Update on Impurity Transport in DIII-D

by

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PPPL

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DIII-D Impurity Transport Experiments Using Fluorine are Validating TGLF Transport Coefficients in Beam Heated H-mode Plasmas

- ELMing, RMP ELM-suppressed and QH-mode plasmas studied with fluorine (Z=9) injection
- Common theme:
  - Under-prediction of turbulent diffusion by TGLF \( \varrho > 0.5 \)
- Impact of core MHD appears to reduce diffusion

ELMing H-mode
RMP ELM-suppressed
QH-mode

\(^1\)B.A. Grierson et. al. Phys. Plasmas 22 (2015)
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\[ D > D^{TGLF} \]
\[ V \sim V^{TGLF} \]
V changes sign

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\[ D > D^\text{TGLF} \]
Core MHD reduces \( D \)

\[ V \sim V^\text{TGLF} \]
\( V \) changes sign

\[ \frac{V}{D} \]
4/3 NTM

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\[ D_{\text{DIII-D}} > D_{\text{TGLF}} \]
\[ V_{\text{DIII-D}} \approx V_{\text{TGLF}} \]
\[ V \text{ inward} \]

ELMing H-mode
RMP ELM-suppressed
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Direct Measurement of Impurity Transport Rate Requires Non-intrinsic, Non-recycling Species

- Intrinsic impurities have sources that are extremely difficult to quantify with high accuracy
  - Carbon walls, interaction in divertor, beam-ion losses (ctr-I_p injection), physical erosion
- Recycling impurities exit and re-enter the plasma if not pumped (He)
- Fluorine is fully-stripped for CER, non-intrinsic and highly reactive
  - Injected through 90% D_2, 10% CF_4 mixture
  - Purely decaying fluorine density after injection provides direct measurement of impurity confinement time, \( \tau_p \)
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STRAHL is Used to Determine Experimental Impurity Transport Coefficients

• F is fully stripped so we use STRAHL\textsuperscript{1} for nZ directly, not emissivity
  
  Could have integrated, propagated errors and fit\textsuperscript{2} but STRAHL is convenient for source parameters and forward modeling the theory-based D & V to overlay on experimental data

• Implementation of STRAHL in OMFIT\textsuperscript{3} now enabling routine analysis and higher-Z on DIII-D

\textsuperscript{1}R. Dux JPP 9/82 MPI (2007)
\textsuperscript{3}O. Meneghini Nucl. Fusion \textbf{55} (2015)
In RMP Plasma Impurity Influx is Most Rapid in Outer Regions of Plasma with Reduced Influx Inside of 4/3 Surface

- **STRAHL + Levenberg-Marquart minimization determines** $D$ and $V$ by least-squares

\[
\frac{\partial n}{\partial t} + \nabla \cdot \Gamma = S
\]

\[
\Gamma = -D \nabla n + V n
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\frac{\partial n}{\partial t} + \nabla \cdot \Gamma = S \\
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\]
Validation Procedure Requires TGYRO Simulations to Match Power Balance

- Both neoclassical transport and turbulence important for describing impurity behavior
  - Competing neoclassical processes of impurity peaking\(^1,2\) (\(\sim Z L_{\text{ni}}^{-1}\)) and temperature screening\(^1,3\) (\(\sim L_{\text{Ti}}^{-1}\))

- Turbulent fluxes have sensitive responses to gradients
  - Turbulent \(\Gamma\) depends on \(a/L_{\text{ne}}, a/L_{\text{Te}}, a/L_{\text{Ti}}\)
  - Motivates TGYRO\(^4\) simulations to match power-balance

- STRAHL\(^5\) used to extract experimental transport coefficients and forward model theory-based coefficients

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TGYRO Used to Match Power Balance and Identify Instabilities Before Computing D & V

- Profiles show generally good matching with TGLF+NEO
  - QH-mode poorer agreement in deep core $n_e$ and $a/L_Ti$ at $q=0.8$
- ITG dominant at outer radii

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TGLF Transport Coefficients Follow Linear Mode Trends with Hints of Neoclassical Screening

ITG region where $\gamma_i/k_y^2 > \gamma E \times B$ shows $D > D_{\text{TGLF}}$ and $V, V_{\text{TGLF}}$ strongly negative
TGLF Transport Coefficients Follow Linear Mode Trends with Hints of Neoclassical Screening

\[ Q_i \sim Q_i^{\text{NEO}} \]

Region with high \( E \times B \) shear shows positive convection zone

Intrinsic carbon also shows localized hollowing

B.A. Grierson / ITPA T&C / Mar 2016
Simulated Fluorine Density with NEO+TGLF Transport Coefficients Exposes the Discrepancy Between the Model and Observations

- Outer channels observe fluorine more quickly than simulation
  - Inward pinch-diffusion more rapid than TGLF
- Inner radii channels observe fluorine more slowly and with a longer near-axis confinement
  - Experimental D smaller or V more positive than NEO+TGLF
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Recent DIII-D Experiments Have Used Active Tracking and NTM Suppression to Determine Impact on Impurity Transport

- Hybrid scenario is key element in advanced operating regimes proposed for ITER
  - JET studies indicate hybrid scenario undergoes catastrophic impurity accumulation with core tearing mode \(^1\)
- Impurity transport with He, F, Ar being studied with controllable levels of MHD

\(^1\)Angioni, C. Nucl. Fusion (2015)
Recent DIII-D Experiments Have Used Active Tracking and NTM Suppression to Determine Impact on Impurity Transport

- Conditions acquired in Jan 2015 Run Campaign:
  - Natural hybrid
  - ECCD NTM Suppression
  - ECH
- Analysis of transport coefficients and Z-scaling in progress
Argon Impurity Transport In Hybrid Regime Benefits from Central ECH compared to Natural Hybrid or NTM-suppressed

- Central SXR emission used as indicator, CER Ar$^{+16}$ profile also measured
- Faster rise and expulsion with ECH indicates strong diffusion (good)
- Intrinsic Carbon peaking correlates with $a/Ln$
- STRAHL+TGLF validation in progress to model profile and impurity transport response in hybrid
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Conclusions

• Fluorine impurity transport coefficients show generally high D than TGLF in outer radii, V has the right sign and magnitude.

• When $Q_i \sim Q_i^{\text{NEO}}$ see effects of screening on both fluorine V/D and intrinsic carbon V/D.

• Analysis of existing data in hybrid scenario will test impact of MHD and electron heating on He, F, Ar.

  - Recent W injections and installation of W tiles on DIII-D permitting high-Z studies.