Transport Studies of L—Mode Edge Radiating Mantle Discharges with Confinement Improvement in DIII—D

by

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Transport Studies of L-mode Edge Radiating Mantle Discharges with Confinement Improvement in DIII-D

M. Murakami, M.R. Wade, Oak Ridge National Laboratory, T.E. Evans, G.L. Jackson, H.E. St. John, G.M. Staebler, General Atomics, J.E. Kinsey, Lehigh University, G.R. McKee, University of Wisconsin, AND THE DIII-D TEAM — Significant confinement improvements are observed with impurity injection into L-mode-edge beam-heated discharges in DIII-D. The global energy confinement increased by a factor of up to 2, with an increasing quantity of injected impurity. Neon injection produced the strongest effect in the plasma, compared with argon and krypton. Reduction of observed turbulence is correlated well with the confinement improvement. Transport coefficients decreased in all transport channels, with ion thermal diffusivity reduced to near neoclassical values. Both gyro-kinetic and gyro-fluid simulations with $E \times B$ shearing indicate that the turbulence linear stability growth rate is reduced for ion temperature gradient turbulence as a result of the impurity density gradient and dilution effects on main ion turbulence and the $E \times B$ shear suppression.

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Prefer Oral Session

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Special instructions: DIII-D Contributed Oral Session, immediately following GL Jackson
OUTLINE

OBJECTIVES: Understand the mechanism for confinement improvement with impurity injection

EXPERIMENT:
- Observed a substantial confinement improvement (up to factor of 2) with impurity injection into L-mode discharges
- Assessed effects of impurity quantity and species (Ne, Ar, Kr) on observed improvement

ANALYSES:
- Improvement correlated with strong reduction of turbulence
- Transport analysis using TRANSP shows all transport channels improve
- Gyro-kinetic analysis and simulations show that the confinement improvement is due to:
  - Reduction of micro-turbulence (ITG/TEM) growth rate
  - ExB shearing suppression
Early NBI $\Rightarrow q_{\text{min}} > 1$ to avoid sawtooth

- Ne, Ar, Kr (recycling gas) injected at 0.8 s and 1.2 s, quantity varied
- Run reference discharges with similar control parameters except no impurity puffed
NEON INJECTION PRODUCES MORE PEAKED DENSITY PROFILES, AND HIGHER AND BROADER $T_i$ AND $T_e$ PROFILES

Density peaking factor:

\[ \frac{n_e(0)}{\langle n_e \rangle} = 1.2 \implies 1.5 \]
TRANSP ANALYSIS SHOWS THE INCREASE IN NEUTRONS WITH NEON INJECTION IS PRIMARILY DUE TO INCREASING THERMAL NEUTRONS

- $Z_{eff}$ profile is determined from CER of carbon and neon
- Carbon density decreases promptly at neon puffing
- $Z_{eff}$ increases from 1.5 (ref.) to 3.4 (full neon)
  \Rightarrow $n_{Ne}/n_e < 3\%$
ION THERMAL DIFFUSIVITY DECREASES STRONGLY WITH NEON INJECTION

- \( (3/2)T_i \nabla n_i \) is used for the convection loss
  - The error bars: \( \alpha = 0 - 5/2 \) in \( \alpha T_i \nabla n_i \)
- \( \chi_i \) is reduced to the neoclassical level throughout the profile
REDUCTION OF ELECTRON THERMAL DIFFUSIVITY IS MODEST

\[ \frac{3}{2} T_e \nabla n_e \] is used for the convective loss

[ the error bars: 0 - 5/2 in \( \alpha T_e \nabla n_e \) ]
IMPURITY SPECIES SCAN WITH A FIXED $P_{\text{rad}}/P_{\text{in}}$ SHOWS THAT ALL TRANSPORT CHANNELS IMPROVE WITH IMPURITY INJECTION, BUT ARGON RESPONDES SLOWER THAN NEON

- $P_{\text{rad}}/P_{\text{in}} \approx 75\%$ (fixed)
- Krypton injection - similar behavior but more modest transport reduction
- Impurity fraction decreases faster than atomic mass increases
CONFINEMENT IMPROVEMENT IS CORRELATED WITH STRONG REDUCTION OF TURBULENCE WITH IMPURITY INJECTION

- BES measures density fluctuations \((k < 3 \, \text{cm}^{-1})\) at \(\rho = 0.68\)

- Reduction of turbulence is also observed by FIR scattering and reciprocating probe

G. McKee: BI2.06
GKS calculations show that ITG and TEM growth rates are significantly reduced in long wavelength region.

- ExB shearing rate increases with neon, further suppressing turbulence:
  \[ \frac{\gamma_{\text{in}}}{\omega_{\text{ExB}}} \approx 2.5 \Rightarrow i/2 \]

- Confirmed by the FULL code with \( E_r \) [G. Rewoldt]
  - ITG/TEM growth rate reduced substantially with neon injection
  - Inclusion of \( E_r \) effect completely stabilizes the instabilities
GLF23 simulation shows that both growth rate reduction and ExB shearing are needed to explain the observed confinement improvement.

- GLF23 model includes both toroidal drift wave turbulence and ExB shear effects on all transport coefficients.
- GLF23 simulation to solve $V_\phi$, $T_i$, and $T_e$ equations self-consistently to the equilibrium with the fixed experimental $n_e(\rho)$ and boundary conditions at $\rho=0.8$.
- Two simulations are shown:
  - Experimental $Z_{\text{eff}}(\rho)$
  - $Z_{\text{eff}} = 1.5$ with carbon

Waltz et al: Plasma Phys. 97
CONCLUSIONS

- Significant confinement improvements are observed with impurity (Ne, Ar, Kr) into L-mode edge plasmas -- Robust and reproducible:
  - Higher stored energy by factor of 2
  - Higher and broader $T_i$ and $T_e$ profiles
  - Higher and more peaked density profiles
- Neon produces strongest effect in the plasma, compared with Ar, Kr
- Reduction of turbulence is correlated well with the confinement improvement
- Improvements with impurity injection are observed in all transport channels:
  - Ion thermal channel -- most significant
  - Electron channel -- modest
- Both gyro-kinetic analysis and simulations indicate that the transport reductions are due to both:
  - Reduction of low-k (ion) turbulence as a result of impurity density gradient effects on main ion turbulence
  - ExB shear suppression

FUTURE DIRECTIONS

Exploit impurity injection as AT tool
Test theory-based models (ITB dynamics)