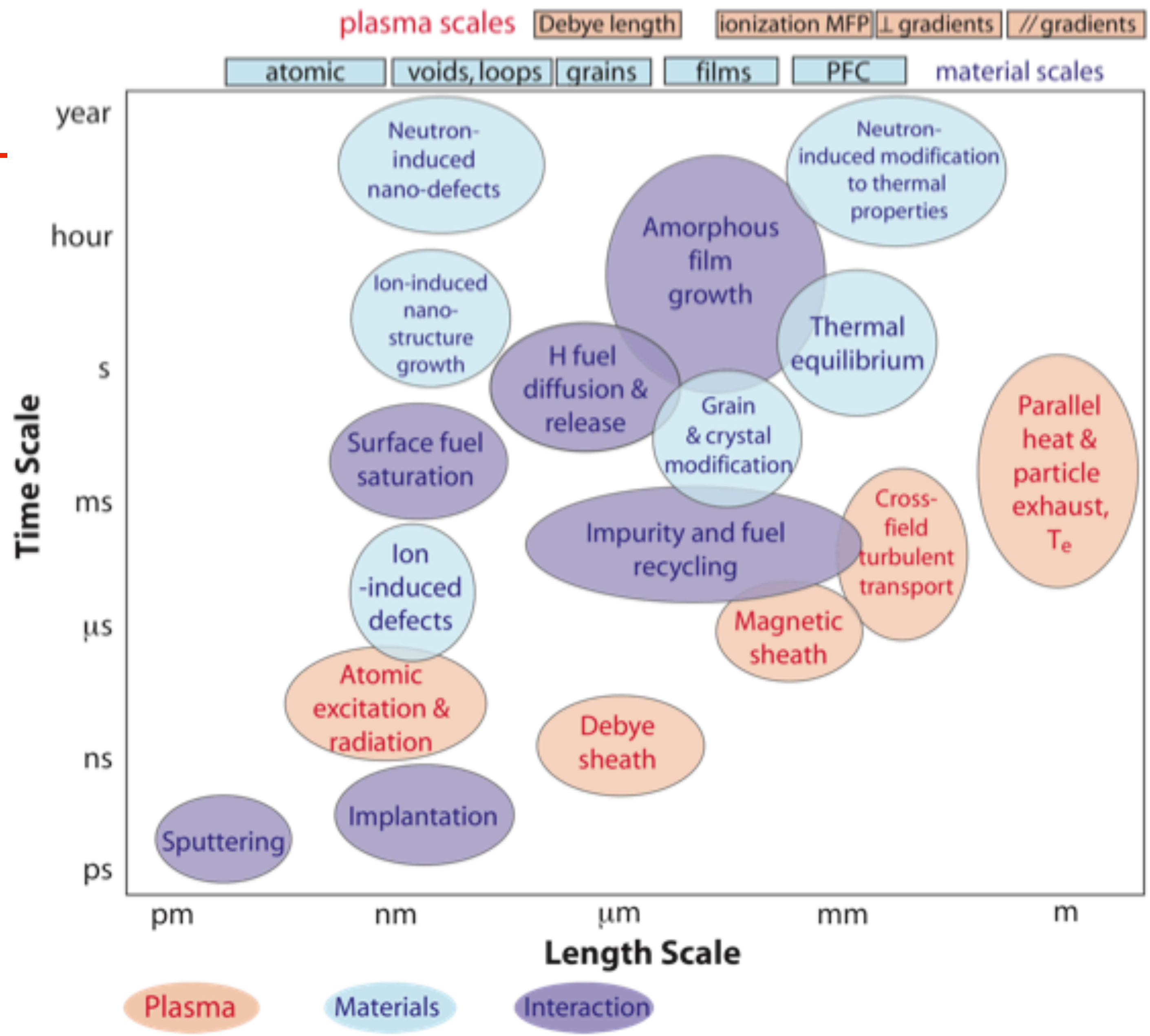
Overview of PSI Science Center Research

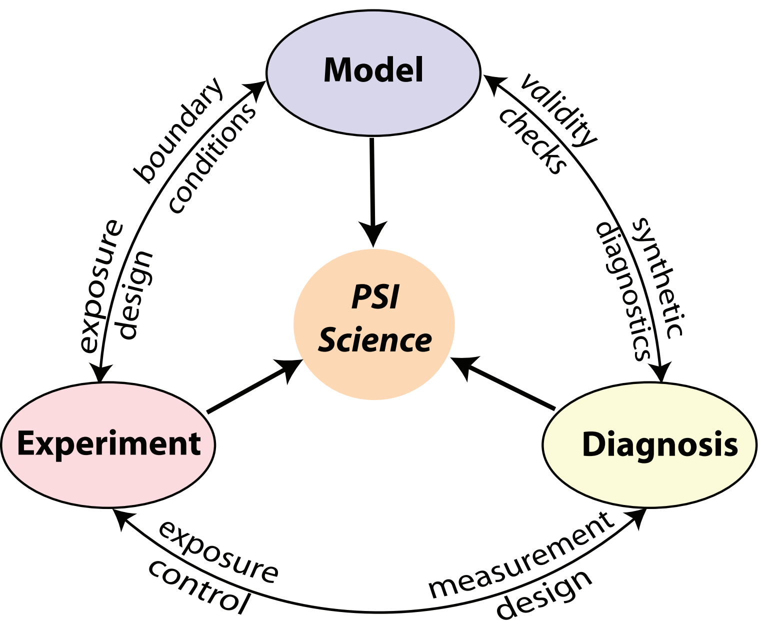
D. Whyte for PSI Science Center

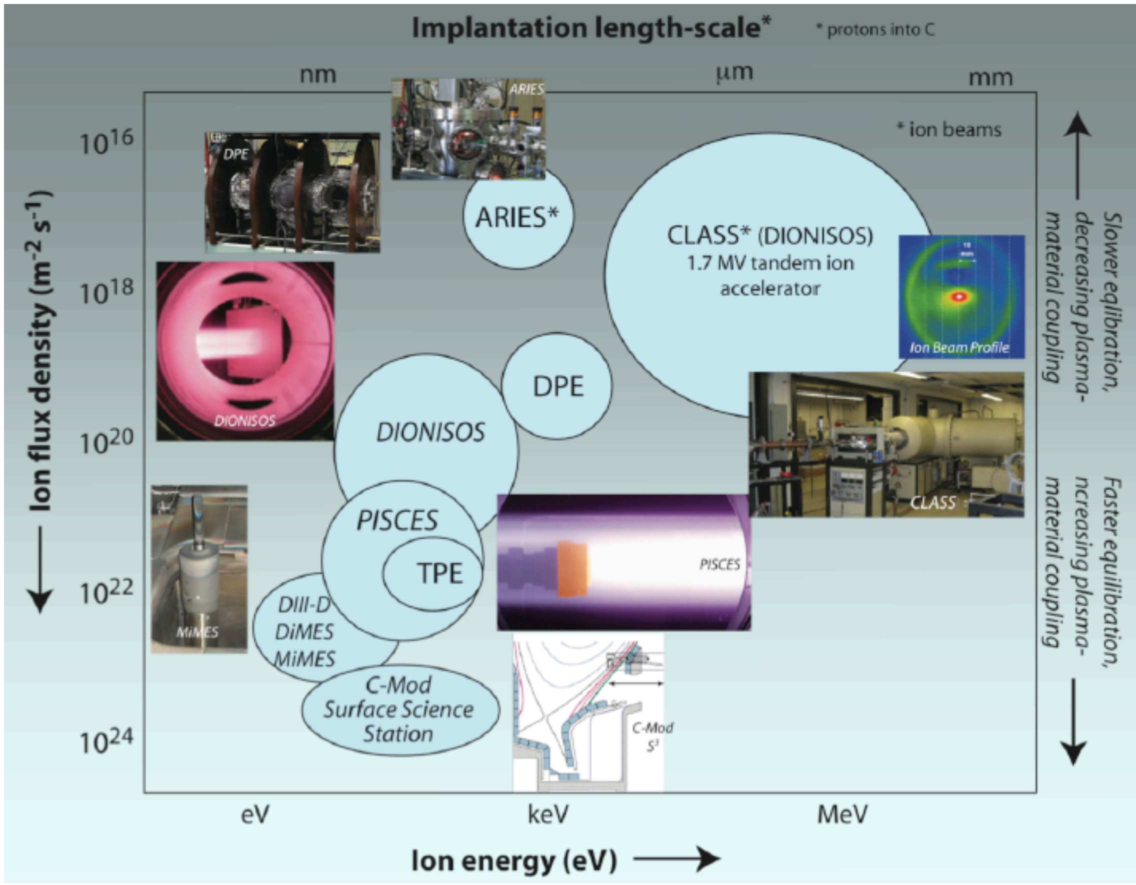
PFC/MASCO Meeting PPPL June 2012

The Challenge

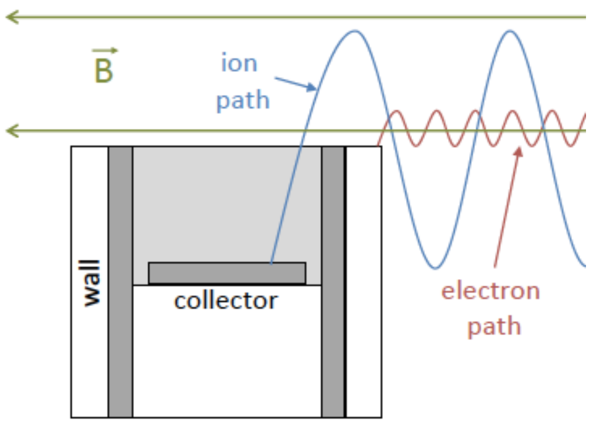


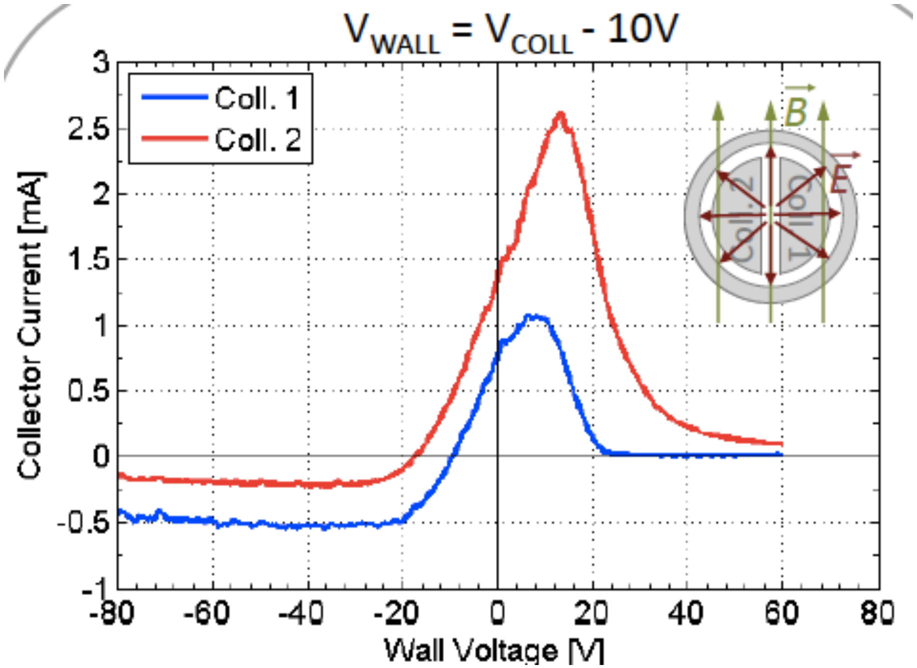
A holistic approach to Plasma-Surface Interaction Science

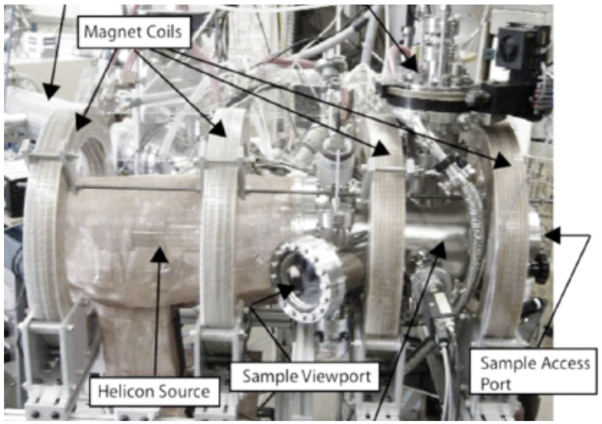




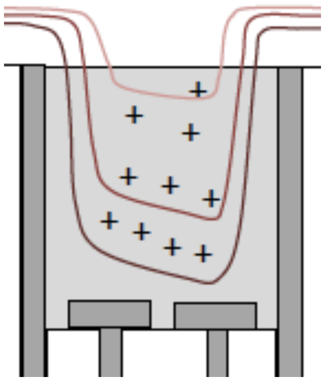
Diagnostic Development: New robust "ion-sensitive probe" for plasma potential → critical to diagnose sputtering in high density SOL







Sullivan PSI 2012



Laboratory developed ISP probe deployed in C-Mod to understand vexing RF-enhanced sheaths → high-Z sputtering

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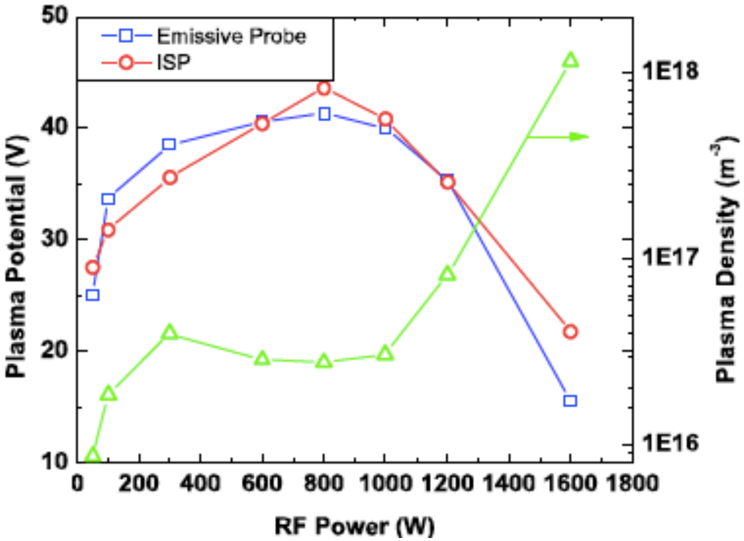
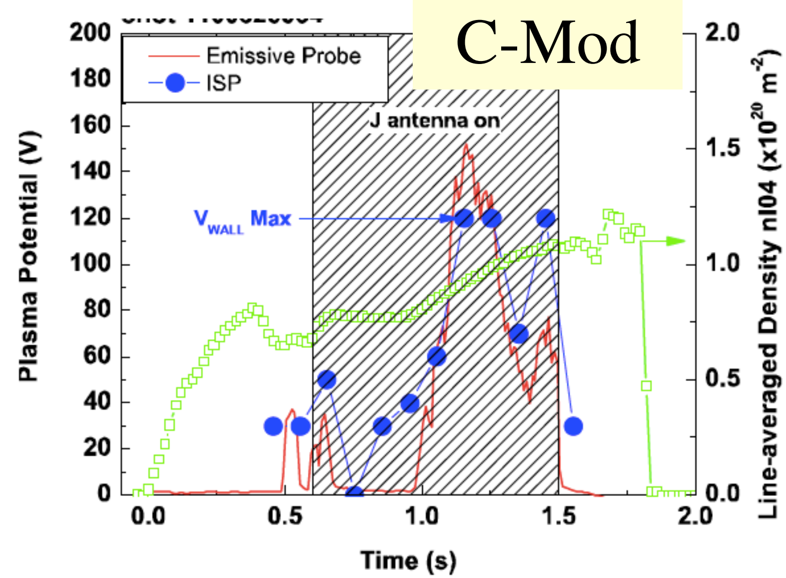
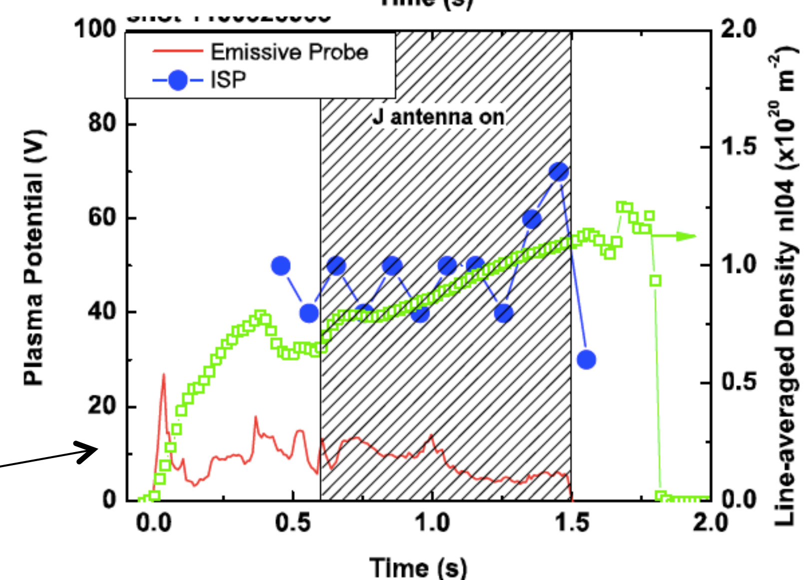
DIONISOS



Ochoukov RSI 2011

C-Mod





ISP functions at high density where emissive probe cannot

Recent significant efforts in validating sheath heat transmission at tokamak strikepoints: Standard theory γ~8 appears to be OK

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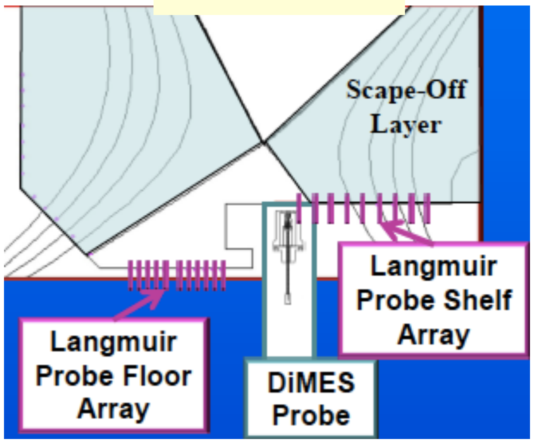
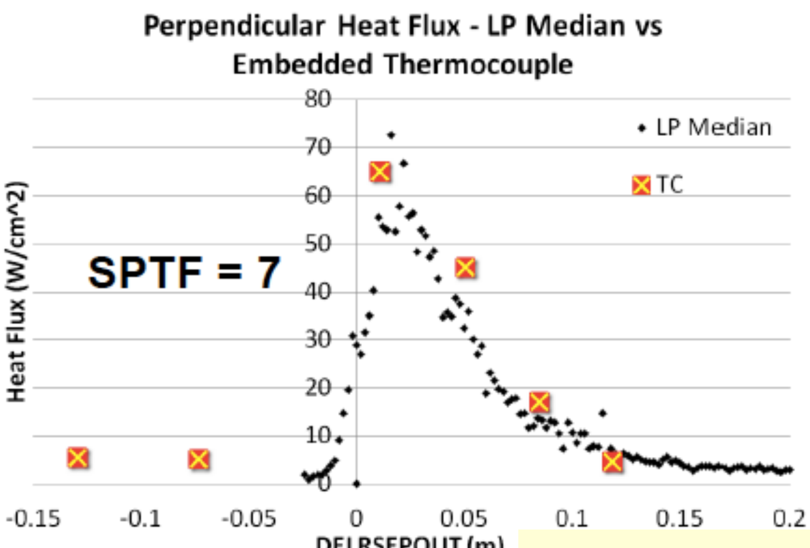
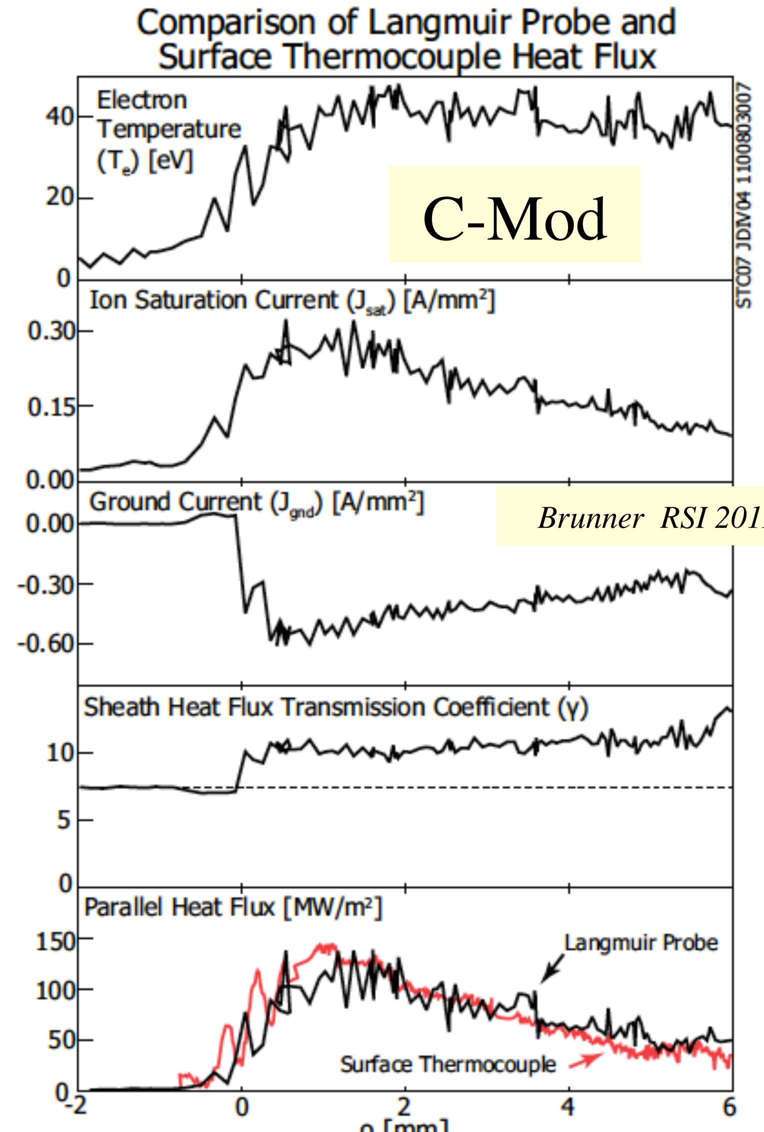
DIII-D





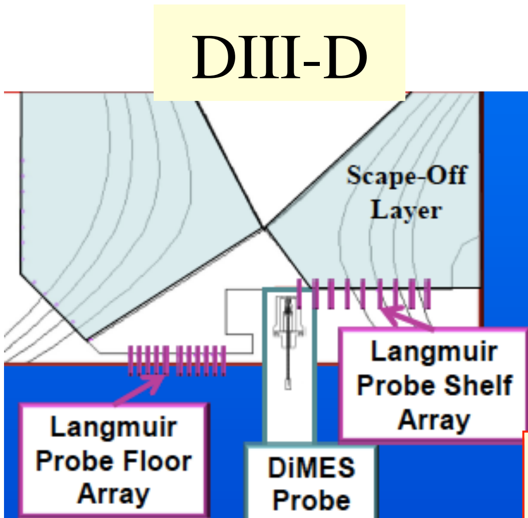
Donavan PSI 2012

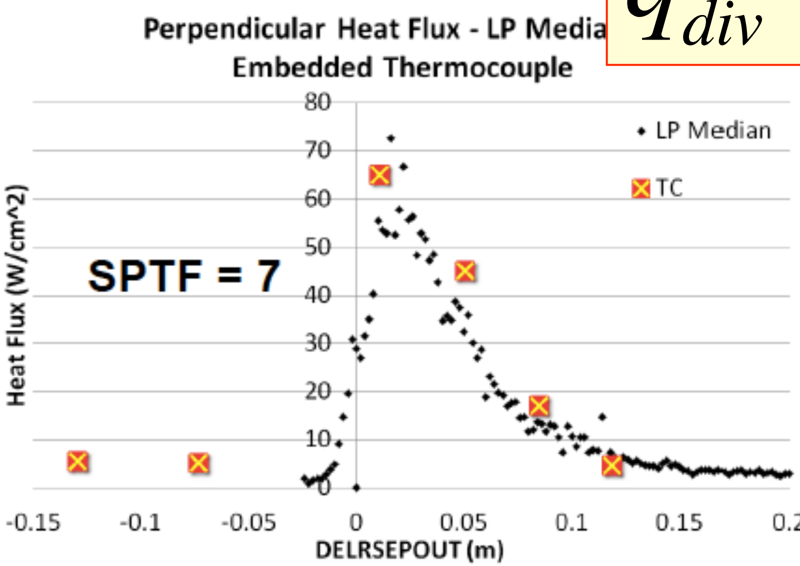


C-Mod

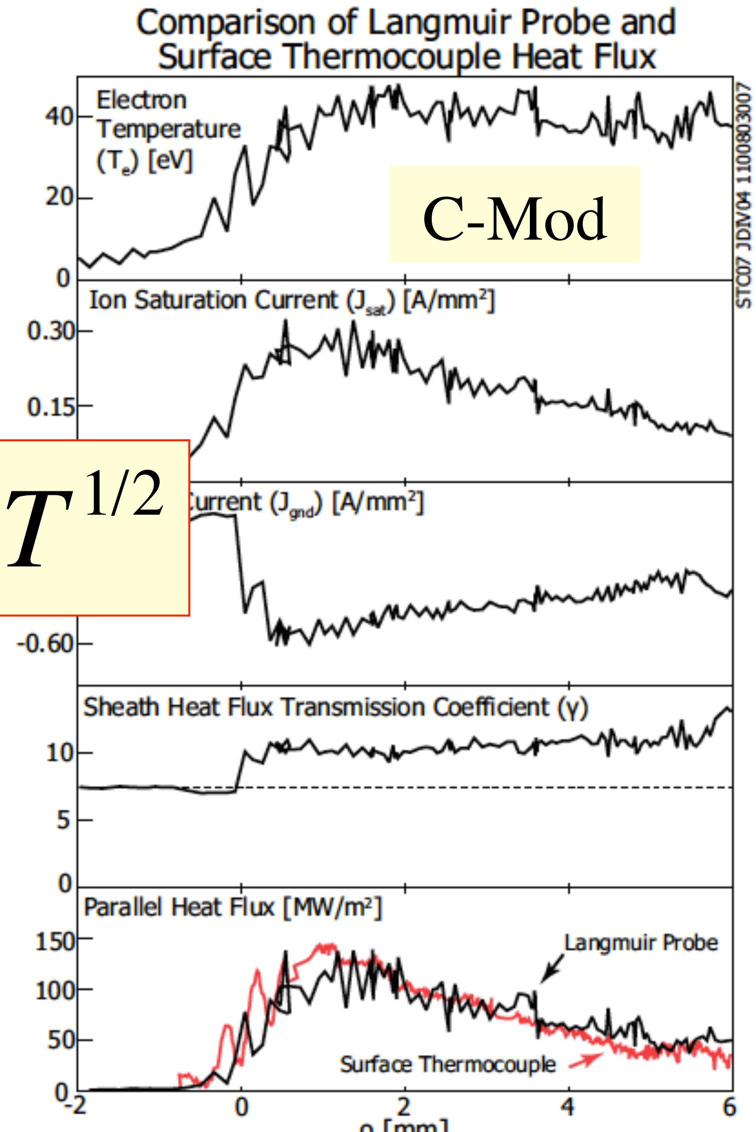
Brunner RSI 2011

Recent significant efforts in validating sheath heat transmission at tokamak strikepoints: Standard theory γ~8 appears to be OK





$$q_{div} \propto \gamma \; p \, T^{1/2}$$



With confidence in sheath heat transmission, edge stability allows one to constrain allowed values of heat width in ITER

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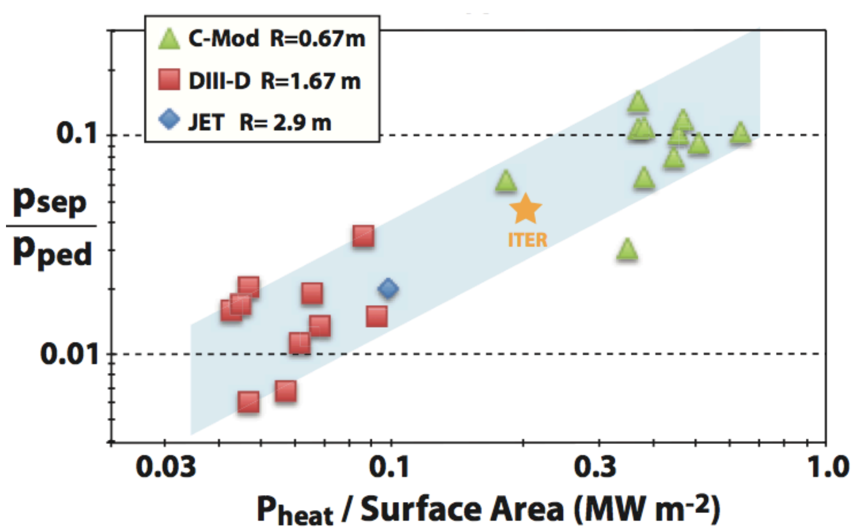
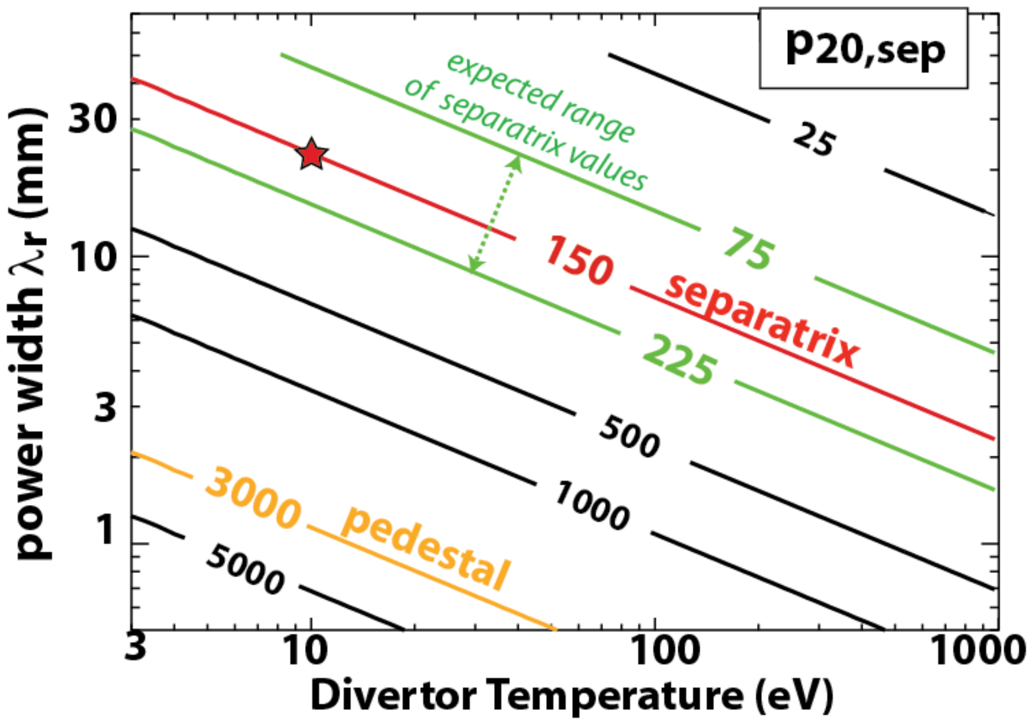
$$p_{20,sep} \simeq 5\%\ p_{20,ped} = 150 \longleftrightarrow p_{20,sep} = \frac{10.8}{T_{div}^{1/2}\ \lambda_r}$$

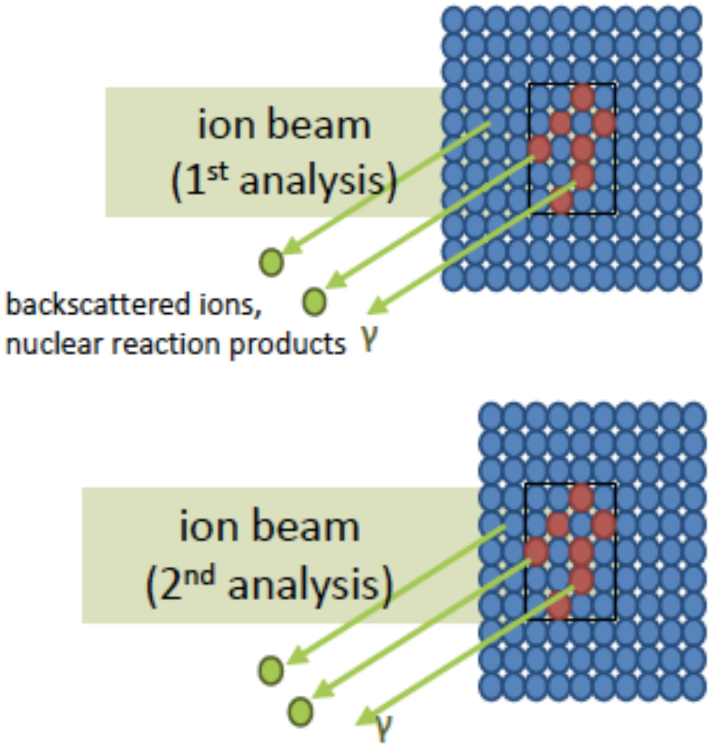


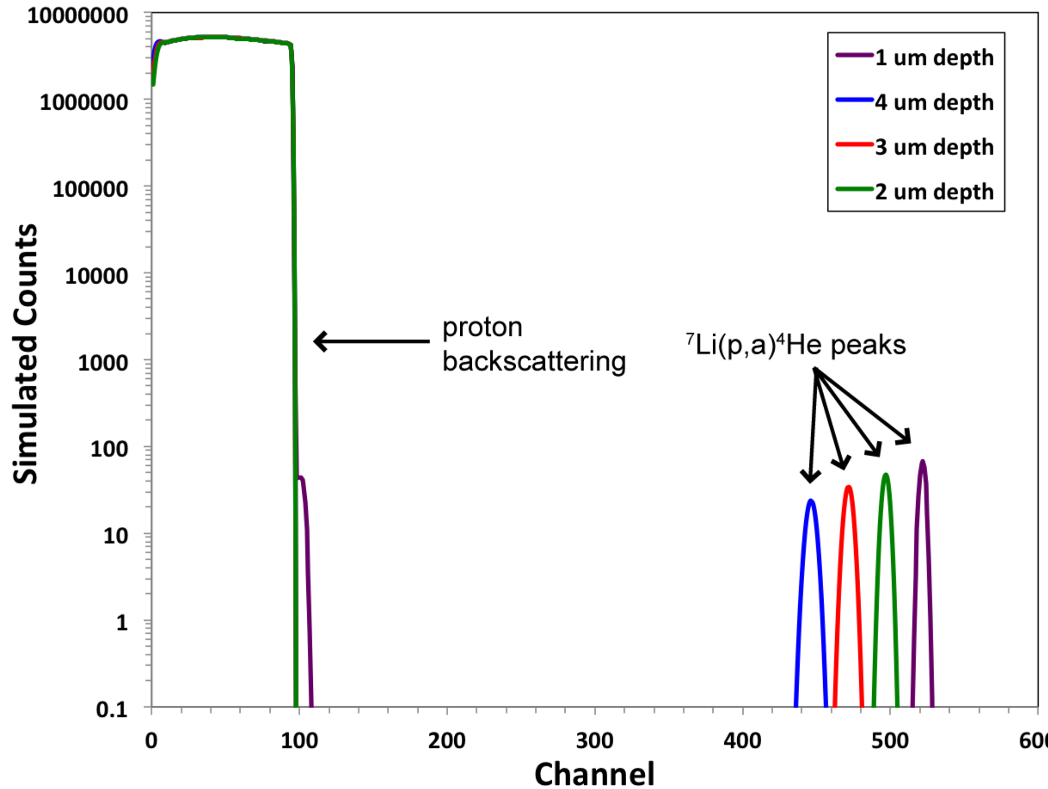


Whyte PSI 2012

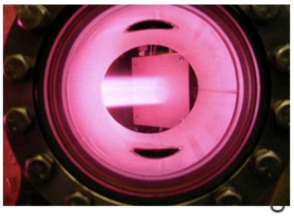
ITER Q=10 P_{div}=50 MW case

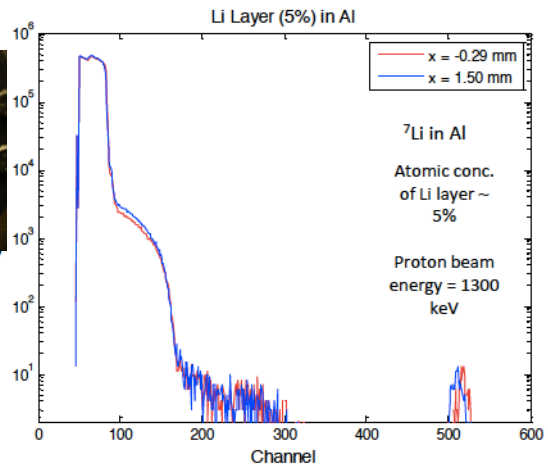
MeV Li implantation + p-Li reaction → depth-marking technique developed for high-Z and ceramics: No coating required

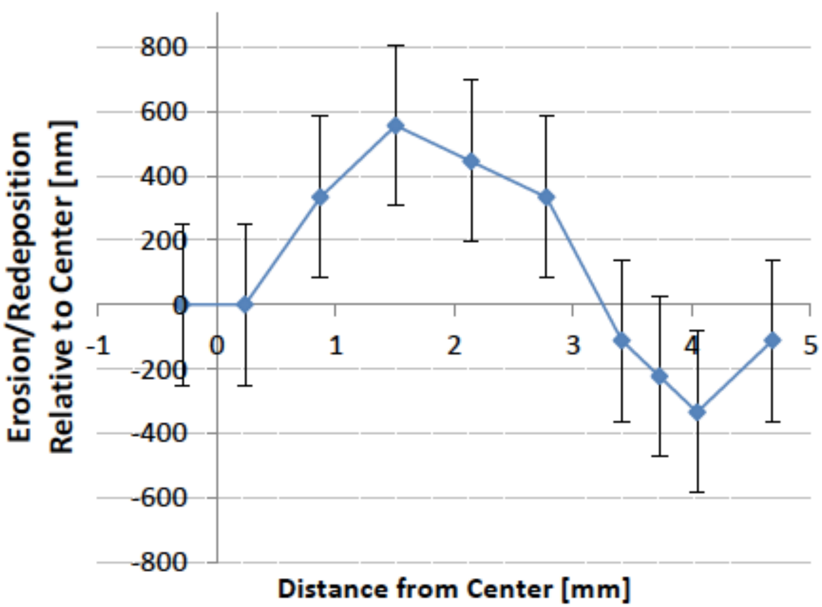


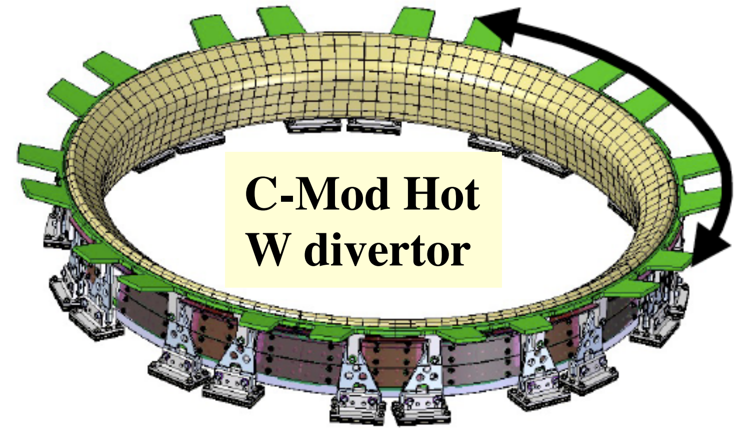


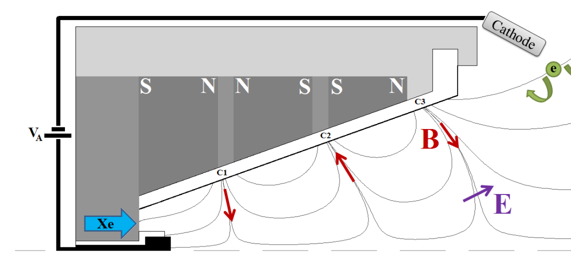
Depth-marking technique being used for in-situ erosion/ deposition in DIONISOS → planning widescale deployment in C-Mod / EAST tungsten divertor + plasma thrusters



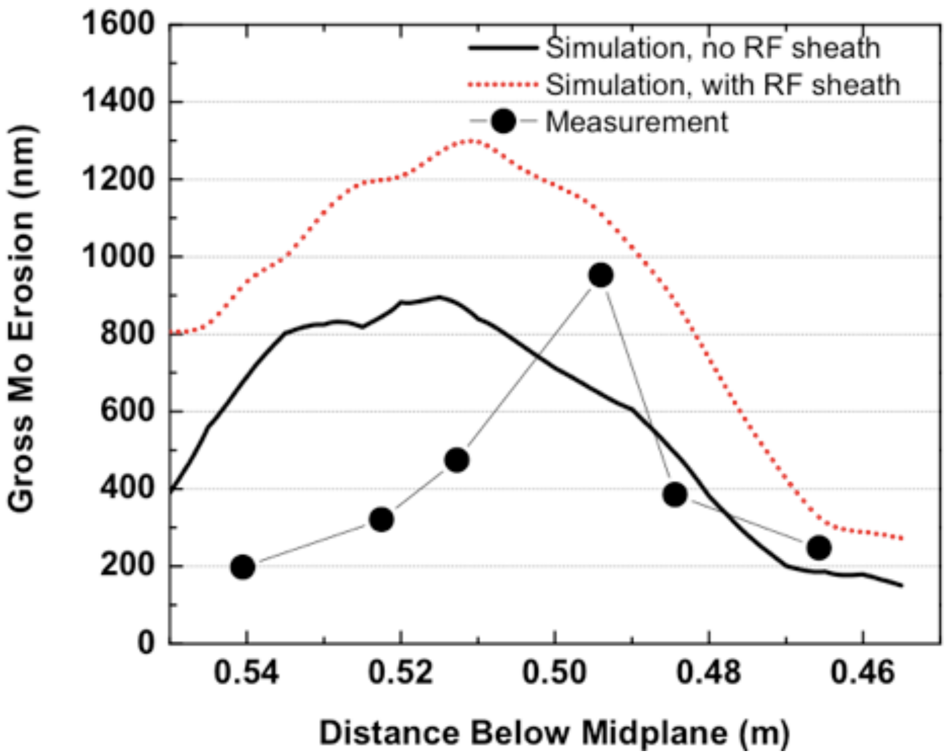


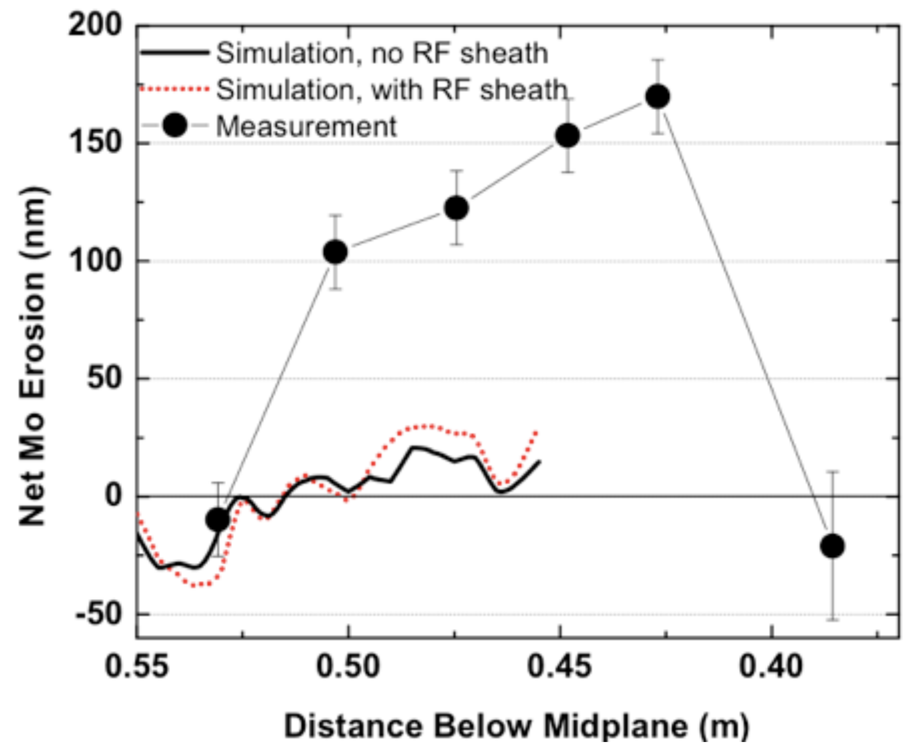






How effective is prompt redeposition at mitigating net erosion? Integrated high-Z erosion results from C-Mod *suggest* not very.





Brooks J. Nucl. Mater. 2011

New PISCES experiments indicate our knowledge of erosion suppression by redeposition is, at best, incomplete

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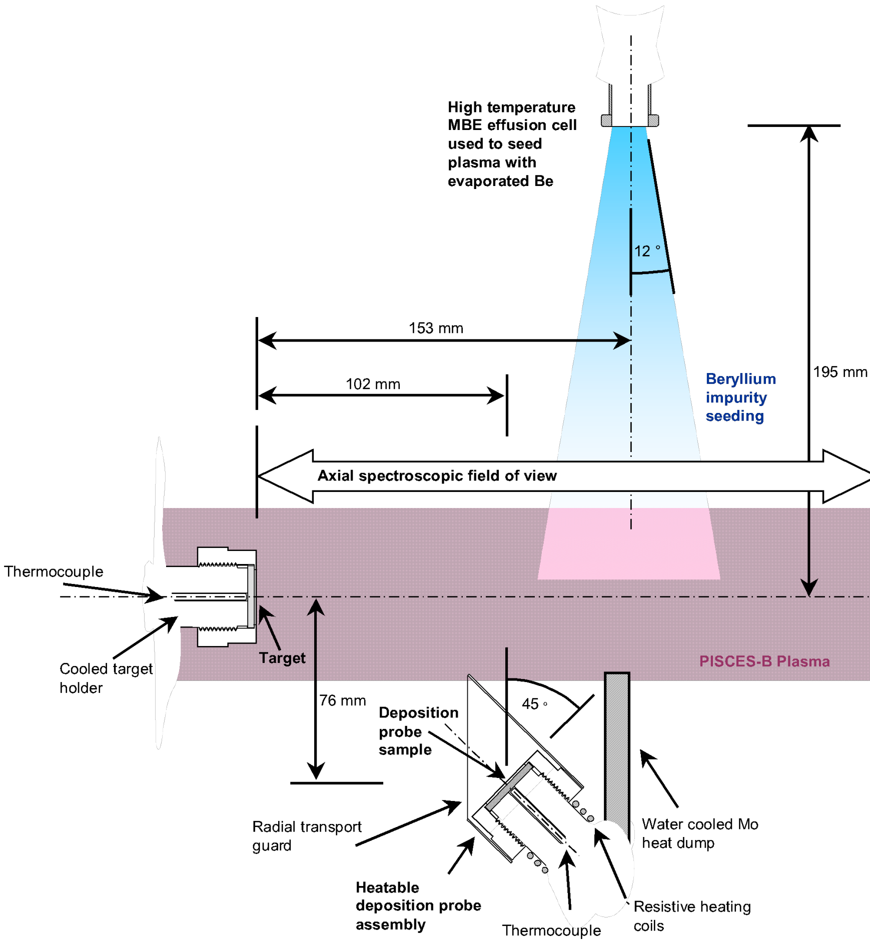
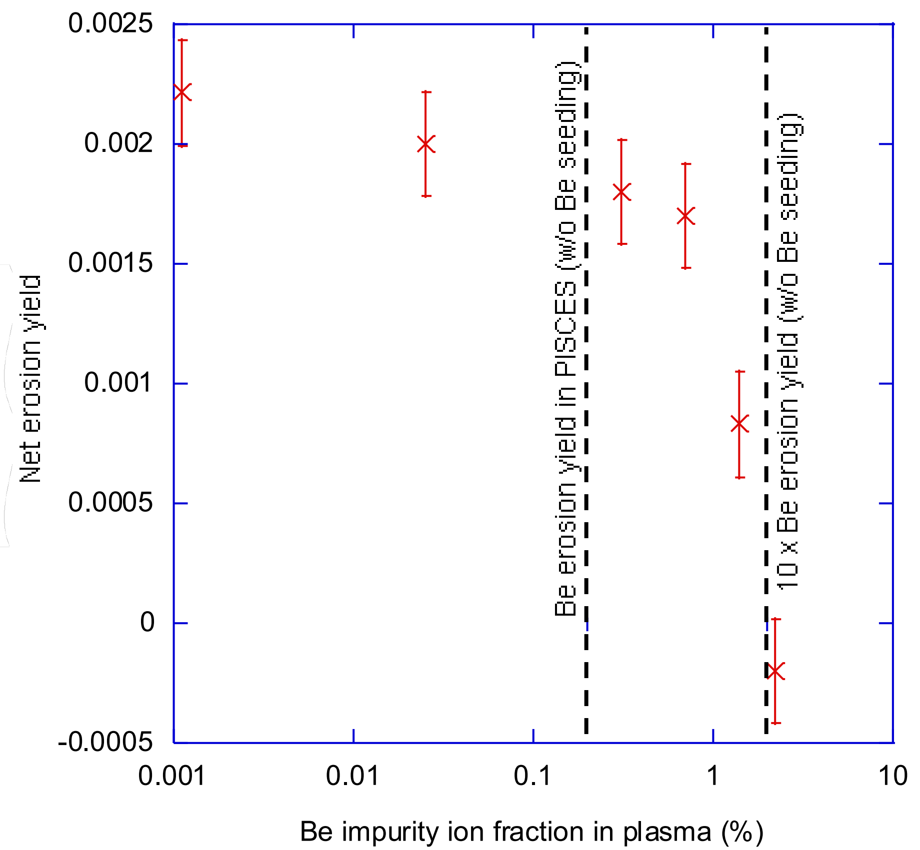


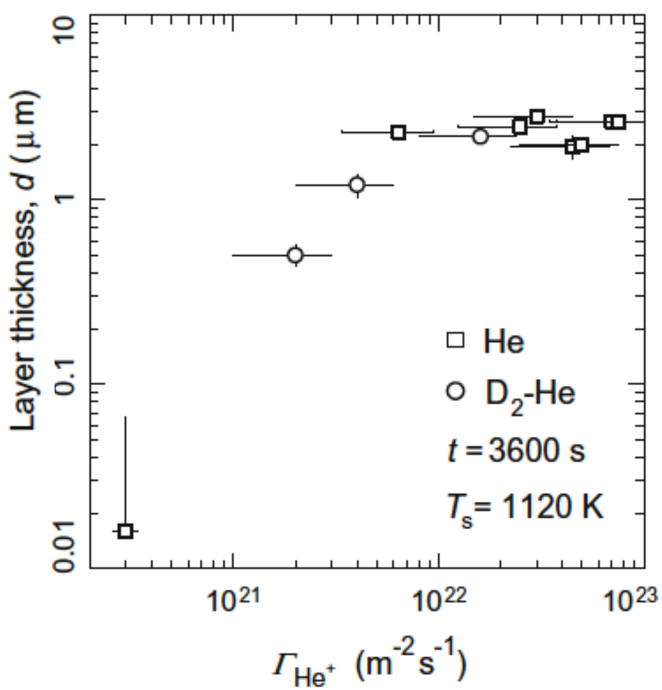
PISCES



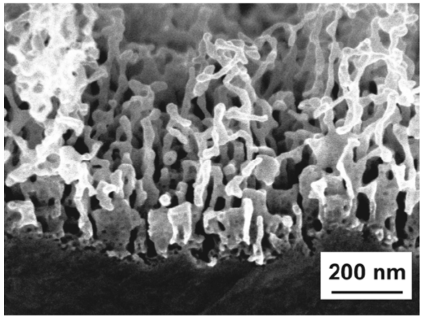
Doerner PSI 2012

Tungsten nano-tendril studies

Center's holistic approach well-suited to study of *W nano-tendrils*



[2] M.J. Baldwin et al. J. Nucl. Mater. **390-391** (2009) 886



- **Under what conditions will it occur?**
  - ➢ **PISCES key in characterizing formation rates and conditions.**
  - ➢ **He fluence, 1000<T<1800 K**
- **What fundamentally causes it?**
- **Can it be mitigated?**
- **Will it occur in confinement devices?**
- **What will be the consequences?**

Grazing Incidence X-ray Diffraction suggest strain is relieved in fuzz → hints growth trigger is stress relief from He bubbles

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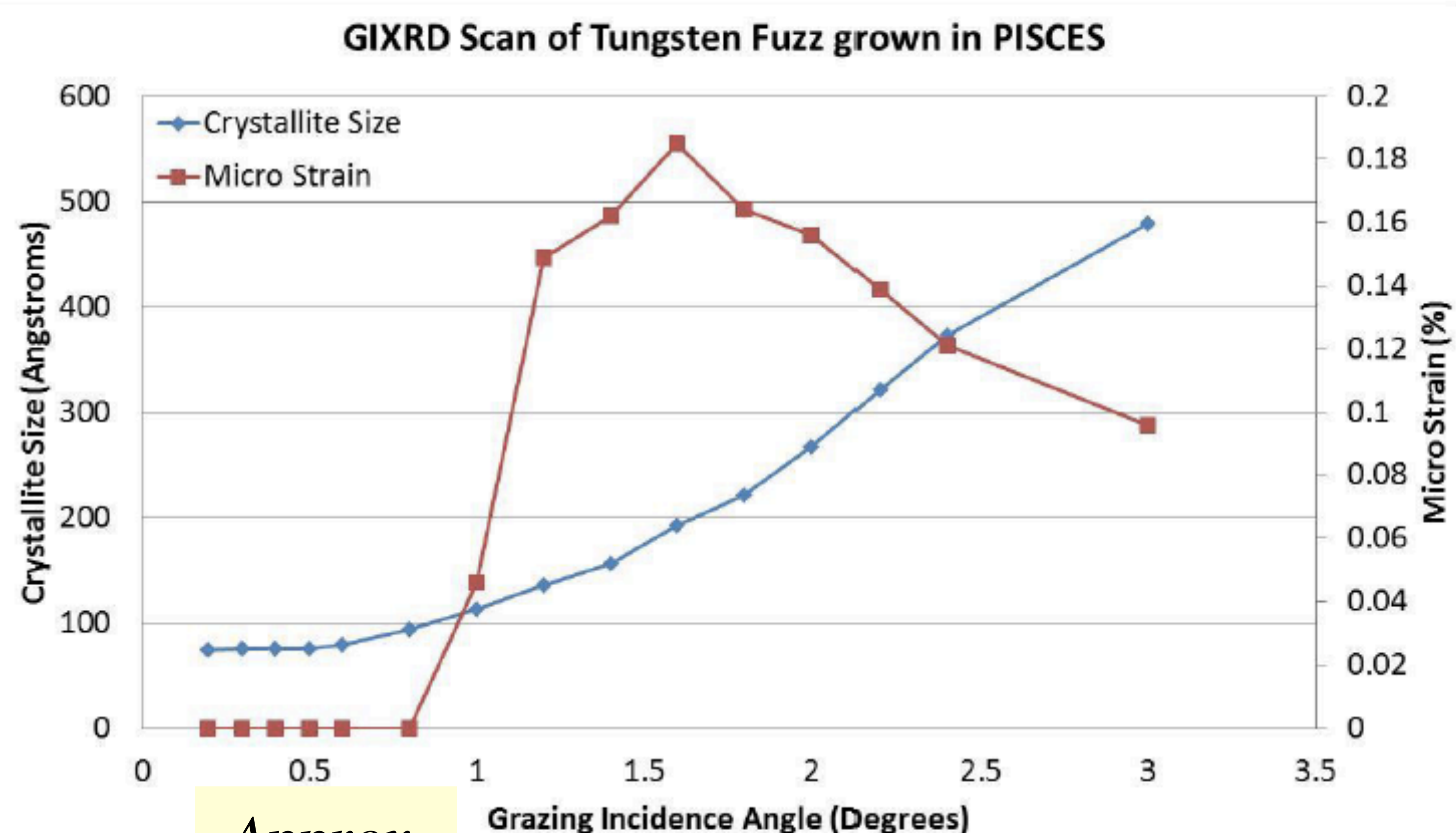
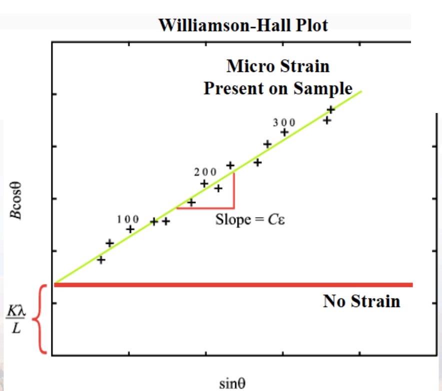
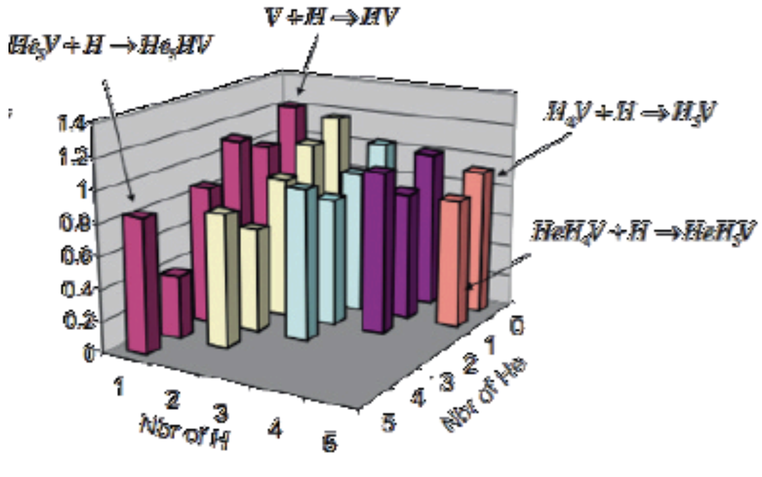


Approx. tendril depth

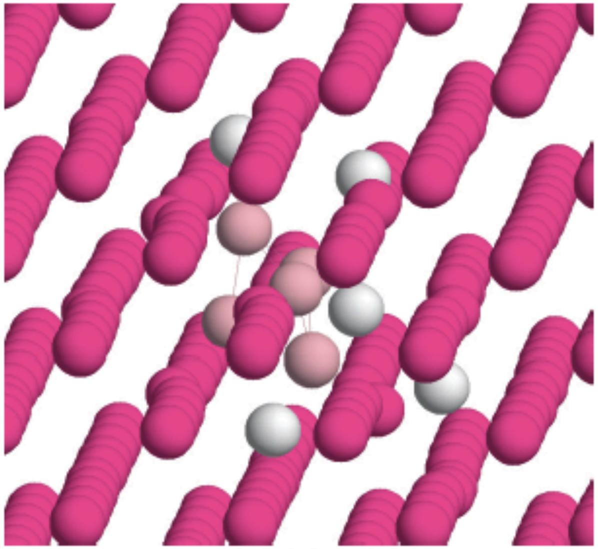


Developing new MD simulations of complex W-He-H system

PSI Science Center

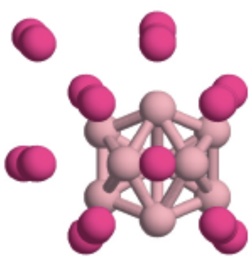


Binding energies (eV) for the reaction: $He_xH_yV + H \rightarrow He_xH_{y+1}V$.

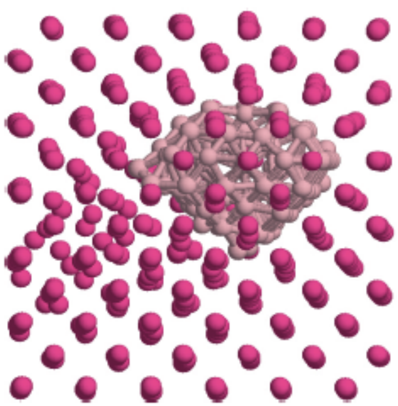


$V_1He_5H_5$

Small clusters are in symmetric structures. Harder to find ground states for large clusters, due to many metastable structures. Room for ~3 to 5 He per V for large clusters.



V_1He_{13}



$V_{10}He_{110}$

Juslin PSI 2012

Developing new MD simulations of complex W-He-H system

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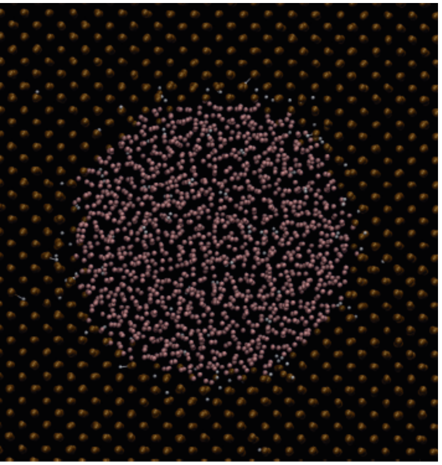
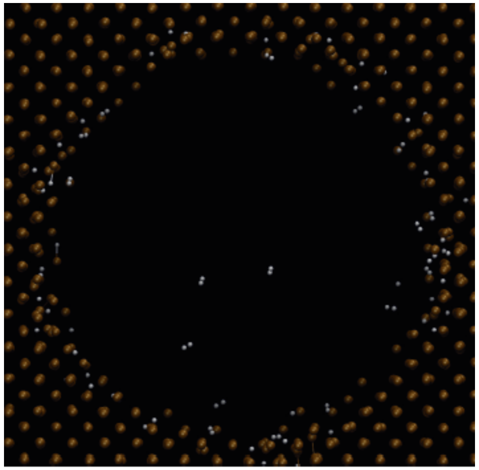
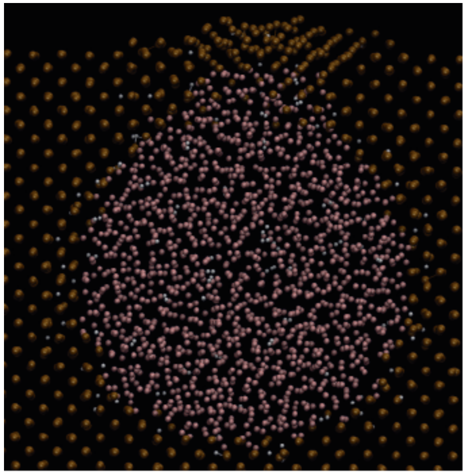


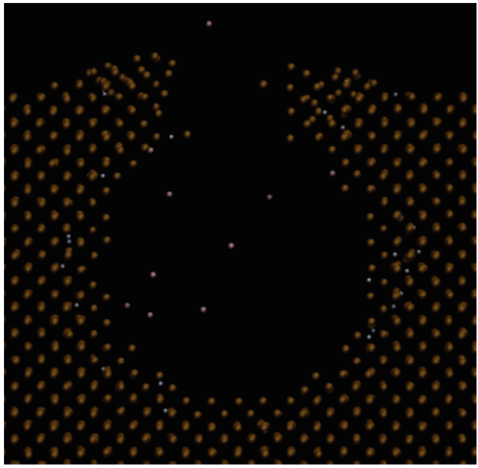
r=2 nm bubble, 900 K
1*n_{vac} He & 0.1*n_{vac} H



r=2 nm bubble, 900 K, He not shown
2*n_{vac} He & 0.1*n_{vac} H



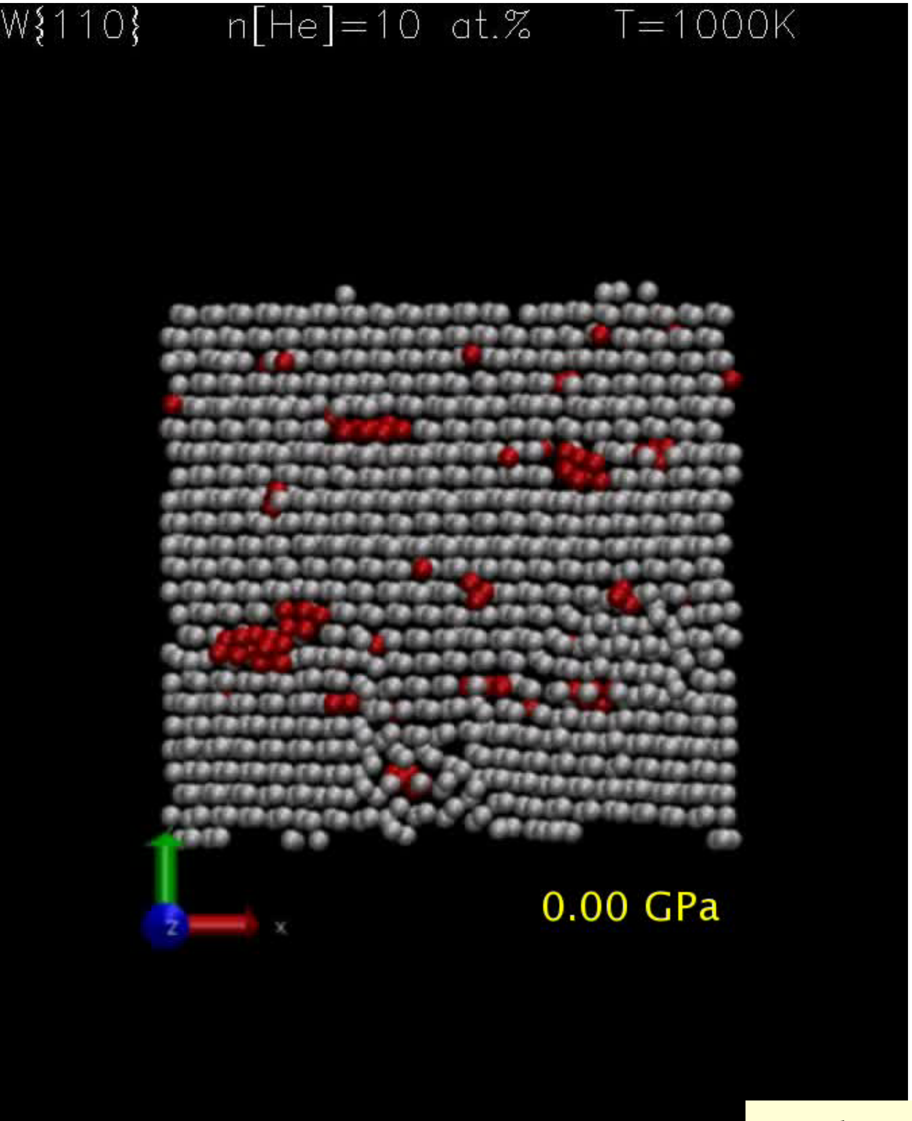
r=2 nm bubble near surface, 900 K

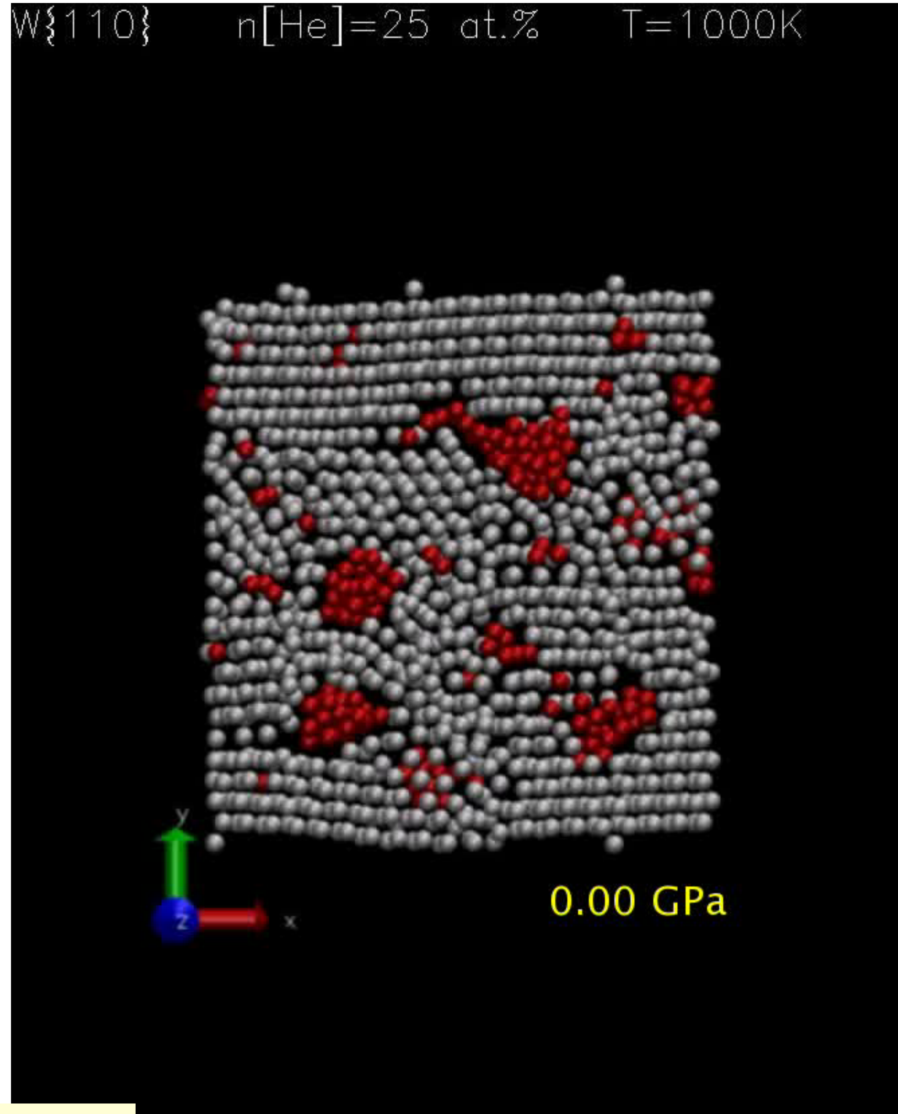


r=2 nm burst bubble
1% He & 35% H retained

Juslin PSI 2012

MD simulation with applied shear stress: tungsten "movement" depends on He %





Krasheninnikov PSI 2012

MD simulations indicate that ~10% He concentrations strongly affect effective yield strength of tungsten

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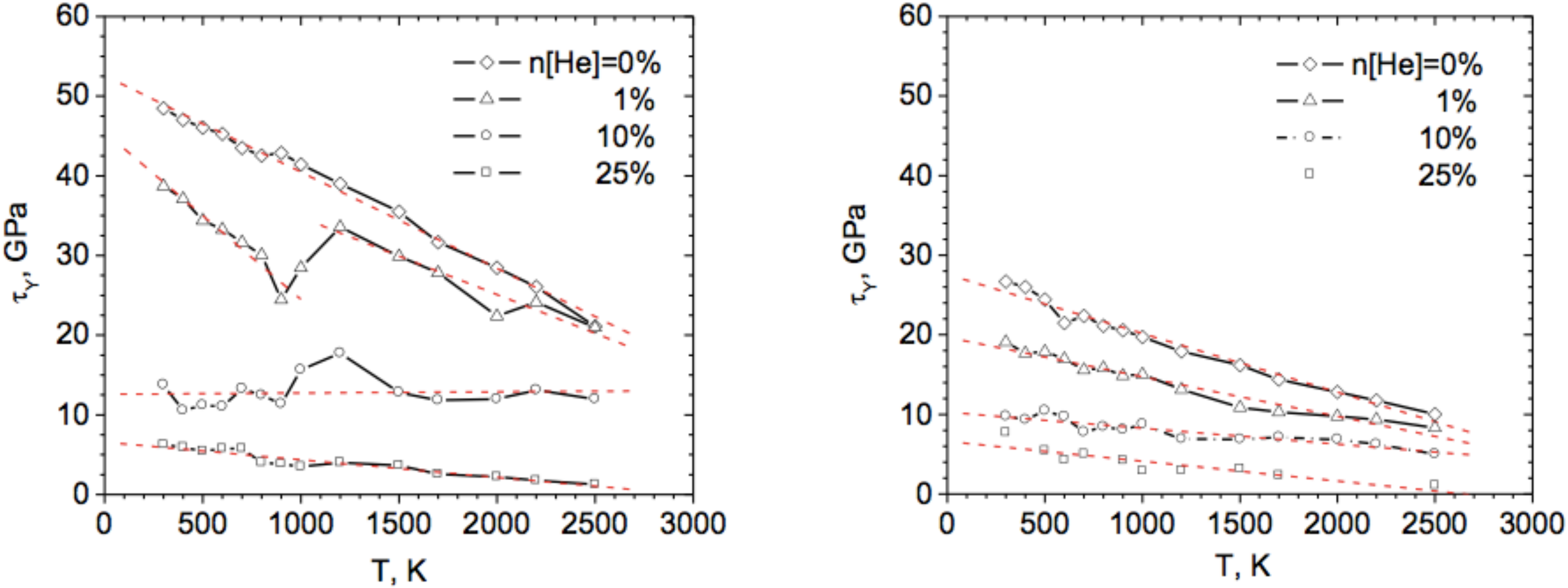


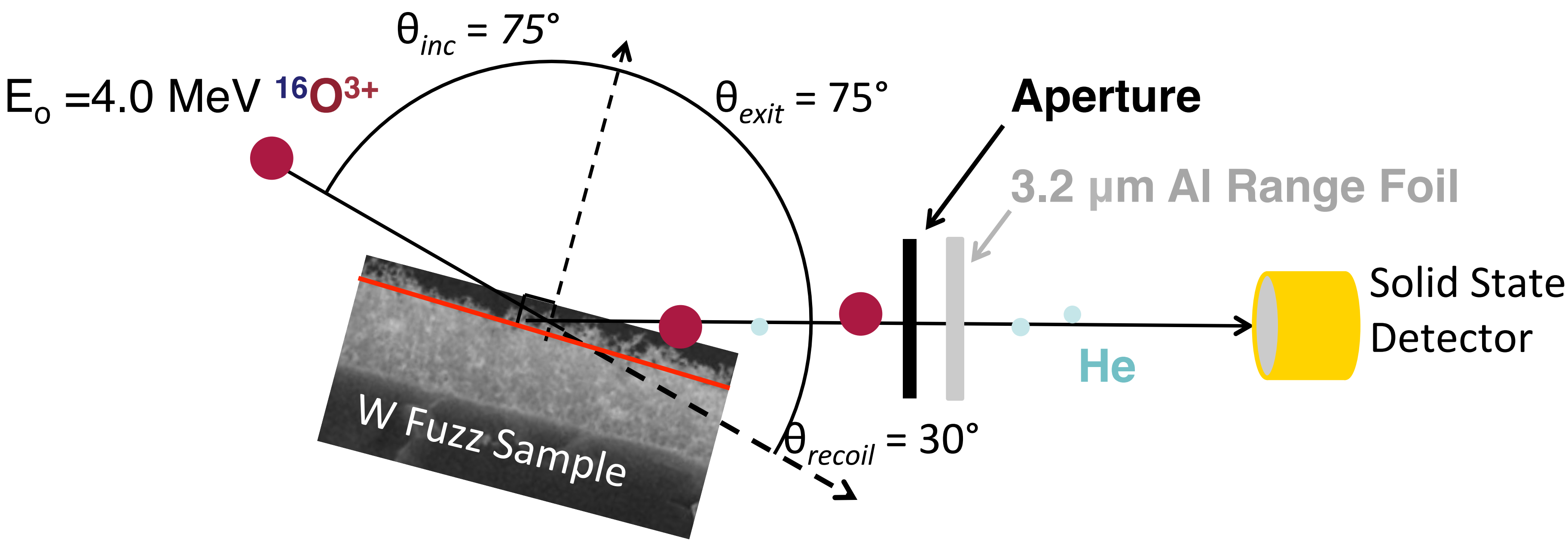
a)

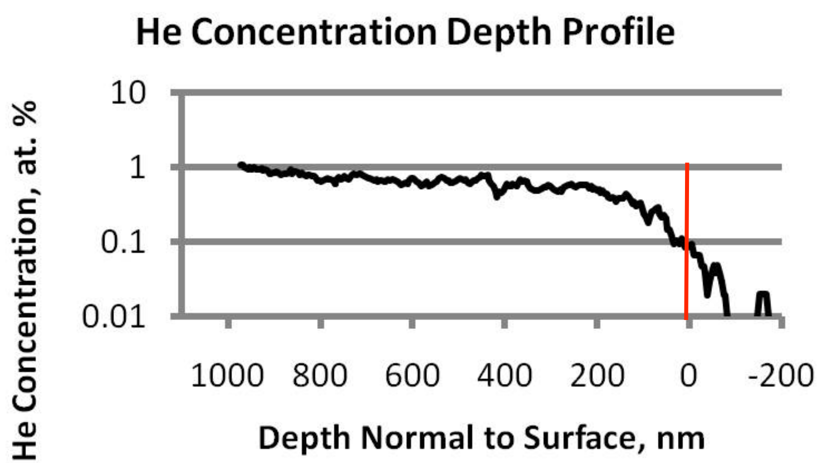
b)

Fig.1 Simulated dependencies of the shear yield strength of tungsten with different initial atomic concentrations of dissolved helium for the cases of shear stress applied in a) {010}<100> and b) {110}<$\bar{1}$11> directions.

Krasheninnikov PSI 2012

Diagnostic: Heavy ion elastic recoil detection allows us to measure the He depth profile in the surface layer/fuzz





Woller PSI 2012

He content in tungsten targets exposed in Pilot-PSI and PISCES indicates a lack of high He pressures in voids

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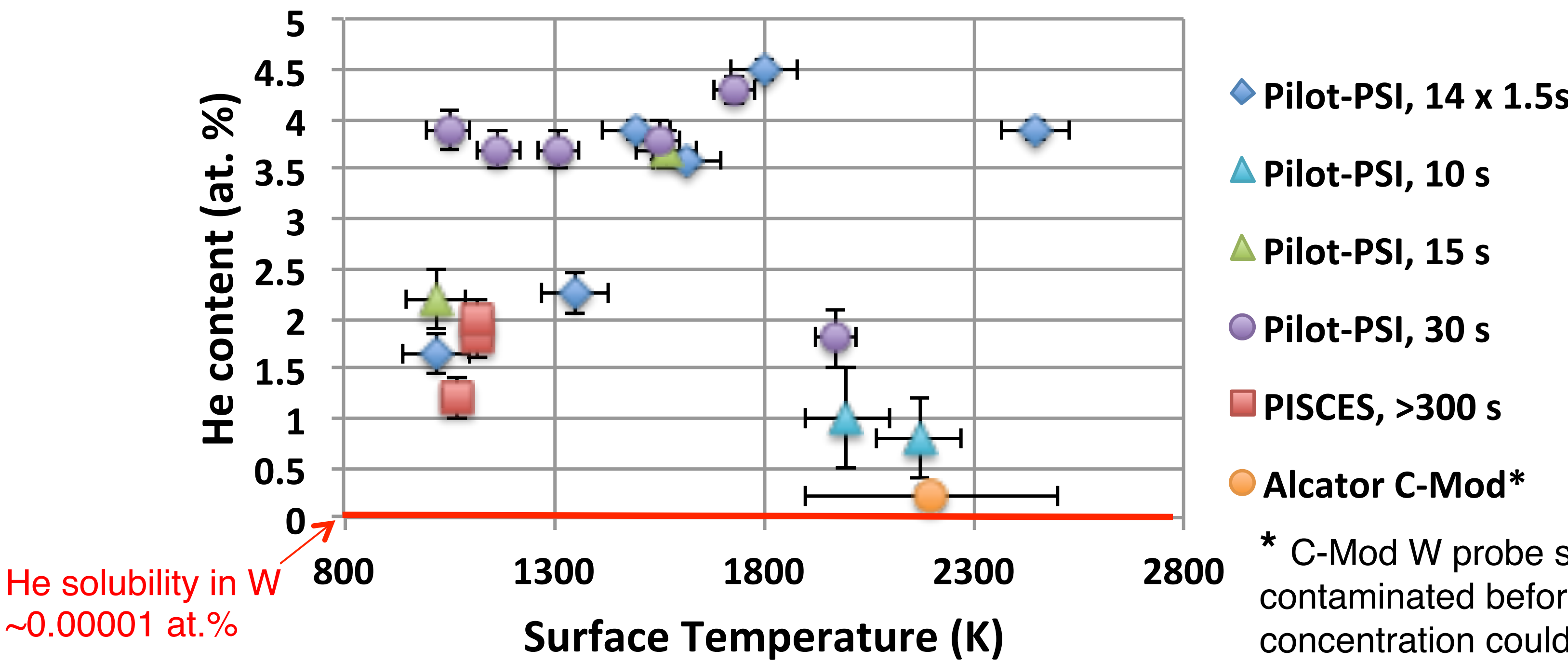

* C-Mod W probe surface was contaminated before true He concentration could be measured.

- Concentration is well above natural solubility, but below what might be expected for ~GPa He pressures in all voids.
- No clear trend vs. surface temperature, despite varying void sizes.

Woller PSI 2012

We are starting dynamic measurement of He content (+ W migration with marker) in DIONISOS

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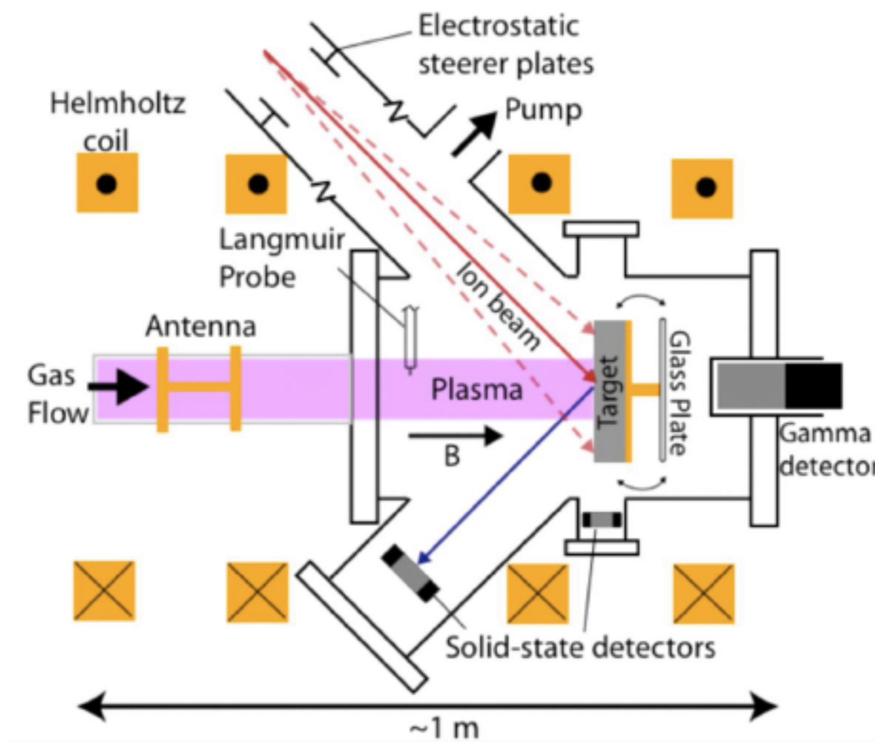
- Is the He content higher when the plasma is present?
- How does the He migrated versus depth at the beginning of growth and as growth saturates?
- In what manner does the tungsten grow from the sample?
  - Grain orientation /w single crystal W?



Woller Ph.D thesis

Alcator C-Mod helium plasmas produced necessary plasma conditions for fuzz growth at the outer strike point

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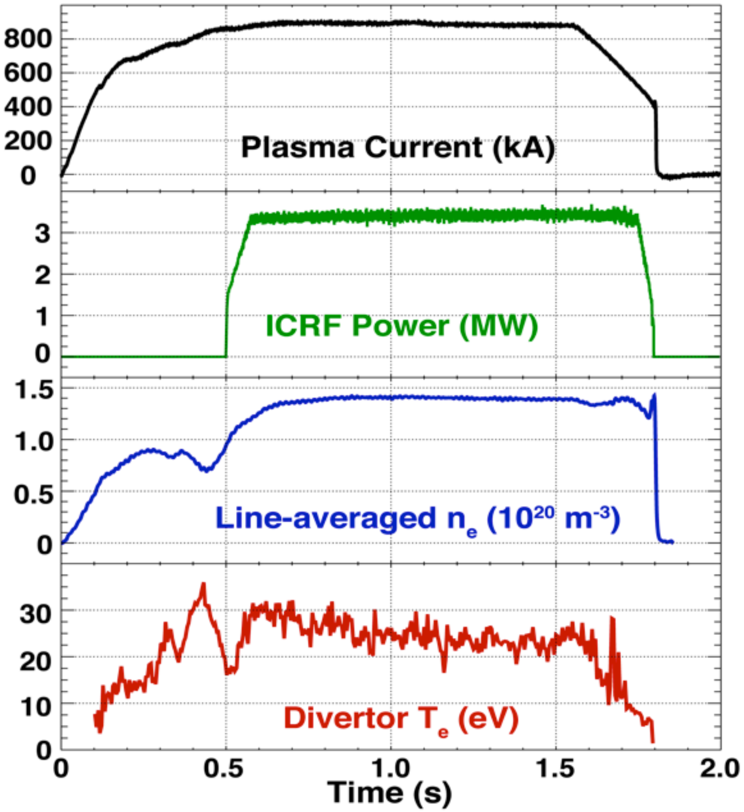
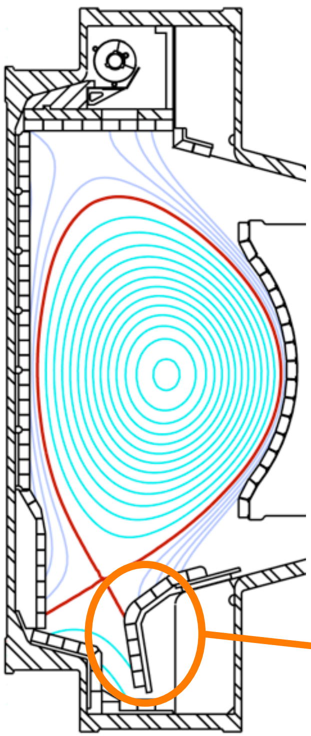
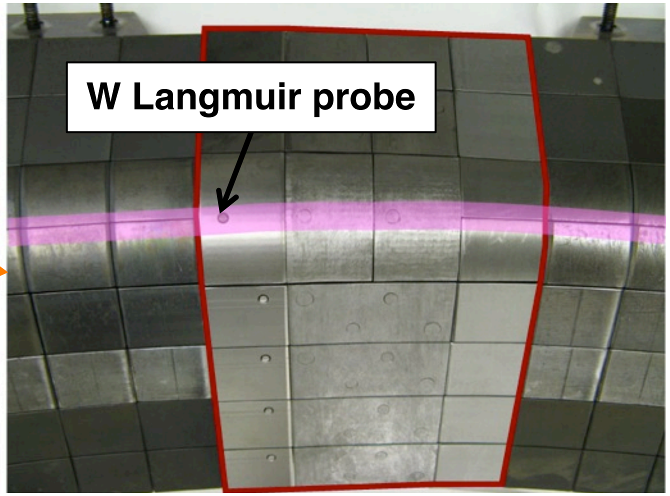
He plasma discharges





Strike point run above vertical divertor face to reduce flux expansion allowing for higher local surface temperatures.



Heat flux instrumented tiles

- 14 repeated L-mode discharges
- $T_{e,divertor}$ 20-25 eV, $q_{||}$ > 0.2 GW/m^2

➔~13 s of total exposure at appropriate growth conditions

Wright PSI 2012

Nano-tendrils are fully formed on tungsten divertor probe exposed to heat fluxes of 30-40 MW/m^2
Will tendrils grow in tokamak divertors? YES

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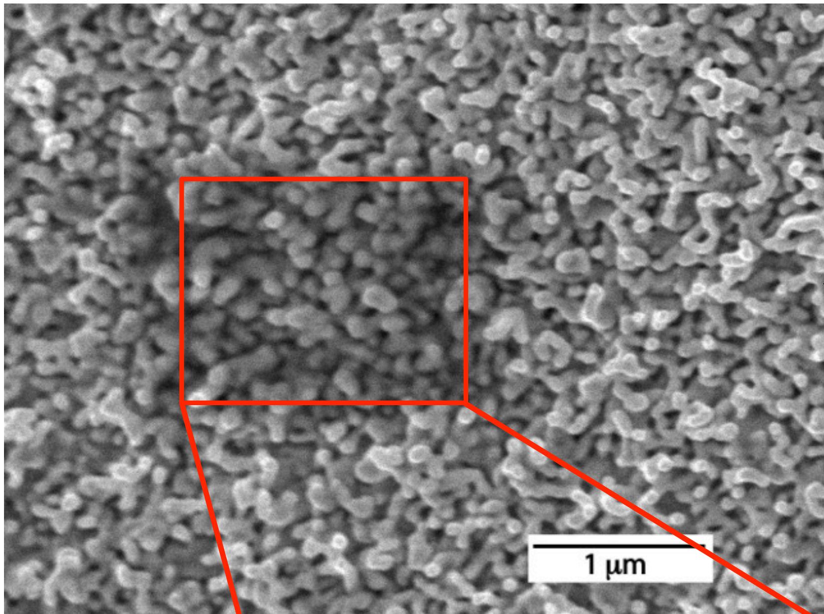
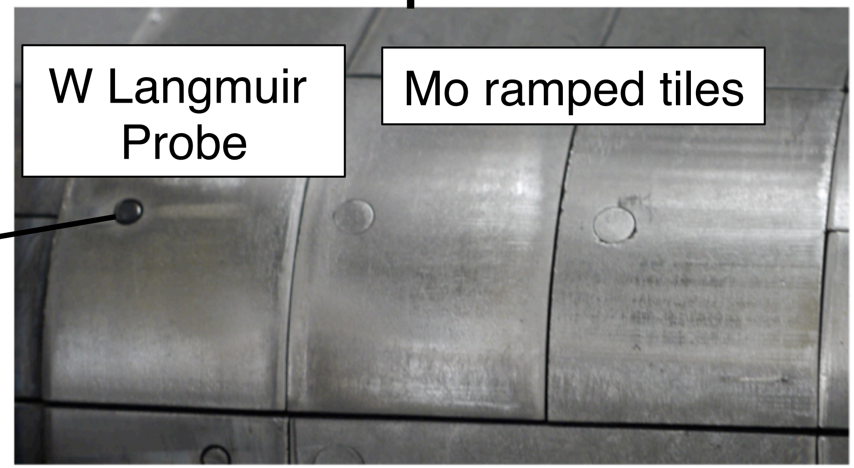
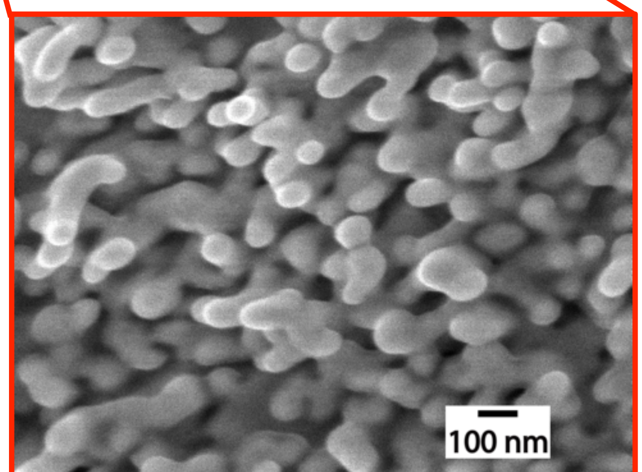


After exposure





Thickness of individual tendril is ~100 nm.

Wright PSI 2012

The PISCES empirical growth rate appears applicable to C-Mod results

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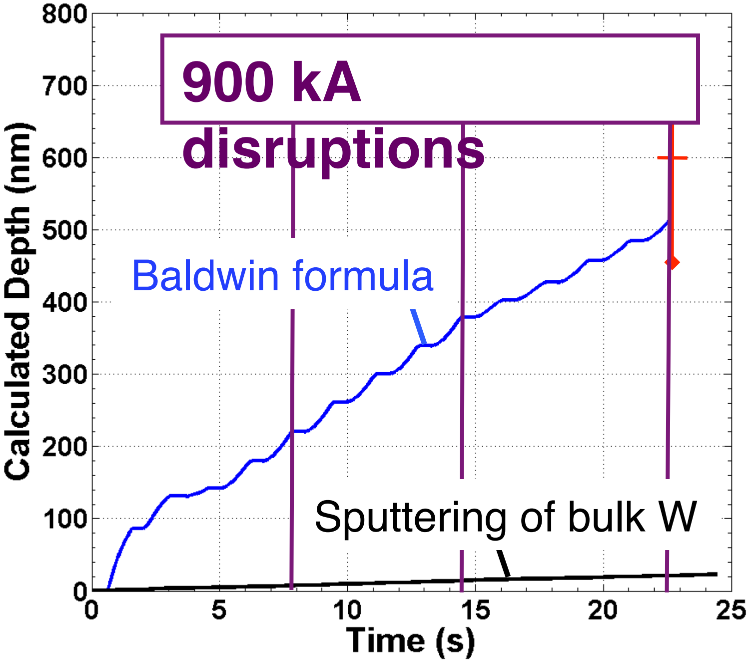


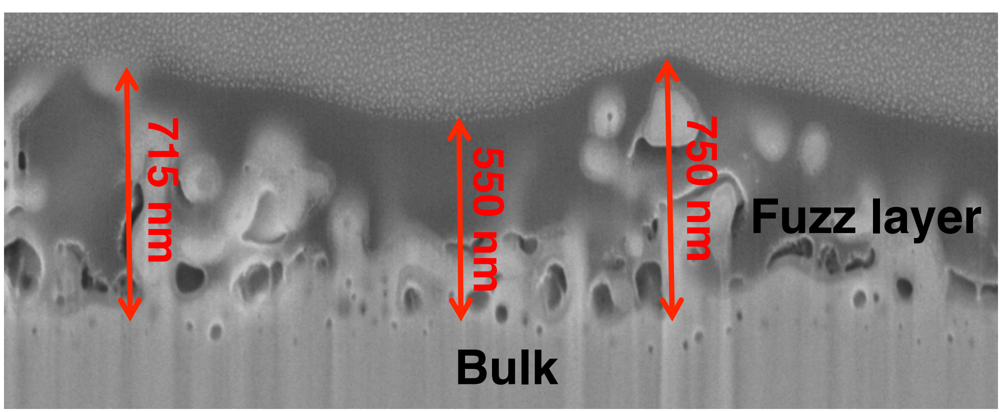
- Growth is estimated through $t^{1/2}$-dependence:

layer depth = $\delta \times G(T_{surf}) \times t^{1/2}$

where G µ $\exp(-E_{act}/kT_{surf})$, $E_{act} = 0.71$ eV

[3] M.J. Baldwin, R.P. Doerner, Nucl. Fusion 48 (2008) 035001

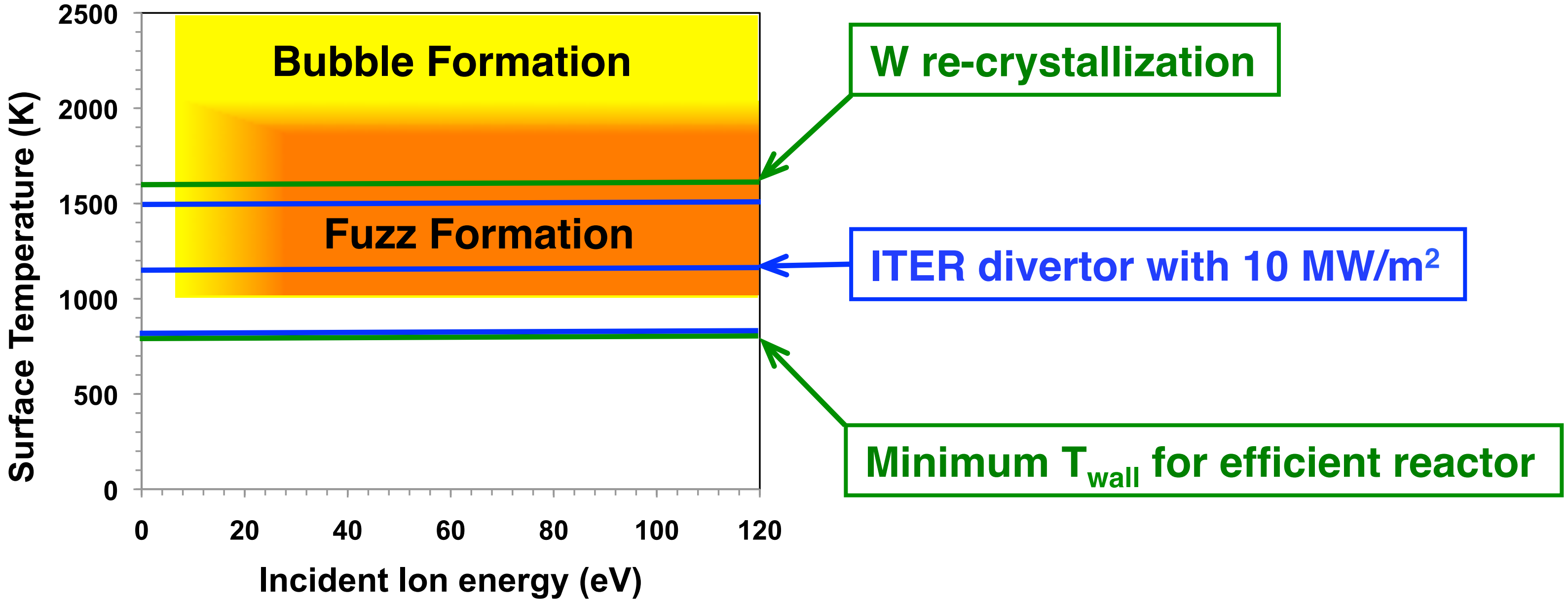
- Calculated cumulative layer depth of ~520 nm for W probe
- Sputtering only a small contribution in W case (~35 nm of calculated bulk W *gross* sputtering)



- The measured fuzz layer thickness was **600 ± 150 nm** from FIB cross-sectioning.

Wright PSI 2012

Unless we can find a mitigation method, nanotendril W surfaces seem nearly inevitable in ITER & reactor



- Tendrils appear right in the "sweet-spot" T for tungsten.

- What will be consequences?
  - Unclear if positive or negative…but it's fairly clear our standard surface picture is out the window

PISCES exploring balance between growth and erosion → understanding equilibrium

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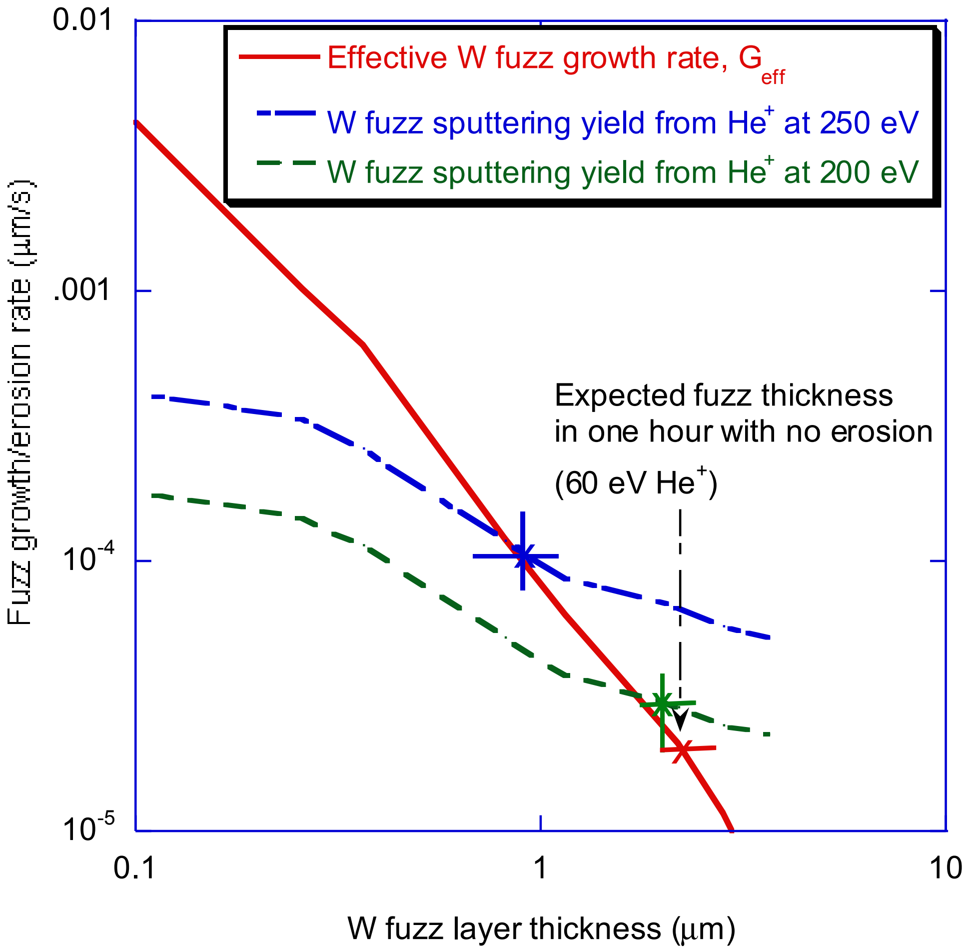

- Use measured erosion yield for He on W (i.e. net yield)
- Erosion from sputtering balances fuzz growth due to sqrt(t) dependence
- But the point of using W in divertor is to turn off sputtering? (basically required for reactor)

Doerner 2012

Educating a new generation of PSI-aware fusion scientists: e.g. conceptual design of 24/7 tokamak for PSI research

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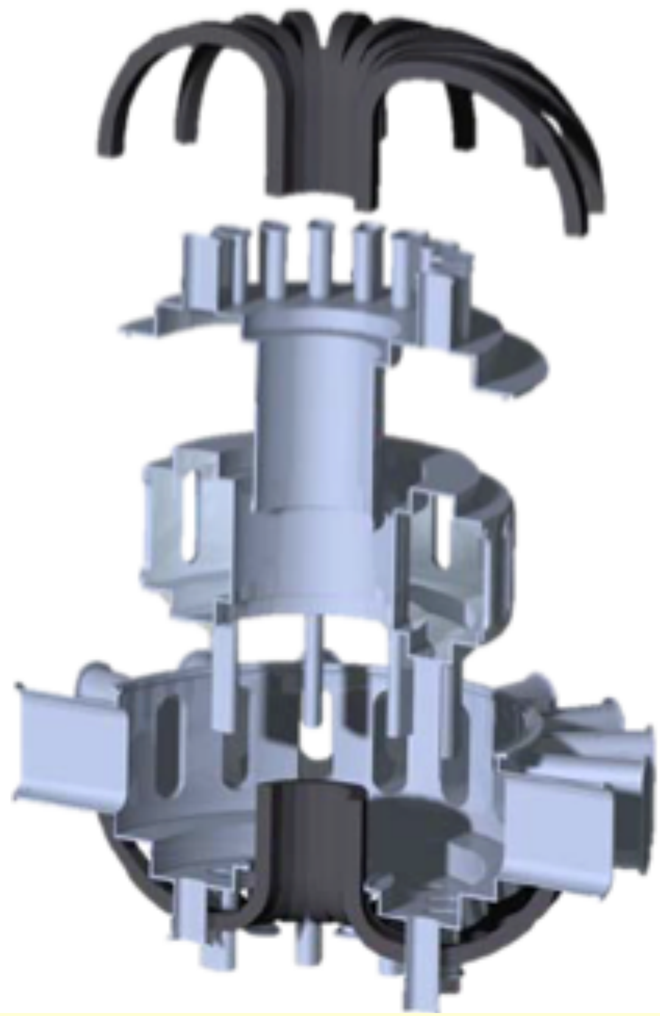
- R~1.2 m, B ~ 6 T, P_{CD}~20 MW
- 800 C vacuum vessel / wall
- Demountable superconducting coils
- Modular replacement of VV and PFCS.
- Used dimensionless similarity arguments to match ~15 key figures of merit for a reactor
  - SOL + divertor plasma
  - PMI, erosion, deposition
  - PFC material response.
- Four of five papers in F.E.D. [2012] special issue first-authored by students



Exploded view of Vulcan tokamak

The idea that PSI is an important *science* area is starting to permeate through the fusion community

PSI Science Center

- There is a growing sense of appreciation in the confinement community about moving → reactor-relevant tests in confinement devices
  - Proper temperature! [FESAC Material report]
  - Center participants at APS-DPP 2012 (review + invited)

- We hope to continue growing this trend through our Center activities although we do face challenges
  - Possible C-Mod shutdown (on advent of heated W divertor)
  - NSTX-Upgrade delayed
  - DIII-D carbon environment.
  - International?

- Experience so far indicates, we believe, the importance of both using a holistic approach and engaging the confinement community and devices to advance PSI science.