Advances in Understanding High-Z Sourcing, Migration, and Transport on DIII-D from L-mode to High-Performance Regimes

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Outline

• **Motivation and Introduction** *(Slide 3)*

• **Tungsten Sourcing**
  – Spectroscopic inference via S/XB method *(Slide 7)*
  – Steady state: gross v. net erosion *(Slide 9)*
  – Transients: Erosion during ELM mitigation *(Slide 12)*

• **Global Tungsten Transport**
  – Impact of ExB drifts on W migration *(Slide 17)*
  – Radial W convection calculated with 3DLIM *(Slide 20)*
Stringent tungsten core contamination limits in ITER and beyond motivate understanding W sourcing and transport

- **W divertor source in ITER expected to be dominated by ELMS**
  - Physical sputtering by energetic ions streaming out from pedestal
  - Motivates developing validated understanding for ELMy W source

- **Models for W 'divertor retention probability' mostly untested**
  - Prompt re-deposition controlled by sheath E field and gyro-motion?
  - SOL transport probably governed by friction force, $\nabla T_i$ forces, and drifts?

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![JET-ILW: ELMy W source persists with detached divertor](image1)

![AUG: W divertor retention scales with $n_e$, $\bar{b}$ + ELM frequency](image2)
DIII-D Strategy: Understand Divertor High-Z Sourcing & Transport in H-mode Through Tracer PMI Studies with Predominately Low-Z Wall

- **Goal:** probe all 3 links in W impurity chain: **Source → SOL Transport → Core**
  - **SOL Transport** is least well understood (difficult to diagnose)

- **First 'large-scale' W PMI studies on DIII-D**
  - Builds upon success of local gross/net W erosion studies using DiMES\(^1,2,3\)

- **DIII-D’s predominantly low-Z wall allows for W source localization studies**
  - Further localize strike-point vs. far-target regions via isotopically-enriched W

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\(^1\) Abrams NF 2017  
\(^2\) Ding NF 2017  
\(^3\) Guterl NME 2018
DIII-D Metal Rings Campaign (MRC) used 2 isotopically distinct W Sources Localized at 2 Locations in Outer Lower Divertor Region

- Rings consist of W-coated TZM Mo inserts
- Different W isotopic mixes used in each ring

"Floor" Ring
Natural W
26.5% W-182
(25±15 µm)

"Shelf" Ring
Enriched W
93% W-182
(2±1 µm)

- Isotopic ratios in W deposits on collector surface resolved via inductively coupled plasma-mass spectrometry (ICP-MS)

Donovan RSI 2018
Unterberg NF 2019
MR Campaign Leveraged Wide Collection of DIII-D Diagnostics, with Several Notable Capability Enhancements

- **4 new views for MDS (high res. spectrometer) + W I filterscopes**¹
  - Diagnose W source via S/XB method

- **Midplane collector probe**²
  - Measure main SOL W flux

- **UV (200-400 nm) spectroscopy**
  - Many WI & WII lines monitored³

- **2 new LPs* at shelf ring radius**

- **Existing: DTS, WI imaging, DiMES**

*Langmuir Probes

¹Abrams IEEE-TPS 2018
²Geier PPCF 2002
³Johnson PPCF 2019

*Langmuir Probes
Prompt Re-Deposition is an Important Process
Regulating Net Erosion in the Divertor

- Prompt re-deposition typically assumed to be regulated by $\lambda_{iz}$ and $\rho_W^{1,2}$
- Recent studies suggest sheath electric field also increases re-deposition$^{3,4,5}$

Understanding W re-deposition physics requires high-fidelity measurement techniques!

Figure adapted from Guterl PET 2019
Tungsten Re-deposition Can be Inferred Through the Ionizations/Photon (S/XB) Method

• Simplified picture of W sourcing, ionization, & re-deposition:
  – Steady state \((d/dt = 0)\)
  – Homogenous near-surface plasma
  – Impurities travel only in \(\hat{z}\) direction
  – Neglect transport, recomb., CX, etc.

• Measure W re-deposition spectroscopically: (from charge states \(0\) to \(N\))

\[
\Gamma_{\text{redep}} = \left( \frac{S}{XB} \Phi_{\lambda} \right)_0 - \left( \frac{S}{XB} \Phi_{\lambda} \right)_N
\]

Refinement of method from previous JET-ILW work\(^1\)

\(^1\)van Rooij JNM 2013
W^+ Re-Deposition Inferred in DIII-D Using Stationary, Attached, L-Mode Plasmas

- Caveats:
  - Uncertainty in S/XB coeffs.
  - Potential contamination of WII spectra (up to 30%?)\(^1\)

\(^1\)Ennis APS-DPP 2020

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**UV spec.**

**W tiles**

**WII 364.1 nm**

**WII 400.9 nm**

**WI, WII Intensity (AU)**

**W^+ Re-Deposition Fraction**

\(f_{\text{redep}}\)
Caveat: WI contamination in WII emission region may result in over-estimation of W net erosion

- Cross-check with W probe and high-res. spectrometer on CTH\textsuperscript{1}

- WI contaminants only add up to 2% of WI 400.9 nm intensity
  - (but 50-60% of WII intensity…)

\begin{table}[h]
\begin{tabular}{|c|c|c|c|}
\hline
Wavelength (nm) & Relative Intensity (NIST) & Relative Intensity (Meas.) & Frac. of light expected within integ. region \\
\hline
WI 364.013 & 40 & 50.6 & 0.649 \\
WII 364.141 & -- & 161 & 0.931 \\
WI 364.185 & 20 & 33.5 & 0.757 \\
WI 364.281 & 20 & 26.8 & 0.618 \\
WI 400.875 & 1000 & 1000 & 0.930 \\
\hline
\end{tabular}
\end{table}
Sheath Model Shows Better Consistency with Experimental Data Than Gyro-Orbit Model (When W Ionizes Close to Surface)

- **Sheath Model** is reasonable lower bound for net erosion at low $\frac{\lambda_{iz}}{\lambda_{sheath}}$.
- **Gyro-orbit model** over-predicts net erosion at low $\frac{\lambda_{iz}}{\lambda_{sheath}}$.
- **SXB Method** not valid at high $\frac{\lambda_{iz}}{\rho_W}$ (W not ionized close to surface).
- **SXB Method** not valid at high $\frac{\lambda_{iz}}{\lambda_{sheath}}$ (W not ionized close to surface).
1D Free-Streaming plus Recycling Model (FSRM) Developed for Particle/Heat Flux During ELMs to Infer W Sputtering at the Targets

- Flux tube from pedestal top detaches into SOL → divertor\(^1,2,3\)
  - No interaction with background (inter-ELM) plasma

Inputs: \( n_{e,ped}, n_{Z,ped}, T_{ped}, L_{ELM}, L_{\|}, R_{eff} \)

\( L_{ELM} = \) Extent of ELM filament\(^4 = 2\pi R q_{edge} \)
\( L_{\|} = \) ELM connection length\(^5,6 = 9 L_{ELM} \)
\( R_{eff} = \) Effective recycling coeff.\(^7 = \) free parameter

Outputs: Target density \( (n_{e,div,FS}) \), ion flux \( (\Gamma_{\|,FS}) \), heat flux \( (q_{\|,FS}) \) vs. time

\( q_{\|,FS} = a_{pol} B_{T,OMP} X_{p,OMP} \)

\( q_{edge} = \frac{a_{pol} B_{T,OMP}}{R_{OMP} B_{p,OMP}} \)

\(^1\)Fundamenski PPCF 2006
\(^2\)Manfredi PPCF 2010
\(^3\)Moulton PPCF 2013
\(^4\)Eich NME 2017
\(^5\)Huysmans PPCF 2009
\(^6\)Guillemaut NF 2018
\(^7\)Abrams NME 2018
Use Free Streaming plus Recycling Model to Predict Tungsten Sputtering During ELMs

- W gross erosion during ELMS includes physical sputtering by:
  - Free-streaming main ions from pedestal
  - Free-streaming impurities from pedestal
  - Recycling main ions in divertor
  - Recycling impurities in divertor

- Assumptions for DIII-D:
  - Equal C concentrations in pedestal & divertor
  - $C^{6+}$ / $C^{2+}$ are the only FS / recycling impurities
  - Ions impact at 45° w/ energy $E_i = q_{\perp}/\Gamma_{ion,\perp}$
  - 50% C coverage on W surfaces, in line with previous studies

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TRIM.SP Calculations of Tungsten Sputtering

<table>
<thead>
<tr>
<th>Energy / ion (eV)</th>
<th>W atoms sputtered per incident ion</th>
</tr>
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<tr>
<td>$C \rightarrow W$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$D \rightarrow W$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>$Be \rightarrow W$</td>
<td>$10^{-2}$</td>
</tr>
</tbody>
</table>

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1G. Xu PSI 2018
2R. Ding NF 2016
3Guterl PSI 2018
4Y. Ueda FED 2006
5Shimada JNM 2004
W gross erosion measured by coherent averaging of WI filterscope signals and applying S/XB method

- **Detect ELM start times**
  - Rising edge of Dα filterscope signal
  - Set threshold to filter similar, large ELMs
- **Shift ELM time bases such that** \( t_0 = t_{ELMSTART} \)
- **Average WI fscope traces together**
- **W gross erosion, \( \Gamma_W \), inferred using time-dependent S/XB method:**

\[
\Gamma_W(t) = \frac{S}{XB}(t) \int_0^\infty I_{W1}(t) \, dz
\]

- WI S/XB coefficients obtained from ADAS atomic physics database\(^1\)
- Dependence of WI S/XB on density during ELMs is important\(^2\)

\(^1\)Brezinsek APiP 2013
\(^2\)Abrams NME 2018
Pellet pacing tends to reduce W sputtering per ELM, but RMPs slightly increase sputtering and lower ELM connection length

- **ELM Mitigation via Pellet Pacing**
  - Pellets reduce \( f_{C,\text{ped}} \), reducing sputtering by free-streaming C\(^{6+}\) impurities
  - Pellets also lower \( T_{e,\text{div}} \), which lowers \( Y_{C \rightarrow \text{W}} \) for recycling C\(^{2+}\)

- **Resonant Magnetic Perturbations (RMPs)**
  - Total W erosion slightly increases, despite slight decrease predicted by FSRM?
  - Peak W erosion rate increases significantly, suggesting RMPs cause a decrease in \( L_{\parallel} \)

\[ \text{Model, } L_{\parallel} = 9L_{\text{ELM}} \]

\[ \text{No pellet pacing} \]

\[ 167354.2200.4400 \]

\[ T_{e,\text{ped}} = 350 \text{ eV} \]
\[ n_{e,\text{ped}} = 6.9 \times 10^{19} \text{ m}^{-3} \]
\[ f_{C,\text{ped}} = 4.5% \]
\[ T_{e,\text{div}} = 32 \text{ eV} \]

\[ \text{Exp. Data} \]

\[ \text{Model, } L_{\parallel} = 9L_{\text{ELM}} \]

\[ 167356.2600.4800 \]

\[ T_{e,\text{ped}} = 330 \text{ eV} \]
\[ n_{e,\text{ped}} = 7.2 \times 10^{19} \text{ m}^{-3} \]
\[ f_{C,\text{ped}} = 2.8% \]
\[ T_{e,\text{div}} = 14 \text{ eV} \]

\[ \text{Exp. Data} \]

\[ \text{No RMP} \]

\[ 167556.1800.2400 \]

\[ T_{e,\text{ped}} = 840 \text{ eV} \]
\[ n_{e,\text{ped}} = 3.7 \times 10^{19} \text{ m}^{-3} \]
\[ f_{C,\text{ped}} = 4.1% \]
\[ T_{e,\text{div}} = 25 \text{ eV} \]

\[ \text{Exp. Data} \]

\[ \text{With RMP, 5 kA, n=3} \]

\[ 167556.2600.3600 \]

\[ T_{e,\text{ped}} = 810 \text{ eV} \]
\[ n_{e,\text{ped}} = 3.0 \times 10^{19} \text{ m}^{-3} \]
\[ f_{C,\text{ped}} = 4.8% \]
\[ T_{e,\text{div}} = 30 \text{ eV} \]

\[ \text{Exp. Data} \]

\[ \text{Model, } L_{\parallel} = 6L_{\text{ELM}} \]

\[ [\text{Abrams PoP 2019}] \]
Higher frequency pellets more effective at reducing W sputtering, but no effect observed with RMPs

- Low-frequency pellets actually increase W erosion above no-pellet level
- No correlation between RMP current and W erosion at any injection power
Time-resolved deposition measurements exhibited non-local W re-deposition patterns during MRC L-mode experiment

- Time-resolved W deposition measured by DiMES slices removed at different stages of the experiment

1. Constant W coverage on inner half of DiMES
2. W deposition increasing in time on outer half of DiMES (4-8 cm from closest W source)

[Rudakov FED 2017]
[Wampler Phys Scr 2017]
Near-surface W transport simulation via OEDGE background reconstruction and DIVIMP/WallDYN mixed-material model

- **OEDGE (OSM-EIRENE) quasi-1D fluid calculation of \( n_e, T_e \)**
  - \( T_{e,target} \) from DTS, \( J_{sat,target} \) from LP
  - \( T_{e,div} \) and \( n_{e,div} \) matched to DTS via volumetric power/mom. Losses

- **DIVIMP: 2D Monte Carlo impurity transport**
  - \( \parallel \) forces, Collisions, \( \parallel/\perp \) diffusion, Ionization/recomb. (ADAS), ExB drifts

- **WallDYN 1.0: Self-consistent mixed-material surf. evolution**
  - Mixed material sputtering/reflection rates
  - Includes multiple re-erosion and re-deposition steps for both W and C

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**OEDGE calculation**

**WallDYN model**

- **SOL plasma model (OEDGE)**
- **Initial surface state**

**DIVIMP-WallDYN**

Time evolution of impurity fluxes to wall, surface areal densities

[Nichols NF 2021, submitted]
Interpretively model spatial patterns of W deposition by scanning through ExB drift strength in DIVIMP-WallDYN

- With no ExB drift, no deposition peak
- With 100% ExB drifts, deposition peak is too small
- Can artificially scale ExB velocity in DIVIMP (without changing background plasma):
  \[ v^{ExB} = (X\%) \times v^{ExB}_{EDGE} \]
- Increasing ExB drift strength:
  - Moves deposition peak radially outward
  - Reduces magnitude of deposition peak
- Best match to deposition data obtained with 60% ExB scaling
  - SOL currents (not included yet) may flatten plasma potential gradients
3DLIM is a new plasma impurity transport code to simulate W deposition on a collector probe in the far-SOL

1. Background plasma in near-SOL obtained from OEDGE/DIVIMP
2. 3DLIM creates plasma solution in region between edge of DIVIMP grid and the wall
3. W density in outermost DIVIMP grid cells is the B.C. inputted to 3DLIM
4. Adjust plasma background, W source, $D_{\perp W}$ or $v_{\perp W}$, etc. to match measured CP deposition patterns
3DLIM successfully reproduces W CP deposition profiles assuming purely convective radial W transport.

Note
Assumes W radially transports via convection, not diffusion
[Zamperini NME 2020]

$$v_{\text{radial}} = 275 \text{ m/s}$$
DIVIMP+3DLIM support hypothesis of a near-SOL W accumulation only when $B_x \nabla B^\uparrow$

- DIVIMP can impose SOL patterns qualitatively similar to measurements
  - $B_x \nabla B^\uparrow$: Near-SOL W accumulation due to $T_i$-gradient force
  - $B_x \nabla B^\downarrow$: Accumulation is flushed out due to fast inner target directed flows

- Measurements and 3DLIM support DIVIMP prediction of a near-SOL W accumulation only for the $B_x \nabla B^\uparrow$ direction

- Highlights the importance of accounting for flows in SOL impurity transport modeling
• First measurements of prompt re-deposition of W⁺ have been conducted in DIII-D divertor and agree fairly well with sheath model

• Higher frequency pellet pacing effective at reducing W sputtering during ELMs, but no clear effect observed with application of RMPs

• WallDYN model agrees well with experimental W re-deposition pattern only when $E \times B$ drifts (adjusted to 60%) are accounted for

• Net force on high-Z impurities in the far-SOL changes with ion $B \times \nabla B$ drift direction in DIII-D, suggesting strong high-Z entrainment in SOL flows
For more information...

  https://doi.org/10.1016/j.nme.2018.10.011

  https://doi.org/10.1063/1.5089895

  https://doi.org/10.1016/j.nme.2020.100811