MECHANISMS FOR REDUCTION OF ION TRANSPORT AND TURBULENCE WITH IMPURITY INJECTION IN DIII-D


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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 ($\times 2$)
  - 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
    $\Rightarrow$ 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
  - H-mode edge stability control
IMPURITY INJECTION SIGNIFICANTLY IMPROVES CONFINEMENT PARAMETERS

- 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 \( (k_0 \rho_s < 0.6) \) 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

\[ \chi_i(\rho = 0.66) \]

- \( \chi_i(\rho) \) 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.
  \[ \gamma_{\text{max}} < |\omega_{E \times B}| \]

- 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 \( \rho \) of carbon impurity.

- Criteria for stabilization: \( |\omega_{E \times B}| > \gamma_{\text{max}} \)
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- Criteria for stabilization: $|\omega_{ExB}| > \gamma_{\text{max}}$
PROMPT LOCAL TRANSPORT REDUCTION AND LOW-k TURBULENCE SUPPRESSION RESULTS FROM AN INCREASING ROTATION GRADIENT ENHANCING THE ExB SHEARING

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

Impurity injection

Reduction of turbulence growth rate

ExB shear suppression

Reduced turbulence \( (\omega_{\text{ExB}} > \gamma_{\text{lin}}) \)

Reduced transport

Increasing rotation & pressure and their gradients

Plasma profile modifications

Reduced turbulence growth rate

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 Demo 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 solved Ti and Te equations with inputs of:
  - \( n_e(\rho,t) \) and \( V_\phi(\rho,t) \)
  - Time-dependent sources, sinks, and equilibria from TRANSPI
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

$\Rightarrow$ Neon injection may be used as a trigger
ADDITIONAL EXPERIMENTS WITH SEVERAL DIFFERENT CONFIGURATIONS EXTENDED OUR UNDERSTANDING OF THE MECHANISMS

- **High-k fluctuation/electron transport correlation**
  - FIR high-k fluctuation measurement:
    - Bursting fluctuations with neon injection and correlation of the average fluctuation levels with $\chi_e$
    - Uncertainty of the fluctuation source exists because of the lack of a large $E \times B$ Doppler shift in the fluctuation spectrum

- **Divertor pumping effects**
  - Initial experiments with a divertor pumping geometry at higher $B_T$ (2.0 T) $\Rightarrow$ Smaller improvement than that at lower $B_T$ (1.6T)
    - Lower neon content found in the core
    - Larger neon puff and reduced neon pumping geometry have produced $\tau_E$ as good as that at 1.6 T

- **Impurity species (Ne, Ar, Kr) scan**
  - Ar and Kr injection can improve the confinement, but Ne is still the best
  - Radiative loss fraction limit precludes mass density increase for stabilization with higher Z under DIII-D conditions

- **Neon injection into a circular, inner-limited discharge**

- **q-scan / $B_T$ scan at constant ($\approx$ maximum) neon injection**
ARGON AND KRYPTON INJECTION CAN ALSO IMPROVE CONFINEMENT, BUT PLASMA RESPONSE IS 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
  - Neon is best theoretically
NEON INJECTION INTO A CIRCULAR, INNER-WALL LIMITED DISCHARGE EXHIBITS SAME FEATURE AS THAT IN A DIVERTED DISCHARGE, IMPLYING THE SAME PHYSICAL MECHANISM IS AT WORK

- Improvement persists during sawtooth phase
- The turbulence suppression mechanism (reduced $\gamma_{\text{max}}$ and increased $\omega_{\text{ExB}}$) appears to be at work:
  
<table>
<thead>
<tr>
<th></th>
<th>Neon</th>
<th>Reference</th>
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<tbody>
<tr>
<td>$\gamma_{\text{max}}$</td>
<td>0.19</td>
<td>0.43</td>
</tr>
<tr>
<td>$\omega_{\text{ExB}}$</td>
<td>0.57</td>
<td>0.51</td>
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- Density peaking factor with neon is even lower than no neon

$\Rightarrow$ Density peaking is not a necessary condition for confinement improvement
STRONG NEON INJECTION REDUCES BOTH LONG-WAVELENGTH TURBULENCE AND ION TRANSPORT TO THE MINIMUM LEVELS

- $B_T$ and $q_{95}$ scans with injection of a fixed (~maximum) quantity of neon
- $\chi_i$ with strong neon injection reaches neoclassical levels almost regardless the initial conditions
- Reduction of the fluctuation reaches near diagnostic detection level
- The overall performance with neon is determined by other parameters
MAGNETIC BRAKING EXPERIMENT SHOWED AN IMPORTANT ROLE OF ExB SHEARING IN IMPROVED CONFINEMENT WITH NEON INJECTION

[D.R. Ernst: MO1.9]
CONCLUSIONS

- External impurity injection in L-mode edge discharges in DIII-D produced:
  - Clear confinement improvement ($\times2$ 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 $E\times B$ shear suppression
- Impurity injection is observed to trigger reduction of long-wavelength turbulence by increasing the gradient of toroidal rotation which enhances $E\times B$ flow shear
- Time-dependent simulations with GLF23 model show the dominant role of $E\times B$ shearing and a possibility of using impurity injection as a trigger
  - Remove impurity source after obtaining confinement improvement
- Impurity species scan shows the neon producing the largest effect
- Neon injection into a circular, inner-limited discharge show similar characteristics, indicating common physics mechanisms with the above
- $B_T$ and $q$ scan with neon injection, showing ion transport approaching the neoclassical level
- Theory-based transport simulations (GLF23) and a magnetic braking experiment show the important role of $E\times B$ shearing suppression