Carbon Scrape-Off Layer Transport and Deposition in DIII-D

By
M. Groth*


*Lawrence Livermore National Laboratory, Livermore, CA
†University of California San Diego, La Jolla, CA
‡General Atomics, San Diego, CA
§University of Toronto (UTIAS), Toronto, Ontario, Canada
#Massachusetts Institute of Technology, Cambridge, MA

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Tritium Retention Due to Co-deposition With Carbon Potentially Limits Duty Cycle of Future Fusion Reactors

- Tritium retention in fusion devices occurs via carbon co-deposition.
- JET deuterium-tritium campaign showed strong tritium accumulation in plasma-shadowed regions.

⇒ What is the primary source of carbon deposited at the inner divertor?
⇒ What are the transport mechanisms involved?
Sources of Carbon in DIII-D Are Distributed Between the Main Chamber and the Divertor Walls

- Relative source contribution depends on tokamak operation
  - Heating power
  - Upstream density
  - Separation of confined plasma from main chamber walls

- Divertor dominant source in low-to-moderate density regimes

- Main chamber walls are significant contributor in high-density regimes
Carbon Deposition in the Divertor Depends on Scrape-off Layer Transport and Divertor Plasma Conditions

- Carbon transport determined by coupling to hydrogen SOL flows and drifts
- In the divertor, carbon deposition occurs predominately along surfaces exposed to detached (T < 3 eV) plasmas
Toroidally Localized Methane Injection From the Main Wall and Outer Divertor Produces Deposition at the Inner Divertor

- Use isotope $^{13}\text{C}$ in hydrated methane as marker on $^{12}\text{C}$ graphite tiles for surface analysis
Transport and Deposition of Carbon From the Main Chamber Walls Were Investigated in DIII-D by Methane Injection

- Toroidally symmetric $^{13}$CH$_4$ injection into L-mode and H-mode plasmas
- $^{13}$C surface analysis: highest $^{13}$C concentration along surfaces exposed to cold divertor plasmas
- Carbon transport from the crown to the inner divertor via frictional coupling to deuterion flow
- Carbon transport and deposition simulations

$^{13}$CH$_4$

$^{13}$C deposition

DIII-D
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# Carbon Transport Studies in DIII-D Lower Single Null Low-density L-mode and High-density H-mode Plasmas

<table>
<thead>
<tr>
<th>Plasma Param.</th>
<th>L-mode</th>
<th>ELMy H-mode</th>
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<tbody>
<tr>
<td>Campaign</td>
<td>2003</td>
<td>2005</td>
</tr>
<tr>
<td>$&lt;n_e&gt; [m^{-3}]$</td>
<td>$3 \times 10^{19}$</td>
<td>$8 \times 10^{19}$</td>
</tr>
<tr>
<td>$P_{NBI} [MW]$</td>
<td>0.2</td>
<td>6.6</td>
</tr>
<tr>
<td>$T_{e,ISP} [eV]$</td>
<td>$&lt;2$ cold</td>
<td>$&lt;2$ detached</td>
</tr>
<tr>
<td>$T_{e,OSP} [eV]$</td>
<td>25 attached</td>
<td>$&lt;2$ detached</td>
</tr>
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- $T_{e,ISP}$ and $T_{e,OSP}$ values indicate the temperature in the internal and outer tangential plasma, respectively.
- $<n_e>$ represents the average electron density.
- $P_{NBI}$ denotes the neutral beam injection power.
- ELMs are expected at 200 Hz.

**Diagram:**
- The diagram illustrates the cross-section of the DIII-D tokamak with the magnetic field lines labeled $B \times \nabla B$.

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Inner and Outer Divertor Plasmas Were Attached in L-mode

Target Langmuir probes

J.G. Watkins

ISP

OSP

L-mode

$\Psi_N$

$|I_{sat}| (A/cm^2)$
Inner and Outer Divertor Plasmas Were Attached in L-mode, but Detached in H-mode Between Elms

Target Langmuir probes
J. G. Watkins

ISP

OSP

○ L-mode
□ H-mode

\[ \psi_N \]

\[ |s|_{\text{sat}} \ (\text{A/cm}^2) \]

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<thead>
<tr>
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<th>H-mode</th>
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<tr>
<td>[Graph of</td>
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<td>[</td>
<td>s</td>
</tr>
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<td>[ \psi_N \</td>
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<td>○</td>
<td>□</td>
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</tbody>
</table>

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Toroidally Symmetric Injection of $^{13}$CH$_4$ Had Minimal Effect on the Core Plasma Conditions

$^{13}$CH$_4$

$\Phi_{CH4}$

$n_{e,ped}$

$P_{rad}$

$q_{OSP}$

$n_{C6+}\rho \sim 0.9$

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Ex-situ Surface Analysis Measured the Poloidal and Toroidal $^{13}$C Surface Density

- **Increase $^{13}$C surface concentration above natural background by repeating plasma discharges**
  - L-mode: $22 \leftrightarrow 1.0 \times 10^{22} \text{ }^{13}\text{C}$
  - H-mode: $17 \leftrightarrow 2.2 \times 10^{22} \text{ }^{13}\text{C}$

- **Representative set of tiles was removed immediately after venting DIII-D (29/64)**

- **Two methods to measure $^{13}$C surface density**
  - Nuclear reaction analysis (SNL: Wampler)
  - Proton-induced $\gamma$ emission (UWM: Whyte)
Highest Concentration of $^{13}$C Deposition Was Measured Along the Divertor Surfaces

$^{13}$C (10$^{17}$/cm$^2$)

Position (cm)

NRA detection limit: 2x10$^{16}$ $^{13}$C/cm$^2$

• L-mode • H-mode
Highest Concentration of $^{13}$C Deposition Was Measured Along the Divertor Surfaces

- L-mode
- H-mode

toroidally symmetric deposition
Highest Concentration of $^{13}$C Deposition Was Measured Along the Divertor Surfaces

- L-mode
- H-mode

- Detection limit
- L-mode
- H-mode

- PIQE: ~30% deposited at low concentration along centerpost

- Ceiling: ~10%
- Divertor: 30-40%
In L-mode, the $^{13}$C Deposition is Peaked at the Corner Formed by Divertor Floor and 45° Angled Divertor Target

- Hypothesis: $^{13}$C ions injected at the crown enter divertor via inner main SOL
- Deposition at the inner plate likely as ions

W.R. Wampler
In H-mode, Heavy $^{13}$C Deposition Was Also Measured Along the Private Flux Surface

- Hypothesis: $^{13}$C ions injected at the crown enter divertor via inner main SOL
- $^{13}$C ions recombine in cold inner divertor plasma, then deposit as neutrals between ELMs
- ELMs may lead to re-erosion of $^{13}$C deposits at the inner strike zone

W.R. Wampler
During ELMs, the ionization front moved toward the targets, which may lead to redistribution of the $^{13}$C deposits.

$\text{CIII } \propto \text{T}_e \sim 8-10 \text{ eV}$

**Between ELMs**

**Peak of the ELM**
Surface Erosion/Deposition Studies Showed Deuterium and Carbon Deposition in Tile Gaps

- $^{13}$C deposits migrate into plasma-shadowed regions

$\Rightarrow$ Long-range migration of $^{13}$C into spaces behind tiles yet to be assessed

- Deposition process is temperature dependent
  
  - Increase of $T_{\text{surf}}$ from 30 °C to 200 °C reduced deposition by 3-4x


W. Jacob, K. Krieger, D.L. Rudakov
Transport and Deposition of Carbon From the Main Chamber Walls Were Investigated in DIII-D by Methane Injection

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CH$_4$ Breakup Followed by Imaging of the Emission From C-H Radical in the Plasma Crown
Emission From Low Charge State Carbon Ions Suggests Carbon Transport Toward Inner Divertor
Maximum C\(^{+}\) Ion Velocity Along the Field Line is 15 km s\(^{-1}\)

\[ v_{\parallel}^{C^{+}} \leq \frac{B}{B_{pol}} \frac{\Delta s_{pol}}{t_{ioniz}^{C^{+} \rightarrow C^{2+}}} \]
Carbon Ions Are Entrained in the Deuteron SOL Flow of $M_{||} \sim 0.5$ Via Frictional Coupling

$T_e \sim 10$ eV: $V_{||}^{D^+} \sim 15$ km s$^{-1}$

Upper single null: $<n_e> \sim 3 \times 10^{19}$ m$^{-3}$

Reciprocating probe

L-mode
Increase in CIII Emission at the Inner Midplane With $^{13}\text{CH}_4$ Injection Indicates Carbon Flow Continues Toward Inner Plate

Increase in CIII Emission at the Inner Midplane With $^{13}\text{CH}_4$ Injection Indicates Carbon Flow Continues Toward Inner Plate
In H-mode, Penetration of Methane is Significantly Shallower
Imaging of the Carbon Emission From the Crown Did Not Indicate Carbon Flow Toward Inner Target

H-mode

CH

C^+ 

C_2^+

CH_4

CH

C^{III}

(10^{13} \text{ph/s/sr/cm}^3)

(10^{13} \text{ph/s/sr/cm}^3)

(10^{13} \text{ph/s/sr/cm}^3)

(10^{13} \text{ph/s/sr/cm}^3)
Increase in CIII Emission at the Inner Midplane With $^{13}$CH$_4$ Injection, However, Indicates Carbon Flow Toward Inner Plate
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$^{13}$C Transport and Deposition Simulations Were Carried Out With the Oedge/Hydrocarbon (HC) and UEDGE Codes

Boundary plasma simulations

- **Interpretative OEDGE/ hydrocarbon model**
  - Prescribed background plasma from experiment
  - Ad-hoc parallel and radial flows
  - Model of CH$_4$ dissociative breakup and ionization

- **‘Predictive’ UEDGE model**
  - Background plasma calculated from first-principle fluid flow physics, and assumed radial transport model
  - Intrinsic carbon
  - Flows are self-consistently calculated from ionization balance and drifts


\[ ^{13}\text{C} \text{ Transport and Deposition Simulations Were Carried Out With the Oedge/Hydrocarbon (HC) and UEDGE Codes} \]

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Interpretative Modeling With OEDGE/HC Uses Ad-hoc Flow of Carbon Ions to Match Measured CIII Emission Profiles

- Hydrocarbon physics model and carbon ion diffusion produce radial profiles consistent with the measured CII and CIII emission.

- Poloidal shift of CIII emission achieved by imposing carbon flow velocity of 10-15 km s\(^{-1}\), consistent with measurements.

J.D. Elder
A.G McLean
Inward SOL Pinch Was Used to Match Measured $^{13}$C Deposition Profile Assuming First Deposition

L-mode

J.D. Elder
Inward SOL Pinch Was Used to Match Measured $^{13}\text{C}$ Deposition Profile Assuming First Deposition

### L-mode

- $M_{||}=0.4, \nu_r=0 \text{ ms}^{-1}$

![Graph showing $^{13}\text{C}$ deposition profile](image)

- OEDGE ad-hoc parallel transport leads to $^{13}\text{C}$ deposition in far SOL only

J.D. Elder
Inward SOL Pinch Was Used to Match Measured $^{13}$C Deposition Profile Assuming First Deposition

- OEDGE ad-hoc parallel transport leads to $^{13}$C deposition in far SOL only

⇒ Apply additional radial pinch ($n\nu_r$) to move $^{13}$C ions closer to separatrix

J.D. Elder
Inward SOL Pinch Was Used to Match Measured $^{13}$C Deposition Profile Assuming First Deposition

**L-mode**

- OEDGE ad-hoc parallel transport leads to $^{13}$C deposition in far SOL only
- Apply additional radial pinch ($n v_r$) to move $^{13}$C ions closer to separatrix
- **H-mode data** may also be modeled by combination of parallel and radial transport (including ELMs)

J.D. Elder
13C Transport and Deposition Simulations Were Carried Out With the Oedge/Hydrocarbon (HC) and UEDGE Codes

- **Interpretative OEDGE/hydrocarbon model**
  - Prescribed background plasma from experiment
  - Ad-hoc parallel and radial flows
  - Model of CH₄ dissociative breakup and ionization

- **‘Predictive’ UEDGE model**
  - Background plasma calculated from first-principle fluid flow physics, and assumed radial transport model
  - Intrinsic carbon
  - Flows are self-consistently calculated from ionization balance and drifts
UEDGE Reproduces Multiple Diagnostics in the Divertor and Main Chamber SOL Simultaneously

- **UEDGE predicts** $T_{e,ISP} \sim 1.5$ eV, **consistent with measurements in inner divertor**
  - Inner strike point $D_\beta/D_\alpha \sim 0.15$
  - Lack of CII emission in the inner leg
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  - Lack of CII emission in the inner leg
- **ExB drifts play an important role in obtaining low $T_{e,ISP}$**
  - Omitting drifts raises $T_{e,ISP}$ from 1.5 eV to 3 eV

$\implies$ **Less consistent with experiment!**
UEDGE Main Chamber SOL Flow is Strongly Dependent on Inner Strike Point Temperature

**L-mode**

\[ T_{e,ISP} = 1.5 \text{ eV} \]

\[ T_{e,ISP} = 3 \text{ eV} \]
Direction of Carbon Flow in the Crown Aligned with the Deuteron Flow

**L-mode**

\[ T_{e,ISP} = 1.5 \text{ eV} \]

\[ T_{e,ISP} = 3 \text{ eV} \]

\[ M = \frac{v(D^+)}{c_s} \]

\( R - R_{sep} \) (cm)

\( Z \) (m)

\( R \) (m)

\( 13C \)

\( \text{CIII} \)
$^{13}$C Deposition at Inner and Outer Target is Strongly Dependent on D$^+$ Flow in Main SOL
$^{13}$C Deposition at Inner and Outer Target is Strongly Dependent on D$^+$ Flow in Main SOL

$T_{e,ISP} = 1.5$ eV

$T_{e,ISP} = 3$ eV

$\Rightarrow$ Main chamber SOL flow and $^{13}$C deposition inconsistent with low $T_{e,ISP}$
Transport and Deposition of Carbon From the Main Chamber Walls Were Investigated in DIII-D by Methane Injection

- Toroidally symmetric $^{13}$CH$_4$ injection into low-density L-mode and high-density H-mode plasmas

- Highest $^{13}$C concentration along surfaces exposed to cold divertor plasmas ($T < 3$ eV)
  - Inner divertor plate in L-mode and H-mode
  - Private flux tiles in H-mode

- Carbon transport from the crown to the inner divertor via frictional coupling to deuterion flow
  - Deuteron flow measurements in USN plasmas
  - Carbon flow from poloidally shifted emission profiles in the crown
Predicting Tritium Retention in Future Fusion Devices With Carbon Walls Requires Further Analysis and Improved Modeling

- 50-70% of the injected $^{13}$C atoms were found along plasma-facing surfaces
  ⇒ Accessible to surface cleanup techniques in future fusion reactor
- Long-range migration into tile gaps, and beyond, may have occurred
  ⇒ Currently being assessed by surface analysis of the tile gaps
- Improvements to predictive capability of carbon sources and deposition in tokamaks are in progress
  ⇒ Simultaneous simulations of multiple diagnostics measurements, including SOL flow and carbon deposition