Status of the BDF Target Design

ESS – CERN Meeting

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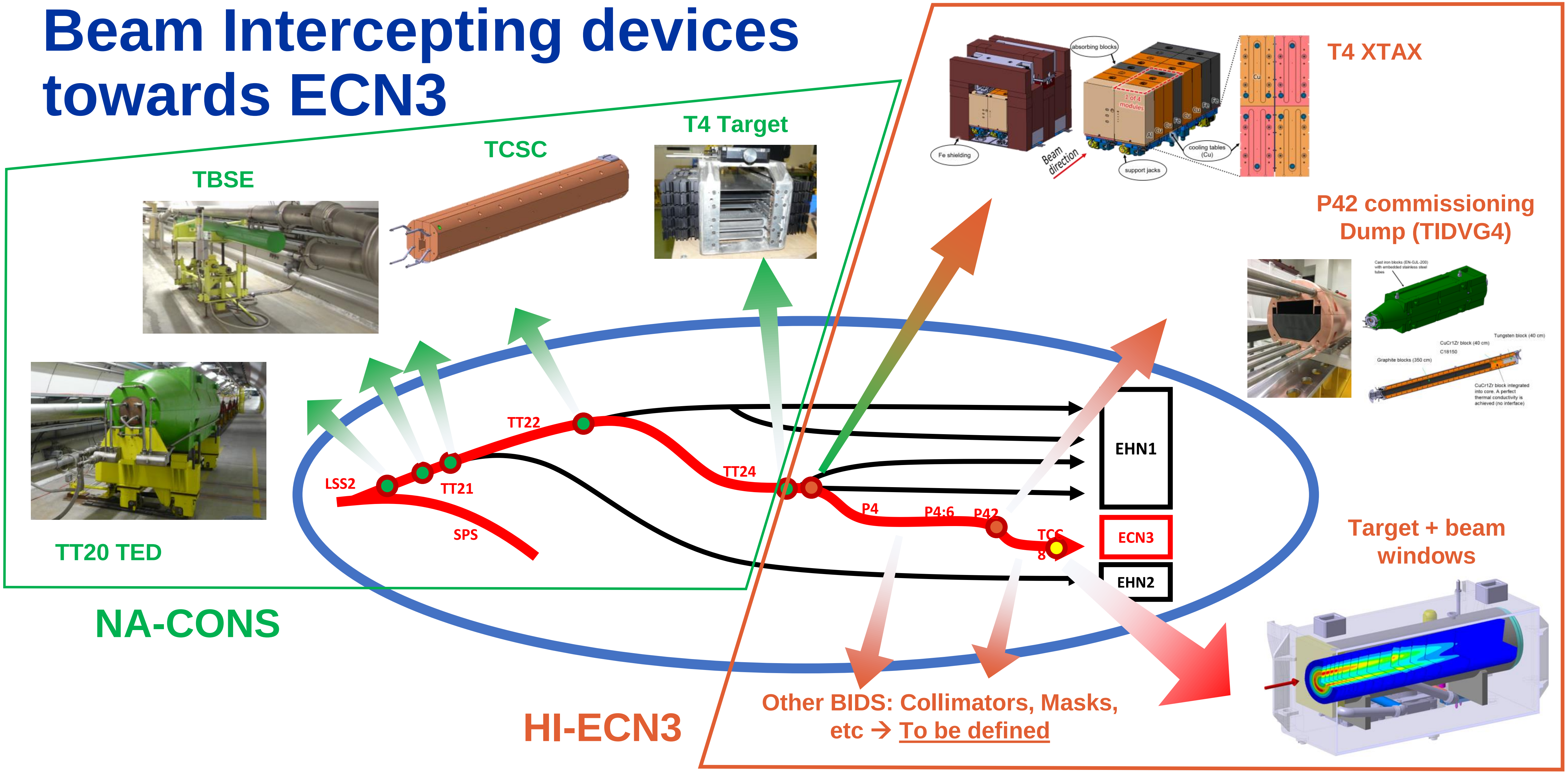
2024/09/20

Content

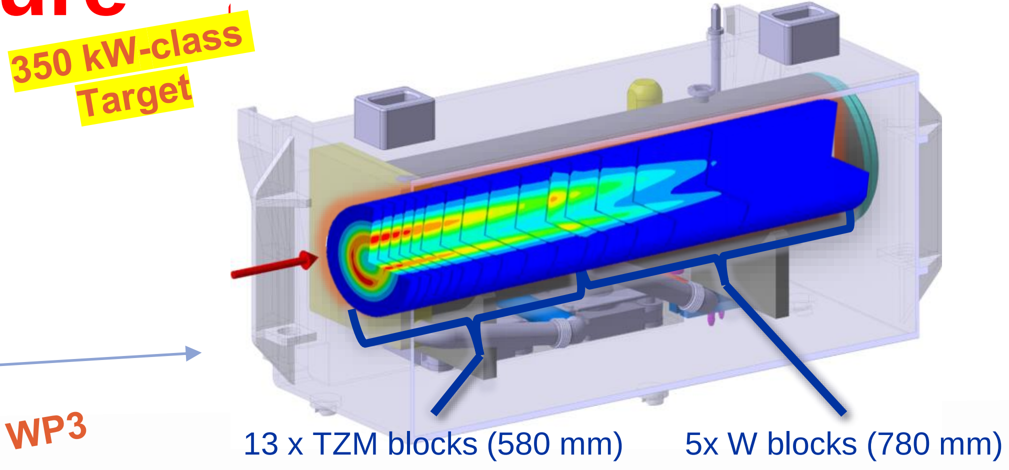
- BDF Target requirements
- Water cooled target (CDR concept)
- He cooled target (new proposal)
- Conclusions & prospects
- Questions to ESS

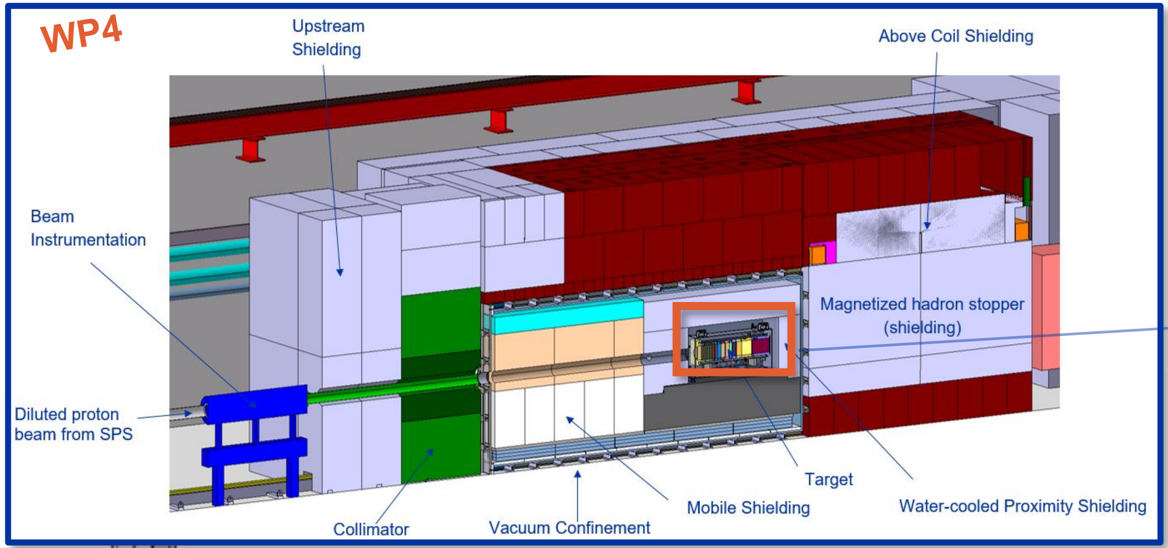
Beam Intercepting devices towards ECN3

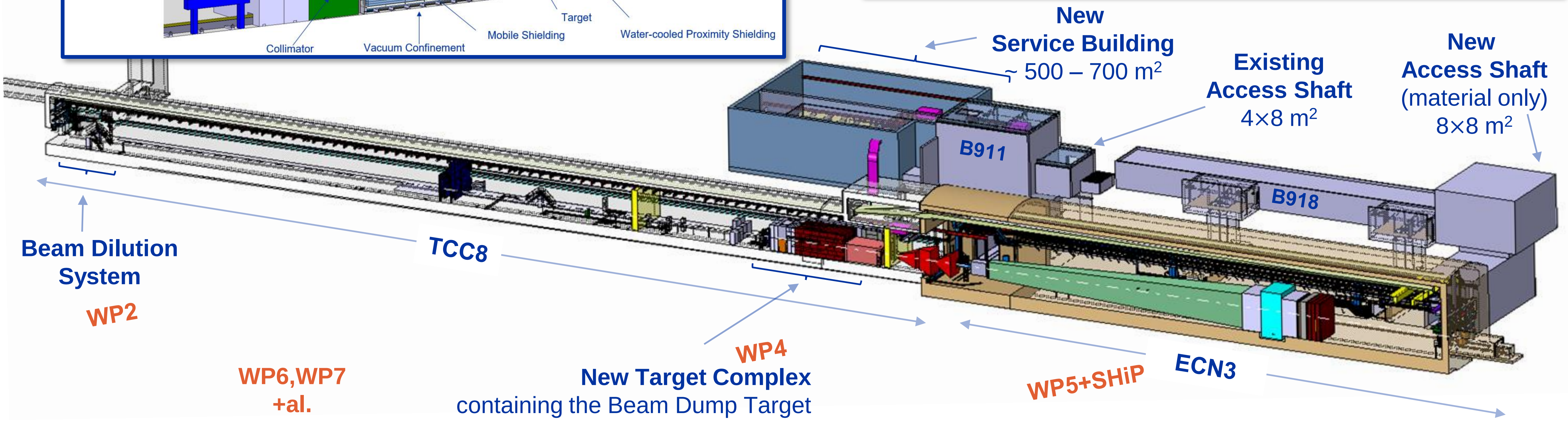


BDF/SHiP Target & Complex (Future ~ 2030)

Baseline Design → To be improved during TDR







BDF/SHiP Target

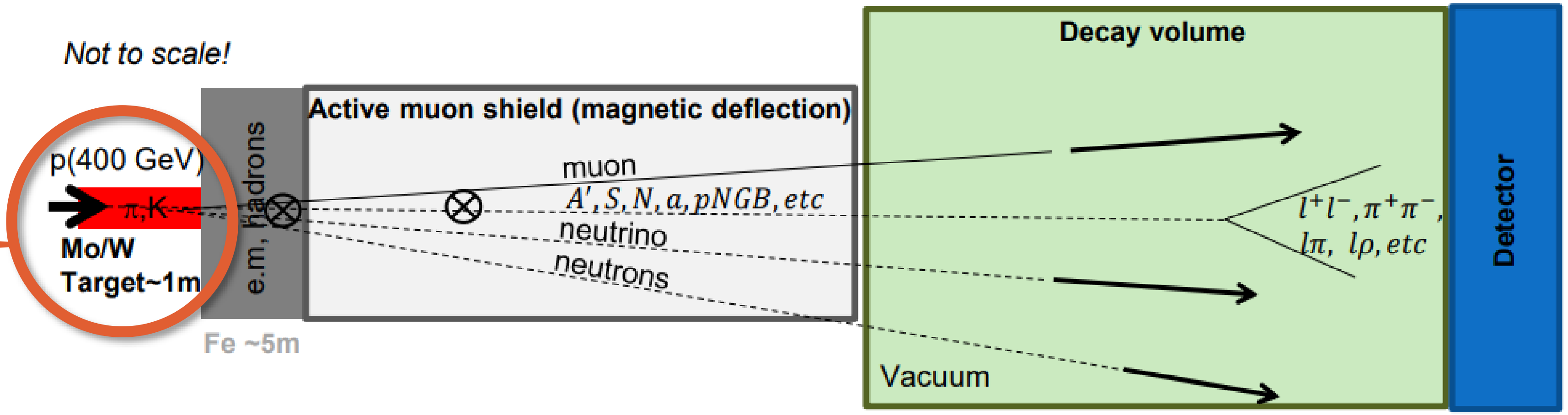
- **Beam Dump Target** / SHiP Target
  - ➢ Fully absorbe all p+, maximize production of charm and beauty hadrons & re-absorption of pions, muons and kaons

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

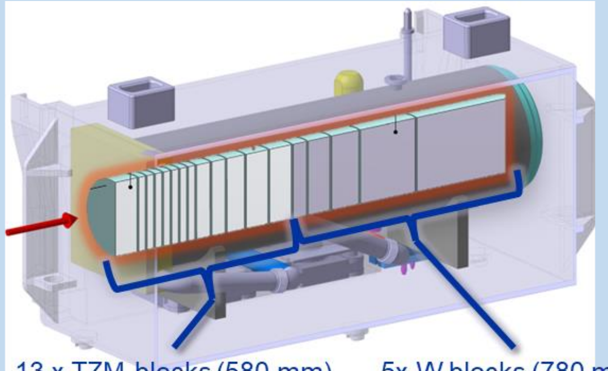
Very similar requirements to a neutron spallation target

Synergies with other labs are being pursued

BDF Target baseline design

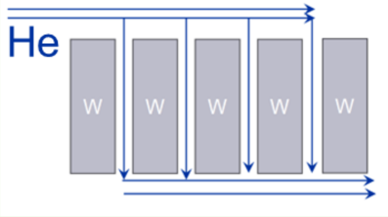
Baseline Design (CDR) – Water cooled, W + TZM cladded w/ Ta2.5W

- Pursued during the conceptual design phase
  https://doi.org/10.1103/PhysRevAccelBeams.22.113001
- Prototype + test with beam + Post irradiation examination
- Still some safety aspects to be addressed
- Could be further optimized for physics



Alternative designs currently being studied in the TDR

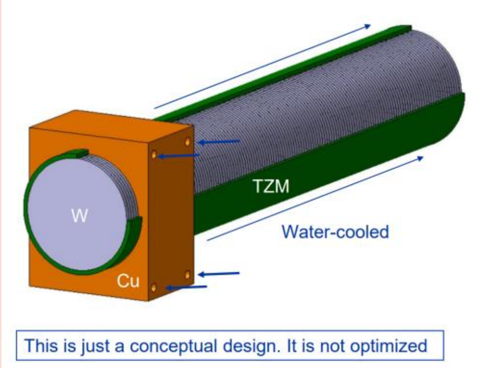
W Helium cooled Target



- Removes water from beam
- Better physics performance
- Reduces decay heat & residual stresses
- Conceptually different system!

Enclosed compact Cu + W Target

- Removes water from beam
- Keeps physics performance
- Reduces decay heat
- Increases T and stress



Other concepts: Baseline with W rolled material, Nb-cladded Target,…

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

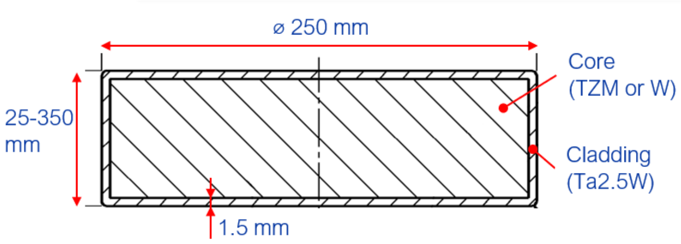
BDF Baseline Target Design

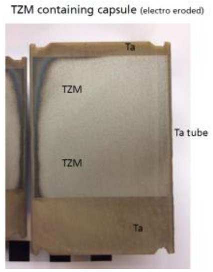
Water-cooled, Ta-cladded TZM + W Core

- TZM: Absorbs most of the power. Higher strength, better creep resistance, higher recrystallisation temp wrt Mo.
- W: Good radiation damage resistance. Best for physics.
- Ta2.5W: To avoid corrosion-erosion of the core materials
- Cooling: 22 bar, 5 m/s, ~660l/min, ~305kW of heat.

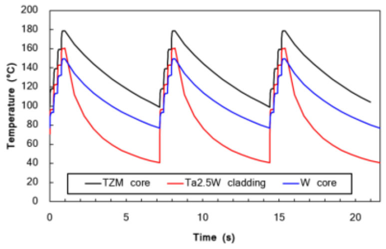
Manufacturing

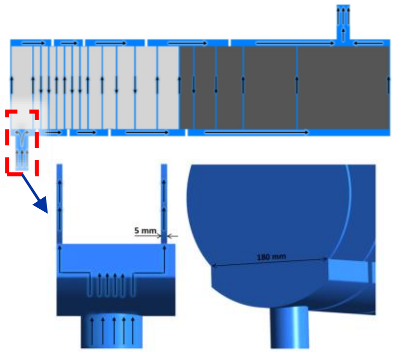
- Forged TZM and sintered W (single blocks)
- Diffusion bonding with cladding via Hot Isostatic Pressing

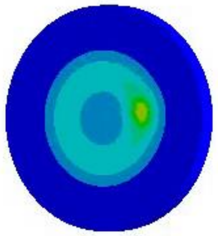




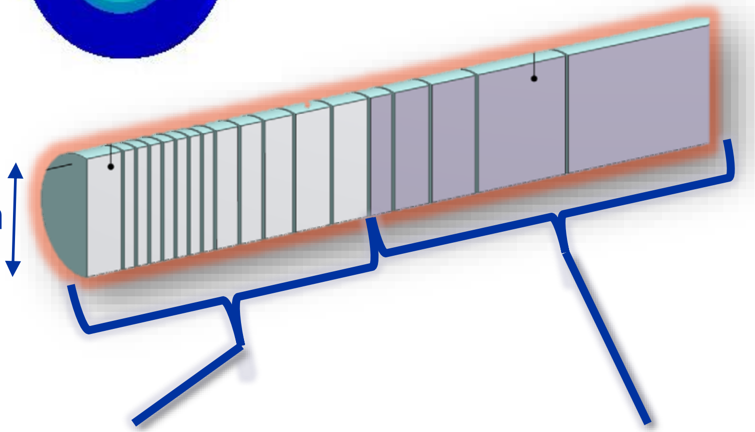
Target Core with reasonable physics performance & that allows diluting (longitudinally) the energy deposition







D250 mm



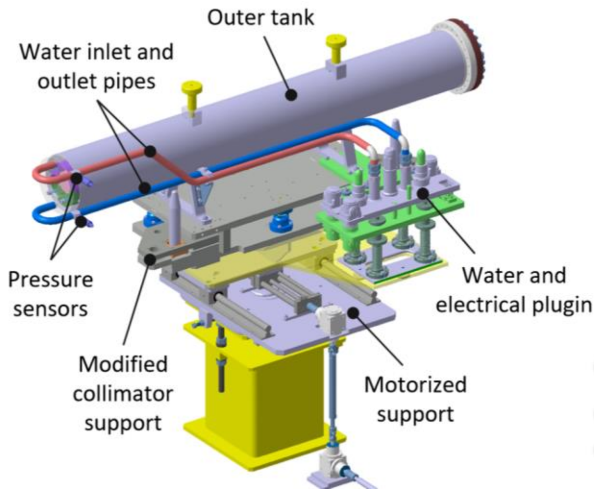
13 x TZM blocks (Z=42, ρ=10.2g/cm^3) (580 mm)

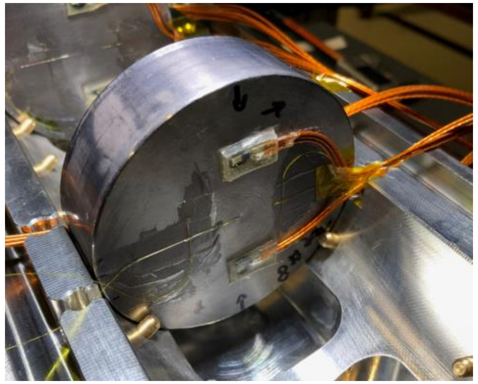
5x W blocks (Z=74, ρ=19.3g/cm^3) (780 mm)

BDF Baseline Target Prototype + PIE

Prototype Beam tests

- 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^+





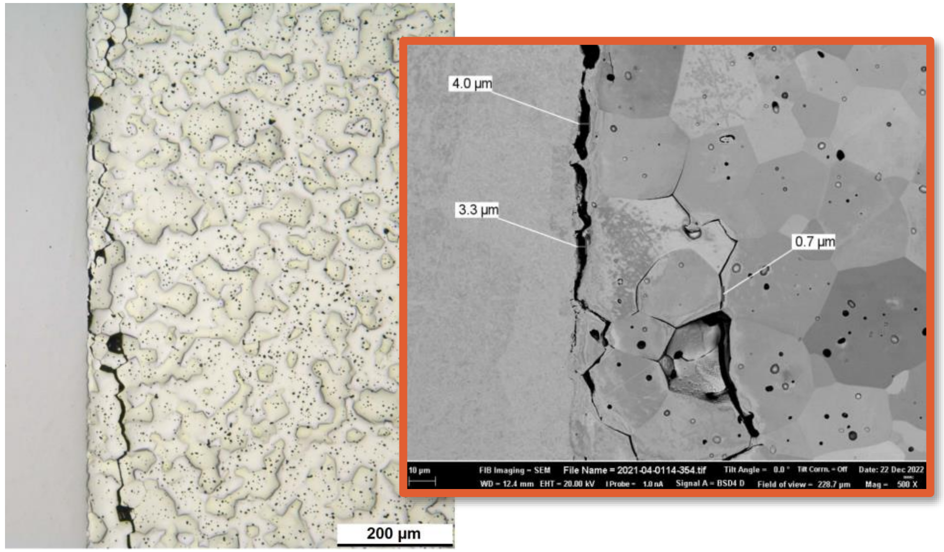
https://doi.org/10.1103/PhysRevAccelBeams.22.123001

Post Irradiation Examination

- Design mostly validated but with few caveats

I. Film Dosimetry | II. Metrology & Microscopy | III. Ultrasonic Testing

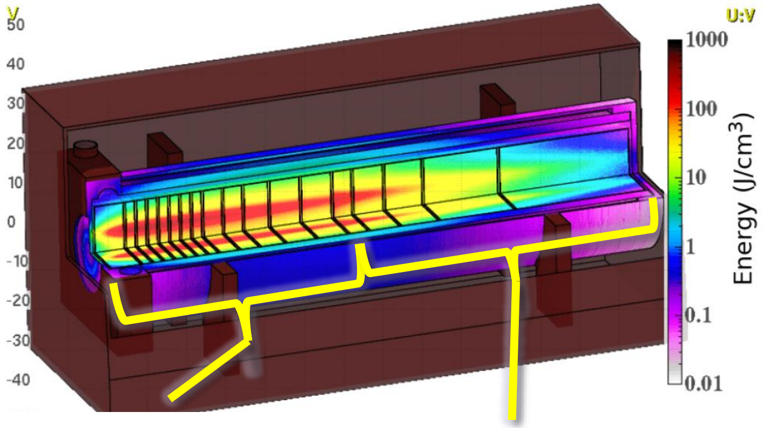
IV. Specimen Extraction | V. Microstructural Characterization | VI. Mechanical Characterization | VII. Thermal Characterization



Post-irradiation examination of a prototype tantalum-clad target for the Beam Dump Facility at CERN, T. Grisemer, R.F.Ximenes (to be published soon!)

In search of an alternative design
Main motivations

- 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 to be addressed or water removed
- Decay heat on baseline target is considerable & driven by cladding. Possibility of LOCA (Loss Of Coolant Accident) poses a critical safety risk → Reduce Ta cladding
- PIE revealed W quality to be poor → Look into more robust W supply



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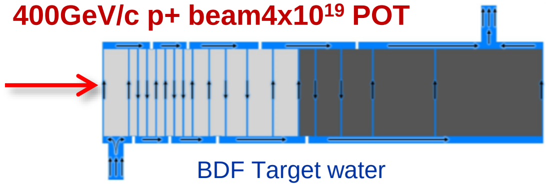
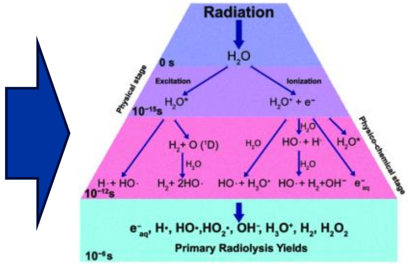
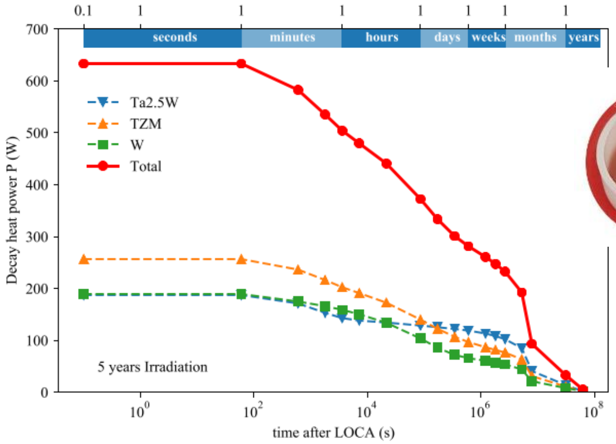
5x W blocks (780 mm)

400GeV/c p+ beam4x10[19] POT



BDF Target water cooling layout (20bar, 5m/s)





Alternative designs: Nb-cladded

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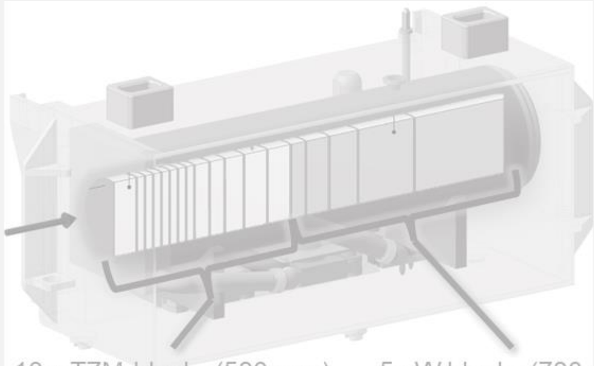

Alternative designs currently being studied in the TDR

W Helium cooled Target

- Removes water from beam
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Enclosed compact Cu + W Target

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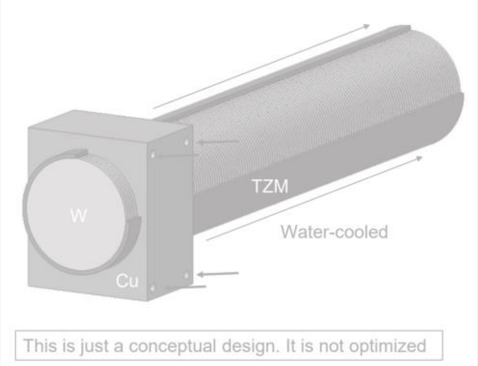


Other concepts: Baseline with W rolled material, Nb-cladded Target,…

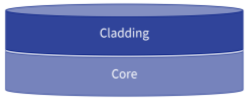
Nb-cladding R&D

Exploring diffusion bonding of niobium and its alloys with tungsten and a molybdenum alloy for high-energy particle target applications,
T. Grisemer, R.F.Ximenes (to be published soon!)

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**

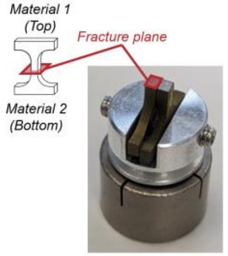
Thermal diffusivity specimens

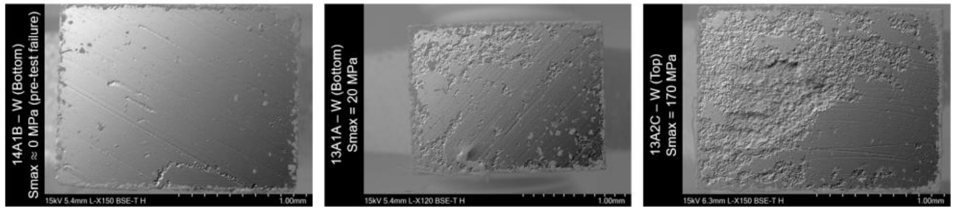
- Excellent thermal contact has been confirmed for all Niobium alloys (Nb, Nb1Zr, C103)



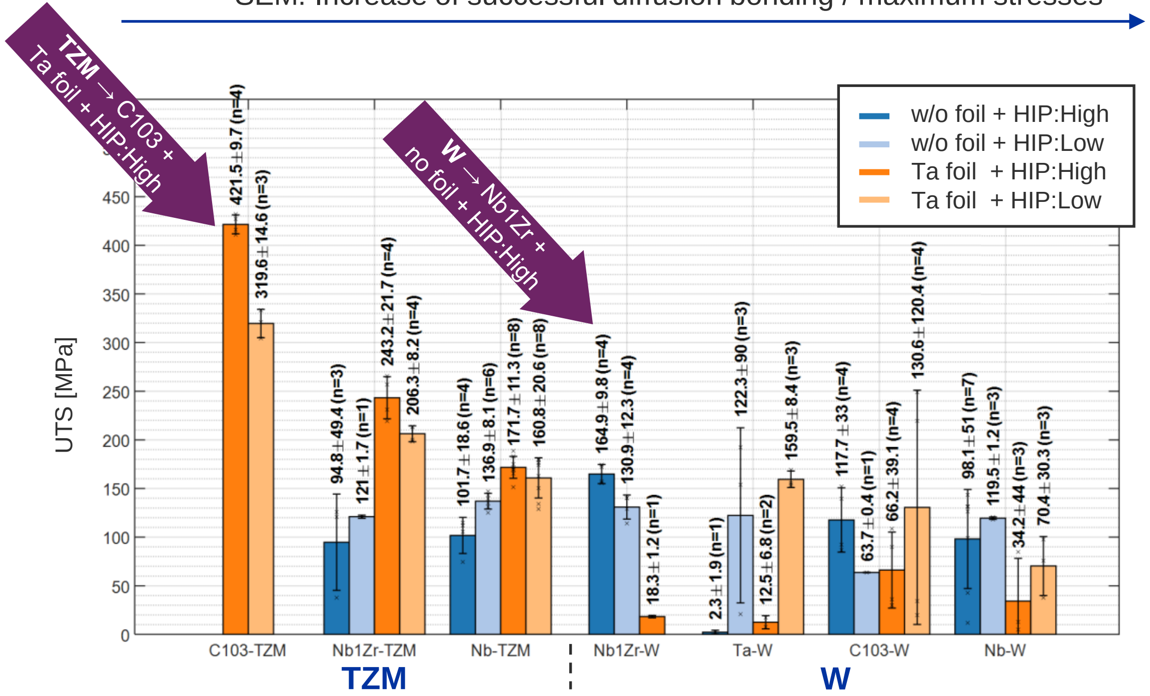
Tensile specimens

- Interface strength for Nb alloys higher for TZM than W
- TZM core :
  - Ta foil + HIP: High increased the strength
  - 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



However, long-lived Nb isotopes pose challenges for waste disposal

Alternative designs: W Helium cooled Target

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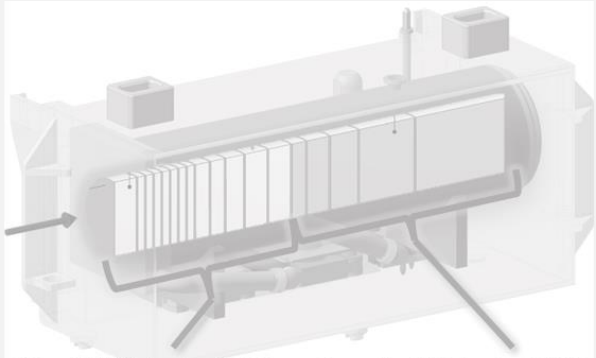

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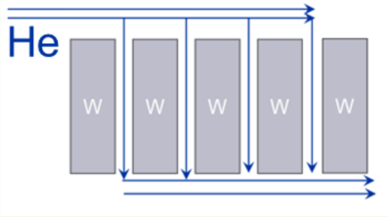

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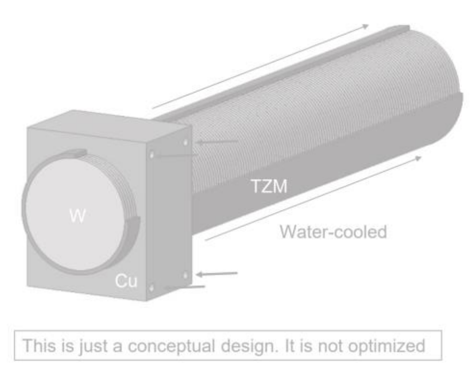

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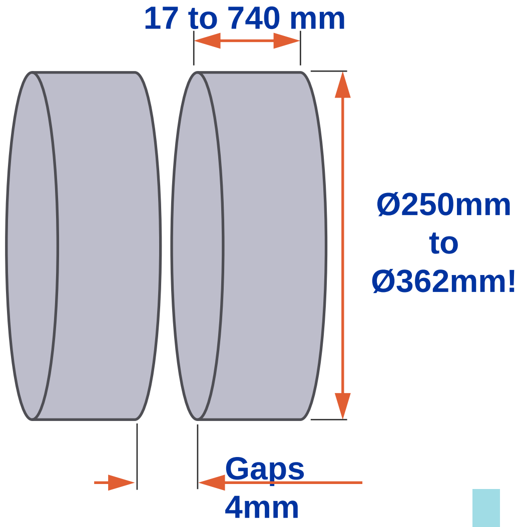
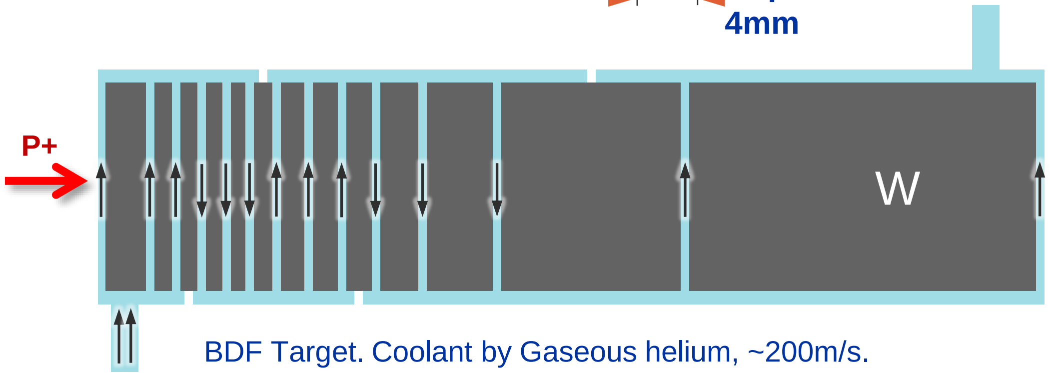
BDF W Helium cooled Target



Helium cooled blocks (without cladding)

- Removes the high stress regions of the baseline design (Ta cladding)
- Allows higher surface block temperatures (no risk of boiling)
- Removes radiological concerns with the water
- All core material is W (good for physics)

- But HTC is lower
- New cooling system complexity and cost



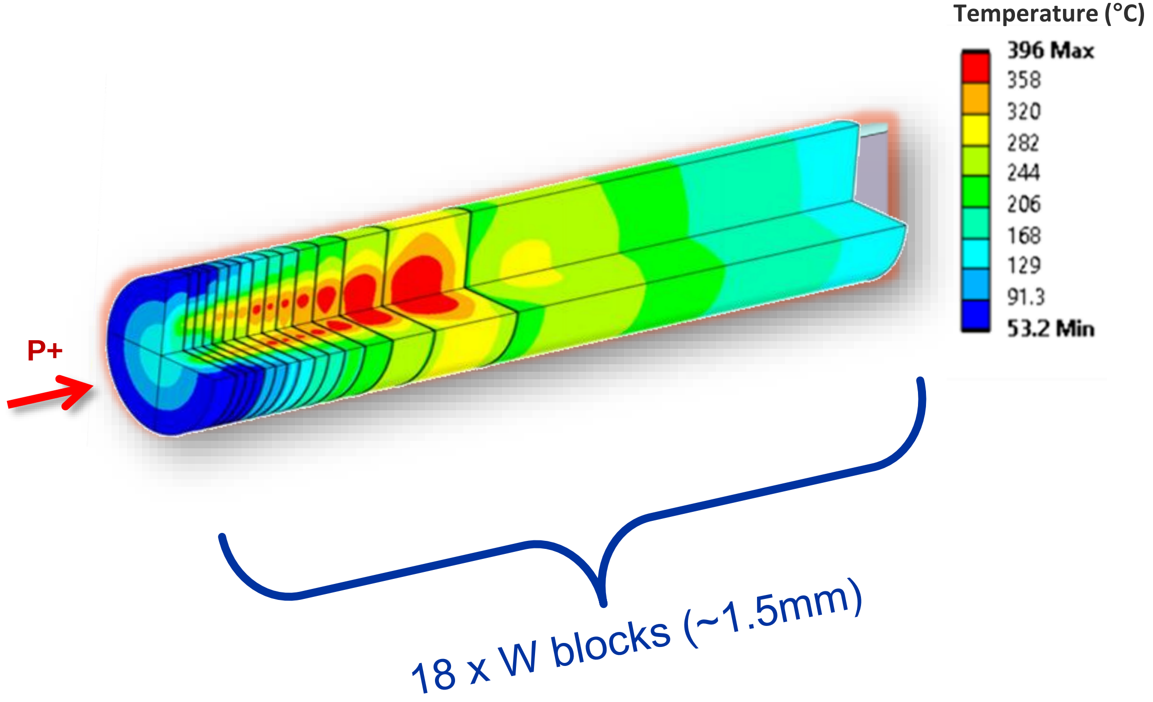
BDF Target. Coolant by Gaseous helium, ~200m/s.
3 or 4 channels in parallel.

BDF He system parameters	
Thermal Power	305 kW
Inlet Pressure	16 bara
Pressure Drop	<2 bar (high estimate)
Mass flow	345 – 400 g/s
Volume flow	0.13 -0.15 m^3/s
Inlet temperature	30 °C
Outlet temperature	200-170 °C
Heat transfer coefficient	1000-2000 $W/m^2/K$

	ESS at 2012CDR	**BDF**	**LBNF** at 2023
Inlet Pressure	3 bar	**16 bara**	4.5 bar
Swept vol. flow rate	4.6m^3/s	**0.13-0.15m^3/s**	0.076m^3/s
Target deposited heat	3MW	**305kW**	35kW

BDF W Helium cooled Target

Operational conditions



BDF operational conditions	
Target design lifetime	5 years
Max dpa	1.6 to 1.2
Max He implantation	220 to 143 appm
Max stresses	150MPa
Max bulk temperature	400°C
Max W-to-He surface Temperature	350°C
Beam parameters	Same as for Baseline, except beam size

BDF W Helium cooled Target

Design approach

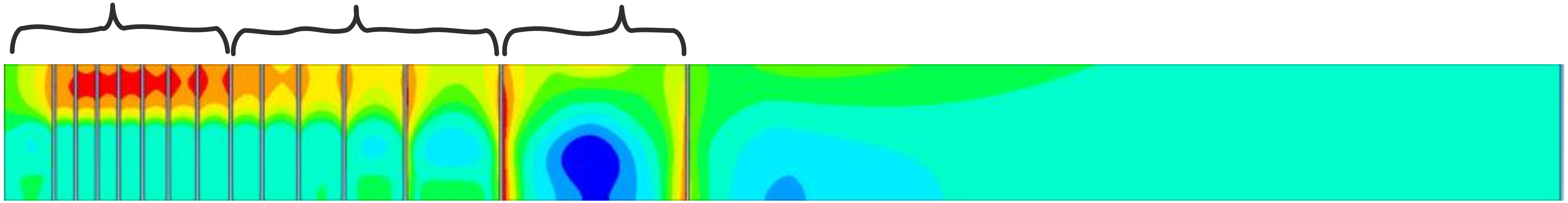
- Cooling station & target have been considered together for system temperatures and pressures
- Design approach has included Defining Design limits
  - ❑ **Stress**
  - ❑ **Fatigue**
  - ❑ **Block Temperature**
  - ❑ **Surface temperature (e.g. limited oxidation)**
  - ❑ **Irradiated properties**
- Applied these limits to target block position optimisation

❑ Used safety margins >2 on irradiated (degraded) material properties at 2dpa. <2dpa expected)

❑ Extrapolation and rule-of-thumb factor used to obtain irradiated fatigue limits due to lack of data

Limited by Stresses | Limited by Surface Temperature | Limited by Stresses

Whole target



BDF W Helium cooled Target

Target Options being Considered

Beam Sigma & sweep radius

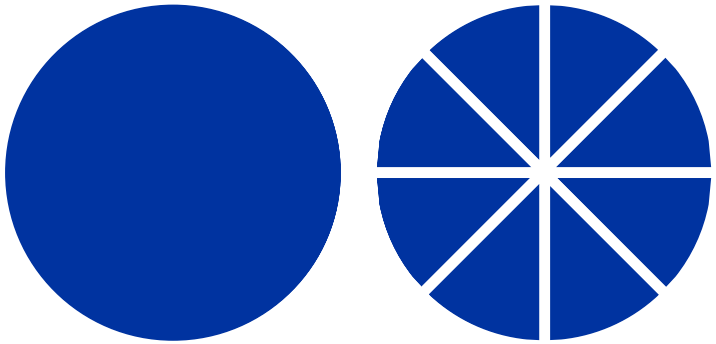
- 16 mm vs 8 mm (baseline)
- 50 mm sweep radius

▪ Benefits for stress and fatigue
▪ Requires slightly larger diameter core for physics
▪ To be seen if compatible with beam dilution system

Core geometry

- Full 360 ° disks
- 45° 1/8th target slices

Full target **1/8th target**



Nominal gaps <0.5mm

▪ 1/8th target requires diagonal cuts to prevent shine path (effective but adds complexity)
▪ Or offset cuts (less effective)

Helium Pressure

- Recently moved to 16 bar due to compressor availability, size, cost and complexity

▪ Beneficial for target pressure drops
▪ Lower than CDR design at 22bar

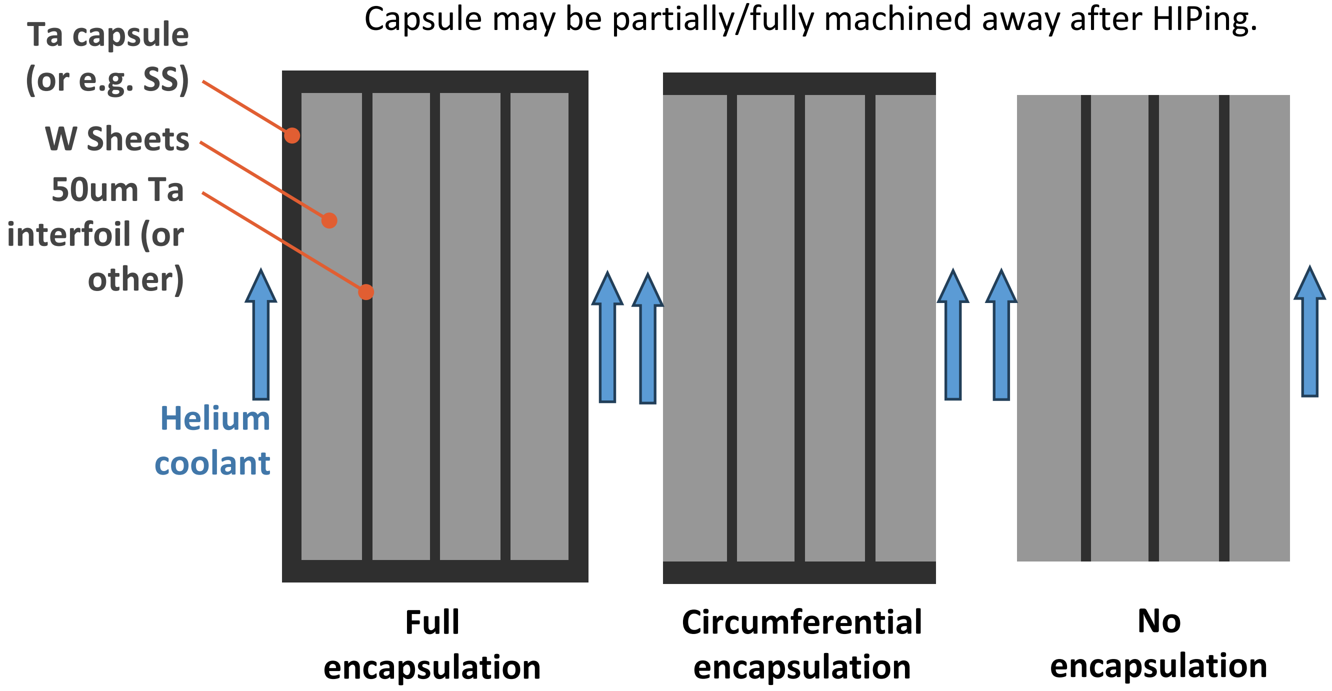
*"Application of hot isostatic pressing (HIP) technology to diffusion bond refractory metals for proton beam targets and absorbers at CERN, " J. Descarrega et al.; Material Design and Processing Communications. 8 August 2019 https://doi.org/10.1002/mdp2.101

BDF W Helium cooled Target

The Core blocks

- **W sheets, HIPed together with interlayers of ~50um Ta foil (or other – to be explored)**
  - → Improved mechanical properties compared to Sintered blocks used for CDR.
- **Using W sheets thickness 10mm ±5mm**
  - → As thick as reasonably possible with the best mechanical properties.
- **Ta interlayer foil**
  - → builds on previous HIPing experience*
- **Options of joining being investigated:**
  - Hot Isostatic Pressing
  - Vacuum Hot Press (used at SNS)
  - Spark Plasma Sintering (used at SY)
  - Tungsten Powder Injection Molding.
  - Electron Beam Tungsten Rapid Prototyping

Capsule may be partially/fully machined away after HIPing.



Drivers:

- Must be clad for HIPing joining process
- Don't want cladding: high stresses at the cladding
- Don't want cladding: Ta produces lots of decay heat
- Do want cladding at circumference: Compressive stresses beneficial to W sheets
- Do want cladding : Protective layer against oxidation / corrosion-erosion

BDF W Helium cooled Target

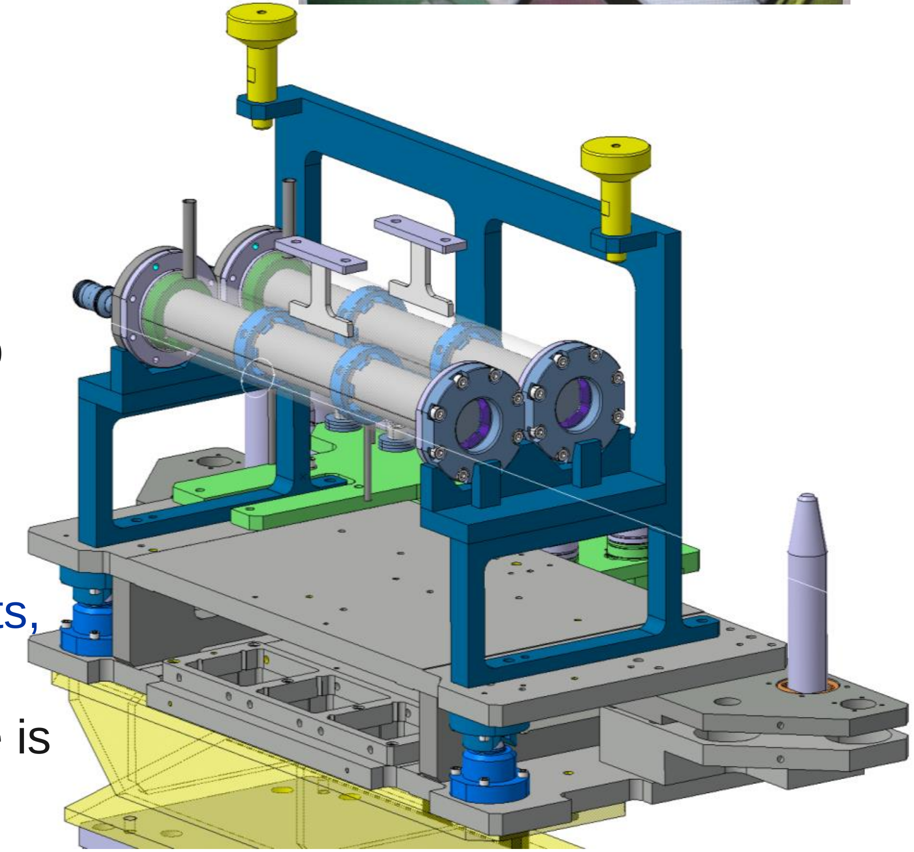
Ongoing Material Studies

- Exact tests and number of tests currently being defined
- **Testing will be performed on**
  - The raw W sheets
  - The joined blocks (*similar to the baseline prototype after HIPing tests)*
  - The joined blocks post-beam (*similar to the baseline prototype tests)*
  - In depth testing from 1 supplier & basic characterization from 2 more suppliers

Summary of tests - Raw W sheets

Priority	Test n#	Type	Property to be reported	Additional information
1	1	Mechanical testing	Yield and Tensile strength, elongation at break	Determine tensile properties of W at different temperature conditions
1	2	Microstructure analysis	Density, purity of W, Hardness, Grain size, etc	OM, SEM, EDS, Hydrostatic weight measurements, VickersHardness, etc...
1	3	Fatigue test	Endurance limit	Series of fatigue tests to determine endurance limit in W and W-W interface, for different temperature conditions
2	4	Erosion test	/icrobalance weight measurement, Volumetric estimat	Series of erosion tests following ASTM : G76 – 13 standard (adapted to BDF conditions) aiming to determine the erosion in W at different He stream angle
3	5	Thermal testing	Thermal conductivity	LFA at different temperature conditions
2	6	Oxidation test	Mass change (µg), Presence of WO_2 and WO_3	TGA testing at peak operation conditions and helium, complement prior oxidation study
1	7	Machining	Machinability (surface condition)	Machinability, e.g. via EDM, grinding, polishing/etching/surface preparation, etc
1	8	NDT	Impurities (pores, etc.)	Quality control, UT, PT?, etc.
1	9	Metrology	surface roughness, planar/waviness, etc.	e.g. classic metrology, quality control of raw product

BDF W Helium cooled Target



Prototype target

- To be constructed and tested in North Area T6 on the existing test stand base

Reproduce temperatures and magnitude & type of thermal-induced stresses

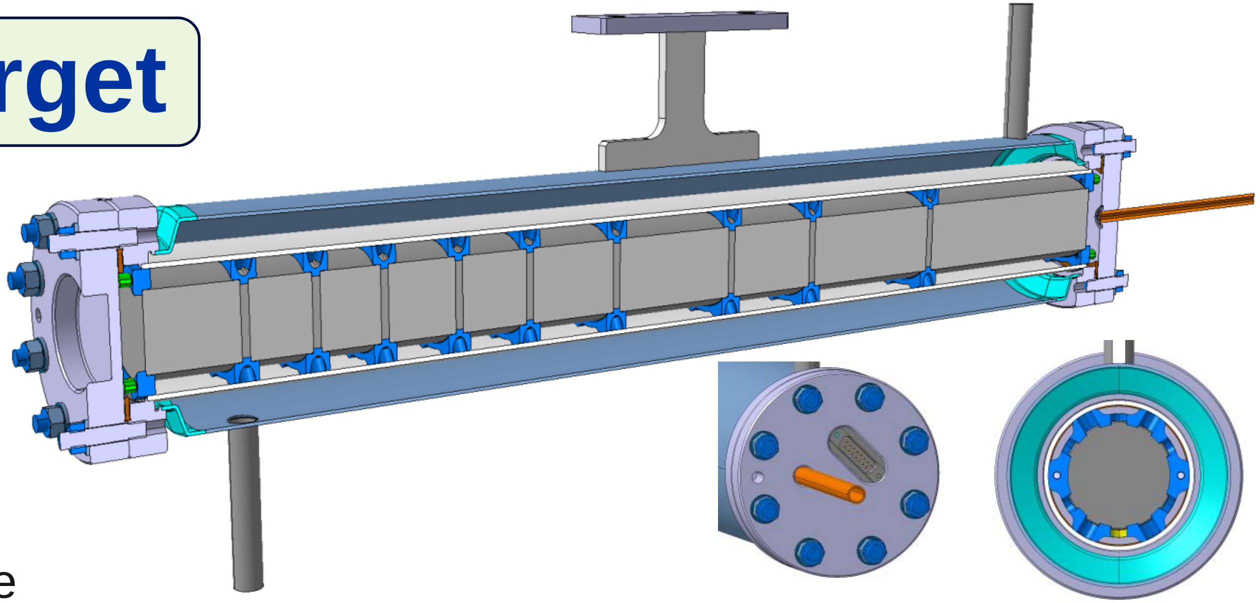
1. Post-beam testing of mechanical properties and interfaces will be performed
2. Potential to cross-check simulations
3. Coolant efficiency could be tested on a separate non-beam mock-up

If time allows, two targets will be tested:

- **Static Helium concept** & actively cooled He concept**
- 3rd option: Water cooled concept (niobium cladding, copper sheets, copper external… TBD)

**In the event of no delay to the North Area long shutdown, the timescale is not possible to have a flowing helium circuit installed and commissioned before the prototype tests…

BDF W Helium cooled Target

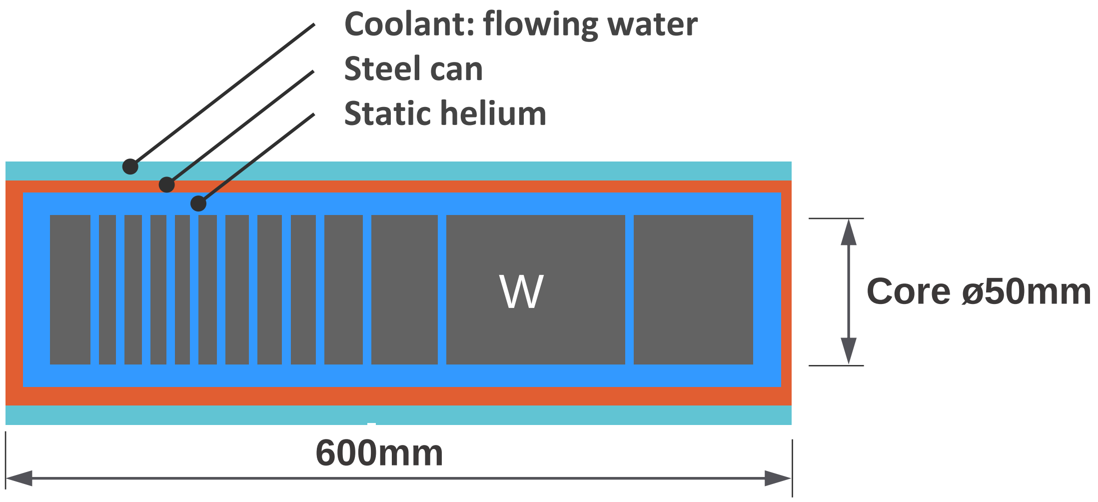


Prototype target

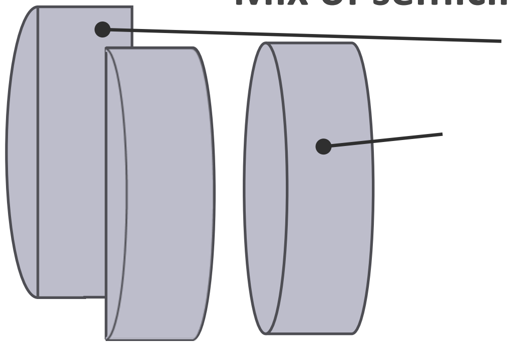
Static Helium concept (baseline for now)

- W in static Helium. Cooled with a water jacket
- Block spacing defined to match maximum stresses and temperatures and stress type.
  - Challenge with static gas. Requires a LONG cycle time = 7.2 minutes, with intensity 1.5e12 ppp.

Beam parameters considered: Beam σ 1mm to 3mm, Intensity 5e11 to 2e13 ppp



Mix of semicircle and full circle blocks



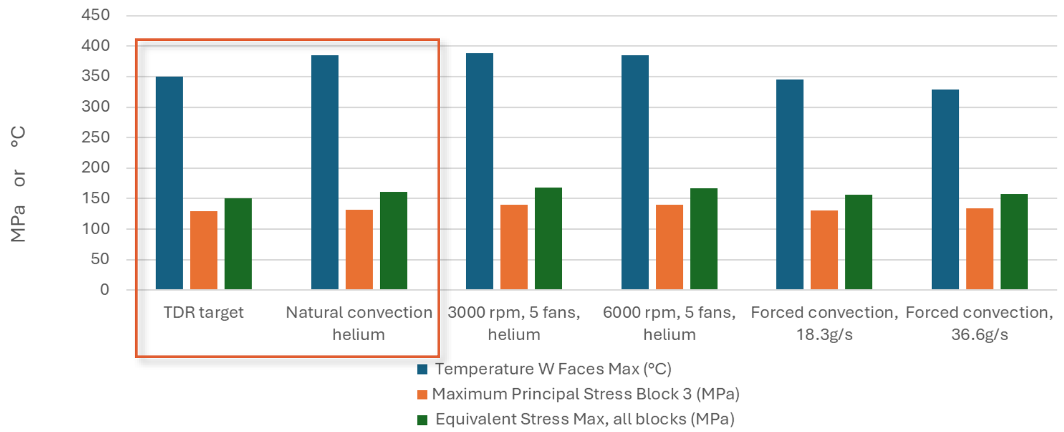
Semi-circle blocks better reproduce stress state of 1/8th target slices.

Full circle blocks better reproduce the stress –state of the 360° target.

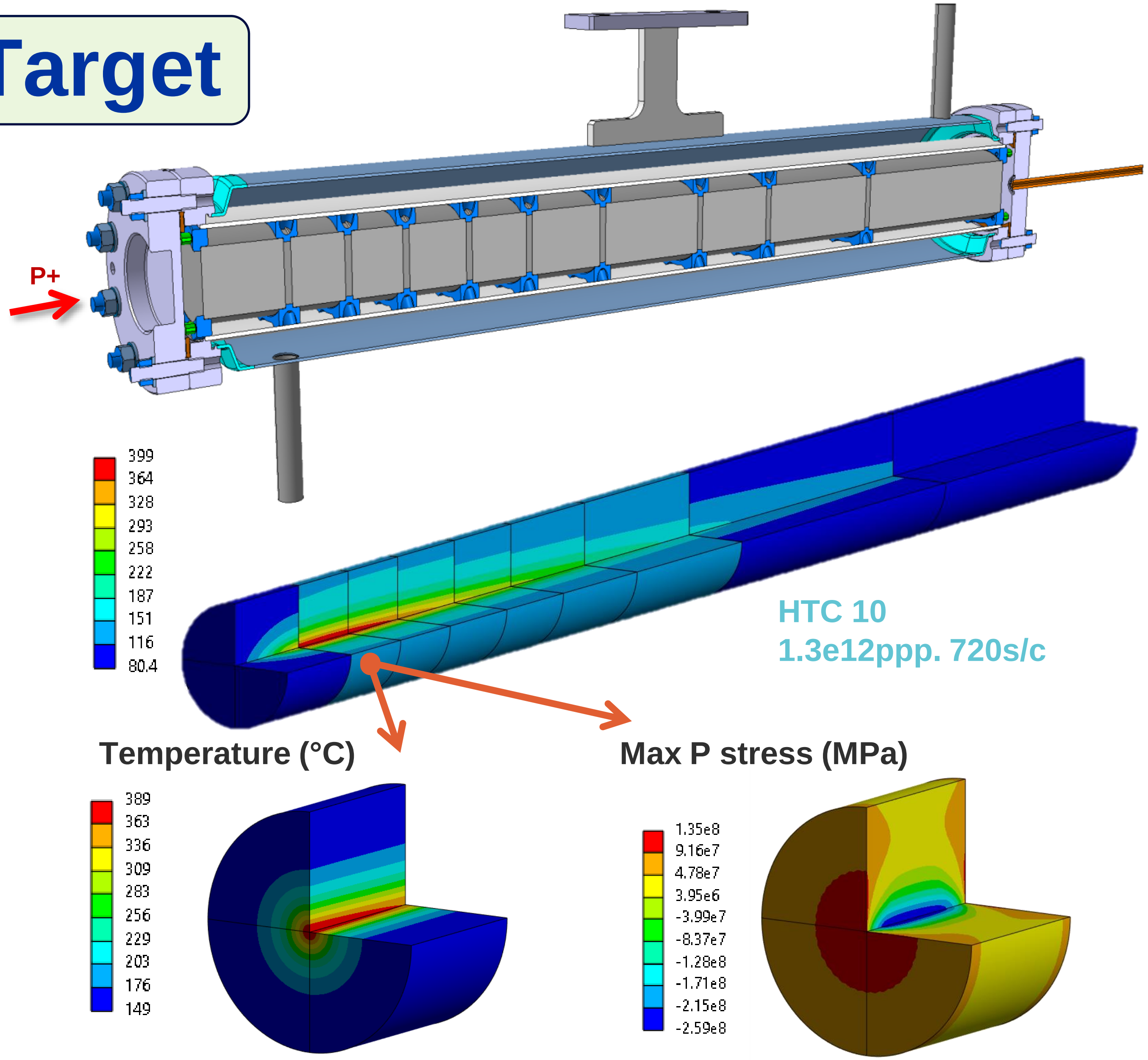
BDF W Helium cooled Target

Prototype target

Static Helium concept (baseline for now)



	Cycle length (385°C max Temperature at pulse)	Number of 7.2 s periods
natural convection	432 seconds (7.2 mins)	60
5 fans at 3000 rpm	350 seconds (5.8 mins)	48.6
5 fans at 6000 rpm	200 seconds (3.3mins)	27.8
Mass flow 18.3g/s	43.2 seconds (0.72 mins)	6
Mass flow 36.6g/s	21.6 seconds (0.36 mins)	3



BDF W Helium cooled Target

Outgassing

- One of the main concerns into moving to a W He-cooled target operating at high temperature is the outgassing of radioactive species.

Being studied:

- Shortlisted highest contributors in terms of total activity, LL and LA as computed by RP
- Assume radioactive isotope as volatile if it makes one chemical compound which is reported as volatile (due to boiling or sublimation) below 500 **°**C
  - Usually containing O, N, H (oxides, nitrates, nitrides, hydrides and hydroxides)
- Some conflicting data, e.g. on W trioxide.
- Other species of concern such as iodine which can make volatile molecules with Cobalt, Hafnium and Tantalum. ?

Possible radioactive volatile chemicals
H_2
H_2O
H_2O_2
NH_3
HNO_3
Re_2O_7
WO_3

→ **Plan to execute offline oxidation tests**

→ **Plan to execute irradiation and out-diffusion measurements**

Conclusions & outlook

- A water-cooled baseline design exists with a core of TZM and W.
- Sound design, yet with potential for physics optimization and with some radiation protection caveats
- W material quality used in the 2018 prototype was not good

Following HI-ECN3 project approval and start of TDR phase

- Multiple alternative designs explored in view of mitigating water radiolysis, decay heat and improve physics performance.
- He-cooled target most promising option. Being explored in detail.
- Presently tackling
  - Definition of core segmentation taking key metrics and safety margins
  - Material R&D for the W base material and bonding of the assembly
  - Detail design of a prototype to be tested with beam in 2025/26
  - Design of the cooling station (Francesco and Nikola’s talks)
  - Addressing Radiation Protection aspects (Claudia’s talk)
  - Many other points to be addressed in the coming months

Questions to ESS (1/2)

1. What safety factors (e.g. mechanical, thermal, cooling etc) have been chosen for the engineering studies of the target blocks?
2. What is the W material used at ESS and what quality assurance plan was adopted?
3. How has fatigue been assessed (both numerically and via testing)?
4. Are there erosion concerns?
5. Are there oxidation & spall concerns?
6. Is radiation damage and gas production a concern at ESS?
7. What radiochemistry is a concern (e.g. from volatile compounds from the irradiated W) and has been particularly addressed, and why?

Questions to ESS (2/2)

8. How significant is decay heat and LOCA for ESS Target?
9. What are the redundancy systems and measures put in place for LOCA?
10. What instrumentation is used to monitor the target and its core ?
11. What design & manufacturing specifications have been adopted for the target assembly and that were mostly driven by the presence of a He coolant ?
12. Considering today's status of the He-cooled pure W target for BDF, what recommendations can you provide?

Many thanks!

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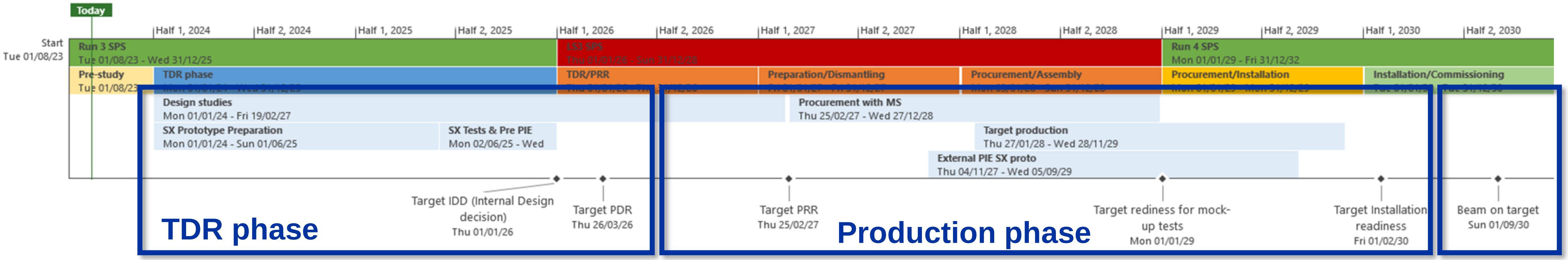
WP3 – Target & BIDs: Planning (key dates)



Commissioning & operation

<u>TDR phase (main activities)</u> – (2024-mid 2026)

1) Target (& BIDs) conceptual design followed by detailed design
2) Prototype(s) Target Design, construction and beam tests
3) Material studies, R&D and Procurement

<u>Production phase</u> – (2026 – 2030)

1) Detailed Design phase
2) Procurement & production of components and systems
3) Tests/dry-run, installation activities
4) Material tests/PIEs

Main Target developments in the coming months

Focus on W quality assurance

→ W via rolled products to ensure low porosity (low brittleness),and high mechanical properties

→ Material R&D on W to W bonding and characterization of interface strength

Further develop alternative target concepts, particularly He cooled option

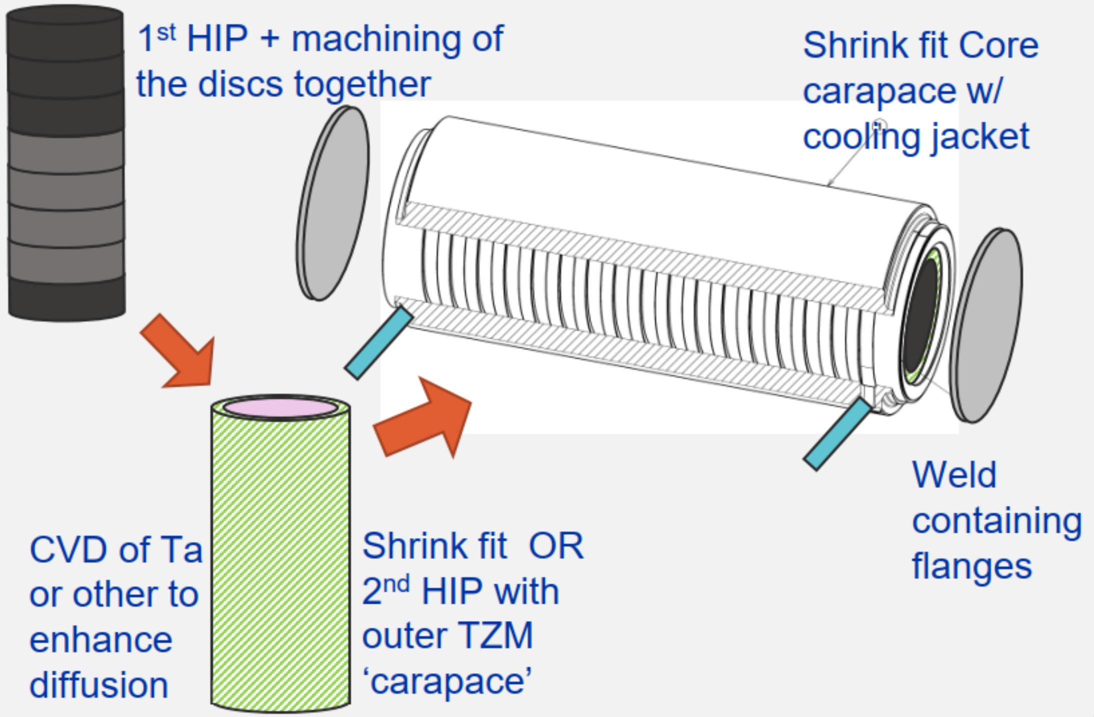
→ Understand & design such He cooling system

→ Design Target core than can withstand higher temperatures and reduce mechanical stresses

Develop prototype Target(s) to be tested at CERN SX test-bench in 2025

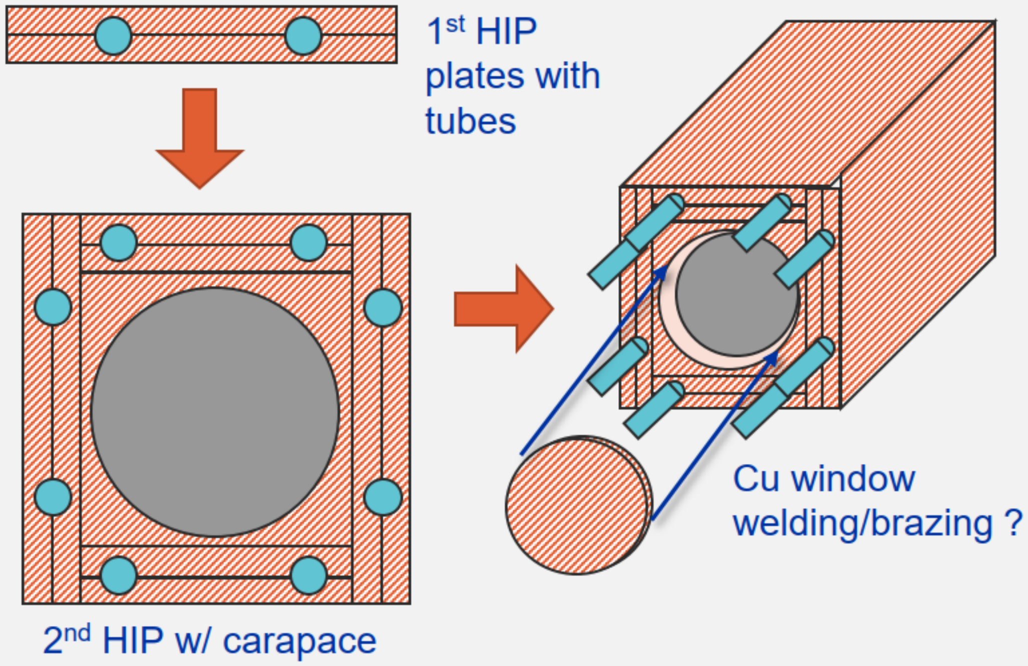
BDF – New ideas to be explored in 2024

The TZM Shroud Concept



L4 Dump-like cooling serpentine jackets (welded beforehand)

The HIPed Copper Concept



HIPed plates like SPS Internal Dump TIDVG5

Ta2.5W cladding – LOCA

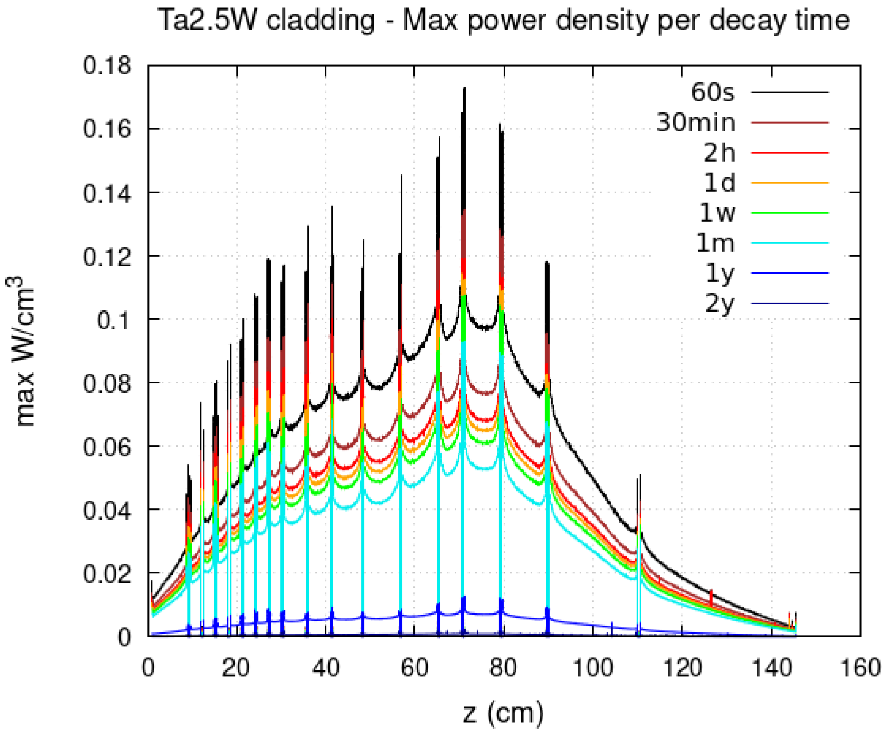
- (Loss-of-Coolant Accident scenario) LOCA hypothetical scenario used as a criterion for assessing the safety of a nuclear installation during its design phase.

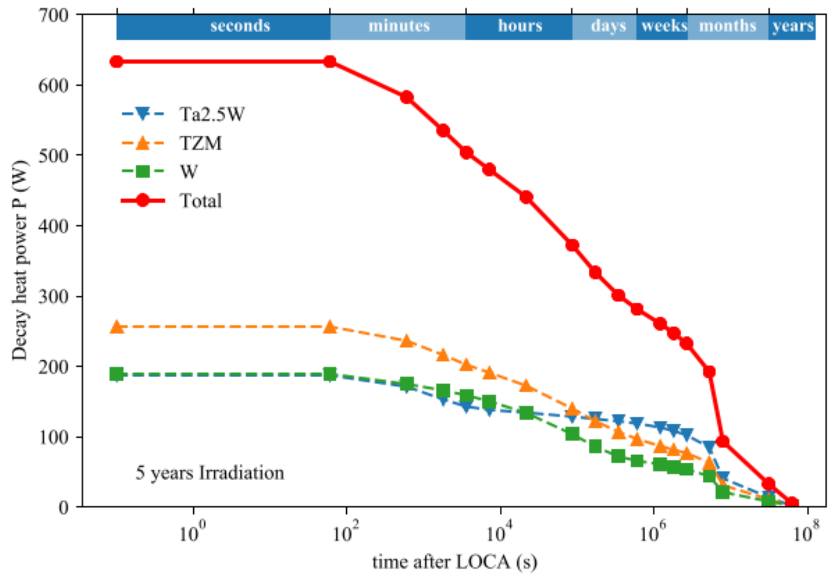
→ Strong implications on the classification of the facility.

- Thermo-mechanical simulations to 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)

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



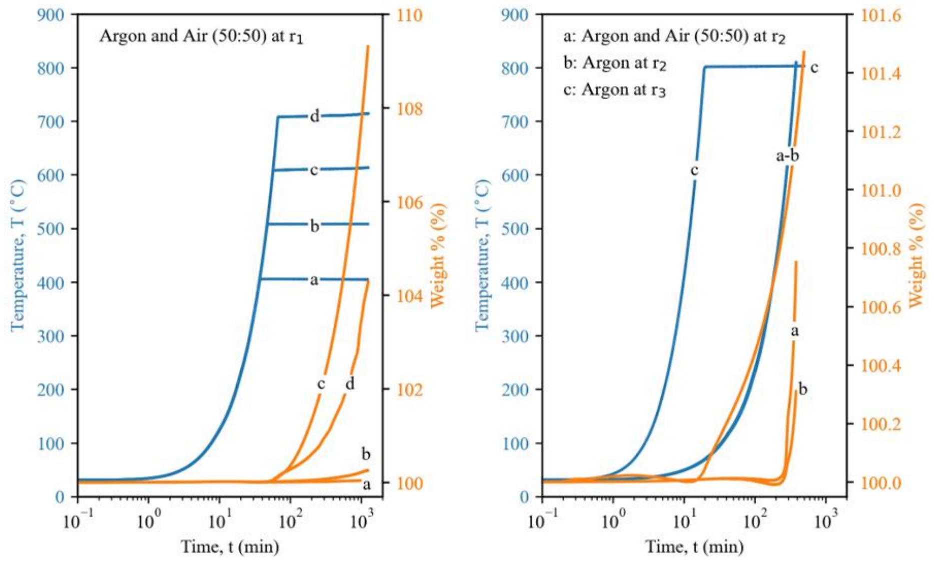


Ta2.5W cladding – LOCA

- Potentially degradation of the material through oxidation with LOCA.

→ Campaign to assess the onset for extensive oxidation and formation of volatile oxides

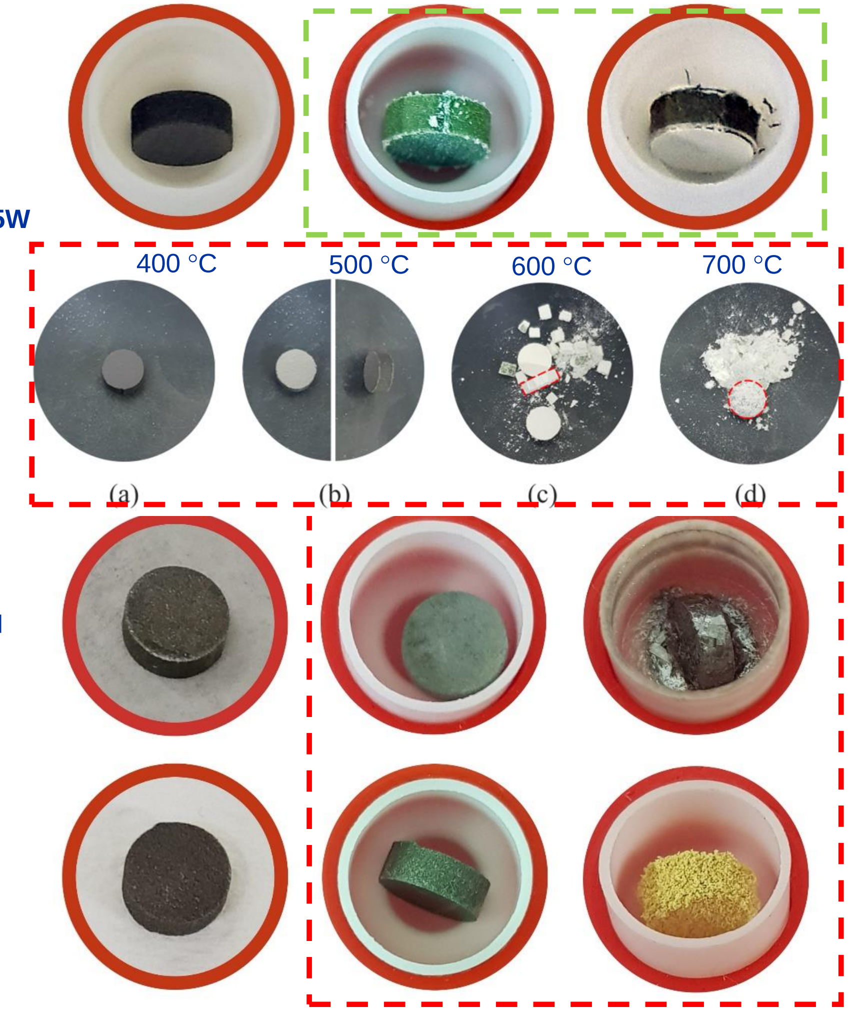
- Thermogravimetric analyses (TGA) performed for Ta2.5W, TZM and W in the range of 400-800 C under active and inert atmospheres.



r1 = 10
r2 = 2
r3 = 40
[°C/min]

Visual inspection of the samples before and after oxidation for different temperatures.

	Raw sample	800 °C at 2 °C/min	800 °C at 40 °C/min



Ta2.5W

400 °C 500 °C 600 °C 700 °C

TZM

W

400 °C at 10°C/min x 7 days 800 °C at 2°C/min

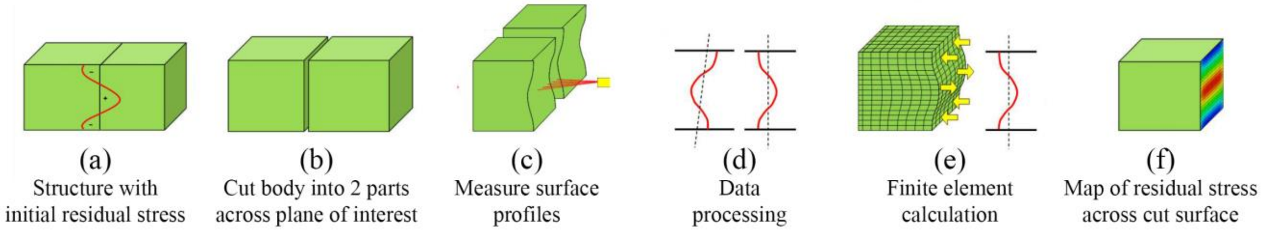
Inert Atmosphere (argon 6.0)

Active Atmosphere (50% argon: 50% air)

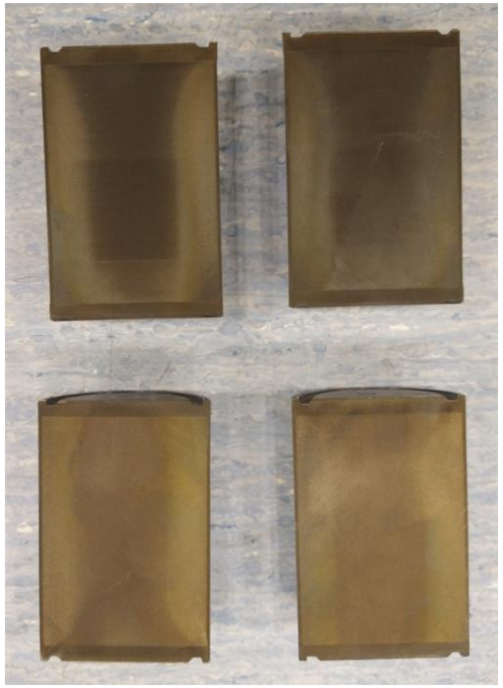
Nb-alloys cladding R&D

Residual stress

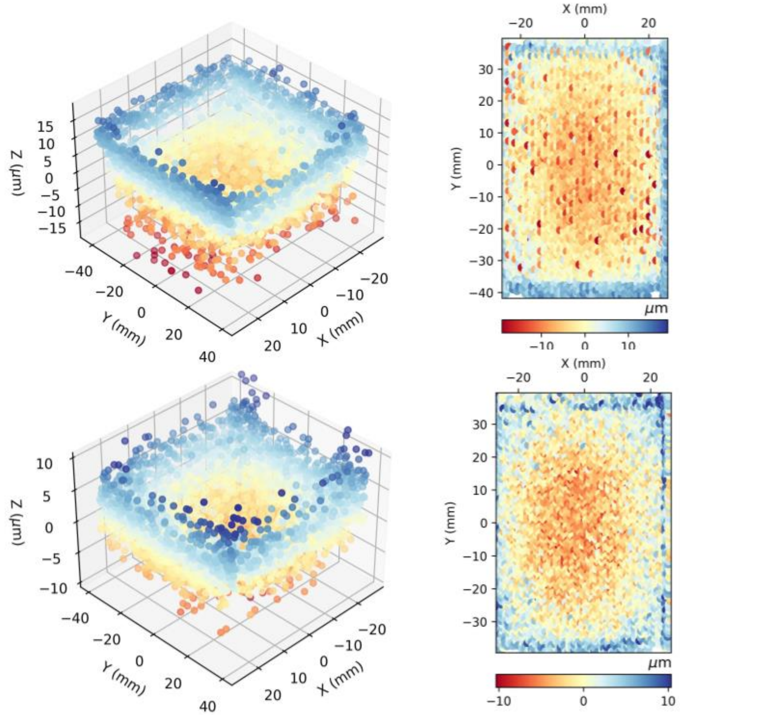
- Presence of residual stresses (RS) during the manufacturing of the target blocks via Hot Isostatic Pressing (HIPing).
- RS defines the onset for plastic deformation and eventually material failure
- **Purpose:** quantify the RS in the BDF target blocks
- Contour method* employed to measure the RS in the BDF target blocks. Ongoing FE model calibration.



The contour method and its different steps to obtain the residual stresses. Adapted from [StressMap 2018]



Resulting left and right parts after EDM cutting (Top) Block 3 and (Bottom) Block 4

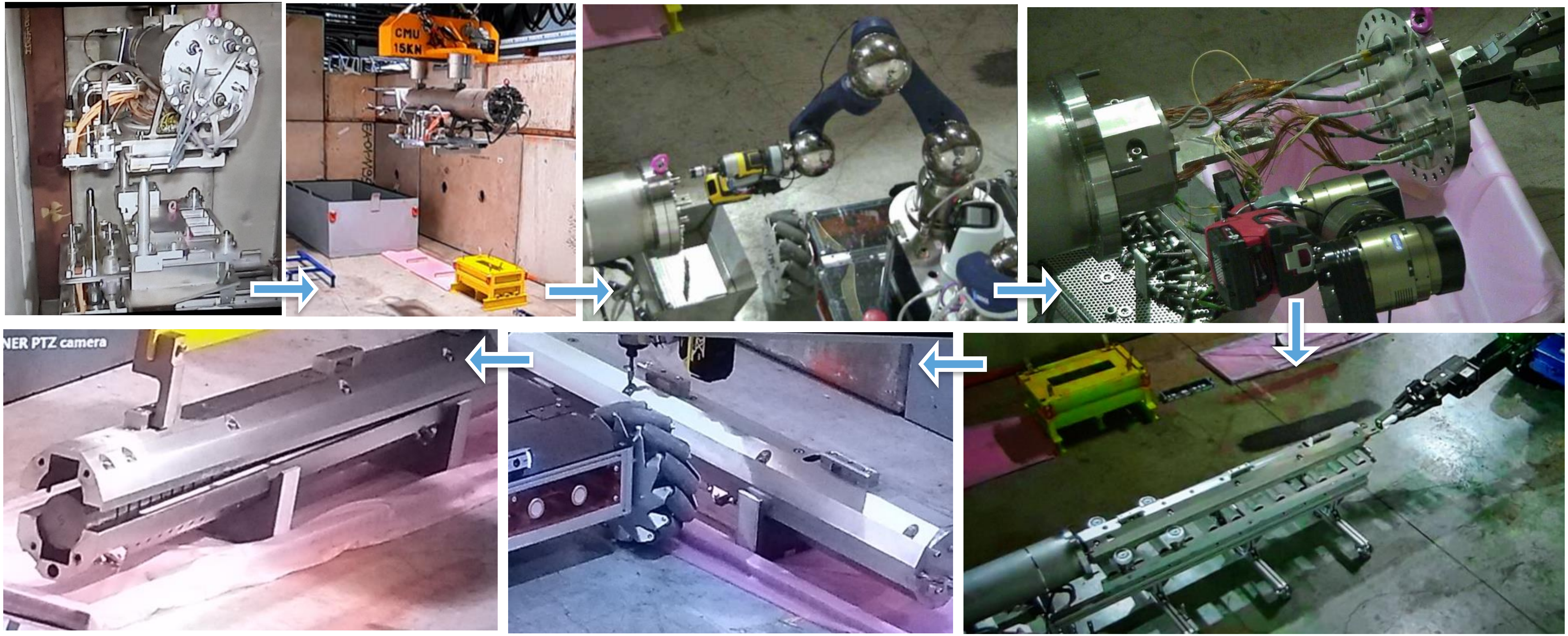


Average flatness measurements of the resulting surfaces (Top) Block 3 and (Bottom) Block 4

* Prime, M. B., 2001, Cross-sectional Mapping of Residual Stresses by Measuring the Surface Contour After a Cut, *Journal of Engineering Materials and Technology* 123(2):162–168

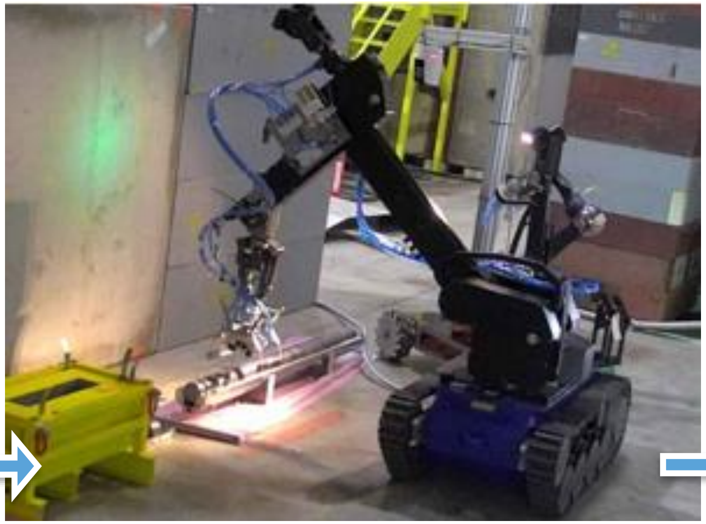
BDF Target Prototype removal (2020)

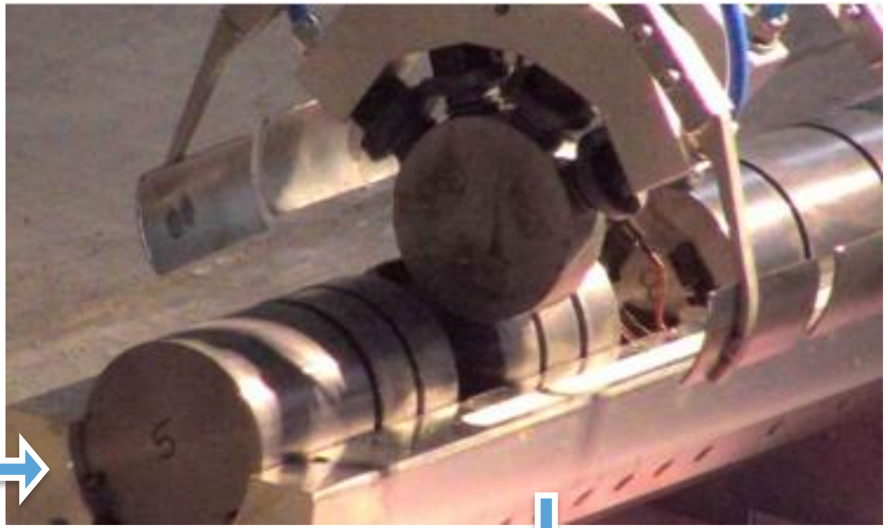
Unplug-in ▸ Transport to the bunker ▸ Unscrew downstream flange ▸ Instrumentation wire cut & flange removal ▸ Extraction half-shells core assembly ▸ Unscrew half-shells ▸ Removal top half-shell & first glimpse of the target blocks

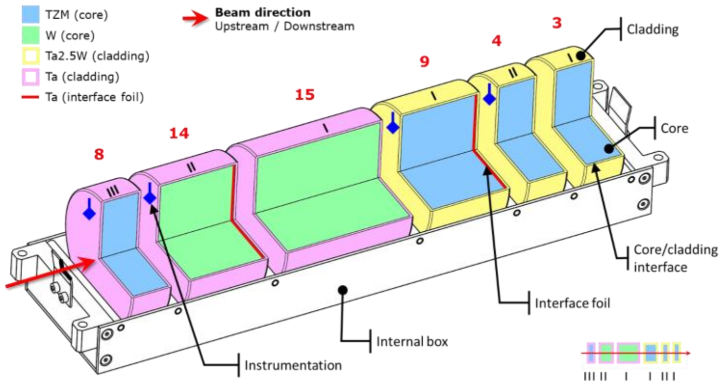


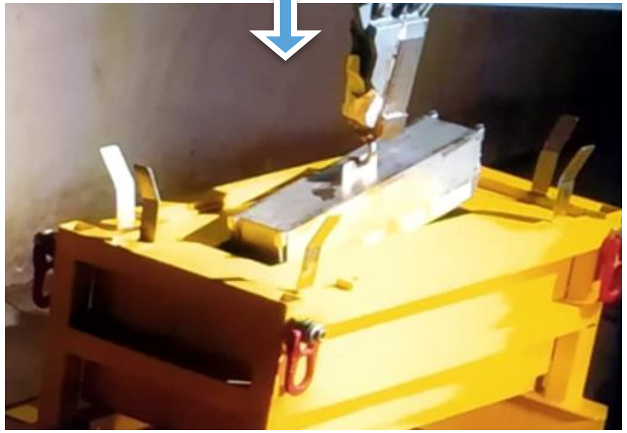
BDF Target Prototype removal (2020)

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



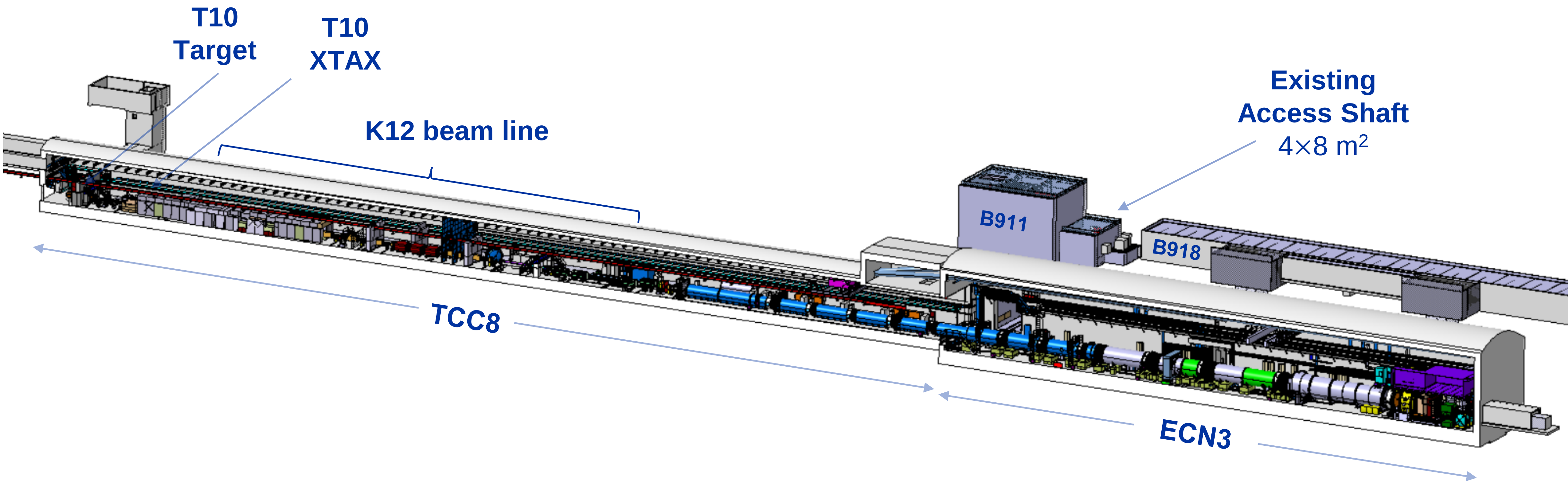






NA62 in ECN3 (Today)

- **T10 target, K12 beamline and NA62 experiment to be dismantled in LS3**



BDF/SHiP Target & Complex (Future ~ 2030)