DIII-D is not ITER: Tungsten PFC's could reduce DIII-D's relevance and uniqueness

D. R. Ernst

Massachusetts Institute of Technology

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Email: dernst@psfc.mit.edu

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ITER can tolerate tungsten according to present predictions

- **ITER is 33× the volume of DIII-D with 2-5× n_e, 2-3× core T_e, low ν_*, low rotation**
  - Core T_e~10 keV on W cooling curve radiates 5-8x less than DIII-D (for same $n_W n_e$)
  - Due to higher n_e, ITER will have an SOL relatively opaque to neutrals
  - Thus, higher n_e^{sep}/n_e^{ped} than DIII-D is expected
  - As a result, ITER pedestals are predicted to screen W

$$\frac{R}{L_{nZ}} = -\frac{RV_Z}{D_Z} = Z\left(\frac{R}{L_{ni}} - 0.5\frac{R}{L_{Ti}}\right) = Z\frac{R}{L_{ni}}(1 - 0.5\eta_i)$$

  - *In local uniform limit*, M=0, temperature gradient screens impurities for $\eta_i > 2$

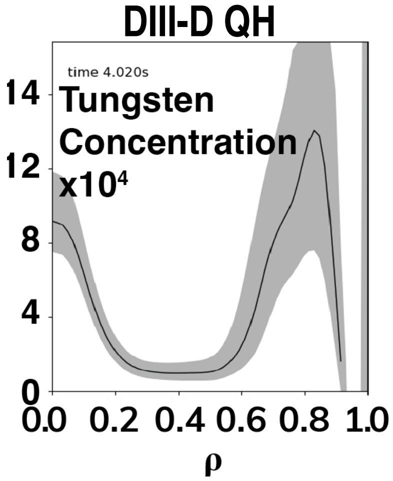
    (qualitative for illustration, very approximate under idealized assumptions, but screening is predicted using NEO+integrated modeling)

- **ITER W concentrations predicted ~100× lower than DIII-D**
  - W concentration profiles in ITER are expected to be ~flat in the core and peaked near the LCFS

"Report on Open Issues in the new ITER Baseline with a W-wall," ITPA Transport and Confinement Topical Group & ITPA Pedestal and Edge Physics Topical Group, April 2024: *"Tungsten transport in the pedestal,"* R. M. McDermott, X. Xueqiao, C. Angioni, D. R. Ernst, C. S. Chang, M. Willensdorfer, S. Q. Korving, T. Odstrcil, B. Victor

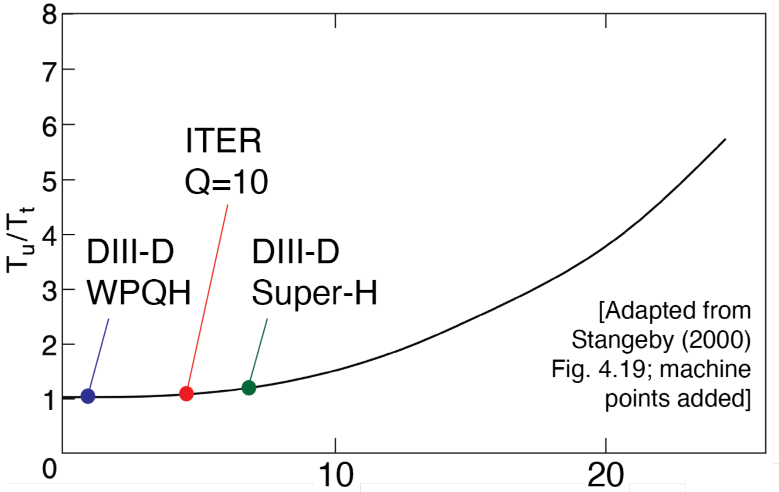
Present understanding suggests DIII-D operates in the wrong part of parameter space for tungsten

- **DIII-D is susceptible to W accumulation and degradation**
  - Lower density, higher SOL temperature increases sheath potential and thus physical sputtering source, located close to pedestal foot
  - W is drawn in by strong pedestal neoclassical convection due to steep pedestal ion density gradient (low n_e^{sep}/n_e^{ped}) and screening is hard to achieve
  - At low ν_*, with 80% of ions trapped and $\rho_\theta \sim w_{ped}$, pedestal T_i is flattened by orbit averaging, difficult to increase pedestal ∇T_i
- **Plasma targets a source-free equilibrium W density**
  - W accumulates on-axis and near pedestal top, reducing $(\mathrm{P_{tot}} - \mathrm{P_{rad}^{core}})/\mathrm{P_{LH}}$ and degrading performance
  - Lower core T_e puts DIII-D in a bad place in the W cooling curve
  - ECH does not reduce W inventory unless ELMy
  - Reducing W source just slows down evolution toward this equilibrium



Target temperatures are generally too high for attached conditions with W divertor in both DIII-D and ITER: Above W sputtering threshold

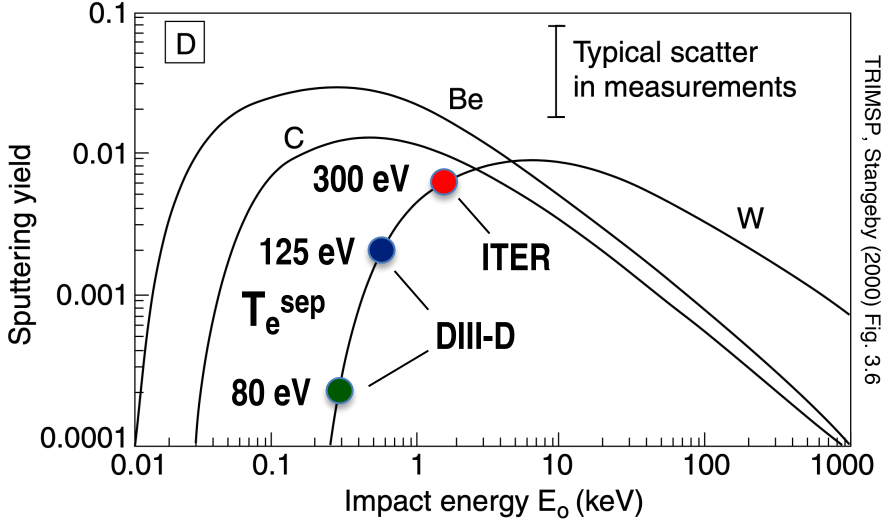
Ratio of upstream to target temperatures



$$\nu_*^{SOL} = 10^{-16} L_{||}[m] n_u[m^{-3}]/T_u^2[eV]$$

$$L_{||} \approx \pi q R$$

- **ITER:**
  - Large $R = 6.2$ m, $n_e^{sep} \sim 4e19\ m^{-3}$ offset by $T_e^{sep} \sim 300\ eV$
- **Ion Impact Energy**
  - Sheath potential $\phi = 3T_e/e$
  - $E_{impact} \simeq 2T_i + e\phi \approx 5T_t$



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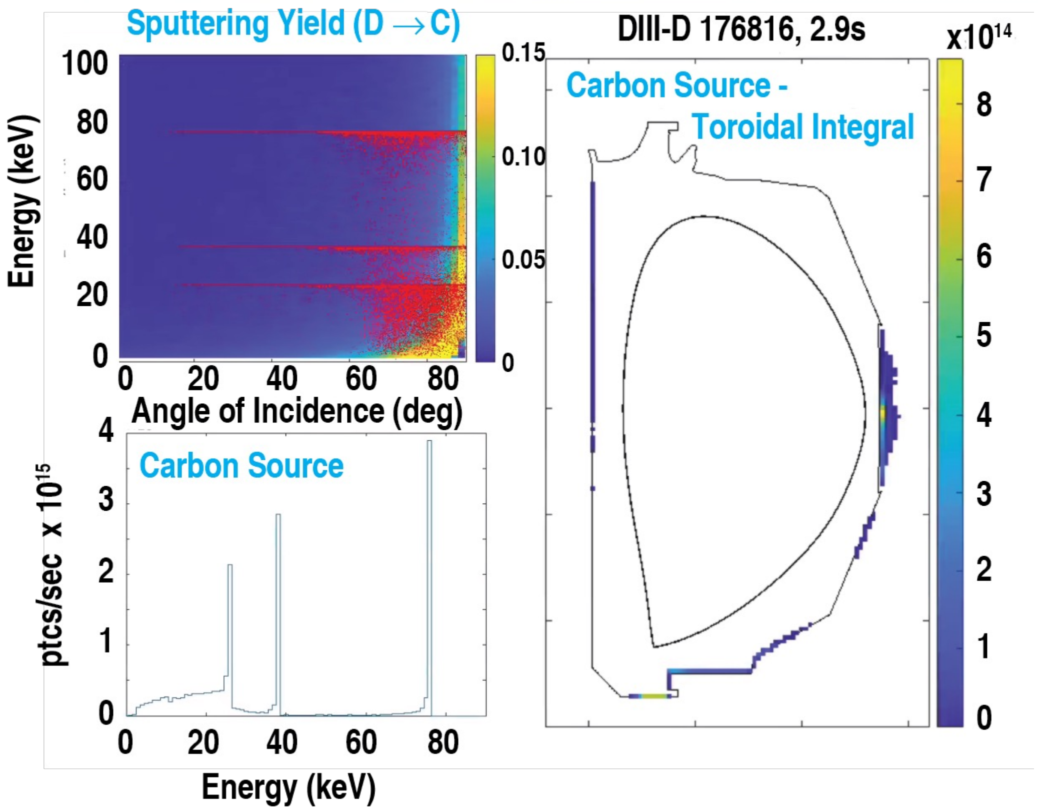
	DIII-D H-Modes	ITER H-Modes [ITPA W report (4/24)]
Pedestal W Profiles	$\mathrm{R/L_{nW}} = RV_{\mathrm{nc}}/D_{\mathrm{nc}}$ • W transport is neoclassical • Strong W pinch due to Z dn_i/dr • Local peak in W near pedestal top • Can only reduce source by cooling divertor, or screen W • Screening W requires high n_e^{sep}/n_e^{ped} • If no screening, need ELMs to flush W	$\mathrm{R/L_{nW}} = RV_{\mathrm{nc}}/D_{\mathrm{nc}}$ • W transport is neoclassical • W screening by Z dT_i/dr predicted due to high n_e^{sep}/n_e^{ped}~0.3-0.5 (opaqueness) • W profile peaks near LCFS • ELMs and turbulence *increase* n_W^{ped} by flattening profile
Core W Profiles	$\mathrm{R/L_{nW}} = RV_{\mathrm{nc}}/D_{\mathrm{turb}}$ • Strong neoclassical pinch • W accumulation on axis & ped. top • ECH helps if ELMy	$\mathrm{R/L_{nW}} = RV_{\mathrm{turb}}/D_{\mathrm{turb}}$ • low ν_*, low Mach # • no W accumulation, flat profile $n_W/n_e \simeq n_W^{ped}/n_e$
Max. allowable core W conc.	$n_W(0)/n_e(0) \sim 10^{-3}$ • $(\mathrm{P_{tot}} - \mathrm{P_{rad}}) > \mathrm{P_{LH}}$, $\mathrm{T_e} \sim 4$ keV • Bad place in W cooling curve	$\langle n_W/n_e \rangle \sim 2 - 3.5\times10^{-5}$ • $(\mathrm{P_{tot}} - \mathrm{P_{rad}}) > \mathrm{P_{LH}}$, $\mathrm{T_e} \sim 10$ keV • $\mathrm{V_{plasma}^{ITER}} = 33\mathrm{V_{plasma}^{D3D}}$ limits $\int dV\, p_{\mathrm{rad}}$
Expected W density	$n_W \sim 10^{15} - 10^{16}\ m^{-3}$ • As measured	$n_W < 2 - 3.5\times10^{15}\ m^{-3}$ • As simulated

Does wall material matter, or just divertor?
Simulated Carbon Sputtering from Beam Ion Loss not significant

- **SPIRAL 6D particle orbit following code finds orbit-lost beam ions**
- **RUST-BCA 3D PIC Plasma Materials Interactions code calculates sputtering from lost beam ions impacting wall**
- **Steady state effect estimated under conservative assumptions (τ_C=1.0 s)**
- **Δn_C= 8x10^{16} m^{-3}**
- **ΔZ_{eff} < 0.1**
- **However, 30L shine-thru has been problematic in QH-Mode, sputtering metals**



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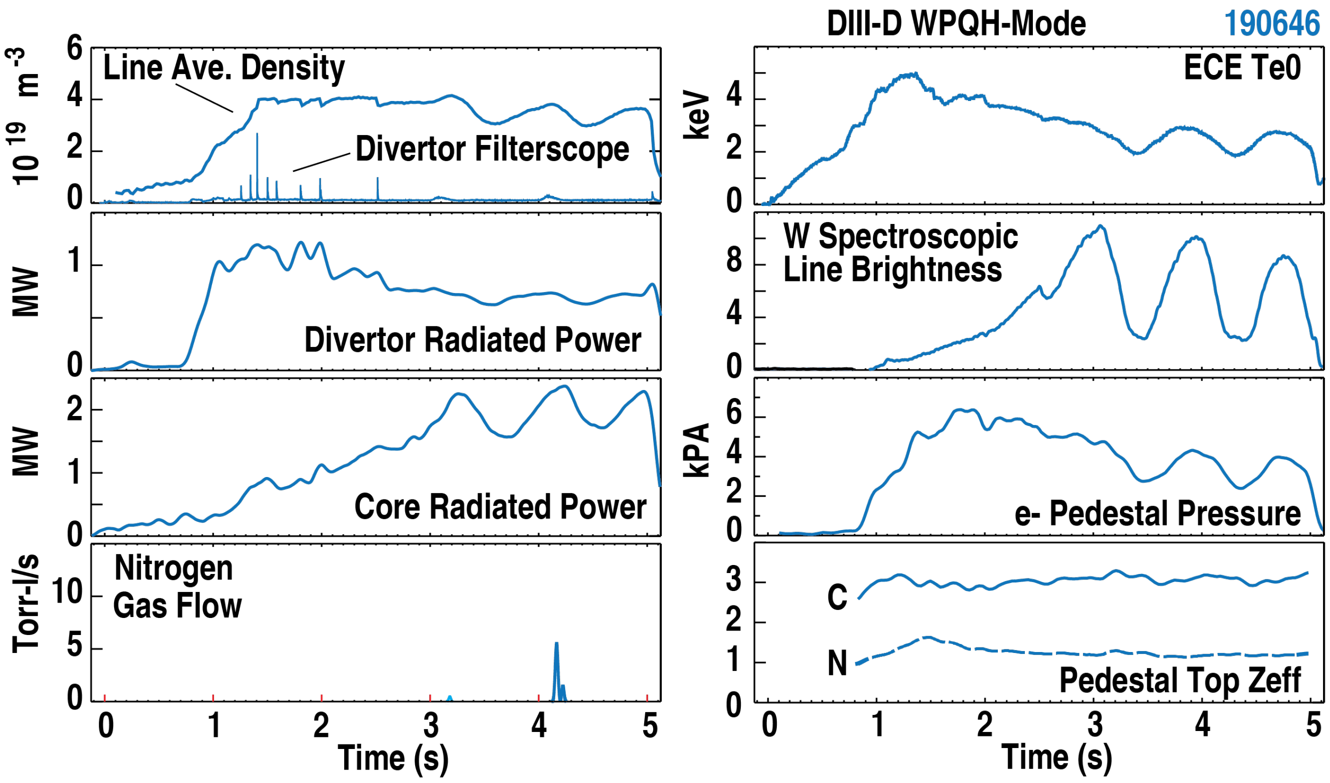
A. Bortolon (PPPL), J. Drobny (Univ. of IL -UC), F. Scotti (LLNL), G. Kramer (PPPL)

Without ELMs, Tungsten can be Problematic (WPQH-Mode): Tungsten Radiative Instability Observed

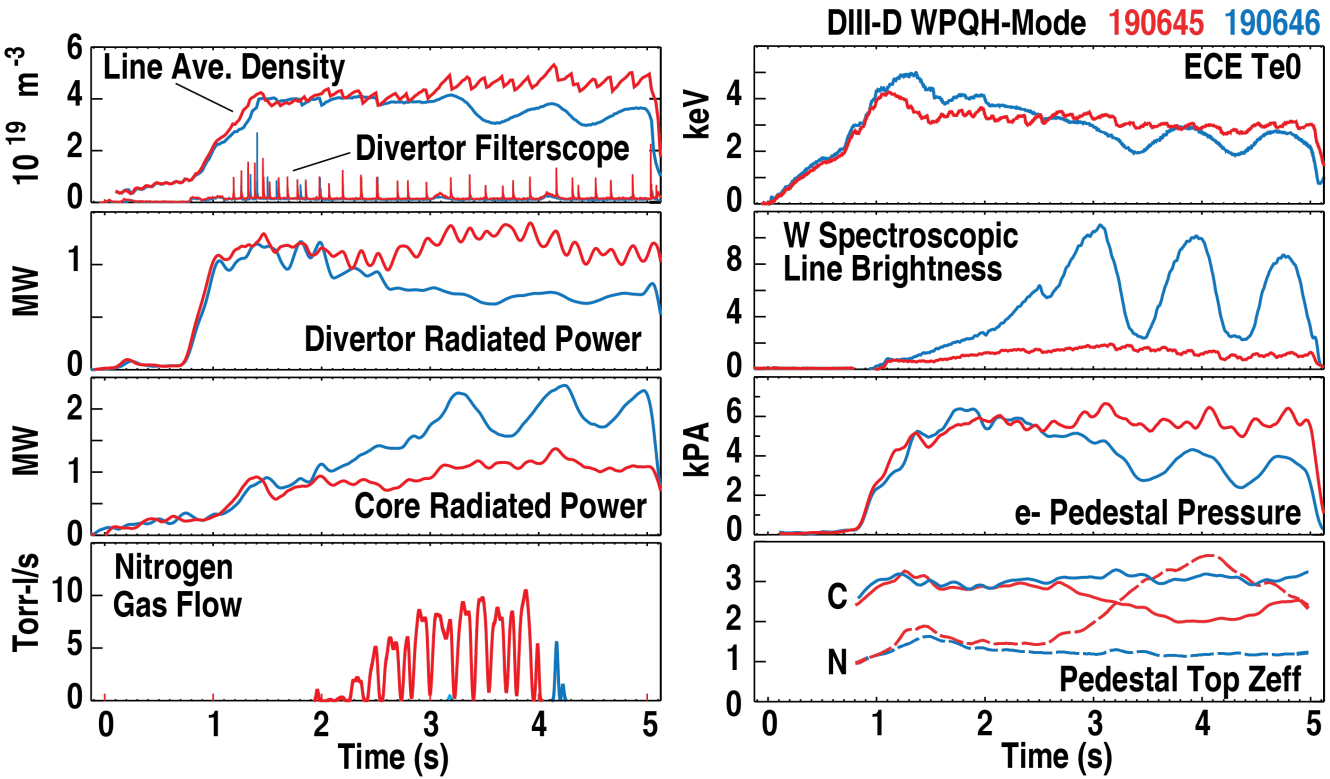
- **Accidental tungsten contamination in DIII-D lower divertor**
- **Large oscillations in core P_{rad} due to W degrading its own confinement by degrading pedestal**
- **Without carbon, the neoclassical influx of W would be several times stronger**



Ernst (MIT), Anand (GA), Bortolon (PPPL), Eldon (GA), Odstrčil (GA), et al.

Nitrogen Injection Controlled Tungsten by Cooling Divertor, Also Reduced Carbon, but Nitrogen Accumulated in the Core

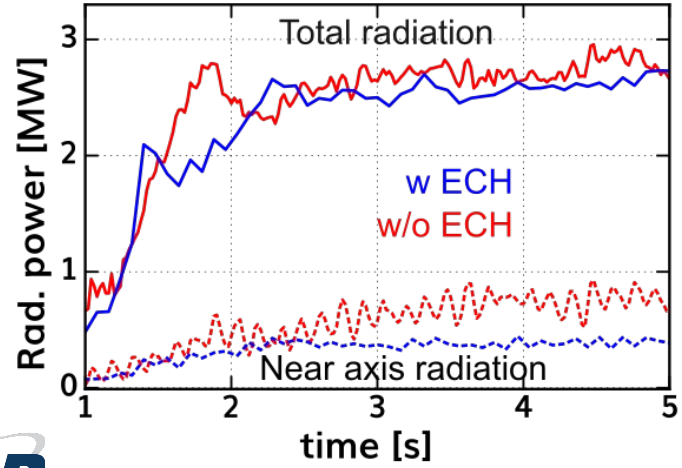
- Nitrogen injection **with feedback to divertor P_{rad}** controls W (x30 reduction in n_W/n_e)
- Impurity seeding contaminates H-Mode core unless screening can be achieved
- ECH reduces on-axis W but does not remove W unless ELMy

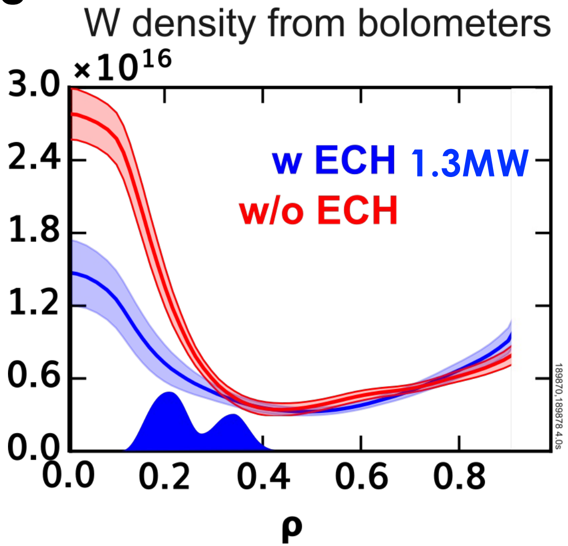


Ernst (MIT), Anand (GA), Bortolon (PPPL), Eldon (GA), Odstrčil (GA), et al.

In WPQH-Mode, ECH removes W from magnetics axis, but total radiation unaffected without ELMs

- **Serious issues with W and Ba contamination in the 2022 campaign**
- **On-axis ECH in WPQH mode can trigger massive sawteeth + ELMs**
  - Requires a fine tuning of ECH power and location
  - Does reduce near-axis W content
- **But if total core P_{rad} not reduced, pedestal is still degraded**

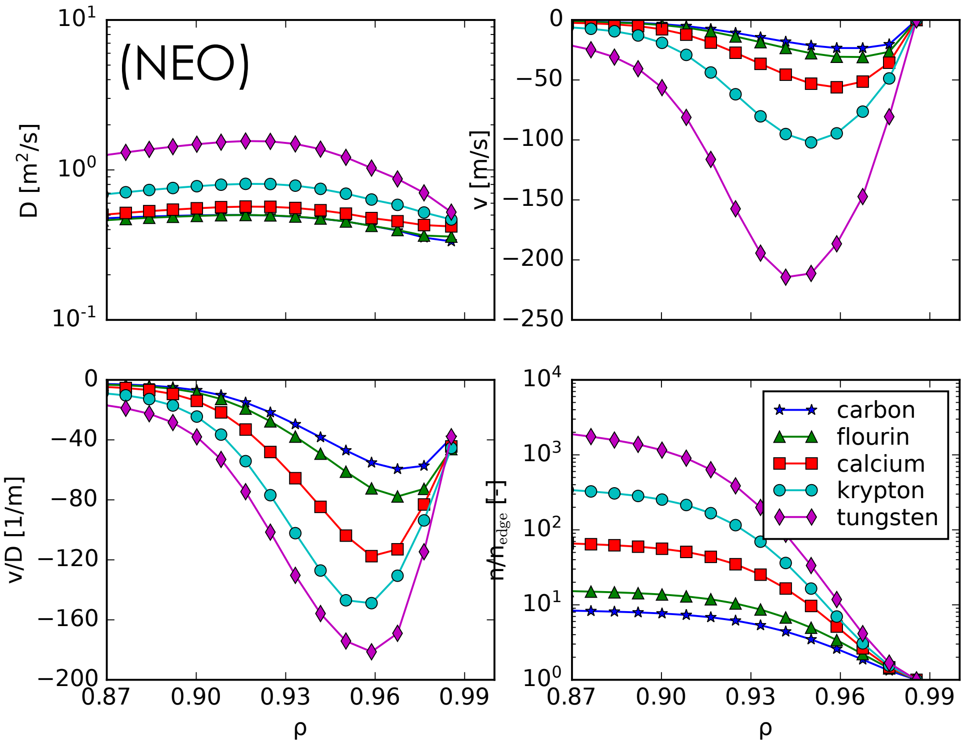




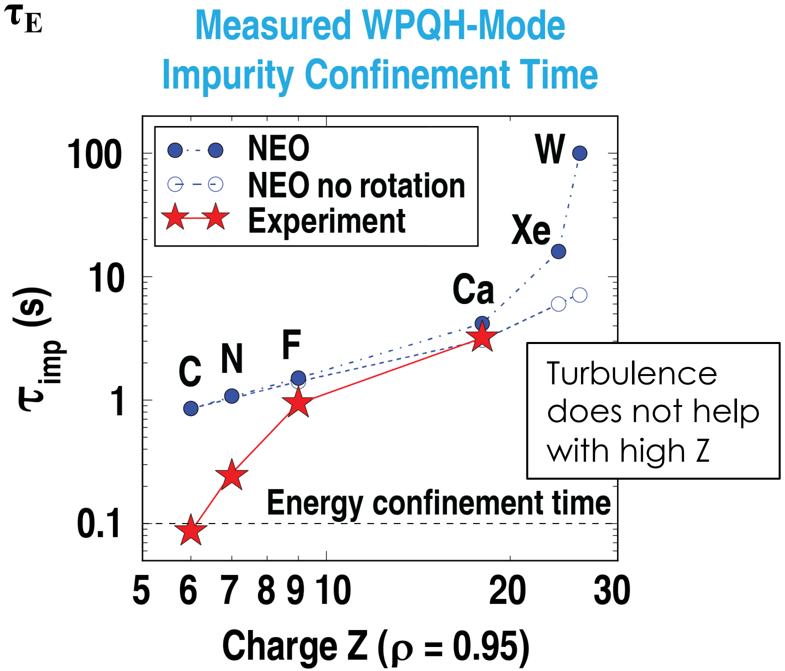
T. Odstrcil et al.

Impurity Confinement Time in WPQH-Mode Measured by Laser Blowoff (LBO) and is Consistent with Neoclassical for High Z

- **Consistent with neoclassical estimates using NEO+Aurora for F, Ca**
- **Much shorter confinement time for C, N, similar to τ_E**



T. Odstrčil (GA) et al.



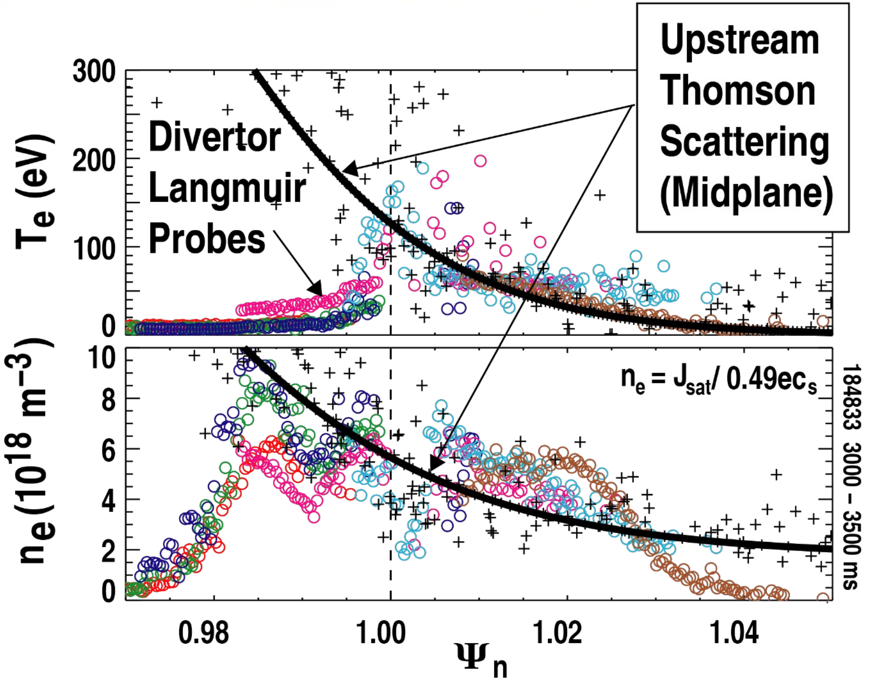
- **Carbon $\tau_p \sim \tau_E$ may be consistent with gyrokinetic turbulence predictions of TEMs**

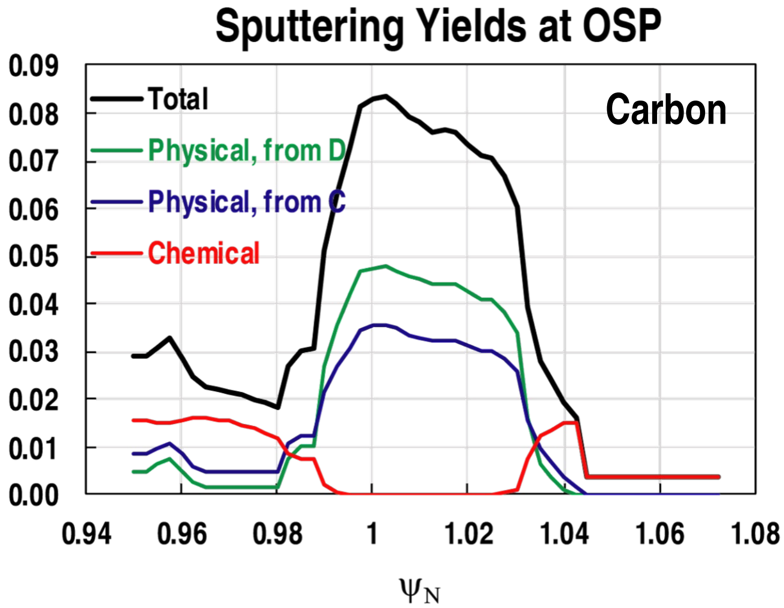
What will we learn from W in DIII-D that makes it worth severely limiting DIII-D operational space and constraining its unique flexibility?

- **ITER is predicted to tolerate tungsten, but in a different regime than DIII-D**
  - ITER expected to have a broader pedestal density profile, helping screen impurities
  - Tungsten radiates 5-8x less for T_e >10 keV
- **Experience shows that even a small areal density of W on the DIII-D lower divertor tiles degrades performance and prevents steady operation**
  - When there are no ELMs and $\nu_{*e} \sim 0.1$ at pedestal top (i.e., future-relevant conditions)
  - Neoclassical impurity screening is hard to achieve in DIII-D due to its lower density and ion orbit-averaging of T_i across the pedestal (though it may be possible in some specific cases)
  - Must increase $\boldsymbol{n_e^{sep}/n_e^{ped}}$ to screen impurities (W and radiative gases) and also to detach divertor
  - Without carbon, it will be worse (neoclassical W pinch stronger)
- **Like JET, ASDEX Upgrade, West, etc., tungsten in DIII-D will introduce major obstacles**
  - H-Mode operation restricted to higher density, higher collisionality regimes with reduced performance, and ELMs will be required to flush tungsten, pushing DIII-D closer to ASDEX Upgrade
  - This will make DIII-D less future-relevant and unique, impacting its flexibility and operating regimes
- **Need accurate and valid integrated simulations of W with PMI and pedestal GK turbulence to scope W impact (not just reduced models or local models)**

Backup Slides

WPQH-Mode Achieved by Wall Conditioning, Lowering SOL Densities to Produce Sheath-limited, High T_e ~ 150 eV SOL

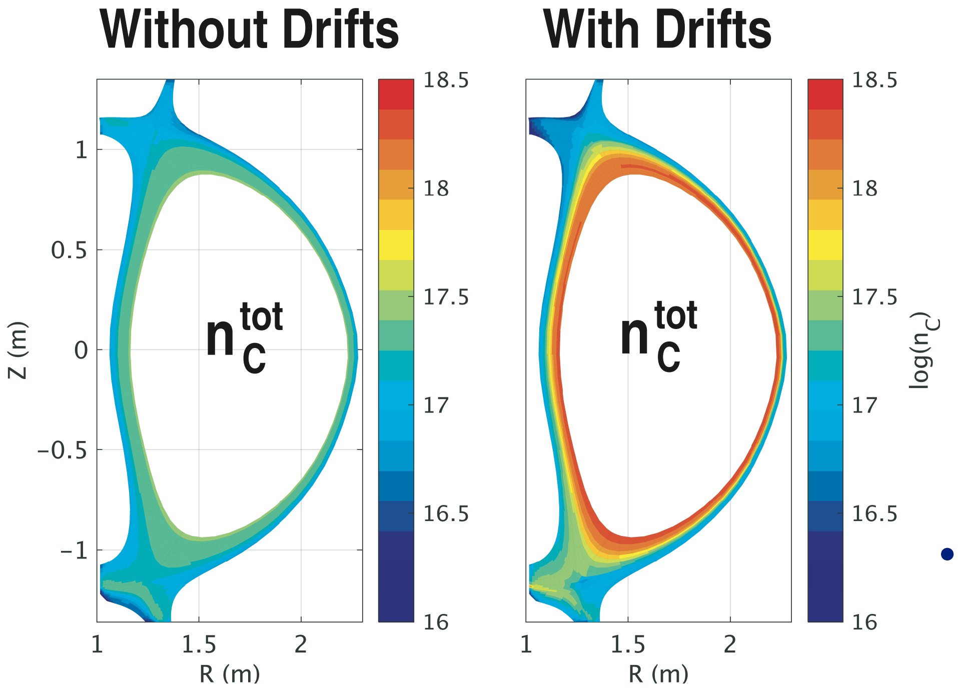


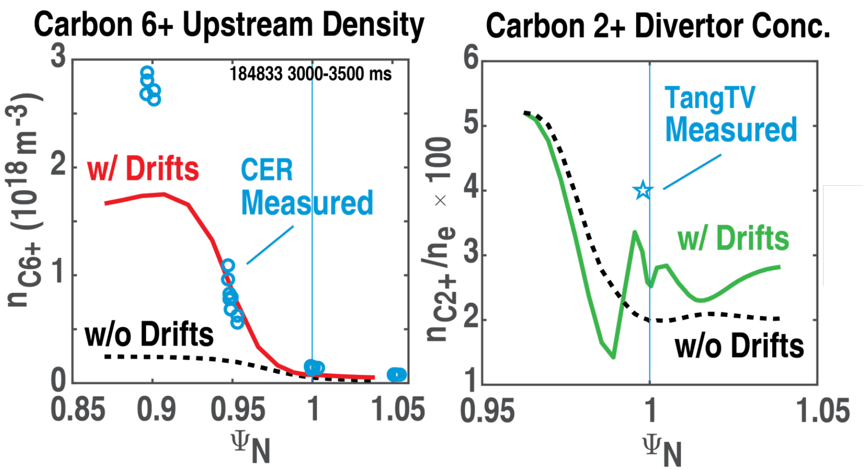


- **High T_e ➜ High Sheath Potential ➜ High Impact Energy ➜ Sputtering**

Xinxing Ma (GA), H. Wang (GA), T. Abrams (GA), D. Ernst (MIT) et al, submitted to Nucl. Fusion

Drifts are Essential to Reproduce Measured Upstream Carbon Impurity Densities in SOLPS-ITER Simulations of DIII-D WPQH-Mode





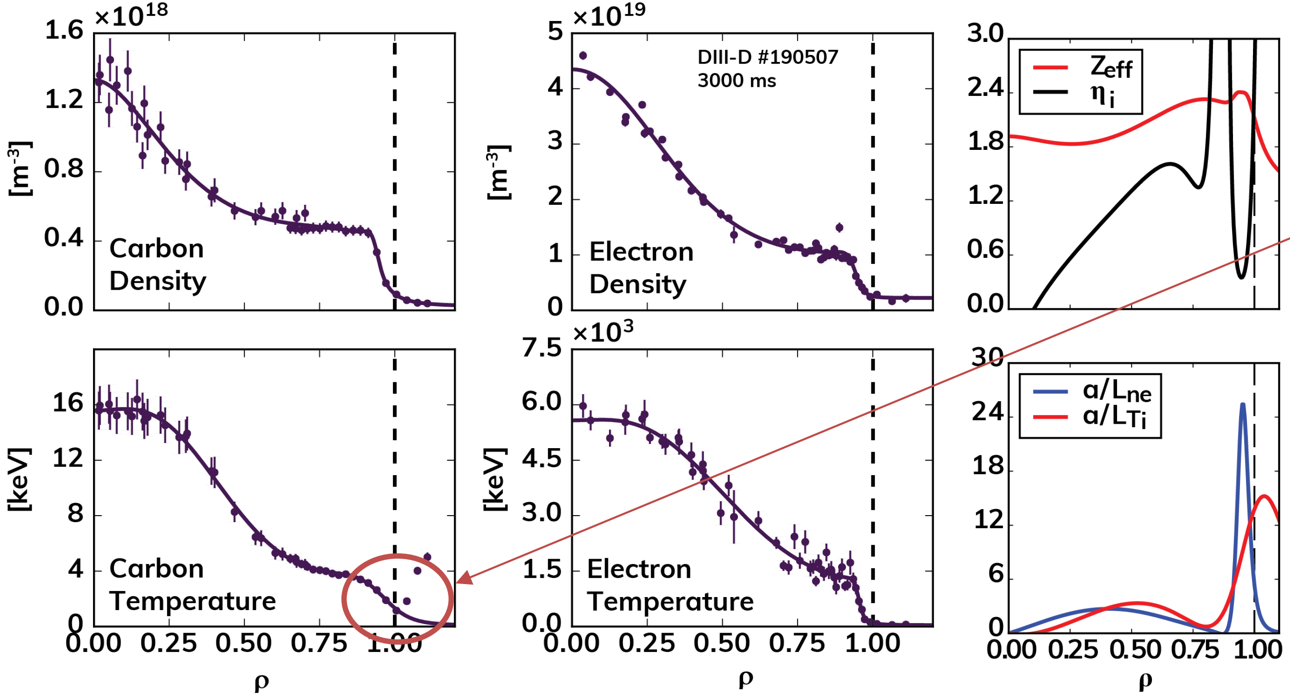
- Drifts move impurities out of private flux region and up inboard side

- High temperature, low ν_*^{SOL} sheath-limited SOL similar to future machines: Strong sputtering in attached conditions
- SOLPS-ITER validation against first divertor measurements in WPQH-Mode

Xinxing Ma (GA), H. Wang (GA), T. Abrams (GA), D. Ernst (MIT) et al, submitted to Nucl. Fusion

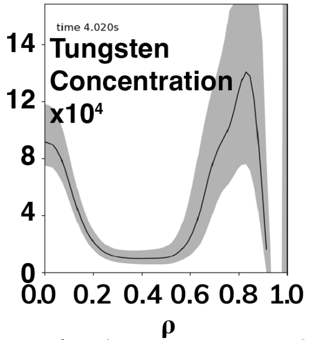
Scheduled Experiment will Screen Impurities by Creating "Super WPQH-Mode" at higher density using the new DIII-D Shape/Volume Rise

- Below shows a Standard QH-Mode from last campaign where pedestal top $\eta_i > 2$
- Core ITB also reduces impurity pinch by increasing $\eta_i \sim 1.5$
- Result: $1.8 < Z_{\mathrm{eff}} < 2.4$ and tungsten concentration is controlled



Notice at low ν_{*i}, with $\rho_{\theta i} \sim$ (pedestal width), and ~85% trapped particles, orbit averaging flattens pedestal ∇T_i:

We must flatten ∇n_i

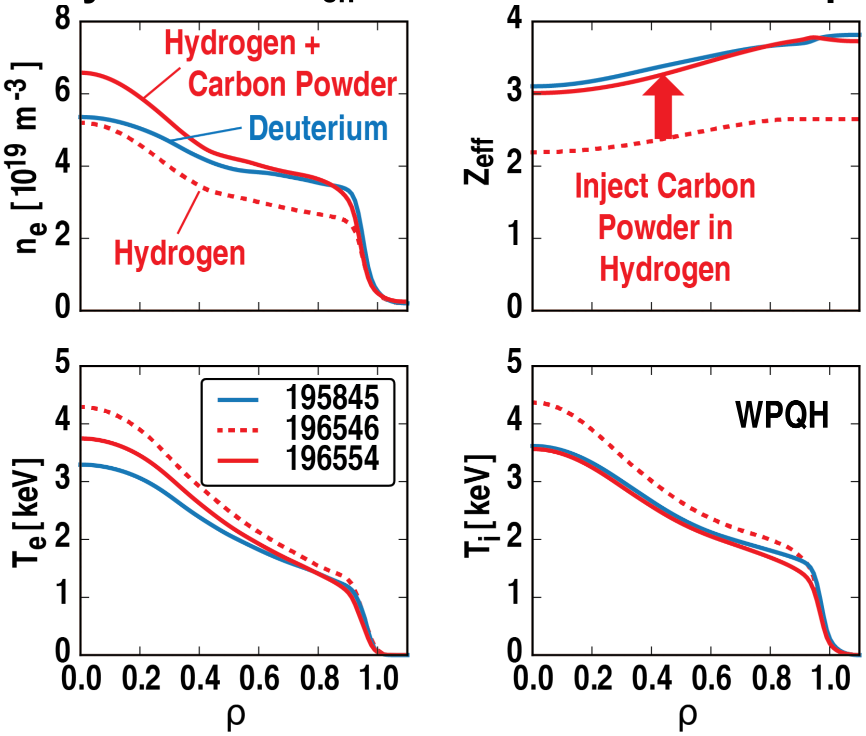


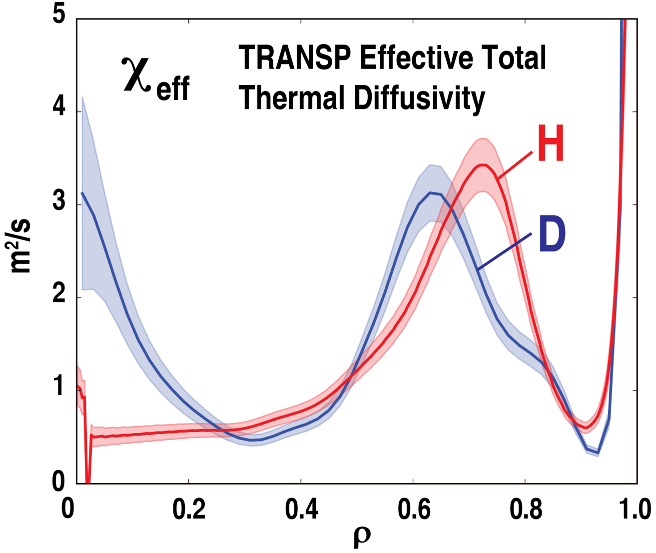
D. Ernst, X. Ma et al.

M. R. Wade et al., Phys. Rev. Lett. **84**, 202 (2000).
A. R. Field et al., Nucl. Fusion **63**, 016028 (2023).

Achieved QH & WPQH-Mode in Hydrogen, reducing Z_{eff} from 3.4 → 2.4; Obtained closely matched H & D pair by injecting carbon powder

- 10x reduction in physical sputtering of carbon by hydrogen relative to deuterium
- Greatly reduced Z_{eff} with reduced carbon sputtering





- H and D profiles match closely with same Z_{eff}, power and torque

D. Ernst (MIT), A. Bortolon (PPPL), T. Wilks (MIT), T. Odstrcil (GA) et al. EPS, APS 2023

Predicted ExB Shear Suppression of Pedestal Turbulent Transport is Much Weaker at Small ρ_* in Future Machines

- **Ratio of shearing rate to drift wave growth rate in pedestal of fixed width Δ scales[1,2] with ρ_*, also increasing radial correlation lengths[3]**

$$e n_i E_r \simeq \frac{dp_i}{dr} \sim \frac{p_i}{\Delta}; \qquad \gamma_{\rm lin} \sim \frac{v_{Ti}}{\Delta}; \qquad \gamma_{\rm E\times B} \simeq \frac{1}{B}\frac{dE_r}{dr}; \qquad \frac{\gamma_{\rm E\times B}}{\gamma_{\rm lin}} \sim \frac{\rho_i}{\Delta} \sim \frac{a}{\Delta}\rho_*$$

- **From theory[4] and global pedestal gyrokinetic simulations,[5] transport reduction due to ExB shear scales asymptotically as[2]**

$$\frac{Q}{Q_{\rm GB}} \sim \left(\frac{\gamma_{E\times B}}{\gamma_{\rm lin}}\right)^{-2} \sim \left(\frac{\Delta}{a}\right)^{2} \frac{1}{\rho_*^2} \sim \frac{\beta_p^{2\alpha_1}}{\rho_*^2}$$

→ Larger turbulent fluxes at smaller ρ_* and higher β_p

KBM (EPED): $\Delta \sim \beta_p^{\alpha_1}$ $\qquad \alpha_1 \sim 0.5 - 0.75$

- **This *suggests* pedestal turbulence *may* be sufficient to maintain ELM stability below the peeling-ballooning boundary[6]**

[1] Kotschenreuther et al. IAEA v1. p.371 (1996).
[2] Kotschenreuther et al. Nucl. Fusion **57**, 64001 (2017).
[3] Chang et al., Phys. Plasmas **28**, 022501 (2021).
[4] Zhang and Mahajan Phys. Fluids B **4**, 1385 (1992).
[5] Hatch et al., Plasma Phys. Control. Fusion **60**, 084003 (2018).
[6] Ernst IAEA 2018 EX/2-2 also D. R. Ernst, Phys. Rev. Lett. **132**, 235102 (2024).