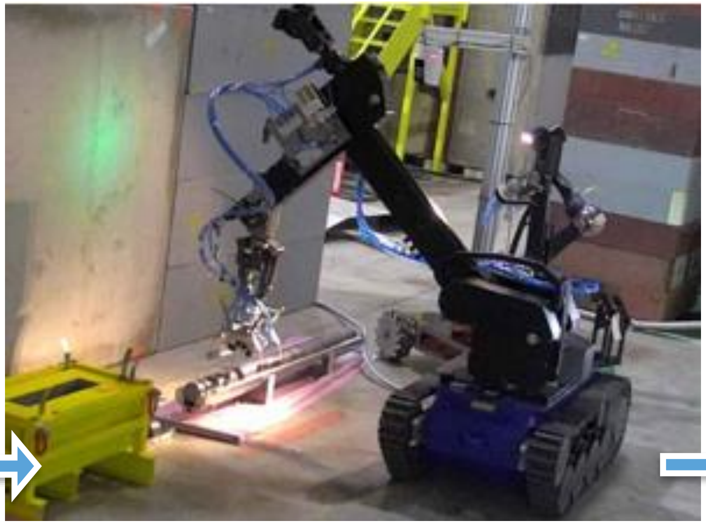
BDF Target Prototype removal (2020)

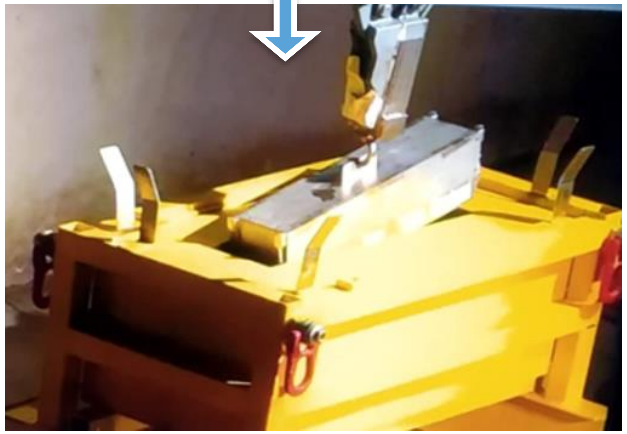
Unplug-in ▸ Transport to the bunker ▸ Unscrew downstream flange ▸ Instrumentation wire cut & flange removal ▸ Extraction half-shells core assembly ▸ Unscrew half-shells ▸ Removal top half-shell & first glimpse of the target blocks

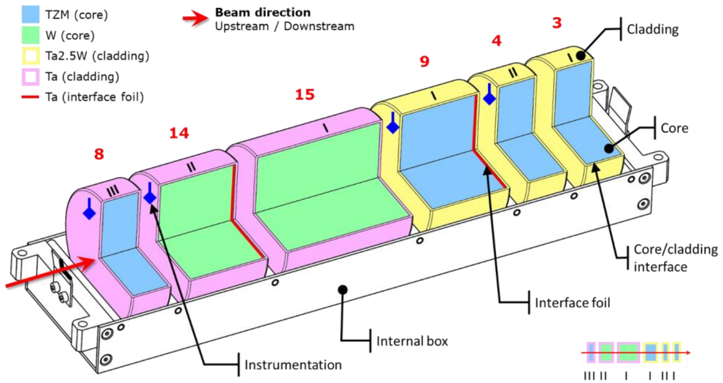


BDF Target Prototype removal (2020)

Identification of the blocks and angular orientation with respect to the beam with a marker ▸ Removal of the target blocks for the post irradiation examination (PIE) campaign ▸ Storage of the extracted blocks in a shielded container







BDF Target Prototype Post Irradiation Examination

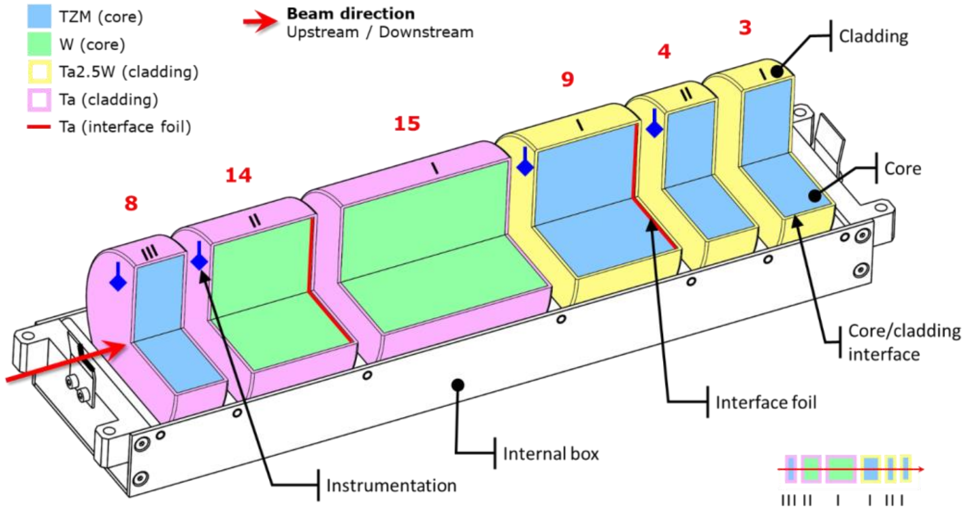
I. Reception | II. Film Dosimetry | III. Metrology and Microscopy | IV. Ultrasonic Tests | V. Specimen Extraction | VI. Microstructural Characterization | VI. Mechanical characterization

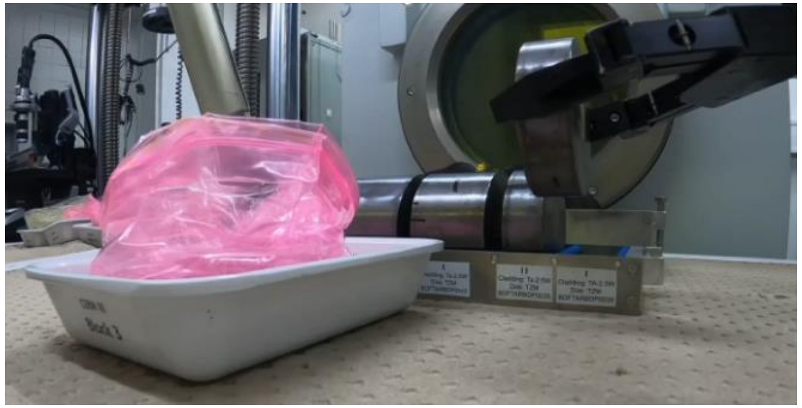
PIE in a step-wise approach

Purpose:

- **Identify any structural, chemical or geometrical changes**
- **Understand survivability of the target materials**
- **Assess if the cladding-core bonding is still reliable**
- **Comparison of un-irradiated characterization studies with irradiated data**

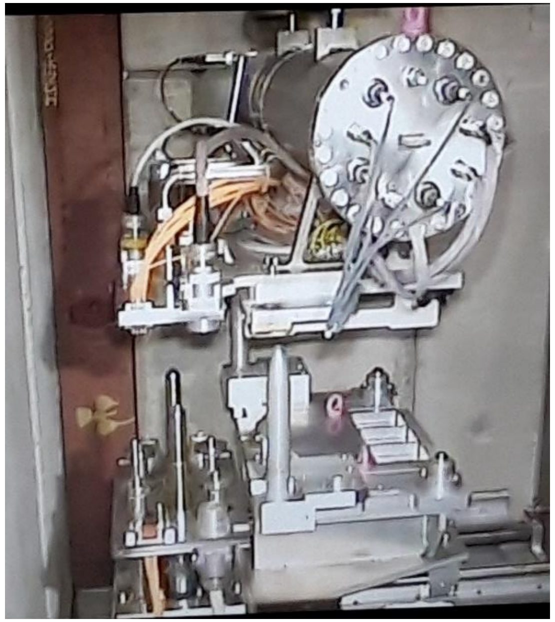
Ultimate Goal: Validate & Refine engineering design.





2018 Prototype conclusions & Missing threads → TDR studies (5/5)

- Gained manufacturing experience on a Ta2.5W-cladded baseline target.
- Gained operational experience & validated engineering studies.
- SX test-bench built & available in T6/TCC2 → Unique opportunity to test with beam (2025) alternative claddings & designs
- PIE (2020-2022), final check of baseline target design. → identified design & material aspects to be improved, particularly W material



→ Tina's presentations ←

Conclusions
Target Baseline design and challenges

✓ **Baseline is a well thought design solution.**

Yet:

- Manny features in the design still need to be addressed (besides the core)
- There is potential for further target physics optimization
- Critical safety aspects such as LOCA & hydrogen production need to be addressed and mitigated, likely via alternative designs
- Materials QA and characterization is still required
- Radiation doses and effects to be further analysed

- TDR, particularly 2025, will be the last (and only) chance to test anything else with beam at the SX testbench
- Synergies with other targetry labs are being pursued

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