Plasma interactions with Be surfaces

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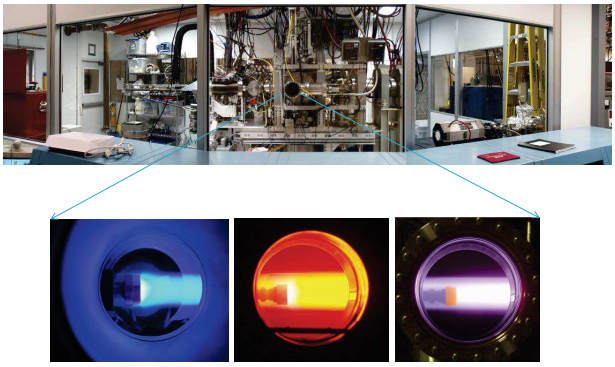
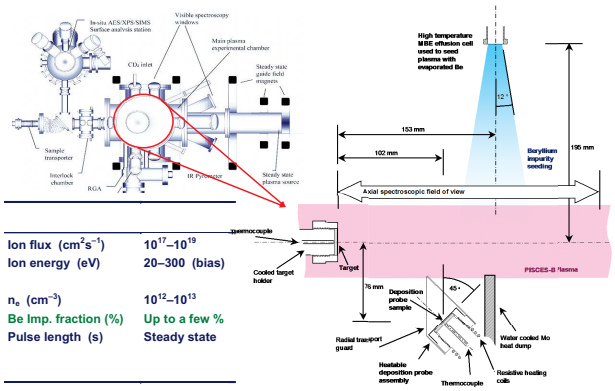
Work performed as part of: DOE PSI Science Center (with MIT and UT- Knoxville)
US-EU Collaboration on Mixed-Material PMI Effects for ITER
US- Japan Technology Exchange Program
PISCES-D3D Collaborations

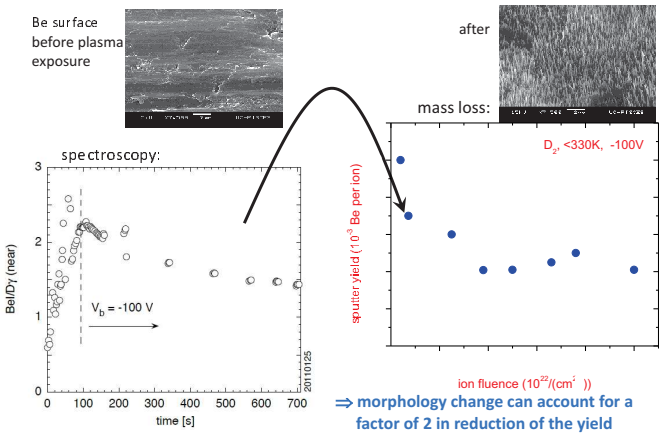


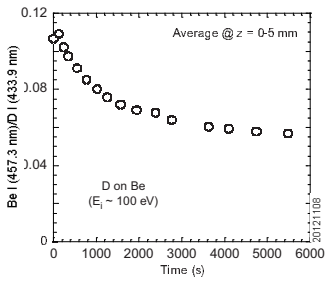
PISCES-B experimental arrangement

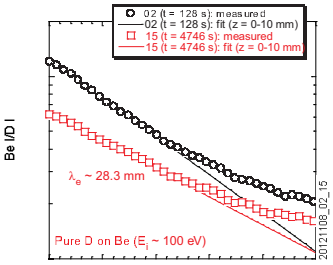


Ion flux (cm^2s^{-1})	10^{17}–10^{19}
Ion energy (eV)	20–300 (bias)
n_e (cm^{-3})	10^{12}–10^{13}
Be Imp. fraction (%)	Up to a few %
Pulse length (s)	Steady state

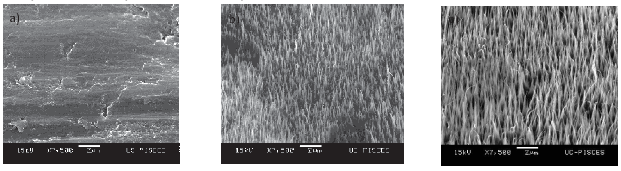
Development of surface morphology decreases erosion



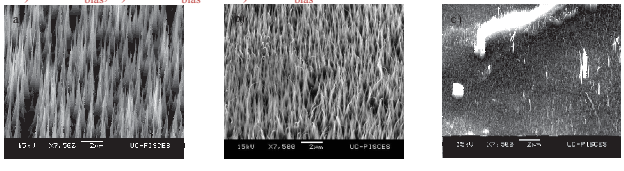


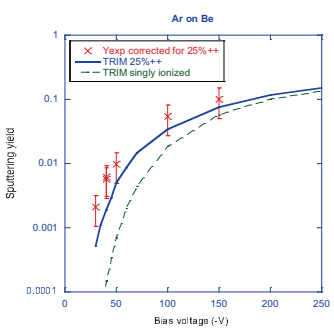


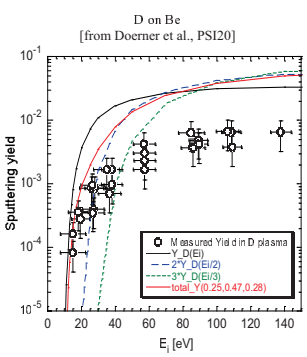
SEM images of Be targets at -100 V bias and deuterium fluence at;
a) 0 fluence, b) 3e25 m^{-2} and c) 3e26 m^{-2} fluence.

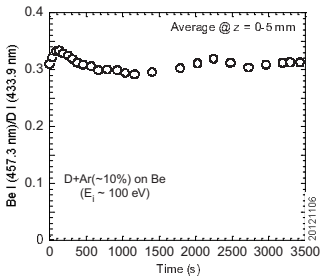


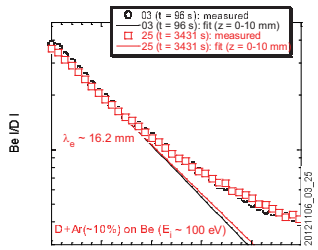
SEM images of Be targets after 3e26 m^{-2} deuterium fluence at;
a) -170 V_{bias}, b) -100 V_{bias} and c) -50 V_{bias}.

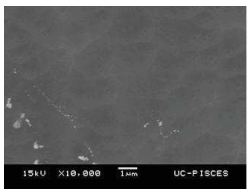


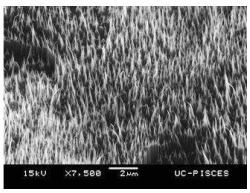




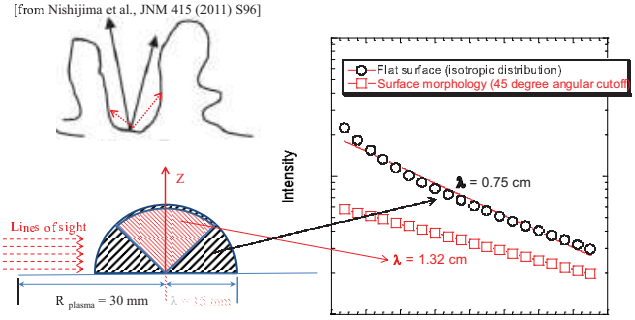


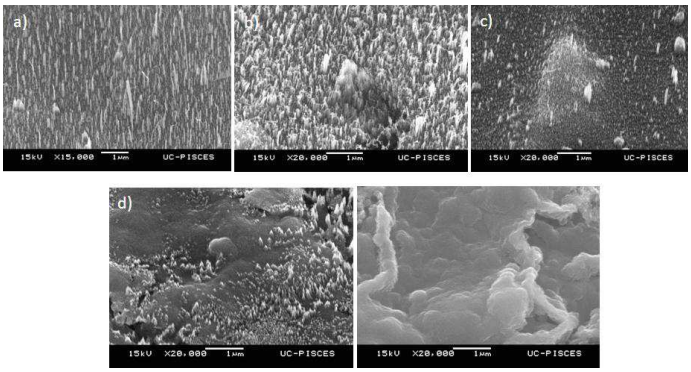


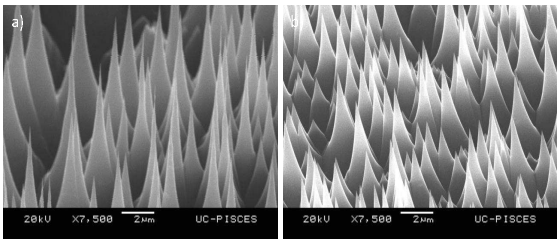




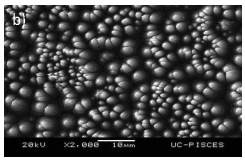
[from Nishijima et al., JNM 415 (2011) S96]

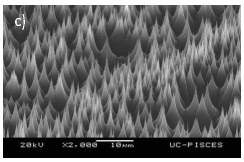






[2] Y. Yamamura, Y. Itikawa, and N. Itoh, "Angular dependence of sputtering yields of monatomic solids," Report No. IPPJ-AM-26, 1983.





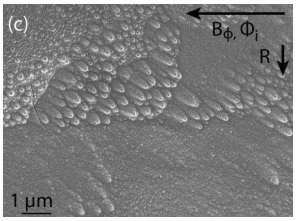
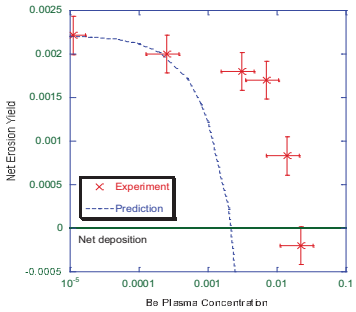
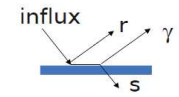


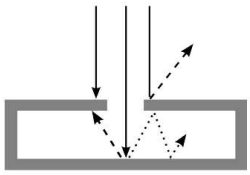
Figure 5. SEM images of the surfaces at 1/10 (a) 1/8 (b) and 3/6 (c). All surfaces show elongated structures that are pointing in a direction 15-20° downwards, with respect to the toroidal direction. The region (c) is slightly depressed with respect to the surrounding layer and has about 4 μm Be deposited, so it seems likely that the cone like structure consists mainly of Be.



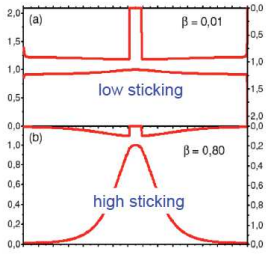


r : reflection
γ : transformation
("chemistry" e.g. $H^0 \rightarrow H_{2)}$
s : sticking

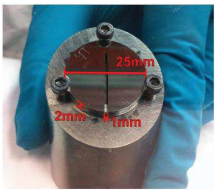
β = γ + s : surface loss probability

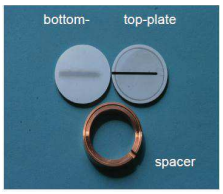


Analysis:
- deposition pattern inside of cavity
- comparison front surface with total deposition on inside surfaces

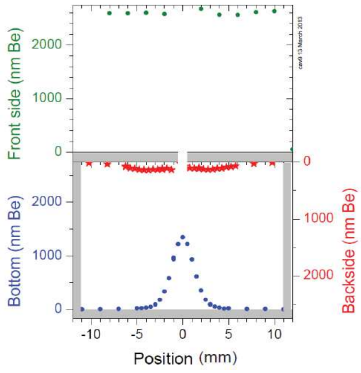


Ch. Hopf et al. JAP **87** (6) p2719 2000





He plasma + Be seeding

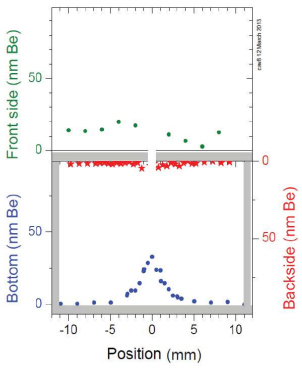


discharge conditions:
$p_{neutrals}$ = 1 Pa
n_e = 1x10^{19} m^{-3}
ion flux = 7x10^{22} m^{-2}s^{-1}
E_{ion} = 15 eV

Result:

- ¼ of the total deposition at the back side of the lid
  ⇒ Surface loss probability 0.8 <β < 1
  - erosion inside cavity?
  - flux dependence of sticking?
- Integral Be amount inside of cavity smaller than one from top
  ⇒ deposition on walls of the slit

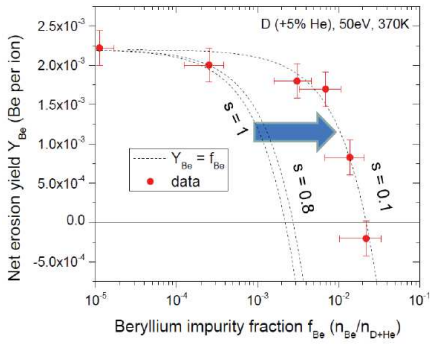
D_2 plasma + Be seeding



discharge conditions:
$p_{neutrals}$ = 1 Pa
n_e = 1x10^{19} m^{-3}
ion flux = 7x10^{22} m^{-2}s^{-1}
E_{ion} = 15 eV

Result:

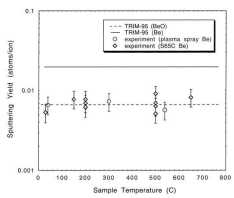
- Integral Be amount inside of cavity twice (!) the one on front surface
  ⇒ flux dependence of sticking?
  ⇒ (chemical?) enhanced re-erosion?
- D/Be = 20% (bottom) - 30% (top)
  ⇒ indication of two species?
- ¼ of the total deposition at the back side of the lid
  ⇒ Surface loss probability 0.8 <β < 1



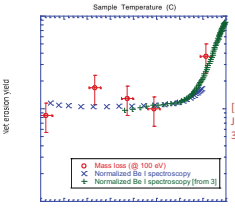
Recall the development of surface morphology is temperature dependent and morphology reduces erosion rate.

But net erosion is temperature independent (until very high temperature).

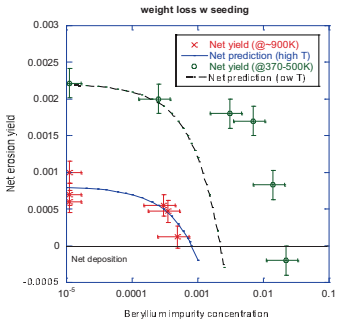
Possible explanation could be the temperature dependent erosion rate of BeD (decreases with increasing temperature) compensates for changes in erosion rate due to morphology (increases erosion as temperature increases).



[from R. P. Doerner et al., J. Nucl. Mater. 257 (1998) 51]



[3] R. P. Doerner et al., J. Nucl. Mater. 337-339 (2005) 877

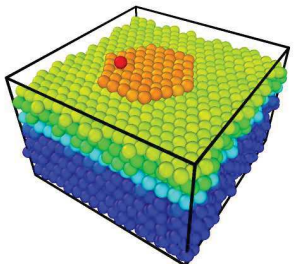


Recall (again)

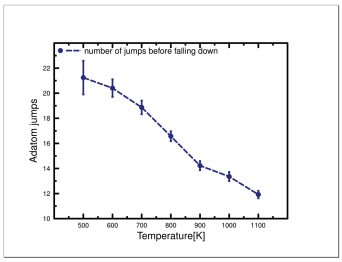
Two possibilities, ~~reduced sticking of depositing Be~~, or increased re-erosion, could explain observations.

Depositing Be may behave differently from lattice Be atoms.

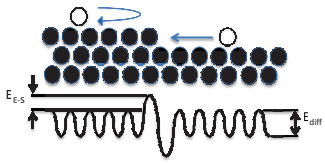
Enlist MD calculations to help understand deposited atom behavior at different surface temperatures.

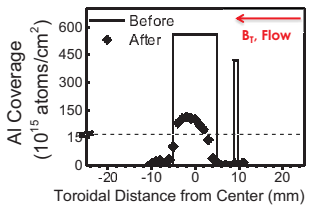


MD simulation results

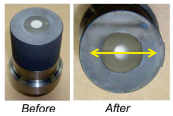


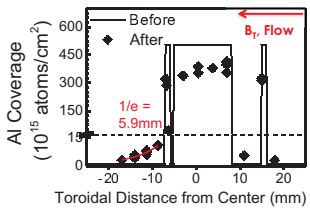
- Below 500 K, the adatom is never observed to descend the step edge (within the time of the MD simulation, ~ 1ns)
- Between 500 and 1000 K a clear Arrhenius relationship (with an activation energy of 0.32 eV) is seen in the rate at which the adatom descends the step
- A nudged-elastic band (NEB) [6] method was also used to calculate the migration energy and Ehrlich-Schwoebel barrier at the edge of the island and obtained 0.22 eV for the migration energy and 0.33 eV for the Ehrlich-Schwoebel energy barrier



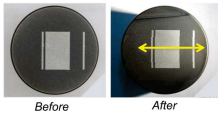


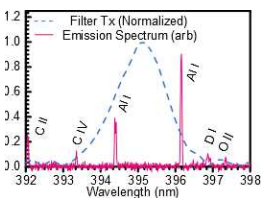
- Gross Erosion: >6.7nm/s
- Net Erosion: 5.6 nm/s
- No detectable re-deposition

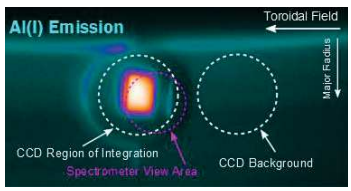




- Gross Erosion: 2.4 nm/s
- Net Erosion: 1.4 nm/s
- Barely detectable re-deposition

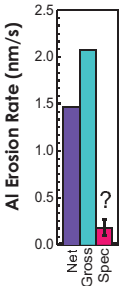


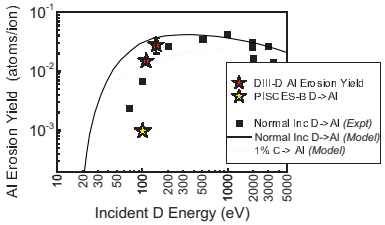


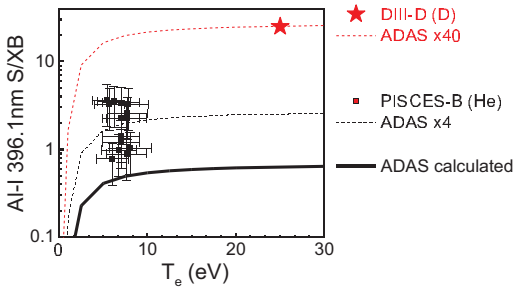


$$\Gamma_{ph}^{Al} \cong 4\pi S^{-1} \frac{\left(I_{Sample}^{CCD} - I_{Background}^{CCD}\right)}{A_s(1+R_s)}$$

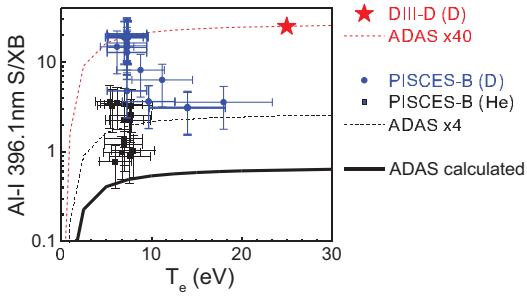
$$\Gamma_{Al \to Al^+} = \Gamma_{ph}^{Al}\left(\frac{S}{XB}\right)_{CCD} = \Gamma_{ph}^{Al}\left(\sum_n \frac{T_n}{S/XB_n}\right)^{-1}$$

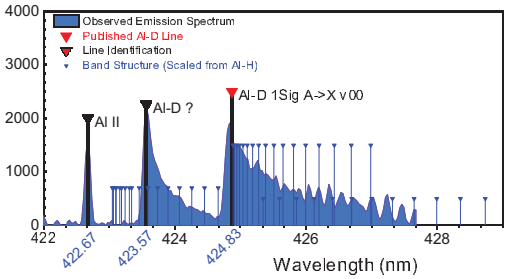






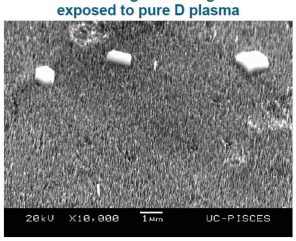
- 2-4x higher than computed ADAS values, but still 10x lower than needed for DIII-D Yield Measurements to Agree w/ Spectroscopic Yield
- Large (3x) scatter possibly due to systematic change in sputtering yield during run (surface roughening)



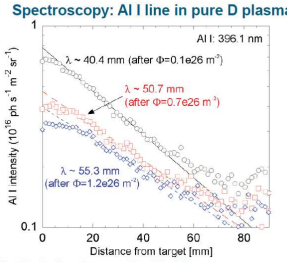


Aluminum as possible Be proxy for studying erosion behaviour

SEM image of Al target exposed to pure D plasma



Spectroscopy: Al I line in pure D plasma



Similar fine grass-like structure as for Be

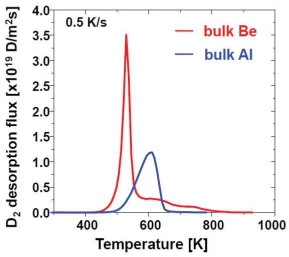
Similar behaviour as for Be I line:
- Decay of Al I intensity (lower erosion) in time
- Increase of Al penetration in plasma

Sputtering yield from mass loss measurements

	Sputtering yield (Experiment)	Ratio Experiment/TRIM
Be target	1.4×10^{-3}	0.05
Al target	2.8×10^{-4}	0.04

Aluminum as possible Be proxy for studying fuel retention

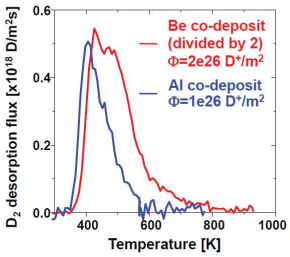
D_2 TDS spectra in bulk Be and Al (T_s=320K, E_i=100 eV, Φ=1.2e26 D^+/m^2)



Be: total retention 3.2e21 D/m^2
Al: total retention 1.9e21 D/m^2

Retention mechanisms in bulk Be and Al are apparently different

D_2 TDS spectra in Be and Al co-deposits collected on witness plate (T_s=290K)



Retention mechanisms in Be and Al co-deposits appear to be similar

Amount of Al in layers is difficult to measure by IBA methods

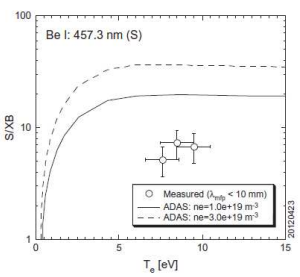


Fig. 5. Comparison of S/XB values for Be I (457.3 nm) between the measurements ($\lambda_{mfp} < 10$ mm, $n_e \sim 1.4$–1.7×10^{19} m^{-3}) and the ADAS database ('96', 'pju').

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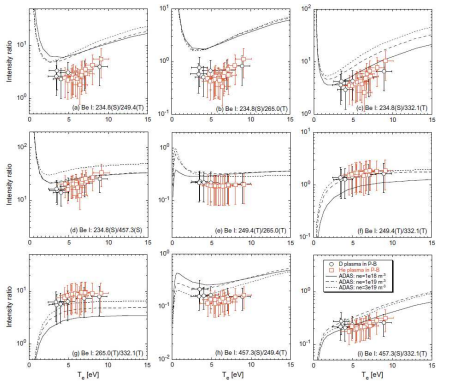

Fig. 2. T_e dependence of various Be I line intensity ratios measured in Be-seeded D (circles) and He (squares) plasmas. For comparison, photon emissivity coefficient ratios from the ADAS database ('96', 'pju') are also plotted with lines. Singlet and triplet transitions are labeled as (S) and (T), respectively.

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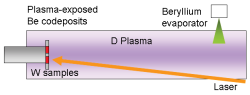
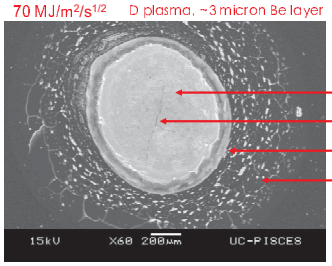
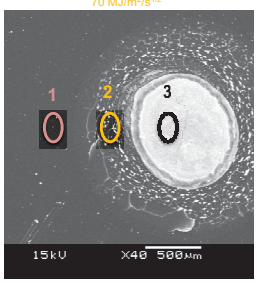


70 MJ/m^2/s$^{1/2}$ D plasma, ~3 micron Be layer

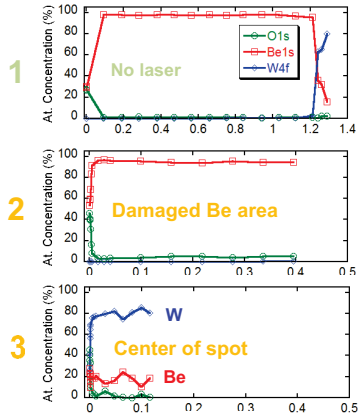


- Ablation of Be, recrystallization of W
- Be-W alloying and cracking
- Be melt flow
- Delamination and holes in Be coating

70 MJ/m^2/s$^{1/2}$



T. Höschen



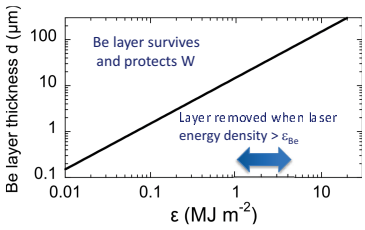
How much energy is needed to remove Be coating?

Sacrificial Be layer

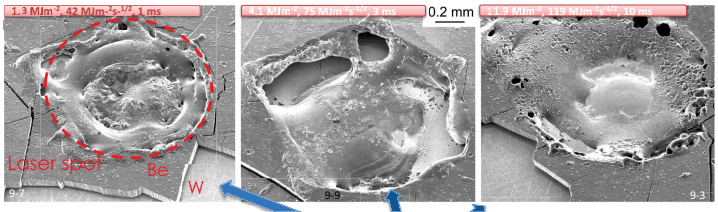
Can eroded wall material that is deposited on the divertor provide protection to the underlying W? How thick does Be layer need to be?

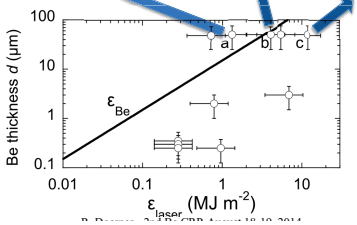
Energy density required to sublimate (or equivalently, melt and evaporate) a layer of Be with thickness d :

ρ is density, μ is molar mass, and enthalpy of formation for Be is ΔH = 324 kJ/mol (*CRC Handbook*)



SEM images support simple estimate for Be layer removal





Be is removed by laser when the absorbed laser energy is greater than the enthalpy of formation of Be layer, $\varepsilon_{laser} > \varepsilon_{Be}$