Observations on the location, mechanisms and consequences of impurity generation with a poloidal divertor in DIII-D

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IAEA TCM on Divertor Concepts

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One of the primary functions of a divertor is to control impurities.

- Unlike current confinement experiments, **burning plasmas must have control over the generation and consequences of impurities in the plasma**
  - Fuel dilution and Z_{eff} must be minimized for ignition
  - Erosion/redeposition (E/R) will limit wall viability
  - Tritium fuel trapping in deposits

- The divertor certainly moves the locations of intense heat and recycling away from the immediate periphery of the core plasma.

- **A vital question to answer**: what is the location, and cause, of the material sputtering that causes the core plasma impurity content in diverted plasmas?
  - ➢ This speaks directly & indirectly to edge impurity issues.

Approach for this impurity study: Rely on empirical evidence rather than modeling codes.

- Perform experimental tests that we believe should affect core impurity levels based on our physics knowledge of SOL transport and erosion.

- **Advantage**:
  By definition we incorporate all the parameters of the edge plasma that are difficult to diagnose and include in modeling codes.

- **Disadvantage**:
  "Independent" experiment variables to affect impurities are difficult to uncover because the particle fuelling/impurity cycle is to large extent self-determined by the plasma.

Empirical impurity studies: Vary the relationship between fuel recycling , impurity sputtering and the expected effect on the core plasma

- Geometry
  - Vary distance of sputtering surface to core.
  - Exploit different penetration distances of fuel and impurity.
- Material properties
  - Change erosion rates through surface modification.
- Plasma properties
  - E.g. Cold plasmas cannot sustain physical sputtering.
- Surface heating
  - Exploit changes of material removal rate with temperature.

Outline of empirical investigation on impurity sources

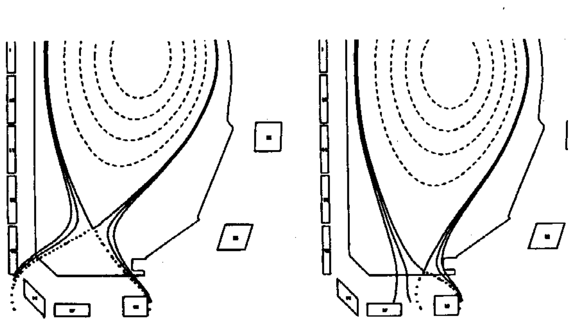
- Exploit single-material wall (carbon) and excellent edge diagnostics and shaping flexibility of DIII-D.
- Divertor target impurity sources do not correlate to core impurity level.
- Main-wall sources do correlate with core impurity level.
- The magnitude and penetration capability of main-wall sources is sufficient to explain core plasma impurity level.
- The magnitude and trends of plasma contact at main-wall surface is consistent with measured erosion and recycling

Outline of empirical investigation on impurity sources

- **Divertor target impurity sources do not correlate to core impurity level.**
  - Review article "Experimental divertor physics"
    Pitcher & Stangeby,
    Plasma Phys. Contr. Fusion **39** (1997) 779.

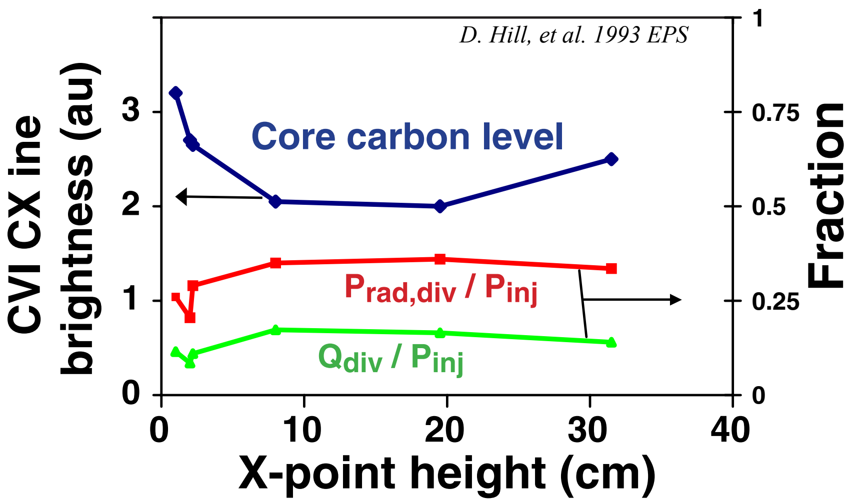
Divertor target geometry does not affect core plasma impurity level

X-point height scan



- Only near-limited case has consistently higher f_{core} in X-point scan.

ELMy H-mode **(P=6.8 MW)**



Divertor target geometry does not affect core plasma impurity level

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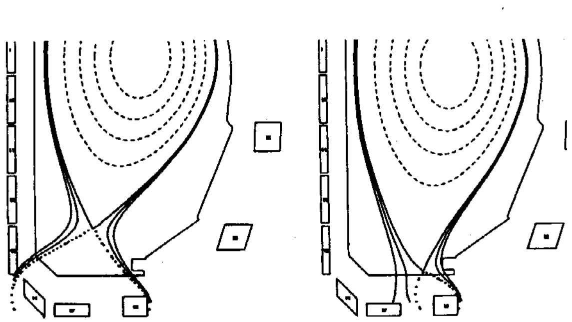
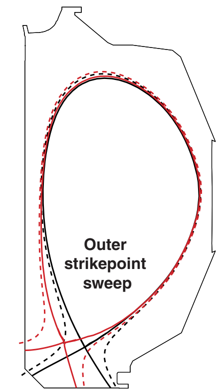
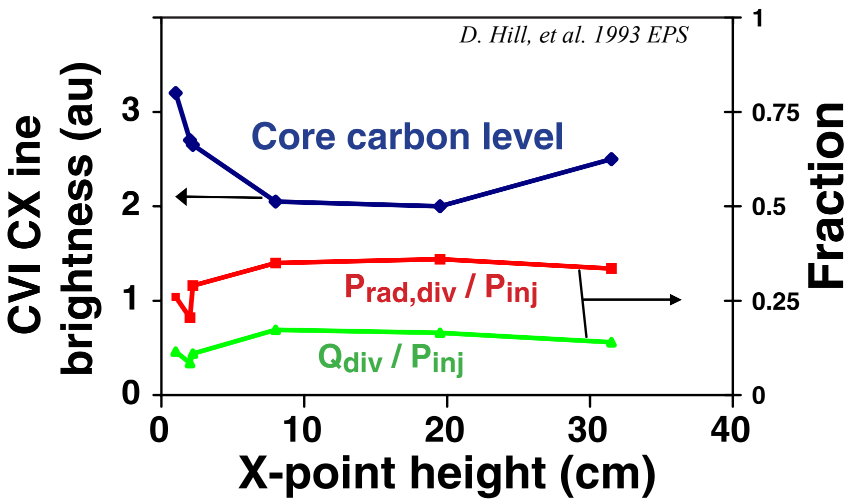


- Only near-limited case has consistently higher f_{core} in X-point scan.

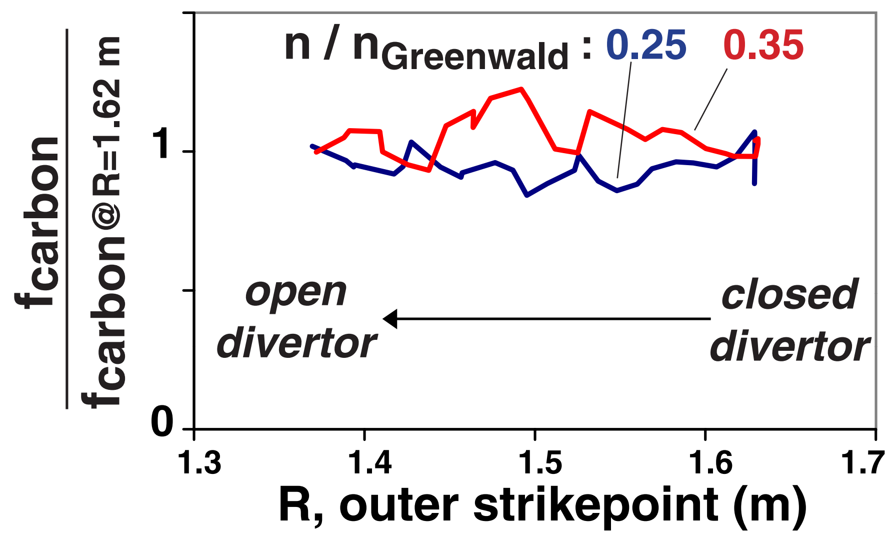
Strikepoint scan



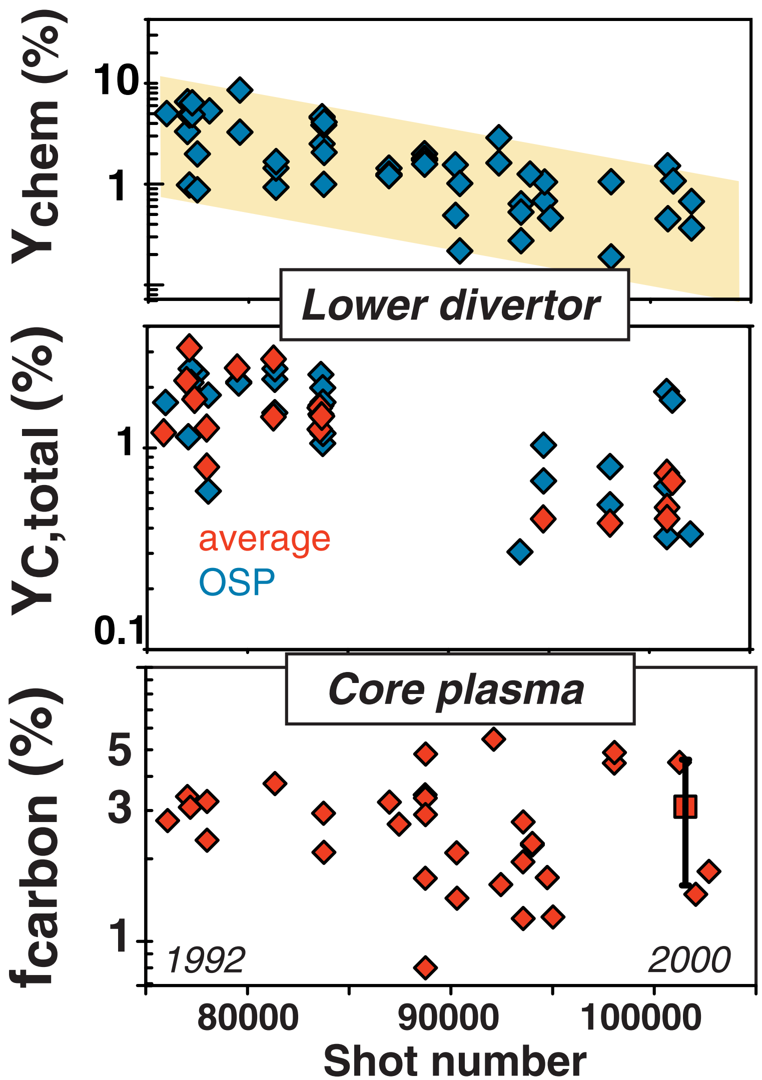
ELMy H-mode (P=6.8 MW)



L-mode (P=1.8 MW)



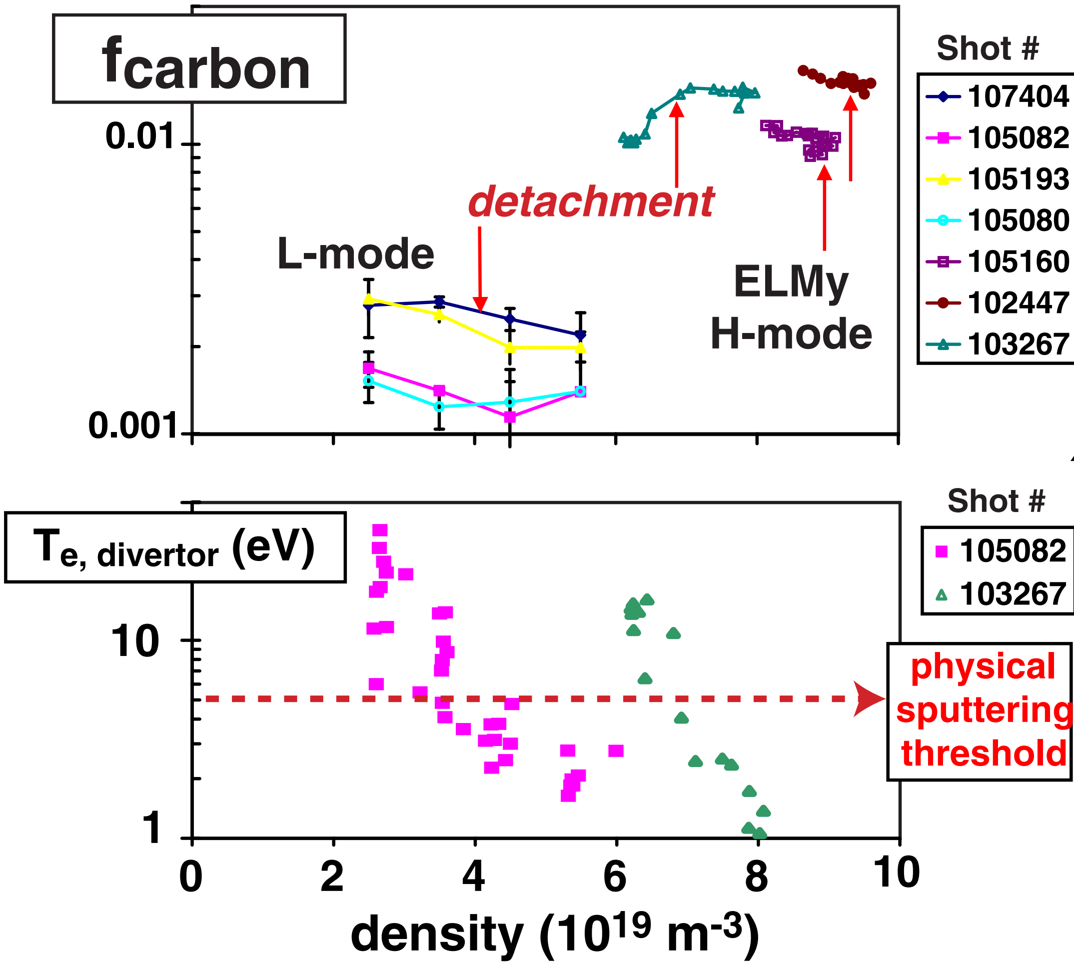
Reducing erosion yield of divertor by boronizations did not affect core plasma impurity level



- Long-term effect of boron doping reduced divertor target chemical erosion and total carbon source [Whyte, et al. PSI-14].

- Comparative database of ELMy H-mode discharges showed no long-term reduction in core plasma carbon level.

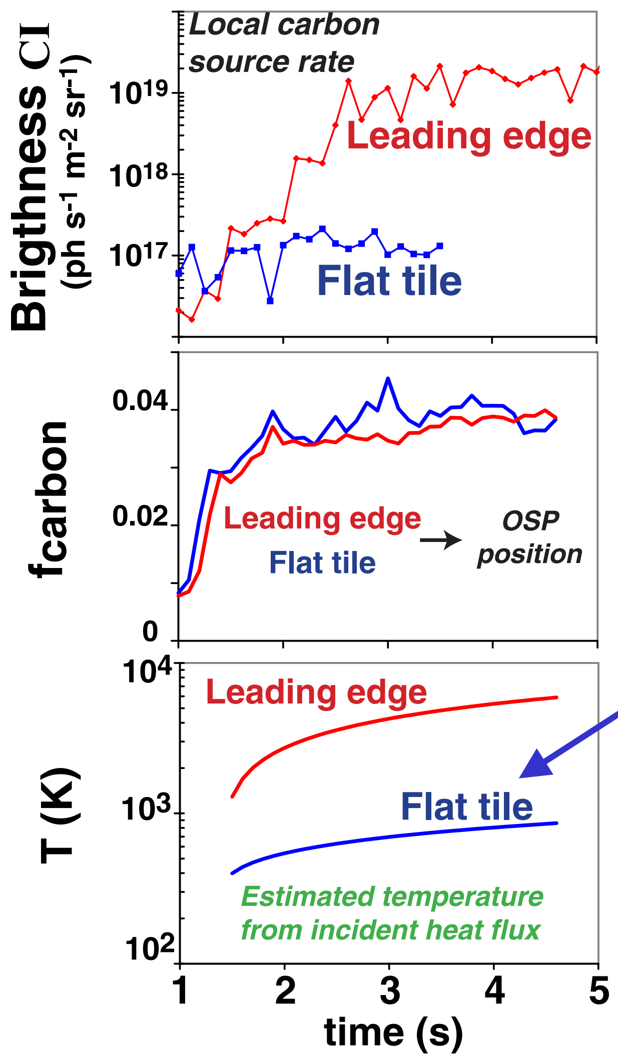
The elimination of physical sputtering at divertor targets via detachment does not consistently reduce the core impurity level



- Outer divertor detachment indicated in each density scan when physical sputtering is eliminated ($T_e < 5$ eV)
  - See examples of T_e in divertor from Thomson scattering.
- No clear trend of reduced f_{carbon} in H-mode or L-mode at detachment.

Increasing the divertor carbon erosion through over-heating does not increase core impurity level: Divertor shields core very well from thermally removed carbon

DiMES with leading edge



- Evolving T_{tiles} through maximum in chemical sputtering at T~600 K does not affect core level either.

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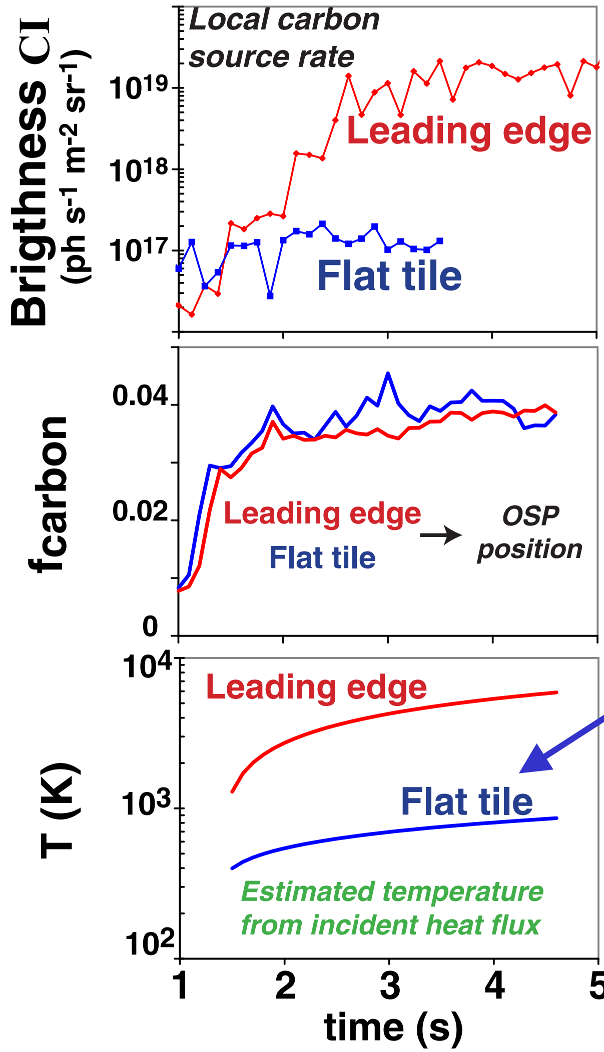

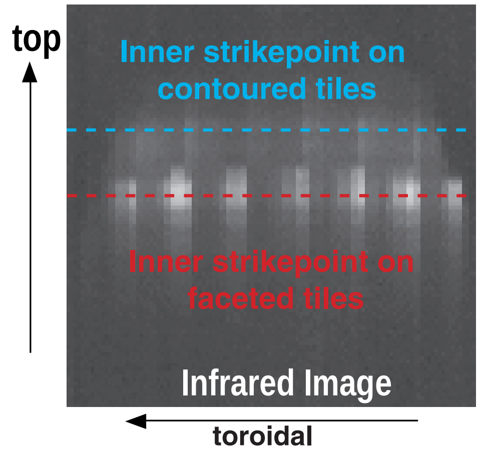

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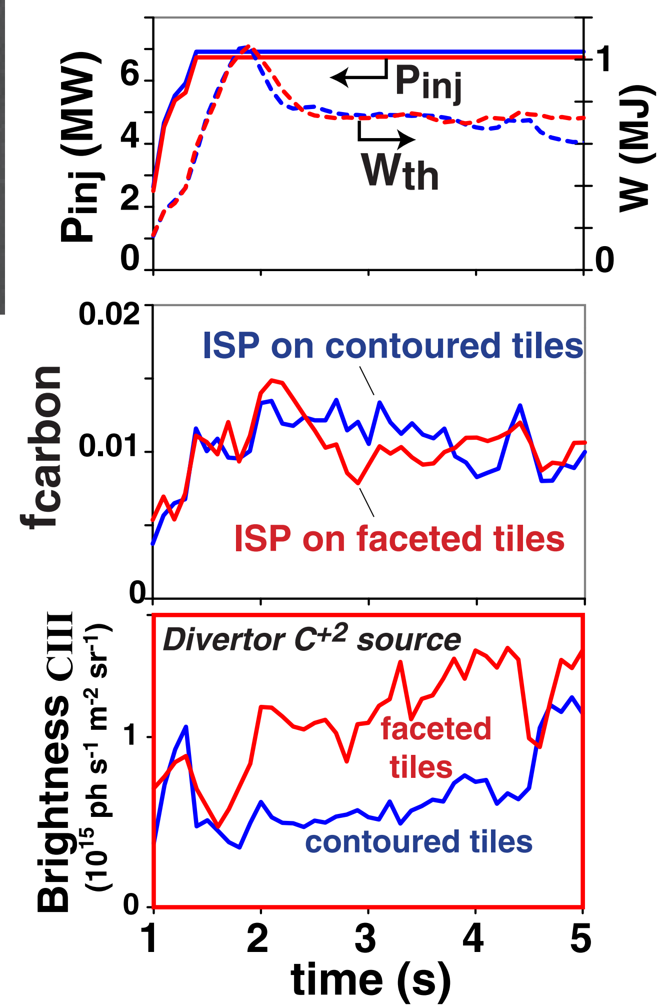
Upper inner divertor



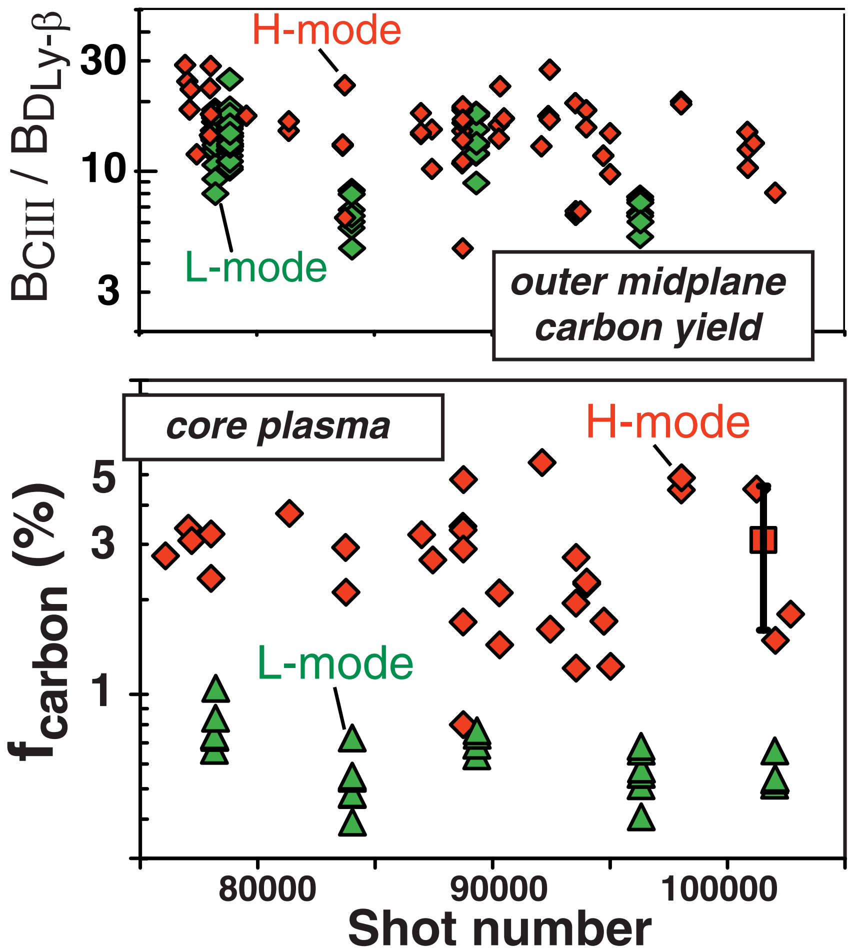
Outline of empirical investigation on impurity sources

- Divertor target impurity sources do not correlate to core impurity level.

- **Main-wall sources do correlate with core impurity level.**
    - **Geometry and material effects are assessed.**
    - **Detachment and sublimation variations not available.**

In contrast to the divertor, the main-wall erosion has not been altered by the history of boronizations, in agreement with constant core impurity level

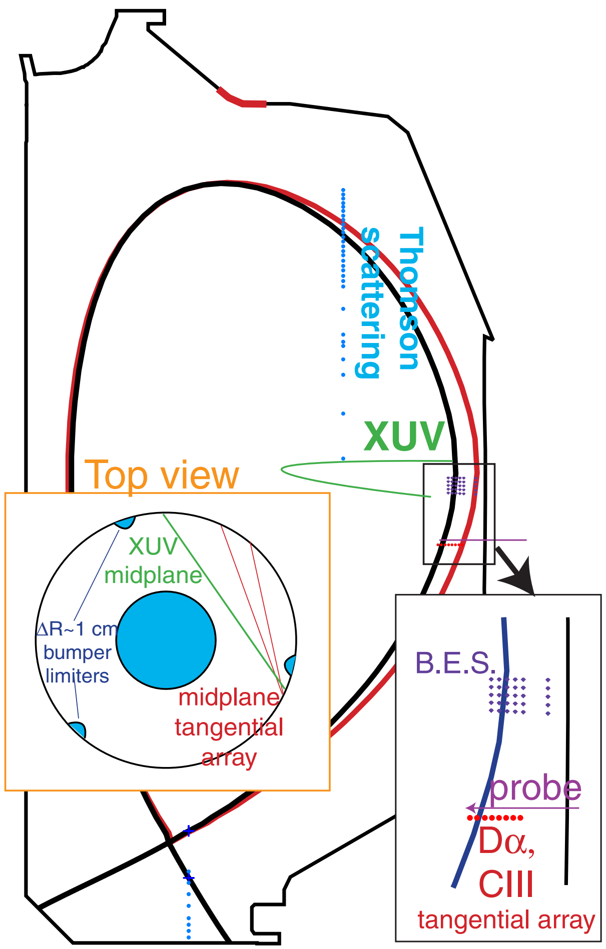
Core carbon fraction vs. main-wall source



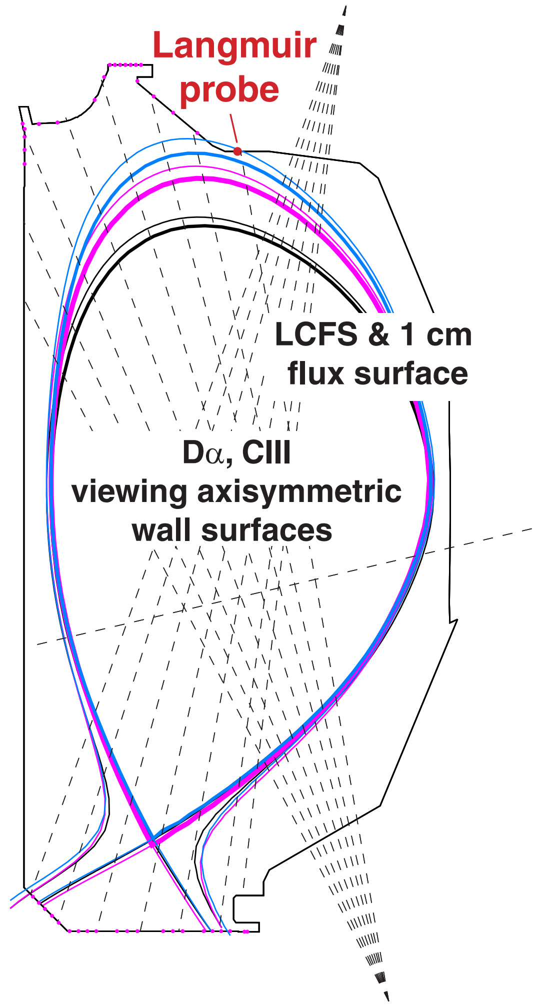
- The boron doping only affects chemical erosion in divertor target regions with T > 150 C.
- Historical correlation of midplane CIII and f_{carbon} in L-mode discharges used for L-H studies.

Geometry/ gap changes are a powerful tool for main-wall surface impurity studies

Outer midplane



Upper baffle knee

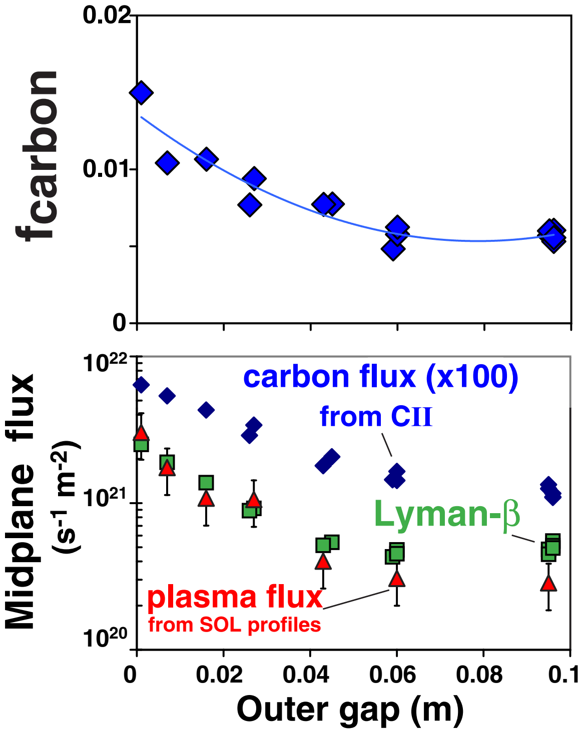


- Core parameters (P_{inj}, W_{th}, n_e, etc.) kept constant during scans.
- **Outer midplane**:
  - Non axisymmetric surface
  - Radially resolved spatial diagnostics.
- **Upper baffle knee**:
  - Axisymmetric surface with probe.
  - No local spatial resolution.

Core impurity level correlates well to gap between separatrix and outer midplane surface in several confinement regimes studied.

L-mode

P~1.5 MW, n~4x10^{19}



- Well-diverted cases have lowest impurities, marginally-limited the highest.

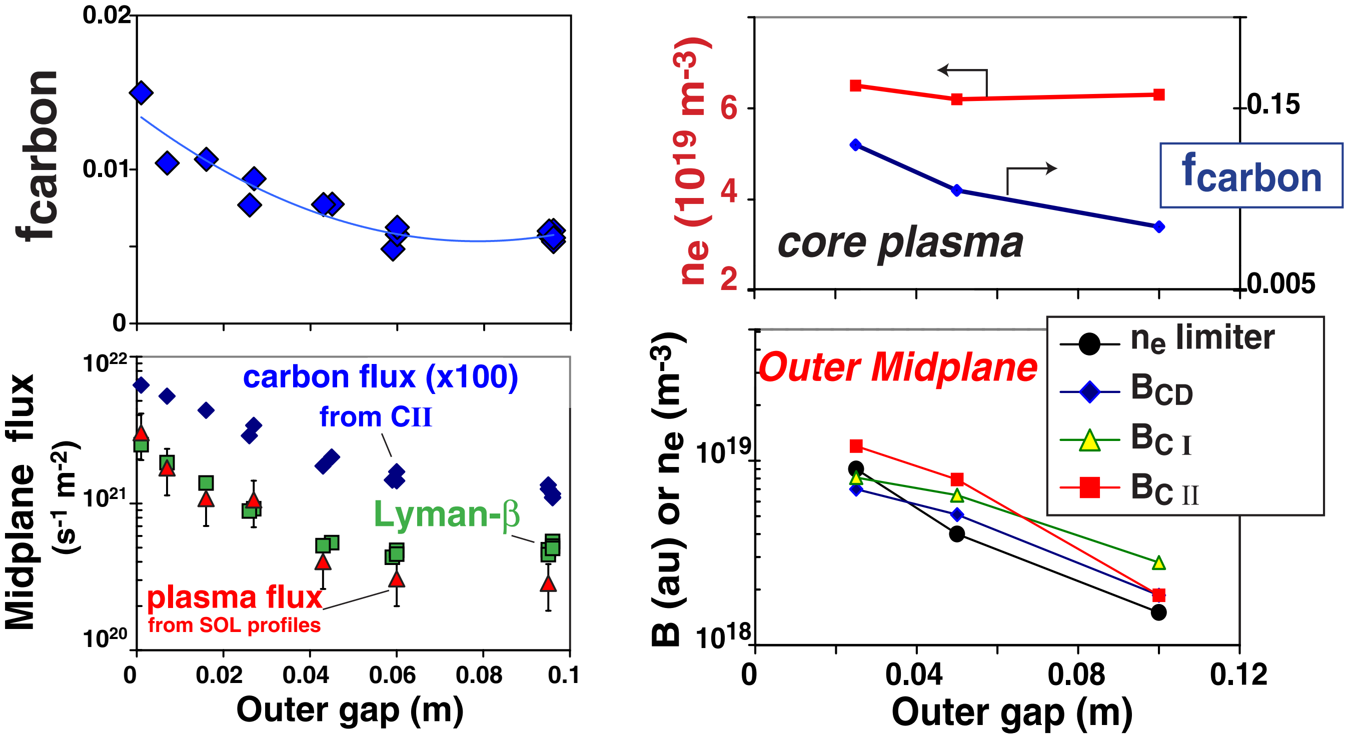
Core impurity level correlates well to gap between separatrix and outer midplane surface in several confinement regimes studied.

L-mode

P~1.5 MW, n~4x10^{19}

ELMy H-mode

P=7 MW, n~6.5x10^{19}



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- Spectroscopy indicates physical and chemical sputtering.

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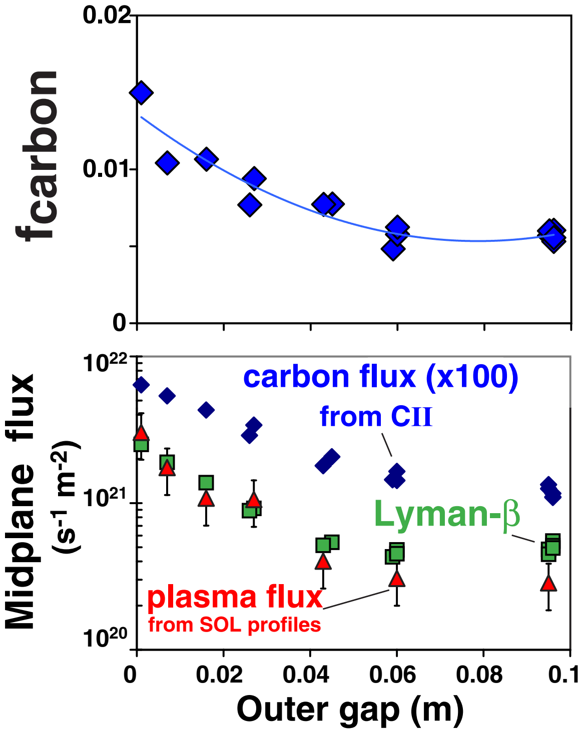

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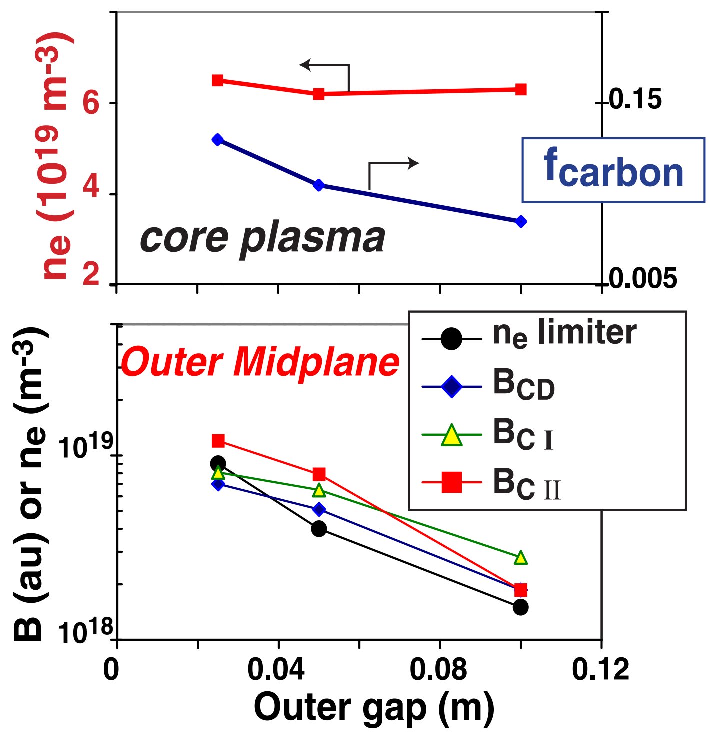
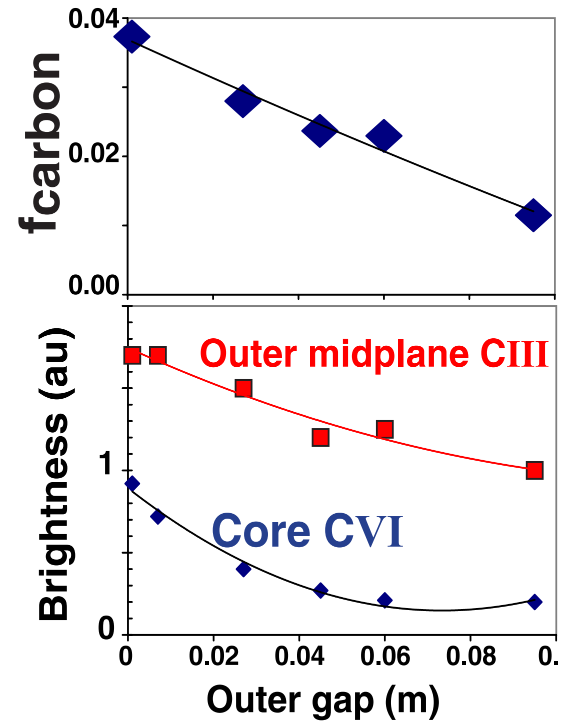


ELM free H-mode

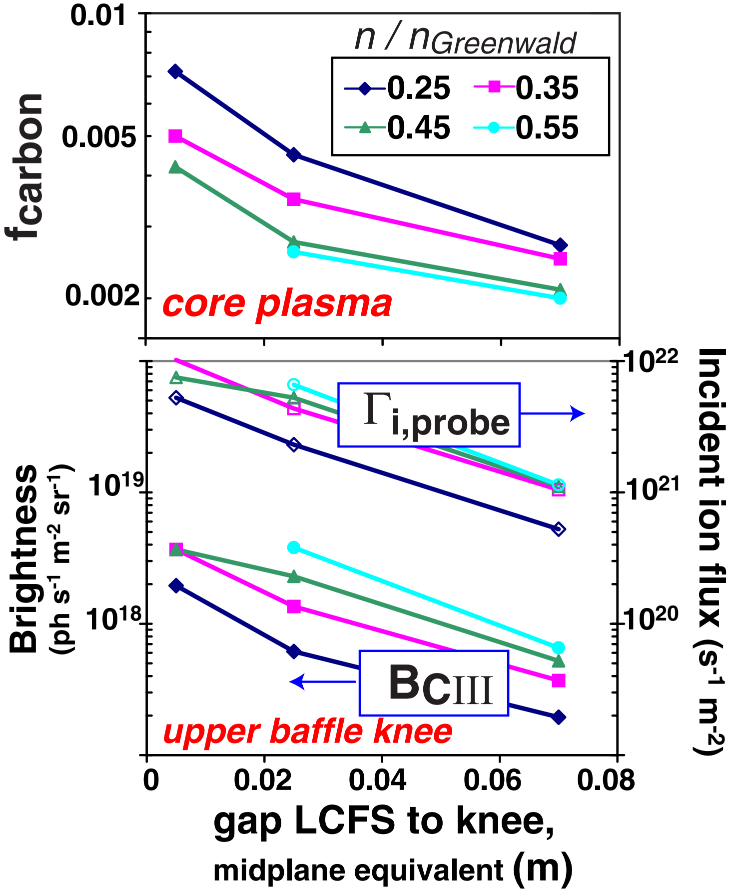
P>2 MW, n=7.5x10^{19}



- Well-diverted cases have lowest impurities, marginally-limited the highest.
- Spectroscopy indicates physical and chemical sputtering.

Main-wall impurity sources are robust over wide range of densities: fully attached divertor through detachment

Upper baffle knee gap scan



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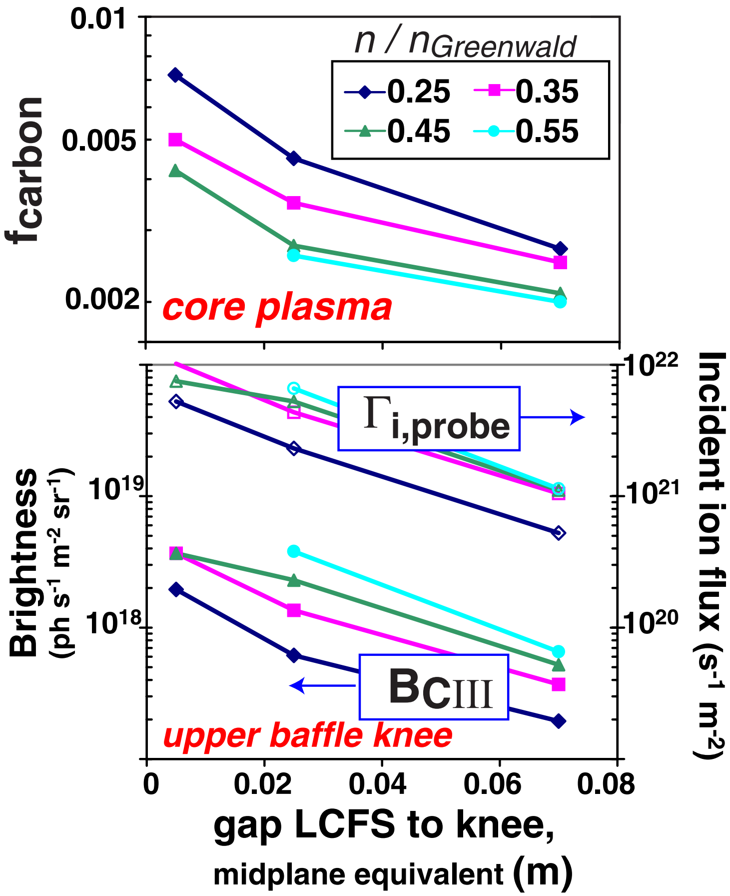
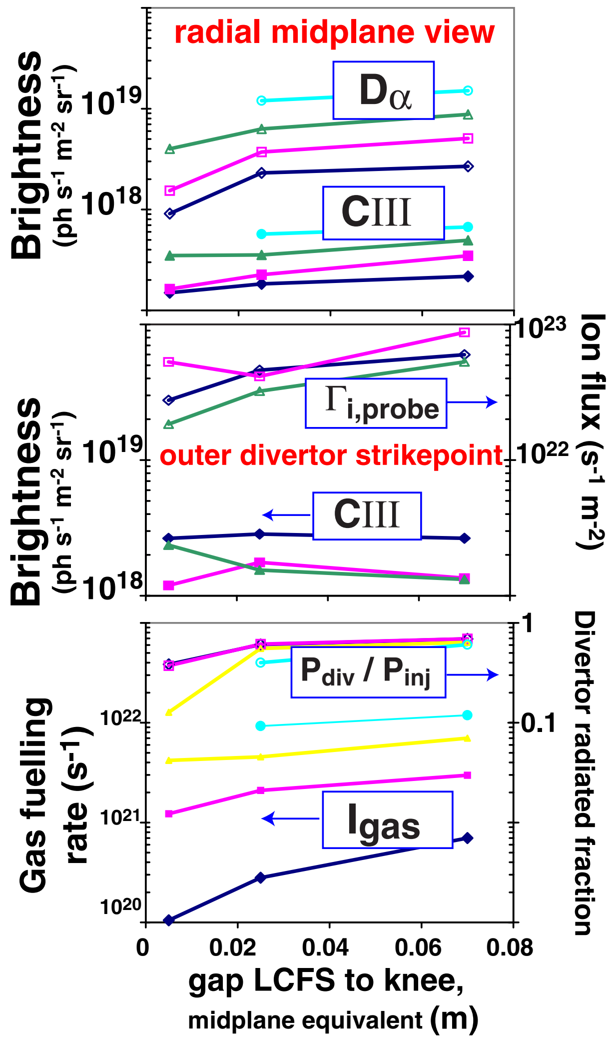


Response of other locations



- Divertor/midplane only affected when limited.
- Recycling not conserved during the gap scan
  - Better fuel penetration from limiter implies better impurity penetration

Outline of empirical investigation on impurity sources

- Divertor target impurity sources do not correlate to core impurity level.
- Main-wall sources do correlate with core impurity level.
- The magnitude and penetration capability of main-wall sources is sufficient to explain core plasma impurity level.

Two methods are used to assess magnitude of main-wall impurity sources as related to core impurity level

Penetration factor

- Known quantity of carbon injected in form of methane near main-wall.
- Penetration factor measured as:

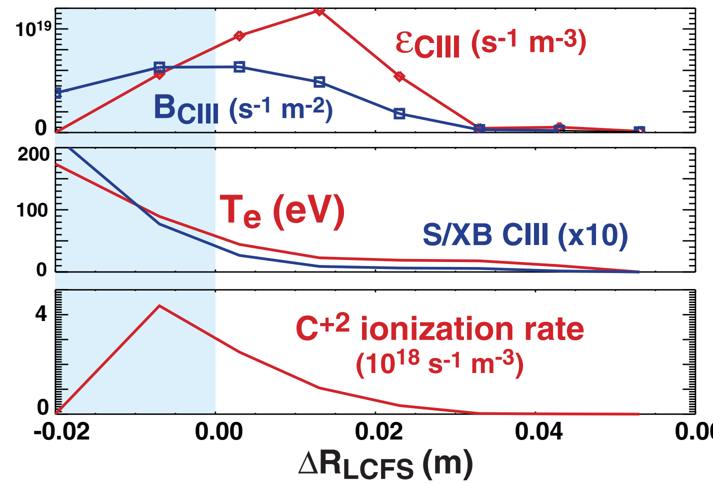
  $PF\ [s] = \Delta N_{carbon,core} / I_{methane}$

- Therefore, get core carbon concentration from ***intrinsically*** measured main-wall carbon flux, Γ_{MW} [$s^{-1}\ m^{-2}$]:

  $f_{carbon} =$

  $\Gamma_{MW} \bullet PF \bullet A_{MW} / (V \bullet n_e)$

Outer midplane C^{+2} ionizations inside LCFS



- C^{+2} is from local sources, but is more dispersed than direct source (CI, CII).
- $f_{carbon} = \int_{core} S_{ion,C+2}\, dr \bullet \tau_e \bullet A_{MW} / (V \bullet n_e)$

  A_{MW} = area of main-wall surfaces

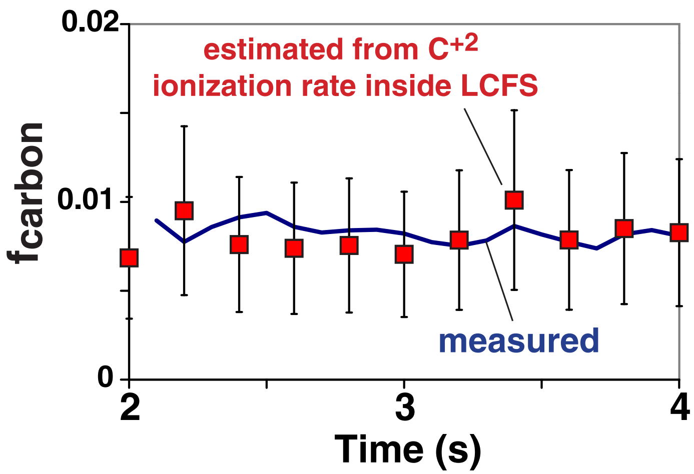
  τ_e = (energy) confinement time

  V = plasma volume

The measured magnitude of main-wall carbon sources is sufficient to account for core impurity levels in various confinement regimes and densities.

L-mode

P~1.7 MW, n_e=2.25x10^{19}



- Uncertainty in f_{carbon} from OM CIII primarily due to inversion and undetermined A_{MW}.

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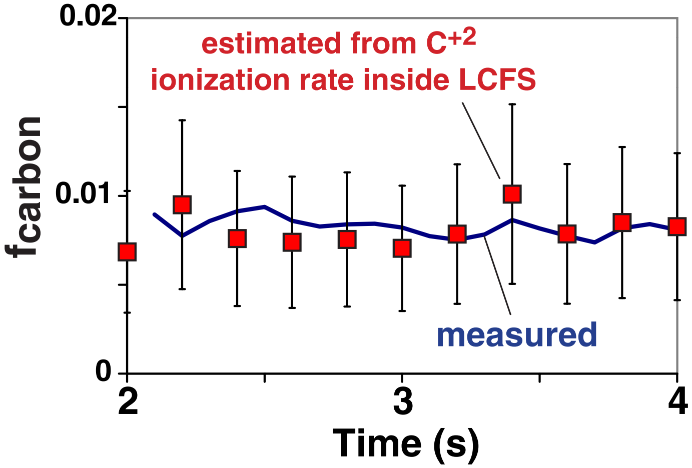
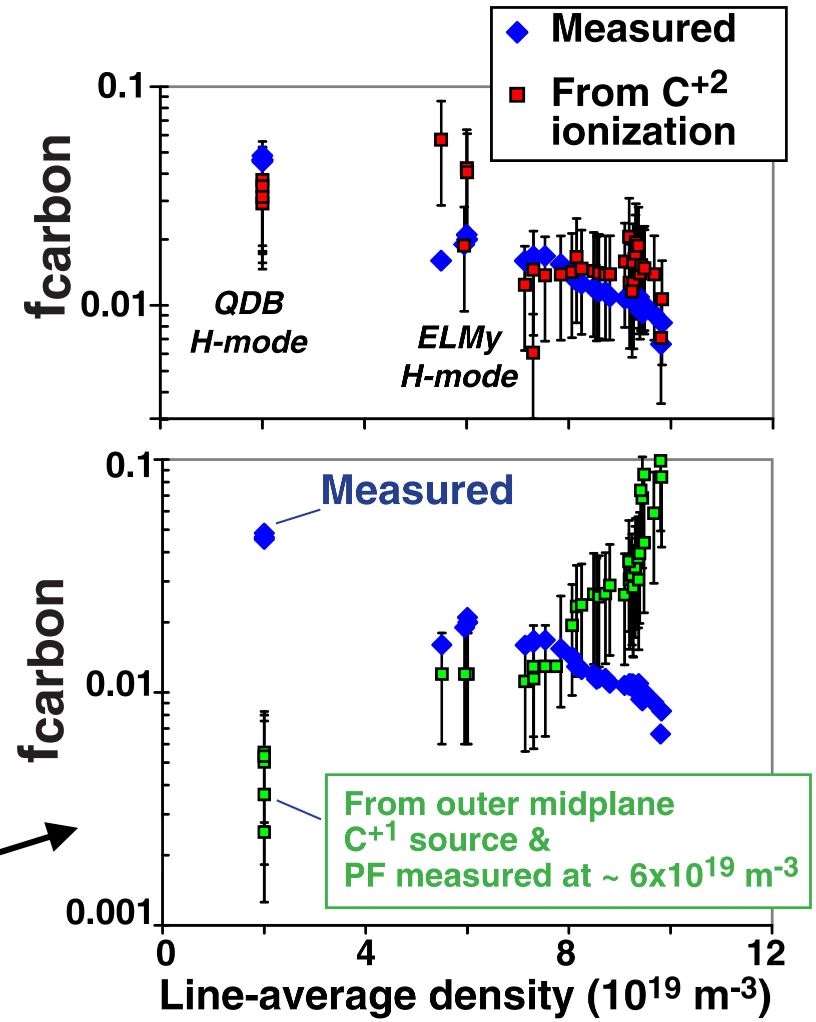


H-mode



- Uncertainty in f_{carbon} from OM CIII primarily due to inversion and undetermined A_{MW}.
- Penetration factor only measured at one density (~6x10^{19}) in ELMy H-mode so far
  - Agreement near n_e~6x10^{19} m^{-3}
  - *OM CII source, and its "screening", increases strongly with density*

Outline of empirical investigation on impurity sources

- Divertor target impurity sources do not correlate to core impurity level.
- Main-wall sources do correlate with core impurity level.
- The magnitude and penetration capability of main-wall sources is sufficient to explain core plasma impurity level.
- The magnitude and trends of plasma contact at main-wall surface is consistent with measured erosion and recycling.
  - *Divertor leakage*: neutral/CX erosion only.
  - *Plasma contact*: plasma + neutral/CX erosion.

We utilize several methods to assess main-wall plasma interactions

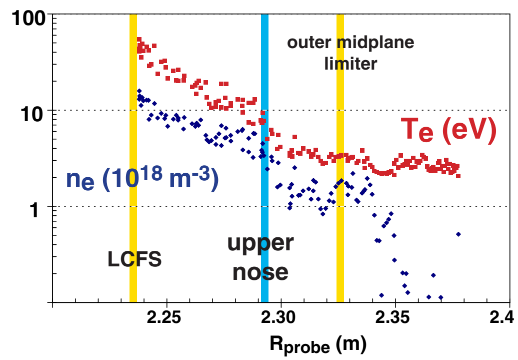
Langmuir probe in baffle knee

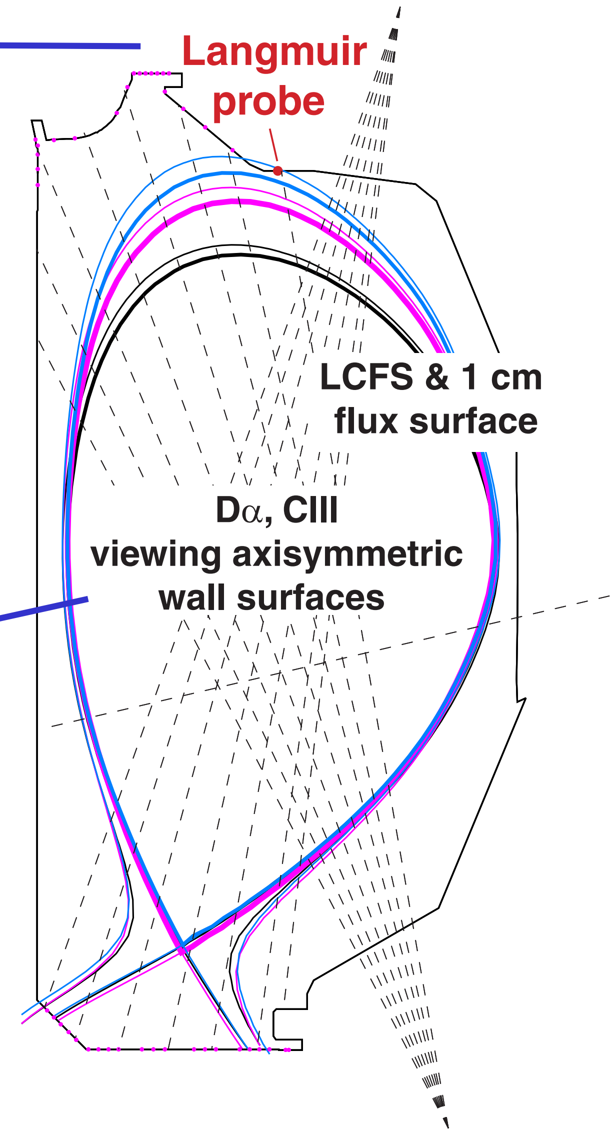
Integrate SOL profiles
(TS or scanning probe)
behind axisymmetric limiting surface

$$\Gamma_{perp} = 2\, n_e \cdot c_s \cdot \lambda_r \cdot (B_p/B_T) / L_p$$

D_α recycling on main-wall surfaces

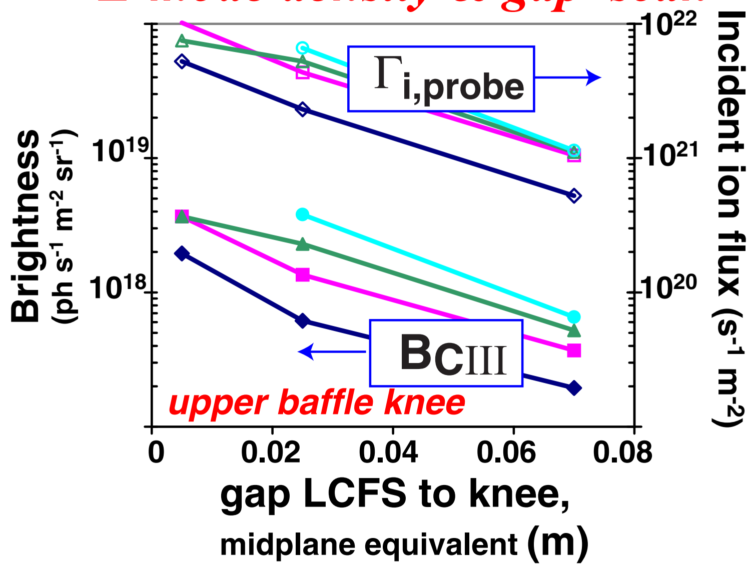
Example from MP scanning probe



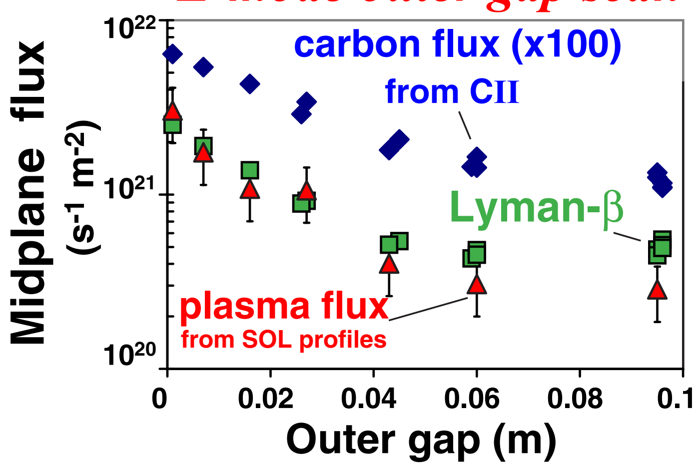


Plasma flux to main-wall surfaces accounts for erosion and recycling, even when gaps are relatively large.

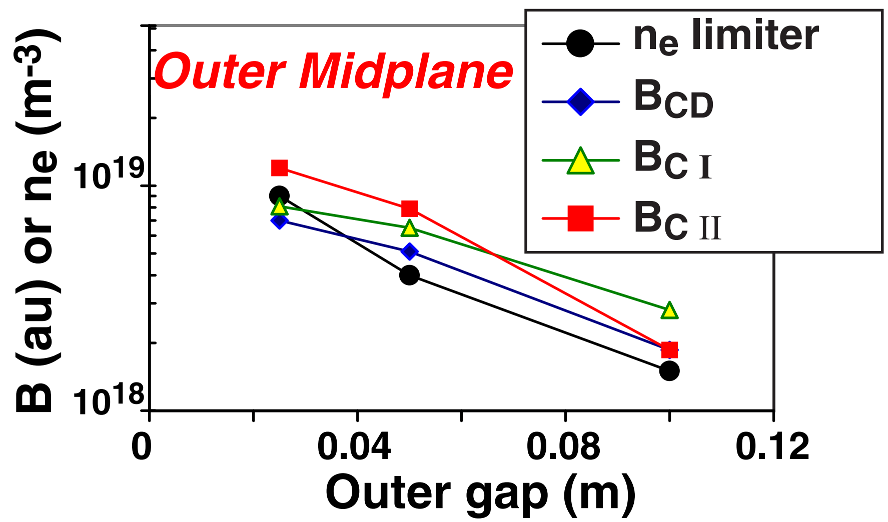
L-mode density & gap scan



L-mode outer gap scan



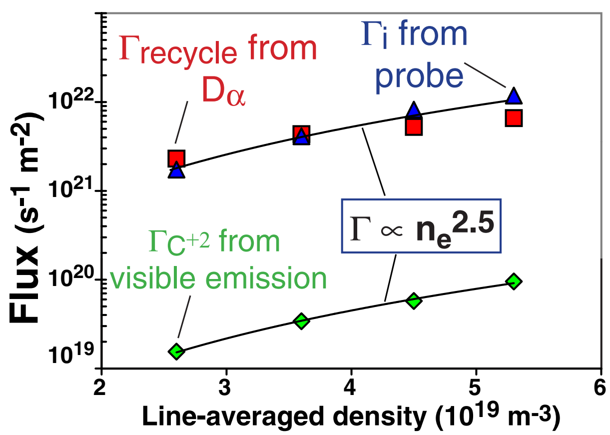
ELMy H-mode outer gap scan



The magnitude and trends of plasma flux are consistent with the recycling and carbon erosion at the main-wall as line-averaged density is scanned.

L-mode **(P~ 1.8 MW)**

Upper baffle knee limiter



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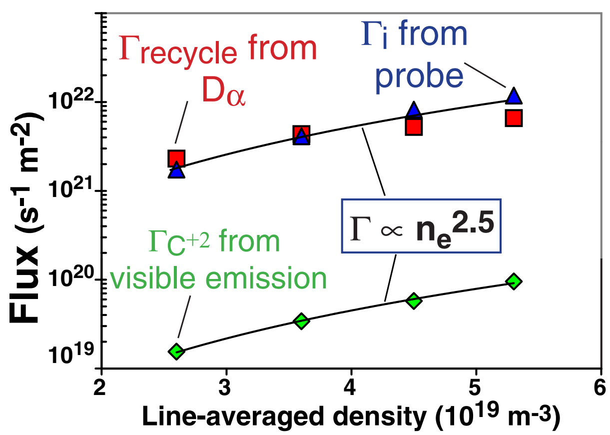
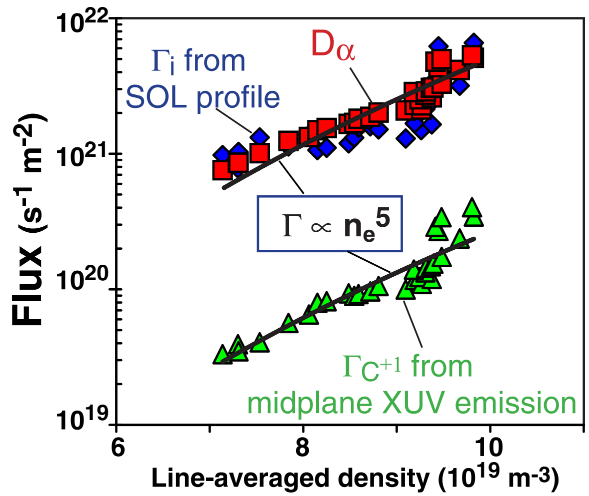


High δ/w gas puff & type-III ELMs



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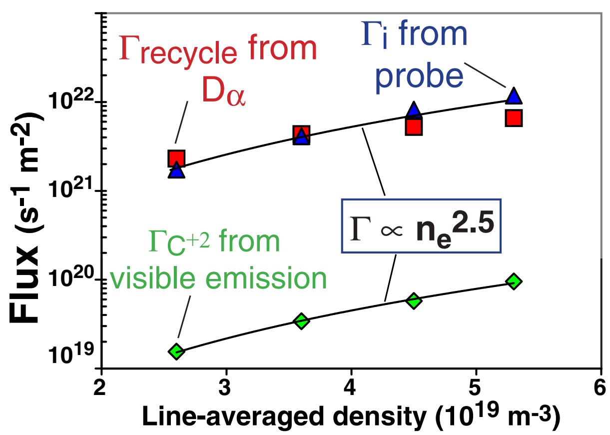

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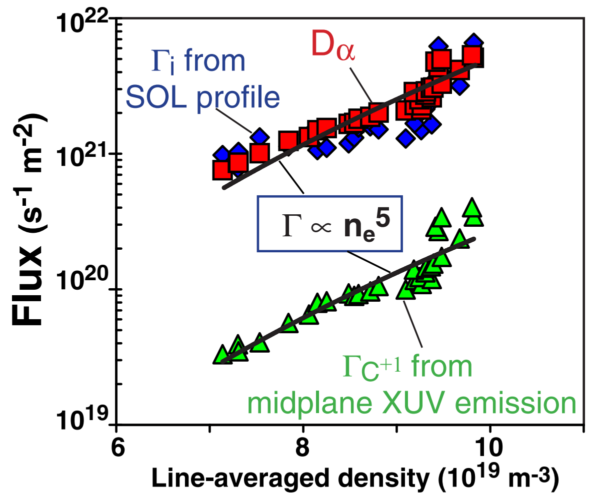
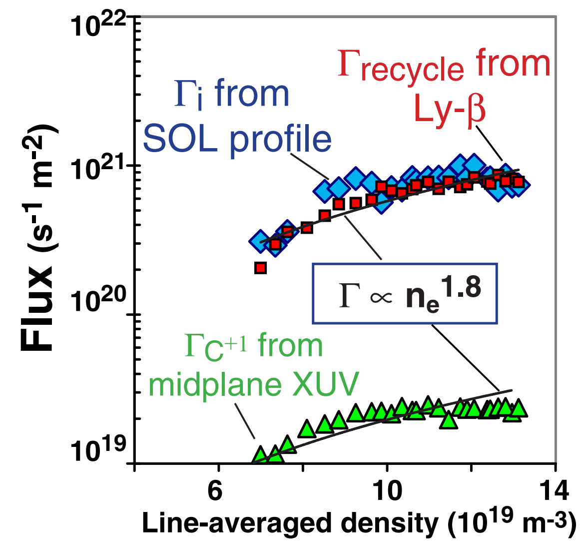


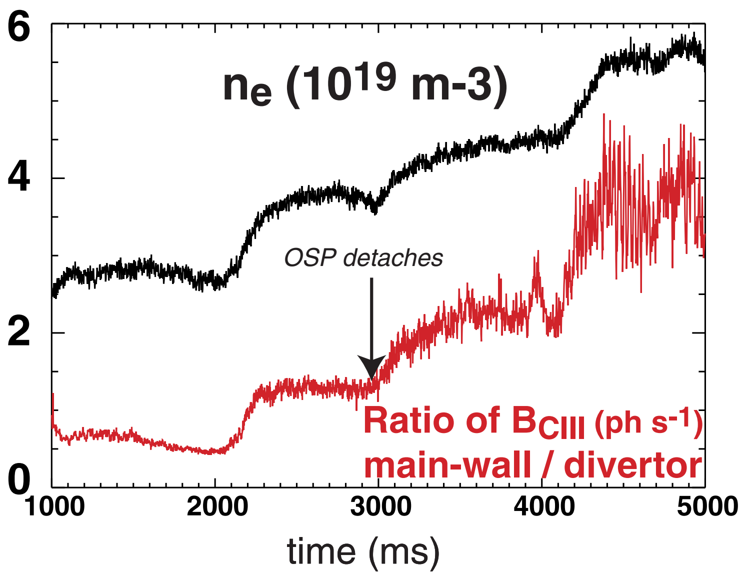
$n > n_{Greenwald}$ & type-I ELMs



- **Plasma flux is consistent with non-linear relationship between recycle and n_e in all cases.**
- **Carbon yield consistent with expectation: ~ 1-3 %**

As the divertor detaches the main-wall is the dominant location of erosion and plasma-conducted heat flux.

L-mode density scan



- **At detachment, the main-wall carbon source dominates**
  - ➢ **The cold divertor no longer sustains physical sputtering.**

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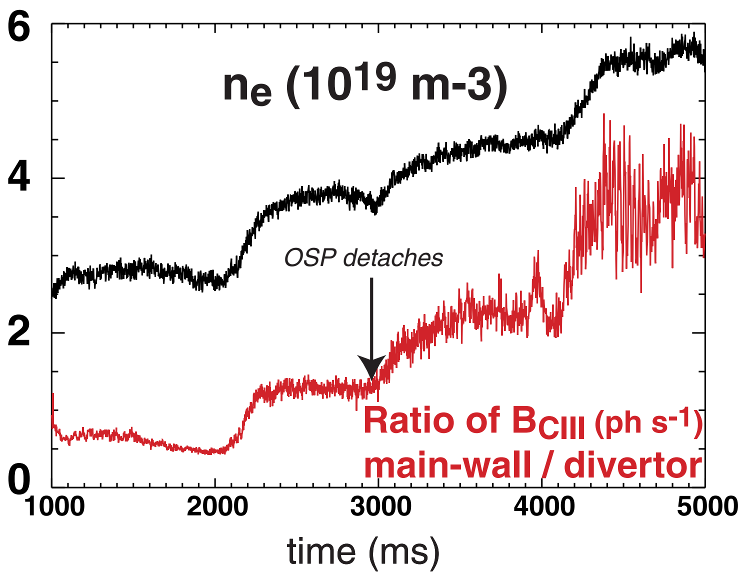

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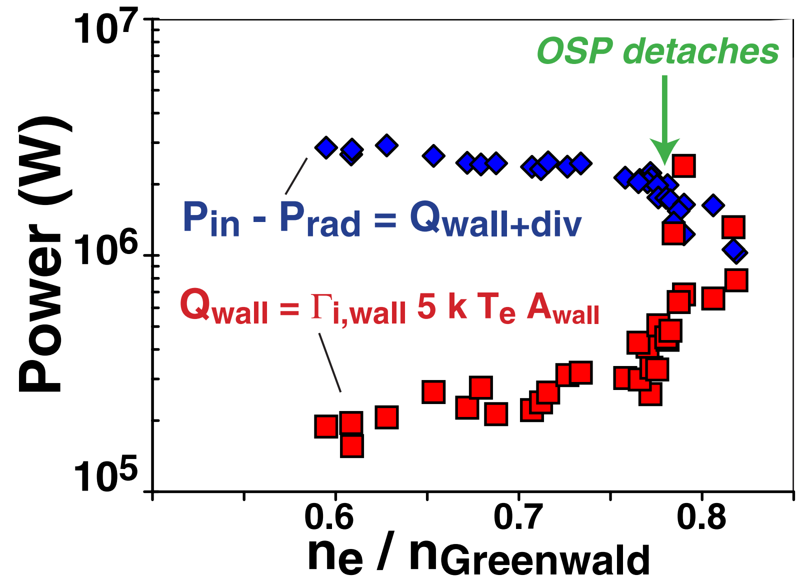
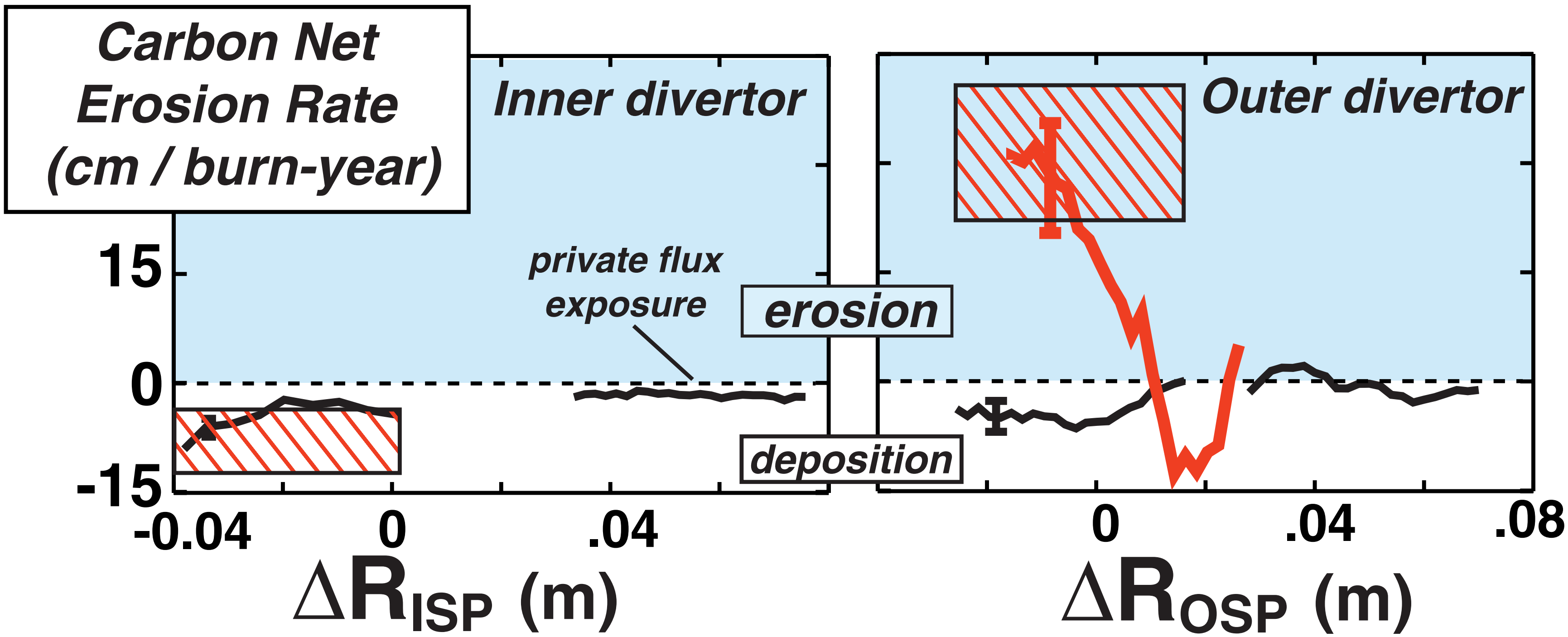
ELMy H-mode power balance



- At detachment, plasma conducted heat to main-wall is significant (~15% P_{in})
  - The cold divertor no longer sustains heat conduction to targets.
  - Main-wall flux satisfies power balance.

In confirmation of main-wall erosion, the entire lower divertor is a location of net deposition in detachment

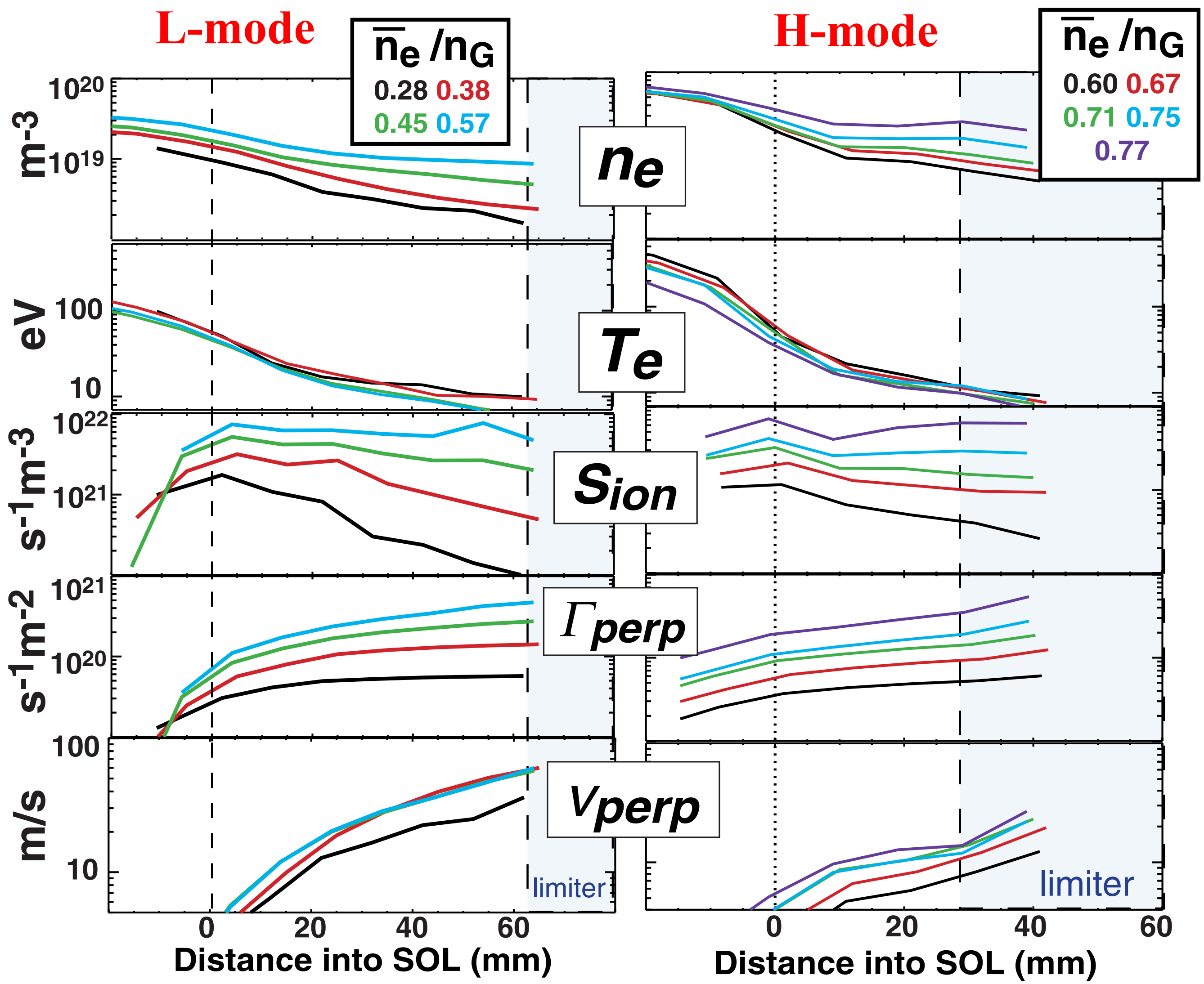
Attached vs. Detached



ELMy H-mode (P~7 MW)

SOL transport analysis based on local, main-wall particle balance (plasma flux ≈ recycle/D_α flux) :

Cross-field plasma transport is large to main-wall.



- **SOL density increases and flattens, extending to limiter**
- **T_e ~ constant > 10 eV**
- **Local ionizations and implied Γ_{perp} increase strongly with n_e.**
- **Radial convective-like transport**
  - **~constant vs n_e**
  - **Changes with confinement mode.**
  - **Turbulent nature?**

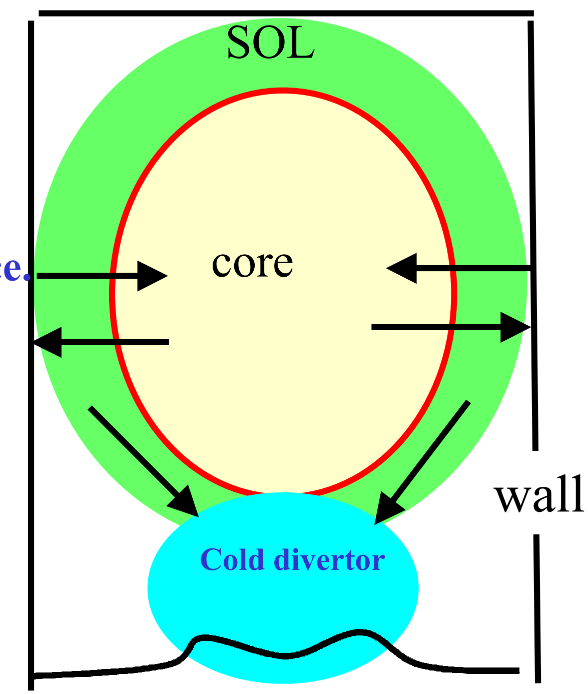
Summary of empirical impurity studies

- Divertor configuration has better impurity control than limiter.
- Main-wall surfaces, not divertor targets, are the controlling location of impurities.
- Plasma flux to the main-wall is sufficiently large to cause the erosion that leads to core impurities.
- As density is increased, through detachment, the main-wall becomes the dominant location of plasma flux and erosion.

Implications of the concept of main-wall erosion ripple through edge issues in current devices

- Large impurity contents in high performance discharges?
  - E.g. f_{carbon}>5% and high-Z metals in low-recycling QDB
- Global E/R patterns are inconsistent with divertor sources only
  - JET Be divertor collected C deposits
  - DIII-D: total divertor net deposition in detachment.
- Tritium retention in JET divertor that must seemingly be explained by substantial non-divertor sources.
- Main-wall impurity source implies that the main-wall recycling also controls refueling
  - Pedestal physics?
- Why do edge models that have only divertor sources work?
  - Lack of proper diagnosis of edge T_i and flow patterns?
  - Other physics (e.g. drifts) make divertor better shield?
  - Is our empirical picture too simple?

Picture of detached plasma: SOL extends to main-wall, causing intense PSI, Cold divertor acts a focal point for deposits



Large plasma flux and erosion at main-wall surface.

Redeposits and H/D/T build up on divertor plates

Pressure builds up. Good for pumping.

Implications for use of poloidal divertor in burning plasma

- Divertor successfully focuses heat by electron conduction.
- Heat load is too large in burning plasma & will destroy
  |normal target plates → let's use detachment!
- SOL transport conspires to push plasma increasingly to main-wall surfaces *(a generic result to detachment?).* ***What now?***

- Wall design?
  - Chemical vs. physical sputtering for carbon
  - Ion energy spectrum in Far SOL? Will high-Z metals sputter?
- Plasma geometry?
  - Maximize gaps vs. non-reacting volume
  - Divertor geometry: do we need a long divertor or a simple baffle to pump?

- **It is clear that we must better understand SOL transport to fully exploit the many excellent properties of poloidal divertor.**

Open vs. closed divertor: outer wall carbon source consistent with changes in core carbon