Mixed-material studies in PISCES-B

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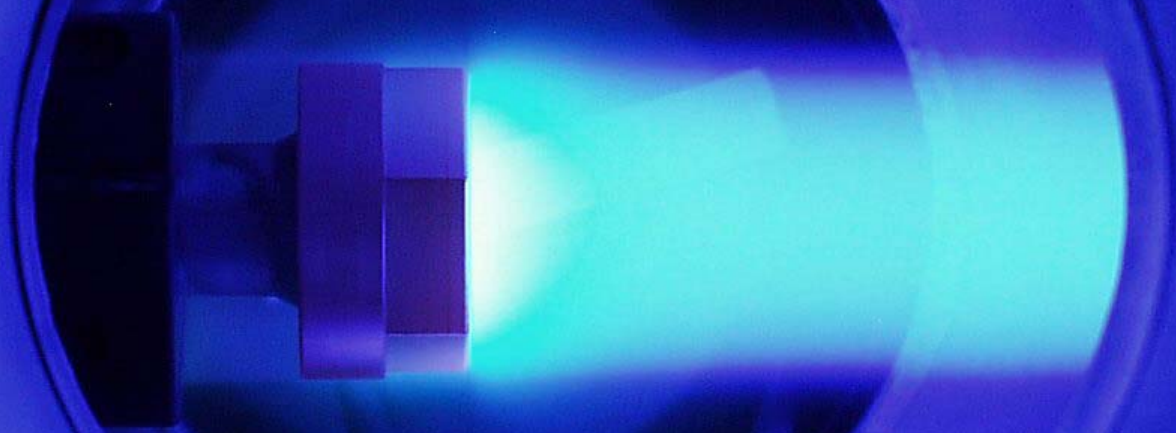

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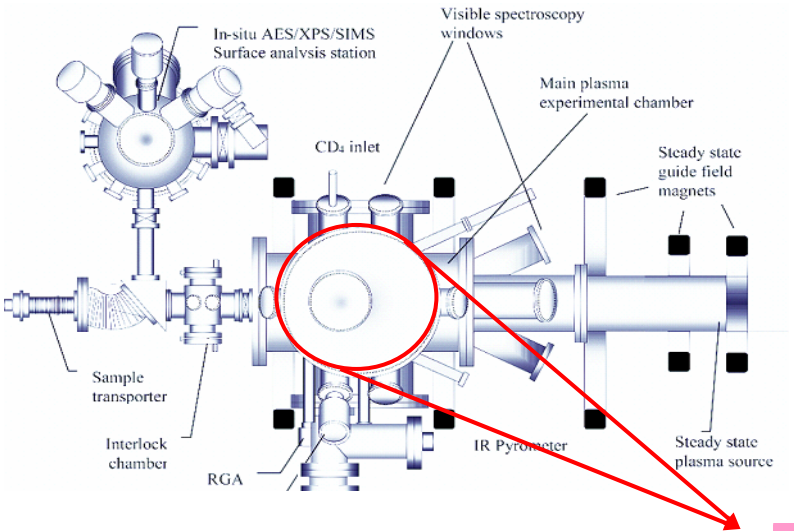
Max-Plank Institute for Plasmaphysics, Garching, Germany

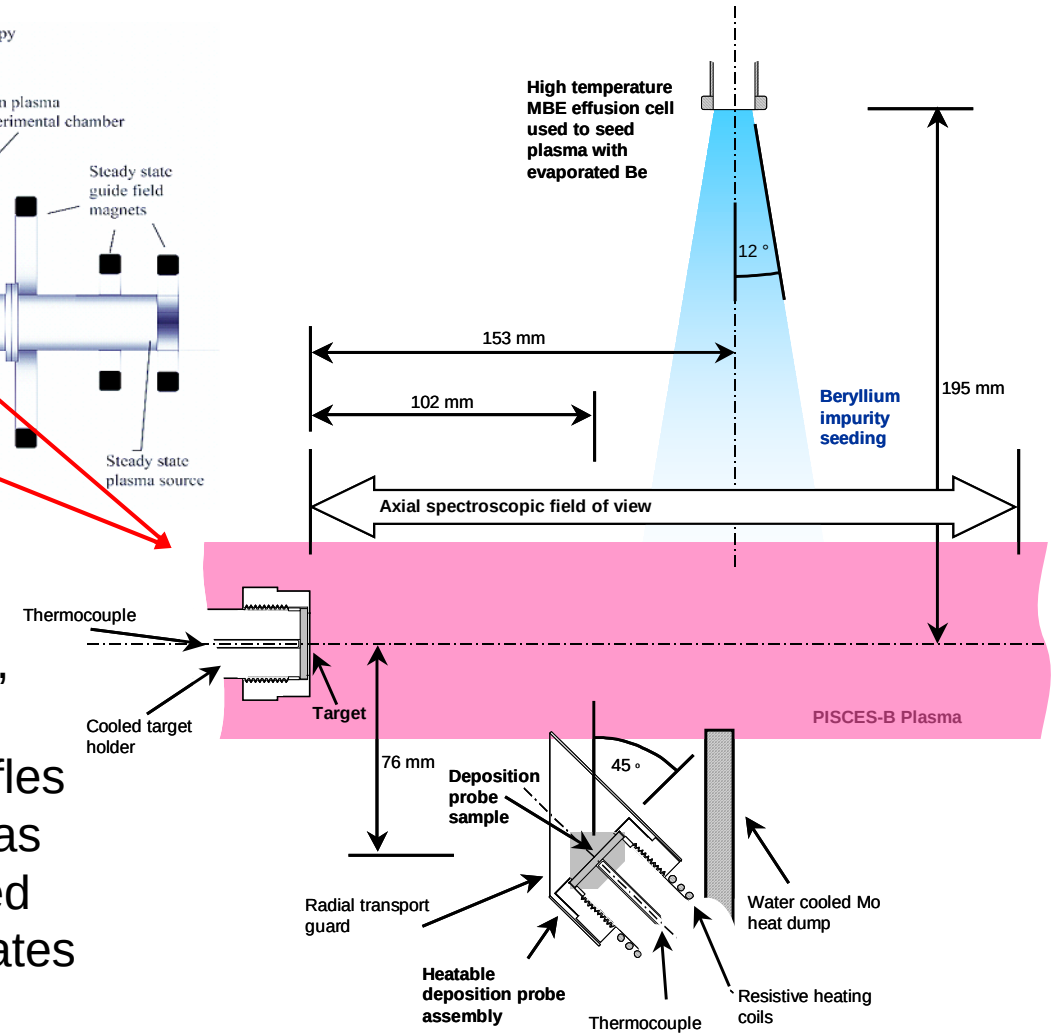
Work performed as part of US-EU Collaboration on Mixed-Material PMI Effects for ITER

Outline

- Introduction
- Technical results
  - Temporal behavior of chemical erosion suppression
  - D retention in, and release from, Be- rich codeposits
  - Response of Be/C to thermal transients
  - Be/W formation conditions
- Summary of possible mixed-material implications for ITER

PISCES-B has been modified to allow exposure of samples to Be seeded plasma



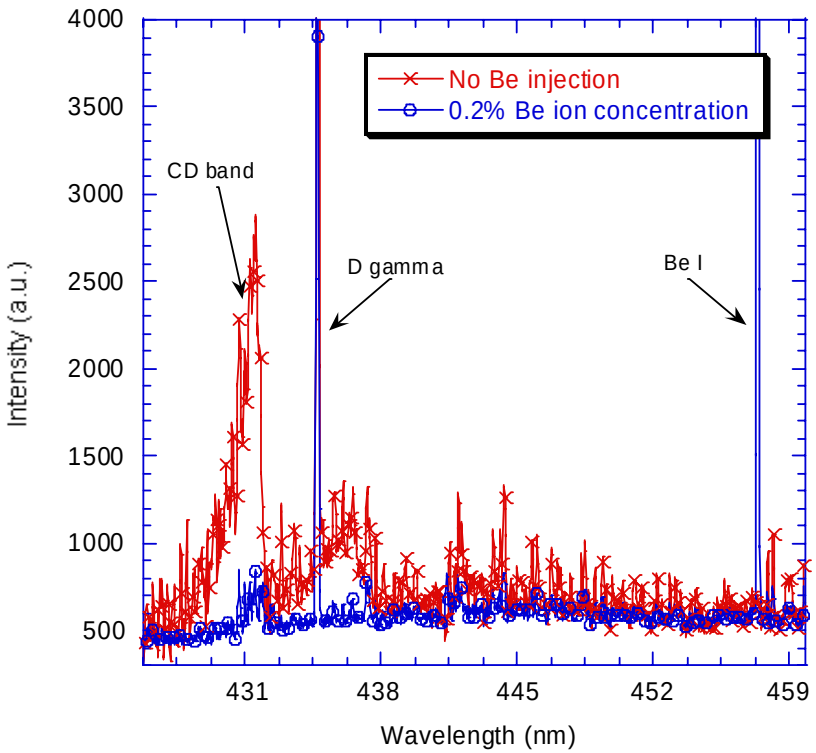


P-B experiments simulate Be erosion from ITER wall, subsequent sol transport and interaction with W baffles or C dump plates, as well as investigation of codeposited materials using witness plates

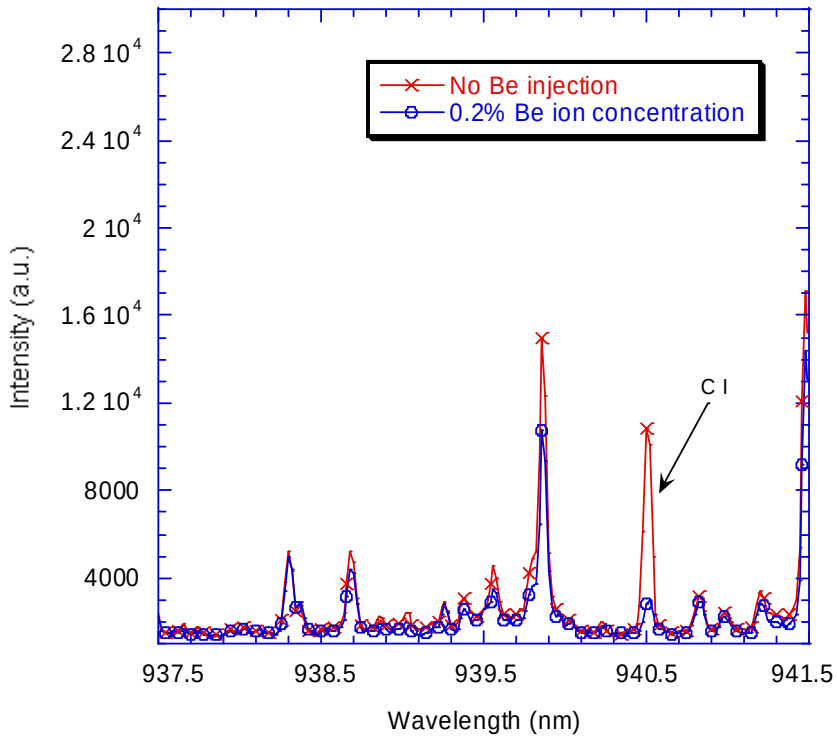
A small beryllium impurity concentration in the plasma drastically suppresses carbon erosion

-50 V bias, 200ºC, T_e = 8 eV, n_e = 3 e 12 cm^{-3}

Chemical erosion

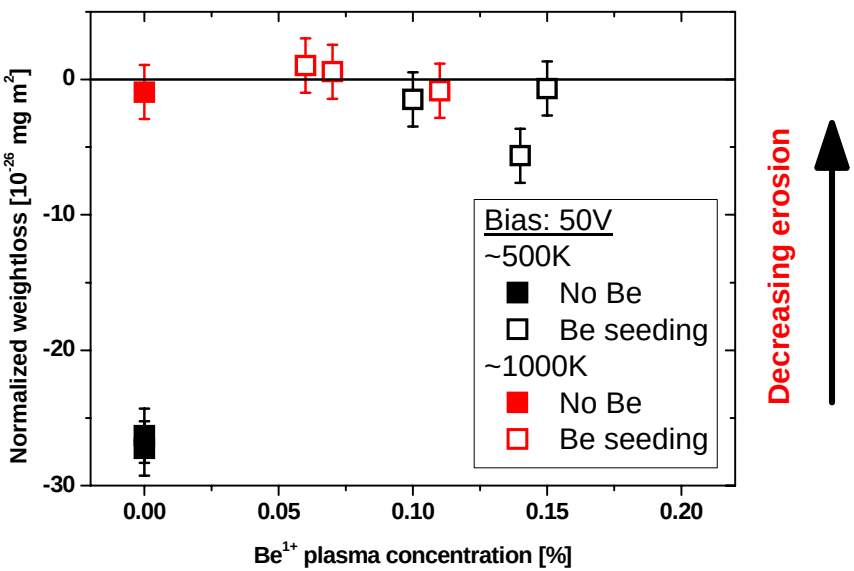


Physical sputtering

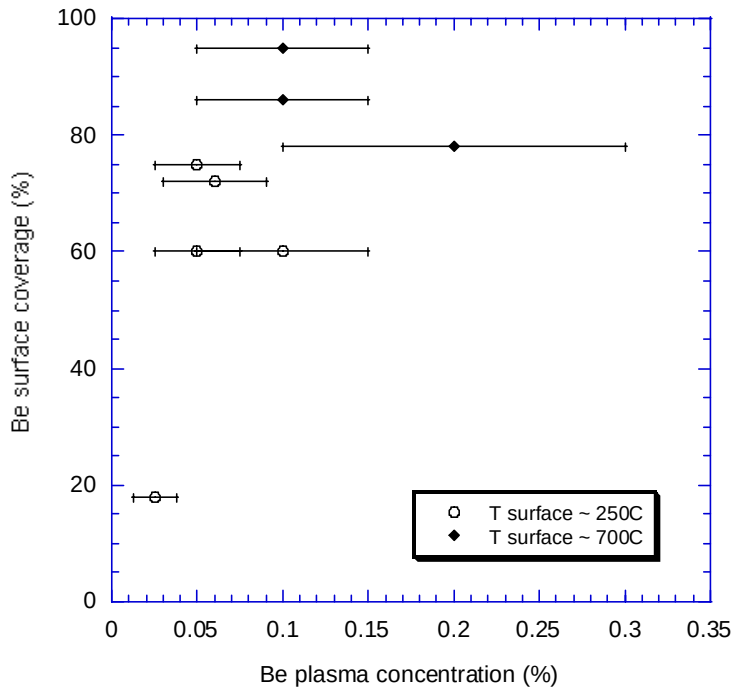


Be-rich surface layers form during exposure and shield underlying carbon from erosion

Weight loss data confirms reduction in erosion seen spectroscopically

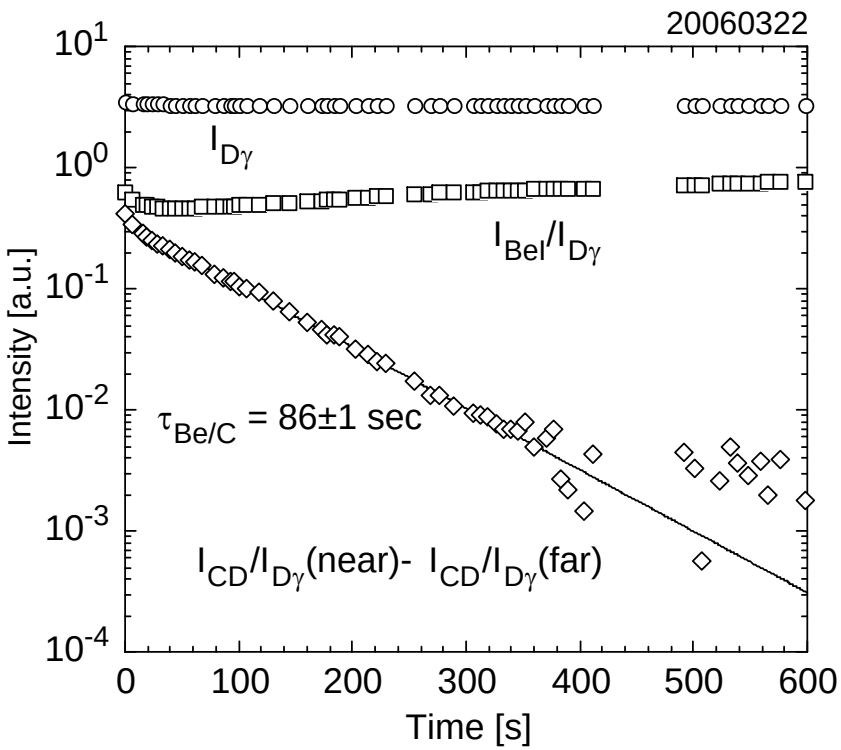


Equilibrium Be surface concentration after P-B exposure.



- ITER is expected to have 1-10% Be impurity concentration in the divertor plasma

Erosion suppression exhibits a temporal evolution ($\tau_{Be/C}$)



- Understanding the temporal behavior is critical to determining the fundamental mechanisms responsible for erosion mitigation
- PMI modeling codes should be able to reproduce temporal behavior to provide confidence (D. Borodin will describe this)

Evolution of a Be/C mixed-material surface

- Incident Be ions react with C target atoms forming Be_2C
- The presence of Be in the surface of the carbon target reduces chemical erosion of the surface
- Once all surface carbon is bound as Be_2C, the Be_2C layer thickness saturates
- Subsequent Be ion bombardment enriches the surface with Be that is easier to erode (compared to the Be in Be_2C)
- Primary species eroding from the target and being codeposited with deuterium is Be

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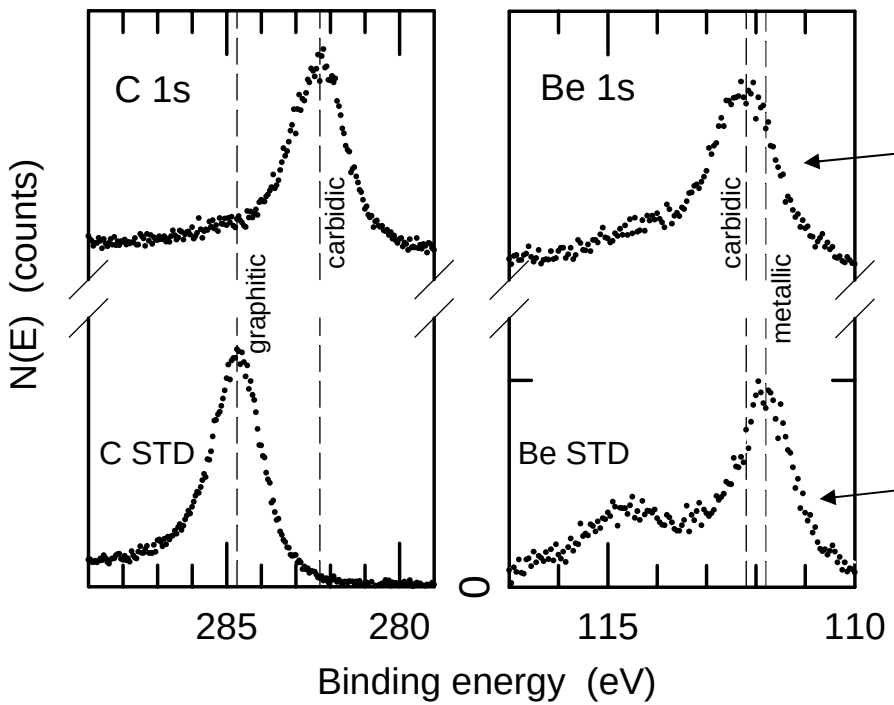
In-situ XPS analysis shows carbidic bonding

- Virtually all C in the surface is bound in carbidic bonds after mitigation of chemical erosion



ATJ graphite sample exposed to Beryllium seeded deuterium plasma

ATJ graphite sample exposed to clean deuterium plasma

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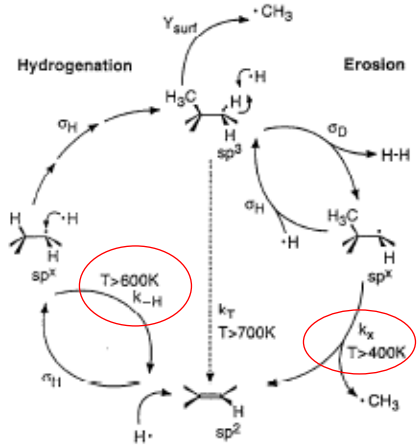
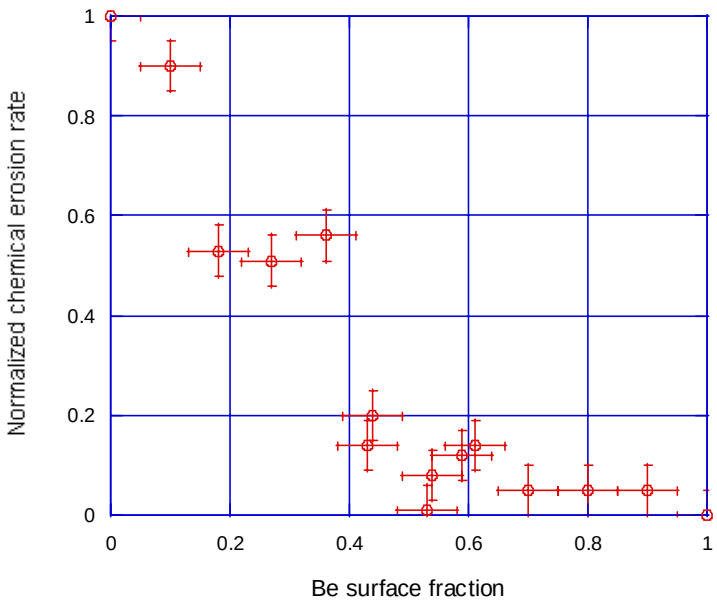
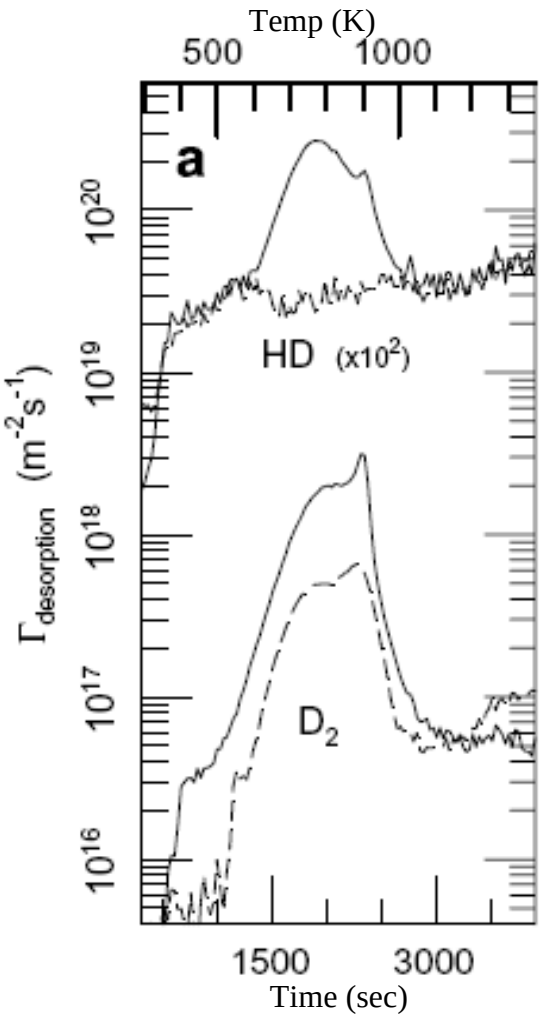
Be doping seems to act like B doping, inhibiting chemical erosion





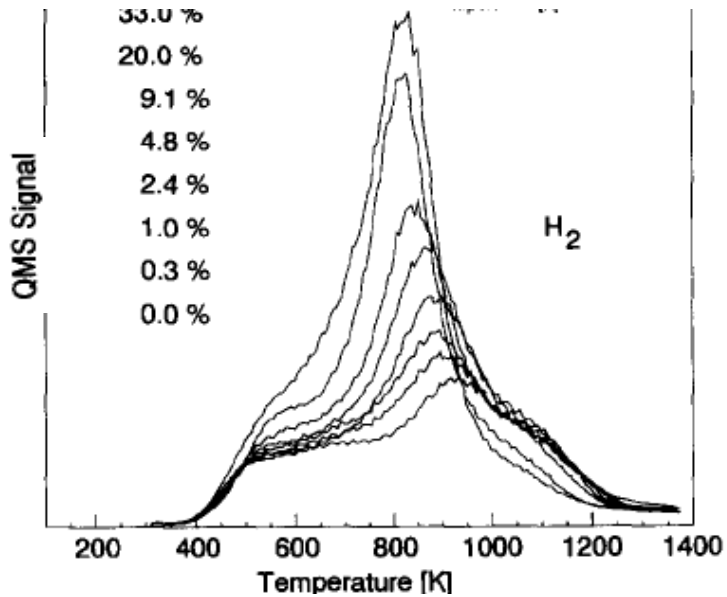
- Graphite dopants can alter the balance between hydrogenation steps that lead to thermal chemical erosion [Roth JNM 266-269(1999)51.]
- In-situ Be seeding (Be_2C surface formation) may also affect chemical sputtering term

In-situ Be doping of graphite exhibits similar behavior to boron doping of graphite



Solid line Be seeding
Dashed line no Be seeding

- Dopant increases retention
- Dopant shifts hydrogenic release to lower temperature



From A. Schenk JNM 220-222(1995)767 (B doping).

Evolution of a Be/C mixed-material surface

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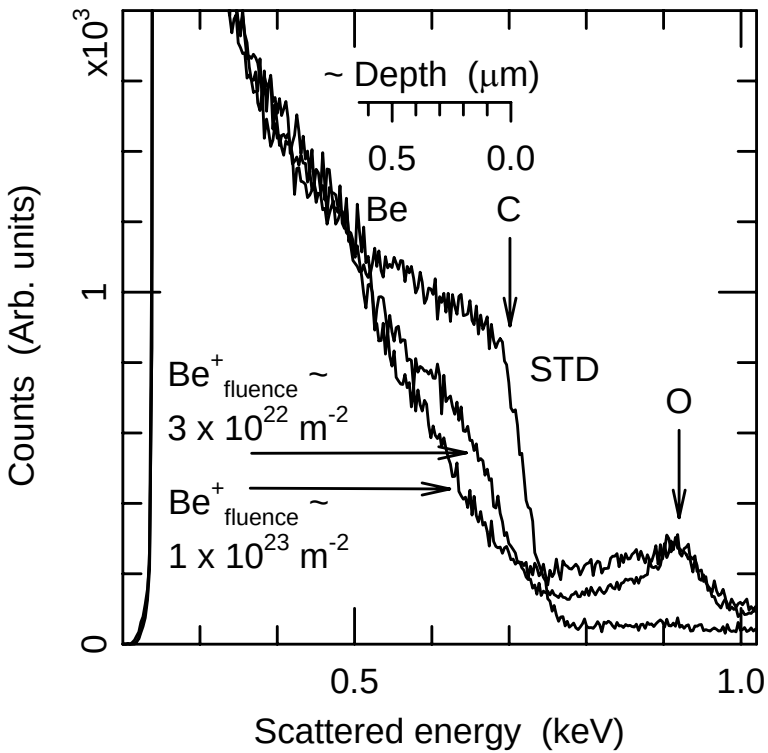
Be_2C layer thickness saturates

UW-Madison RBS spectra of P-B samples exposed to unseeded and Be-seeded plasma



From M. Baldwin et al., in press JNM

- Be layer observed after ~3E22 Be^+/m^2 (i.e 1600 s) accounts for virtually all incident Be
- Be layer after 1E23 Be^+/m^2 (i.e 4800 s) accounts for only ~30% of incident Be
- $\tau_{Be/C}$ under these plasma exposure conditions would be ~ 2000 sec

Evolution of a Be/C mixed-material surface

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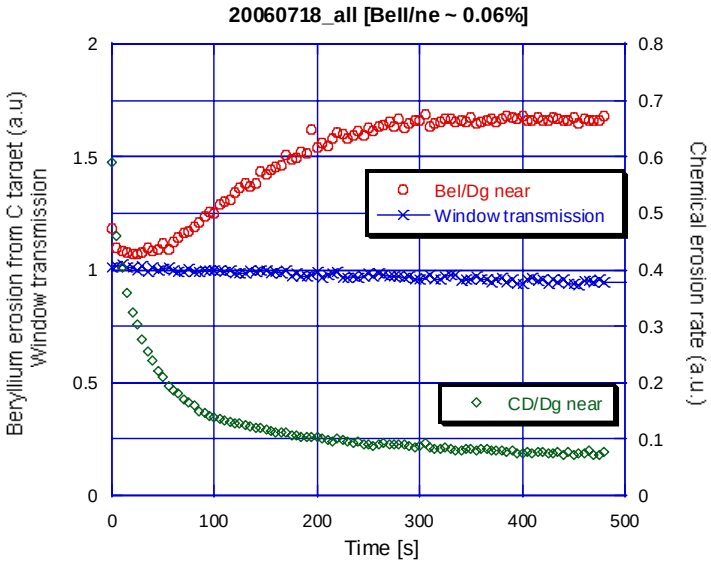
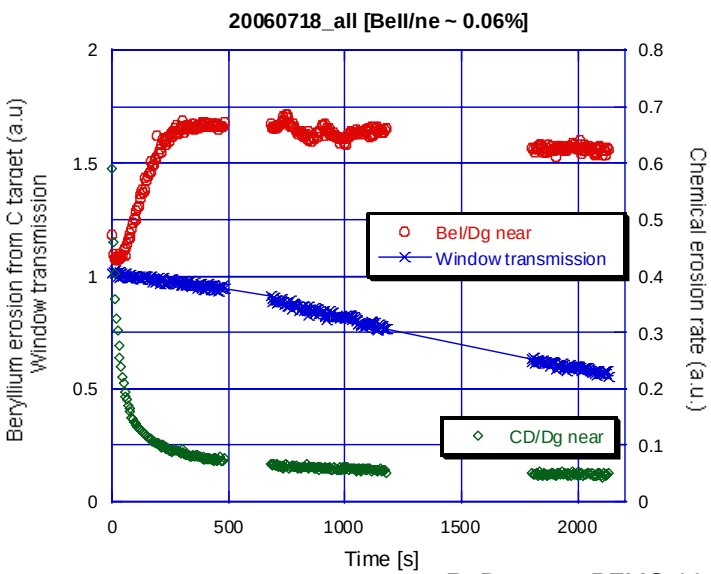
- Primary species eroding from the target and being codeposited with deuterium is Be

Be first shuts down C chemical erosion, then subsequent Be re-erodes from surface





- Be oven opens at t = 0 sec.
- Be ions arriving at t < 50s shut down chemical erosion by forming Be_2C surface layer [Baldwin JNM 2006 available on-line]
- Be_2C surface thickness saturates after carbide forms 50s in this exposure [Baldwin JNM 2006]
- Once Be_2C is formed, subsequent Be arriving (T > 50 s) is more easily eroded and begins coating windows

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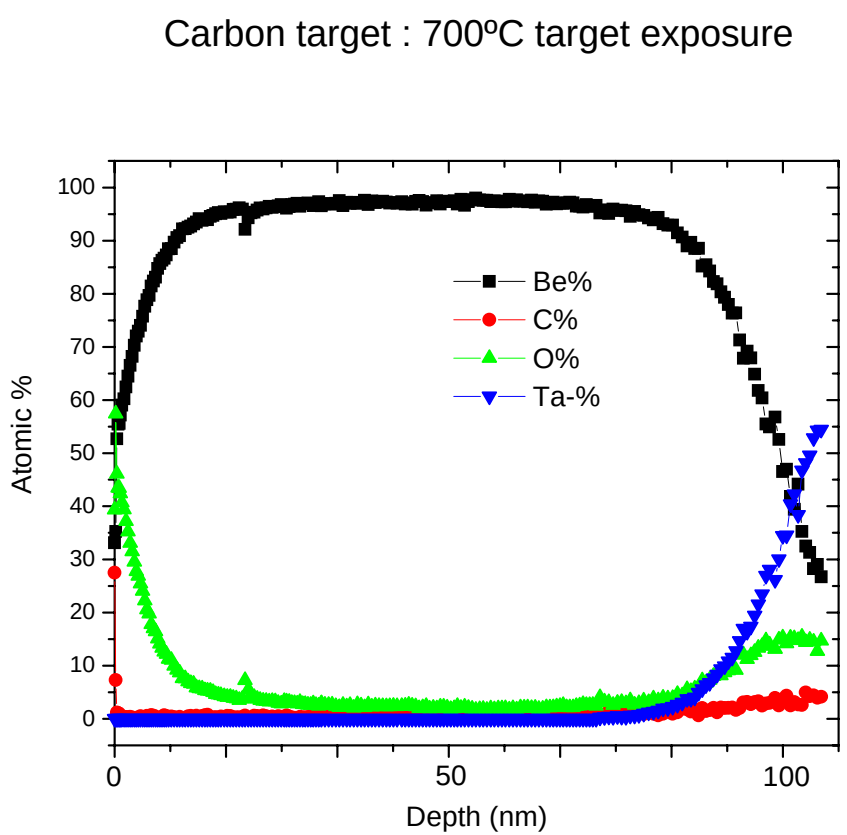
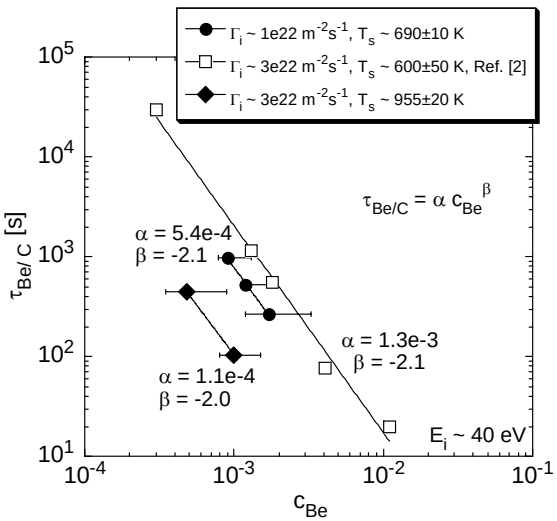
- Primary species eroding from the target and being codeposited with deuterium is Be

WPM samples show collection of beryllium-rich codeposits during Be seeding runs

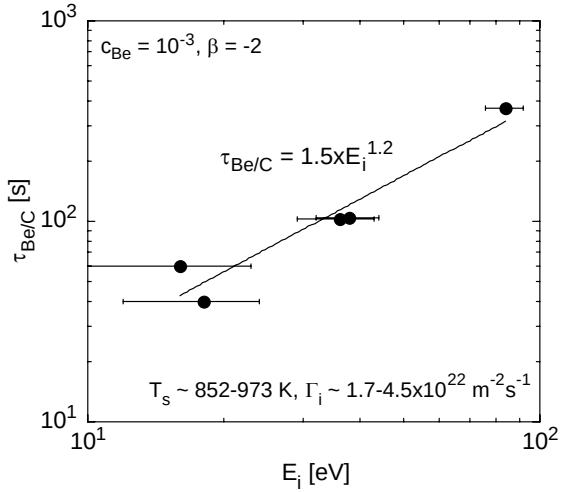


- t = 0 sec codeposited layer begins to form on Ta witness plate (100 nm in depth scale)
- Only a small amount of C is initially collected (90 – 100 nm depth scale)
- Almost pure Be (little O) continues to be deposited until discharge terminates (0 nm depth scale, surface of codeposited film)

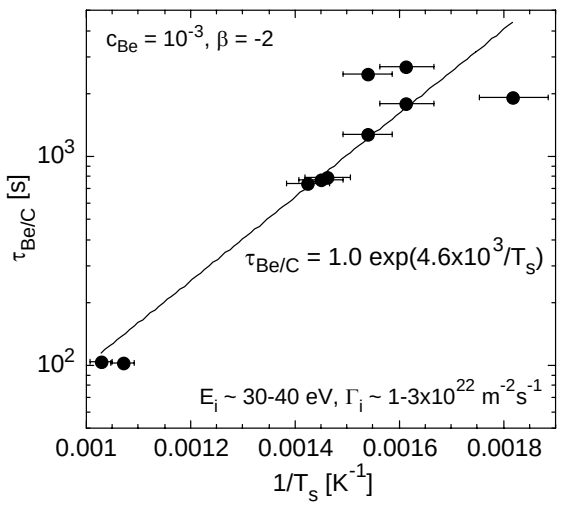
Chemical erosion suppression time ($\tau_{Be/C}$) depends on several variables that can be varied almost independently



Be concentration in plasma



Incident ion energy



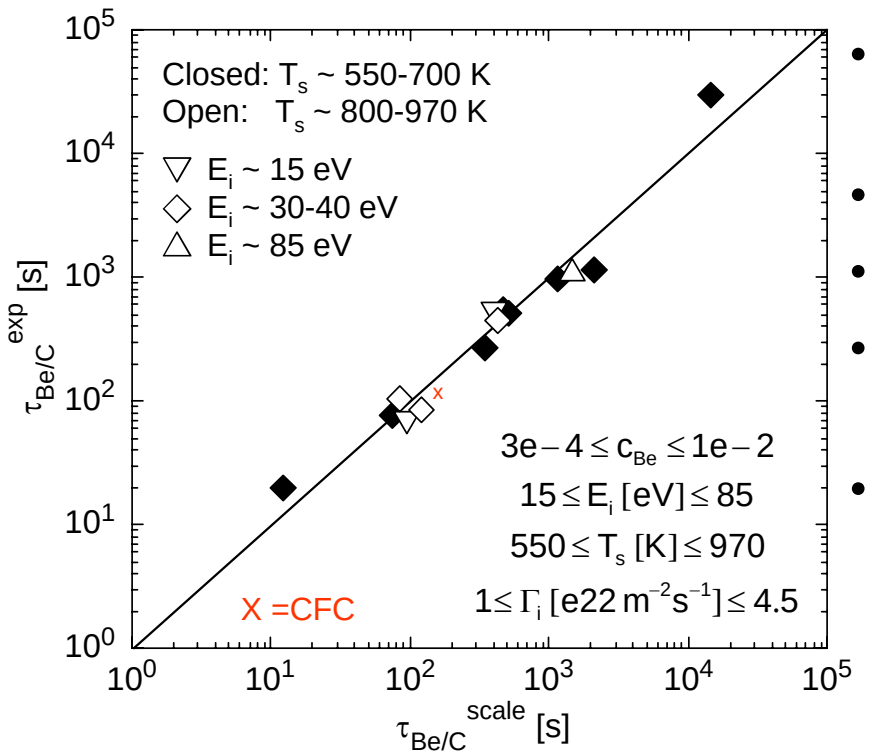
Surface temperature of target

From D. Nishijima et al., PSI17.

PISCES chemical erosion mitigation time scaling predicts suppression between ELMs in ITER

$$\tau_{Be/C}^{scale}\,[s] = 1.0\times10^{-7}\, c_{Be}^{-1.9\pm0.1}\, E_i^{0.9\pm0.3}\, \Gamma_i^{-0.6\pm0.3}\, \exp((4.8\pm0.5)\times10^3/T_s)$$

From D. Nishijima et al., PSI17.

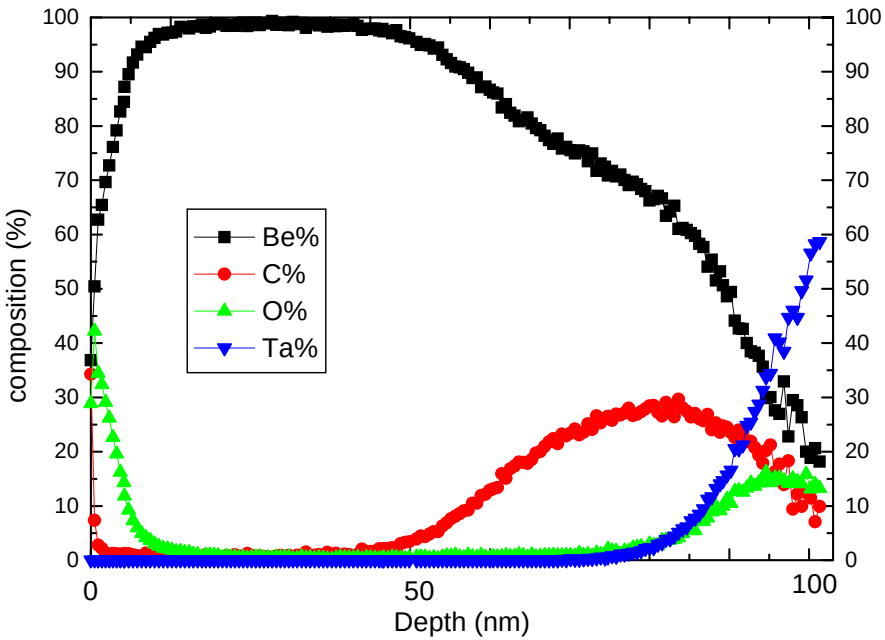


- Surface temperature effects reaction rate
- Be plasma concentration effects arrival rate at surface
- Ion energy effects erosion rate
- Ion flux impacts through redeposition
- Type of graphite does not seem to play a significant role (ATJ vs. CFC) (R. Pugno poster)
- Scaling law using these variables has been developed to allow extrapolation to ITER conditions ($\tau_{Be/C}^{ITER} \sim 6$ msec)

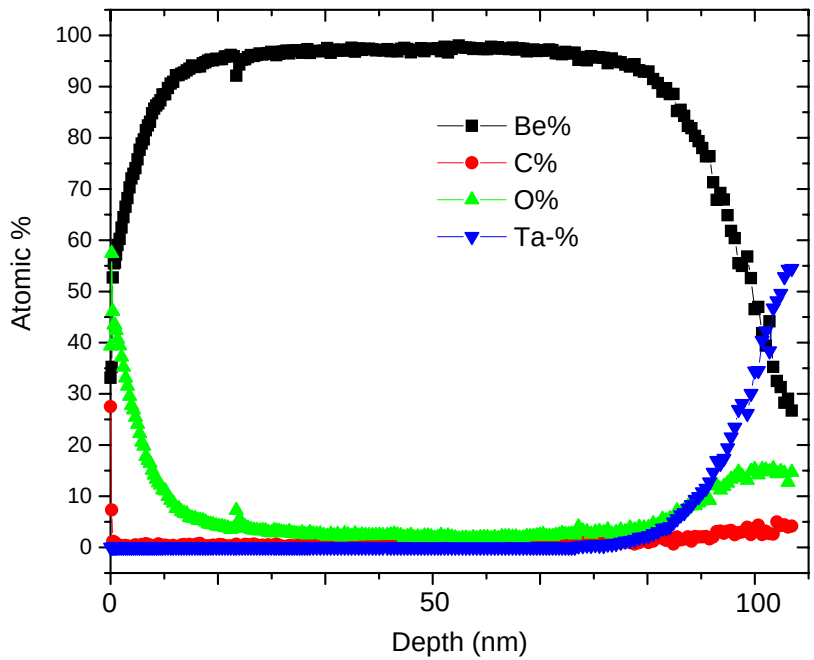
  [$c_{Be} = 0.05$, $E_i = 20$ eV, $T_s = 1200$ K and $\Gamma_i = 10^{23}$ m^{-2}s^{-1}]

Faster mitigation time results in less C content in witness plate codeposits

Carbon target : 300ºC target exposure

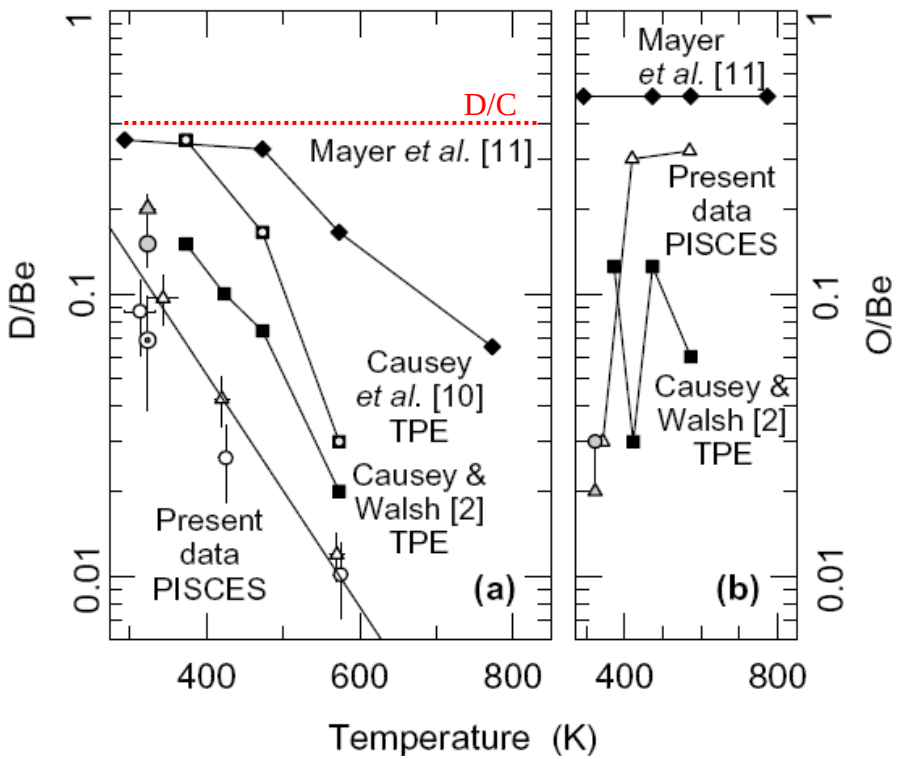


Carbon target : 700ºC target exposure



More C is detected in codeposits during lower C target temperature exposure (possibly due to a combination of lower chemical erosion yield and/or quicker beryllium carbide layer formation at higher temperature)

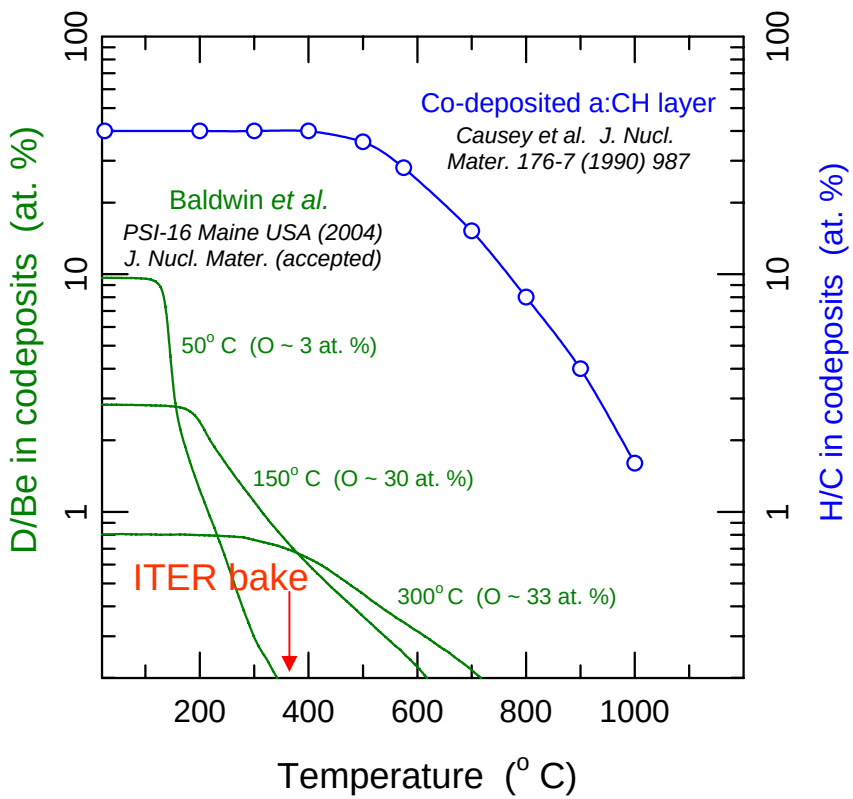
T accumulation in ITER is dominated by codeposited material



From Baldwin et al. JNM 337-339(2005)590.
Refs. 2, 10 & 11 therein

- Impurity content in Be codeposits impacts D retention level
- Surface temperature during codeposition has a more pronounced effect on retention
- Be codeposits will be in line-of-sight of erosion location
- Role of oxygen (i.e. BeO) in codeposits still needs to be determined

T retained in Be rich codeposits can be more easily removed during divertor bakeout

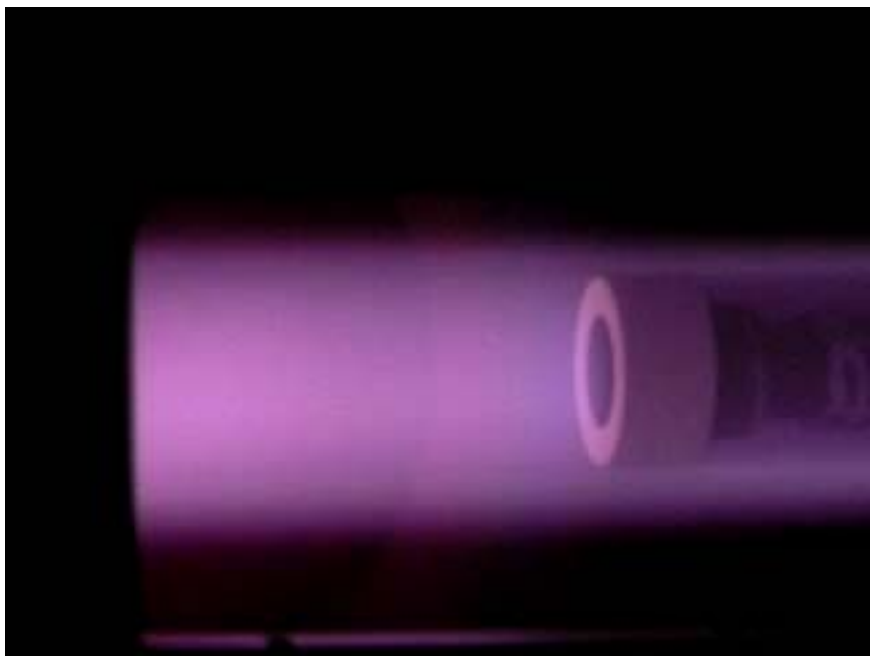


- Although more hydrogen isotopes are retained during lower surface temperature Be codeposition, they are more easily desorbed (role of oxygen needs to be determined)
- ITER can bake divertor to 375°C (after coolant drain)
- Oxygen bake may not be needed to remove fuel atoms from codeposits

Thermal transient experiments: Motivation for positive pulse biasing

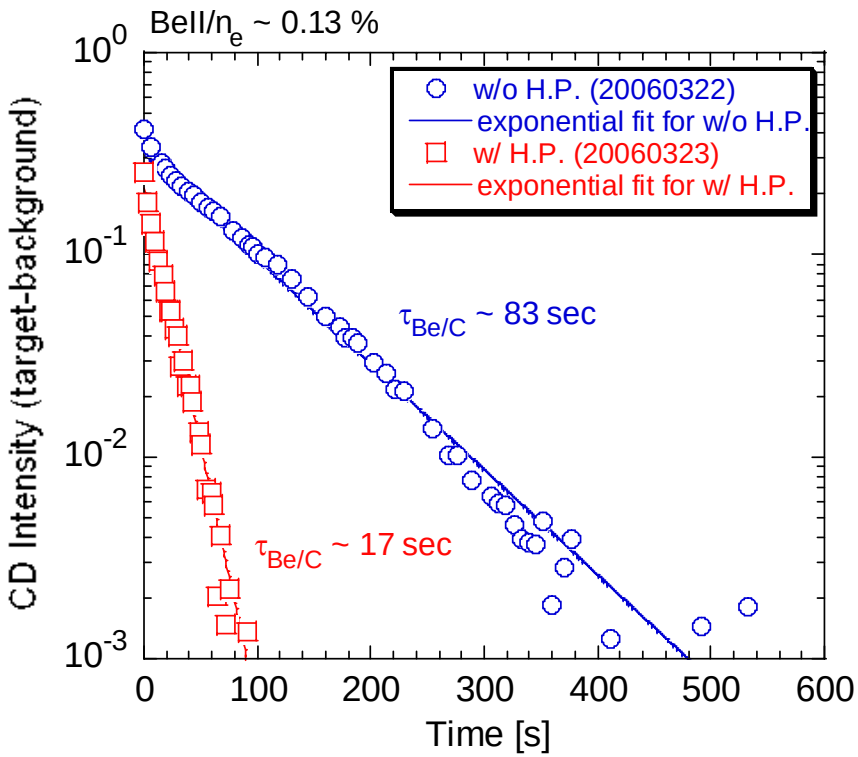
- PISCES has shown that Be plasma impurities suppress carbon target erosion at temperatures up to 1000°C
- ITER will experience large temperature excursions (up to 3800°C) at the carbon dump plates during periodic ELMs
- Will the thin, surface Be, Be/C layers survive such dramatic temperature excursions?
- It is possible to simulate the large temperature excursions associated with ITER ELMs in PISCES-B using positive sample biasing during plasma discharges.

Large power loads can be drawn to P-B sample during positive biasing



- During 1.5 MW/m^2 power pulse graphite surface temperature rises to ~2000°C (by pyrometers)
- Bulk graphite temperature rise at back of sample ~20°C during 0.1 s. pulse (thermocouple)
- Surface temperature rise is limited by power supplies (IPP has supplied a new power supply as part of US-EU collaboration)

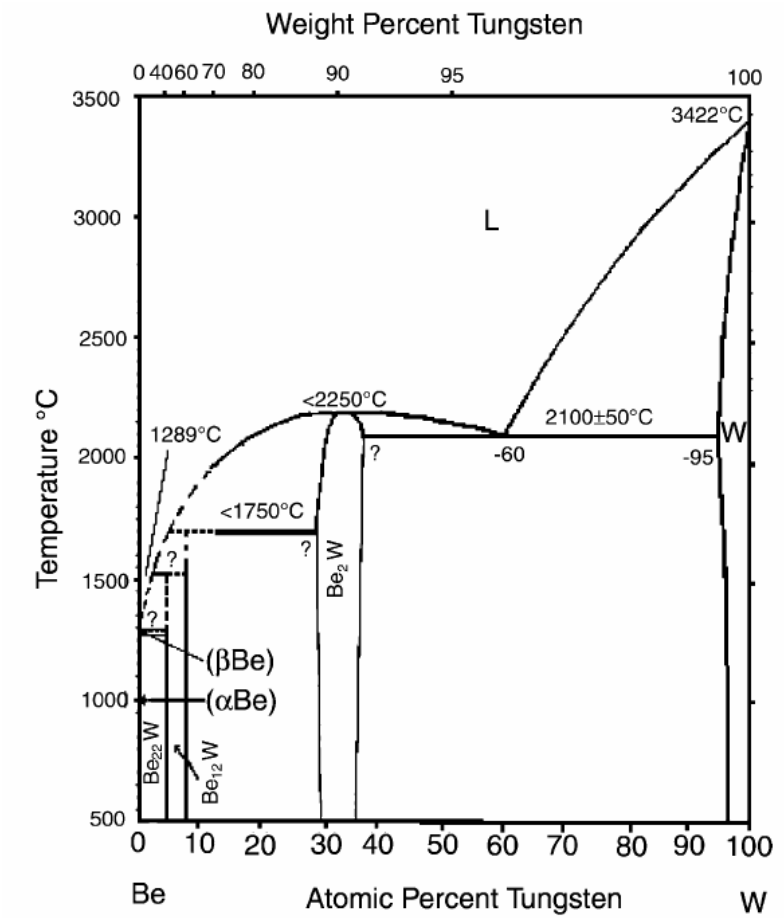
Transient surface heating promotes Be_2C formation leading to shorter mitigation times



Surface temperature during heat pulse ~ 1200°C
[from R. Pungo et al., PSI17]

- Pulsing surface temperature to the 1200°C range results in faster chemical erosion suppression
  - Be_2C disassociates at ~2200°C at 1 atm
  - Beryllium boiling point = 2471°C at 1 atm
- D retention during transient surface heating also increases by ~50% both with and without Be plasma seeding

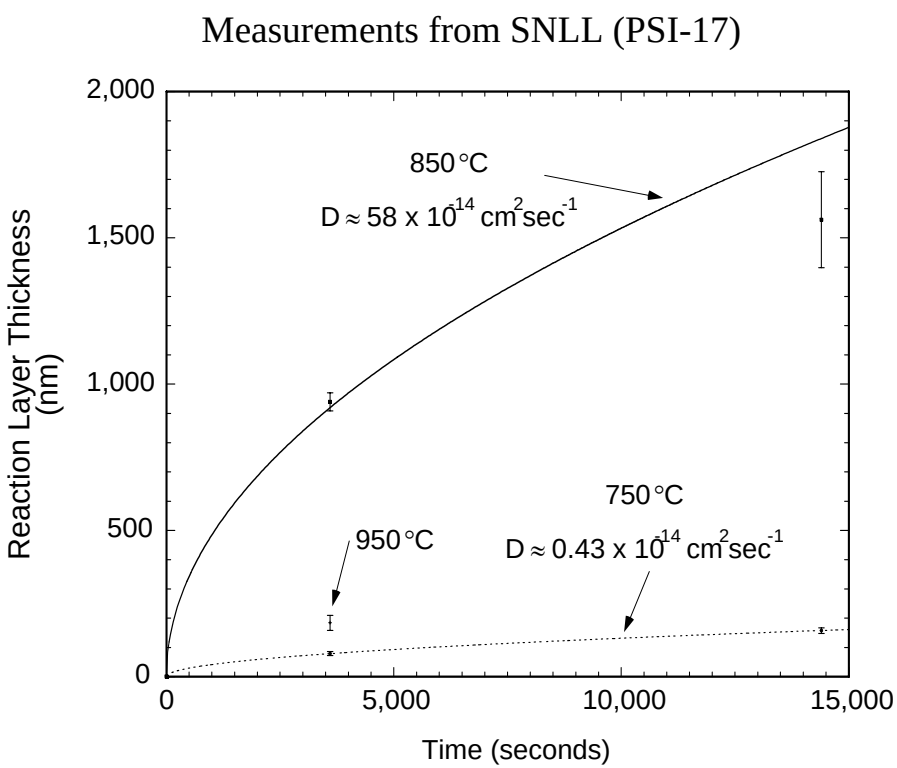
Tungsten beryllides (Be/W) have very recently become a big mixed-material concern



- Be_2W, $Be_{12}W$ and $Be_{22}W$ are all stable beryllides with significantly lower melting temperature than W
- Possibility for a major malfunction was realized (fortuitously?) during PISCES Be seeding experiments, where the W crucible holding molten Be experienced melting during operation at only ~1200ºC

R. P. Doerner et al., J. Nucl. Mater. 342(2005)63.

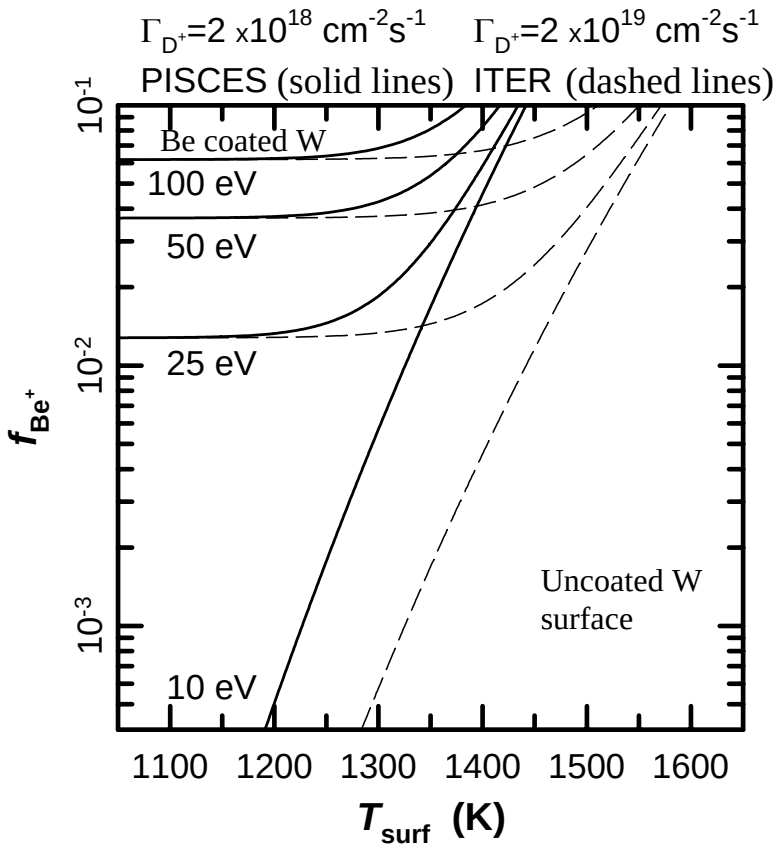
Tungsten beryllide (Be_xW) formation may plague hot W plasma facing components



- Be_2W and $Be_{12}W$ appear preferred ($Be_{22}W$ not seen)
- Beryllides only form in high temperature W surfaces (> 600°C)
- Be diffusion rate into W becomes significant above ~800°C
- At high temperature, Be availability (high vapor pressure of Be) on the surface can limit growth rate

Plasma conditions play a dominant role in determining the Be availability on the surface

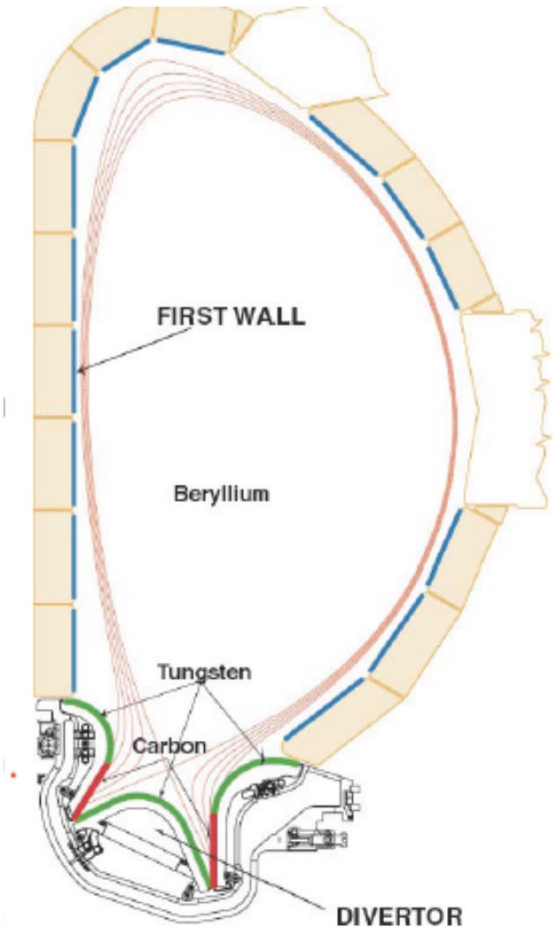
$$f_{Be}\,\Gamma_{plasma}(1-R_f) = Y_{D\text{-}Be}\Gamma_{plasma}(1-R_d) + f_{Be}Y_{Be\text{-}Be}\Gamma_{plasma}(1-R_d) + \Gamma_{evap}(1-R_e) + D_{bulk}$$



M. J. Baldwin et al., PSI17

- At high surface temperature, Be sublimation may prevent significant beryllide formation
- Sputtering at higher incident ion energies also tends to prevent significant beryllide formation
- Higher incident plasma flux tends to push energy, and temperature, necessary to limit beryllium availability to larger values

How might mixed materials impact ITER?



- Due to elevated temperature of C dump plates, carbides will likely form and limit C erosion
- Be deposition on W baffles will likely not result in significant beryllide formation (T_W ~ 400°C)
- If a full C divertor were employed, carbide formation on regions of the baffles, where the temperature is lower, would take longer, resulting in more C erosion and thereby more hard-to-remove tritium
- If a full W divertor were used, beryllide formation near the strike points could be a concern (perhaps an issue for the JET ITER-like wall experiments)
- Beryllide formation in ITER may be a concern on the W cassette liner ‘louvers’ (that are designed to be hot surfaces)