Long Term Reduction of Divertor Carbon Sources in DIII-D

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DIII–D
NATIONAL FUSION FACILITY
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UC San Diego

Abstract Submitted
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Long-term Reduction of Divertor Carbon Sources in DIII-D[1] D.G. WHYTE, R. DOERNER, University of California, San Diego, W.P. WEST, R.L. LEE, N.H. BROOKS, General Atomics, R.C. ISLER, M.R. WADE, Oak Ridge National Laboratory, G.D. PORTER, Lawrence Livermore National Laboratory — The long-term evolution of carbon sputtering from the DIII–D tokamaks graphite-covered lower divertor is studied using *in-situ* spectroscopy and *ex-situ* laboratory erosion yield measurements. The total effective yield and, hence, the impurity source amplitude has gradually decreased a factor > 4 since installation of the tiles in 1992. This reduction is likely caused by the $\sim$ 20-fold reduction in the chemical erosion yield of the graphite, the effect of > 30 applied boronizations. Despite this great success in wall conditioning, there has been no concomitant decrease in the core plasma carbon contamination during the same period. Two explanations are being explored: (1) the nature of parallel impurity transport decouples the wall source and content, and (2) the first wall is the principal source of carbon in the core.

[1]Supported by U.S. DOE Grant DE-FG03-95ER-54294 and Contracts DE-AC03-99ER54463, DE-AC05-96OR22464, and W-7405-ENG-48.

☐ Prefer Oral Session
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Special instructions: DIII-D Poster Session 2, immediately following RJ Colchin

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Outline

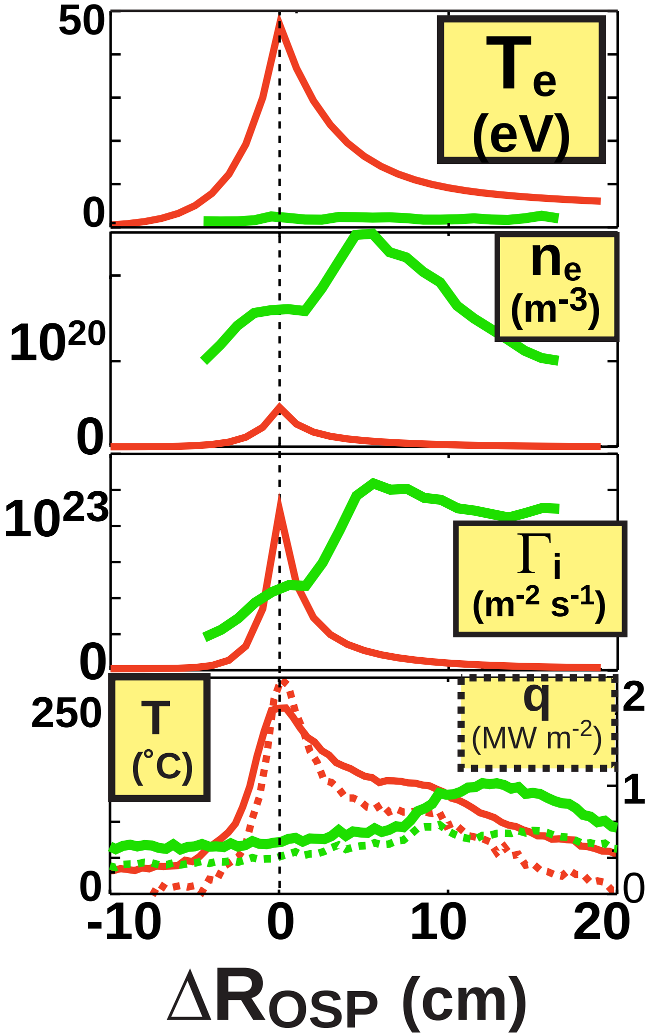
- Background & Motivation
- History of chemical and total erosion yields in DIII-D lower divertor (1992- present).
- Effect of lower divertor carbon erosion yield on core plasma carbon contamination.
- Laboratory studies of DIII-D graphite tiles
- Summary & discussion.

Background & Motivation

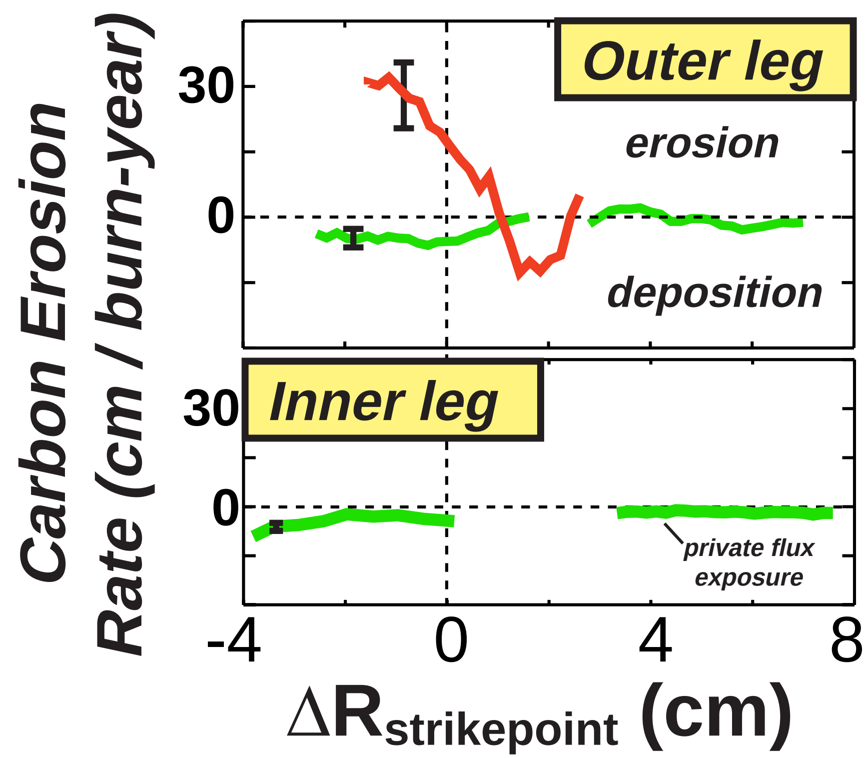
- Previous results suggest chemical erosion of carbon plays an **important** role in DIII-D
  - Helium plasmas: reduced carbon radiation in core and divertor.
  - UEDGE modeling: a “distributed” chemical carbon source (using University of Toronto Y_{chem}) provided radiation to induce detachment and match C spectroscopy.
- Previous results suggest that chemical erosion of carbon plays a **minor** role in DIII-D
  - CD-band emission not observed in divertor ($Y_{chem} < 10^{-3}$).
  - Divertor detachment, which eliminates physical sputtering, showed only carbon deposition in divertor (DiMES, PSI 98) ..total yield reduced by x100.

- Current carbon-based tokamaks show divertor erosion and tritium retention will seriously limit operations of next-step DT devices.

Divertor detachment eliminates net carbon erosion in the entire lower divertor! ...yet carbon density in core plasma remains constant?

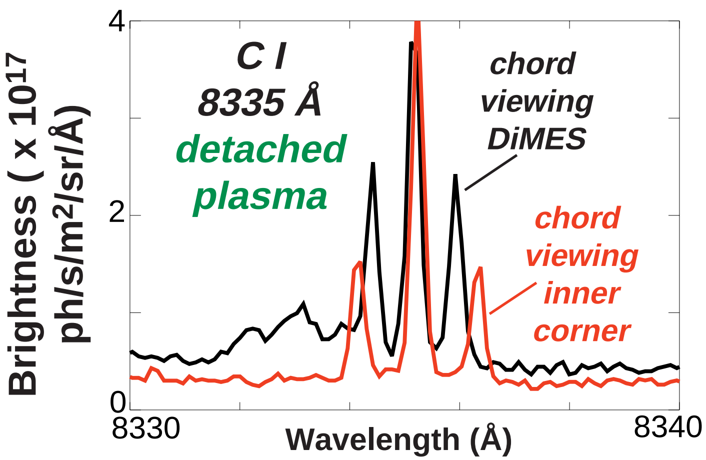


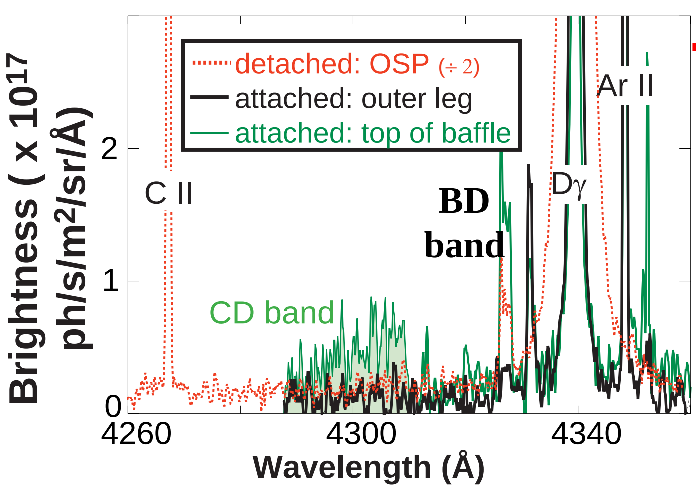
Attached
vs.
Detached



D_2 Torr L /s	I_p MA	P_{aux} MW	W_{th} MW	n_e / n_C $10^{19} m^{-3}$	f_C %
0	1.4	7.2	1.2	4 / .16	4
~100	1.35	6.9	0.9	10 / .15	1.5

Atomic and molecular spectroscopy suggest chemical erosion plays a minor role in DIII-D divertor.



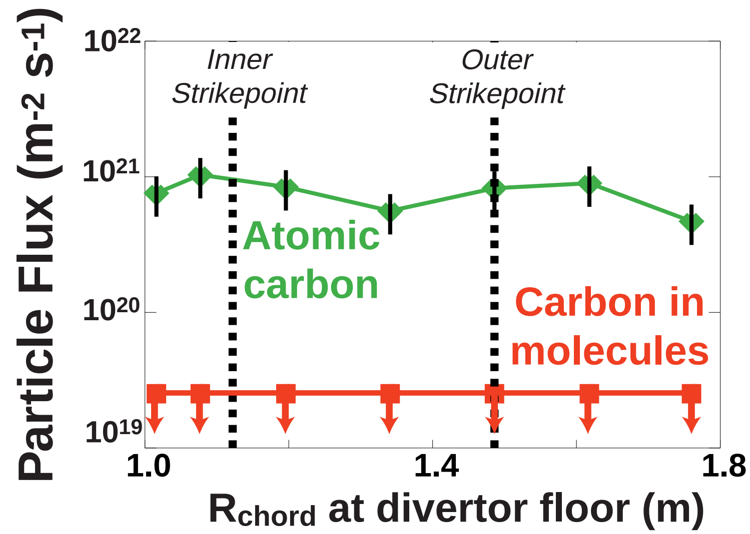


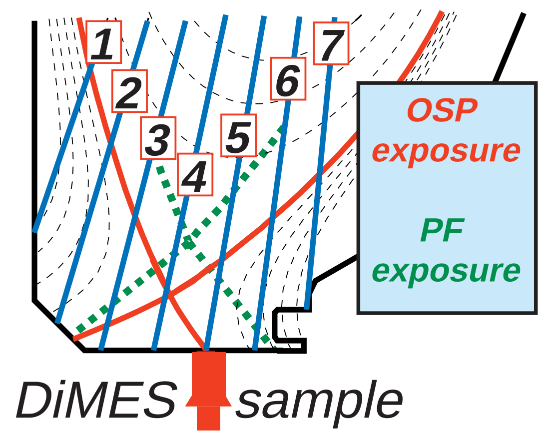
Atomic Carbon
SXB ~ 300

Molecular Carbon (C_xH_y)
DXB ~ 100

Assumption	Y_{chem}
Ions only	$\leq 10^{-3}$
Ions=neutrals	$\leq 10^{-4}$

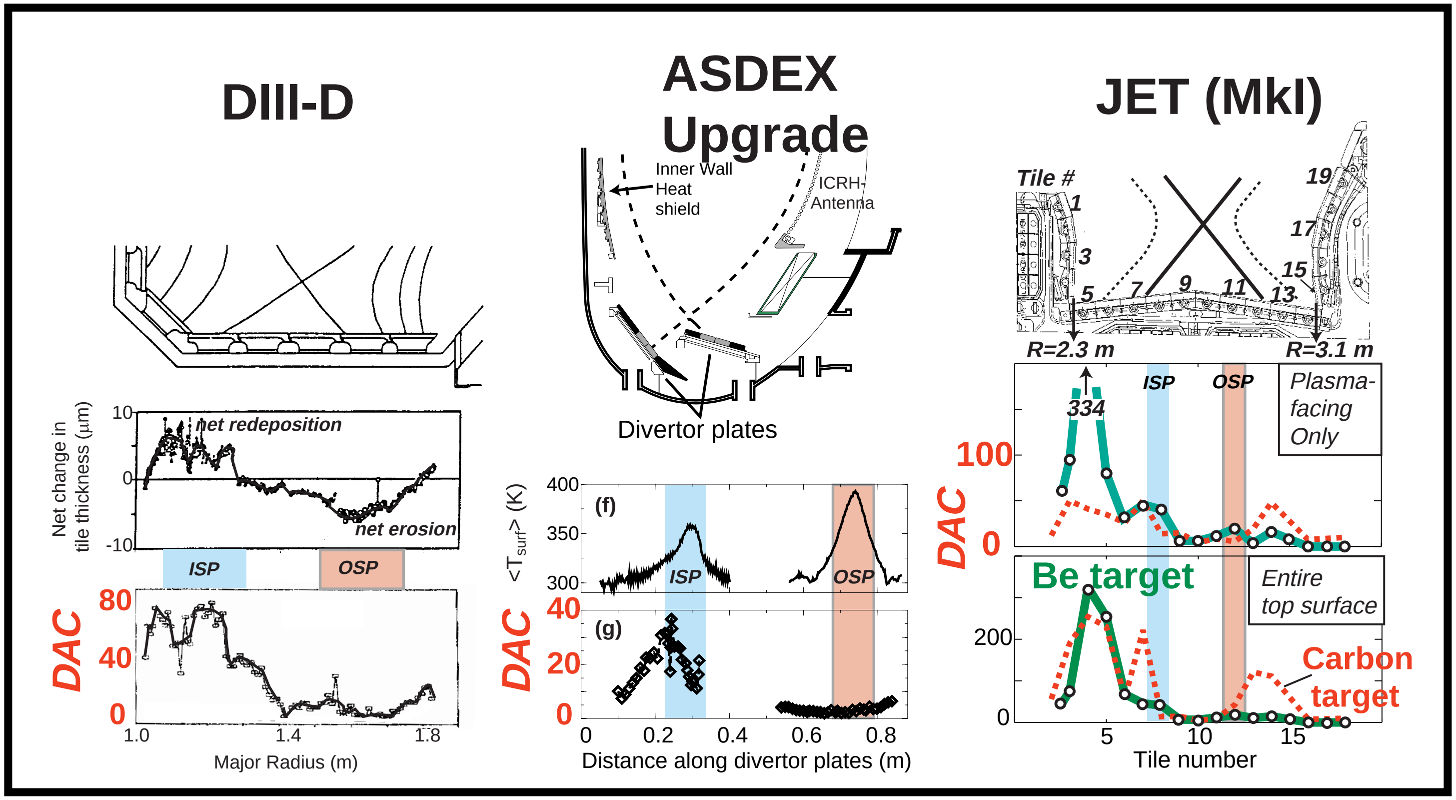
Detached DiMES exp't





Based on carbon-based tokamaks' standard operation, erosion will severely limit operation of D-T burning device.

- **Pervasive in/out asymmetry.**
- **Outer divertor net erosion rate: > *10 cm / burn-year*!**
- **T trapping in erosion caused layers: ~ *1 kg / m^2 / burn-year*!**



***Poloidal erosion / redeposition patterns from 3 tokamaks: > 1 year of operations*.**

DAC: trapped D concentration

D.G. Whyte, et al. Nucl Fusion (1999).

History of carbon chemical erosion yields in the DIII-D lower divertor (1992- present).

Relative spectroscopy can be used to measure carbon erosion yields in situ

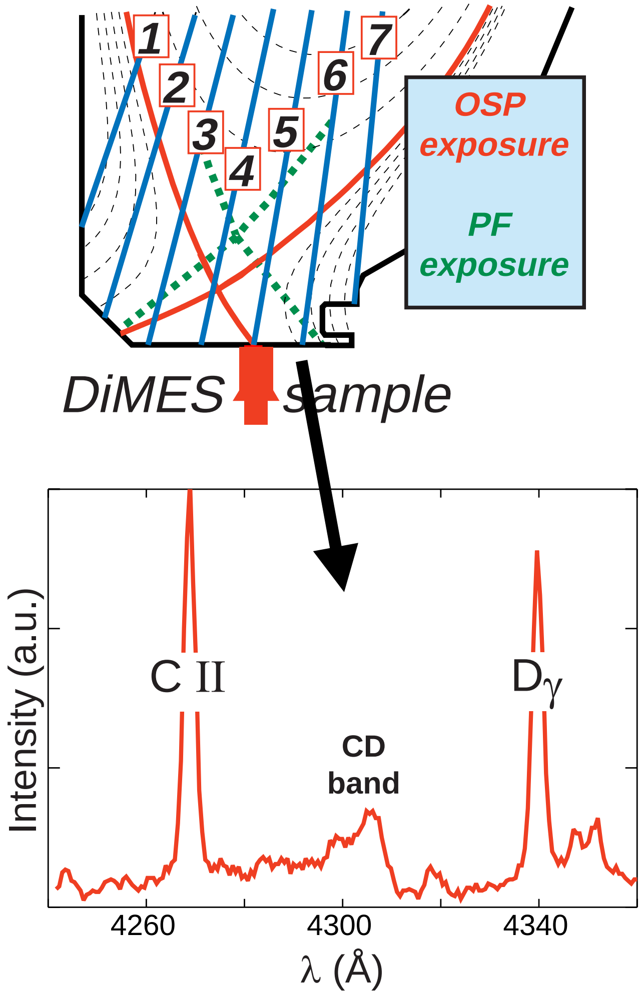
- Technique relies on S/XB (loss events per photon) and relative intensities:
  - Fairly insensitive to T_e and n_e.
  - Insensitive to photometric calibration.

- Chemical erosion yield

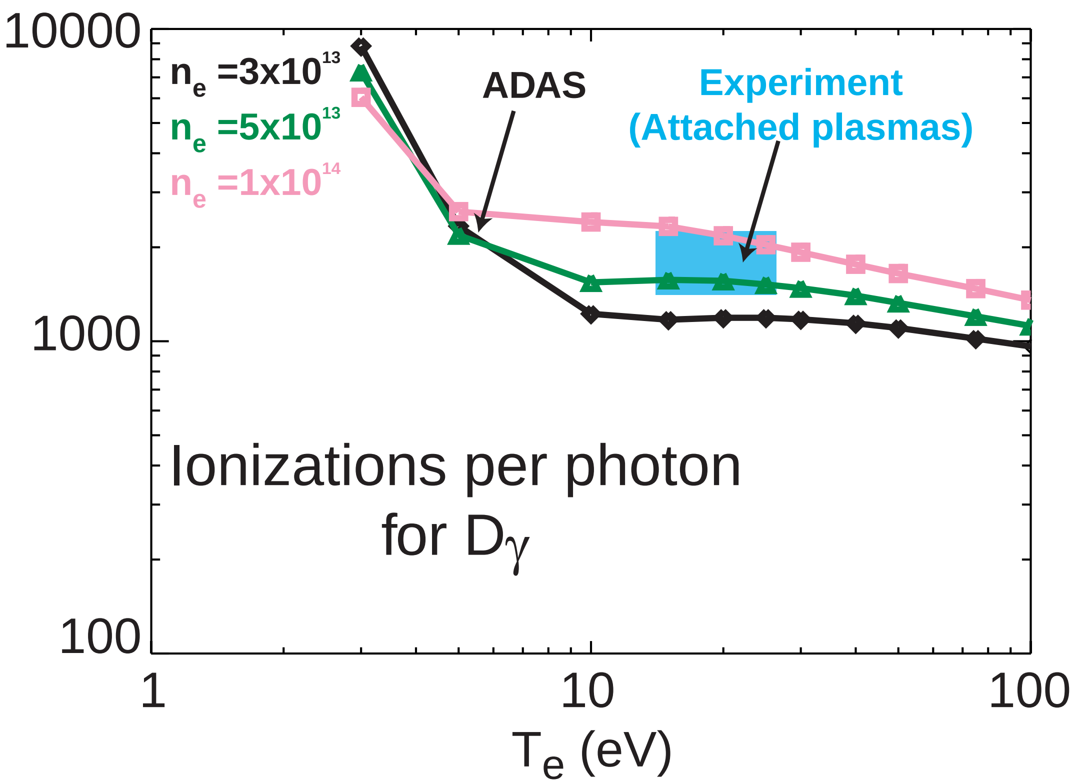
$$Y_{chem} = \frac{\Gamma_{C_xD_y}}{\Gamma_D} = \frac{B_{CD} \cdot D/XB_{CD}}{B_{D_\gamma} \cdot S/XB_{D_\gamma}}$$

- Total erosion yield

$$Y_{total} = \frac{(\Gamma_{C_xD_y} + \Gamma_{C_0})}{\Gamma_D} \propto \frac{B_{CII} \cdot S/XB_{CII}}{B_{D_{\alpha,\gamma}} \cdot S/XB_{D_{\alpha,\gamma}}}$$



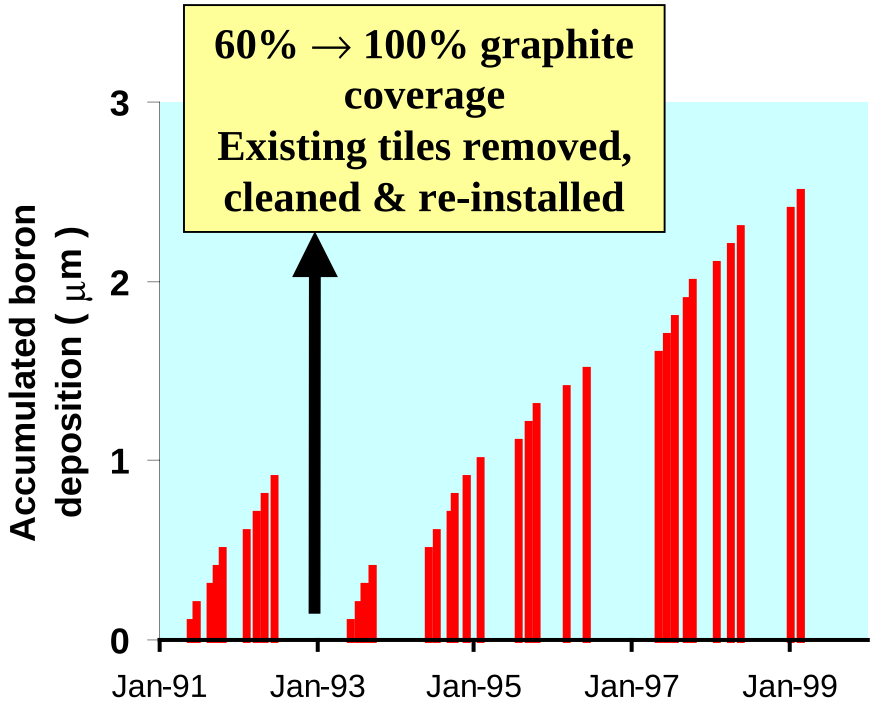
S/XB and D/XB values are fairly constant for attached plasma (T_e > 10 eV) conditions.

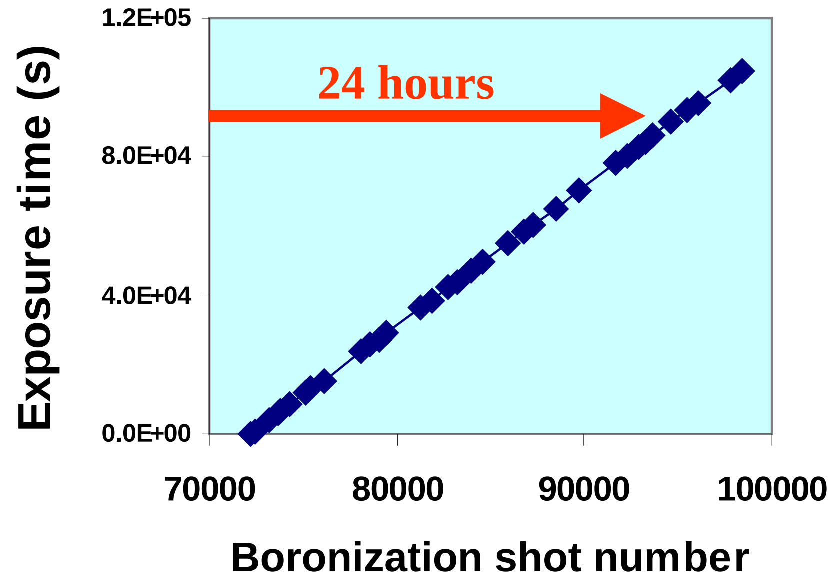


- Derived values for D_γ S/XB
  - Atomic rate calculations.
  - Experimental comparison to probes & DTS.
  - Agreement / scatter to within a factor of 2.
  - Assumes recycling ~ influx.

- D/XB is derived from controlled CD_4 injections:
  - **JET: D/XB ~40-50 for attached plasmas.**
  - **PISCES: D/XB ~50-100 for T_e > 10 eV.**

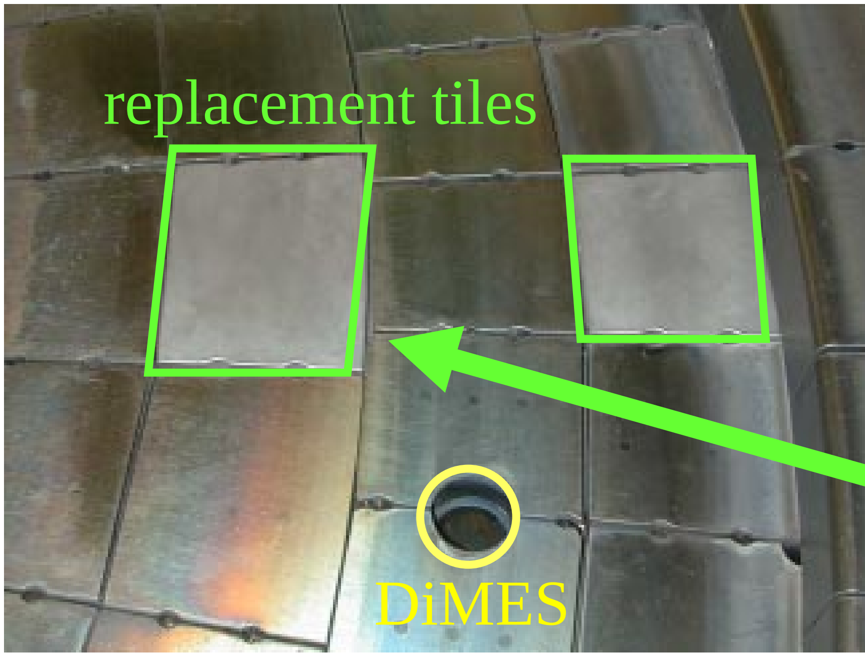
DIII-D tiles have accumulated ~2.5 μm of boronization layers & ~10^5 seconds (25,000 shots) of plasma exposure without significant alterations to lower divertor tiles.





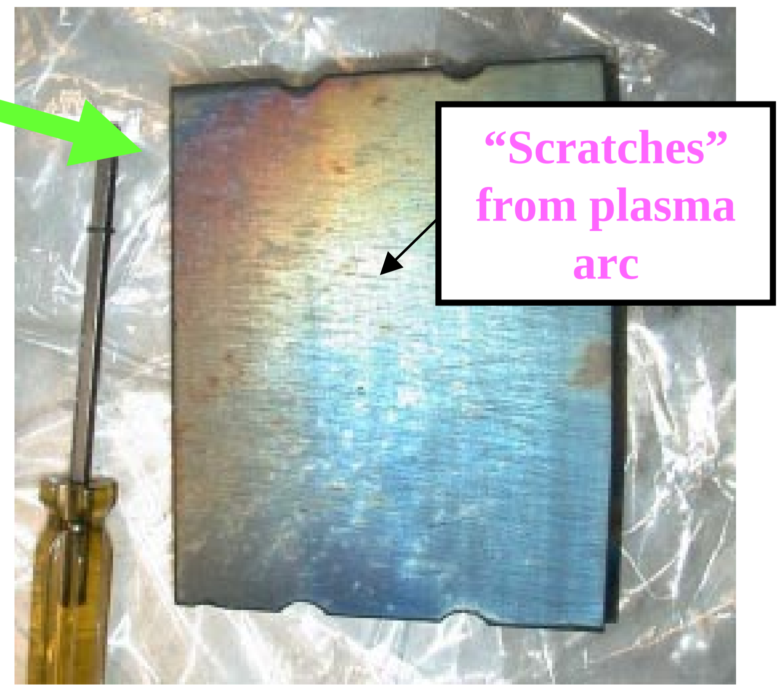
Single boronization = ~100 nm uniform B layer deposited

Graphite tiles are visibly altered by tokamak exposure.

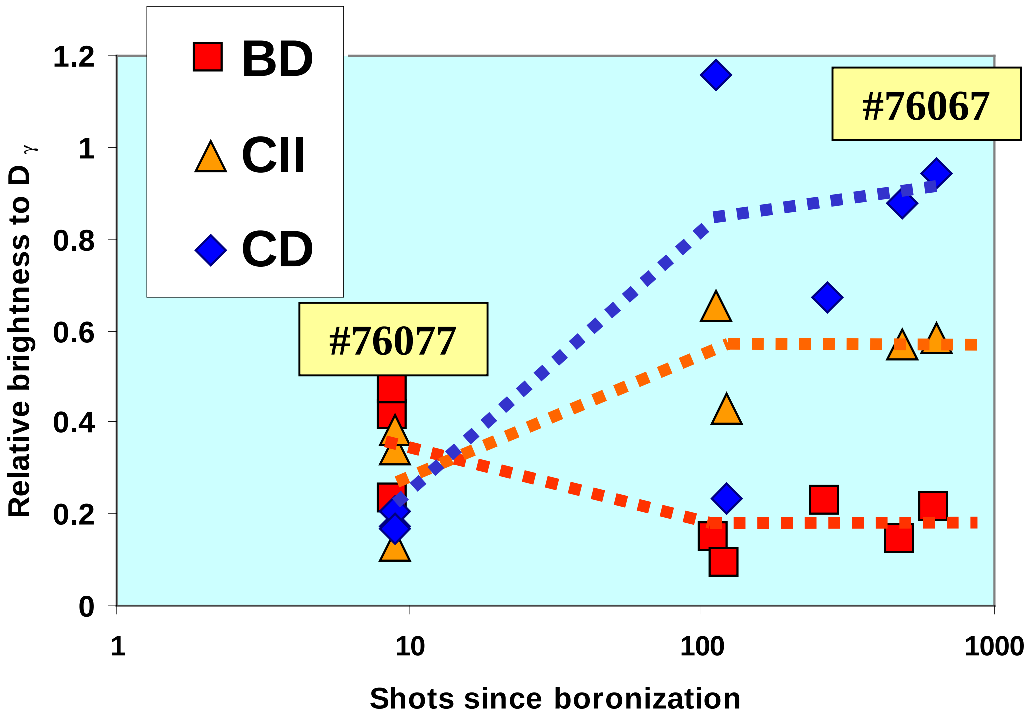


DIII-D Lower Divertor near DiMES (August 1998)

Plasma-exposed tile removed from DIII-D for PISCES exposure



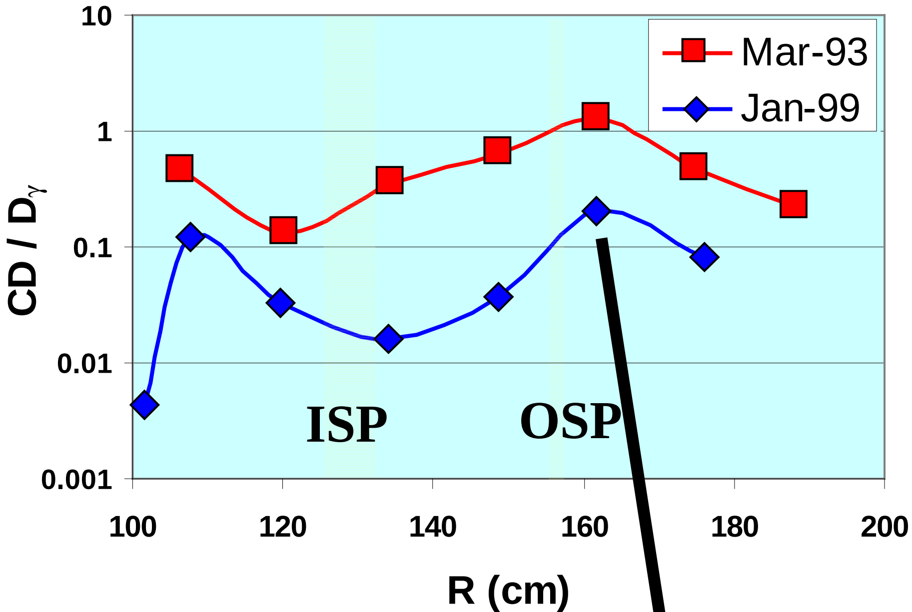
In 1992-1993, a single boronization would cause an immediate, but temporary, reduction in Y_{chem} and Y_{total}.



Averaged over lower divertor chords

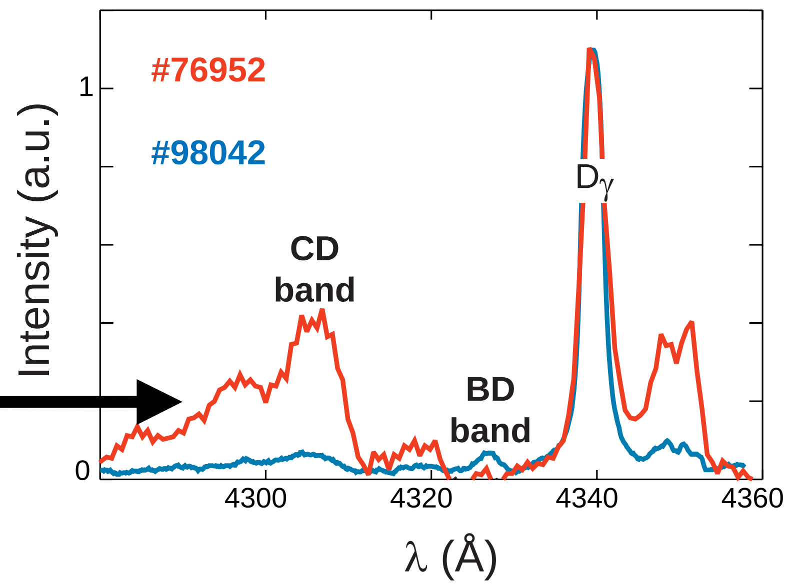
- Direct comparison before and after boronization.
  - Y_{chem} reduced ~x4
  - Y_{total} reduced ~x2
- BD band reduced, but not eliminated by plasma exposure.
- Substantial removal of 100 nm boron layer consistent with measured OSP net erosion rates ~ 2 nm/s

Comparison of nearly identical plasmas show that Y_{chem} has decreased significantly in DIII-D since 1993.



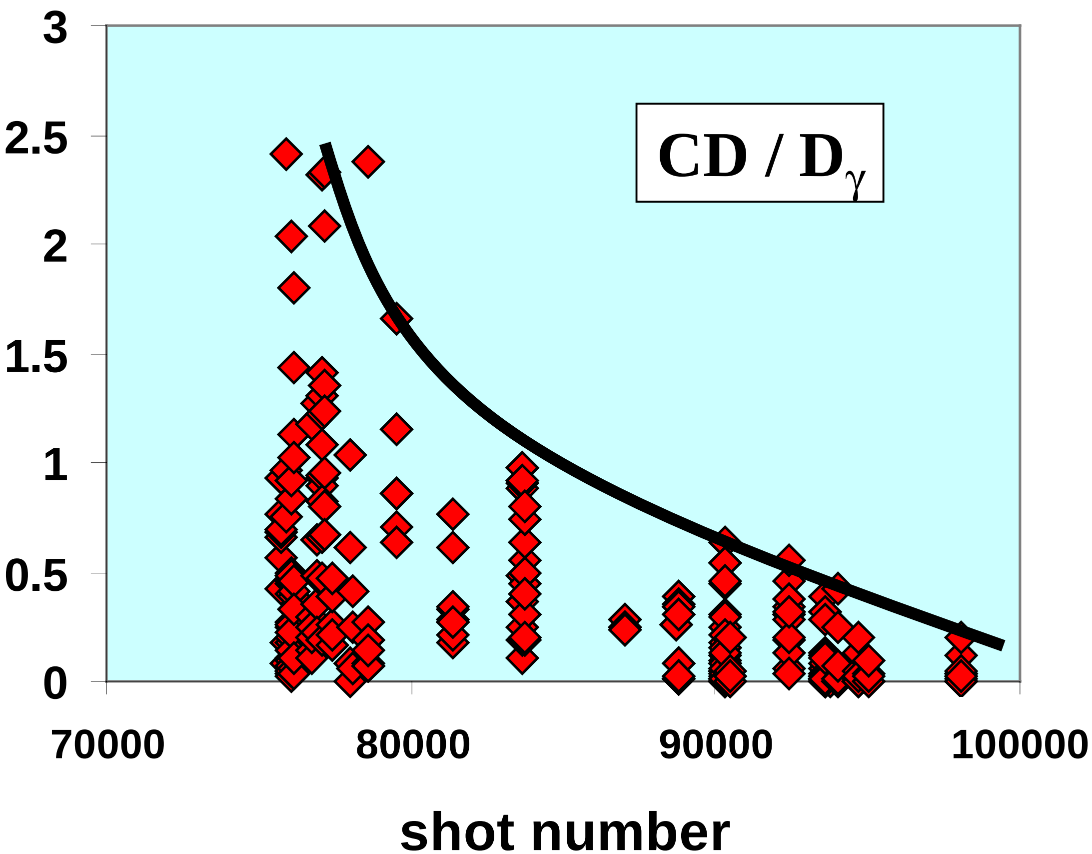
	#76952	#98042
I_p (MA)	1.5	1.4
n_e (cm^{-3})	$7.6x10^{13}$	$6.8x10^{13}$
P_{inj} (MW)	6.9	6.6
W_{dia} (MJ)	1.2	1.1

Spectra normalized to D_γ intensity & for different detector responses (intensified vs. non-intensified)



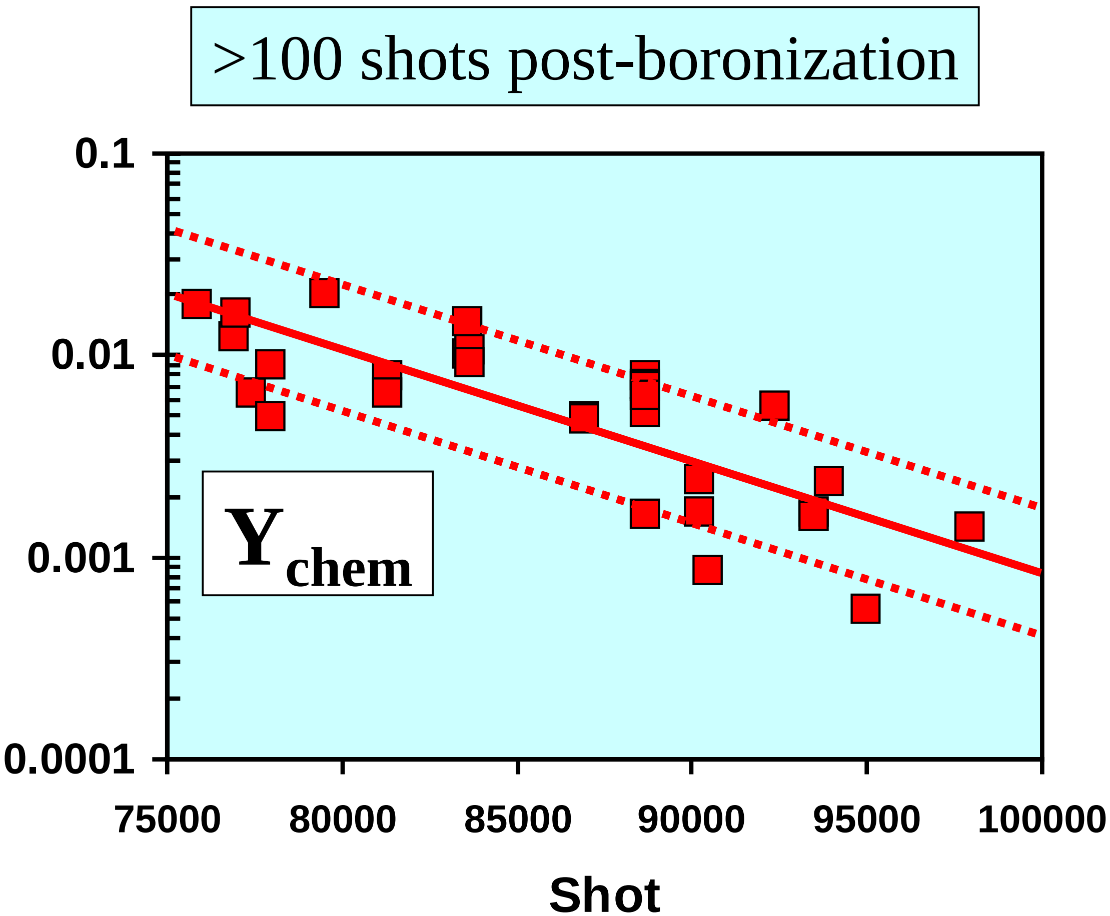
A database of lower divertor CD band spectroscopy (1992-1999) clearly shows a large reduction in Y_{chem}.

All chords, all plasma types



- Includes all discharges where spectrometer was tuned to 430 nm:
  - **LSN & DN**
  - **Ohmic, L, ELMy H**
  - **Attached & detached.**

Average lower divertor Y_{chem} for attached ELMy H-mode plasmas has gradually decreased a factor of 20 from ~2% to ~0.1% since 1992.

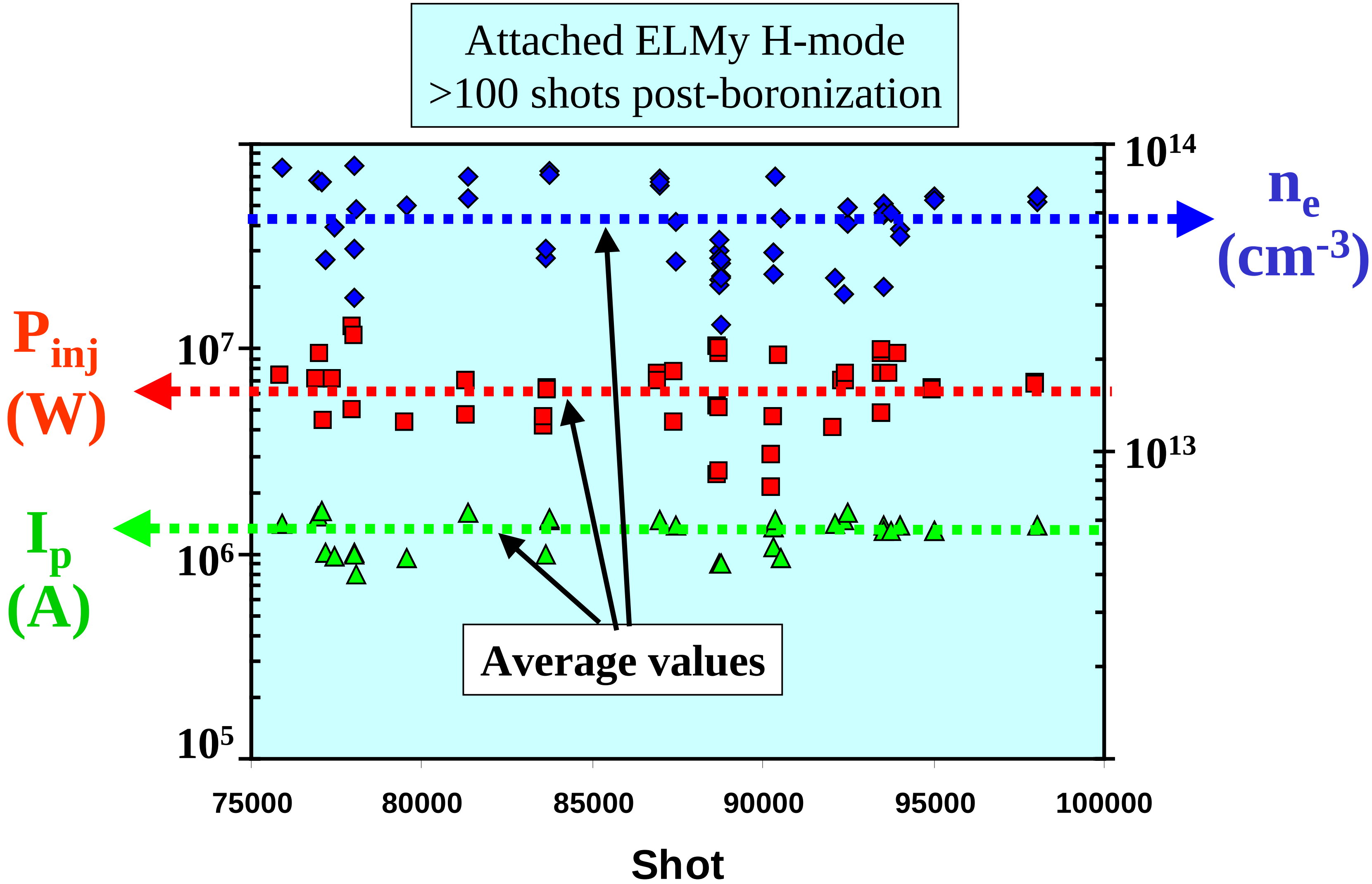


- Yield measurement fairly reliable since for attached divertor T_e > 10 eV:
  - **D/XB_{CD} ~ 50**
  - **$S/XB_{D\gamma}$ ~ 2000**

$$Y_{chem} = \frac{\Gamma_{C_x D_y}}{\Gamma_D} = \frac{B_{CD} \cdot D/XB_{CD}}{B_{D_\gamma} \cdot S/XB_{D_\gamma}}$$

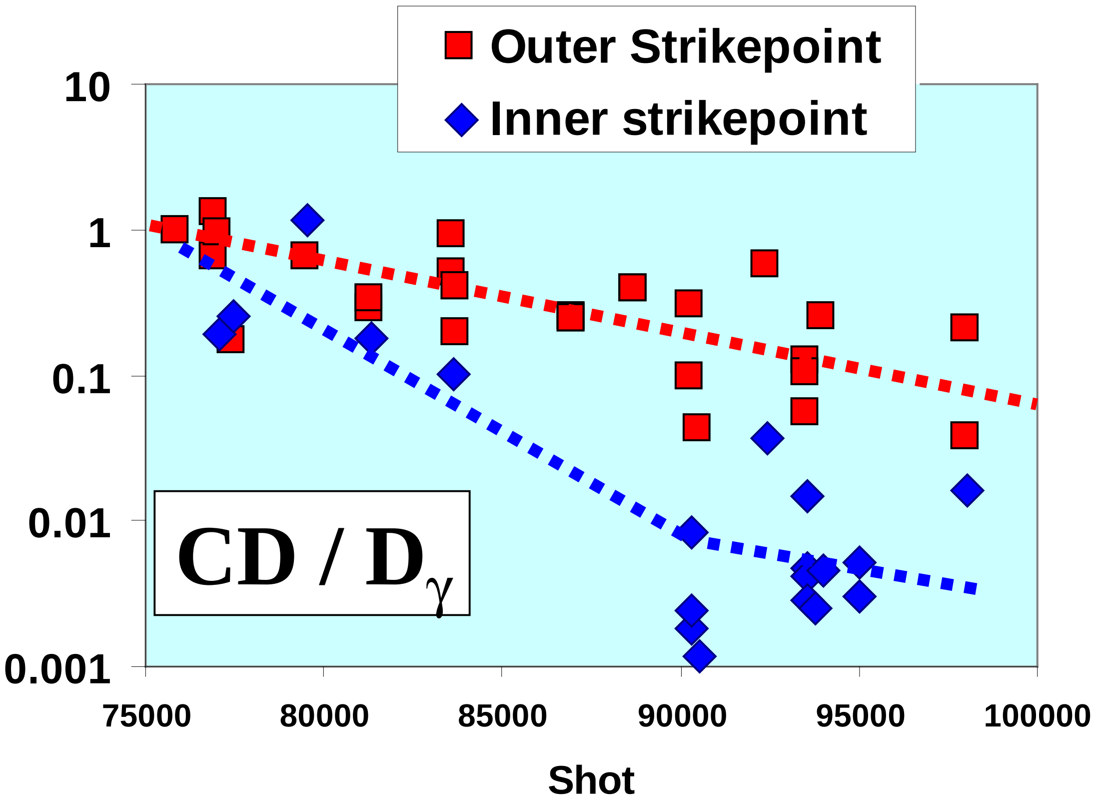
- Scatter in yield probably indicative of uncertainty in T_{plate}, Γ & S/XB .

Observed yield reductions are *not* due to any systematic "drift" of plasma parameters used in spectroscopy database.



Y_{chem} reduction is even larger at ISP, consistent with plasma redeposition of both boron and carbon at the inner divertor leg reducing the yield.

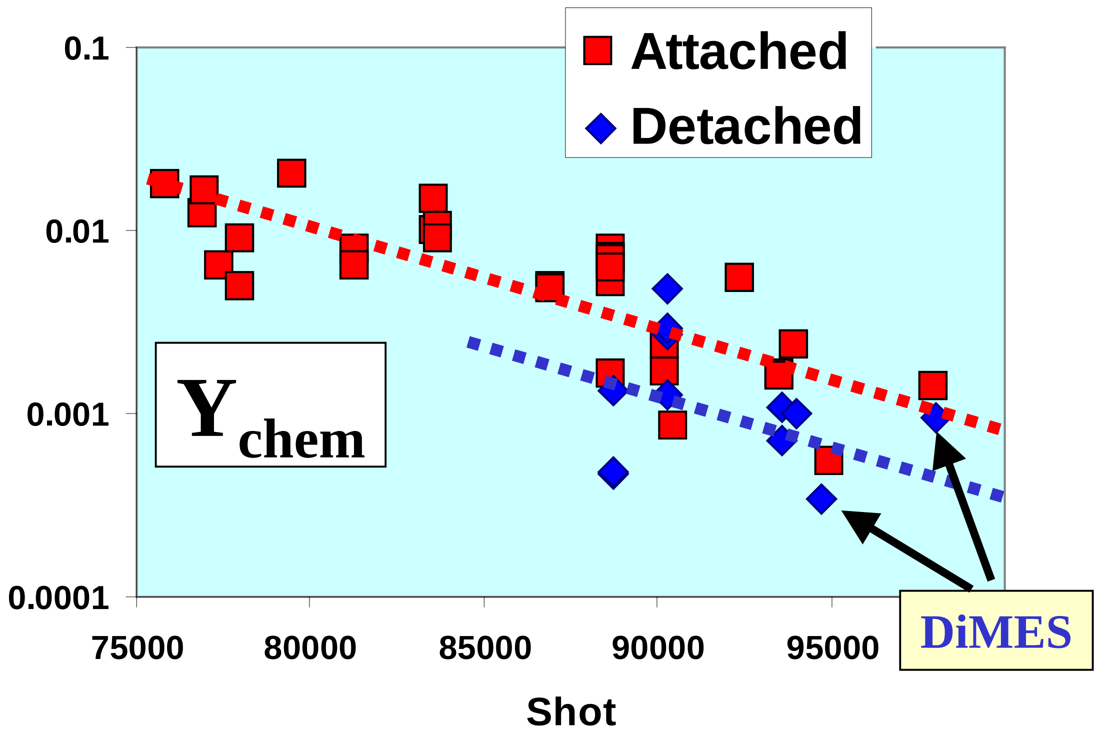
Attached ELMy H-mode
>100 shots post-boronization



- Absolute yield comparison not available because of poor plasma diagnosis at ISP.

Smaller subset of detached plasmas show a lower erosion yield than attached plasmas, consistent with lower incident energy at tiles.

ELMy H-mode
>100 shots post-boronization

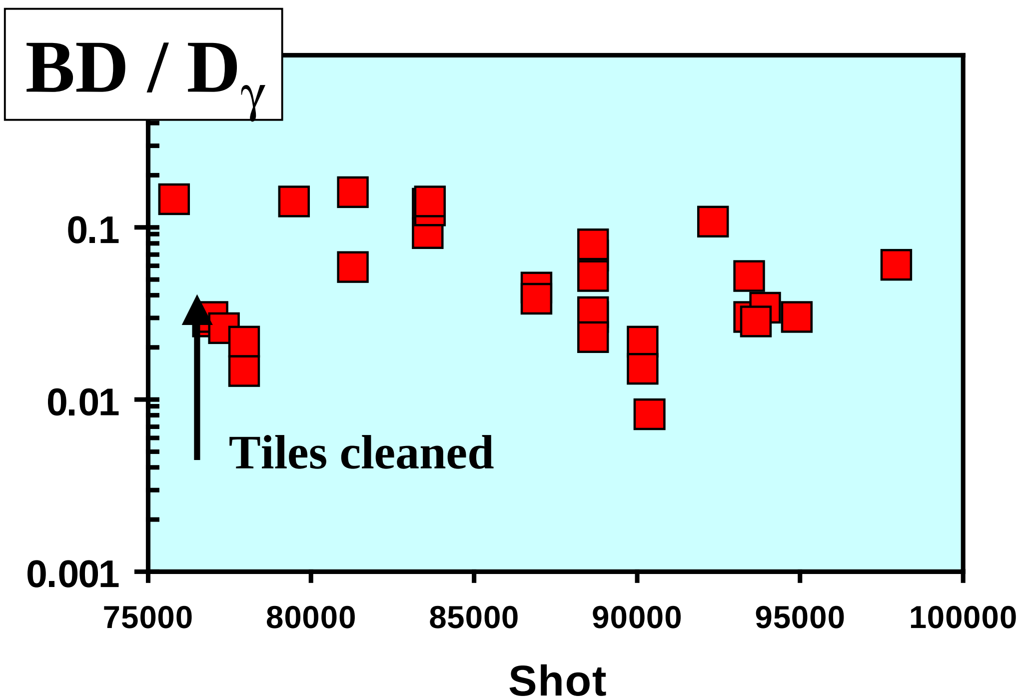


- Yield comparison depends on changes due to recombining divertor plasma (T_e < 2 eV):
  - **D/XB_{CD} ~ 20** **(PISCES)**
  - **$S/XB_{D\gamma}$ ~ 350** **(Experiment)**

$$Y_{chem} = \frac{\Gamma_{C_x D_y}}{\Gamma_D} = \frac{B_{CD} \cdot D/XB_{CD}}{B_{D_\gamma} \cdot S/XB_{D_\gamma}}$$

The average BD band in the lower divertor has not changed significantly with accumulative boronizations.

Attached ELMy H-mode
>100 shots post-boronization



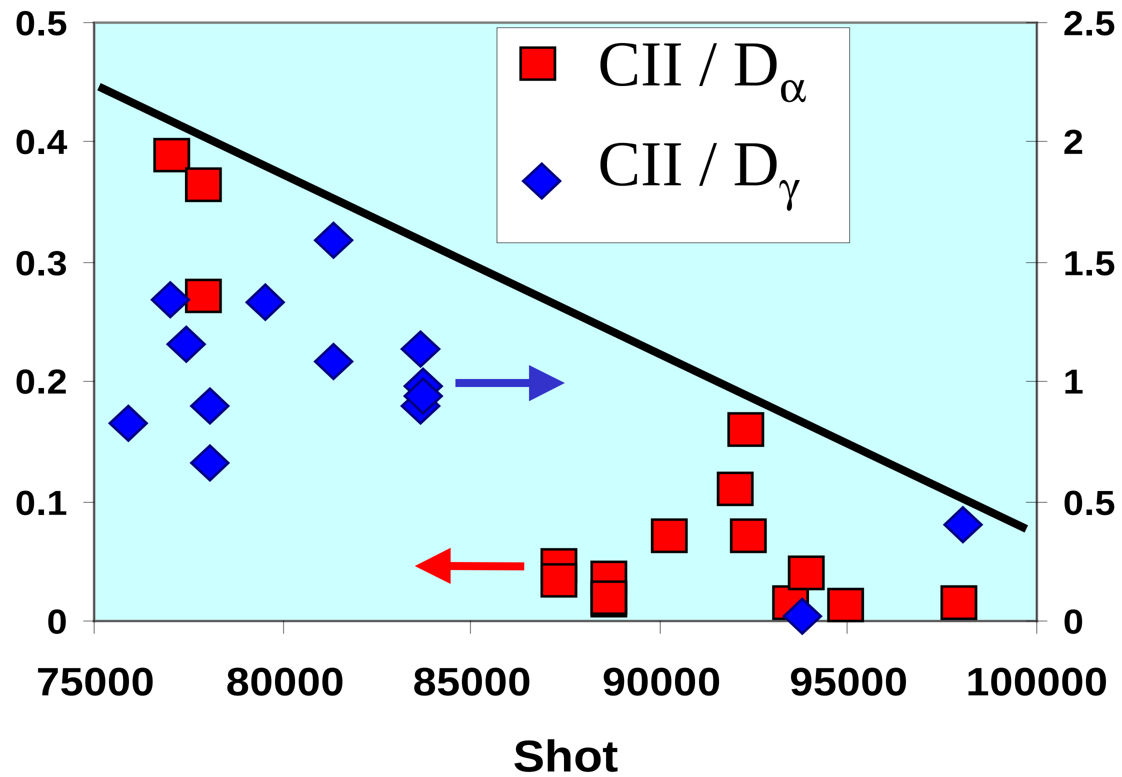
- BD band is a measurement of boron *chemical* erosion yield
  - **B II measurements would better indicate relative boron content…but rarely tuned to lines with spectrometer.**
  - **Results could indicate substantial boron-carbide bond formation, which would be resistant to chemical erosion.**

Reduction of total lower divertor carbon sources & core plasma carbon contamination

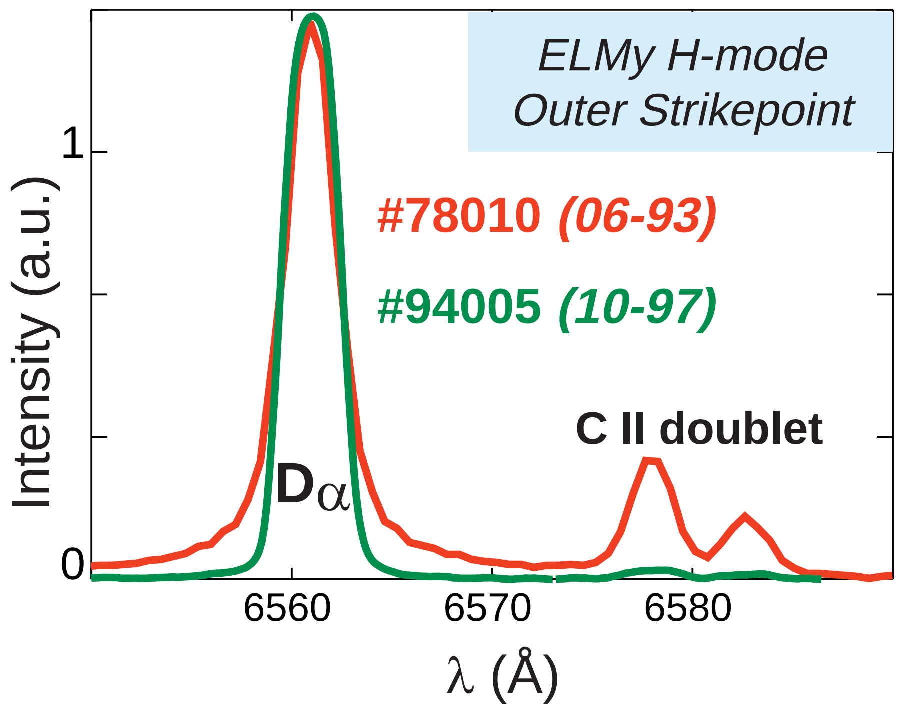
Simultaneous with the reduction in Y_{chem} of ~x10, the lower divertor Y_{total} has decreased at least x4.

Attached ELMy H-mode
>100 shots post-boronization
Maximum value in lower divertor

$$Y_{total} = \frac{(\Gamma_{C_xD_y} + \Gamma_{C_0})}{\Gamma_D} \propto \frac{B_{CII} \cdot S/XB_{CII}}{B_{D_{\alpha,\gamma}} \cdot S/XB_{D_{\alpha,\gamma}}}$$



Comparison of nearly identical ELMy H-mode plasmas show that the total divertor carbon source has decreased significantly in DIII-D since 1993, without any subsequent change in core carbon concentration!

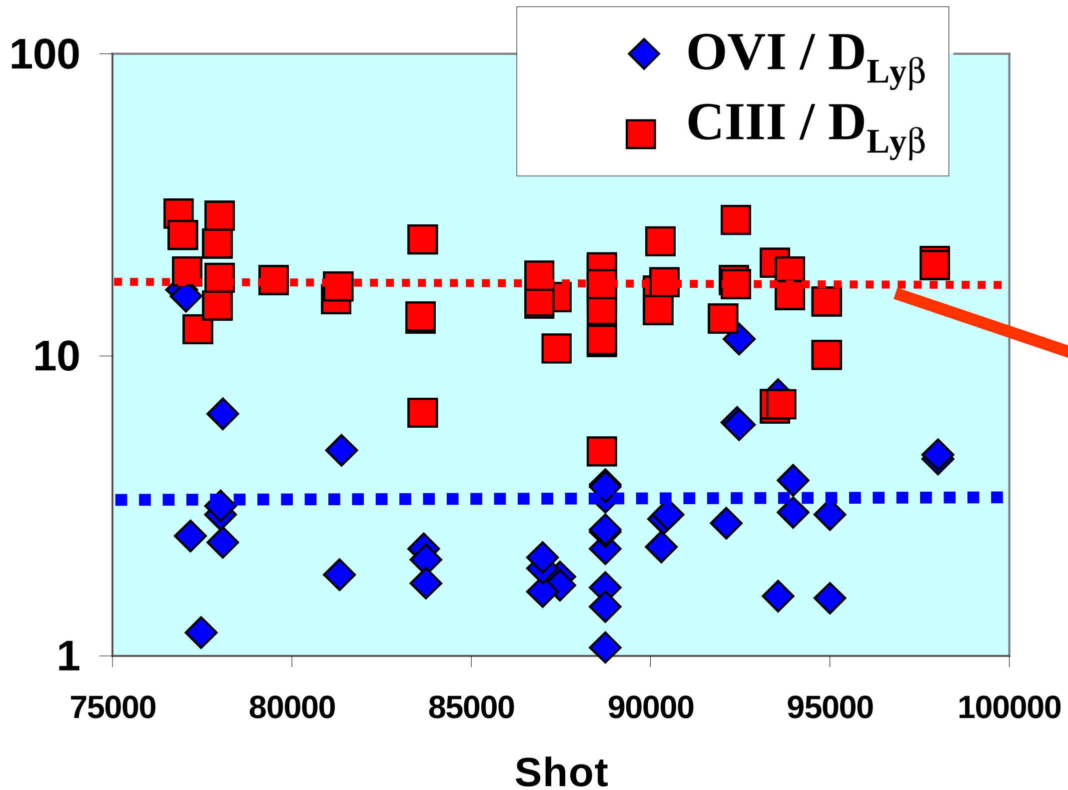


Spectra normalized to D_α intensity & for different detector responses (intensified vs. non-intensified)

LSN plasmas	#78010	#94005
I_p (MA)	1.0	1.3
n_e (cm^{-3})	4.6×10^{13}	5×10^{13}
P_{inj} (MW)	5	4.8
W_{dia} (MJ)	0.85	1.2
R_{OSP} (cm)	158	146
CII / D_{α} (OSP)	0.23	0.02
$f_{core, C}$ (%)	2.3	2.3

The outer mid-plane carbon source has remained large and constant, in contrast to the significant decrease in lower divertor yield / sources.

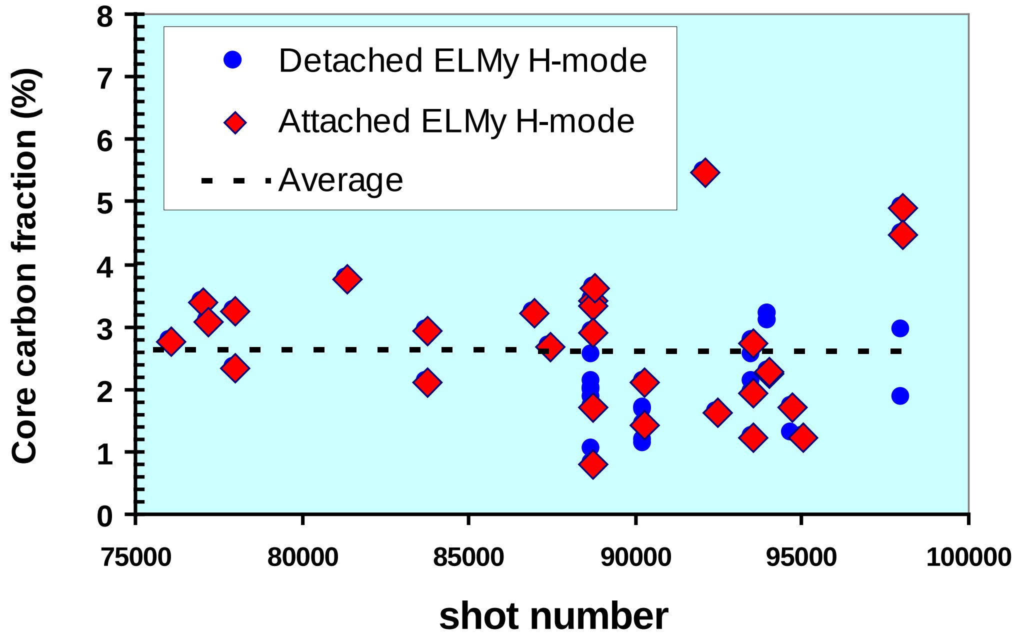
Attached ELMy H-mode
>100 shots post-boronization



- Relative midplane XUV spectroscopy of impurity resonance lines:
  - CIII (977 Å)
  - OVI (1030 Å)
  - $D_{Ly\beta}$ (1025 Å)
- Average carbon yield using S/XB technique and absolute calibration:
  $Y_{midplane}$ ~ 1-2%
- Absolute CIII & CII intensities and S/XB technique indicate significant carbon influx from first wall (~200 A).

Despite the significant decrease in lower divertor yield / source, the core carbon fraction has not decreased.

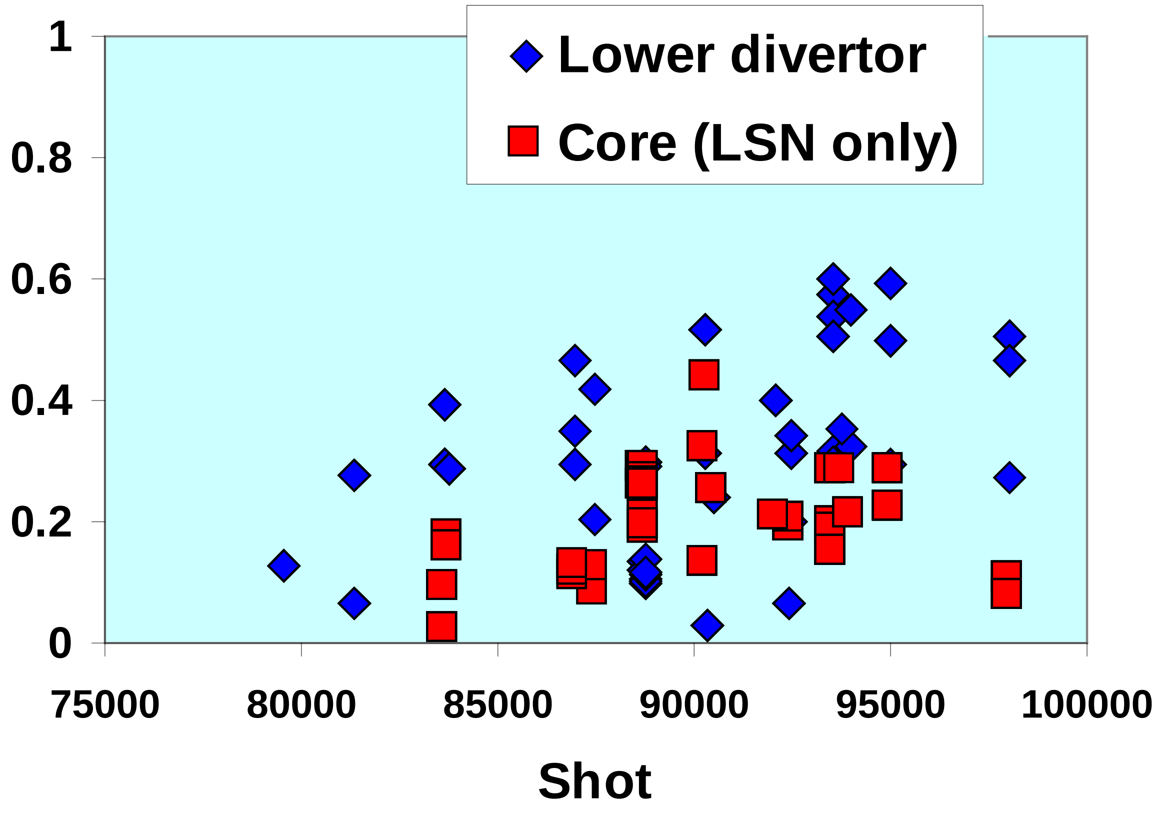
Attached ELMy H-mode
>100 shots post-boronization



- Based on r/a = 0.72 carbon concentration from visible CER.
- Consistent with larger f_{carbon} database compiled by M. Wade & "day-to-day" experience.
- Some shots unavailable.

Fractional radiated power, which is typically dominated by carbon, has not significantly decreased either.

Attached ELMy H-mode
>100 shots post-boronization



- Agrees qualitatively with CER core carbon spectroscopy results.

Summary: DIII-D Y_{chem} Study

- **Old** DIII-D results for Y_{chem} are in agreement with other tokamaks...
  - **JET:** **Y_{chem} = 2 %** **T_{surf}=450K**
  - **ASDEX-U:** **Y_{chem} = 1-2 %** **T_{surf}=350K**
  - **DIII-D (1992-93)** **Y_{chem} ~ 2 %** **T_{surf}~400 K**

- …**But present chemical and total yields are greatly reduced**
  - **DIII-D (1999):** **Y_{chem} ~ 0.1%** **T_{surf}~400K**
  - **DIII-D tile:** **Y_{chem} = 0.16-0.4 %** **T_{surf}=600K (PISCES)**

- Boronizations are the most likely cause for the Y_{chem} reduction
  - 30+ boronizations have applied ~2.5 microns of boron.
  - No major tile changes or clean-ups in lower divertor in over six years…both JET and ASDEX have refit lower divertor several times.

Summary on Y_{total} & Carbon sources

- **Reduced Y_{chem} (and other effects?) have significantly reduced the measured total carbon outflux from the lower divertor**.
  - Chemical erosion is now a minor player in lower divertor erosion with Y_{chem} ~0.1% << Y_{phys} ~1-5%.

- **No simultaneous decrease in core carbon fraction is found**. Two explanations are possible:

  1. Carbon ion SOL transport always adjusts to equilibrate thermal gradient vs. diffusive forces, making the source amplitude unimportant (preliminary UEDGE results show this effect).

  2. The divertor is the not the principal source of carbon in the core plasma (e.g. All Be divertor in JET had carbon as main core impurity).

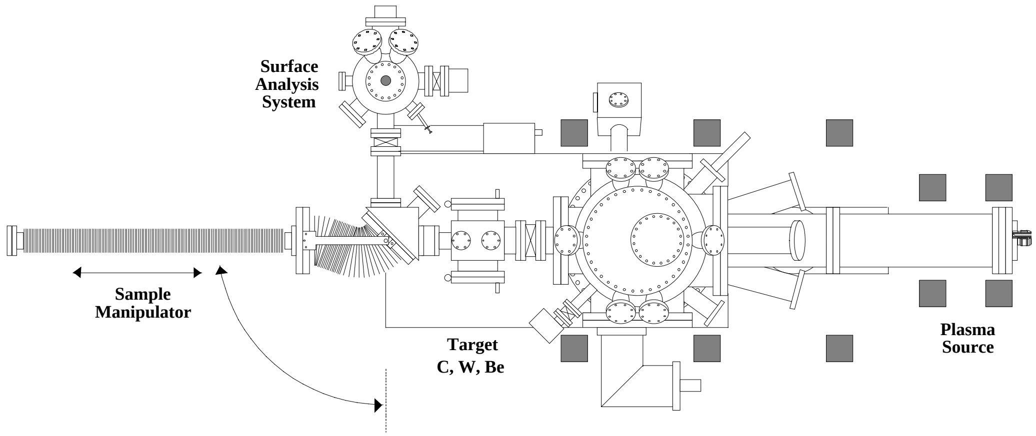
Laboratory studies of DIII-D graphite tiles — effect of boronization on chemical erosion yield.

Plan: Use PISCES at UCSD to directly assess Y_{chem} of DIII-D divertor tiles

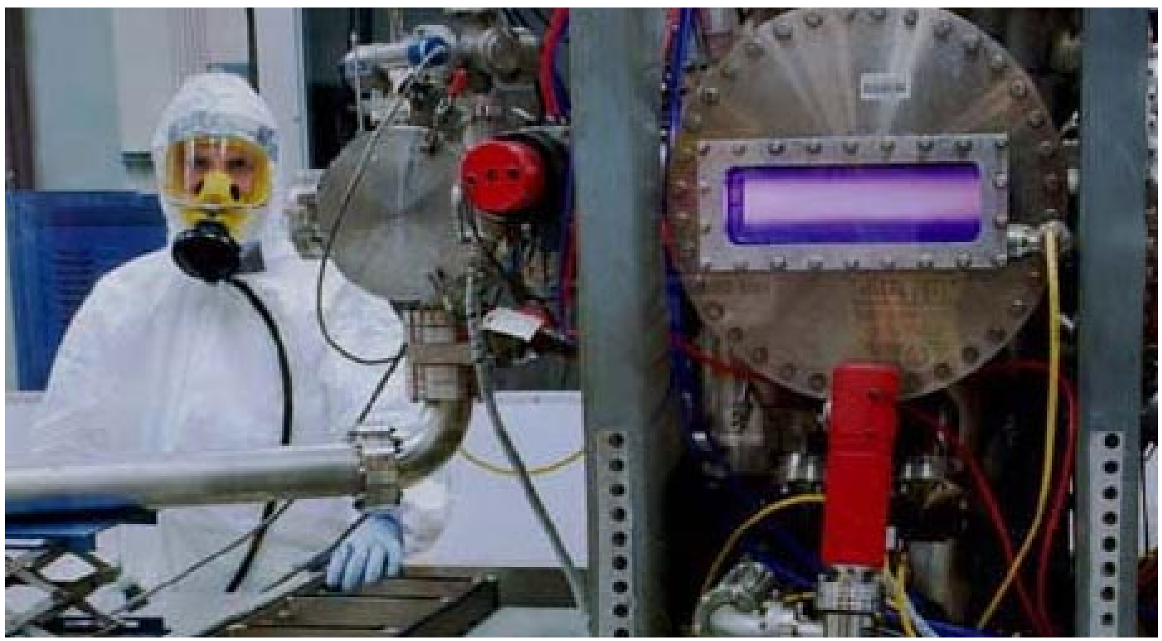
- Two DIII-D lower divertor tiles removed (Summer '98)
  - SEM and profilimetry revealed a >micron-depth low-Z deposition layer at the inner divertor.
  - ~800 discharges since last boronization.
  - Visual inspection shows a metallic-like surface substantially different than virgin ATJ graphite.

- Section of tile exposed in PISCES-B linear plasma device
  - Steady-state exposure with similar Γ and T_e to DIII-D divertor.
  - 30 eV incident energy fixed by target bias…minimal $Y_{phys.}$
  - In-situ surface analysis station.

PISCES-B Experimental Configuration



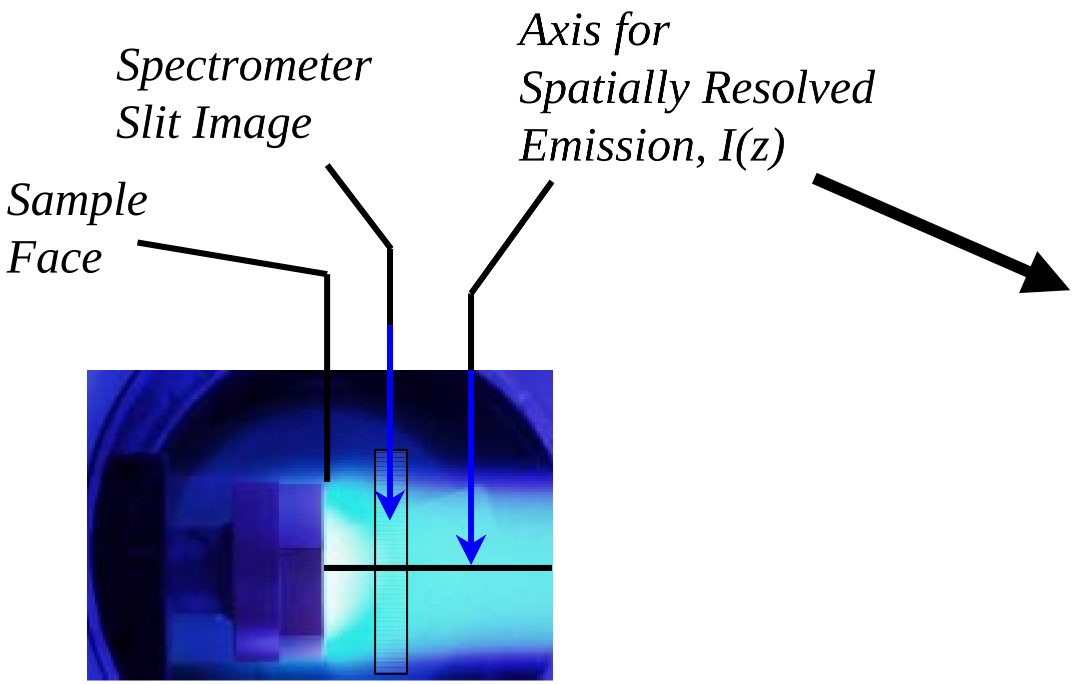
PISCES-B Linear Plasma Device



Y_{chem} Measurements on PISCES

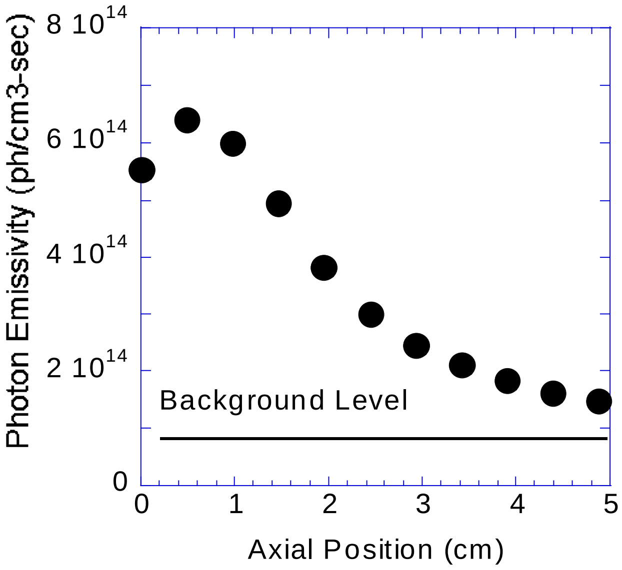
- Weight loss of sample
  - net yield -> gross yield correction from modeling.
- CD band spectroscopy
  - Calibrated visible spectrometer.
  - Benchmarked with CD_4 puffing through target.

Calibrated CD_4 injection through PISCES target & High resolution spectroscopy provide detailed information about hydrocarbon transport & Y_{chem}



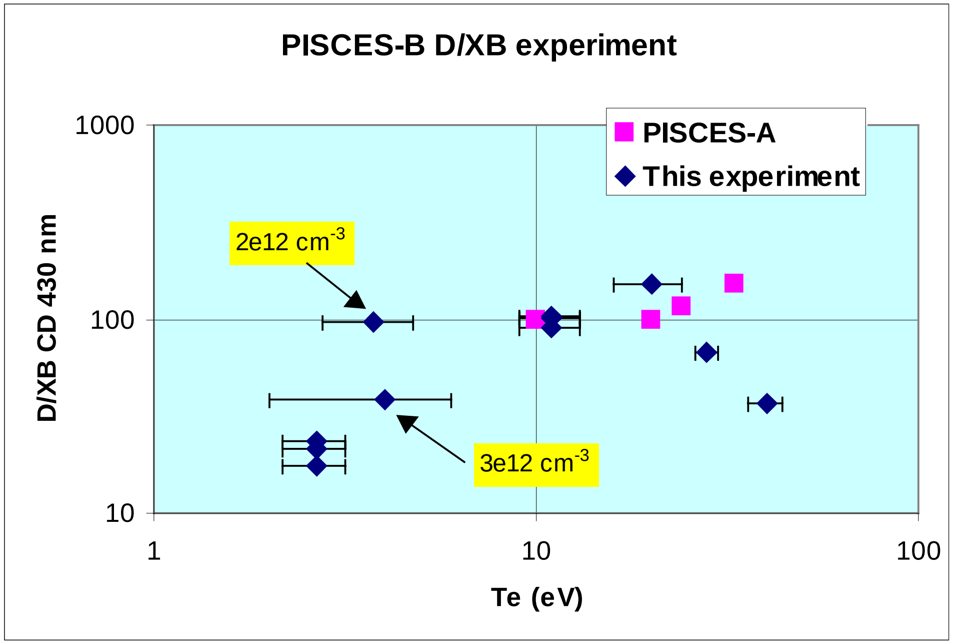
CD_4 injection

CD radical band (430 nm) axial profile



Summary of PISCES & UTIAS erosion tests on DIII-D tiles

- DIII-D CD-band molecular excitation rates measured
  - Apparent $Y_{chem} < 10^{-3}$ in DIII-D.
- Energy dependence: $\mathbf{Y_{chem}} \propto E^{-(0.5-1)}$
- Surface composition
  - 5% boron initially on surface.
  - **Y_{chem} reduced x4** compared to virgin porous graphite.
  - < 10 minutes of plasma exposure removed most of the carbon from the surface!
- Flux dependence?: ***apparently not needed to explain low Y_{chem}.***
- Preliminary result from UTIAS indicates portion of DIII-D redep film is resistant to O_2 chemical removal



D/XB Measurements (Molecules / Photon ratio)

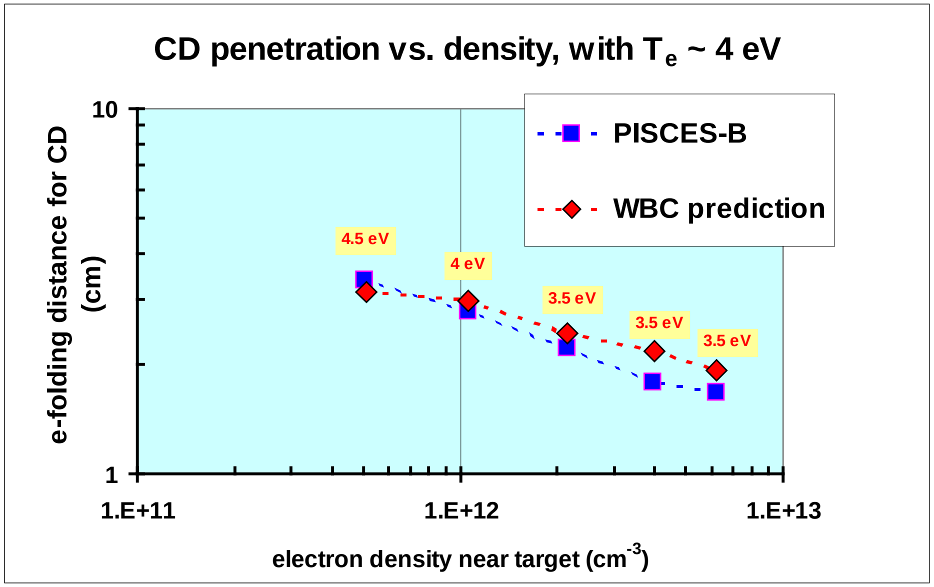
- D/XB~100 is a maximum.
- Reproduces previous result.

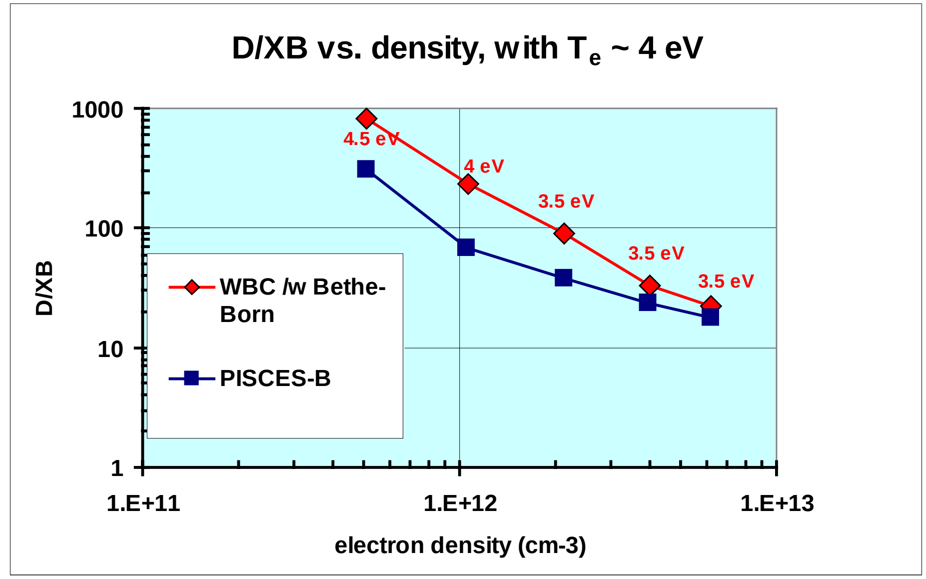
Implication:

- DIII-D CD-band spectroscopy used D/XB=100.
  ..but T_e< 5 eV in PDD.

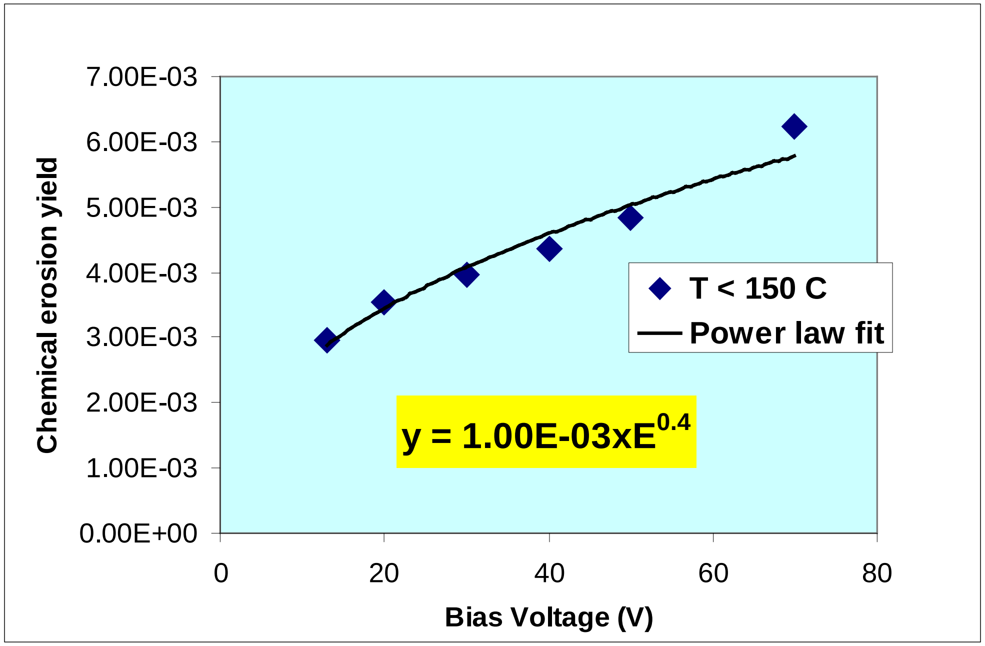
- **Revised upper limit from CD-band spectroscopy:**
  $Y_{chem}< 3\text{-}4\times10^{-4}$

WBC Erosion Code Has Been Thoroughly Benchmarked Against PISCES Data.





- WBC sub-gyro Monte-Carlo model (J. Brooks, ANL)
  - includes full dissociative reactions for CD_4.
- Model matches both CD penetration and photon efficiency.
  - Strongly non-linear penetration vs. n_e
  - Very large n_e dependence on D/XB for approx. constant T_e.
- Questions constant D/XB used in tokamak experiments during density scan



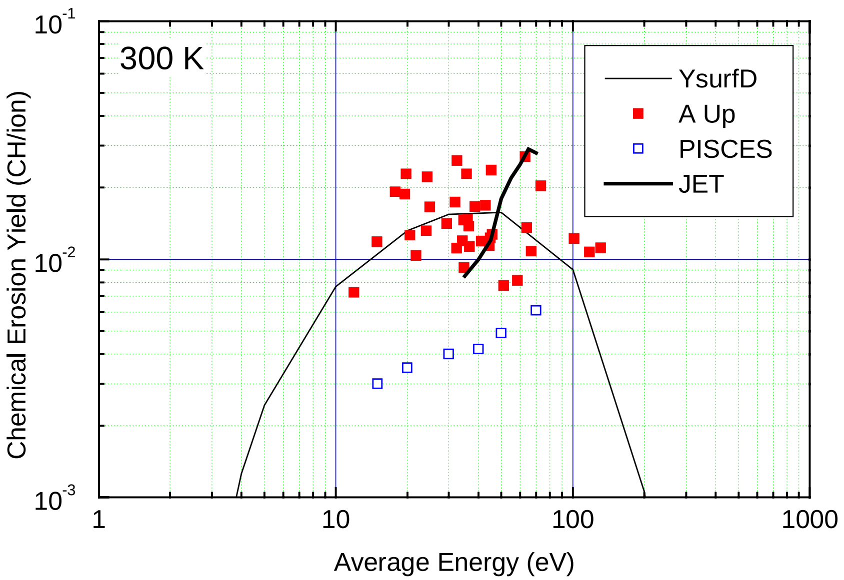
Energy dependence on Y_{chem}

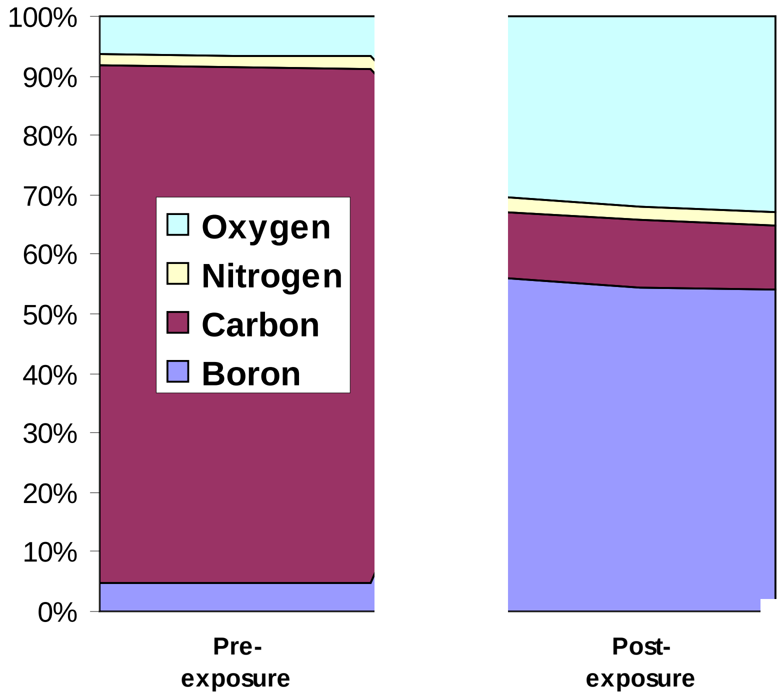
$$Y_{chem} \propto E^{-0.4}$$

$$\Gamma = 10^{23}\ s^{-1}\ m^{-2}$$

$$T_e \sim 4\ eV$$

Different energy dependence on chemical erosion yield from one experiment to another.
PISCES data is more reliable in the sense that bias voltage is directly controlled...and all other exposure conditions are constant.





Auger surface analysis of DIII-D tile surface pre and post exposure on PISCES-B

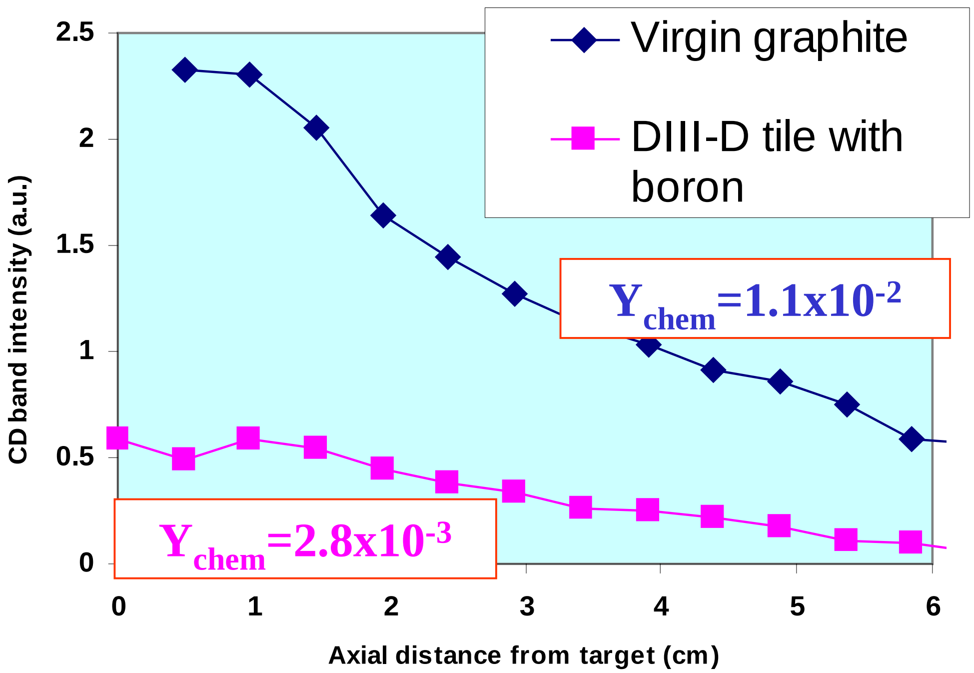
Exposure conditions:

E = 30 eV

$\Gamma = 10^{23}\ s^{-1}\ m^{-2}$

$T_e \sim 5$ eV

$n_e \sim 1.5\times10^{13}\ cm^{-3}$



Discussion

- Chemical erosion in the lower divertor is NOT the source of carbon in detached plasmas.
  - Yet substantial atomic carbon radiation / flux is measured despite $T_e < 5$ eV, i.e. no physical sputtering?
  - Net erosion is eliminated everywhere in lower divertor!
- Strong indications that boronizations have substantially reduced the chemical and total effective yields of carbon in the DIII-D tokamak.
  - In-situ and laboratory experiments show Y_{chem} reduced ~4-10x compared to “virgin” graphite.
  - No need to invoke flux dependence as method of reduced Y_{chem}
- **Future work**
  - Test more tile samples (PISCES and UofT)
  - Remove more complete poloidal set of tiles during next vent?
  - Incorporate Y_{chem} into DiMES / WBC modeling & mixed material modelling

Discussion (continued).

- These results are very encouraging for the use of carbon in the "learning" phase of any next-step, high duty-cycle DT device.
  - Graphite is very forgiving of disruptions, ELMs, etc.
  - Detached plasmas necessary for power handling…Y_{phys}=0…
  - …But large Y_{chem} for graphite produces significant erosion / redeposition and Tritium retention.

- Based on the DIII-D results, ~24 hours of plasma exposure, including frequent boronizations, should condition graphite divertor tiles to obtain order of magnitude reduction in Y_{chem}.