Gyrokinetic Simulations of Diluted Plasmas in the LOC Regime in Alcator C-Mod *

M. Porkolab, P. Ennever, J. Dorris, M.L. Reinke¹, J. E. Rice, J. C. Rost, N. Tsujii, E. Davis, D. Ernst, C. Fiore, M. Greenwald, A. Hubbard, J. Hughes, E. Marmar, Alcator C-Mod Team, MIT PSFC and

J. Candy, G.M. Staebler and R. Waltz, General Atomics

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Energy confinement time in ohmically heated plasmas in tokamaks follows a linear scaling with density (LOC regime), followed by a saturated regime (SOC);
Can gyrokinetic theory explain this result?

Alcator C-Mod data
Work on C-Mod up to 2009 found disagreement between GYRO and experiment based on TRANSP

- TRANSP analysis in the linear ohmic regime (LOC, where $\tau \approx n_e, T_i < T_e$) indicated that $\chi_i \leq \chi_e$
- However, nonlinear GYRO code simulations for the measured profiles predicted the opposite, namely $\chi_i \geq \chi_e$ (L. Lin et al, Phys Plasmas 2009, 16 012502)
- GYRO found turbulent transport only in the strong gradient region, $0.6 < r/a < 0.8$, but no transport in the core ($r/a < 0.5$)
- Varying the $T_i$ profile and its gradient up to 30 % did not help, ITG modes (and hence ion transport) remained dominant over TEM/ETG and electron transport
- Varying $T_e/T_i$, collisionality ($Z_{eff}$) or $\beta_e$ did not help
Measured transport coefficients at low densities deviated from GYRO predictions in spite of varying $R/L_{\text{Ti}}$, $R/L_{\text{ne}}$.

Diffusivities averaged at $r/a = 0.6-0.8$, $Z_{\text{imp}} = 12$, $Z_{\text{eff}}$ varies with density (Lin, 2009).

\[ \epsilon \text{ is the reduction factor of } a/L_{\text{Ti}}: \left. \frac{a}{T_i} \frac{\partial T_i}{\partial r} \right|_{\text{sim}} = (1 - \epsilon) \left. \frac{a}{T_i} \frac{\partial T_i}{\partial r} \right|_{\text{sim}} \]
Performed extensive parameter scans with the TGLF Gyro-Fluid Code\textsuperscript{1} and agreement with experiment can be achieved locally even in the LOC regime by using moderate impurity ion species ($Z_{\text{imp}} = 8$) which results in $^1\text{D}$ depletion.

TGLF predicts $\chi_i$ to be strongly reduced with increasing $Z_{\text{eff}}$ as long as $Z_{\text{imp}} < 10$; $\chi_e$ is only weakly affected.

Reduction in $\chi_i$ is due to depletion of the main ion species

- **Molybdenum, $Z=42$** does not significantly reduce the TGLF predicted ion transport ($\chi_i$), the high $Z$ impurity does not deplete the main ion density.

TGLF Transport, $\bar{n}_e = 0.64 \times 10^{20} \text{ m}^{-3}$, $Z_{imp} = 42$ (Molybdenum)

- The reduction in ion transport is due to a depletion in the main ion density, not simply due to an increase in $Z_{eff}$
TGLF shows $E_r$ effect on transport levels is weak

- Including $E_r$ in the TGLF model produces a small but finite reduction in the electron transport and has only a slight effect on ion transport.
GYRO shows the same trend as TGLF, namely ion transport is reduced as the main ion species is depleted at higher $Z_{\text{eff}}$; however, both codes predict negligible transport for $r/a < 0.5$. 
Linear growth rates from GYRO show reversal from ion to electron diamagnetic drift direction as the majority ion species density is depleted relative to electrons.

Black is for the old case, with $Z_i = 12$; All other colors are for the new cases, with $Z_i = 8$.

- Electron direction
- Ion direction
Measured heat fluxes in “reasonable” agreement with nonlinear GYRO and TGLF predictions at $r/a = 0.7$ but some discrepancies remain.

$q_i, q_e$ correspond to $r/a = 0.7$, $Z_i = 8$, and $Z_{\text{eff}}$ as measured.
Predicted heat fluxes in good agreement with experiment if gradients of $T_e$ and $n_e$ are increased in GYRO by 10 - 20% above nominal values, well within experimental error.

Initial values of $a/L_{Te}$, $a/L_{ne}$ are near marginal stability; if increase the inverse gradients by 15 \%, $\gamma_{lin}$ exceeds marginal stability and electron transport increases dramatically.
Linear growth rates near marginal stability for nominal electron and ion temperature gradients; increasing $a/L_{Te}$ (red color) leads to TEM dominated transport.

**Linear Growth Rate Plot for $n_e \text{bar} = 0.92 \times 10^{20} \text{ m}^{-3}$**
New results based on iteration between TGYRO$^1$ and TGLF improve agreement locally.

\[ n_{\text{e,bar}} = 1.08 \times 10^{20} \, \text{m}^{-3}, \text{Unseeded} \]

\[ Z_{\text{eff}} = 1.65, \, n_D/n_e = 92\% \]

Phase Contrast Imaging (PCI) is used in Alcator C-Mod to measure turbulence and compare measurements to GYRO Spectrum by a Synthetic Diagnostic Technique.

- CW, CO$_2$ laser
- $k_R = 1.5-16$ cm$^{-1}$
- $f = 5-5000$ kHz
- 32 channel HgCdTe photoconductive detector array
- Heterodyne frequency: 40-80 MHz
Phase Contrast Imaging measures the phase shift of the laser due to electron density fluctuations.

\[ E = E_0 e^{i\phi} \approx E_0 (1 + i\phi) \rightarrow E_0 (i + i\tilde{\phi}) \]

\[ I \propto |E|^2 = |E_0|^2 (1 + 2\tilde{\phi}) \sim r_e \lambda_0 \int dz \tilde{n}_e + \text{const.} \]
Experimentally measured power spectrum with Phase Contrast Imaging (PCI) in qualitative agreement with global nonlinear GYRO as interpreted with a synthetic PCI technique.

Power spectrum versus $k$ averaged over 100-300 kHz;

“Global “GYRO” spectrum Doppler shifted with $E_r = 14$ kV/m, as measured.
Relative direction of ExB drift in LOC and SOC
Masking blocks top (bottom) of plasma reveals asymmetry of spectrum in bottom (top)

\[ \mathbf{E} \times \mathbf{B} \parallel \text{Ion Drift} \]

In LOC \( \mathbf{E}_r > 0 \)

In SOC \( \mathbf{E}_r < 0 \)

\[ k_R > 0 \text{ (Electron Diamagnetic Direction)} \]

\[ k_R < 0 \text{ (Ion Diamagnetic Direction)} \]
PCI signal after masking bottom(top) of plasma shows propagation in ion diamagnetic direction in the SOC regime.

\[ I_p = 1.0 \, \text{MA}, \quad n_e = 1.1 \times 10^{20} \, \text{m}^{-3} \]
Dilution of deuterium density with Nitrogen ($Z_i = 7$) seeding in the SOC regime indicates reduced fluctuation intensity in the ion drift direction as measured with the PCI masking technique.

![Graph showing ion and electron directed turbulence with different seeding scenarios.](image-url)
Some evidence of increasing $\tau_E$ with decreasing relative fluctuation level at $r/a = 0.7$ versus $n_e$ in the LOC regime. $I_p = 1.0$ MA, $q_{95} = 3.2$.
Impurity Measurements

• Impurity line brightnesses were measured by an uncalibrated spectrometer

• The calibration constants for the different impurity lines were found from the equation for $Z_{\text{eff}}$:

\[ Z_{\text{eff}} = 1 + \sum_{\text{species}} \frac{Z_i \times (Z_i - 1)}{n_e} \times (\text{Brightness}) \times (\text{Calibration Constant}) \]

• $Z_{\text{eff}}$ was inferred from neoclassical resistivity when one impurity dominated

• The impurities are identified via soft X-ray (SXR) and vacuum ultraviolet (VUV) line emission (1-6 nm, and 10-30 nm, respectively)

• Additional experiments were performed by injecting impurity gases ($\text{N}_2, \text{Ar}$) and results are being analyzed

• Recent measurements indicate flat $Z_{\text{eff}}$ profiles
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<th>$n_e$ ($10^{20}$ m$^{-3}$)</th>
<th>N$_2$Puff</th>
<th>$Z_{\text{eff}}^a$</th>
<th>$n_N/n_e$</th>
<th>$n_O/n_e$</th>
<th>$n_{Ar}/n_e$</th>
<th>$n_{Mo}/n_e$</th>
<th>$Z_{\text{eff}}^b$</th>
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$Z_{\text{eff}}^a$ from neoclassical conductivity

$Z_{\text{eff}}^b$ from least-squares solution of line brightness

$Z_1^c$ and $n_i/n_e^c$ consistent with both $Z_{\text{bright}}$ and $n_D/n_e$
LOC/SOC transition density and rotation reversal density correlated and both increase with $I_p$

$V_{\text{tor}}$ gives $E_r$; $E_r$ localized to $r/a = 0.85$, hence Doppler shift core plasma fluctuations; J. E. Rice, et al., Nucl Fusion 51 083005 (2011)
Core confinement issues: the ohmic electron drift speed increases to $6c_s$ at the lowest density in the LOC regime.

- Do current driven drift waves play a role in the plasma core?
- Or perhaps current gradient driven modes? Or mild sawteeth?
Summary

- After extensive analysis with TGLF/GYRO we find that in the LOC regime, using an “effective” impurity ion species $Z_i \approx 8$, electron modes (TEM), rather than ITG modes dominate as a result of significant (up to 35%) dilution of the main ion species (deuterons).

- In agreement with experiment, electron thermal diffusivities and heat fluxes dominate over those of ions in the radial range $r/a = 0.5 - 0.8$.

- The fluctuation spectrum intensity measured with Phase Contrast Imaging is in qualitative agreement with synthetic PCI predictions from global GYRO; $E_r$ shear is not important for stability calculations.

- In the inner plasma core ($r/a < 0.5$) transport predicted by TGLF/GYRO is too small relative to experimental values; potential candidates for enhanced transport may be current driven drift waves ($U_\parallel/C_s = 2-5$) or mild sawtooth activity, and hence we still do not fully understand the variation of global energy confinement with $n_e$ or $q n_e$. 