A detailed study of carbon chemical erosion in L-mode plasmas in the DIII-D divertor

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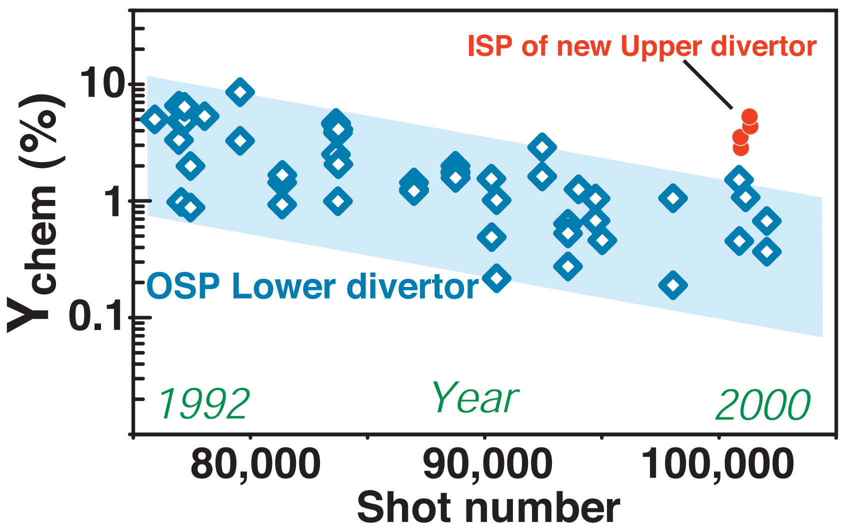
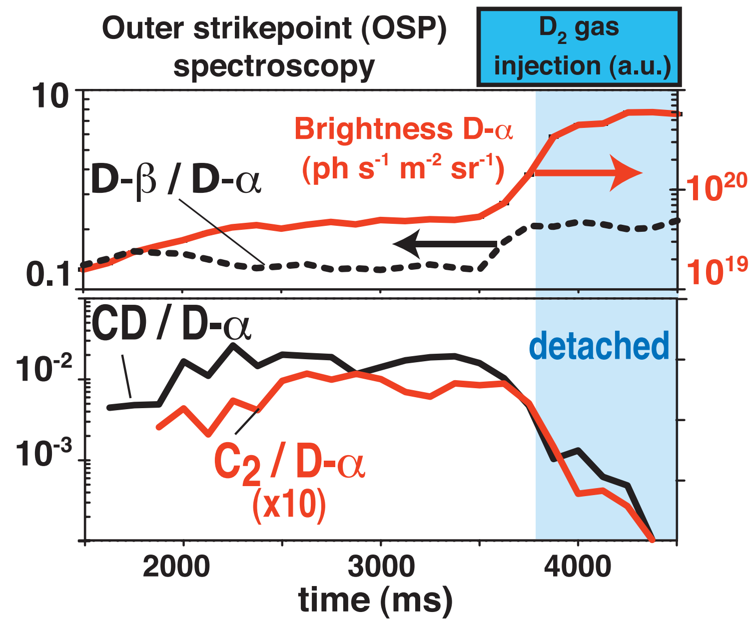
Outline

- L-mode plasmas for carbon erosion studies
- Erosion modeling and interpretation
- Erosion with attached divertor plasma
  - Divertor tile vs. main-wall tile
  - Determination of Y_{chem} at outer strikepoint
  - Atomic carbon velocity distribution
- Effect of plasma detachment on carbon erosion.
- Discussion & Summary

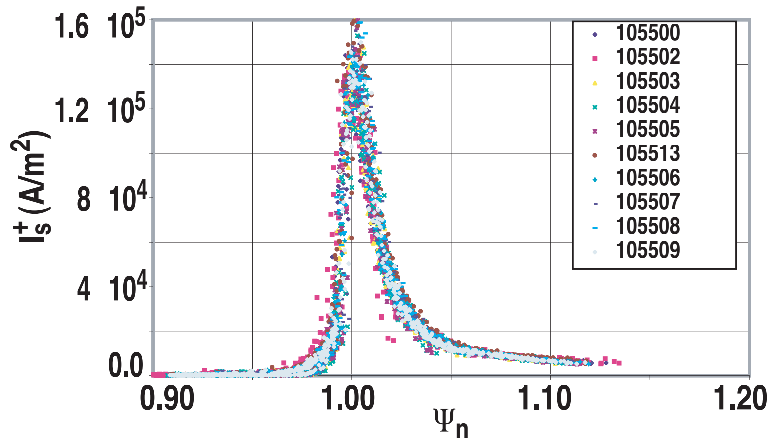
H-mode plasma studies showed unexpected reduction in carbon erosion in the DIII-D divertor

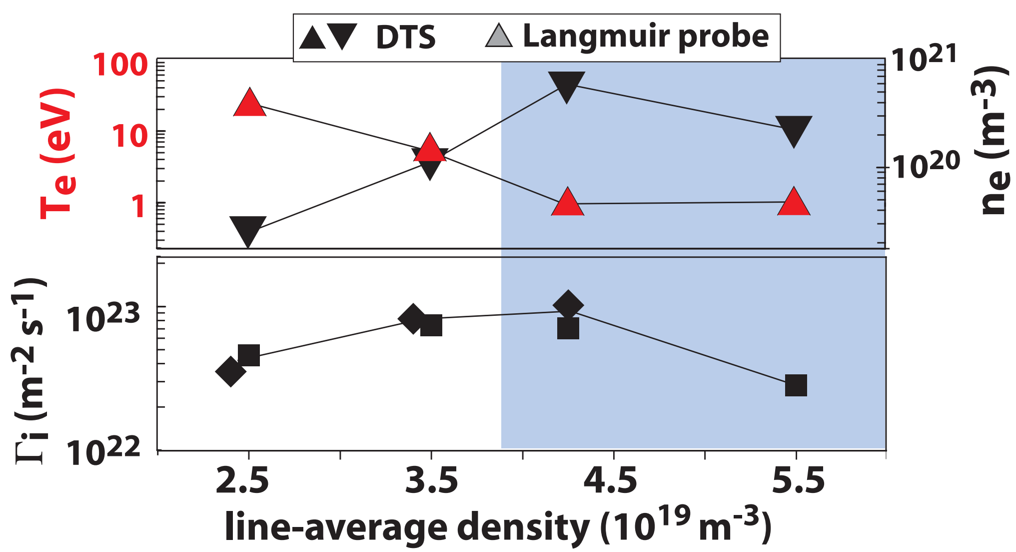




- Encouraging results on the use of carbon:
  - In-situ Y_{chem} reduction at lower divertor.
  - Detachment, necessary for heat flux control, greatly reduces HC signals
- …but *tentative* results:
  - Inconsistent plasma conditions over long-term study
  - ELMs in H-mode complicate interpretation of erosion and spectroscopy.

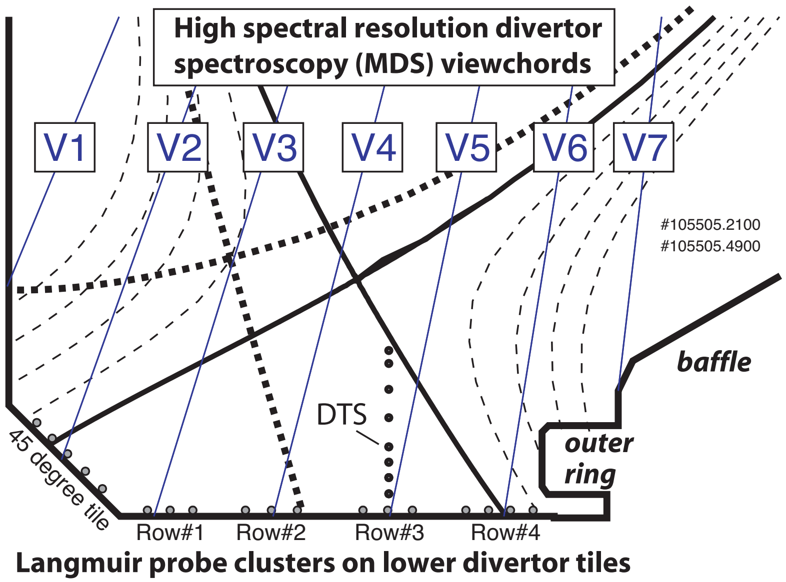
L-mode, simple-as-possible plasmas ideal for carbon studies

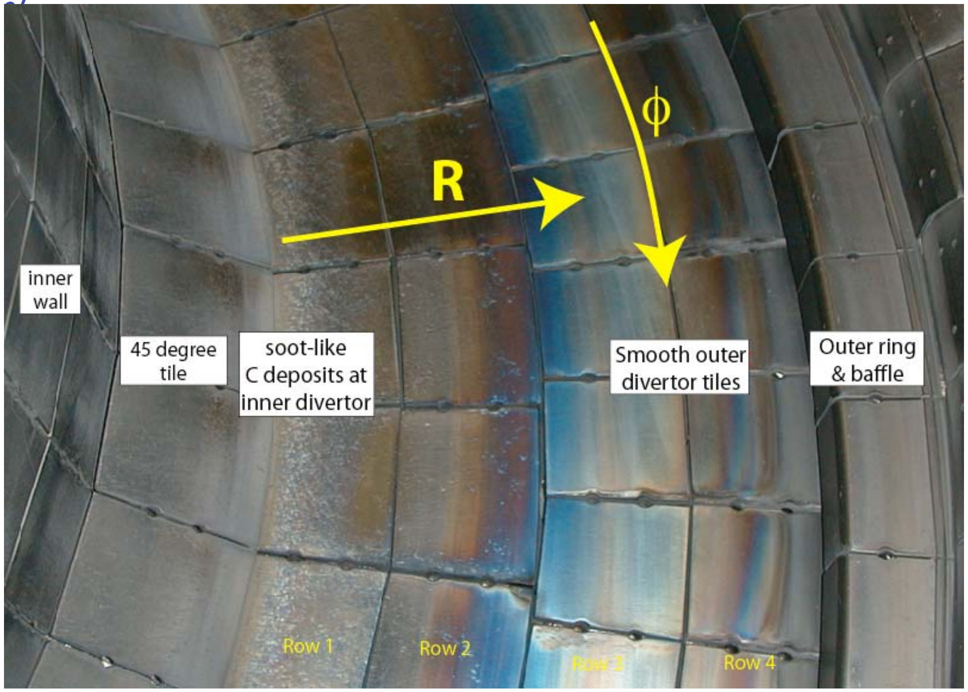




- Low power leads to ~ constant T_{surf}~375 K
- No ELMs
- Density control leads to good detachment control
- Multiple discharges
  - Improved DTS statistics
  - Redundant divertor diagnosis
  - Multiple C & HC emissions measured.

High resolution spectroscopy and divertor sweeping diagnose erosion over wide variety of surfaces





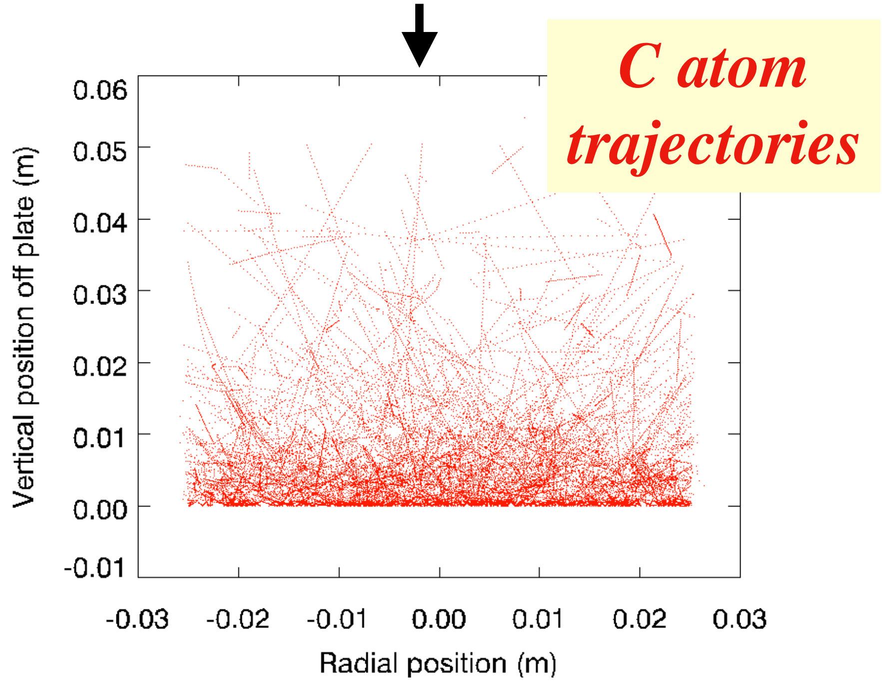
- Absolute wavelength calibration from discharge lamps during plasma shot (+/- 0.001 nm ~ 300 m/s).
- Can resolve $T_C < 0.5$ eV.

- Divertor tiles made from ATJ graphite, an isostatically molded fine grain graphite
- Multiple (>50) boronization layers applied over +10 year lifetime.

WBC Monte-Carlo code is used to interpret HC spectroscopy

- Full dissociation chains of methane & higher order HC's
- MOLDYN reflections vs. E
- Full HC spectrum launched into OSP plasma (DTS) with sonic flow to plate.
- Particle followed until redeposition or leave simulation zone (~5-10 cm)
- Added C_2 and C_3 rates for C_2 spectroscopic interpretation.
  - Close to C for ionization & diss. CX negligible in H plasma
- Excitation rates of CD, C_2, C I and CII vs. $T_{e,}n_e$ to calculate expected emission --> photon efficiency.

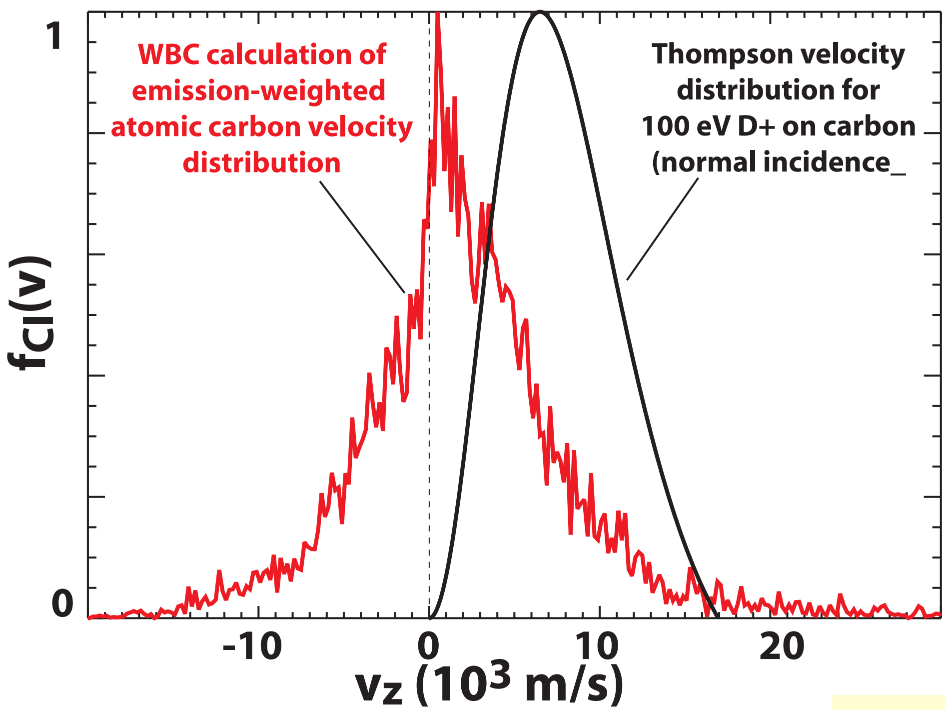
43.5% CD_4, 3.7% C_2D_2, 24.8% C_2D_4, 11% C_2D_6, 16% C_3D_6



CI photon efficiency

$$\left(\frac{XB}{S}\right)_{CI,910nm} = \sum_i n_e \; X_{CI,910nm}(T_e) \; \Delta t_{i,CI}$$

Atomic carbon velocity distribution can be an indicator of erosion source

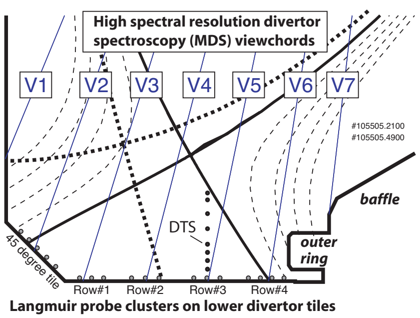


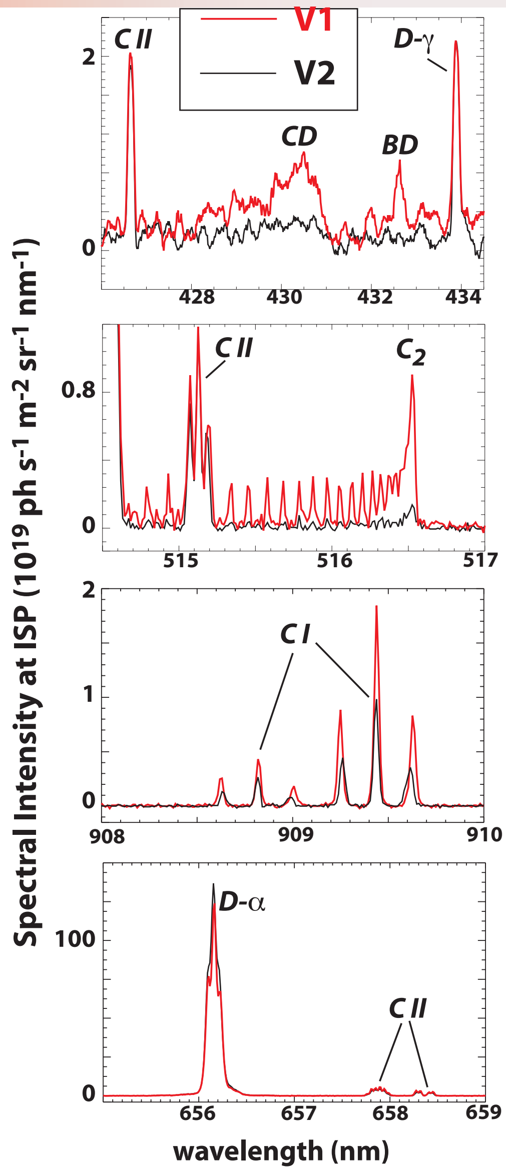
- WBC computes emission weighted $f(v_z)$ arising from HC dissociation into C I.
- Thompson model with light-ion energy cutoff/correction predicts direct CI $f(v_z)$ from D+ on C physical sputtering.

$$\frac{df_v(E)}{dv} \propto \left(\frac{E^{3/2}}{(E+E_B)^3}\right)\left(1-\left(\frac{E_B+E}{\gamma(1-\gamma)E}\right)^{1/2}\right)$$

$$\gamma = \frac{4m_C m_D}{(m_C+m_D)^2} \sim 0.49$$

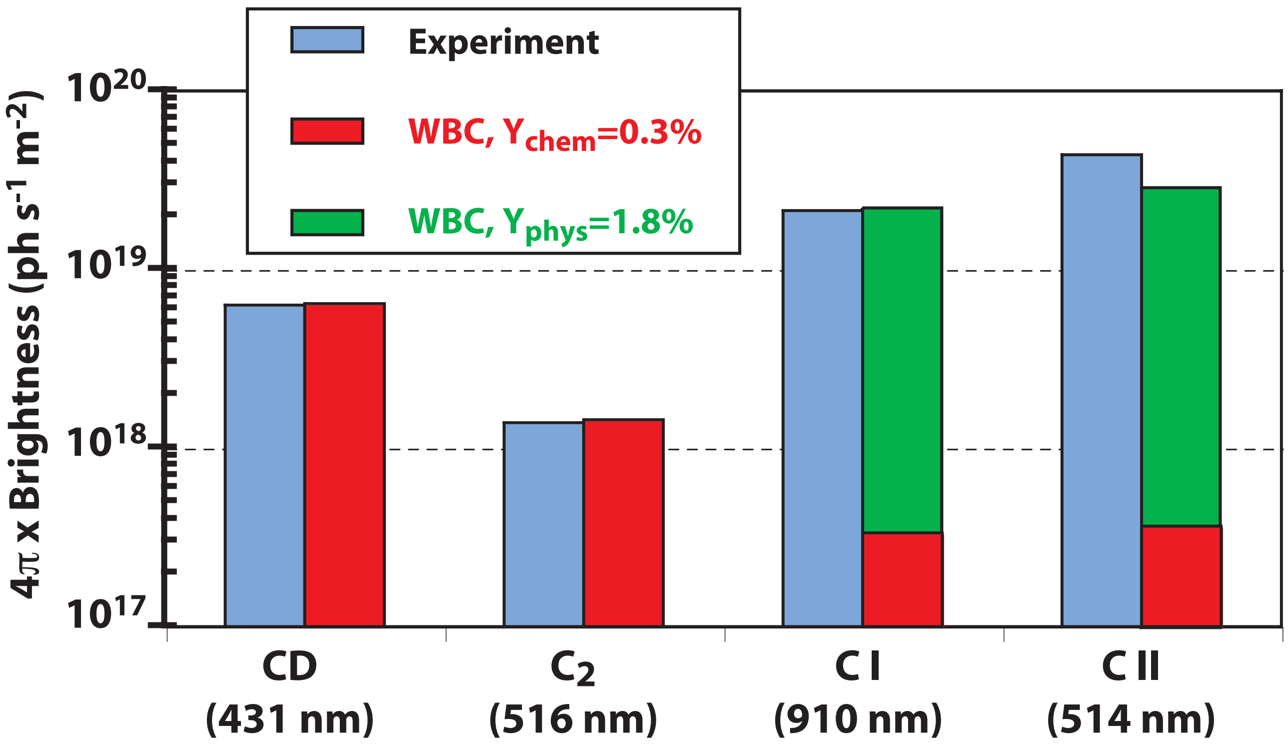
The main/inner wall tiles has 5-6 times higher Y_{chem} than the inner divertor tiles





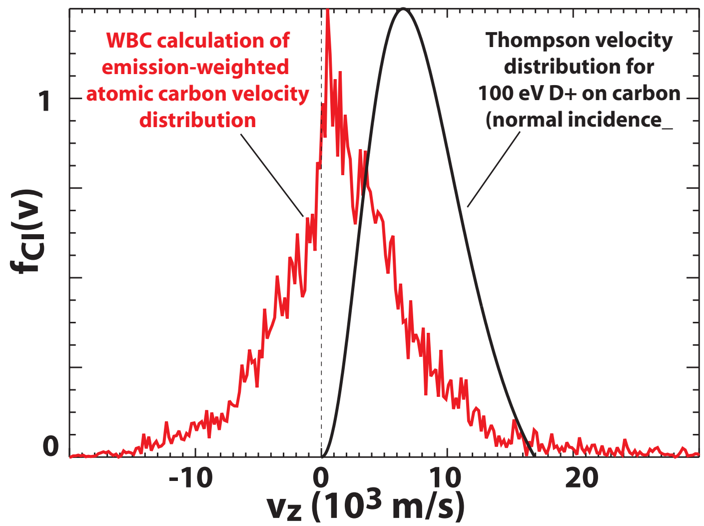
- V1 is a rare location for ISP, small particle/energy fluence.
- Spectroscopy verifies ~identical ISP plasmas at two locations:
  $T_e \sim 10$ eV
  $n_e \sim 1.5\times10^{19}$ m^{-3}
- Boron (BD) higher from inner wall.

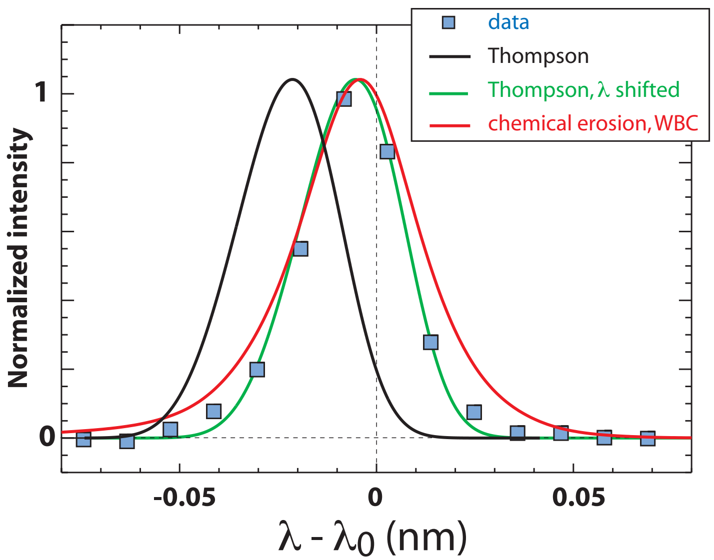
Attached outer strikepoint is dominated by physical sputtering , Y_{chem}= 0.3%



- Incident plasma: T_e=20 eV, E_i~5 T=100 eV, n_e ~2.5×10^{19} m^{-3}
- Matches of CD/C_2 ratio gives confidence in HC modeling.
- Match of CII/CI ratio gives confidence in ion transport modeling.

Neither erosion model fits the CI spectral features.





- Calculated $f(v_z)$ convoluted with spectrometer instrumental function for comparison to measured CI spectra.

- Discrepancy with sputtering models unresolved.
  - Physical: T_{eff} ~ 1 eV OK, shift too large
  - Chemical - WBC: shift OK, but T_{eff}~3 eV too large.

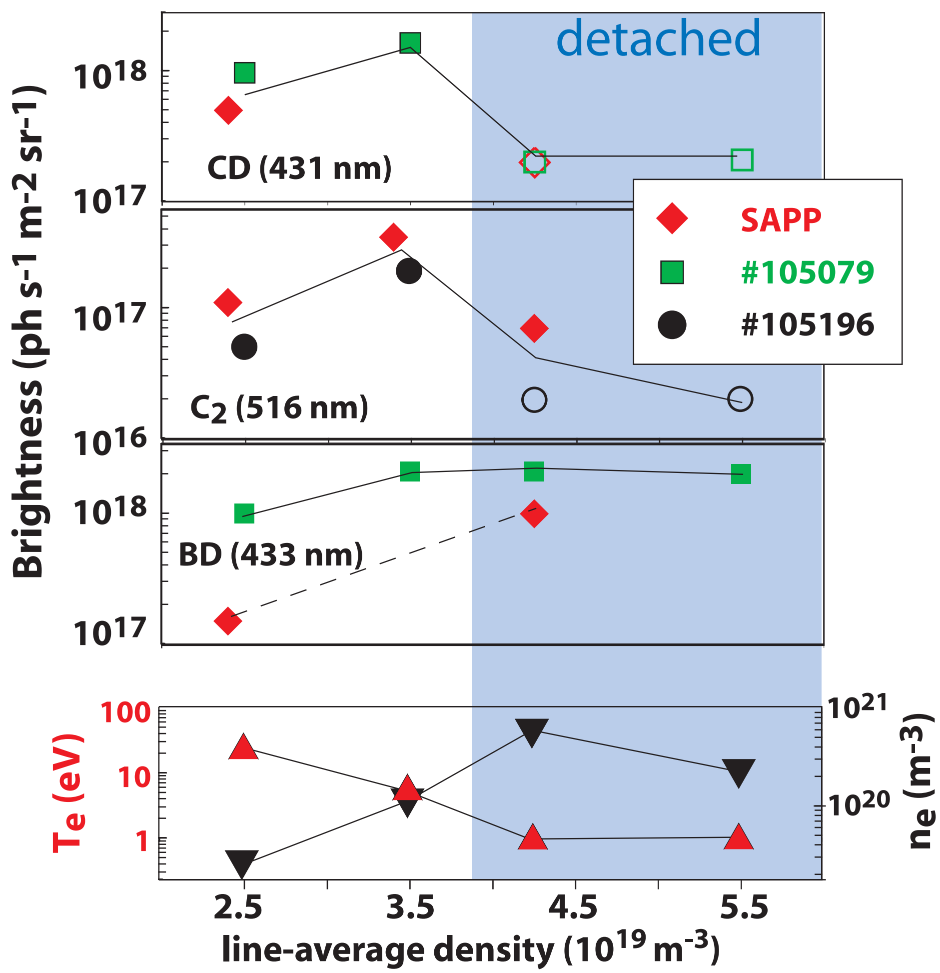
- *N.B. chemical erosion can actually lead to higher $T_{eff,CI}$ than physical sputtering*

WBC modeling predicts increasing photon efficiency in detached plasmas

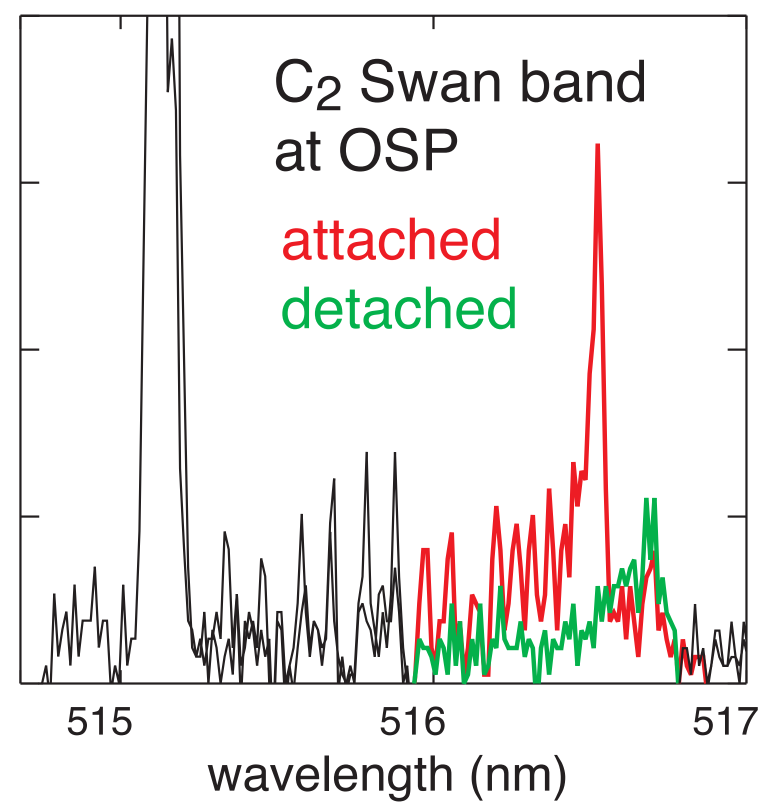
CASE	***WBC-20***	***WBC-21***	***WBC-22***
Plasma parameters at outer strikepoint			
Te (eV)	20	5	1
n_e *(m^{-3})*	2.5e19	1.05e20	5.6e20
Photon-emission excitation rate coefficients (m^3 / s)			
C I (910 nm)	1.7e-15	1.5e-17	5.e-19
CD (431 nm)	5.6e-15	7e-15	1.5e-15
C_2 *(516 nm)*	2e-14	4e-14	1.16e-14
C^+ *(514 nm)*	5e-16	nil	nil
Photon efficiencies: Full hydrocarbon spectrum launched			
C I	4.4e-03	1.6e-3	1.7e-3
CD	5.1e-2	0.45	0.22
C_2	**1.1e-2**	**0.83**	**9.8**
C II	4.2e-3	---	---

- C_2 is particularly interesting case: in 1 eV plasma no e- impact ionization /dissociation but readily excited by e- impact (E_{th}~2.4 eV).
- In qualitative agreement with C_2D_4 injection on JET at high density…C_2 most easily excited (Stamp et al.)

Detachment strongly suppresses signatures of chemical erosion at the OSP



- HC brightness decreases to or below detection limits (open symbols) in detachment.



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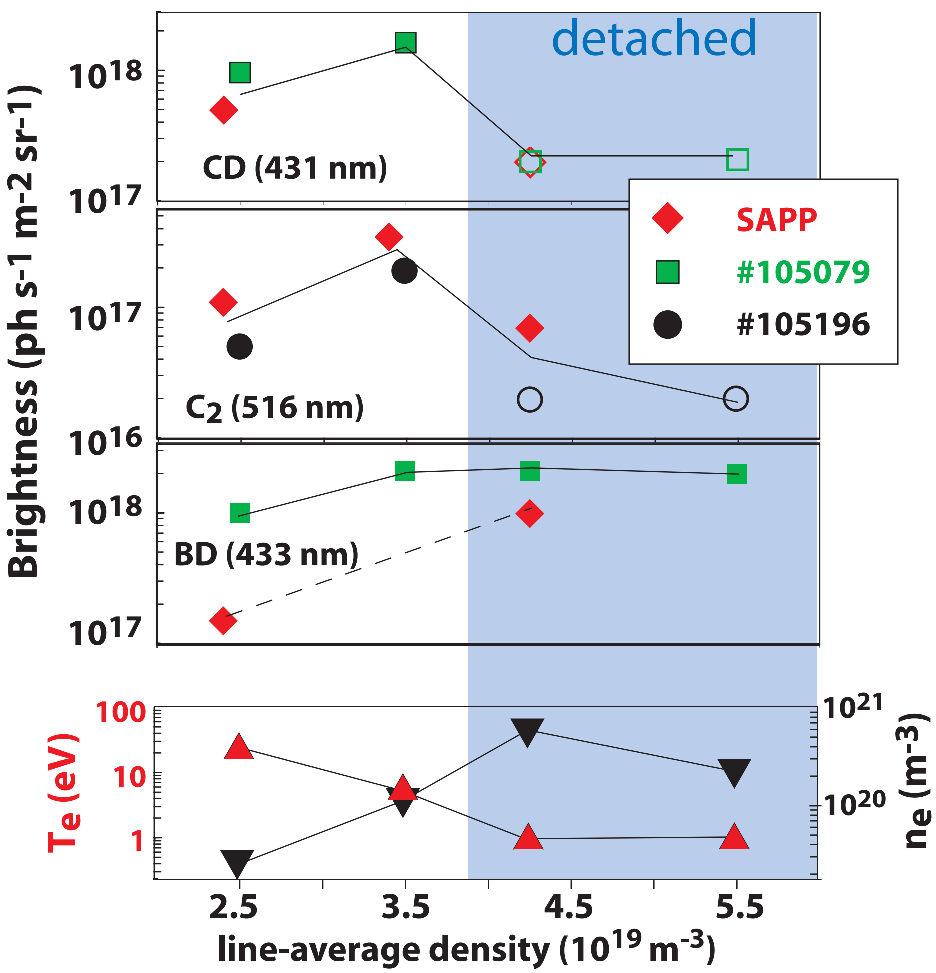
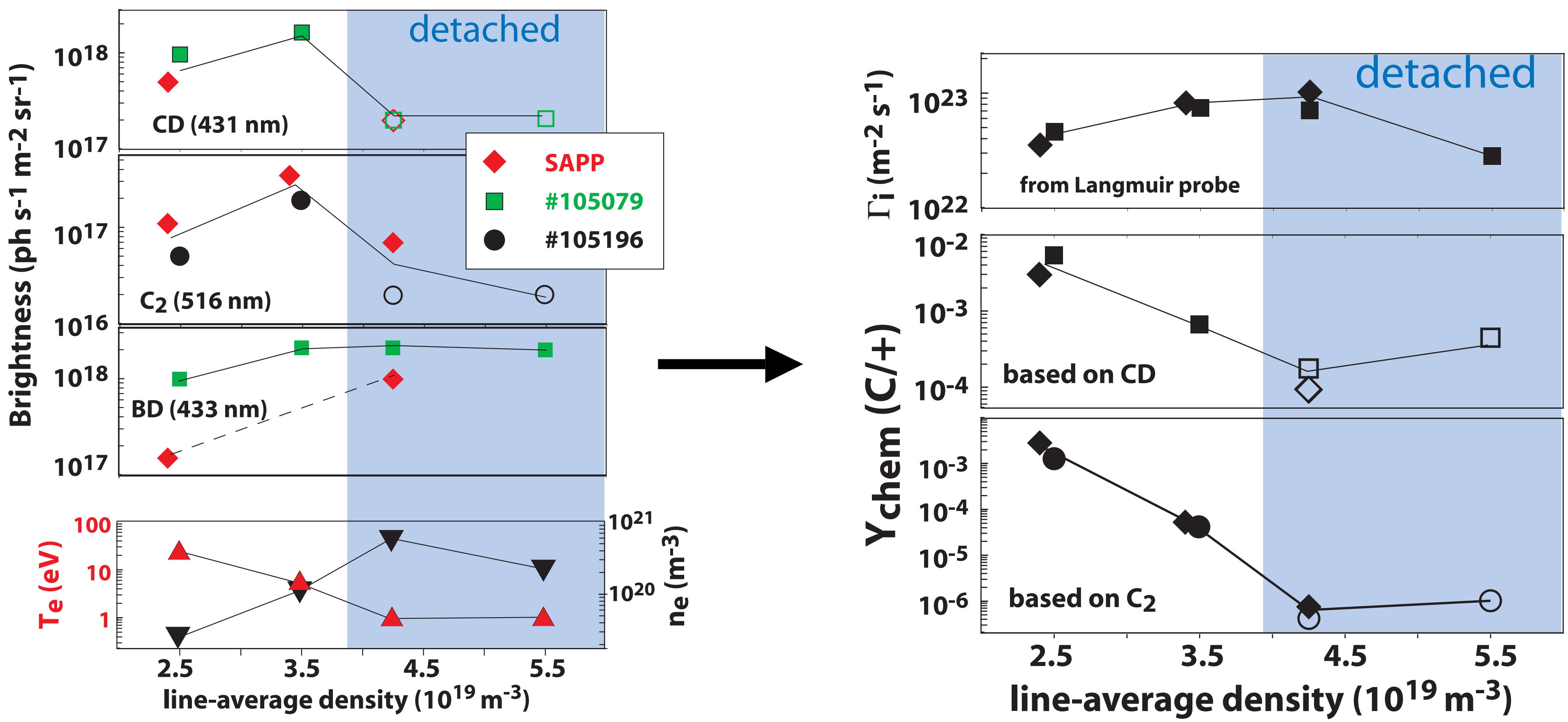


- HC brightness decreases to or below detection limits (open symbols) in detachment.

- BD behavior significant:
  - Must radiate in detached plasma (MFP ~1 mm)
  - Verifies T_e ~ 1 eV to sustain BD emission.
  - Ultra-low T_e cannot be cause of extinction of HC emission, since E_{th} ~ identical between BD & CD.

Detachment strongly suppresses signatures of chemical erosion at the OSP: $Y_{chem} \leq 10^{-4}$

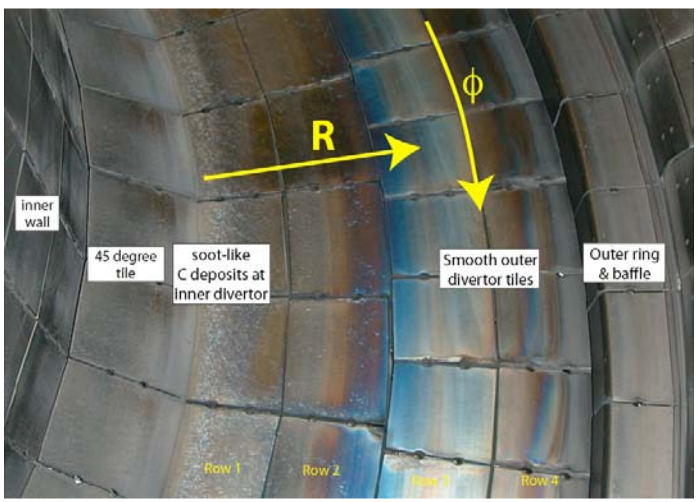


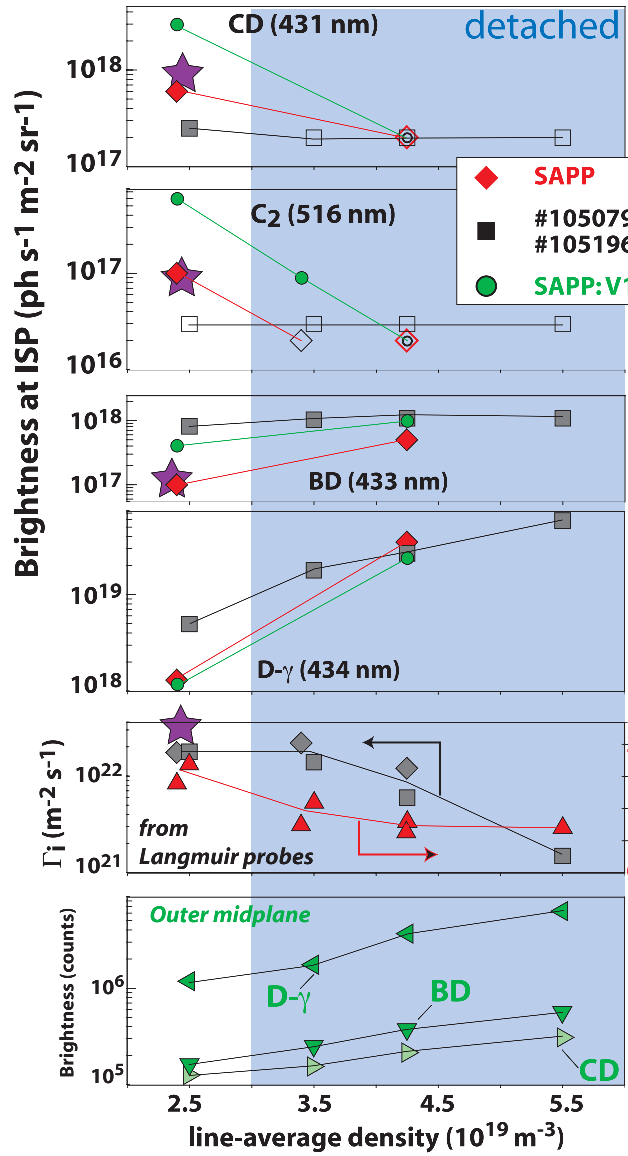
ISP behaves nearly identical to OSP:

No apparent difference between locations in Y_{chem}

- Implies Y_{chem} ~0.3% in attached case.
  - ➢ No DTS for modeling.

- No difference between net erosion dominated OSP (stars) and sooty, redeposited ISP tiles.





ISP vs. $\langle n_e \rangle$

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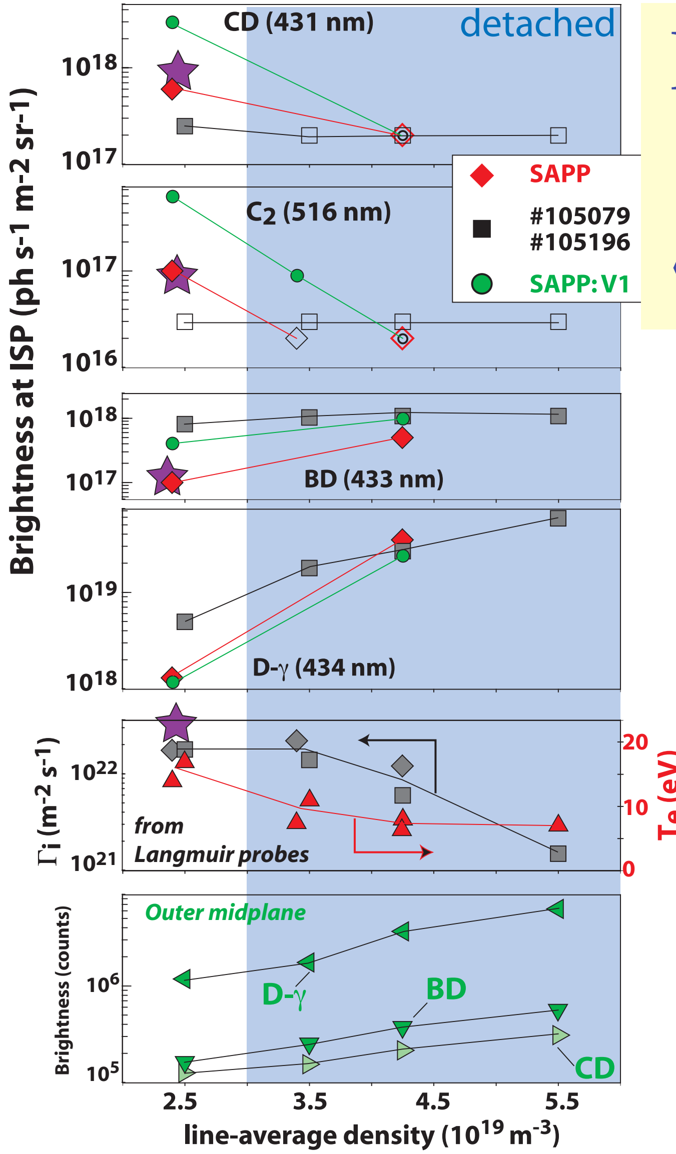
FURTHER OBSERVATIONS

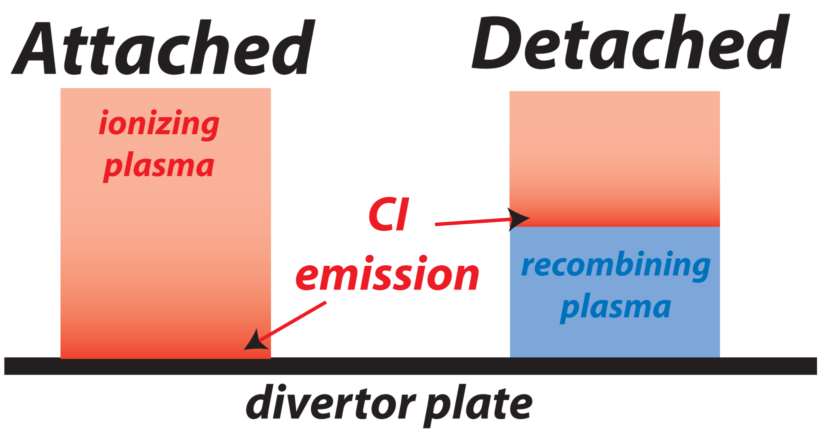
- BD presence: T_e can support HC emission.
- Lack of HC emission --> little chemical erosion in detached ISP.
- In stark contrast to the divertor, main-wall chemical erosion increases with ~ constant yield.

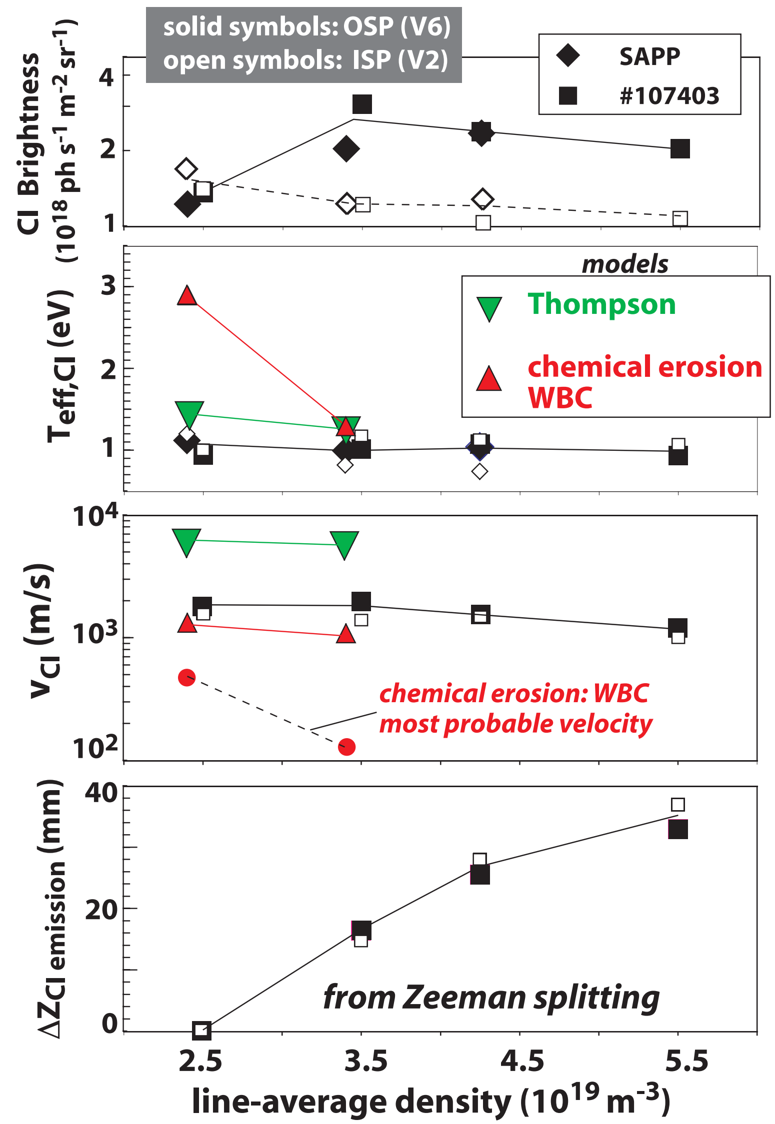


ISP vs. ⟨n_e⟩

Divertor atomic carbon response to detachment varies greatly from HC

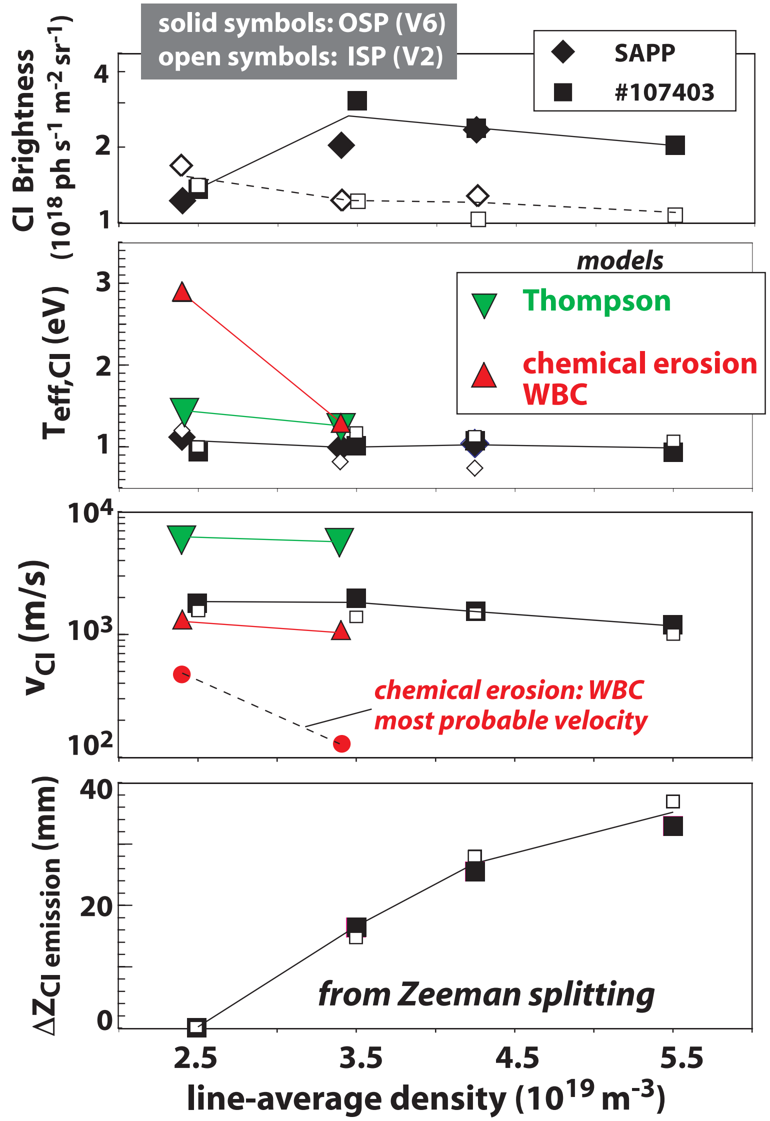
- CI brightness is ~ proportional to ion flux.
- Change in Zeeman splitting indicates CI emitted from ionization front.





Divertor atomic carbon response to detachment varies greatly from HC

- CI brightness is ~ proportional to ion flux.
- Change in Zeeman splitting indicates CI emitted from ionization front.
- Little or no change in T_{eff}, contradictory to chemical erosion.
- Doppler shift remains inconsistent with physical sputtering.



Discussion on dependence of location for Y_{chem}

- Redeposited layers, e.g inner divertor do **not** have higher chemical erosion.
  - No difference between ISP & OSP, regions yet dominated by net erosion &deposition respectively.
  - At strikepoints, almost all C atoms/HC eroded are from a deposited film, since prompt redepositon on ~90%.
- Results indicate **against** importance of boron in reduction.
  - Slighter higher Y_{chem} after boronization
  - Upper inner wall and main-wall, strong boron presence with no apparent reduction
- Large energy / particle fluence in divertor remains as the “cause” in the relative reduction.

Discussion on the (near) extinction of HC emission in detachment.

- Accuracy of yield < 10^{-4} unknown, but the general results of WBC follow from simple examination
  - ➢ The HC dissociation chain is simplified by the lack of ionizing event, → the HC should produce C_2 &/or CD
  - ➢ BD shows C_2 and CD should radiate efficiently.

- The absence of C_2 &/or CD argues strongly **against**:

1. The importance of chemical erosion as a carbon source for the plasma (*does not produce C ions*) and

2. A large role for chemical erosion in determining net erosion / deposition (*MFP of HC molecules < mm << MFP CI, CII*).

In summary we have verified and further quantified previous H-mode results of carbon erosion, with some new obervations

- Chemical erosion is weak in the DIII-D lower divertor, Y_{chem} ~0.3 % with attached plasma.

- Same shot comparison indicates that the divertor tiles have less chemical erosion than main, inner wall.
  - Boron does not appear to be cause of reduction.

- Detachment eliminates the spectroscopic signature of chemical erosion, with a inferred yield through modeling < 10^{-4}.