Fluctuation and Electron-Heat Transport in a Reversed-Field-Pinch Plasma

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Fluctuations are experimentally studied using Langmuir probes and magnetic probes in the $a/2 \lesssim r \leq a$ region of the REPUTE-1 reversed-field-pinch plasma. An electron-heat flux q_E^e due to electrostatic fluctuations is too small to account for the total electron-heat flux $q_{\rm total}^e$. It is implied that magnetic fluctuations mainly determine the electron energy confinement in the interior region.

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Anomalous transport has generally been attributed to plasma turbulence, including the electrostatic one and the magnetic one [1]. It has been reported for various tokamaks that the measured particle flux due to electrostatic fluctuations can account for the total flux determined by particle-balance analysis in the edge region [2–4]. However, only a few experimental results have shown that the total electron-heat flux $q_{\rm total}^e$ from energy balance can be explained by the measured electron-heat flux q_E^e due to electrostatic fluctuations at the edge region, except for the case of the lowest-density discharges [5]. The levels of the magnetic fluctuation $\tilde{\mathbf{B}}$ observed at the edge are too small to account for $q_{\rm total}^e$ [5,6]. However, a clear anticorrelation has been found between the edge $\tilde{\mathbf{B}}$ level and the global energy confinement time in many tokamaks [6–8]. For the interior region, this problem remains an open question, although there has been some indirect evidence [8–10] which suggests the important role of $\tilde{\mathbf{B}}$ in the electron-heat transport in tokamaks.

The reversed field pinch (RFP), whose configuration is different from that of the tokamak, also suffers from anomalous transport. However, there have been no direct measurements of the particle or heat flux driven by the electrostatic fluctuations until now. The relative magnetic fluctuation levels measured in RFPs are more than 1 order higher than those in the tokamaks [11]. It is natural to attribute anomalous energy transport to the magnetic fluctuations [12,13]. The ZT-40M experiments [14] show that fast electrons detected by an electrostatic energy analyzer in the edge ($r \sim a$) could carry a large portion of energy which is lost to the wall. Recent fluctuation measurements [15] in ZT-40M are also noteworthy. In this Letter, we report the results of fluctuation measurements with respect to the electron-heat transport in the $a/2 \lesssim r \leq a$ region of the REPUTE-1 [16] RFP plasma, which has a major radius of $R = 82$ cm and a minor radius of $a = 22$ cm. The outward electron-heat flux q_E^e due to the electrostatic fluctuations is directly measured. Some discussion about the electron-heat flux q_B^e due to the magnetic fluctuations is also given.

A four-channel triple-probe and magnetic-probe array is used to measure the profiles of the mean and fluctuation parts of the plasma density n, electron temperature T_e, space potential ϕ_s (with respect to the wall potential), and magnetic fields B_t, B_p, and B_r at four radial positions (15 mm separation). Each channel consists of a triple probe, a single probe, and a three-component magnetic probe. Plasma parameters such as n, T_e, and ϕ_s can be determined by using a triple probe [17], in which a constant voltage is applied between two tips, and the third one is floating. T_e and n are determined from the probe current flowing through the biased two tips and the potential difference between the positively biased tip and the third floating tip [17]. ϕ_s is obtained from T_e and the floating potential ϕ_f. A nonuniform space potential $\tilde{\phi}_s$ between the tips may affect the measurements, but with the use of an additional (fourth) tip, its effects are reduced sufficiently, i.e., introducing ambiguities of only $\sim 2.5\%$ and $\sim 6\%$ in T_e and n measurements. Fast electrons also may have effects on the interpretation of probe data. As an estimation, in the case of n^F (density of fast electrons) equal to $5\% \times n$, T_e^F (temperature of fast electrons) equal to $5T_e$, and γ (secondary emission coefficient) equal to 1.2 as in the ZT-40M edge [14], T_e is underestimated by $\sim 3\%$ while n is overestimated by $\sim 8\%$. In order to examine the effects due to the fast electrons experimentally, we inserted a triple probe with an obstacle nearby into the plasma. Comparing the results obtained in three cases, i.e., with or without the obstacle upstream or downstream from the field line, we found no more observable differences between them than the shot-by-shot variation; therefore, we do not expect a significant perturbation to our triple-probe measurements.

A complex probe is constructed to measure correlations between the fluctuations. Six probe tips are fixed within an area of 10 mm×3 mm at the front plane which is perpendicular to the radial direction. Four of the tips are used as a triple probe measuring $\tilde{n}$ and $\tilde{T}_e$, and the rest are used as a floating double probe. The second double probe consists of two floating tips; one is from the triple probe and another is from the first double probe. These two floating double probes are used to measure fluctuations in the toroidal and poloidal components of an electric field, $\tilde{E}_t$ and $\tilde{E}_p$.

The experiments presented here were carried out at a relatively low plasma current ($I_p \sim 110$ kA). All measured quantities mentioned in this paper are taken in the time interval of 0.2 ms around the current flattop. The loop voltage, the reversal ratio F, the pinch parameter Θ, and the chord-averaged density $\bar{n}_e$ are $V_l \sim 220$ V, $F \sim -0.4$, $\Theta \sim 2.0$, and $\bar{n}_e \sim 4.4\times 10^{19}$ m^{-3}, respectively.

A time-varying quantity can be decomposed into mean ($f < 5$ kHz, denoted by overbars) and fluctuation parts (5 kHz $\le f \le 70$ kHz, denoted by tildes) using a numerical filter. Radial profiles of the mean values and the relative fluctuation levels are shown in Fig. 1, where the error bars indicate the shot-by-shot variation. As the radius decreases, $\bar{n}$, $\bar{T}_e$, and $\bar{\phi}_s$ increase to $\sim 6.0\times 10^{19}$ m^{-3}, ~ 22 eV, and $\sim +25$ V at $r \sim a/2$, respectively. At $r \sim a$, $|\tilde{B}_t|/\bar{B}_0$ is about twice $|\tilde{B}_p|/\bar{B}_0$ and $|\tilde{B}_r|/\bar{B}_0$, but at $r \sim a/2$, $|\tilde{B}_r|/\bar{B}_0$ is about twice the others (the vertical bars denote rms level). The relative level of $\tilde{B}_r$ increases from $< 1\%$ at $r \sim a$ to $\sim 3\%$ at $r \sim a/2$. The relative level

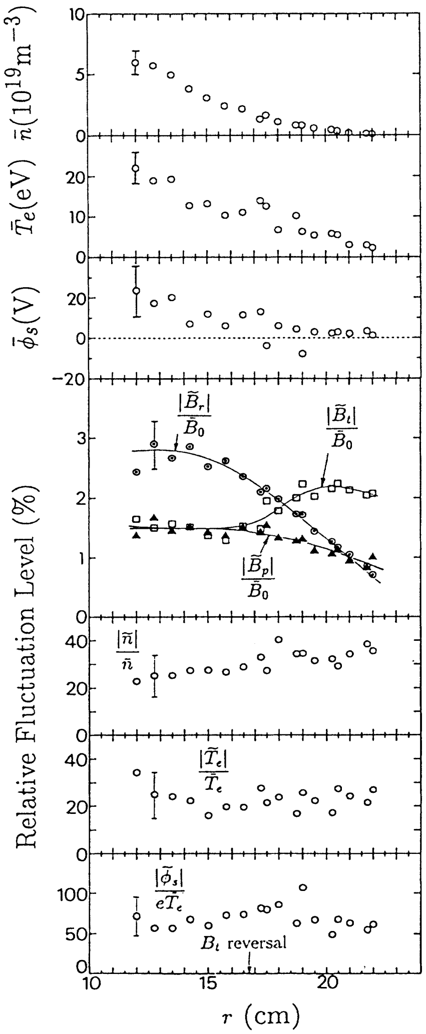

FIG. 1. Radial profiles of the mean values and the relative fluctuation levels of magnetic field (B_t, B_p, B_r), density n, electron temperature T_e, and space potential ϕ_s. Here, B_0 is the total magnetic field.

$|\tilde{T}_e|/\bar{T}_e$ of (15–30)% is comparable to $|\tilde{n}|/\bar{n}$ of (20–40)% and is smaller than $e|\tilde{\phi}_s|/\bar{T}_e$ of (50–100)%. As the radius decreases to $r \sim a/2$, $|\tilde{E}_t|$ and $|\tilde{E}_p|$ measured by the complex probe increase to ~ 0.5 kV/m and ~ 0.7 kV/m, respectively.

When $\tilde{v}_r$ denotes the radial fluctuating velocity induced by $\tilde{\mathbf{E}}\times\mathbf{B}$, the electron-heat flux q_E^e due to electrostatic fluctuations can be expressed as

$$q_E^e = \tfrac{3}{2}\langle \tilde{p}_e \tilde{v}_r\rangle = \frac{3}{2}\frac{\bar{p}_e}{\bar{B}_0^2}\left[\bar{B}_t|\tilde{E}_p|\frac{|\tilde{p}_e|}{\bar{p}_e}C_{p_e,E_p} - \bar{B}_p|\tilde{E}_t|\frac{|\tilde{p}_e|}{\bar{p}_e}C_{p_e,E_t}\right], \quad (1)$$

where $p_e = nT_e$ is the electron pressure, and the normalized correlation coefficient between $\tilde{\alpha}$ and $\tilde{\beta}$ is defined by $C_{\alpha,\beta} = \langle\tilde{\alpha}\tilde{\beta}\rangle/|\tilde{\alpha}||\tilde{\beta}|$. Note that

$$\frac{|\tilde{p}_e|}{\bar{p}_e}C_{p_e,E} = \frac{|\tilde{n}|}{\bar{n}}C_{n,E} + \frac{|\tilde{T}_e|}{\bar{T}_e}C_{T_e,E} \quad (E = E_t, E_p). \quad (2)$$

A correlation between fluctuations is described by the coherence and phase as a function of frequency [3]. Fluctuations measured by the complex probe are well correlated with each other, i.e., coherences are not less than ~ 0.5 in most frequency ranges. It is found that the density fluctuation $\tilde{n}$ is almost in antiphase with $\tilde{E}$ ($C_{n,E} \sim -0.4$), while the electron-temperature fluctuation $\tilde{T}_e$ is in phase with $\tilde{E}$ ($C_{T_e,E} \sim +0.4$). $\tilde{n}$ and $\tilde{T}_e$ are almost in antiphase ($C_{n,T_e} \sim -0.4$). Since the two terms on the right-hand side of Eq. (2) have almost the same absolute values but the opposite signs, the left-hand side becomes much smaller. When Eq. (2) is substituted into Eq. (1), q_E^e can be expressed by a sum of four terms as shown in Fig. 2. The error bars indicate the shot-by-shot variation again. We find that $|q_E^e|$ is smaller than 0.1 MW/m^2. If $\tilde{T}_e$ and $\tilde{n}$ were in phase and had perfect correlations with $\tilde{E}$, the resulting q_E^{eM} could be ~ 0.56 MW/m^2 at $r \sim a/2$. As the radius increases to $\sim a$, all four terms in Fig. 2 become zero because of both small

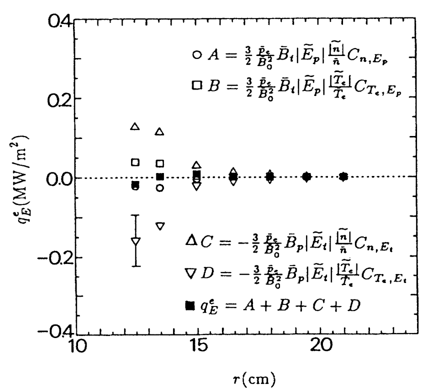

FIG. 2. Radial profiles of the electrostatic-fluctuation-induced electron-heat flux q_E^e (solid squares) expressed by a sum of four terms (open symbols).

$|\tilde{E}|$ and small $\bar{p}_e$.

The total input power into the plasma at the current flattop is given by $I_p V_l$, and $\int \eta j^2 dv$ of it heats electrons. The remainder of the power is usually assumed to heat ions [18]. Generally, the ratio of $\int \eta j^2 dv$ to the total power depends on the magnetic configuration and resistivity profile. In our case of $F \sim -0.4$ and $\Theta \sim 2.0$, we can assume that approximately half of the total power $I_p V_l$ heats the electrons [18] and the balance goes to an outward electron-heat flux $q^e_{\rm total}$:

$$q^e_{\rm total}(a) \sim 0.5 I_p V_l / S_{\rm surface} \sim 1.8 \ {\rm MW/m^2}.$$

For $r = a/2$, with the use of

$$r q^e_{\rm total}(r) = a q^e_{\rm total}(a) - \int_r^a \eta j^2 r\, dr$$

and Spitzer's formula for resistivity η (assuming $Z_{\rm eff} = 2$), we obtain $q^e_{\rm total}(a/2) \sim 2.3$ MW/m^2. Ignoring radiation and collisional transfer to ions in the outer half radius may lead to an underestimate for $q^e_{\rm total}(a/2)$, while the assumption of classical resistivity may lead to an overestimate. Although a further reliable estimate is impossible without future relevant measurements, here we might consider 20% of $I_p V_l$ as a possible error bar; i.e., $q^e_{\rm total}(a/2) = 2.3 \pm 0.9$ MW/m^2. Our measurements show that electron-heat flux q^e_E due to $\tilde{\mathbf{E}}$ is small [$\lesssim (3\text{–}7)\%$ of $q^e_{\rm total}$], while $q^{eM}_E \sim 0.56$ MW/m^2 is about (20–40)% of $q^e_{\rm total}$ at $r \sim a/2$. This result is in contrast to that obtained in the edge region of tokamaks [5].

Several ambiguities could arise here. First, the positional spread of $d = 10$ mm in the complex probe may introduce additional errors to the correlation measurements. A typical wave number of the fluctuations can be estimated simply by $\bar{k} \sim |\tilde{E}|/|\tilde{\phi}_s| \lesssim 0.5$ cm^{-1}, so an error of $kd \lesssim 0.5$ (corresponding $\lesssim 30°$) may arise in measuring the phase between fluctuations. This uncertainty could bring relative errors of $\sim 15\%$ to Fig. 2. Second, $\tilde{E}$ ($\equiv -\nabla\tilde{\phi}_f$) measured by the double probes is different from $\tilde{E}^*$ ($\equiv -\nabla\tilde{\phi}_s$), due to the large $\tilde{T}_e$ in the relation

$$\tilde{E} = \tilde{E}^* + c\nabla\tilde{T}_e \qquad (3)$$

(i.e., $c|\tilde{T}_e| \sim |\tilde{\phi}_s|$), where c is a constant $\simeq 2.1$ in our case. If it is assumed that the fluctuation can be expressed as a sum of plane waves with a constant phase velocity (i.e., the fluctuation has a linear dispersion relation as measured in tokamaks [3] and ZT-40M [15]), we have

$$\langle\tilde{\alpha}\tilde{\beta}\rangle \equiv \lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2}\tilde{\alpha}(x,t)\tilde{\beta}(x,t)\,dt\,|_{x=x_0}$$
$$= \lim_{X\to\infty}\frac{1}{X}\int_{-X/2}^{X/2}\tilde{\alpha}(x,t)\tilde{\beta}(x,t)\,dx\,|_{t=t_0},$$

where x is the toroidal-poloidal coordinate and t is the time. We multiply Eq. (3) by $\tilde{T}_e$ and take its correlation. Since the last term $(c/2)\lim_{X\to\infty}X^{-1}[\tilde{T}_e^2]^{x=X/2}_{x=-X/2}$ is zero, we obtain $\langle\tilde{T}_e\tilde{E}\rangle = \langle\tilde{T}_e\tilde{E}^*\rangle$. Next we multiply Eq. (3) by $\tilde{n}$, $\tilde{E}$, and $\tilde{E}^*$ and use the fact that $\tilde{n}$ and $\tilde{T}_e$ are almost in antiphase, and the fact that $\tilde{T}_e$ and $\tilde{E}$ ($\tilde{E}^*$) are almost in phase, to derive $\langle\tilde{n}\tilde{E}\rangle \simeq \langle\tilde{n}\tilde{E}^*\rangle$ and $|\tilde{E}|^2 \simeq \langle\tilde{E}\tilde{E}^*\rangle \simeq |\tilde{E}^*|^2$ in the same way. Therefore, we can obtain $\langle\tilde{T}_e\tilde{E}^*\rangle$, $\langle\tilde{n}\tilde{E}^*\rangle$, and $|\tilde{E}^*|$ without direct measurements of $\tilde{E}^*$, but the phase error ($\lesssim 30°$) due to the positional spread may introduce a relative error of $\lesssim 35\%$ in Fig. 2. Finally, if the fast electrons exist, an additional term $[c'(\nabla\tilde{n}^F/n^F - \nabla\tilde{n}/n) + c''\nabla\tilde{T}^F_e/T^F_e]T_e$ must be added to the right-hand side of Eq. (3), where $c' \simeq -0.12$ and $c'' \simeq -0.11$ in the case of $n^F/n = 5\%$, $T^F_e/T_e = 5$, and $\gamma = 1.2$. Although the fast electrons are not measured, this term is expected to be small ($\lesssim 20\%$ of $c\nabla\tilde{T}_e$). These ambiguities could double the error bars in Fig. 2, but do not significantly affect the result of $|q^e_E| \lesssim 0.1$ MW/m^2. According to a bolometer measurement [19], another mode of electron-heat loss, due to radiation, is about 20% of the total input power. A neoclassical electron-heat flux [11,20] $q^e_{\rm class}$ is estimated at $r \sim a/2$:

$$q^e_{\rm class} = \rho_e^2 \nu_{ei} p_e (4.66\nabla T_e/T_e + 5.67\nabla n/n)$$
$$\sim 0.026 \ {\rm MW/m^2},$$

which is about 1% of $q^e_{\rm total}$.

Harvey *et al.* [21] have derived expressions of particle flux Γ^e_B and heat flux q^e_B due to stochastic magnetic fields [22,23], combining the effect of an ambipolar radial electric field E^a. If an ambipolar particle flux is assumed ($\Gamma^e_B = \Gamma^i_B \equiv \Gamma^a_B$), the electron thermal diffusivity χ^e_B is calculated as $\chi^e_B = (8/\pi)^{1/2} v^e_{\rm th} L_\parallel (|\tilde{B}_r|/B_0)^2$, where $v^e_{\rm th}$ is the electron thermal velocity, and $L_\parallel$ is the correlation length of $\tilde{B}_r$ along the unperturbed field, defined as $L_\parallel = \pi/\Delta k_\parallel$ [23]. Here, $\Delta k_\parallel$ is the spectral width of a parallel-wave-number spectrum of $\tilde{B}_r$. Since $B_p \gg B_t$ at $r \sim a$ in a RFP, we have $k_\parallel \simeq m/a$, where m is the poloidal mode number. The m spectrum of $\tilde{B}_r$ is measured by an eight-channel poloidal array of magnetic-field pickup coils [24]. It is found that most fluctuation power is concentrated in the $m = 0, \pm 1$ modes, so we estimate $L_\parallel \sim \pi a/\Delta m \sim \pi a/2 \sim 35$ cm. Then the estimated q^e_B of ~ 2.0 MW/m^2 is comparable to $q^e_{\rm total}$ at $r \sim a/2$, suggesting that $\tilde{B}_r$ plays an important role in the electron energy confinement in the interior region.

This suggestion is supported by experimental evidence. First, a positive space potential ϕ_s of order of T_e/e is observed inside the plasma (Fig. 1). This fact can be explained by an ambipolar electric field

$$E^a = -(T_e/e)(\nabla n/n + \nabla T_e/2T_e);$$

therefore, $\phi_s(r) = -\int_a^r E^a dr \sim T_e(r)/e$, expected in the kinetic treatment [21]. Second, a scaling study shows that the electron energy confinement time at the center, $\tau^e_{E0} \equiv \frac{3}{2}\bar{n}_e T_e(0) V_{\rm plasma}/0.5 I_p V_l$, is approximately in inverse proportion to $(|\tilde{B}_r|/|\bar{B}_p|)^2$ ($\propto \chi^e_B$). Finally, the fast electrons detected at the edge of ZT-40M are considered to be generated from leakage of hot electrons at the center along the stochastic field lines due to $\tilde{B}_r$ [14].

The particle flux due to electrostatic fluctuations $\Gamma_E = \langle \tilde{n}\tilde{v}_r \rangle \sim 2.2\times 10^{22}/\mathrm{m}^2\mathrm{s}$ is measured at $r \sim a/2$. The total particle flux $\Gamma_{\rm total}$ is given by $\Gamma_{\rm total} = \bar{n}_e V_{\rm plasma}/\tau_p S_{\rm surface}$ but there is no information on the particle confinement time τ_p. To estimate the *order* of $\Gamma_{\rm total}$, we assume $\tau_p = 2\tau_{E0}^e \sim 80$ μs as an example, since τ_p is usually longer than τ_E [25]. We obtained $\Gamma_{\rm total} \sim 6.1 \times 10^{22}/\mathrm{m}^2\mathrm{s}$. On the other hand, the ambipolar particle flux Γ_B^g due to $\tilde{B}_r$ is given by

$$\Gamma_B^g = -D_B^i[(1+T_e/T_i)\nabla n + n\nabla(T_e+T_i)/2T_i]\,,$$

where $D_B^i = (2/\pi)^{1/2} v_{\rm th}^i L_\parallel (|\tilde{B}_r|/B_0)^2$. The central ion temperature $T_i(0) \sim 100$ eV, measured from the Doppler broadening of the O V line, is about twice $T_e(0) \sim 50$ eV, measured by a Thomson scattering system. At $r \sim a/2$, if $T_i \sim 2T_e$ is assumed, the value of Γ_B^g is estimated to be $\sim 2.1\times 10^{22}/\mathrm{m}^2\mathrm{s}$, which is comparable to Γ_E. A particle flux due to neoclassical process [11,20] is

$$\Gamma_{\rm class} = 3.78 \rho_e^2 \nu_{ei} \nabla n \sim 0.1\times 10^{22}/\mathrm{m}^2\mathrm{s}\,.$$

In the region of $r \sim a$, neither q_E^e nor q_B^e (Γ_E nor Γ_B^g) can explain $q_{\rm total}^e$ ($\Gamma_{\rm total}$). This region is sensitive to the toroidal and poloidal asymmetry, such as large field errors, ripplings, displacement of plasma column [24], etc. The fast electrons may be important also. For further discussions on this region, relevant considerations or measurements about these effects are necessary.

In conclusion, $\tilde{n}$ shows negative correlations with $\tilde{T}_e$ in the $a/2 \lesssim r \leq a$ region. The electron-heat flux q_E^e due to electrostatic fluctuations is too small to account for the total electron-heat flux $q_{\rm total}^e$. It is implied that the magnetic fluctuations mainly determine the electron energy confinement in the interior region, consistent with previous works [12,13].

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