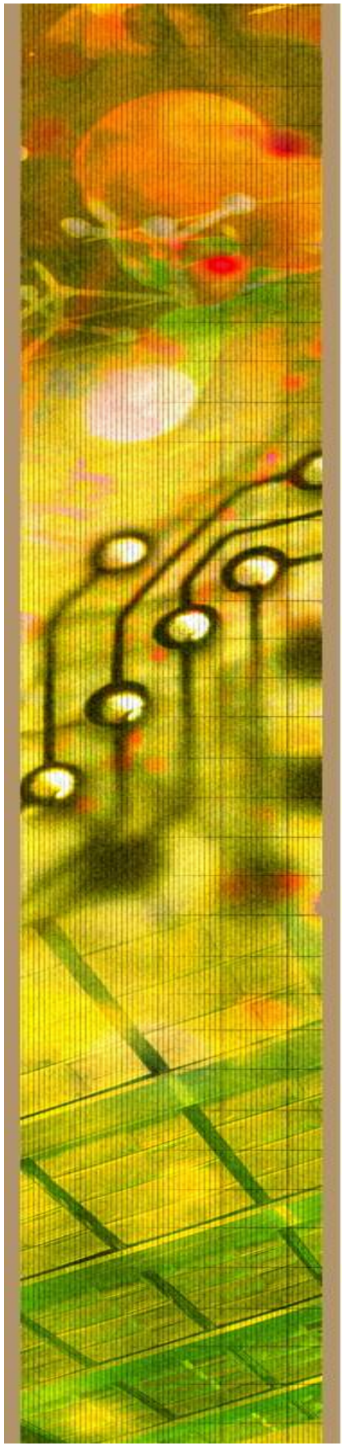

Analysis of PFC erosion experiments in DIII-D and status of C-MOD and ITER analysis

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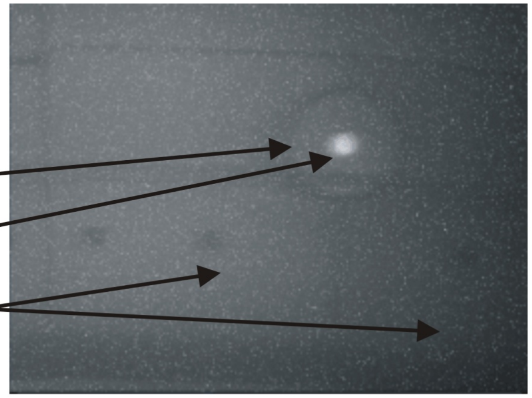
DIII-D DiMES high-Z (Molybdenum) erosion experiments



- 3 experiments conducted (GA, SNL): focus here on the August 1, 2011 experiment
- Purpose: test if net erosion << gross erosion for high-Z material.
- 1 cm dia. 25 nm deposited Mo metallic film on Si substrate, on DiMES probe.
- 7 Mo exposure shots, 4 s/shot, well-characterized, ~ same plasma conditions.
- Post exposure, ex-situ probe measurement of net erosion (Wampler et al, SNL.)

[1] J.N. Brooks, A. Hassanein, T. Sizyuk, “Advanced simulation of mixed-material erosion/evolution and application to low and high-Z containing plasma facing components”, PSI-20, J. Nuc. Mat. to be published.

[2] P.C. Stangeby et al., “An experimental comparison of gross and net erosion of Mo in the DIII-D divertor”, ibid.

[3] W. R. Wampler et al., “Measurements of net erosion and redeposition of molybdenum in DIII-D”, ibid.

[4]. D.L. Rudakov et al., “ Reduction of Net Erosion of High-Z Divertor Surface by Local Redeposition in DIII-D “, IAEA2012, to be presented.

TABLE I. Features of the 3 Mo experiments.

date	exposure time [s]	initial thickness of 1 cm sample [nm]	probe data. T_e-max [eV], n_e-max [10^{19} m^{-3}]	MoI filter passband [nm]	with 1 mm sample
8/1/2011	28	24.16	30, 1.5	10	no
4/23/2012	12	23.81	no data	1	no
5/1/2012	4	16.13	40, 1.2	1	yes

DiMES probe for 5/1/12; 1 cm and 1 mm Mo spots on carbon probe

Mixed-material response is key to understanding DIII-D Mo results

- We analyzed D/Mo/C divertor plasma interactions with mixed-material surfaces using advanced modeling of time-dependent surface evolution and erosion*.

- Simulations use the **REDEP/WBC** sputtering erosion/redeposition code package coupled to the HEIGHTS package **ITMC-DYN** mixed-material formation/response code, with plasma parameter input from codes and data.

- **The DIII-D/DiMES probe experiment simulation predicts that sputtered molybdenum from a 1 cm dia. central spot quickly (~ 4 sec.) saturates in the 5 cm dia. surrounding carbon probe surface, with subsequent re-sputtering and transport to off-probe regions, and with high (~50%) redeposition on the Mo spot.**

- **Predicted Mo content in the carbon agrees well with post exposure probe data.**

*Mixed-material work partially supported by the U.S. Department of Energy Office of Fusion Energy Sciences, and by Purdue University.

DIII-D Mo-DiMES: Key Data to be explained

1. Net erosion rate, Mo sample: 0.4 nm/s

2. Gross/Net erosion rate: ~2.0

3. Fraction of net eroded Mo found in DiMES "probe cap" (carbon portion of probe): 19%   (Thus, 81% not on probe).

4. Mo deposition profiles on DiMES graphite surface.

Simulation Method

REDEP/WBC code package, full-kinetic (3D/3V), impurity sputtering, transport, sheath structure, etc, with ITMC-DYN input/output

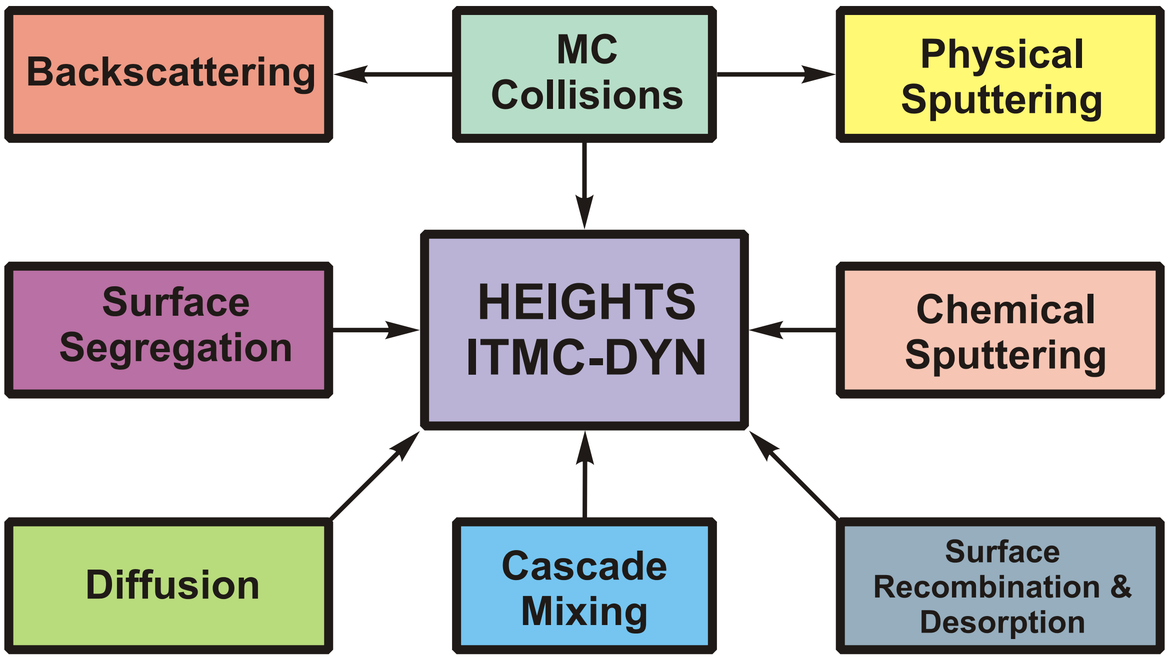
ITMC-DYN: **HEIGHTS-Package** BCA code accounting for time-dependent changes in target composition, due to penetration and mixing, scattering, reflection, sputtering, thermal diffusion, hydrogen isotope molecular recombination, and surface segregation.

DIII-D/DiMES experiment of Aug. 1, 2011
1 cm diameter Mo spot on 5 cm dia. graphite probe

Background plasma from codes/data:
7 shots x 4 seconds/shot = 28 s exposure; Te=30 eV, Ne=1.5 x10^{19} m^{-3}
1% C^{+3}/D^{+}, magnetic + Debye sheath, Mach-1 flow
Other REDEP/WBC etc. plasma parameters

Dynamic evolution of mixed materials bombarded with multiple ion beams:
ITMC-DYN Computer Simulation Package

ITMC-DYN Integrated Models



- A. Hassanein, “Surface effects on sputtered atoms and their angular and energy dependence”, Fusion Technology 8 (1985) 1735.
- T. Sizyuk and A. Hassanein, "Dynamic analysis and evolution of mixed materials bombarded with multiple ions beams", J. Nucl. Materials, 40(2010)60
- T. Sizyuk and A. Hassanein “Dynamic analysis of mixed ion beams/materials effects on the performance of ITER-like devices“, to be published J. Nucl. Mat. (2010)

Coupled simulation: WBC/ITMC

- Mo atoms launched randomly from the 1 cm dia. spot, per ITMC-DYN energy and angle probability distributions for C^{+3} on Mo sputtering

- Mo ionization and transport then followed.

- Ion history terminates if redeposited on the Mo spot or deposited off-probe.

- Mo ion incident on the probe carbon is re-sputtered per ITMC-DYN calculation, which also takes into account the simultaneous D ion flux.

- 10^6 histories/run, with spot-sputtered particle numerical weighting calibrated to the measured net erosion rate of 0.4 nm/s.

Key simulation outputs are redeposition rates, gross/net erosion ratio, deposition profles, and Mo content in the carbon.

DiMES WBC/ITMC Coupled Modeling-cont.

- *Moderate computational resources and numerical requirements needed/used here--due to small divertor area involved, near-constant plasma parameters, limited exposure time.*

- *{Most future, mixed-material simulations would need petascale computing}*

Table 1 REDEP/ITMC analysis summary for DiMES probe sputtered molybdenum, 10^6 histories

Parameter	Value
Ionization mean-free-path[a]	1.2 mm
Charge state[b]	1.7 (0.73)
Energy[b]	156 (86) eV
Incidence elevation angle (from normal)[b]	22 (11)
Transit time[c]	0.98 μs
Redeposition fraction on Mo spot	0.54
Redeposition fraction on divertor[d]	~1
Mo content in carbon portion of probe; at end of discharge	0.75×10^{16} atoms

[a] For sputtered Mo atoms, perp. to surface; from Mo spot and carbon

[b] Average (and standard deviation where indicated) for redeposited Mo ion

[c] Average for Mo ions, ionization-to-redeposition

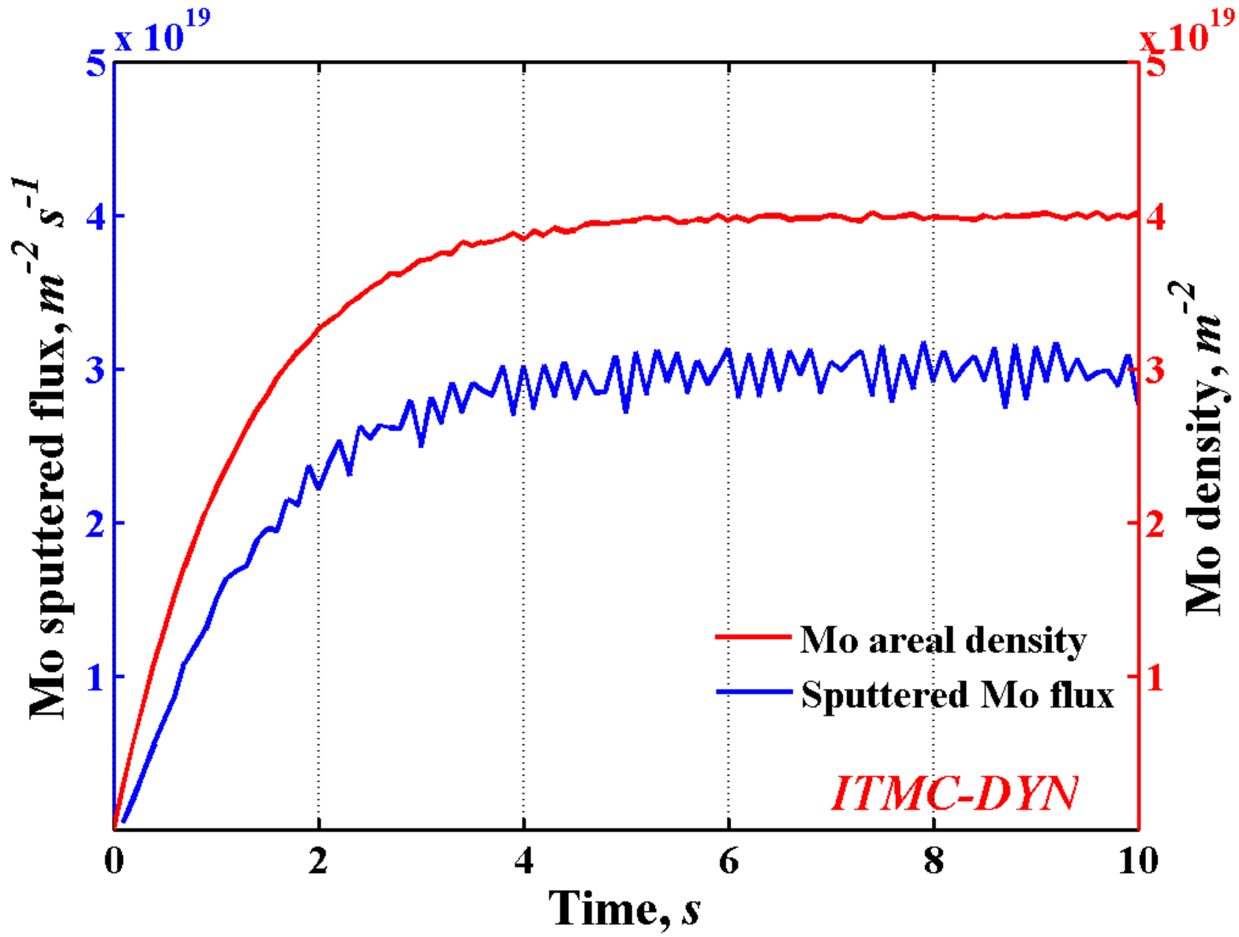
[d] Including probe; essentially 100% redeposition on divertor

--- High redeposition fraction on 1 cm dia. Mo spot

--- ~ 2-to-1 gross/net erosion ratio predicted

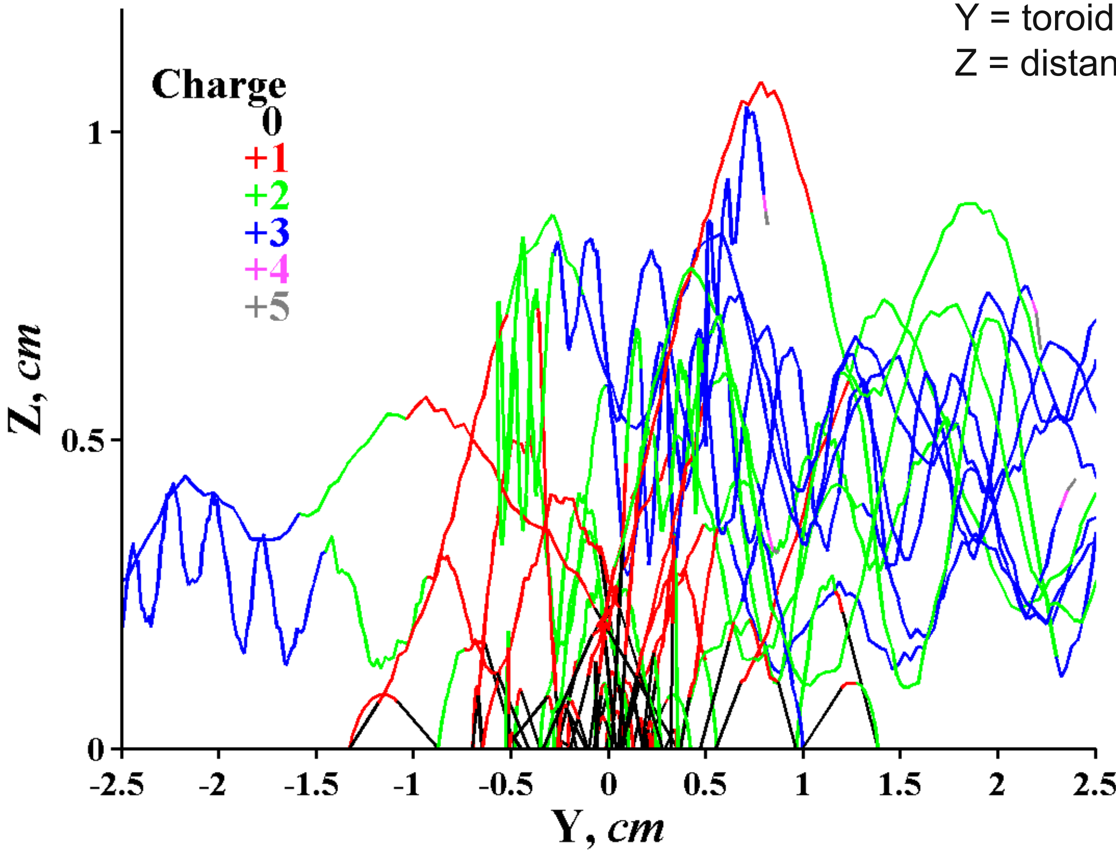
--- Essentially zero core plasma contamination predicted

Fig. 1 Time-dependent sputtered Mo flux from, and areal density in, DIII-DiMES carbon probe surface, for $3 \times 10^{19} m^{-2} s^{-1}$ incident Mo ion flux. WBC/ITMC simulation (at typical point near Mo spot).



- Steady-state reached in ~ 4 seconds

Fig. 2 WBC/ITMC DiMES Simulation: Typical sputtered Mo trajectories (50 histories); 2-D plot.
Y = toroidal direction through probe center
Z = distance above probe



Trajectories show:

- Approximately straight line motion from sputtering to first ionization.
- Ion gyro-rotation, charge-changing, and velocity-changing collisions with the background plasma.
- Resulting spot-redeposition, on-probe non-spot redeposition and re-sputtering, and off-probe transport.

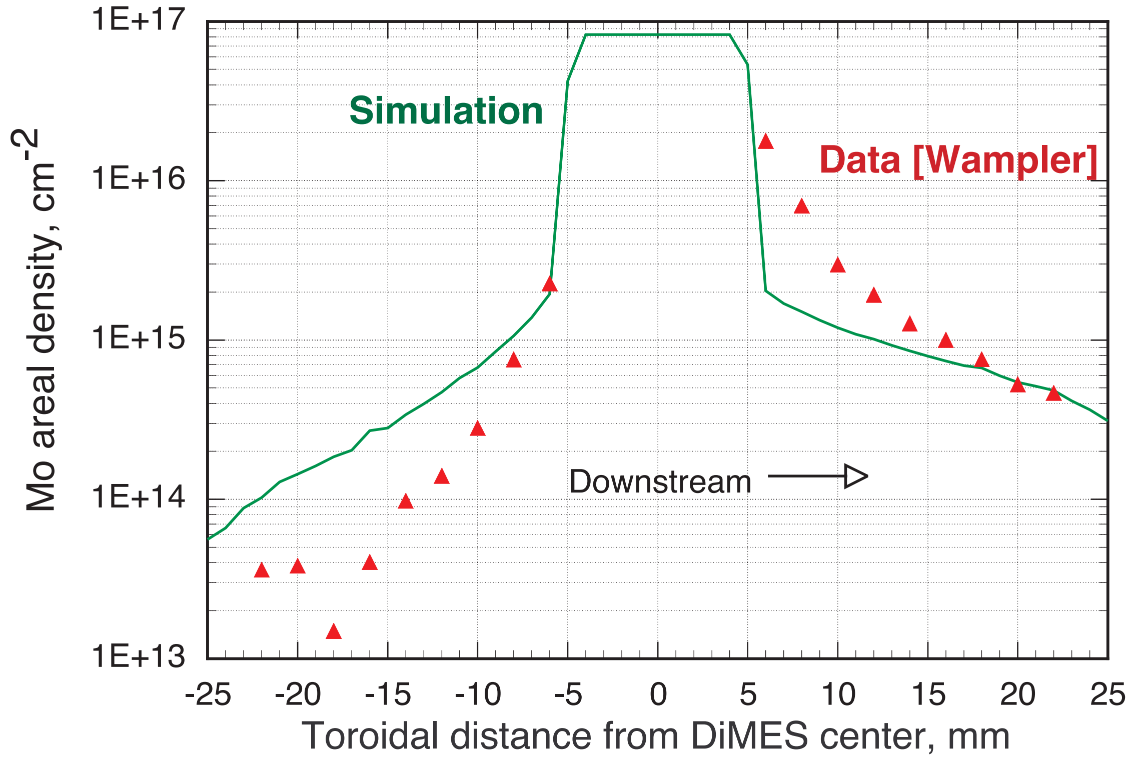


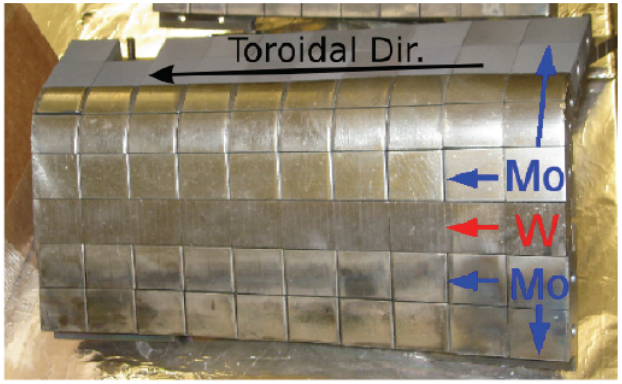
Fig 3 DiMES Mo areal density at end of 28 s exposure; along toroidal direction

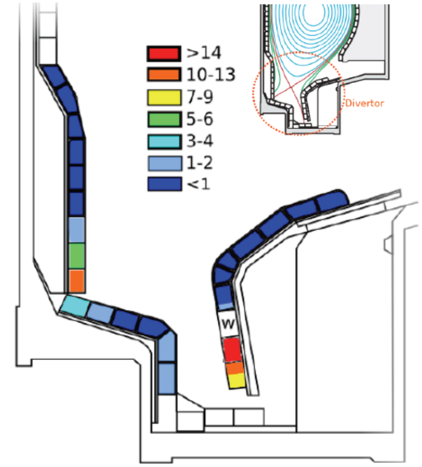
---Good code/data match to Mo content in the carbon; 0.75 x 10^{16} vs. 1.1 x 10^{16} Mo atoms.

---"OK" code/data agreement to Mo toroidal profile-higher predicted upstream deposition.

W Migration in Alcator C-Mod

H. Barnard , B. Lipschultz, D. Whyte, MIT
(ITPA Seoul Korea, 2010)





Tungsten deposition, 10^{20} atoms / m^2

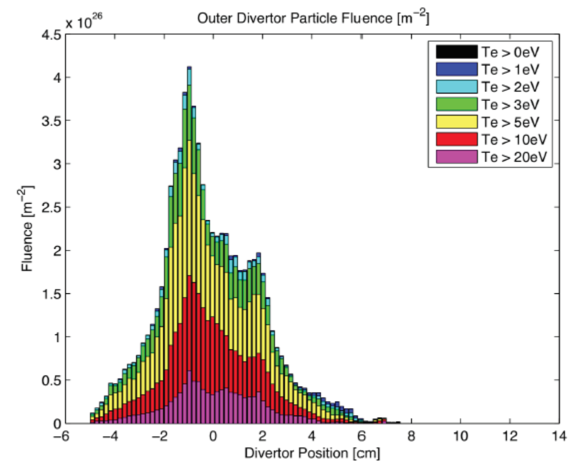
Toroidally symmetric tungsten tiles at/near outer divertor strike point. Exposed for ~10^3 s at various plasma conditions.

D +1% B plasma. Total ion fluence ~ 10^{26} D/m^2.

Post-exposure deposition measured by external MeV ion beam. (2 MeV protons; PIXE, PIGE)

A net effective thickness 4×10^{21} W/m^2 $\approx$ 60 nm was removed.

Modeling goal: Compare code/data erosion and impurity transport. Key focus on net/gross erosion



Plasma shot Te histogram

Modeling of C-MOD Tungsten Migration

- Initial steps:
  1) BPHI code analysis of C-MOD outer divertor sheath conditions and boron ion impingement.
  2) ITMC code computation of B on W sputter yields and velocity distribution functions. (Pure W assumed)
  3) Tungsten gross erosion, rough estimate; per fluence data and above results.
  – Initial results, consistent with >90% redeposition fraction. Encouraging.

- Underway: Detailed REDEP/WBC code package analysis of C-MOD tungsten sputtering, transport, gross and net erosion.

  ---including-self-consistent self-sputtering, convolution over discrete plasma conditions.

  ---compute tungsten transport to outer and inner divertor; compare with data.

ITER-PFC Modeling Issues

- A key PFC issue is the effect of the ~700 m^2 wall-sputtered beryllium on the ~50 m^2 tungsten outer divertor, this potentially affecting Be/W alloy formation, thermal properties, divertor erosion, and T/Be codeposition in re-sputtered and off-divertor deposited beryllium.

- A previous study—using a simplified material response model—indicated no significant Be growth over most of the outer tungsten divertor, but with high Be growth at the strike point [J.N. Brooks, J.P. Allain, J. Nuclear Materials, 390-391 (2009)123]. *Generally encouraging results, but uncertain.*

- High-confidence, predictive ITER analysis can be performed with the advanced simulation method used here, however, the numerical issues become orders of magnitude greater. This is due to the ~50 cm long ITER divertor, with highly varying plasma parameters—compared to the 5 cm DiMES probe with near constant parameters. (An added complication for ITER is the multiple particle impingement, due to D, T, He, and any trace impurity.)

- An ITER full mixed-material divertor evolution study would require petascale computation.

Conclusions

- **It is clear that mixed-material formation and plasma/surface interaction are key issues for fusion.**

- We modeled this with advanced simulations using coupled erosion/redeposition and surface response code packages; but still with numerical simplifications–adequate for the small-area DiMES geometry.

- **For DIII-DiMES, the analysis explains the important scientific result of high-Z material high-redeposition, quick saturation of W in probe C, and resulting transport of Mo to off-probe divertor surfaces.**

- **Results appear encouraging for high-Z material (W) use in ITER: low net sputter erosion, very low core plasma contamination.**

- **Predictive analysis for other mixed-material situations, such as ITER Be/W, and NSTX Li/C/Mo, with large area plasma facing surfaces, is highly amenable to our advanced simulation technique, but would require petascale computing.**