Measurements of Electron Thermal Transport due to Electron Temperature Gradient Modes in a Basic Experiment

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Measurements of Electron Thermal Transport due to ETG Modes in a Basic Experiment

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Abstract

Production and identification of electron temperature gradient (ETG) modes have been already reported [X.Wei, V.Sokolov, and A.K. Sen, Phys. Plasmas **17**, 042108 (2010)]. Now a measurement of electron thermal conductivity via an unique high frequency triple probe yielded a value of $\chi_{\perp e}$ ranging between 2-10 m^2/s, which is of the order of several gyro-Bohm diffusion coefficient. This experimental result appears to agree with a value of non-local thermal conductivity obtained from a rough theoretical estimation, and not inconsistent with gyrokinetic simulation results for tokamaks. The first experimental scaling of the thermal conductivity vs the amplitude of ETG fluctuation is also obtained. It is approximately linear, indicating a strong turbulence signature.

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The anomalous electron thermal transport is a fundamental open physics issue in magnetic confinement systems. The most plausible physics scenario for this anomalous electron transport seems to be based on Electron Temperature Gradient (ETG) instabilities [1-3]. Ion turbulent transport is fairly understood and has been explained by an interaction between the ion temperature gradient (ITG) instabilities and the zonal flow (ZF) [4]. In contrast, experimental validation of theories of electron transport is lacking. Extensive theoretical and computer simulation work clearly establish its dynamic behavior, both linear and nonlinear [1,2,5-11]. Some simulation results of the transport consequences have been controversial [5, 9]; this controversy appears to be resolved in [10].

The number of experiments with identifications of ETG mode and consequent electron transport is very limited [12-14] due to certain diagnostic problems with the high frequency and short wavelengths of electron turbulence. Although the electron scale fluctuations were identified in a tokamak experiment [14], the ETG characterization was not complete and its role in the electron transport was not directly verified. Production and identification of slab ETG mode have been successfully demonstrated in a basic experiment in Columbia Linear Machine (CLM) [15]. Using a dc bias heating scheme of the core plasma, we were able to produce sufficiently strong electron temperature gradient to excite ETG modes in CLM experiments [15], which has been recently verified partially in numerical simulation [16]. These results and our novel diagnostic technique for local measurement of electron thermal transport enabled the first determination of its direct measurement. Furthermore, we are able to obtain the first scaling of electron thermal conductivity with the amplitude of ETG fluctuations.

The layout of CLM has been described in Ref. 17 and 15. A steady-state collisionless cylindrical plasma column in a uniform axial magnetic field is created in CLM [Fig.1.] The typical plasma parameters in CLM are: $n \sim 5\times10^{9} cm^{-3}$, $B \approx 0.1T$, $T_e \approx 5-20eV$, and $T_i \approx 3-5eV$, the diameter d ~ 6cm and plasma column length L ~ 150cm, respectively [15.16]. The electrons of the plasma core are effectively heated via parallel acceleration by a positively biased (+20V) disk mesh (See Fig.1.). The moderate neutral pressure in the transition region guarantees that the accelerated electrons are thermalized to a Maxwellian distribution. This is confirmed by the parallel electron energy distribution measurement. [15]. We used an especially designed miniature twin Langmuir Probes [15] for the measurement of plasma parameters. Figure 2 shows typical radial profiles of plasma density, electron temperature and its gradient. We have a strong gradient of electron temperature (~ 30eV/cm) at radius ~ 1.8cm, while the profile of density is flat enough so that an ETG mode is excited. Figure 3 shows the typical average power spectra of plasma potential fluctuations. The mode with frequency $f \sim 2.3MHz$ has been identified as ETG mode with azimuthal mode numbers *m =14-16*, and $k_{//} \approx 0.01cm^{-1}$, which is much smaller than $k_{\perp} \sim 8cm^{-1}$ [15]. It should be noted that in our experiment the azimuthal Doppler shift due to the equilibrium electric field is about $m\cdot\omega_{\vec{E}\times\vec{B}}/2\pi \sim m\cdot135\times10^{3} \approx 2MHz$ for $m = 15$. The frequency in the plasma frame is $f_{plasma\ frame} = f_{lab\ frame} - m\cdot f_{\vec{E}\times\vec{B}} \approx +0.3MHz$. The positive sign of the frequency suggests this mode propagates in the same direction as the mode in the lab frame, i.e. the electron diamagnetic direction. In CLM it is the same as the equilibrium $\vec{E}\times\vec{B}$ rotational direction, which is consistent with the propagation of a ETG mode.

The electron thermal conductivity coefficient can be determined by straight forward calculation of the anomalous electron thermal flux from various fluctuation measurements. The radial turbulent thermal flux due to temperature fluctuations is

$$\Gamma_r = \mathrm{Re}\left\{\left\langle \tilde{\upsilon}_r \tilde{T}_e \right\rangle\right\}, \qquad (1)$$

where $\tilde{\upsilon}_r$ is the radial velocity fluctuation and $\tilde{T}_e$ is the electron temperature fluctuation, both represented in complex notation, and $\langle \cdots \rangle$ denotes the cross-correlation. For a drift mode in cylindrical geometry, the plasma potential fluctuation has the form $\tilde{\phi}_p \sim f(r)\exp[i(m\theta + k_{//}z - \omega t)]$, where $f(r)$ is radial mode structure determined by profile variation, m is the azimuthal mode number, and $k_{//}$ is axial wave number. Hence

$$\tilde{\upsilon}_r = \frac{\tilde{E}_\theta}{B} = -\frac{im}{rB}\tilde{\phi}_p,$$

where $\tilde{E}_\theta$ is the azimuthal electric field, and B is the axial magnetic field. Using this, Eq. (1) becomes

$$\Gamma_r = \frac{m}{rB}\mathrm{Re}\left\{i\left\langle \tilde{\phi}_p \tilde{T}_e \right\rangle\right\}$$

The time average of the fluctuations can be obtained through the average of the cross-correlation of the two quantities, or by integrating the cross-power spectrum in the frequency domain:

$$\Gamma_r = \frac{m}{rB}\int \left|P_{\Phi T}\right| \sin\Theta_{\Phi T}\, df \qquad (2)$$

where $P_{\Phi T}$ is the cross-power spectrum of $\tilde{\phi}_p$ and $\tilde{T}_e$, and $\Theta_{\Phi T}$ is the phase of the cross-power spectrum, and f denotes the frequency. We isolate the transport caused by the dominant modes by integrating only across the mode peak in the fluctuation power spectrum. The radial electron thermal conductivity is then given as

$$\chi_{e,r} = -\Gamma_r \cdot (\partial T_e / \partial r)^{-1} = -\Gamma_r \cdot (L_{T_e} / T_{e0}) \qquad (3)$$

The key diagnostic for the measurement of electron thermal transport is the use of a novel high frequency triple probe for measurement of electron temperature fluctuation $\tilde{T}_e$. Usually, a triple probe technique is used for dc measurements of electron temperature of quasi-stationary plasma [18,19]. We used an especially designed miniature triple probe with tungsten tips having a diameter ~ 0.2 mm, and length ~2.0 mm. The triple probe tips are located at the apexes of an equilateral triangle with base ~1mm, and careful alignment allows the tip positions to be separated by less than 1mm in the azimuthal direction (See Fig.1.). For measurement of the floating potential fluctuations $\tilde{\phi}_f$ we put a very small capacitance (0.1pF) as a capacitive probe [20] with impedance ~10^6 Ohm and use preamplifier with $Z_{input} = 10^6 Ohm$; therefore we have input impedance of same order and bandwidth ~3 *MHz*. The same circuit is used for measurement of the floating potential fluctuations of the positive probe $\tilde{\phi}_f^+$ of a double probe. For the sake of minimal perturbations, we use miniature SMD's (surface mounted devices) for resistors and capacitors both in probes and OPAMPs. With our probe arrangement, the temperature fluctuation of $\tilde{T}_e$ is given by [19]: $\tilde{T}_e \approx e(\tilde{\phi}^+ - \tilde{\phi}_f)/\ln 2$, where $\tilde{\phi}_f$ is the floating potential fluctuations of a single probe and $\tilde{\phi}^+$ is the floating potential fluctuations of positive pole of the double probe.

Using the above with previously measured radial gradient of electron temperature in Eqs (2) and (3) the electron thermal conductivity is estimated as

$$\chi_{e,r} \sim 4\ m^2/s \quad \text{for typical CLM plasma parameters in paragraph 3.} \qquad (4)$$

The value of gyroBohm transport coefficient calculated for the same parameters is $\left(\rho_e / L_{Te}\right)\upsilon_{Te}\rho_e \approx 2m^2/s$.

We now consider finding the scaling of electron thermal conductivity vs amplitude of the ETG mode. The variation of ETG mode amplitude was achieved by changing the discharge current and neutral pressure and fine adjustment of annular mesh potential (See Fig.1) for the robust changes of both electron and ion temperatures. The variation of discharge current from 200ma to 400ma leads to increasing electron temperature in the center of the experimental cell from 10eV to 20eV; the ion temperature increases from 3eV to 5 eV, the value of parameter $(L_{Te})^{-1}$ also slightly increases. The growth rate of ETG mode from linear dispersion relation [15] is $\gamma_{ETG} \sim \left(k_{//}^2 \cdot \upsilon_e^2 \cdot \omega_{Te}^* / \tau\right)^{1/3} \sim (T_e \cdot T_e \cdot (L_{Te})^{-1} / (T_e / T_i))^{1/3} \sim T_e^{1/3} \cdot T_i^{1/3} \cdot (L_{Te})^{-1/3}$ which will increase with increasing discharge current.

The resulting scaling of electron thermal conductivity $\chi_{\perp e}$ vs amplitude of ETG mode (normalized potential fluctuation $\tilde{\phi}_f / T_e$) is shown in Fig.4. We observe an almost linear dependence of transport coefficient vs amplitude in range 3%- 7 % of the amplitude of ETG mode, indicative of strong turbulence signature. The corresponding values of the gyroBohm transport coefficient are also shown in Fig.4.

We now discuss a simple theoretical model for transport estimation. The plasma in CLM is an axially uniform column in the experimental region (See Fig.1) as verified by measurements of profiles of plasma parameters in different axial positions. For a rough estimation of radial thermal transport coefficient we used the model from Ref. [21]

and modified Eq.30 therein. There is a hot electron core plasma (heated by disk mesh Fig.1) and colder electron halo plasma formed via diffusion and heated by radial thermal conduction. All electrons carry energy $\propto T_e$ to the endplate. The equality of the divergence of the radial and axial electron energy fluxes can be written [20] as:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\frac{3}{2}n\chi_{\perp e}\frac{\partial}{\partial r}T_e)\cdot L = \alpha T_e n \upsilon_{pl} \qquad (5)$$

where L is length of plasma column, υ_{pl} is plasma flux velocity and α is a coefficient which depends on flux model near end plate. For CLM parameters

$L_{Te} = 0.5\,cm, \quad L \approx 150\,cm, \quad \upsilon_{pl} \approx 2*10^6\,cm/s,$ and $\alpha \sim 6,$ the estimate of the thermal conductivity yields $\chi_{\perp e} \sim L_{Te}^2 \alpha \frac{\upsilon_{pl}}{L} \approx 2\frac{m^2}{s}$, which is consistent with our measurement in Eq.(4).

In conclusion, measurement of electron thermal conductivity $\chi_{\perp e}$ using an unique triple probe ranged between 2-10 m^2/s, which is of the order of several gyro-Bohm diffusion coefficient. This result appears to agree with a value of non-local thermal conductivity obtained from a rough theoretical estimation, and not inconsistent with gyrokinetic simulation results for tokamaks. The first experimental scaling of electron thermal transport coefficient vs amplitude of ETG mode was obtained indicating a linear scaling, a signature of strong turbulence.

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Fig. 1. (Color online) Scheme of CLM and electron heating method.

Fig. 2. (Color online) Radial profiles of electron / ion temperature and plasma density.

Fig. 3. (Color online) Power Spectra of potential fluctuations.

Fig. 4. (Color online) Experimental scaling of electron thermal conductivity vs potential fluctuation level and corresponding gyro-Bohm diffusion coefficient.

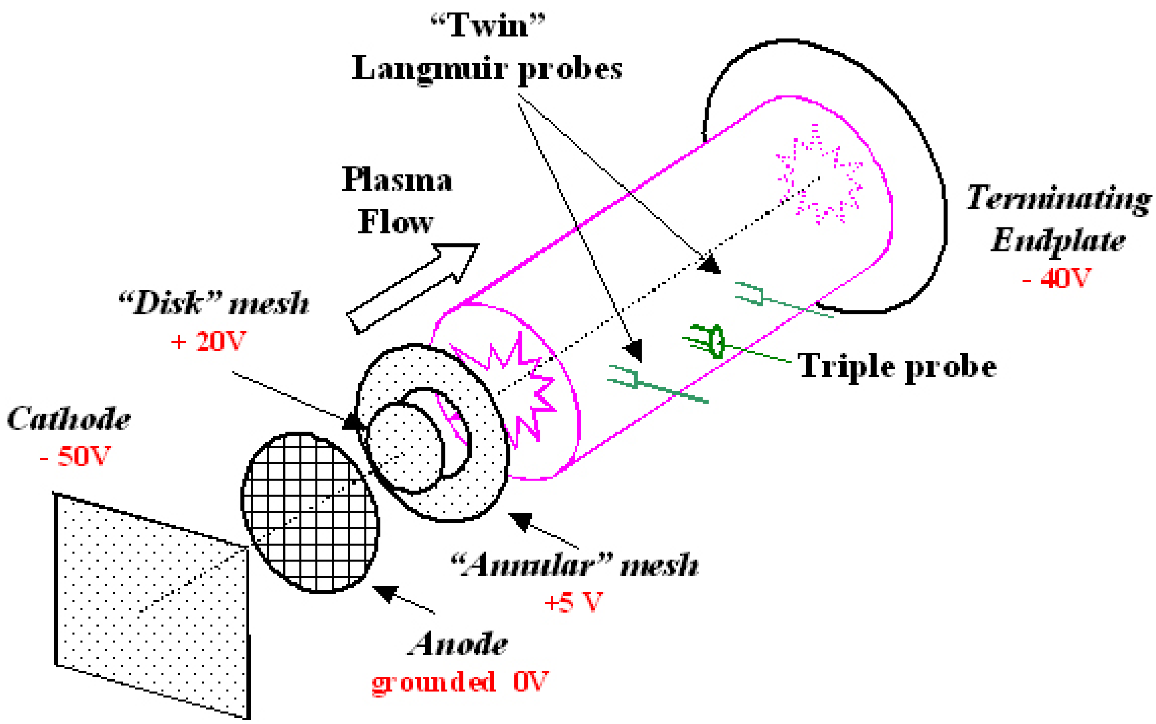

"Twin"
Langmuir probes
Plasma
Flow
Terminating
Endplate
- 40V
"Disk" mesh
+ 20V
Triple probe
Cathode
- 50V
"Annular" mesh
+5 V
Anode
grounded 0V

Fig.1.

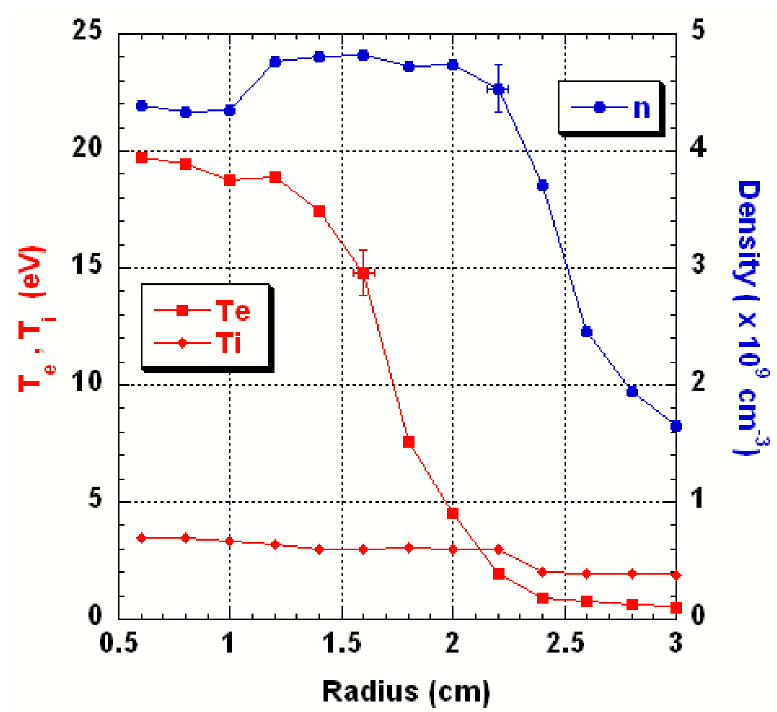
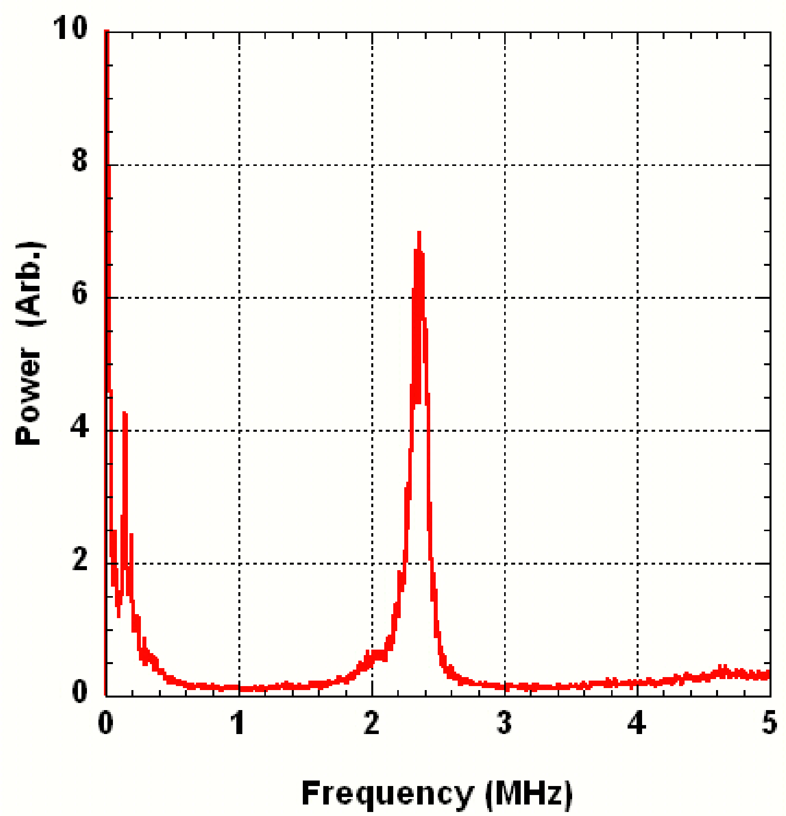
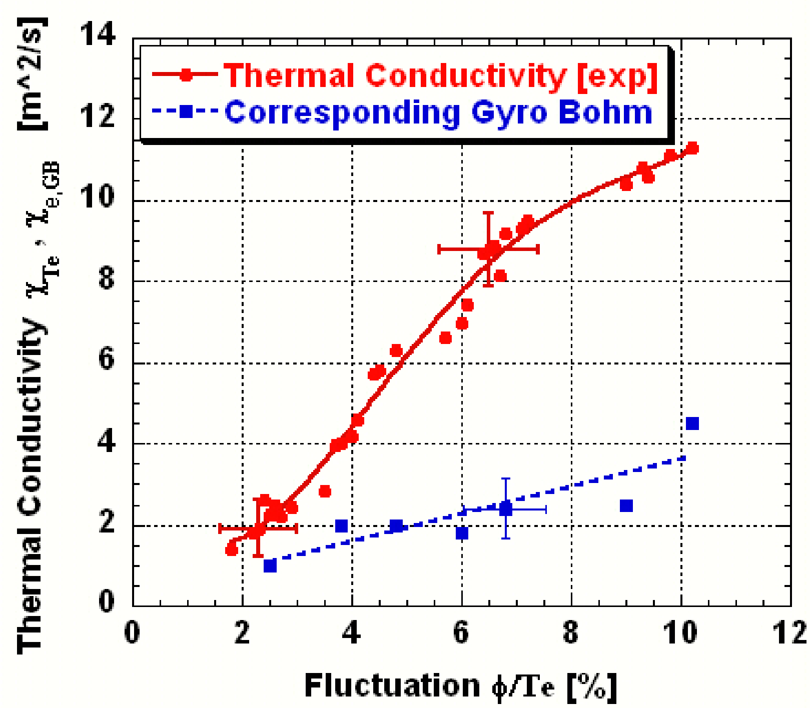

n
Te
Ti
T_e, T_i (eV)
Density (x 10^9 cm^{-3})
Radius (cm)

Fig.2.



Power (Arb.)
Frequency (MHz)
0
2
4
6
8
10
0
1
2
3
4
5

Fig.3.



Thermal Conductivity [exp]
Corresponding Gyro Bohm
Thermal Conductivity χ_{Te} , $\chi_{e,GB}$ [m^2/s]
Fluctuation ϕ/Te [%]
0
2
4
6
8
10
12
14
0
2
4
6
8
10
12

Fig.4.