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Electron Transport Dominated Regimes in Alcator C-Mod

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In ohmically heated low density plasmas where $\tau_E \propto n_e$, the so-called neo-Alcator regime, TRANSP results indicate that $\chi_i < < \chi_e$, while nonlinear gyrokinetic analysis for the measured profiles predicts the opposite inequality [1]. This regime is of great interest for transport studies since $T_i < T_e$, and the electron and ion transport channels can be separated and studied separately. At the same time, measurements of turbulent fluctuations with Phase Contrast Imaging diagnostic (PCI) indicated reasonable agreement with GYRO predictions at frequencies 80-250 kHz, corresponding to core ITG turbulence. The turbulent spectrum at lower frequencies could not be identified since the PCI technique does not allow separation of the core plasma fluctuations from those at the edge. Here we present measurements and analysis from a more extensive set of plasma regimes than previously. Of particular current interest is the role of electron drift wave turbulence driven by ohmic electron drift, $U$ [2], since in these low density regimes $U/C_s < 6$, and experimentally we find that the global confinement $\tau_E \propto C_s/U$ where $C_s = (T_e/m_i)^{1/2}$.

Well known experimental results from Alcator C (Greenwald, Parker, 1984), as well as other tokamaks up to the present time, indicate that Ohmic confinement follows a linear scaling with density, followed by a saturated confinement regime in L mode; Why? Gyrokinetics?

The results imply that in the linear confinement (neo-Alcator) regime the electron thermal diffusivity should decrease as the density increases.
Work up to 2009 November APS DPP meeting did not include experimental measurements of $T_i$ and also, $Z_{\text{eff}}$ measurements may have been in error.

- TRANSP analysis in the linear ohmic regime indicates that $T_i < T_e$ and therefore $\chi_i \leq \chi_e$ since $P_{\text{OH}} = P_{\text{electrons}}$
- However, nonlinear GYRO code simulations for the measured profiles predicted the opposite, namely $\chi_e < \chi_i$
- It should be noted that experimental measurements of $T_i$ profiles were not available and they were calculated from TRANSP by several internal ion transport packages, in particular, $\chi_i \equiv \text{const}\chi_e$ until the predicted neutron flux agreed with experiment.
- The predicted ion temperature gradients may have been in error, thus overestimating the role of ITG versus TEM modes, or indeed, ion versus electron transport even for ITGs.
In the linear ohmic regime, $\chi_i$ is much smaller than $\chi_e$.

(Experimental results using TRANSP analysis)

- As $n_e$ increases, $\chi_e$ decreases, but $\chi_i$ increases slowly, $\chi_{\text{eff}}$ also decreases.
- In the saturated ohmic regime, $\chi_e$ becomes comparable to $\chi_i$.

\[
\chi_{\text{eff}} = \frac{n_e \chi_e \nabla T_e + n_i \chi_i \nabla T_i}{n_e \nabla T_e + n_i \nabla T_i}
\]
Measured transport coefficients at low densities significantly deviate from the GYRO code prediction and cannot be resolved even with variation of density and temperature profiles.

\[ \varepsilon \text{ is the reduction factor of } \frac{a}{L_{T_i}} : \]
\[ \left( \frac{a \frac{\partial T_i}{\partial r}}{T_i \frac{\partial r}{\partial r}} \right)_{\text{sim}} = (1 - \varepsilon) \frac{a \frac{\partial T_i}{\partial r}}{T_i \frac{\partial r}{\partial r}} \]
At the lowest density, inclusion of high-k turbulence in the ETG range $k_\theta \rho_s = 2-8$ accounts for less than 5% of total simulated electron transport; it is not known if including even higher values of $k_\theta \rho_s$ would significantly change this result.

Linear ohmic $\bar{n}_e = 0.35 \times 10^{20} m^{-3}$

- The short wavelength turbulence in the range of $8.0 > k_\theta \rho_s > 2.0$ only can contribute to the electron thermal transport by less 5.0%.

- After adding $E \times B$ shear suppression and/or reducing $\nabla T_i$, the electron transport from high-k turbulence is not significantly affected.

- Measurements to date by PCI indicate very low levels of high-k turbulence, falling into the background noise level.
As density increases the drift speed decreases to $c_s$ and confinement improves.

- A correlation exists between the energy confinement time and the ohmic drift velocity.

*Do current driven drift waves play a role?*
Phase Contrast Imaging (PCI) in Alcator C-Mod

- PCI measures density fluctuations along 32 vertical chords.

  **Wavenumber Range:**
  
  \[ 0.5 \text{ cm}^{-1} < |k_R| < 55 \text{ cm}^{-1} \]

  **Frequency Range:**
  
  \[ 2 \text{ kHz} \sim 5 \text{ MHz} \]

- The localization upgrade allows PCI to resolve the direction of propagation of the measured turbulence in ITG and TEM range.

- The improved calibration also allows for the intensity of the observed fluctuations to be determined absolutely.
Turbulence measurements in Alcator C-Mod plasmas as a function of density show good agreement with the nonlinear global GYRO in ohmic plasmas at frequencies above 80 KHz with phase velocities dominantly in the ion diamagnetic direction.

(Liang Lin, Invited talk, APS DPP meeting, Atlanta, November, 2009)
New experimental runs in December 2009 included $T_i$ profile measurements with HIREX and the predicted values of $R \nabla T_i$ and $Z_{\text{eff}}$ changed, requiring new analysis with TRANSP and gyrokinetics.

- New experimental runs on Dec 15,16 (2009), including measurements of $T_i$ with HIREX indicate flatter $T_i$ profiles and reduced values of $\eta_i$ compared to previous predictions by TRANSP.
- Obtained new profiles, including that of $T_i$, and performed new TRANSP analysis for $\chi_i$ and $\chi_e$.
- Found reduced values of $\eta_i$ ($\approx 1.5-2.0$) relative to old values in 2007-2009 ($\approx 3.0$) which were based on TRANSP modeling.
- Found higher values of $Z_{\text{eff}}$ than in 2007.
- Performed new gyrokinetic analysis with TGLF, TGYRO, and iterated to obtain transport with TGLF based on quasilinear estimates (Staebler, Waltz, Candy); obtained “agreement” with experiment near $r/a = 0.6-0.7$.
- Differences in the core transport at $r/a < 0.5$ are still substantial, where profiles are rather flat and negligible transport is predicted by TGLF.
TRANSP Profiles and calculated gradients at low density, $n_e = 0.35 \times 10^{20} \text{m}^{-3}$; The solid lines are for the 2009 data, and the dashed lines are for the 2007 data.
TGLF modeling indicates reversal of electron and ion thermal diffusivities with new $T_i$ profiles and $Z_{\text{eff}}$ in 2009

Low density case, $n_e=0.35 \times 10^{20} \text{ m}^{-3}$

New profiles in 2009

$Z_{\text{eff}} = 7.2 \ (5.4)$
$Z_i = 8 \ (\text{Oxygen})$

New profiles in 2009

$Z_{\text{eff}} = 2.7$
$Z_i = 8$

Old profiles in 2007

$Z_{\text{eff}} = 2.7$
$Z_i = 12$
TRANSP Profiles and calculated gradients at medium density, $n_e=0.60 \times 10^{20} \text{m}^{-3}$; The solid lines are for the 2009 data, and the dashed lines are for the 2007 data.
TGLF modeling indicates reversal of electron and ion thermal diffusivities with new $T_i$ profiles and $Z_{\text{eff}}$ in 2009.

Medium density case, $n_e = 0.60 \times 10^{20} \text{ m}^{-3}$

New profiles in 2009
- $Z_{\text{eff}} = 3.5$ (2.7)
- $Z_i = 8$

New profiles in 2009
- $Z_{\text{eff}} = 1.5$
- $Z_i = 8$

Old profiles in 2007
- $Z_{\text{eff}} = 1.5$
- $Z_i = 12$
TRANSP Profiles and calculated gradients at high density, n_e=0.90x10^{20} m^{-3}; The solid lines are for the 2009 data, and the dashed lines are for the 2007 data.
TGLF modeling indicates reversal of electron and ion thermal diffusivities with new $T_i$ profiles and $Z_{\text{eff}}$ in 2009

High density case, $n_e=0.90\times10^{20}\text{m}^{-3}$

New profiles in 2009
$Z_{\text{eff}} = 2.8\ (2.3)$
$Z_i = 8$

New profiles in 2009
$Z_{\text{eff}} = 1.2$
$Z_i = 8$

Old profiles in 2007
$Z_{\text{eff}} = 1.2$
$Z_i = 12$
Gyro and TGLF predict strong inverse variation of growth rates and thermal heat diffusivities with $Z_{\text{eff}}$; the strongest impact is on $\chi_i$.

$n_e = 0.6 \times 10^{20} \text{m}^{-3}, \ 2009 \text{ data};$

$n_e = 0.9 \times 10^{20} \text{m}^{-3}, \ 2009 \text{ data};$
TGLF modeling indicates reversal of electron and ion thermal diffusivities with new $T_i$ profiles and $Z_{\text{eff}}$ in 2009.

High density case, $n_e = 1.05 \times 10^{20} \text{m}^{-3}$

New profiles in 2009
$Z_{\text{eff}} = 2.4$
$Z_i = 8$

New profiles in 2009
$Z_{\text{eff}} = 1.9$
$Z_i = 8$

New profiles in 2009
$Z_{\text{eff}} = 1.5$
$Z_i = 8$
Gyro and TGLF predict strong inverse variation of growth rates and thermal heat diffusivities with $Z_{\text{eff}}$; the strongest impact is on $\chi_i$

$n_e = 1.05 \times 10^{20} \text{m}^{-3}$; 2009 data;
Linear growth rates and angular frequencies from GYRO for $n_e = 0.60 \times 10^{20} \text{m}^{-3}$, $Z_i = 8$; Black lines for 2007 data and red for 2009; Negative frequencies are in the ion diamagnetic drift direction and positive frequencies in the electron drift direction.

$\frac{r}{a} = 0.6$

$\frac{r}{a} = 0.7$

Fastest gamma versus $\frac{r}{a}$
Calculated NEUTRON rates for measured ion temperature profile (HIReX), $Z_{\text{eff}}$ and density profiles (Thomson scattering) in reasonable agreement with experimental neutron measurements.
Variation of confinement with $U_{||}/c_s$ similar to the 2007 data; Variation with $Z_{eff}$ is new discovery; do current driven drift waves contribute to transport at $r/a < 0.5$?

Dominant factor in transport reversal between electrons and ions at $r/a = 0.65$ is most likely due to $Z_{eff}$ and $a/L_{Ti}$.
Summary and Conclusions

- New $T_i(r)$ profile measurements became available on C-Mod in December 2009 (HIREX) and the ohmic linear confinement regime (neo-Alcator regime) was repeated and compared with the results from 2007 (L. Lin, APS, 2009;)
- The measured $T_i$ profiles in 2009 were found flatter by factors of 2 as compared to the TRANSP modeled profiles in 2007
- The values of $Z_{\text{eff}}$ in 2009 were typically a factor of two higher than assumed in 2007 for similar discharges
- New analysis with TGLF/TGYRO for oxygen like impurities ($Z_i=8$) predict dominant electron modes, rather than ITG modes, thereby reversing the electron and ion thermal diffusivities near $r/a=0.6-0.8$, in agreement with TRANSP predictions; for moly impurities ($Z_i=42$) ion transport would dominate once more, indicating the importance of impurity species
- In the inner plasma core ($r/a < 0.5$) the diffusivities predicted by TGLF and neoclassic transport are too small by more than an order of magnitude; potential candidates for enhanced transport may be current driven drift waves ($U_\parallel/C_S = 2-5$) or mild sawtooth activity, or ???
- Future work includes nonlinear global GYRO modeling and turbulence measurements with synthetic PCI diagnostics