Physics of Confinement Improvement of Plasmas with Impurity Injection in DIII–D

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18th IAEA Fusion Energy Conference Sorrento, Italy

October 7, 2000
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INTRODUCTION

- Confinement improvement in discharges with impurity seeding have been observed in a number of tokamaks:
  - ISX-B (Z-mode)
  - TEXTOR-94 (RI-mode)
  - TFTR, ASDEX, DIII-D, JET, ...

- In the present DIII-D experiment, injection of noble gas (Ne, Ar, Kr) into L-mode edge discharges has produced:
  - Clear confinement improvement ($\approx 2$)
  - Transport reduction in all transport channels ($\chi_i$ by $\times 5$)
  - Simultaneous reduction in long-wavelength turbulence

- These observations provide opportunities to test understanding of theory-based transport models
  - Gyro-kinetic analysis
    ⇒ Synergistic effects of impurity-induced reduction of toroidal drift wave turbulence and ExB shearing suppression
  - Theory-based transport modeling (GLF23)

- Impurity seeding is also a useful tool for:
  - Reduction of heat flux to plasma facing components
  - L-mode edge with improved confinement
  - Internal Transport Barrier control – [E. Doyle: EX6/2]
  - H-mode edge stability control
USN with L-mode edge
- 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 HIGHER AND BROADER $T_i$ AND $T_e$ PROFILES, AND MORE PEAKED DENSITY PROFILES

- Density peaking factor: $n_e(0)/\langle n_e \rangle = 1.2 \Rightarrow 1.5$
- Charge Exchange Recombination spectroscopy, showing $n_{Ne}/n_e < 2.2\%$
CONFINEMENT IMPROVEMENT IS CORRELATED WITH STRONG REDUCTION OF TURBULENCE WITH IMPURITY INJECTION

- BES measures density fluctuations ($k_\theta \rho_s < 0.6$) at $\rho = 0.68$

- Reduction of turbulence is also observed by FIR scattering
- Reciprocating probe observed reduction of particle flux $\Gamma \sim \langle \tilde{n}\phi \rangle$ at edge
TRANSP ANALYSIS SHOWS THAT ION THERMAL DIFFUSIVITY DECREASES STRONGLY WITH NEON INJECTION

- $\chi_i(\rho)$ is reduced throughout the profile to the neoclassical level
NEON INJECTION REDUCES TURBULENCE GROWTH RATES AND INCREASES ExB SHEARING RATE

- Gyro-Kinetic Stability (GKS) code is used to calculate linear growth rates based on experimental profiles
- Growth rates (primarily ITG) reduced by main ion dilution, direct mode stabilization with impurities and profile effects
- ExB shearing rate is calculated from radial electric field based on measured $V_\phi$, $V_\theta$, and $\rho_i$ of carbon impurity
- Criteria for stabilization: $|\omega_{\text{ExB}}| > \gamma_{\text{max}}$
The initial drop in \( \gamma_{\text{max}} \) triggers the rise of \( \omega_{\text{ExB}} \) with neon injection.

ExB shear suppression is clearly established in the latter phase.
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PROMPT LOCAL TRANSPORT REDUCTION AND LOW-k TURBULENCE SUPPRESSION RESULTS FROM AN INCREASING ROTATION GRADIENT ENHANCING THE $\text{ExB}$ SHEARING

- Some density peaking $\Rightarrow$ Only modest effect on $\gamma_{\text{max}}$
- Rapid change in $V_{\phi}$ $\Rightarrow$ Increase in $\nabla V_{\phi}$ $\Rightarrow$ Increase in $\omega_{\text{ExB}}$ $\Rightarrow$ reduce low-k fluctuations
DIRECT IMPURITY EFFECTS ACT SYNERGISTICALLY WITH THE ExB SHEARING SUPPRESSION

Impurity injection → Reduction of turbulence growth rate

Plasma profile modifications → ExB shear suppression

Increasing rotation & pressure and their gradients → Reduced turbulence

Reduced transport → Reduced turbulence ($\omega_{\text{ExB}} > \gamma_{\text{lin}}$)
PLASMA PROFILES ALSO EVOLVE, HELPING TURBULENCE STABILIZATION

Can we separate these three effects?

- Direct impurity effects for \( \gamma_{\text{max}} \)
- ExB shear suppression
- Other profile evolutions
ROLES OF DIRECT IMPURITY EFFECTS AND ExB SHEAR SUPPRESSION ARE Explored WITH A THEORY-BASED TRANSPORT MODEL

- Gyro-Landau Fluid (GLF23) model allows to study both effects on transport
  [R. Waltz et al.: Phys. Plasmas ‘97]
- The GLF23 model was carried out using a time-dependent transport code, NTCC Demonstration Code
- The National Transport Code Collaboration (NTCC) project is to develop:
  — Library of transport code modules
  — Web-invokable data server and demonstration code
- DIII-D Neon shots have been selected as the principal test case for the NTCC Demonstration Code
- The code solves $T_i$ and $T_e$ equations with inputs of:
  - $n_e(\rho,t)$ and $V_\phi(\rho,t)$
  - Time-dependent sources, sinks and equilibria from TRANSP
INCREASE IN ExB SHEARING RATE IS A NECESSARY CONDITION FOR CONFINEMENT IMPROVEMENT

Simulations are used to test:

- Effects of ExB shearing from experimental $\omega_{ExB}$ to 0
- Effects of changing $Z_{eff}$ (3.2 → 1.4) and $n_e(\rho)$ after the improved state is established

⇒ Neon injection may be used as a trigger
CONCLUSIONS

• External impurity injection in L–mode edge discharges in DIII–D produced:
  — Clear confinement improvement ($\times 2$ in $\tau_E$ and $S_n$)
  — Reduction in all transport channels ($\chi_i$ to neoclassical)
  — Simultaneous reduction of long-wavelength turbulence

• Reduction in fluctuations and ion thermal transport is attributed to two impurity-induced effects working synergistically: reduction of toroidal drift wave turbulence and ExB shear suppression

• Impurity injection is observed to trigger reduction of long-wavelength turbulence by increasing the gradient of toroidal rotation which enhances ExB flow shear

• Time-dependent simulations with GLF23 model show the dominant role of ExB shearing and a possibility of using impurity injection as a trigger
  — Remove impurity source after obtaining confinement improvement