Effects of Main Ion Dilution on Turbulence and Transport in Alcator C-Mod and Comparisons With Gyrokinetic Simulations

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Ohmic Plasmas Exhibit a Characteristic Scaling Where $\tau_e$ Increases up to a Critical Density After Which it Saturates

- At low densities, $\tau_e$ scales linearly with $n_e$ (the LOC Regime)

- At a critical density, $\tau_e$ becomes independent of $n_e$ (the SOC Regime)

- Many attempts have been made to reproduce this trend in $\tau_e$ with gyrokinetic simulations of core energy transport
Ion Transport in Ohmic Plasmas Was Over-Predicted by Gyrokinetic Codes Unless it was Reduced by Main Ion Dilution

- Recent measurements show $Z = 8$ to be a good assumption for C-mod ohmic plasmas.
- No change with $Z_{\text{eff}}$ was observed if Mo ($Z \sim 30$) was the impurity.

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Experiments were Performed to Test the Dilution Effect by Seeding Nitrogen (Z=7) into Ohmic Plasmas

- Ohmic plasmas at various densities across the LOC-SOC transition were seeded with nitrogen.
- A cryopump kept the density constant during the seeding.
- The experiments succeeded in making nitrogen the dominant impurity.
Nitrogen Seeding Decreased Ion Energy Diffusivity, Consistent with Predictions Made by TGLF

- Diffusivities were calculated by TRANSP
- Electron diffusivity increased only slightly
- Seeding increased dilution by 10-15%
\( \nabla T_i \) increased during seeding, which offsets dilution reduction of linear ITG drive.

Unseeded LOC, \( r/a = 0.7 \)
\( Z_{\text{eff}} = 2.2, \frac{n_D}{n_e} = 86\% \)

Seeded LOC, \( r/a = 0.7 \)
\( Z_{\text{eff}} = 2.7, \frac{n_D}{n_e} = 76\% \)
Global GYRO Simulations Show a Significant Decrease in Energy Flux after Seeding Despite Increase in Ti Gradient
TGYRO with TGLF Shows that Globally Matching Flux Requires Unrealistic Ti Profile Modification

Unseeded LOC

Seeded LOC

Te (keV) vs. r/a for Unseeded LOC and Seeded LOC.
Ohmic Plasmas In C-Mod Exhibit a Characteristic Rotation Reversal When Crossing the LOC – SOC Critical Density

\[ n_e = 0.65 \times 10^{20} \text{ m}^{-3} \]
LOC Density

\[ n_e = 0.85 \times 10^{20} \text{ m}^{-3} \]
Slightly SOC Density

\[ n_e = 1.05 \times 10^{20} \text{ m}^{-3} \]
SOC Density

\[ V_{\text{toroidal}} (\text{km/s}) \]

\[ r/a \]

Nitrogen Seeding Can Cause a Similar Reversal at Densities Slightly Above the LOC-SOC Critical Density

<table>
<thead>
<tr>
<th>Density Type</th>
<th>Electronic Density (m$^{-3}$)</th>
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</thead>
<tbody>
<tr>
<td>LOC Density</td>
<td>ne = 0.65 x 10$^{20}$ m$^{-3}$</td>
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<tr>
<td>Slightly SOC Density</td>
<td>ne = 0.85 x 10$^{20}$ m$^{-3}$</td>
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<tr>
<td>SOC Density</td>
<td>ne = 1.05 x 10$^{20}$ m$^{-3}$</td>
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The diagrams show the toroidal velocity ($V_{toroidal}$) as a function of $r/a$ for different densities and seeding conditions. The graphs illustrate the behavior of the system under nitrogen seeding and unseeding at the LOC and slightly above the SOC critical density.
GYRO Simulations Show Reduced Momentum Flux Magnitude with Seeding, Closer to the Experimental Value

GYRO Toroidal Momentum Flux for Reversal Case

- Being in steady state with no input momentum, $\Pi = 0$ is the experimental value
- GYRO only simulates momentum flux from ExB drifts (missing diamagnetic drifts)
Conclusions

- Nitrogen seeding experiments showed a decrease in ion transport qualitatively consistent with gyrokinetic simulation predictions.

- Global GYRO simulations showed a reduction in ion transport and momentum transport with seeding, which bring them closer in agreement to the experimental results.
  - Ion energy flux is still being over-predicted.

- Based on TGYRO results, global quantitative agreement of ion heat flux requires temperature profile modification outside of experimental error, so discrepancy between experiment and simulation is not simply profiles needing adjustment.

- The effect of dilution on turbulence is evident in both experiments and GYRO simulations, but quantitative agreement is lacking.
Density Fluctuations Measured by PCI are Either Consistent or Under-Predicted by Global GYRO

Unseeded LOC Plasma

Seeded LOC Plasma
Ion Collisionality Did Not Change Significantly With Seeding

Ion Collisionality $r = [0.5, 0.6]$
Global GYRO Simulations Show a Significant Decrease in Ion Energy Flux after Seeding Despite Increase in Gradient Electron Energy Flux LOC Plasma Ion Energy Flux

Electron Energy Flux

<table>
<thead>
<tr>
<th>Q_e (MW/m²)</th>
<th>Unseeded Global GYRO</th>
<th>Unseeded TRANSP</th>
<th>Unseeded Local GYRO</th>
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r/a

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0.6 0.5 0.4 0.3 0.2 0.1 0.0

Ion Energy Flux

<table>
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<tr>
<th>Q_i (MW/m²)</th>
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r/a

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Magnetic Fusion Energy

MIT - PSFC

Graphs showing experimental profiles and flux-matched profiles fixed at r/a = 0.9 for T_e, T_i, T_o, and T_0 as a function of r/a.