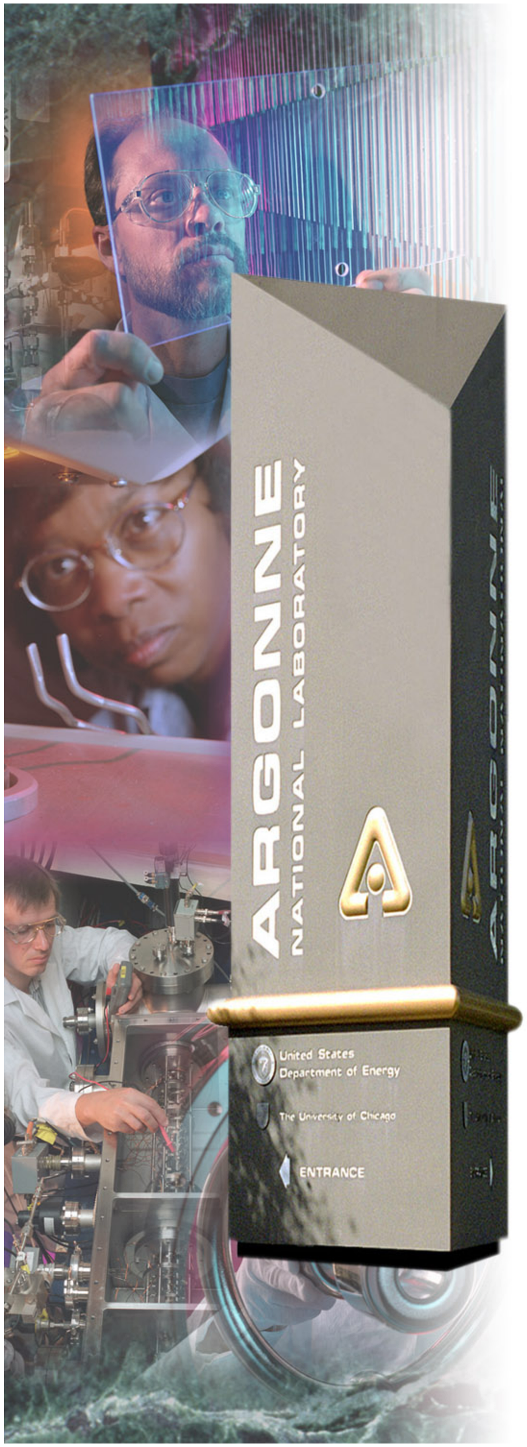


Low energy beryllium and carbon sputtering issues in ITER

Jeffrey N. Brooks

US-Japan Workshop on low energy ion sputtering
May 19-20, 2005, University of Wisconsin-Madison

Argonne National Laboratory

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Plasma Facing Component sputtering erosion/redeposition issues for ITER

- ***Lifetime*** *of* ***first wall*** *beryllium coating due to sputtering erosion*.
- ***Lifetime*** *of carbon (tungsten)* ***divertor*** *with mixed material (Be/C) sputtering/transport.*
- ***Tritium codeposition*** *in deposited carbon and beryllium.*
- ***Plasma contamination*** *by divertor and wall sputtering.*

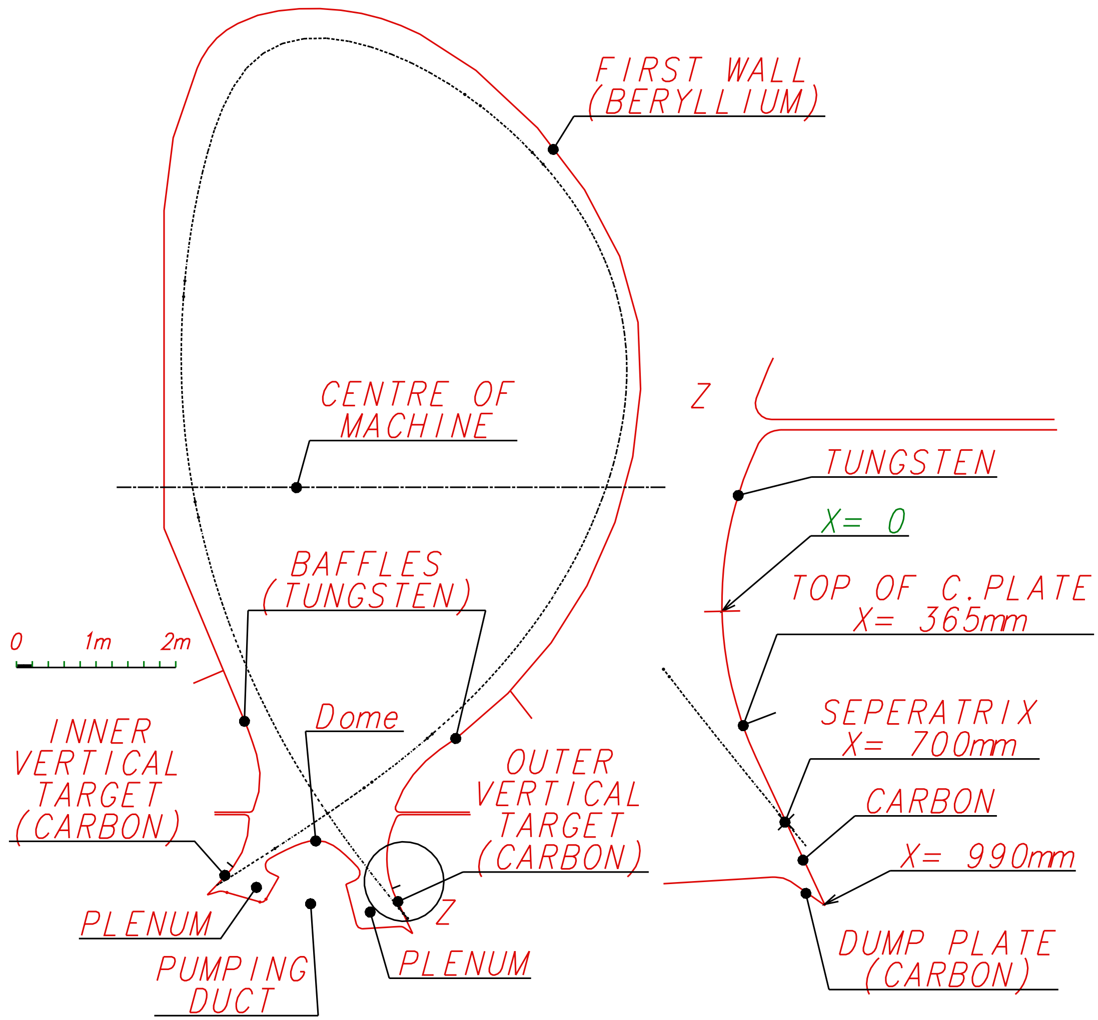
--Erosion/redeposition analysis helps us to choose: 1) surface materials, 2) plasma regimes, 3) tritium removal schemes, recoating methods, etc.

--Previous studies have focused on **single material divertor** analysis; we are focusing now on **wall** and wall/divertor **mixed-material** effects; PFC response with **convective** plasma boundary transport.

Critical sputtering issues in ITER

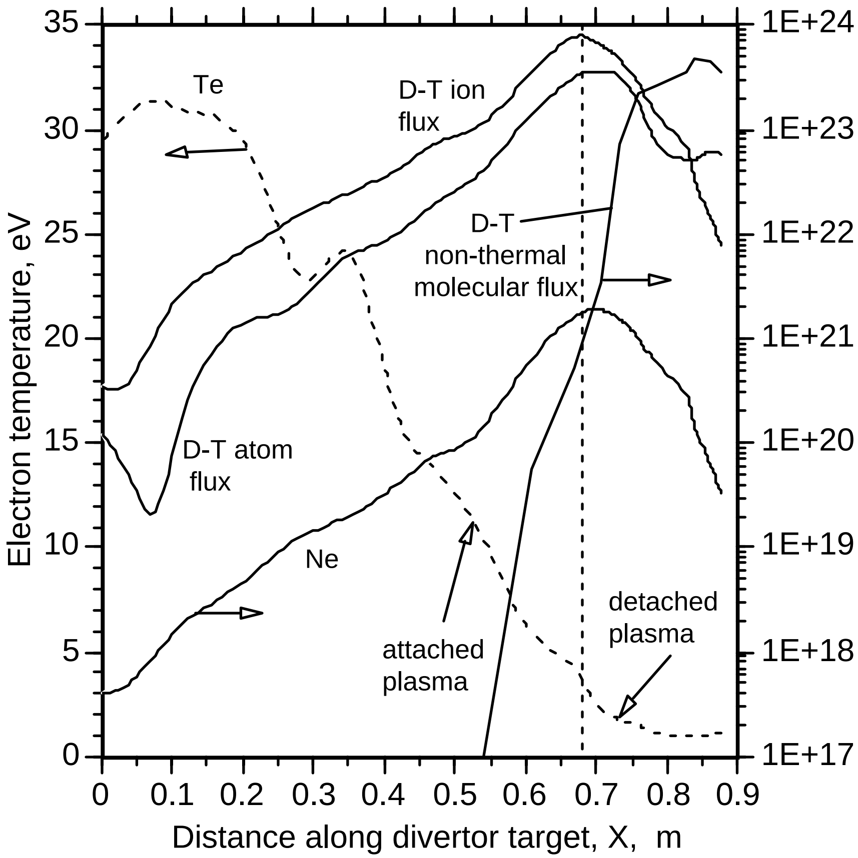
- **Carbon divertor chemical sputtering and transport for ~ 5-20 eV D, T (plasma temperature T_e = 1-4 eV)**
- **Beryllium wall sputtering/transport for ~ 20-300 eV D, T**
- **Mixed material (Be, C) sputtering of divertor by D-T, O, self-sputter.**
- **Tritium codeposition in redeposited Be and C; role of oxygen.**
- **Important to understand, but not critical: physical sputtering of carbon (all energies), carbon chemical sputtering for > 20 eV incidence (T_e > 4 eV), tungsten sputtering**

ITER "carbon analysis" *[1] J.N. Brooks et al., J. Nucl. Mat. 266-269(1999)58. [2] J.N. Brooks et al., J. Nucl. Mat. 313-316(2003)424. [3] G. Federici et al. ibid p11.*



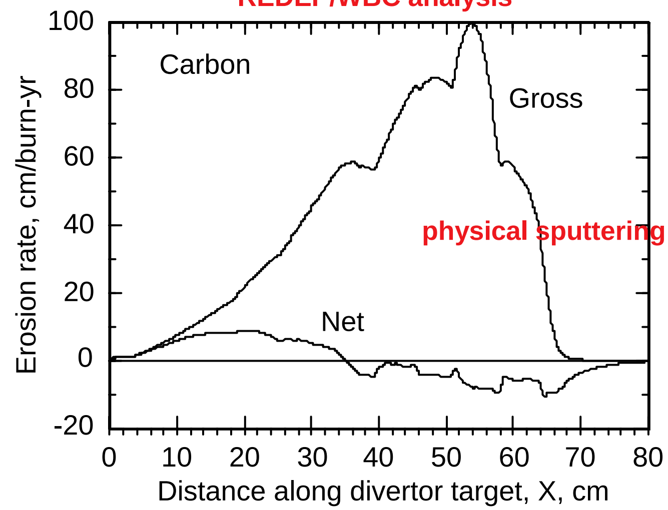
Chemical sputtering is critical in detached plasma

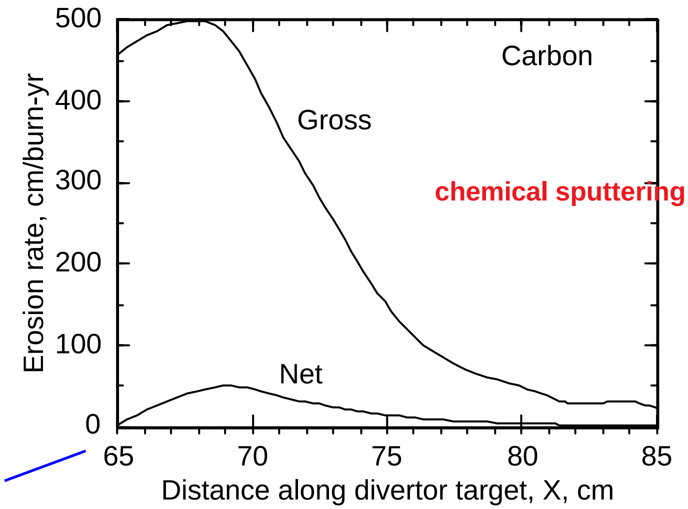
ITER "semi-detached regime"



Plasma temperature, density and particle fluxes
along the ITER outer divertor target

Carbon erosion
REDEP/WBC analysis





detached plasma

REDEP/WBC Analysis, ITER Tritium Codeposition, Semi-Detached Plasma Regime

Case	Tritium Codeposition Rate*
1. Reference **	**14 g/1000s pulse**
2. No fast-molecule chemical sputtering $(Y_{MOL} = 0)$	13
3. $Y_{MOL} = 0.01$	24
4. No chemical sputtering (physical sputtering only)	2
5. Carbon erosion reduced due to beryllium mixing	11
6. Shallow detached plasma - "Case 133"	17

* total (inner + outer divertor) resulting from ITER carbon coated vertical target sputtering.

** reference: "Case 98" plasma, physical and chemical sputtering, non-thermal D-T molecule sputtering yield $Y_{MOL} = 0.001$

ITER Plasma Facing Component Tasks at ANL

- **Initiate analysis of ITER mixed material (Be/C/W) Plasma Facing Component performance. (ANL, LLNL)**

  (J.N. Brooks, J.P. Allain, M. Nieto, T. Rognlien)

- **Supporting science: PISCES beryllium/carbon mixed-material experiments modeling. (ANL, UCSD)**

  (J.N. Brooks, J.P. Allain, M. Nieto, R. Doerner, D. Nishijima)

Initiate analysis of mixed material PFC erosion/redeposition performance for ITER

- Key issues: first **wall lifetime**, effect of transported beryllium on carbon (tungsten) **divertor erosion** and **tritium codeposition**, **plasma contamination**. Steps (2 yr goal):
- Method (follows FIRE-type analysis*): **Package-OMEGA**
- 1) Compute sputtering of ITER beryllium wall with and without plasma convective flux to wall.
- 2) Compute transport of sputtered beryllium to wall, divertor, plasma.
- 3) Mixed material code analysis of Be/C mixing/sputtering on the ITER vertical divertor target.
- 4) Compute erosion/redeposition, and surface-temperature dependent tritium codeposition in resulting growth layers of beryllium and carbon with inputs of oxygen flux to divertor and Q/Be and Q/Be-O codeposition rates.

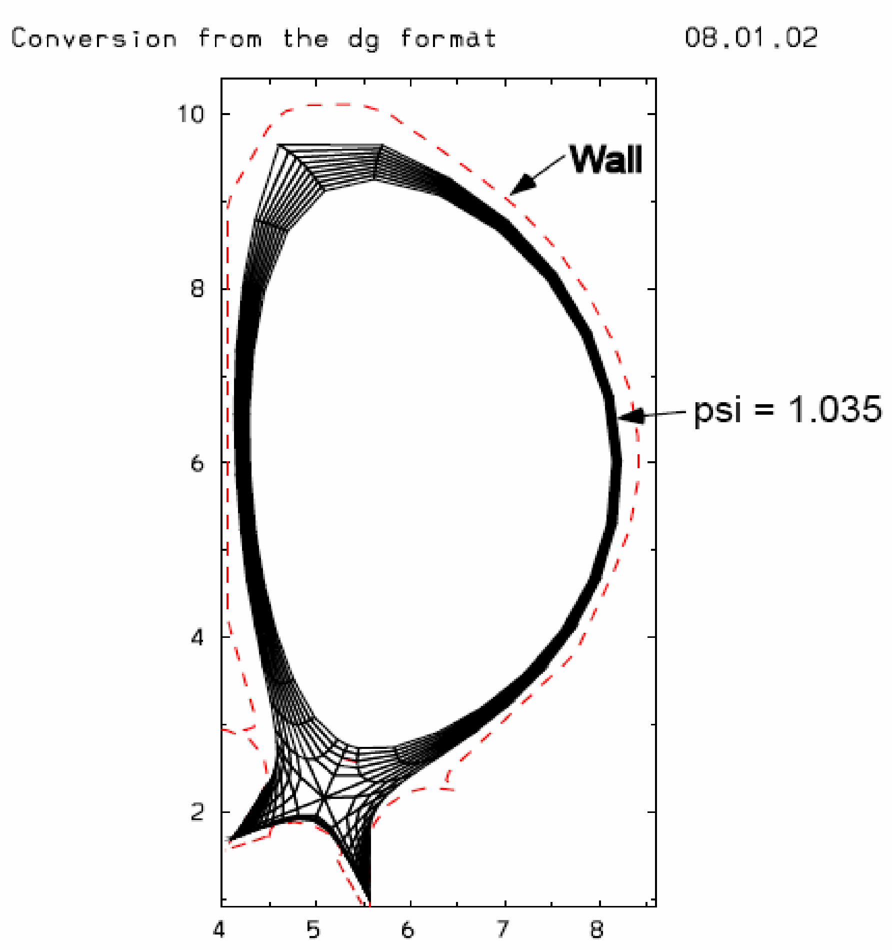
- *J.N. Brooks, J.P. Allain, D.A. Alman, D.N. Ruzic, Fus. Eng. Des. 72(2005)363.

Package-OMEGA*

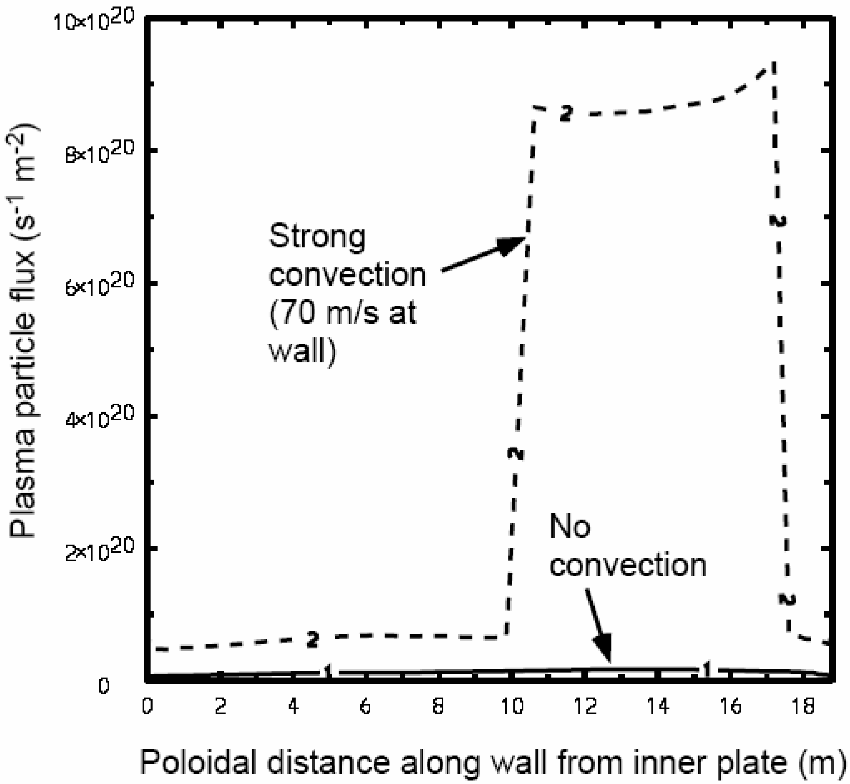
- **UEDGE/DEGAS:** D-T ion and neutral flux to wall, scrape-off layer (sol) plasma parameters
- **TRIM-SP, ITMC**: wall sputter yields
- **WBC$^+$**: wall-sputtered beryllium transport in scrape off layer
- **REDEP/WBC**: divertor erosion/redeposition analysis
- **ITMC, SIBIDET:** mixed-material evolution, divertor sputter yields
- **BPHI-3D**: Sheath analysis
- **Data** (where available)

* **O**mnibus **M**odeling of **E**rosion **G**eneralized **A**nalysis

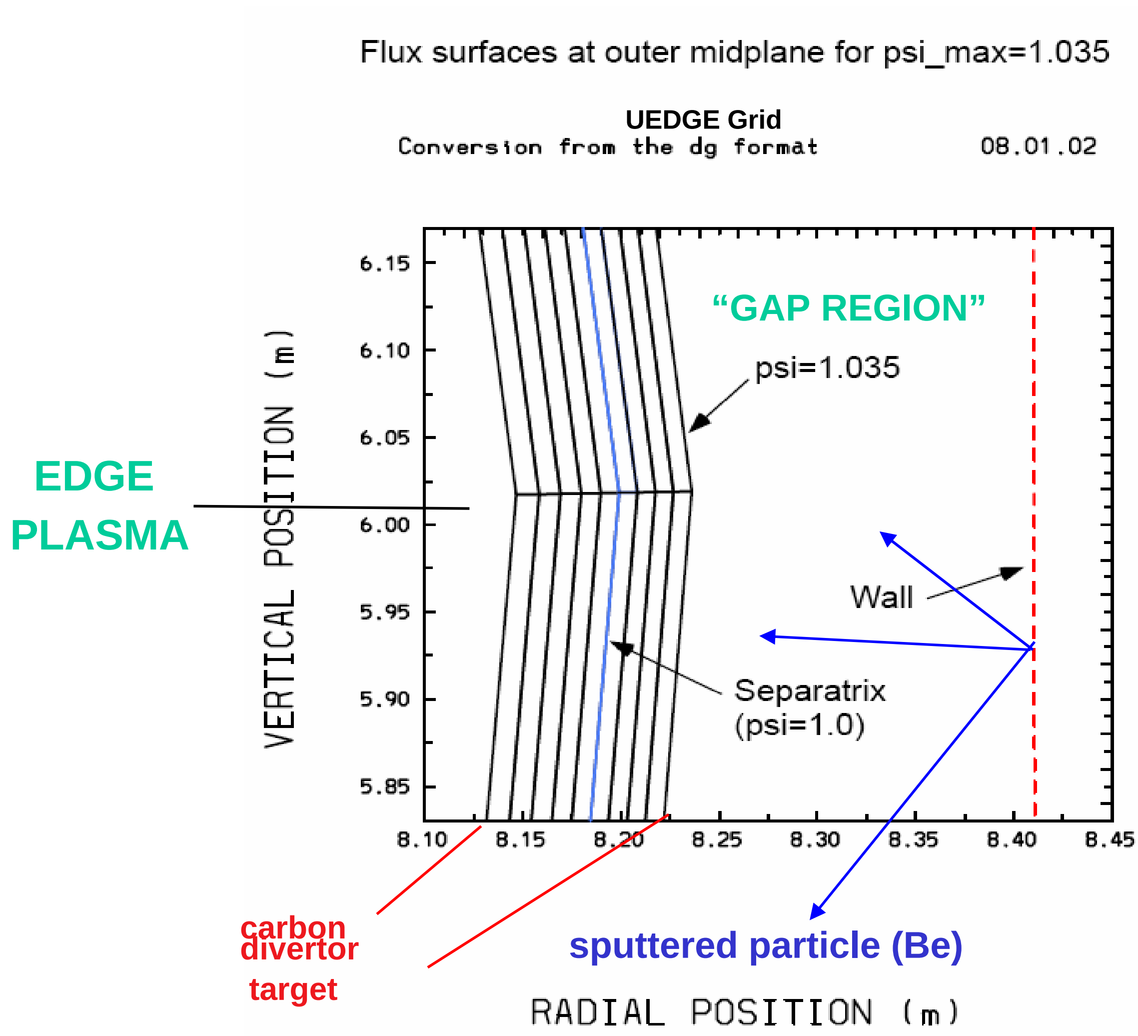
UEDGE ITER boundary plasma results (Rognlien LLNL)

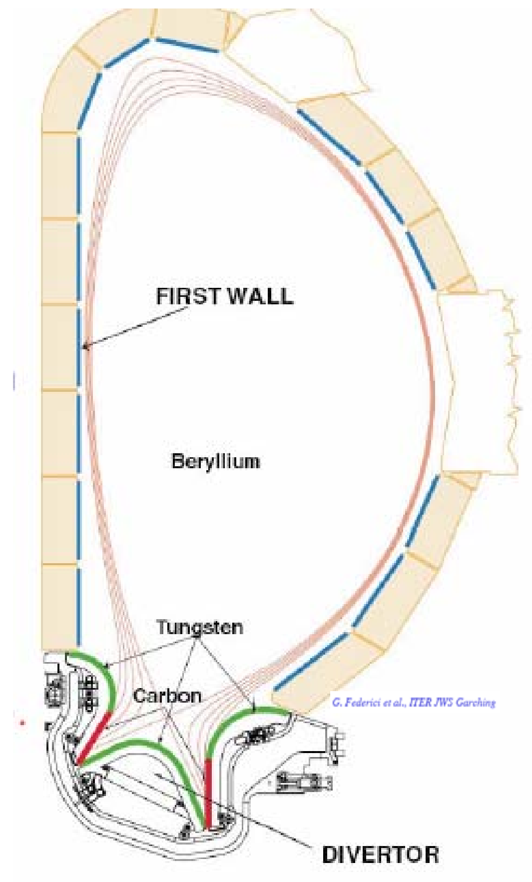


Ion flux to the "wall" (at psi = 1.035) comparing standard case and on with strong convection



Detail of divertor-to-wall PACKAGE-OMEGA ITER calculation geometry

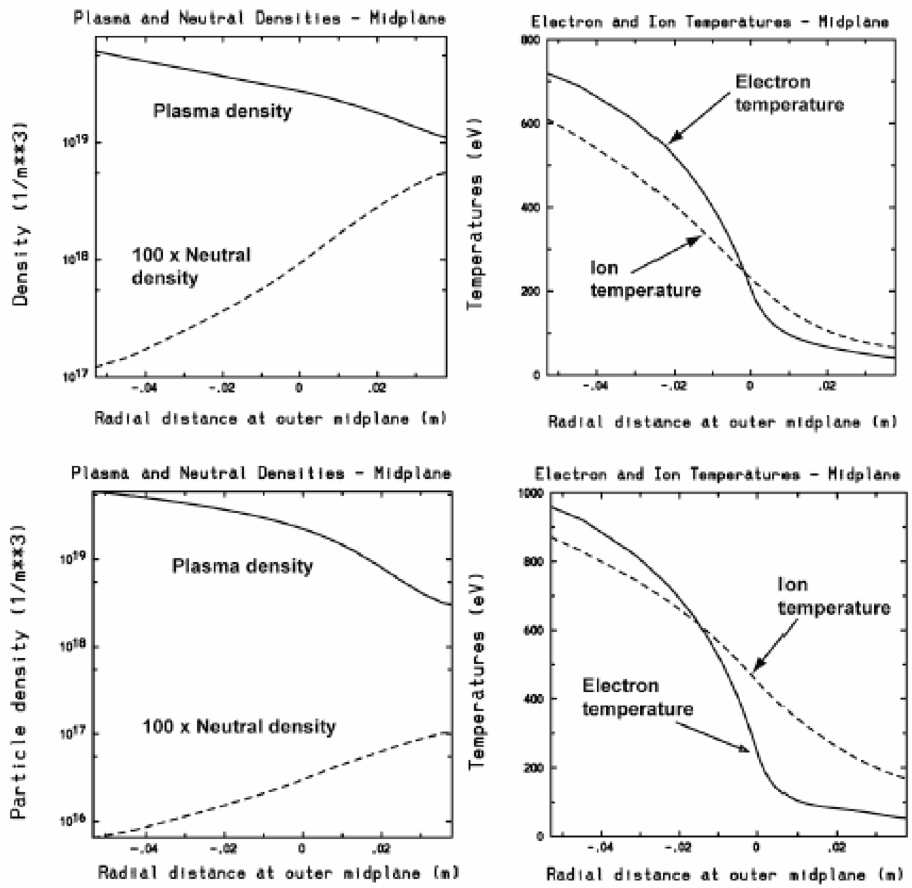




Plasma parameters near ITER wall-UEDGE code

with convection

no convection



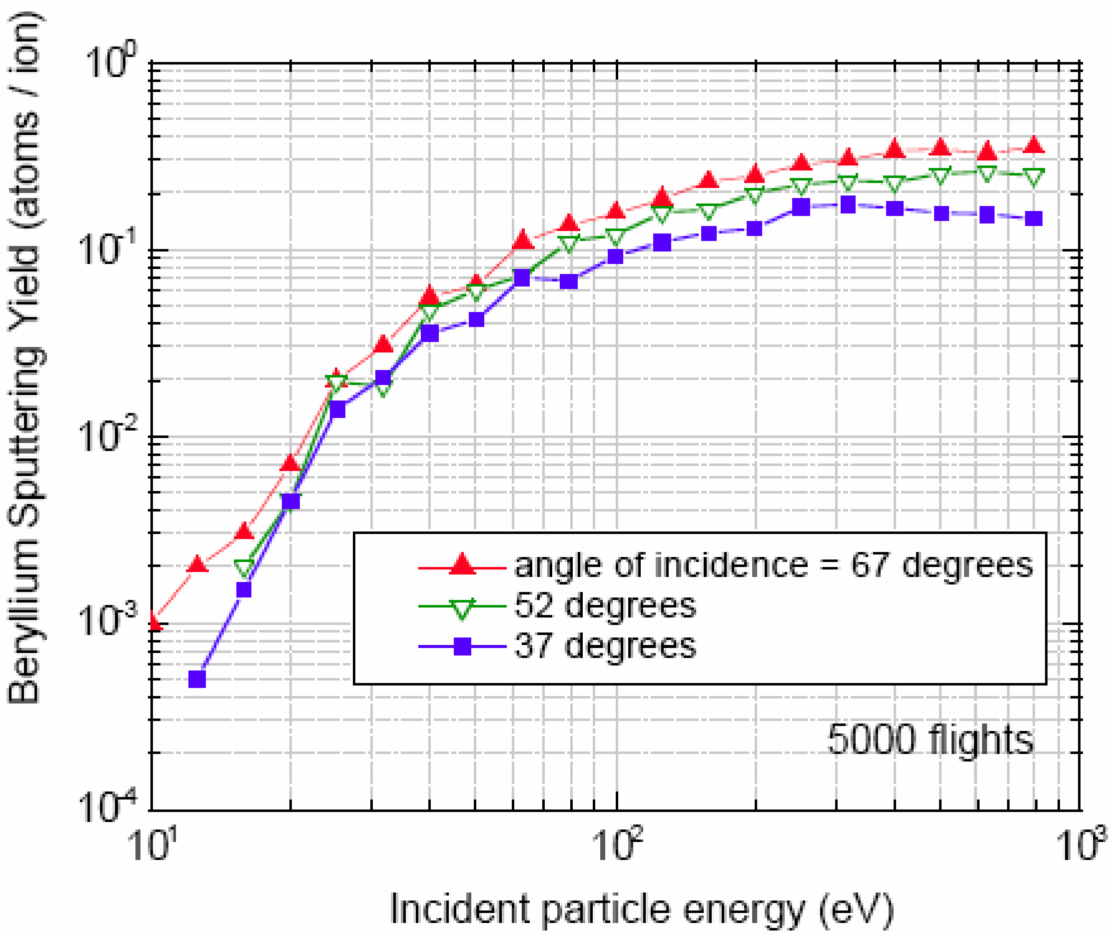
wall impingement energy

D, D^+ ~ 100-200 eV

wall impingement energy

D, D^+ ~ 300-500 eV

Sputtering yields for D^+ on Be with incident energies between 10 and 1000 eV, and with incident energies of 37°, 52°, and 67° (TRIM)



Package-OMEGA wall sputtering/transport calculation/assumptions

- Wall beryllium sputtering computed using UEDGE ion and neutral flux (@45° D yields).
- Gas puffing not included.
- Plasma sheath at wall.
- Neutral beryllium transport: initial/simplified Be/plasma elastic collision model, electron impact ionization w/ADAS rates.
- Divertor-Wall "gap region" density, $n_e(x)=n_0 \exp(-x/\lambda)$
- Ionized, Be^{+k}, transport in gap region: initial/simplified collision model.
- Partially self-consistent code-coupling.

ITER Package-OMEGA **preliminary** results: beryllium sputtering and transport

Plasma Case	Sputtered berylium current from wall	Peak wall erosion rate*
With convection	**3.9 x10^{22} s^{-1}**	**1 nm/s**
Diffusion only	**1.8 x 10^{21}**	**0.02**

* w/o gas puffing

ITER Package-OMEGA: beryllium sputtering and transport, **preliminary** results

Plasma Case	Sputtered berylium current from wall	Wall-sputtered fraction to carbon divertor target	Average beryllium growth rate on carbon divertor target*	Wall-sputtered fraction to edge plasma
With convection	**$3.9\ x10^{22}\ s^{-1}$**	**5.1%**	**1 nm/s**	**0.37%**
Diffusion only	**1.8×10^{21}**	**50**	**0.6**	**3.7**

* gross, not including sputtering/redeposition processes at divertor

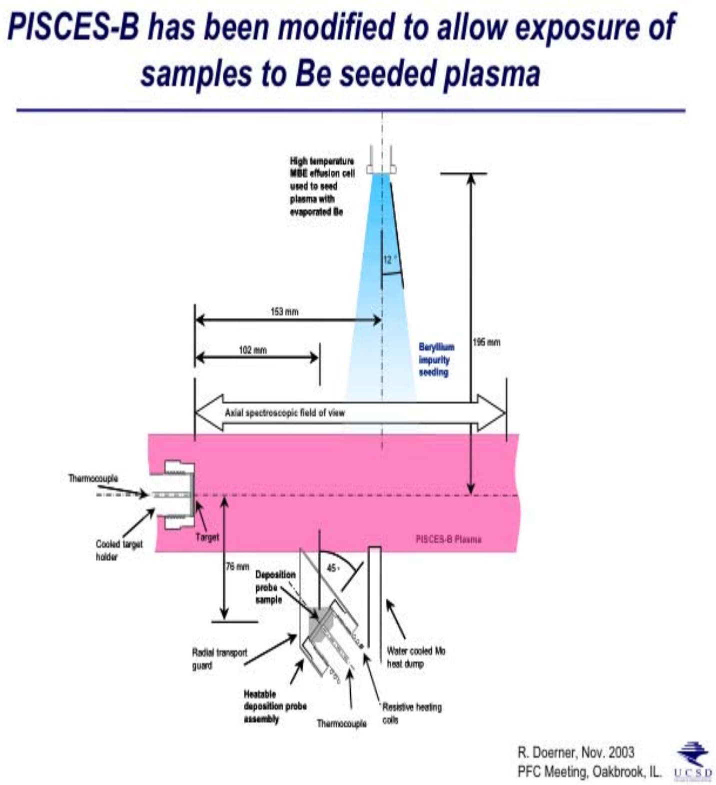
ITER Package-OMEGA tritium/beryllium codeposition; initial, **rough estimate**

Plasma Case	Q/Be trapping data assumption	Codeposition for 400 s pulse
With convection	**Mayer et al.* (ỊabundantÓ oxygen)**	**12 g T**
	Causey et al. (low/no oxygen)**	**2**
Diffusion only	**Mayer et al.* (ỊabundantÓ oxygen)**	**0.5**
	Causey et al. ** (low/no oxygen)	**0.1**

* (Q/Be ~ 0.3 @ 250 C
M. Mayer et al, "Codeposition of hydrogen with Be, C, and W", J. Nuc. Mat. 230(1996)67. M. Mayer et al., "Codeposition of deuterium with BeO at elevated temperatures", J. Nuc. Mat. 240(1998)84.

** (Q/Be ~ 0.05 @ 250 C
R.A. Causey, D.S. Walsh, "Codeposition of deuterium with beryllium", J. Nuc. Mat. 254(1998)84. R.A. Causey, "Hydrogen isotope retention and recycling in fusion reactor plasma facing components", J. Nuc. Mat. 300(2002)91.

Modeling of PISCES mixed material; Be/C experiment



- Purpose: Understand mixed-material Be/C sputtering and transport, Q/Be codeposition.
- Similar to expected conditions on ITER carbon divertor target subject to high beryllium flux from wall sputter/transport.
- Key code/data comparisons: Be-I photon emission and Be-I density profiles, surface growth of Be/C target.

Modeling of PISCES beryllium seeded mixed-material experiment

REDEP/WBC code simulation of 2.1 cm diameter carbon target bombarded by T_e = 5, 7, 8 eV, Be-seeded multispecies deuterium plasma. Key inputs from TRIM-SP code.

- *T_e = 5,7,8 eV, uniform in plasma. N_e = ~3.0 x 10^{18} m^{-3} at target center, uniform over target radially, radial variations (past-target) and axial variations in N_e per PISCES data*
- *Pre-sheath field, radial diffusion coeff. per previous work (D.G. Whyte et al., Nuclear Fusion 41(2001)47.). Plasma Mach number varies from 1.0 at target to 0.2 at 20 cm axially from target.*
- *Be/plasma-electron/ion collisions from full kinetic theory. Ion mass = 2.0 AMU in collision routine (corrections for D_2, D_3 mass should make 2^{nd} order difference).*

\- *Be/background-neutral collisions (elastic) using 5 mtorr D_2 @ rt.*

\- *Be atoms launched from points on the target per incident D^+, D_2^+, D_3^+ flux profile, with velocity per results of TRIM-SP runs w/ 40, 70 eV D^+ normal incidence on Beryllium-Carbide.*

\- *Detailed Be-I photon emission diagnostic simulated.*

–ADAS rate coefficients (per T. Evans GA) for electron-impact ionization of Be-I, Be-II, at 5-8 eV, at. e.g., at 5 eV, N_e = 2.5 x10^{18} m^{-3} :

BeI->BeII, $<\sigma v>$ = 1.428 x10^{-14} m^3/s,

- *BeII->BeIII, $<\sigma v>$ = 5.171 x10^{-16} m^3/s*

PISCES deuterium ion composition and sputter yields*

Plasma Species	Ion fraction	Sputter Yield Be target 40 eV	Be$_2$C target 40 eV	Be target 70 eV	Be$_2$C target 70 eV
D^+	55%	.0071	.0025	.0135	.0063
D_2^+	25%	.0040	.0019	.0100	.0053
D_3^+	20%	.0012	.0006	.0045	.0027
Y_{eff}		**.0052**	**.0020**	**.0108**	**.0053**

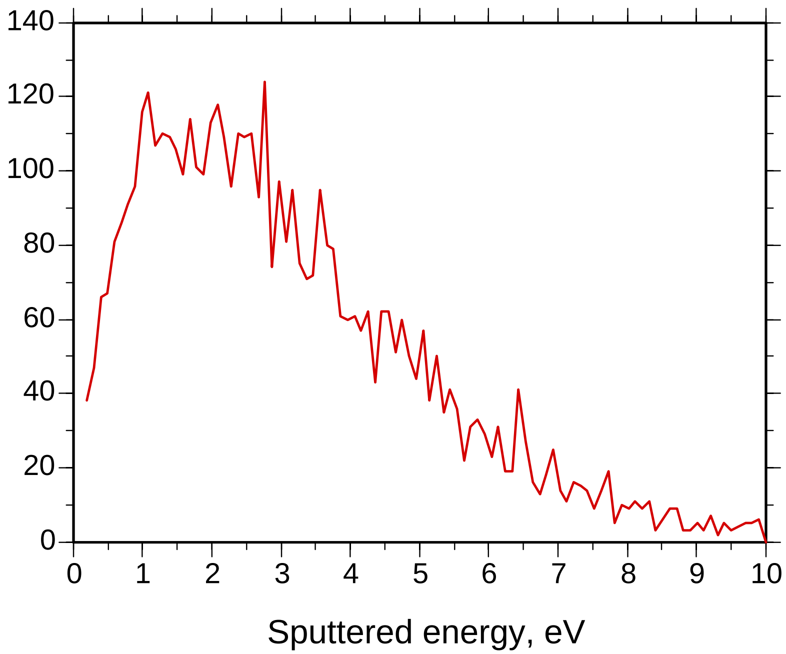
*Be/ion, normal incidence ions, TRIM-SP code

Sputtered beryllium energy distribution for PISCES analysis

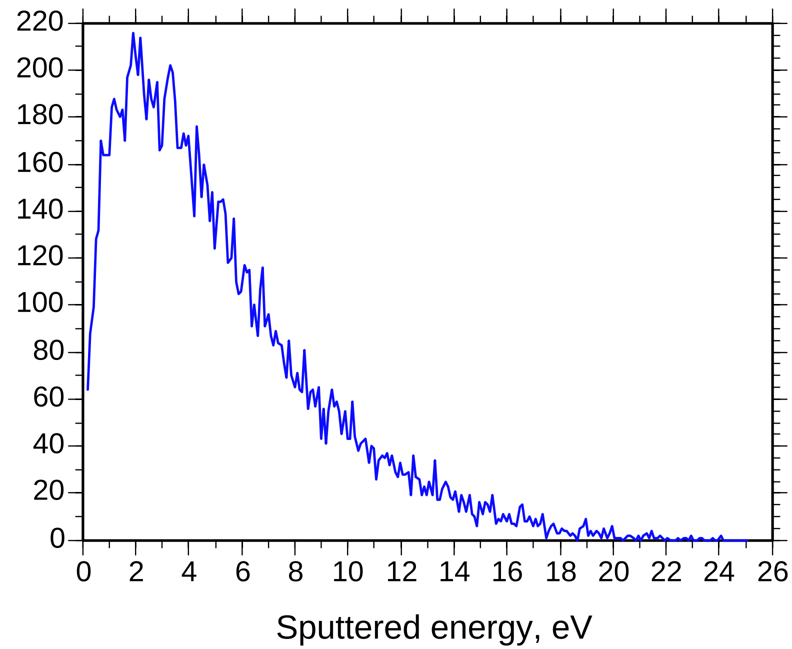
D^+, D_2^+, D_3^+ on Be_2C, normal incidence [TRIM-SP, J.P. Allain]

distribution shown for PISCES combination of incident particles

40 eV incidence

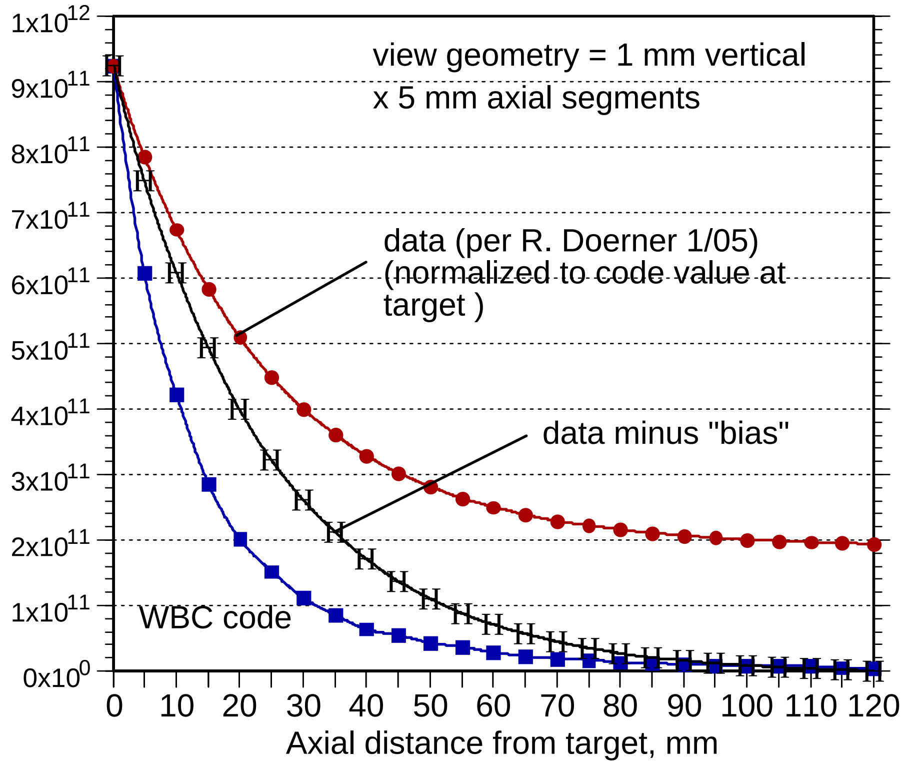


70 eV incidence



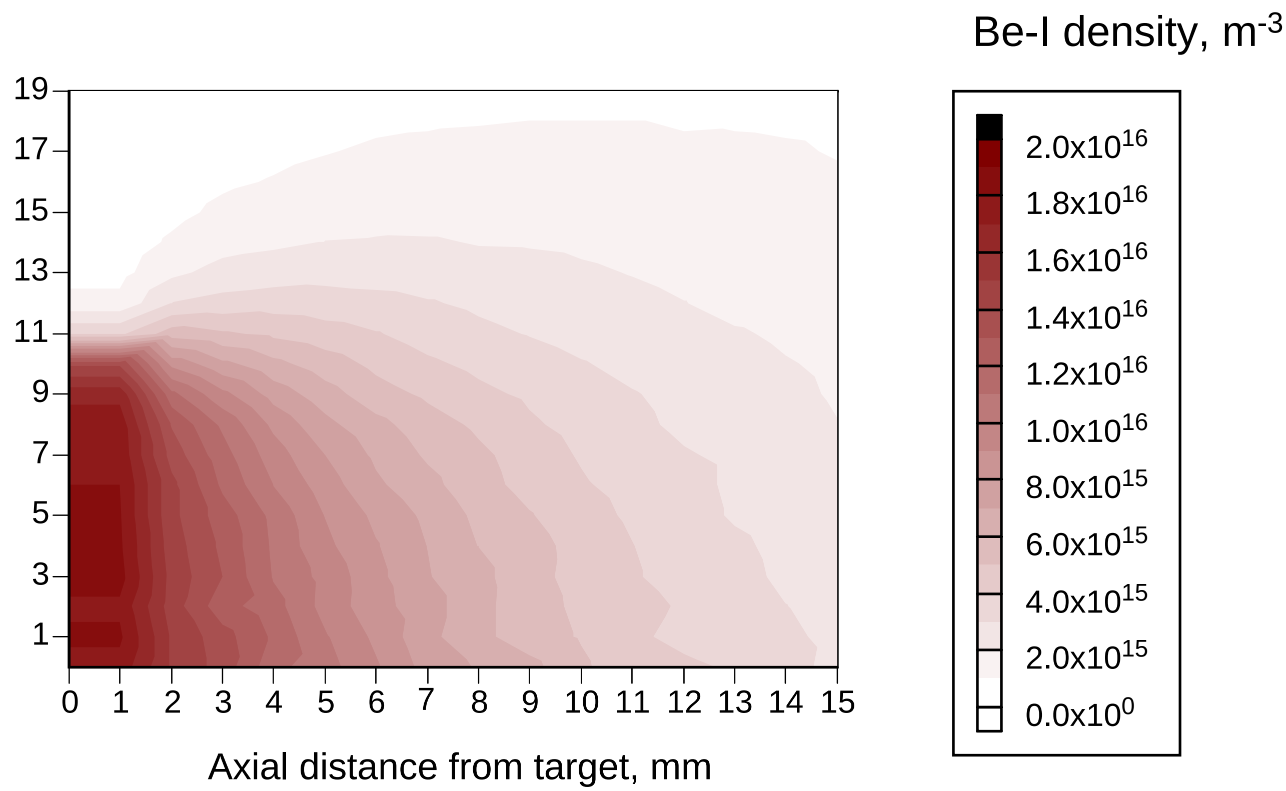
PISCES PHOTON DIAGNOSTIC SIMULATION

PISCES Be sputtering experiment- WBC computed
BeI photon emission axial dependence
(sample dia. = 2.2 cm, Te = 5 eV)



---code/data comparison is marginally acceptable

WBC code computed Be-I density, PISCES “8 eV Case (Nishijima et al. 3.14.05)”



Next steps-near future

- Refine estimates of D-T ion and neutral flux to the ITER first wall, and sputtered beryllium flux.
- Refine calculations for sputtered Be neutral and ion collisions with plasma ions/neutrals/electrons in divertor/wall region.
- Compute spatial profiles of beryllium transport to the ITER carbon divertor target, tungsten dome, wall.

- Continue code/validation effort on PISCES Be/C target.
- ANL IMPACT facility tests on exposed PISCES Be/C targets.

- DIII-D/DiMES Carbon “slot” experiment modeling.

Conclusions

- **Preliminary results for ITER 1st wall sputtering/transport obtained with Package-OMEGA coupled code analysis show:**
  - Major effect of convective transport on wall erosion, codeposition.
  - Wall erosion rates may be tolerable (for low duty-factor ITER).
  - Substantial flow of wall material (Be) to divertor; might be beneficial?
  - Significant potential for tritium codeposition in redeposited beryllium.

- **PISCES Be/C ITER simulation mixed-material modeling and code/data comparison underway.**
  - **Be-I photon emission comparison being used to validate REDEP code mixed-material sputtering and transport models.**
  - **Be density, Be, C growth profiles under comparison.**