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)**

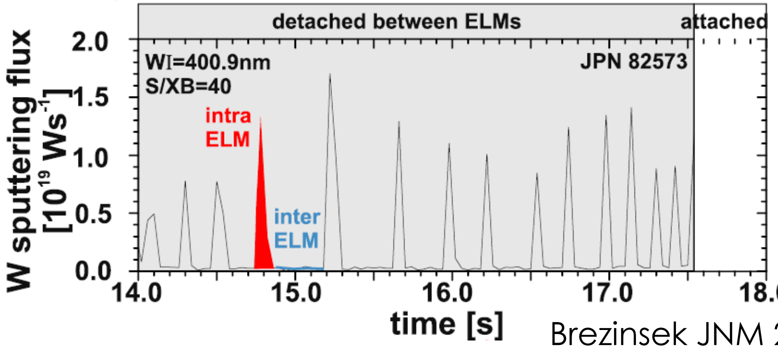
- **Tungsten Sourcing**
  - Spectroscopic inference via S/XB method **(Slide 7)**
  - Steady state: gross v. net erosion **(Slide 9)**
  - Transients: Erosion during ELM mitigation **(Slide 12)**

- **Global Tungsten Transport**
  - Impact of ExB drifts on W migration **(Slide 17)**
  - Radial W convection calculated with 3DLIM **(Slide 20)**

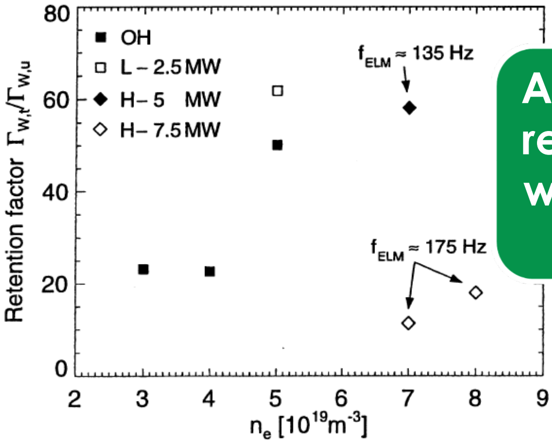
Stringent tungsten core contamination limits in ITER and beyond motivate understanding W sourcing and transport

- **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?

JET-ILW: ELMy W source persists with detached divertor



Brezinsek JNM 2015



AUG: W divertor retention scales with $n_{e,bar}$ + ELM frequency

Krieger JNM 1999

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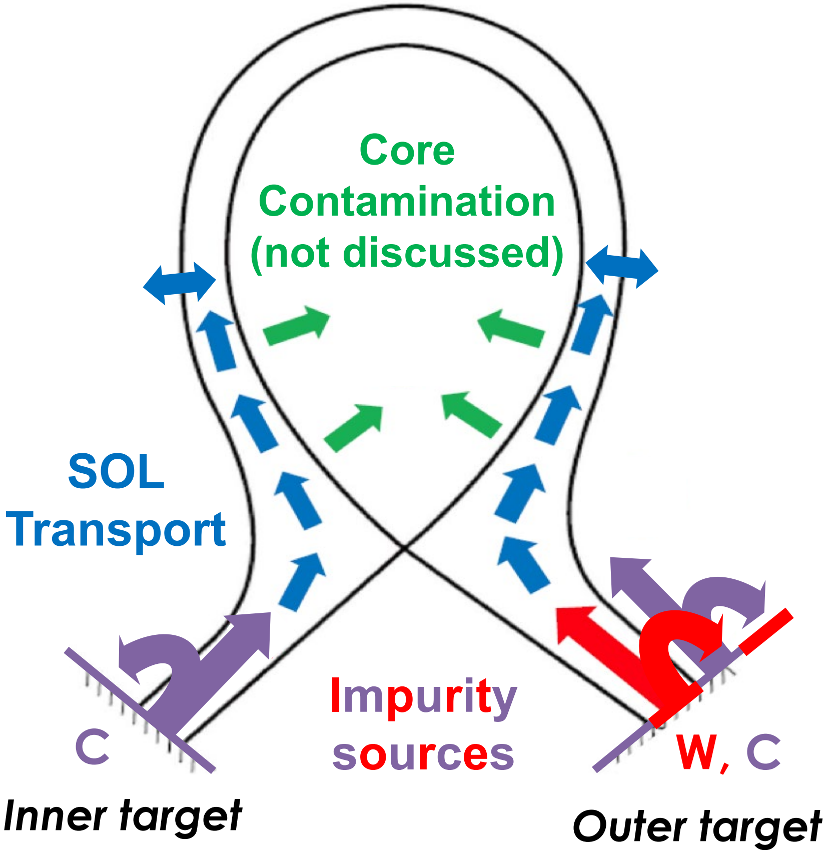
DIII-D Strategy: Understand Divertor High-Z Sourcing & Transport in H-mode Through Tracer PMI Studies with Predominately Low-Z Wall

- **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



[1]Abrams NF 2017
[2]Ding NF 2017
[3]Guterl NME 2018

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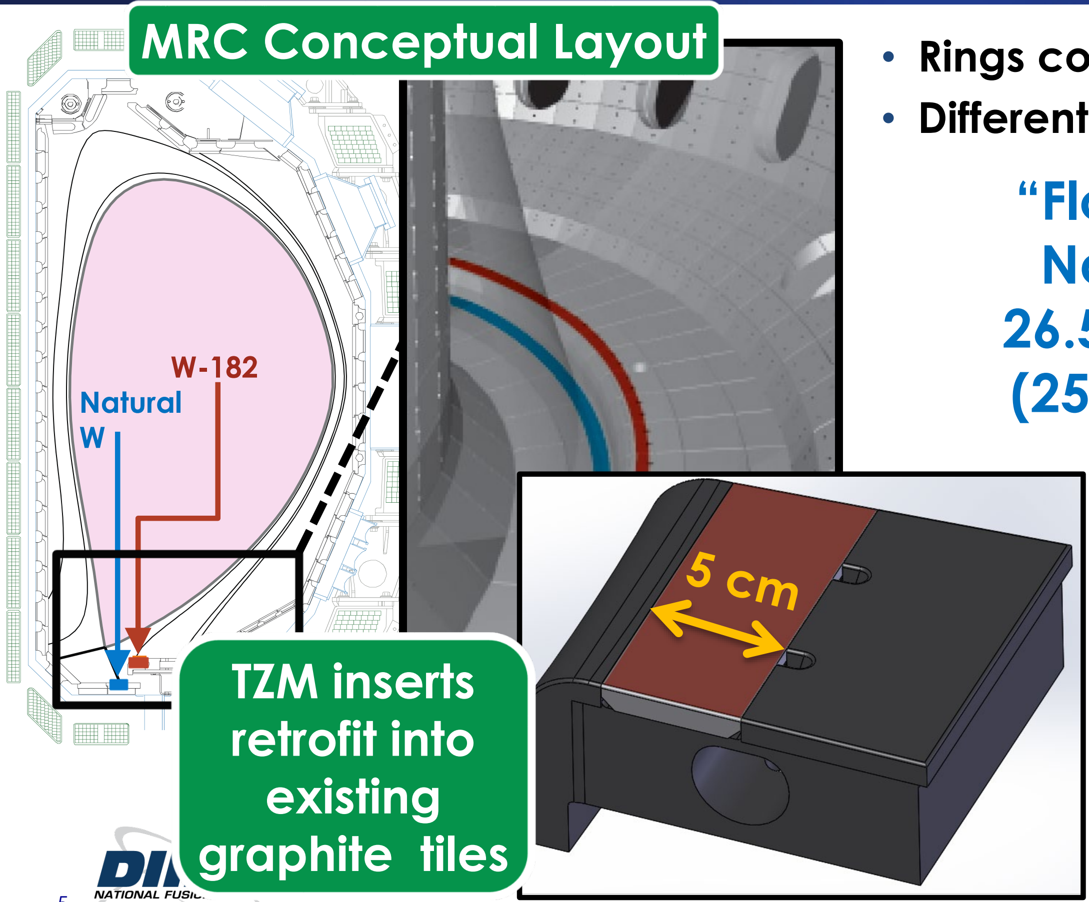
DIII-D Metal Rings Campaign (MRC) used 2 isotopically distinct W Sources Localized at 2 Locations in Outer Lower Divertor Region



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

"Floor" Ring	**"Shelf" Ring**
Natural W	**Enriched W**
26.5% W-182	**93% W-182**
(25±15 μm)	**(2±1 μm)**

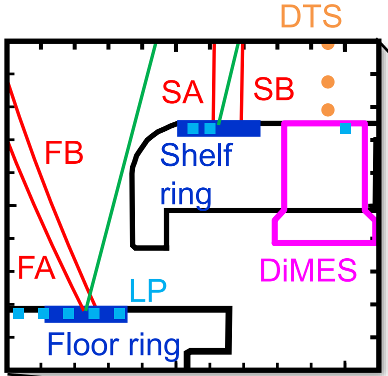
- **Isotopic ratios in W deposits on collector surface resolved via *inductively coupled plasma-mass spectrometry (ICP-MS)***

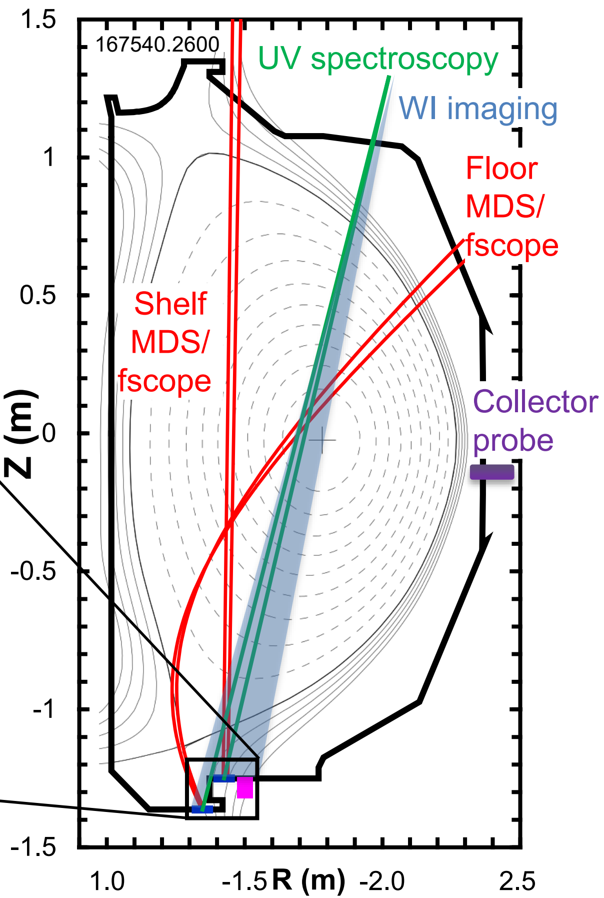
Donovan RSI 2018
Unterberg NF 2019

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 monitored[3]
- **2 new LPs* at shelf ring radius**
- **Existing: DTS, WI imaging, DiMES**

[1]Abrams IEEE-TPS 2018
[2]Geier PPCF 2002
[3]Johnson 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 λ_{iz} and ρ_W[1,2]**
- **Recent studies suggest sheath electric field also increases re-deposition[3,4,5]**

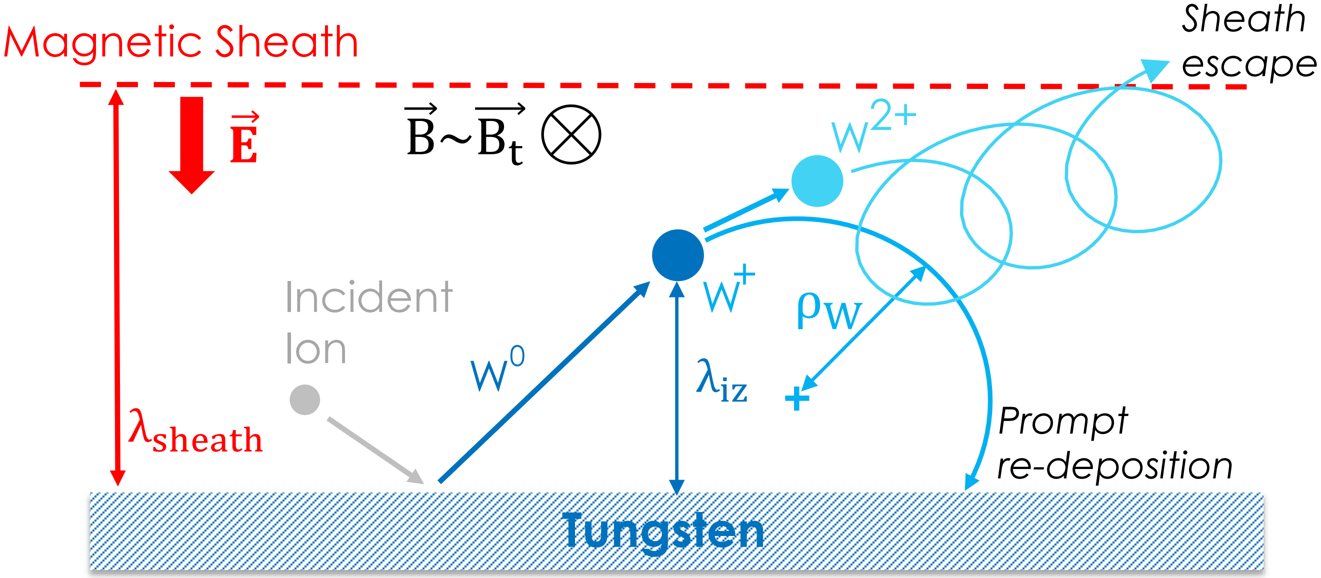


Figure adapted from Guterl PET 2019

[1]Naujoks NF 1996
[2]van Rooij JNM 2013
[3]Tshakaya NME 2018
[4]Guterl PET 2019
[5]Johnson PSI 2021

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

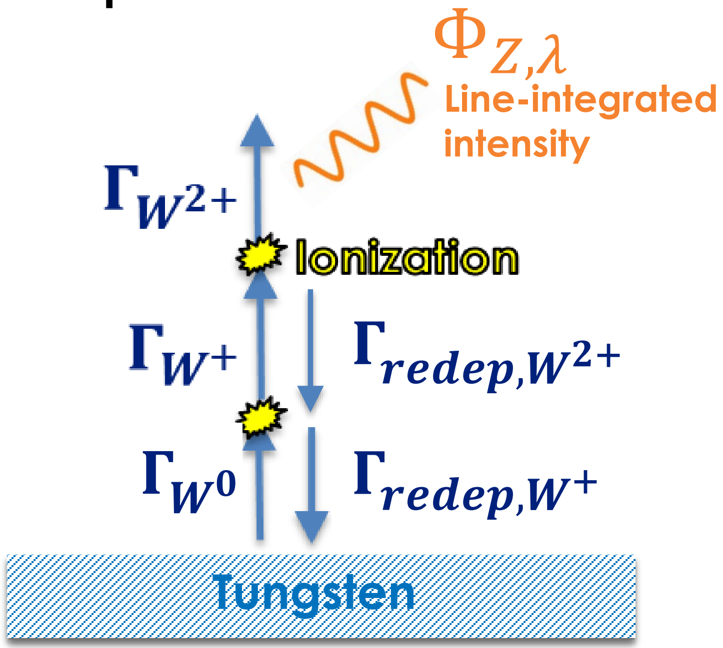
Tungsten Re-deposition Can be Inferred Through the Ionizations/Photon (S/XB) Method

- **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***)

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

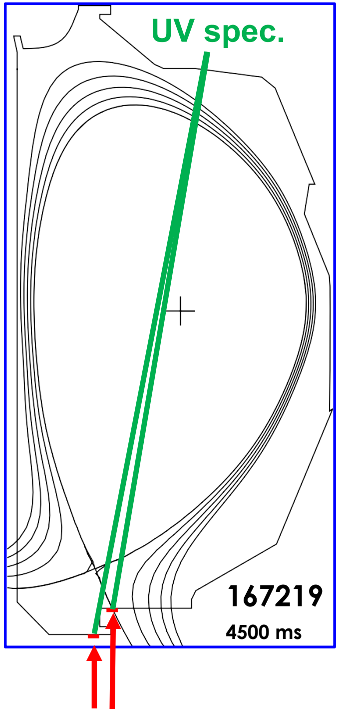
Gross Erosion — "Escaping" Tungsten

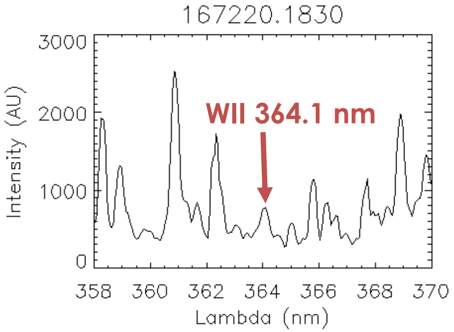


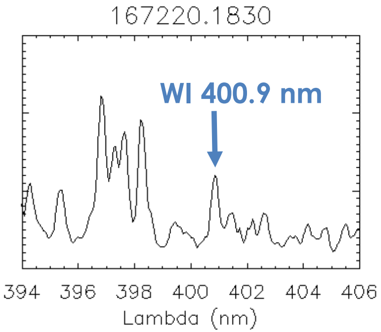
Refinement of method from previous JET-ILW work[1]

[1]van Rooij JNM 2013

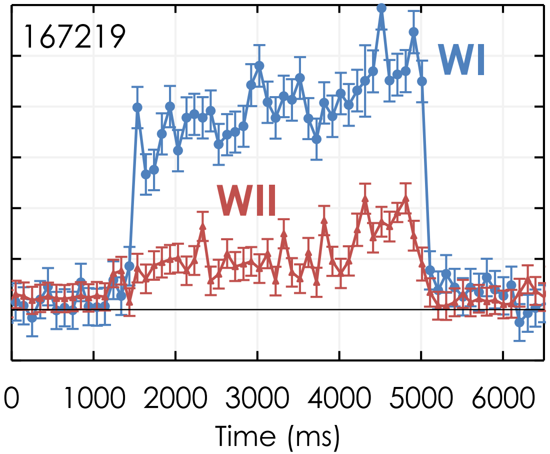
W^+ Re-Deposition Inferred in DIII-D Using Stationary, Attached, L-Mode Plasmas

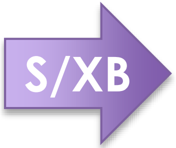




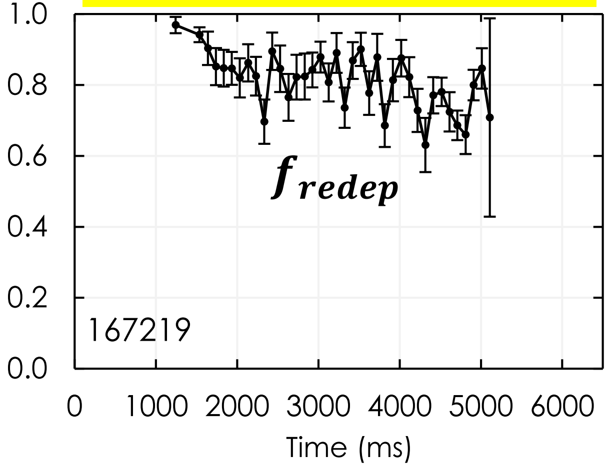


WI, WII Intensity (AU)





W^+ Re-Deposition Fraction (Re-Deposition / Gross Erosion)

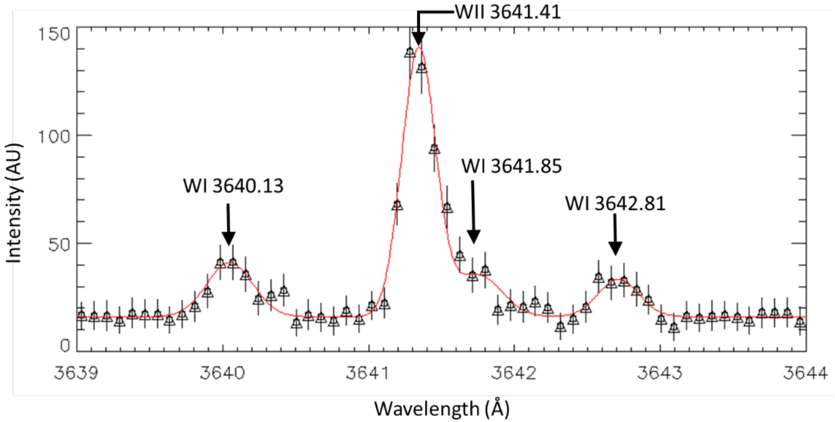


- **Caveats:**
  - Uncertainty in S/XB coeffs.
  - Potential contamination of WII spectra (up to 30%?)[1]

[1]Ennis APS-DPP 2020

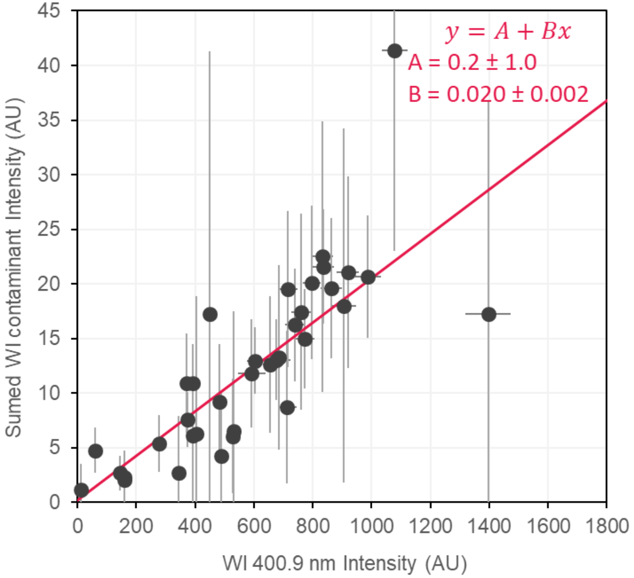
Caveat: WI contamination in WII emission region may result in over-estimation of W net erosion

- **Cross-check with W probe and high-res. spectrometer on CTH[1]**



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

Wavelength (nm)	Relative Intensity (NIST)	Relative Intensity (Meas.)	Frac. of light expected within integ. region
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



[1]Johnson APS-DPP 2019

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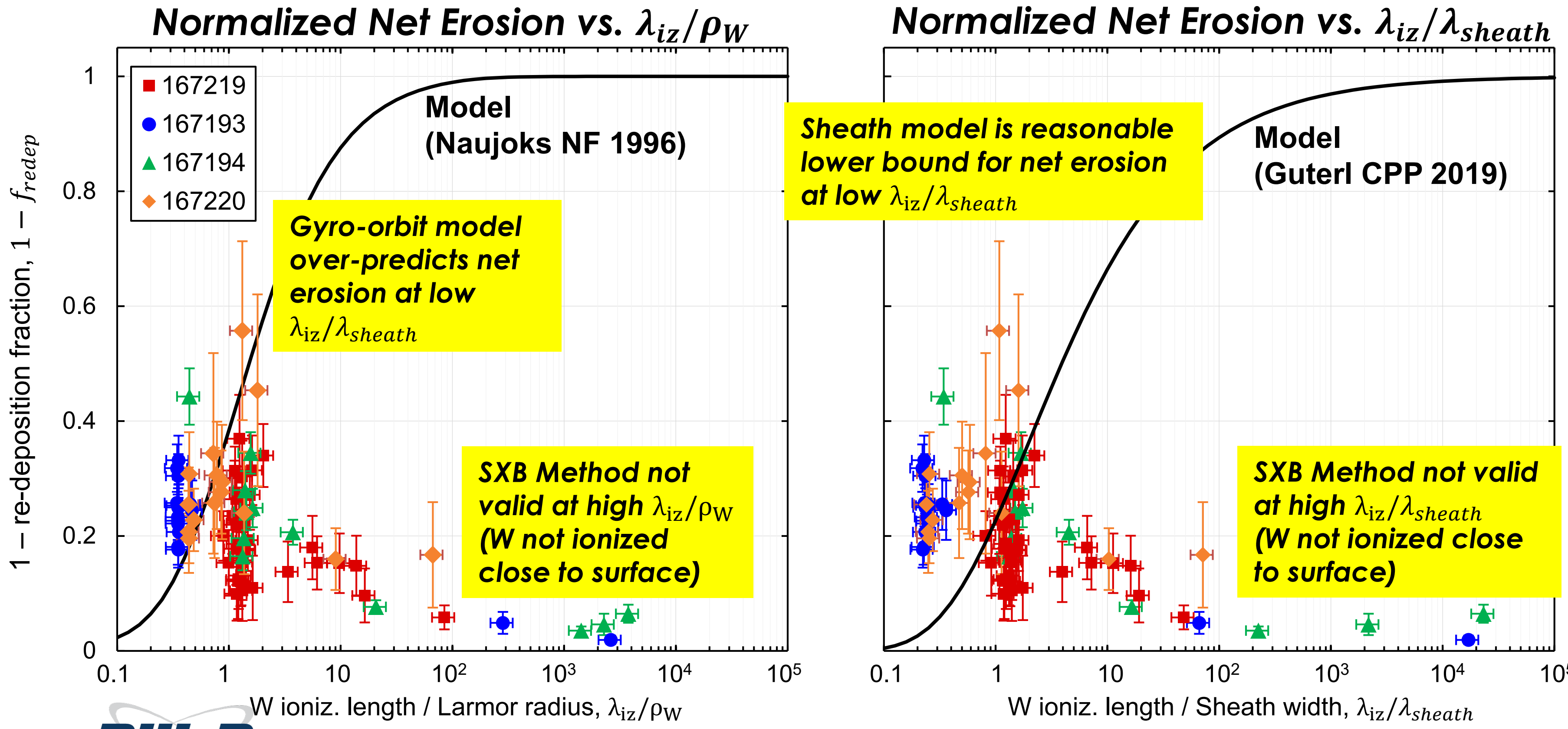
Sheath Model Shows Better Consistency with Experimental Data Than Gyro-Orbit Model (When W Ionizes Close to Surface)



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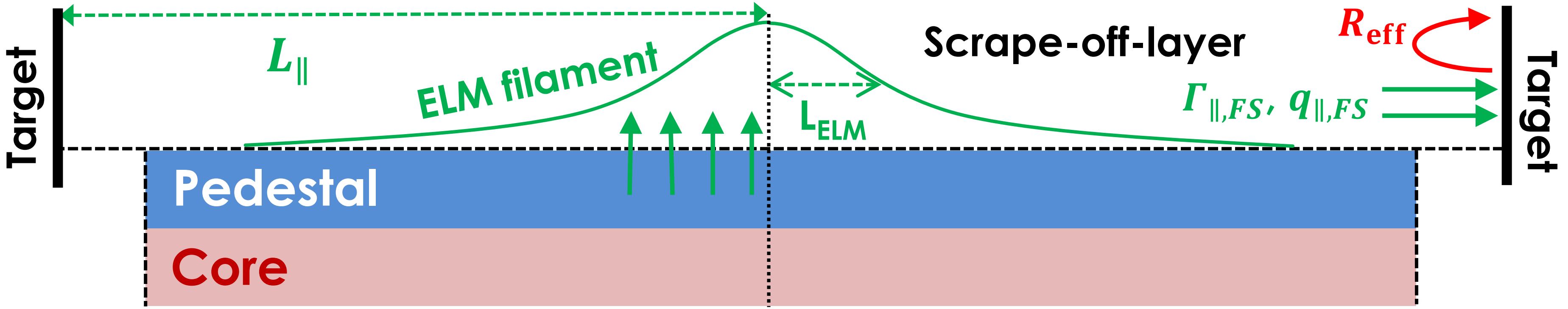
Abrams et al./IAEA-P1-660

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

$$q_{edge} = \frac{a_{\rm pol}}{R_{\rm OMP}} \frac{B_{\rm T,OMP}}{B_{\rm p,OMP}}$$

Inputs: $n_{e,ped}$, $n_{Z,ped}$, T_{ped}, L_{ELM}, $L_\parallel$, $R_{\rm eff}$

$\boldsymbol{L_{ELM}}$ = Extent of ELM filament[4] = $\boldsymbol{2\pi R q_{edge}}$

$\boldsymbol{L_\parallel}$ = ELM connection length[5,6] = $\boldsymbol{9 L_{ELM}}$

$\boldsymbol{R_{\rm eff}}$ = Effective recycling coeff.[7] = **free parameter**

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

[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

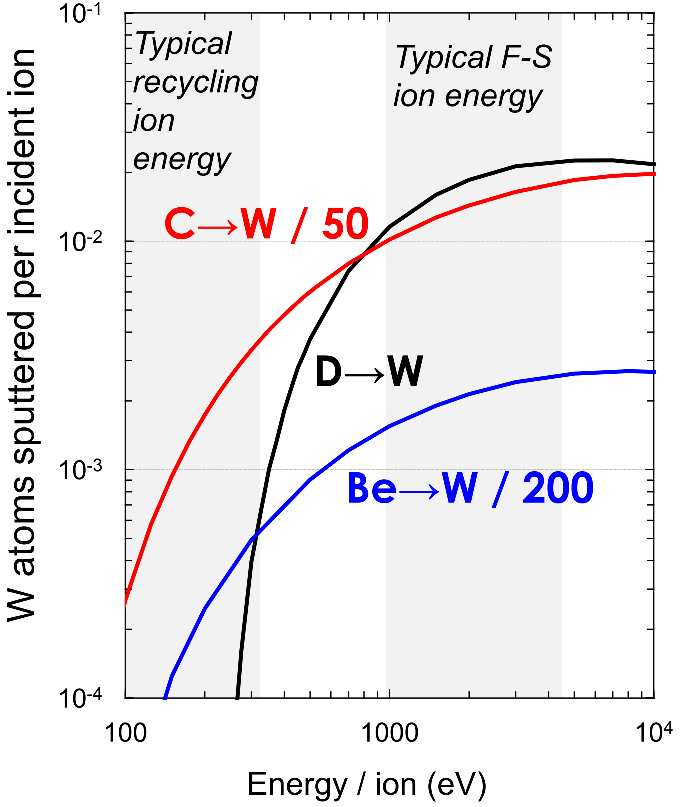
Use Free Streaming plus Recycling Model to Predict Tungsten Sputtering During ELMs

- **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[1-3]
  - Ions impact at 45° w/ energy $E_i = q_{\perp}/\Gamma_{ion,\perp}$
  - 50% C coverage on W surfaces, in line with previous studies[1-5]

[1]G. Xu PSI 2018
[2]R. Ding NF 2016
[3]Guterl PSI 2018
[4]Y. Ueda FED 2006
[5]Shimada JNM 2004

TRIM.SP Calculations of Tungsten Sputtering



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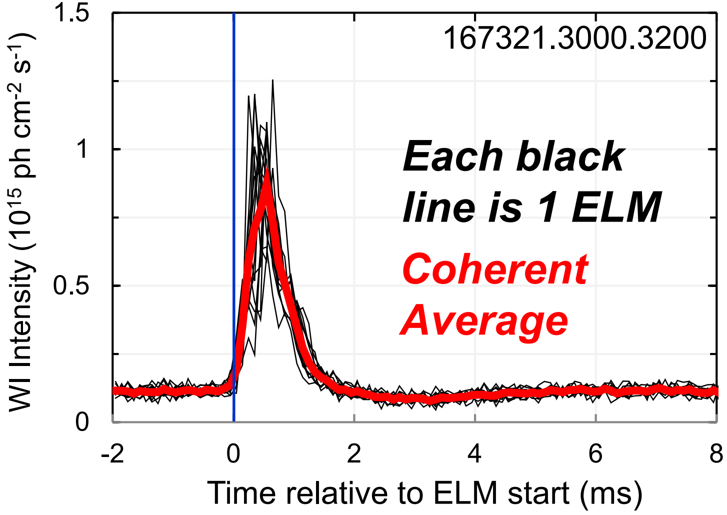
W gross erosion measured by coherent averaging of WI filterscope signals and applying S/XB method

- **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, Γ_W, inferred using time-dependent S/XB method:**



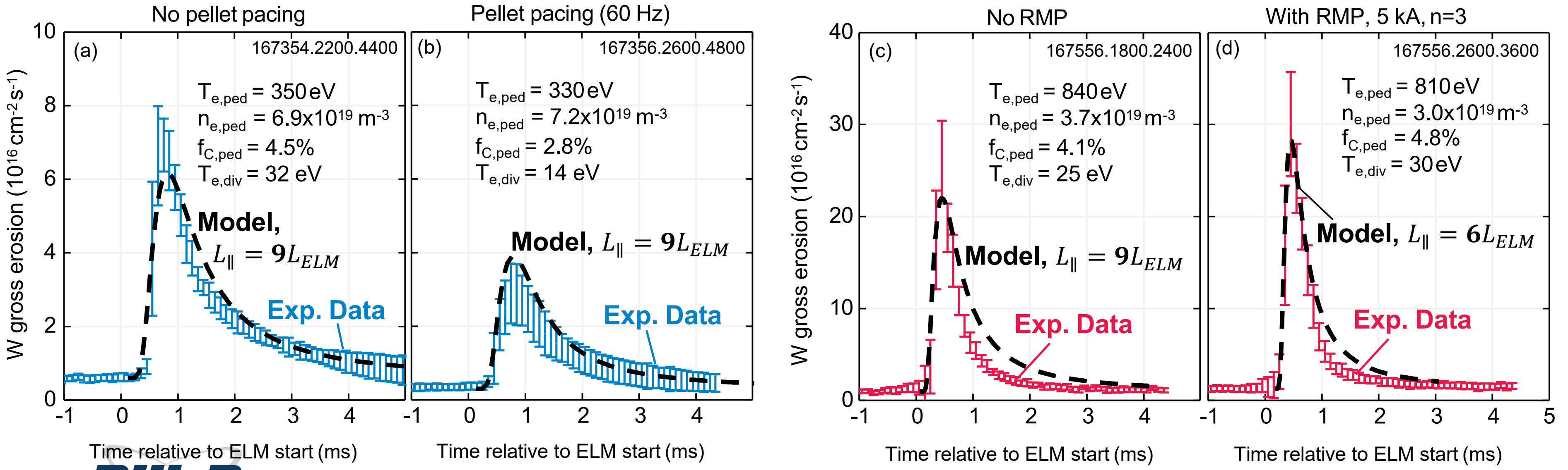
$$\Gamma_W(t) = \frac{S}{XB}(t) \int_0^\infty I_{WI}(t)\, dz$$

- **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

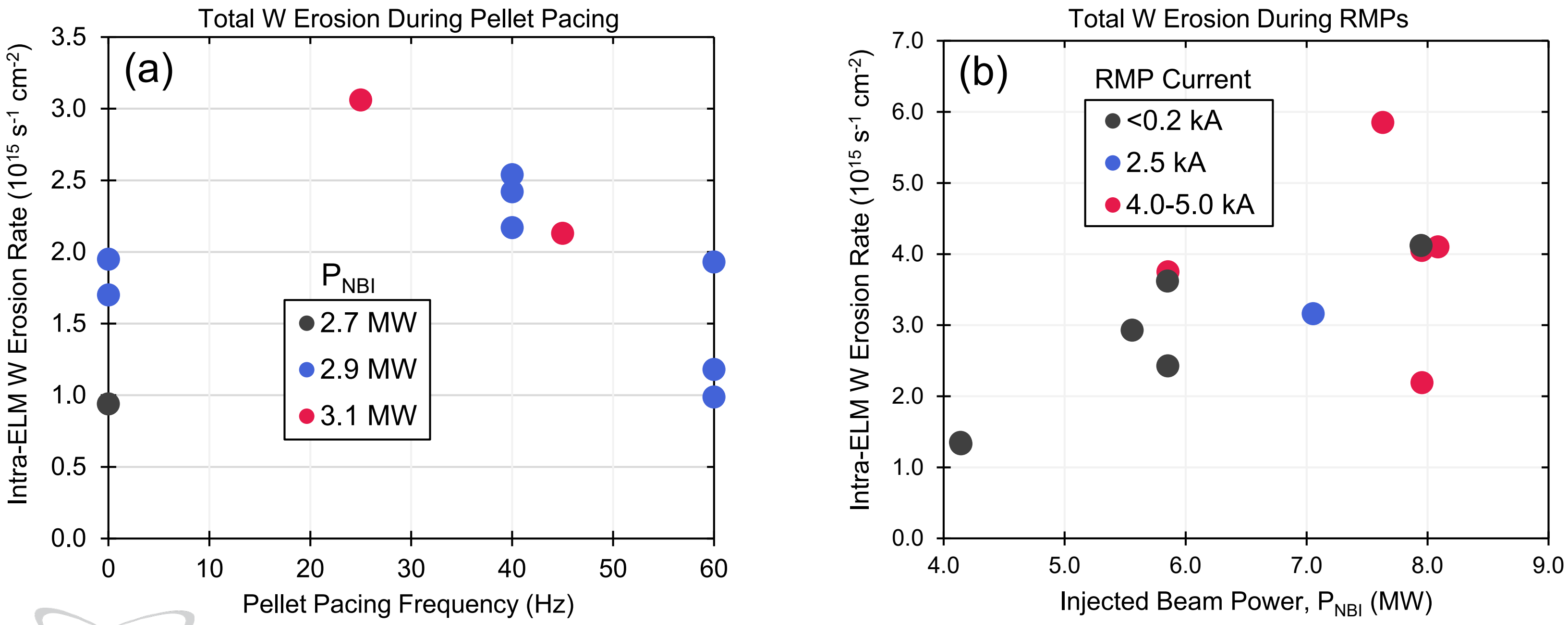
- **ELM Mitigation via Pellet Pacing or Resonant Magnetic Perturbations (RMPs)**
  - Pellets reduce $f_{C,ped}$, reducing sputtering by free-streaming C^{6+} impurities
  - Pellets also lower $T_{e,div}$, which lowers $Y_{C\rightarrow W}$ for recycling C^{2+}
  - Total W erosion slightly increases, despite slight decrease predicted by FSRM?
  - Peak W erosion rate increases significantly, suggesting RMPs cause a decrease in $L_{\parallel}$



[Abrams PoP 2019]

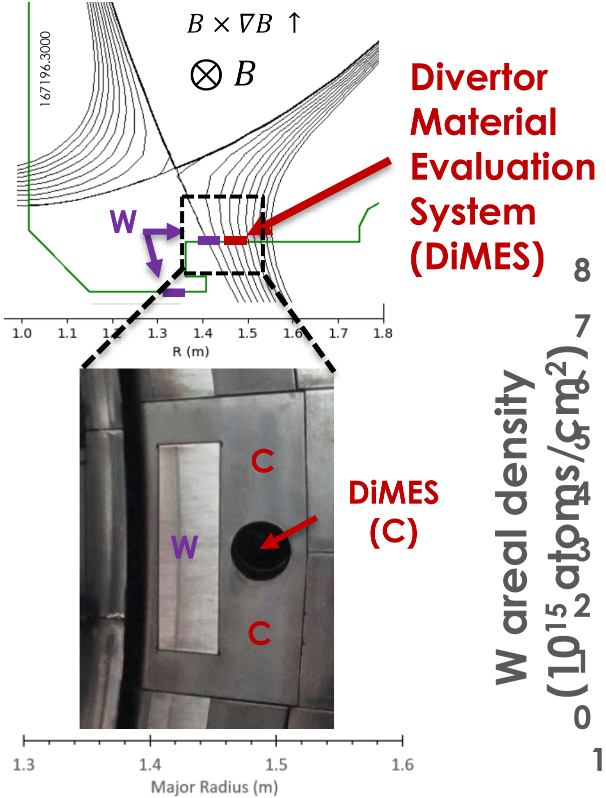
Higher frequency pellets more effective at reducing W sputtering, but no effect observed with RMPs

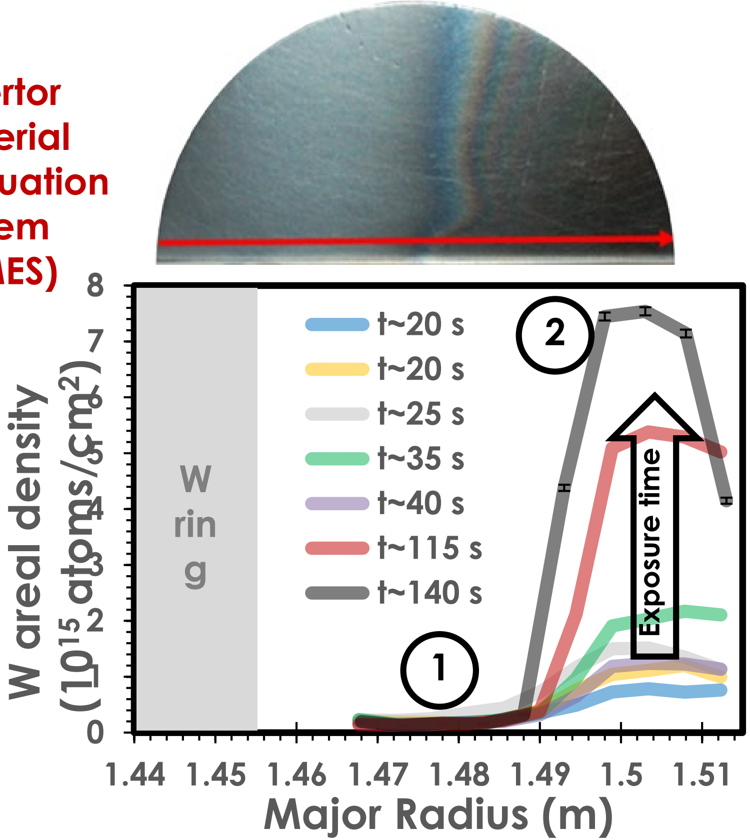
- **Low-frequency pellets actually increase W erosion above no-pellet level**
- **No correlation between RMP current and W erosion at any injection power**



[Cacheris APS-DPP 2020]

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**

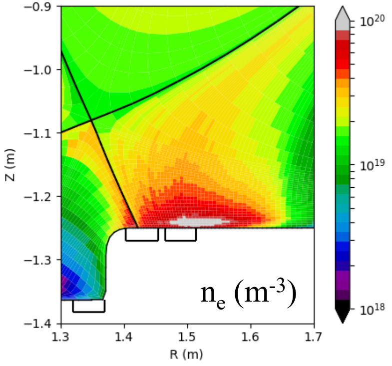
(1) Constant W coverage on inner half of DiMES

(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]

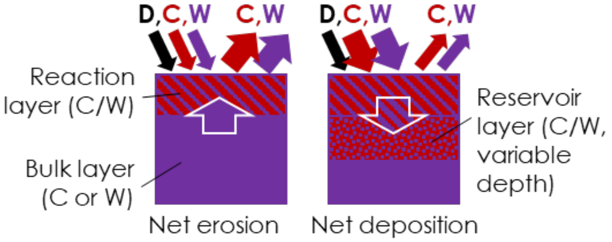
Near-surface W transport simulation via OEDGE background reconstruction and DIVIMP/WallDYN mixed-material model

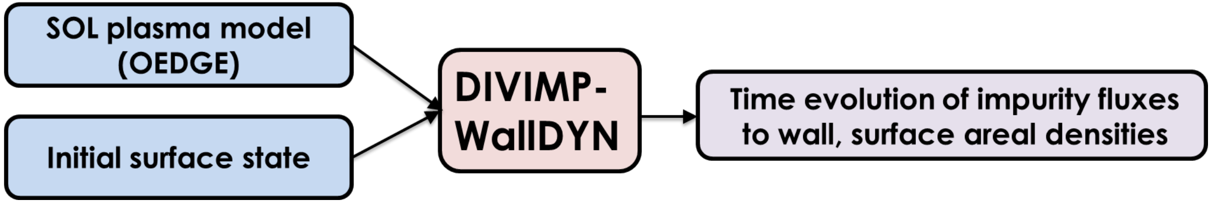
OEDGE calculation



- **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**
  - ∥ forces, Collisions, ∥/⊥ 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

WallDYN model





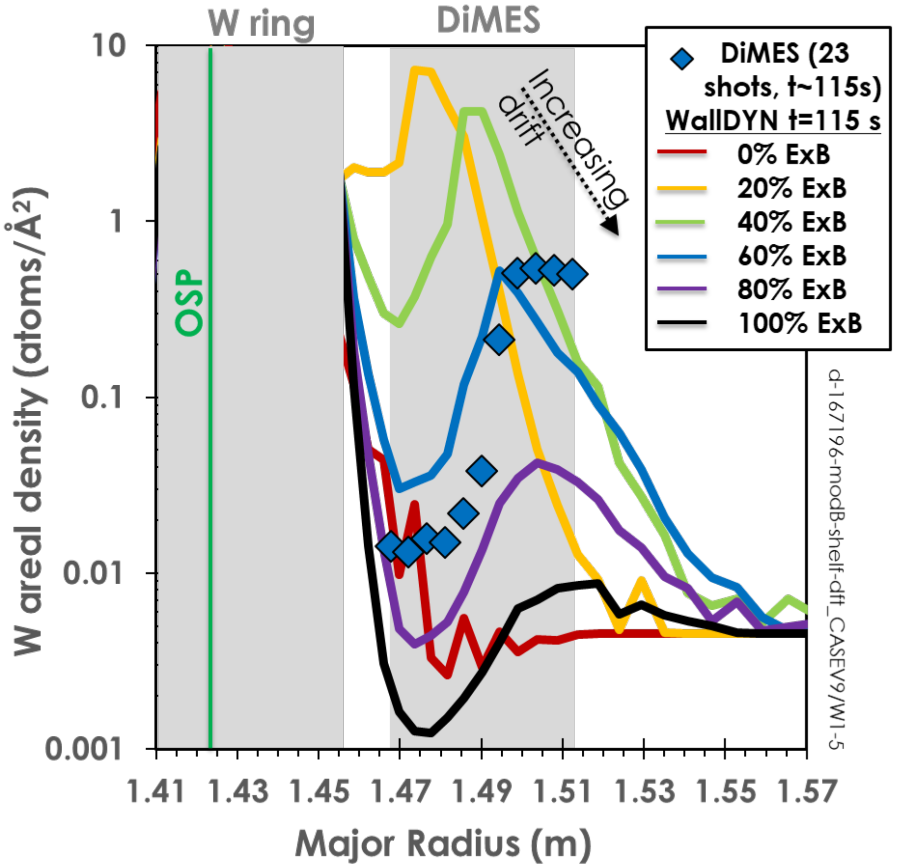
[Nichols NF 2021, submitted]

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):**

$$v^{ExB} = (X\%) * v^{ExB}_{OEDGE}$$

- **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



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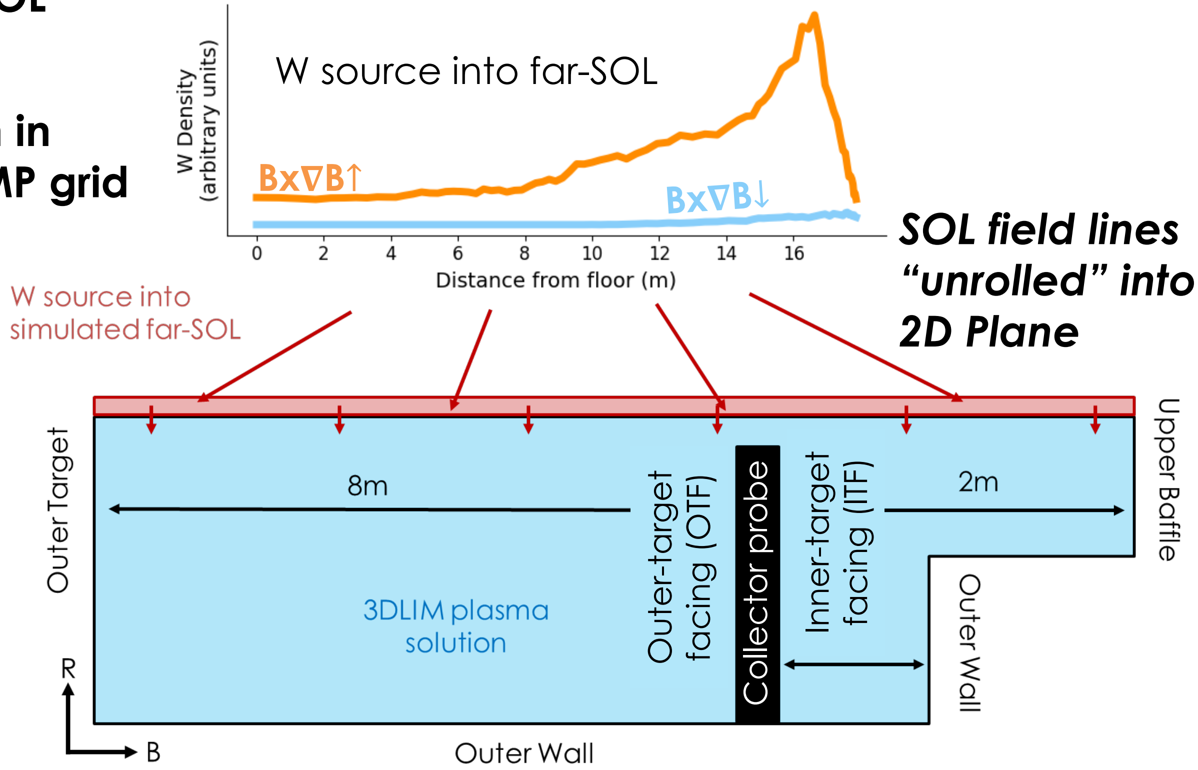
3DLIM is a new plasma impurity transport code to simulate W deposition on a collector probe in the far-SOL

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**



SOL field lines "unrolled" into 2D Plane

Zamperini NME 2021

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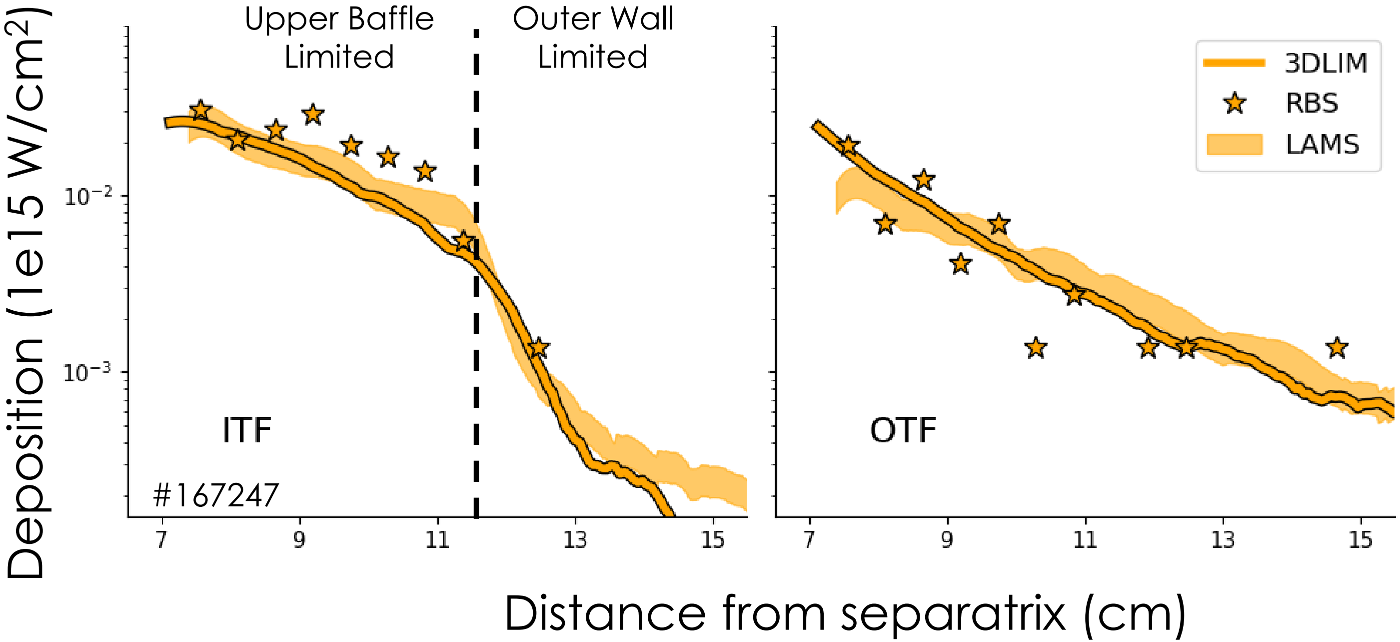
3DLIM successfully reproduces W CP deposition profiles assuming purely convective radial W transport

Bx∇B↑ 3DLIM Results

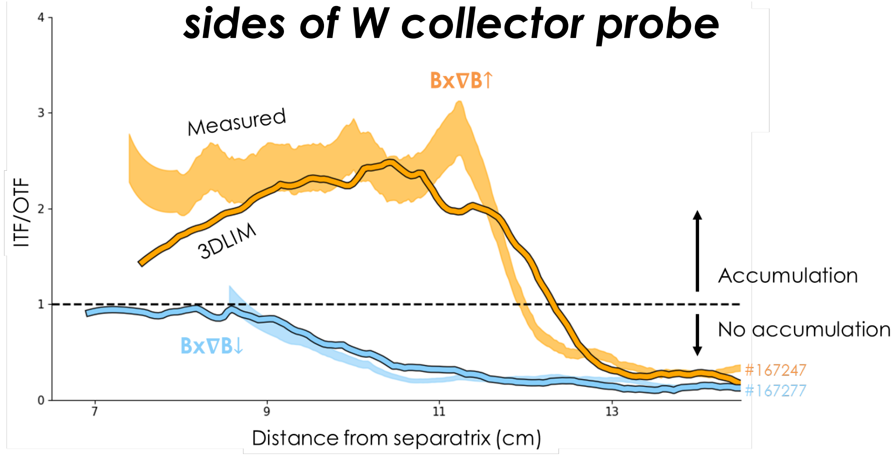


<u>Note</u>
Assumes W radially transports via convection, not diffusion [Zamperini NME 2020]

v_{radial} = 275 m/s

DIVIMP+3DLIM support hypothesis of a near-SOL W accumulation only when Bx∇B↑

Ratio of W deposited on inner-target facing (ITF) and outer-target facing (OTF) sides of W collector probe



- **DIVIMP can impose SOL patterns qualitatively similar to measurements**
  - Bx∇B↑: Near-SOL W accumulation due to T_i-gradient force
  - Bx∇B↓: 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 Bx∇B↑ direction**
- **Highlights the importance of accounting for flows in SOL impurity transport modeling**

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Abrams et al./IAEA-P1-660

Summary

- **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…

- T. Abrams et al., *Nucl. Mater. Energy* **17** (2018) 164–173
  https://doi.org/10.1016/j.nme.2018.10.011
- T. Abrams et al., *Phys. Plasmas* **26** (2019) 062504
  https://doi.org/10.1063/1.5089895
- S.A. Zamperini et al., *Nucl. Mater. Energy* **25** (2020) 100811
  https://doi.org/10.1016/j.nme.2020.100811
- J.H. Nichols et al., "Modeling of ExB effects on tungsten re-deposition and transport in the DIII-D divertor," *Nucl. Fusion* (2021) submitted