Results from the US-EU Collaboration on mixed-material PMI effects for ITER

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US-EU Collaboration on Mixed-Material PMI Effects for ITER

U.S. - R. Doerner – UCSD E.U. – A. Loarte - EFDA

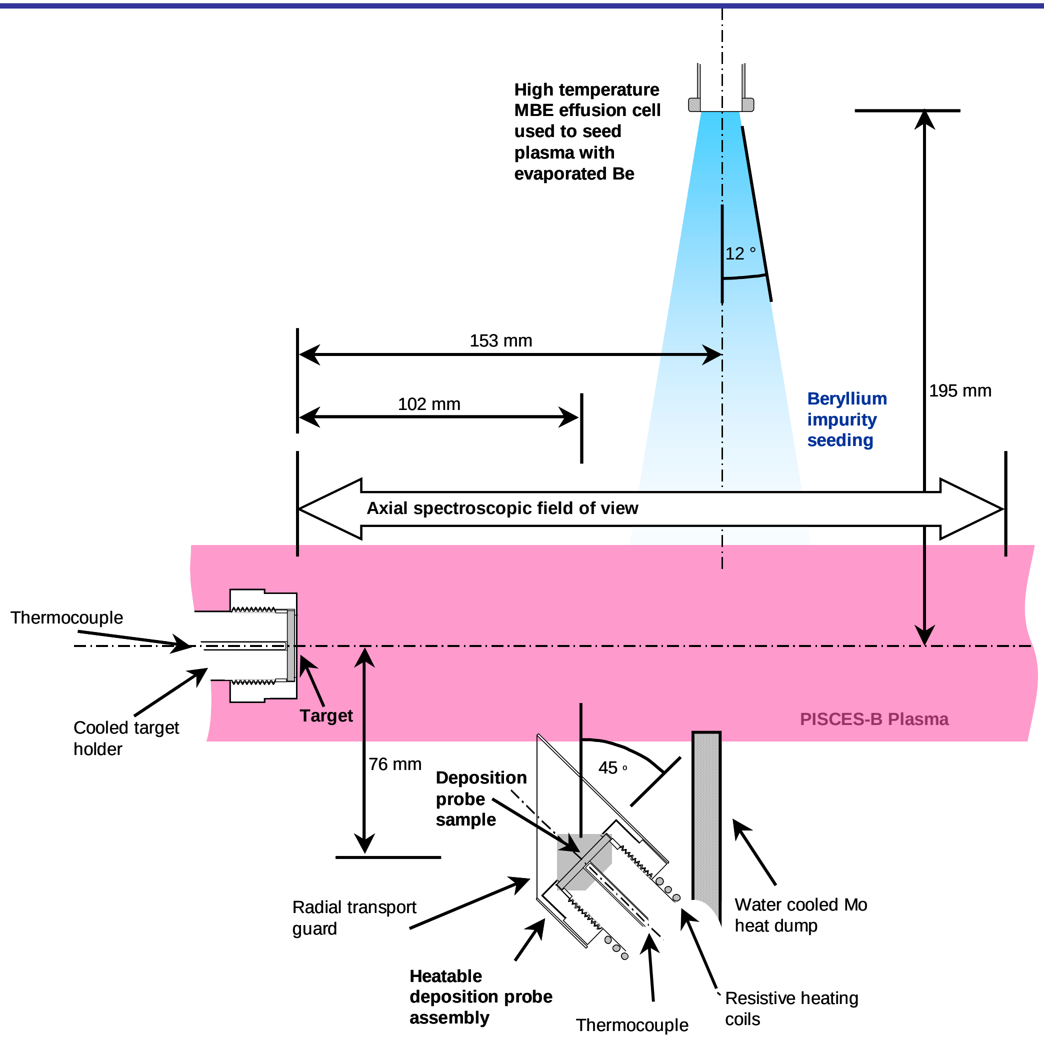
Three main experimental aspects:

- The erosion, deuterium retention and codeposition properties of graphite exposed to a beryllium-containing deuterium plasmas
- The erosion, deuterium retention and codeposition properties of tungsten exposed to deuterium plasma containing beryllium impurities (as well as with and without (in TPE) carbon impurities)
- The erosion and deuterium retention behavior of beryllium exposed to deuterium plasma at temperatures approaching the Be melting temperature

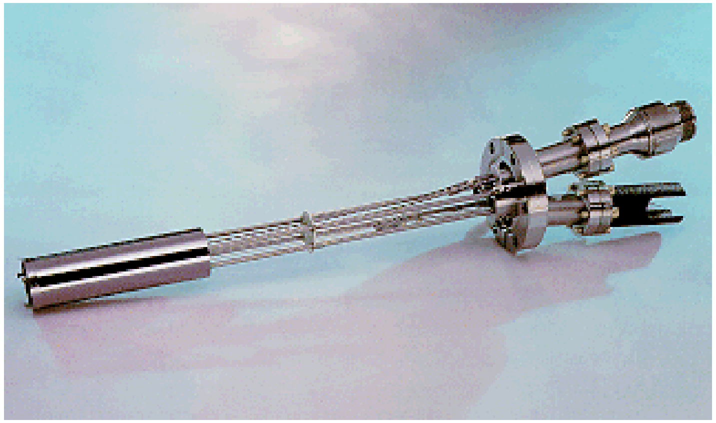
Verification of surface and edge plasma models:

TRIDYN (IPP), ERO (KFA), WBC (ANL), UEDGE (UCSD)

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



A commercial dopant cell (from Veeco EPI) is used to seed PISCES-B plasma with Be atoms.



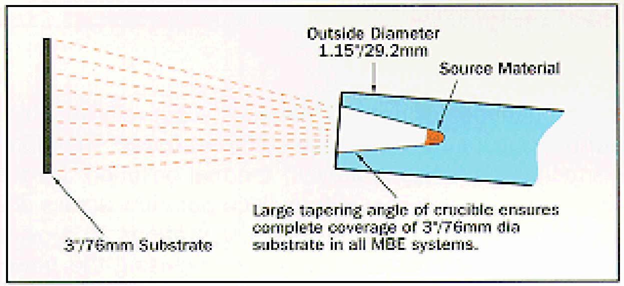
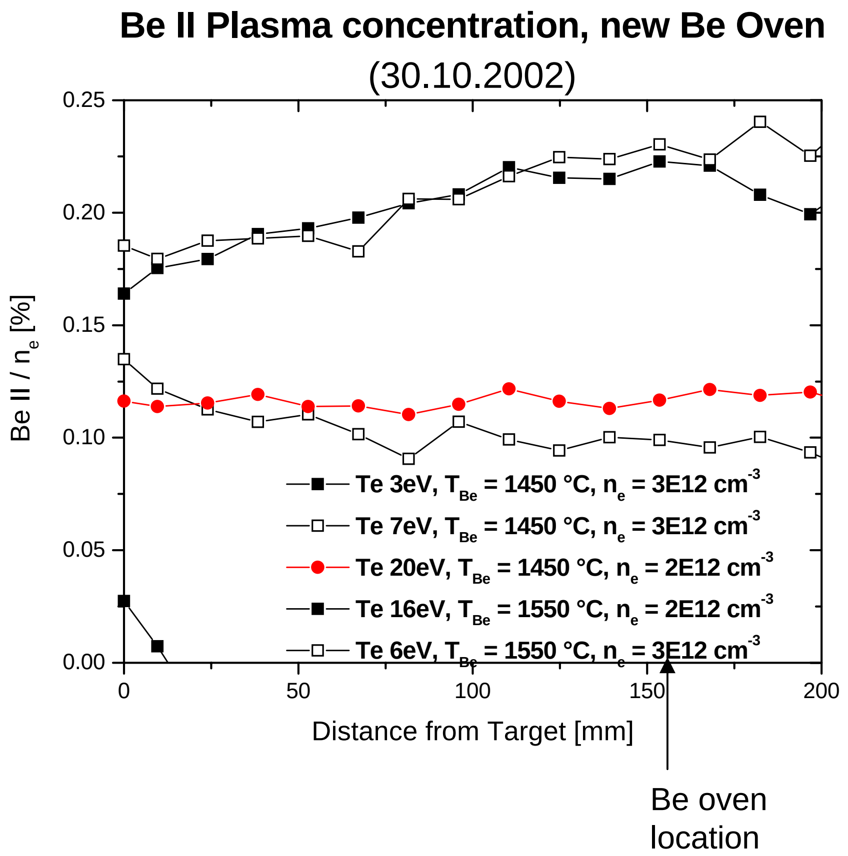


Figure One – Principle of operation, EPI Dopant Cell.

- 2000°C maximum temperature
- 1x 10^{22} Be atoms/sec maximum seeding rate (>plasma flux)
- 12° beam spread (measured with Li)
- Shutter for blocking beam during warm up and cool down
- PISCES plasma provides high ionization efficiency

PISCES-B operation above 6 eV T_e provides complete ionization of the thermal Be atom beam

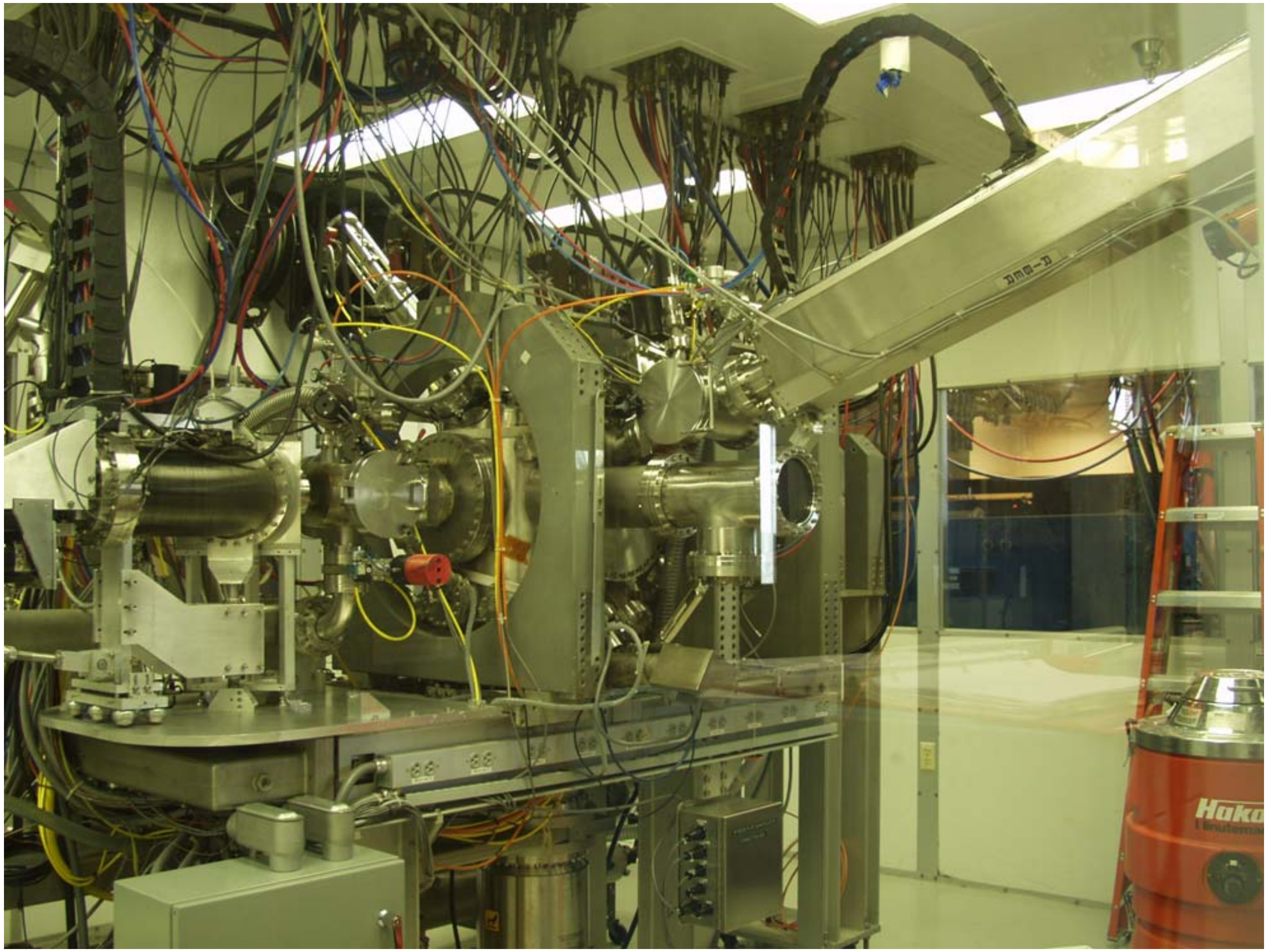


- Be II line emission @ 467 nm is used to measure Be ion density (along with ADAS rate coefficients)
- Be oven temperature controls Be ion density in the plasma
- Be concentration is fairly constant along the plasma column

IPP supplied witness plate manipulator system collects eroded material in PISCES-B

- Witness plate is shielded from cross-field plasma flux
- Independent control of witness plate temperature (r.t. – 500°C)
- Be containing samples will be analyzed at UCSD and IPP-Garching

WPM is installed on PISCES-B



Results from experimental task #1

Task 1

- The erosion, deuterium retention and codeposition properties of graphite exposed to a beryllium-containing deuterium plasmas

Task 2

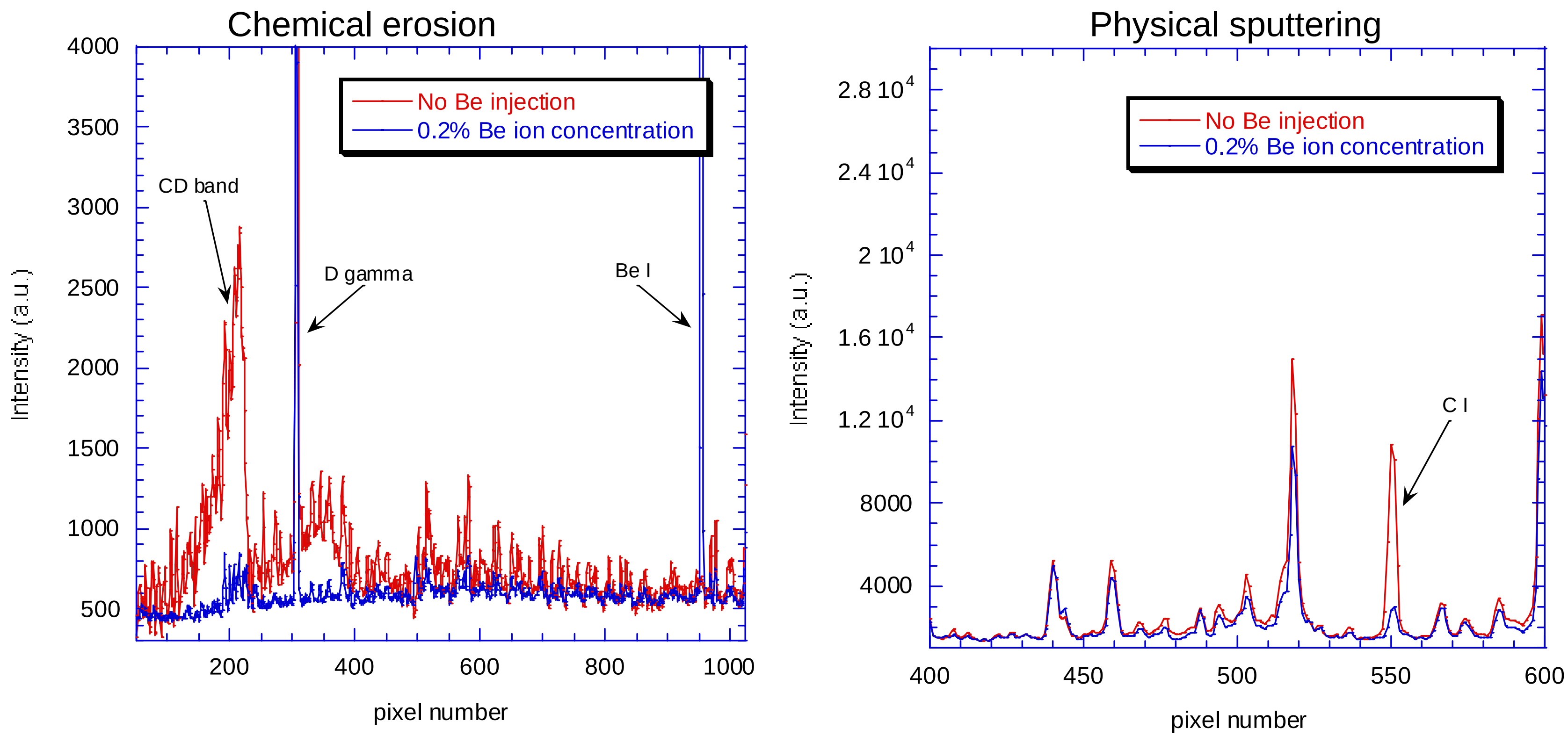
- The erosion, deuterium retention and codeposition properties of tungsten exposed to deuterium plasma containing beryllium impurities (as well as with and without (in TPE) carbon impurities)

Task 3

- The erosion and deuterium retention behavior of beryllium exposed to deuterium plasma at temperatures approaching the Be melting temperature

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}



Beryllium particle balance can give an estimate of expected equilibrium surface concentration

Be Film Growth Rate = Deposition Rate – Removal Rate = 0

Be Deposition Rate = $f_{Be}(1-R_f)\Gamma_{pl}$

where, f_{Be} is the Be concentration in the plasma, Γ_{pl} is the incident plasma flux and R_f is the Be ion reflection coefficient

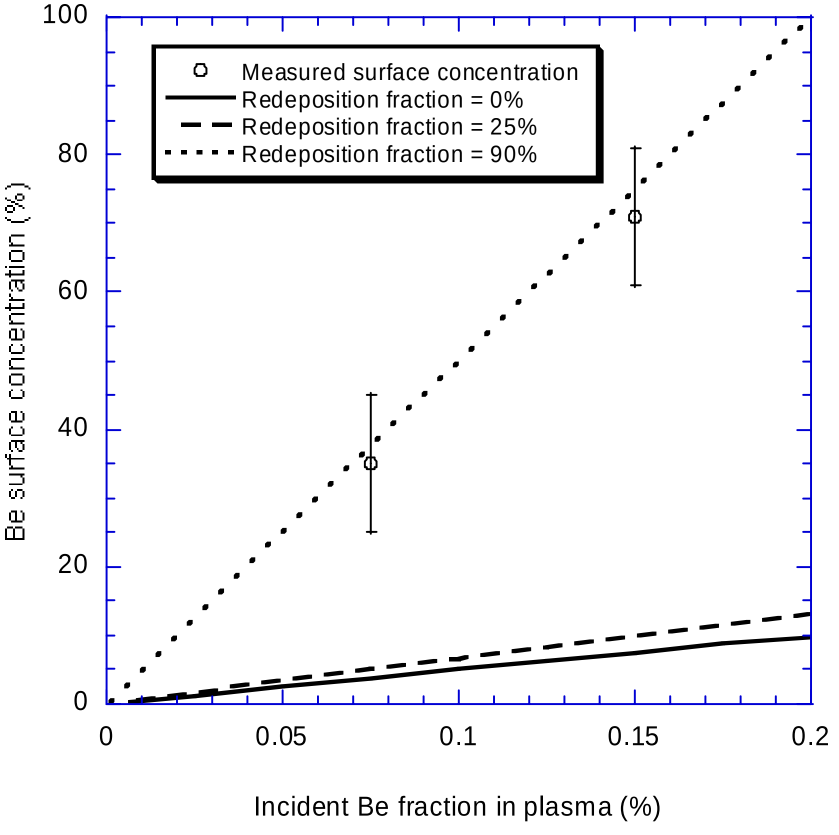
ignorable at low temp

Be Removal Rate =

$[c_{Be}Y_{Be}\Gamma_{pl}(1-R_d) + D_{bulk}(T) + c_{Be}Y(T)\Gamma_{pl}(1-R_d)]$

where, c_{Be} is the Be surface concentration, Y_{Be} is the low temp. sputtering yield of Be, R_d is the redeposition fraction, $D_{bulk}(T)$ accounts for diffusion of Be into the C bulk, and $Y(T)$ is the temperature dependent erosion yield term.

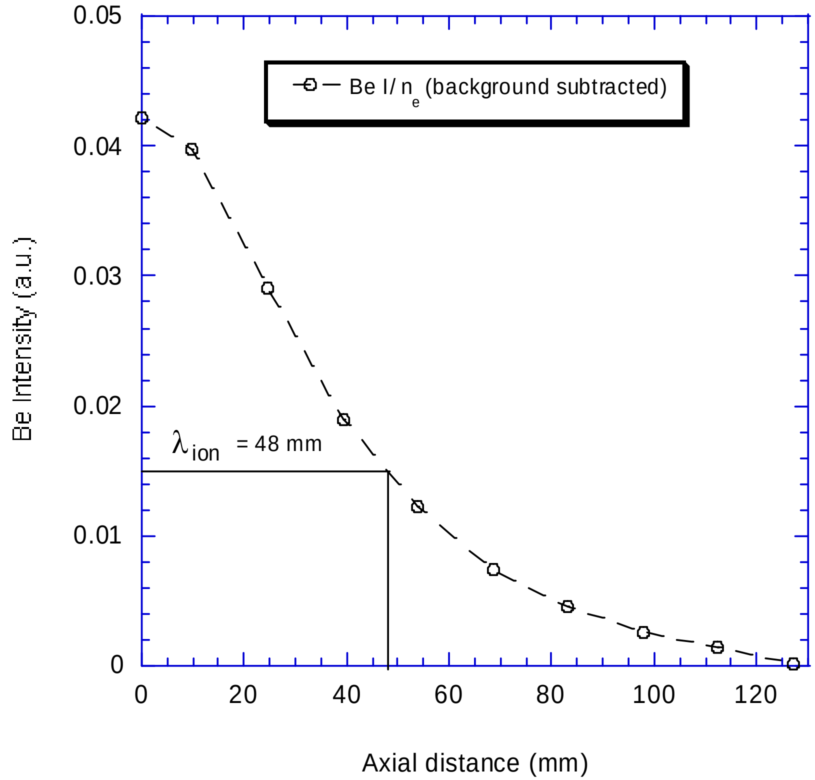
Exposure of graphite to plasma containing a small Be concentration quickly leads to complete surface coverage by Be coatings.



- Deuterium plasma w/Be injection
- Graphite sample temp = 60ºC
- Exposure duration = 10,000sec
- 3e18 ions/cm^{2}s
- 50 eV ion bombarding energy

- Experimental data consistent with 90% redeposition

Redeposition in these PISCES-B plasmas should be only about 25%



- Measured ionization mean-free path agrees with ADAS calculations
- Assume cosine sputtering distribution
- Redep fraction ~ (r_s/λ_{ion}) = 25%
- Be layers cover witness plate samples

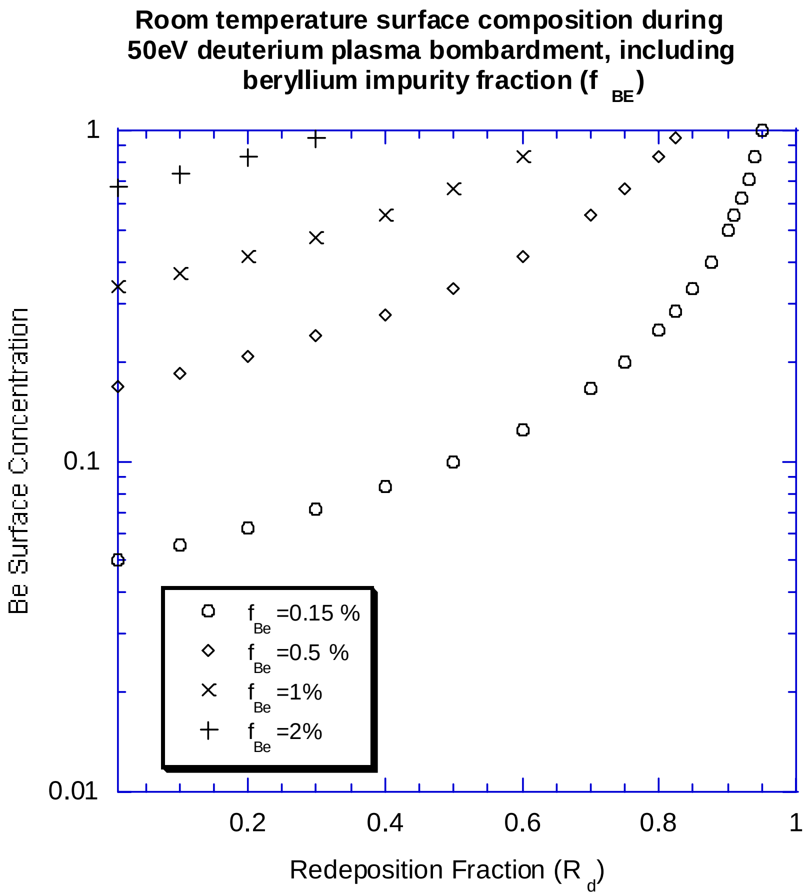
Modeling may help unravel this mystery

- TRIDYN is focusing on the evolution of a multi-component surface (i.e. preferential carbon erosion may increase Be surface concentration)
- ERO is examining effects associated with plasma physics effects (i.e. redeposition, transport)
- Molecular deuterium ions may also be important (i.e. D^+, D_2^+, D_3^+)

What does this all mean for ITER?

(What does this all mean for Carbon?)

Be surface coverage depends not only on f_{Be}, but also strongly on R_d



- Even for low Be impurity concentrations in the incident plasma full Be surface coverage is likely
- For Be impurity concentrations above 2%, full surface coverage always occurs (i.e., $f_{Be} > Y_{D\text{-}Be}$)
- ITER will have f_{Be} ~1-10% and large valves of R_d, so full Be surface coverage of in vessel components should be expected

Will everything change due to high surface temperature of the ITER divertor plates?

Be Film Growth Rate = Deposition Rate – Removal Rate

Be Deposition Rate = $f_{Be}(1-R_f)\Gamma_{pl}$

where, f_{Be} is the Be concentration in the plasma, Γ_{pl} is the incident plasma flux and R_f is the Be ion reflection coefficient

Be Removal Rate =

$[c_{Be}Y_{Be}\Gamma_{pl}(1-R_d) + D_{bulk}(T) + c_{Be}Y(T)\Gamma_{pl}(1-R_d)]$

where, c_{Be} is the Be surface concentration, Y_{Be} is the low temp. sputtering yield of Be, R_d is the redeposition fraction, $D_{bulk}(T)$ accounts for diffusion of Be into the C bulk, and $Y(T)$ is the temperature dependent erosion yield term.

First a brief summary of results from experimental task #3

Task 1

- The erosion, deuterium retention and codeposition properties of graphite exposed to a beryllium-containing deuterium plasmas

Task 2

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Task 3

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Radiation Activated Adatom Sublimation Model of High-Temperature Erosion

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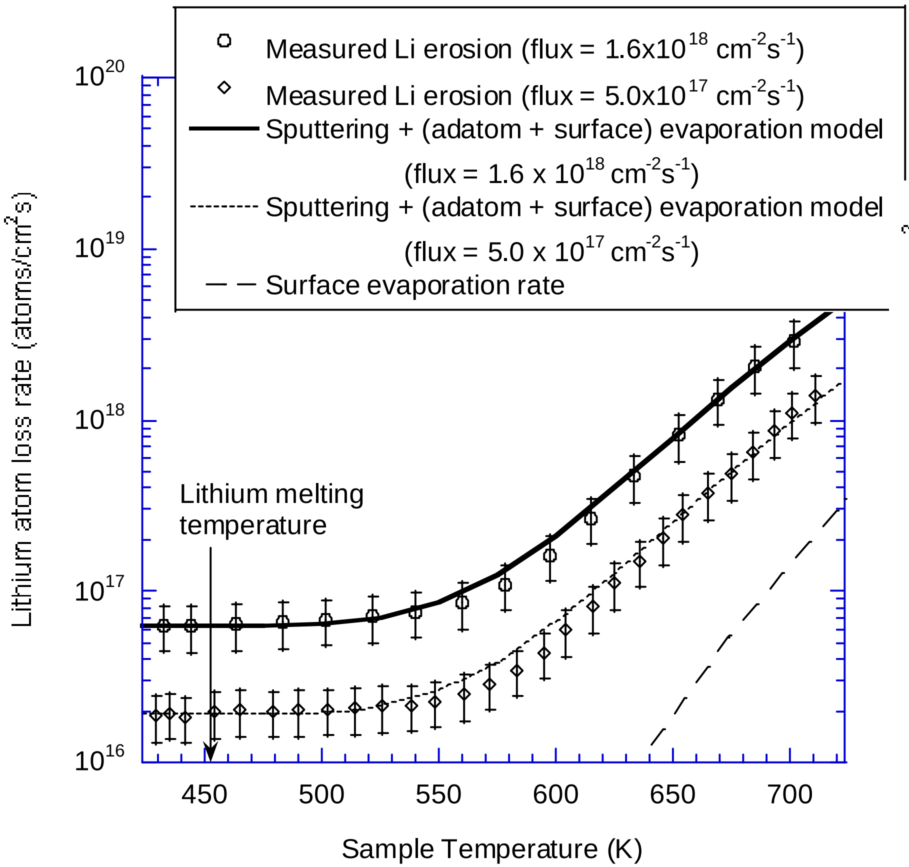
- Experiments observe enhanced loss of thermally released particles during bombardment of surfaces at elevated temperature
- Energetic particle bombardment of surfaces creates mobile surface adatoms
- Adatoms are less tightly bound to surface and therefore evaporate/sublimate more readily at lower temperature
- Measured enhanced erosion follows an Arhenius scaling with a reduced effective evaporation/sublimation energy
- Calculation of the adatom binding energy agrees with measured effective evaporation energy

RAAS Model Explains Observations of Enhanced Erosion from both Solid and Liquid Surfaces

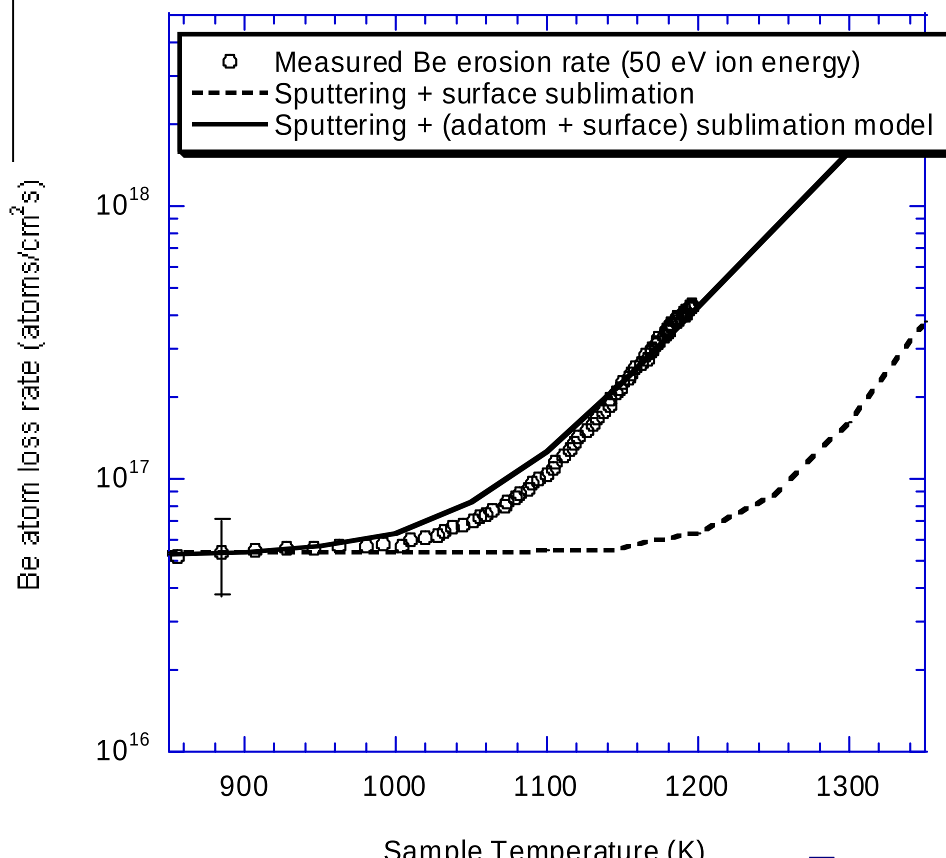
Liquid Lithium Erosion

(He plasma at 175 eV)



Solid Beryllium Erosion

(D plasma flux = $4x10^{18}$ $cm^{-2}s^{-1}$, 50 eV)



RAAS model can be used to predict temperature dependent erosion rates of Be layers in ITER

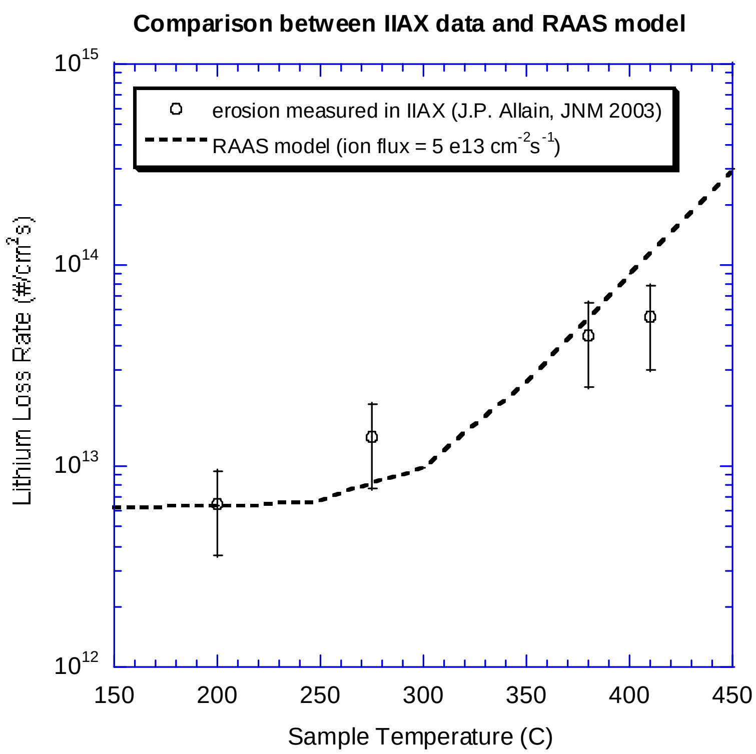
- Temperature dependent erosion rate R(T) can be written:

$$R(T) = J_{in}\left\{Y_{ps} + Y_{eff}\exp(-E_{eff}/T)\right\} + K_o n_o \exp(-E_o/T)$$

  – Where $Y_{eff} = K_{ad} Y_{ad} \tau^{o}_{ad}$ and $E_{eff} = E_{ad} - E_D$

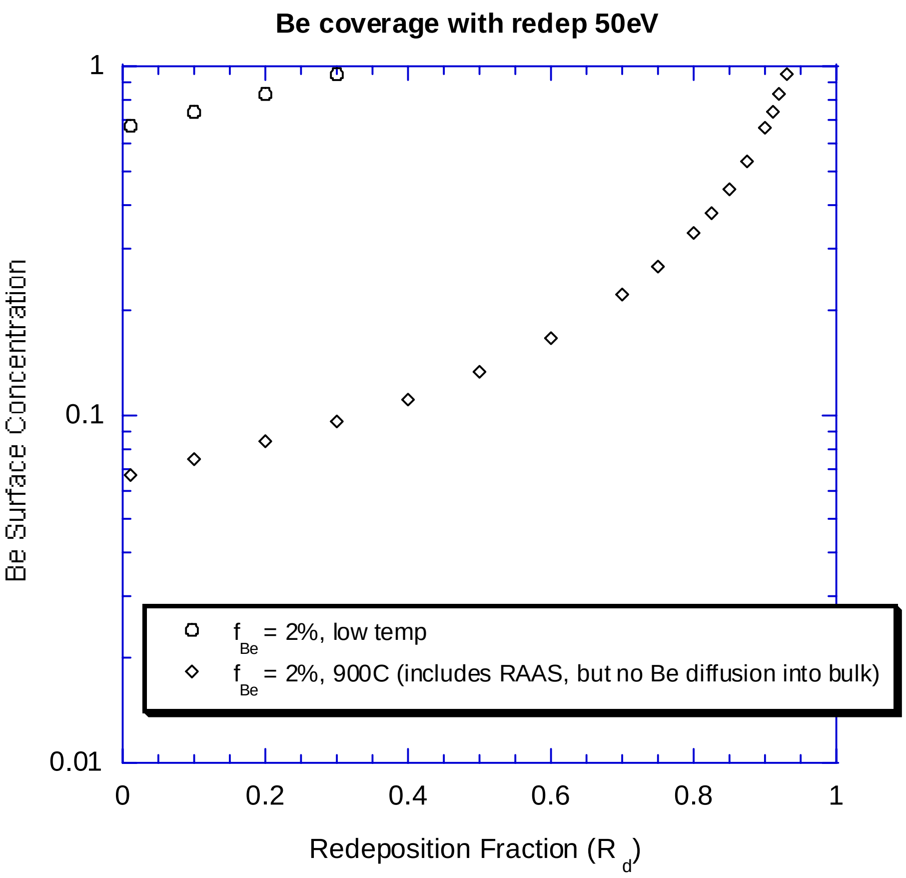
- E_{eff}, K_o, n_o and E_o are material constants
- Y_{ps}, Y_{eff} depend on the incident ion energy
- J_{in} is the incident ion flux to the surface (i.e. depends on experimental condition)

RAAS model also agrees with the Li erosion increase observed in ion beam data, where flux is 10^5 lower.



- PISCES-B plasma flux is 2e18 cm^{-2}s^{-1}
- IIAX flux is 5e13 cm^{-2}s^{-1}, equilibrium evaporation was subtracted from data by the authors in the publication [J.P. Allain et al., JNM 313-316 (2003) 641.]
- Y_{ad} increased by 3 (from TRIM Y_{ps} increase) to account for incident particle trajectory (700 eV, 45º angle)

When high temperature enhanced erosion is included in the analysis Be surface layers are still expected to form



- High temperature erosion is dominated by thermal release of particles, so redeposition is even higher
- Erosion mechanisms are relatively unimportant in high redeposition regimes
- Diffusion into the bulk is small at 800ºC [K. Schmid, A. Wiltner, Ch. Linsmeier, "Measurement of Beryllium Depth Profiles in Carbon", submitted to Nucl. Inst. Meth B. (2003).]

Redeposited material collected on the WPM during Be seeding shows reduced carbon concentration

- Primarily Be deposition on WPM during Be seeding runs
- C content in WPM films decreases during Be seeding
- C content decreases with increasing sample exposure temperature (up to 750ºC) [recent measurements extend sample temperature up to 1060ºC, but results are still being analyzed]
- D content in WPM films will be determined by IPP-Garching using NRA and RBS

What should ITER Team worry about?

Conclusions:

- Carbon physical and chemical erosion disappear when Be layers form on PISCES-B targets
- ELMs may vaporize any Be surface layer, but that layer will quickly redeposit and reform
- Redeposited material is primarily Be

Issues:

- Is chemical erosion of graphite still important for ITER?
- Will tritium accumulation may be dominated by the beryllium surfaces that form at locations with line-of-sight views of the strike points?
- What will the role of exfoliation, dust, detachment without carbon erosion, … be?

Recommendation:

- Given the implications of these results, experiments should be devised to verify these effects in a toroidal geometry.