Development and testing of refractory additively manufactured materials for fusion applications

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DCD meeting W7-X Greifswald 05/03/2024

Outline

- Wisconsin HTS Axisymmetric Mirror WHAM

- Functional tantalum Plasma-Facing Components:
  - cold spray deposition
  - plasma irradiation experiments
  - deuterium retention

- Additively manufactured tungsten

- WHAM status update

- Conclusions and perspectives

WHAM Team: We're growing

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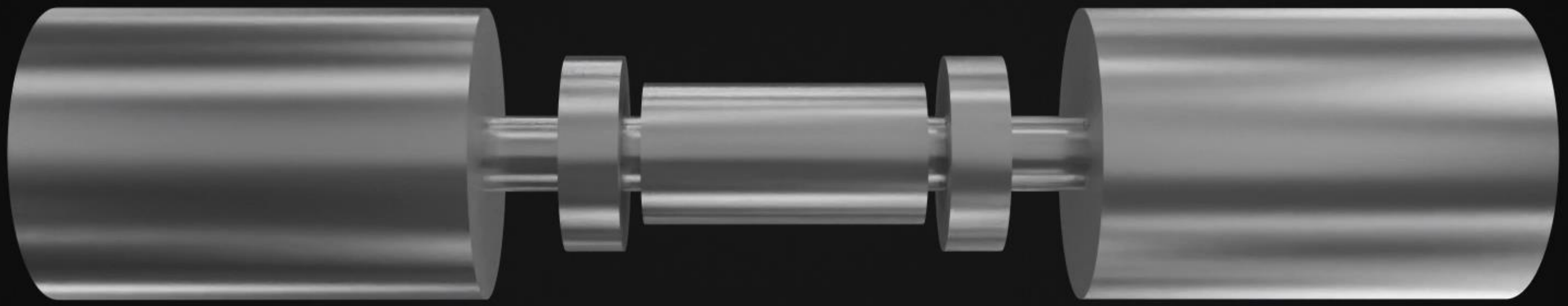
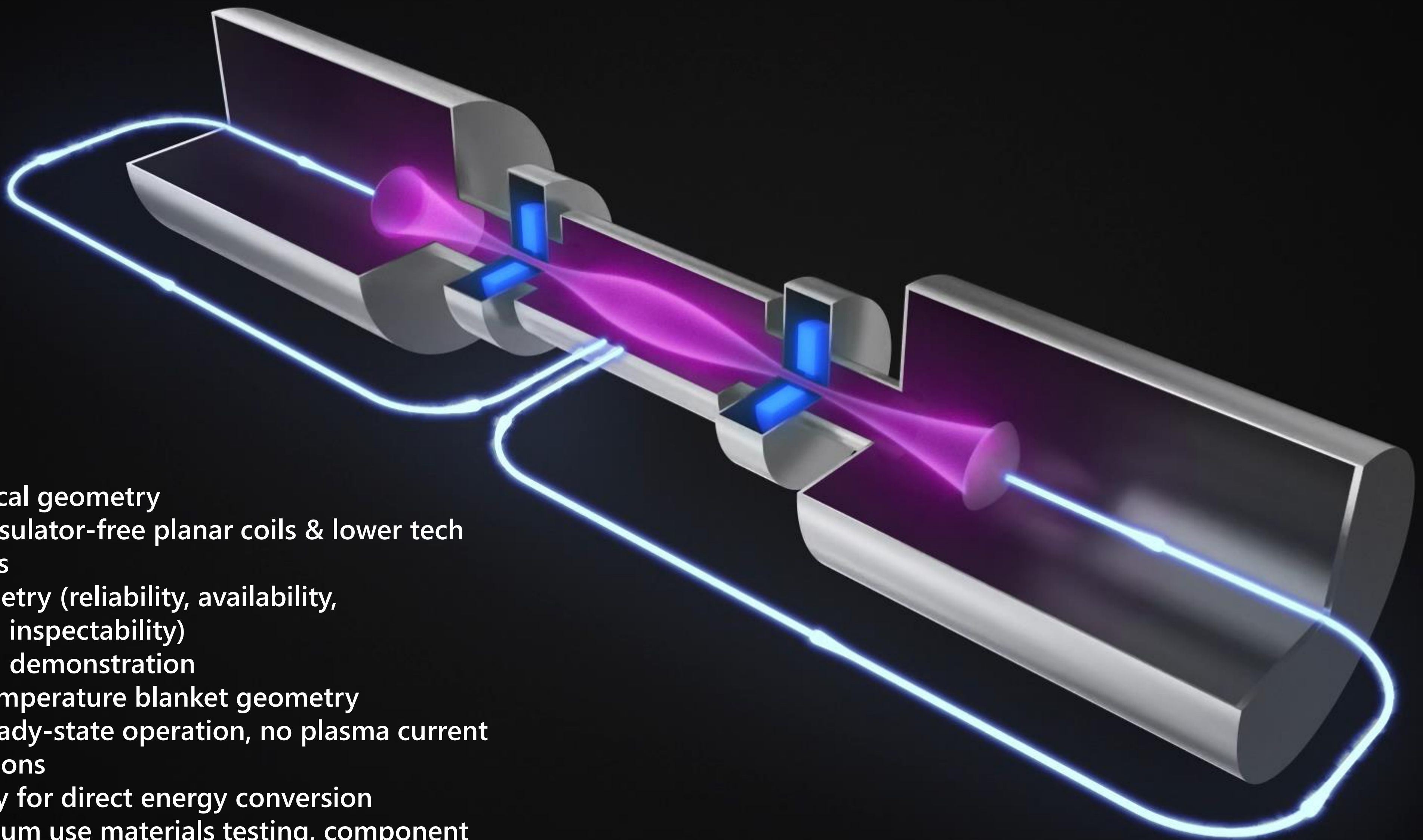
UW Physics, Engineering Physics and Physical Sciences Lab

Magnetic mirrors concept



Magnetic mirrors concept



- Simple cylindrical geometry
  → high-field insulator-free planar coils & lower tech central cell coils
  → Linear geometry (reliability, availability, maintainability, inspectability)
- Less costly Q>1 demonstration
- Simple high-temperature blanket geometry
- Intrinsically steady-state operation, no plasma current and no disruptions
- Open geometry for direct energy conversion
- Allows low-tritium use materials testing, component testing fuel cycle demonstration etc.

WHAM goals

WHAM (Wisconsin HTS Axisymmetric Mirror) experiment to demonstrate "Breakthrough" physics for fusion energy on tandem mirror path.

Physics Missions:

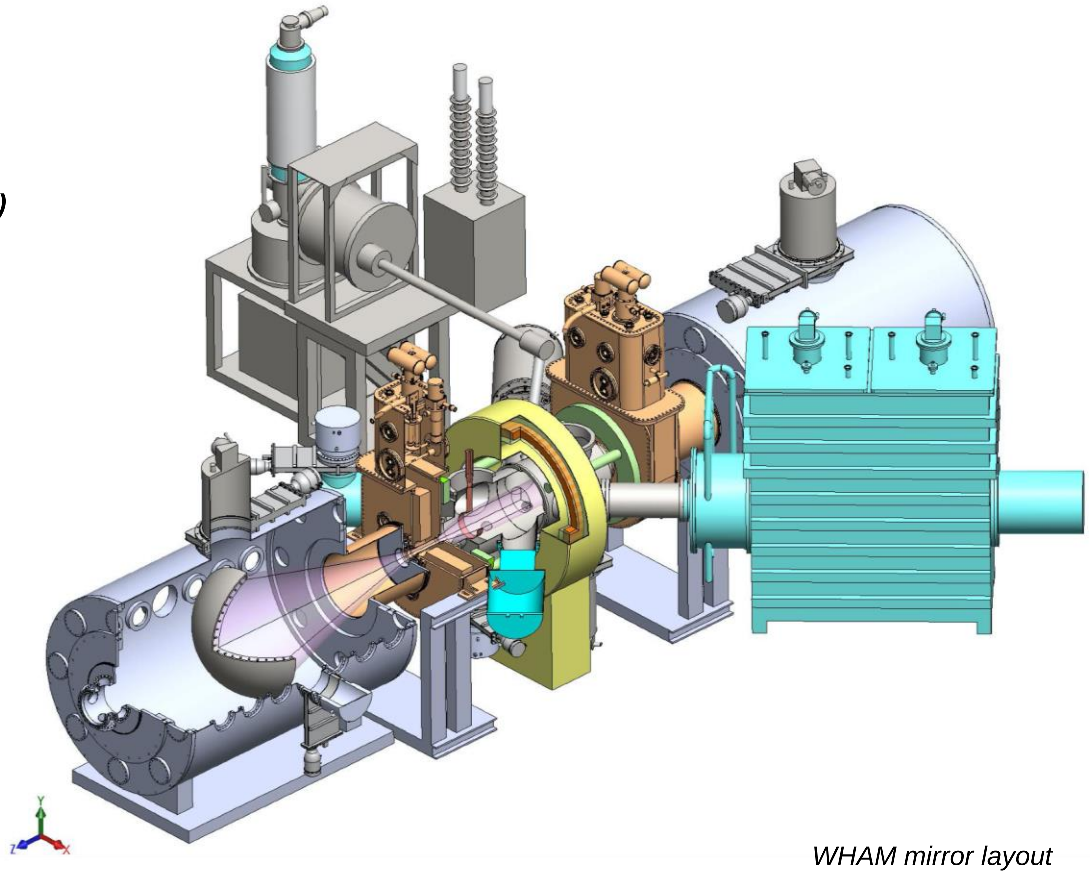
1. *Confine MHD stable, high Te plasma in axisymmetric mirror (endcell prototype)*
    - Requires simultaneous MHD stability + high power ECH
    - Requires negligible cross-field transport, axial loss only

2. *Demonstrate novel in-situ ion acceleration*
    - Requires high power RF system and NBI
    - Verify wave damping characteristics (on which particles, where in plasma column)
    - Verify sufficient *kinetic stability* to reap confinement benefits of high energy ions

Technology Missions: (intertwined with physics goals)

1. *Actualize HTS mirror reactor coils:* CFS.
    - Build 17 T, 5.5 cm bore HTS coils; design 25 T, 32 cm.

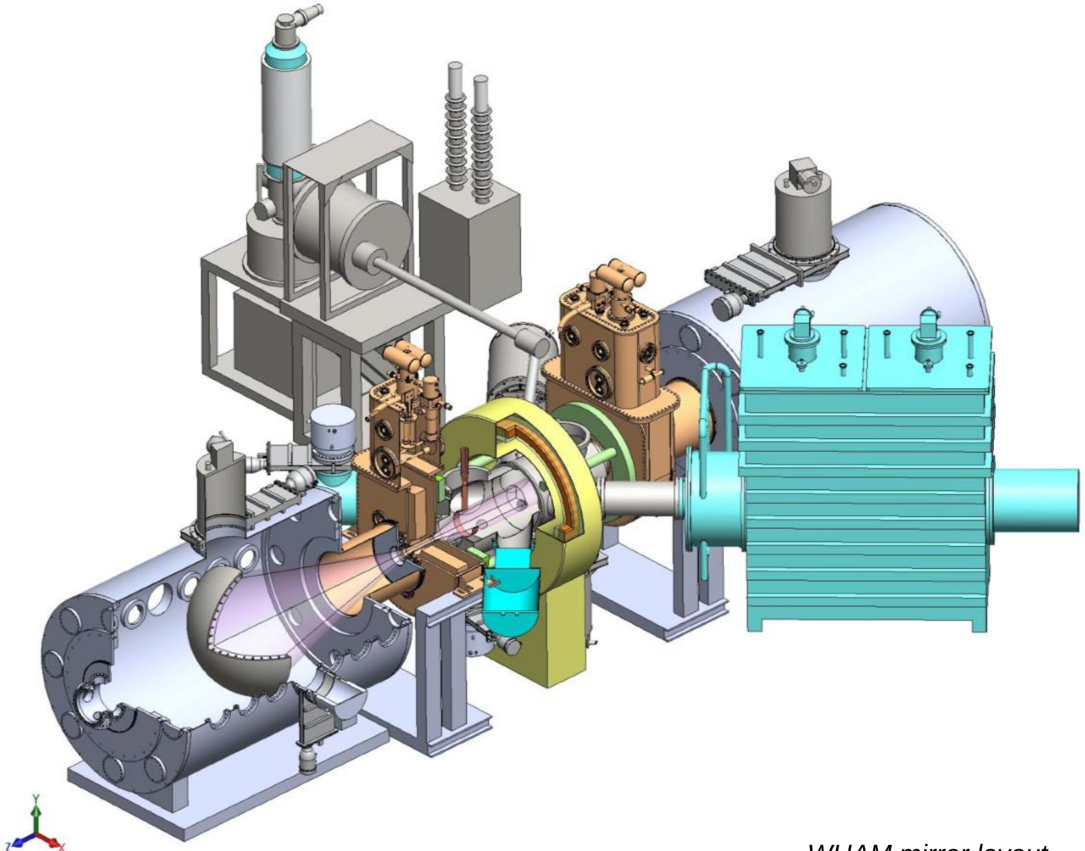
2. *Demonstrate expander particle handling techniques*
    - Create low neutral pressure, low recycling, low sputtering (in short pulse length) with high ion energies.



WHAM mirror layout

WHAM parameters

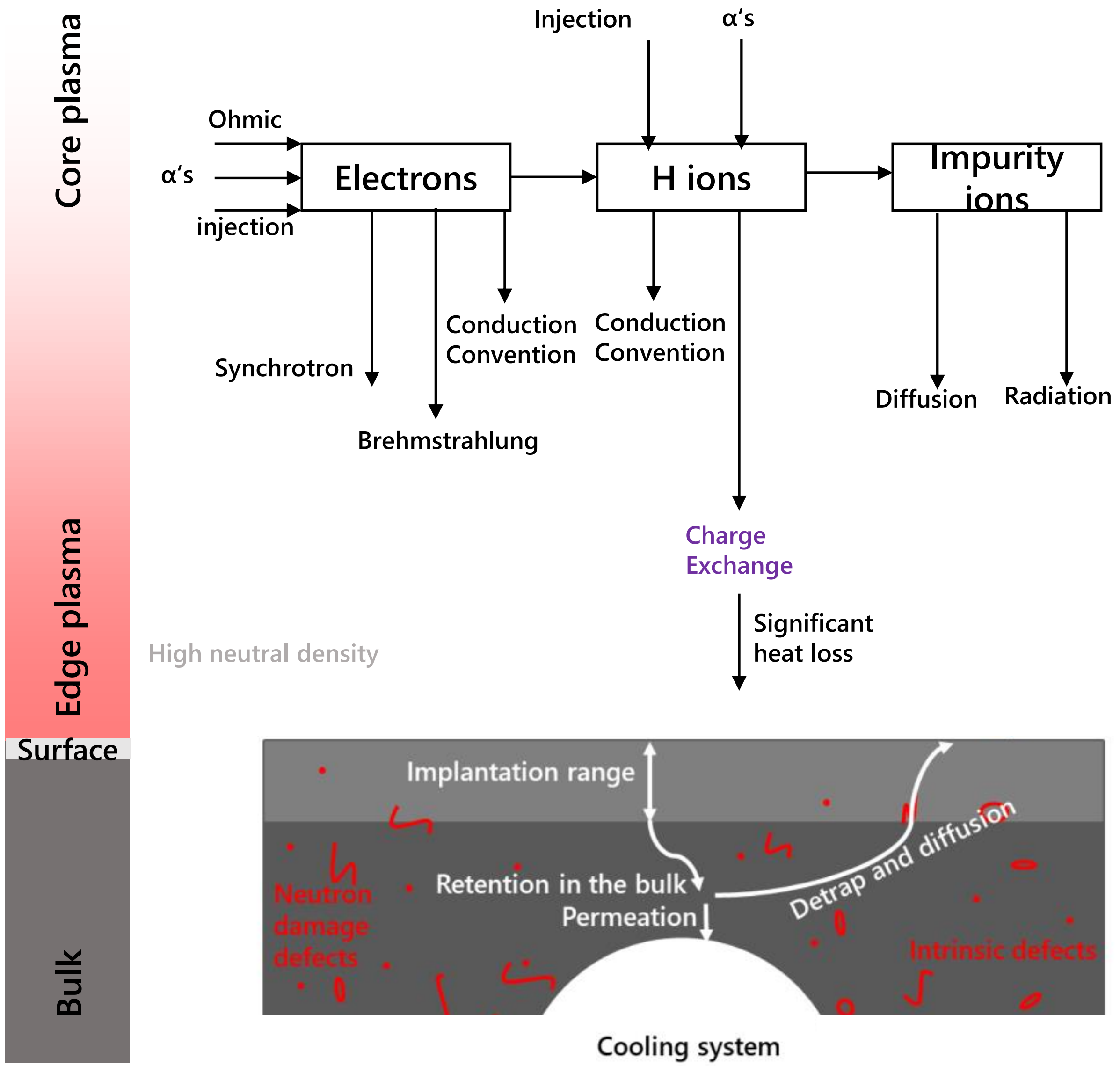
	WHAM
Q_{DT}	~ 0.05
β	0.3
L_p (m)	2.0
a_0 (m)	0.12
a_M (m)	0.025
R_M	20
B_0 (Tesla)	0.85
B_M (Tesla)	17
E_{NBI} (keV)	30
P_{NBI}(MW)	< 1
T_i (keV)	17
T_e (keV)	2.5
n_{20} (m^{-3})	0.3
τ_p (sec)†	0.15
$nT\tau$ ($10^{20}\mathrm{m}^{-3}\cdot$keV$\cdot$sec)	0.7
pulse length (sec)	< 2
kA$\cdot$m of HTS tape	$\sim 10^4$
Cost of tape ($M)	$\sim$1



WHAM mirror layout

D. Endrizzi et al. J. of Plasma Physics, 89, 5, 2023
C. Forest et al. J. of Plasma Physics, 90, 1, 2024

A key to success: minimizing charge-exchange events



Charge exchange (CX) – exchange of an electron between a positive ion and a neutral particle. The ion in the plasma edge is converted to a neutral which is not confined.

Effective control of hydrogen isotopes (HIs) partial pressure in the plasma edge in small fusion devices is important to limit energy losses associated with the charge exchange events.

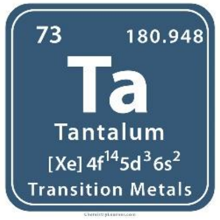
CX losses is the key issue for small devices like WHAM

=>

Functional first wall interface for HIs neutral absorption

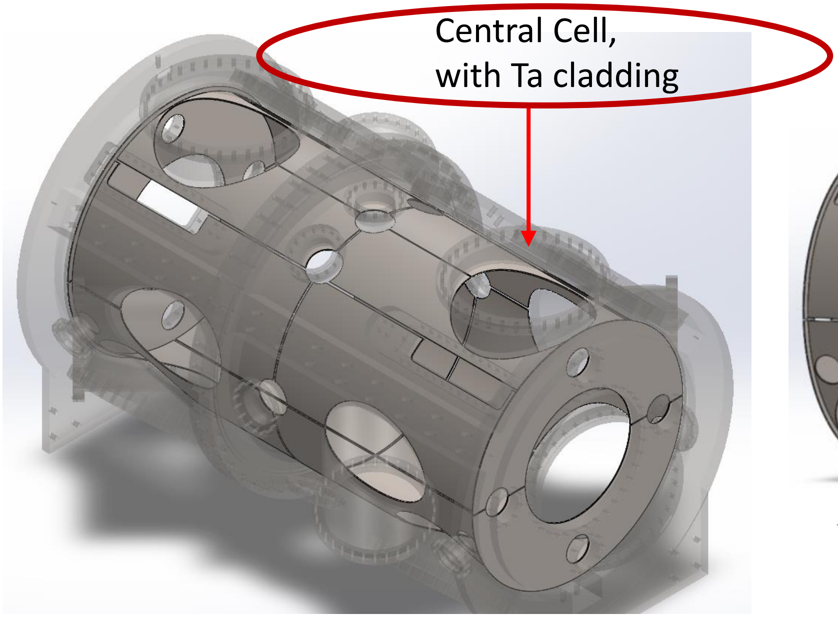
Functional first-wall concept

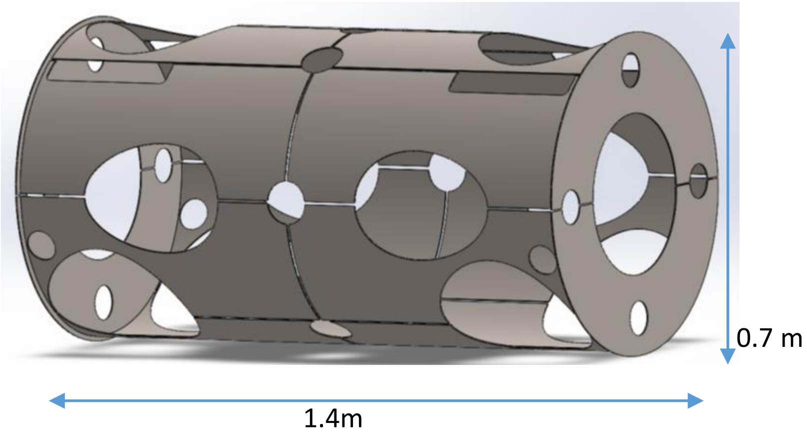
- Functional first wall for effective neutrals and energetic H (D) ions absorption at certain temperature and pressure conditions.



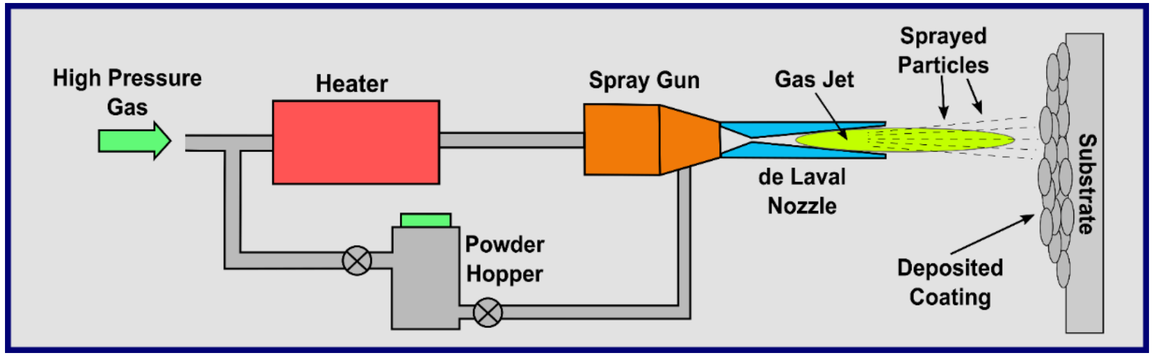
- excellent hydrogen storage capacity,
- high threshold for particle sputtering,
- excellent room-temperature ductility,
- unique corrosion properties

	Ti	Mo	Ta	W
Melting point, K	1941	2896	3123	3687
Thermal conductivity (293 K), W/(m K)	22.4	138	57.4	182
Sputtering TRH (by D), eV	33.2	90	315	244
Hydrogen retention	high	lower	high	low

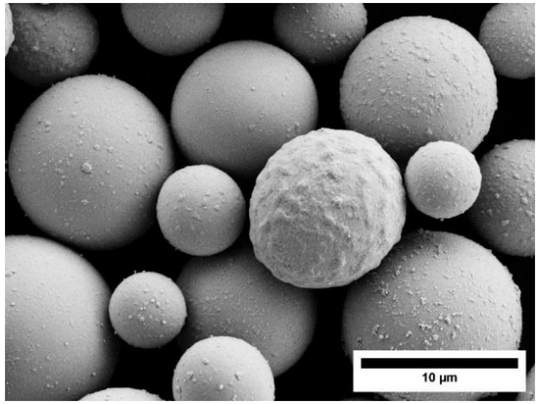




Cold-spray deposition process

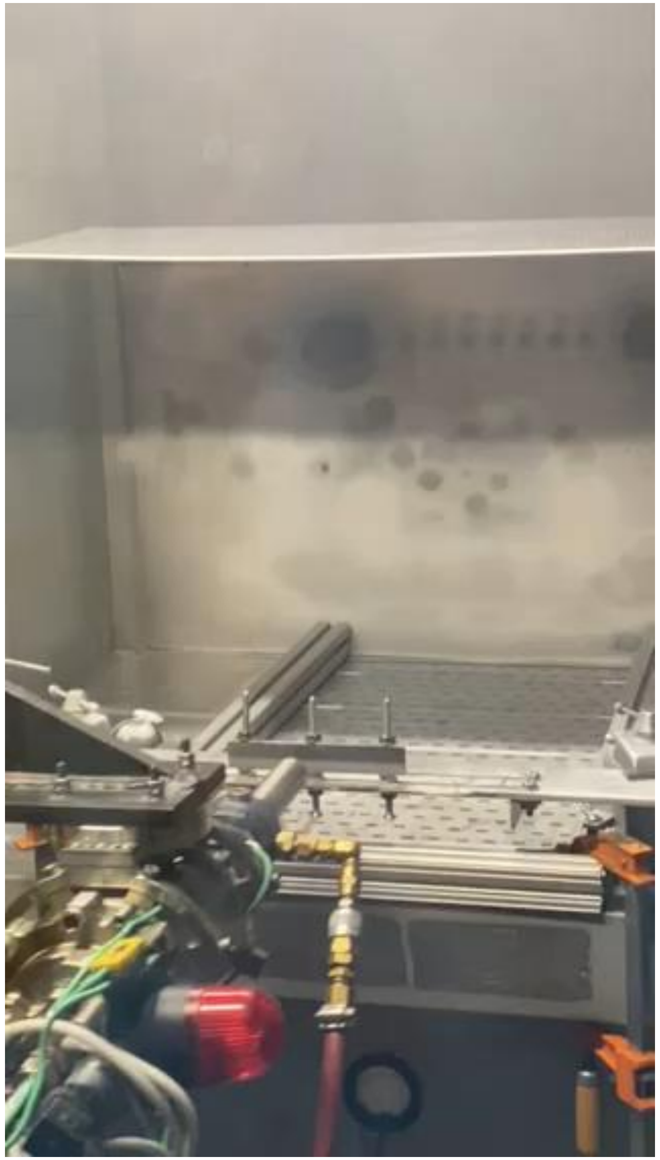


- On-site component manufacturing & repair
- Potentially in-situ
- Deposition of any thickness
- Various shapes (for stellarator divertor, specially shaped vacuum chambers)
- Commercially available



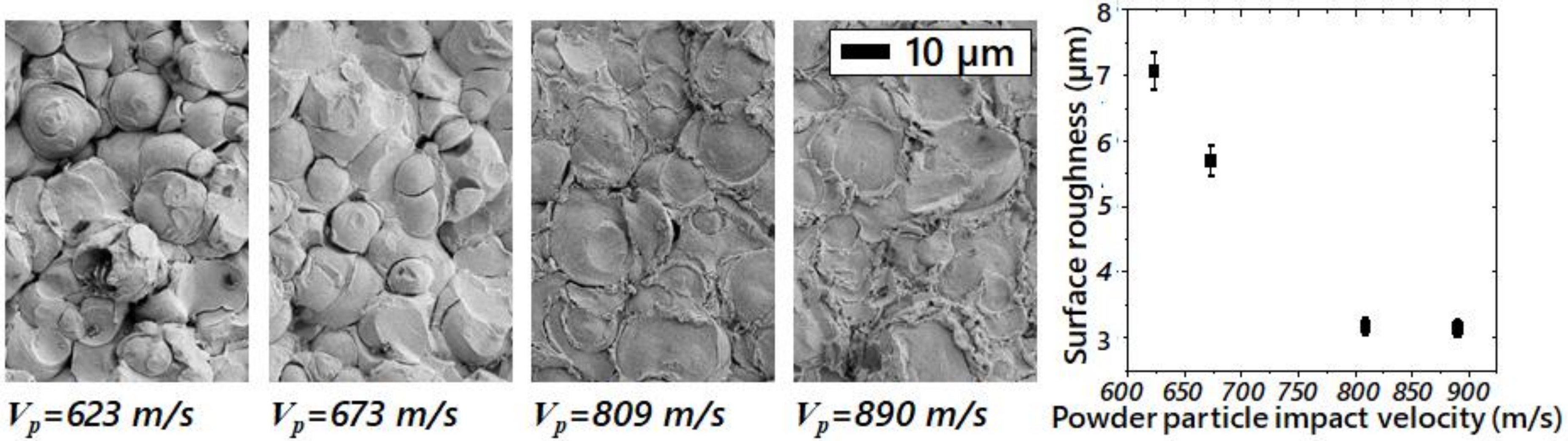
SS substrate before deposition

Ta(CS) N_2, 1023 K, 4.0 MPa, 400 mm/s; V_p= 673 m/s , T_p= 590 K

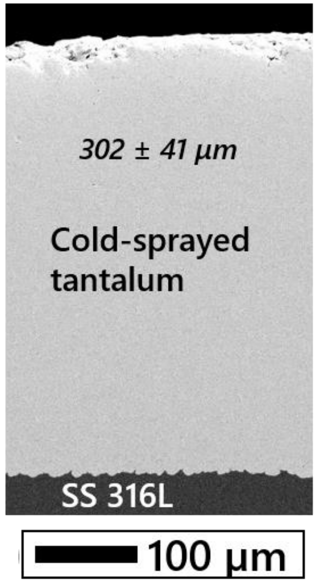


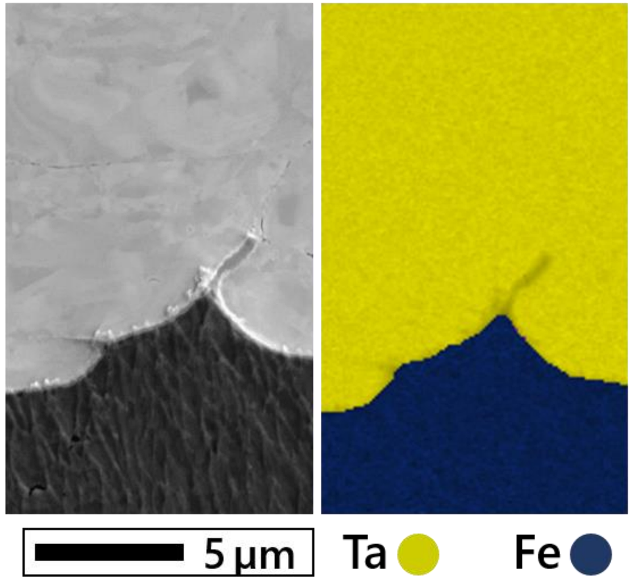
Characterization of Ta cold spray coatings

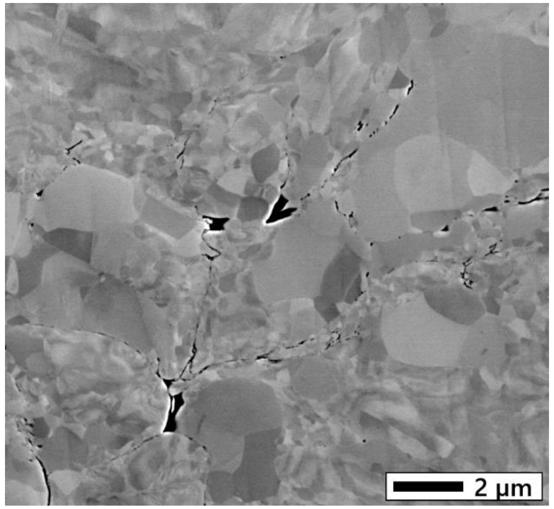
Surface



Cross-section





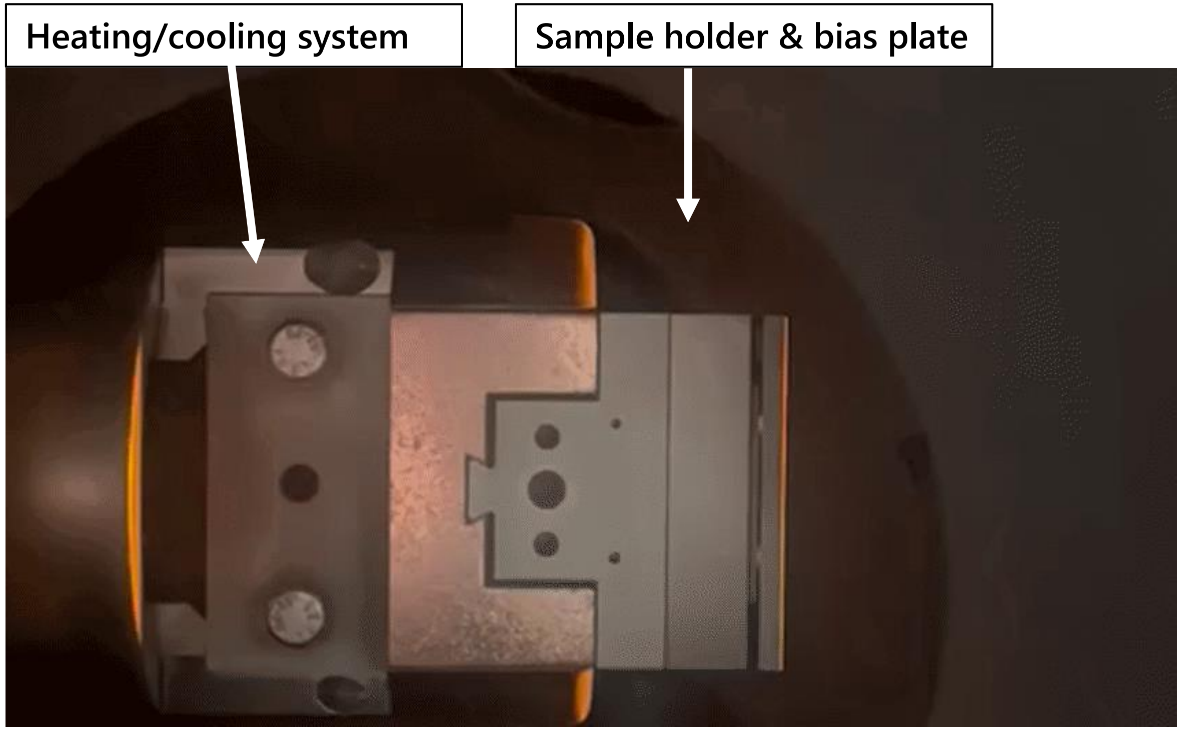


- Particle velocity determines particle bonding, surface and bulk morphology, stress, etc
- Dense, well-adhered coatings
- Controlled porosity level

D irradiation tests on cold spray Ta coatings

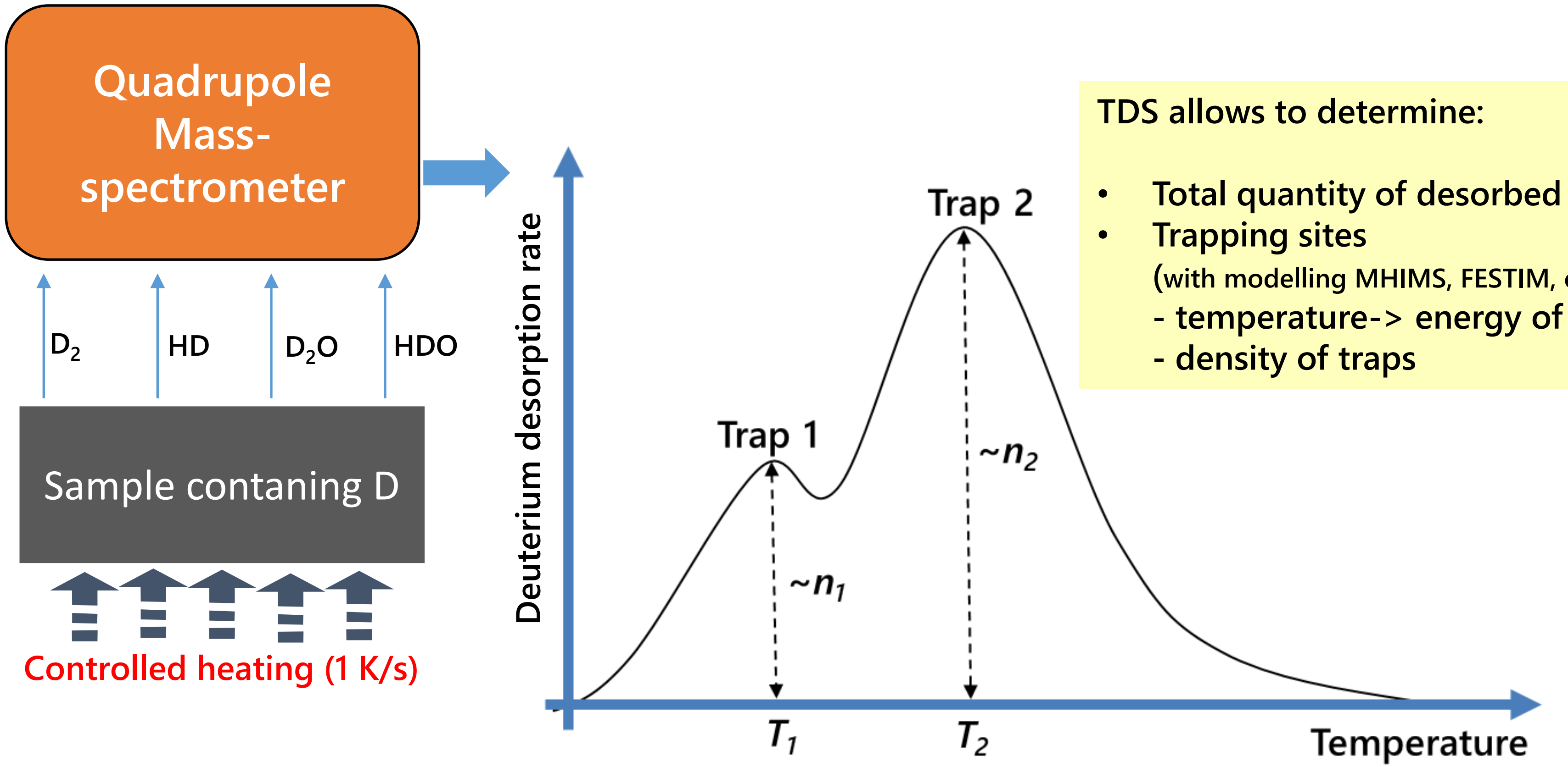
Choice of plasma-exposure parameters:

- D plasma
- E_{kin}=95 eV: no erosion,
  no damage due to the exposure
- Constant (high) flux 1.6e21 D $m^{-2}s^{-1}$
- Incident fluence [1.6e22, 3e25] D m^{-2}
- Surface temperature [420,950] K



Experimental methods: Thermodesorption

Main technique: Thermodesorption Spectrometry (TDS)



TDS allows to determine:

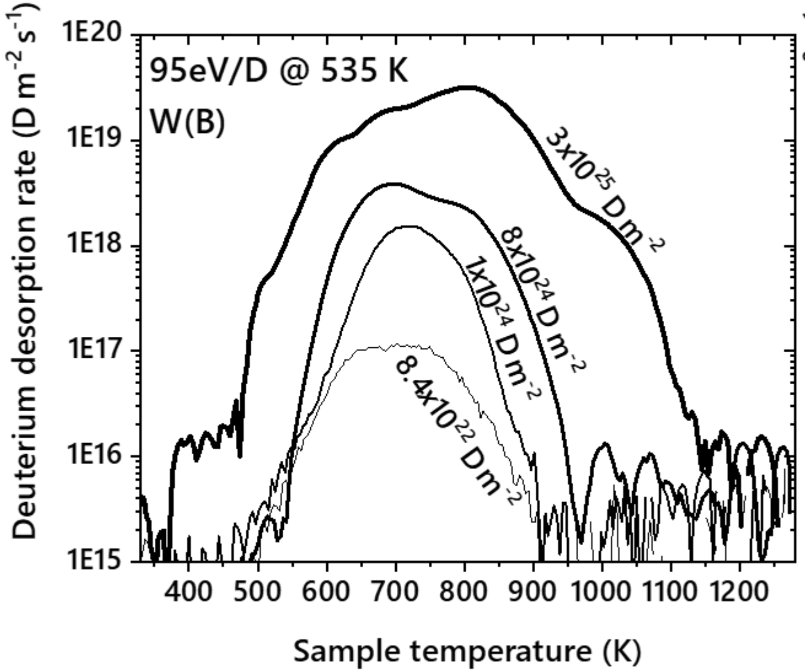
- Total quantity of desorbed species
- Trapping sites
  (with modelling MHIMS, FESTIM, etc.):
  - temperature-> energy of traps
  - density of traps

$$I(T) \sim -\frac{d\theta}{dt} = \nu(\theta,T)\cdot\theta^{n}\cdot\exp\left(\frac{-E_{des}(\theta,T)}{k_B T}\right)$$

ν	Frequency factor
θ	Instantaneous coverage
n	Kinetic desorption order $(0 \le n \le 2)$
E_{des}	Activation energy to desorption

Polanyi-Wigner Equation

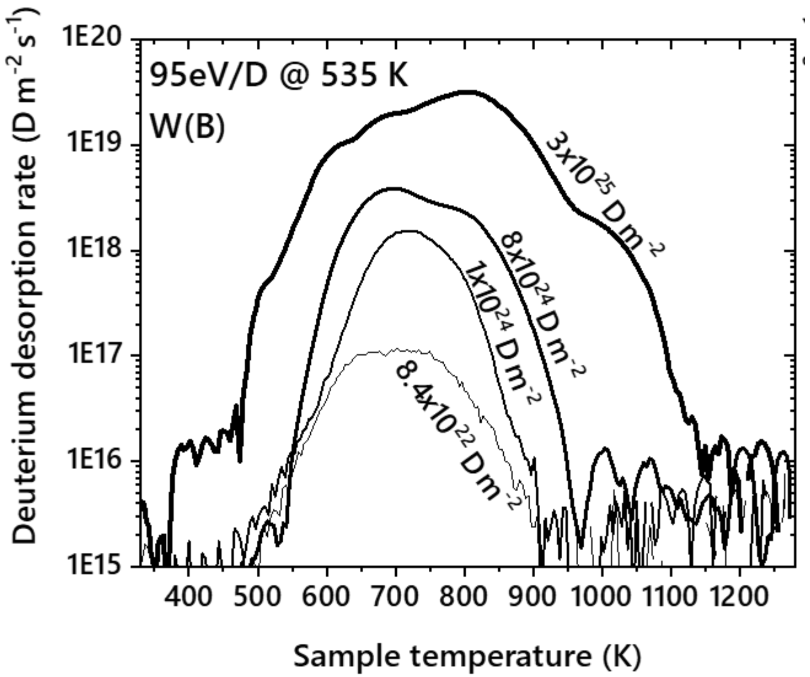
D retention in reference tungsten (bulk)



Desorption can be expressed:

$$-\frac{d\Theta}{dT} = \frac{\nu_0}{\beta}\Theta^m \exp\left(-\frac{E_d}{k_B T}\right), \quad \Theta = \frac{c_{surface}}{n_{surface}}$$

D retention in reference tungsten (bulk)

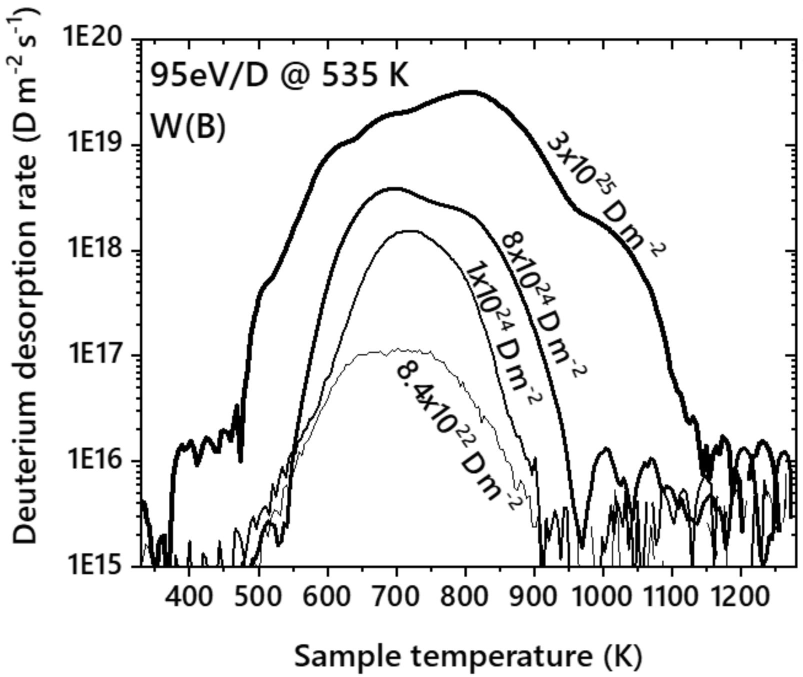


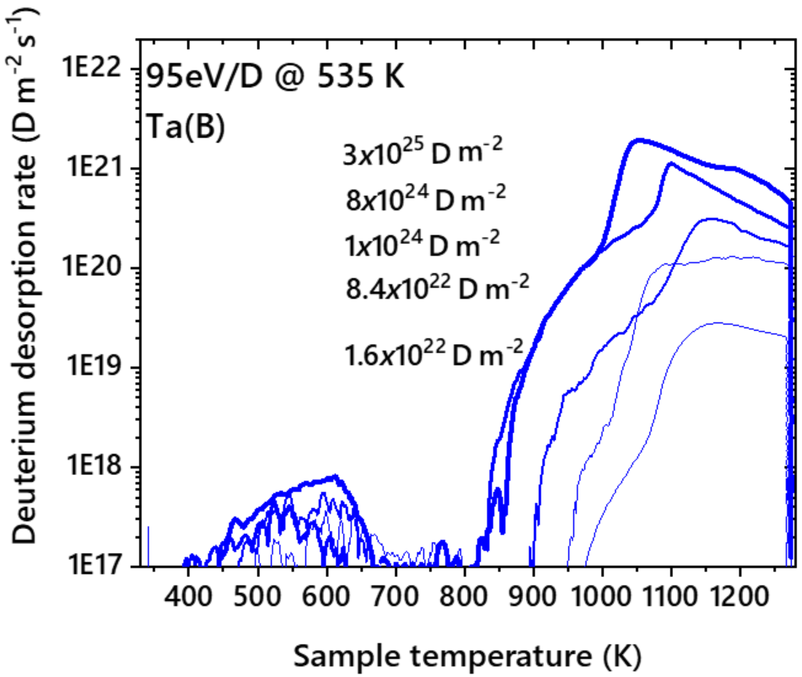
First order desorption kinetics

$$\frac{\beta}{k_B T_m^2} = \frac{\nu_0}{E_d} \exp\left(-\frac{E_d}{k_B T_m}\right) \qquad E_d = 2.0\,\mathrm{eV}$$

De-trapping from grain boundaries and voids

D retention in reference tantalum (bulk)





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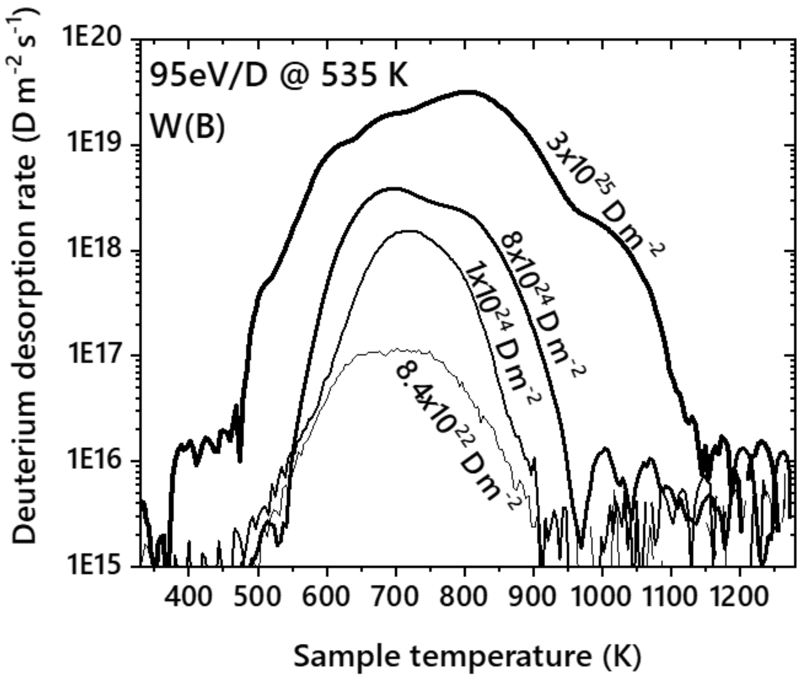
De-trapping from grain boundaries and voids

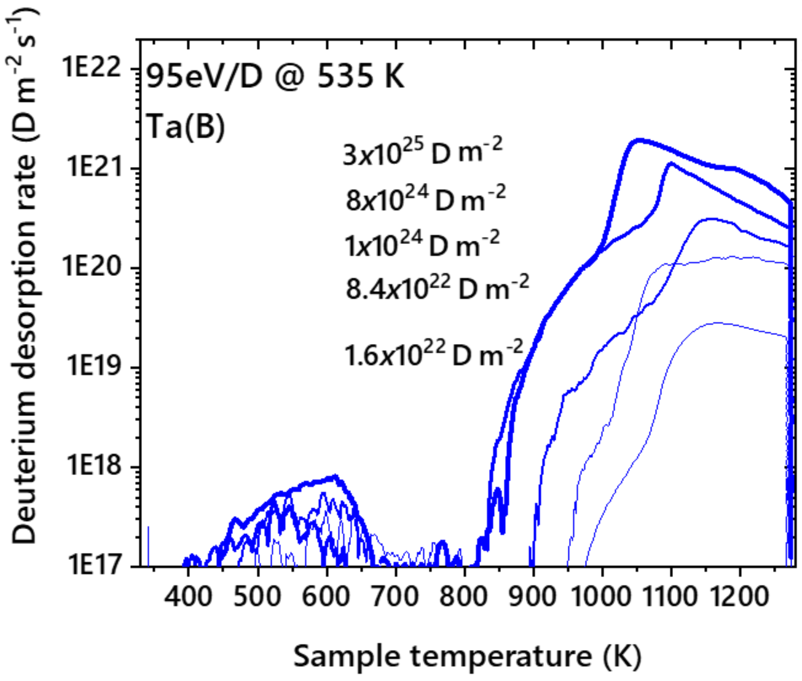
Second order desorption kinetics

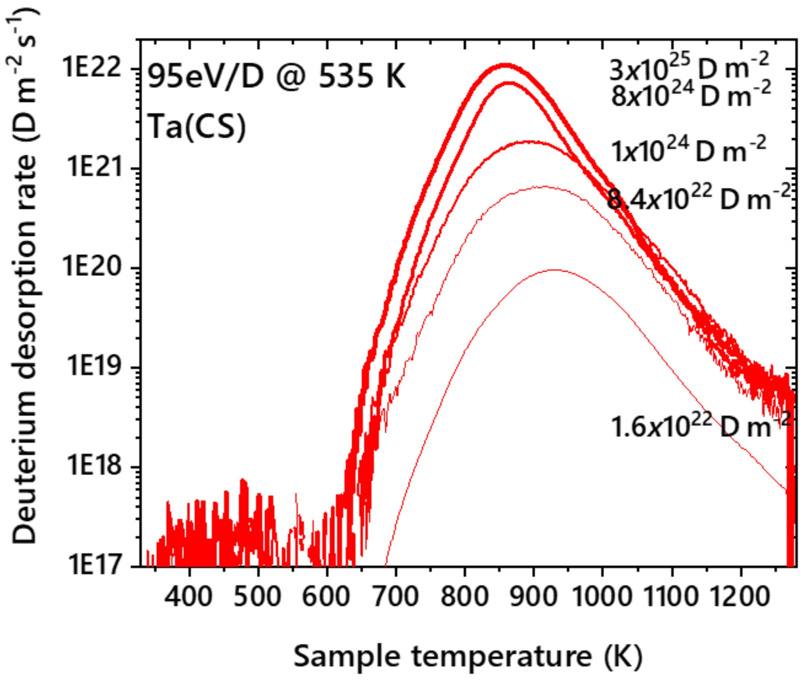
$$\frac{\beta}{k_B T_m^2} = 2\Theta \frac{\nu_0}{E_d} \exp\left(-\frac{E_d}{k_B T_m}\right) \qquad E_d = 3.15\,\mathrm{eV}$$

Dedicated modelling is necessary to identify the trapping mechanisms

D retention in tantalum cold spray







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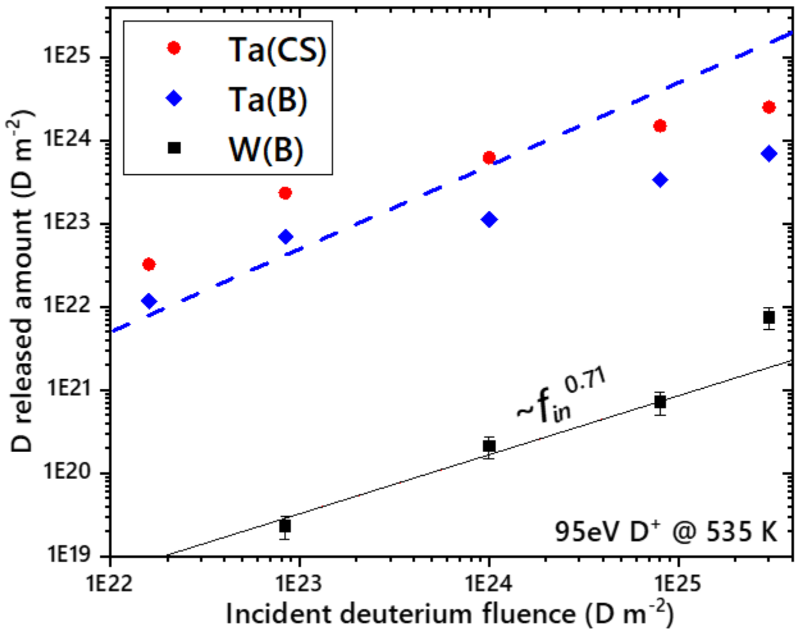
Second order desorption kinetics

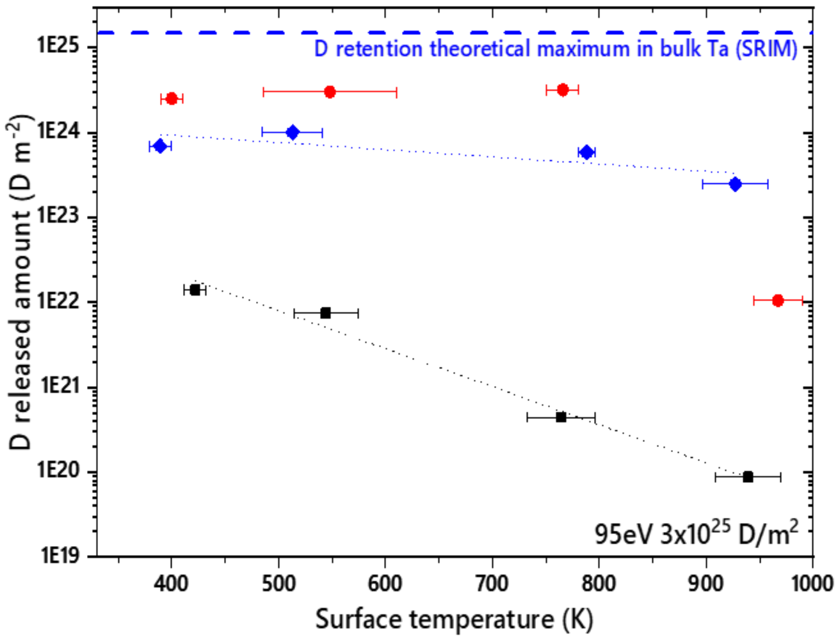
$$E_d = 2.56\,\mathrm{eV}$$

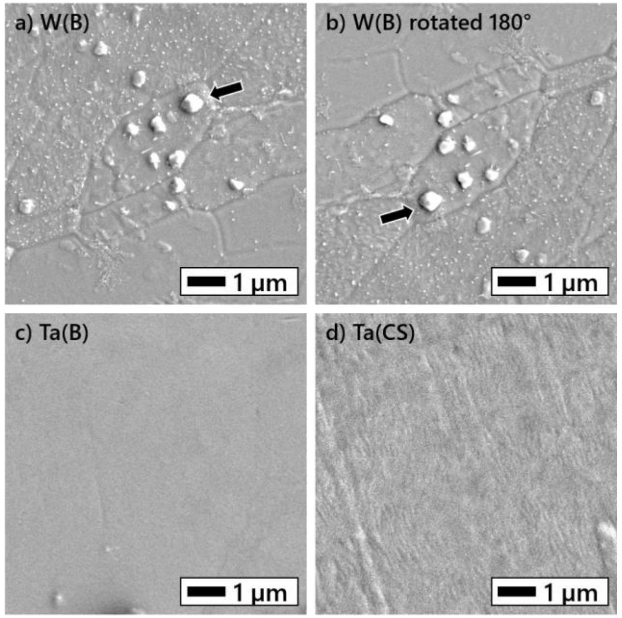
De-trapping from grain boundaries and voids

Dedicated modelling is necessary to identify the trapping mechanisms

Enhanced D retention in tantalum cold spray







- 2 orders of magnitude greater retention in Ta than in W
- 3.5 times enhanced retention in cold spray compared to bulk Ta

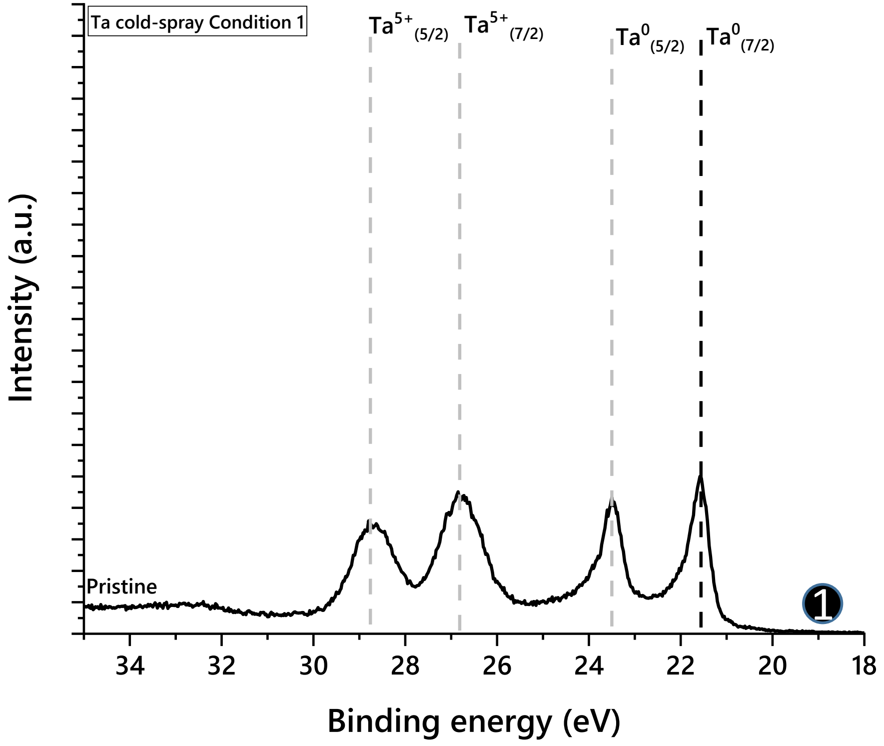
- Retention is independent on the Ta substrate temperature up to ~800 K
- Morphology of the coatings may promote D diffusion/outgassing

- Blisters on W surface may play a role in D trapping
- No surface modification on Ta samples

M. Ialovega et al. Phys. Scr. 98, 2023
M. Ialovega et al. Nucl. Fusion (submitted), 2024

Surface composition of pristine cold-spray Ta

X-ray photoelectron spectroscopy (XPS) – compositional analysis at the surface
XPS is not able to detect D directly



Pristine cold-sprayed sample:

1. Tantalum pentoxide at the surface
- Natural passivating layer

D implantation: Near-surface composition evolution

X-ray photoelectron spectroscopy (XPS) – compositional analysis at the surface
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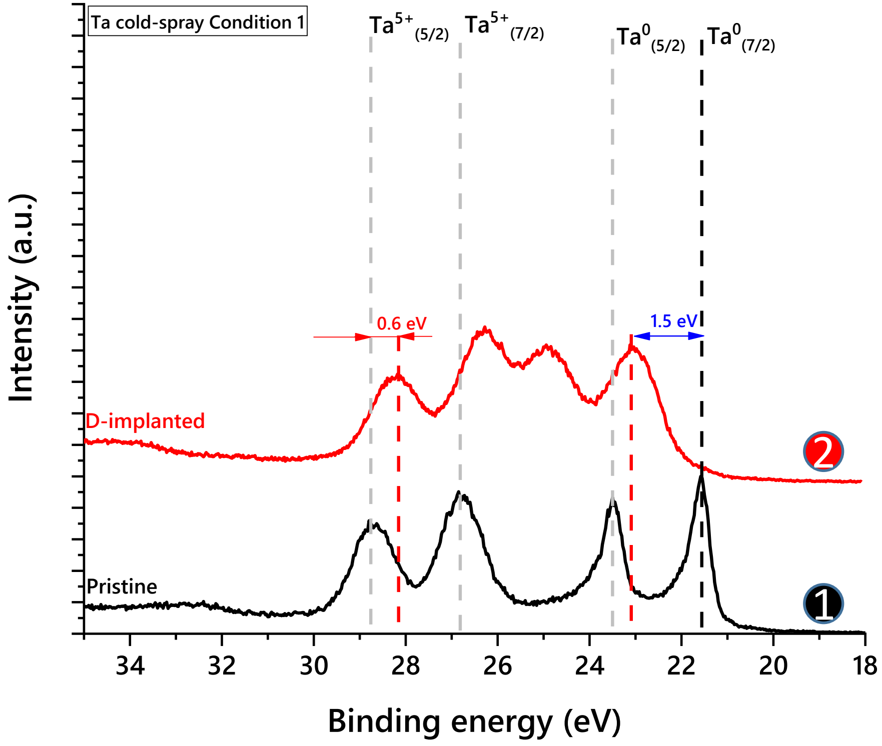

Pristine cold-sprayed sample:

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2. D-implanted tantalum:
- Peak shift:
  lower oxidation states?
  possible chemical interaction between Ta, D and O results in the formation of TaD_xO_y
- Peak shift for Ta → Tantalum Deuteride?

D implantation depth estimation

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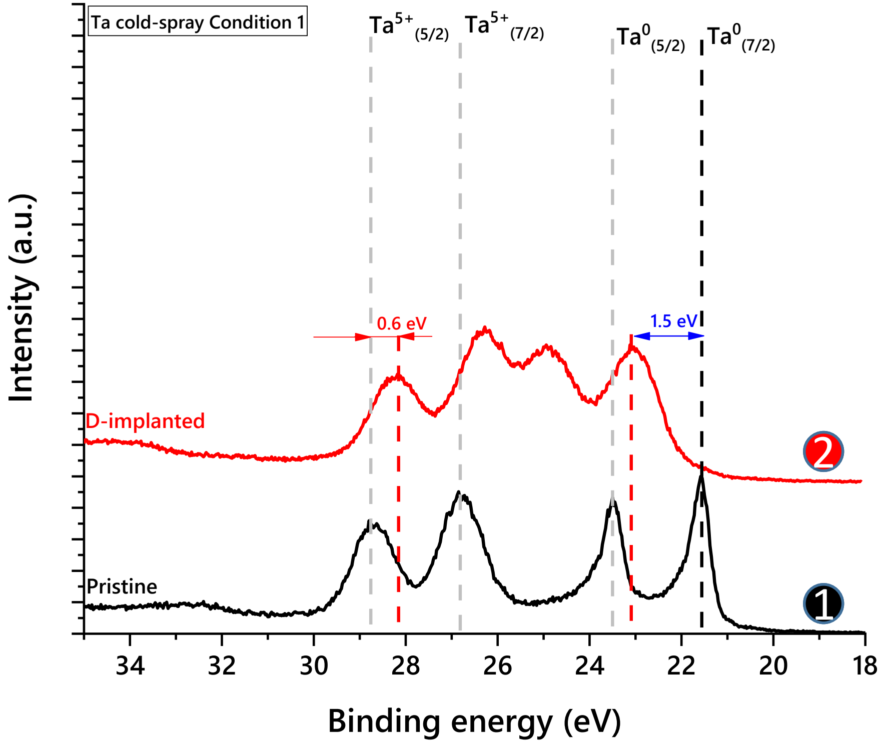

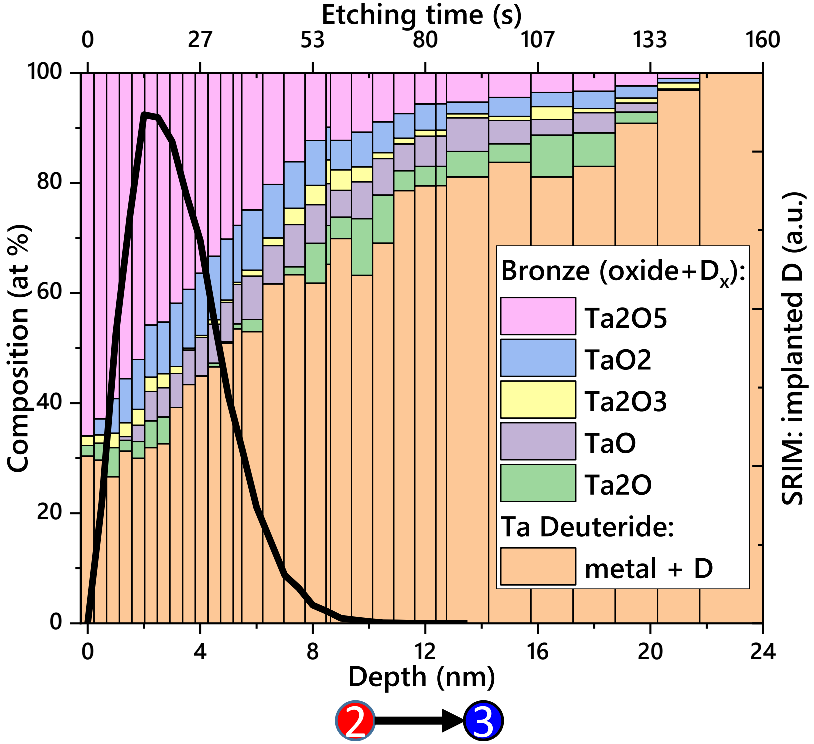

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3. Etching (2 keV Ar, 0.15 nm/sec) removes the oxide

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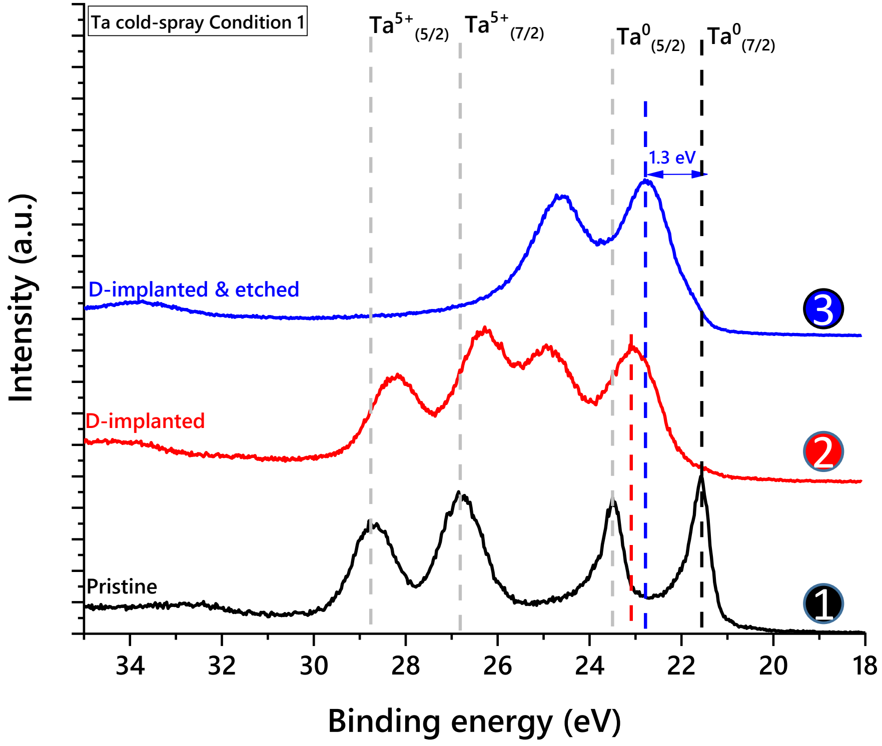

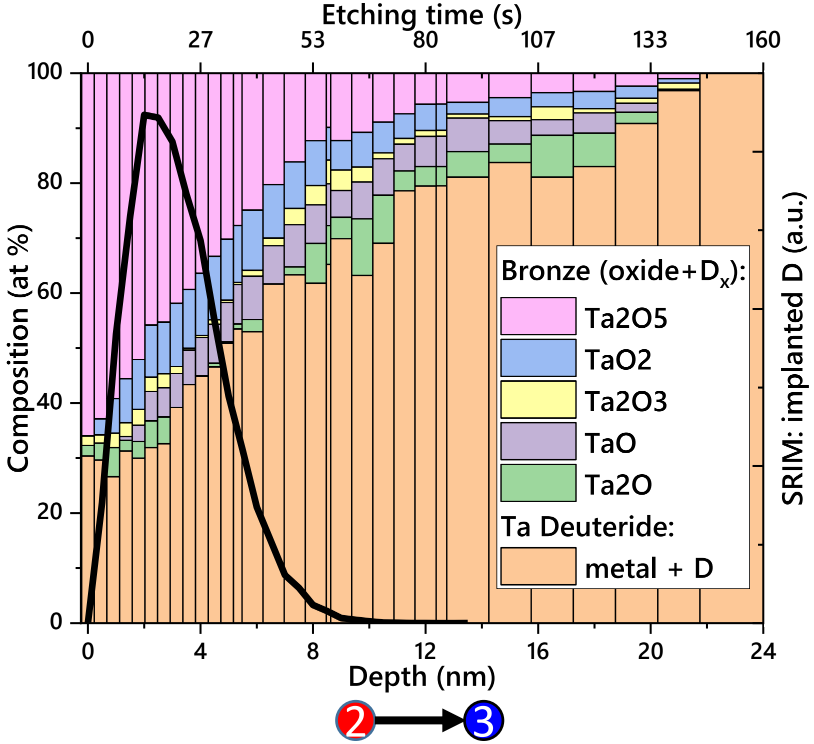

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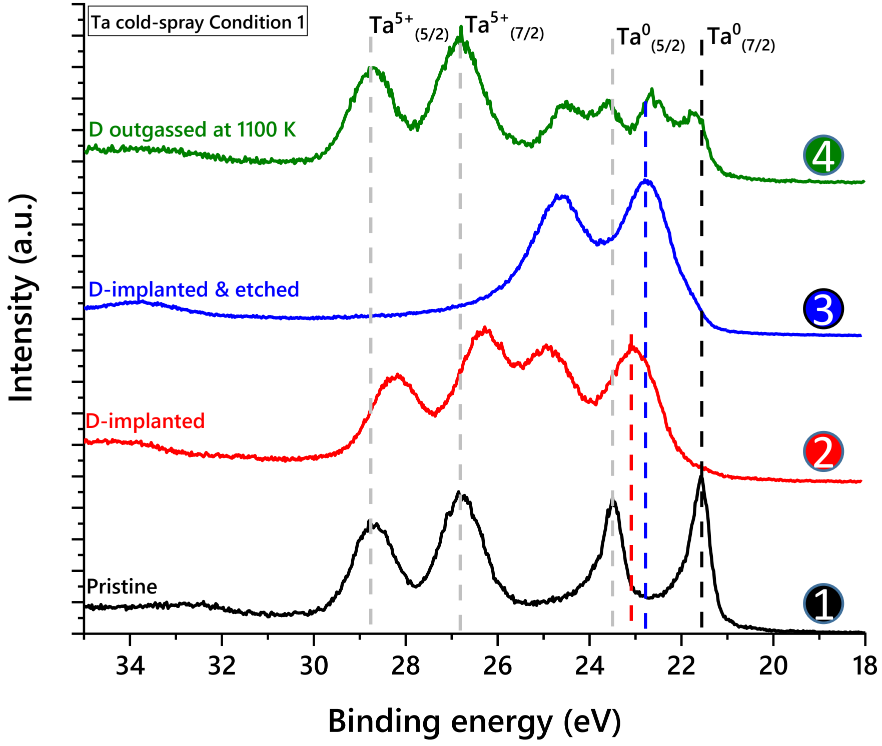
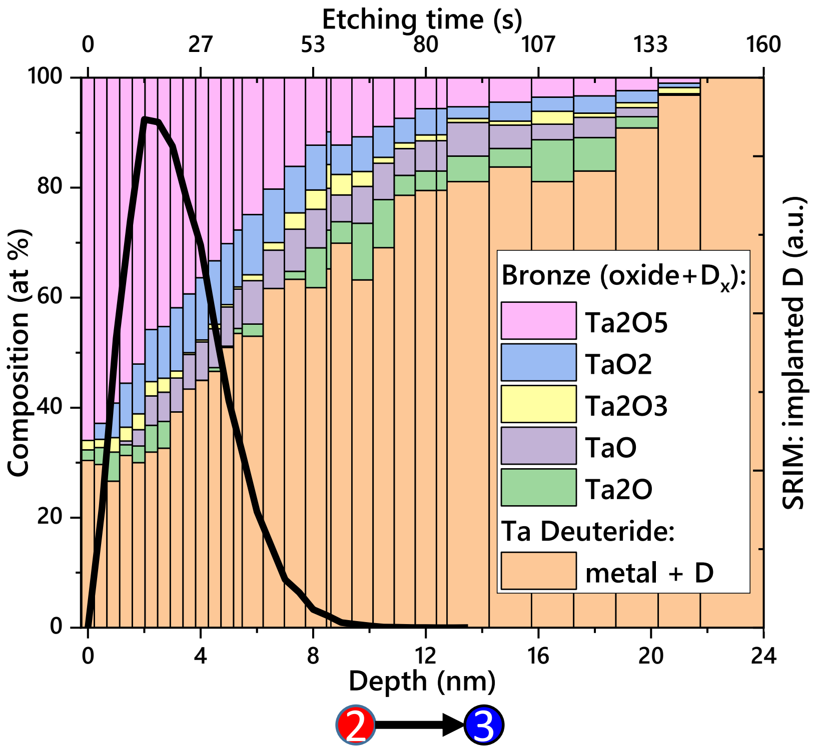
- D implantation depth estimate: < 24 nm?

D outgassing: recovery of metallic Ta

X-ray photoelectron spectroscopy (XPS) – compositional analysis at the surface
XPS is not able to detect D directly





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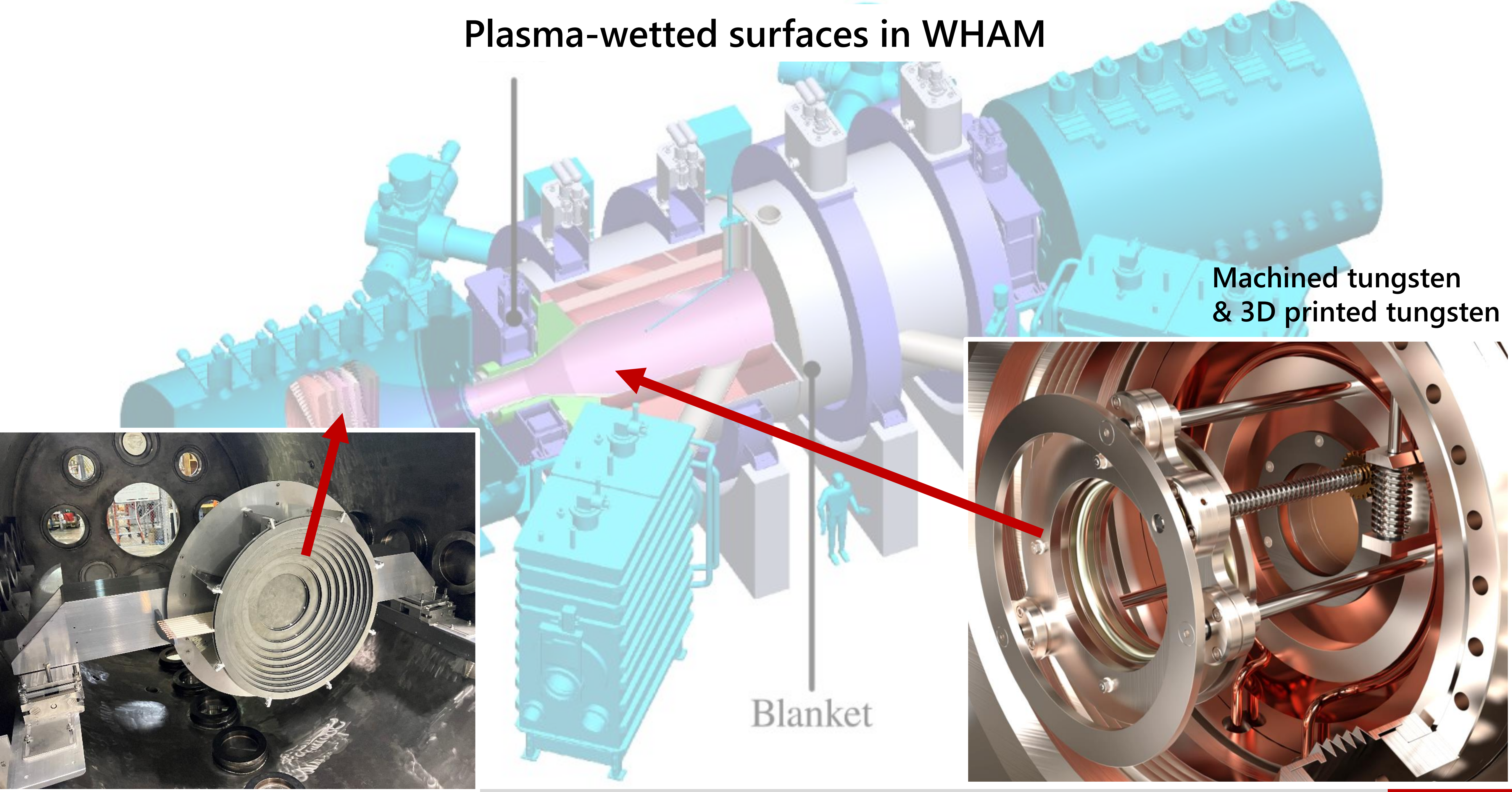
4. Thermal outgassing of D up to 1100 K
→ peaks positions restored
→ complete D outgas at a higher temperature

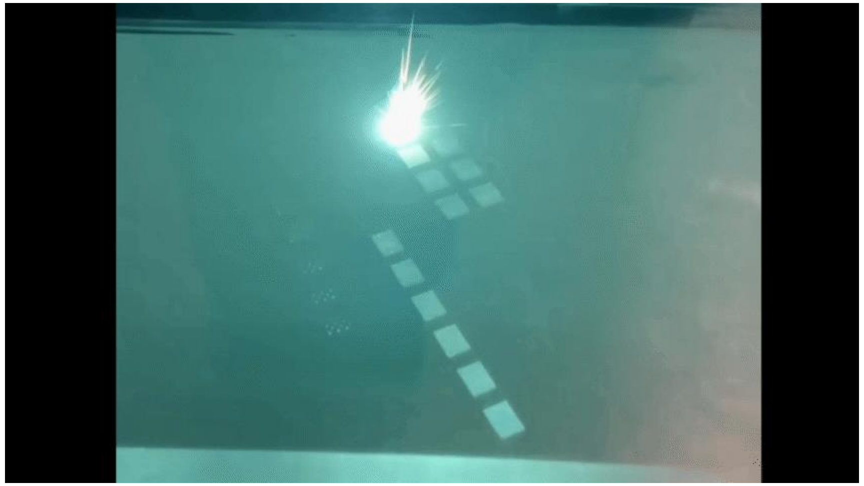
M. Ialovega et al. Phys. Scr. 98, 2023

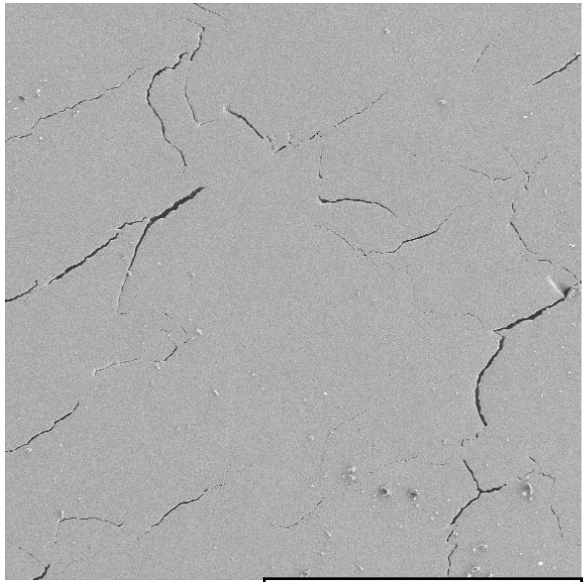
Plasma-wetted surfaces in WHAM



3D-printed tungsten

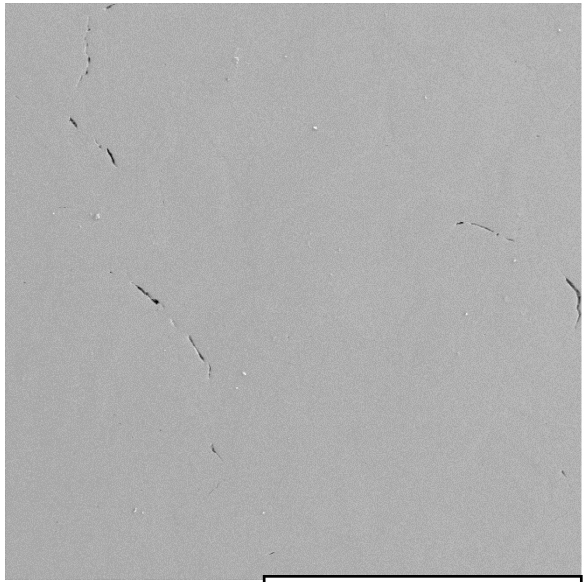
- UW ADDLab (Alloy Design and Development) is testing 3D-printed tungsten for fusion applications. First results are quite promising





#3DW2 100 µm

Particle interfaces (voids) or cracks



#3DW3 100 µm

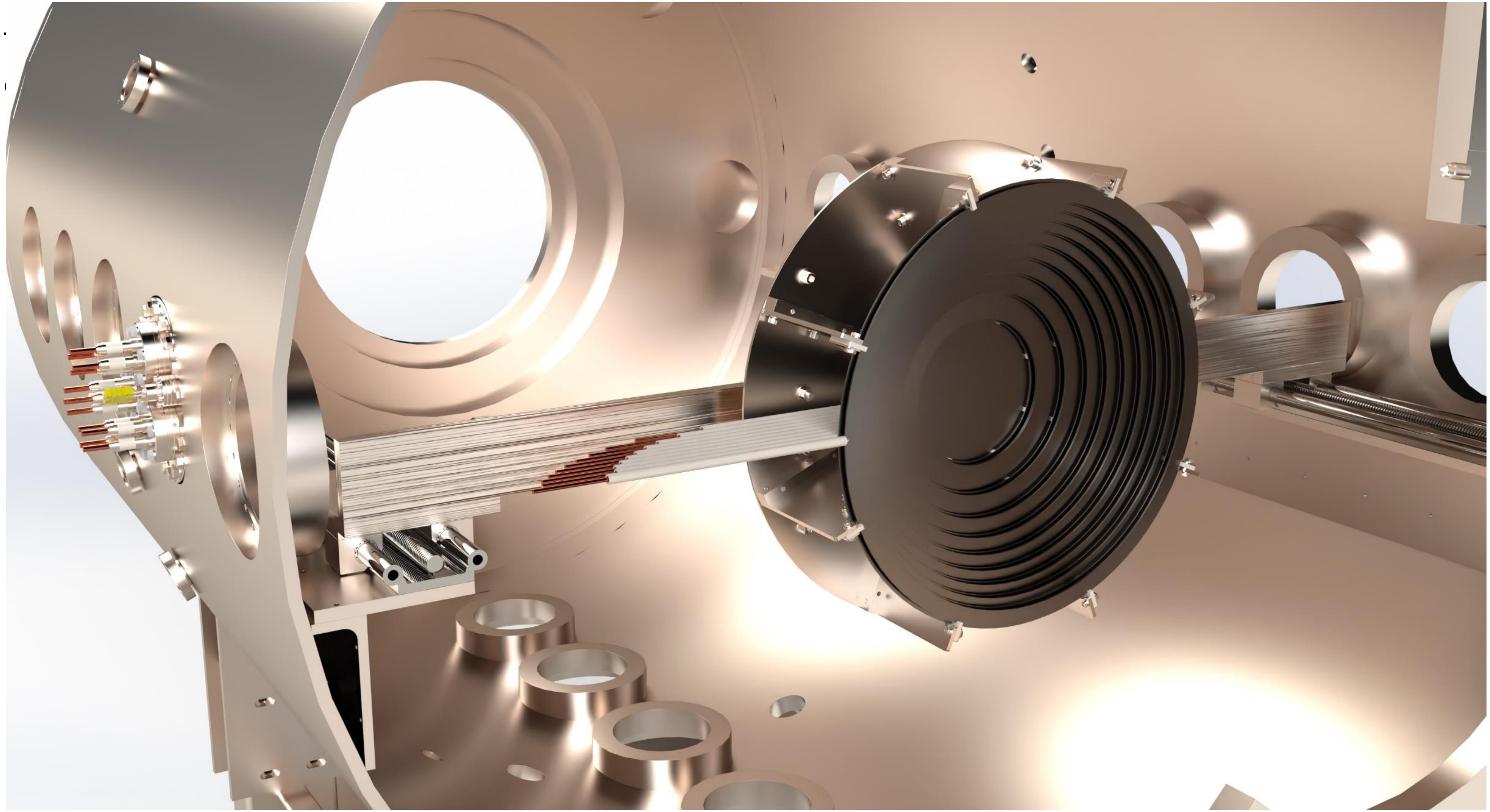
Very few particle interfaces (and voids)

WHAM construction status update

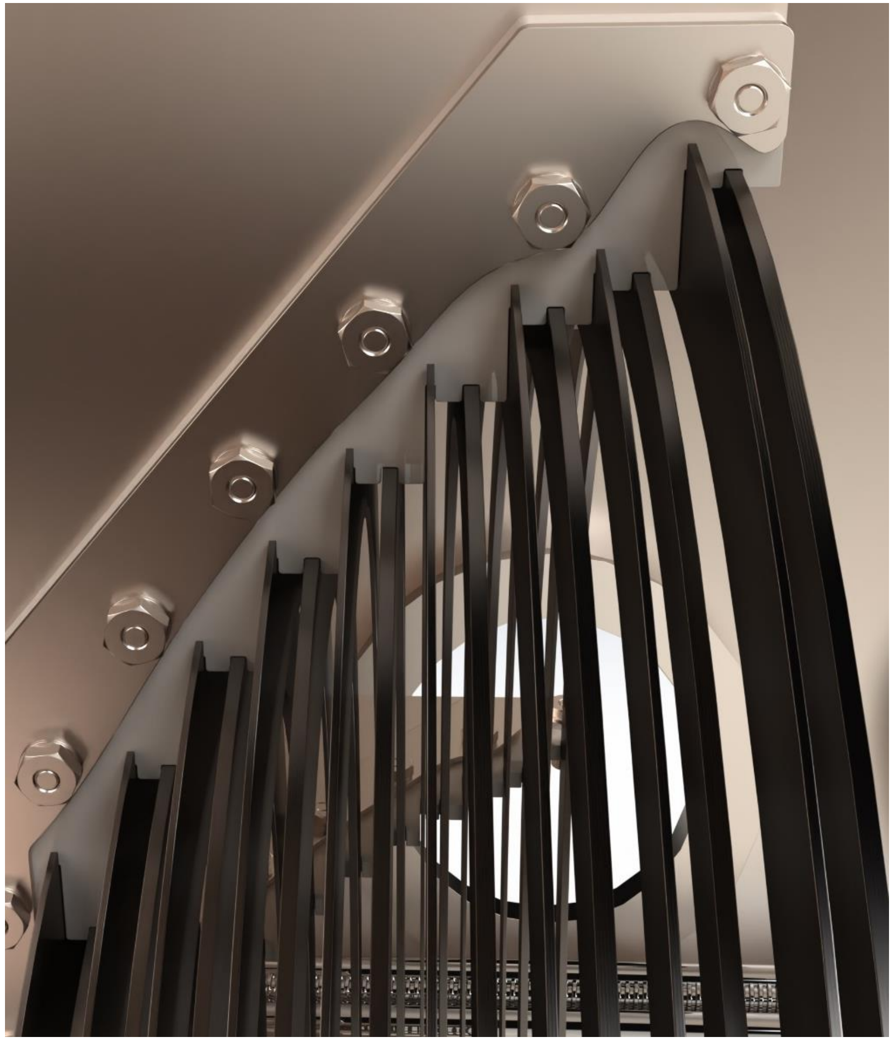
WHAM plasma-facing components

WHAM construction update

WHAM construction update: rings assembly

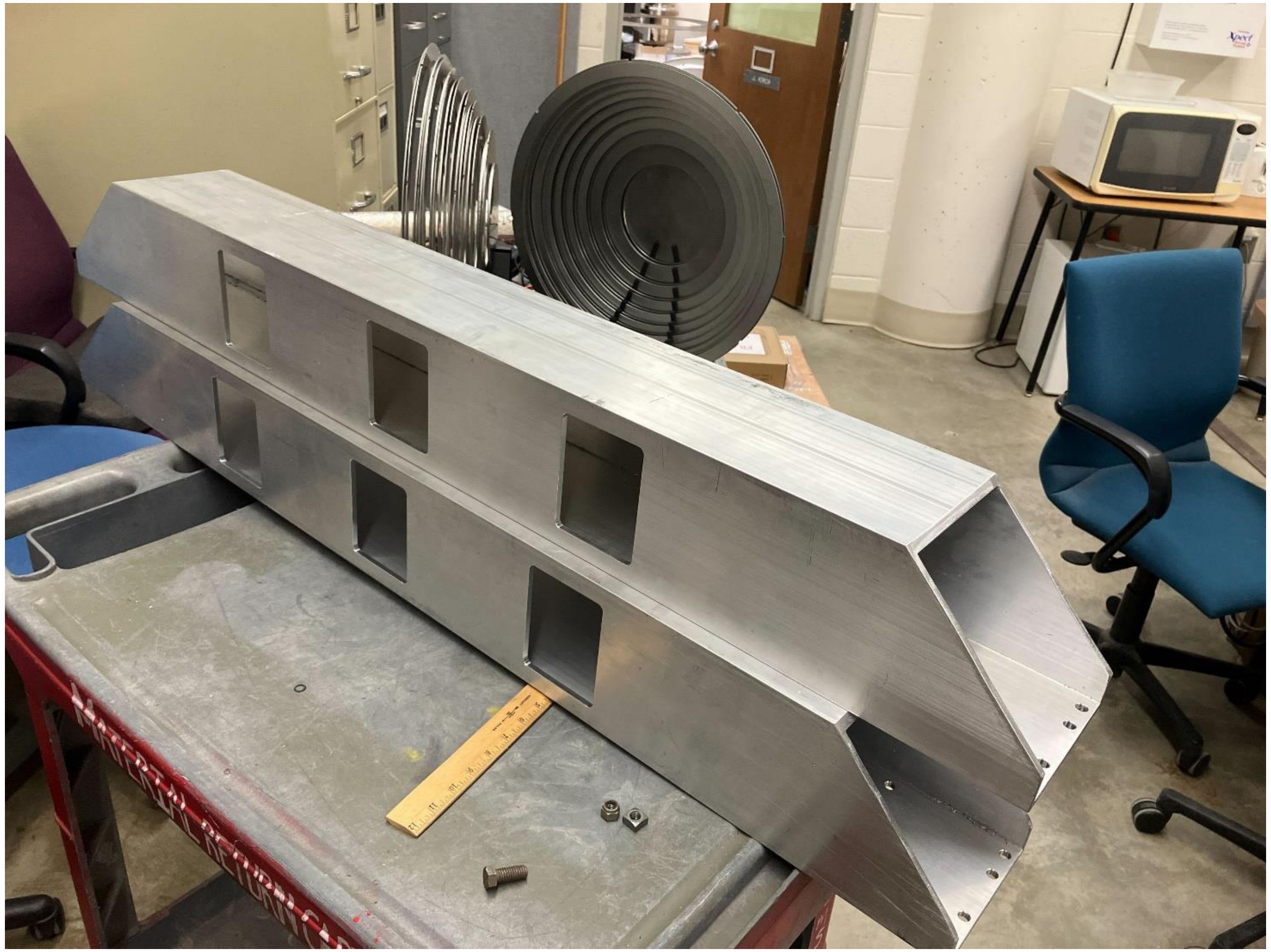


WHAM construction update: rings assembly

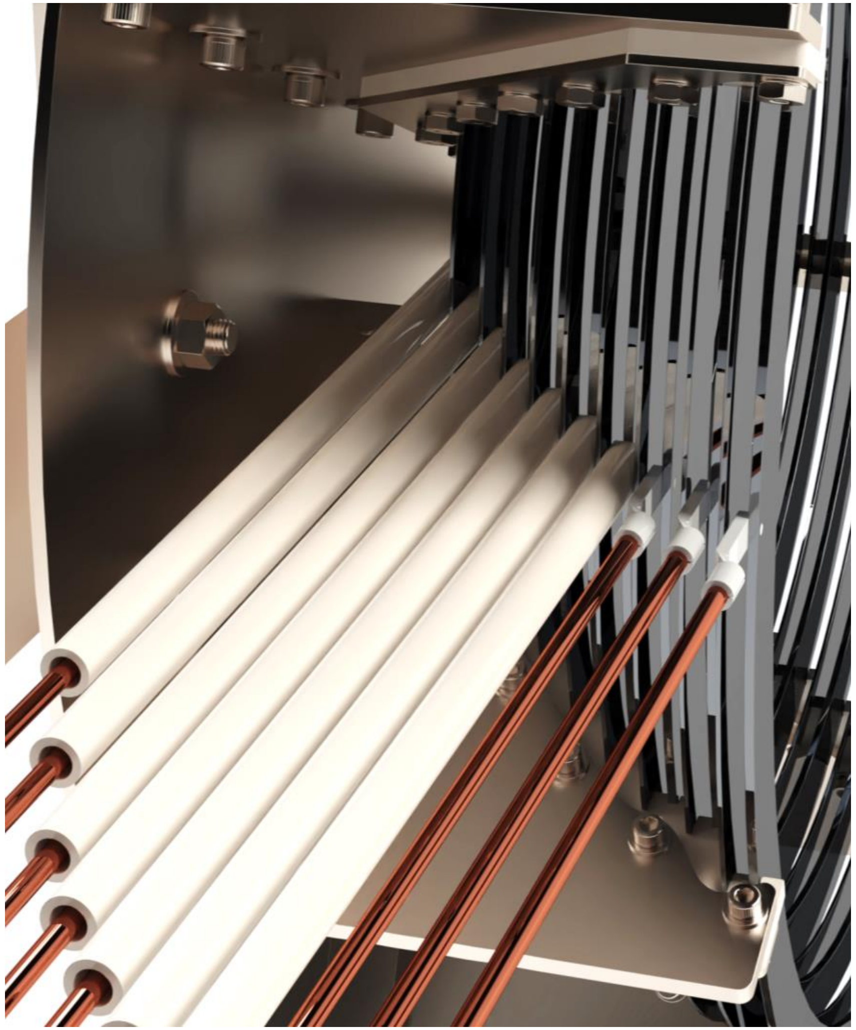


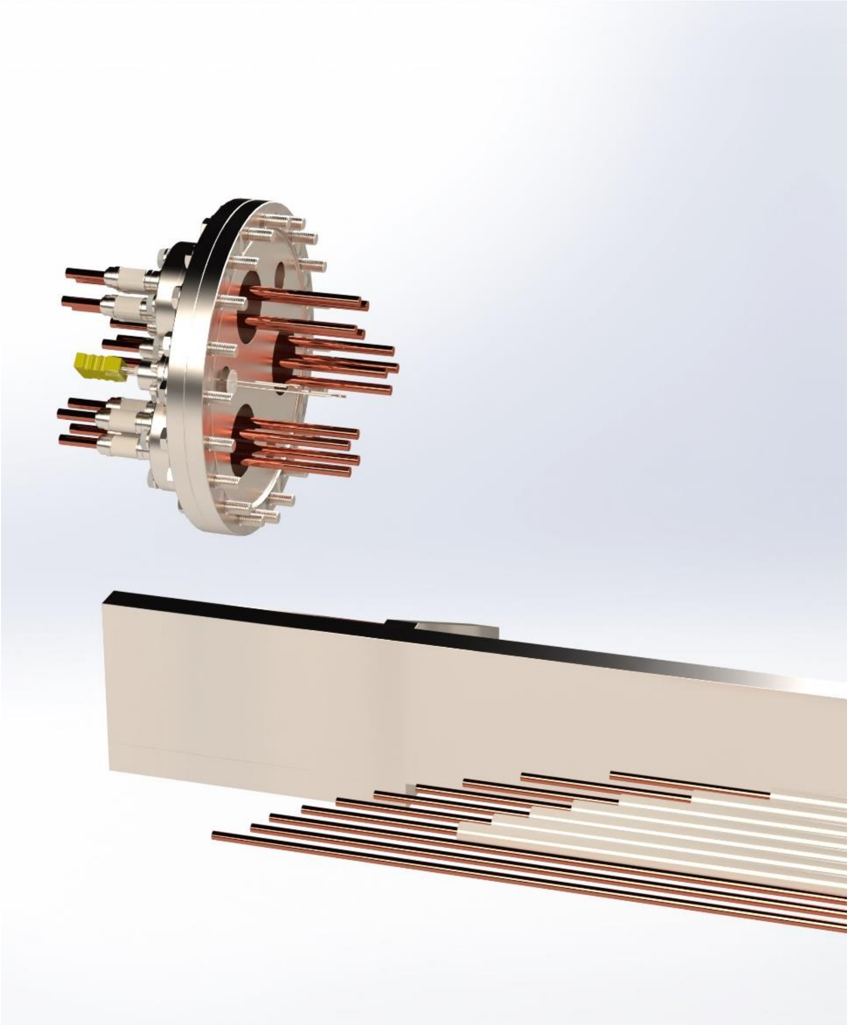
WHAM construction update: rings assembly

The ring assemblies will be mounted to these beams. The beams span across the diameter of the end cells and sit on a pair of linear rails.

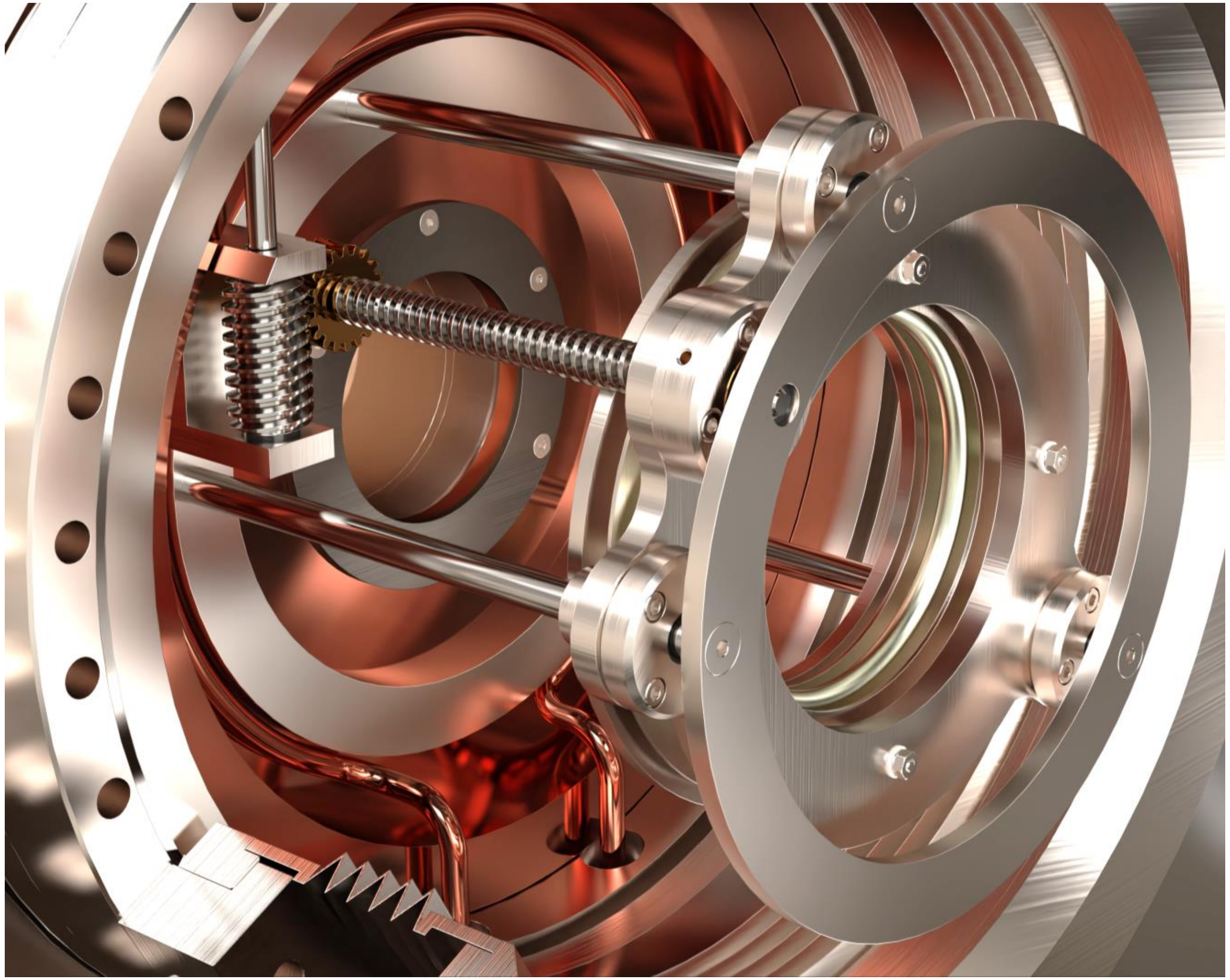


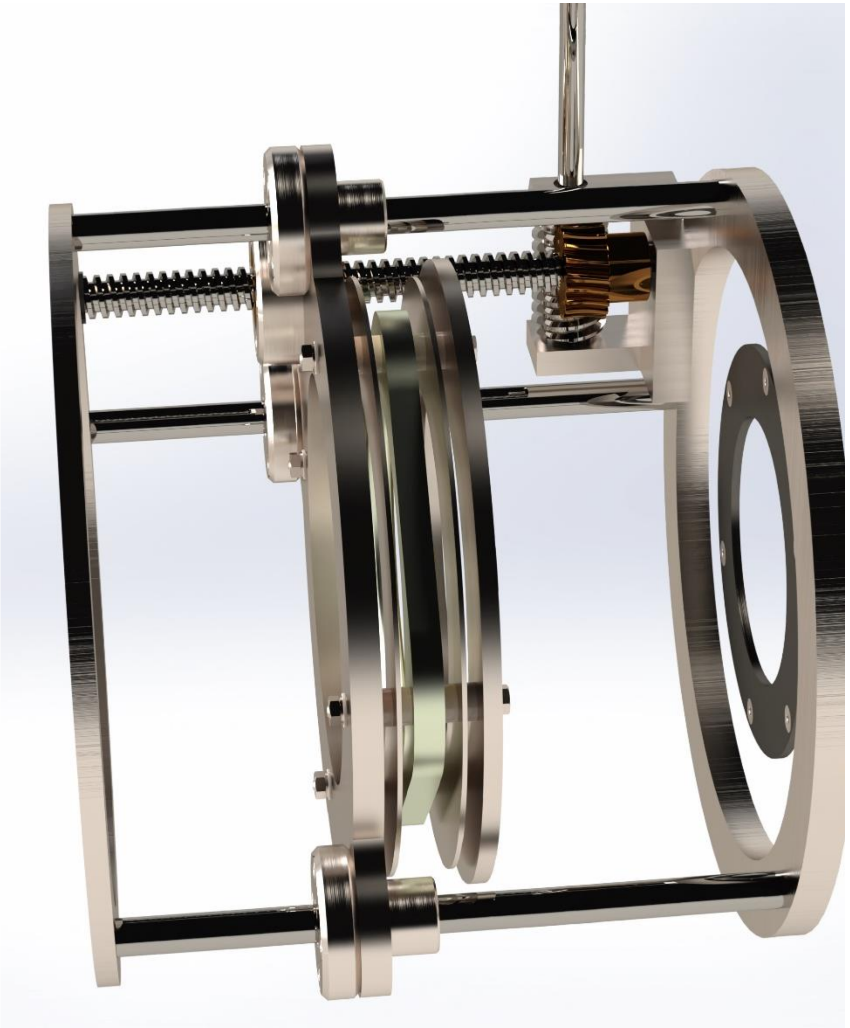
WHAM construction update: rings assembly



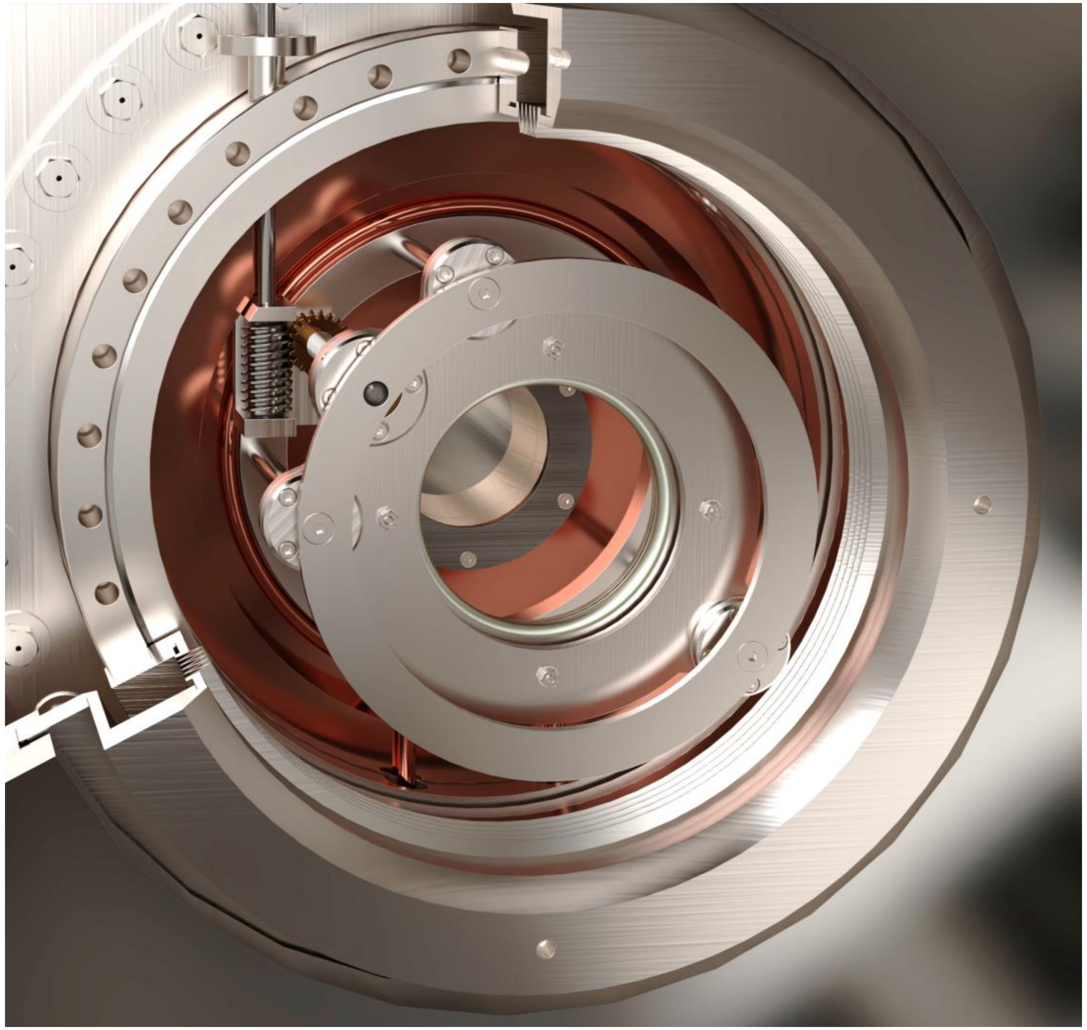


WHAM construction update: limiter assembly



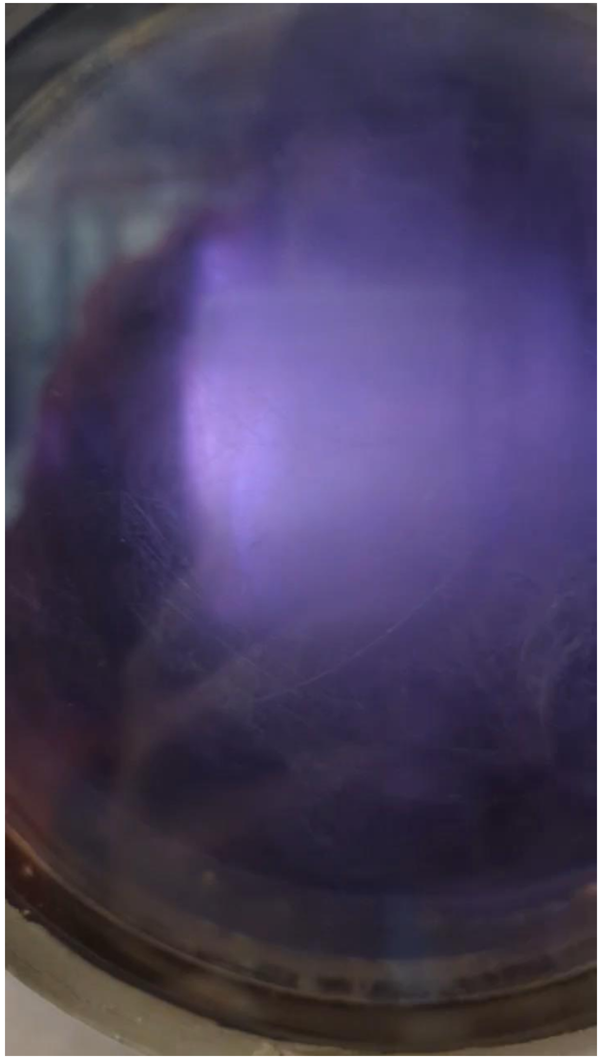


WHAM construction update: limiter assembly



Do not forget to mention the 3D-printed W

WHAM construction update: Argon glow discharge



All systems are being tested and the site is ready for arrival of the HTS magnets

WHAM construction site timelapse

Conclusions and Perspectives

- Small fusion devices require novel pumping strategies, ideally in-vessel absorbing walls
- Cold spray allows on site deposition and repair of PFCs
- High D trapping in tantalum: two orders of magnitude compared to sintered tungsten
- Enhanced D trapping in cold-spray Ta coating likely due to internal morphology
- Cold spray Ta coating can be regenerated (i.e., absorbed D releases by heating)

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Perspectives and open questions:

- Development of additively manufactured tungsten and its alloys: tailoring PFMs to the needs of FES
- Testing of cold spray components in real fusion experiments (WHAM and DIII-D), trial-error approach

P.S.: WHAM team is exited to have the first plasma this spring. Stay tuned!

Extra slides