Outstanding Questions from Experimental Observations of Erosion in Fusion Devices

Dennis Whyte, *University of Wisconsin-Madison*

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Summary

- Erosion, and related transport of eroded materials, are the underlying mechanisms controlling PSI effects in fusion devices.

- Direct, time-resolved measurements of erosion are scarce and confined to small areas.

- Erosion measurements, direct or inferred, and accompanying modeling have typically left more puzzles than answers
  - Unacceptable uncertainties remain for important engineering ($$$) questions, such as choices of PFC materials.

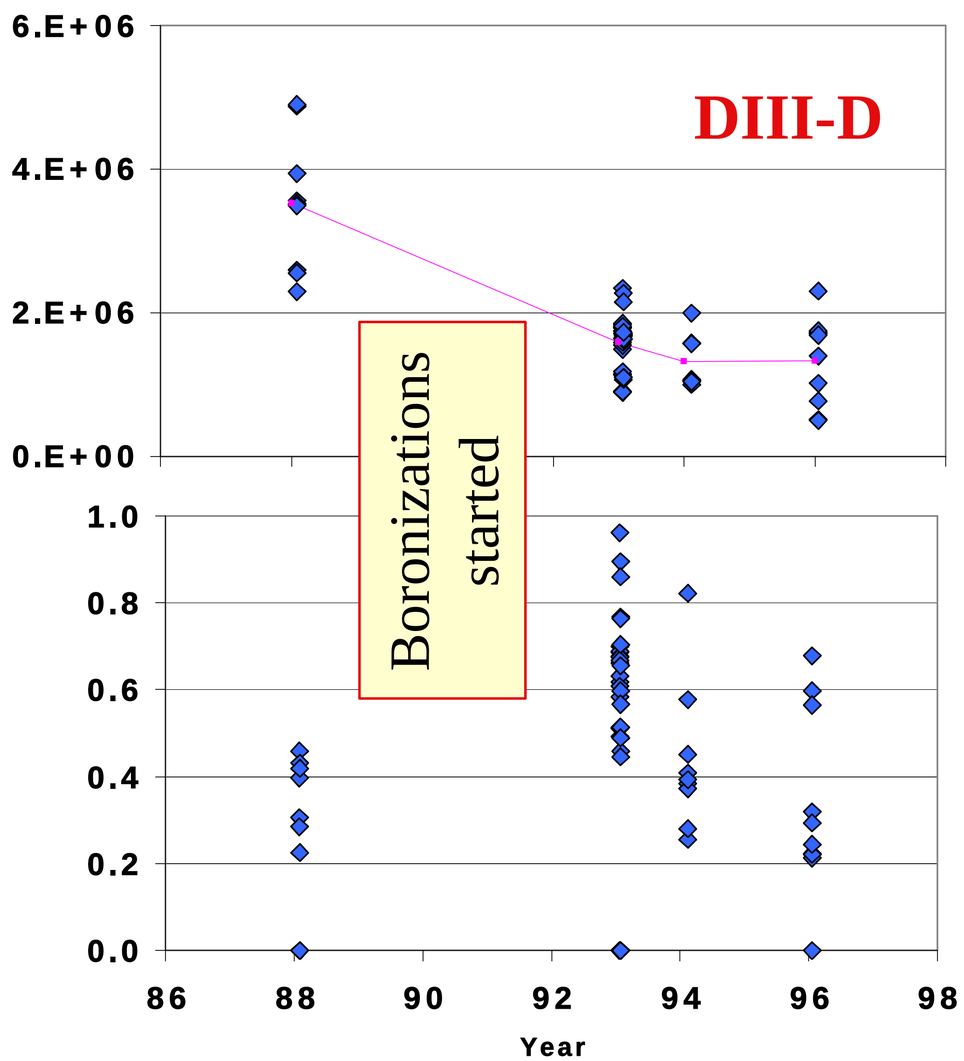
- What are the outstanding questions on erosion?
  - **And what tools (experiments + models) do we need to answer them?**

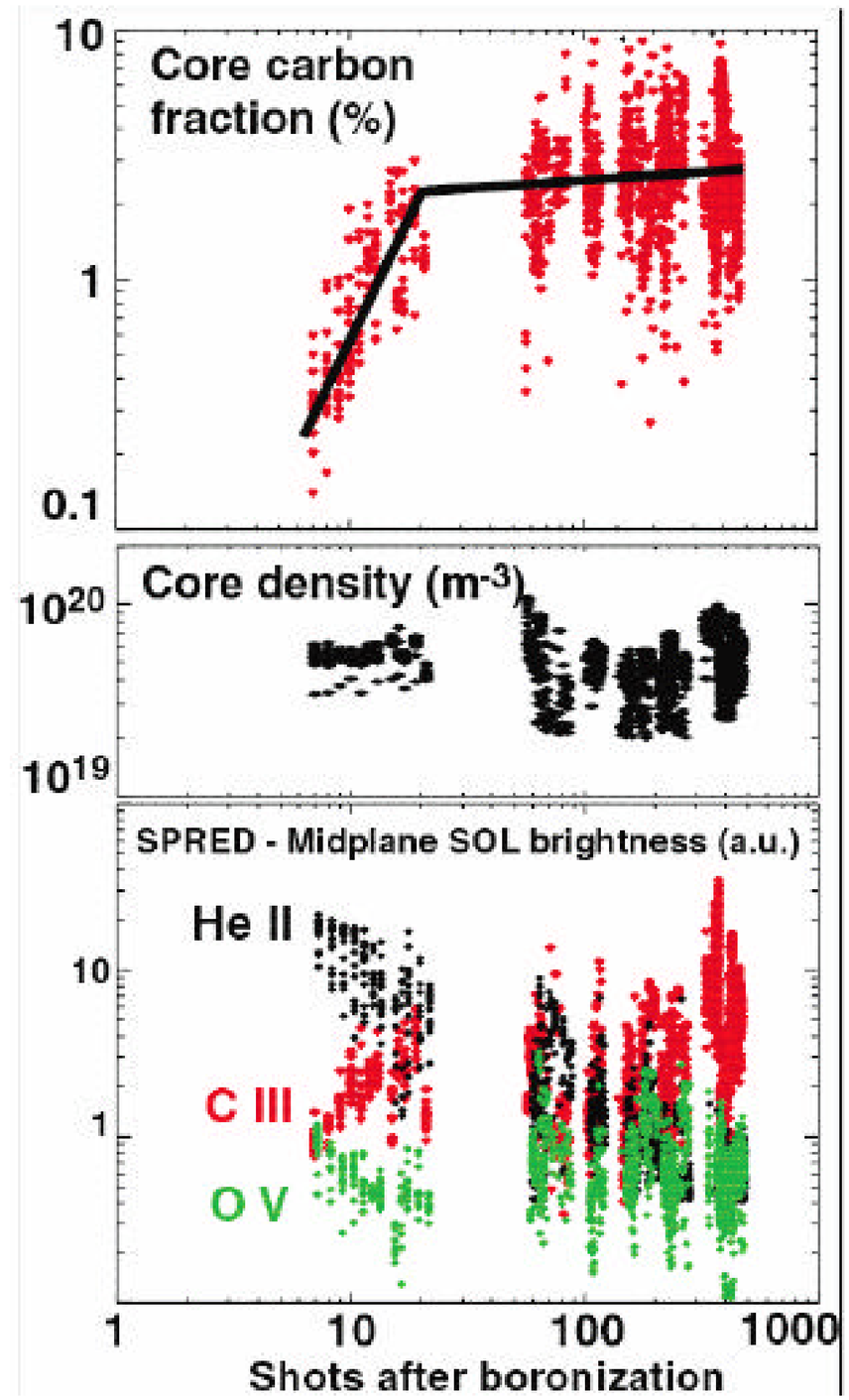
Outline*

- Low-Z boronization films.
- Erosion in low-T_e detached plasmas.
- 3-D nature of erosion.
- Intermittent erosion and H/D/T recovery
- New PSI experiments and diagnostics in development.

** Focus on DIII-D, C-Mod, UW*

Boronization film applications are prevalent, but what are their effects?





Intermittent, but persistent, introduction of boron can have tangible effects on carbon material and erosion.

DIII-D
2-40% B/C on all surface
Boric Acid Crystals

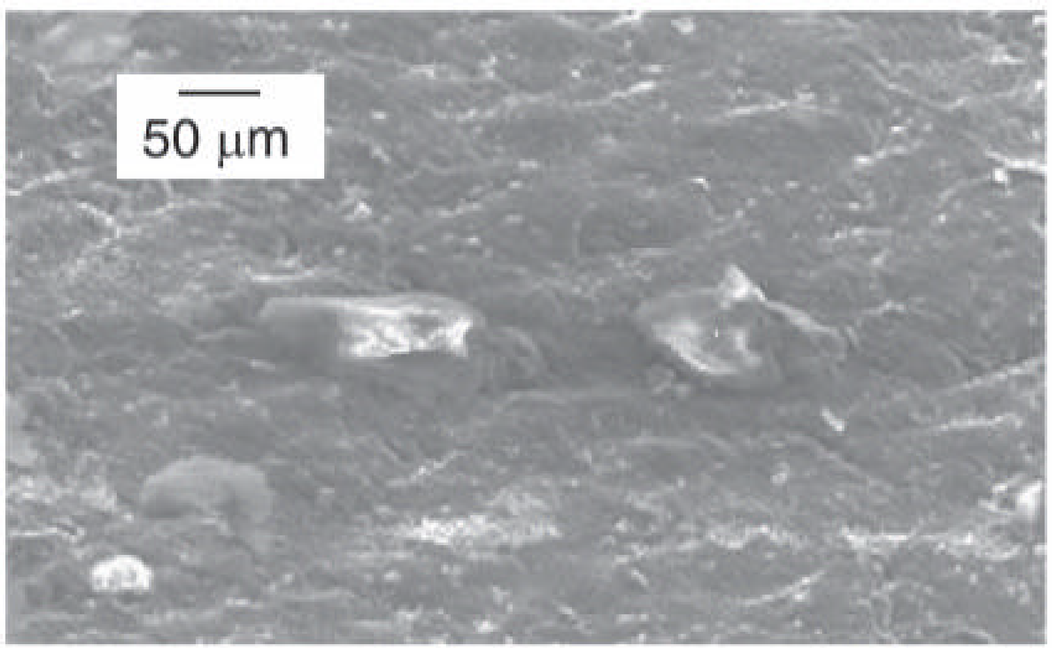
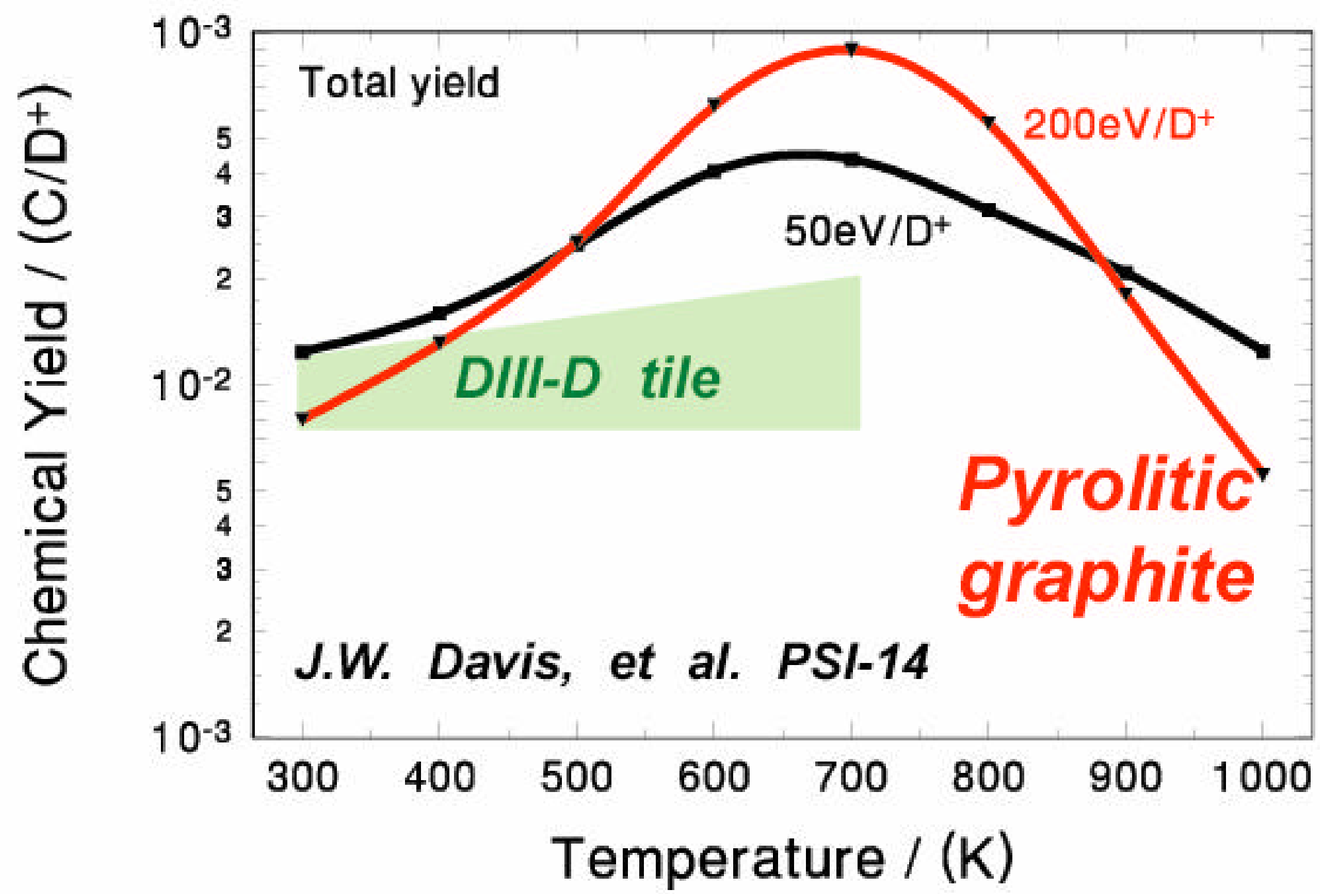


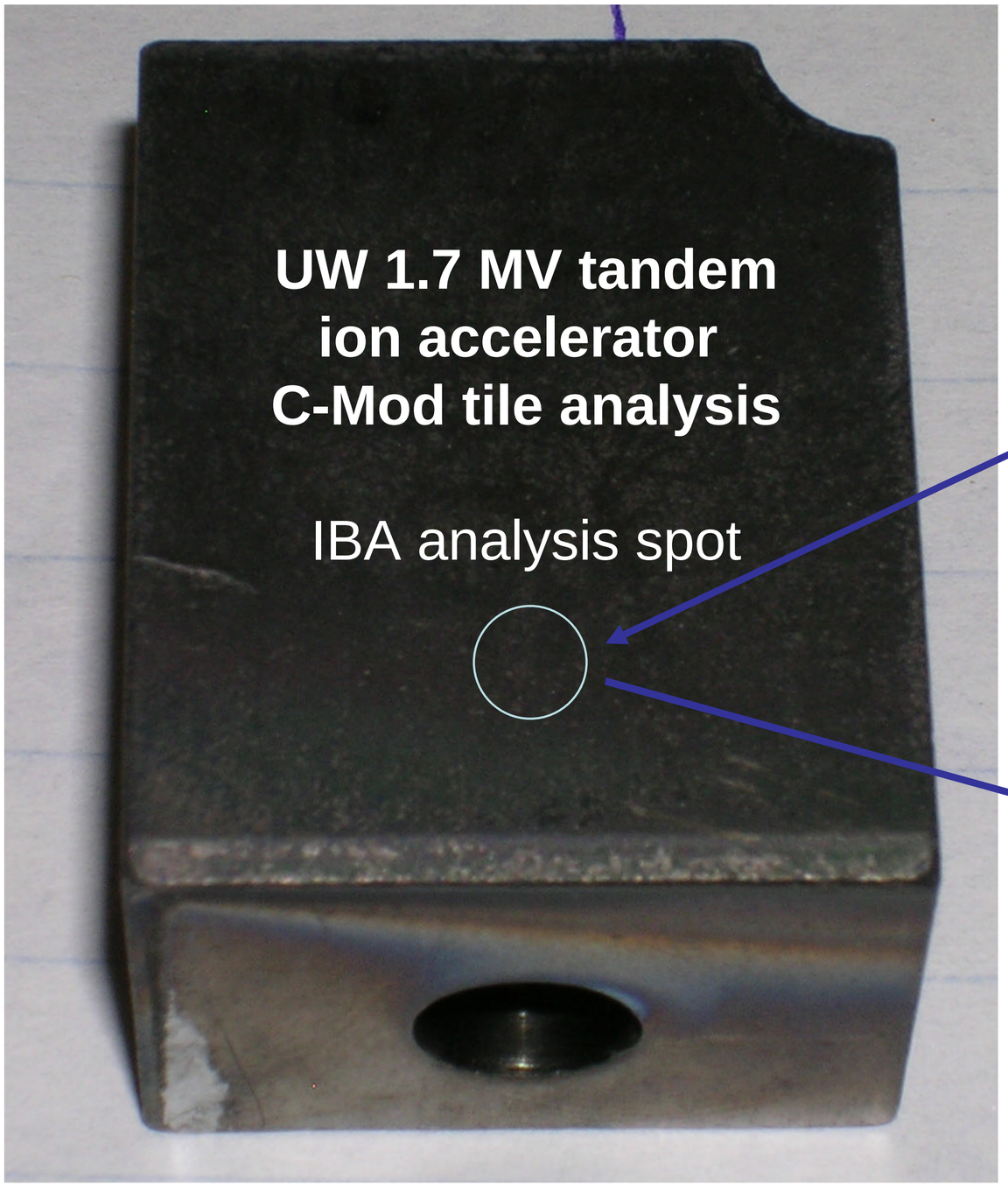
Fig. 4. SEM photographs (45° tilt) of lower divertor DIII-D tile (row 4) showing embedded boric acid crystals.

Whyte CW 2000

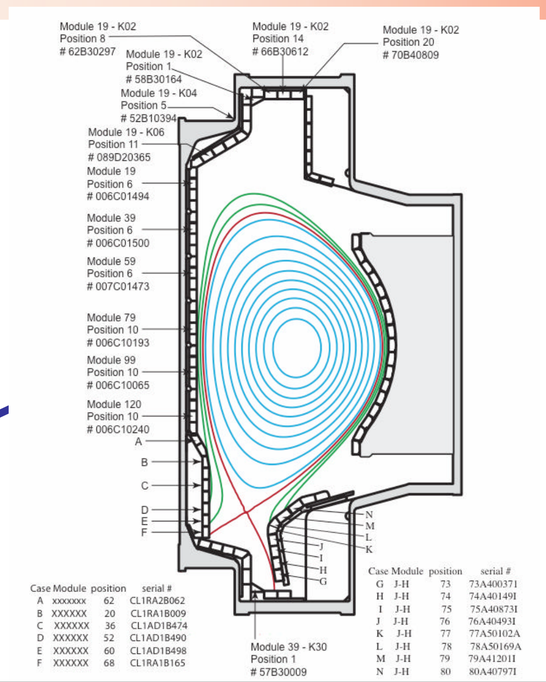
Boron-Doping Effects
At high T_{surf}



Boronization has bigger impact on Mo tiles: Thick boron with "diffuse" tail into the Mo substrate…but also Mo at surface ~1-5%?

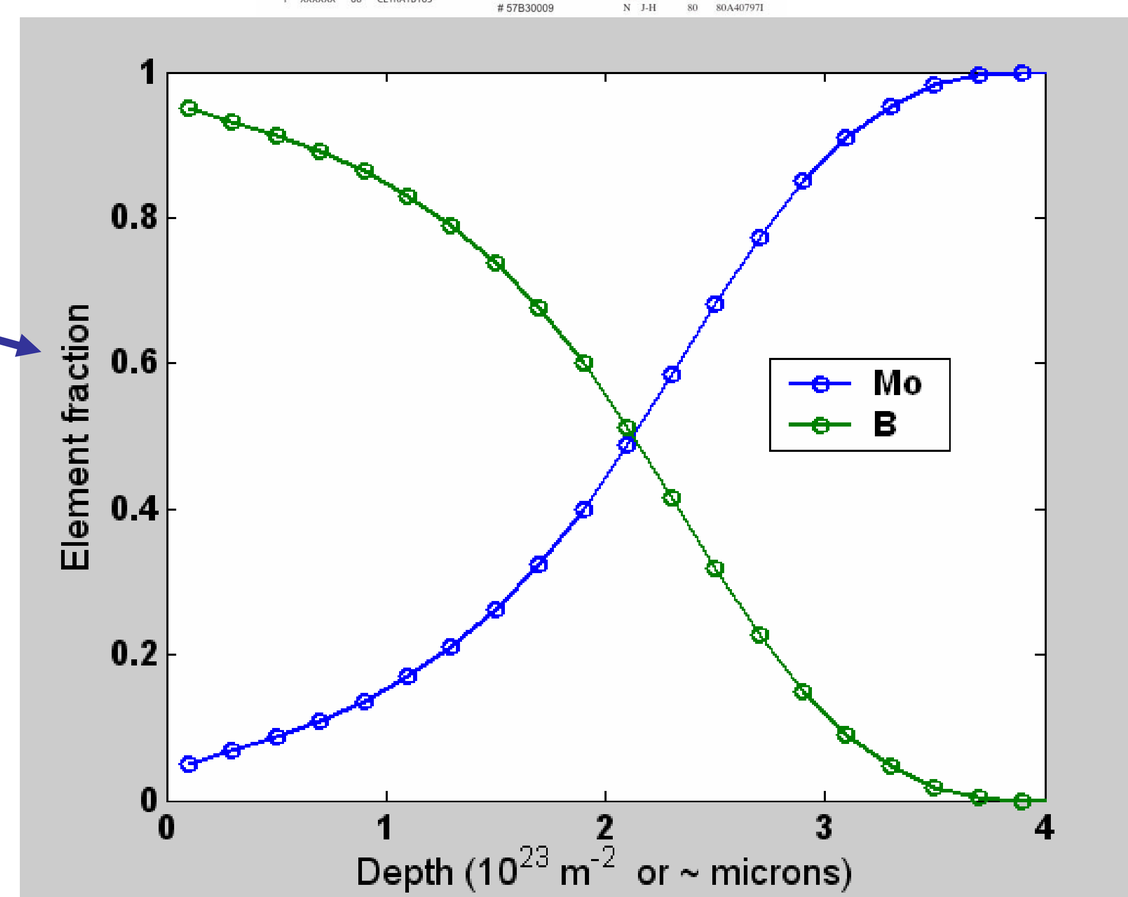


6C10193: Midplane centerpost



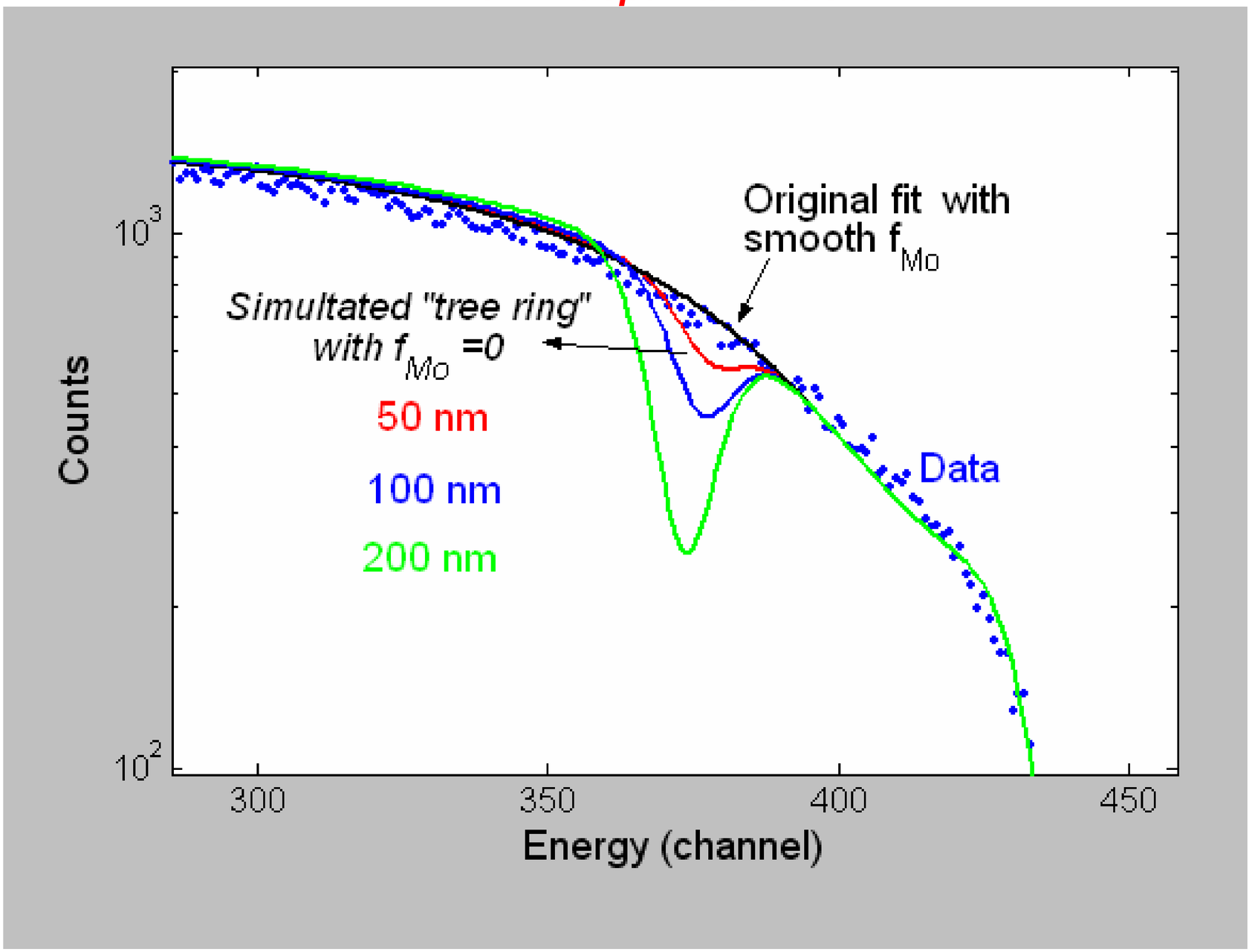
ALCATOR
C-Mod

Whyte PFC Dec 04



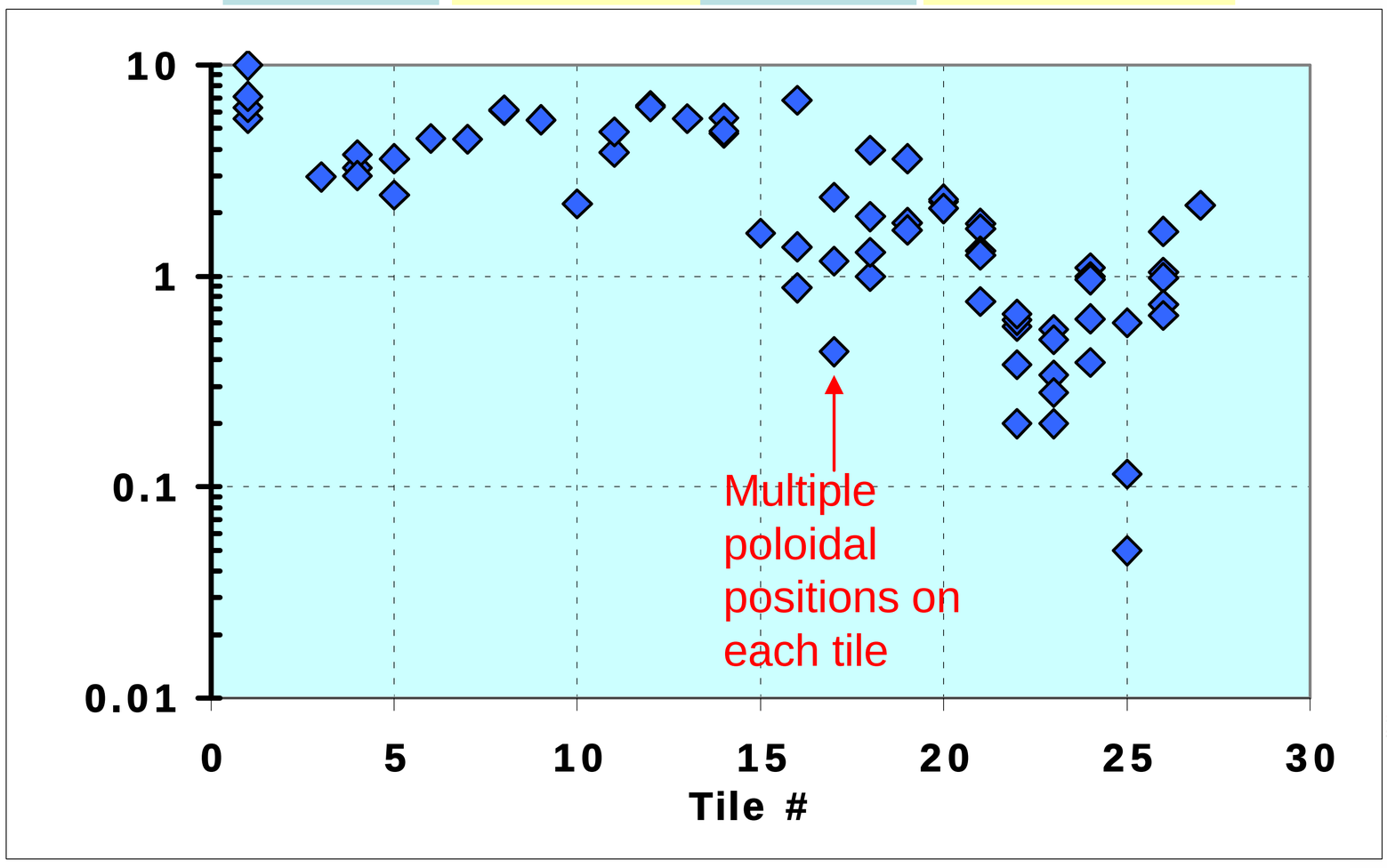
There is no evidence of discrete B film applications (i.e. tree-rings) expected from intermittent boronizations. Material is a 'plasma-deposited compound'

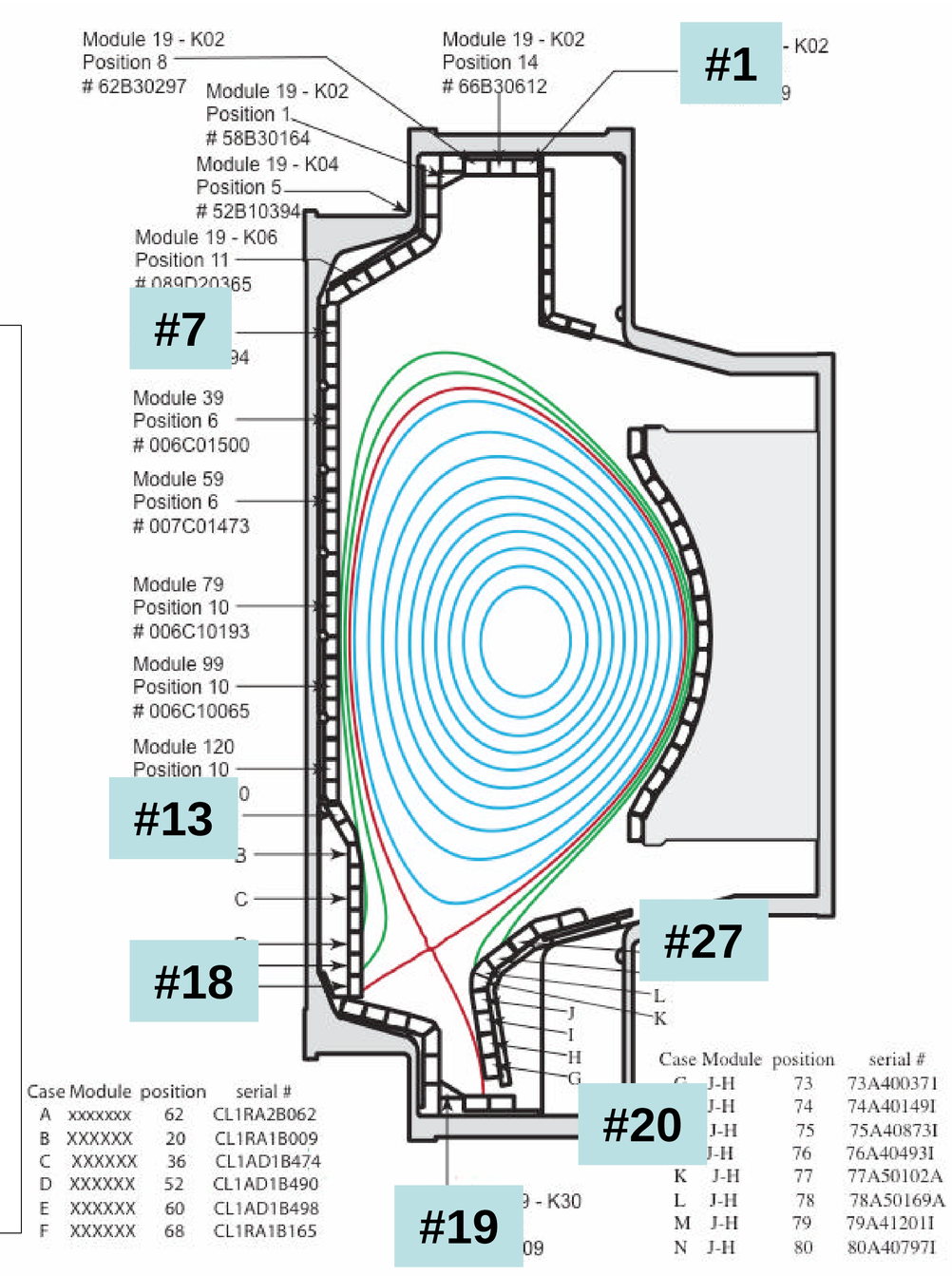
3.5 MeV Alpha RBS provides ~20 nm depth resolution



Boron dominated the C-Mod wall erosion pattern after ~7 years of boronizations.

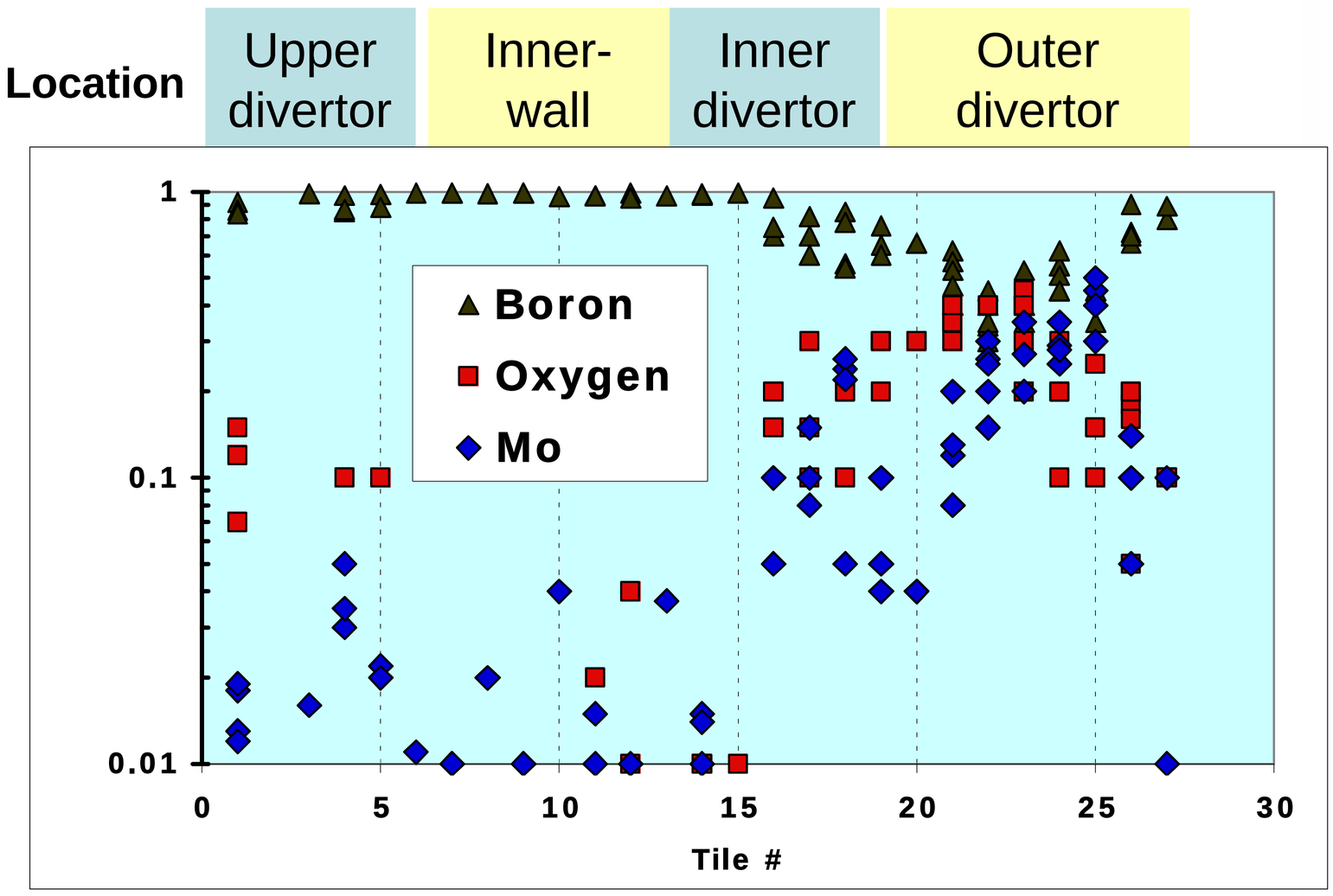
Process	*~40 x 100 nm boronization films*		*Plasma deposition*	*Plasma erosion*
Location	Upper divertor	Inner-wall	Inner divertor	Outer divertor

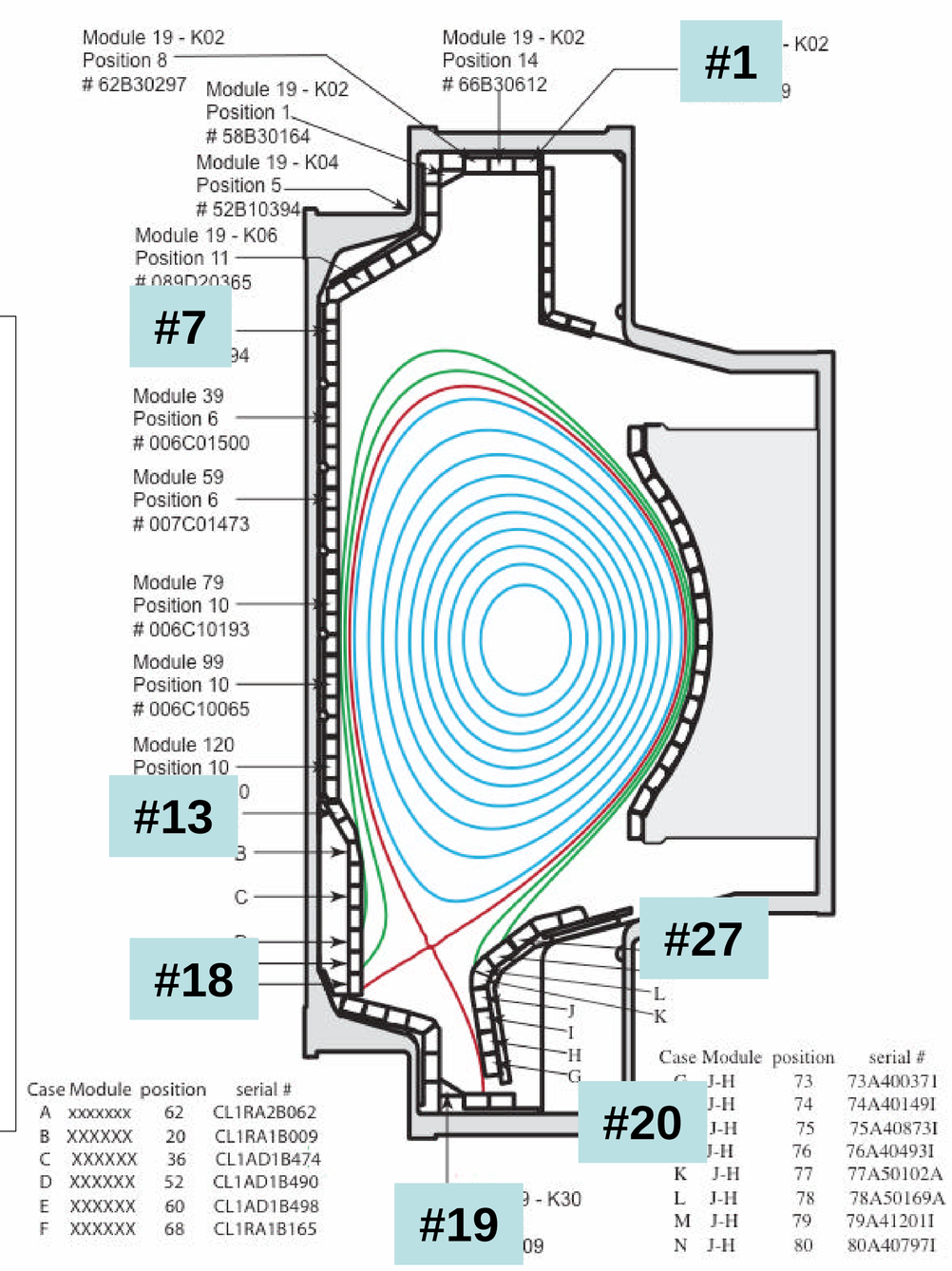




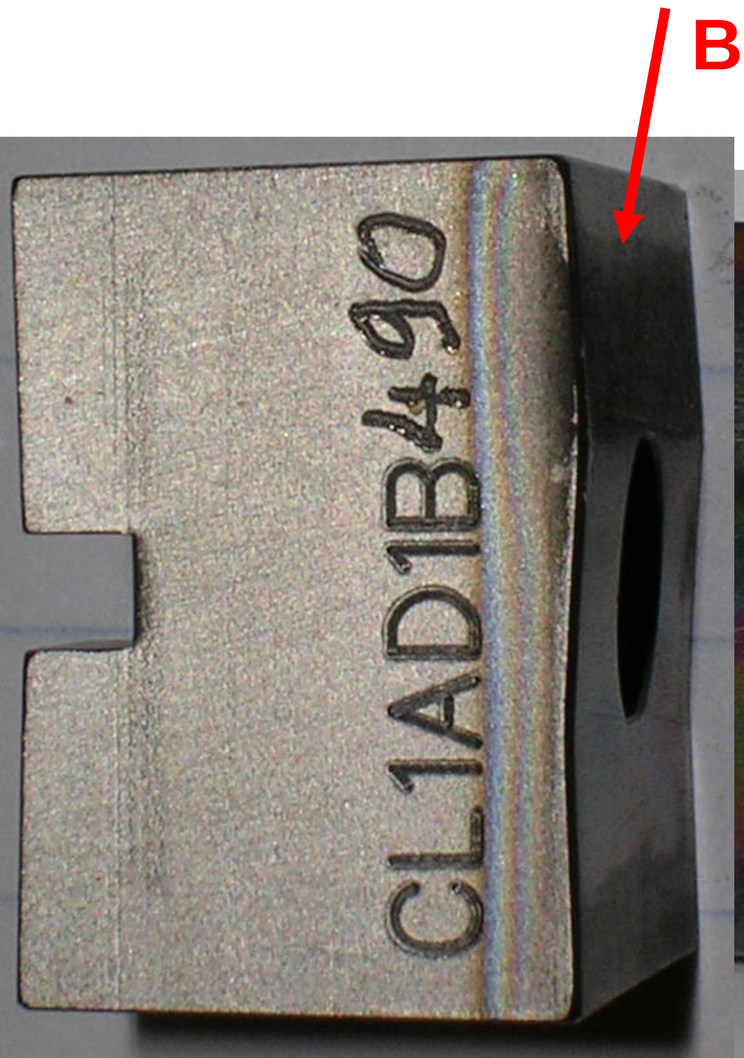
Whyte PFC 2004

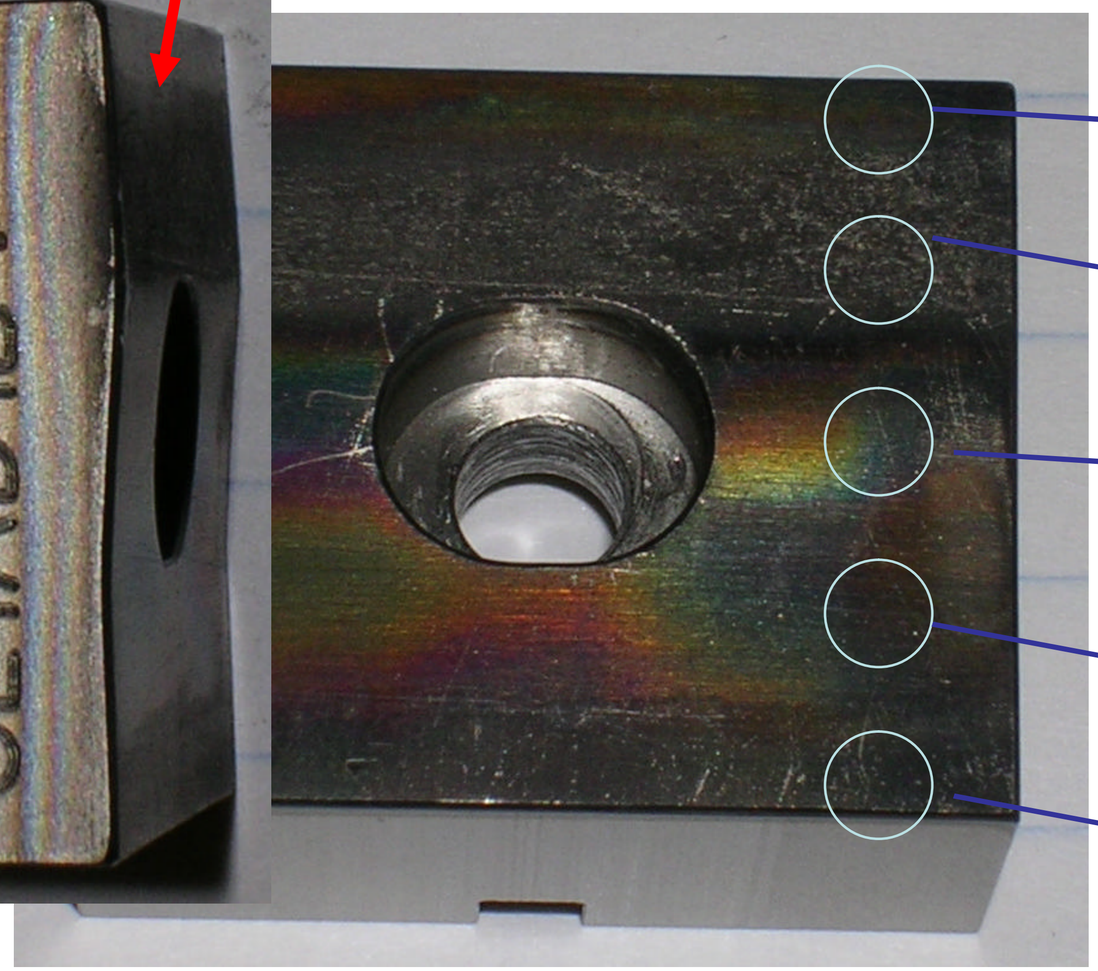
How did the plasma self-consistently produce these mixed material surface layers?

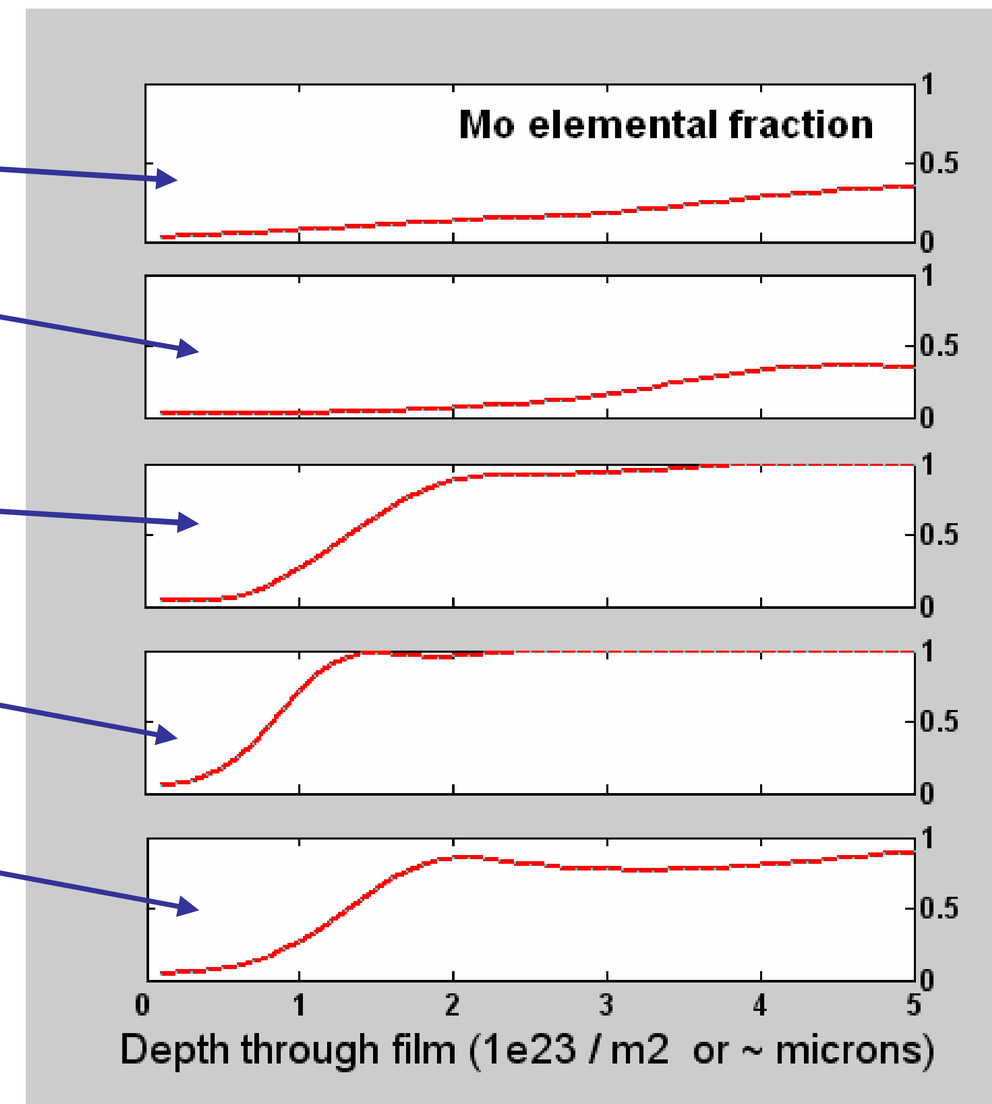


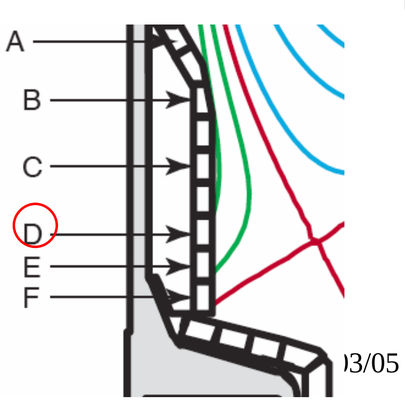


Inner divertor tile toroidal “slopes” indicate plasma-caused net Boron deposition







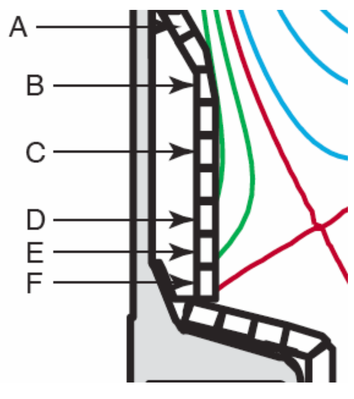


“D” Inner Strikepoint Tile

Alpha (3.5 MeV) RBS

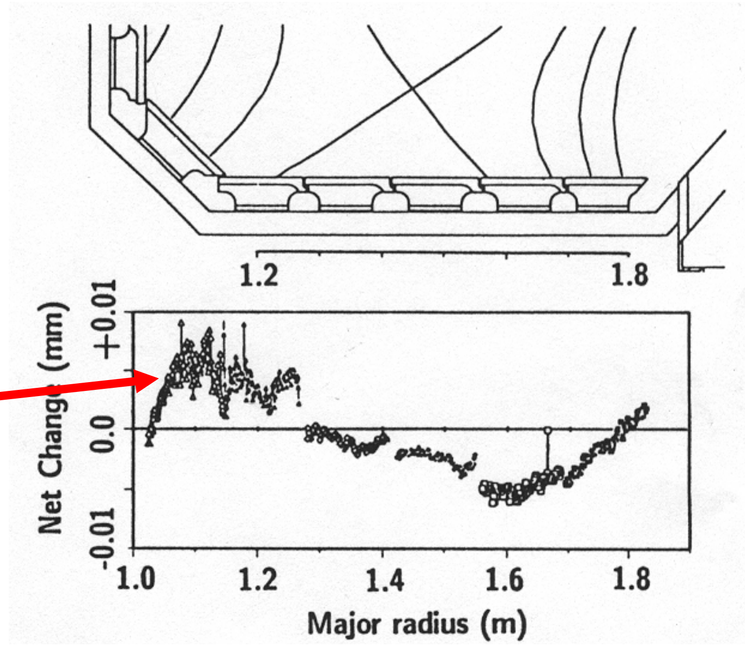
Inner divertor low-Z deposition is roughly consistent with Carbon tokamaks? Boron deposition rate ~ 1 nm/s

"E" Tile ~ Inner Strikepoint.
Shadowed region:
$d_{B1/2}$ = 0.2 microns



	C-Mod	DIII-D
PFC	B / Mo	C
Location	Inner div.	Inner Div.
Deposits	~ 3-5 μm	~3-6 μm
Δt	~4000 s	~4000 s
Inner div. deposition	**~ 1 nm/s**	**~ 1nm/s**
Outer div. erosion	~0.1 nm/s (Mo)	~1-3 nm/s (C)
Bzn. film	2.5 μm	0.5 μm

C erosion/deposition In DIII-D in one year

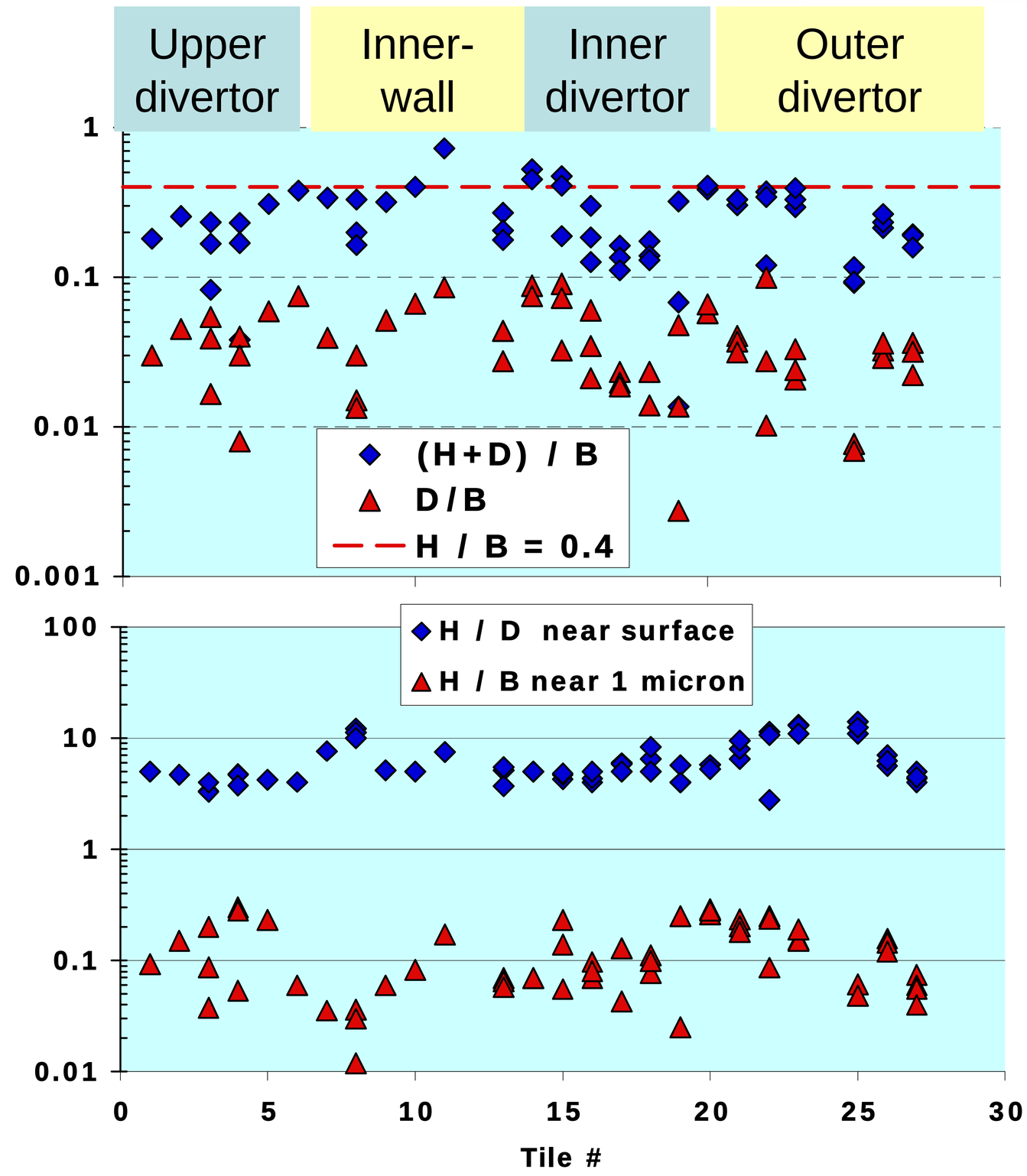


Walsh, J.Vac.Sci. Tech. 1992
Whyte, Nucl. Fusion 1999

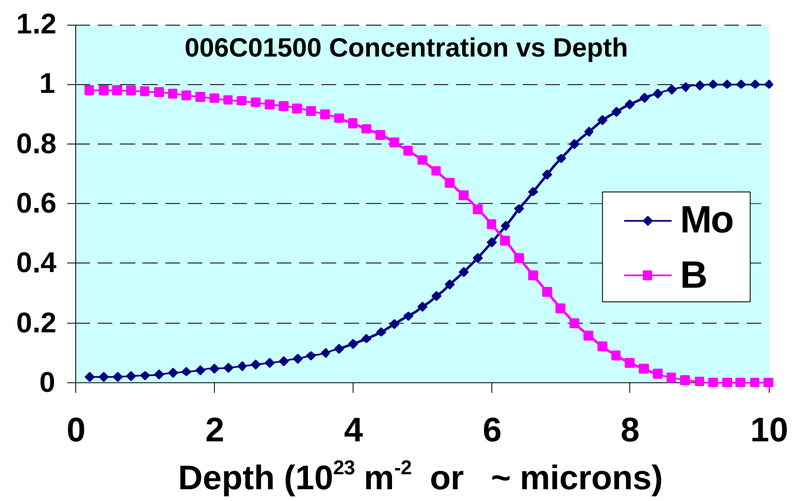
Wall surfaces appear saturated with (H+D)/B ~ 0.2 - 0.4.

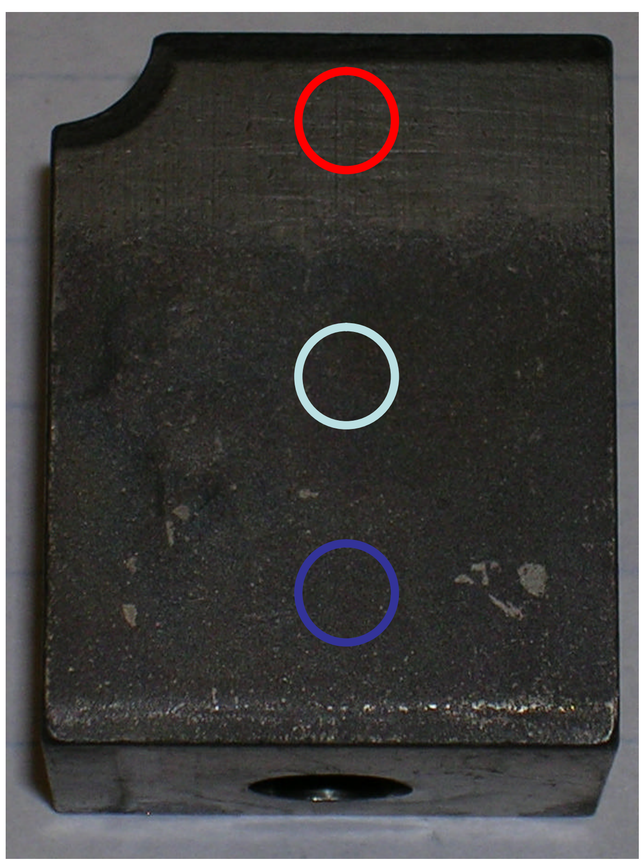
Raises several questions on retention

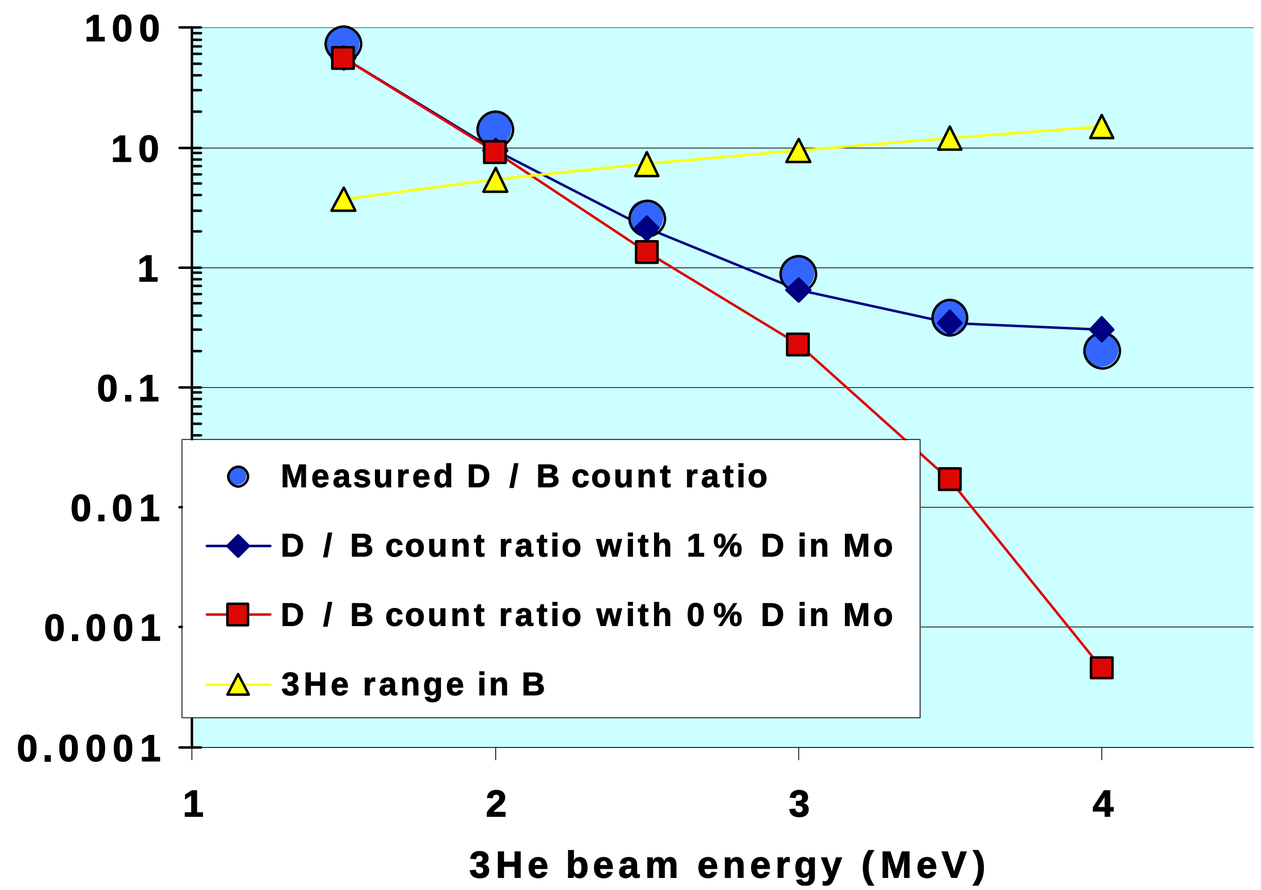
- D plasma fueling and deuterated boronizations.
- H arrives from air/H_2O exposure & subsequent plasma recycling.
- Implies similar global retention rate for H/D/T as a carbon device?
  - Supported by gas balance measurements showing strong net wall pumping.
- **But is this codeposition?**
- **What is in-situ H/D ratio?**
- **Implications for H isotope control?**



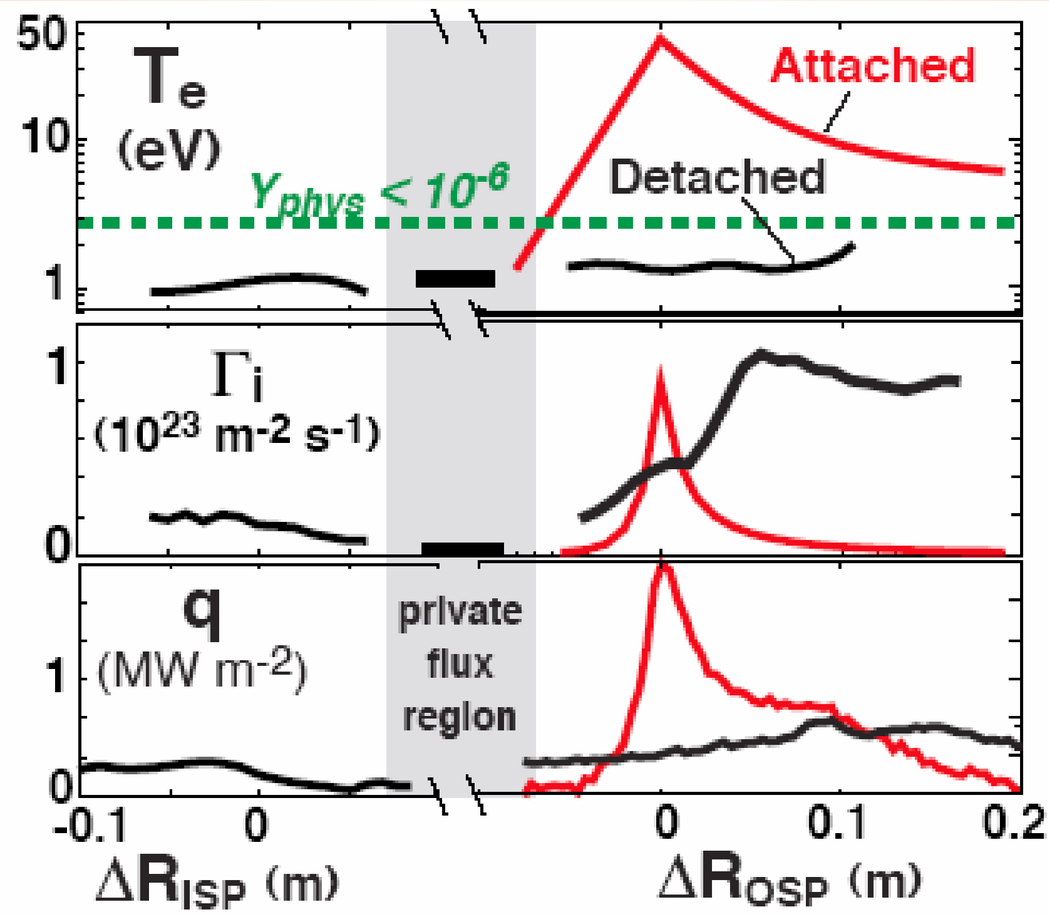
And 1-2% D content deep into both B *and Mo* to detection limit of ~ 10 microns.





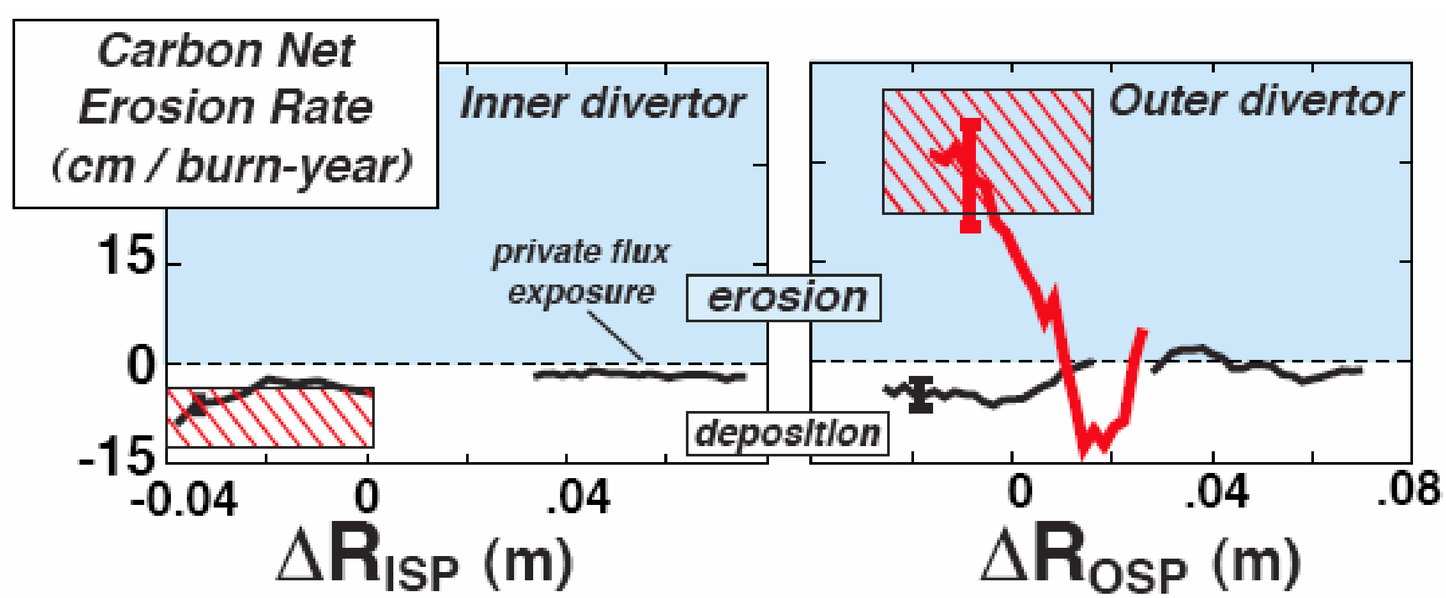


Low T_e detached divertors are necessary for heat flux control. Detachment can solve erosion?



Whyte, IAEA 2000

DIII-D:
Map
of divertor
Erosion /
deposition



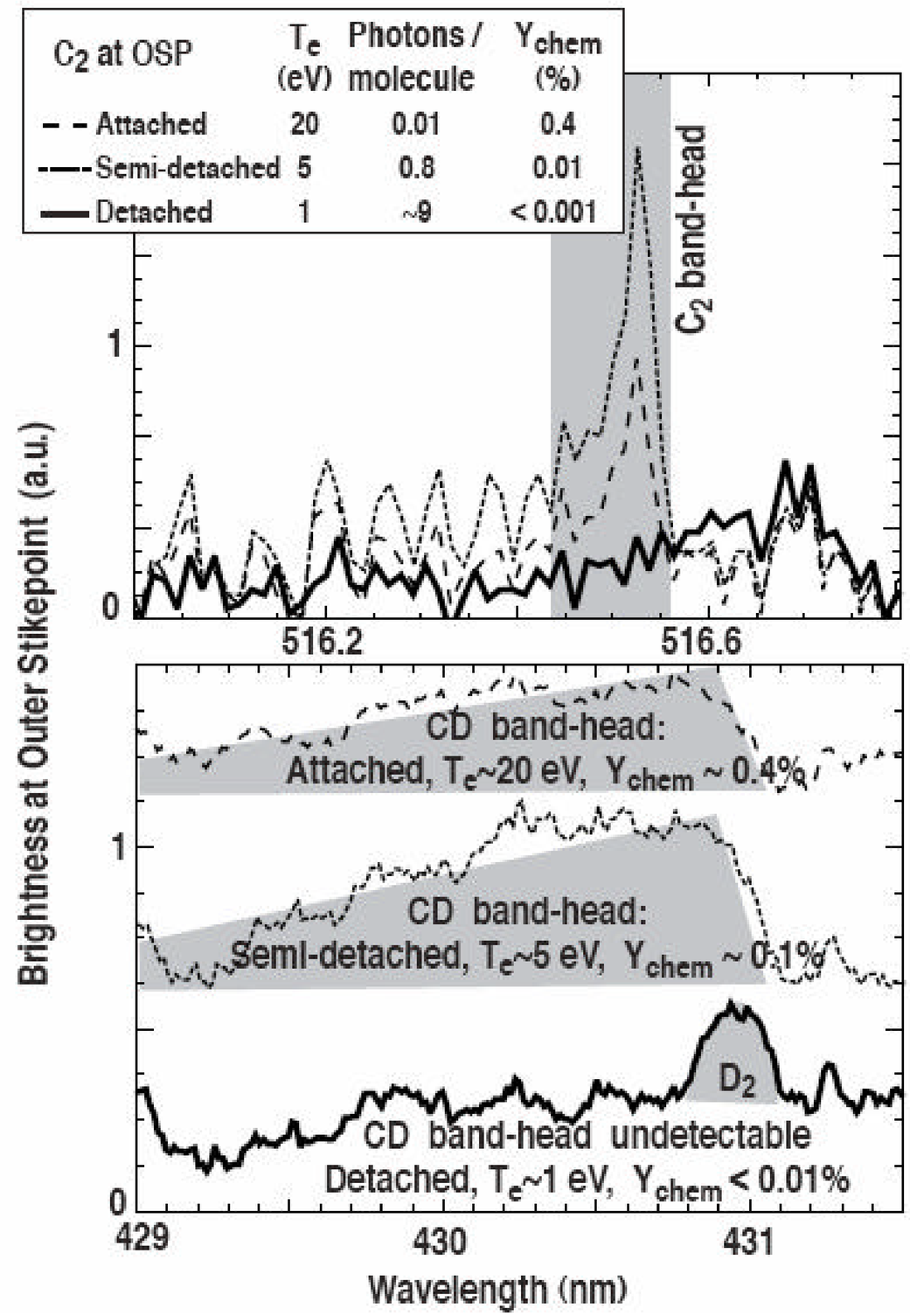
DIII-D shows a strong suppression of chemical erosion in detached plasmas

- Spectroscopy of CD/C_2 interpreted first with code and now confirmed with CH_4 puff experiments (A. Mclean, U. Toronto)

- T_e decreases to ~1-2 eV, E_{D+} below energy threshold for chemical sputtering.
  - Also flux high and T_{surf} < 100 C.

- **Demonstration suggests proper choice of T_{surf} and graphite may greatly reduce chemical erosion in ITER.**

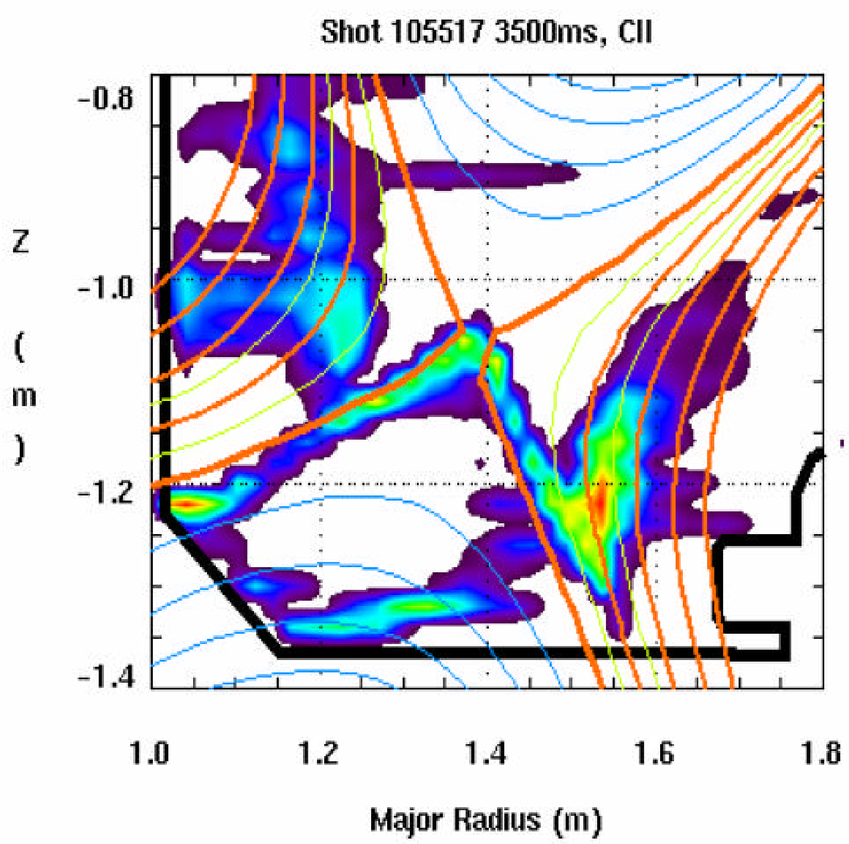
- **Other detached divertors?**
  - **AUG: suppression of CH**
  - **JET JT-60U: Y_{chem} ~ 5%**

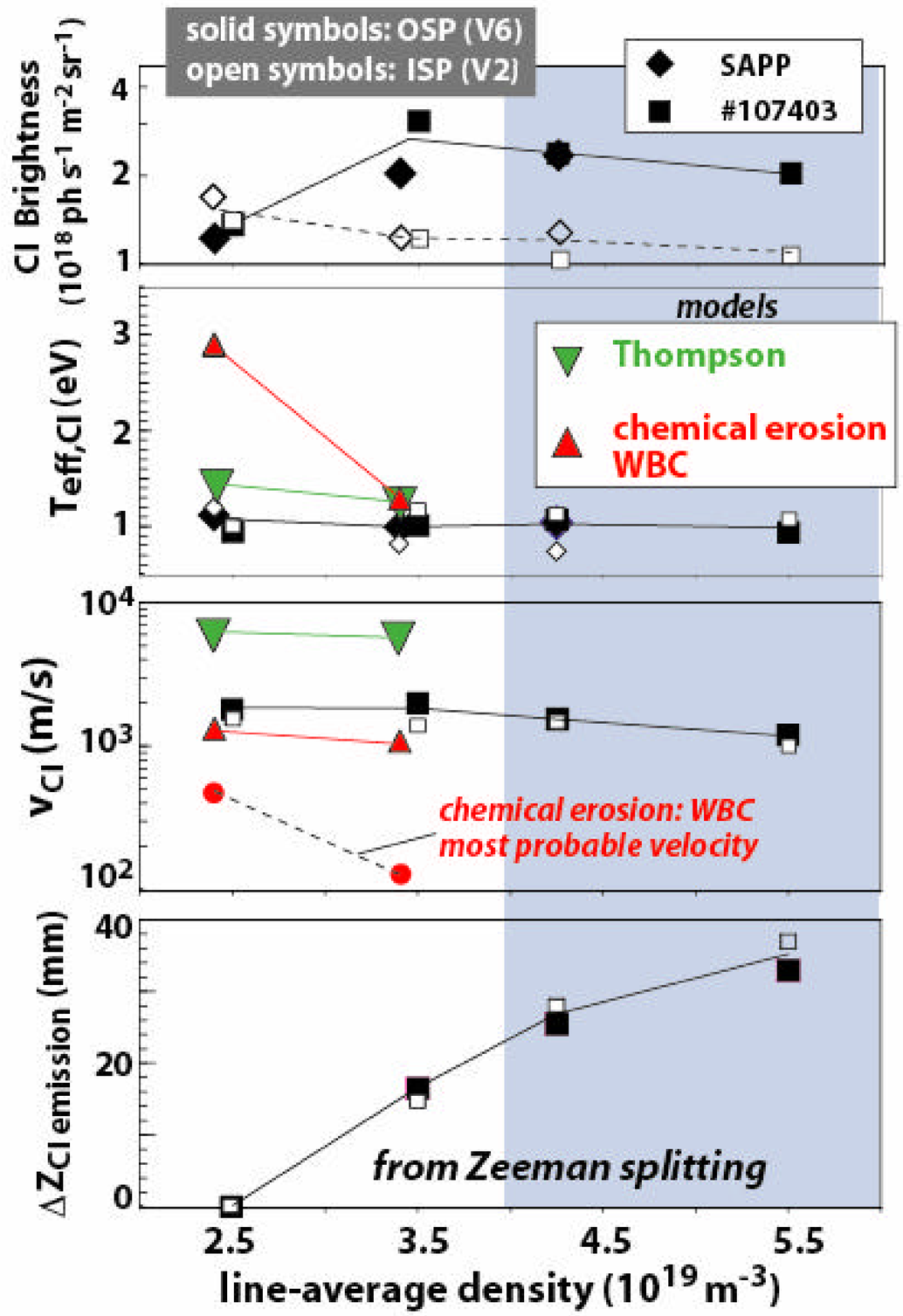


Whyte CW 2003 Physic Scripta

But can we identify controlling C source outside "principal" target area?

DIII-D outer divertor

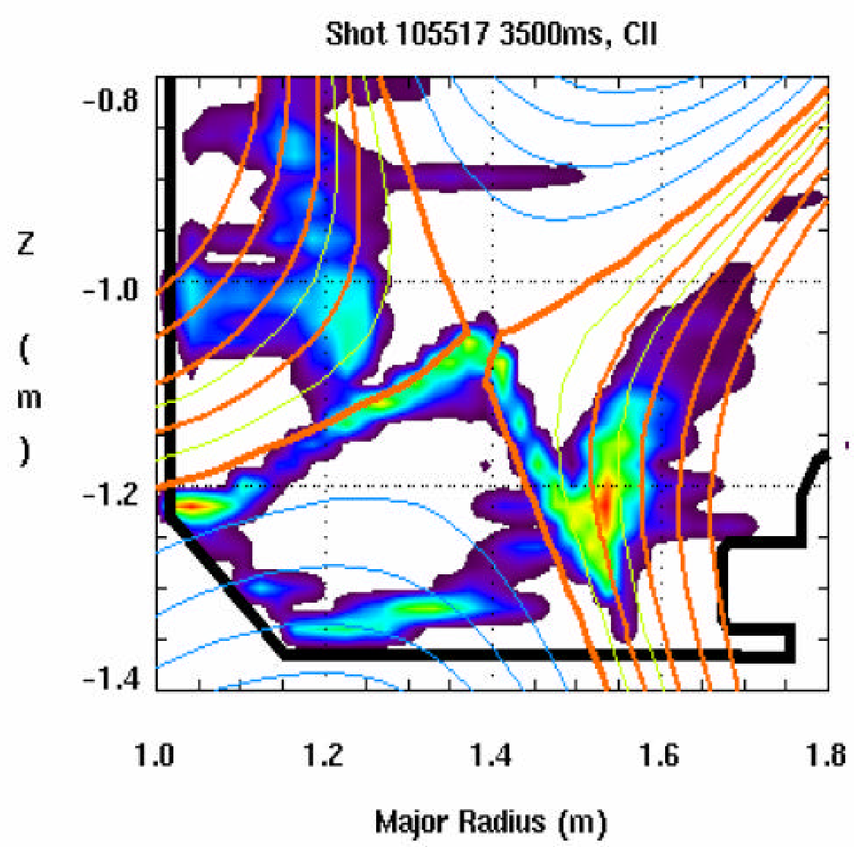


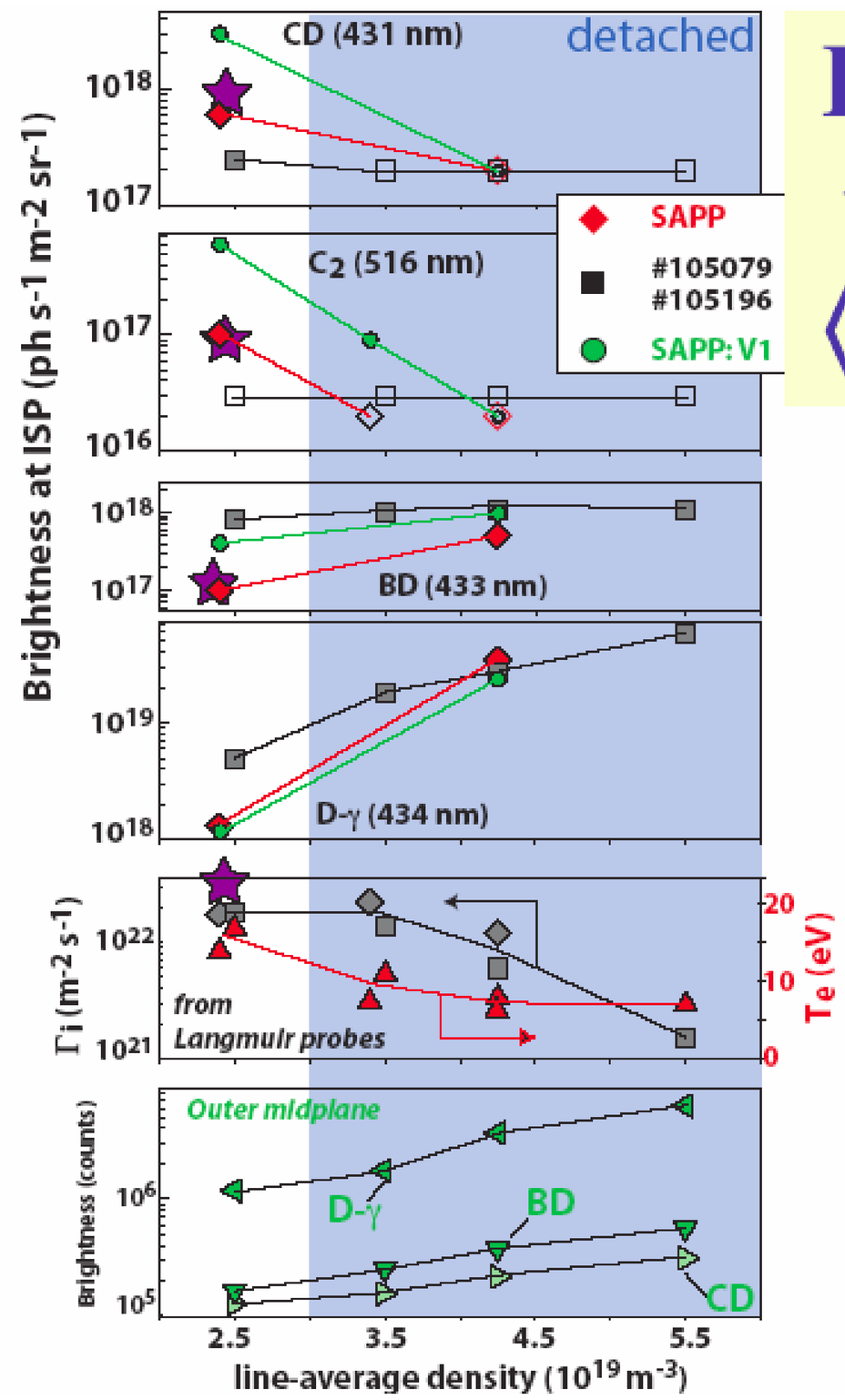


Whyte CW 2003

But can we identify controlling C source outside "principal" target area?

DIII-D inner divertor



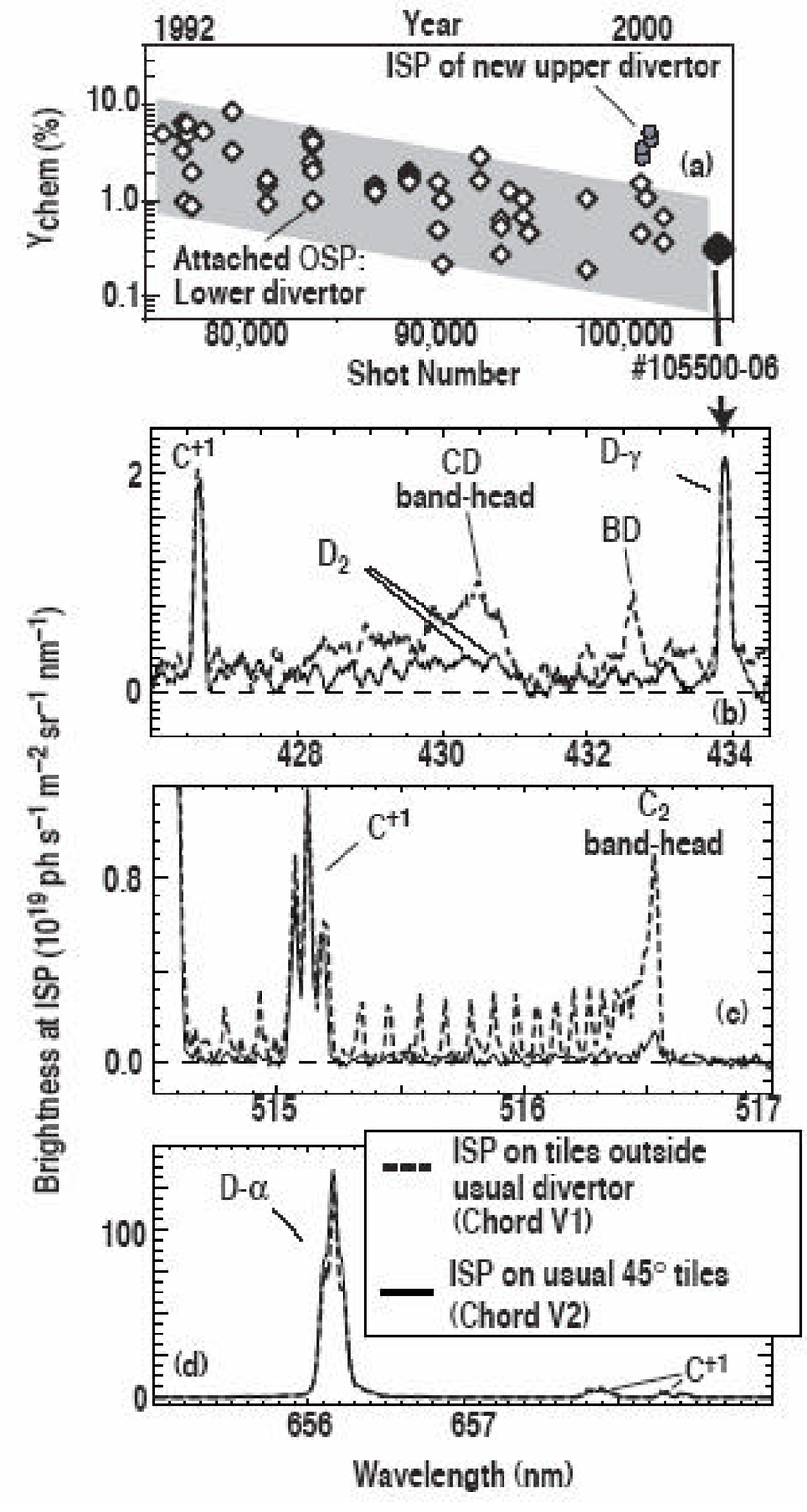


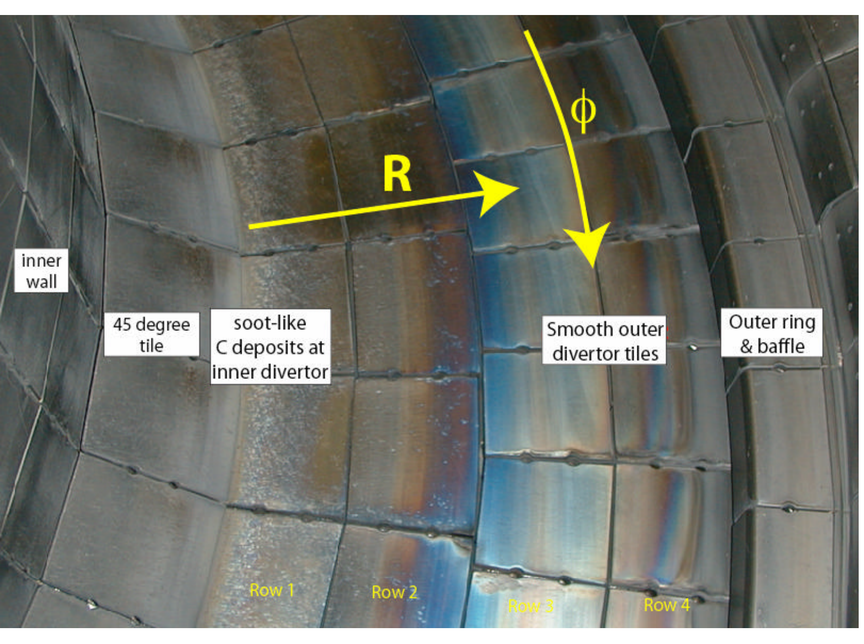
ISP vs. $\langle n_e \rangle$

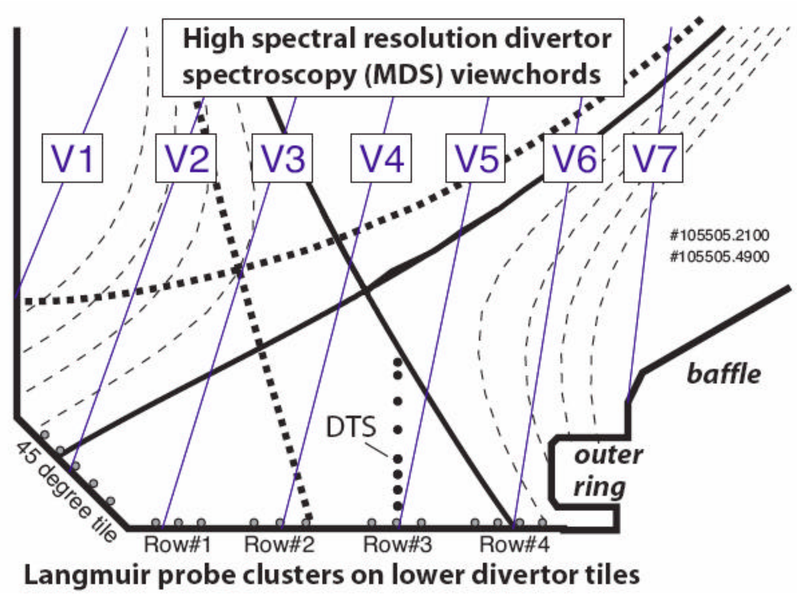
Whyte CW 2003

A further complication with chemical erosion is a long-term dependence on material conditions, but which ones?

- Chemical erosion reduced versus time?
  - **YES**: (DIII-D, AUG) Y_{chem} ~ 0.5%
  - **NO**: (JET, JT-60U) Y_{chem} ~ 5 - 10%



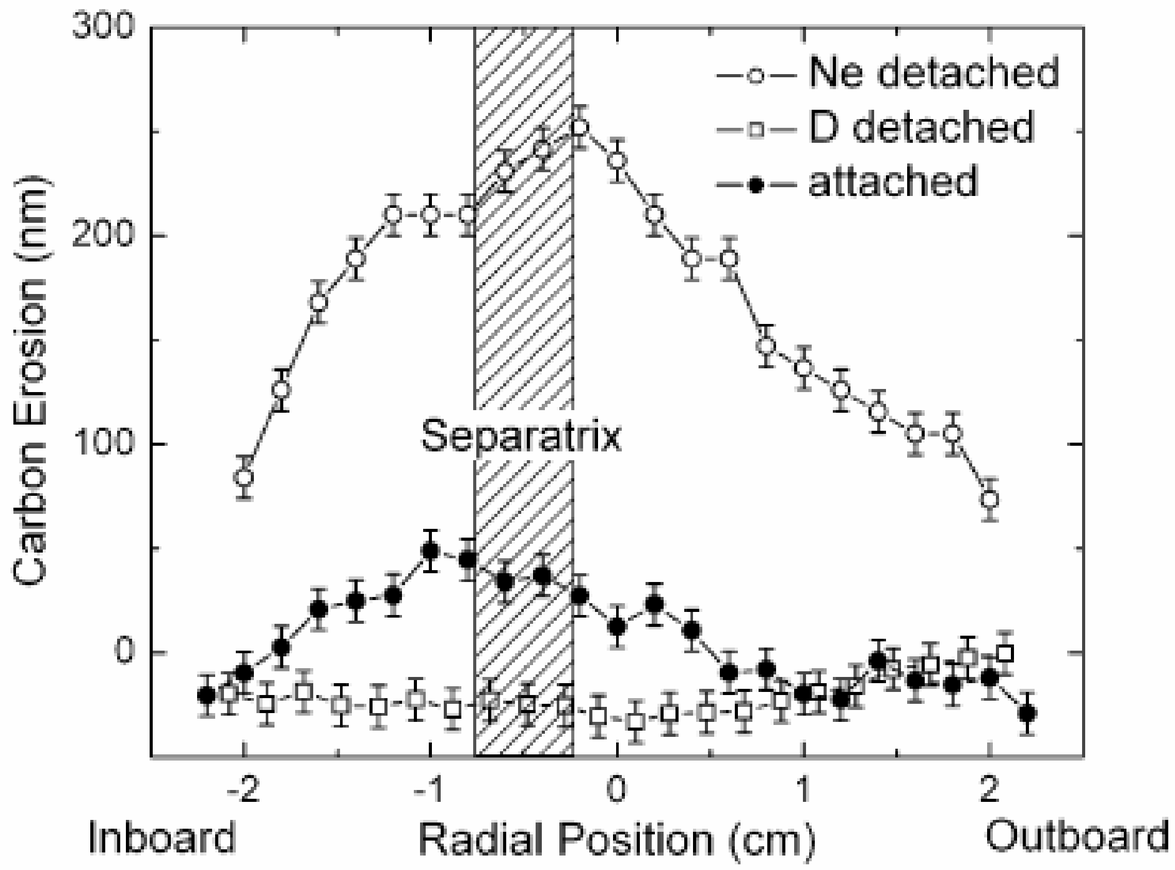


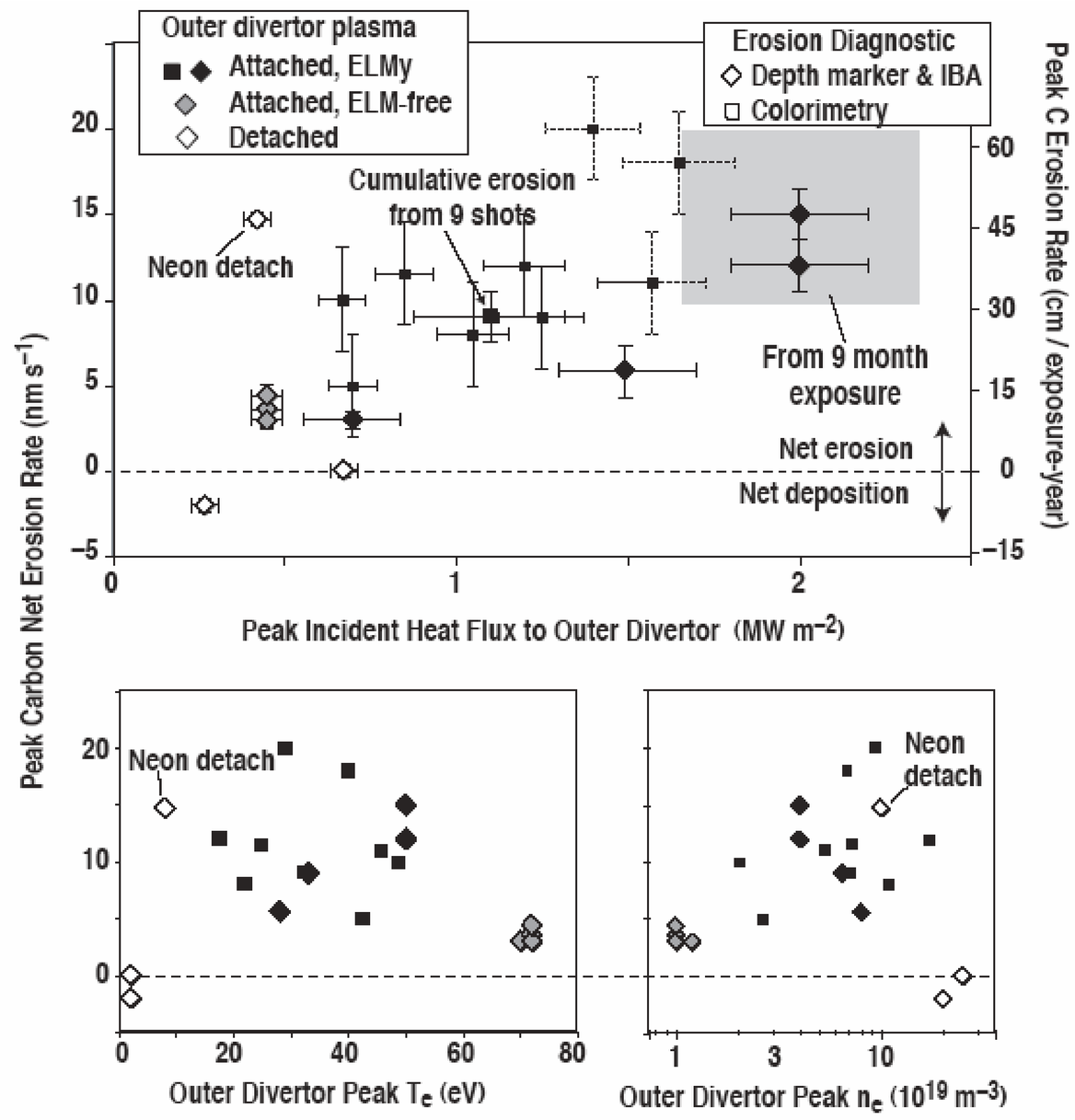


DIII-D

Whyte CW 2003

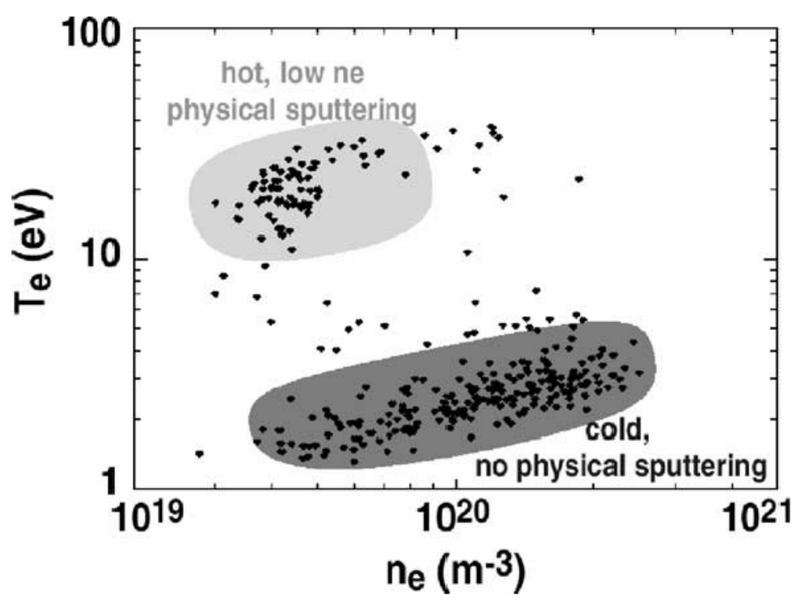
Can we resolve erosion hyper-sensitivity to small changes in plasma conditions? Neon-induced sputtering in detachment?





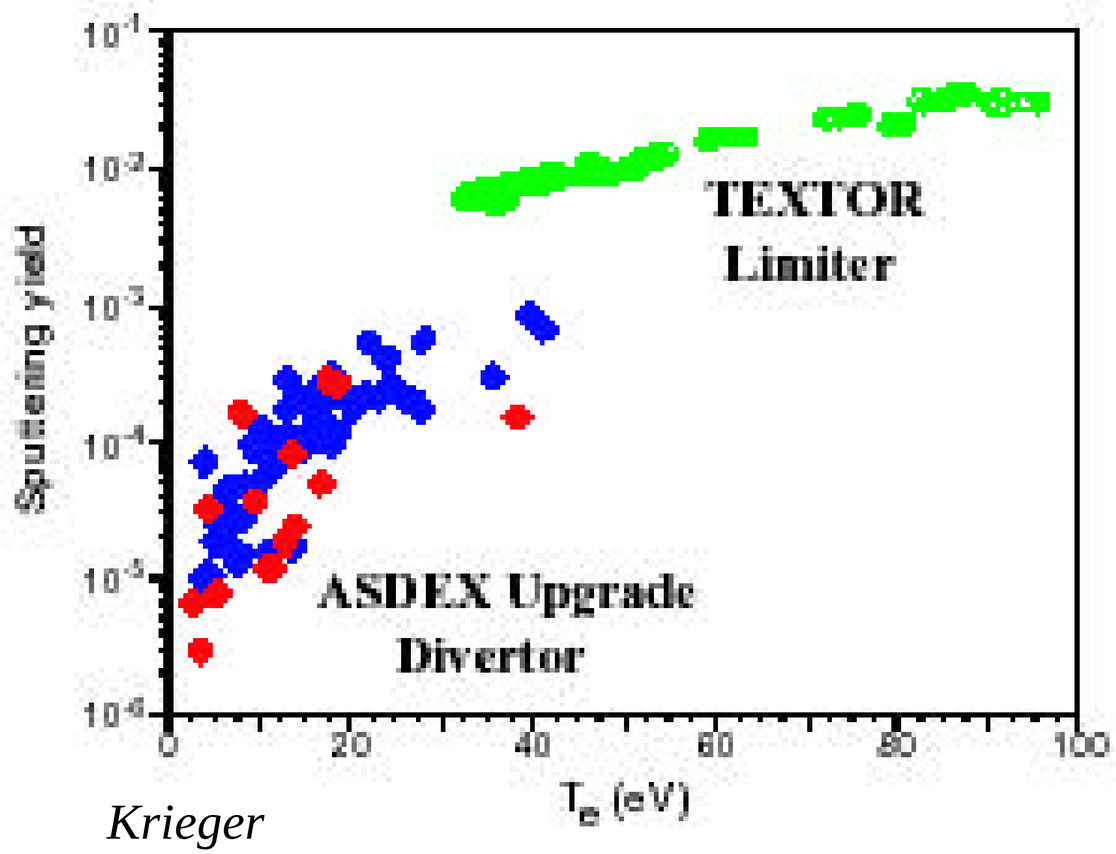
DIII-D

Wampler 2002



Whyte FS&T 2005

Can we resolve erosion hyper-sensitivity to small changes in plasma conditions? High-Z erosion by low-Z ions

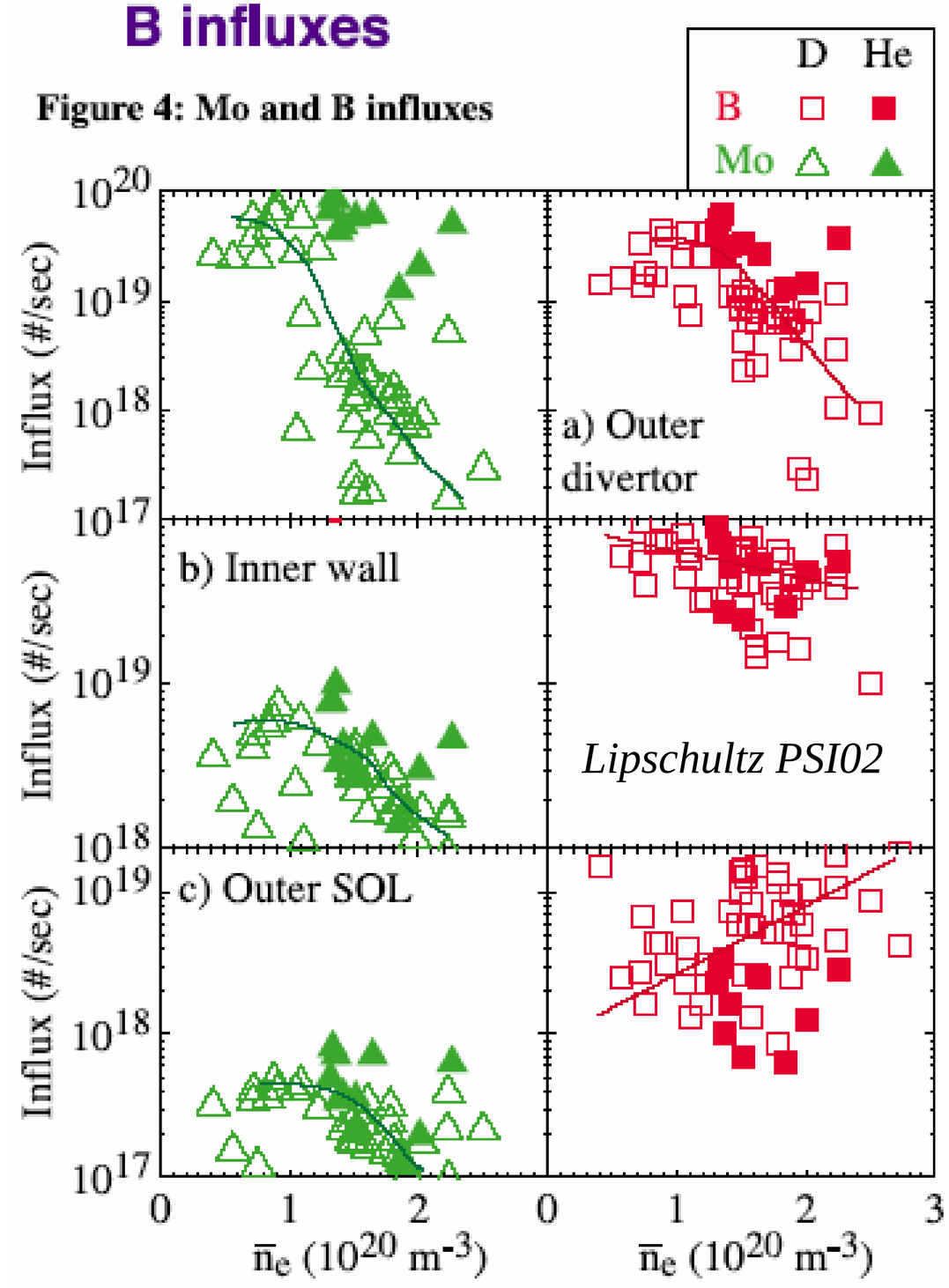


Krieger

No "post-diction" capability with regard to erosion in detached plasmas.

4. Observations of Mo and B influxes

Figure 4: Mo and B influxes



Lipschultz PSI02

What caused such high deposition at JET louvers? Could not answer by chemical erosion even "cheating" on the external carbon source

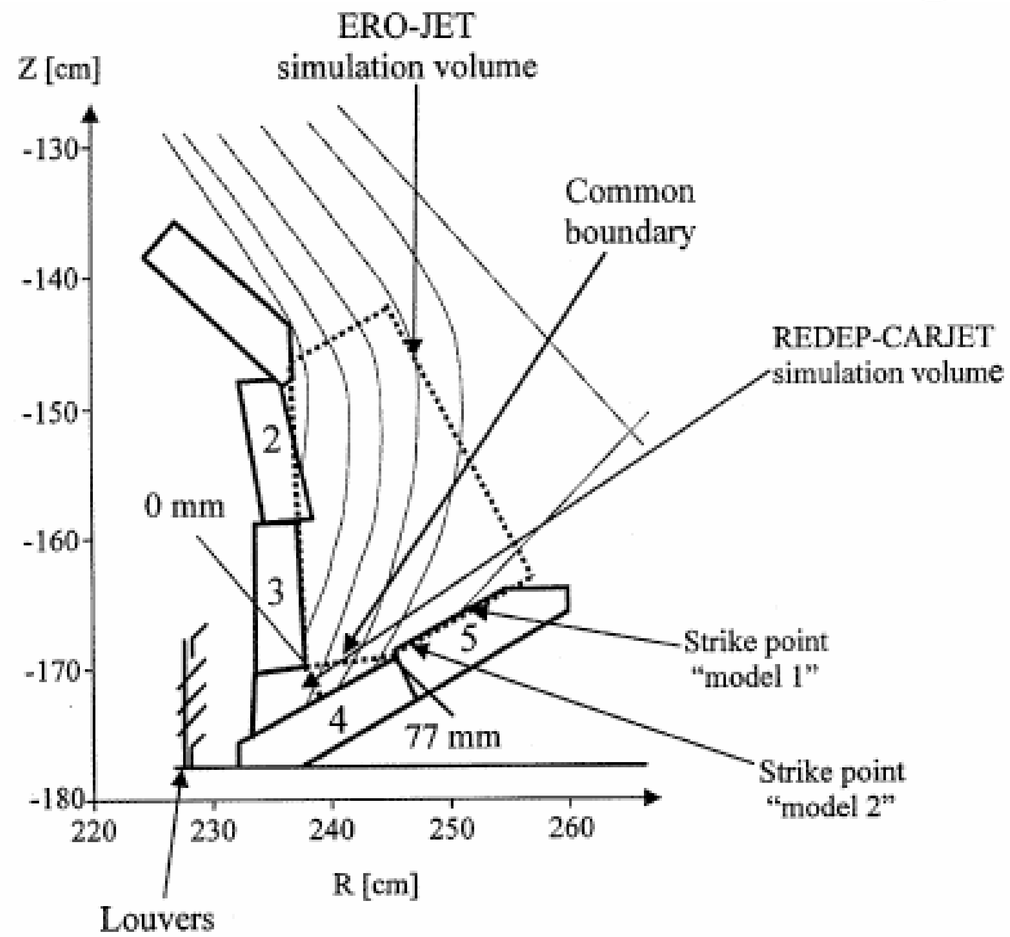


Fig. 3. JET MkIIA inner divertor geometry and calculation set-up.

Brooks PSI02

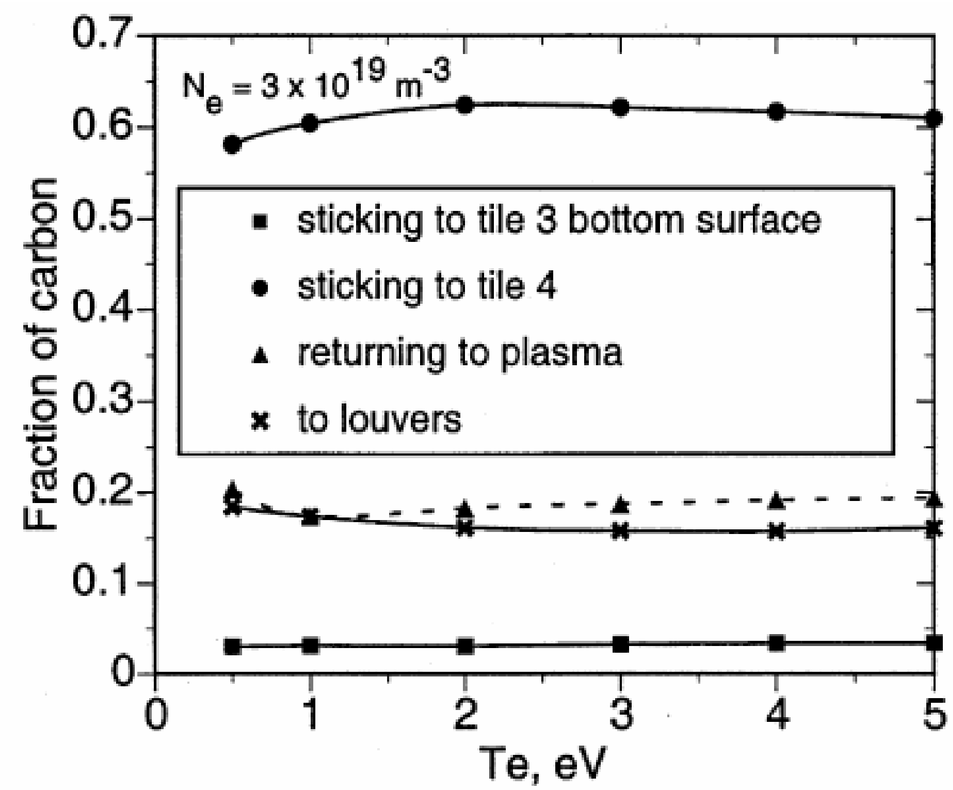


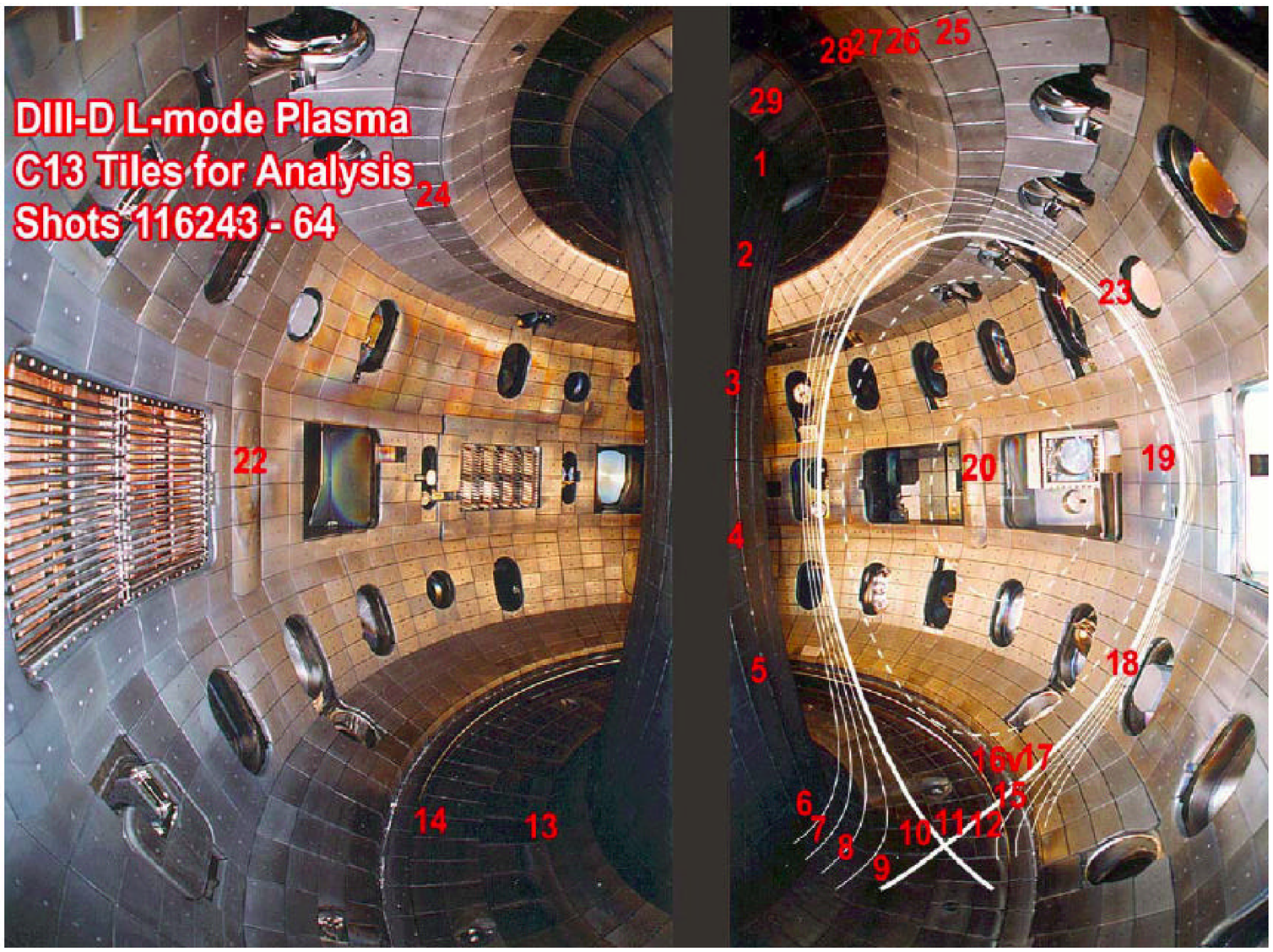
Fig. 4. Fate of 100 000 carbon atoms and ions entering the REDEP/CARJET simulation volume along the common boundary. Boundary conditions given by ERO-JET results. As a function of plasma electron temperature in CARJET volume, for the fixed density shown.

Model: (Y_{chem}~7%) $\Phi_{C,Louver} \sim 0.7\% \times \Phi_{D+}$

Experiment: $\Phi_{C,Louver} \sim 5\% \times \Phi_{D+}$

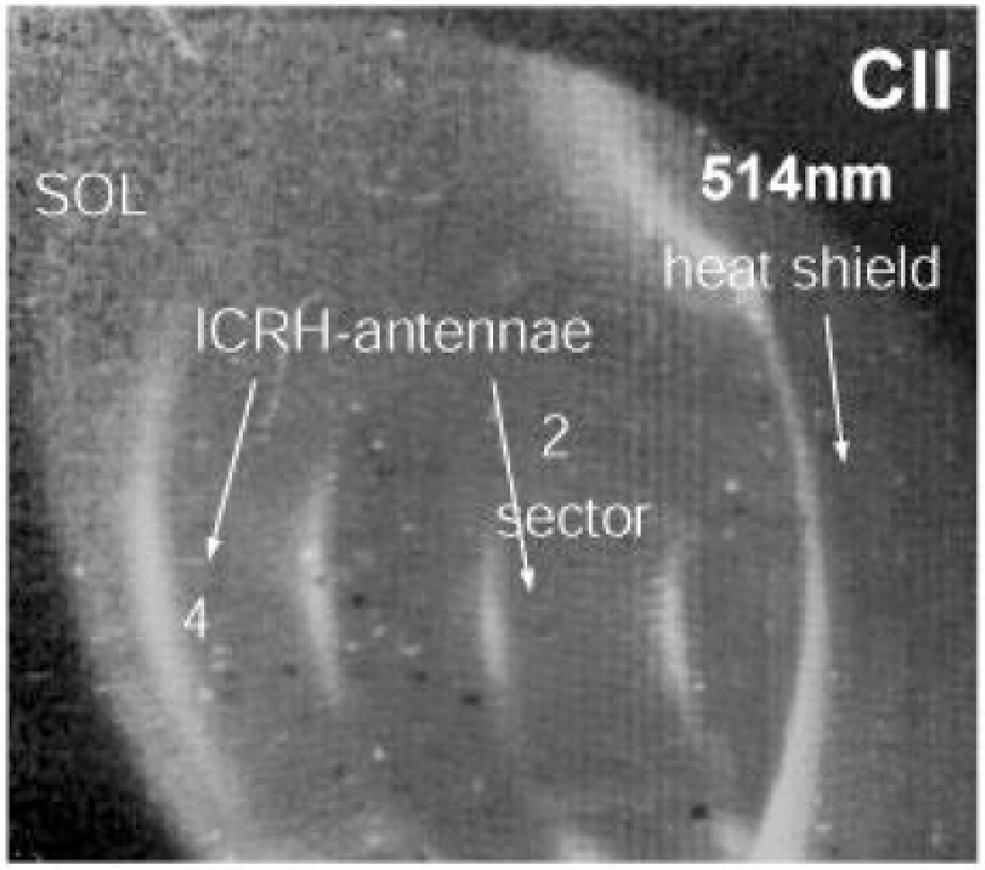
What is the erosion/deposition pattern outside the divertor?

Large, irregular surface area



DIII-D, Mclean, APS04

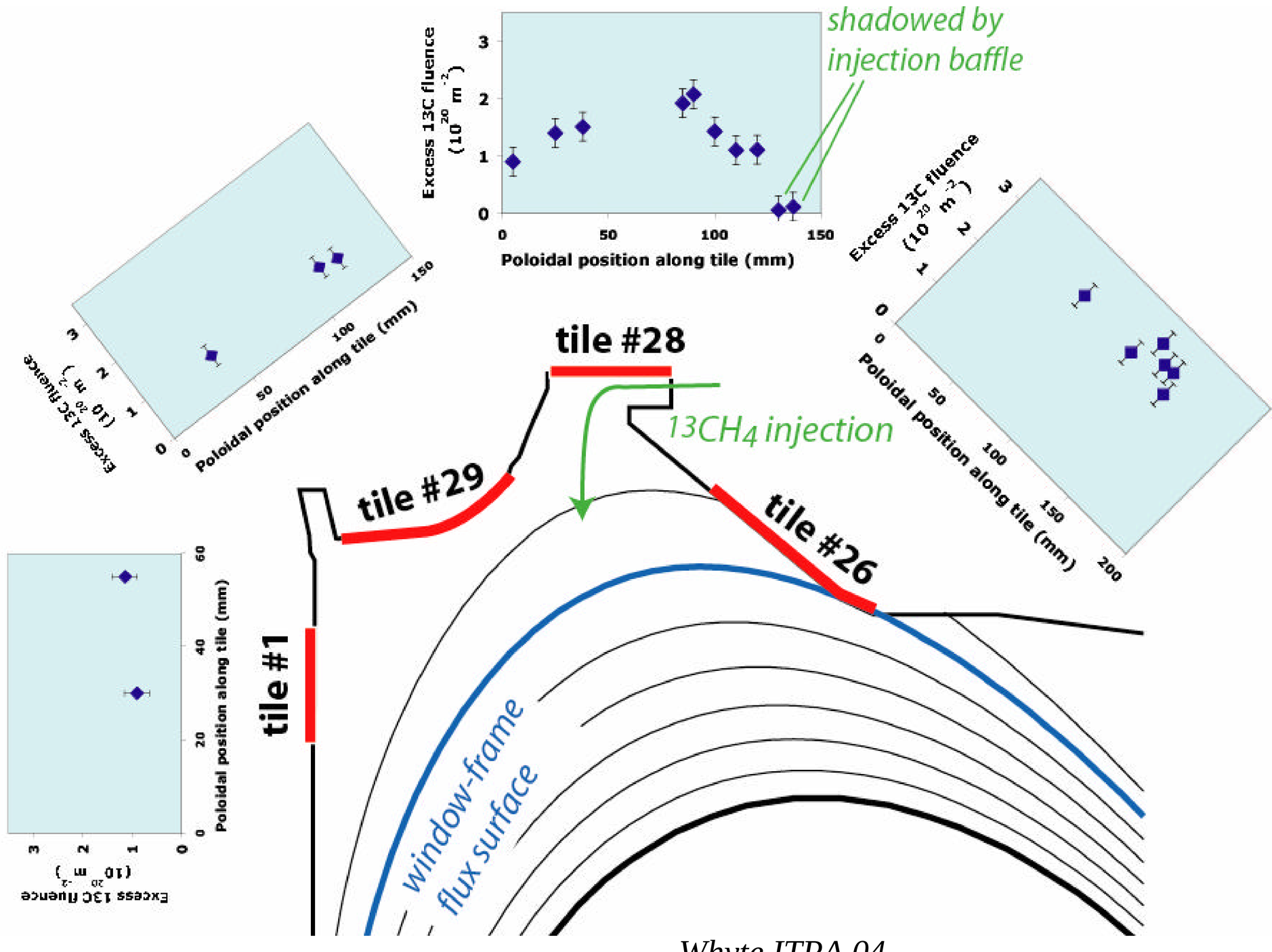
Non-uniform erosion source



ASDEX-Upgrade, Rohde CW2003

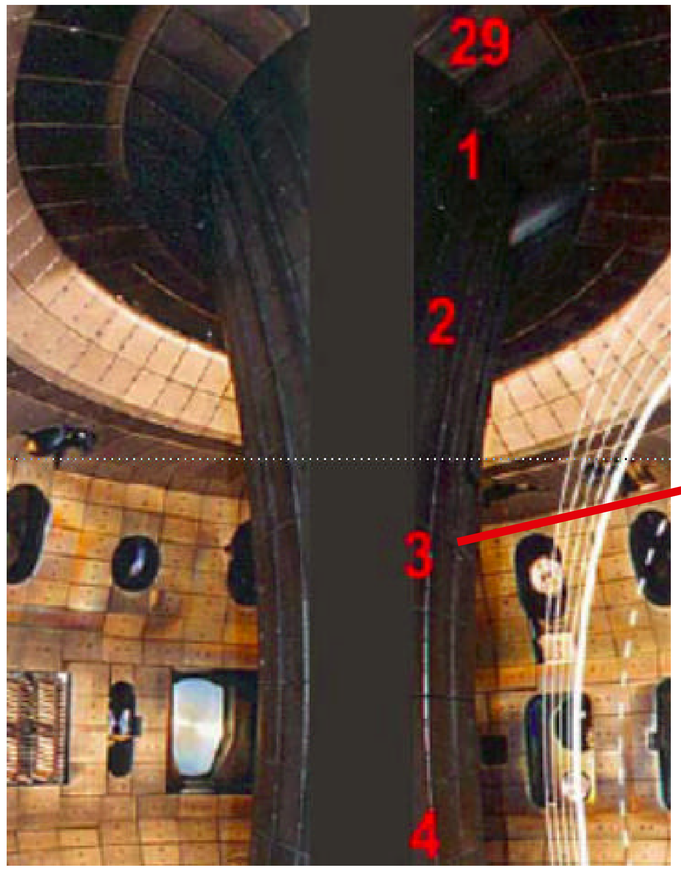
13-C tracer experiments on DIII-D: Deposition also occurs at main-wall.

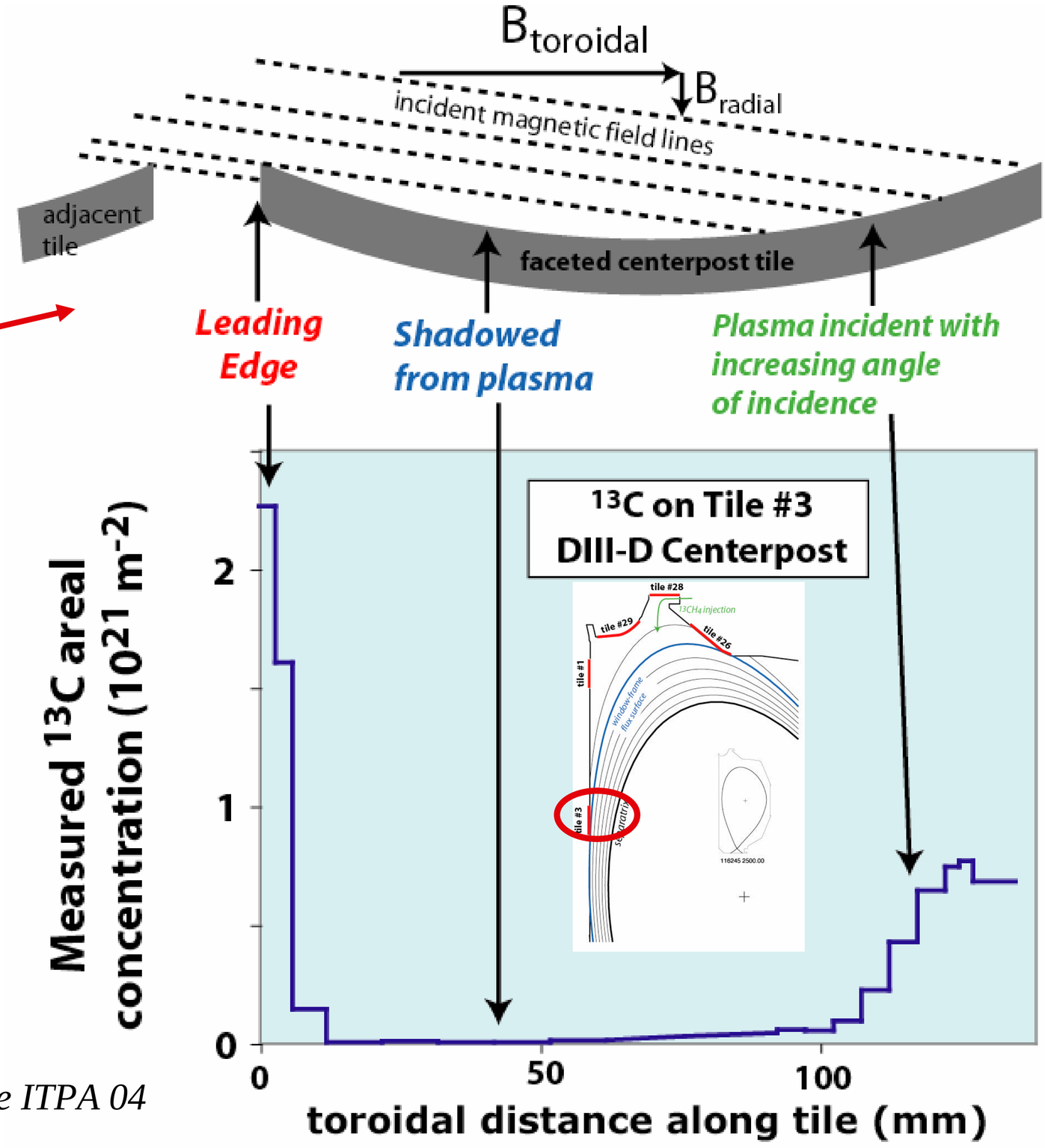
- PIGE diagnostic (UW measures ~ 1-2 nm equivalent of 13-C enrichment around injection location.



Whyte ITPA 04

Measurements at centerpost are consistent with plasma/ion deposition of 13C, with strong toroidal asymmetry on a tile due to faceting.

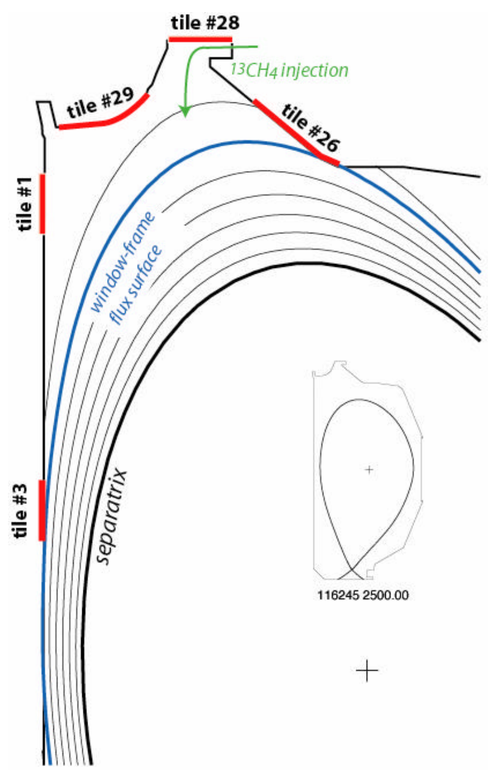




The main-wall probably has a more complicated erosion/deposition pattern than divertor.

Whyte ITPA 04

Preliminary inventory suggests that the inner main-wall is an equally important location as the lower divertor for 13C deposition.



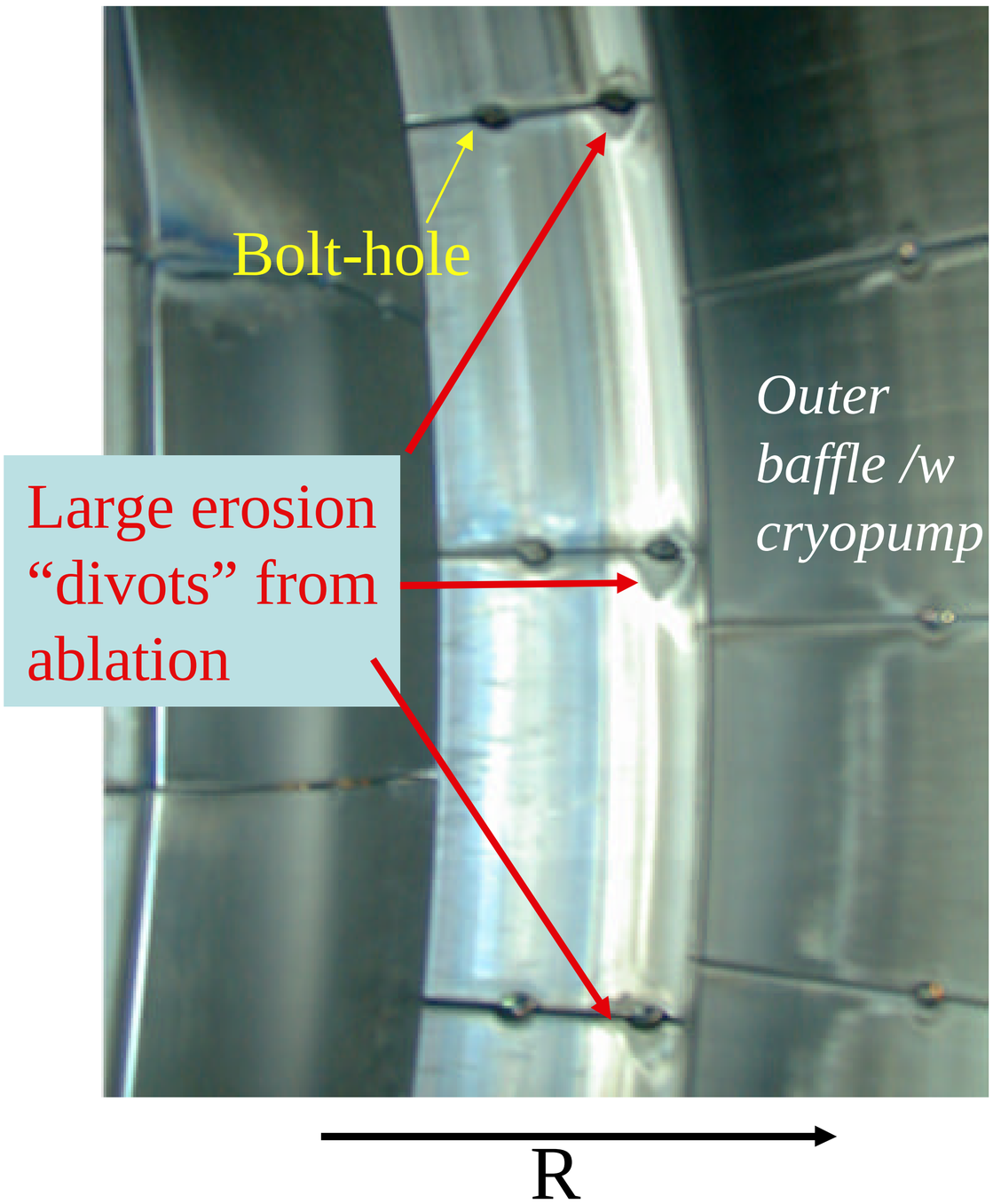
Location	Tiles	Area m^2	^{13}C fluence (10^{20} m^{-2})	13-C (10^{22})
Upper dome, divertor plate, centerpost	1, 28, 29	8	1.3	0.1
Upper divertor baffle	26	3.6	2.8	0.1
Centerpost below 6 cm flux surface	3	11	2	0.22
Total inner wall				0.42
Total inner divertor				0.3
Total injected				**1.0**

Allen PSI 04, Wampler PSI 04, Whyte ITPA 04

Tracer experiments must really be interpreted as testing SOL plasma transport

Neglecting 3-D can have large erosion consequences, but other effects?

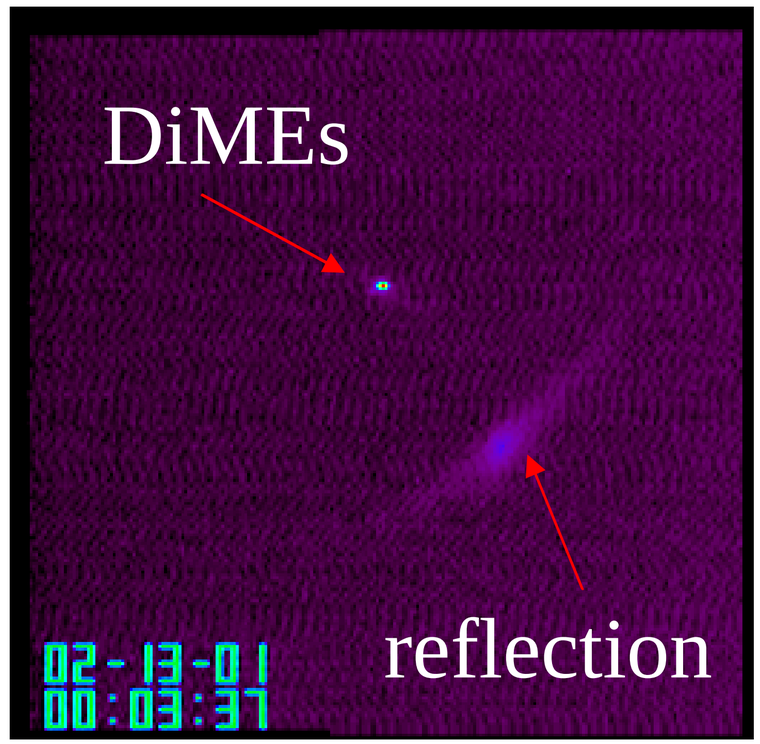
Looking up at DIII-D top divertor

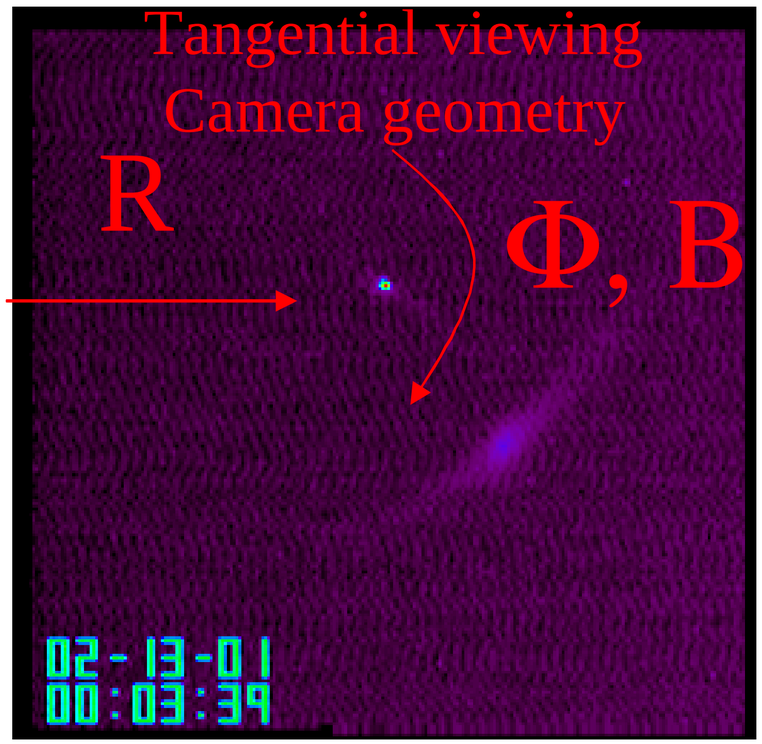


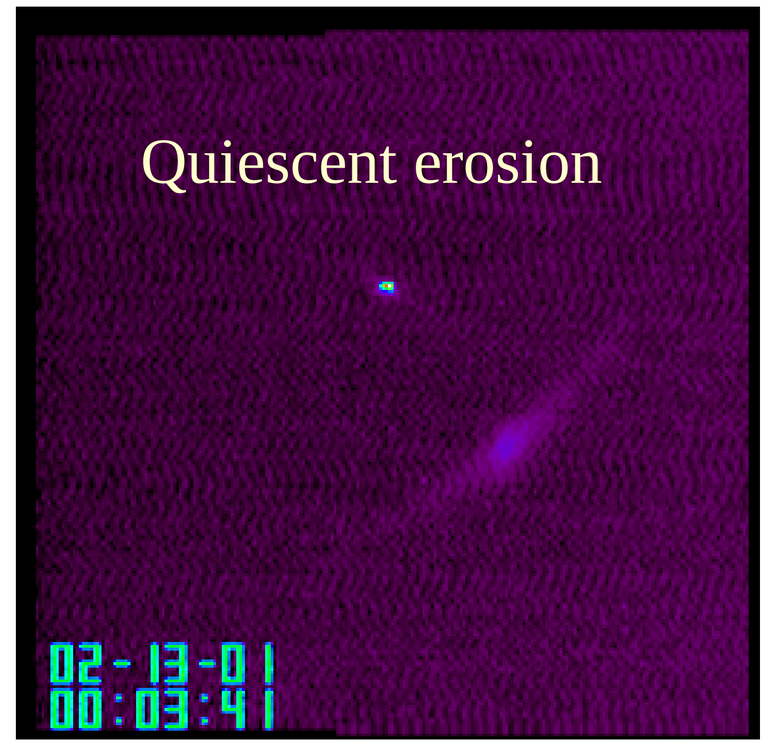
- Prolonged outer strikepoint exposure to high power plasmas ablated ~cm^3 of graphite.
- A thick sooty carbon layer was found underneath the outer baffle with line-of-sight to bolt-holes.
- **But no detrimental effects on plasma operations!**

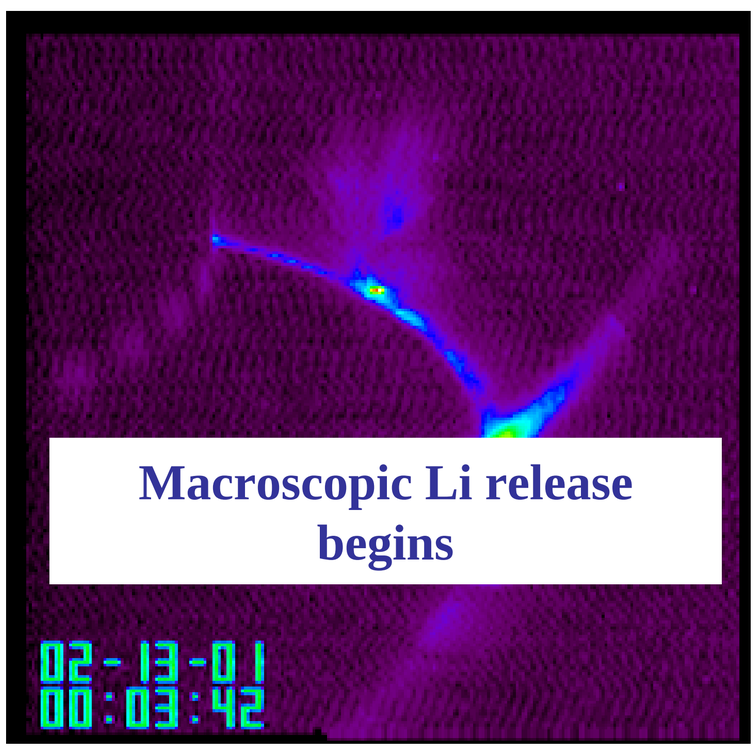
…but transient "macroscopic" MHD movement can often have severe results.

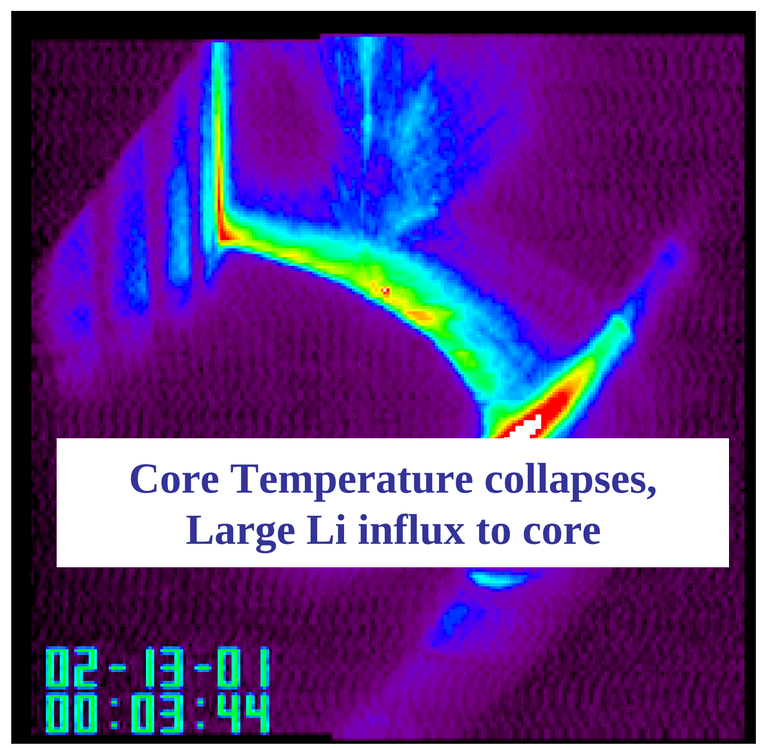
Example: DIII-D lithium exposure

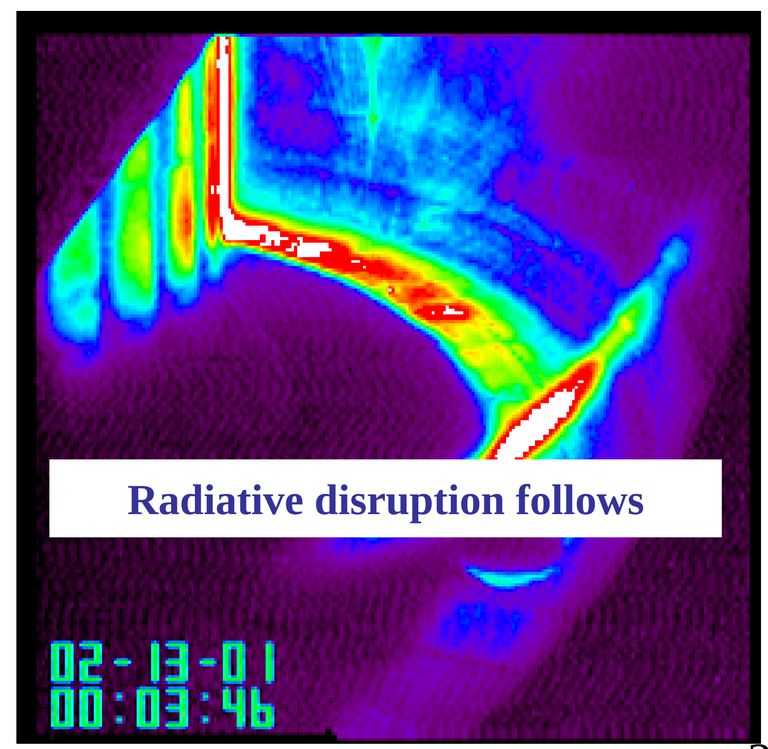






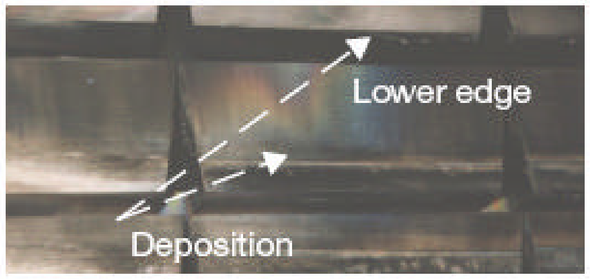


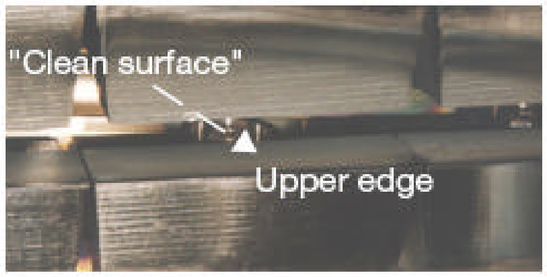


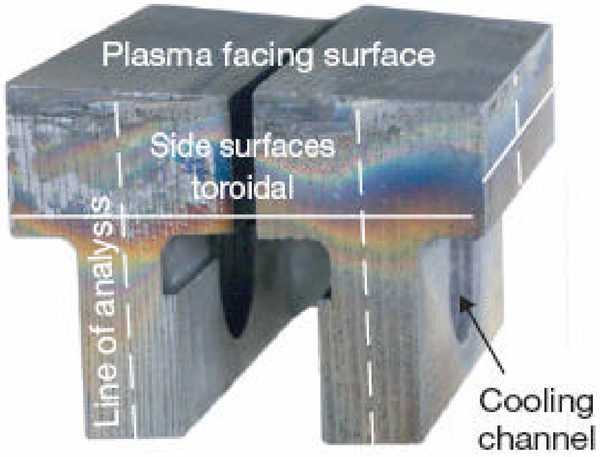


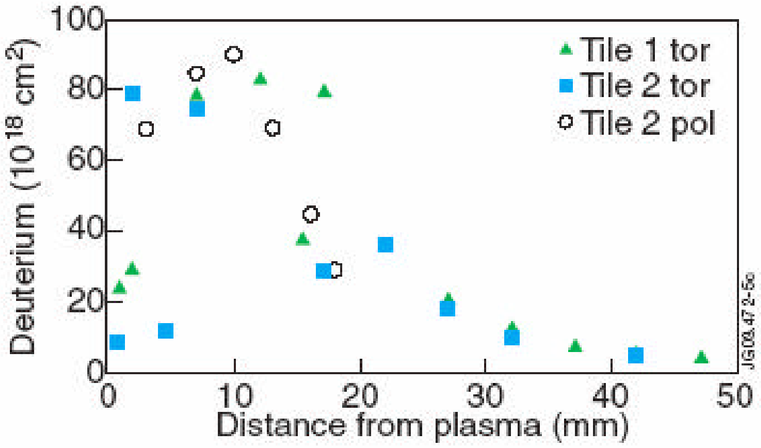
What causes and controls tile gap deposition?

~ 30-60% Deuterium in gaps, but near surface









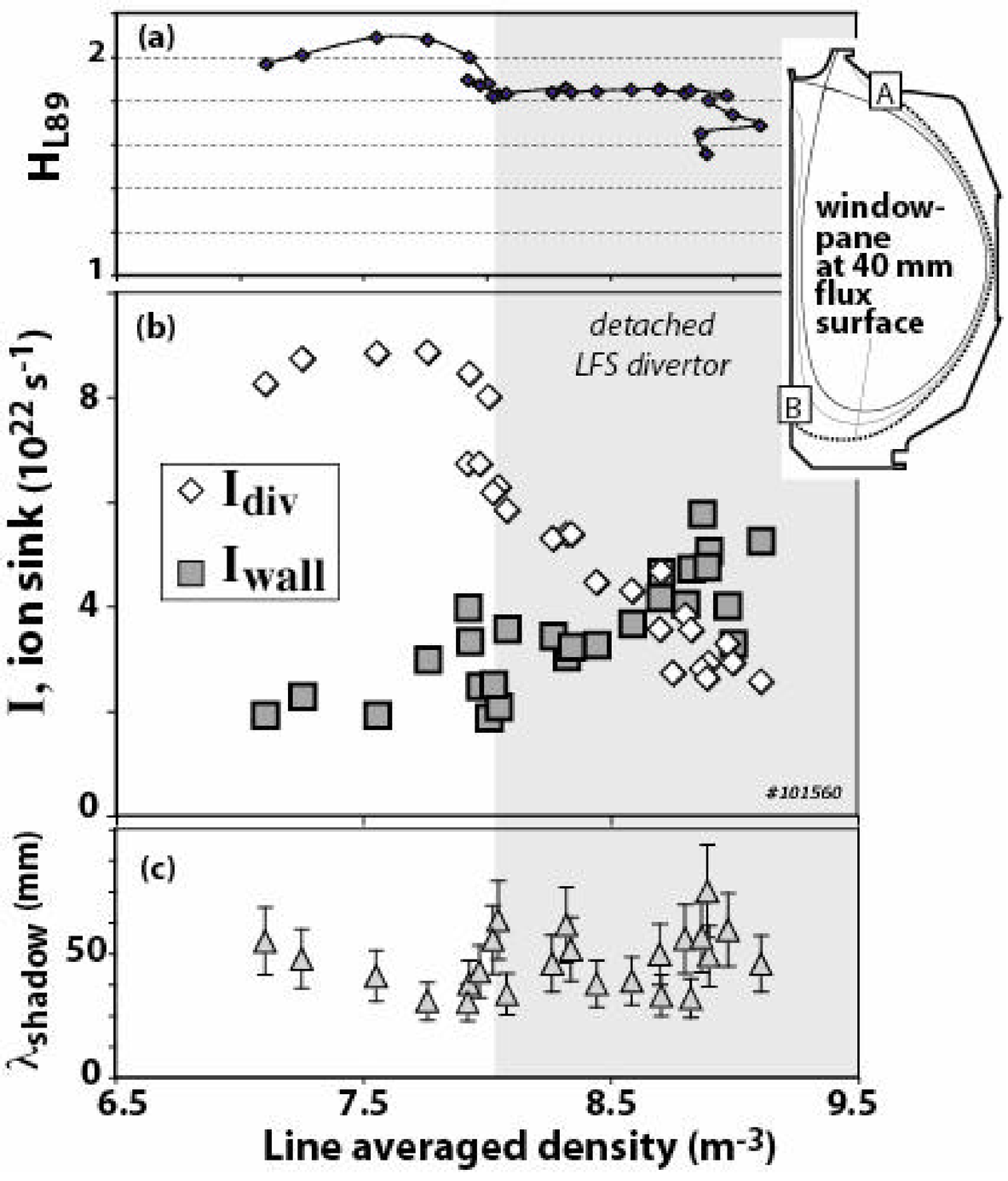
Carbon
In TEXTOR

Rubel CW 2003

Boron
In C-Mod

To what degree does intermittent transport dictate main-wall erosion processes?

Flux, ionization, redeposition are linked.



QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

S. Zweben, J. Terry, C-Mod

Whyte PPCF 05

Proposal for ITER: Tritium recovery by Radiative Plasma Terminations

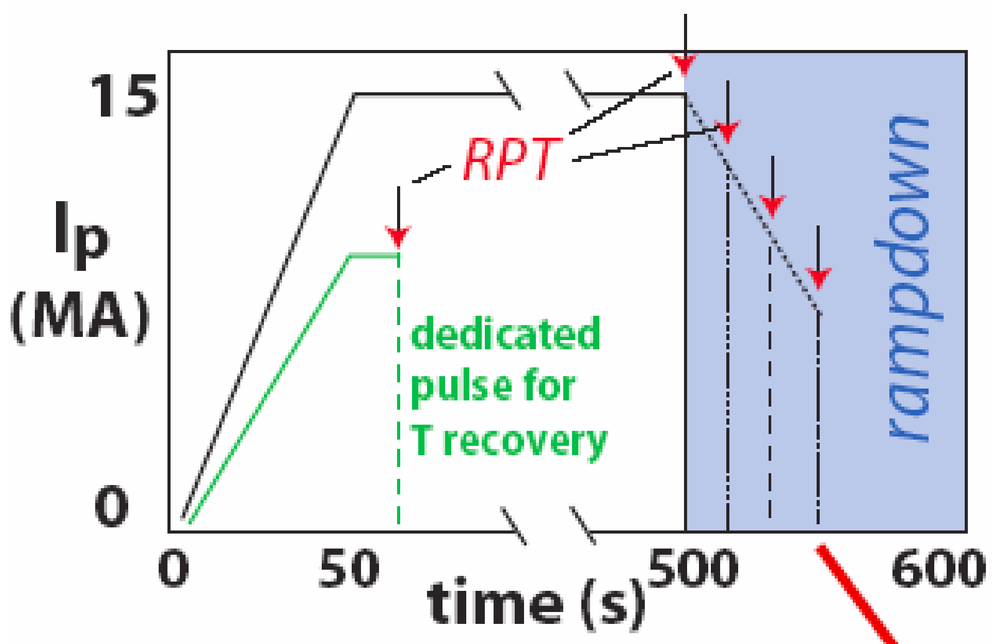
- Exploit the high energy density of the ITER plasma.

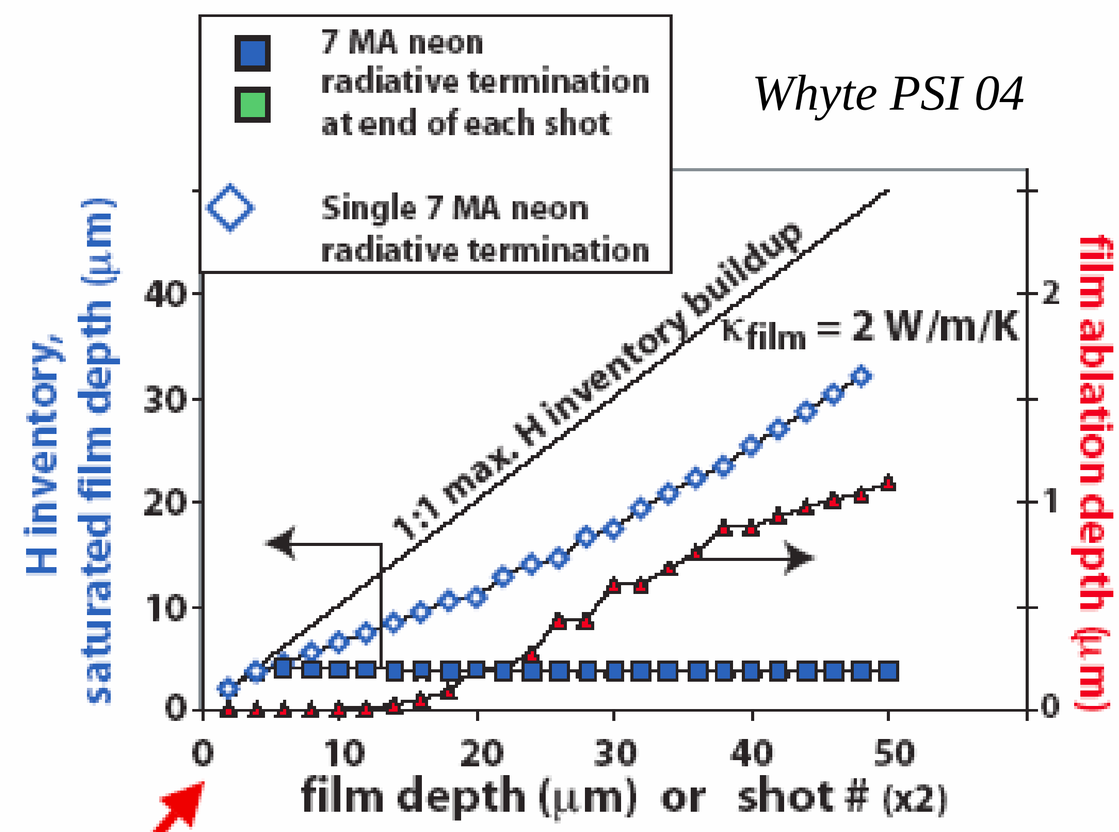
- Convert plasma energy into a quasi-uniform radiation pulse by massive impurity injection
  - Benign termination of the plasma discharge.

- ***The radiation pulse transiently heats all plasma-viewing surfaces in order to desorb the tritium, which is released into the vessel as molecules and recovered by pumping.***

- Significant tritium recovery at reduced plasma current, ~ 6-10 MA, indicating the possibility of *routine* T recovery
  - Current rampdown phase of each discharge
  - Dedicated, short pulse tritium recovery discharges at low current.

Calculations show routine repetitive application of RPT in current rampdown can limit T inventory by continually removing codeposited T from plasma-viewing surfaces.

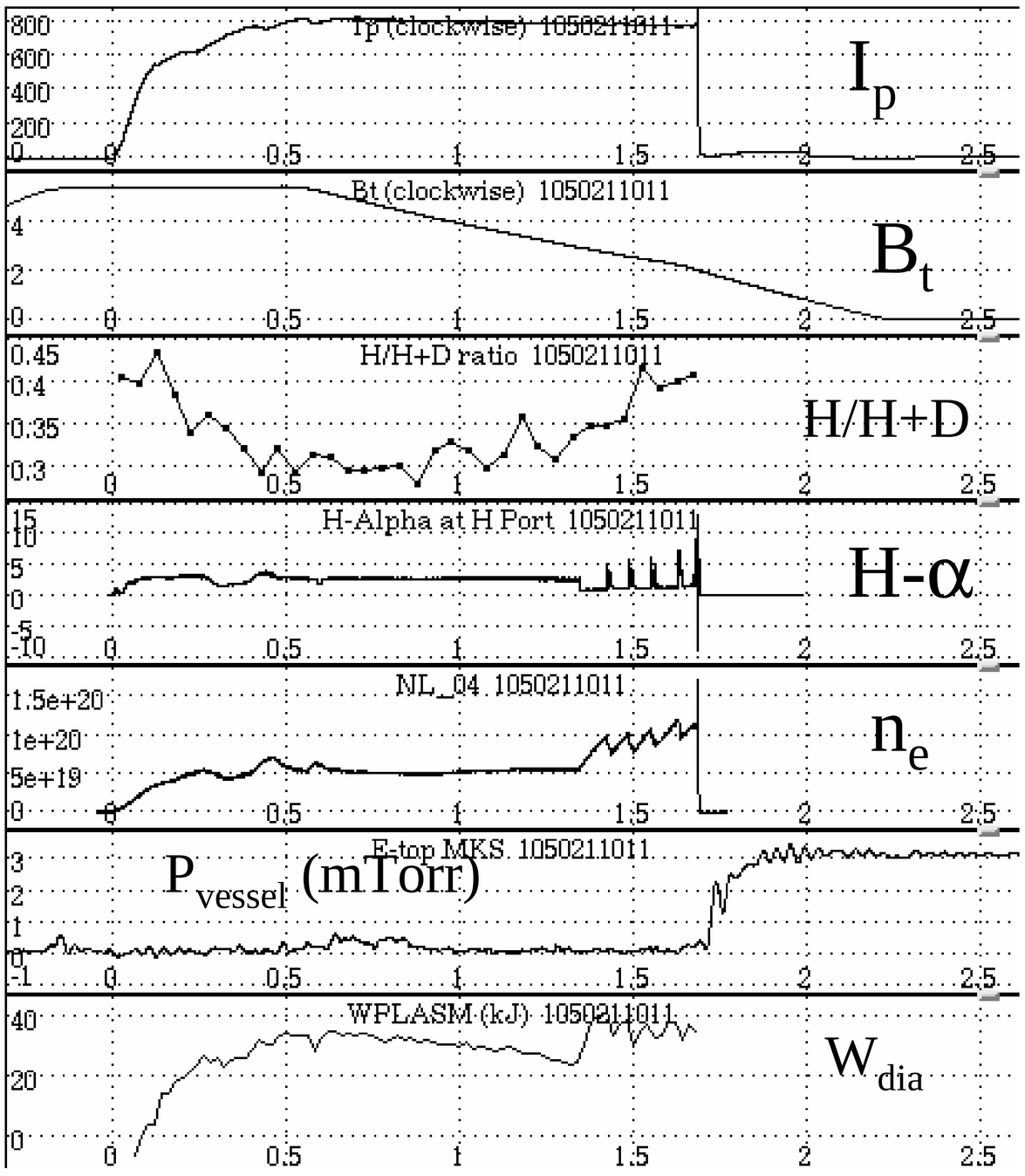




Application of 7 MA RPT on a Film that grows 2 μm per shot

C-Mod: H/D recovery using plasma surface heating

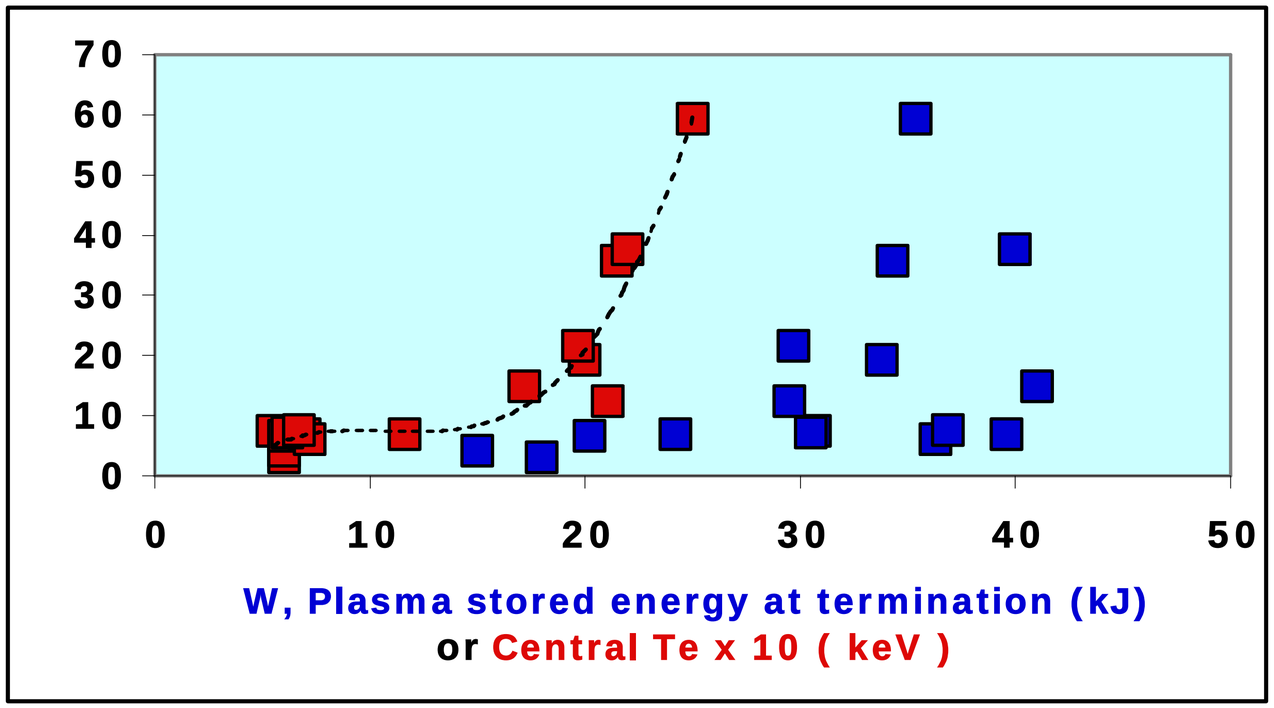
15 of 18 discharges: planned termination

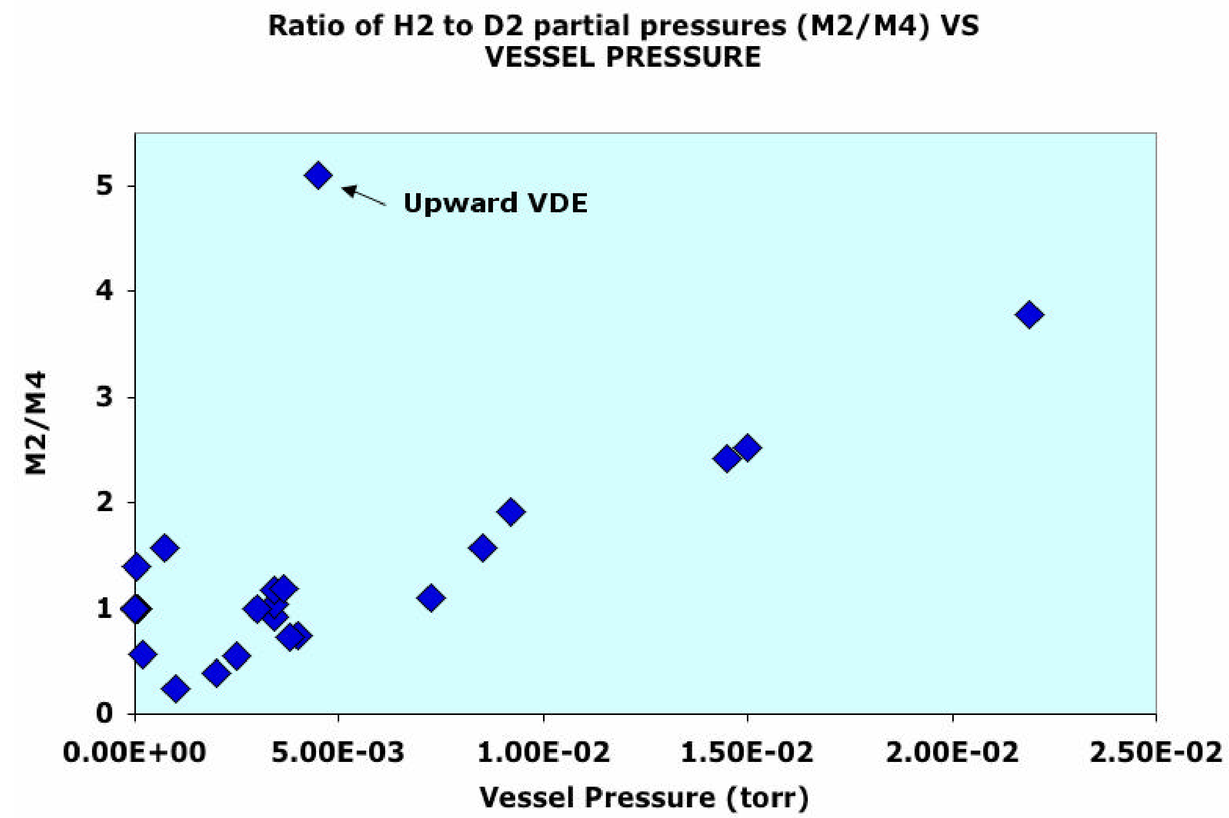


Example q=2 planned disruption.

- B_t rampdown in I_p flattop
- 4 m^3 Vessel pressure: 3 mTorr --> ~ **12 Torr-L of gas recovered**.

Principles of H2 desorption and recovery were generally validated.



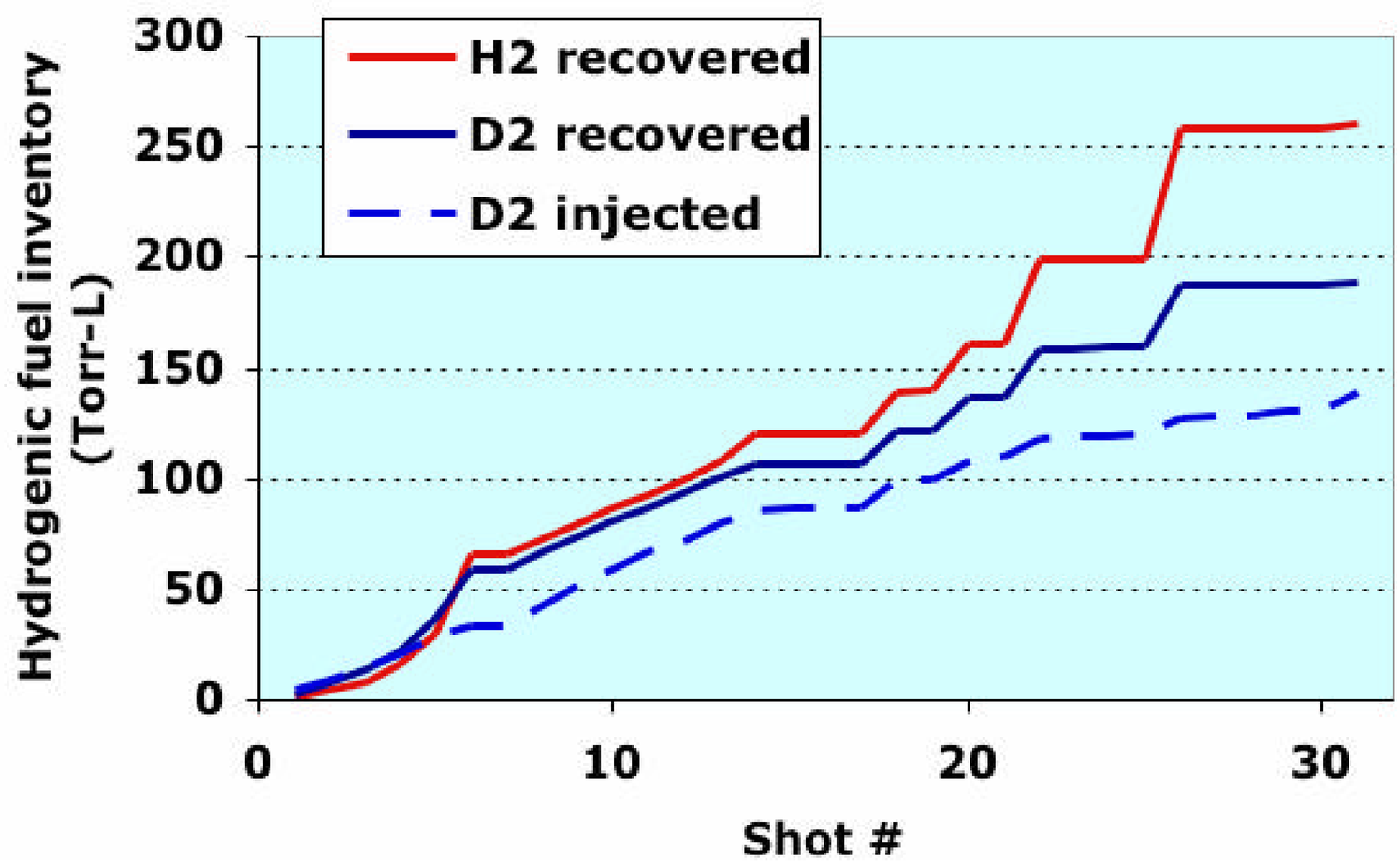


- Higher plasma T (> 2 keV) key to efficient H2 desorption
  - Heat conduction ($\propto T^{5/2}$) loss dominated disruption provides better localized heating of the wall surfaces
  - .
- Up to 60 Torr-L of H2 recovered in single termination (1 MA VDE).
- Gas released into the vessel becomes dominated by H2 “reservoir” as total desorption increases

H_2 recovery rate increased a factor of 5-10

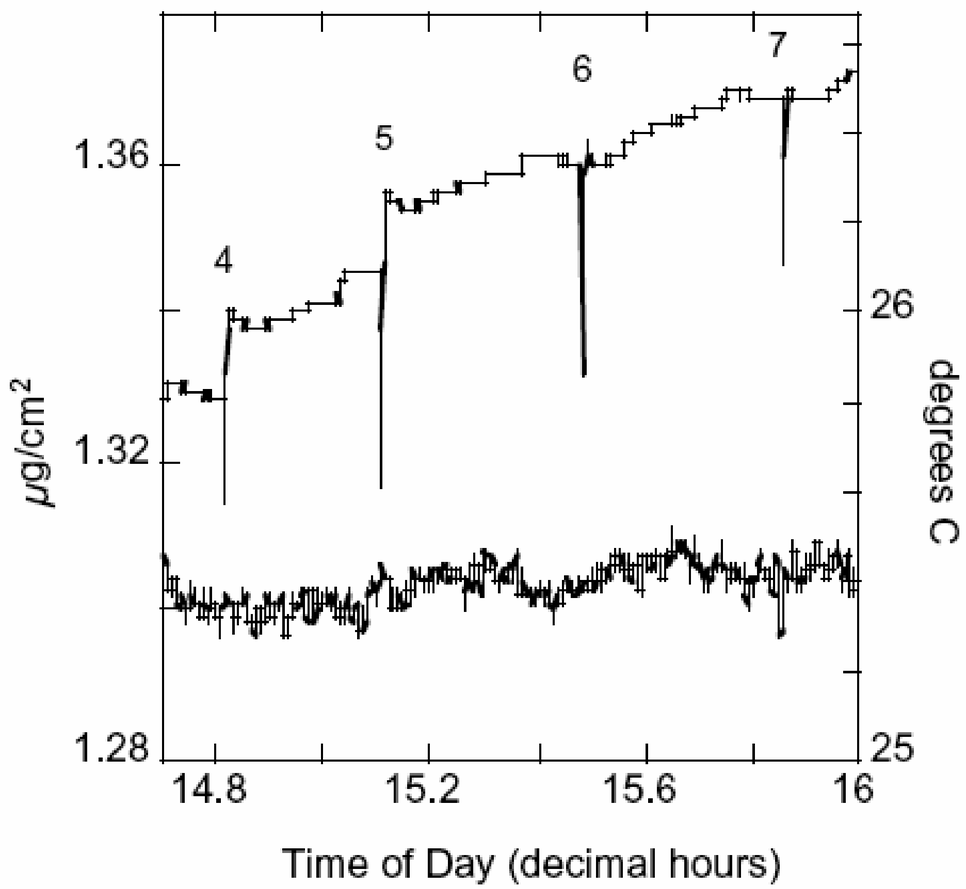
& Demonstrated control of H/D/T fuel inventory.

- Recovered ~25% of estimated H2 reservoir in walls.
- Wall pump ~ 5 Torr-L / shot without terminations!
  - Similar to C tokamaks.
- Disrupting most plasmas resulted in a net **surplus** of recovered fuel (i.e. the *opposite* of global H/D/T retention).



Most issues raised show critical need to resolve temporal dynamics of erosion

- PSI "archeology" of limited use for interpretation.
- Spectroscopy is indirect:
  - Long term changes clearly seen (DIII-D) or not (JET) but why?
- Important first step: **QMB** (Esser, Skinner)
  - Result: surprises! (deposition in between discharges!)



NSTX, Skinner PSI04

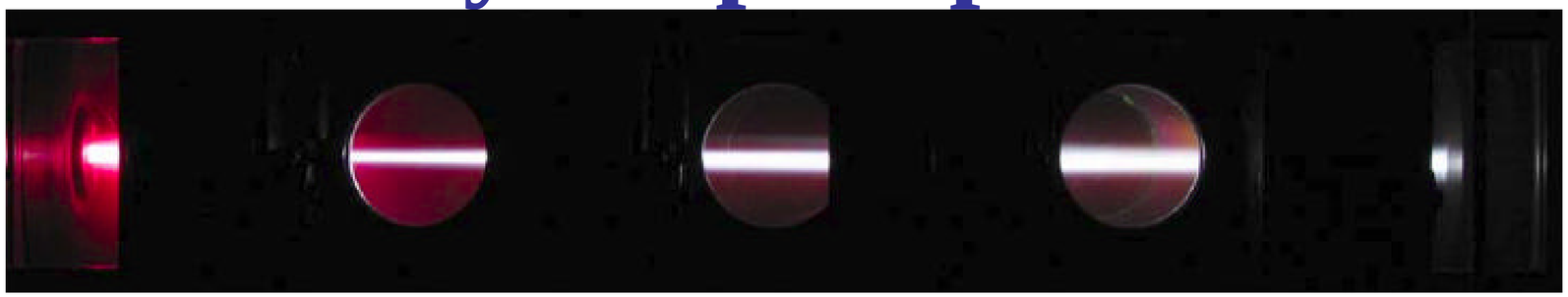
Need to resolve large range of timescales --> Diverse tools

- Intermittent transport (~ microseconds)
- Transient heating (~ms)
- Energy confinement (~s)
- Application of low-Z films. (1000 s)
- Long-term changes in material properties (months-to-years)

PSI needs to expand from dedicated, small-area experiments in confinement devices

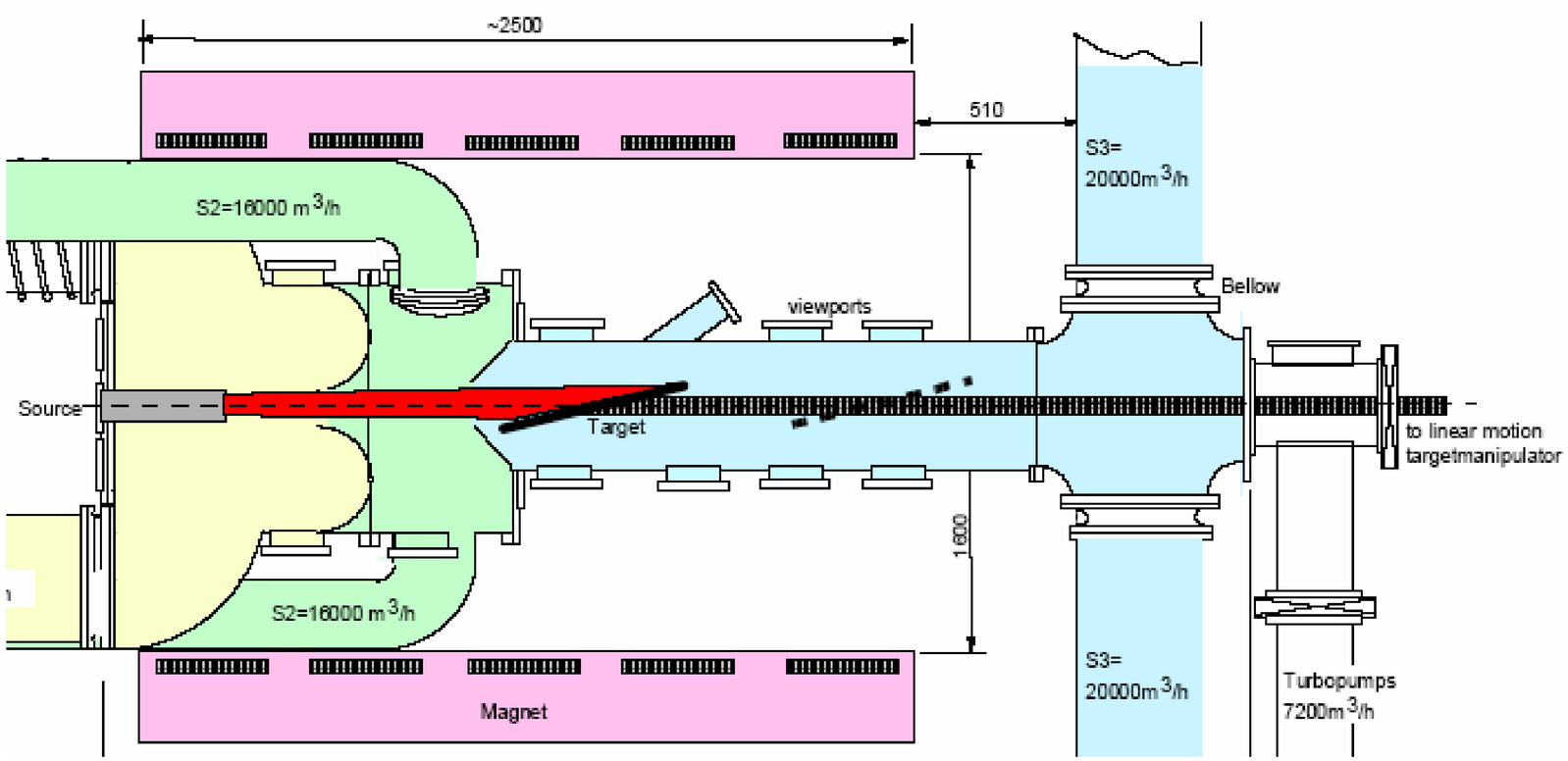
- Mapping of lower divertor erosion took ~5 run days at ~ $1 M / day in DIII-D
- Need dedicated facilities that address these issues (and exploitation of present facilities like PISCES).
- & New in-situ diagnostics.

MAGNUM PSI: New facility dedicated to erosion studies at T_e ~1-3eV and collisionally coupled plasma-surface

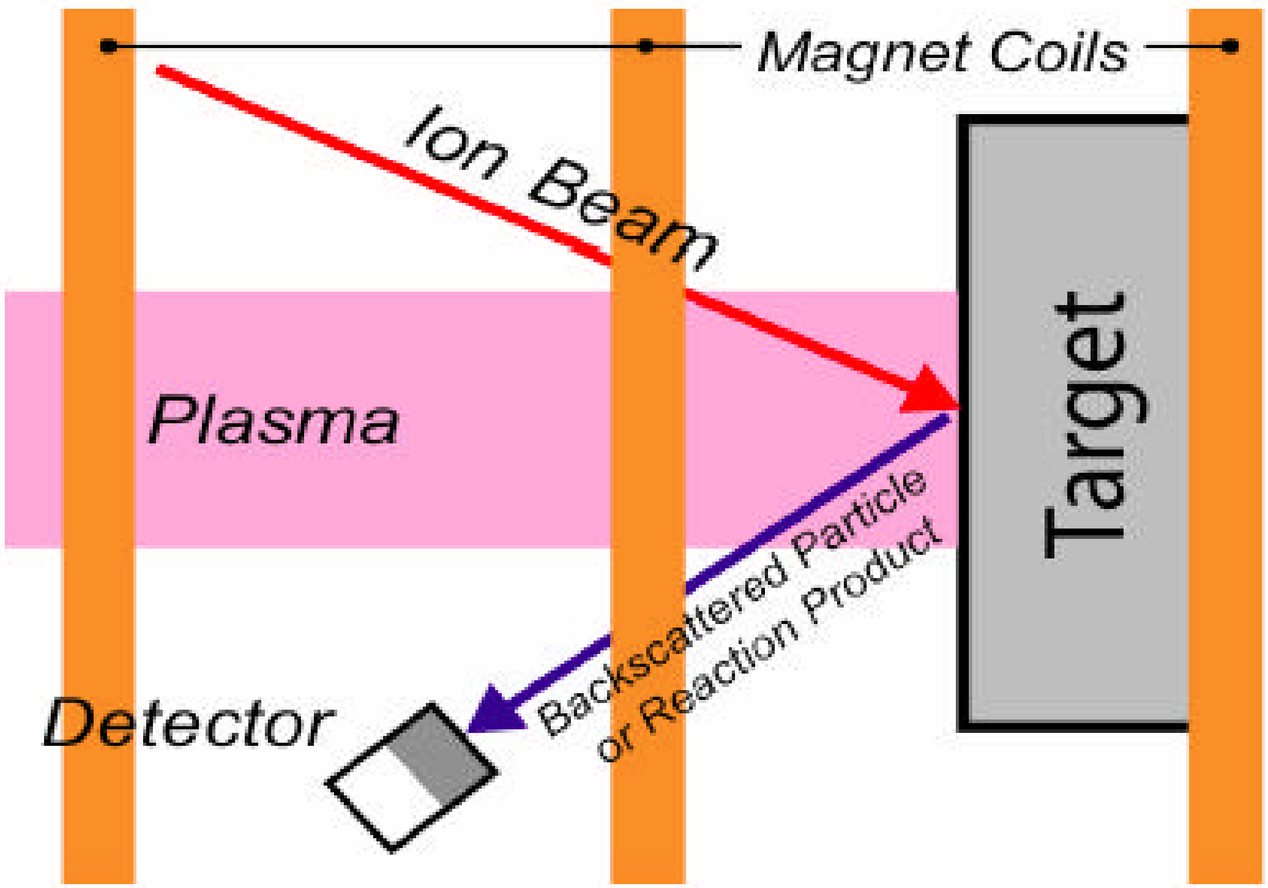


Facility at FOM (NL): Steady-state, 3 T, L~3 m

H plasma: $n_e \sim 10^{21}$ m^{-3}, $\Gamma \sim 10^{24}$ m^{-2}s^{-1}, $l_{MFP} << a \sim 10$ cm



DIONISOS: New facility at UW to study dynamics of PSI combines plasma exposure with in-situ Ion Beam Analysis.

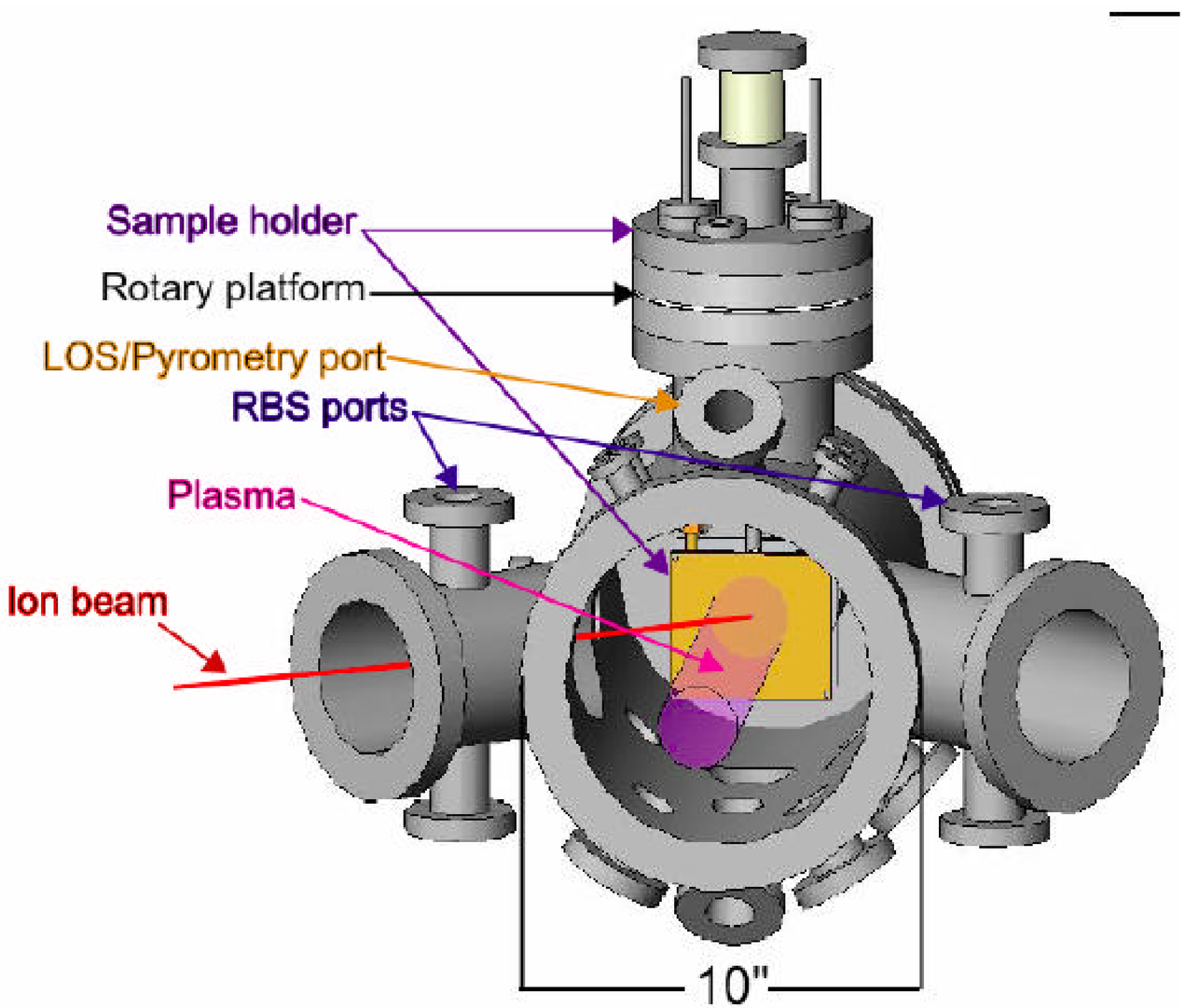


Analysis Available with DIONISOS

- Non-destructive depth profiling
- Elemental discrimination
- Hydrogen detection
- Quantitative surface concentrations with the proper references
- Ion beam steering across face provides spatial profile

Dynamics of ION Implantation & Sputtering On Surfaces

DIONISOS: Plasma and IBA designed for maximum flexibility



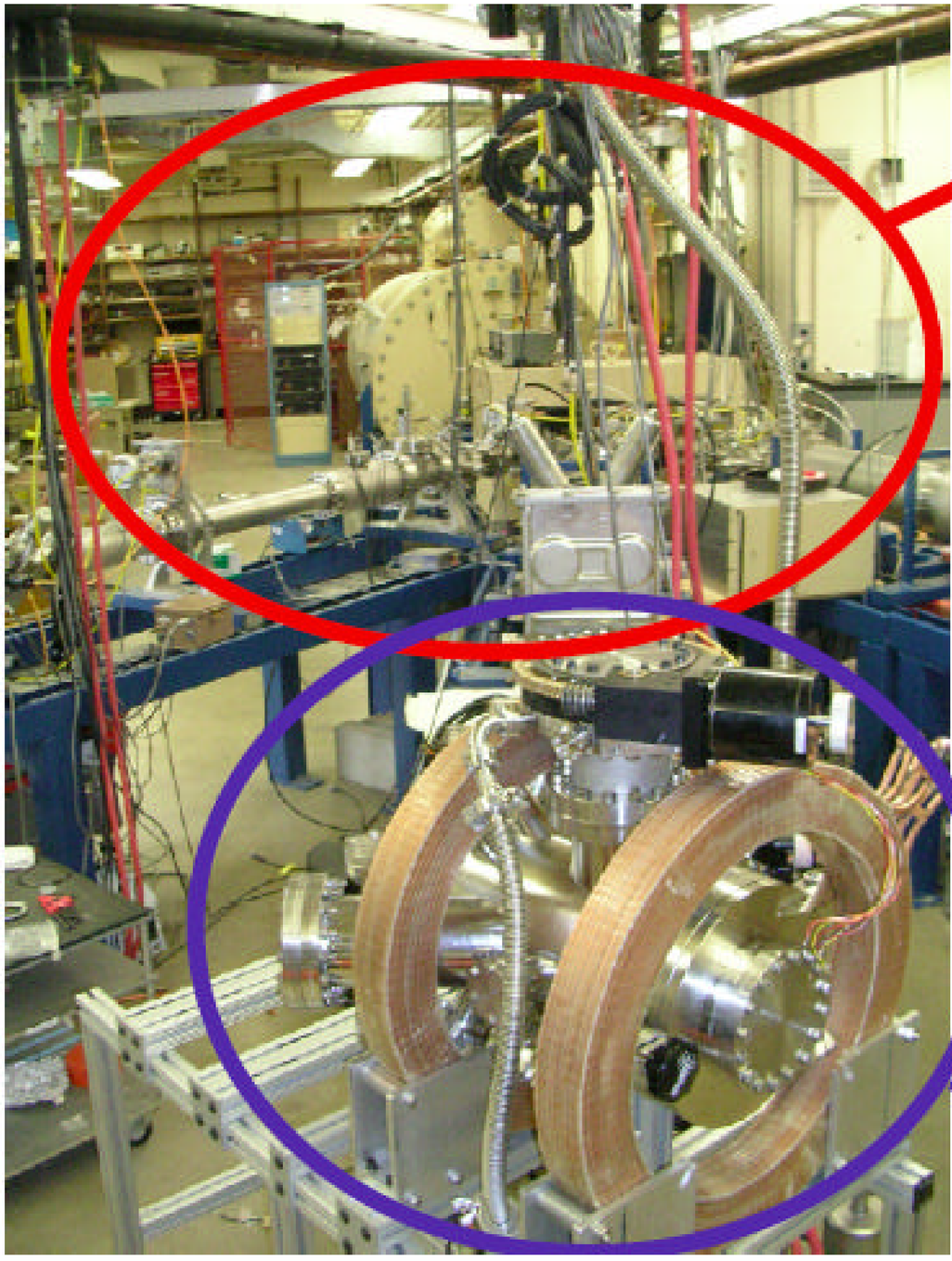
Steady-state helicon source

Axial magnetic field	≤ 1 kG
Plasma density (n_i)	≤ 5 x 10^{13} cm^{-3}
Plasma ion energy (V)	$eV_{float} \rightarrow$ 500 eV
Plasma diameter	5 cm
Ion beam diameter	0.2 cm
Target temperature	300 K - 1000 K
q_{plasma}	≤ 2 MW/m^2

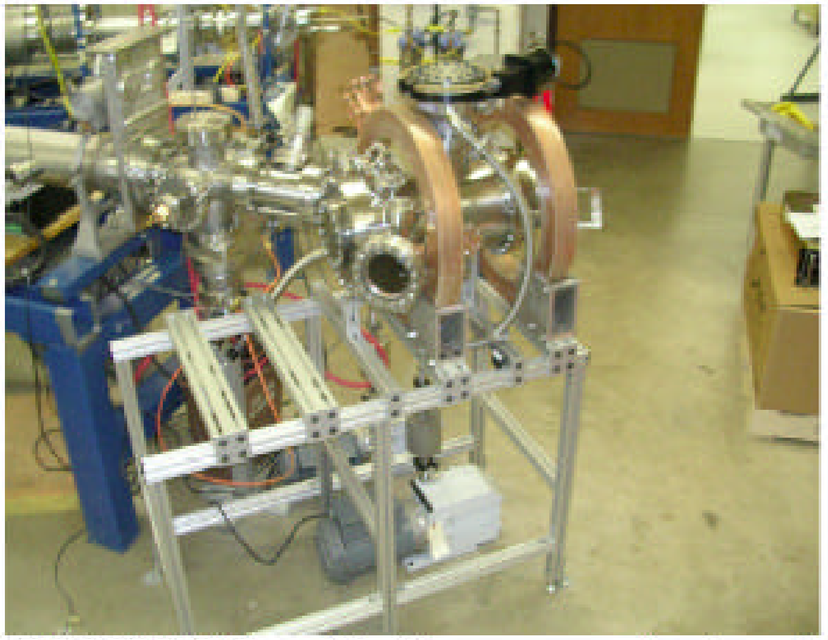
Pulsed Plasma Gun

- **Pulsed (~1-10 ms) H/D plasmas .**
- **T_e~20 eV high density**
- **n_e ~10^{20} m^{-3}**
- **10 $MJ/m^2/s^{1/2}$ per 100 V bias surpasses ablation/melt limits.**
- **j ~ kA / cm^2**

DIONISOS: Facility in operation this spring.



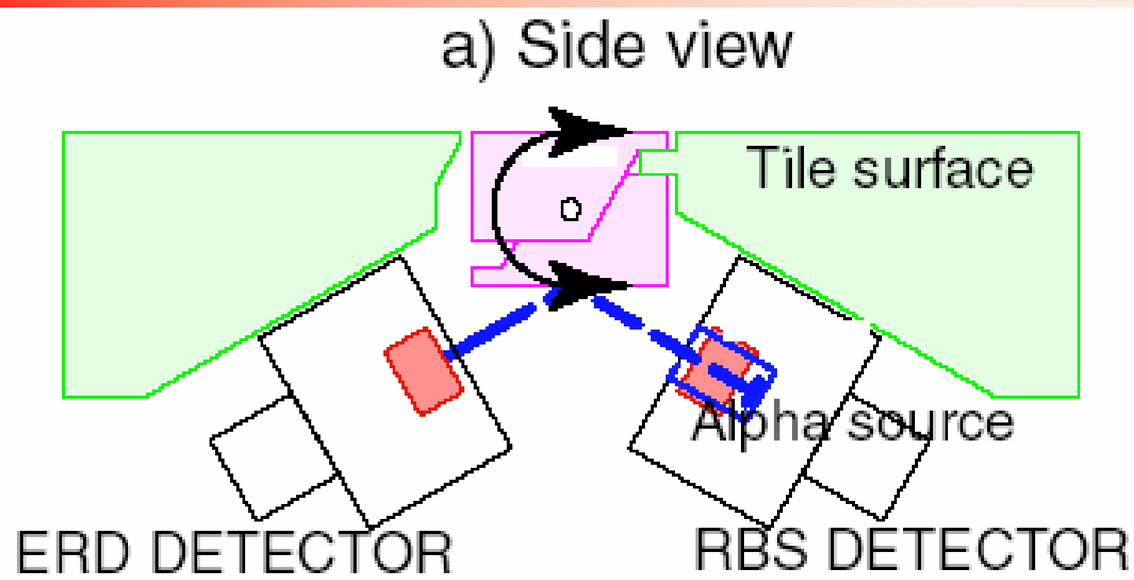
Ion Accelerator (diagnostic)

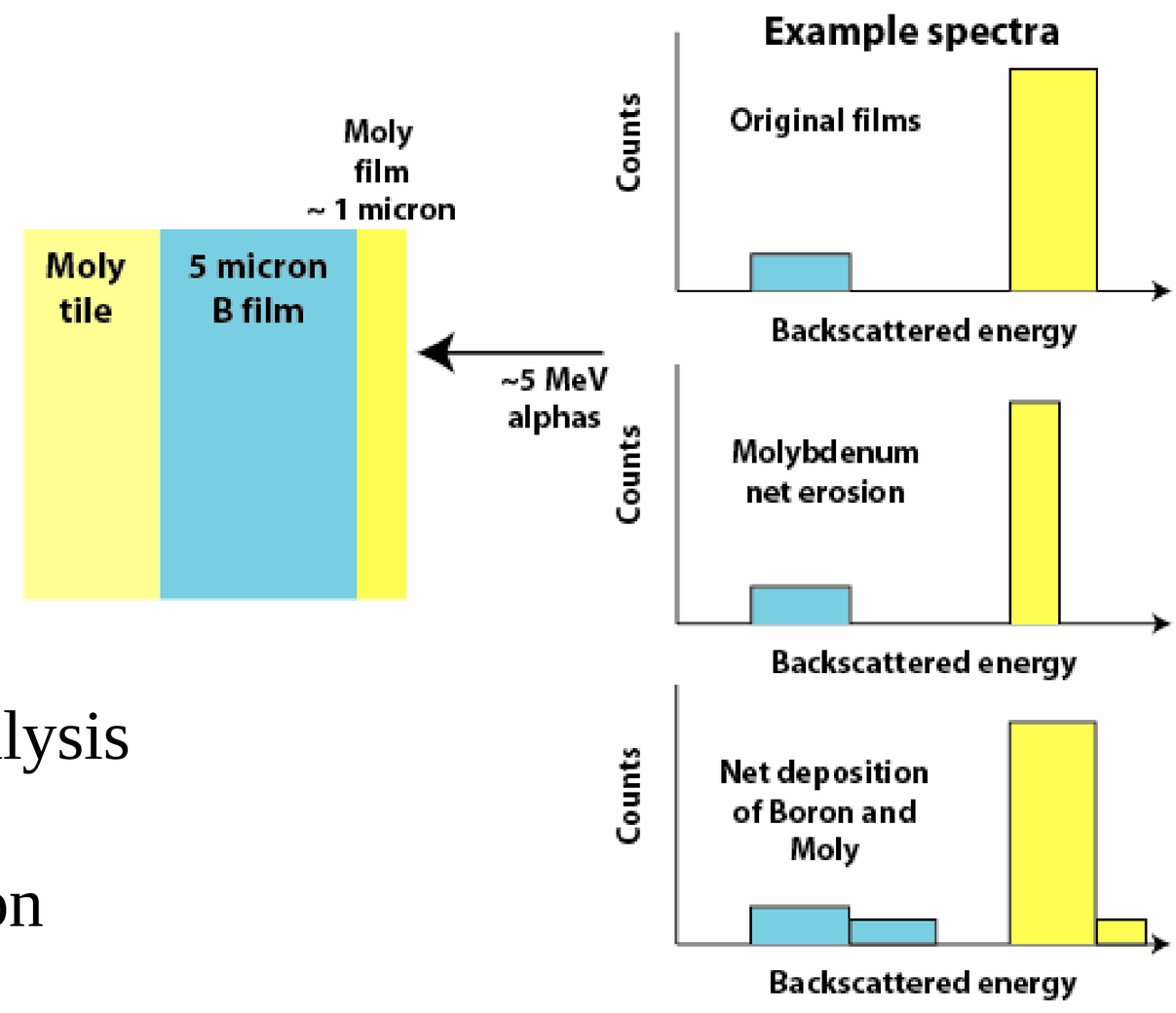


DIONISOS with its support structure and beamline components.

DIONISOS (experiment)

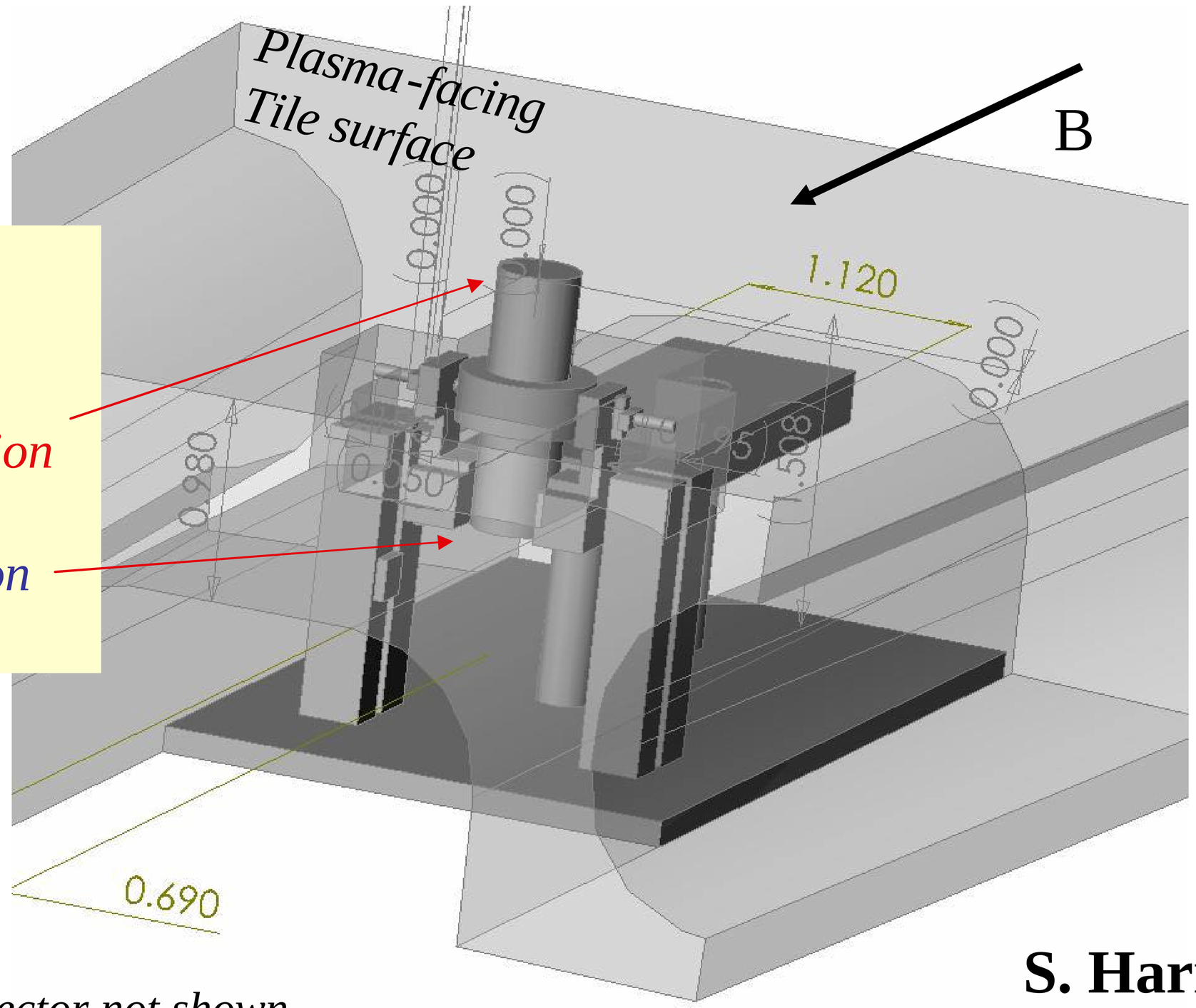
New diagnostic development for in-situ erosion/deposition/H retention measurements on shot-to-shot basis





- Alpha Radioisotope Remote Ion Beam Analysis
- Routine material diagnostic on robotic Moon and Mars missions.
  - Alpha source: ~ 1 mCi Curium with ~ 12 year lifetime
- Thermally contacted to vessel PFC surfaces
  - Implementation at regions of high heat flux.
  - Remote solid-state electronics allow wide distribution.

ARRIBA: Implementation on DIII-D



Twin sample surfaces:

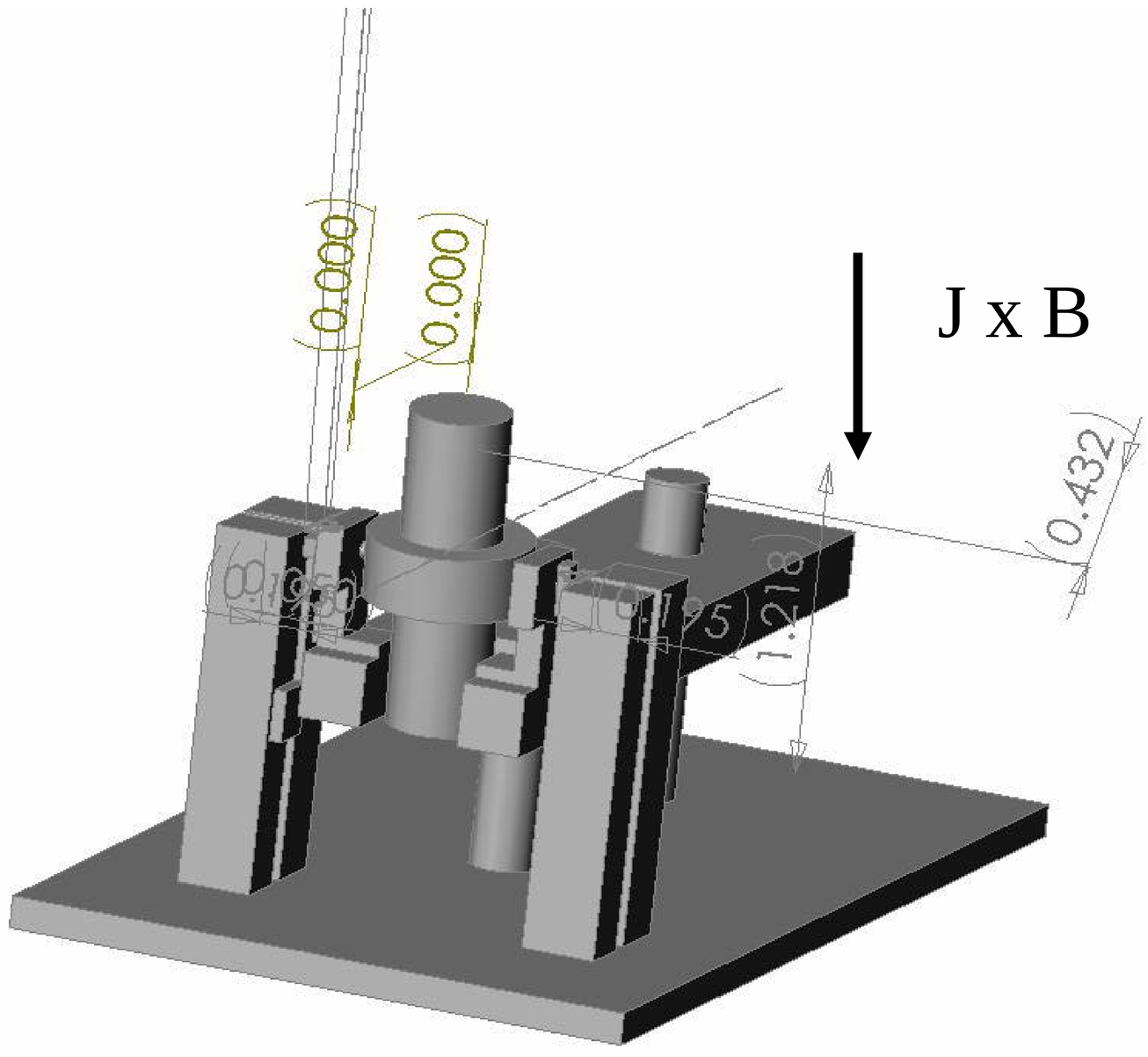
***Exposure** position*

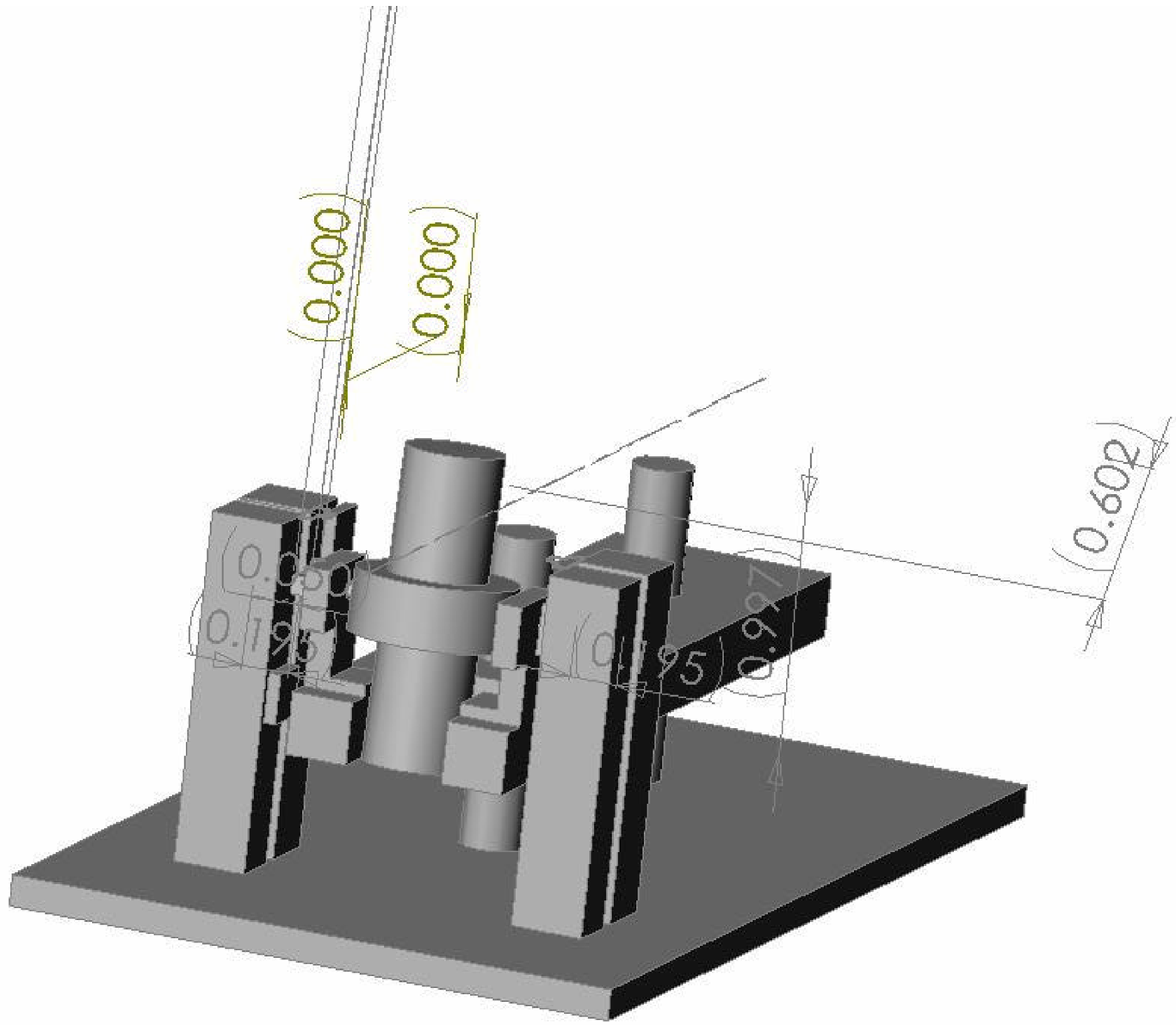
***Analysis** position*

Source & detector not shown

S. Harrison

ARRIBA in motion

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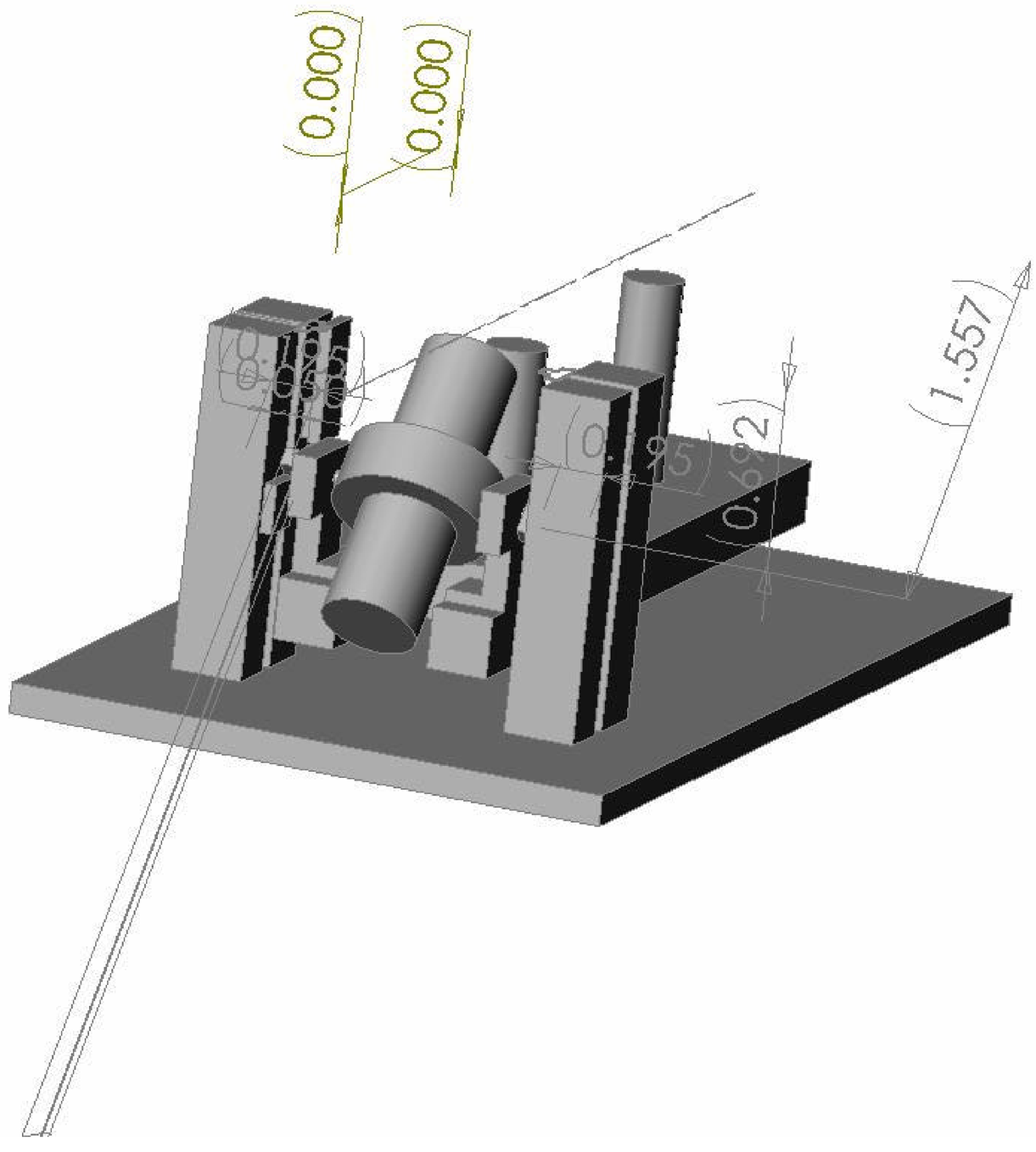
0.602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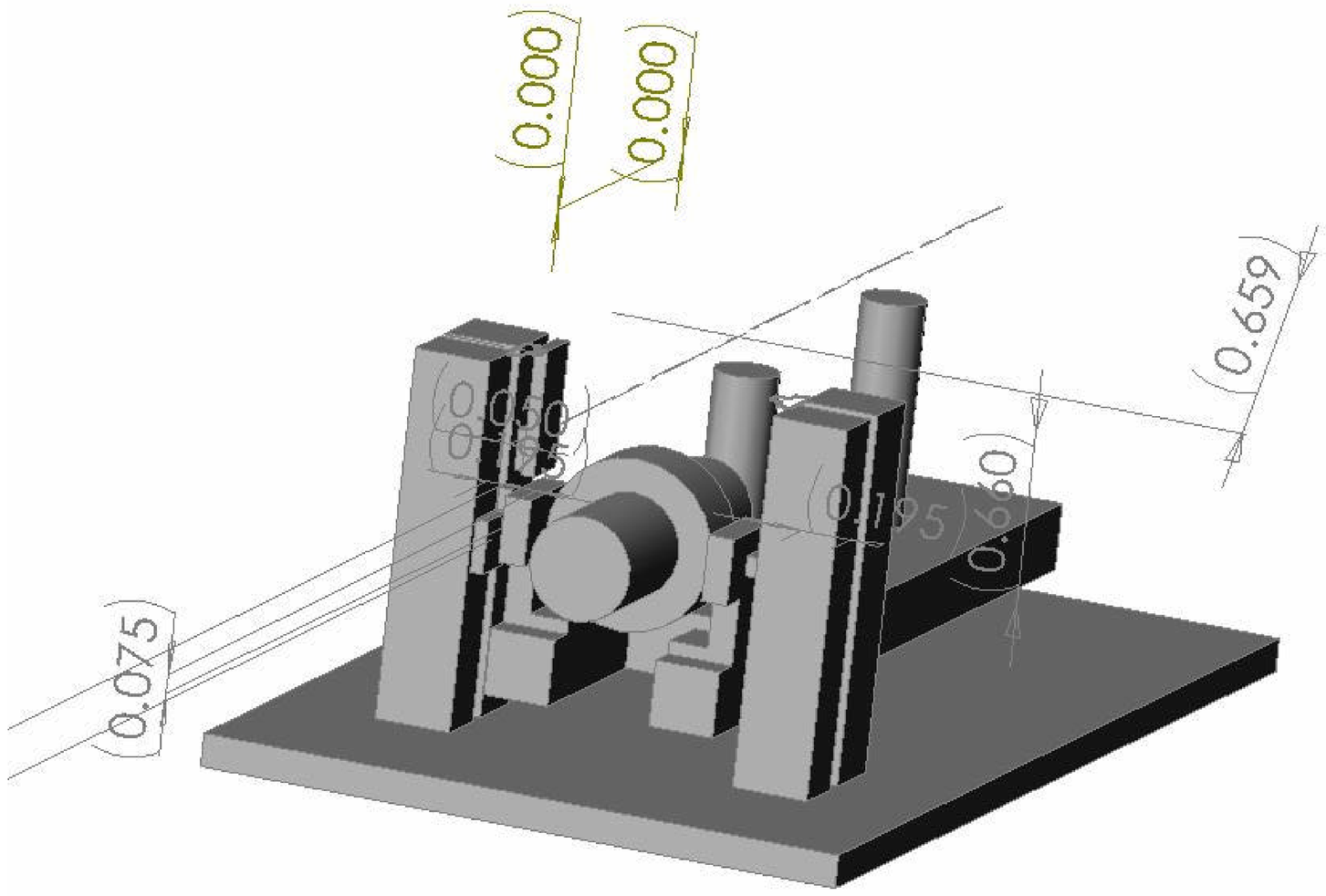
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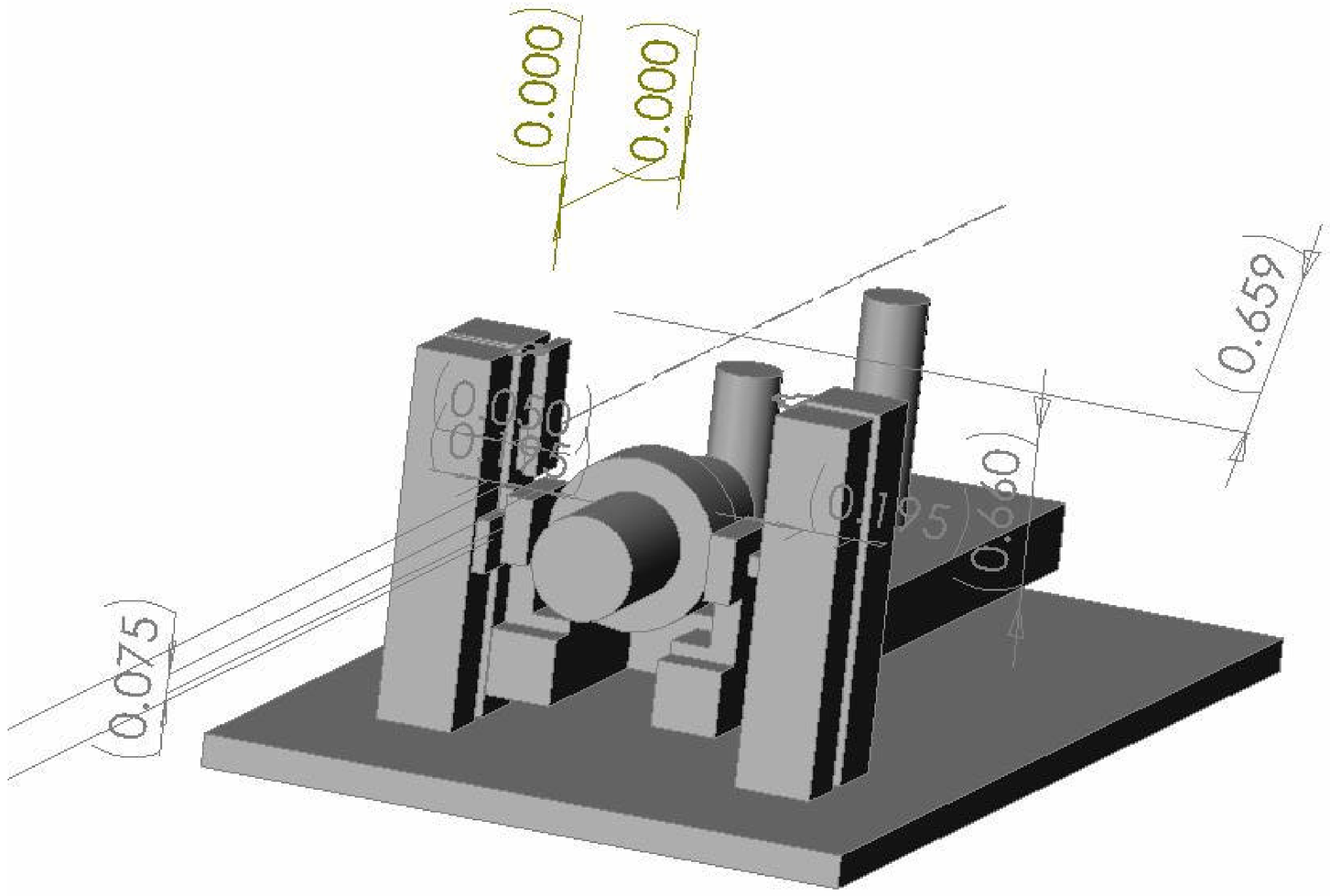
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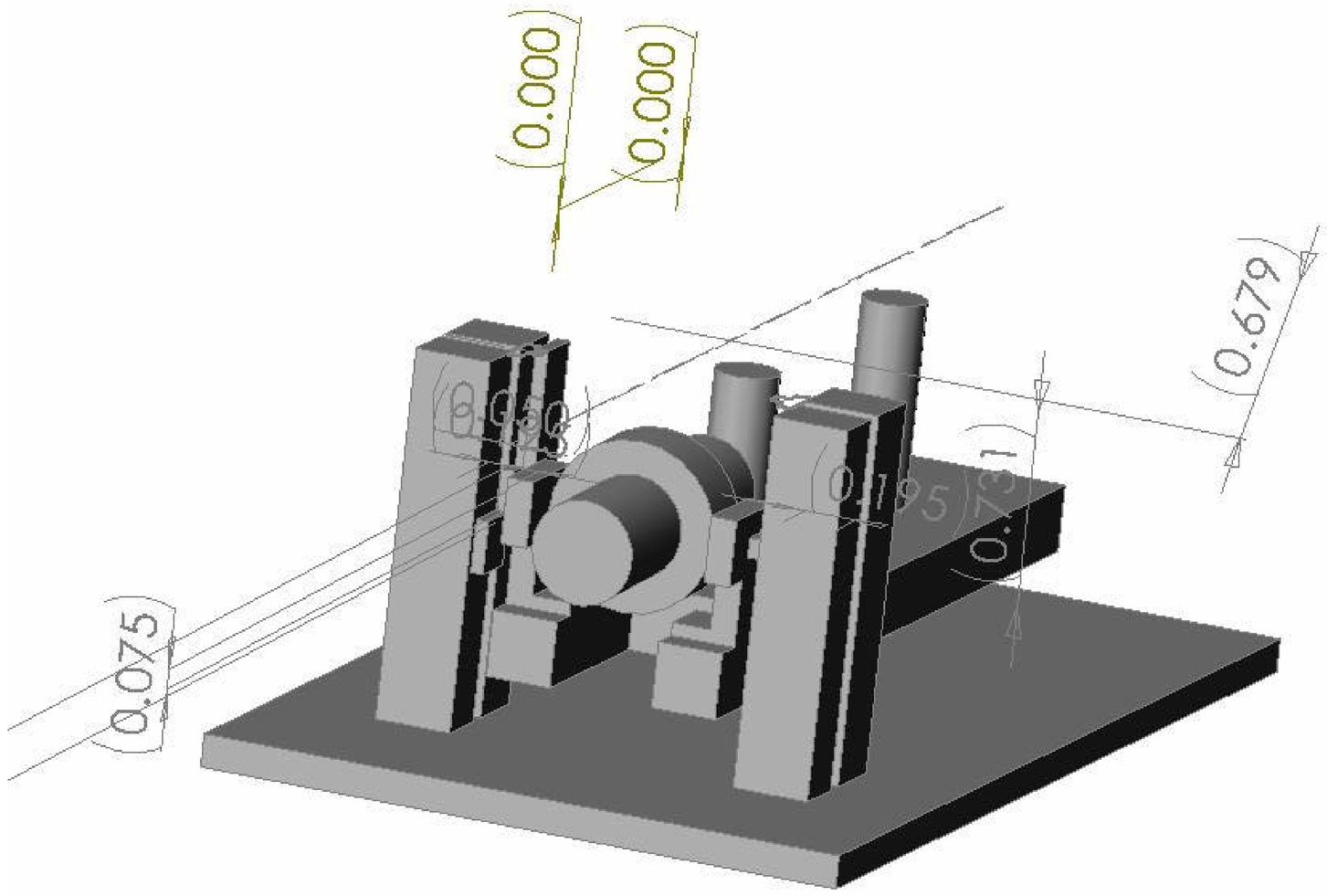
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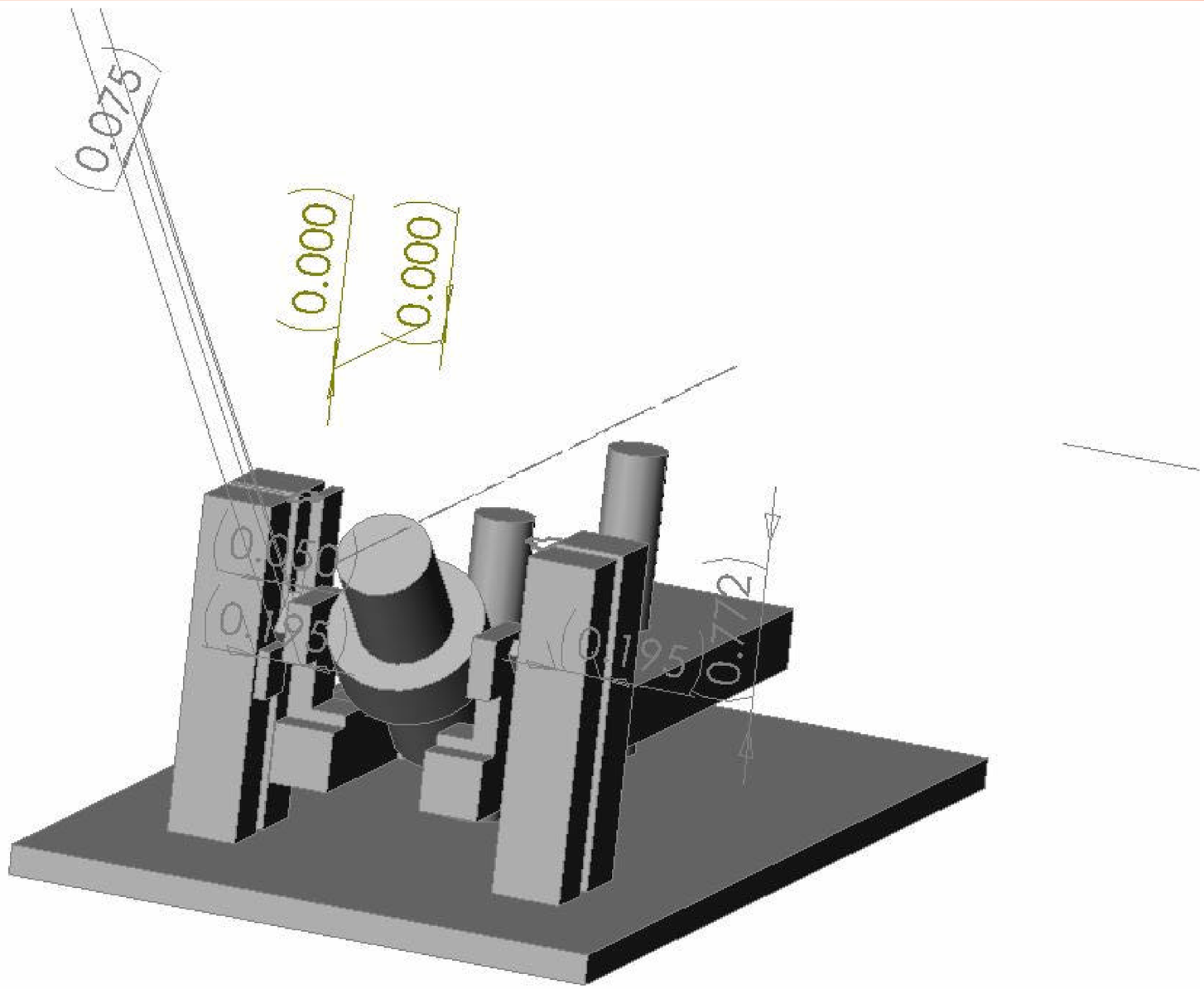
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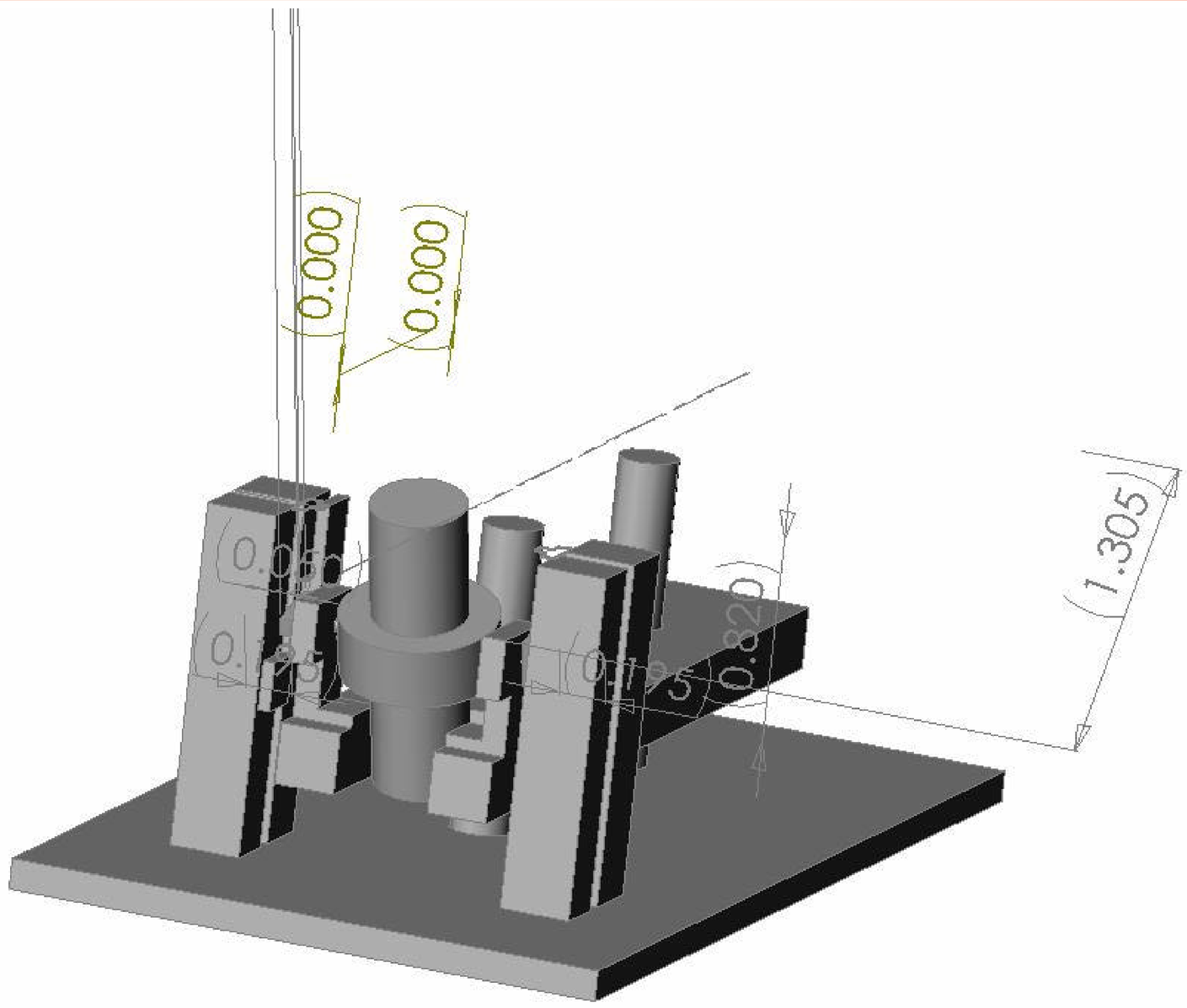
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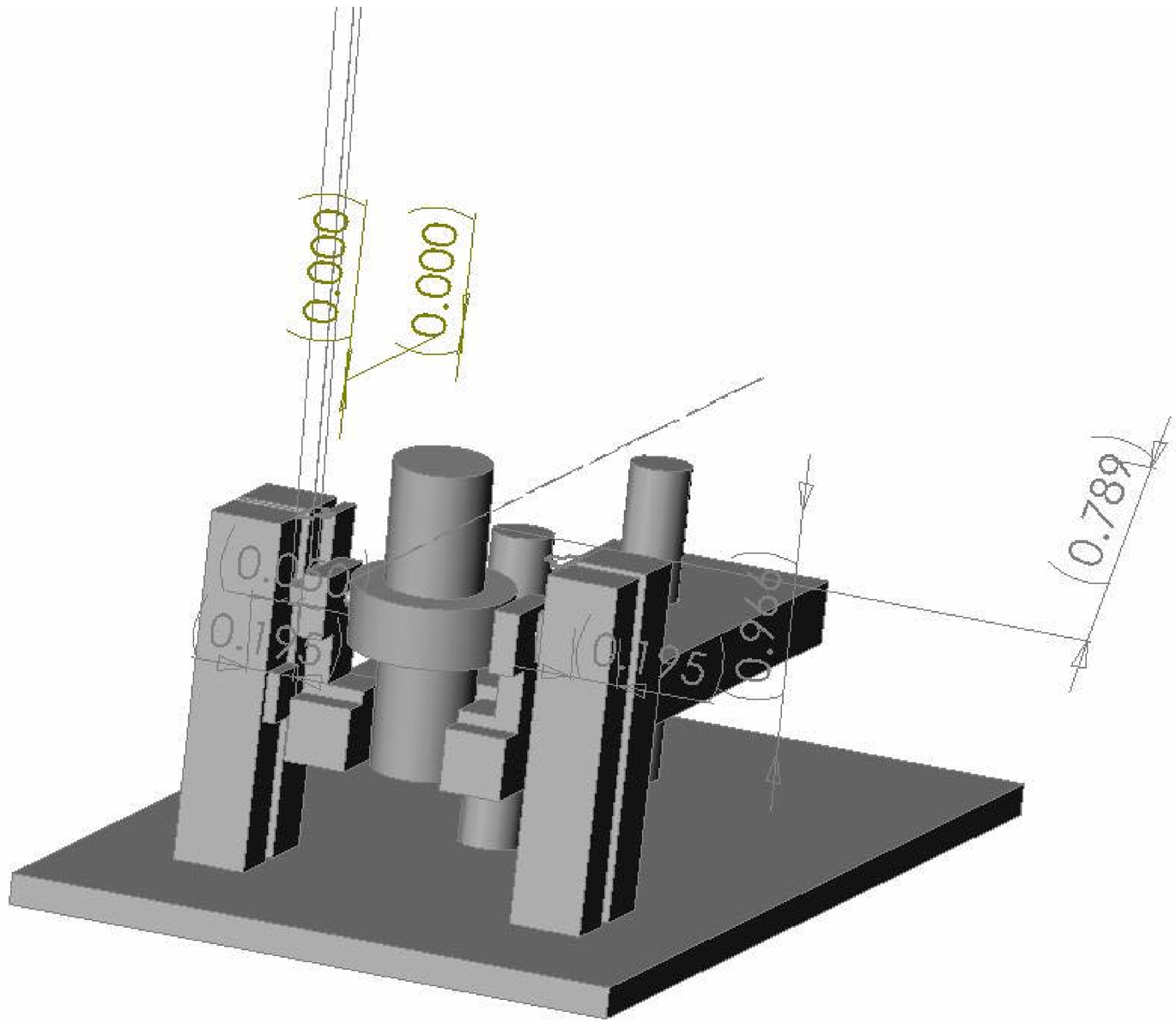
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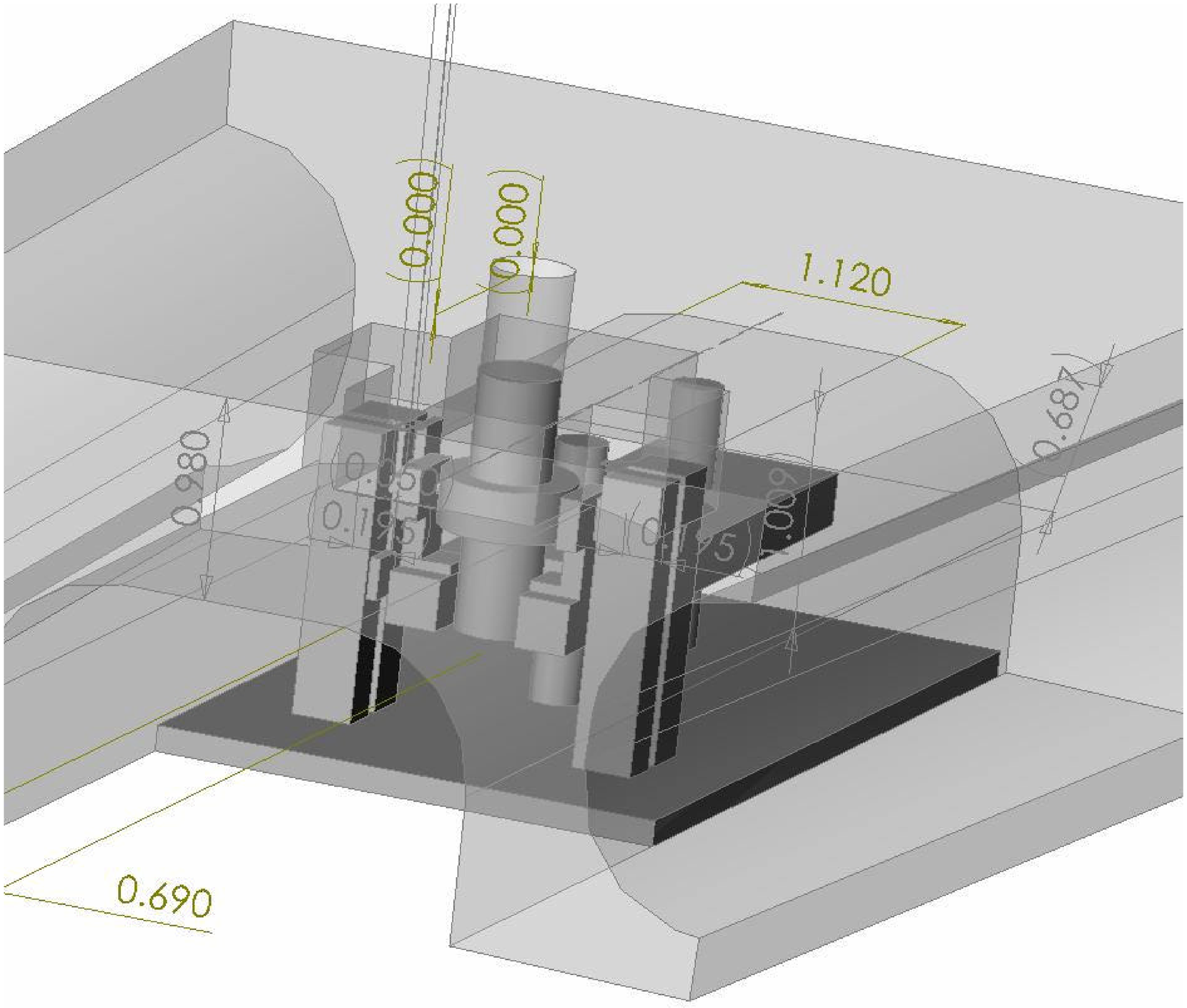
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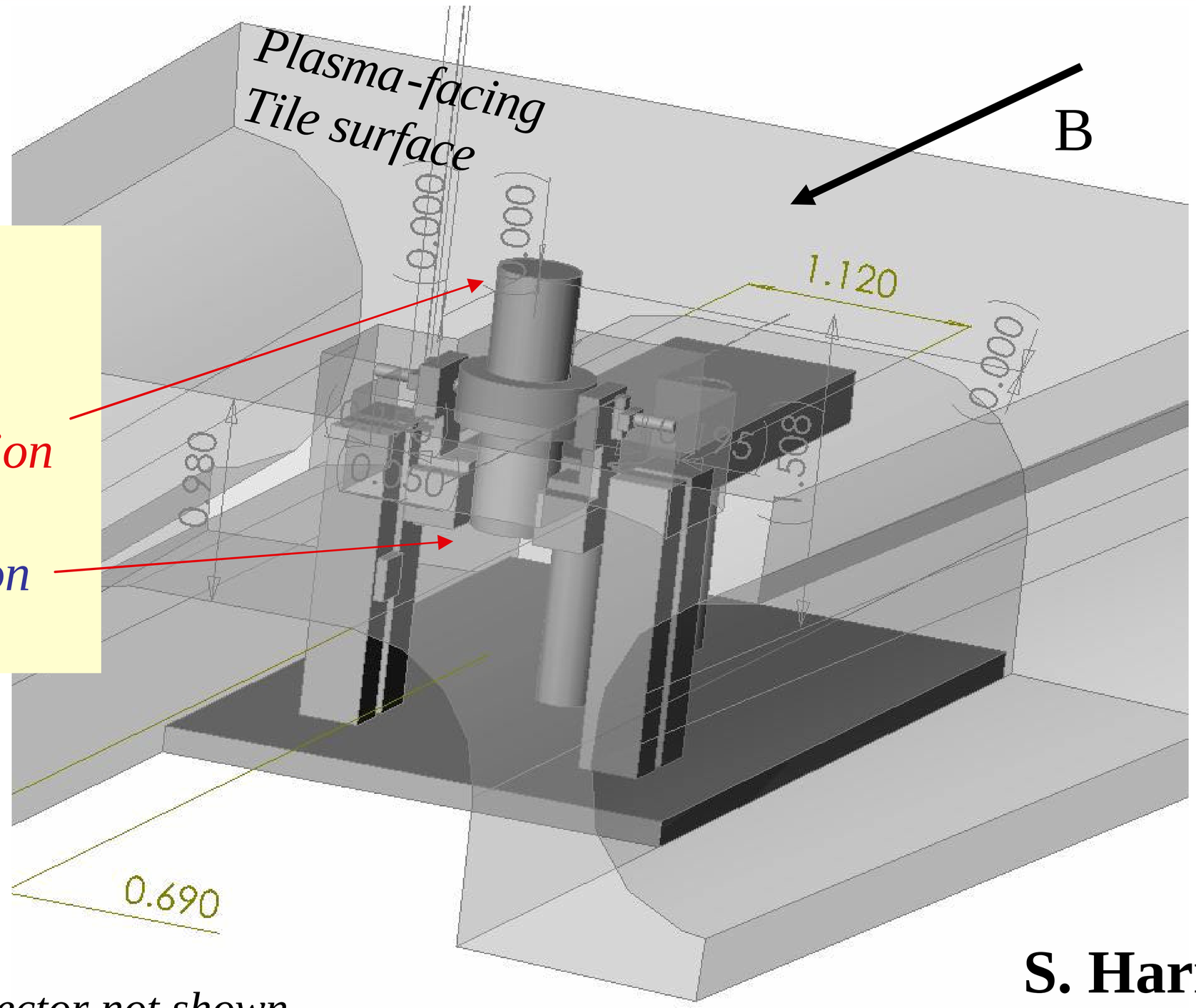
ARRIBA: Implementation on DIII-D



Twin sample surfaces:

***Exposure** position*

***Analysis** position*

Source & detector not shown

S. Harrison

Conclusions

- **Many** outstanding questions for PSI.
  - Scarce empirical data from fusion devices.

- Critical need for temporally & spatially resolved erosion & retention measurements.

- Supporting model & computation tools:
  - Interpretative.
  - 3-D
  - Intermittency