Mixed Material PMI for ITER:

Summary of PISCES Group Results

Presented by G.R. Tynan

on behalf of

M. Baldwin, J. Boedo, R. Doerner, C.Holland, E. Hollmann, D. Nishijima, J. Hanna, J. Yu, R. Moyer, S. Mueller, F. Najmabadi, D. Rudakov, R. Seraydarian, G.R. Tynan, K. Umstadter

L. Cai, A. James, M. Shimada, Z. Yan, M. Xu

J. Roth, K. Schmid, R. Puno, A. Kreiter
(EU Visitors)

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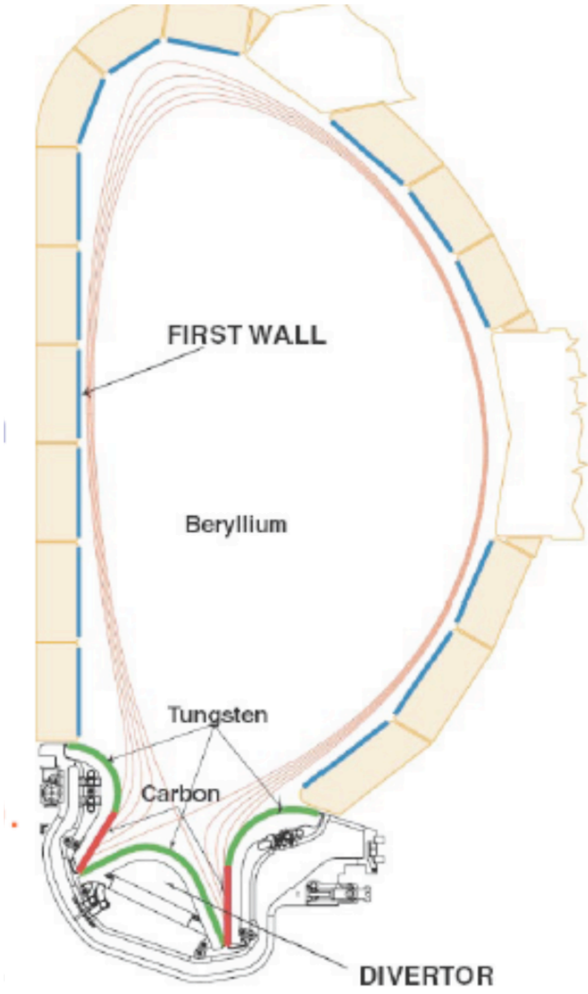
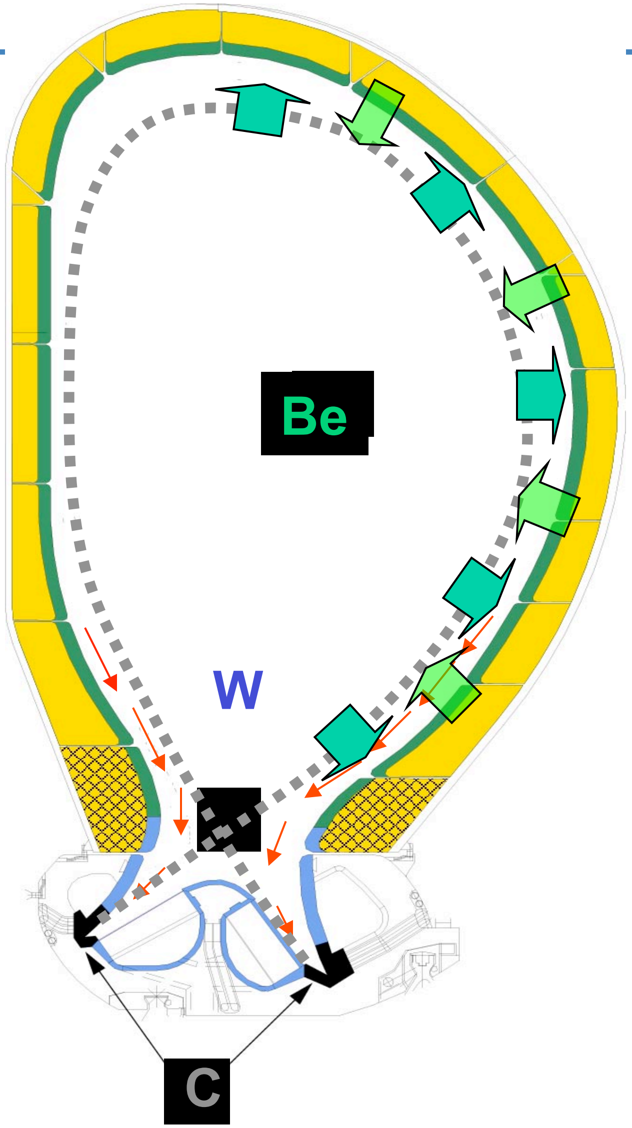
Why Care About Mixed Material PMI in ITER?

- ITER First Wall/Divertor Is a Mixture of Be/W/C Materials
- Plasma Will Contact w/ Material Surfaces
- Material Migration Results in Formation of Mixed Materials



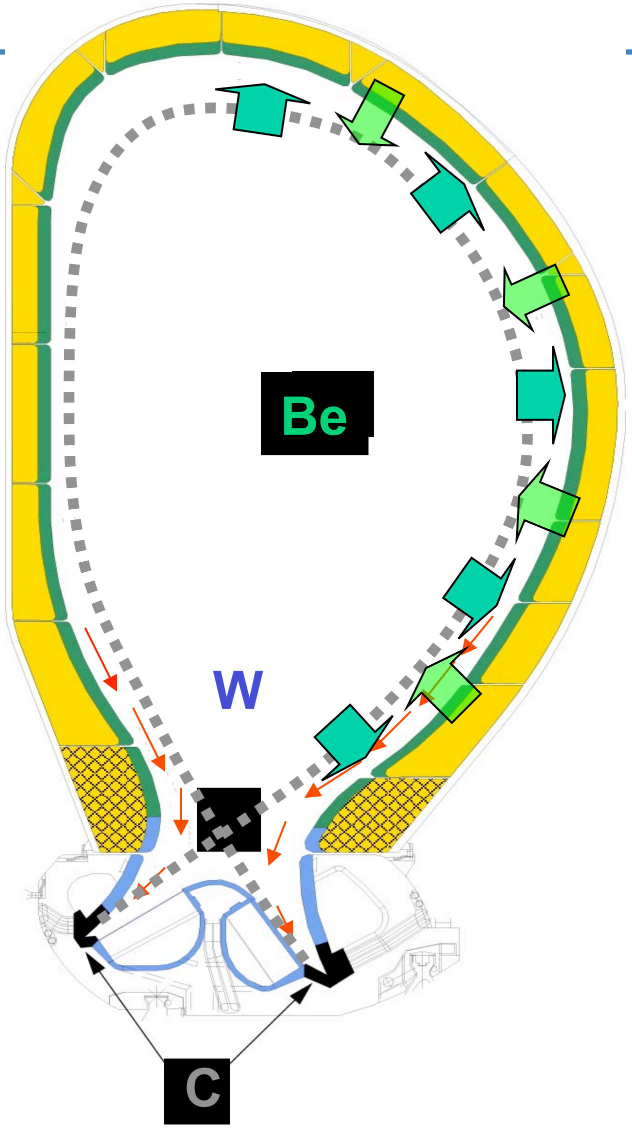
Comprehensive Approach to Essential ITER PFC Issues



PISCES

- Cross-field Main Plasma Transport into SOL
- Impurity Transport Thru SOL
- Bulk Convective Flows within SOL
- Fundamental PFC Erosion & Redeposition Studies
- Mixed Materials Issues
  - –Steady-state
  - –Transient ELM-like
- Model Development & Validation

Comprehensive Approach to Essential ITER PFC Issues



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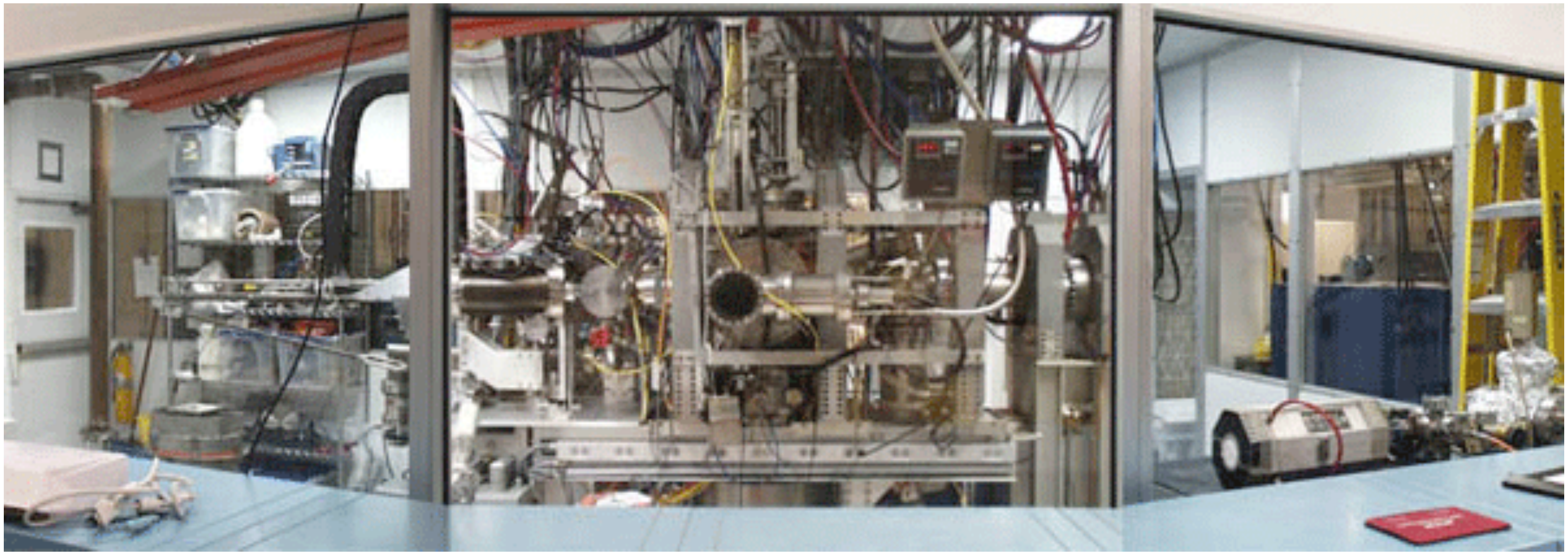
PISCES Divertor Simulator Facility

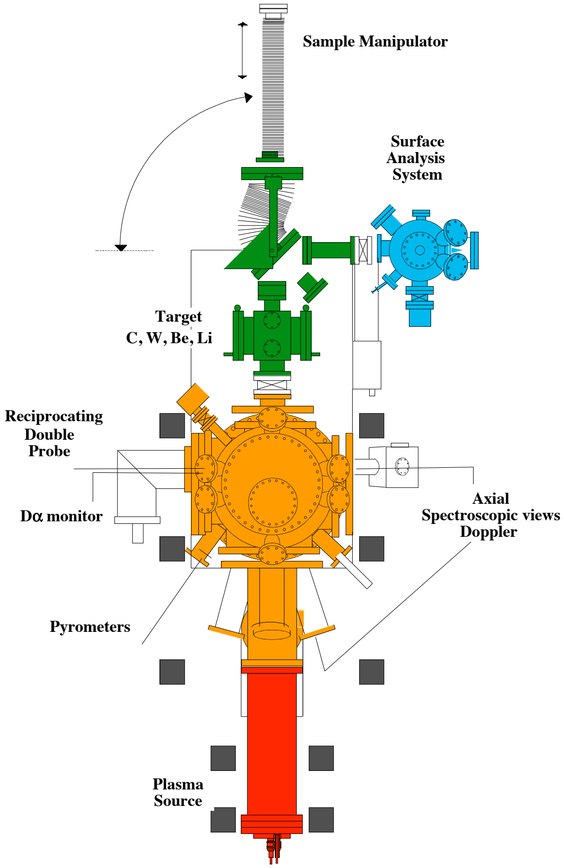
Be-Compatible PISCES-B Facility



Surface Science Diagnostics

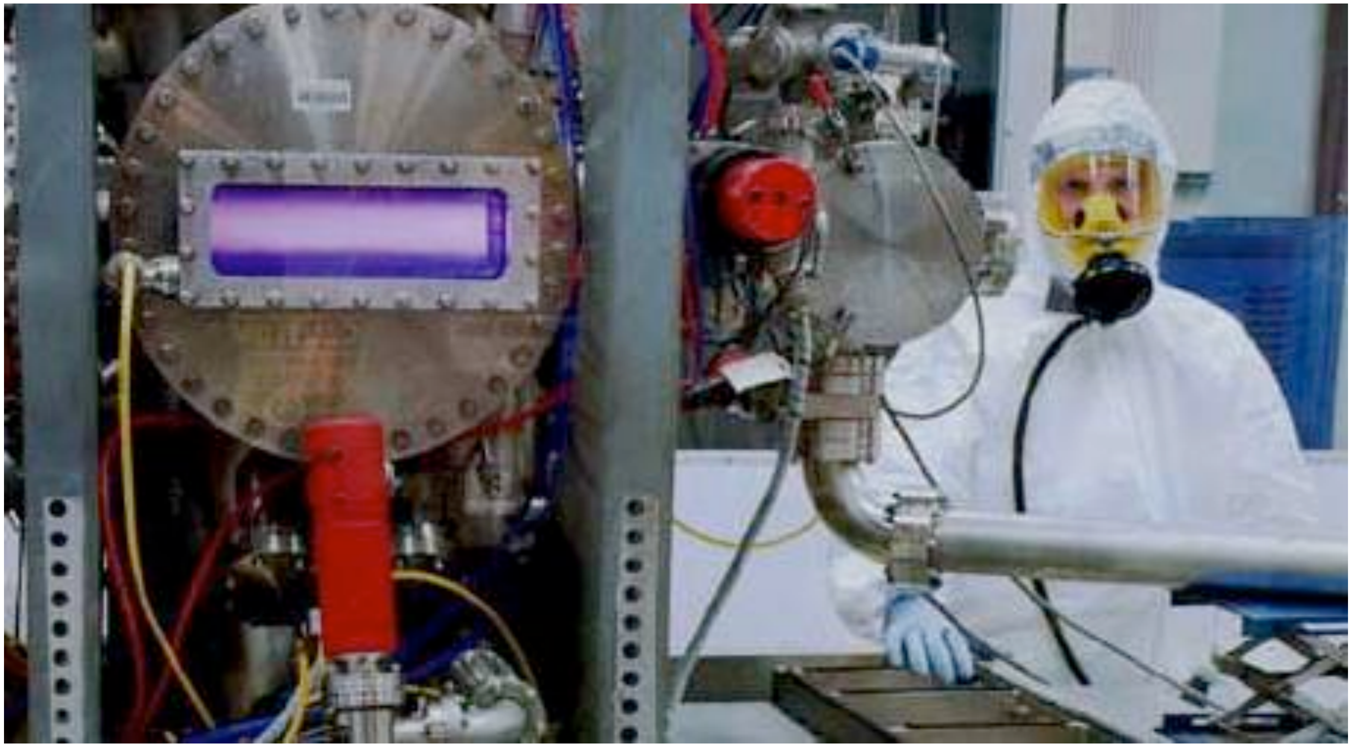
- *In-situ XPS, Auger, SIMS*
- *SEM & EDX*
- *Ex-situ SIMS, XPS, TDS*

PISCES is a steady-state reflex arc plasma source that provides parameters relevant to edge physics and PMI issues in present and future confinement machines

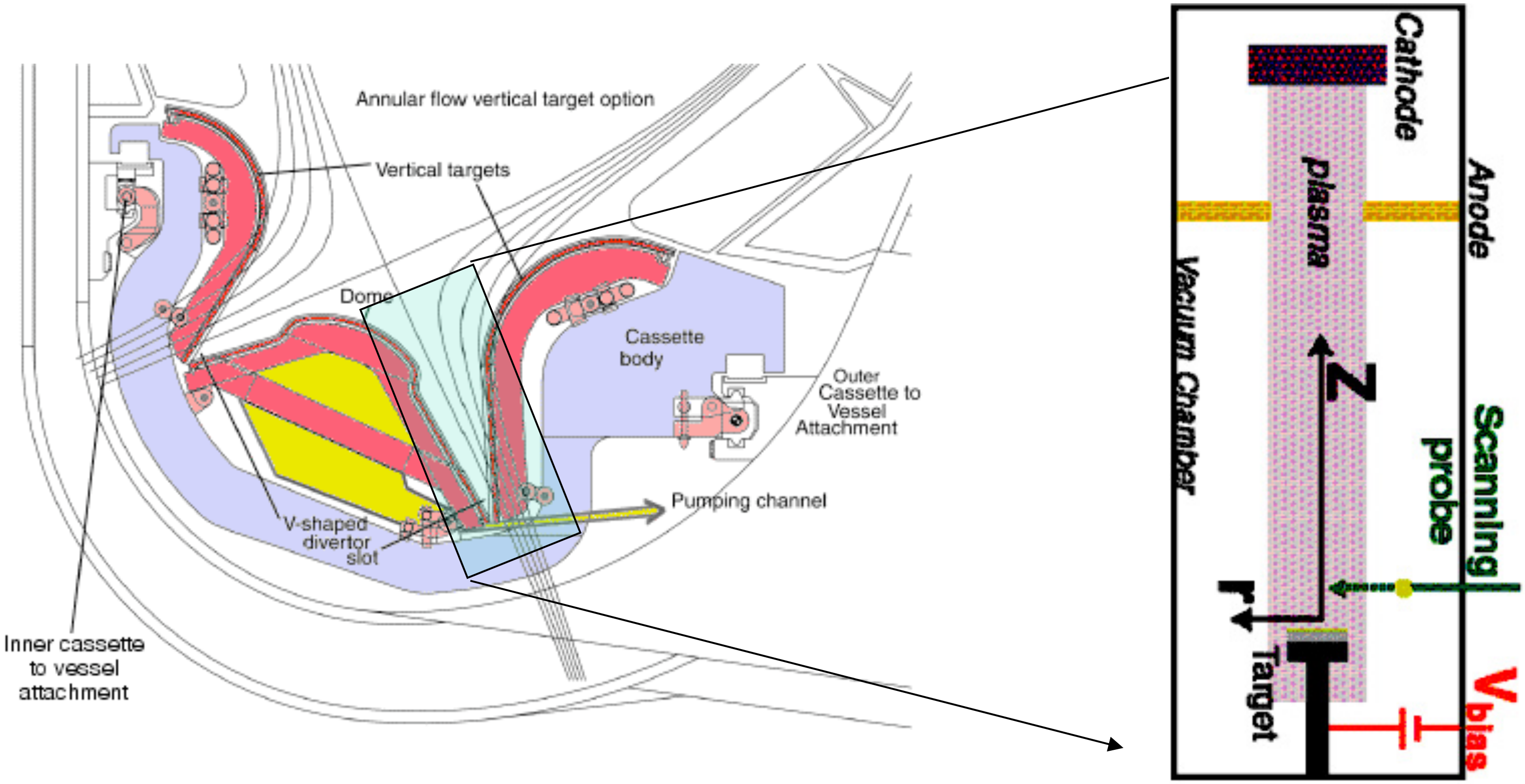


	PISCES-B	Confinement Devices
Ion flux ($m^{-2}\ s^{-1}$)	10^{23}	10^{23}
Ion energy (eV)	20-300 (bias)	10-300 (thermal)
Heat flux (MW/m^2)	1-10	1-10
T_e (eV)	2-40 (thermal)	1-100 (thermal)
n_e (m^{-3})	10^{17}-10^{19}	10^{18}-10^{20}
Impurity fraction (%)	0.03-10	1-10
Pulse length sec	continuous	10-30
Target materials and coatings	C,W,Be,Li	C,W,Be,etc. (essentially any)
Plasma species	H,D,He	H,D,T,He

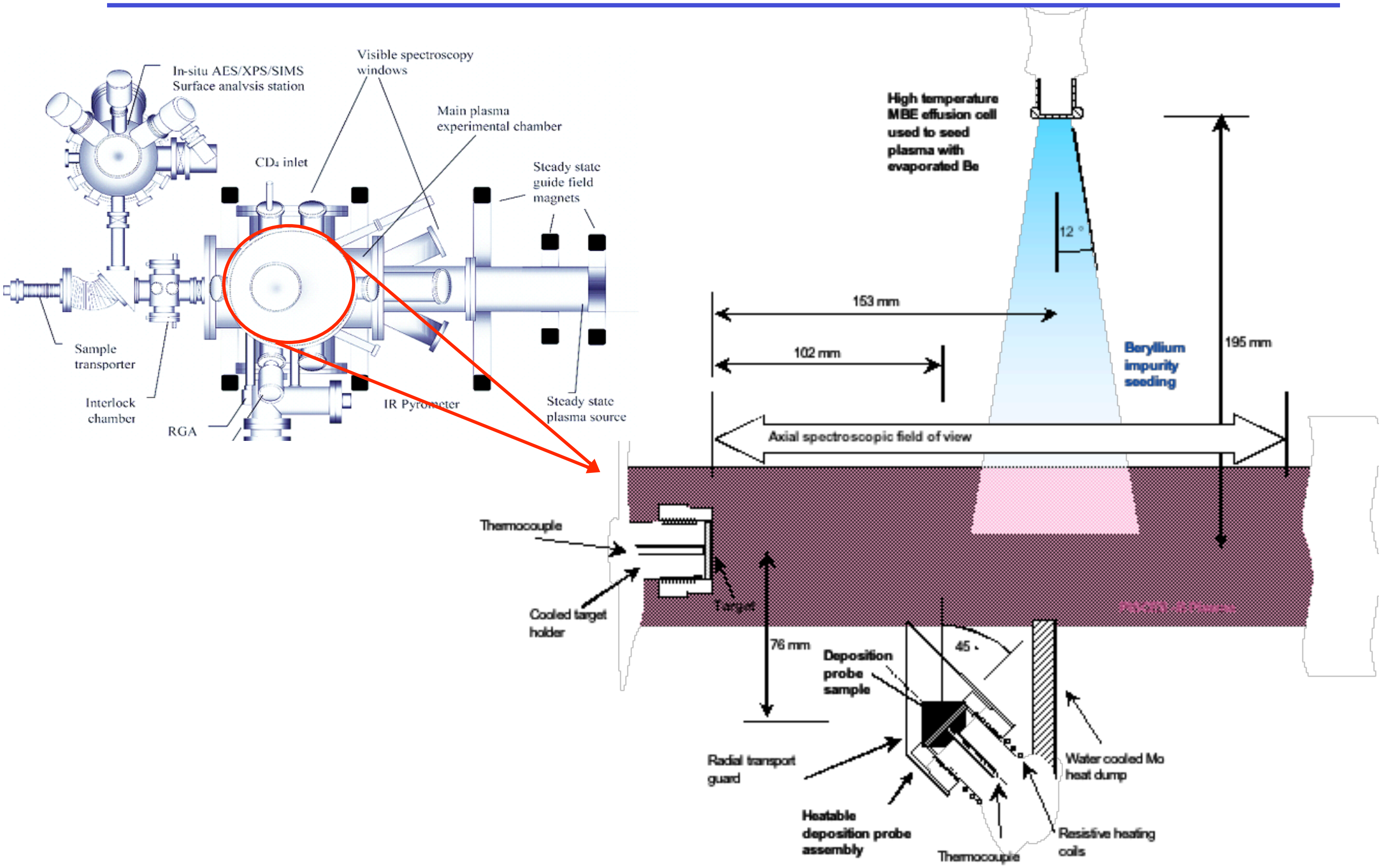
PISCES-B, and Its Associated Surface Analysis Laboratory, Are Compatible with Beryllium Operations.



Simulating ITER divertor geometry in linear device



Controlled Mixed Mat'l PMI Expt's in Be seeded PISCES-B Plasmas



Some Recent ITER Mixed Material Studies by PISCES Group & Collaborators

- Be Impurity Effects:
  - Be-C Reduction of C Erosion
  - Redeposited Be Erosion
  - Be-W Alloying
- D/He Plasma Effects on W:
  - Nanostructure formation
  - D Retention Reduction
  - Be Effects
- ELM Thermal Transient Effects
- D or T Retention in Mixed Materials

Be-C experiments

Evolution of chemical erosion in Be seeded D plasma.

Properties of C target surfaces after exposure.

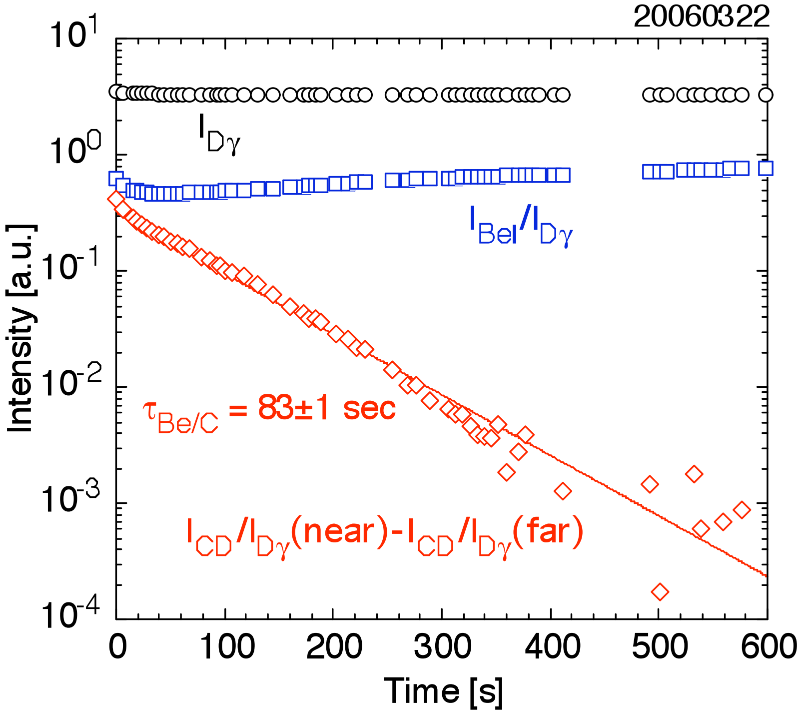
Extrapolation to ITER.

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

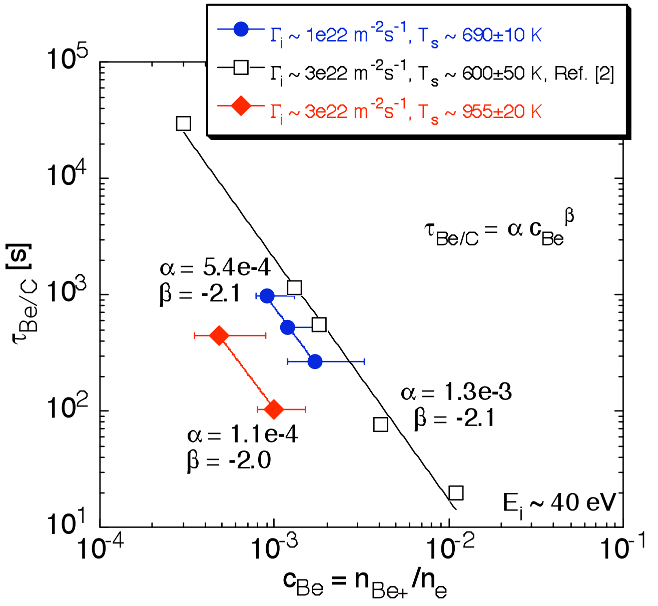
PISCES

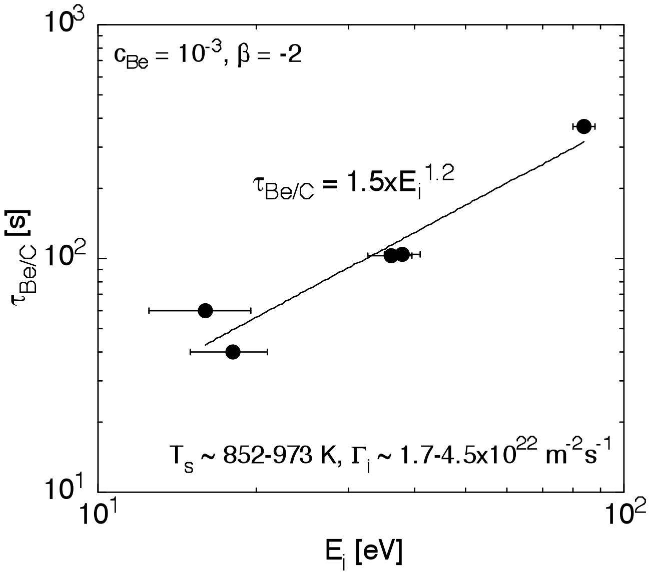
- CD band intensity near C target drops w/ time as Be erosion signal from target increases

- 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.



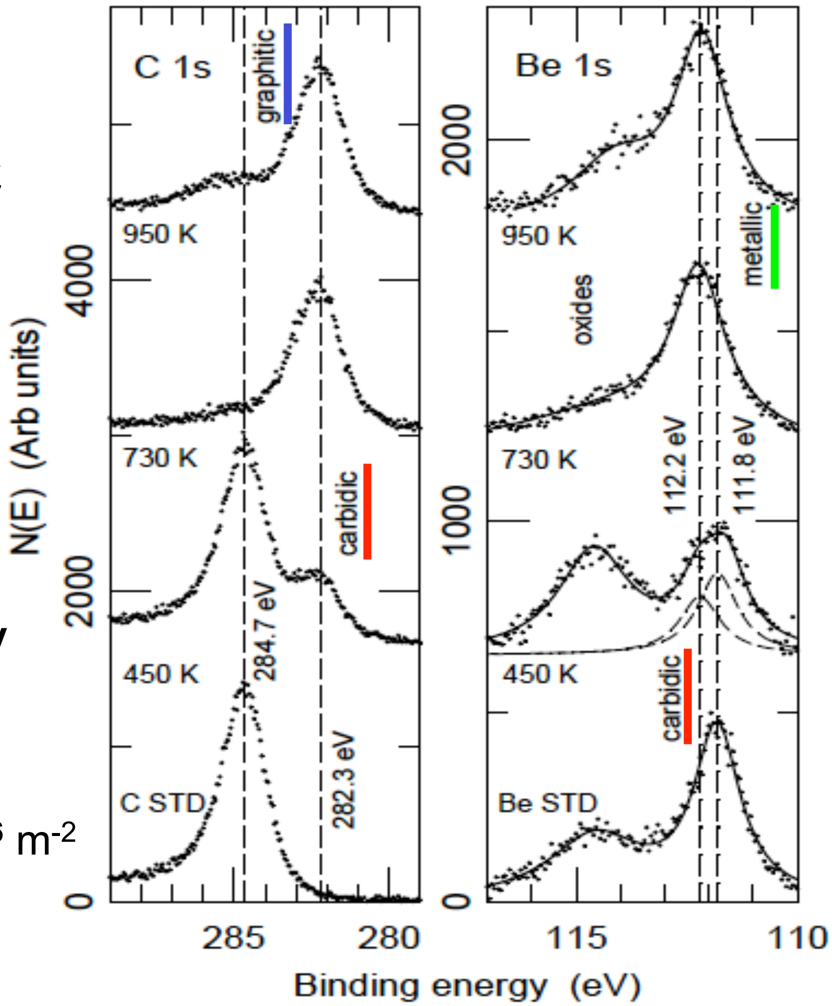


- c_{Be} scanned keeping other parameters, E_i, T_s and G_i constant.

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

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

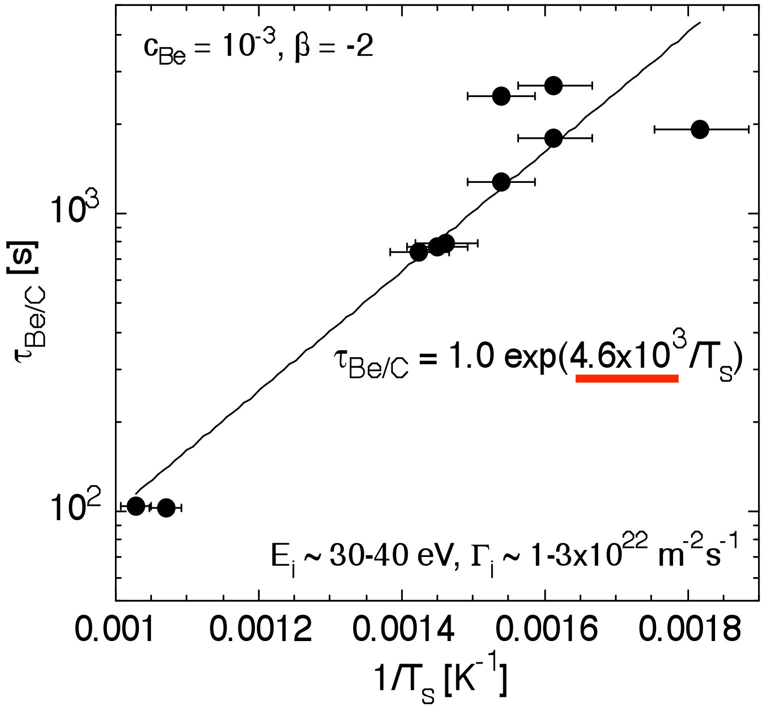
$\tau_{Be/C}$ strongly depends on T_s.

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

- Enthalpy of formation of Be_2C:
$\Delta H_{298}(Be_2C)$ = -117.0±1.0 kJ/mol

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

- Pure Be and Be_2C must also|
contributes to the carbon
erosion reduction especially at
lower T_s and/or $\Delta H_{298}(Be_2C)$
may be lower in a PSI environment
than the equilibrium value.



Be-C Formation Should Occur Between ITER Type-I ELMS

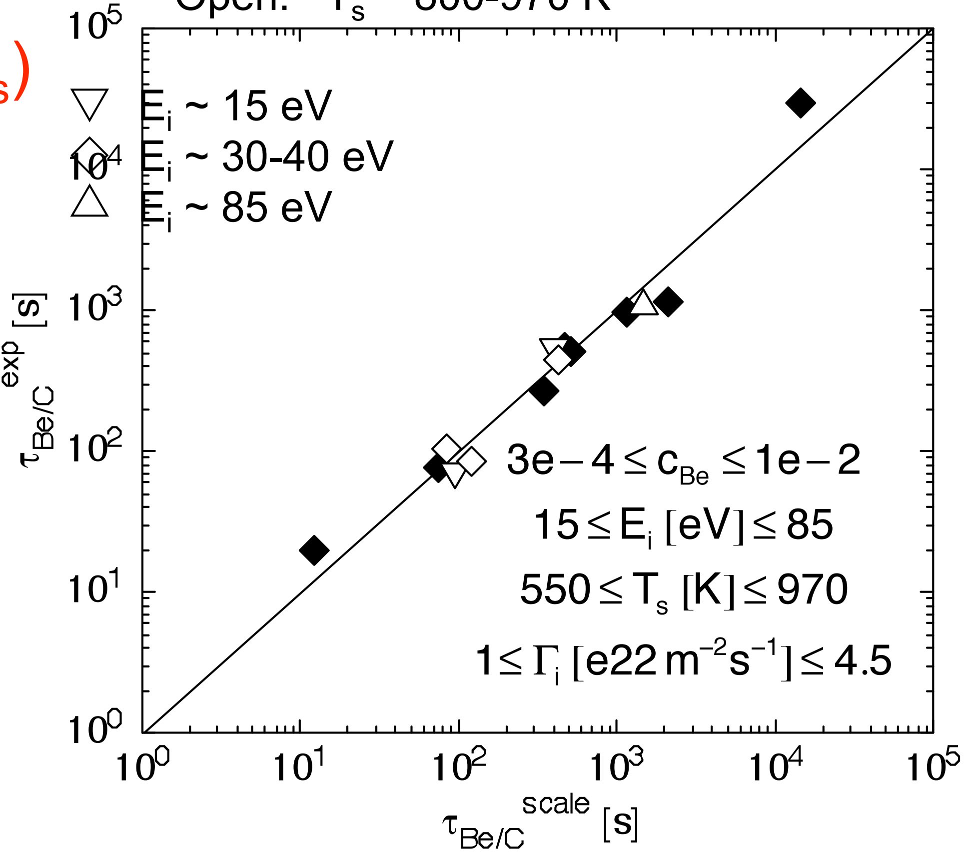
$$\tau_{Be/C}^{scale}\,[s] = 10^{-7}\, c_{Be}^{-1.9\pm0.1}\, E_i^{0.9\pm0.3}\, \Gamma_i^{-0.6\pm0.3} \times \exp((4.8\pm0.5)\mathrm{x}10^3/T_s)$$

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

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

➡ $t_{Be/C}$ ~ 6 ms << 1 s (ITER ELM Period)

Closed: T_s ~ 550-700 K
Open: T_s ~ 800-970 K



Be erosion experiments

Erosion of Redeposited Be Layers

Chemical Erosion of Be by D2 Plasmas

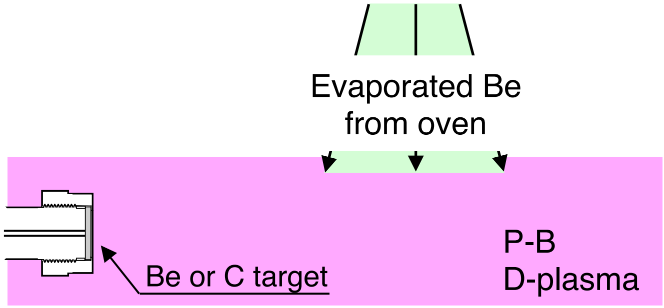
PMI of Redeposited Be

- *Sputtered Be from first wall will (re-)deposit on Be first wall and divertor C and W materials.*

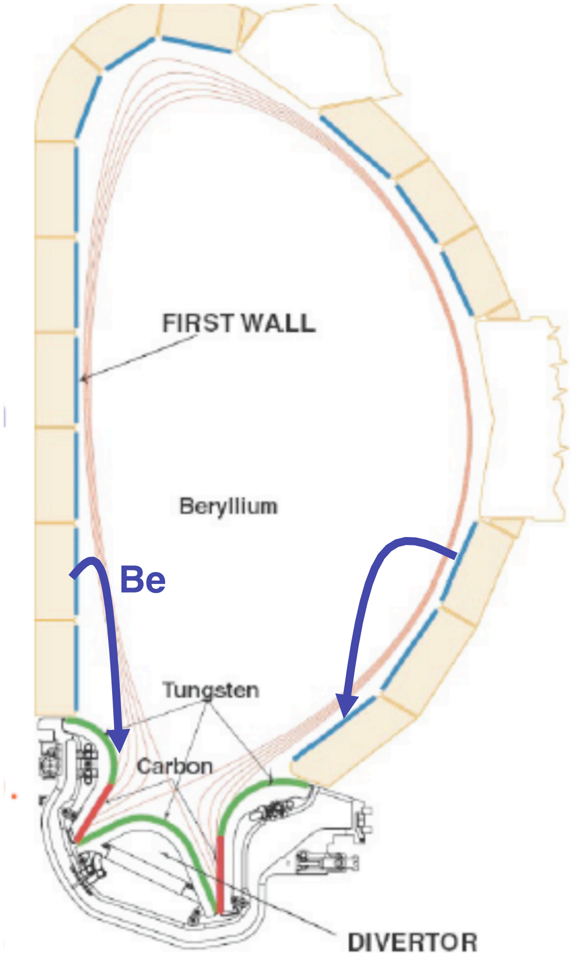
⇨ *Is the sputtering yield of deposited Be layer the same as PC-Be?*

-- DP-Be/Be: *in-situ* plasma-deposited Be on Be

-- DP-Be/C: *in-situ* plasma-deposited Be on C



ITER



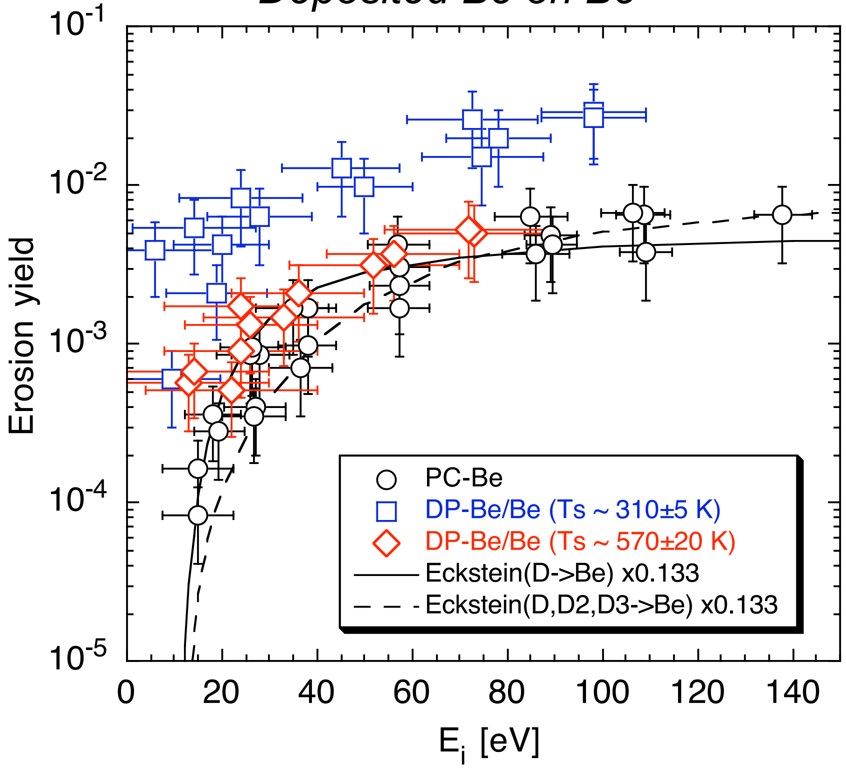
Sputtering of ReDep-Be/Be at lower T_s enhanced, while no enhanced erosion at higher T_s

PISCES

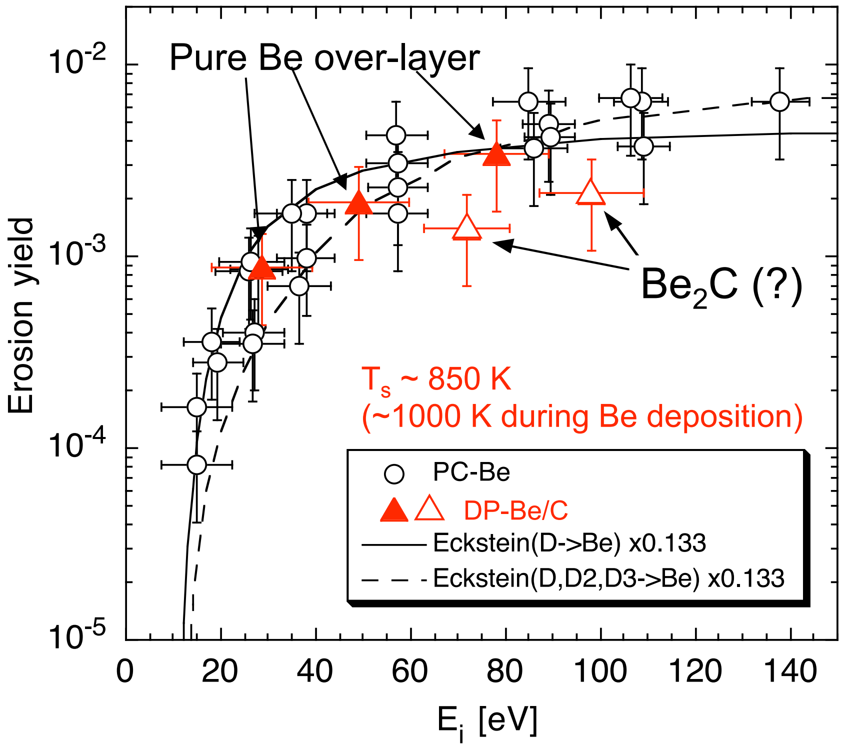
- Higher D-retention at lower T_s
  - ⇨ Lower surface binding energy
  - ⇨ Enhanced sputtering

- Formation of Be_2C with higher surface binding energy
  - ⇨ Sputtering yield slightly decreased

Deposited Be on Be

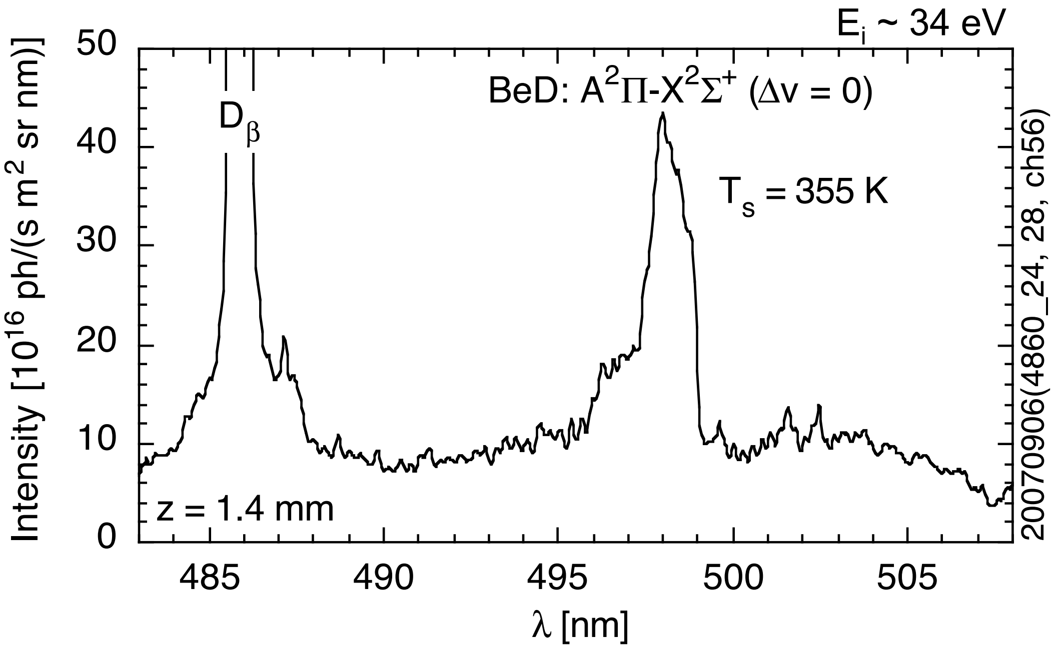


Deposited Be on C



Chemical sputtering of Be released as BeD

- Surface temperature dependence
- Incident ion flux dependence

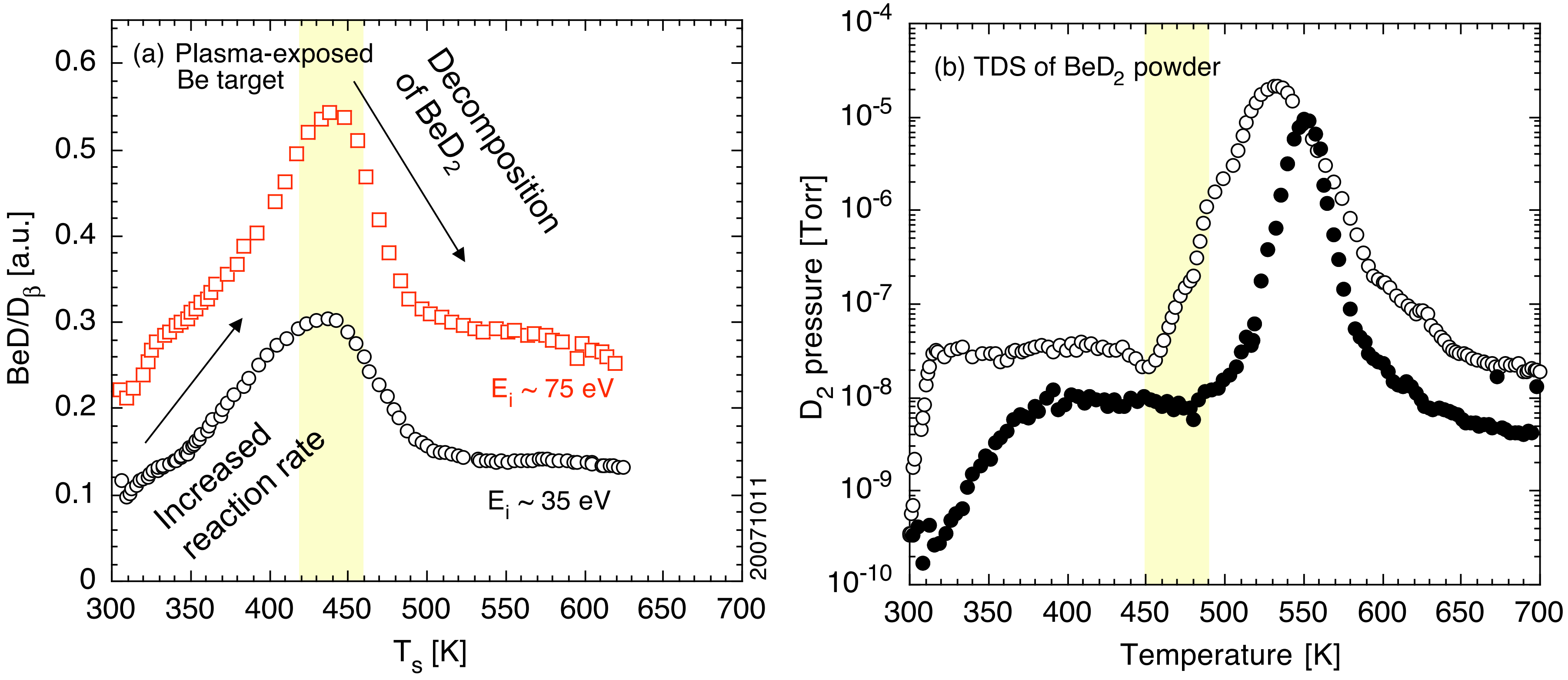


After Jacob & Roth 2007, this erosion process is categorized as “chemical sputtering”, since D-ions bombardment of a Be target causes a chemical reaction to form BeD_2 on the surface.

The chemical sputtering yield of Be released as BeD is peaked at T_s ~ 440 K.

- The peak T_s ~ 440 K is consistent with the onset temperature of the decomposition of BeD_2 powder.

⇨ BeD_2 formation on Be surface exposed to D-plasma



Tungsten (W) PMI Studies

D/Be mixed plasmas

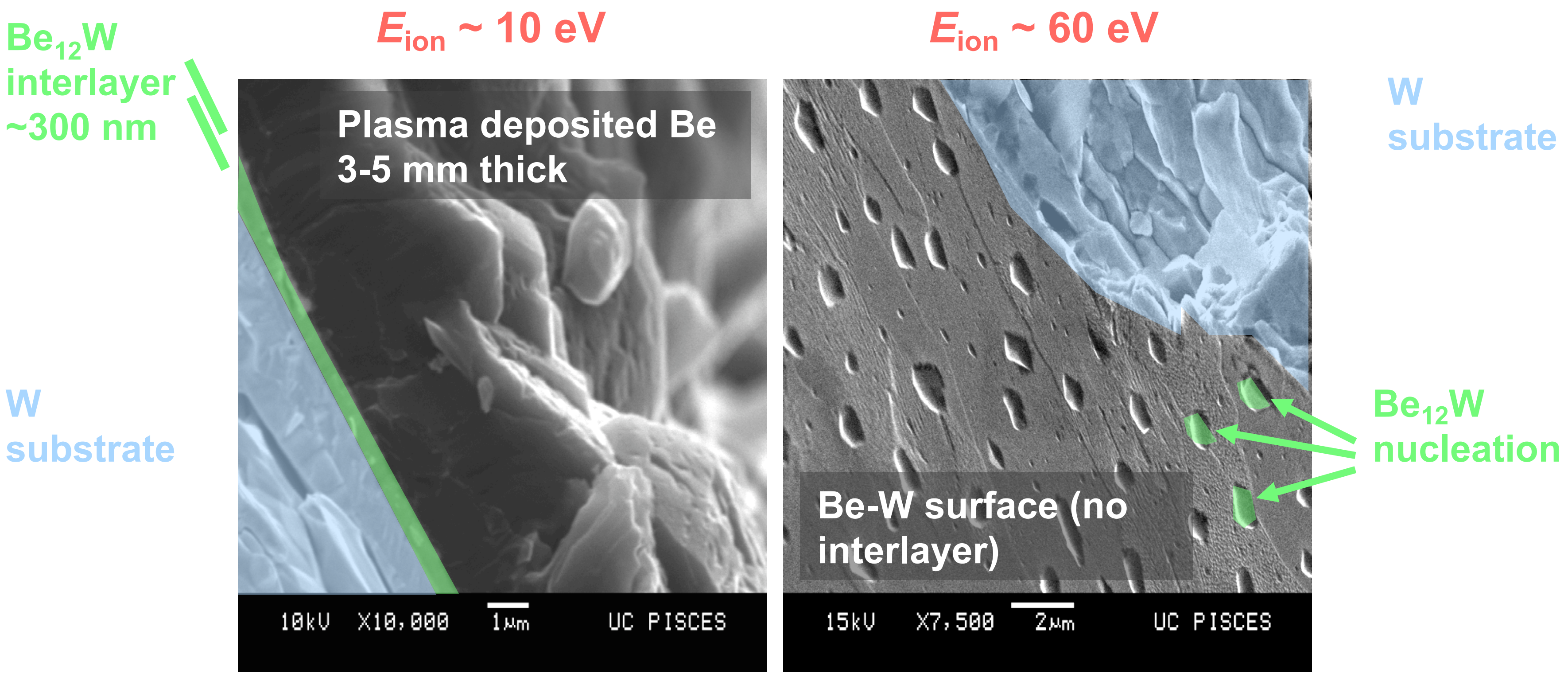
-W-Be formation

D/He & D/He/Be mixed plasmas

--- W surface morphology

--- D Migration and Retention

Be-W Alloy Formation Depends on T_{surf}, E_{ion}, G_{ion}

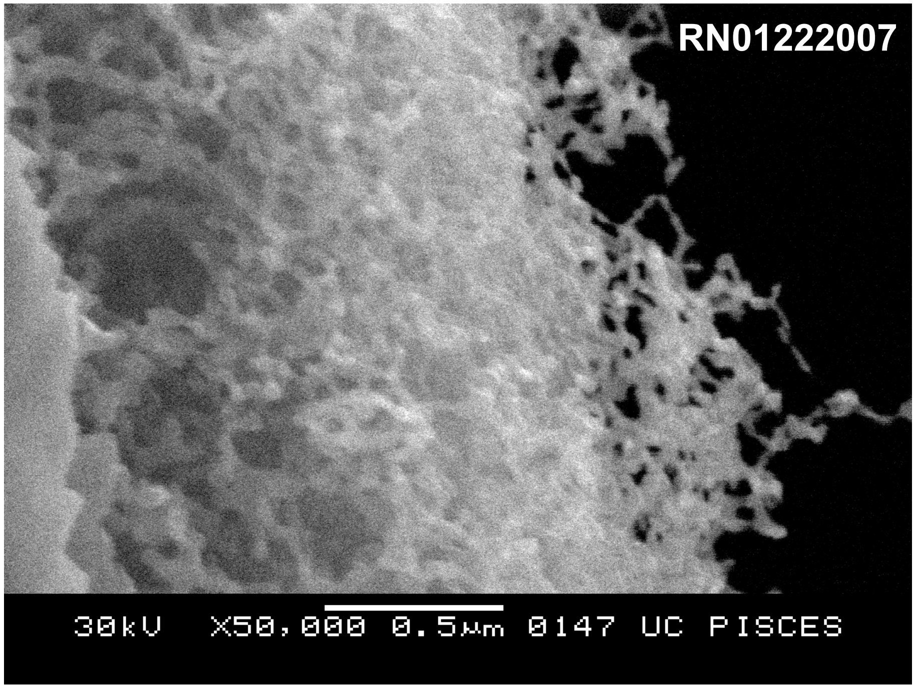


M. Baldwin et al, PSI 2006

Plasma simulators observe morphology change on W surfaces exposed to pure He plasma.

PISCES-B: pure He plasma

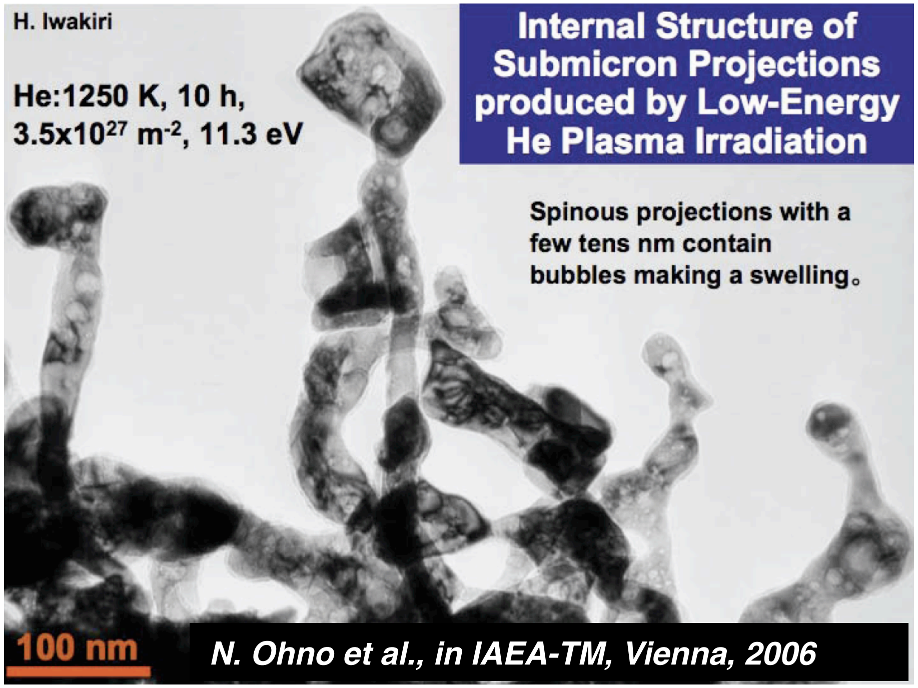
T_s = 1200 K, Dt = 4290 s,
Fluence = 2×10^{26} He^+/m^2, E_i = 25 eV



Scanning electron microscope (SEM)

NAGDIS-II: pure He plasma

T_s = 1250 K, Dt = 36,000 s,
Fluence = 3.5×10^{27} He^+/m^2, E_i = 11 eV



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

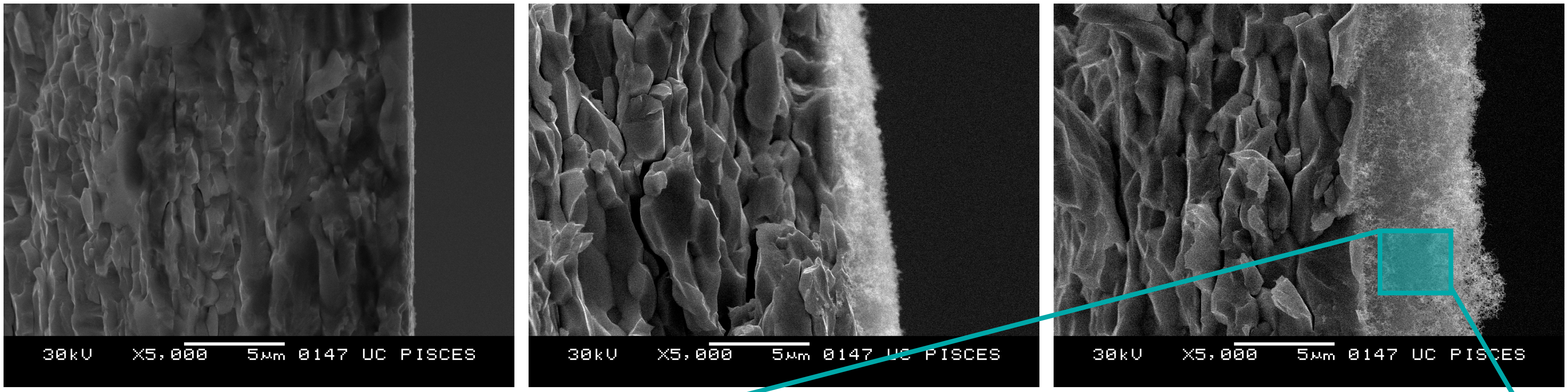
Spinous projections with a few tens nm contain bubbles making a swelling。

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

Transmission electron microscope (TEM)
in Kyushu Univ.

SEM analysis reveals time dependent growth of nano-structured layer at T_s ~ 1120 K.

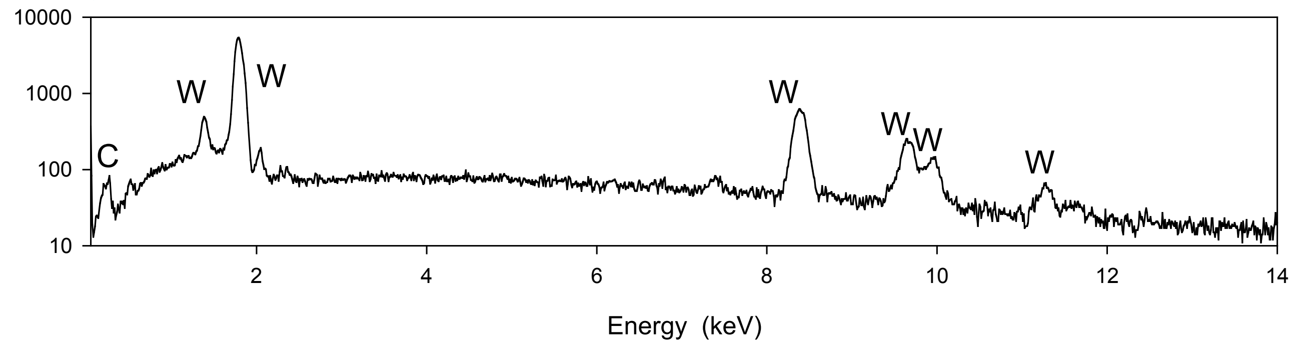
Pure He plasma, **E_i = 60 eV**, T_s = 1120 K, He^+ flux ~ 4 x 10^{22} $He^+/m^2/s$


1.2 x 10^{25} He^+/m^2

2.0 x 10^{26} He^+/m^2

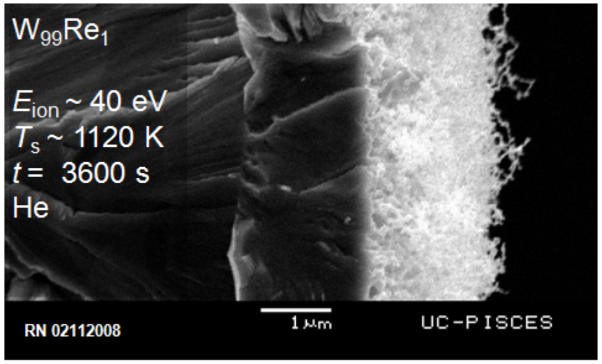
10^{27} He^+/m^2

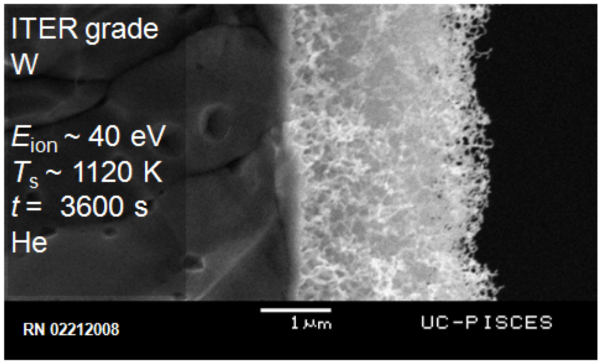
Nano-structures are almost pure W as indicated x-ray microanalysis with EDS

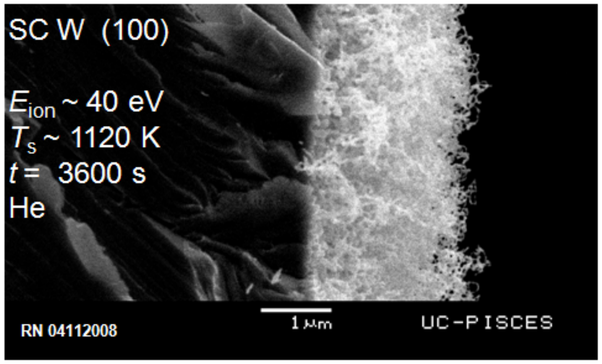


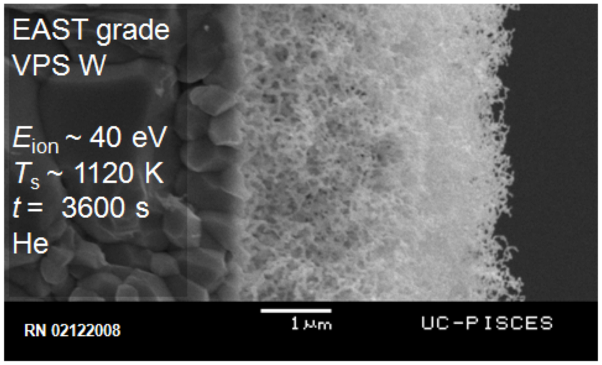
Effect of He plasma on various grades of W

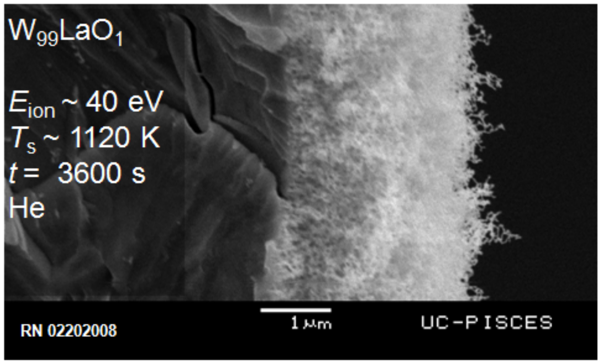
$G_{He} = \sim 5\times10^{22}\ m^{-2}s^{-1}$ for all cases

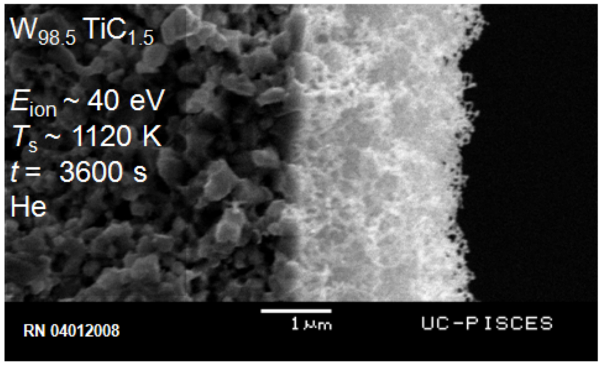












Rather similar growth rates of nanostructure on all types of tungsten exposed to plasma above 900K.

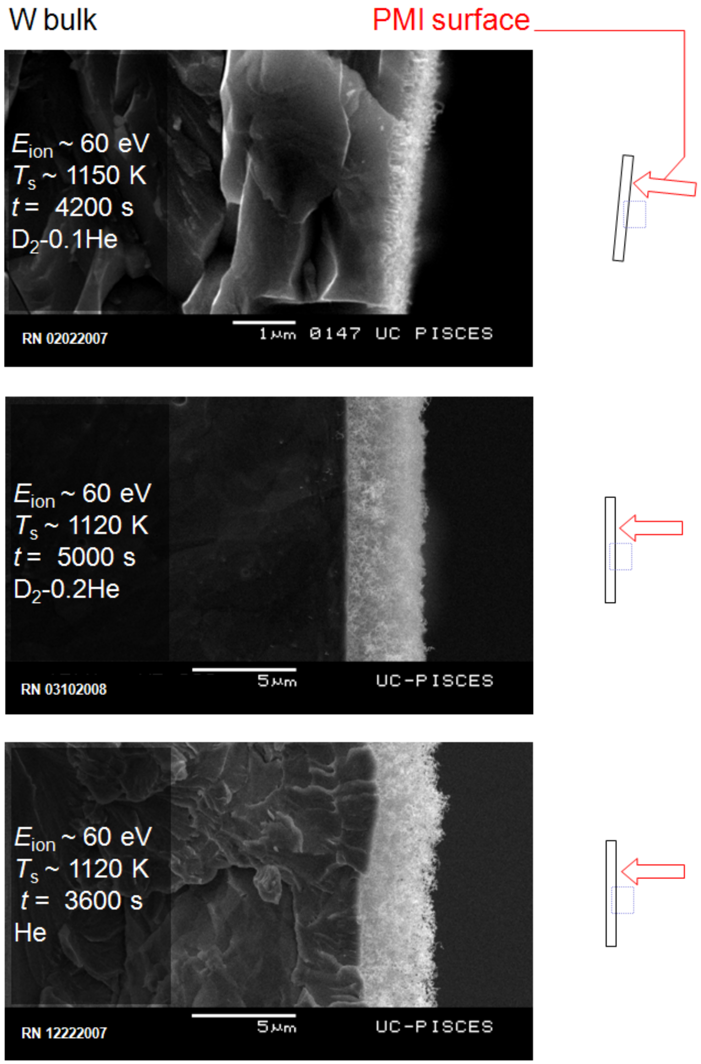
In D_2–He plasmas, nano-morphology persists, but growth rate depends on He^+ flux.

- The presence of D_2 does not appear to affect nano-morphology structure.

- But growth rate can be affected.

- After a little more than 1 h of He plasma exposure in D_2–0.1He, layer thickness is only ~0.5 mm.

- Layer thickness, ~2.0 mm in D_2–0.2He is comparable to pure He.



From M. J. Baldwin et al.,
JNM 2009, in press.

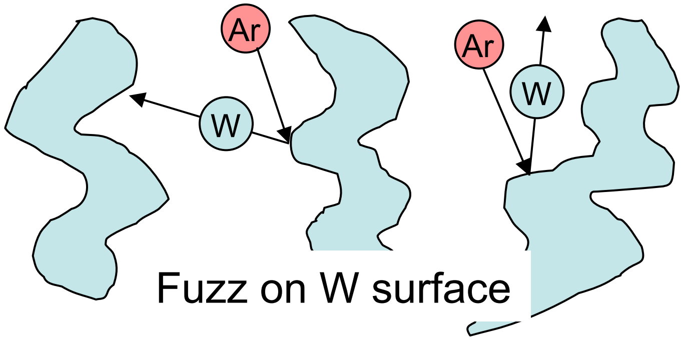
$\Gamma_{D+He} = 4–6\times10^{22}\ m^{-2}s^{-1}$

Sputtering yield of W is reduced with He-induced fuzz by a factor of 6-8.

- 2 effects can be considered:

  -- Reduced areal density

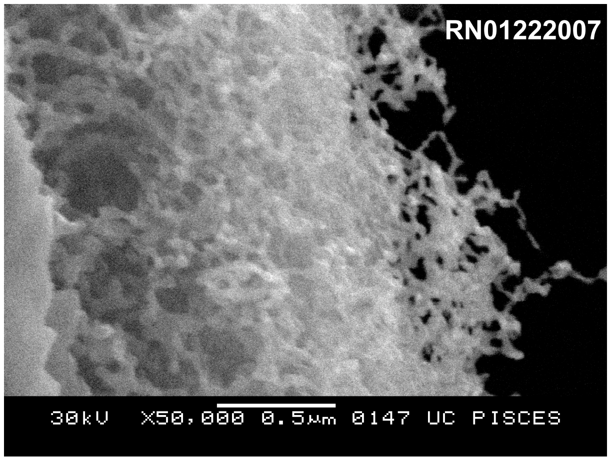
  -- Re-deposition of sputtered W atoms on surface before ejection

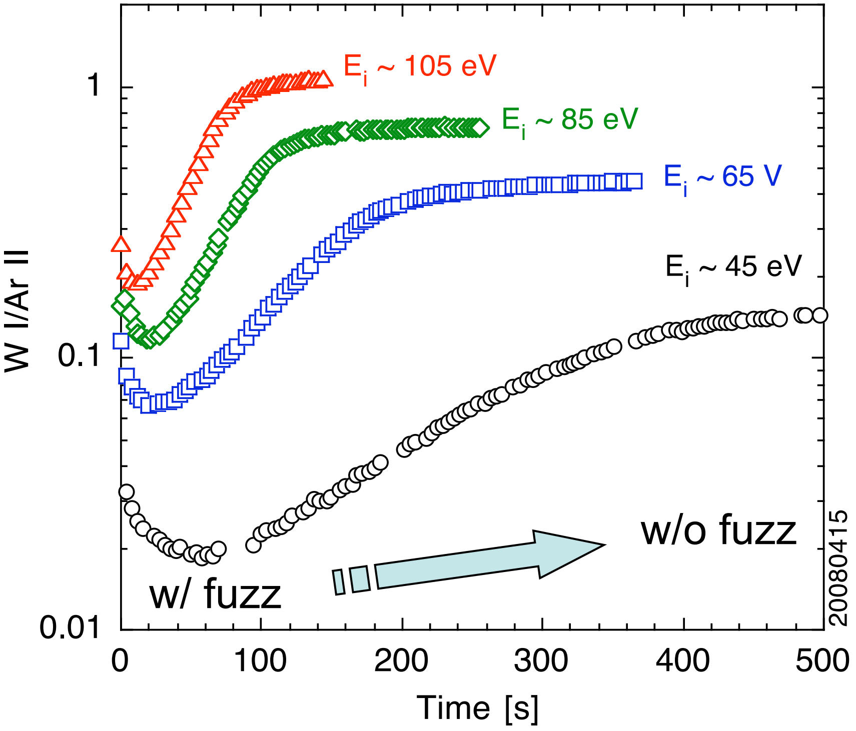


Fuzz on W surface

- Produce fuzz on W surface due to He plasma exposure.

⇨ Measure the time evolution of sputtered W I emission in Ar/He mixture plasma.

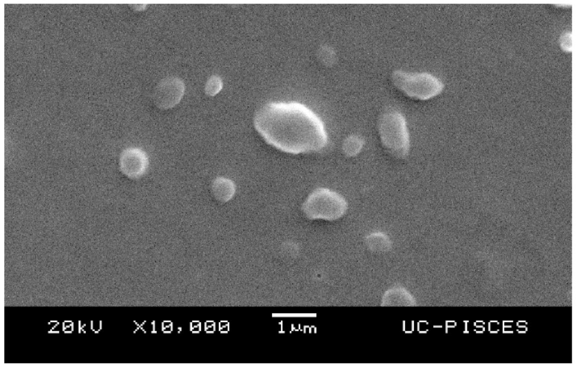




Mixing He with D-plasma suppresses blisters on W surface and reduces D-retention in W.

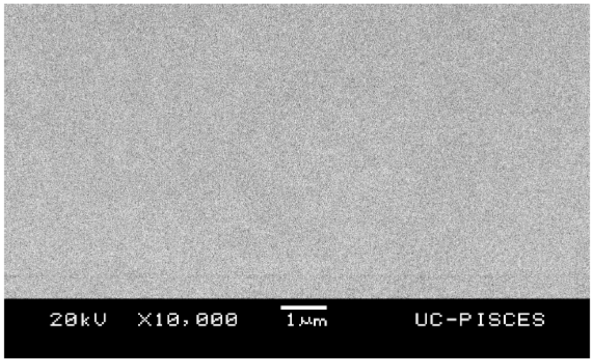
- Pure D_2 plasma (SRWM-3b)

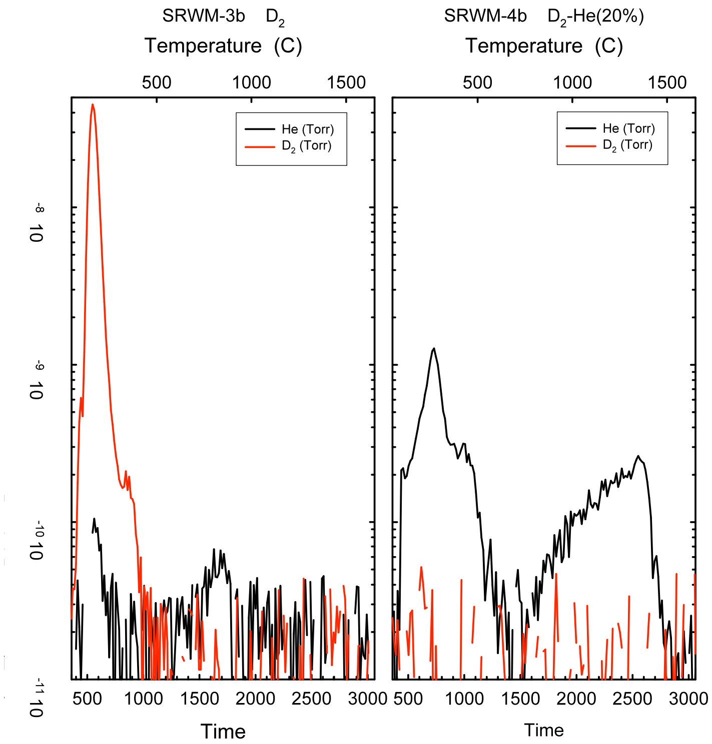
D-fluence ~ 5e25 m^{-2}, G_D ~ 1.0e22 $m^{-2}s^{-1}$,
T_s ~ 573 K, E_i ~ 60 eV



- D_2-He mixture plasma (SRWM-4b)

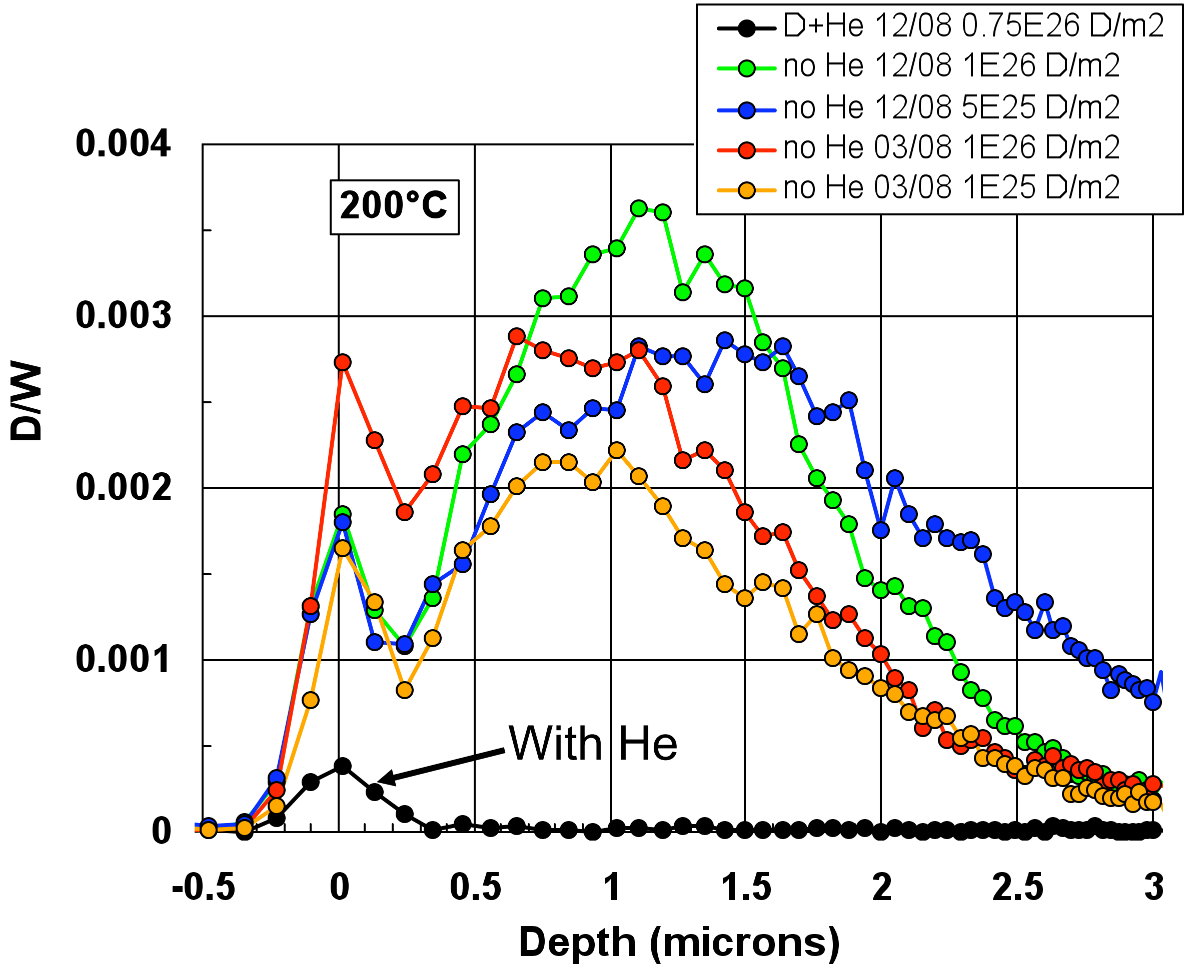
D-fluence ~ 5e25 m^{-2}, G_D ~ 0.9e22 $m^{-2}s^{-1}$,
T_s ~ 573 K, E_i ~ 50 eV, n_{He+}/n_e ~ 20 %





From M. Miyamoto et al., NF 2009, accepted for publication.

Helium reduces D retention in undamaged tungsten



PISCES

See more details in talk of W. Wampler

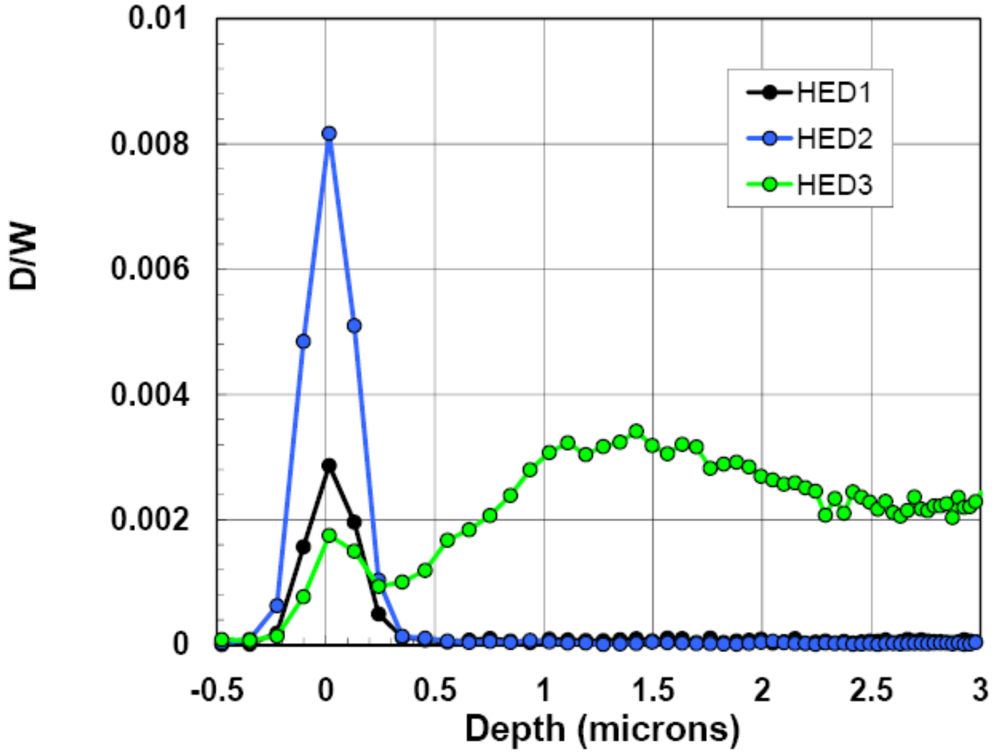
date	D Fluence 10^{26} D/m^2	D retained 10^{20} D/m^2
12/08	0.75 (+He)	0.109
12/08	1	3.77
12/08	0.5	3.84
03/08	1	3.27
03/08	0.1	2.37

1e21 D/m^2 ~ 3 mg/m^2

- Addition of He to the D plasma reduced D retention by about a factor of 35.
- With He, D retention is mainly at the surface, whereas without He, D retention peaks ~ 1 micron beneath the surface.

Sequential He then D plasma exposure reveals He ion flux dependence for D suppression

PISCES



W.R.Wampler
Sandia National Laboratories

HeD1 : G_{He+} = 3.5e22 $m^{-2}s^{-1}$ for 200 sec.
200C, then D fluence 8e25m^{-2}
HeD2 : G_{He+} = 3.3e22 $m^{-2}s^{-1}$ for 600 sec.
500C, then D fluence 8e25m^{-2}
HeD3 : G_{He+} = 1.8e20 $m^{-2}s^{-1}$ for 8460 sec.
200C, then D fluence 5.5e25m^{-2}

- He bubbles appear to form and suppress D retention at 200 C and 500 C when He ion flux is large
- Low He ion flux is not effective in suppressing D retention (TEM shows no nanobubbles)
- Recall He ion flux dependence of W fuzz growth, suggesting these effects are possibly related

Mixed D/He plasma exposure in PISCES-A results in the appearance of small (nm) bubbles near the surface (< 50 nm) of the tungsten

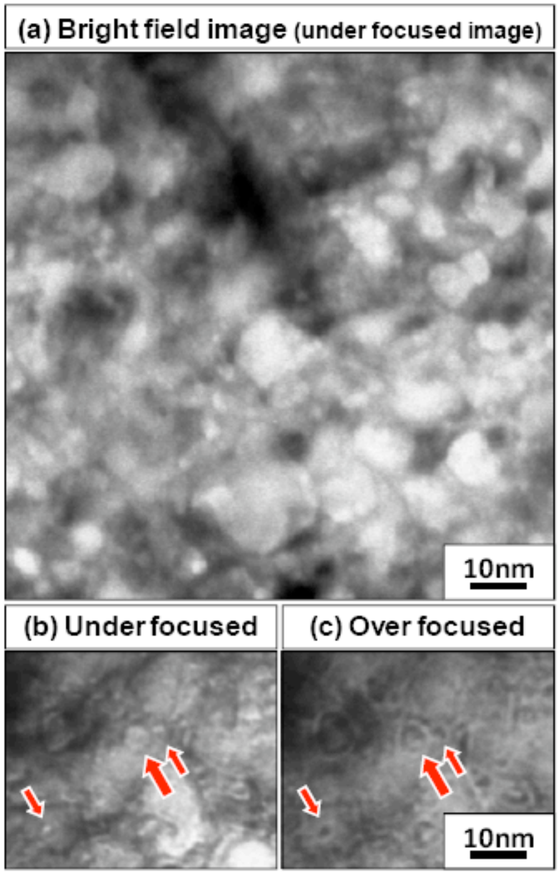


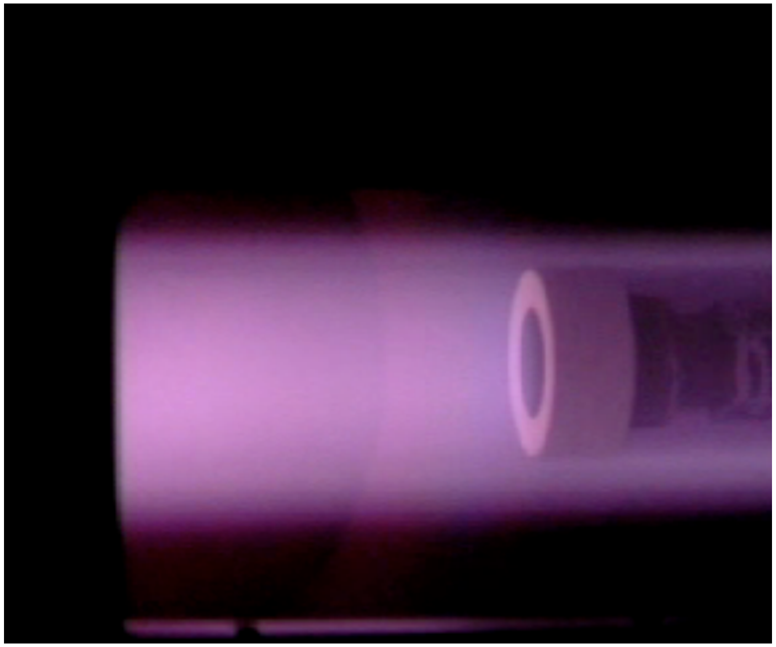
Figure 5. He bubbles, observed with TEM, formed in pre-thinned RC-W exposed to D+He ($c_{\mathrm{He+}}$ ~ 20 %) mixture plasma at $T_s \sim 373$ K (< 773 K). $\Phi_D \sim 1\mathrm{x}10^{25}$ m^{-2}. As pointed with arrows, He bubbles have bright and dark contrasts in under (b) and over (c) focused images, respectively.

From M. Miyamoto et al.,
NF 2009, in press.

Simulated ELM Thermal Transient Effects on PMI:

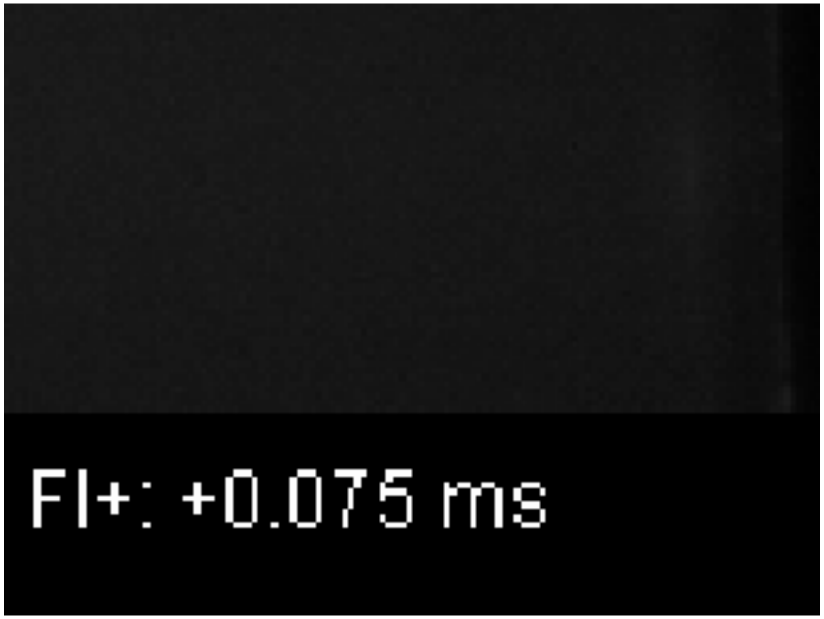
- Pulsed Biasing
- Laser Heat Load

Simulated ELM Thermal Transient in PISCES-B



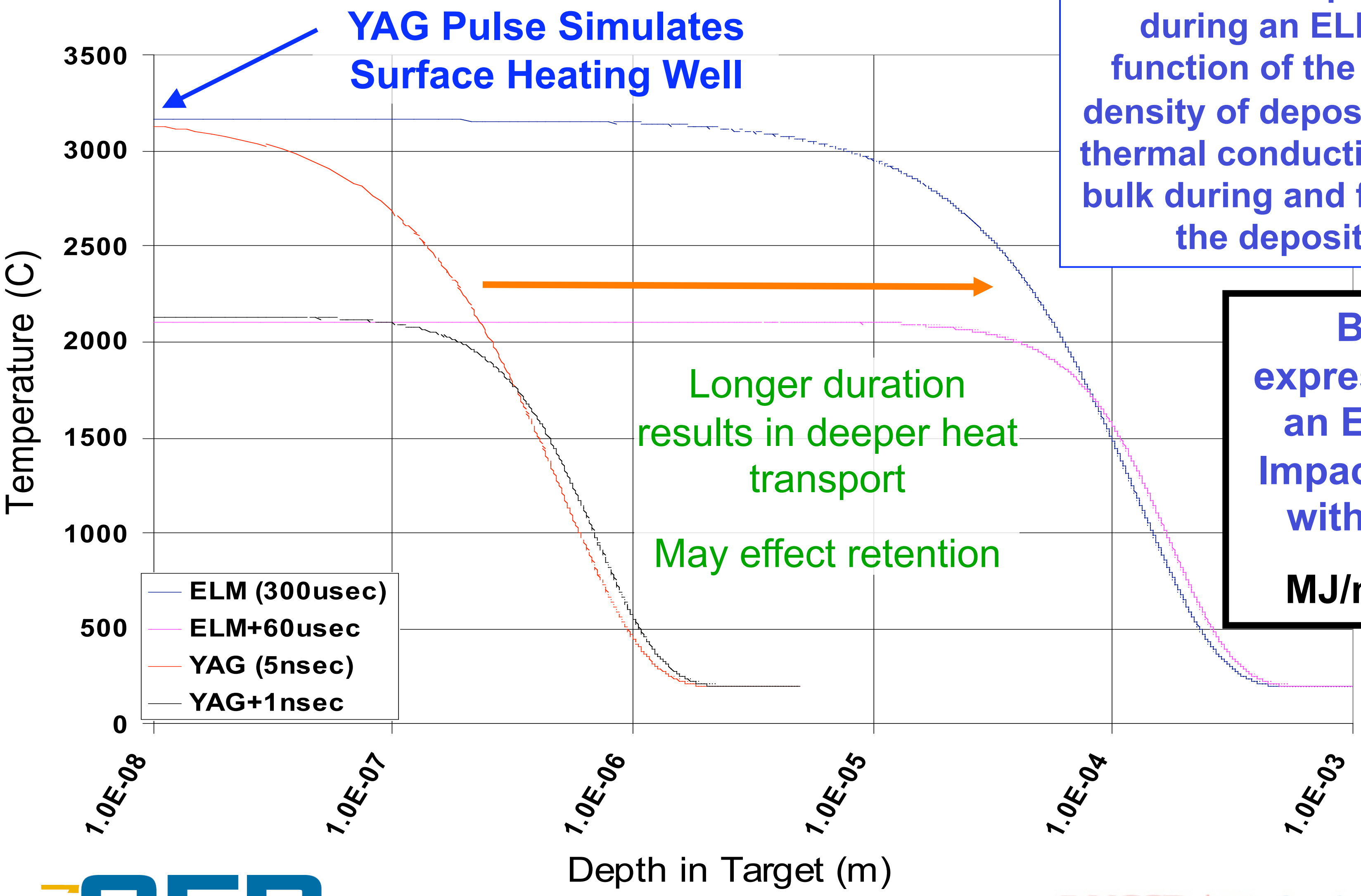
- During 1.5 MW/m^2 power pulse graphite surface temperature rises to ~2000°C (by pyrometers)
- Bulk graphite temperature rise at back of sample ~20°C during 0.1 s. pulse (thermocouple)
- Examine Effect of Heat Pulse on C & C-Be PMI

Simulated ELM Thermal Transient in PISCES Using Pulsed Laser Thermal Deposition



- Operate BELOW Ionization Threshold
- Close to or Below Ablation Thresholds
- Match Expected ELM Surface Heating

Q-Switch Nd:YAG as ELM Simulation



YAG Pulse Simulates Surface Heating Well

Longer duration results in deeper heat transport

May effect retention

Surface temperature during an ELM is a function of the energy density of deposition and thermal conduction to the bulk during and following the deposition

Best expressed as an Energy Impact Value with units

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

ELM Simulation on W

Laser Exposure of W at 200C for 15min

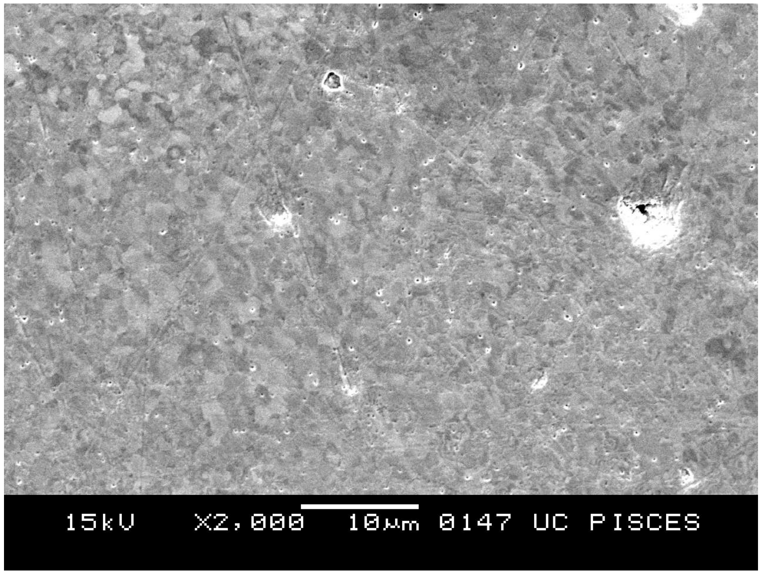
- Laser Parameters
  - 5nsec
  - 4mm spot
  - 166mJ per Shot
  - ~10^8 W/cm^2

Absorbed Energy Impact ~58 MJ/m^2 s$^{1/2}$

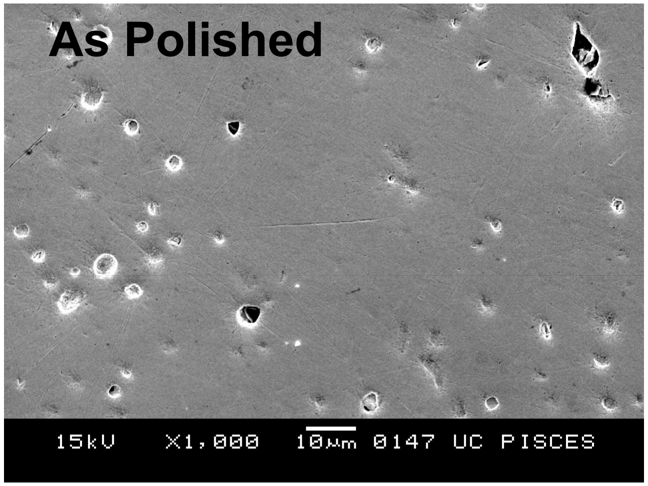
$R_{W\ (l=1064nm)}$ ~ 70%

ELM Equivalent
1MJ/m^2 @ 0.3msec

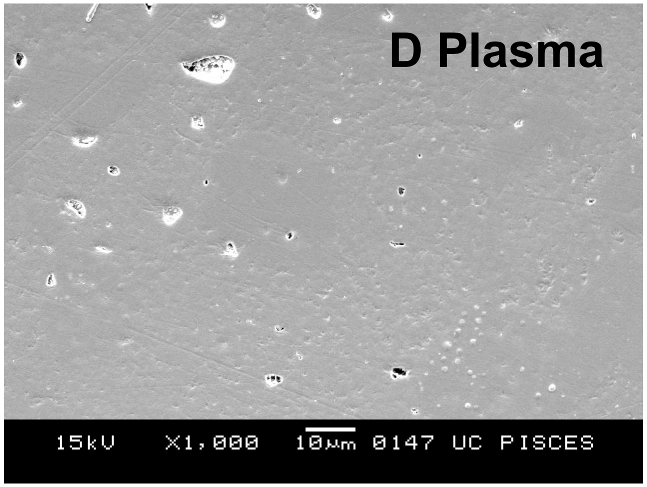
- Plasma Parameters
  - Total Fluence ~ **10^{25} D$^+$/m^2**
  - Ion Energy ~100eV

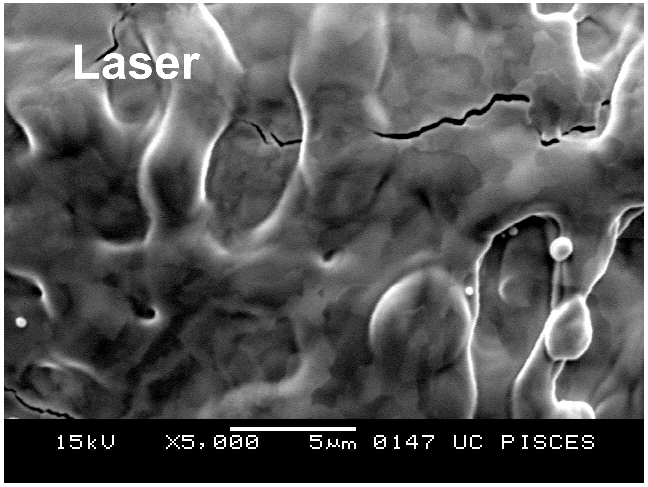


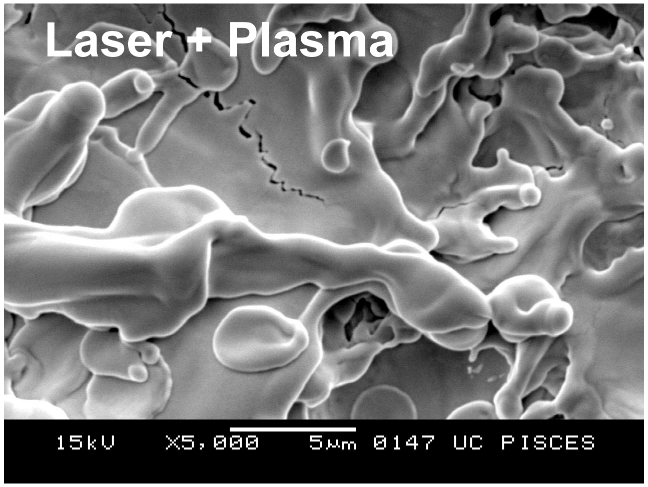
W Surface Analysis



No Change







Synergistic effect between heat pulse and deuterium plasma causes greater surface roughening & material removal

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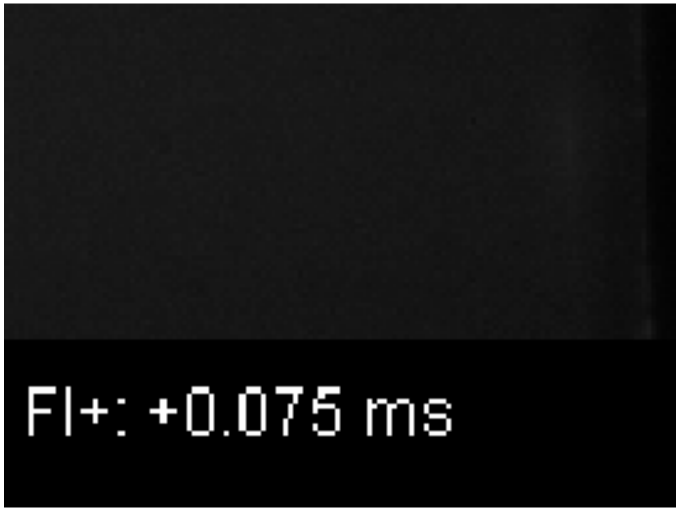
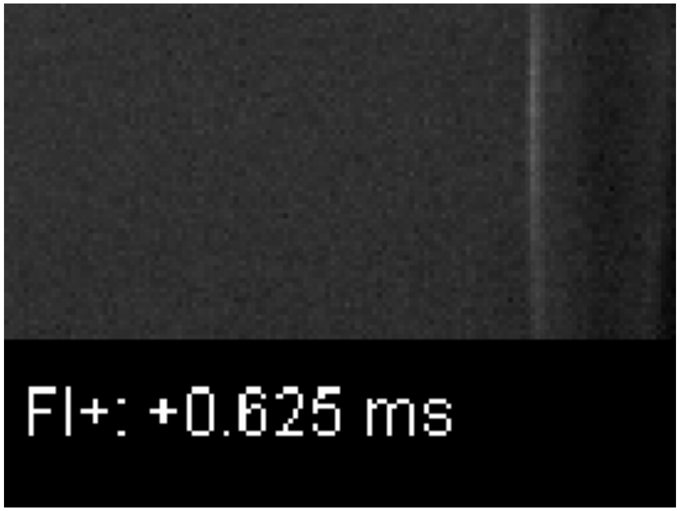
ELM Thermal Load w/ Sufficient Sheath E-field & Saturated Surface Results in Arcing



Laser + Plasma

Saturated Surface,

Esheath~15 V



Laser + Plasma

Saturated Surface,

Esheath~90 V

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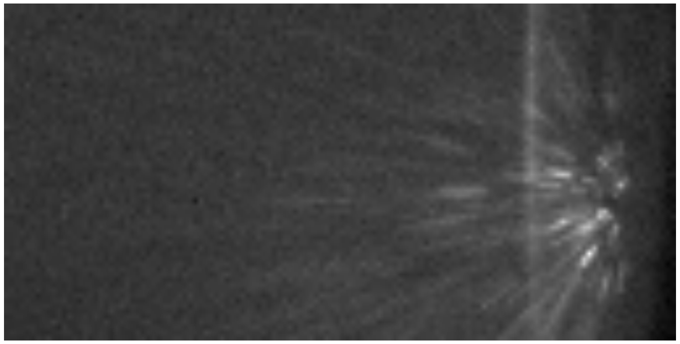
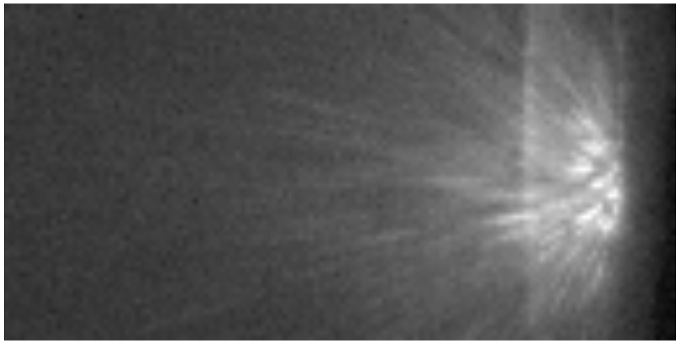
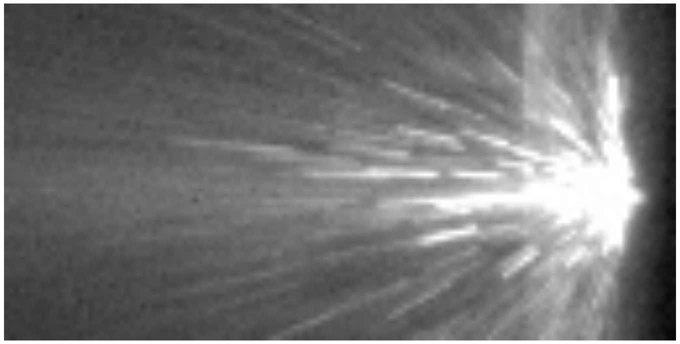
Effects of Loading on Damage



$\Phi = 5{\times}10^{22}/m^2$



$\Phi = 5{\times}10^{23}/m^2$



$\Phi = 2{\times}10^{24}/m^2$

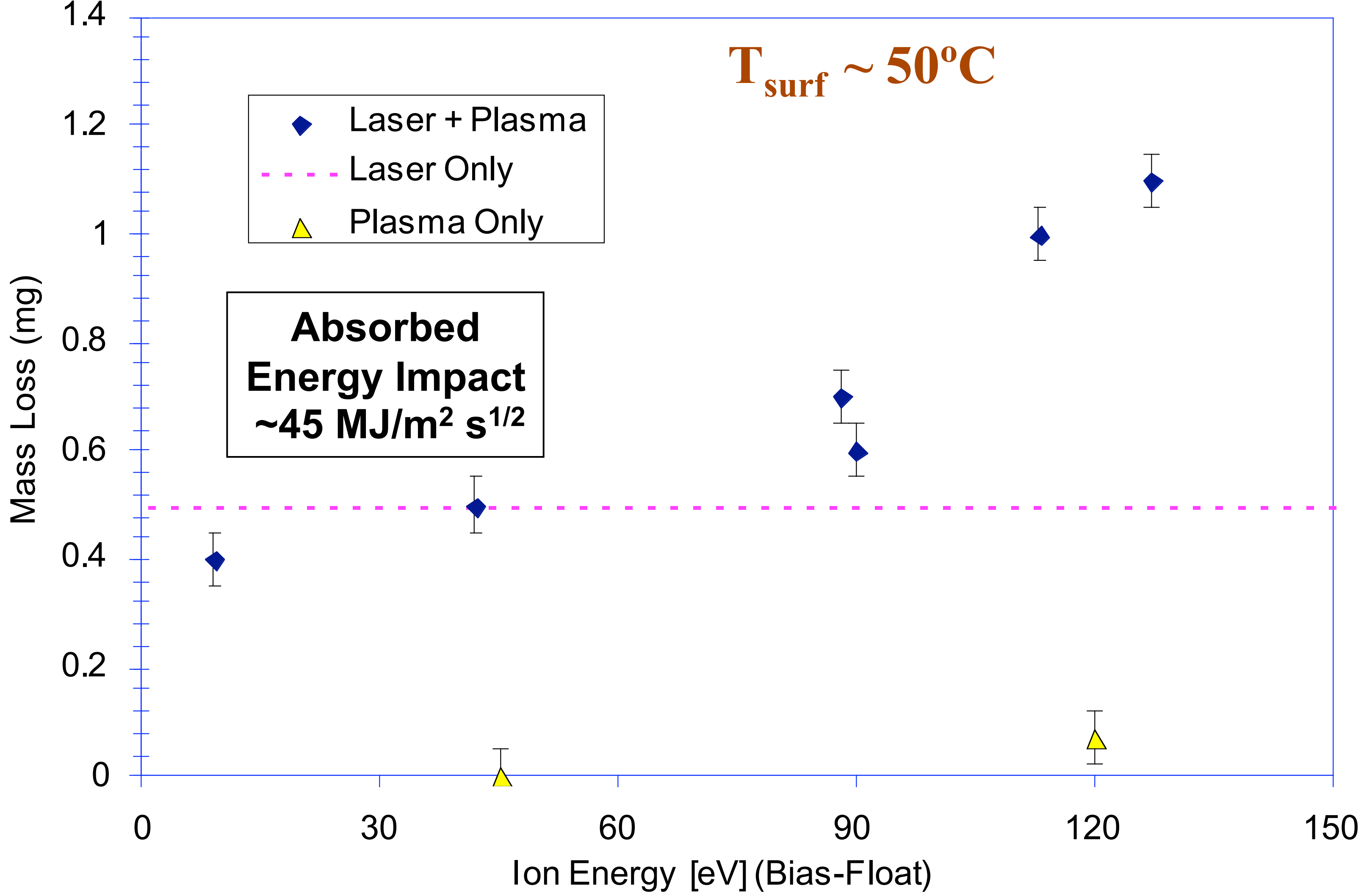
Varying Fluence

$V_{bias}=125V$
$\Gamma=2x10^{22}/m^2\text{-sec}$
$T_e=11eV$
$n_e=2x10^{24}/m^3$

Enhanced Erosion of W PFC

G~ 10^{26} D^+/m^2

T_{surf} ~ 50°C



Absorbed Energy Impact ~45 MJ/m^2 $s^{1/2}$

Center for Energy Research

K.Umstadter – PFMC 2008

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Fundamental Be and W Erosion Studies

- The following topics on beryllium sputtering behavior will be investigated in conjunction with validation of simulation codes (WBC etc);
  - Angular distribution
  - Energy distribution
  - Sputtering yield
  - Metastable state fraction

For both crystalline Be and deposited Be on Be/C/W

➔ Validation for WBC Erosion/Redep Code

- Sputtering behavior of tungsten (in collaboration with NAGDIS)
  - Surface temperature dependence of sputtering yield of W
  - Measurement of S/XB values for W I (400.9 nm)
  - Angular and energy dependences of sputtered W atoms

Sputtered Be atom emission distribution: Experiments

1. Intensity I(y) measurement

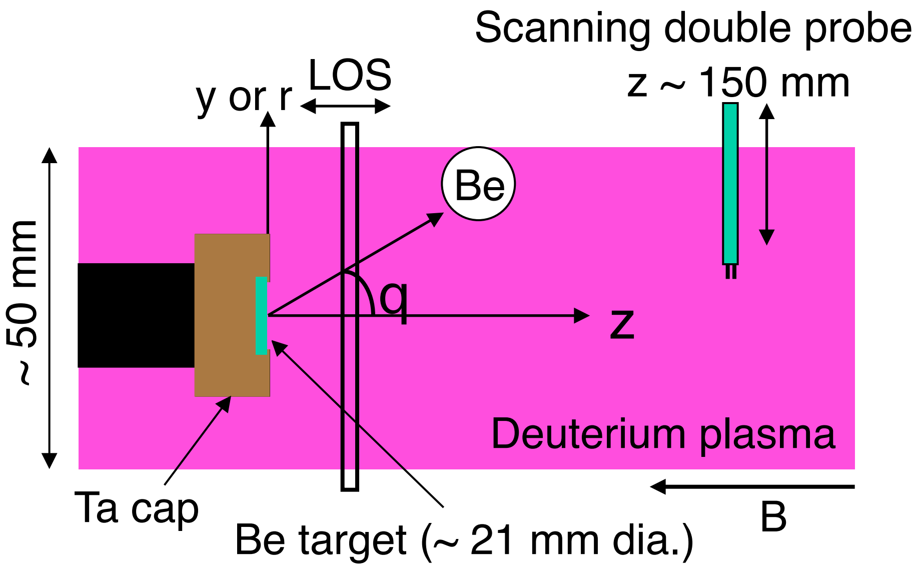
2. Abel inversion:

$$\varepsilon(r) = -\frac{1}{\pi}\int_r^a \frac{dI(y)}{dy}\frac{dy}{\sqrt{y^2-r^2}}$$

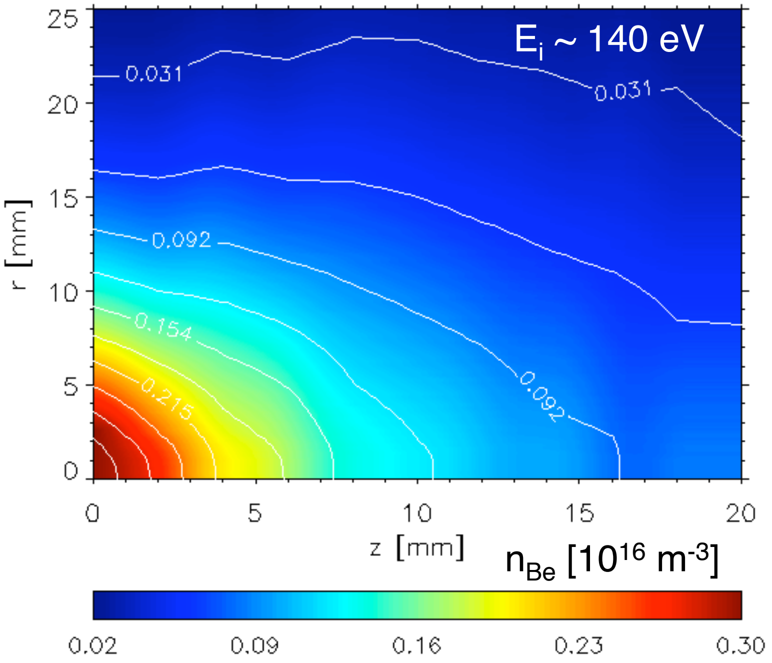
3. Local ground state Be atom density:

$$n_{Be} = \frac{4\pi\varepsilon}{\langle\sigma v\rangle_{457.3nm}\, n_e}$$

Target region viewed through axial window

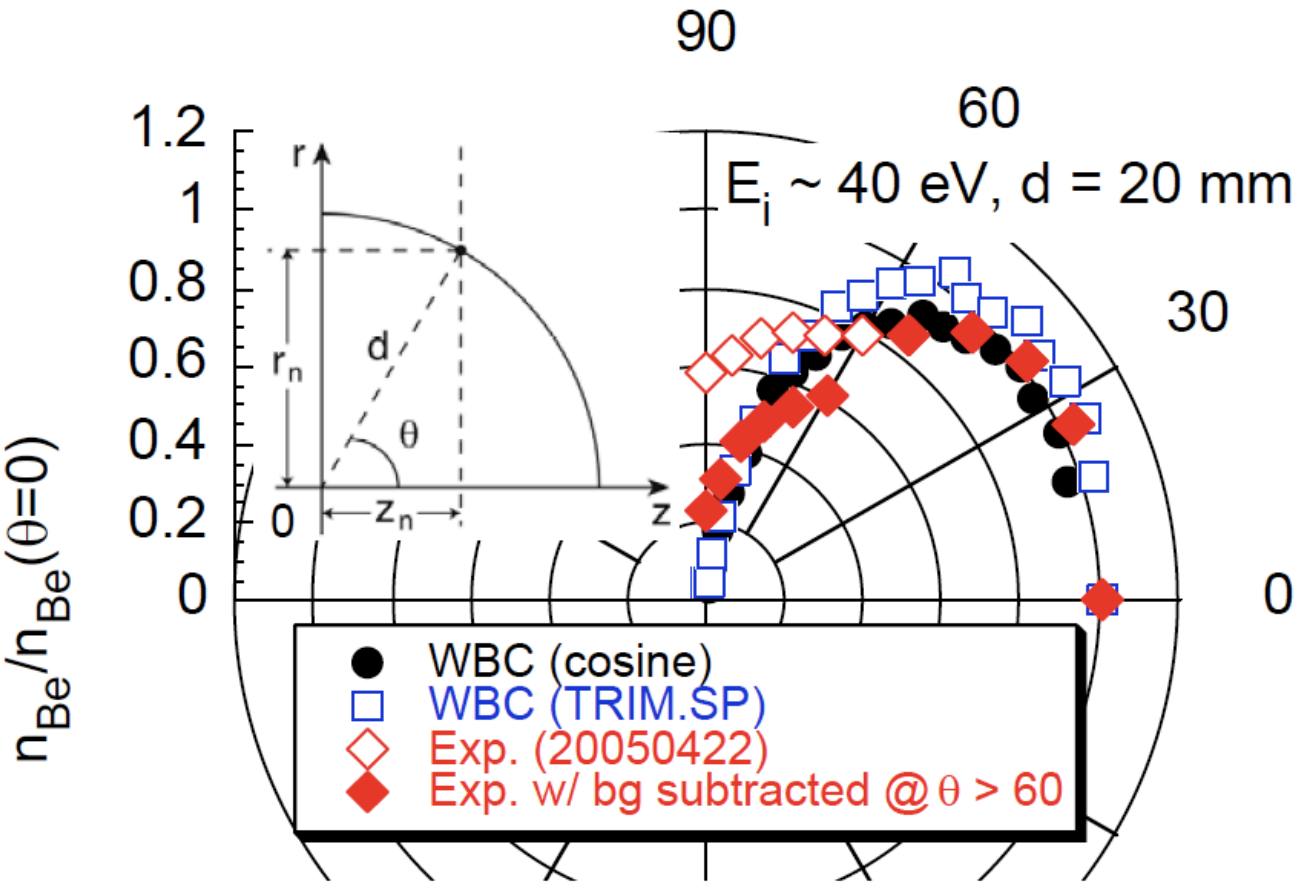


2-D profile of Be atom density



Sputtered Be atom emission distribution: Modeling

PISCES



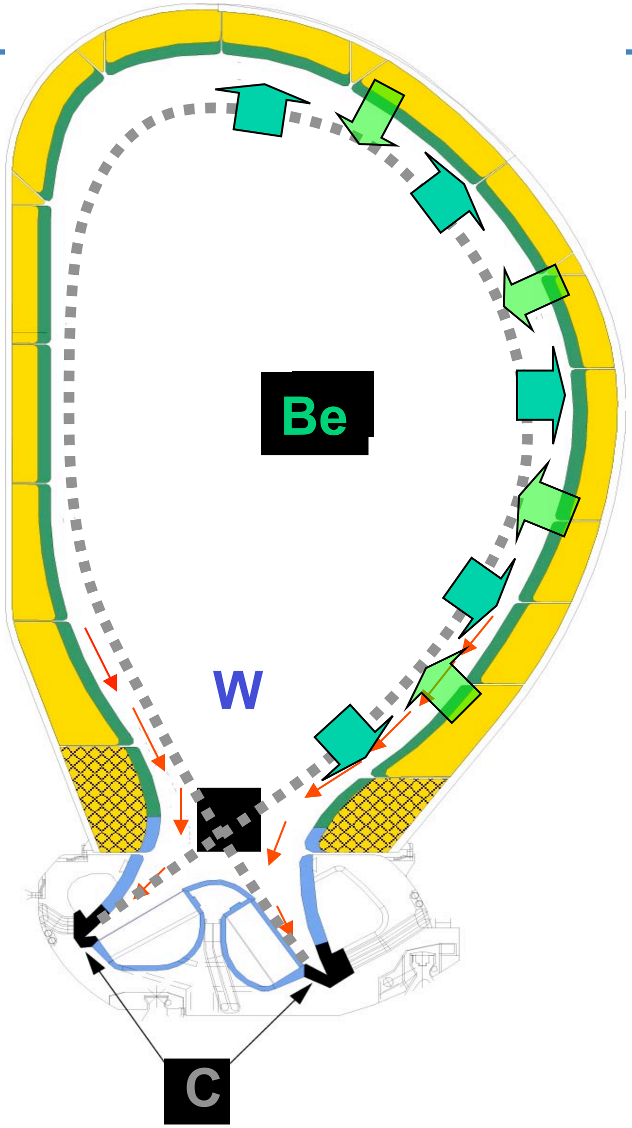
Nishijima, Brooks et al

Key Parameters Governing Mixed Mat'l PMI

- **Impurity concentration** in upstream SOL Plasma
- SOL **Plasma Flows** (Perp. & Parallel)
- SOL Plasma **Density, Temperatures**

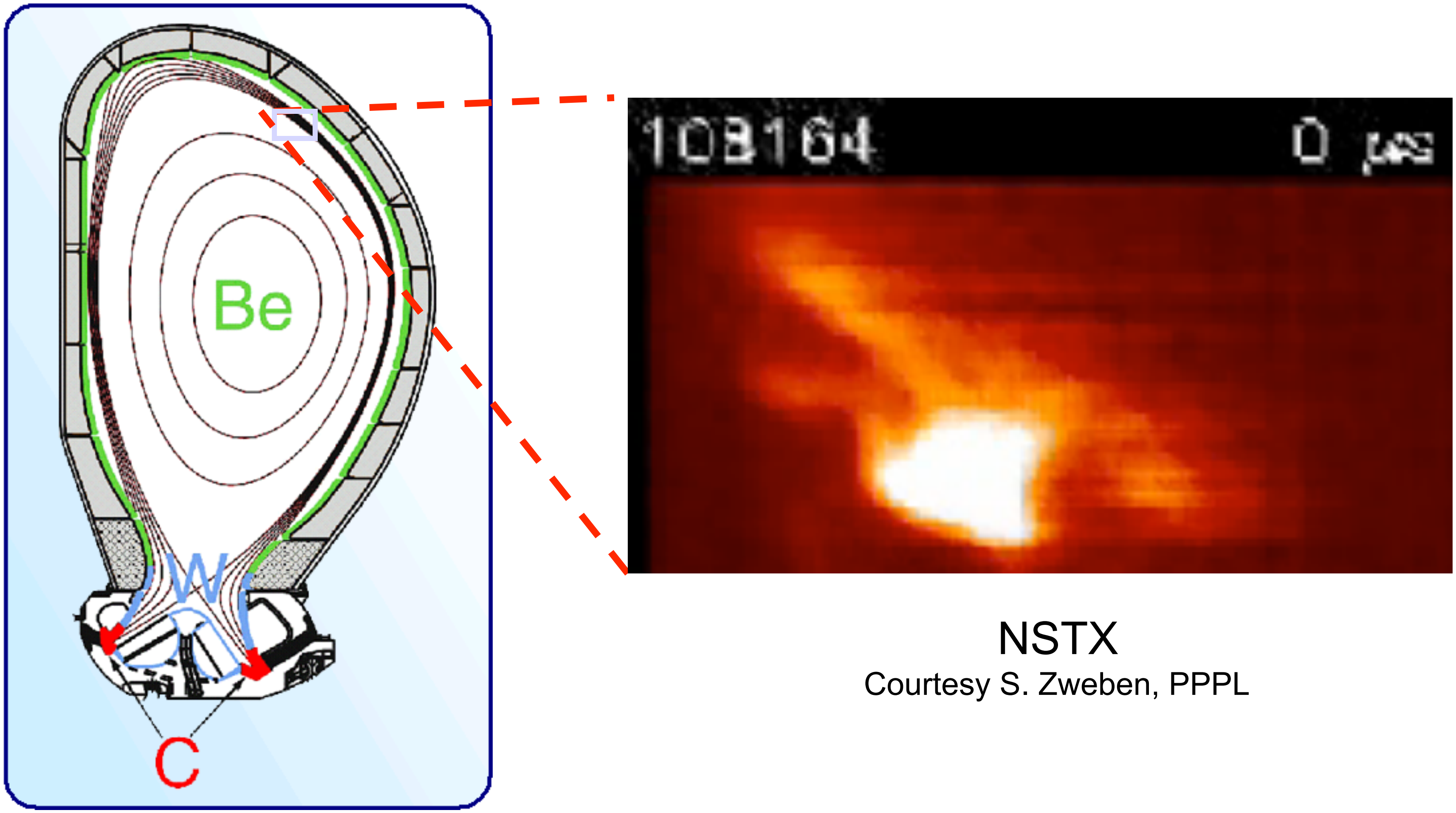
These Parameters Governed by Edge/SOL Transport Physics…

Comprehensive Approach to Essential ITER PFC Issues



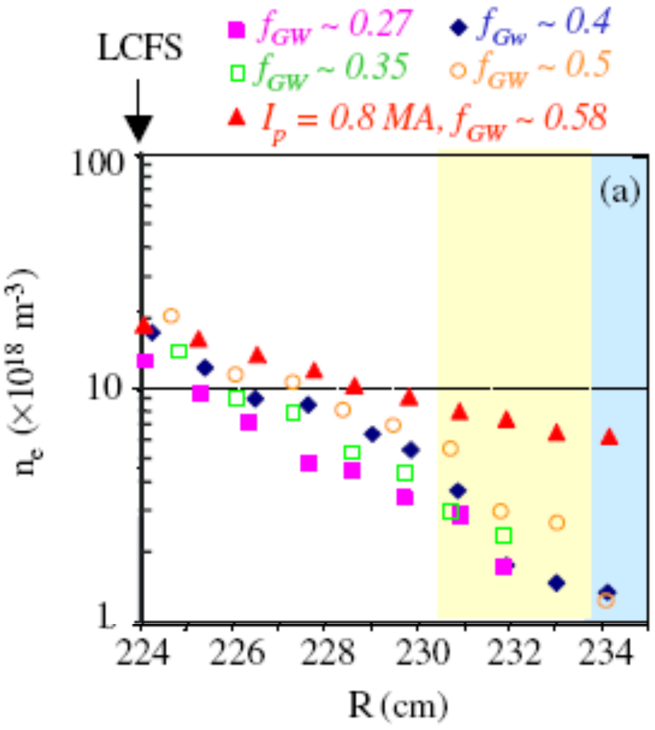
- Cross-field Main Plasma Transport into SOL
- Impurity Transport Thru SOL
- Bulk Convective Flows within SOL
- Fundamental PFC Erosion & Redeposition Studies
- Mixed Materials Issues
  - –Steady-state
  - –Transient ELM-like
- Model Development & Validation

Turbulent Transport Dominates Cross-field Transport in the Edge/SOL Region

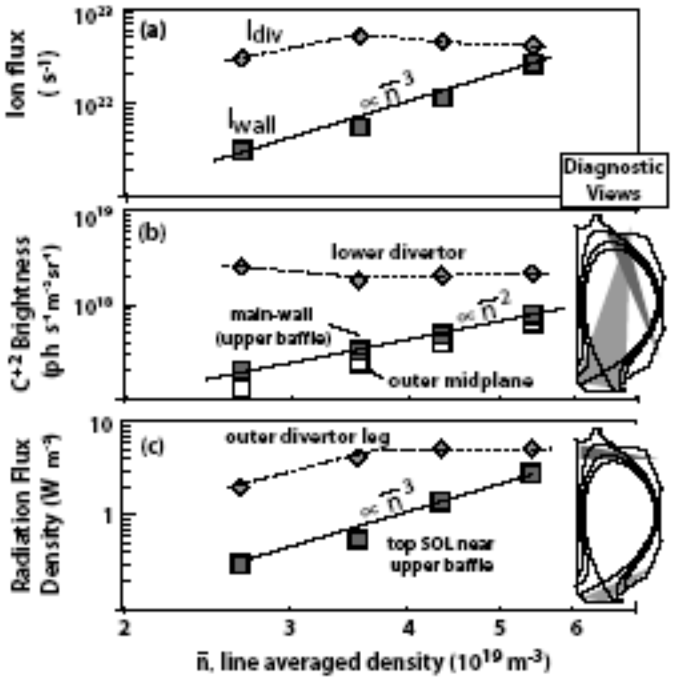


NSTX
Courtesy S. Zweben, PPPL

Significant First Wall PMI at High Density Due to Blob Transport Across SOL



Rudakov et al, Nuc Fus 45, 1589 (2005)



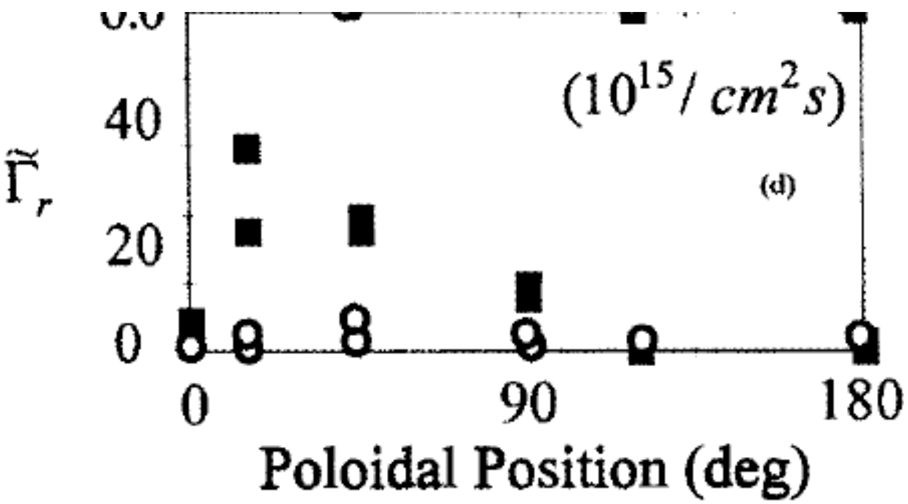
Whyte et al, PPCF 47, 1579 (2005)

Need to Understand Origin and Dynamics of Bursty Cross field Transport

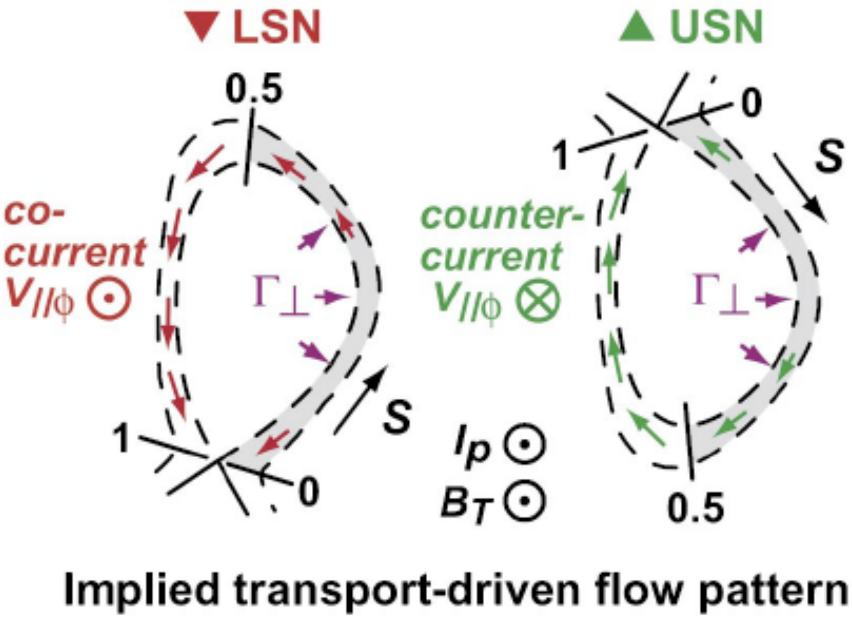
What Determines Plasma Flow - I

- Classical, Neoclassical Effects
- **Turbulent Transport-driven Equilibrium Flows**
- Turbulent Stresses

$$\tau_\perp = \frac{L_n^2}{\Gamma_r} \approx \tau_\parallel = \frac{qR}{C_s}$$



Tynan, PPCF 1995

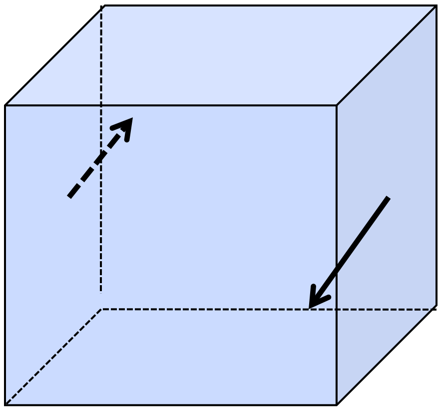


LaBombard, PoP 2005

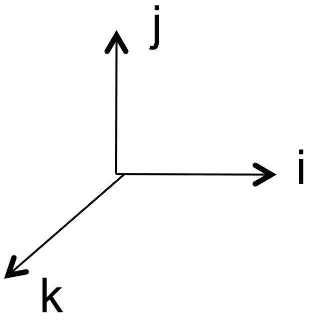
What Determines Plasma Flow - II

- Classical, Neoclassical Effects
- Turbulent Transport-driven Equilibrium Flows
- **<u>Turbulent Stresses</u>**

$$\Pi_{ik}(x_i) = \langle \tilde{v}_i \tilde{v}_k \rangle$$

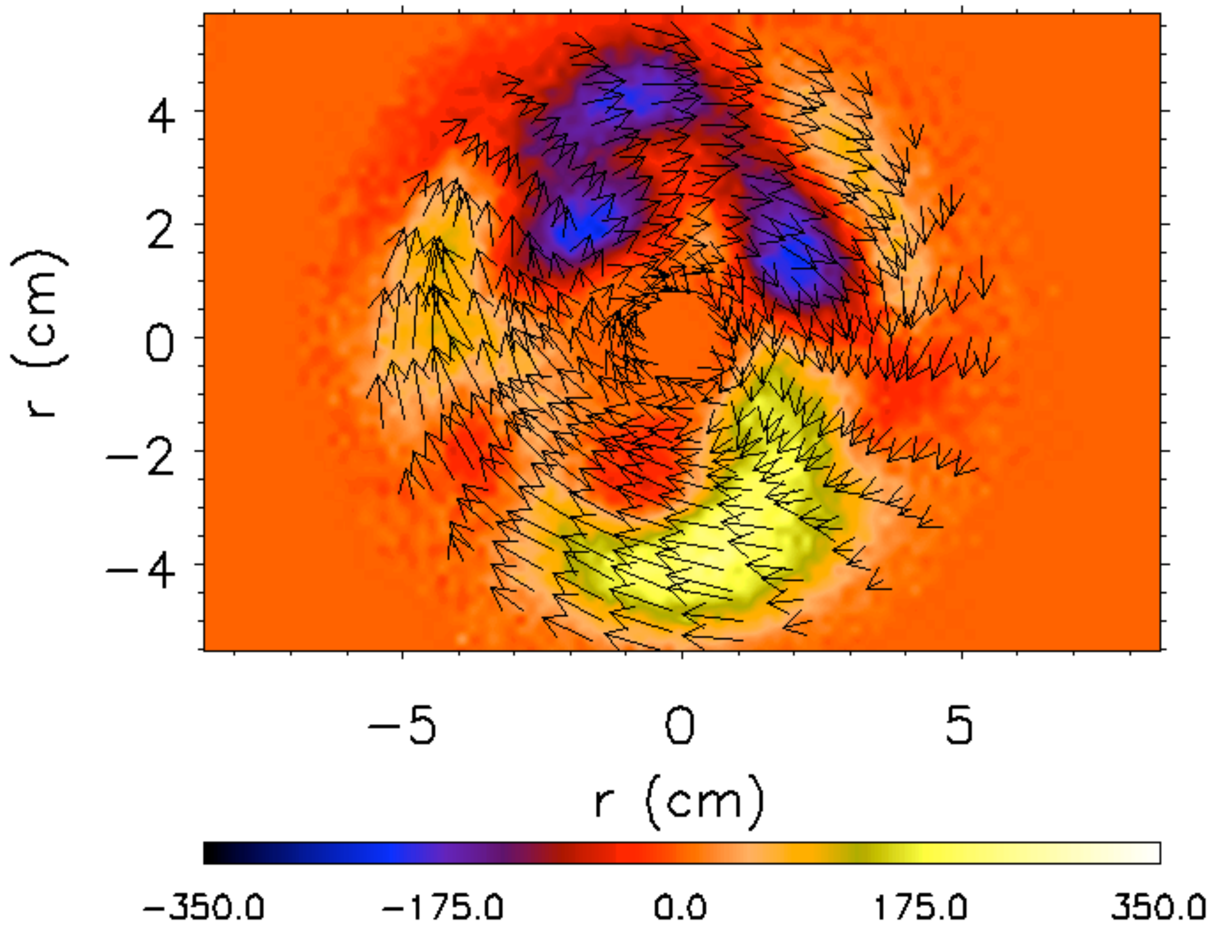


$$\Pi_{ik}(x_i + dx_i) = \langle \tilde{v}_i \tilde{v}_k \rangle$$

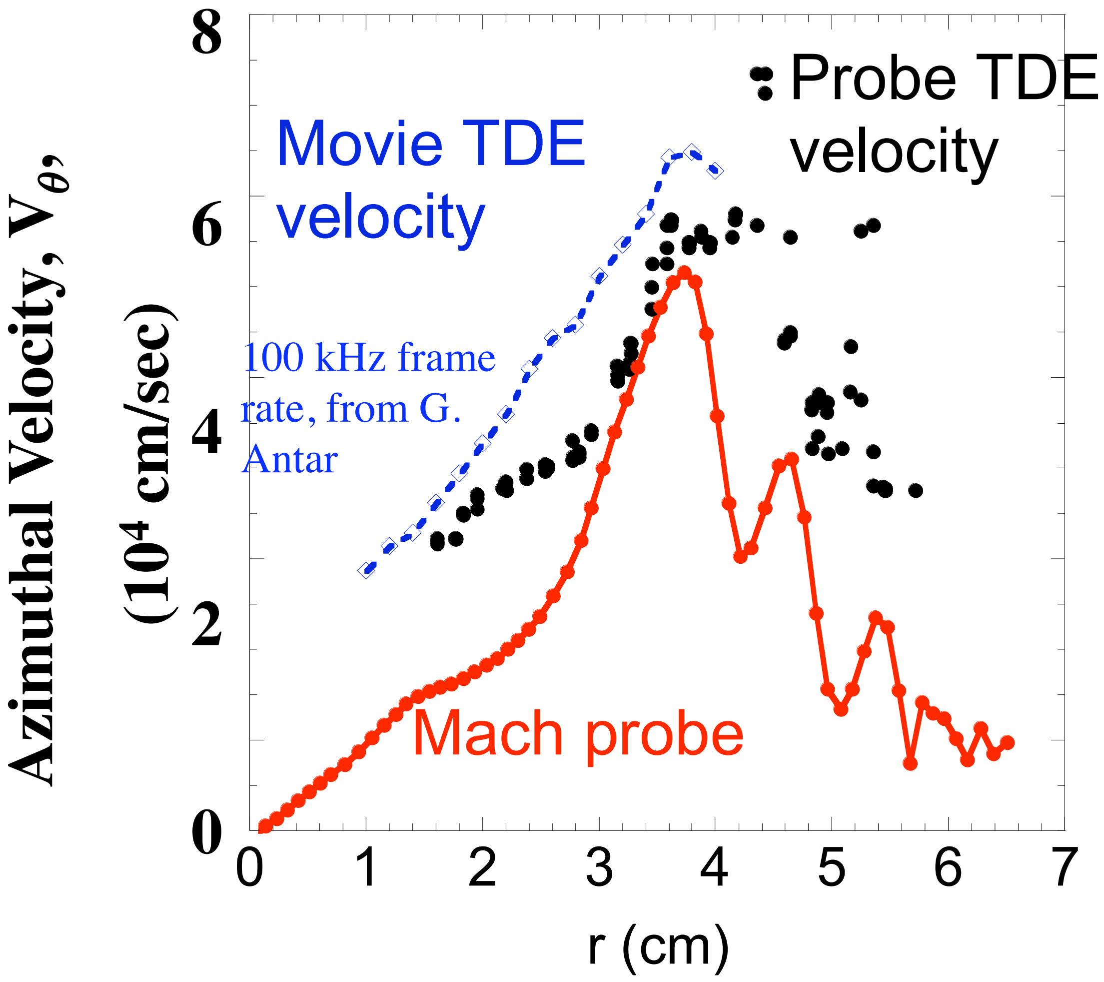


Net Force in k-th direction: $F_k = \dfrac{\partial}{\partial x_i} \Pi_{ik}$

Radially Sheared Azimuthally Symmetric Flowfield



Independent Measurements of Shear Layer

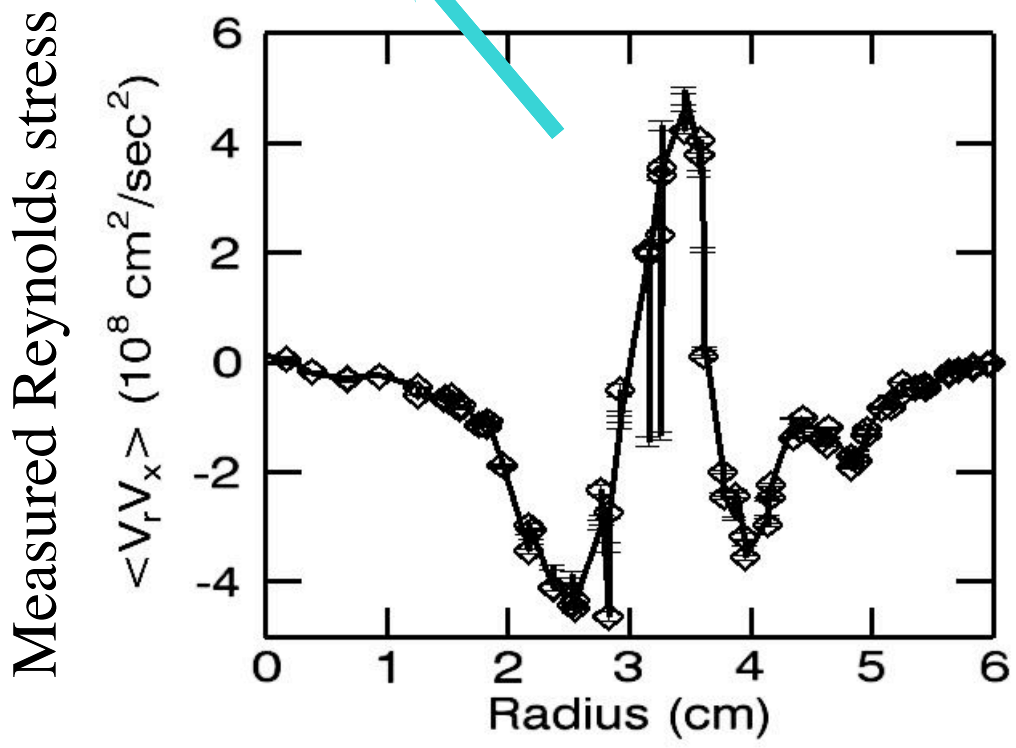


Yu, J. Nuc. Mat'l. 2007

Sound speed
$c_s = (T_e/M_i)^{1/2}$
$= 2.8 \times 10^5$ cm/s

Use Measured Reynolds Stress in Azimuthal Momentum Balance & Solve for V Profile

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left\langle\tilde{v}_r\tilde{v}_\theta\right\rangle\right) = -\nu_{io}\overline{V}_{i\theta} + \mu_{ii}\nabla^2\overline{V}_{i\theta}$$



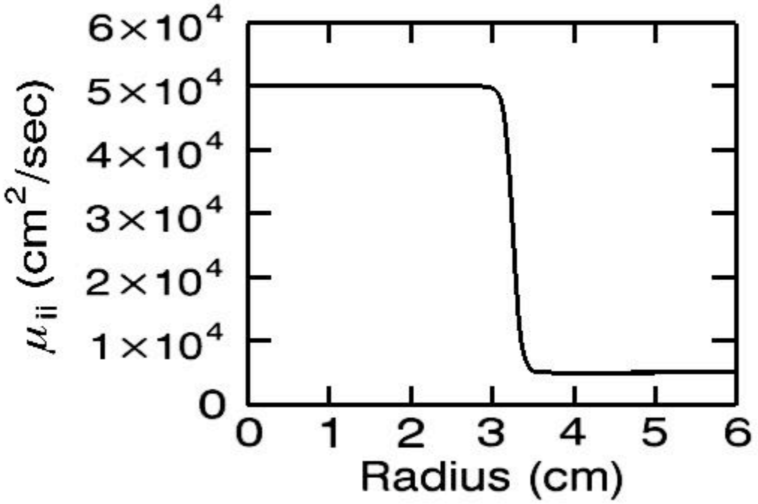
Tynan et al April 2006 PPCF Holland et al, in press, PRL

Estimate Dissipation from Measurements

Measure:

$$\int_{-a}^{a} T_i dl = 0.7eV$$

$$\int_{-a}^{a} T_{gas} dl = 0.4eV$$



Assume:

$$T_i(0) > T_i(a)$$

$$T_{gas}(a) = T_{wall}$$

$$\mu_{ii} = \frac{3}{10}\rho_i^2 \nu_{ii}$$

$$P_{gas} = n_{gas} T_{gas} = const$$

$$\mu_{ii} \propto n_i T_i^{1/2}$$

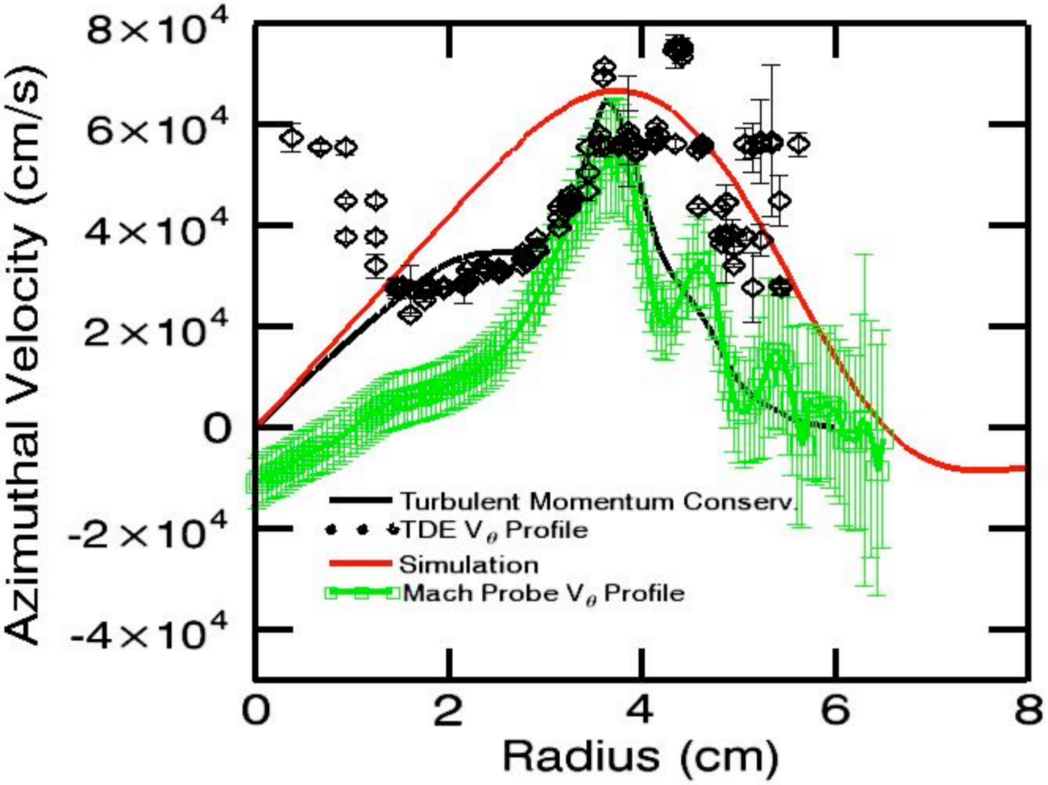
$$\bar{\mu}_{ii} \approx 4\times10^4 cm^2/\sec$$

$$\mu_{ii}(0) > \mu_{ii}(a)$$

$$\nu_{i0} \sim 6\times10^3 \sec^{-1}$$

Tynan et al, April 2006 PPCF, Holland et al, in press, PRL

Measured Velocity Profile Consistent with Turbulent Momentum Balance

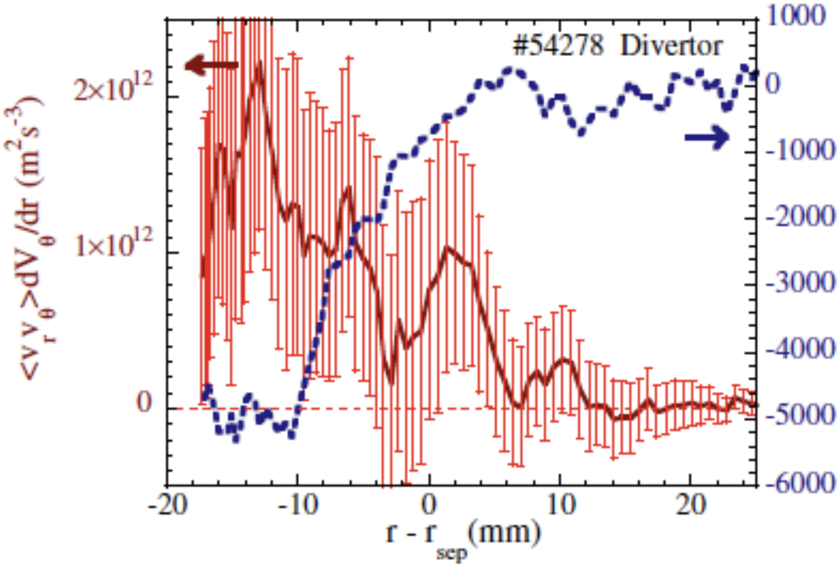


Tynan et al, PPCF-06, Holland et al, PRL-06

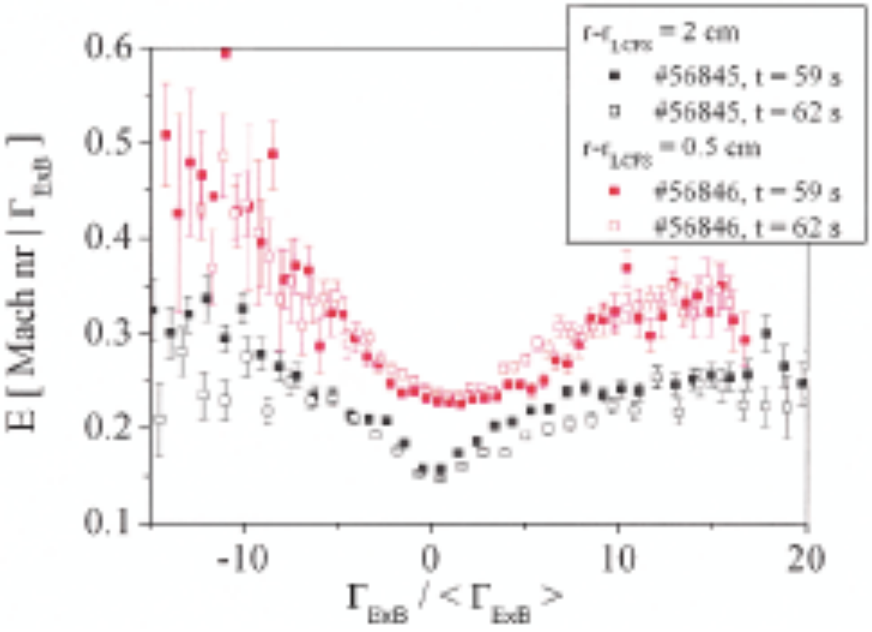
Evidence Linking Turbulent Stresses & Flows in Tokamaks

PISCES

Sanchez, JNM'05



Hidalgo, PRL'03



Need to Include This Physics in Edge/SOL Plasma Models – May Be a Significant Contributor to Edge Flows!

Concluding Comments

- Mixed Material Phenomena Often Emerge in Surprising Ways
  - Need to Investigate Relevant Permutations in Off-line Facilities & Existing Tokamaks
- Can Govern Key ITER PMI Issues
  - T Inventory Management
  - PMI Robustness & Lifetime
  - Divertor Performance
  - Dust Formation, ….
- Formation Mechanisms Strongly Link PMI and Edge/SOL Transport Physics
  - Must Understand Edge Flow Physics & Incorporate into PMI Modeling