13th PFMC Workshop / 1st FEMaS Conference
Kultur + Kongress Zentrum Rosenheim, Rosenheim, Germany, May 9-13, 2011

Influences of ELM-like pulsed plasma bombardment on deuterium retention in tungsten

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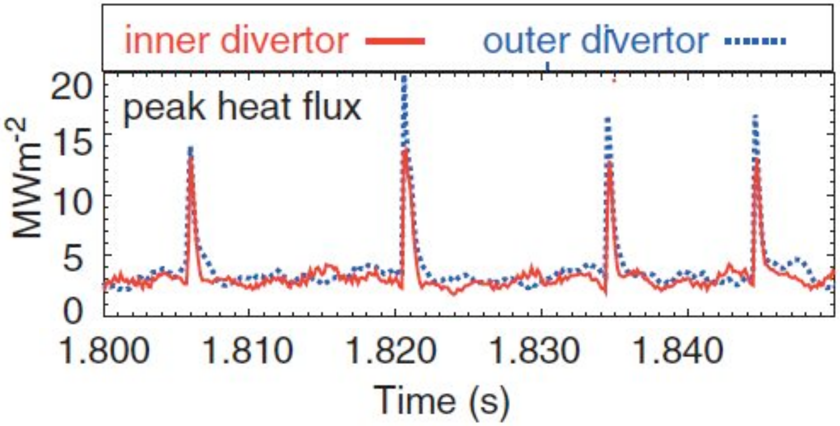
Tungsten is subjected to both steady-state and transient plasma loads.

- Linear divertor plasma simulators
  - ⇨ Steady-state plasma-material interactions
  - ⇨ Surface morphology changes (blisters, bubbles, holes, fuzz, …), H-isotope and He retention, etc
- Plasma guns
  - ⇨ Transients (ELMs, VDEs, and disruptions)
  - ⇨ Cracking, melting, evaporation, etc

Periodic high heat & particle fluxes induced by ELMs reach divertor plates.



T. Eich et al., PPCF2005

- *Does steady-state plasma exposure affect response of W to transients?*
  - ⇨ **In this study, sequential exposure of W to**
    1. **steady-state D or He plasma in PISCES-A at UCSD**
    2. **pulsed D plasma in MCPG at Univ. of Hyogo**

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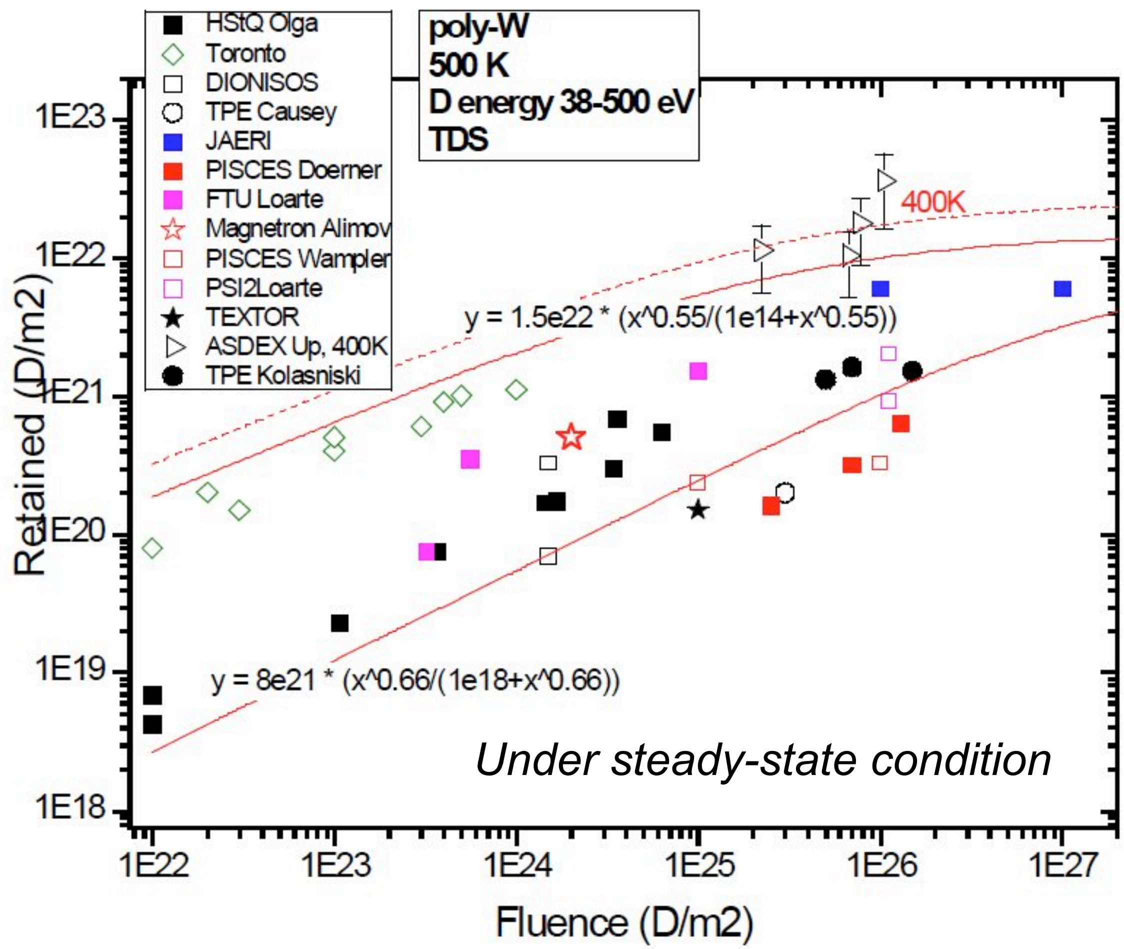
Effects of ELMs on T retention in W?

- In-vessel T retention limited to 700 g for safety reasons in ITER.
- Significant effort to accurately predict T retention.
- Influences of transients on T retention properties have not been included in the estimation of T retention in ITER.



B. Lipschultz et al., MIT report 2010

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Four kinds of W surfaces bombarded by ELM-like pulsed D plasmas

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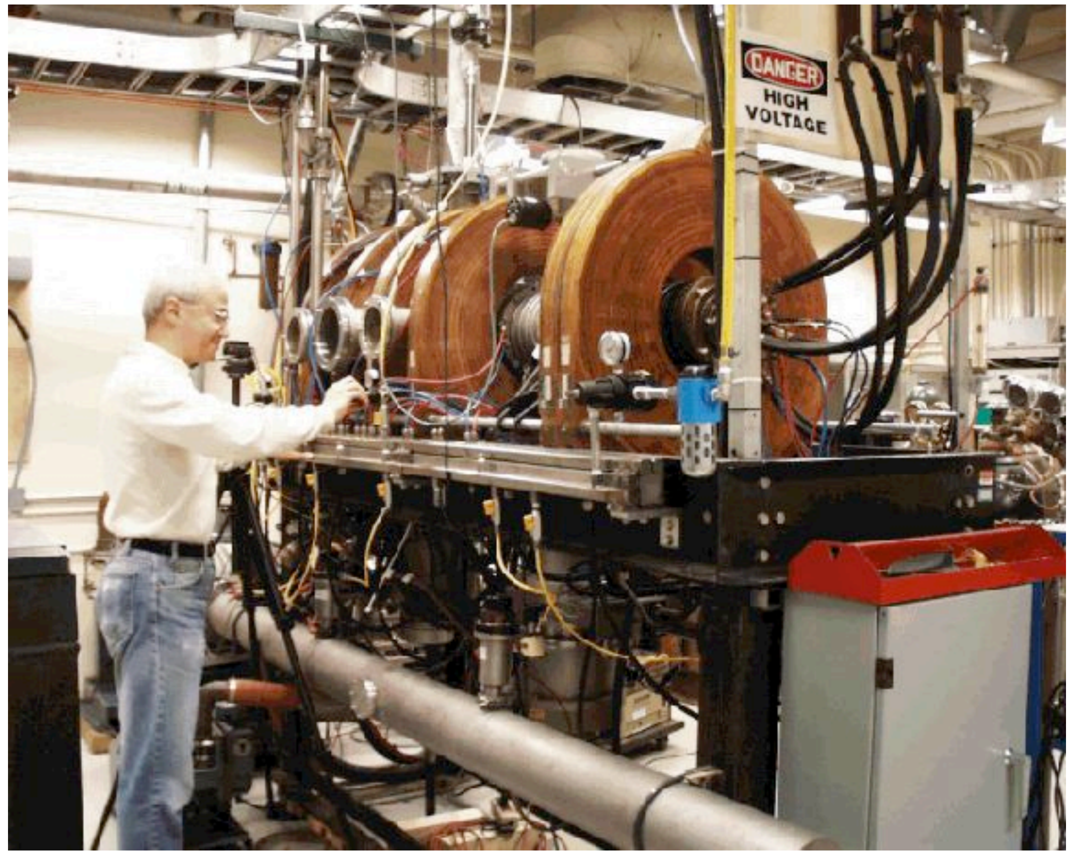
Sample	Steady-state plasma exposure				Pulsed D plasma bombardment			Retention
	Gas	T_s [K]	F	Surface	# of shot	Q [MJ/m^2]	F (r~65 mm)/10shots	[D/m^2]
WU-2	N/A	N/A	N/A	mirror-polished	10	0.5	1.5E+22 D/m^2	1.78E+20
WU-4	N/A	N/A	N/A	mirror-polished	10	0.7	2E+22 D/m^2	3.86E+19
WHe-B2	He	~573	6E+25 He/m^2	nano-sized He bubbles	10	0.5	1.5E+22 D/m^2	1.47E+20
WHe-B4	He	~573	6E+25 He/m^2	nano-sized He bubbles	10	0.7	2E+22 D/m^2	1.82E+19
WHe-F2	He	~1100	7E+25 He/m^2	fuzz (L_{fuzz} ~ 3 μm)	10	0.5	1.5E+22 D/m^2	2.40E+19
WHe-F4	He	~1100	7E+25 He/m^2	fuzz (L_{fuzz} ~ 3 μm)	10	0.7	2E+22 D/m^2	1.64E+19
WD-2	D	~573	5E+25 D/m^2	blister	10	0.5	1.5E+22 D/m^2	9.66E+20
WD-3	D	~573	5E+25 D/m^2	blister	N/A	N/A	N/A	9.85E+20

- The ion fluence, F, to the target during pulsed plasma exposure is expected to be ~5-10 times higher than at r ~ 65 mm.

Steady-state plasma exposure in PISCES-A

- Steady-state plasma is produced in the reflex-arc source (LaB_6 cathode and Cu anode).
- Cylindrical plasma is radially confined with axial magnetic field of ~ 0.09 T.
- Stress-relieved pure W (A.L.M.T. Corp.)
  - -- Diameter: 25.4 mm
  - -- Thickness: 1.5 mm
  - -- Grains are elongated, perpendicular to surface, similar to proposed ITER grade
- E_i ~ 60 eV
  - -- below the threshold energies for sputtering and displacement damage of W
- $\Gamma_i \sim (0.5\text{-}1.5)\times10^{22}\ m^{-2}s^{-1}$



Steady-state plasma exposure produces D blisters, nano-sized He bubbles, and He-induced W fuzz.

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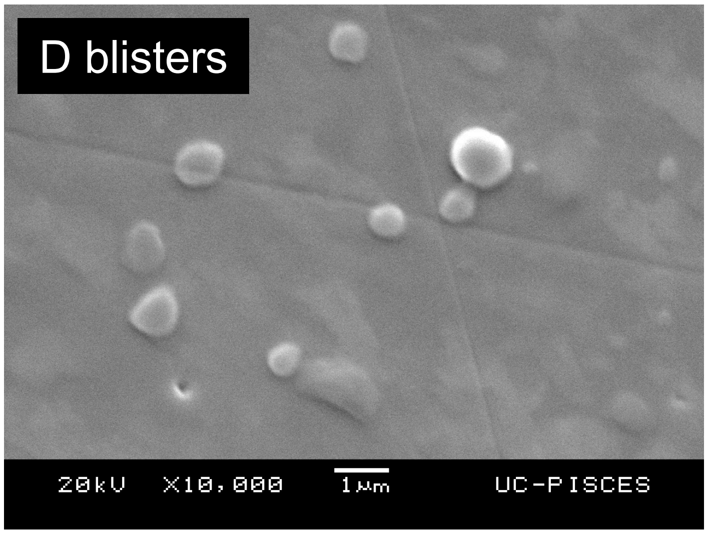
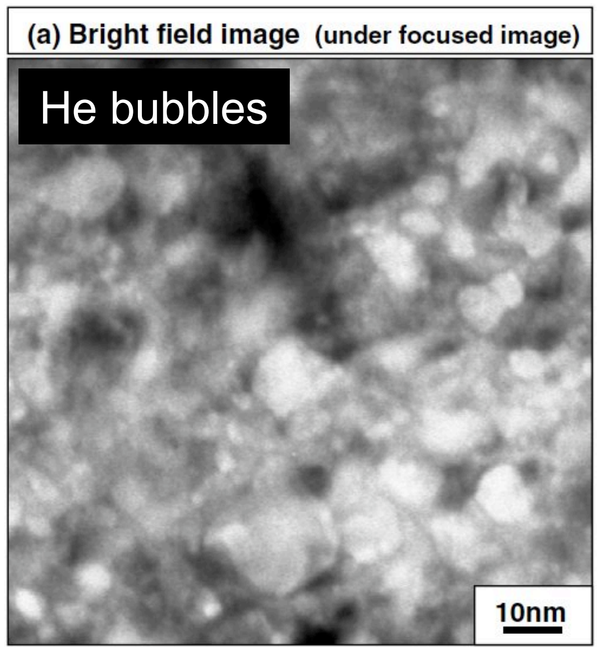


- ~ µm size blisters

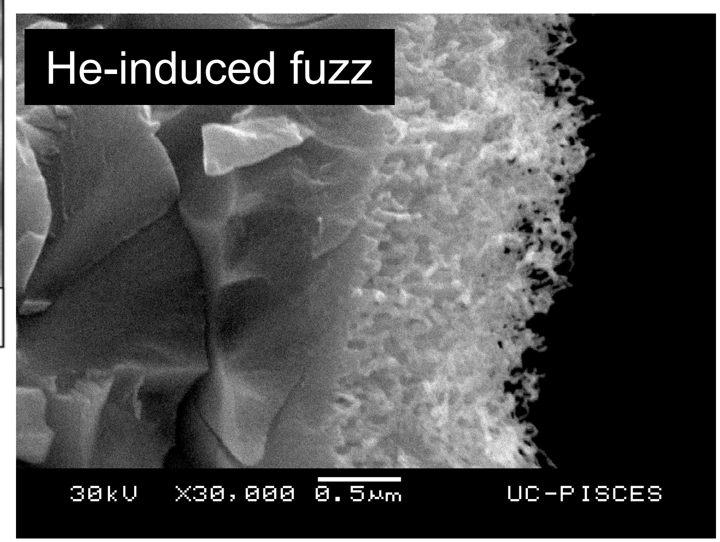
- He bubbles (~1-10 nm) exist in sub-surface region.
- Surface is flat.



M. Miyamoto et al. NF2009

- Produced at high T_s > 1000 K.
- He bubbles contained in each tendril.
- Surface is porous/rough.
- Fuzzy layer thickness was controlled with plasma exposure time.

(M.J. Baldwin et al., NF2008)



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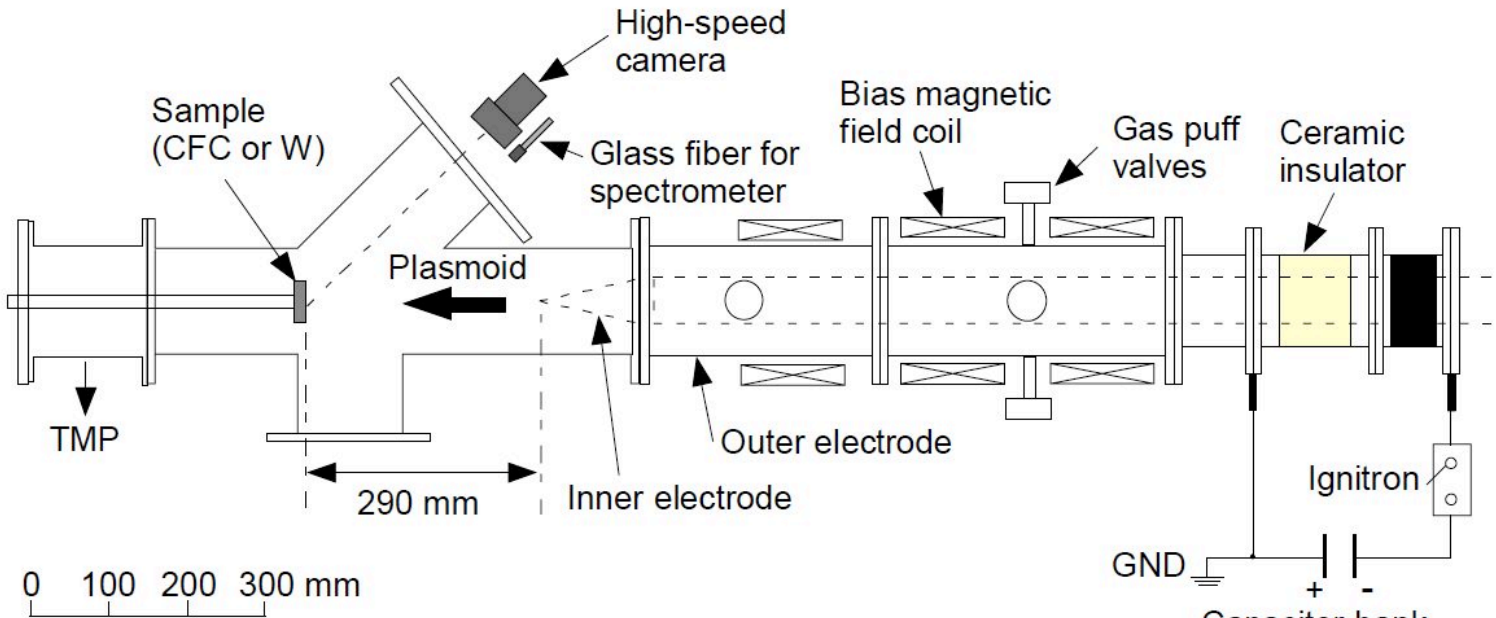
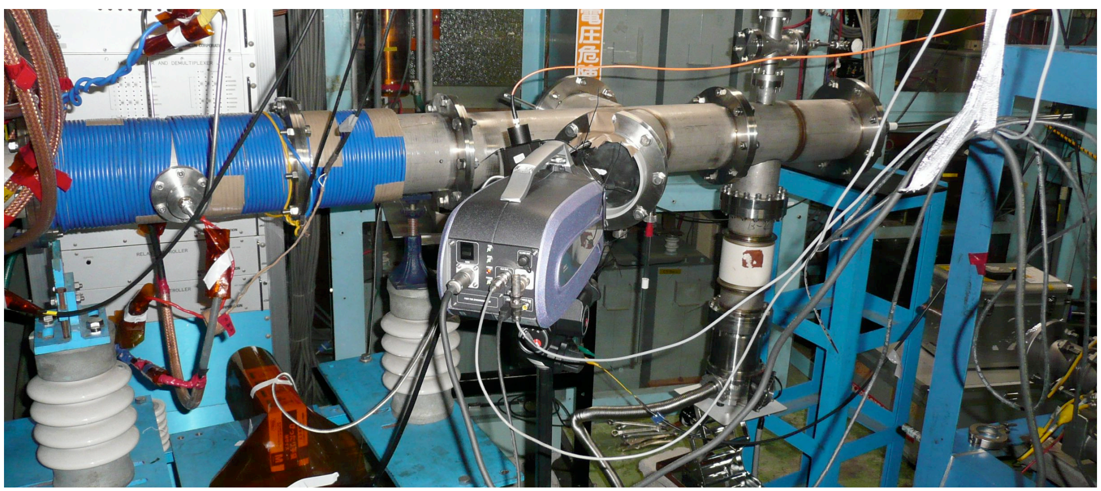
Pulsed plasma bombardment in magnetized coaxial plasma gun (MCPG) at Univ. of Hyogo.

W sample





- Duty cycle: 8 min.
- Working gas: D_2
- Initial sample temperature: 300 K
- Electrodes: SUS304
  (Mo coating of ~300 μm
  on the tip of inner electrode)

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Plasma parameters in MCPG are comparable to those expected for mitigated ELMs in ITER.

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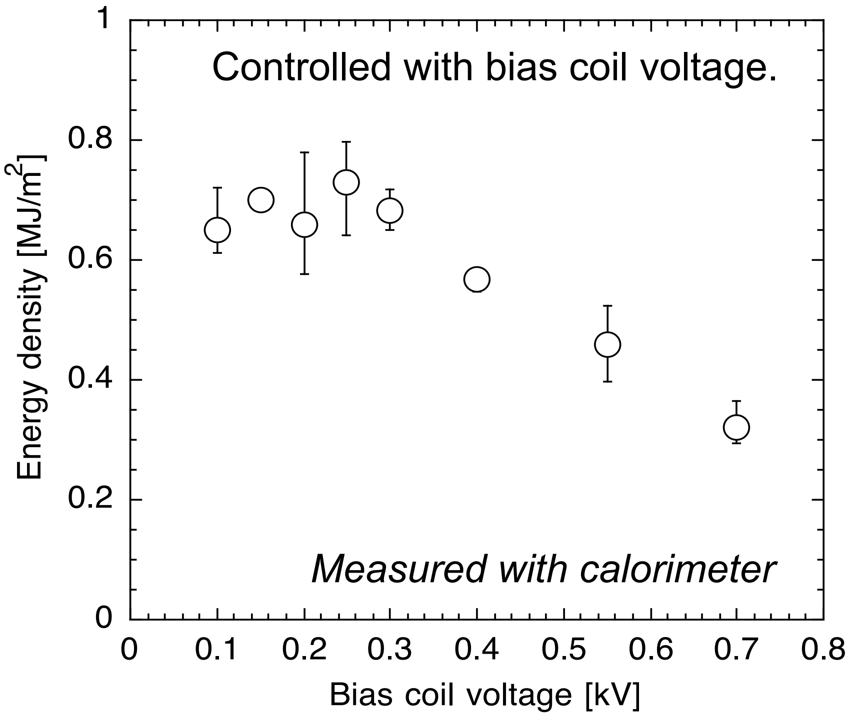
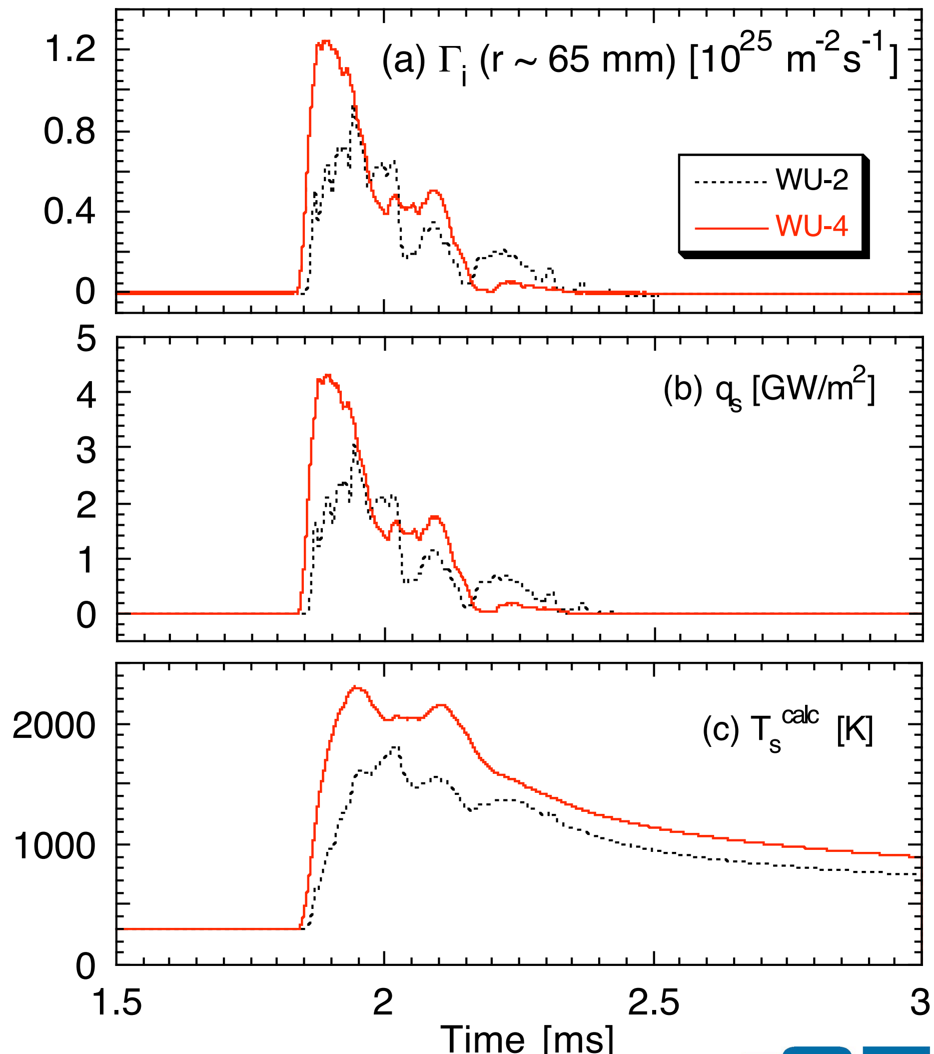
- Energy density: up to ~0.7 MJ/m^2
- Pulse width: ~0.3-0.5 ms

⇨ Mitigated type I ELMs in ITER

- Plasmoid velocity: ~50 km/s
  (ion energy for D^+: ~30 eV)



WU-2: 0.5 MJ/m^2, WU-4: 0.7 MJ/m^2



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There are two desorption peaks around 800-900 K and 1000-1100 K.

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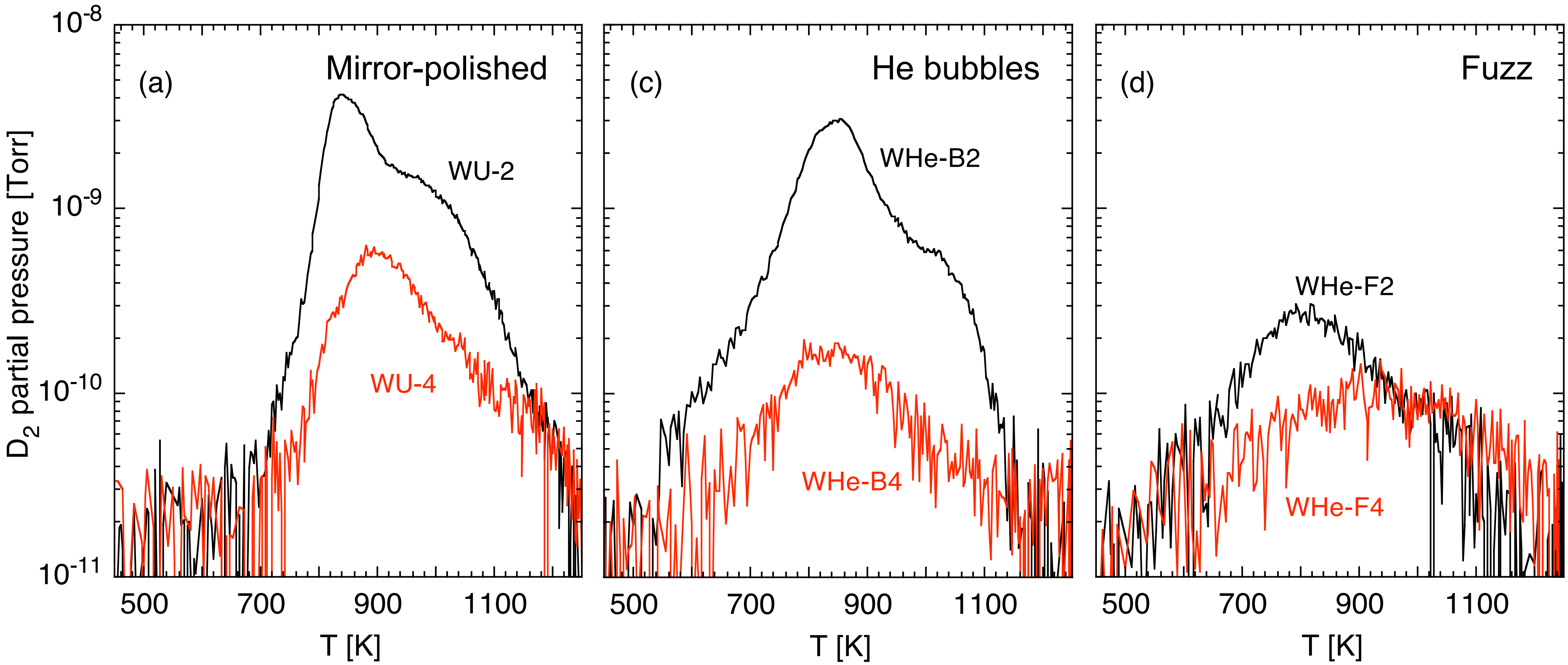
-- At Q ~ 0.7 MJ/m^2, the high temperature peak is not prominent.

-- Desorption starts from a lower temperature for He plasma pre-exposed samples.



WU-2, WHe-B2, WHe-F2: 0.5 MJ/m^2
WU-4, WHe-B4, WHe-F4: 0.7 MJ/m^2

Total D retention becomes lower with He plasma pre-exposure.

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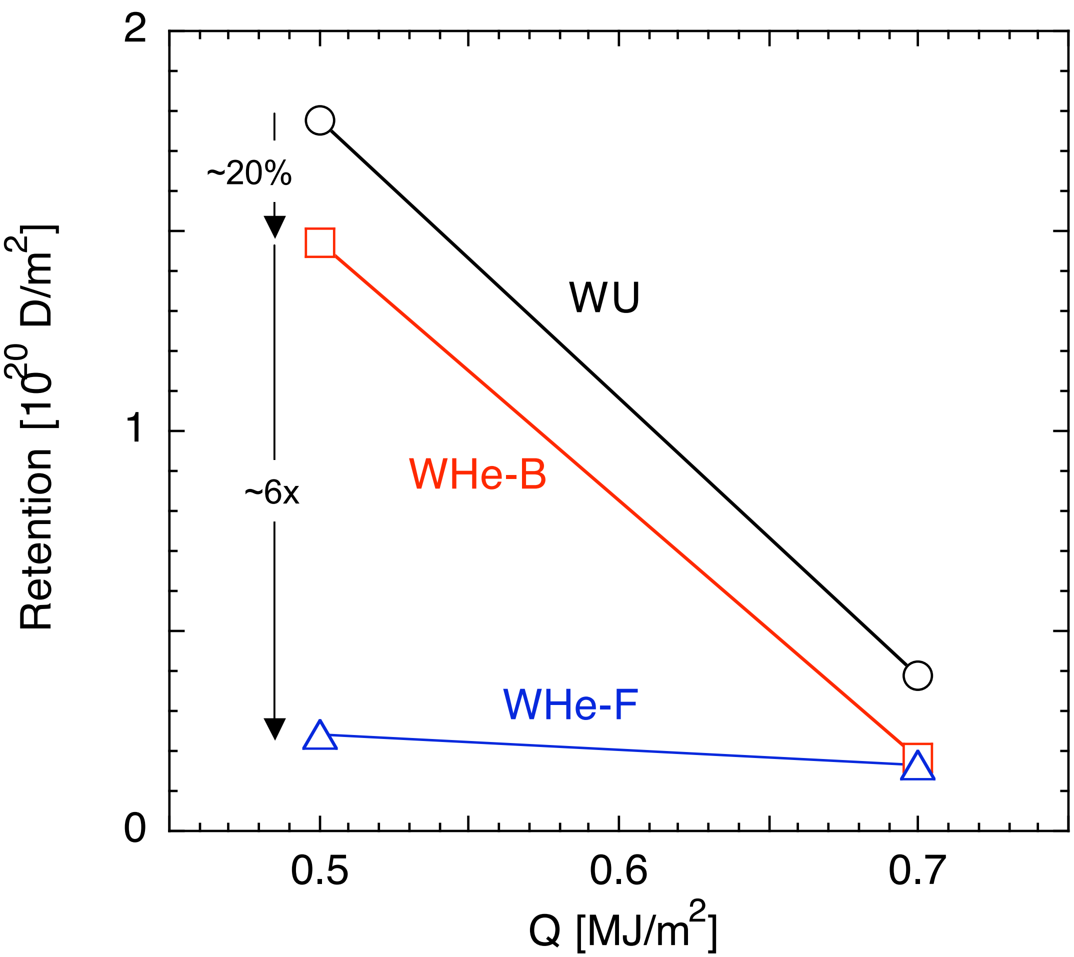
- Consistent with steady-state plasma exposure experiments.
- With fuzz, D retention at Q ~ 0.5 MJ/m² is significantly lower than others.
- At higher Q ~ 0.7 MJ/m², D retention in WU and WHe-B becomes ~5-8x lower than those at lower Q.



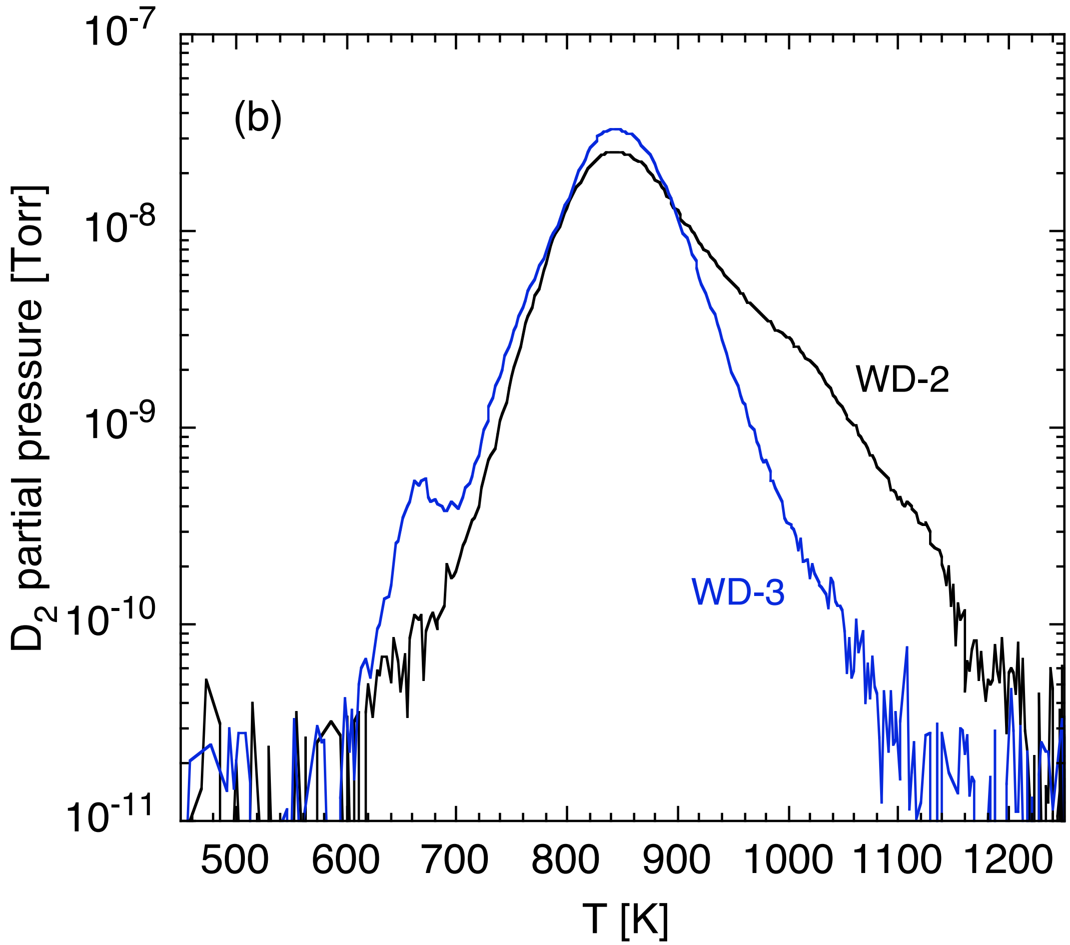
A high temperature is necessary to desorb D from pulsed plasma exposed materials.

-- WD-2: sequentially exposed to steady-state & pulsed D plasmas

-- WD-3: only with steady-state D plasma exposure

- A small low temperature peak at ~650 K disappears with transients.
- Instead, a high temperature peak at ~1000-1100 K appears.
- Regardless of the different spectra, total D retention in WD-2 & WD-3 is similar (~1×10^{21} D/m^2).

⇨ Some of D pre-implanted by steady-state plasma exposure is released during transients.



ELMs will make it more difficult to remove T from PFMs by baking.

- A high-temperature desorption peak of D_2 is found to emerge at ~1000-1100 K due to pulsed D plasma exposure of W.
- A higher Q pulse at ~0.7 MJ/m^2 can significantly lower D retention.
- High density He bubbles in the sub-surface region slightly reduces D retention, associated with pulsed D plasma bombardment.
- A fuzzy surface further reduces D retention.