The Impact of Nitrogen Seeding on Turbulent Transport in Ohmic Plasmas in Alcator C-Mod and Gyrokinetic Simulations

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Ohmic plasmas have two confinement regimes: linear and saturated ohmic confinement (LOC and SOC)

- At low values of $n_e q_{95}$, energy confinement time scales linearly with density
- At high values of $n_e q_{95}$, energy confinement time is independent of density (follows L-Mode scaling)
- LOC and SOC plasmas also have different intrinsic rotation profiles, LOC plasmas are flat and co-current, while SOC plasmas are hollow and counter-current
Main ion dilution is predicted by TGLF to reduce ITG transport for \( r/a > 0.5 \), from Porkolab et. al. PPCF 2012.
Talk Outline

- Nitrogen seeding experiments were performed to investigate the effect of main ion dilution on transport.

- The nitrogen seeding had a stabilizing effect on the ion energy transport and density fluctuations.

- GYRO simulations reproduced this stabilizing effect on the ITG turbulence, and predict that the dilution affects both the stiffness and critical gradient of the ion energy transport.
Ohmic plasmas on C-Mod at a range of $q_{95}$ and $n_e$ values were seeded with nitrogen while $n_e$ was held fixed using a cryopump.

- $q_{95}$ was changed by changing $I_p$, $B_T = 5.4T$ for all shots.
- Changing $I_p$ changed $P_{OH}$, $T_e$, $T_i$.
- Seeding increased $Z_{eff}$ by about 1.
- Seeding decreased $n_D/n_e$ by 10-20%.
Density scans spanned the LOC and SOC regimes. Seeding did not change overall $\tau_{E'}$, meaning the increase in $P_{rad}$ was offset by decrease in transport.

Energy Confinement Times

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<tr>
<th>$q_{95}$</th>
<th>Unseeded</th>
<th>Seeded</th>
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<tbody>
<tr>
<td>4.5</td>
<td>![Unseeded Circle]</td>
<td>![Seeded Diamond]</td>
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<td>3.9</td>
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Density scans spanned the LOC and SOC regimes. Seeding did not change overall $\tau_r$, meaning the increase in $P_{rad}$ was offset by decrease in transport.
Nitrogen seeding caused reversals of intrinsic rotation for SOC plasmas near the LOC-SOC transition, no effect with seeding for LOC plasmas.
Core rotation direction in both seeded and unseeded plasmas displays a critical $n_D q_{95} \sim 4$ that separates co-current and counter-current cases.

As shown in poster by Porkolab on Monday in C-Mod poster session, seeding induced reversal not due to change in $v_{ei}$.
Nitrogen seeding increased normalized ion temperature gradients, but reduced normalized ion energy flux at $r/a = 0.8$; implies that turbulence was being stabilized.

$q_{95} = 3.9$, SOC, $n_D/n_e = 0.95$ (unseeded), 0.84 (seeded) 

$Q_{GB} \equiv n_e T_e c_s (\rho_s/a)^2$
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$\frac{q_{95} = 3.9, \text{SOC, } n_D/n_e = 0.95 \text{ (unseeded), } 0.84 \text{ (seeded)}}{Q_{GB} \equiv n_e T_e c_s (\rho_s/a)^2}$
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\[
Q_{GB} \equiv n_e T_e c_s (\rho_s / a)^2
\]
In contrast, the nitrogen seeding did not have a significant impact on either the electron temperature gradient or electron energy flux.

\[ q_{95} = 3.9, \text{ SOC, } n_D/n_e = 0.95 \text{ (unseeded), } 0.84 \text{ (seeded)} \]

\[ Q_{GB} \equiv n_e T_e c_s (\rho_s/a)^2 \]
Line integrated $n_e$ fluctuations with $k_R \in [0.5 \text{ cm}^{-1}, 20 \text{ cm}^{-1}]$ were measured with phase contrast imaging (PCI) both before and after nitrogen seeding.

- Has 32 channels that measure fluctuations through vertical chords.
- Line-integration means that fluctuations from the core and edge, top and bottom, are added together.
- Measures $k_R$ of turbulence, which is approximately $k_\theta$ in the core.
- Absolutely calibrated before every shot.
Low $q_{95}$ (high $I_p$) PCI spectra show high frequency ($F > 150$ kHz) feature that is significantly decreased by seeding, unrelated to change in the plasma rotation.

$q_{95} = 3.4$, SOC case
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$q_{95} = 3.4$, SOC case
Nitrogen seeding significantly reduced high frequency (F > 150 kHz) PCI spectral feature in both LOC and SOC $q_{95} = 3.4$ cases
Only reflectometer channels measuring at $r/a = 0.85$ showed a decrease in $n_e$ fluctuations with seeding, implies high-F PCI feature is located near $r/a = 0.85$.
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Normalized energy fluxes at \( r/a = 0.85 \) are large (\( Q/Q_{GB} \gtrsim 10 \) as a rule-of-thumb), which implies that turbulence there is well above marginal stability.

\[
q_{95} = 4.5, \quad \text{SOC Case}
\]

\[
Q_{GB} = n_e T_e c_s (\rho_s/a)^2
\]

\[
Q_{GB} \sim n_e T_e^{5/2}
\]
Normalized energy fluxes at $r/a = 0.85$ are large ($Q/Q_{GB} \gtrsim 10$ as a rule-of-thumb), which implies that turbulence there is well above marginal stability.

$Q_{GB} = Q_e + Q_\nu = n_e T_e c_s (\rho_s/a)^2$

Reflectometer shows large decrease in fluctuations with seeding.
The nonlinear gyrokinetic code GYRO was used to investigate the theoretical effects of the seeding and dilution on ion energy flux

- **GYRO simulation parameters:**
  - \( k_\theta \rho_s \leq 1 \) (ITG and TEM, not ETG)
  - Only electrostatic (Because \( \beta < 0.5\% \))
  - ExB shear not included (tested in a few cases, but was found to be negligible)
  - Average impurity ion species used that matched \( Z_{\text{eff}} \) and \( n_D/n_e \)
  - Electron-ion collisions included

- **GYRO analysis will focus on ion energy transport at** \( r/a = 0.8 \), where turbulence is above marginal stability and where seeding was observed affected experimental ion energy transport and fluctuations
  - Seeding and dilution found to have a negligible direct effect on GYRO electron energy transport

- Analysis at \( r/a = 0.6 \) (where \( Q/Q_{GB} \sim 1 \)) was considered in poster CP12.00008 by Porkolab on Monday, and in Ennever et. al. Phys. of Plasmas 2015
Scans of linear GYRO simulations at $r/a = 0.8$ varying $a/L_{Ti}$ and $a/L_{Te}$ show seeding strongly decreased ITG growth rates, slightly decreased TEM growth rates.

Unseeded Growth Rates

Seeded Growth Rates

$q_{95} = 3.9$, SOC, $a/L_n \sim 2$, $n_D/n_e = 0.95$ (unseeded), 0.84 (seeded)
To map out the stiffness and critical gradient of the ion energy transport, several nonlinear GYRO runs were performed varying $a/L_{Ti}$ keeping other parameters fixed.

$n_D/n_e = 0.95$ (unseeded), 0.84 (seeded)
An offset linear fit was performed on the GYRO simulations to determine the stiffness and critical gradient of the ion transport.

\[ q_{95} = 3.9, \text{SOC} \]

\[ \frac{n_D}{n_e} = 0.95 \text{ (unseeded), } 0.84 \text{ (seeded)} \]
In $q_{95} = 3.9$ SOC case seeding increases critical gradient and reduces stiffness; GYRO reproduces change in transport with seeding.

$n_D/n_e = 0.95$ (unseeded), 0.84 (seeded)
In $q_{95} = 4.5$ LOC case seeding increases critical gradient but does not change stiffness; GYRO again reproduces change in transport with seeding.

$n_D/n_e = 0.81$ (unseeded), 0.71 (seeded)
GYRO simulations with and without dilution included (but with the same $Z_{\text{eff}}$) show that including dilution can significantly reduce the ion energy flux.

$q_{95} = 4.5$
Decreasing $n_D/n_e$ reduces stiffness and increases critical gradient, but affects stiffness more at SOC densities and critical gradient more at LOC densities.
Conclusions

- Experiments on C-Mod demonstrated that nitrogen seeding reduced the ion energy transport and density fluctuations at $r/a = 0.8$, and affected the intrinsic core rotation
- GYRO simulations reproduce the seeding-induced change in the ion energy fluxes
- GYRO predicts that main ion dilution reduces the ion stiffness in SOC discharges and increases the ion critical gradient for LOC discharges
Implications

- Dilution will be present in future fusion devices such as ITER, due to both helium ash buildup and extrinsic impurity seeding that will be necessary to reduce divertor heat loads.

- Increased critical gradient would benefit ITER because it is predicted to be close to marginal stability.

- The reduction in ion transport stiffness with dilution could explain observations on DIII-D and Textor wherein low-Z seeding increased $\tau_E$ in NBI heated ITG dominant L-Mode plasmas.

- Dilution could also be a factor in the observed degradation in performance when changing from carbon to metallic walls in ASDEX-U and JET which is partially recovered through low-Z seeding.
Open Questions & Future Work

- Investigate seeding induced rotation reversals, compare to different theoretical models
  - Is relationship of the rotation to $n_D$ related to the dilution stabilization of turbulence or just a correlation?
- Compare the density fluctuations from the GYRO simulations to the PCI measurements in low $q_{95}$ cases where high-F fluctuations were reduced in the experiment
- Extend the work to other regimes of parameter space
Extra Slides
Core rotation direction no longer shows critical value of $n_e q_{95}$ for both seeded and unseeded cases at all $q_{95}$.

As shown in poster by Porkolab on Monday in C-Mod poster session, seeing induced reversal not related to $v_{ei}$.
Seeding increased inverse $T_i$ gradient scale lengths, while normalized ion energy fluxes decreased - implies that seeding changed ion stiffness or critical gradient.

Unseeded and Seeded Ion Fluxes And Gradients at $r/a = 0.8$

$$Q_{GB} \equiv n_e T_e c_s \left( \rho_s / a \right)^2$$

$$a / L_{Ti} = a \nabla T_i / T_i$$
Seeded plasmas have a different critical $\nu_{\text{eff}}$ for intrinsic rotation direction compared to unseeded plasmas, implies that collisionality may not be responsible for seeding induced rotation reversal.
Nonlinear GYRO using nominal experimental temperature and density profiles and experimental energy fluxes generally agree at $r/a = 0.8$
Linear GYRO simulations show seeding decreased ITG growth rates
Local nonlinear GYRO at r/a = 0.6 over-predicts exp., has $Q_i > Q_e$
At \( n_e = 0.8 \times 10^{20} \text{ m}^{-3} \) (SOC regime) and \( r/a = 0.6 \) GYRO shows the seeding decreasing the slope, but GYRO over-predicts the experimental fluxes.

\[ r/a = 0.6 \quad n_e = 0.8 \times 10^{20} \text{ m}^{-3} \text{(SOC), } n_D/n_e = 0.89, 0.74 \]
Accounting for radial variation of $a/L_{Ti}$ reduces simulated $Q_i$ & $Q_e$.
Decreasing $n_D/n_e$ also reduces GYRO simulated ETG linear growth rates, despite no change in the $Z_{\text{eff}}$ in the simulation

$q_{95} = 3.9$, SOC case at $r/a = 0.6$
Decreasing $n_D/n_e$ reduces the ETG stiffness and increases the ETG linear critical gradient.

$q_{95} = 3.9$, SOC case at $r/a = 0.6$
In $q_{95} = 4.5$ SOC case seeding decreases stiffness, but does not change crit. gradient; GYRO qualitatively reproduces change in transport with seeding.

$n_D/n_e = 0.89$ (unseeded), 0.76 (seeded)
Using GYRO simulations at several values of $n_D/n_e$ and $a/L_{Ti}$, the effects of dilution on stiffness and critical gradient can be quantified.