An Experimental Comparison of Gross and Net Erosion of Mo in the DIII-D Divertor

by

P.C. Stangeby

with thanks to co-workers

D.L. Rudakov, W.R. Wampler, J.N. Brooks,
N.H. Brooks, D.A. Buchenauer, J.D. Elder, A.Hassanein,
A.W. Leonard, A.G. McLean, A. Okamoto, T. Sizyuk , J.G. Watkins,
D.G. Whyte and C.P.C. Wong

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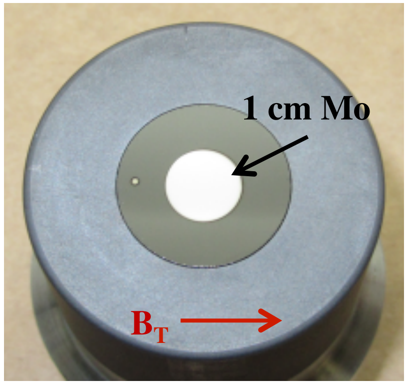
DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

UTIAS
University of Toronto
Institute for Aerospace Studies

Summary: Net Erosion of Molybdenum in DIII-D Divertor is Reduced Compared to Gross Erosion

- Net erosion = gross erosion – deposition
- ITER, FNSF require that target *effective* i.e. *net erosion* be very *small*
- Net erosion of high-Z material in a divertor *should* be reduced cf gross erosion due to prompt local redeposition *but* existing experimental evidence is inconsistent, calling for a *definitive test*
- Experiments on erosion of Mo under stable well-diagnosed plasma conditions were conducted in DIII-D



DiMES head

- Net erosion is reduced by ~x2 compared to gross erosion for a 1 cm diameter Mo sample under attached L-mode plasma conditions
- Result in good agreement with simple estimates and code modeling
- Good news for ITER, FNSF but more work to be done

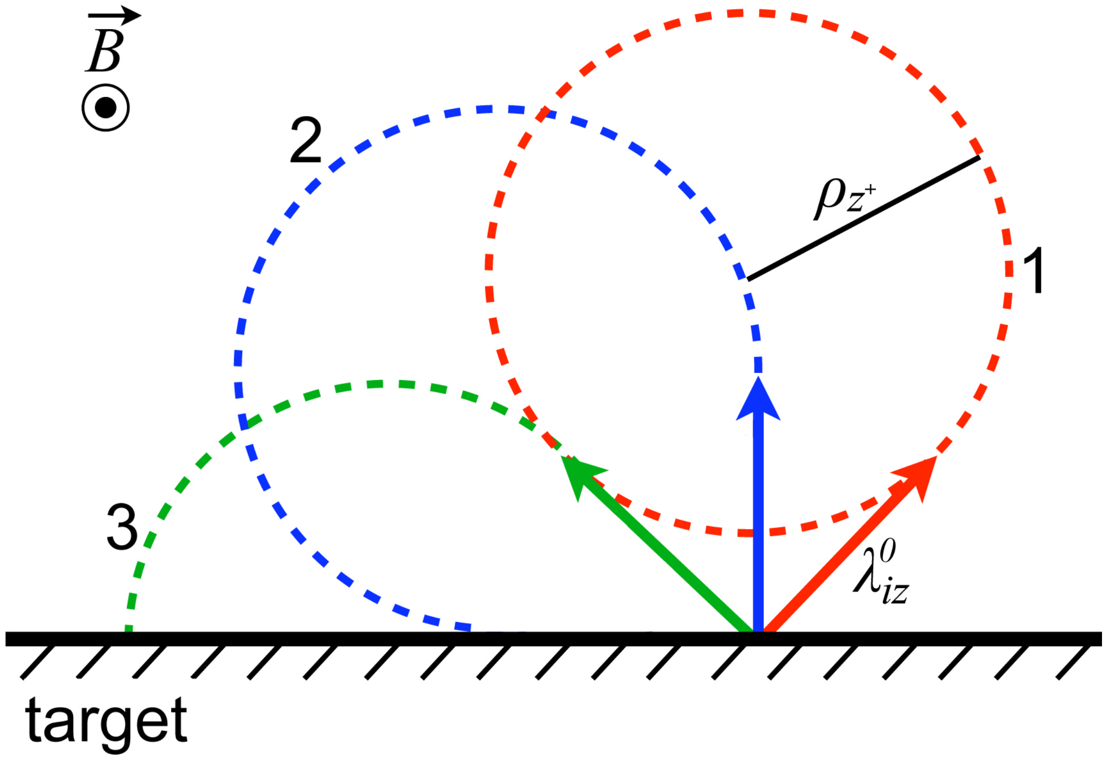
Gross Erosion Rates in Future Devices will be Enormous but *Net* Erosion is What Matters

device	P_{heat} [MW]	annual run time [s/year]	E_{load}^{year} [TJ/yr] (ktonTNT/yr)	carbon gross erosion rate [ton/yr]	tungsten gross erosion rate [ton/yr]
DIII-D	20	10^4	0.2 (0.05)	0.0005	0.0007
EAST	24	10^5	2.4 (0.6)	0.005	0.008
ITER	100	10^6	100 (24)	0.3	0.4
FNSF	100	10^7	1000 (240)	2	3
Reactor	400	2.5×10^7	10000 (2400)	23	35

1 kton TNT = 4.1 TJ

- Present → future tokamaks E_{load}^{year} ↑ 10^5 X
- Annual gross erosion ∝ E_{load}^{year} → 10 m/yr (targets)
- Must be avoided. One way: make net << gross erosion
- *Should* happed (prompt local deposition) but experimental evidence inconsistent
- A definitive test needed

Prompt Deposition During the First Gyro-orbit of the Newly Ionized Sputtered Neutral



When $\lambda^{o}_{iz} \sim \rho_{Z^+}$ (as shown) then the impurity ion may return to the target during the first Larmor orbit. Examples 2 and 3 do so here

When $\lambda^{o}_{iz} < \rho_{Z^+}$ (not shown) then all impurity ions return

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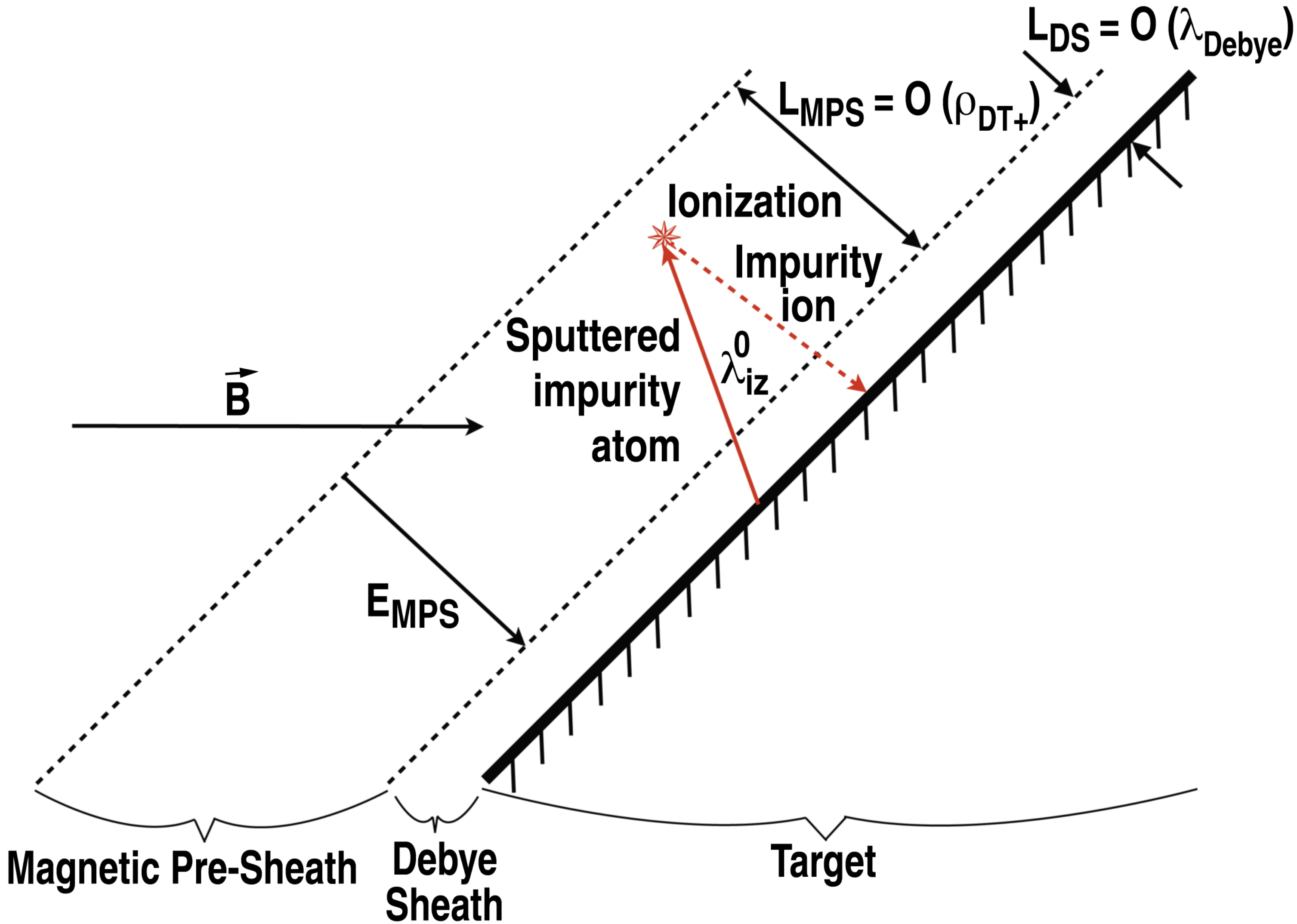
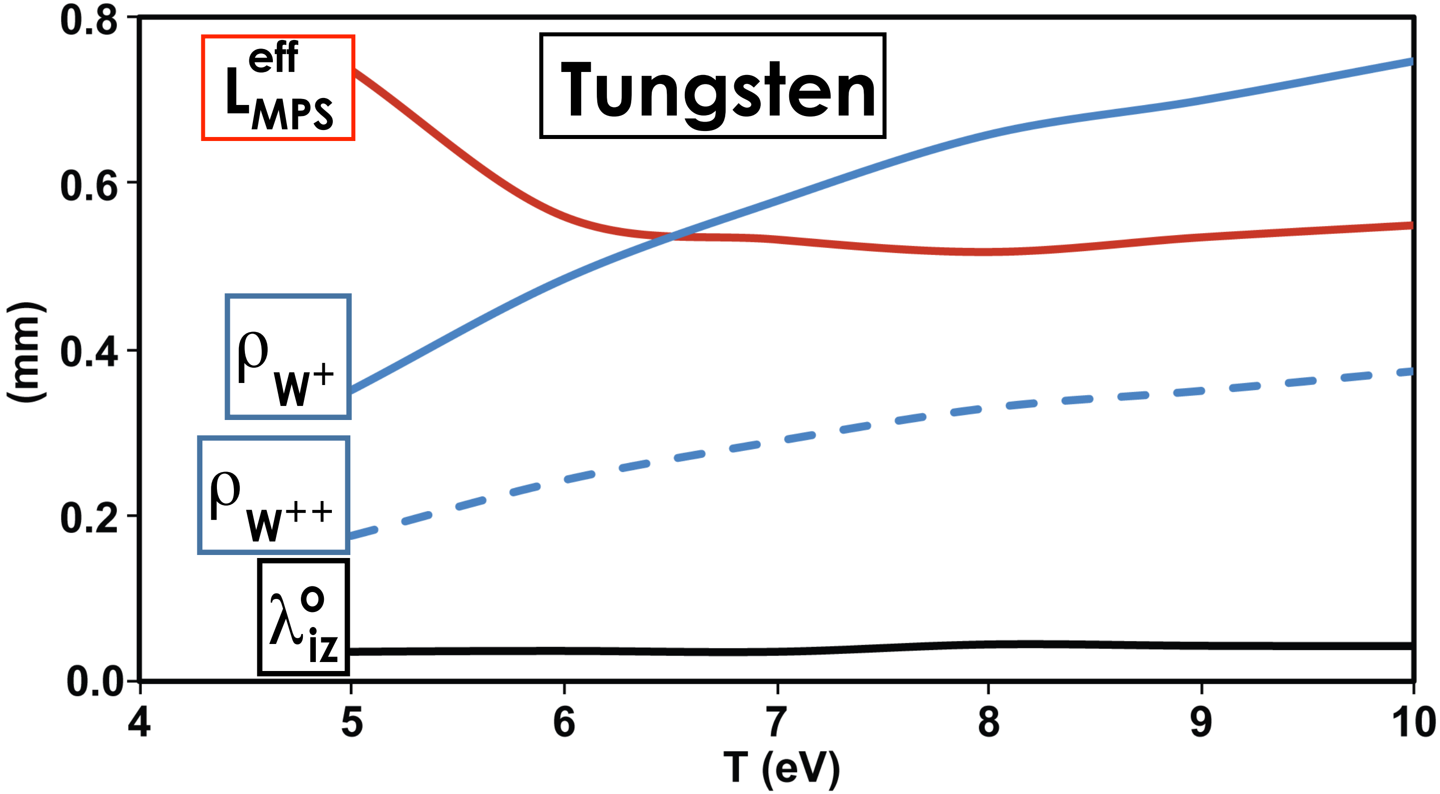
Fast Deposition Due to the Strong E-field in the Magnetic Pre-sheath (MPS) and Friction with Fast Plasma Flow

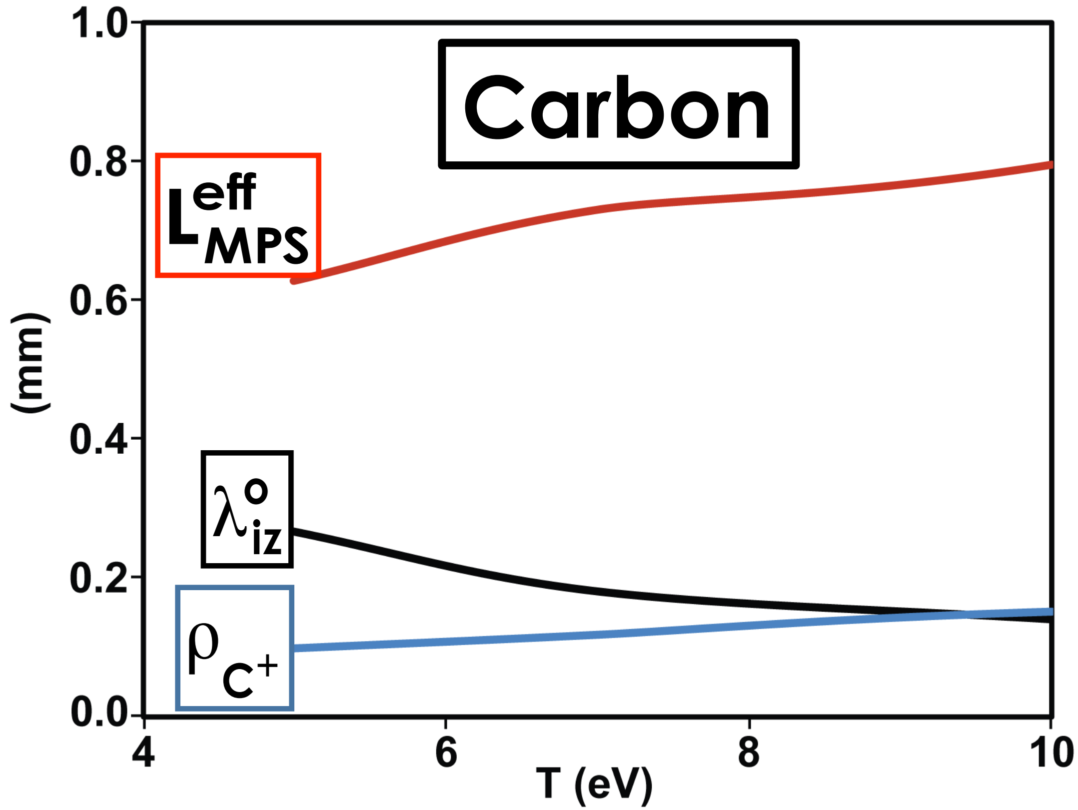


For Tungsten, Prompt Deposition Should be Effective in DT Devices Via Both Strong MPS Forces and Short ρ_w-Effect



ITER outer strike-point conditions: n = 10^{21} m^{-3} , B = 5T

For Carbon, Prompt Deposition Should Also be Effective Due to Strong MPS Forces (but Only Marginally Via Short ρ_C -Effect)



For typical outer target strike point conditions expected in fusion power devices e.g. ITER and FDF of
$n = 10^{21}\ m^{-3}$
B = 5T

However, a Puzzling Result from C-Mod: for Mo at OSP, Net Erosion ~Gross Erosion, Apparently

- **Although the theoretical ideas here are basic and while there is also evidence for their validity**
- **…in C-Mod measured net erosion of Mo ~ *order of magnitude larger* than expected from simple estimates and also code modeling**
- **The C-Mod measurements were *campaign-integrated*, making them difficult to interpret**
- **Exposure conditions are required using *well characterized, repeat* discharges *only*, to provide the interpretable data needed for a *definitive test* of the relation between net and gross erosion**

C-mod

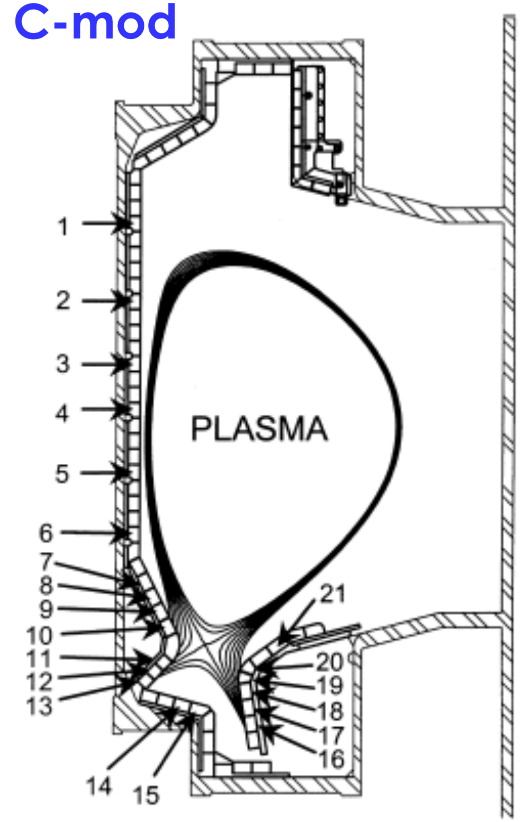


Fig. 1. Diagram of Alcator C-Mod showing the location of the 21 tiles with the Cr depth marker.

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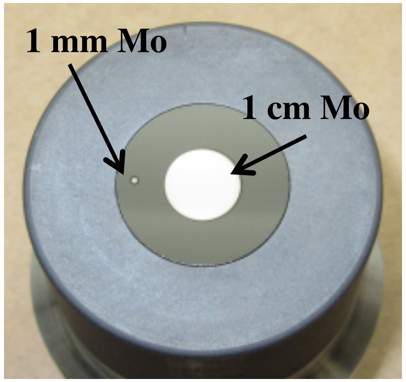
In DIII-D Such a Test has been Carried Out of Net vs Gross Erosion

- DiMES was used to expose thin Mo film samples to repeat, well-controlled, well-characterized, low density shots. L-mode, no ELMs. Attached
- Strike point moved onto DiMES for 4 s flat top only
- ~15 nm Mo film on Si substrate, set flush in 5 cm diameter graphite DiMES head. 1 cm and 1 mm diam Mo samples

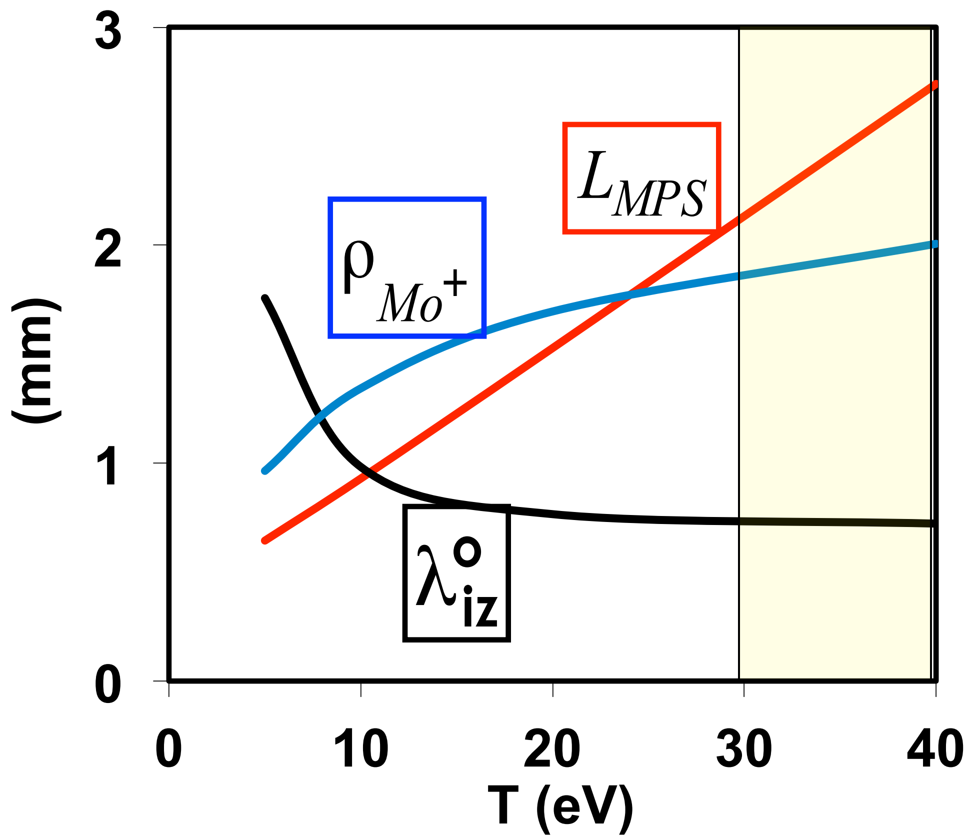


DiMES head

- RBS* measured change in thickness of 1 cm sample → net erosion
- RBS* measured change in thickness of 1 mm sample → gross erosion
- Gross erosion also measured spectroscopically (MoI line at 386 nm)

*RBS: Rutherford Backscattering *ex situ* surface analysis

For 1 cm Diam Mo Sample, Prompt Deposition Should be Effective for Low Density SAPP Conditions at the OSP in DIII-D



Sputtering by C ions
$n = 1.5 \times 10^{19}\ m^{-3}$, B = 2T

- However, for a small (1 mm) diam Mo sample, WBC/REDEP code gives only 5% redeposition, thus net ~ gross for small Mo sample
- Provides a non-spectroscopic way to measure gross erosion

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We Did Three Experiments

Experiment	Exposure time (s)	Probe data. T_e-max (eV), n_e-max (10^{19} m^{-3})	MoI filter passband (nm)	With 1 mm sample
Sample # 1	28	30, 1.5	10	no
Sample # 2	12	no data	1	no
Sample # 3	4	40, 1.2	1	yes

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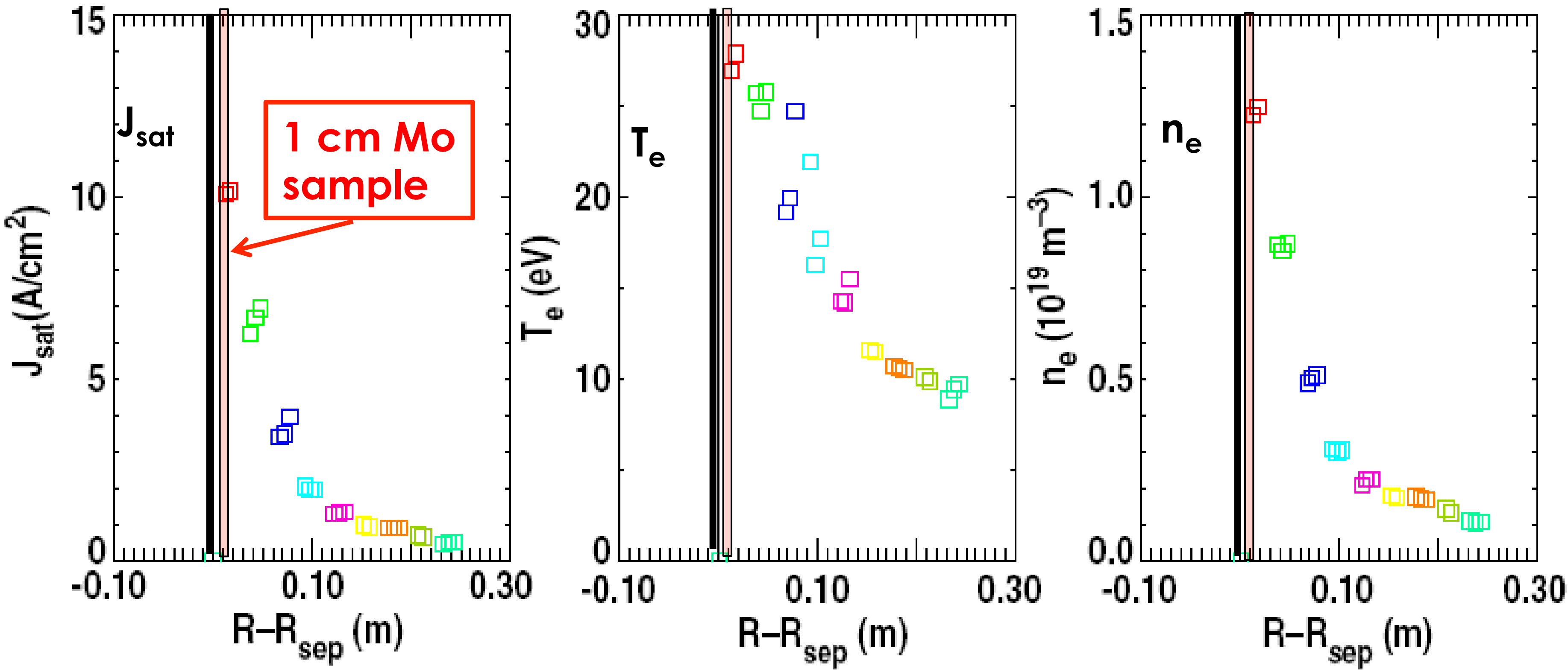
Plasma Conditions ~ Constant Across the DiMES Mo Sample



J.G. Watkins

Mo sample center at ~1 cm outside OSP

Profiles for Sample # 1

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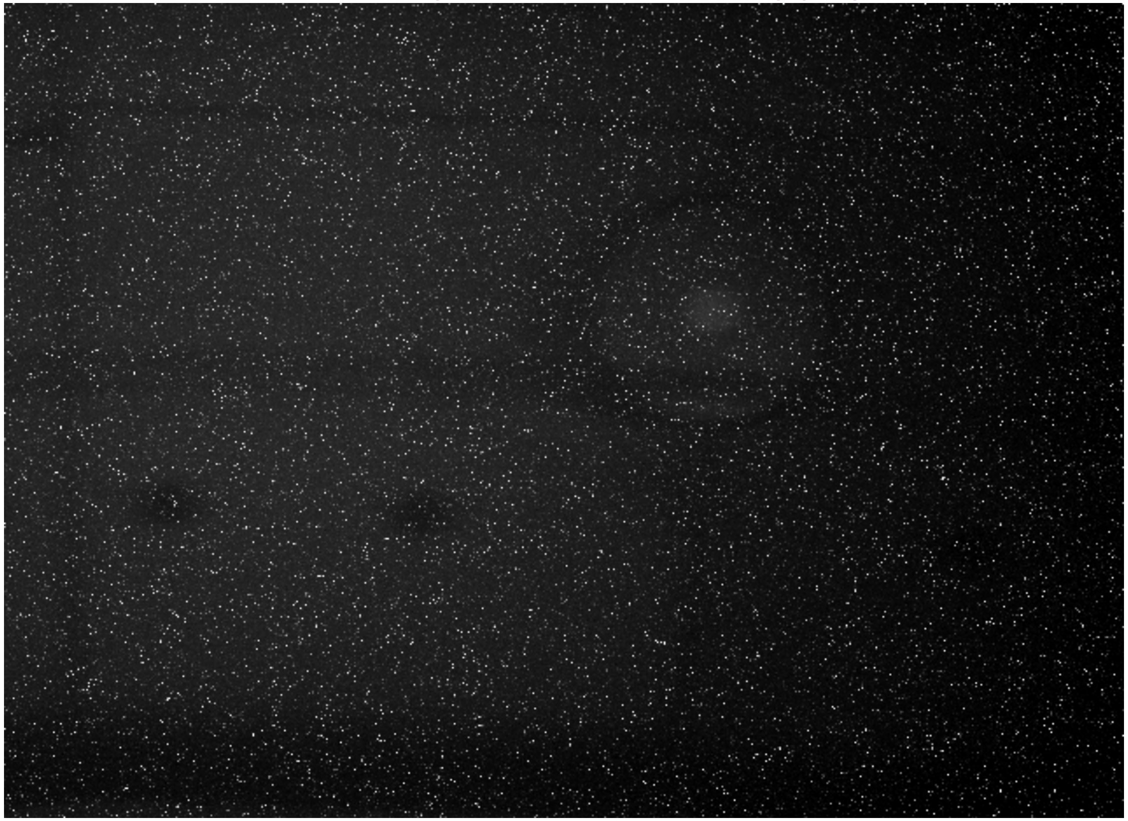
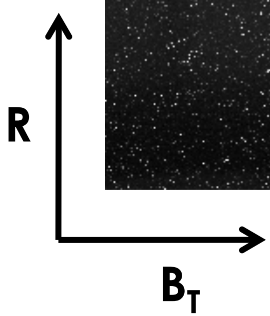
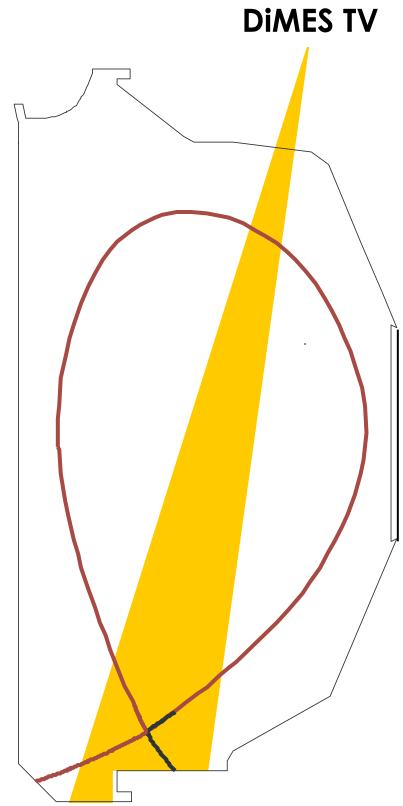
MoI Light Observed by CCD Camera

Shot number 145673





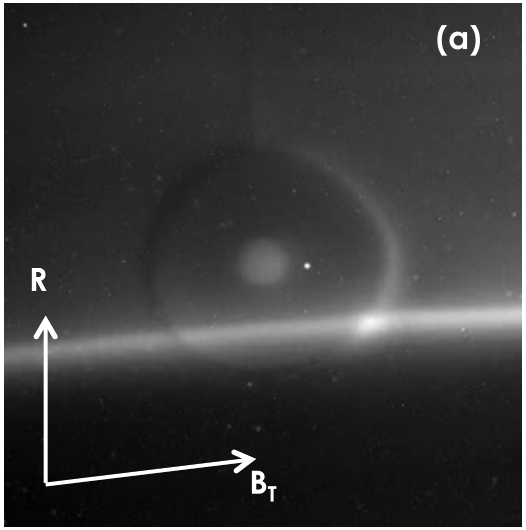


DiMES TV, looking down in lower divertor, MoI filter 390 nm, frame rate 5 Hz, integration time 50 ms

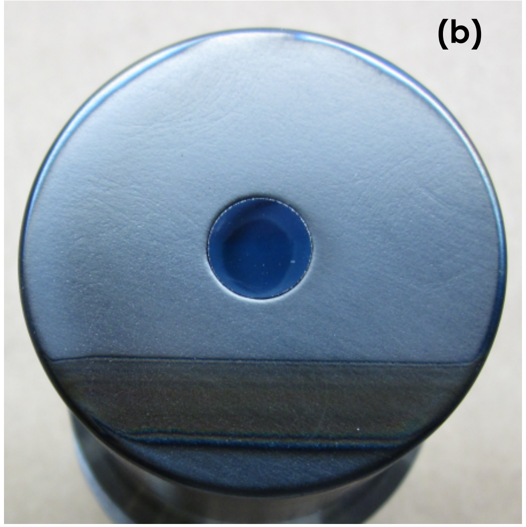
Courtesy of N. Brooks

DiMES During and After Experiment (Sample # 1)

(a) image of the sample taken during the exposure by a CCD camera with MoI 390 nm filter (10 nm passband)

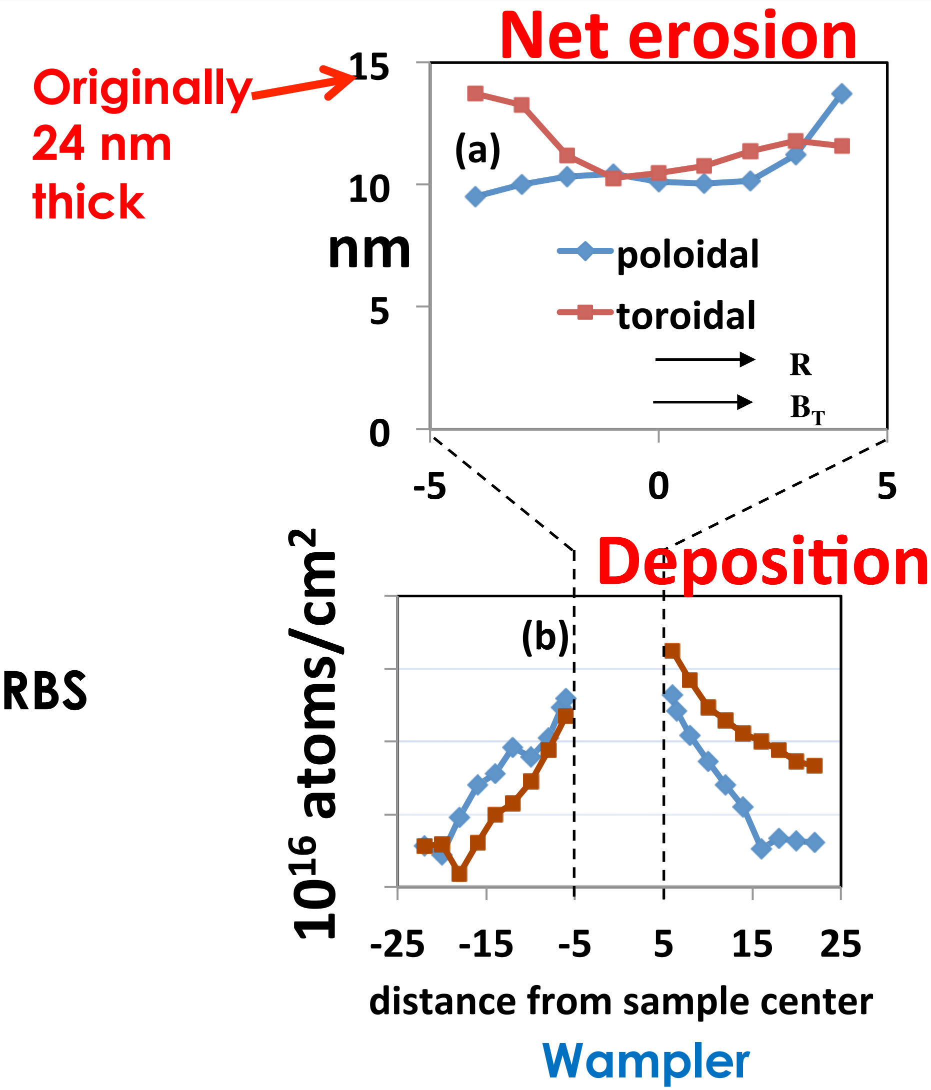


(b) post-exposure photograph of the DiMES holder with Mo sample



Mo was Net Eroded from 1 cm Sample and was Deposited on Surrounding Graphite Surface

- Sample # 1
- Top. RBS measurements of net erosion of Mo from the 1 cm sample
- Bottom. Mo deposition on the graphite holder measured by RBS



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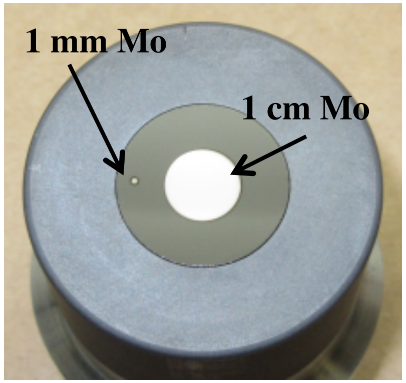
RBS-measured Net/Gross Erosion ~0.5 Agrees with Code Modeling

For Sample # 3 (1 shot, 4 s exposure):

- **RBS net/gross erosion:** **0.53 ± 12%**
- **Compares well with code net/gross ratio:** **0.46**

Gross erosion *rate*: 1.4 nm/s



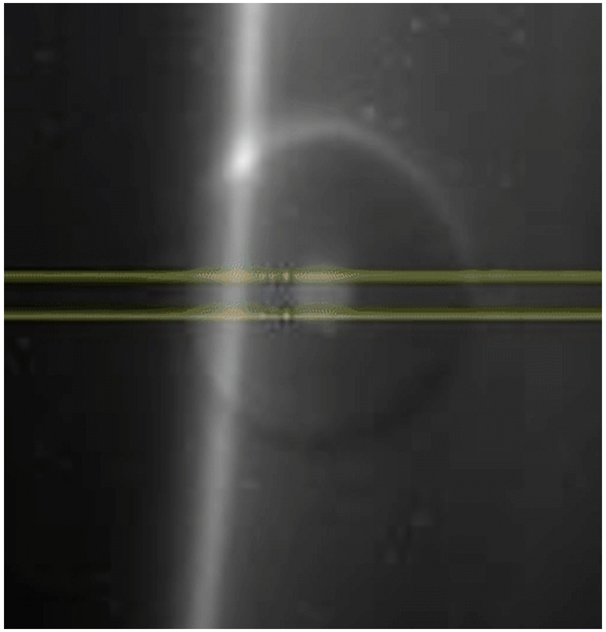
DiMES head

Gross Erosion Rate Also Measured Spectroscopically

- **An absolutely calibrated CCD camera with MoI filter centered at 386 nm, bandwidth 1 nm, was used to measure the gross erosion rate**

- **Used S/XB ~ 1 photon efficiency measured by Nishijima et al in PISCES. 1 MoI photon ~1 Mo atom sputtered**

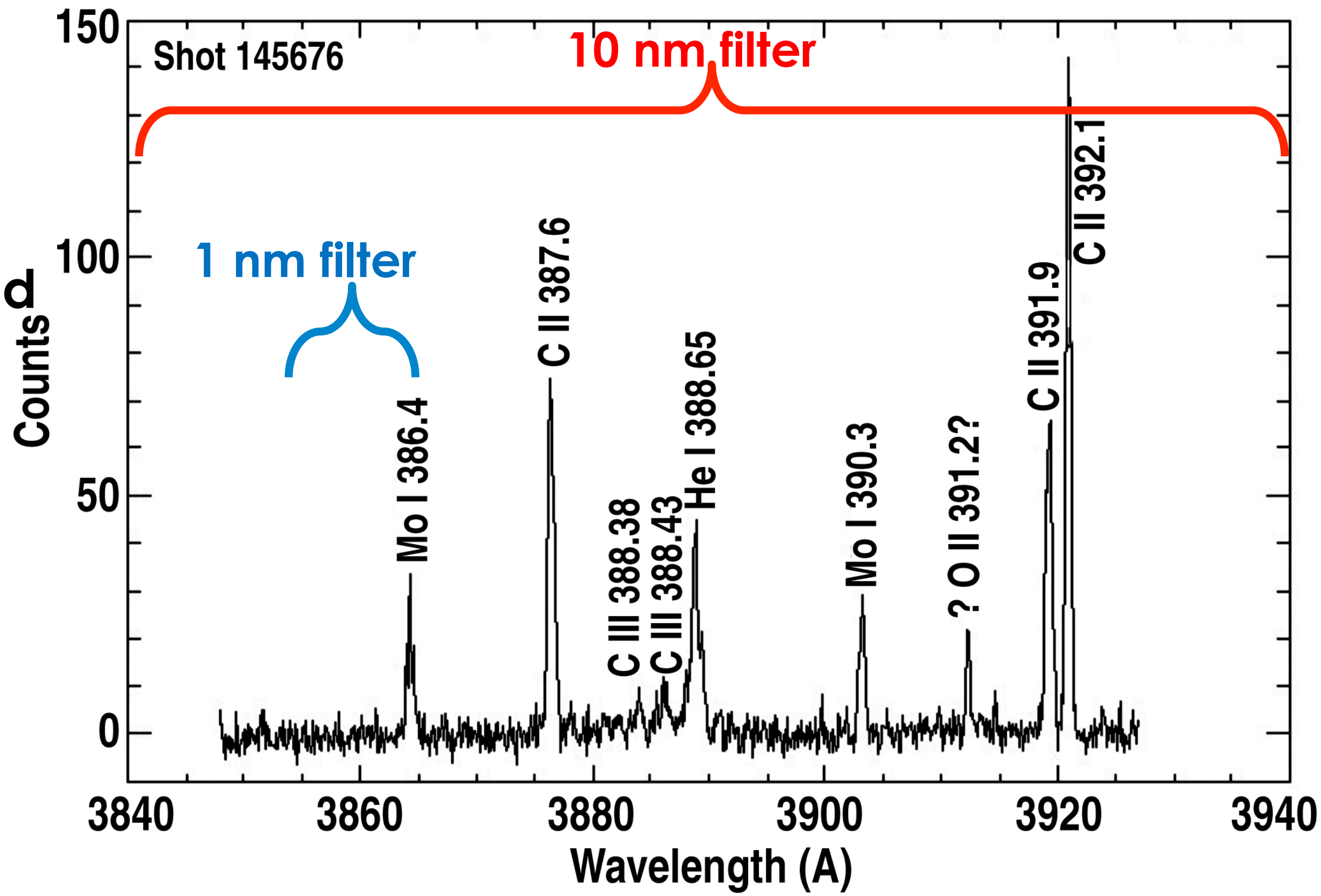
- **Factor of 2 uncertainty:**
  - Transmission of 1 nm filter
  - Transmission of 2^{nd} filter to block D-alpha
  - Transmission of vacuum window
  - Light reflection from Mo surface
  - Correction for 380, 390 nm MoI lines not passed by filter



Narrow Pass Filter Needed to Isolate MoI Line at 386 nm

- **For Sample # 1:**
  a 10 nm filter was used, which passed non-MoI lines

- **For Sample # 3**
  a 1 nm filter was used



N.H. Brooks and A.G. McLean

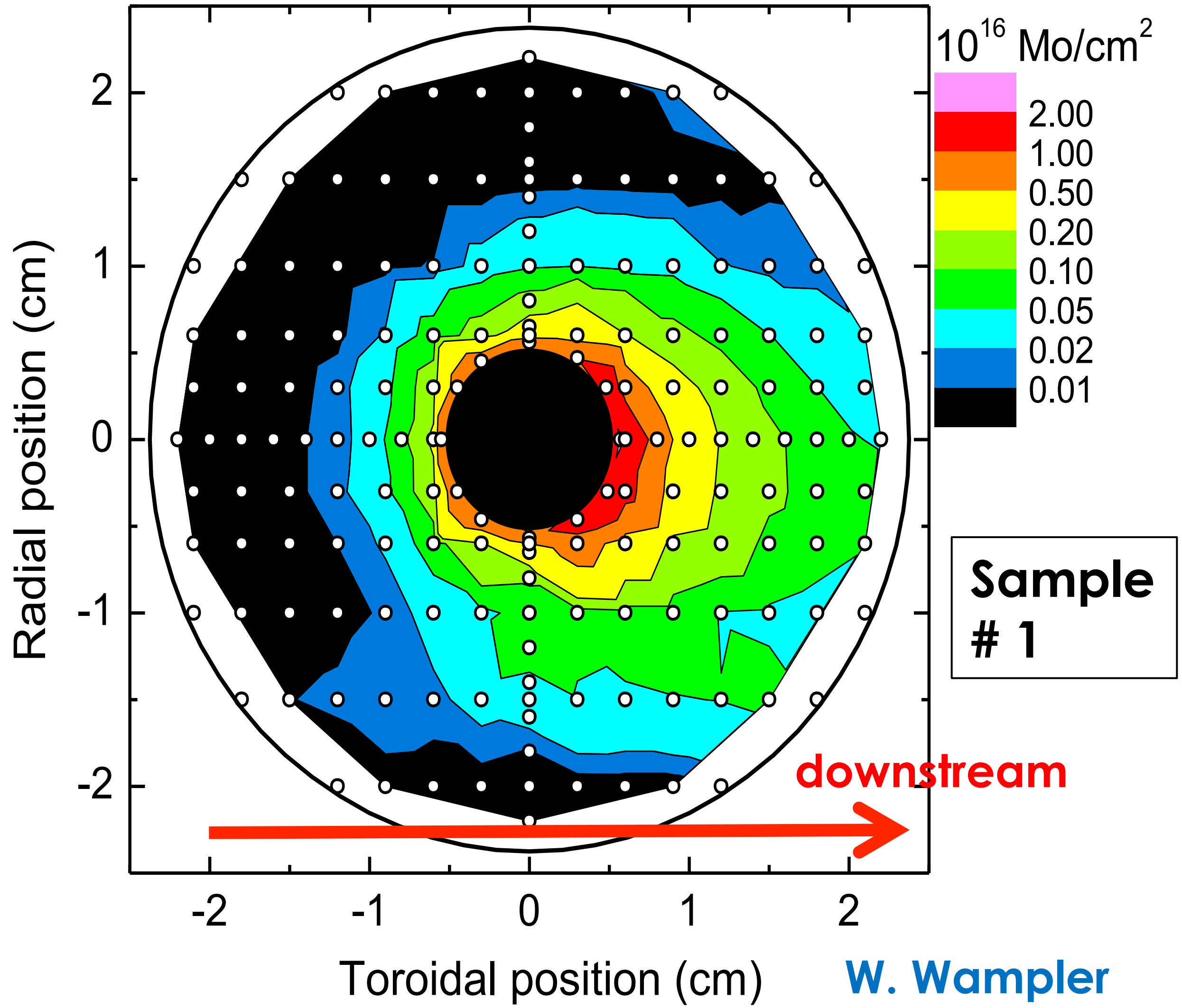
Spectroscopic Measurement of Gross Erosion Rate Agreed with RBS Rate

- For Sample# 3 spectroscopic measurement of gross erosion rate: 2.45 nm/s
- Compare with RBS-measured gross erosion rate in same expt: 1.4 nm/s
- Agreement is within the uncertainty of the spectroscopic method, factor $\underline{+}$ 2

Evidence for Both Local Deposition *and* Long Range Transport of Mo Sputtered from 1 cm Sample

- **RBS found only 19% of the Mo lost from the 1 cm sample, on the surrounding graphite DiMES surface**

- **WBC/REDEP/ITMC calculation gave 13%. Long range migration is due to multiple step erosion of Mo on C surface**



W. Wampler

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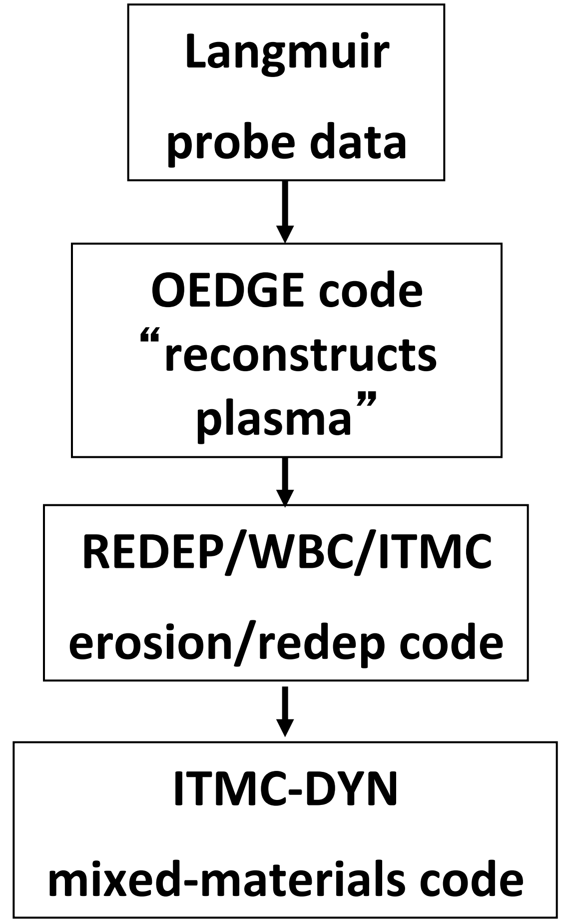
Computer Code Modeling

- Langmuir probe data input to OEDGE code to generate a 2D plasma solution
- The latter then input to the REDEP/WBC/ITMC erosion/redeposition code coupled to the ITMC-DYN mixed-material code for re-sputtering of Mo deposited on the C surface
- WBC computes the 3-D, sub-gyro-orbit, full-kinetic motion of sputtered atoms/ions, subject to the Lorentz force motion, and velocity-changing and charge-changing collisions with the plasma

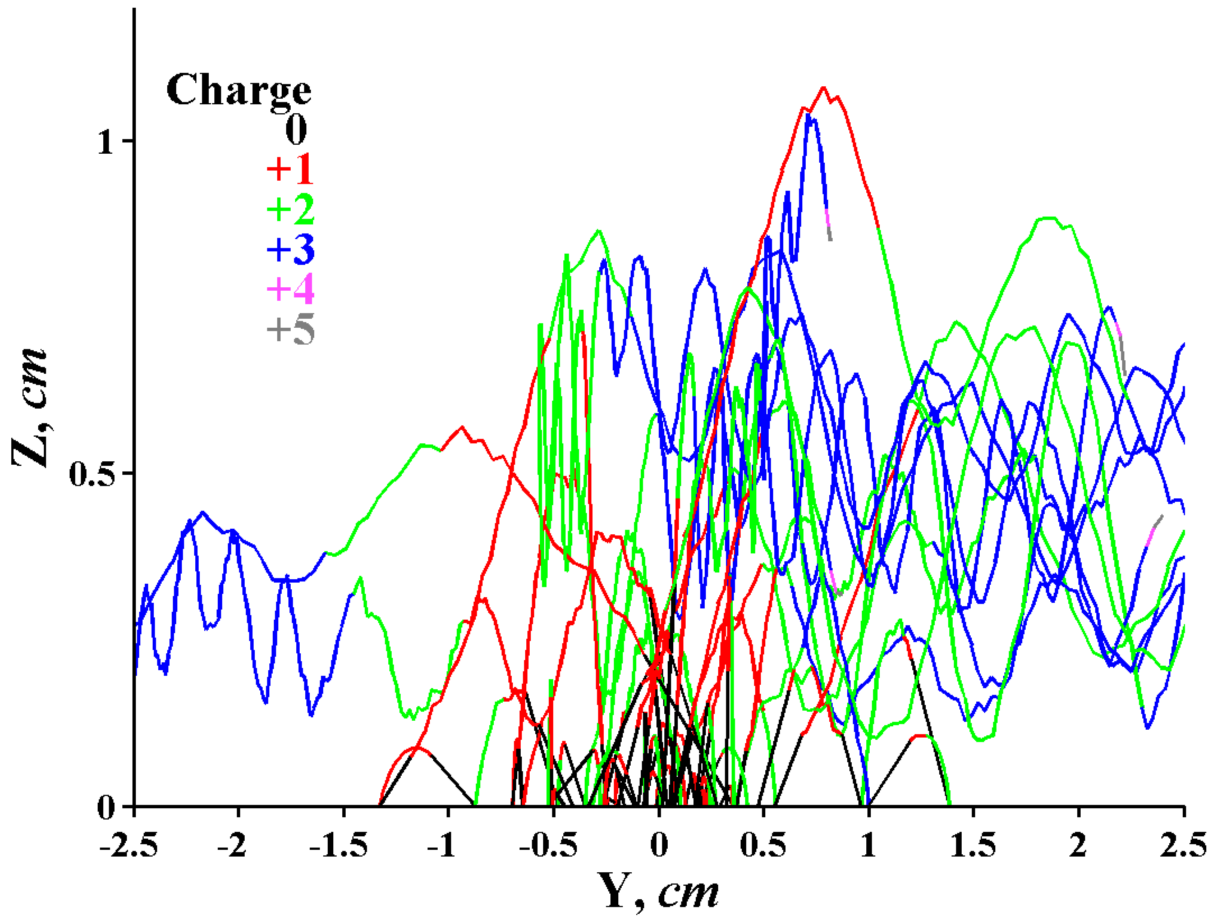


The Monte Carlo WBC/REDEP/ITMC Code Finds Significant Local Deposition but Also Long-range Transport

Typical sputtered Mo trajectories (50 histories), 2-D plot

Y= toroidal direction through probe center

Z=distance above probe



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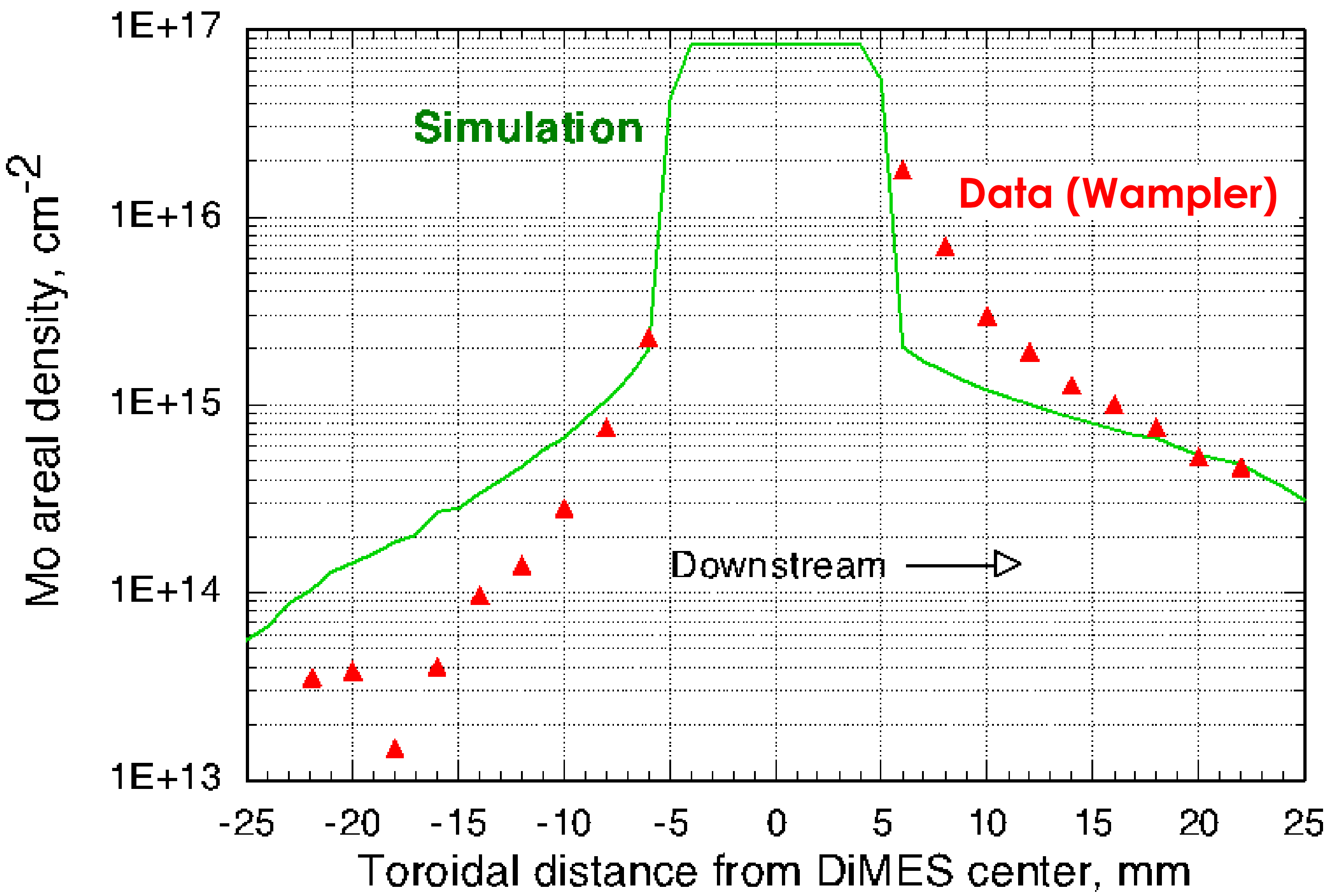
Mo Deposition Pattern on Graphite Surface Matched Fairly well by WBC/REDEP/ITMC Code Simulation



Conclusions and Future Work

- For the specific divertor plasma condition tested, measured net/ gross erosion agrees with the "standard" idea of prompt, local re-deposition
- Positive implications for reduction of net erosion for high-Z in ITER, FNSF
- There is also long range transport of some ions, evidently a mixed materials effect
- A new, non-spectroscopic method for measuring gross erosion rates has been demonstrated
- Future studies: use W; Al (proxy for Be). For the weakly-ionizing plasma used here, net erosion was only slightly < gross erosion; in future studies stronger-ionizing plasmas will be used

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