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Fuel Retention and Erosion of Metallic Plasma-Facing Materials under the Influence of Plasma Impurities

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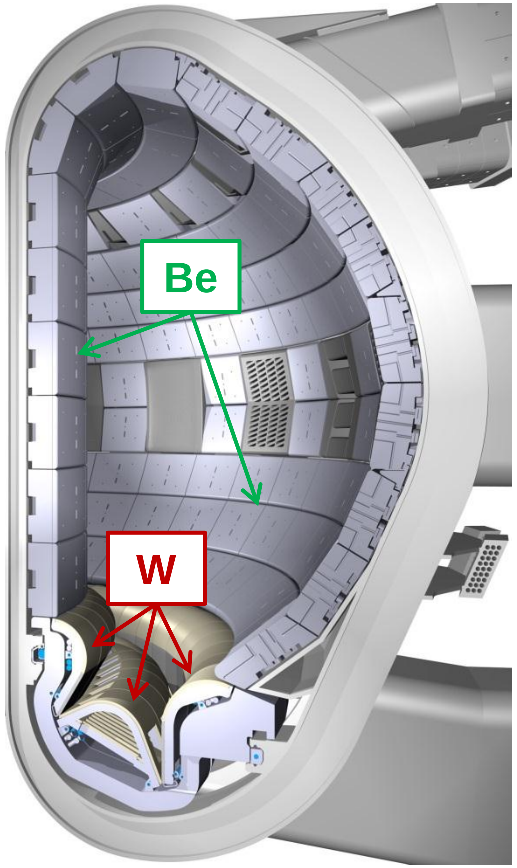
Plasma-wall interaction largely defines the availability of fusion reactor



Crucial issues for reactor availability

- ❖ Erosion of plasma-facing components
  - ⇒ Limited lifetime of plasma-facing components
- ❖ Fuel retention in bulk wall material and deposited layers
  - ⇒ Accumulation of radioactive tritium in vacuum vessel
    (amount of in-vessel retained tritium is limited in ITER due to safety regulations to ~1kg)

First wall materials in ITER

- ❖ Beryllium for main chamber wall
- ❖ Tungsten for divertor and baffle

Impurities in reactor

- ❖ Helium from D-T reactions
- ❖ Impurity seeding for edge plasma cooling, argon is one of the candidates
  - ➢ Influence of impurities needs to be investigated

This contribution: interaction of impurity containing plasma with beryllium and tungsten

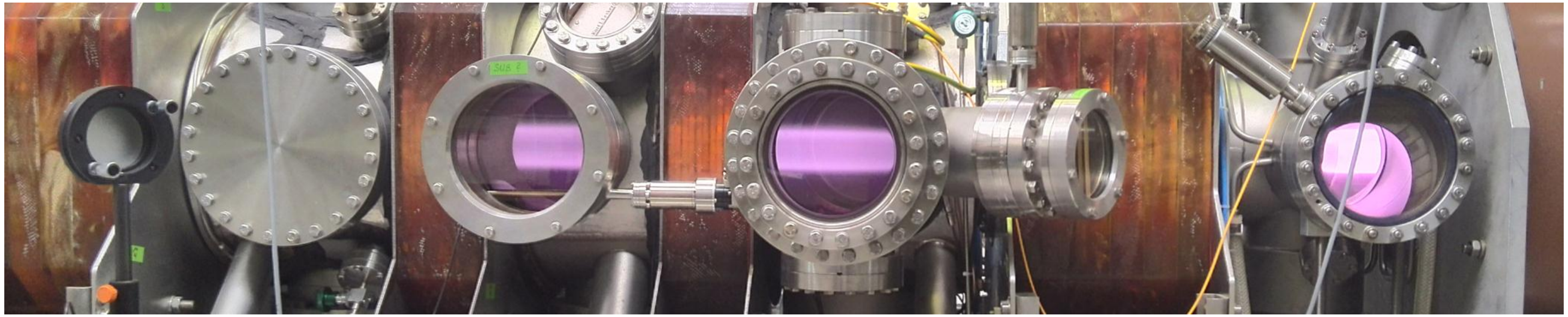
Beryllium

- ❖ Erosion and fuel retention under influence of helium and argon
- ❖ Qualification of aluminium as possible substitute for beryllium in relevant studies

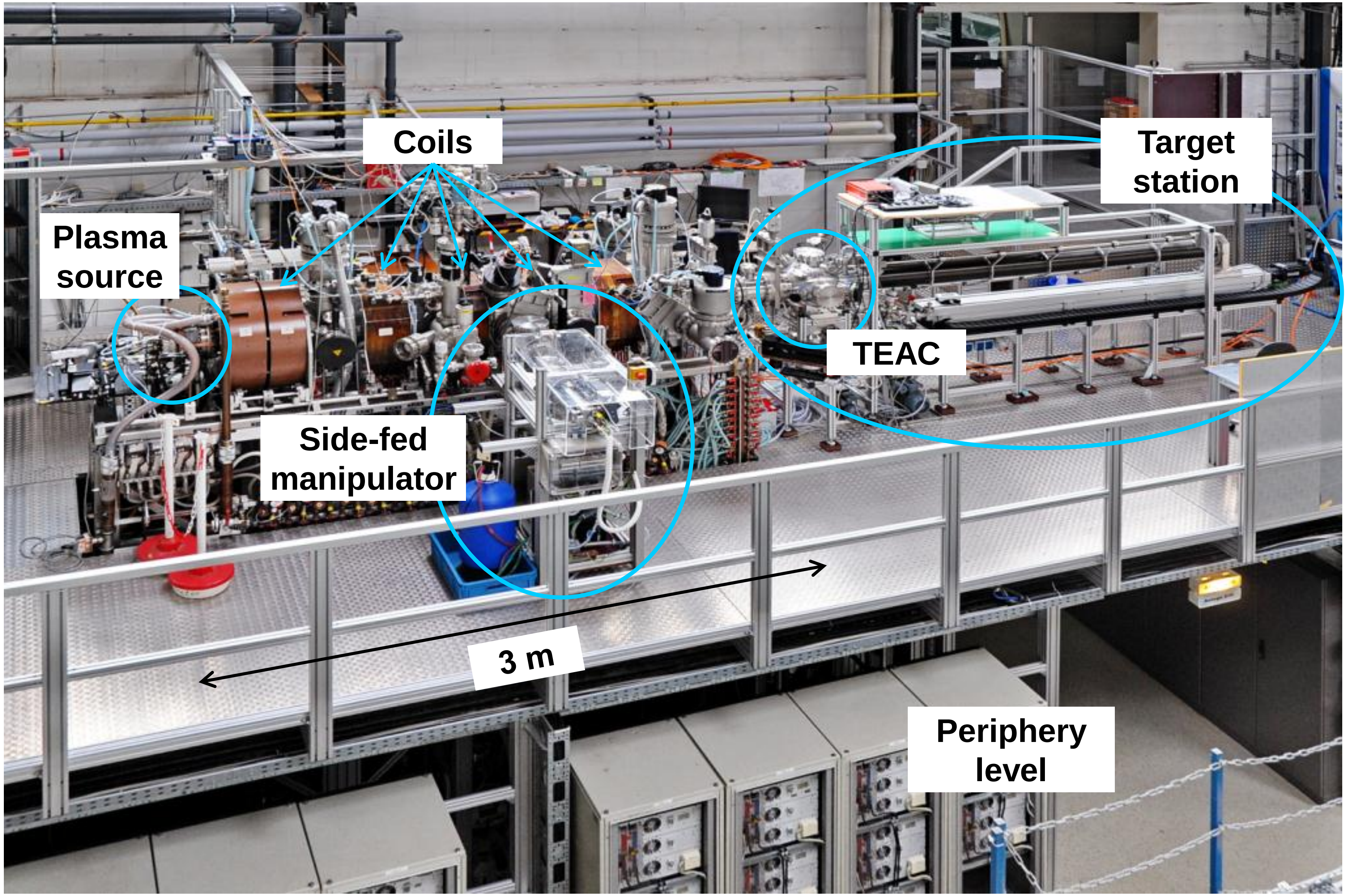
Tungsten

- ❖ Influence of the incident ion flux on fuel retention and surface morphology
- ❖ Fuel retention under influence of helium and argon

Experimental studies were performed in linear plasma devices PSI-2, PISCES-B and Magnum-PSI

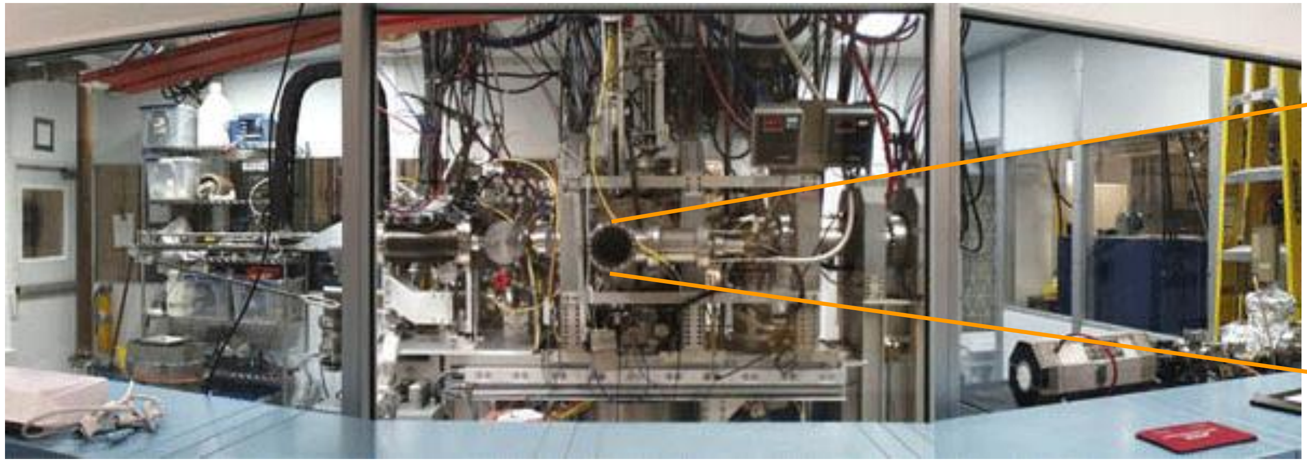


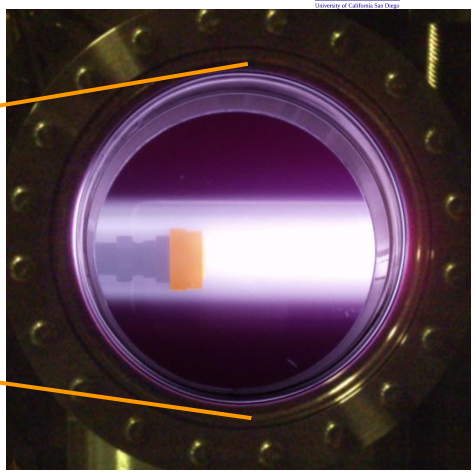
Linear plasma device PSI-2 (FZJ)



Linear plasma devices
PISCES-B and Magnum-PSI

PISCES-B (UCSD): compatible with beryllium





[R. P. Doerner et al, Phys. Scr. T111 (2004) 75]

Magnum-PSI (FOM-DIFFER): high particle and heat loads

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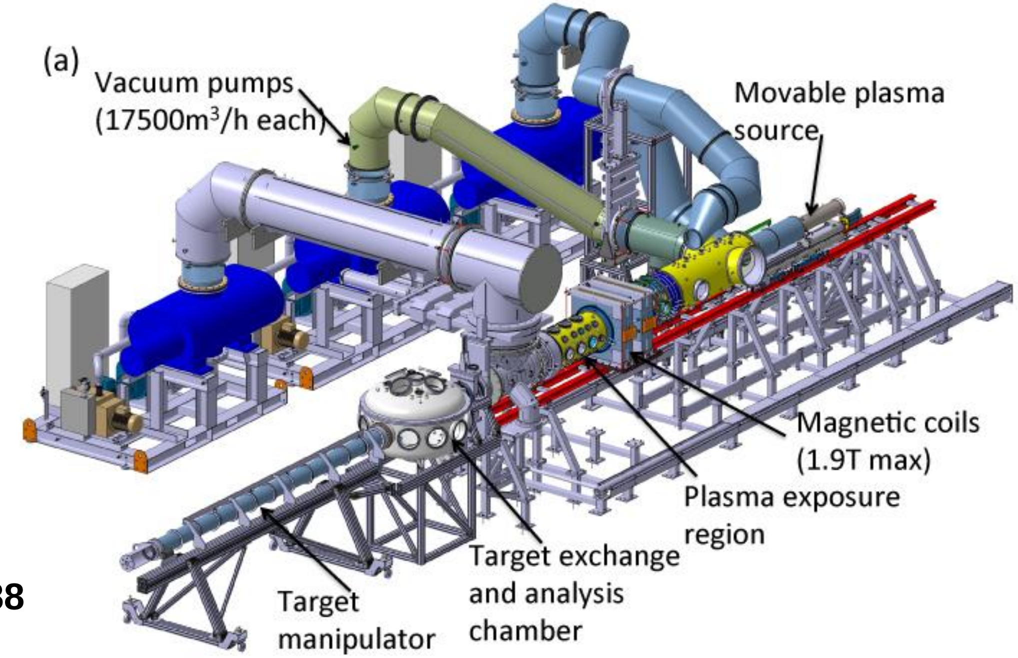


[G. De Temmerman et al., Fusion Eng. Des. 88 (2013) 483]

Plasma exposure parameters in linear plasma devices

Parameter	PSI-2	PISCES-B	Magnum-PSI	ITER divertor
Electron temperature	1 - 40 eV	3 - 50 eV	0.1 – 10 eV	~1 - 10 eV
El. density	~10^{17} - 10^{19} m^{-3}	~10^{17} - 10^{19} m^{-3}	~10^{19} - 10^{21} m^{-3}	~10^{20} - 10^{21} m^{-3}
Particle flux	~10^{21} - 10^{22} $m^{-2}s^{-1}$	~10^{21} - 10^{23} $m^{-2}s^{-1}$	~10^{23} - 10^{25} $m^{-2}s^{-1}$	~10^{24} - 10^{25} $m^{-2}s^{-1}$
Particle fluence	up to ~10^{27} m^{-2} per exposure	up to ~10^{27} m^{-2} per exposure	up to ~10^{27} m^{-2} per exposure	~10^{26} - 10^{27} m^{-2} per pulse (400 s)
Incident ion energy	10 - 300 eV (negative bias)	10 - 300 eV (negative bias)	1 - 300 eV (negative bias)	~10 eV
Wall (sample) temperature	300 - 2000 K	300 - 2000 K	300 - 2000 K	500 - 1300 K
Special features		Beryllium compatibility	High particle flux	

- Transients (ELMs, disruptions) can be simulated by laser or pulsed plasma irradiation
- Fluence per experiment is ~10x – 100x higher than in present pulsed tokamaks
- Exposure parameters can be pre-selected to simulate particular ITER conditions

Erosion and fuel retention

of beryllium and aluminium

Erosion of beryllium and aluminium

PISCES-B / PSI-2 exposure conditions

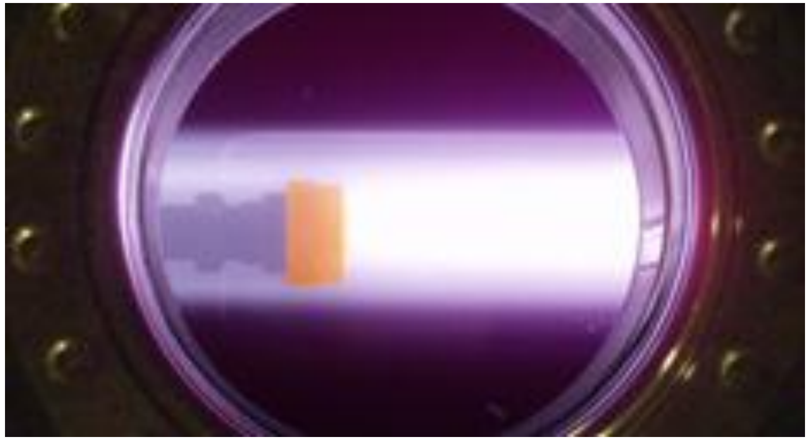
- Controlled Ar or He seeding 0-100% (controlled by spectroscopy: uncertainty in Ar fraction due to presence of Ar^{2+} and ArD^{+})
- Steady-state and reproducible plasma
- $\Gamma_i \sim 10^{22}\ m^{-2}s^{-1}$
- $\Phi \sim 1 \cdot 10^{26}\ m^{-2}$
- E_i = 40-100 eV
- T_s = 350±30 K
- Be (press-sintered Brush Wellman S-65C) and Al targets

Diagnostics and sample analysis

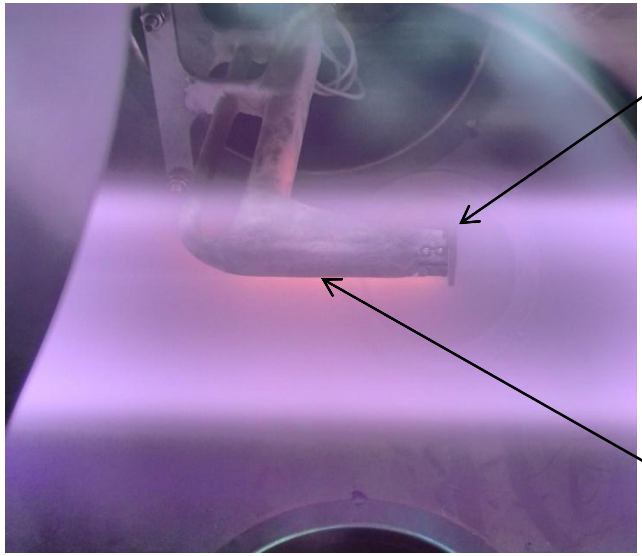
- Erosion from target is measured by spectroscopy and mass loss

PISCES-B data published in
A. Kreter et al, Phys. Scr. T159 (2014) 014039

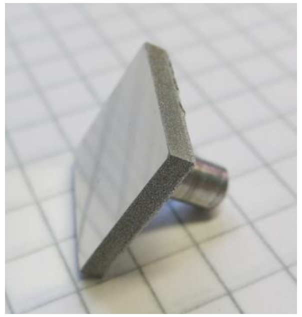
PISCES target in plasma



PSI-2 target in plasma



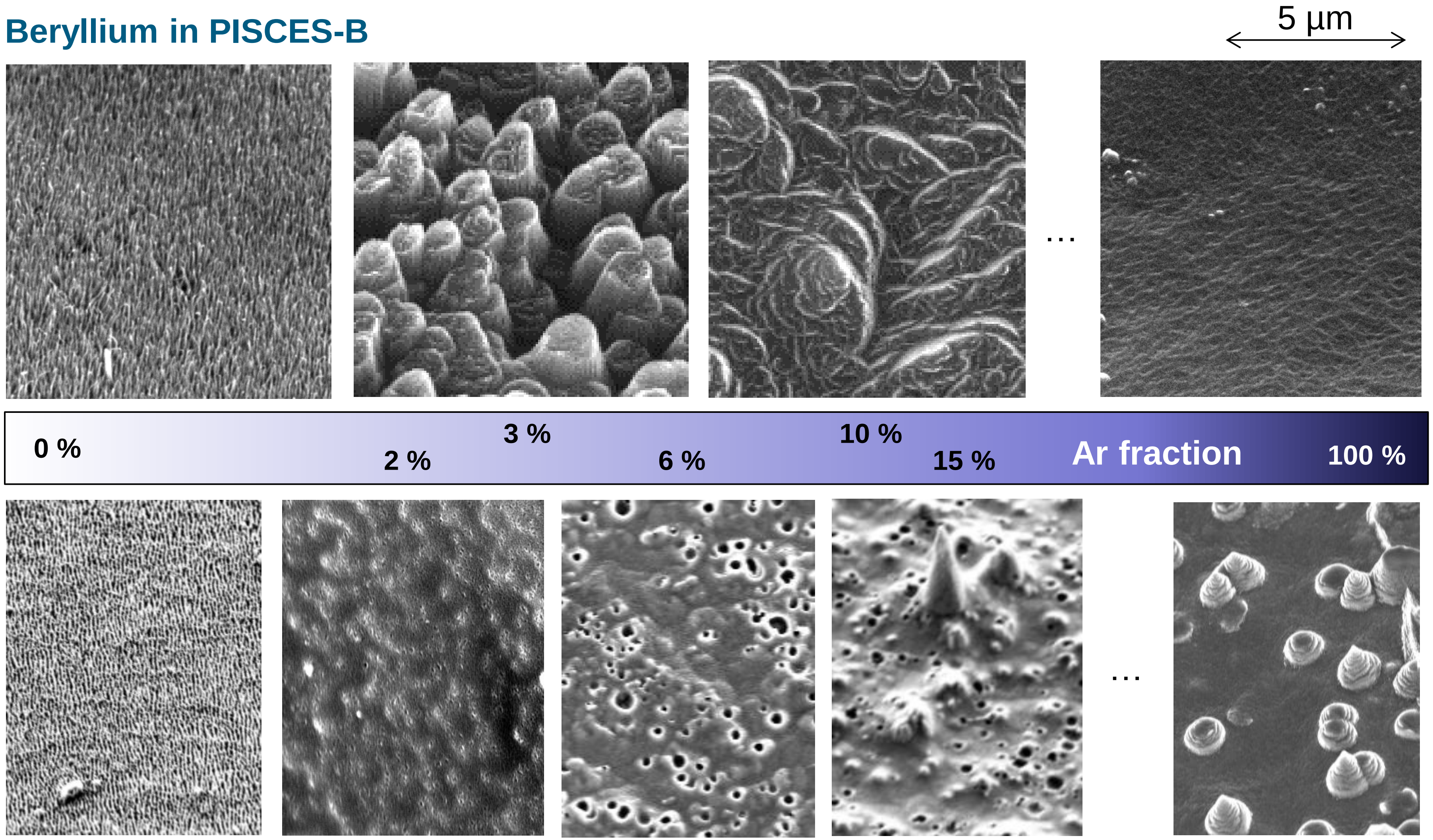
Al sample



Sample holder

Surface morphology of Be and Al after exposure to D/Ar plasma

Beryllium in PISCES-B



Aluminium in PSI-2

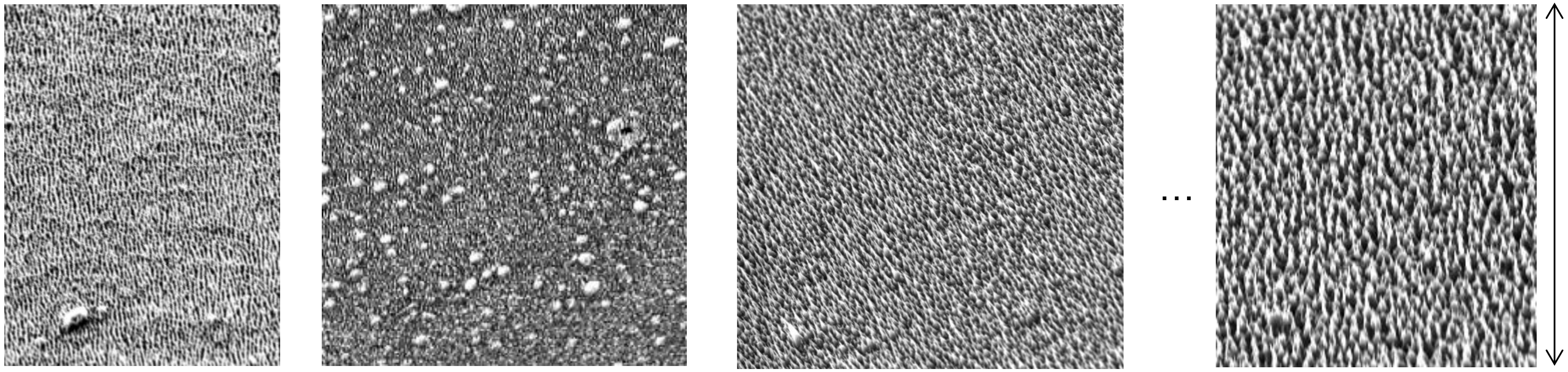
Fine-scale grass-like structure in pure D plasma

Gradual smoothing out of surface with increase of Ar fraction

Surface morphology of Be and Al after exposure to D/He plasma

Aluminium in PSI-2

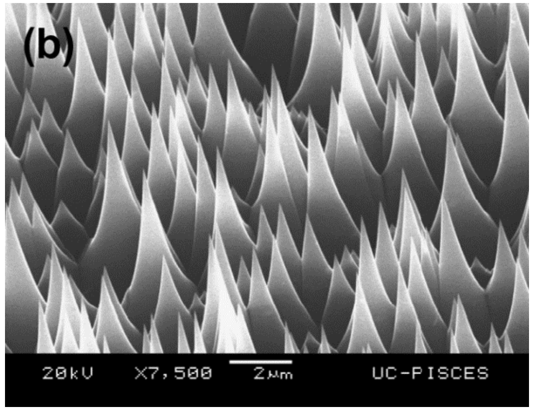
0 % 1 % 15 % He fraction 100 %



10 µm

Beryllium in PISCES-B in pure helium plasma

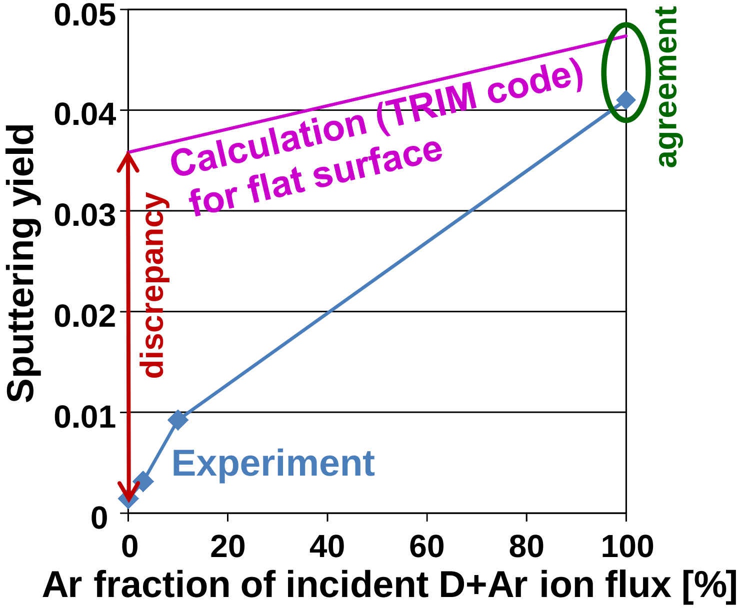
[R. Doerner et al., JNM 455 (2014) 1]



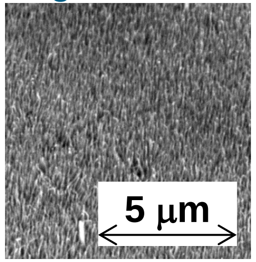
Helium does not suppress formation of grass-like structure, unlike argon

Measured and calculated sputtering yields in deuterium-argon plasma

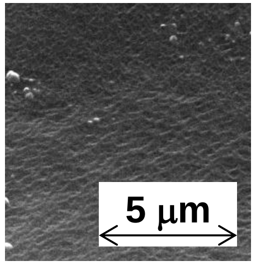
Beryllium erosion by argon studied in PISCES-B



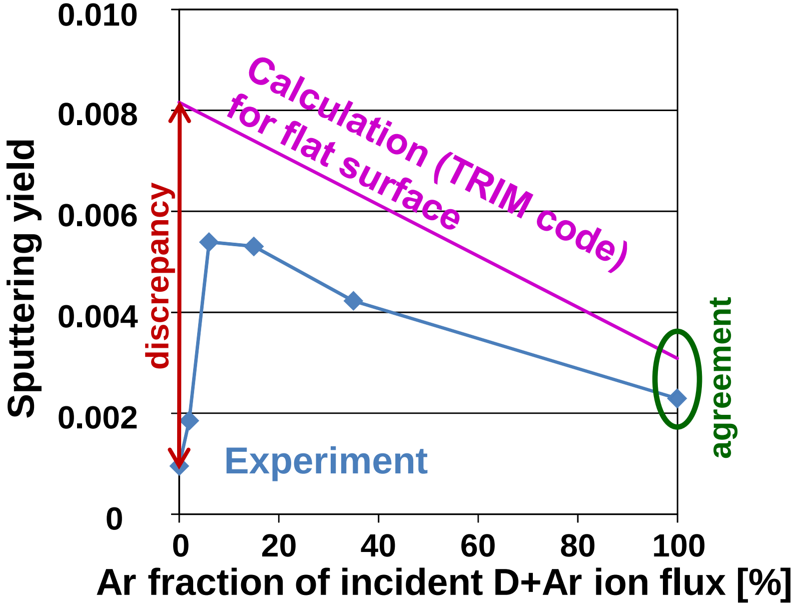
Pure D:
Rough Be surface



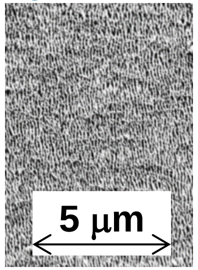
Pure Ar:
Smooth Be surface



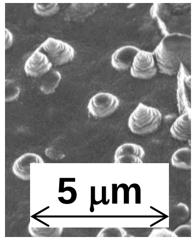
Aluminium erosion by argon studied in PSI-2



Pure D:
Rough Al surface



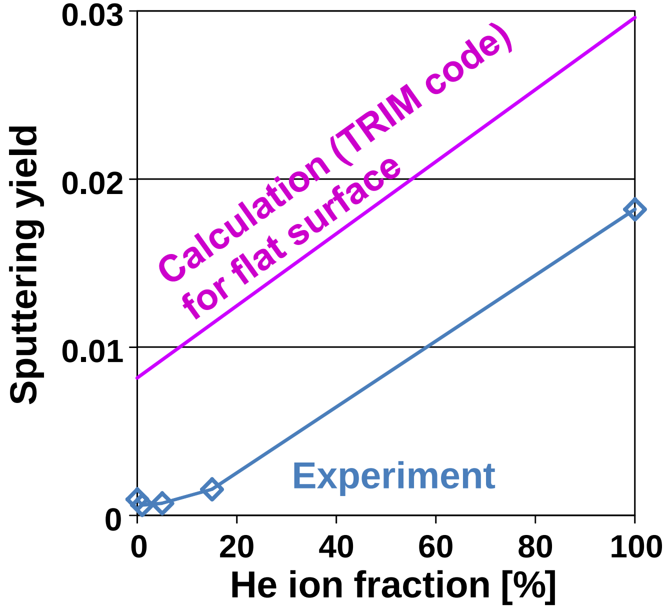
Pure Ar:
Smooth Al surface

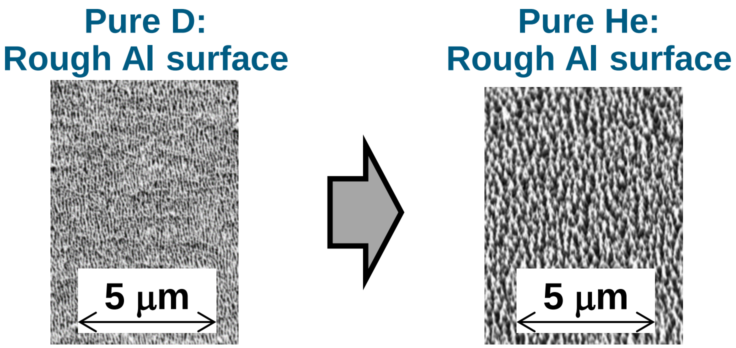


- Reduced erosion of Be and Al in pure D plasma due to rough grass-like surface and dilution of subsurface layer by deuterium
- Admixture of Ar to D plasma recovers erosion to expected values

Measured and calculated sputtering yields in deuterium-helium plasma

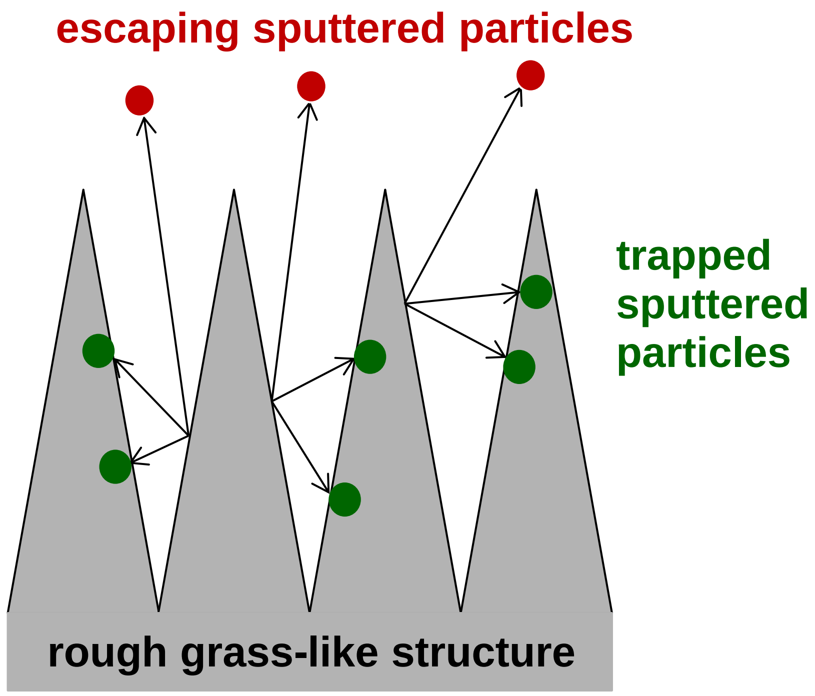
Aluminium erosion by helium studied in PSI-2





- Discrepancy also for pure He plasma → rough grass-like surface still present

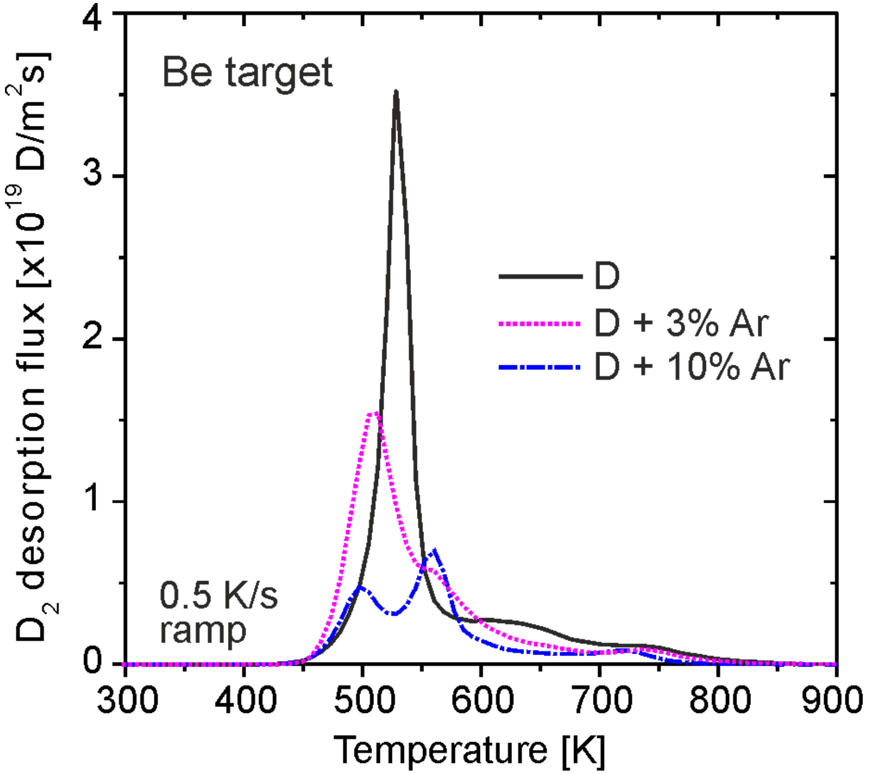
Influence of surface roughness on effective sputtering



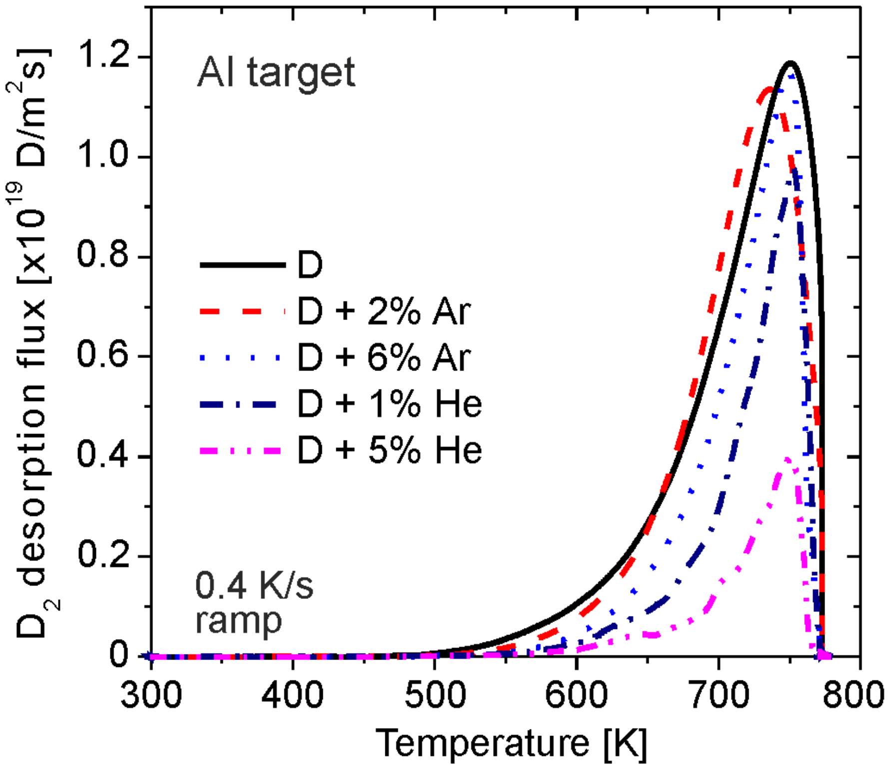
- Rough grass-like structures can significantly reduce effective sputtering yield

Deuterium retention in Be and Al under influence of argon and helium

Deuterium retention in beryllium studied in PISCES-B



Deuterium retention in aluminium studied in PSI-2



- **Different TDS spectra of Al and Be**
  - **Typical several-peak structure for beryllium incl. low-temperature supersaturation peak**
  - **Single broad peak for aluminium**
- **Different behaviour of retention Al and Be under influence of argon**
- **Aluminium cannot be used as beryllium surrogate for fuel retention studies**

Deuterium retention in tungsten as function of incident ion flux

Incident ion flux for this study:

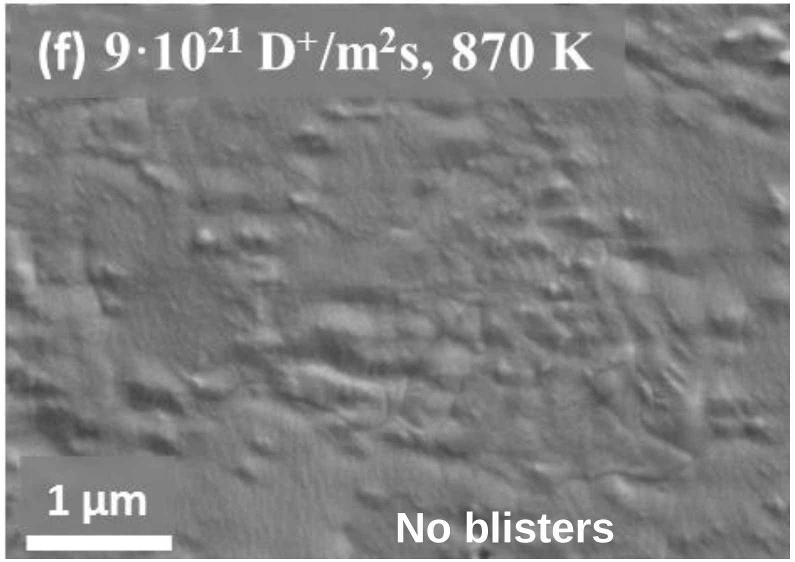
Magnum-PSI	**≈ 5×10^{23} $m^{-2}s^{-1}$**
PSI-2	**≈ 1×10^{22} $m^{-2}s^{-1}$**

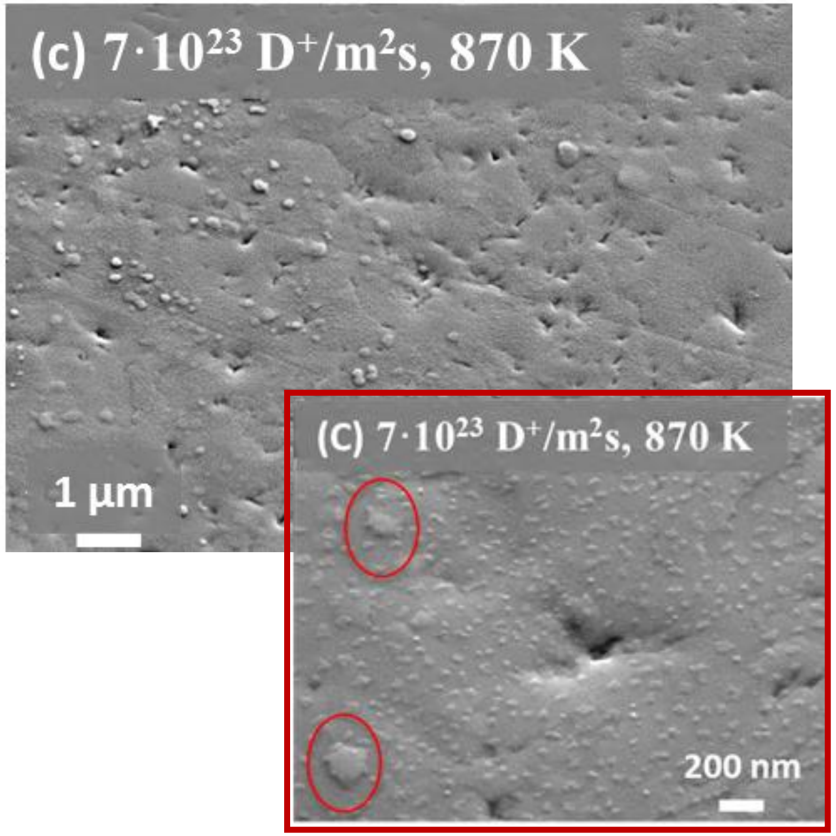
Incident ion fluence kept constant by longer exposures in PSI-2 !

Blister formation in tungsten by deuterium irradiation at high surface temperatures

SEM images of tungsten exposed to

low flux in PSI-2 | high flux in Magnum-PSI



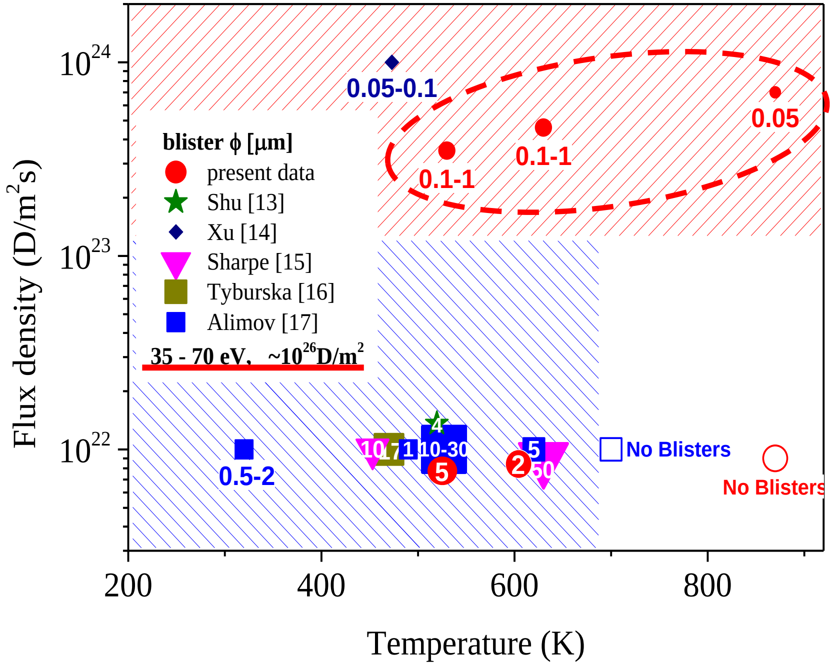


At high flux, blistering occurred for T_s > 800 K !

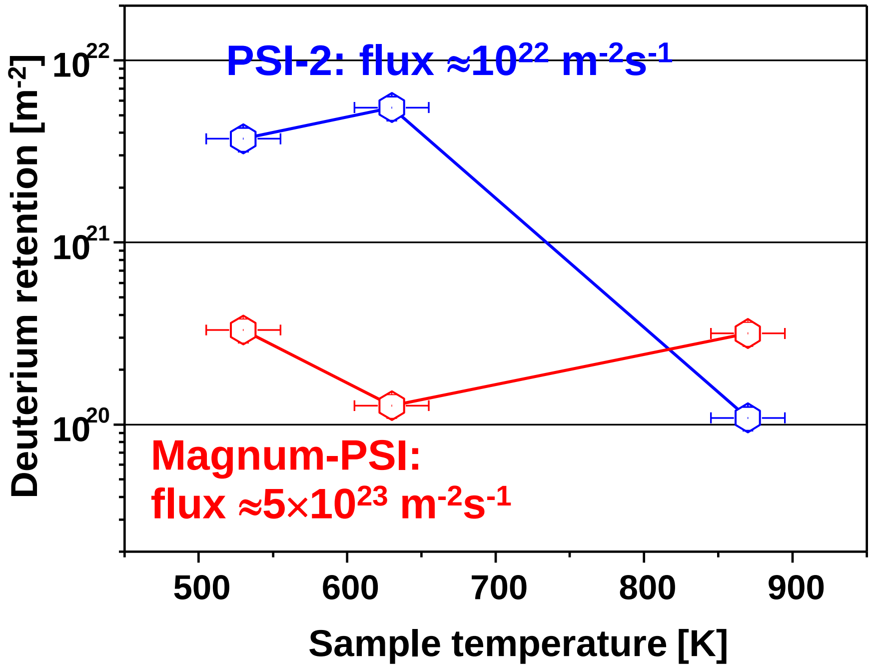
[L. Buzi et al., J. Nucl. Mater. 455 (2014) 316]

Blistering and deuterium retention in tungsten exposed to different ion fluxes

Domain of blister formation



Deuterium retention for different ion fluxes and sample temperatures (total fluence kept constant!)



The presence of blisters correlates with the total amount of retained deuterium

At low and moderate exposure temperatures: higher retention for lower flux

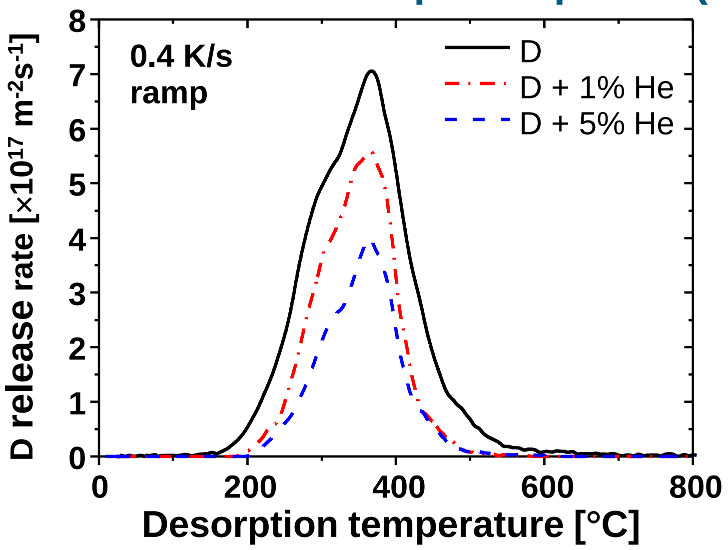
At high exposure temperatures: higher retention for higher flux

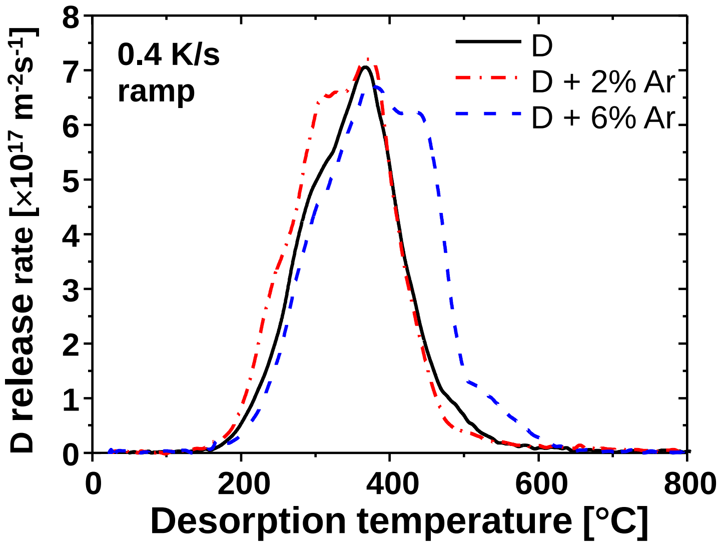
[L. Buzi et al., J. Nucl. Mater. 455 (2014) 316]

Deuterium retention in tungsten under influence of helium and argon

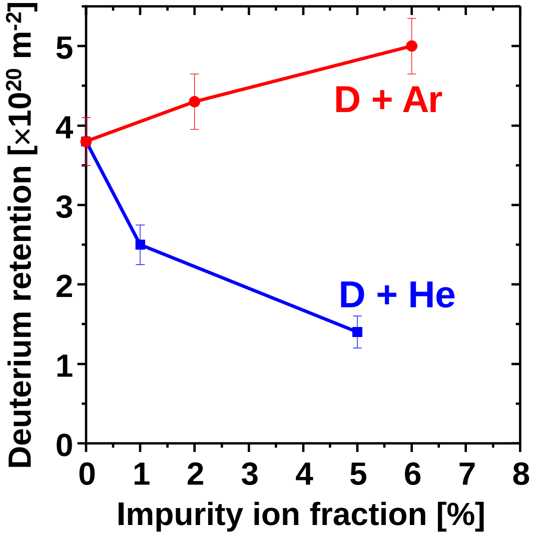
Deuterium retention in tungsten under influence of helium and argon

Thermal desorption spectra (TDS) of tungsten exposed to mixed plasmas





Total amount of deuterium retained in exposed tungsten



Effect of helium:

- **Total deuterium retention is reduced by a factor of 3**
- **Nano-size bubbles observed by TEM in depth up to ~10 nm**

Effect of argon:

- **Total deuterium retention slightly increased**
- **TDS spectra show different shapes**
  $\rightarrow$ **Change in trapping sites due to material damage by argon**

[M. Reinhart et al., PSI 2014 Kanazawa, submitted to JNM]

Conclusions

Beryllium

- Erosion of beryllium and aluminium exhibits similar features
  - Pure D plasma: Fine-scale grass-like structures, reduced measured sputtering yield than calculated (factor ~10)
  - Addition of Ar: Grass-like structures are suppressed, sputtering increases to calculated values
- Mechanisms of deuterium retention in aluminium are different than in beryllium

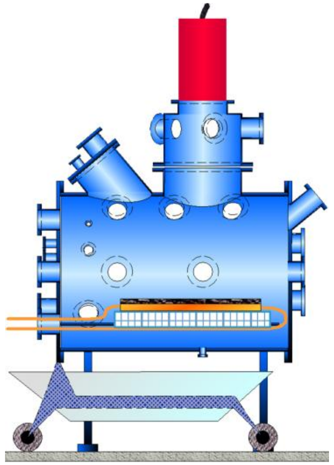
Tungsten

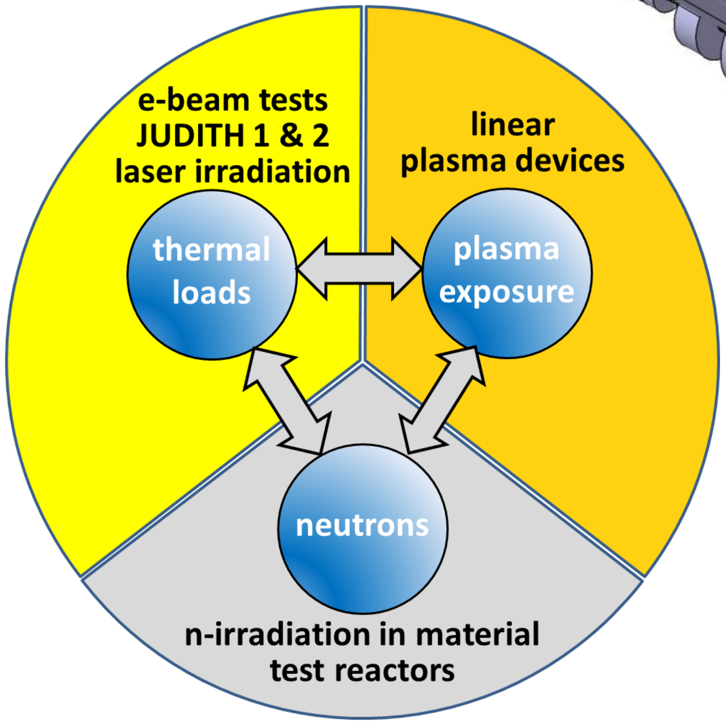
- Relation of retention for low and high fluxes is temperature-dependent
- Blistering occurred for high flux at surface temperatures of >800 K
- Helium significantly reduces deuterium retention in tungsten, while argon slightly increases it

Jülich beyond TEXTOR: integral concept on plasma-material interaction in nuclear environment

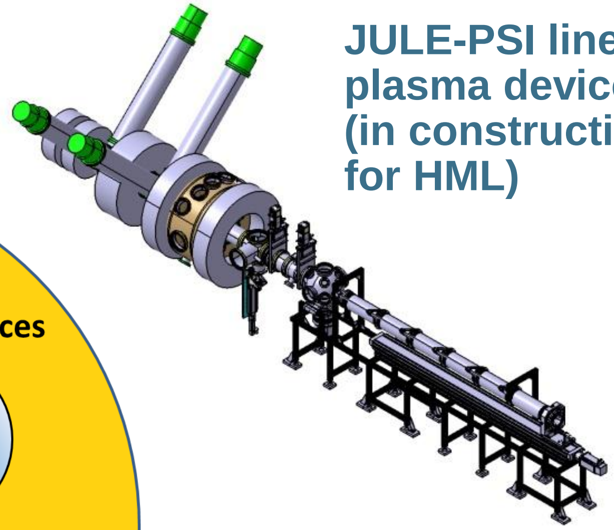
- Development and integrated characterization of thermo-mechanical and physical-chemical properties of neutron irradiated and toxic plasma-facing materials under high heat loads and plasma exposure
- Focus on material optimization for plasma-material interaction processes (tritium retention, embrittlement, erosion)

JUDITH 1 and JUDITH 2
HHF e-beam facilities

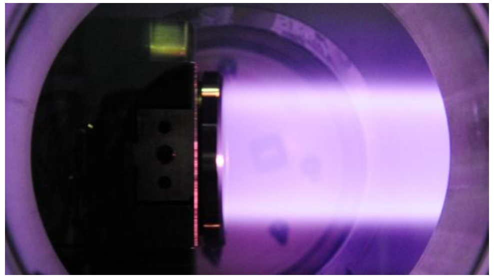


JULE-PSI linear plasma device (in construction for HML)



PSI-2 linear plasma device (operational outside HML)



Nuclear infrastructure (Hot Material Labs) available at FZJ