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

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(Received 20 May 2011; published 5 October 2011)

Production and identification of electron temperature gradient modes have already been reported [X. Wei, V. Sokolov, and A. K. Sen, Phys. Plasmas **17**, 042108 (2010)]. Now a measurement of electron thermal conductivity via a unique high frequency triple probe yielded a value of $\chi_{\perp e}$ ranging between 2 and 10 $\mathrm{m^2/s}$, which is of the order of a several gyrobohm diffusion coefficient. This experimental result appears to agree with a value of nonlocal 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 versus the amplitude of the electron temperature gradient fluctuation is also obtained. It is approximately linear, indicating a strong turbulence signature.

DOI: 10.1103/PhysRevLett.107.155001 PACS numbers: 52.25.Fi, 52.35.Kt

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 well understood and has been explained by an interaction between the ion temperature gradient instabilities and the zonal flow [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 Ref. [10].

The number of experiments with identifications of the 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 the slab ETG mode have been successfully demonstrated in a basic experiment in the Columbia Linear Machine (CLM) [15]. Using a dc bias heating scheme of the core plasma, we were able to produce a sufficiently strong electron temperature gradient to excite ETG modes in CLM experiments [15], which has been recently verified partially in a 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 the CLM has been described in Refs. [15,17]. A steady-state collisionless cylindrical plasma column in a uniform axial magnetic field is created in the CLM [Fig. 1.] The typical plasma parameters in the CLM are $n \sim 5 \times 10^9\ \mathrm{cm^{-3}}$, $B \approx 0.1$ T, $T_e \approx 5$–20 eV, and $T_i \approx 3$–5 eV, the diameter $d \sim 6$ cm, and plasma column length $L \sim 150$ cm [15,16]. The electrons of the plasma core are effectively heated via parallel acceleration by a positively biased (+ 20 V) 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 especially designed miniature twin Langmuir probes [15] for the measurement of plasma parameters. Figure 2 shows typical radial profiles of the plasma density, the electron temperature, and its gradient. We have a strong gradient of electron temperature (~ 30 eV/cm) at radius ~ 1.8 cm, 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 $f \sim 2.3$ MHz has been identified as the ETG mode with azimuthal mode numbers $m = 14$–16,

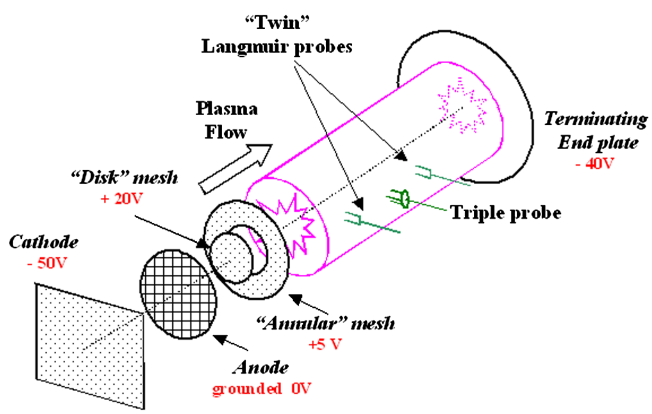

FIG. 1 (color online). Scheme of the CLM and electron heating method.

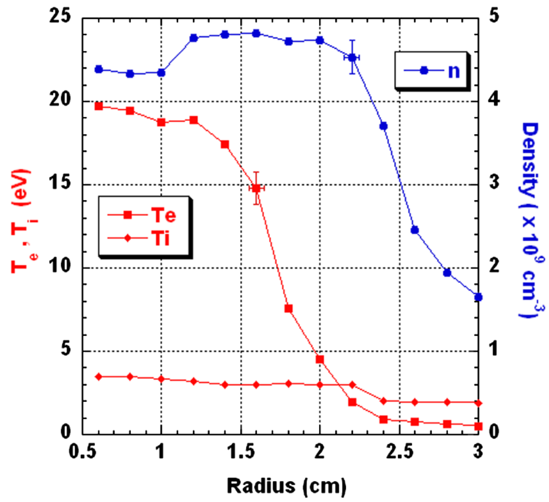

FIG. 2 (color online). Radial profiles of electron and ion temperature and plasma density.

and $k_{\|} \approx 0.01\ \text{cm}^{-1}$, which is much smaller than $k_{\perp} \sim 8\ \text{cm}^{-1}$ [15]. It should be noted that in our experiment the azimuthal Doppler shift due to the equilibrium electric field is about $m\omega_{\vec{E}\times\vec{B}}/2\pi \sim m(135 \times 10^3) \approx 2$ MHz for $m = 15$. The frequency in the plasma frame is $f_{\text{plasma frame}} = f_{\text{lab frame}} - mf_{\vec{E}\times\vec{B}} \approx +0.3$ MHz. The positive sign of the frequency suggests that this mode propagates in the same direction as the mode in the lab frame, i.e., the electron diamagnetic direction. In the CLM it is the same as the equilibrium $\vec{E} \times \vec{B}$ rotational direction, which is consistent with the propagation of an ETG mode.

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

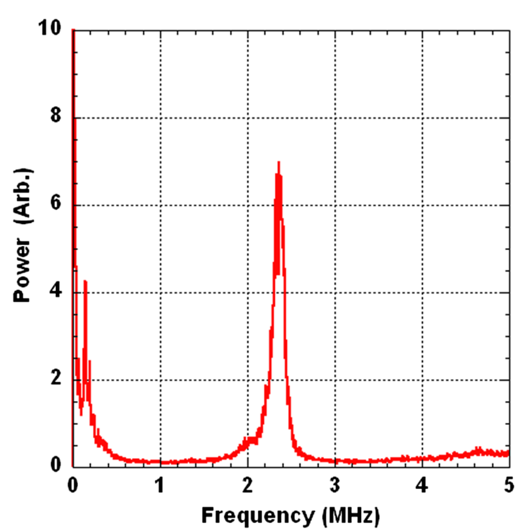

FIG. 3 (color online). Power spectra of potential fluctuations.

$$\Gamma_r = \mathrm{Re}\{\langle \tilde{v}_r \tilde{T}_e \rangle\}, \tag{1}$$

where $\tilde{v}_r$ 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 the radial mode structure determined by profile variation, m is the azimuthal mode number, and $k_{\|}$ is the axial wave number. Hence

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

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

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

Alternatively, the above can be found by integrating the cross-power spectrum in the frequency domain:

$$\Gamma_r = \frac{m}{rB}\int |P_{\Phi T}| \sin\Theta_{\Phi T} df, \tag{2}$$

where $P_{\Phi T}$ is the cross-power spectrum of $\tilde{\phi}_p$ and $\tilde{T}_e$, $\Theta_{\Phi T}$ 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

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

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 the electron temperature of quasistationary 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 ~1 mm, and careful alignment allows the tip positions to be separated by less than 1 mm in the azimuthal direction (see Fig. 1). For measurement of the floating potential fluctuations $\tilde{\phi}_f$, we put a very small capacitance (0.1 pF) as a capacitive probe [20] with impedance $\sim 10^6$ Ohm and use preamplifier with $Z_{\text{input}} = 10^6$ Ohm; therefore, we have input impedance of the 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 surface mounted devices for resistors, capacitors, and operational amplifiers in both probes. 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 the positive pole of the double probe.

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

$$\chi_{e,r} \sim 4\ \mathrm{m}^2/\mathrm{s} \tag{4}$$

for the typical CLM plasma parameters in paragraph 3.

The value of the gyrobohm transport coefficient calculated for the same parameters is $(\rho_e/L_{Te})v_{Te}\rho_e \approx 2\ \mathrm{m}^2/\mathrm{s}$.

We now consider finding the scaling of electron thermal conductivity versus the amplitude of the ETG mode. The variation of the ETG mode amplitude was achieved by changing the discharge current and neutral pressure and a fine adjustment of the annular mesh potential (see Fig. 1) for the robust changes of both electron and ion temperatures. The variation of discharge current from 200 to 400 ma leads to an increasing electron temperature in the center of the experimental cell from 10 to 20 eV; the ion temperature increases from 3 to 5 eV, and the value of parameter $(L_{Te})^{-1}$ also slightly increases. The growth rate of the ETG mode from the linear dispersion relation [15] is

$$\gamma_{\mathrm{ETG}} \sim (k_\parallel^2 v_e^2 \omega_{Te}^*/\tau)^{1/3} \sim [T_e T_e (L_{Te})^{-1}/(T_e/T_i)]^{1/3} \sim T_e^{1/3} T_i^{1/3} (L_{Te})^{-1/3},$$

which will increase with an increasing discharge current.

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

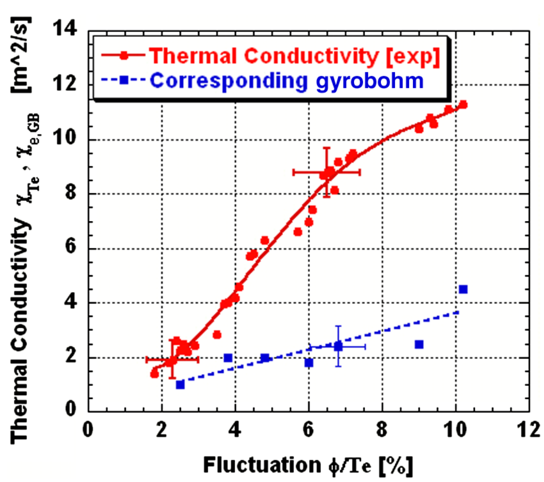

FIG. 4 (color online). Experimental scaling of electron thermal conductivity versus the potential fluctuation level and the corresponding gyrobohm diffusion coefficient.

We now discuss a simple theoretical model for transport estimation. The plasma in the 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 the 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 the disk mesh; see Fig. 1) and a colder electron halo plasma formed via diffusion and heated by radial thermal conduction. All electrons carry energy $\propto T_e$ to the end plate. The equality of the divergence of the radial and axial electron energy fluxes can be written [20] as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{3}{2}n\chi_{\perp e}\frac{\partial}{\partial r}T_e\right)L = \alpha T_e n v_{pl}, \tag{5}$$

where L is length of plasma column, v_{pl} is plasma flux velocity, and α is a coefficient which depends on the flux model near the end plate. For CLM parameters $L_{Te} = 0.5$ cm, $L \approx 150$ cm, $v_{pl} \approx 2 \times 10^6$ cm/s, and $\alpha \sim 6$, the estimate of the thermal conductivity yields $\chi_{\perp e} \sim L_{Te}^2 \alpha \frac{v_{pl}}{L} \approx 2 \frac{m^2}{s}$, 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 and 10 m^2/s, which is of the order of a several gyrobohm diffusion coefficient. This result appears to agree with a value of nonlocal thermal conductivity obtained from a rough theoretical estimation and not inconsistent with gyrokinetic simulation results for tokamaks. The first experimental scaling of the electron thermal transport coefficient versus the amplitude of the ETG mode was obtained, indicating a linear scaling, a signature of strong turbulence.

The authors acknowledge fruitful discussions with Yu. Tsidulko on the model of Eq. (5). This research was supported by the U.S. Department of Energy Grant No. DE-FG02-98ER-54464.

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