Multi-Machine Determination Of SOL-To-Core Multi-Z Impurity Transport in Advanced Confinement Regimes

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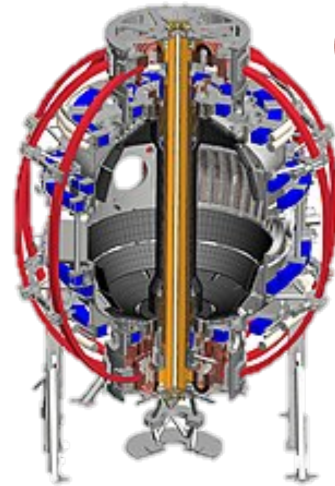
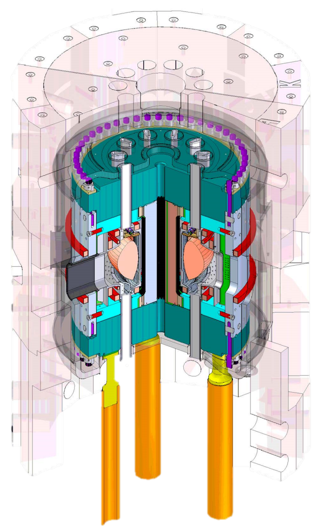
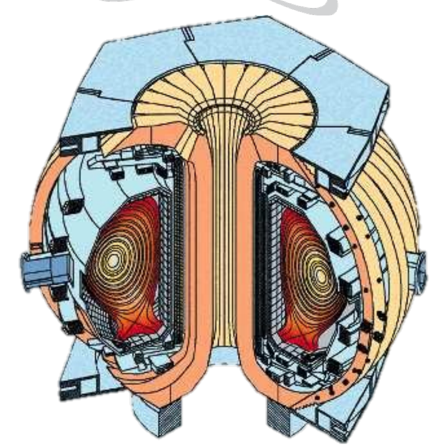
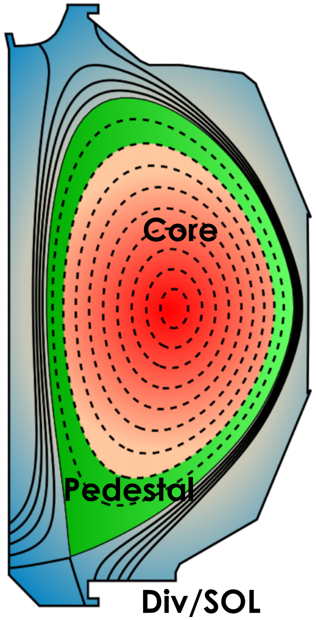






Coordinated Research Highlights Our Current Understanding of Impurity Transport and the Status of Our Modeling Capabilities



- **9 Datasets (3 US devices) used to study core to edge impurity transport for FY20 JRT**
  - Validate leading transport models in the core, pedestal, & SOL/div.
  - Establish common features of impurity transport that span device and regime
- **Neoclassical transport in the deep core. Generally well predicted by modeling & controlled via ECH regardless of impurity Z and regime**
- **Outside of deep core, turbulence dominates. Some success reproducing experiment with gyrokinetic modeling**
  - Clear disagreements in inferred/modeled impurity pinch are common
- **Neoclassical impurity transport reproduces time dependent measurements in pedestal region on multiple devices**
- **3D Monte Carlo modeling in the SOL and divertor able to qualitatively reproduce measurements of impurity deposition and transport**
  - Evidence of near-SOL impurity accumulation

The accumulation of impurities in the reactor core can lead to fuel dilution and excessive radiative losses.

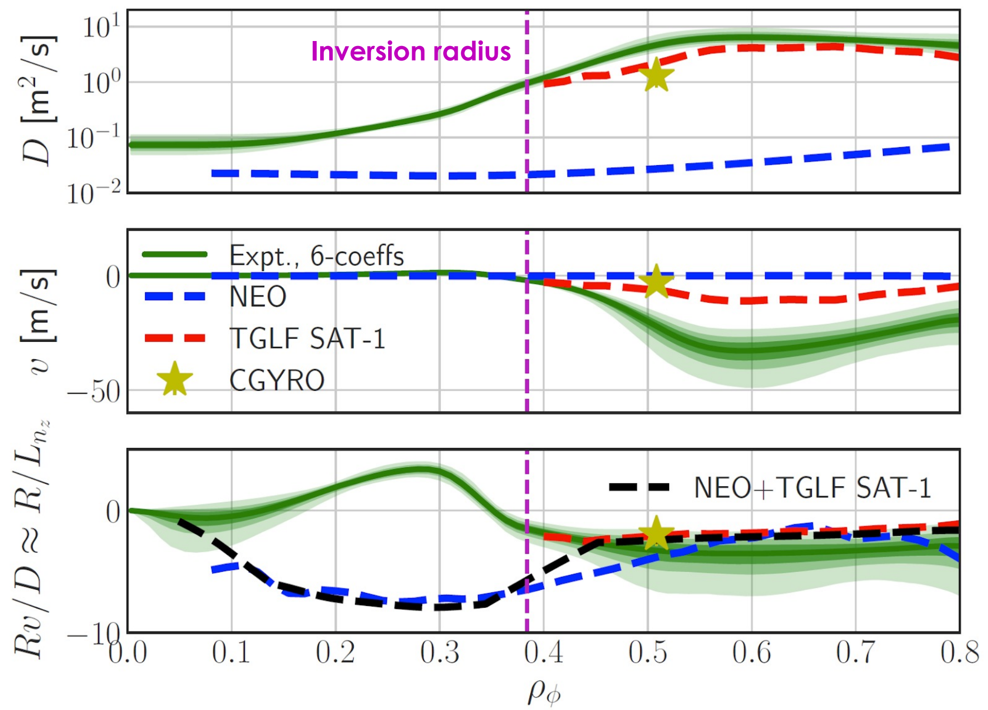
Can we understand, model, and control core accumulation of impurities in current devices?

Modeled, Turbulent Diffusion in Good Agreement With Inferred Mid-Z Transport, Convection Not Well Captured By Modeling

- Calcium impurities injected via laser blow-off monitored via x-ray spectroscopy (XICS)

- Transport coefficients derived using Bayesian inference + impurity transport code Aurora [F. Sciortino NF 2020]

- TGLF SAT1 and nonlinear CGYRO display reasonable agreement with diffusion, disagreement in convection for I-mode conditions



  - Disagreement with NEO modeling inside q=1
  - Convection discrepancy not resolved within uncertainties in inputs

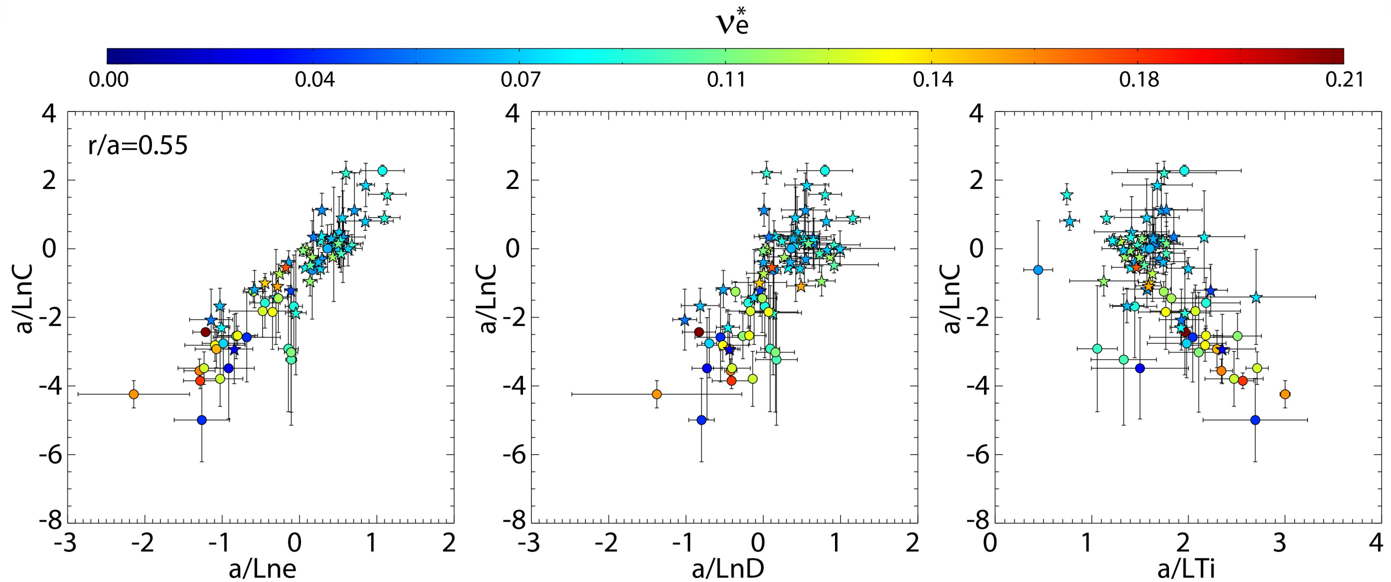
Alcator C-Mod

- Nonlinear CGYRO suggests a correlation between measured electron density peaking and mid-Z impurity peaking in L, I, H-modes

Low-Z Impurity Peaking Consistent with Neoclassical Transport at Mid Radius, Deviations Observed at Larger Major Radii

NSTX

Guttenfelder OV/4-5Rb

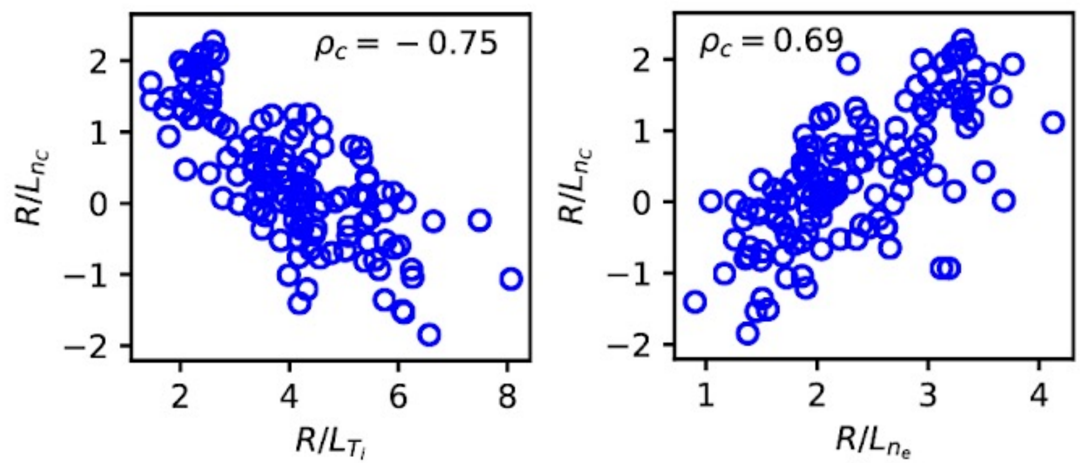


- **In an 66 discharge NSTX, H-mode database, C peaking correlated w/ n_e and n_D gradients, negatively with T_i**
  - ***@ Mid radius:*** *exp. measurements consistent with Neo. transport (NEO)*
  - ***Outside mid radius*** *: Deviations from neoclassical are clearly observed*

- **CGYRO simulations (ρ = 0.65 – 0.85) of the database indicate a mix of unstable modes cause discrepancies from neoclassical predictions**
  - Micro-tearing mode at high ν_e^* (~no particle transport)
  - Ballooning modes at reduced ν_e^* (quasilinear inward carbon impurity pinch)
  - Turbulent calculations unable to explain measurements

Carbon Profiles on DIII-D Correlated with a/L_{Ti} and a/L_{ne}, Roto-Diffusion Found to Play a Negligible Role

- **150+ discharge ELM-y H-mode database assembled and compared with NEO and CGYRO modeling**
  - Strong correlations of impurity peaking were found with a/L_{Ti} and a/L_{ne}
  - Weaker but non-negligible correlation was also observed with u’, T_e/T_i and q’



- **Systematic discrepancy between experimental and QL CGYRO-modeled a/L_{nC} in ITG dominated discharges, agreement in TEM dominated conditions**

- **Rotodiffusion (a u’ dependent pinch term), a previous explanation[1,2], shown to play no role in DIII-D cases via dedicated rotation scans**
  - Beam configurations allowed for decoupling of rotation and a/L_{Ti}

[1] Angioni NF 2011
[2] Casson NF 2013

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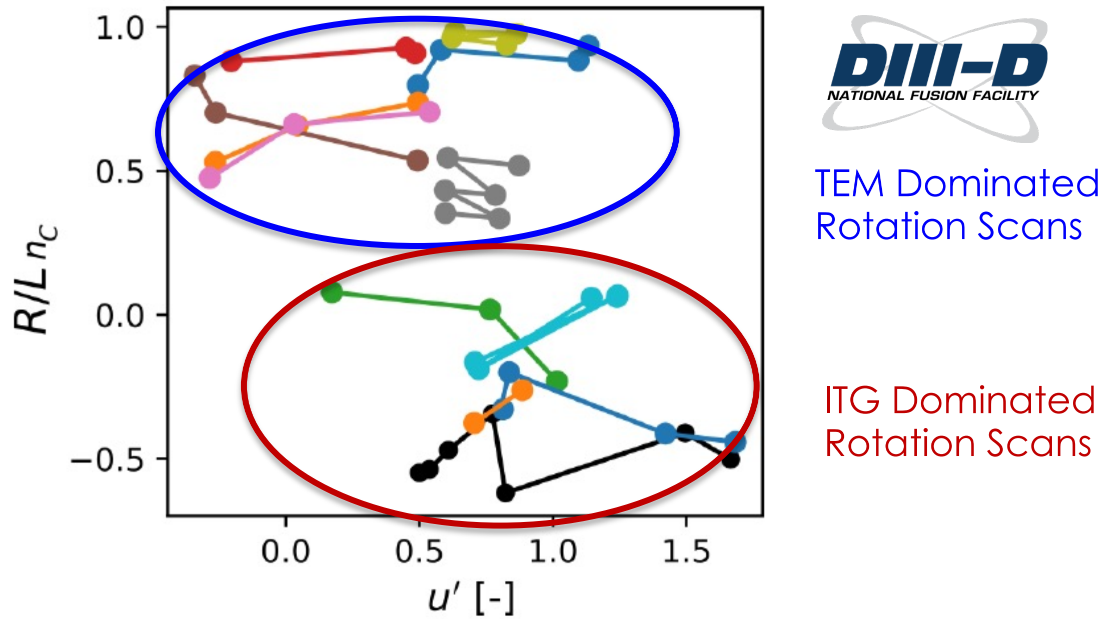

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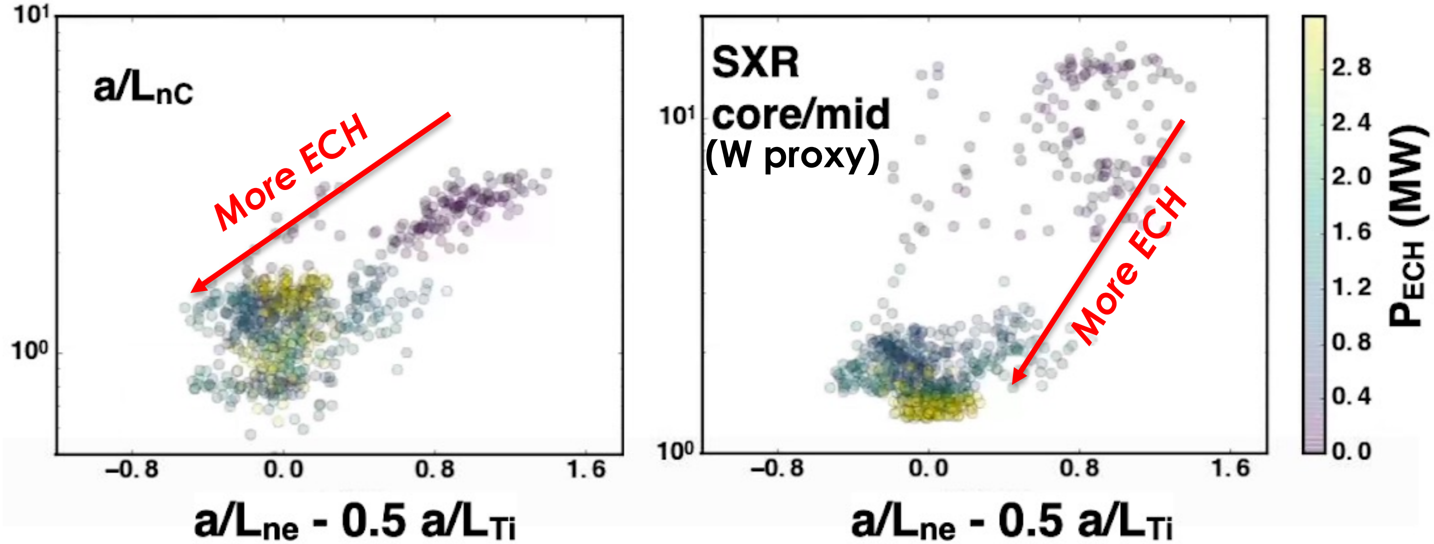
Modest ECH Eliminates Neoclassical Impurity Accumulation in the Core Independent of Z and Regime of Operation



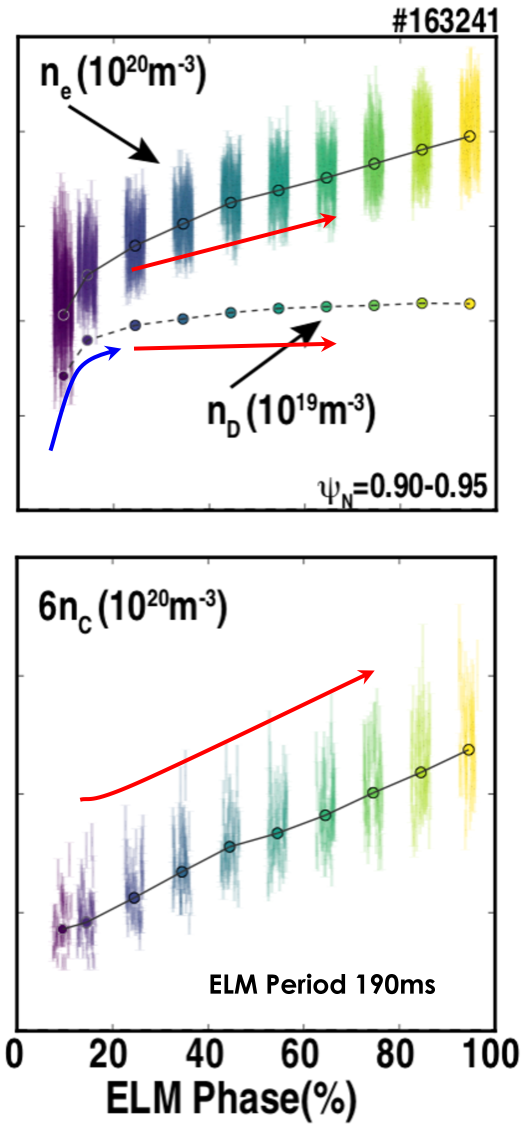
- **Core peaking of C, Ar, and W studied in a database of advanced regimes**
- **Measured peaking consistent with neoclassical expectations.**
  - NC peaking proxy: $a/L_n - 0.5a/L_{Ti}$ (**+** = inward pinch ; **-** = outward convection)
- **Modest (~1MW) of core ECH eliminates or reduces core peaking, confirming existing results [1][2]**
  - Independent of impurity Z & regime of operation

[1]Dux NF 2003
[2]Kallenbach NF 2009

In the absence of burning plasma conditions, impurities originate at the edge and move through the pedestal to the core

What mechanisms dictate impurity propagation through the pedestal?

Neoclassical Impurity Pinch and Impurity Ionization Shown to Play an Important Role in ELM Recovery



- **Pedestal recovery occurs in two phases:**
  - Initial pedestal recovery dominated by main-ion fueling
  - Slower, secondary recovery dominated by C impurity influx
- **Indicates formation of main-ion density may establish impurity pinch**
- **STRAHL modeling using neoclassical transport coefficients, able to reproduce measured time histories**
  - Strong evidence for neoclassical impurity pinch in the pedestal
  - Consistent with [Putterich JNM 2011]

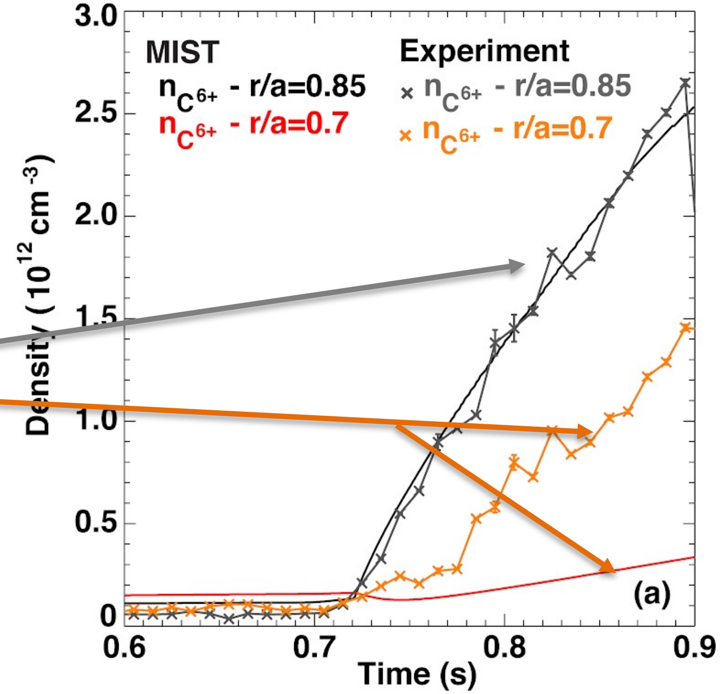
Impurity Profiles Following L-H Transitions Well Described by Neoclassical Transport Outside of r/a = 0.85

- **Carbon profiles following L-H transition on NSTX-U were compared with NEO modeling**

- **Experimental profile shape consistent with neoclassical estimates in the pedestal/steep gradient region (r/a > 0.85)**

NSTX-U

MIST simulation compared to measurement following L-H at r/a = 0.85 and 0.7



- **Impurity transport simulation (MIST) using neoclassical transport well described L-H carbon profile dynamics in pedestal region -**Consistent with [Putterich JNM 2011]

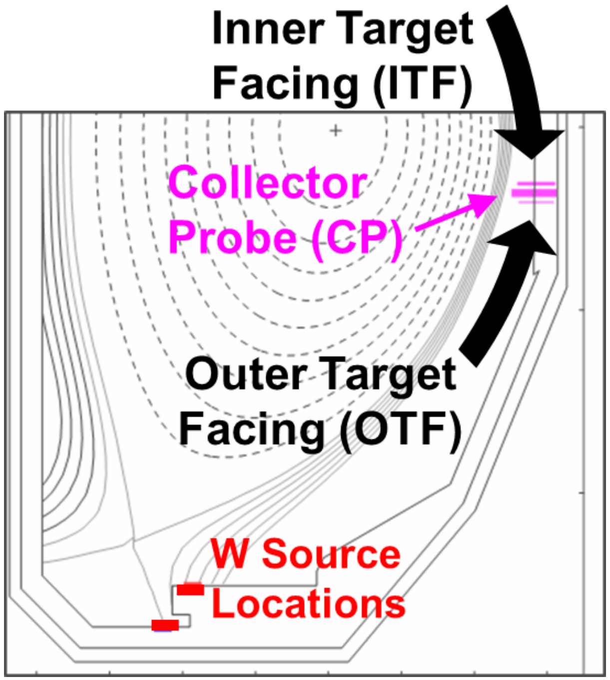
  - Larger diffusion appears needed inside pedestal top ; consistent with turbulent transport and observations from NSTX database

Control of impurities starts at the plasma edge by limiting impurity generation and transport to the pedestal

Can we understand and model impurity generation and transport in the SOL and divertor?

Collector Probe Experiments Point Towards Convective Transport in the Far-SOL and Provide Evidence of Near-SOL W Accumulation

- **Collector probe data obtained during DIII-D W rings campaign analyzed using 3DLIM.**
  - 3D, Monte Carlo, SOL code
- **Convective transport needed to reproduce W profiles on both the inner (ITF) and outer target facing (OTF) sides of collector probes**



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- **Near-SOL impurity accumulation required to reproduce measured ITF/OTF deposition >1**
  - Predicted for unfavorable-B_T drift direction only
  - Near- SOL accumulation unlikely for most projected reactor conditions

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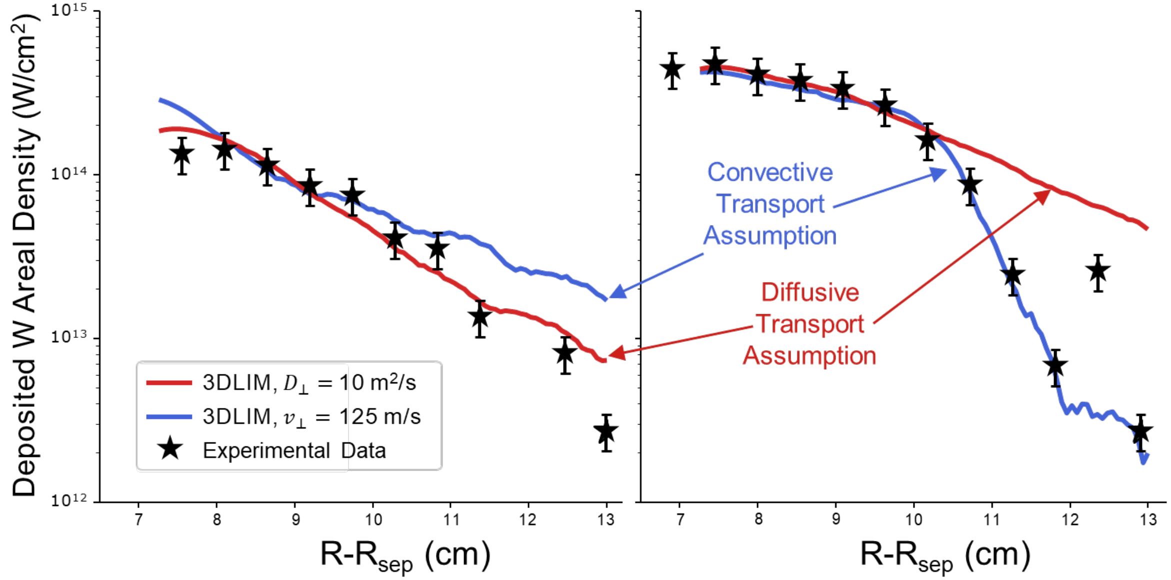
Calculated W deposition profiles on the midplane CP



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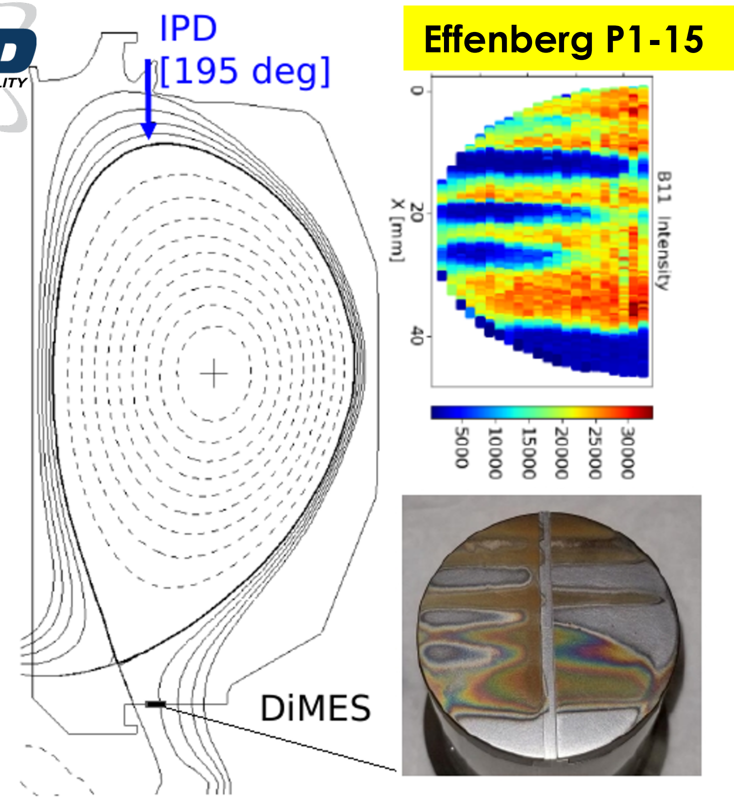
Real Time Conditioning Experiments Have Been Modeled with the 3D EMC3-EIRENE Fluid Code for the First Time

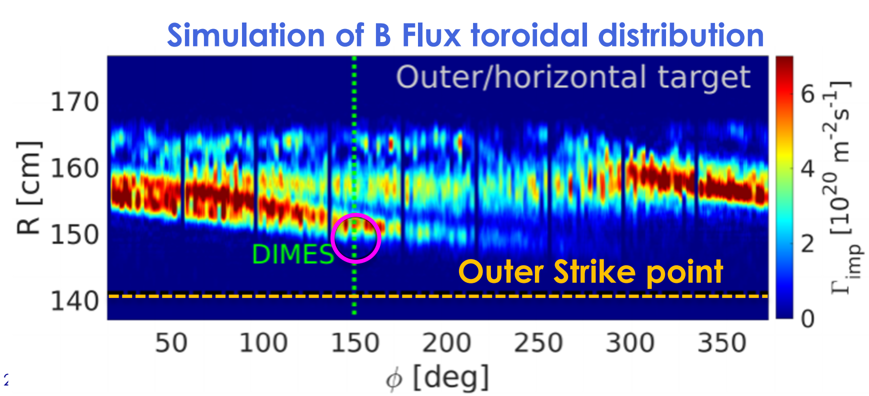
- **Boron powder dropper experiments demonstrated intra-shot wall conditioning**

- **DiMES probe revealed striations of boron deposition with 3D structure**

- **EMC3-EIRENE modeling indicates a localized boron source can lead to asymmetric boron flux at divertor**
  - Spatial scales incompatible with measurement
  - Error fields likely play a role

- **Simulation indicates competition between ∇T_i and SOL friction sets deposition into far SOL**
  - Low density conditions found to yield more uniform boron coatings



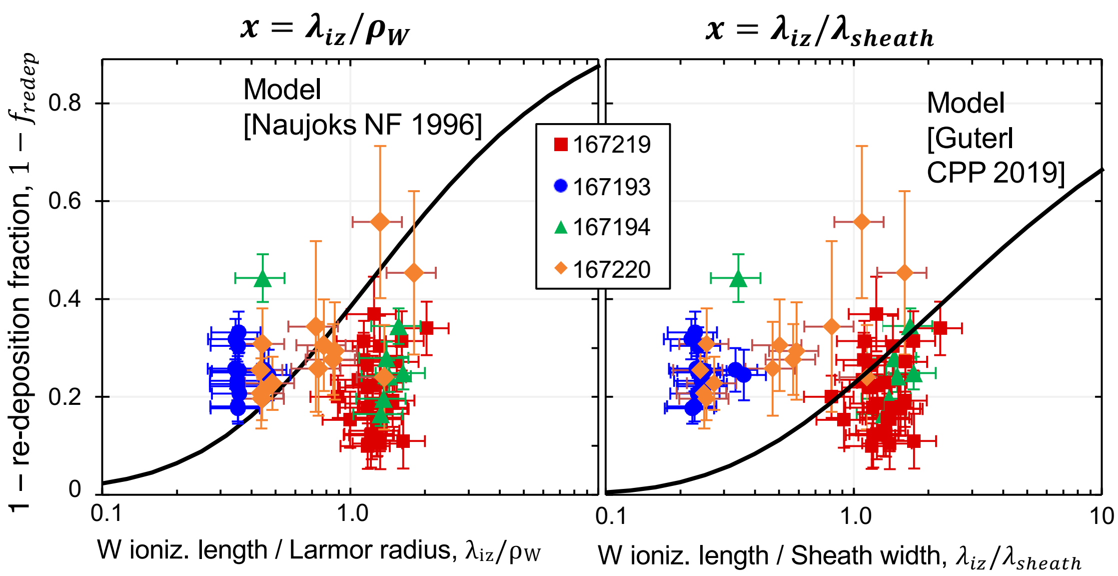


Charge States Higher Than W^{1+} Are Likely Important For Determination of W Redeposition

- **W re-deposition fractions inferred from ratio of WI to WII spectroscopy**
  - Models predict W redep. scales with ionization length normalized to W^+ Larmor radius, ρ_W[1] or width of magnetic sheath, λ_{sheath}[2]

[1]Naujoks NF 1996
[2]Guterl CPP 2019

- **Measured W re-deposition probabilities up to 90%**



- **For $\lambda_{iz} \sim \rho_W \sim \lambda_{sh}$: Sheath model more accurately accounts for W net erosion**
  - Consistent with W re-deposition dominated by sheath electrostatic fields
- **For $\lambda_{iz} \ll \rho_W, \lambda_{sh}$: measured W redep. is lower than predicted**
  - Charge states higher than W^{1+} are likely important (not measured)

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Coordinated Research Provided Insights Into Features of Low-to-High-Z Impurity Transport that Span Device and Operational Regime

- **Neoclassical transport determines impurity transport in the deep core with turbulence dictating outside of mid-radius**
  - All databases/modeling show > mid radius impurity peaking correlated with electron density
  - Modest ECH reduced core neo accum., independent of Z and/or confinement regime
- **Clear deviations from turbulent modeling, particularly in the direction of imp. pinch in the core**
  - Modeling generally more pessimistic (inward pinch) compared with measurements
  - Rotodiffusion found not to play a significant role in impurity pinch
  - Turbulent modeling in the ST core, unable to explain impurity peaking
- **Neoclassical transport describes impurity dynamics in the pedestal**
  - ELM recovery and L-H time histories explained on DIII-D and NSTX by neoclassical transport
- **3D modeling is able to qualitatively reproduce many features of SOL/ divertor impurity transport**
  - Evidence of near SOL W accumulation observed, only in unfavorable grad B direction, unlikely for reactor operation