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

Nathan Howard

on behalf of the 2020 JRT leaders:
Nathan Howard[1], Tyler Abrams[2], Filippo Scotti[3]

with additional input from:
B. Grierson[4], T. Odstrcil[2], F. Sciortino[1],
W. Guttenfelder[4], R.E. Bell[4], B. Victor[3], S. Haskey[4],
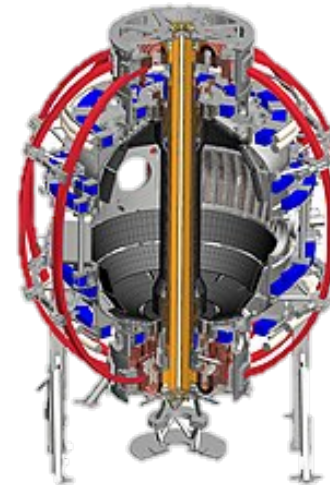J. Nichols[5], S. Zamperini[5], A. Bortolon[4], F. Effenberg[4]

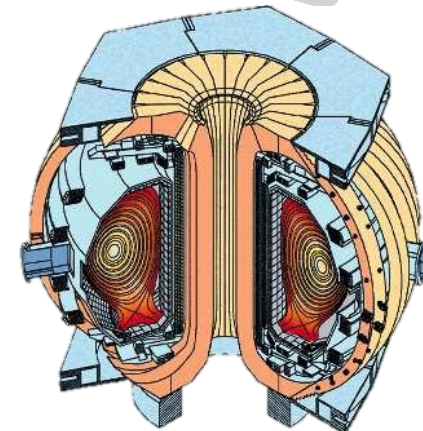[1]**Massachusetts Institute of Technology**
[2]**General Atomics**
[3]**Lawrence Livermore National Laboratory**
[4]**Princeton Plasma Physics Laboratory**
[5]**University of Tennessee – Knoxville**

N.T. Howard at IAEA-FEC 2021

- **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.

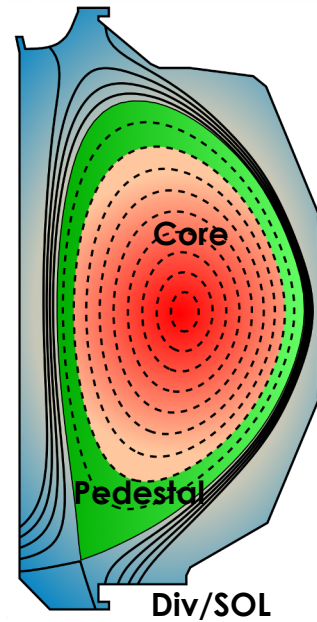 - Establish common features of impurity transport that span device and regime
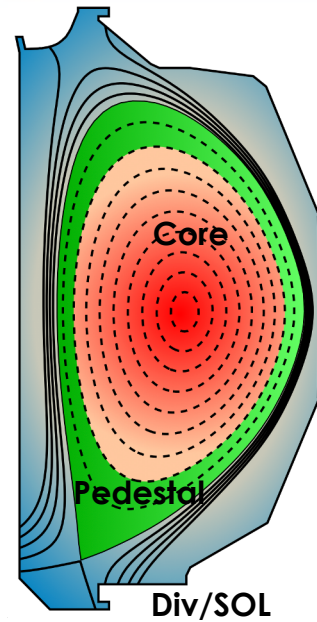

Core

Pedestal

Div/SOL

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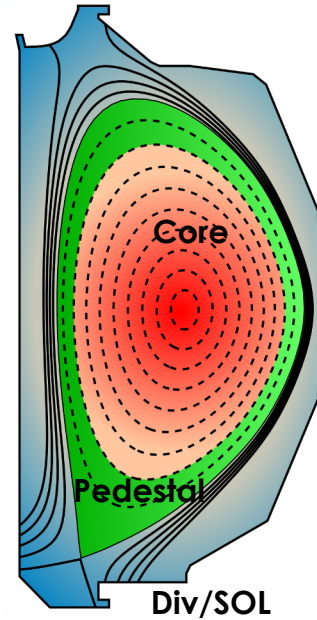

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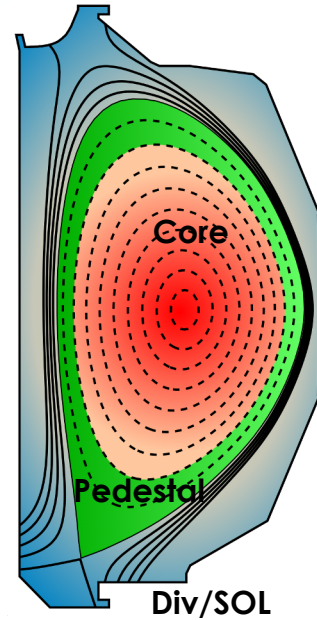 - Clear disagreements in inferred/modeled impurity pinch are common

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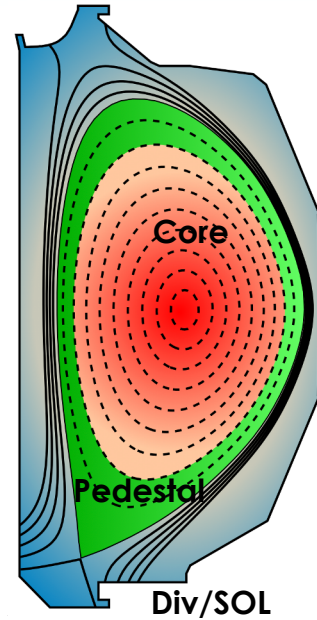

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- **3D Monte Carlo modeling in the SOL and divertor able to qualitatively reproduce measurements of impurity deposition and transport**

  - Evidence of near-SOL impurity accumulation


Core

Pedestal

Div/SOL

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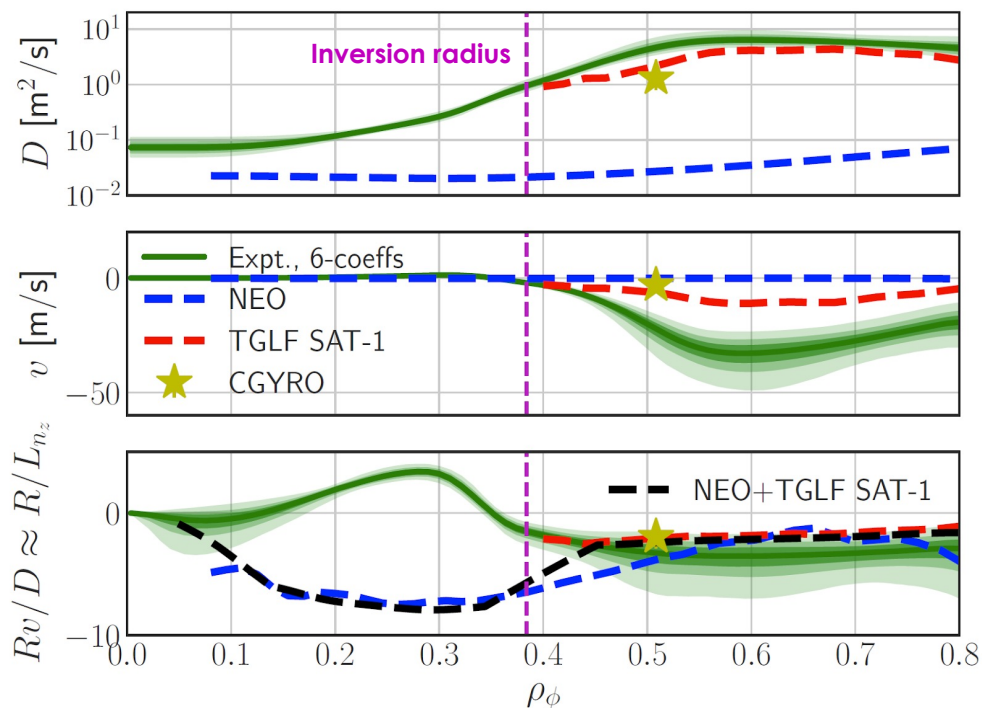
  - Disagreement with NEO modeling inside q=1
  - Convection discrepancy not resolved within uncertainties in inputs

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

Alcator C-Mod

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

NSTX

Guttenfelder OV/4-5Rb
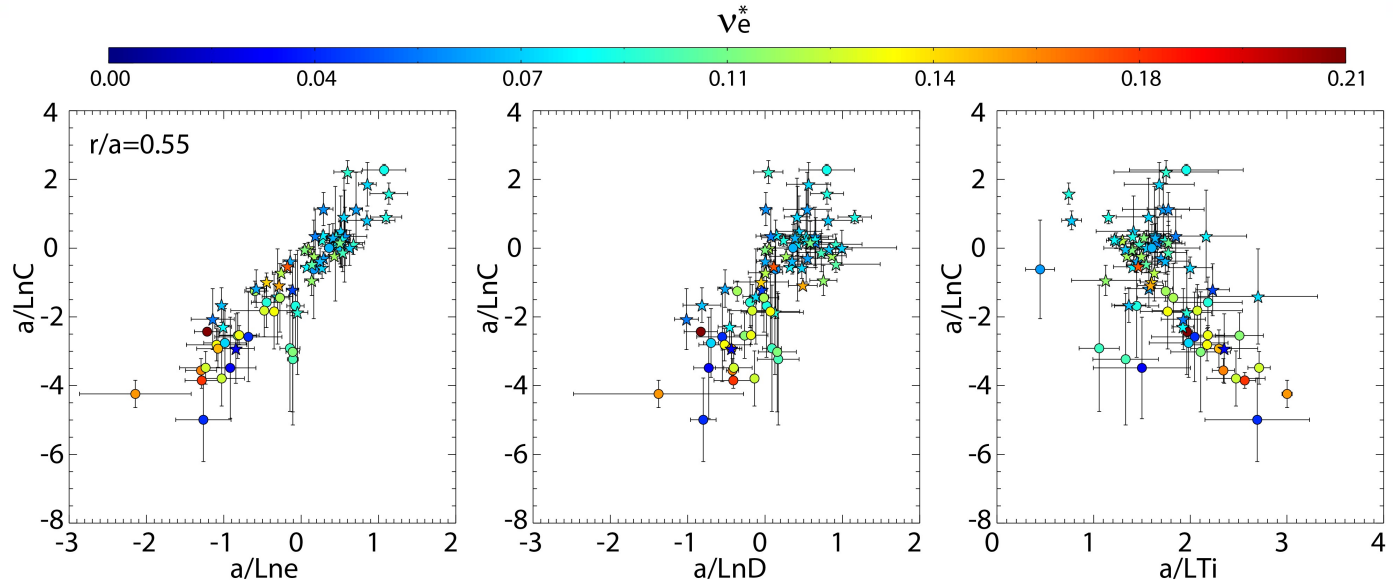
- **In an 66 discharge NSTX, H-mode database, C peaking correlated w/ n_e and n_D gradients, negatively with T_i**

  - **@ _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

- **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 υ', 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 υ' 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

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

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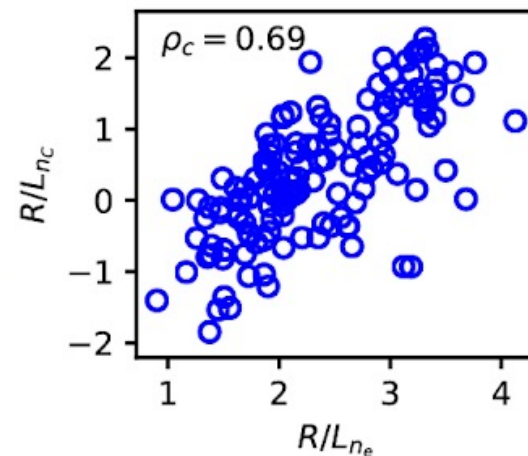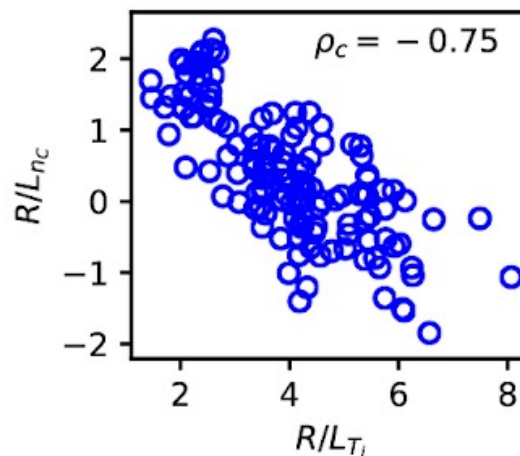
DIII–D
NATIONAL FUSION FACILITY

TEM Dominated
Rotation Scans

ITG Dominated
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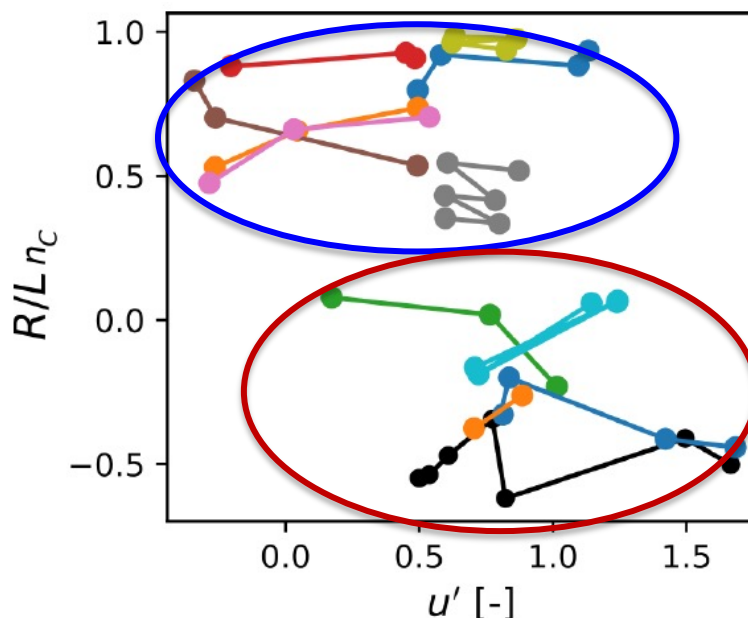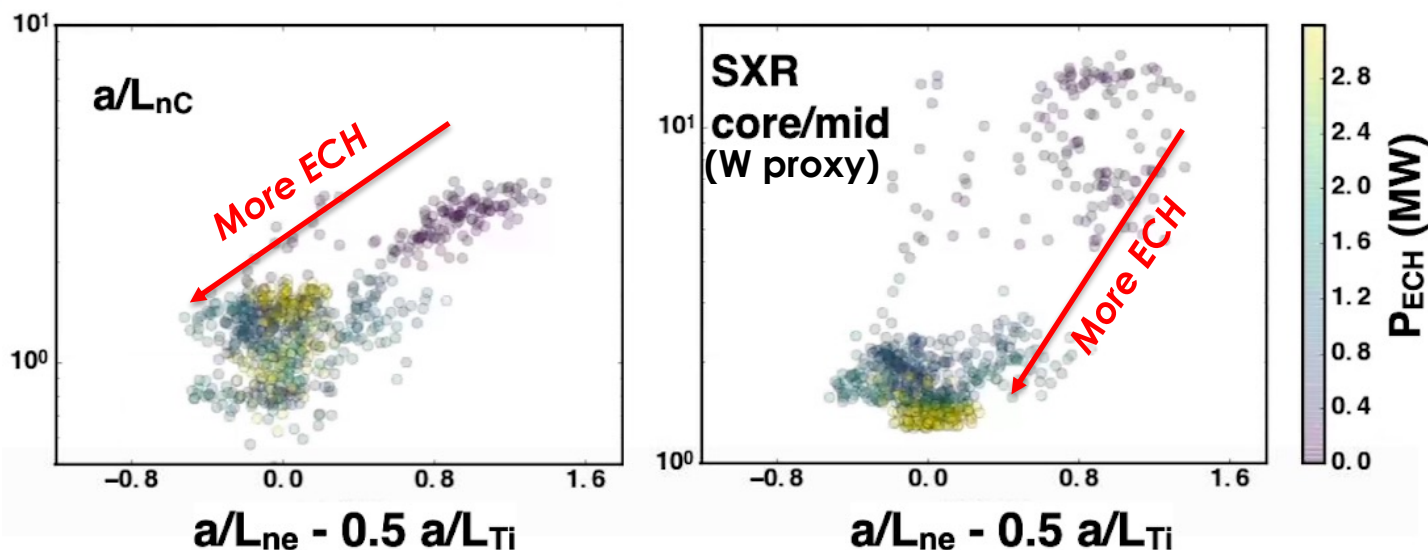 – Beam configurations allowed for decoupling of rotation and a/L_{Ti}

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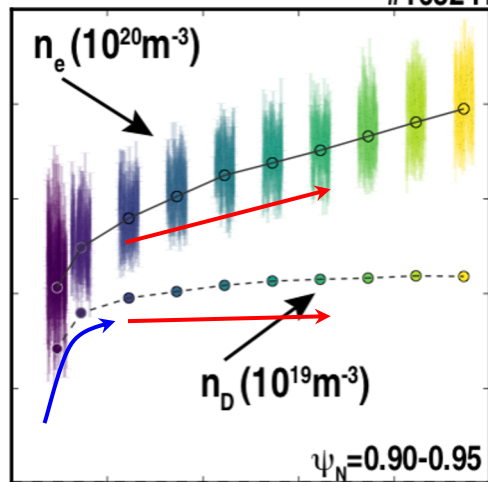
[1]Dux NF 2003
[2]Kallenbach NF 2009

In the absence of burning plasma conditions, impurities originate at the edge and move through the pedestal to the core
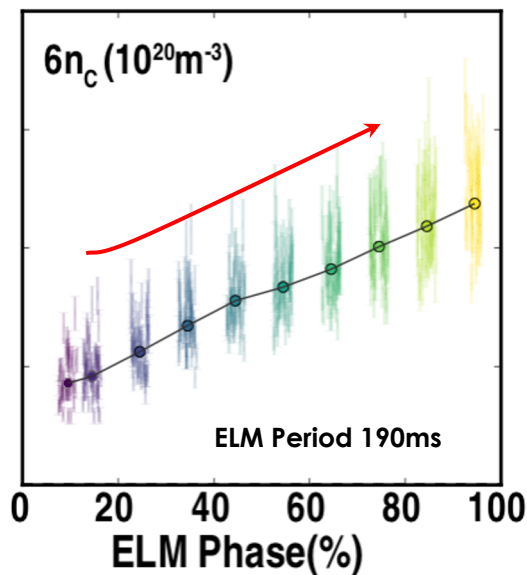
What mechanisms dictate impurity propagation through the pedestal?

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

#163241

n_e (10^{20} m^{-3})

n_D (10^{19} m^{-3})

ψ_N = 0.90-0.95

$6n_C$ (10^{20} m^{-3})

ELM Period 190ms

ELM Phase(%)

- **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]

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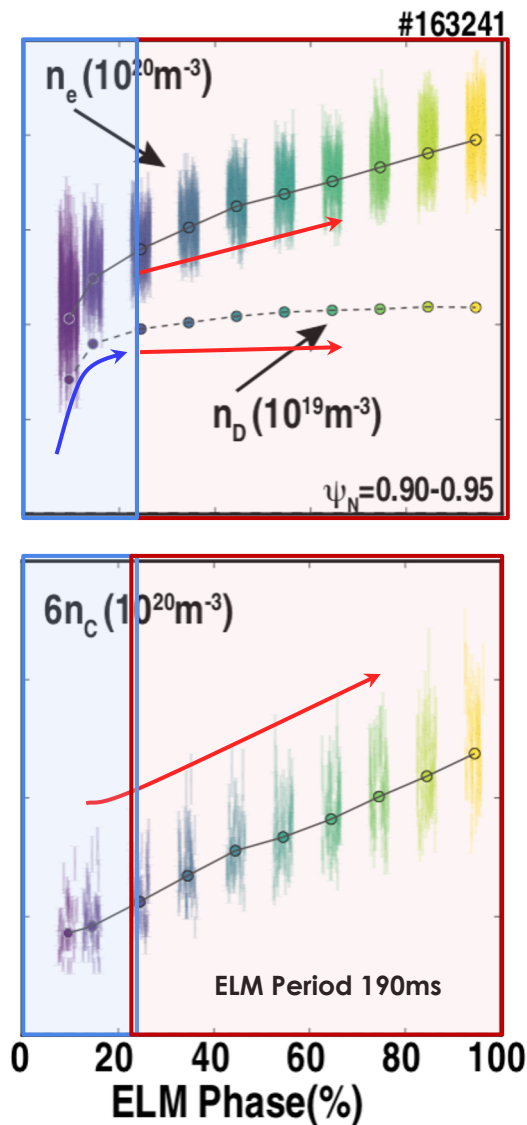$6n_C\ (10^{20}\mathrm{m}^{-3})$

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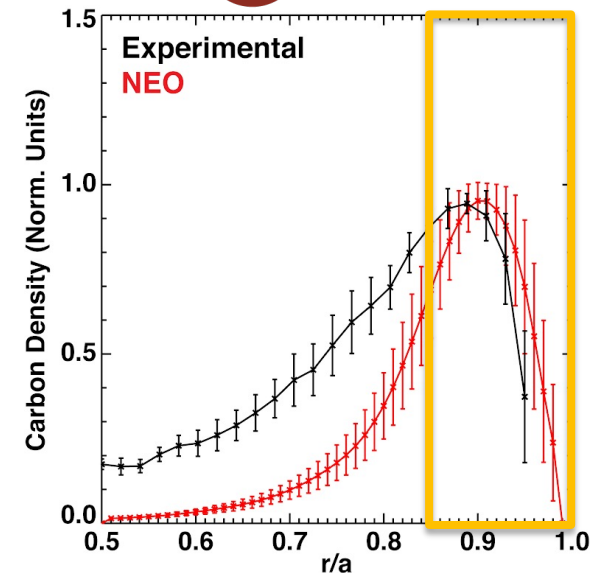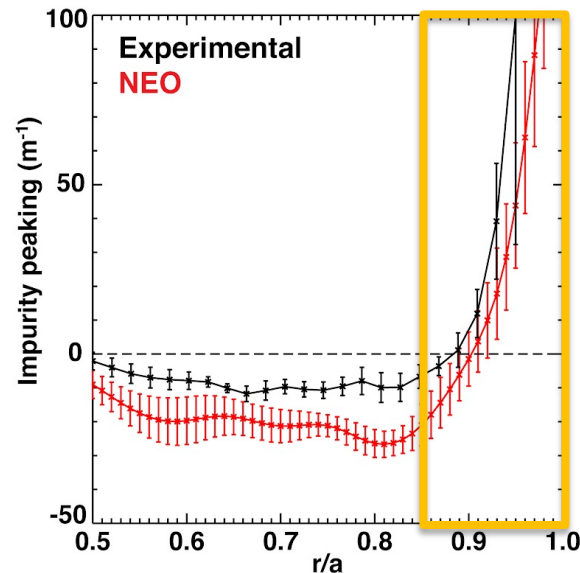
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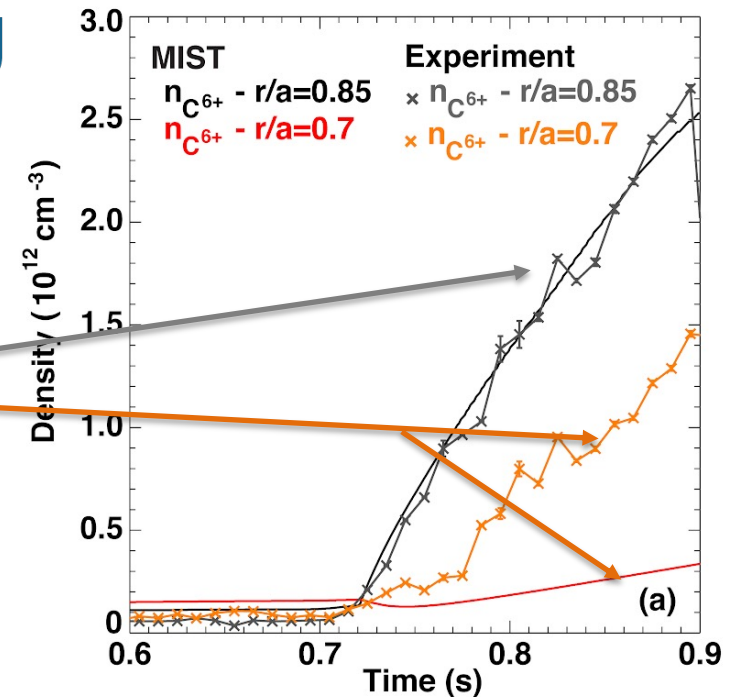# Impurity Profiles Following L-H Transitions Well Described by Neoclassical Transport Outside of r/a = 0.85

- **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)**

- **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

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

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Control of impurities starts at the plasma edge by limiting impurity generation and transport to the pedestal
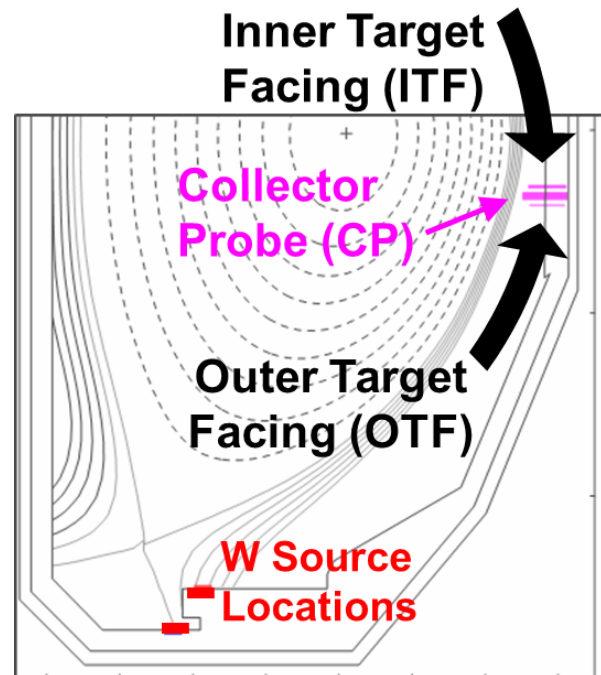
Can we understand and model impurity generation and transport in the SOL and divertor?

- **Collector probe 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**

Inner Target Facing (ITF)

Collector Probe (CP)

Outer Target Facing (OTF)

W Source Locations

S. Zamperini NME 2020

Abrams P1-660

- **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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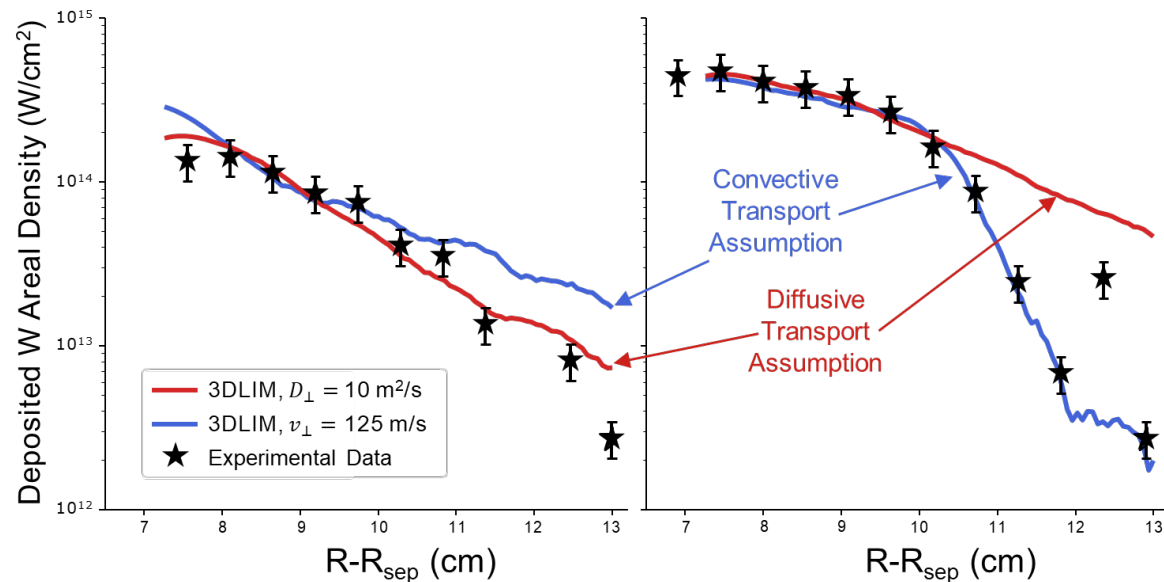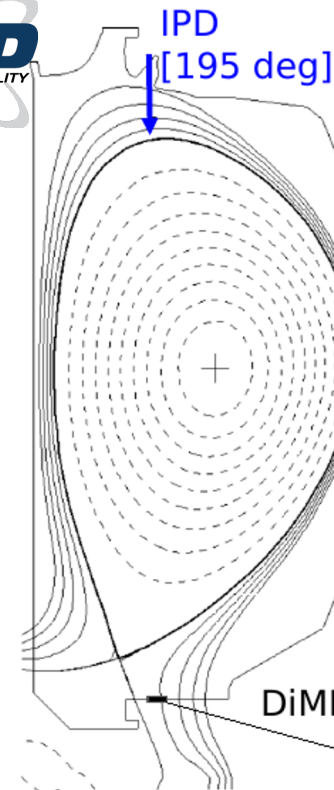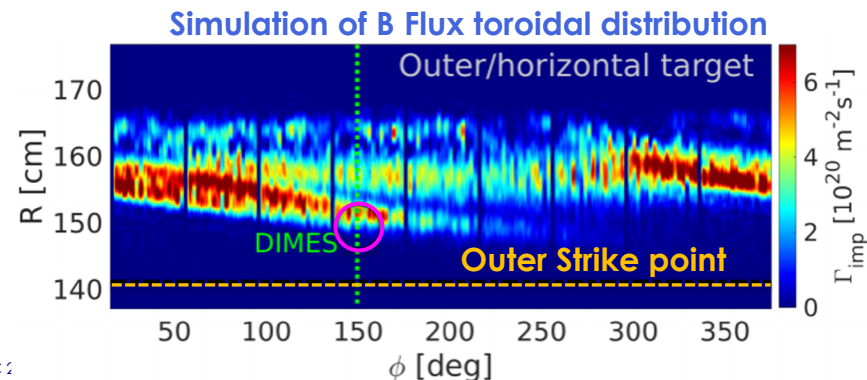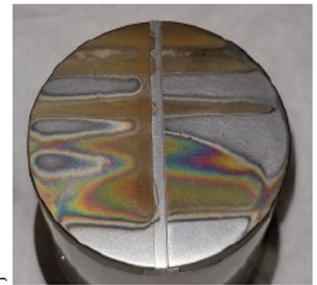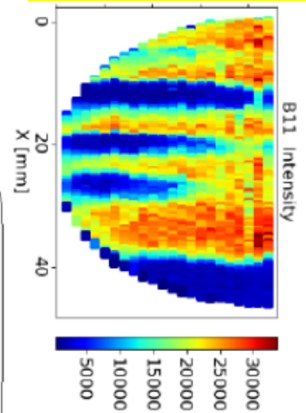 - Near- SOL accumulation unlikely for most projected reactor conditions

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**

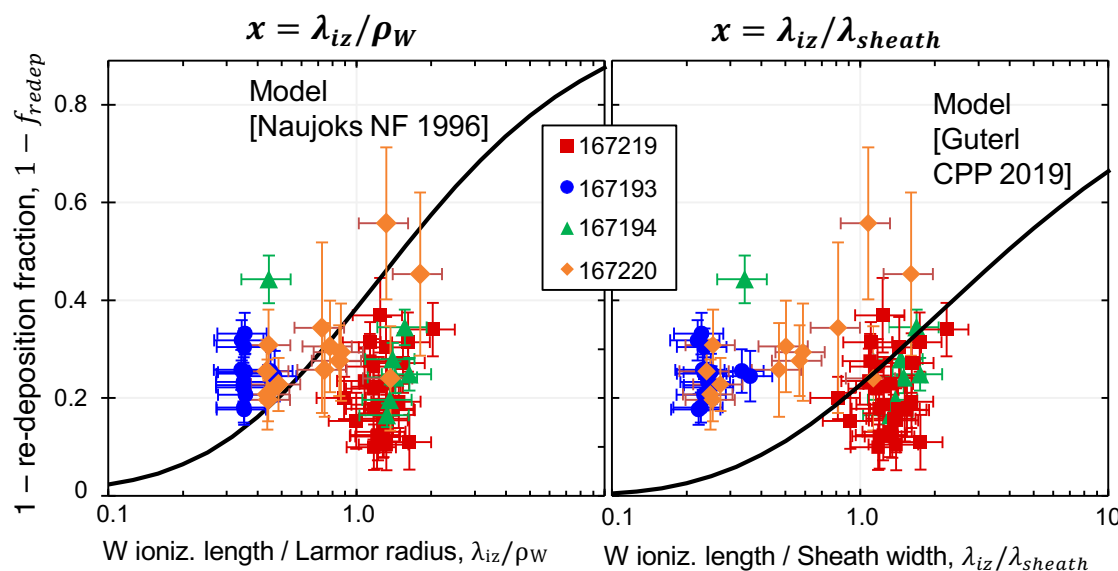 - Low density conditions found to yield more uniform boron coatings

DIII-D *NATIONAL FUSION FACILITY*

IPD [195 deg]

Effenberg P1-15

DiMES

Simulation of B Flux toroidal distribution

Outer/horizontal target

DIMES

Outer Strike point

- **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%**

$x = \lambda_{iz}/\rho_W$

$x = \lambda_{iz}/\lambda_{sheath}$

Model [Naujoks NF 1996]

Model [Guterl CPP 2019]

167219
167193
167194
167220

1 – re-deposition fraction, $1 - f_{redep}$

W ioniz. length / Larmor radius, λ_{iz}/ρ_W

W ioniz. length / Sheath width, $\lambda_{iz}/\lambda_{sheath}$

Abrams P1-660

- **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)

- **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

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- **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