Search for TEM and ETG Modes with the Upgraded PCI Diagnostic in Alcator C-Mod

L. Lin, M. Porkolab, D. R. Ernst, N. P. Basse, E. M. Edlund, C. L. Fiore, Y. Lin, S. J. Wukitch, MIT PSFC.

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Outline

• Introduction
  - Phase Contrast Imaging (PCI) Technique
  - PCI System in Alcator C-Mod

• Recent Experimental Results from PCI System and Linear Gyrokinetic analysis
  - Comparison of L-Mode and EDA H-Mode
    - Linear Gyrokinetic Analysis with GS2 (ITG)
  - PCI measurement during ITB formation
    - Linear Gyrokinetic Analysis with GS2 (TEM)

• C-Mod Discharges Surveyed with ETG Critical Gradient Formula

• Future Plans
PCI Geometry

Upper mirror mount, focusing mirror, phase plate, detector array, etc.

Laser, modulators and expansion optics

Lower mirror mount
PCI Technique

OBJECT:
Plasma density fluctuations introduce phase variations to the laser beam.

\[ n = n_0 + \tilde{n}\cos(k_p x) \]

\[ E = E_0 \left(1 - \frac{\Delta^2}{2}\right) + E_0 \frac{i\Delta}{2} \cos(k_p x) \]

\[ + E_0 \frac{i\Delta}{2} \cos(-k_p x) \]

\[ \Delta = -\lambda_0 r_e L \tilde{n} \ll 1 \]

\[ I = E \cdot E^* \approx E_0^2 = I_0 \]

IMAGE:
Laser phase variations are converted to intensity variations by the phase plate.

\[ E = iE_0 \left(1 - \frac{\Delta^2}{2}\right) + E_0 \frac{i\Delta}{2} \cos(k_p x) \]

\[ + E_0 \frac{i\Delta}{2} \exp(-k_p x) \]

\[ I = E \cdot E^* \approx I_0 \left[1 + 2\Delta \cos(k_p x)\right] \]
PCI System in C-Mod

PCI measures line integrated electron density fluctuations along 32 vertical chords.

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>Wave number Range:</th>
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<tbody>
<tr>
<td>$10^{12}$ m$^{-2}$/Hz$^{1/2}$ (direct)</td>
<td>$0.5$cm$^{-1}$&lt;$</td>
</tr>
<tr>
<td>$3 \times 10^{13}$ m$^{-2}$/Hz$^{1/2}$ (Heterodyned)</td>
<td>Localization</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>Laser</td>
</tr>
<tr>
<td>2kHz~5MHz tunable 50 or 80 MHz (Heterodyned)</td>
<td>25 Watt CO$_2$ CW $\lambda$ =10.6 µm</td>
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PCI Advantages: (PCI vs. Reflectometry)

- Entire spectrum of wavenumbers is measured simultaneously and separately.
- Spatial structure is revealed over a wide area.
Future Plans Include Spatial Localization Capability

Nominal operation has poor localization along the beam path.

Vertical Localization will be attempted in the new campaign.

- For modes with $k_{∥} \ll k_{⊥}$, scattering is perpendicular to $B_R(z) + B_Φ$.

- Laser scattered from different $z$ is focused on different parts of the phase plate.

- Masking phase plate selects fluctuations by $z$.

H-Mode Discharges Studied

\[ B_T = 6.4 \, \text{T} \]
\[ I_p = 1 \, \text{MA} \]

L-H Transition
Up to 1 MHz, the amplitude of turbulence during EDA H-Mode is stronger than that of L-Mode.
• The L-Mode turbulence exists up to 1MHz.
• In the EDA H-mode, broadband turbulence up to 1.5 MHz is visible on PCI during H-Mode.
The turbulence amplitude increase after L-H transition is contributed by:

• low frequency (20kHz-80kHz) turbulence, $k_R$ centered at 3 cm\(^{-1}\)
• high frequency (200kHz-2MHz) turbulence, $k_R$ centered at 5 cm\(^{-1}\)
• Quasi-Coherent mode turbulence
2-D FFT Analysis of PCI Measurement

Positive $k$ corresponds the fluctuation traveling toward the HFS
Negative $k$ corresponds the fluctuation traveling toward the LFS
Using Linear GS2 to Determine Unstable Modes


• GS2 runs are prepared from TRANSP by GS2_PREP and analyzed with GS2_PLOT [D. R. Ernst et al., Phys. Plasmas 7, 615, (2000)].

• Linear microstability growth rates are calculated on a wavenumber by wavenumber basis with an implicit initial-value algorithm in the ballooning limit.

For stable modes, the frequency and wavenumber is set to zero.
Discussion

- From GS2 linear simulations, ITG with frequency spectrum (20kHz-80kHz) is unstable for both L-Mode and H- mode. There is no substantial difference of frequency, wavenumber or growth rate between two cases.

- ITG is very sensitive to ion temperature gradient, which is not accurately measured.

- The amplitude of broadband turbulence measured by PCI has a marked increase at L-H transition.

- There is no apparent correspondence between observed spectra and simulated core turbulence.
  - PCI measures line integrated spectra

- Future studies to be done using the upgraded PCI, which will include localization along beam.
ITB Formation

\[ B_T = 5.5 \, \text{T} \]
\[ I_p = 800 \, \text{kA} \]
Spectra of PCI Measurement

- Blue: Trange=[0.99, 1.01] sec, off-axis RF heating
- Red: Trange=[1.19, 1.21] sec, off-axis and on-axis RF heating

Graph showing autopower spectrum with and without on-axis ICRF.
Wavenumber vs. Time for Frequency Band

1021024021 PCI 20kHz-60kHz

Total power vs time and wavenumber

Time (sec) On-axis RF heating added
- The frequency band has been chosen from 20 kHz to 60 kHz to avoid the contribution from QC mode turbulence.
- The amplitude of turbulence has increased substantially after on-axis RF heating added.
• From GS2 simulations, there is no marked changes of ITG after on-axis ICRF heating added.

• TEM is clearly more unstable after on-axis ICRF heating added. [D. R. Ernst, et al., Phys. Plasmas 11, 2637, (2004); D. R. Ernst, N. Basse, et al., IAEA TH/4-1, (2004)]

• The unstable mode in the barrier region has negative frequency spectrum (20kHz-60kHz), which means its phase velocity is in the electron direction.
Discussion

• An amplitude increase of broadband turbulence with frequency (20kHz-60kHz) and wavenumber $k_R$ (1cm$^{-1}$-3-cm$^{-1}$) has been measured by PCI.

• Linear GS2 simulations show that TEM with frequency spectrum (20kHz-60kHz) and poloidal wavenumber spectrum (6cm$^{-1}$-12cm$^{-1}$) becomes clear unstable during on-axis ICRF heating. However, in nonlinear simulations, we would expect a downshift of a wavenumber spectrum.

• The measured frequency and wavenumber spectrum by PCI would be consistent with such nonlinear simulation.

• Further studies of TEM modes will be continued using the upgraded PCI in the next campaign.
ETG Turbulence Estimate from GS2

• ETG similar to ITG with electrons and ions interchanged.

\[ k_0 \rho_e \sim 1 \quad k_0 \rho_i \gg 1 \quad \frac{n_i}{n_i} = \exp \left( -\frac{e\phi}{T_i} \right) \]

Ions behave adiabatically

• ETG modes have large growth rates, but short wavelengths.

\[ \gamma_{ETG} \sim \frac{V_{the}}{L_T} \gg \gamma_{ITG} \sim \frac{V_{thi}}{L_T} \]

\[ \chi_e^{ETG(ML)} \sim \rho_e^2 \frac{V_{the}}{L_T} \sim \frac{1}{60} \chi_i^{ITG(ML)} \]

• Despite small mixing length estimate, radial ETG streamers are seen in gyrokinetic simulations, for large shear \( \hat{\gamma} \) and small normalized beta gradient \( \alpha \), giving experimentally relevant transport levels [W. Dorland, PRL (2000)].

Nonlinear simulation results [W. Dorland et al., PRL (2000)].
ETG Estimate from GS2

Using a fit to the ETG critical temperature gradient [F. Jenko et al, Phys. Plasmas, 8, 4096 (2001)], reinterpret the estimate for $\chi_{\text{e}}$ in terms of $\tilde{n}/n$ to find:

$$\tilde{n}_i \approx \frac{0.15\tau^{3/2}}{n} \left(\frac{qR_0}{L_T}\right)^3 \frac{\rho_e}{L_T} \times H\left(\frac{R}{L_T} - \frac{R}{L_{\text{crit}}^{\text{Te}}}\right)$$

$$\hat{\nu} = 0.53q\left(k_\theta \rho_e\right) + \max\left\{0.09, 0.19\hat{s}^2\right\} \frac{q}{\tau} \left(k_\theta \rho_e\right)^2$$

$$\frac{R}{T_{\text{crit}}^{\text{Te}}} = \max\left\{(1 + \tau)(1.33 + 1.91\hat{s}/q)(1 - 1.15\varepsilon)\left(1 + 0.3\varepsilon \frac{d\kappa}{d\varepsilon}\right), 0.8\frac{R}{L_n}\right\}$$

Fits reproduce large number of linear gyrokinetic code runs, and a range of nonlinear runs:

**Linear Gyrokinetic Simulations of ETG turbulence [F. Jenko et al, Phys. Plasma, 8, 4096 (2001)]**

ETG Estimates from GS2

- ETG is unstable for large fraction of cross section for C-Mod L-Mode discharges.
- For C-Mod EDA H-Mode, EDA H-Mode with ITB, density fluctuation level and $k_\rho e$ for the unstable ETG is in the same order as L-Mode discharges.
GTC (global gyrokinetic particle) simulations find that the ETG electron heat conductivity is much smaller than the experimental value.

ETG instability saturates via nonlinear toroidal coupling, which transfers energy successively from unstable modes to damped modes, preferentially with longer poloidal wavelengths.

The length of the streamers scales with the device size and is much longer than the distance between mode rational surfaces or electron radial excursions. Both fluctuation intensity and transport level are independent of the streamer size.

The electron transport level from GTC simulations is an order of magnitude smaller than the GS2 simulation result.

Using the upgraded PCI, the ETG streamers will be searched for in the next campaign.
Upgrade Status and Future Plans

Hardware

• To increase the frequency and spatial resolution
  - The number of channels has been increased from 12 to 32, the $k_R$ will be resolved up to 30 cm$^{-1}$
  - New digitizers are capable of sampling at up to 40 MHz

• To increase the density fluctuation sensitivity
  - CO2 laser power will be increased from 25 W to 60 W
  - Pre-amplifiers can adjust the bias current to detector

• Vertical localization through rotating mask will be attempted

Physics

• Microscale turbulence (ITG, TEM) will continuously be investigated with upgraded PCI system
• We will search for radial ETG streamers predicted by gyrokinetic simulations
• Linear Gyrokinetic analysis with GS2 for ETG
• Non-linear Gyrokinetic analysis with GS2 for ETG/ITG/TEM
References


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