A Basic Experiment on the Production and Identification of ETG Modes

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Abstract

One of the strongest candidates for the anomalous electron energy transport is believed to be electron temperature gradient (ETG) mode [1, 2]. However, the high frequency (few *MHz*) and short wave length ($k_\perp \rho_e << 1$) make the direct observation of ETG modes difficult in experiments. Using a DC bias heating scheme of the core plasma, we are able to produce the drive parameter $1/L_{Te}$ above the critical value in Columbia Linear Machine (CLM). A high frequency mode at ~*2.3MHz* has been observed. Its azimuthal wave number (*m ~ 15*) and parallel wave number ($k_{//} \approx 0.01 cm^{-1}$) has been measured. These values are consistent with the results of a simple kinetic dispersion relation on appropriate $\vec{E}_0 \times \vec{B}_0$ Doppler shift. The scaling of ETG fluctuation level versus L_{Te}, as well as the radial structure of the mode is reported.

When the ion transport is strongly suppressed in tokamaks, the particle and energy loss rates for electrons exceed neoclassical transport estimates by one and two orders of magnitude, respectively. The most plausible physics scenario for this anomalous electron transport seems to be based on ETG instabilities. Extensive theoretical and simulation work clearly establish its dynamic behavior, both linear and nonlinear [1-6]. However, the simulation results of the transport consequences remain controversial. Moreover, due to the high frequency and short wave length of ETG modes, no direct experimental evidence of its existence in tokamaks has been found till today [7, 8]. All of the above motivate a basic experiment on the production and identification of ETG modes with a wide range of parameter variation in CLM.

CLM is a cylindrical steady-state linear machine that produces a quiescent, magnetically confined, collisionless plasma. The typical plasma parameter in CLM is: $n \sim 5\times10^{8} - 5\times10^{9}\,cm^{-3}$, $B \approx 0.1T$, $T_e \approx 5-15eV$, and $T_i \approx 3-25eV$. In order to measure the ETG modes, a Langmuir probe with the good frequency response up to *10 MHz* and high spatial resolution (~*mm*) is specially designed. This frequency response is obtained through minimizing the input capacitance by putting the resistor (SMD *100kΩ*) close to the probe tip. Because the magnetic field in CLM is uniform, the Electron Cyclotron Heating (ECH) method doesn't work. The electron temperature gradient profile is obtained by the discharge current adjustment, DC bias acceleration and thermalization. A positively biased circular tungsten mesh of diameter *1.2cm* is placed at the center of the plasma cross-section. The range of the bias voltage used is from *+5V* to *+20V*, which accelerates the electrons. The medium neutral pressure in the transition region guarantees that the electrons being accelerated are thermalized to the Maxwellian distribution. And the ions are insensitive to this kind of heating method. The temperature profiles as well as density profiles are shown in Fig. 1. It can be seen that the sharp electron temperature gradient is obtained while ion temperature profile is almost flat. Moreover, the density profile has no gradient within the region of the electron temperature gradient. So the ETG instability in this case is driven by L_{Te}, not $\eta_e (= d\ln T_e / d\ln n)$. The power spectra with different L_{Te} are shown in Fig. 2. It's clear that the potential fluctuation level increases when L_{Te} decreases, as we expect.

For ETG mode, the azimuthal wave number is much larger than the parallel wave number. When we measure the azimuthal wave number through the two very close probe tips (twin probes), the phase difference coming from the z-direction can be ignored. So we fix the radial position *r* and rotate the twin probes to find the maximum phase shift $\phi_{\max}$. Because the maximum phase shift calculated from the cross power spectra may include several 2π, we rotate the probes continuously and confirm that $\phi_{\max}$ is real phase shift. If the distance between the two tips of the twin probes is *l*, the azimuthal wave number can be calculated as $m = 2\pi \cdot r \cdot \phi_{\max} /(360 l)$. In our case, $\phi_{\max} \approx 130^\circ$, $r \approx 1.9cm$ and $l \approx 0.28cm$, so m can be estimated as ~ 15, which corresponds to $k_\perp \rho_e \approx 0.05$. From the phase measurement we can also see that there are about 3 modes with different *m* hidden inside the peak ($|m|=14, 15, 16$) in the power spectrum. The minus sign of the phase shift corresponds to the electron diamagnetic direction.

The parallel wave number is very difficult to measure because it is mixed up with the much larger azimuthal wave number. We make a very careful probe position calibration by maximizing the plasma conductance between the two probe tips in the different z-directions ($L_z \approx 28cm$) and find the parallel wave length is about 4 times of CLM machine length. From this we can estimate that $k_{//} \approx 0.01cm^{-1}$, which is much smaller than $k_\perp$.

The linear dispersion relation for the slab ETG modes can be derived from the kinetic theory. Linearized Vlasov equation gives the perturbed electron density [3]:

$$\tilde{n}_e = \frac{en_0}{T_e}\tilde{\phi}\left[1-(1-\frac{\omega_{ne}^*}{\omega})\Gamma_0 - \frac{k_\perp^2\rho_e^2}{2}(\Gamma_0-\Gamma_1)\frac{\omega_{Te}^*}{\omega} + (1-\frac{\omega_{ne}^*}{\omega})F_1\Gamma_0 - \frac{\omega_{Te}^*}{\omega}(F_2\Gamma_0 - F_1\frac{k_\perp^2\rho_e^2}{2}(\Gamma_0-\Gamma_1))\right],$$

where $\omega_{ne}^* = \frac{cT_e k_\perp}{eBL_n}, \omega_{Te}^* = \frac{cT_e k_\perp}{eBL_{Te}}, k_\perp = k_y, \Gamma_n = I_n(b)e^{-b}, b = \frac{k_\perp^2\rho_e^2}{2}$,

$$\rho_e^2 = \frac{2T_e}{m\Omega_e^2}, F_1 = 1+\lambda_e Z(\lambda_e), F_2 = \lambda_e^2 + (\lambda_e^2 - \frac{1}{2})\lambda_e Z(\lambda_e), \lambda_e = (\omega/|k_{//}|\upsilon_e).$$

Since $k_\perp\rho_i > 1$, the ion response is adiabatic $\tilde{n}_i = -e\tilde{\phi}n_0/T_i$. Using quasi-neutrality and taking the limit $\omega_{ne}^* \to 0, \omega_{Te}^* >> \omega$, we obtain the linear dispersion relation for the slab ETG instabilities:

$$\omega_{ETG} \approx \frac{1}{2}\left(\tau \cdot k_{//}^2 \cdot \upsilon_e^2 \cdot \omega_{Te}^*\right)^{1/3} + i\frac{\sqrt{3}}{2}\left(\tau \cdot k_{//}^2 \cdot \upsilon_e^2 \cdot \omega_{Te}^*\right)^{1/3}, \qquad (1)$$

which is similar to the slab ITG modes. Plugging the CLM parameters into the equation (1), we get the ETG frequency in the plasma frame is about *0.3MHz*. The Doppler shift due to equilibrium electric field is about $\omega_{\vec{E}\times\vec{B}}/2\pi \sim 135\times10^3 \cdot m \sim 2MHz$. So the frequency of ETG modes in the lab frame is about $\omega_{Lab}/2\pi = (\omega + \omega_{\vec{E}\times\vec{B}})/2\pi \sim 2.3MHz$.

The frequencies measured in the power spectra v.s. those estimated through the dispersion relation with different plasma parameters are shown in Fig. 3. It can be seen that the experimental results match the theoretical estimation from the simple linear dispersion relation fairly well.

The temperature gradient length L_{Te} is changed though D.C. accelerating voltage and discharge current. As we mentioned before, the potential fluctuation level increases with decreasing of L_{Te}, a trend in agreement with theory and simulation results. Here in Fig. 4 we show the potential fluctuation scaling v.s. L_{Te}. When we elongate the line to the zero fluctuation level, we obtain the threshold value for ETG instabilities $(L_{Te})_{critical} \approx 0.5cm$. With $k_{\perp}\rho_e << 1$, the $(L_{Te})_{critical}$ can be estimated roughly as:

$$(L_{Te})_{critical} = (2 \cdot (1+\tau) \cdot \tau)^{-1/2} \frac{k_{\perp} T_e}{k_{//} \upsilon_{te} eB} \approx 0.8cm \tag{2}$$

for CLM magnetic geometry with flat density profiles [9], where $\tau = T_e / T_i$.

Finally, we show the radial profiles in Fig. 5. The maximum fluctuation level is located at the point of the sharpest electron temperature gradient (L_{Te} smallest), as we expected. The fluctuation level is near the noise level in the center or close to the edge of the plasma, where the electron temperature gradient is very weak. This is another direct support that the instability is driven by electron temperature gradient.

In conclusion, with radially localized D.C. bias heating and appropriate discharge current, desired electron temperature radial profiles with a range of L_{Te} are obtained, sufficient for exciting ETG modes. Potential fluctuations at ~ *2.3MHz* is correlated with a sharp electron temperature gradient. This frequency is consistent with the theoretical estimation of the ETG mode. The modes have the azimuthal wave number *m~14–16* $(k_\perp \cdot \rho_i > 1, k_\perp \cdot \rho_e << 1)$ and propagate in the electron diamagnetic direction. These modes have a very large parallel wavelength (*~4* times CLM machine length). The potential fluctuation of the modes increases with decreasing L_{Te} as expected and the radial location of the maximum amplitude of the mode coincides with the steepest electron temperature gradient. With the signatures described above, the ETG mode is definitively identified in the CLM. We will try to measure the electron transport due to this kind of ETG modes in our future research.

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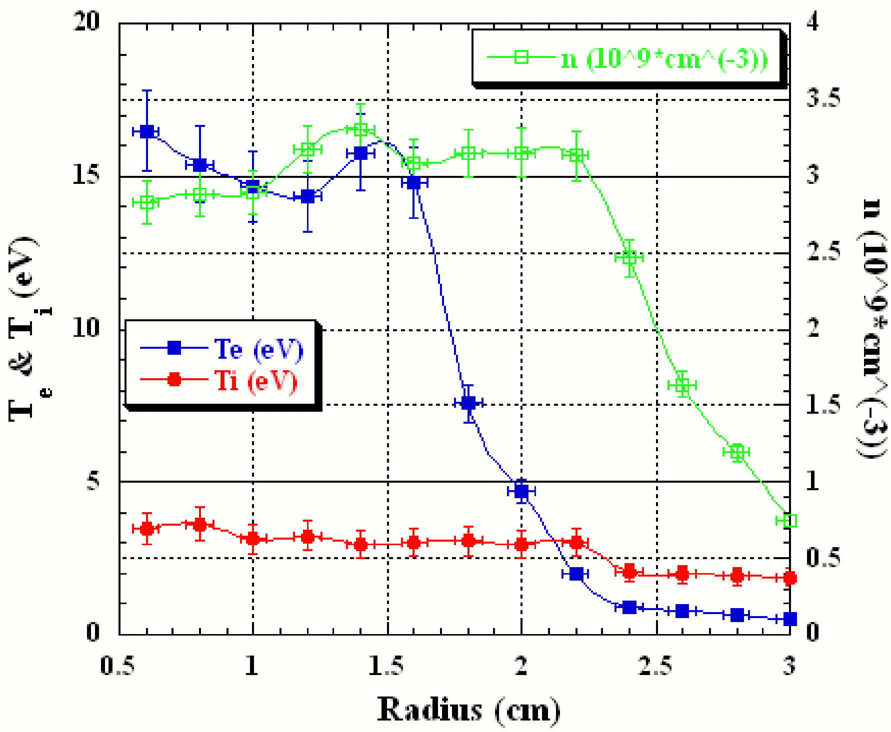
Fig. 1. Radial profiles of electron / ion temperature and plasma density.

Fig. 2. Power Spectra of potential fluctuation with different L_{Te}.

Fig. 3. Frequency measured in power spectra v.s. estimated from the dispersion relation.

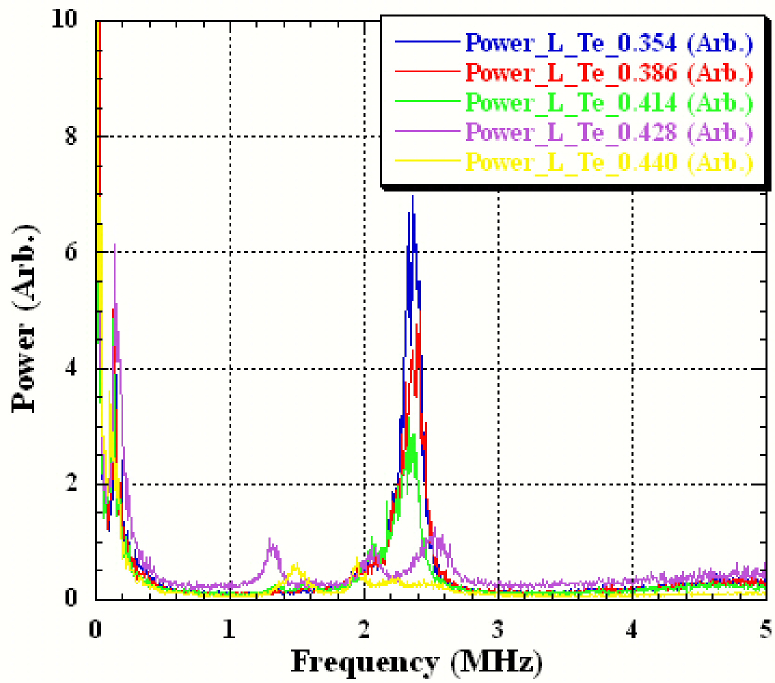
Fig. 4. Potential fluctuation level v.s. L_{Te}.

Fig. 5. Radial profiles of potential fluctuation level.



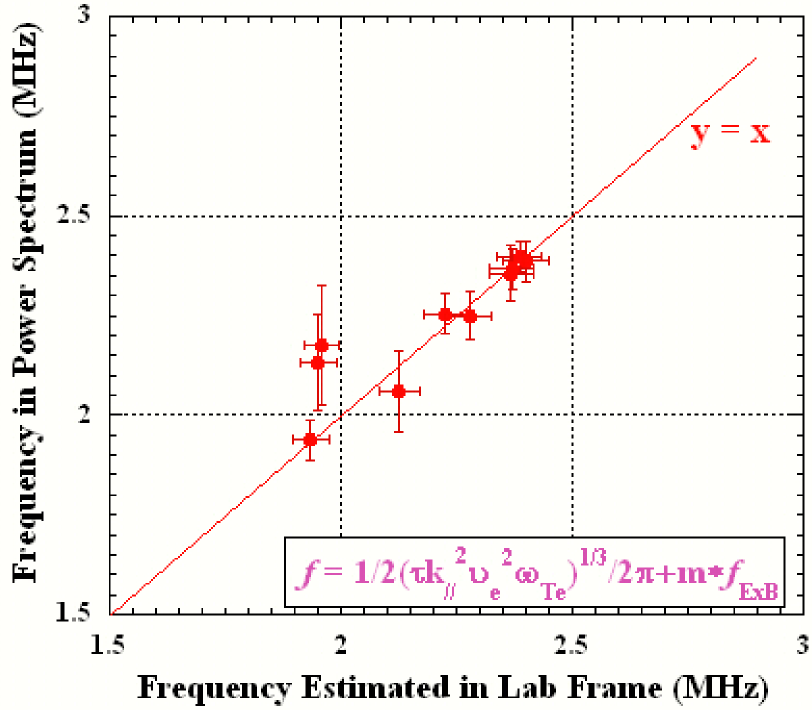
n (10^9*cm^(-3))
Te (eV)
Ti (eV)
T_e & T_i (eV)
n (10^9*cm^(-3))
Radius (cm)

Fig. 1.



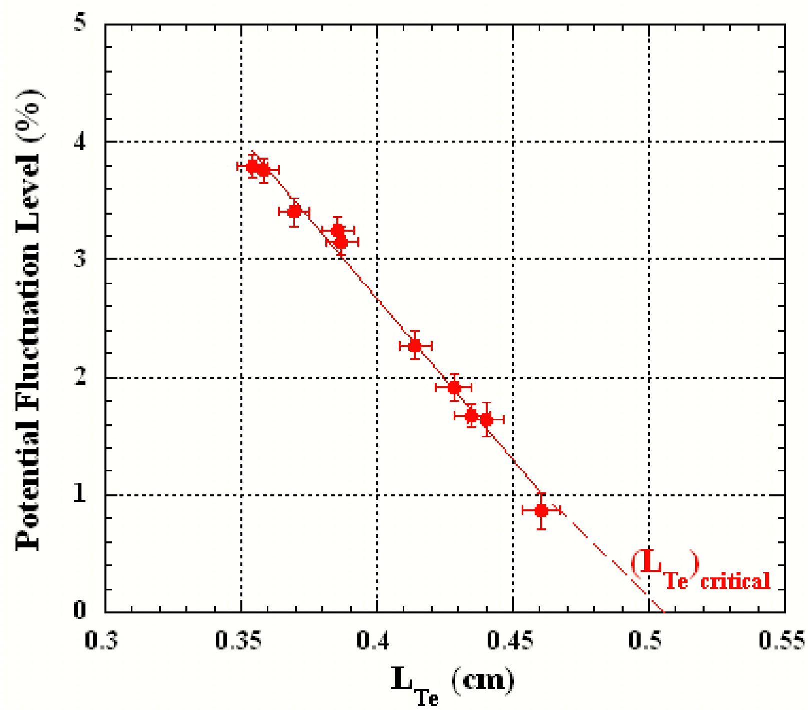
Power_L_Te_0.354 (Arb.)
Power_L_Te_0.386 (Arb.)
Power_L_Te_0.414 (Arb.)
Power_L_Te_0.428 (Arb.)
Power_L_Te_0.440 (Arb.)
Power (Arb.)
Frequency (MHz)

Fig. 2.



Frequency in Power Spectrun (MHz)
Frequency Estimated in Lab Frame (MHz)
y = x
$f = 1/2(\tau k_{//}^2 \upsilon_e^2 \omega_{Te})^{1/3}/2\pi + m * f_{ExB}$

Fig. 3.



Potential Fluctuation Level (%)
L_{Te} (cm)
$(L_{Te})_{critical}$

Fig. 4.

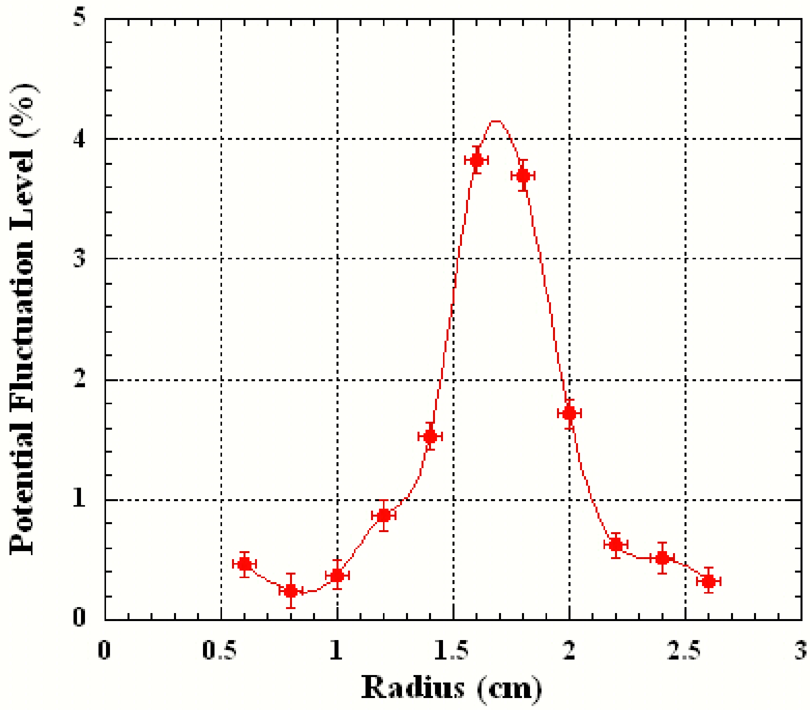


Fig. 5.