1st NIFS-CRC International Symposium and 1st Korea-Japan Workshop
on Edge-Plasma and Surface Component Interactions in Steady State Magnetic Fusion Devices
May 20-22nd, 2007

PISCES-B mixed material PSI experiments and their implications for ITER

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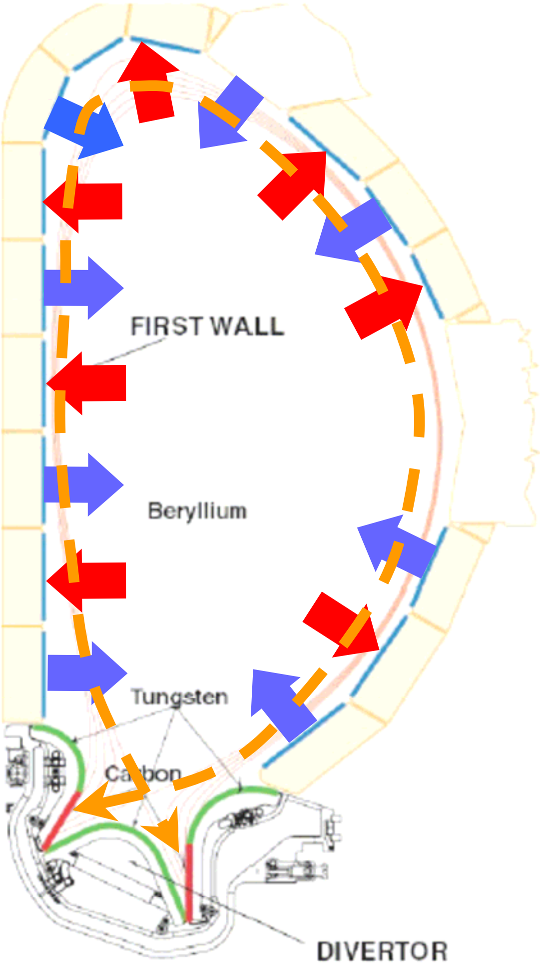
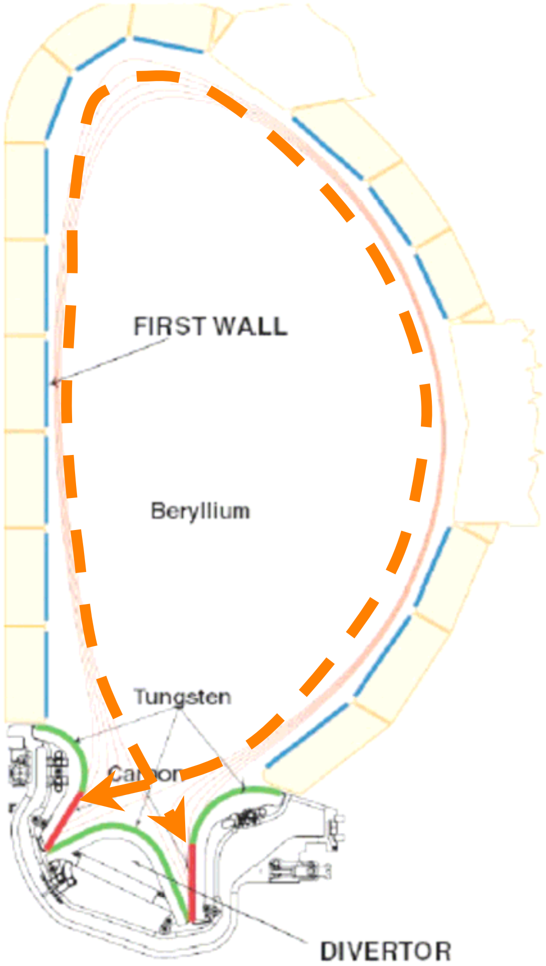
ITER steady state PSI will involve mixed material surfaces.

- PFC material is lost from walls due to:
  - –Diffusive or bursty transport
  - –Erosion during off normal events
  - –Toroidal asymmetries
- Material transport is caused by:
  - –Inward bursty transport of impurities
  - –SOL flows
- Material migrates to divertor
  - –Degree of shielding in divertor plasma

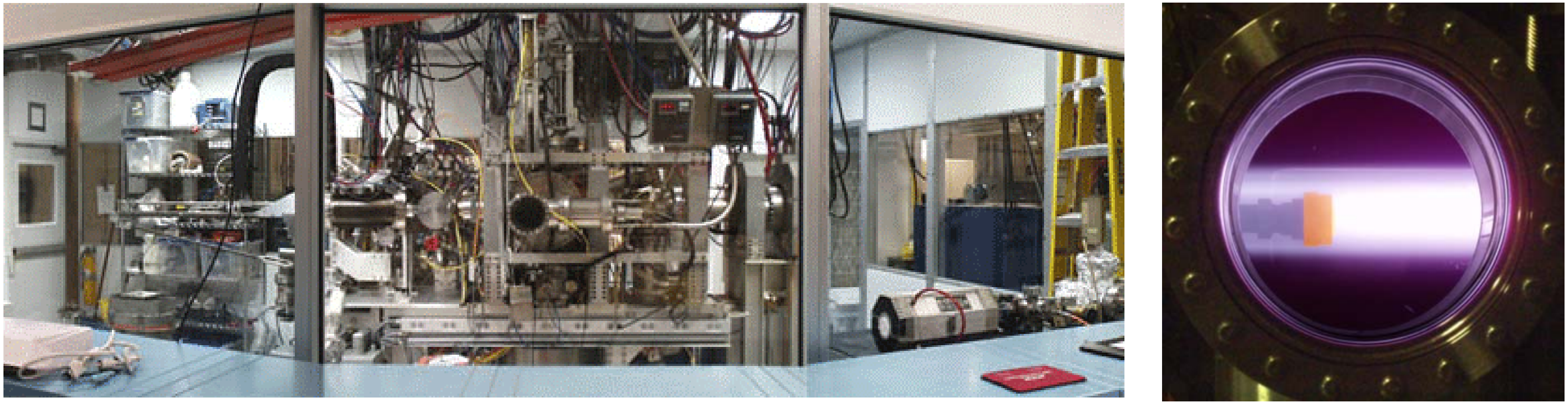


PISCES is investigating mixed materials PSI in collaborations with Europe & Japan.

- EU Collaboration (2003 – present)
  - –Studies of erosion, deuterium retention and codeposition properties of:
    - –D-Be plasma on C targets
    - –D-Be plasma on W targets
    - –Be targets (near Be melting point)
- Involved in TITAN program (2007 - 2013)
  - –Mixed plasma (D, He) species effects on W surface morphology
  - –Response of plasma facing materials (MFE, IFE) to transient power loads



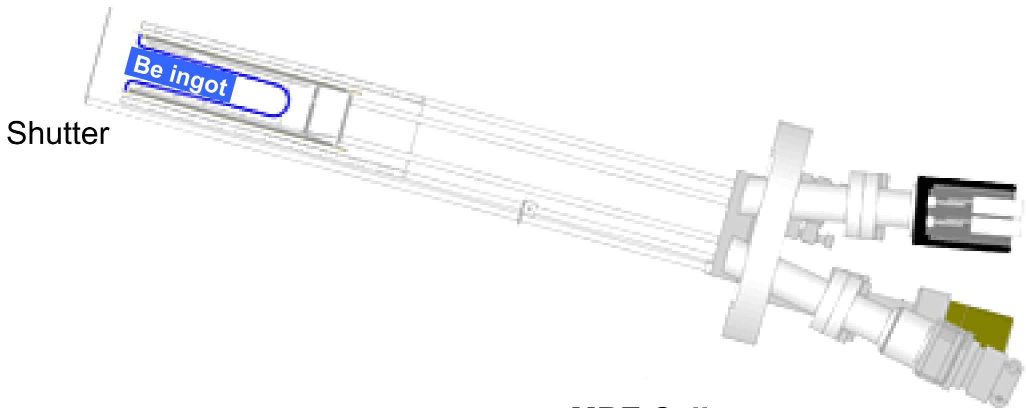
The PISCES-B divertor plasma simulator is used to simulate ITER mixed materials PSI.

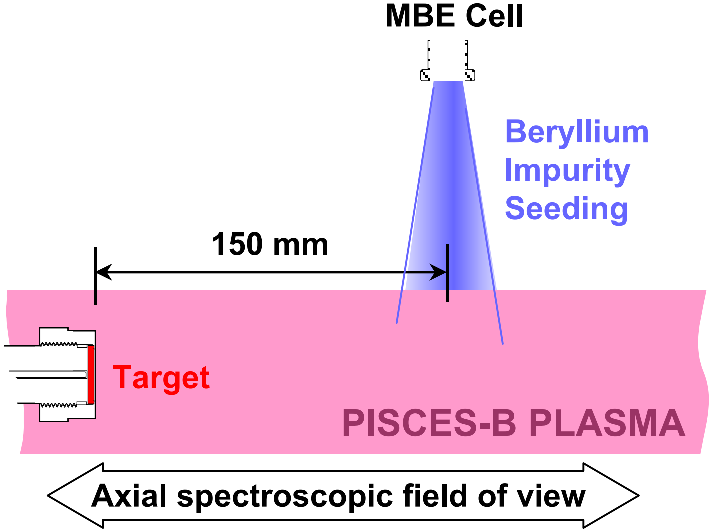


- PISCES-B is contained within an isolated safety enclosure to prevent the release of Be dust.

	PISCES	ITER (edge)
Ion flux (cm^{2}s^{-1})	**10^{17}–10^{19}**	**~10^{19}**
Ion energy (eV)	**20–300 (bias)**	**10–300 (thermal)**
T_e (eV)	4–40	1–100
n_e (cm^{-3})	**10^{12}–10^{13}**	**~10^{13}**
Be Imp. fraction (%)	**Up to a few %**	**1–10 (ITER)**
Pulse length (s)	**Steady state**	**1000**
PSI materials	C, W, Be	C, W, Be ..
Plasma species	H, D, He	H, D, T, He

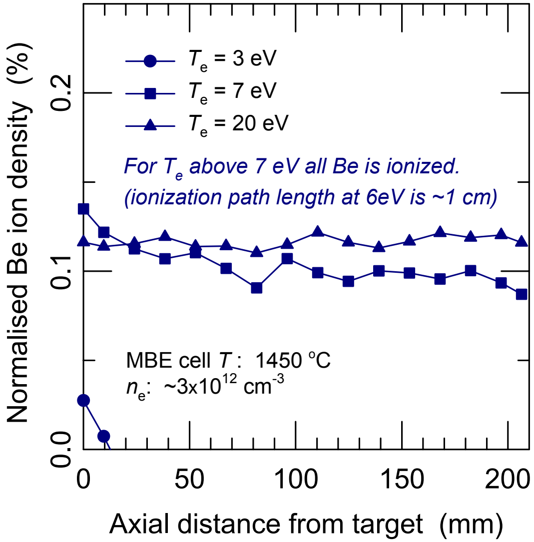
A MBE effusion cell is used to provide a Be impurity flux in PISCES-B plasma.





- Veeco Applied HT MBE effusion Cell provides temperature controlled Be impurity seeding in the plasma

Normalized Be impurity ion fraction in deuterium plasma as a function of T_e.



Be-C experiments

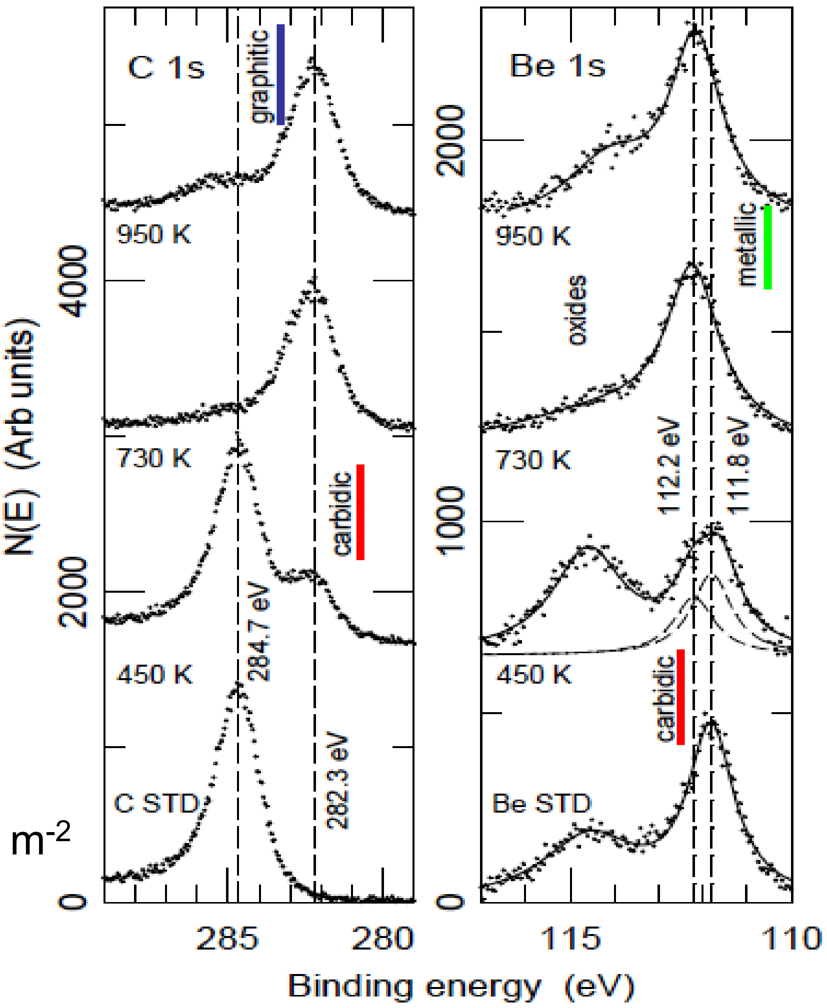
Evolution of chemical erosion in Be seeded D plasma.

Properties of C target surfaces after exposure.

Extrapolation to ITER.

XPS analysis shows formation of (Be_2C) as exposure temperature, T_s, is increased.

- A carbidic peak appears and a graphitic peak disappears in C 1s spectra.
- In Be 1s spectra, metallic peak shifts to a carbidic peak.
- Carbide forms more efficiently at higher surface temperature

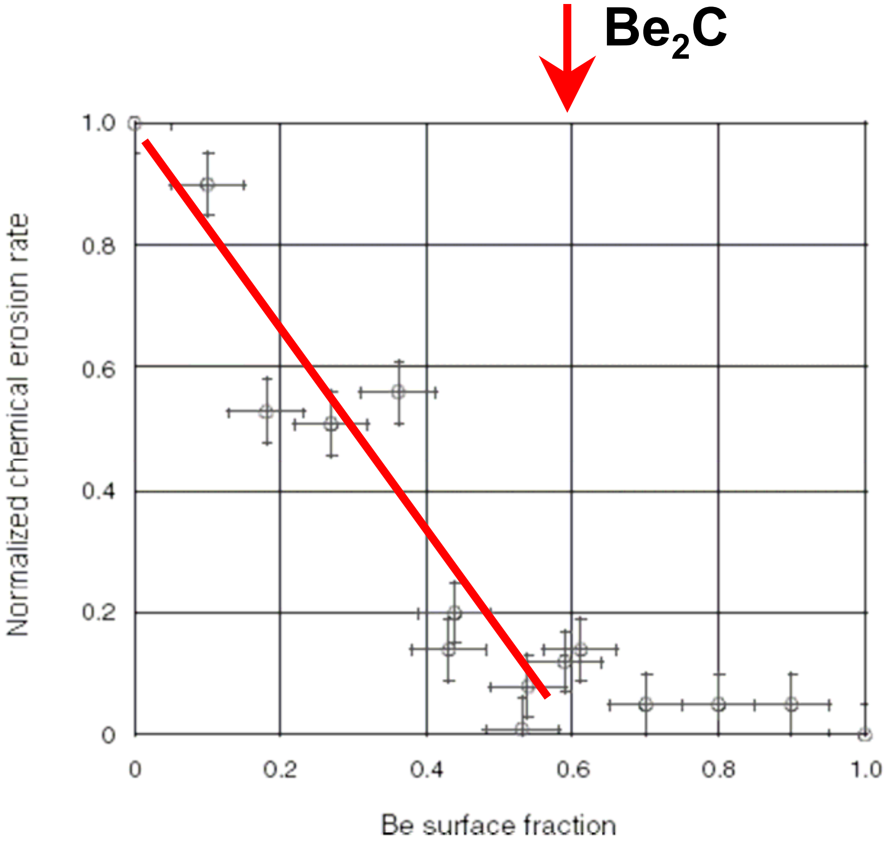


D ion fluence ~ $1.2 \times 10^{26}\ m^{-2}$
$n_{Be+}/n_e \sim 0.1\ \%$,

Chemical erosion rate drops monotonically until graphite is converted to Be_2C.

- Be ions implant into carbon surface and bond with carbon atoms to form beryllium carbide (Be_2C).
- Be_2C in the surface may act to inhibit the reaction chain responsible for chemical erosion and also reduces physical sputtering of carbon atoms from the surface through dilution of surface C atoms.
- Similar effects have been noted for B doped graphites. See for example:

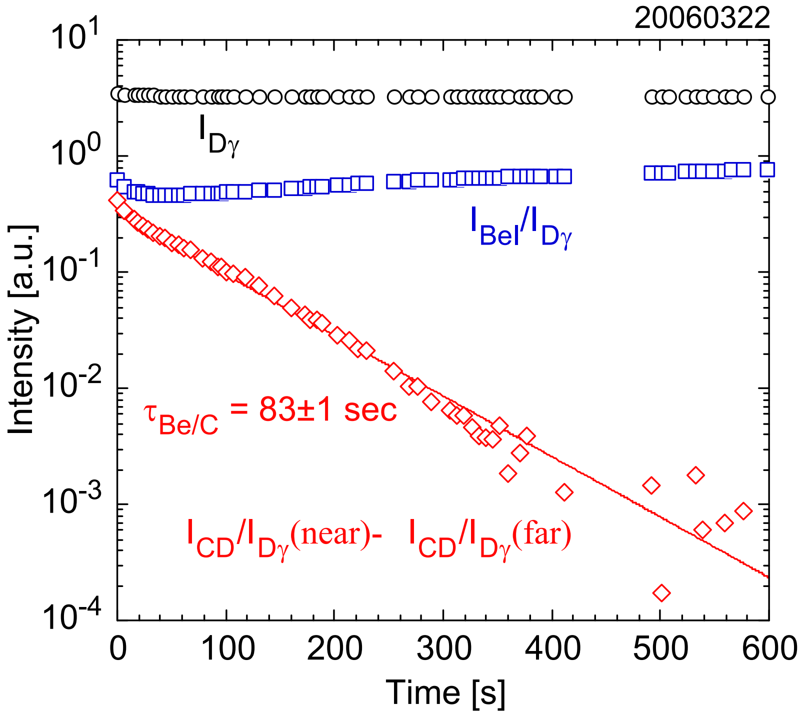
[Roth J 1999 *J. Nucl. Mater.* **266–269** 51]


Be_2C

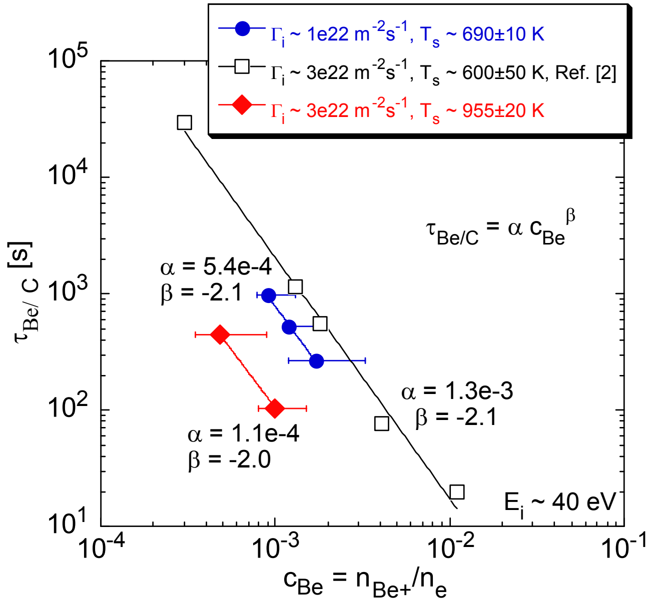
Carbon chemical erosion is mitigated in D-Be plasmas with characteristic decay time, $\tau_{Be/C}$.

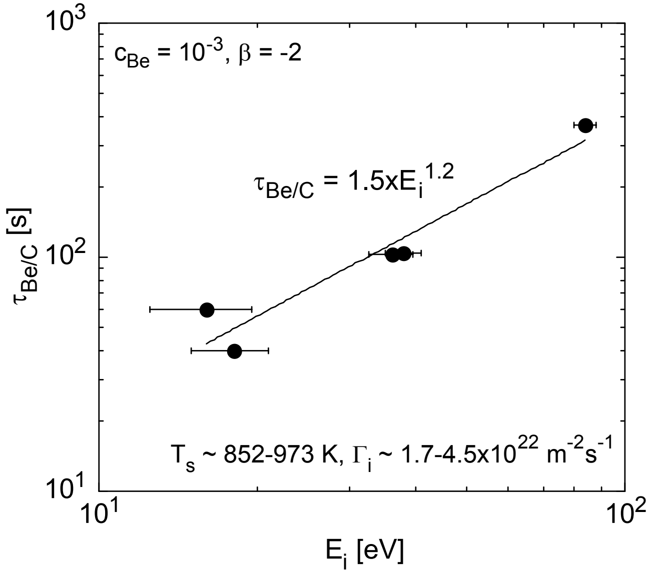
- CD band intensity near C target drops w/ time as Be erosion signal from target increases

- The subtraction of CD band intensity taken in a region far from the target (z ~ 70 mm) is used to eliminate the effects of the intensity originating from wall carbon erosion



$\tau_{Be/C}$ decreases with increased Be ion conc. in plasma, c_{Be}, but increases with E_i < 85 eV.





- c_{Be} scanned keeping other parameters, E_i, T_s and Γ_i constant.

- Deposited Be on C target can be more readily sputtered at higher E_i, thus resulting in a longer $\tau_{Be/C}$.

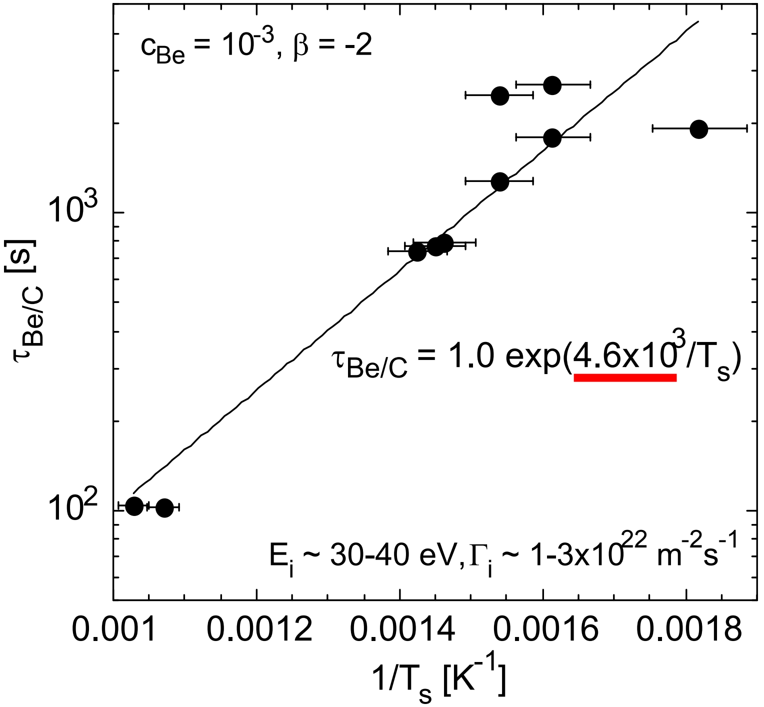
$\tau_{Be/C}$ strongly depends on T_s.

- Higher T_s leads to reduced $\tau_{Be/C}$ Increased carbidic reaction with T_s may play a role

- Enthalpy of formation of Be_2C: $\Delta H(Be_2C) = -117.0 \pm 1.0$ kJ/mol

⇨ $$\tau_{Be2C} \propto \frac{1}{K_{Be2C}} \propto \exp\left(\frac{1.4e4}{T_s}\right)$$

- Pure Be and Be_2C must also contribute to the carbon erosion reduction especially at lower T_s and/or $\Delta H(Be_2C)$ may be lower in a PSI environment than the equilibrium value.



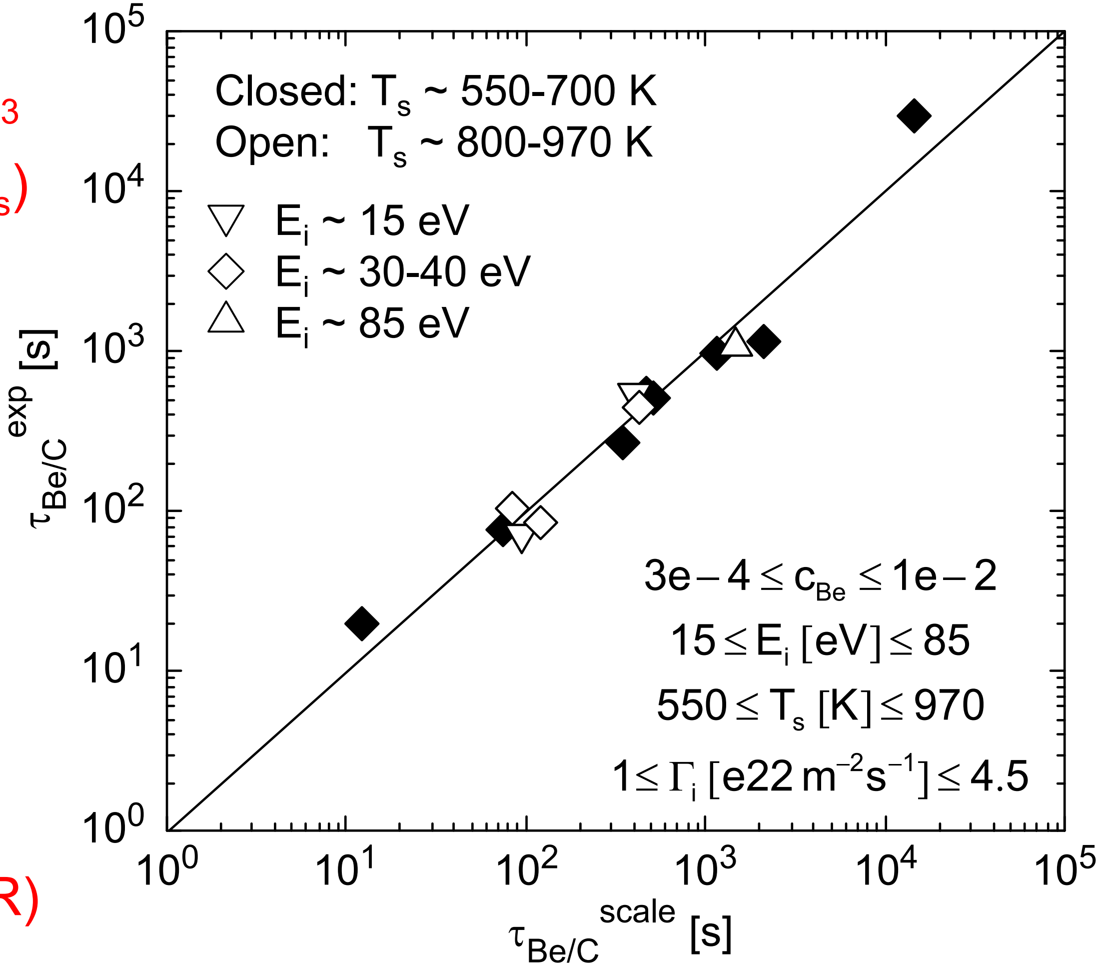
In ITER, type one I ELMs may not be deleterious to erosion mitigation effects of Be.

$$\tau_{Be/C}^{scale}\ [s] = 10^{-7}\, c_{Be}^{-1.9\pm0.1}\, E_i^{0.9\pm0.3}\, \Gamma_i^{-0.6\pm0.3} \times \exp((4.8\pm0.5)\times10^3/T_s)$$

- $\tau_{Be/C}$ has a negative power law dependence on Γ_i.
- At higher fluxes, Be redeposition fraction is larger leading to increased $\tau_{Be/C}$
- Under ITER like conditiions

c_{Be} = 0.05, E_i = 20 eV
T_s = 1200 K, $\Gamma_i = 10^{23}\ m^{-2}s^{-1}$
Federici et al., JNM 266-269 (1999)

⇨ $\tau_{Be/C}$ ~ 6 ms << 1 s (ITER)



Be-W experiments

Implications of Be-W alloying for ITER.

Properties of W target surfaces after exposure to Be seeded plasama.

Extrapolation to ITER.

Stable Be-W alloys are known and have melting points closer to that of Be than W.

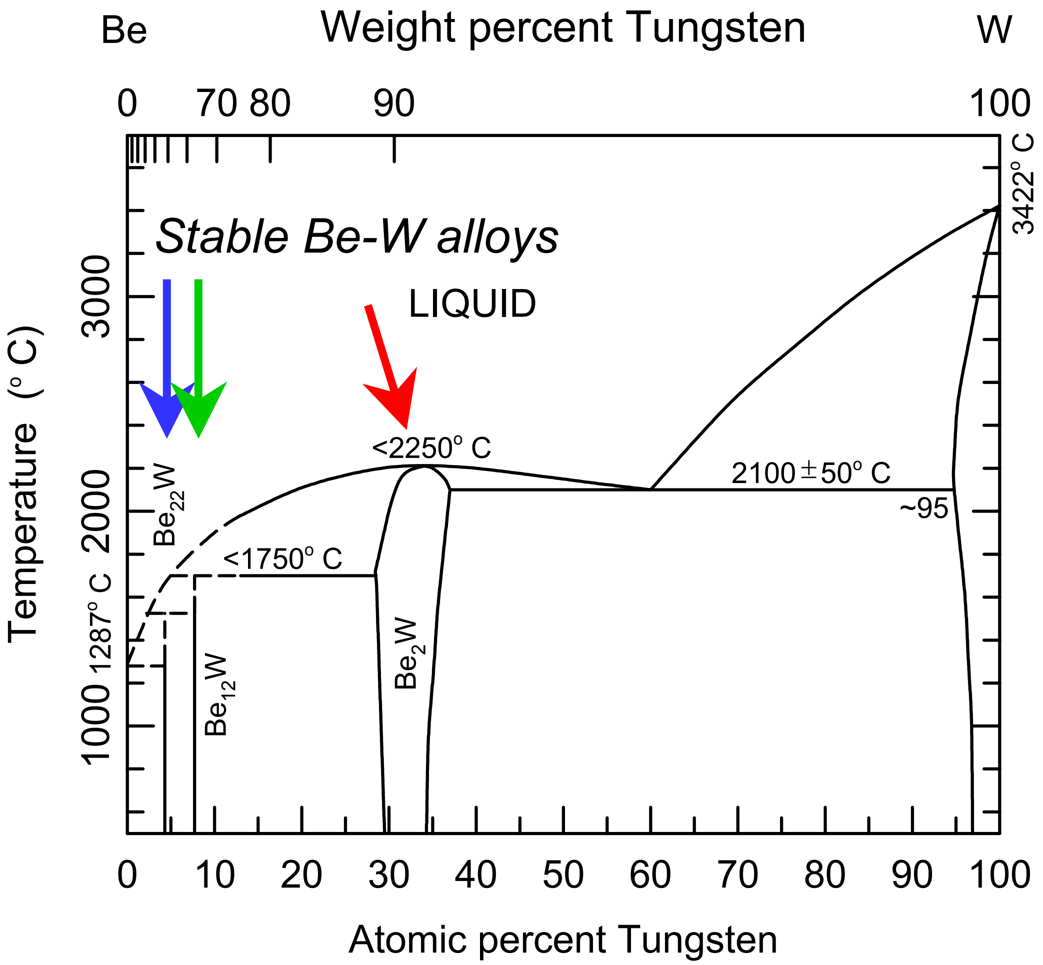
- Stable Be-W inter-metallics are:

~2200°C (Be_2W)

~1500°C ($Be_{12}W$)

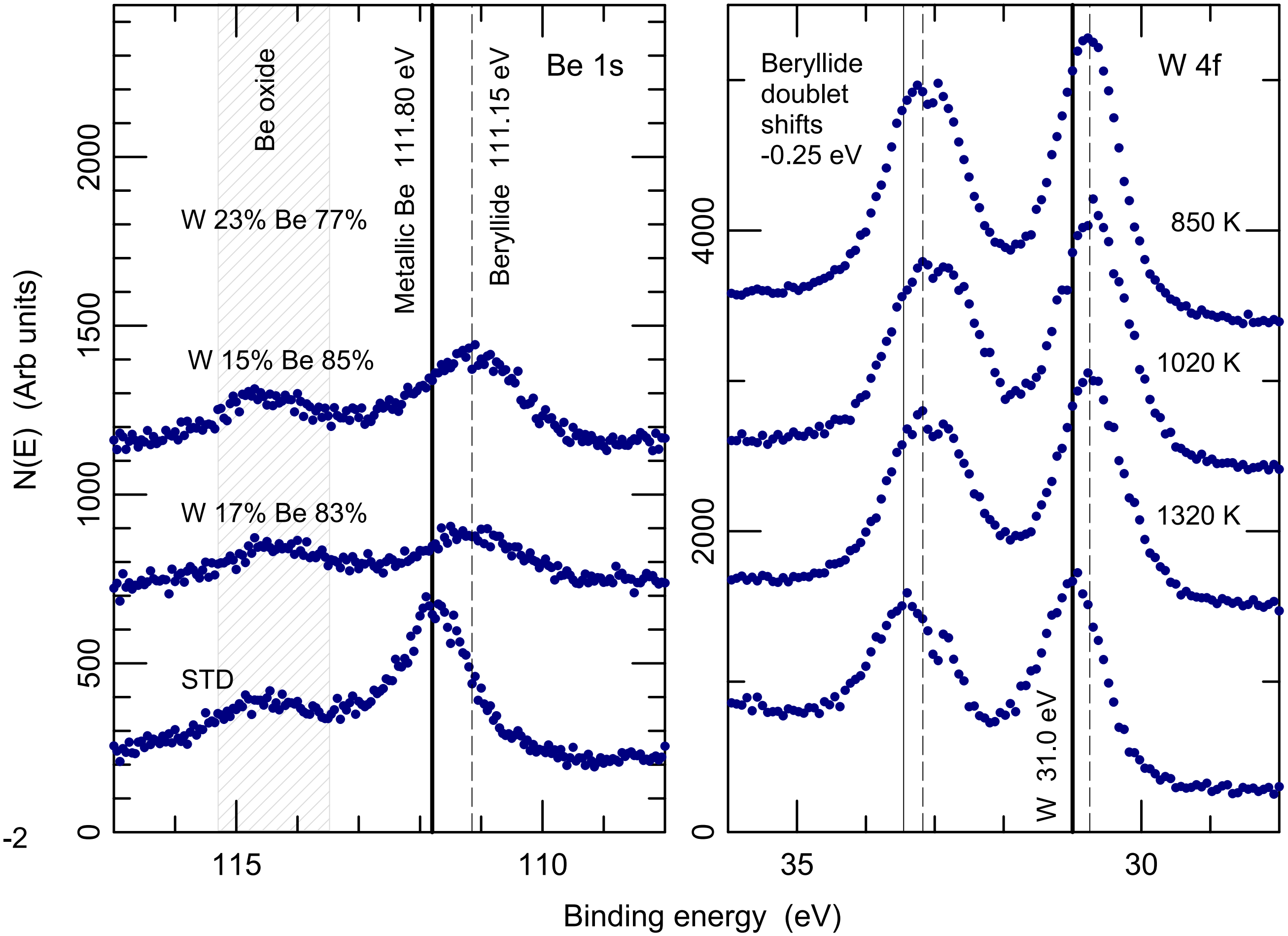
~1300°C ($Be_{22}W$)

- What will happen if Be transport into the W bulk is rapid enough that alloy formation is not limited to the near surface?



XPS confirms Be-W alloy formation on W target surfaces exposed in range 850-1320 K.

- Be-W alloy line shifts are consistent with: Wiltner & Linsmeier, *JNM* 337–339 (2005)



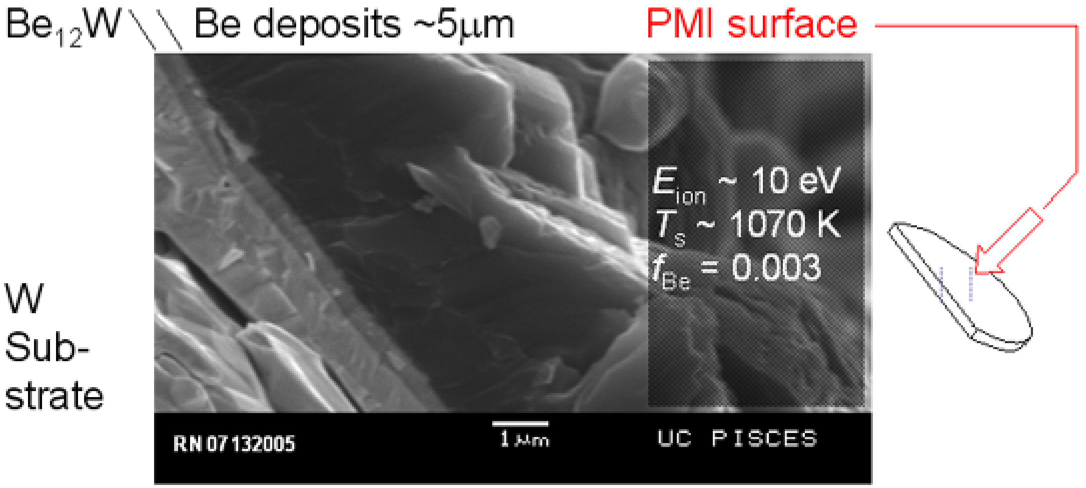
D ion fluence ~ 1.2x10^{26} m^{-2}
n_{Be+}/n_e ~ 0.1 %,

The availability of surface Be is found to be critical for Be-W alloy formation ($\Delta t \sim 1$ h).

- A 0.3 µm $Be_{12}W$ layer forms at W-Be interface.

$$f_{Be^+}\Gamma_{D^+} > Y_{D\to Be}\Gamma_{D^+}$$

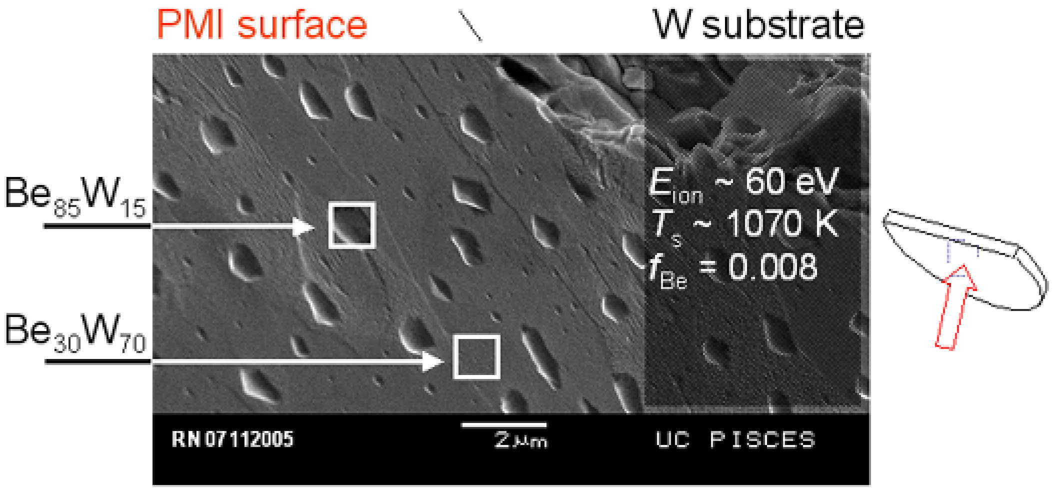
$$f_{Be^+}\Gamma_{D^+} > \Gamma_e$$



- $Be_{12}W$ nucleation on W rich surface.
- No Be sub-surface.

$$f_{Be^+}\Gamma_{D^+} < Y_{D\to Be}\Gamma_{D^+}$$

$$f_{Be^+}\Gamma_{D^+} > \Gamma_e$$

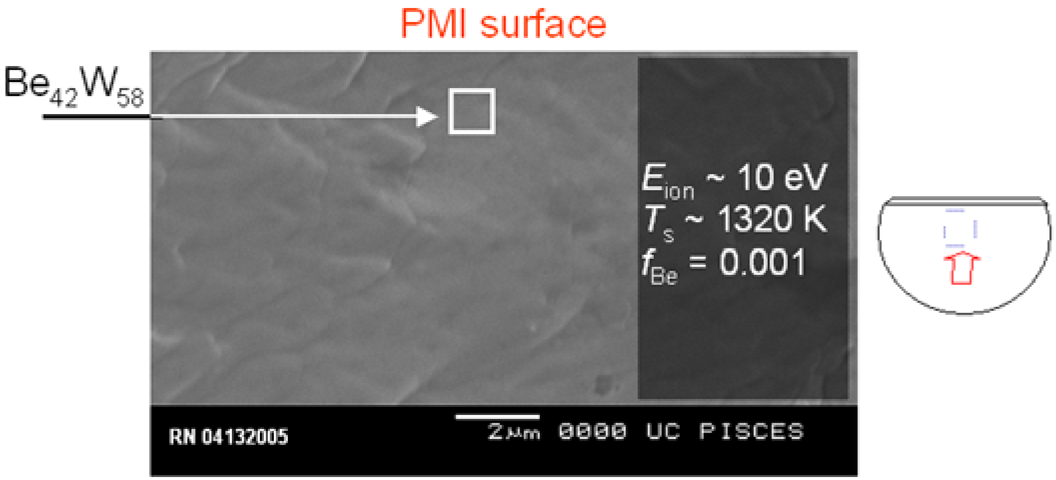


Be re-erosion and evaporation reduce surface Be availability, reducing alloy formation rate.

- Surface composition below stoichiometry for Be_2W. No Be sub-surface.

$$f_{Be^+}\Gamma_{D^+} > Y_{D\rightarrow Be}\Gamma_{D^+}$$

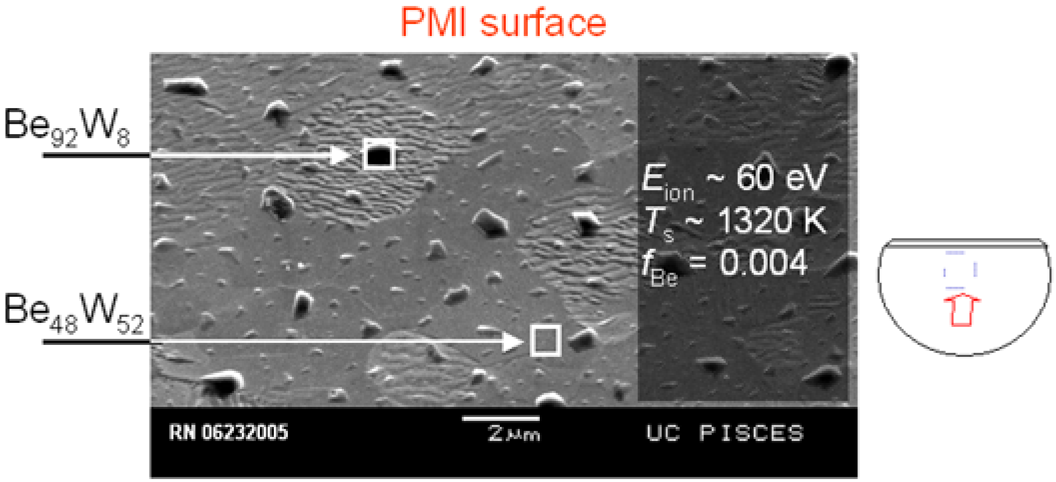
$$f_{Be^+}\Gamma_{D^+} << \Gamma_e$$



- $Be_{12}W$ surface nucleation over almost identical surface to (d).

$$f_{Be^+}\Gamma_{D^+} < Y_{D\rightarrow Be}\Gamma_{D^+}$$

$$f_{Be^+}\Gamma_{D^+} << \Gamma_e$$



Simple particle transport model predicts Be overlayer formation (most efficient alloying).

$$J_{\mathrm{in}}^{\mathrm{Be}} = f_{\mathrm{Be}^+}\Gamma_{\mathrm{D}^+}\left(1 - R_{\mathrm{r}}\right)$$

$$\begin{aligned} J_{\mathrm{out}}^{\mathrm{Be}} &= Y_{\mathrm{D}\to\mathrm{Be}}\Gamma_{\mathrm{D}^+}\left(1 - R_{\mathrm{d}}\right) \\ &+ f_{\mathrm{Be}^+}Y_{\mathrm{Be}\to\mathrm{Be}}\Gamma_{\mathrm{D}^+}\left(1 - R_{\mathrm{d}}\right) \\ &+ \Gamma_{\mathrm{e}}\left(1 - R_{\mathrm{e}}\right) + \xi\left(T_{\mathrm{s}}\right) \end{aligned}$$

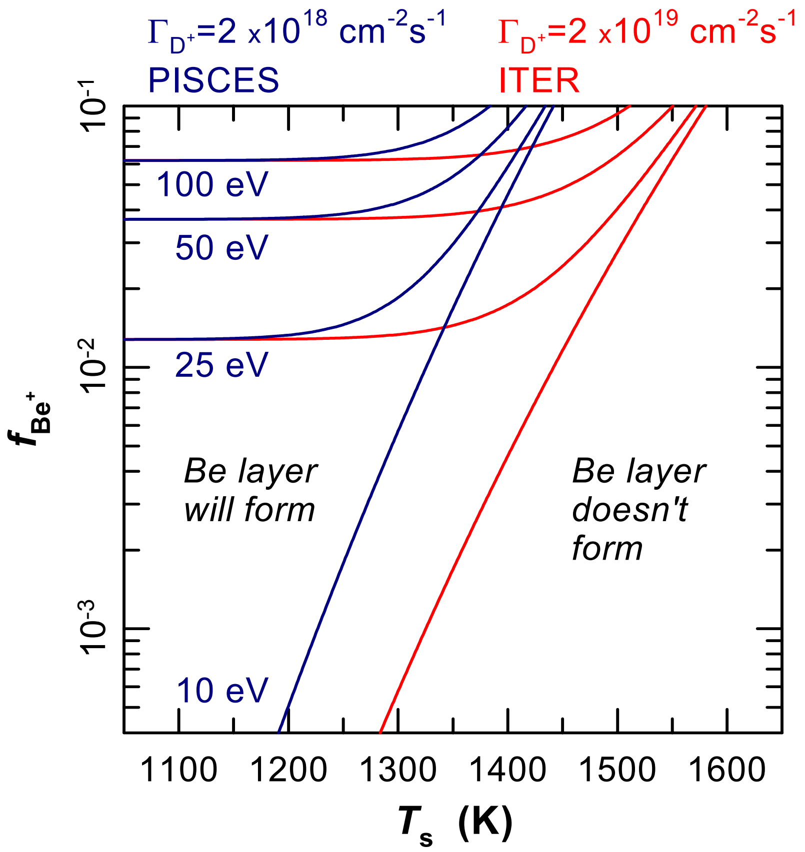
R_{r}, Be → W refl. coef

$R_{\mathrm{d}}, R_{\mathrm{e}}$, redep. fractions

$Y_{\mathrm{D}\to\mathrm{Be}}, Y_{\mathrm{Be}\to\mathrm{Be}}$, sputter yields

Γ_{e}, evap. flux

$\xi(T_{\mathrm{s}})$, bulk diffusion flux



Values taken from:
W. Eckstein, IPP Report ***9/17****, (1998)*
D. R. Lide, CRC Handbook of Chem. & Phys., Internet Version (2005)

Mixed D-Be/C-He on W experiments

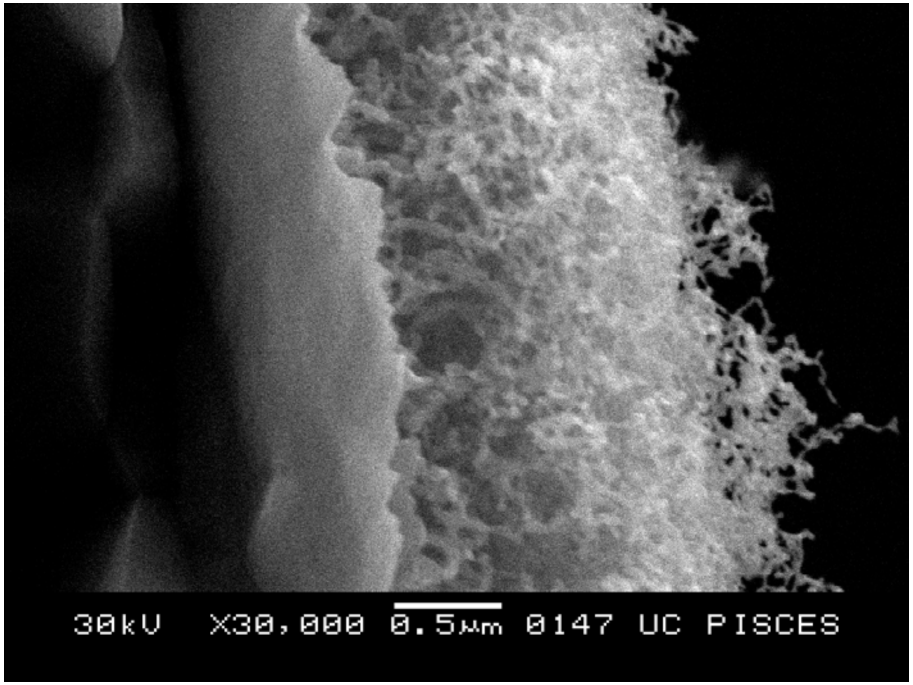
Effects of He and D-He plasma on W.

Influence of plasma impurities Be and C on these effects.

Similar morphology on W surface has been observed in PISCES-B pure He plasma.

PISCES-B: pure He plasma

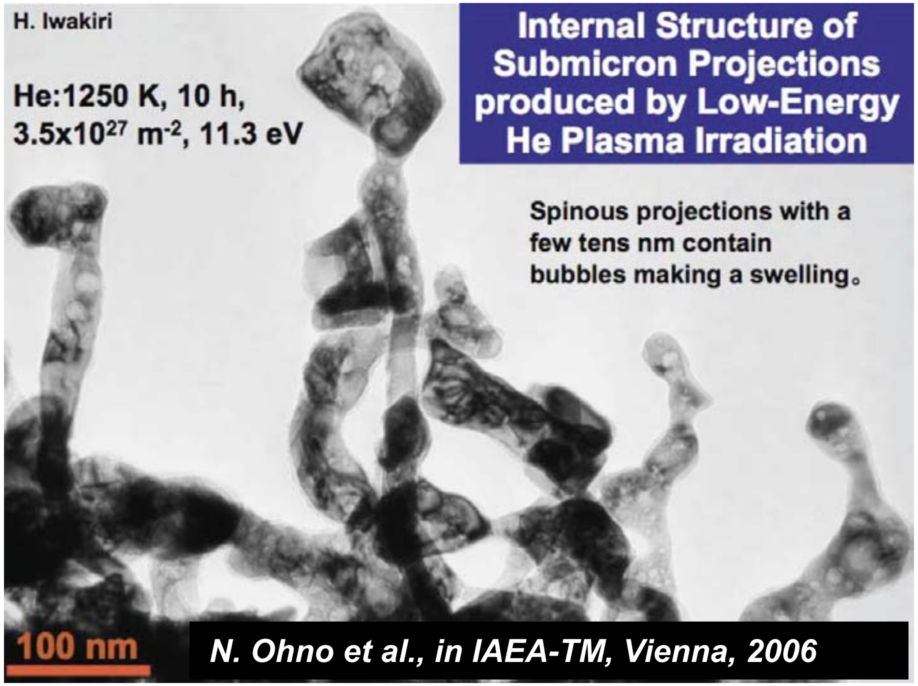
T_s = 1200 K, Δt = 4290 s,
Fluence = $2\text{x}10^{26}$ He^+/m^2, E_i = 25 eV



Scanning electron microscope (SEM)

NAGDIS-II: pure He plasma

T_s = 1250 K, Δt = 36,000 s,
Fluence = $3.5\text{x}10^{27}$ He^+/m^2, E_i = 11 eV



Internal Structure of Submicron Projections produced by Low-Energy He Plasma Irradiation

Spinous projections with a few tens nm contain bubbles making a swelling.

N. Ohno et al., in IAEA-TM, Vienna, 2006

Transmission electron microscope (TEM) in Kyushu Univ.

For controlled experiments, He^+ ion density must to be known.

- A spectroscopic technique can readily yield the He^+ ion density .

Use absolute intensity of He II line at 468.6 nm (I_{HeII})

- However, in D-plasma, with small concentrations of He species, it is hard to detect the He II line at 468.6 nm ($I_{HeII)}$).

Because of low n_e and D_2 molecular emission

- A semi-empirical formula based on a 0-D model, validated with I_{HeII} data taken in PISCES-B He, Ne-He, Ar-He and He rich D_2-He plasmas is used to infer I_{HeII} in low He D_2-He mixture plasma…

Measured He II line intensities obey the model reasonably well.

- Line-integrated intensity:

$$I_{HeII(4686)} = \frac{L}{4\pi}\langle\sigma v\rangle_{HeII(4686)} n_e n_{He+}$$

- 0-D continuity eq:

$$\cancel{\frac{\partial n_{He+}}{\partial t}} = \langle\sigma v\rangle_{He->He+} n_e n_{He} - \frac{n_{He+}}{\tau_{He+}}$$

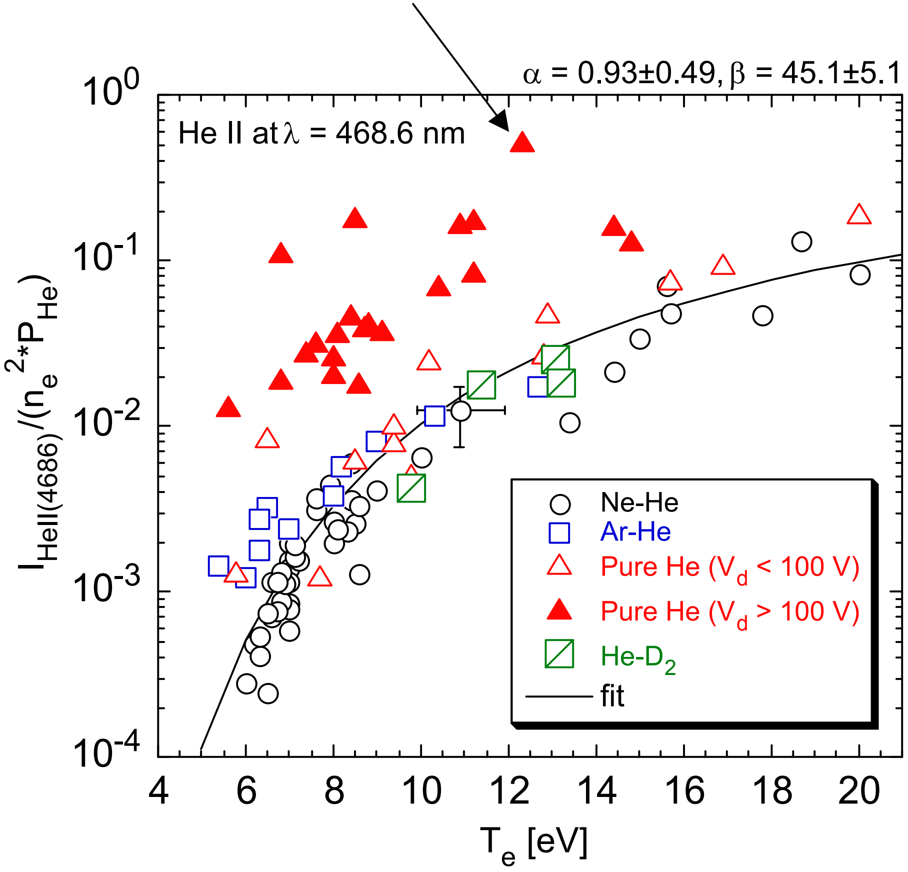
$$\Rightarrow \quad n_{He+} = \alpha' \langle\sigma v\rangle_{He->He+} n_e P_{He}$$

$$\left(n_{He} = \frac{P_{He}}{T_{He}} \right)$$

⇩

$$I_{HeII} = \alpha\, n_e^2 P_{He} \exp\left(-\frac{\beta}{T_e}\right)$$

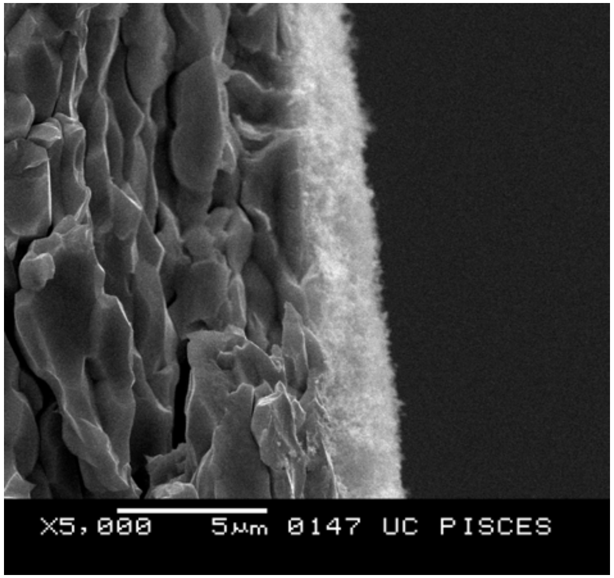
Due to “non-thermal hot electrons”



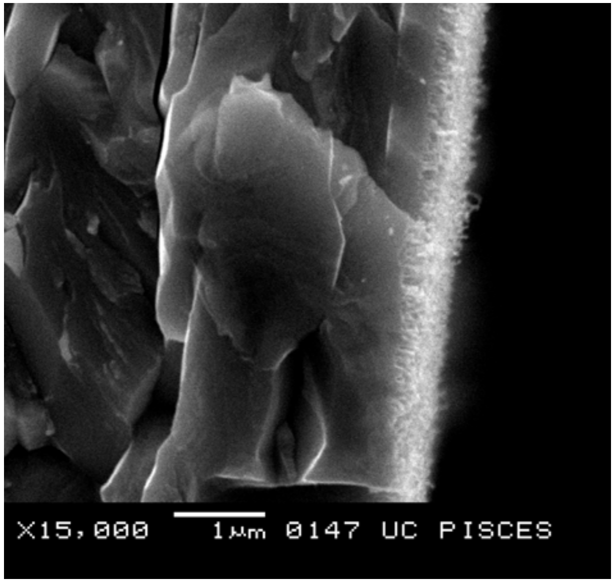
Effect of D_2-He plasmas at T_s = 1100-1200 K.

He plasma, E_i = 25 eV

Δt = 4290 s
2×10^{26} He^+/m^2

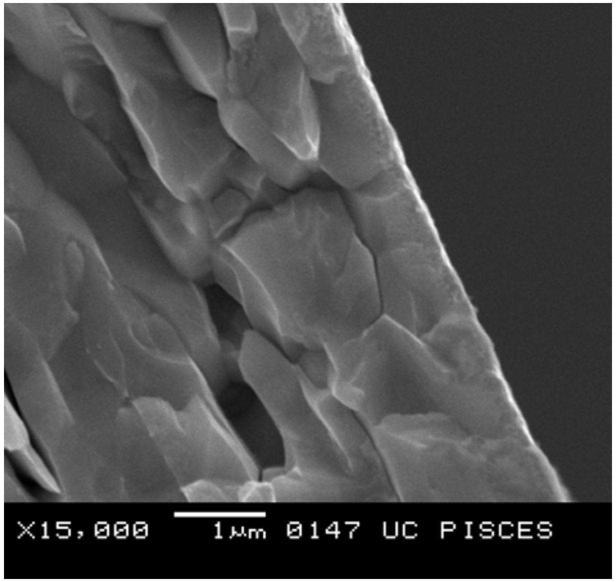


D_2-He plasma, E_i = 60 eV
n_{He+}/n_e ~ 10 %
Δt = 4200 s
10^{25} He^+/m^2



He plasma, E_i = 60 eV

Δt = 420 s
10^{25} He^+/m^2



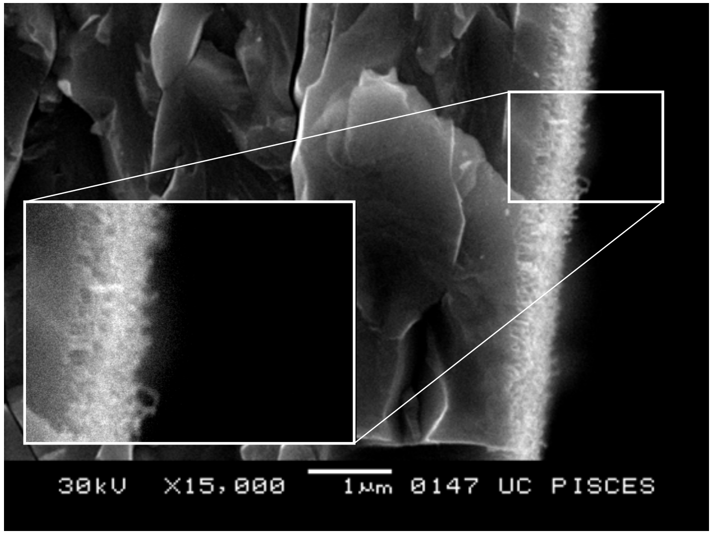
- **Plasma exposure time, Δt, is a stronger influence than He ion flux or fluence**

D_2-He mixture plasma w/wo Be induces morphology on W at T_s = 1100 K & E_i = 60 eV.

E_i = 60 eV, T_s = 1100 K, Fluence = 10^{25} He^+/m^2

D_2-He plasma

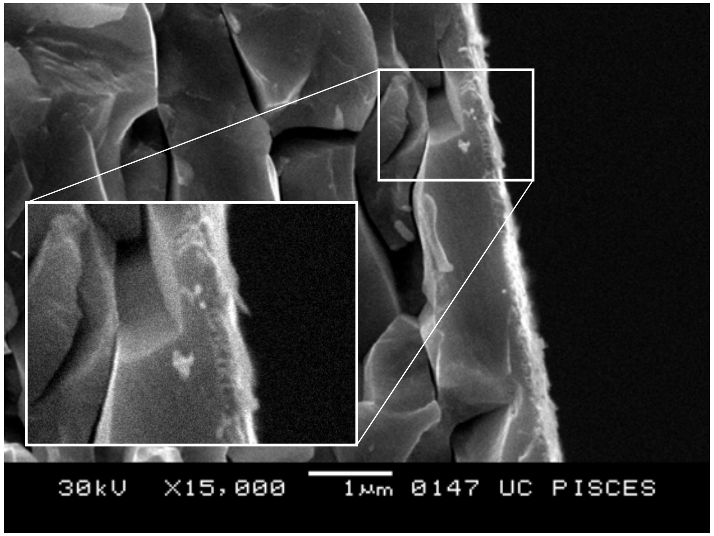
$n_{He+}/n_e \sim 10$ %,
Δt = 4200 s



- Finger-like structures observed, similar to pure He plasma

D_2-He plasma with Be

$n_{He+}/n_e \sim 10$ %, $n_{Be+}/n_e \sim 0.2$ %,
Δt = 4200 s



- Ion bombardment at E_i = 60 eV prevents Be layer growth.

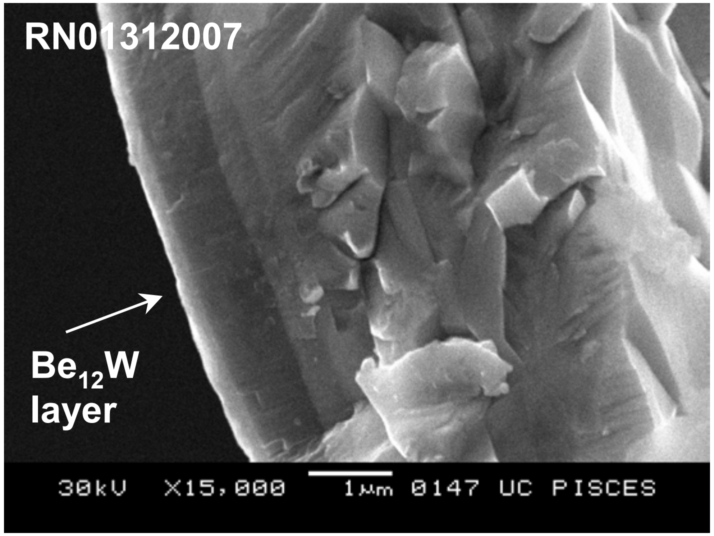
⇨ But, Be somewhat inhibits morphology.

Be or C plasma impurities can inhibit morphology at T_s = 1100 K & E_i = 15 eV.

E_i = 15 eV, T_s = 1100 K, Fluence = 10^{25} He^+/m^2

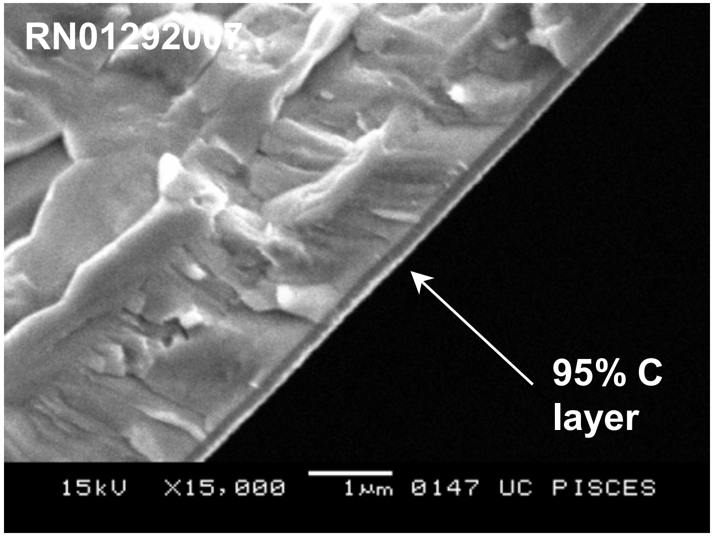
D_2-He plasma with Be

$n_{He+}/n_e \sim 10$ %, $n_{Be+}/n_e \sim 0.5$ %,
Δt = 5000 s



D_2-He plasma with C

$n_{He+}/n_e \sim 10$ %, $n_{C+}/n_e < 0.1$ %,
Δt = 3600 s



- Surface layer composition determined by x-ray microanalysis (WDS).
- At E_i = 15 eV, Be and C deposited on W are not sputtered away.

⇨ **Be-W alloy and W-C layers inhibit He induced morphology**.

Summary

- PISCES-B experiments continue to focus on mixed materials and/or mixed plasma species effects on steady state reactor relevant PMI.

- ITER will have significant levels of SOL Be impurities and diverted plasma will involve mixed species (D, Be, He) PMI with (C, W) PFC's.

- Collaborations on Be/C/W have produced significant new results:
  - Be reacts readily with C forming Be_2C.
  - Be mitigates erosion effects on C.
  - Be alloys readily with W.
  - He induces morphology on W at elevated temperature.
  - Be, C plasma impurities can mitigate He on W morphology but more work is needed.