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

D. G. Whyte, *University of Madison - Wisconsin*

J.N. Brooks, *Argonne National Laboratory*

P.C. Stangeby, *University of Toronto*

N.H. Brooks, *General Atomics*

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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 $Y_{\text{chem}}$ 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 $Y_{\text{chem}}$ 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 $\sim$ constant $T_{\text{surf}} \sim 375 \text{ K}$
- 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 C₂ and C₃ rates for C₂ spectroscopic interpretation.
  - Close to C for ionization & diss. CX negligible in H plasma
- Excitation rates of CD, C₂, C I and CII vs. Tₑ, nₑ to calculate expected emission --> photon efficiency.

\[
\frac{XB}{S}_{CI,910nm} = \sum_i n_e X_{CI,910nm}(T_e) \Delta t_{i,CI}
\]

- 43.5% CD₄, 3.7% C₂D₂, 24.8% C₂D₄, 11% C₂D₆, 16% C₃D₆

C atom trajectories
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.

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

$$\gamma = \frac{4m_cm_D}{(m_c + m_D)^2} \sim 0.49$$
The main/inner wall tiles has 5-6 times higher $Y_{\text{chem}}$ than the inner divertor tiles

- V1 is a rare location for ISP, small particle/energy fluence.

- Spectroscopy verifies ~identical ISP plasmas at two locations:
  $T_e \sim 10 \text{ eV}$
  $n_e \sim 1.5 \times 10^{19} \text{ m}^{-3}$

- Boron (BD) higher from inner wall.
Attached outer strikepoint is dominated by physical sputtering, $Y_{\text{chem}} = 0.3\%$

- Incident plasma: $T_e = 20\text{ eV}, E_i \sim 5\text{ eV}, T = 100\text{ eV}, n_e \sim 2.5 \times 10^{19}\text{ m}^{-3}$
- 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: \( T_{\text{eff}} \approx 1 \text{ eV} \) OK, shift too large
  - Chemical - WBC: shift OK, but \( T_{\text{eff}} \approx 3 \text{ eV} \) too large.
- N.B. chemical erosion can actually lead to higher \( T_{\text{eff,CI}} \) than physical sputtering
WBC modeling predicts increasing photon efficiency in detached plasmas

<table>
<thead>
<tr>
<th>CASE</th>
<th>WBC-20</th>
<th>WBC-21</th>
<th>WBC-22</th>
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<tbody>
<tr>
<td><strong>Plasma parameters at outer strikepoint</strong></td>
<td></td>
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<tr>
<td>$Te$ (eV)</td>
<td>20</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>$n_e$ ($m^3$)</td>
<td>2.5e19</td>
<td>1.05e20</td>
<td>5.6e20</td>
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<tr>
<td><strong>Photon-emission excitation rate coefficients ($m^3 / s$)</strong></td>
<td></td>
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<td></td>
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<tr>
<td>$CI$ (910 nm)</td>
<td>1.7e-15</td>
<td>1.5e-17</td>
<td>5.5e-19</td>
</tr>
<tr>
<td>$CD$ (431 nm)</td>
<td>5.6e-15</td>
<td>7e-15</td>
<td>1.5e-15</td>
</tr>
<tr>
<td>$C_2$ (516 nm)</td>
<td>2e-14</td>
<td>4e-14</td>
<td>1.16e-14</td>
</tr>
<tr>
<td>$C^+$ (514 nm)</td>
<td>5e-16</td>
<td>nil</td>
<td>nil</td>
</tr>
<tr>
<td><strong>Photon efficiencies: Full hydrocarbon spectrum launched</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$CI$</td>
<td>4.4e-03</td>
<td>1.6e-3</td>
<td>1.7e-3</td>
</tr>
<tr>
<td>$CD$</td>
<td>5.1e-2</td>
<td>0.45</td>
<td>0.22</td>
</tr>
<tr>
<td>$C_2$</td>
<td>1.1e-2</td>
<td>0.83</td>
<td>9.8</td>
</tr>
<tr>
<td>$CH$</td>
<td>4.2e-3</td>
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</tbody>
</table>

- $C_2$ is particularly interesting case: in 1 eV plasma no e- impact ionization/dissociation but readily excited by e- impact ($E_{th} \sim 2.4$ 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.

![Graphs showing detachment effects on brightness and line-average density](image)
Detachment strongly suppresses signatures of chemical erosion at the OSP

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

- BD behavior significant:
  - Must radiate in detached plasma (MFP ~1 mm)
  - Verifies $T_e \sim 1$ eV to sustain BD emission.
  - Ultra-low $T_e$ cannot be cause of extinction of HC emission, since $E_{th} \sim$ identical between BD & CD.
Detachment strongly suppresses signatures of chemical erosion at the OSP: $Y_{\text{chem}} \leq 10^{-4}$
ISP behaves nearly identical to OSP:
No apparent difference between locations in $Y_{\text{chem}}$

- Implies $Y_{\text{chem}} \approx 0.3\%$ in attached case.
  - No DTS for modeling.
- No difference between net erosion dominated OSP (stars) and sooty, redeposited ISP tiles.
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**FURTHER OBSERVATIONS**

- BD presence: $T_e$ can support HC emission.

- Lack of HC emission $\rightarrow$ little chemical erosion in detached ISP.

- In stark contrast to the divertor, main-wall chemical erosion increases with $\sim$ constant yield.
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.

**Attached**

- Ionizing plasma

**Detached**

- Recombining plasma

**Diagram:**

- CI Brightness
  - Solid symbols: OSP (V6)
  - Open symbols: ISP (V2)

- Line-average density (10^{19} \text{ m}^{-3})

- Change in Zeeman splitting from Zeeman splitting

- Chemical erosion: WBC
  - Most probable velocity
Divertor atomic carbon response to detachment varies greatly from HC

- CI brightness is $\sim$ proportional to ion flux.
- Change in Zeeman splitting indicates CI emitted from ionization front.
- Little or no change in $T_{\text{eff}}$, contradictory to chemical erosion.
- Doppler shift remains inconsistent with physical sputtering.
Discussion on dependence of location for \( Y_{\text{chem}} \)

- 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 re-deposition on ~90%.

- Results indicate against importance of boron in reduction.
  - Slighter higher \( Y_{\text{chem}} \) 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 $< \text{mm}$ $< < \text{MFP CI, CII}.*)
In summary we have verified and further quantified previous H-mode results of carbon erosion, with some new observations:

- Chemical erosion is weak in the DIII-D lower divertor, $Y_{\text{chem}} \approx 0.3\%$ 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 $< 10^{-4}$. 