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Fluctuation and Edge Current Sustainment in a Reversed-Field-Pinch

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Abstract

Simple Ohm's law $\eta j_{\|} = E_{\|}$ is not satisfied in $a/2 \lesssim r \leq a$ region of the REPUTE-1 RFP plasma. Fluctuation-induced electric fields, such as $\left\langle \tilde{\boldsymbol{v}} \times \widetilde{\boldsymbol{B}} \right\rangle$, are not sufficient to account for $\eta j_{\|} - E_{\|}$ at the edge. It is implied that current-diffusions due to magnetic fluctuations, carried by fast electrons rather than bulk cold electrons, sustain the edge parallel equilibrium current.

Keywords: Fluctuation, dynamo effect, Ohm's law, current diffusion, REPUTE-1, RFP

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The field reversal phenomenon, *i.e.* the toroidal field reverses its direction at plasma edge in a reversed-field-pinch(RFP), has attracted much theoretical and experimental interest constantly since its first observation in 1960s. Taylor's relaxed state theory[1] has successfully described the field reversal configuration as a state of minimum energy, but it did not give a physical picture of the relaxation process. Many efforts have been made in order to clarify the governing physical mechanism, especially during the sustainment phase of RFPs, in which the reversed field is continuously generated against classical resistive diffusion. Various theoretical models proposed so far can be classified into two broad classes: stochastic field models and MHD turbulent dynamo models. The standard former model is the so-called kinetic dynamo theory(KDT)[2,3], in which RFP configuration is sustained by radial diffusions of the parallel current due to the stochastic field. The fast electrons, observed recently in the edge[4] or even in the core[5] plasma, are considered as a experimental evidence[6] for KDT. Besides this model, there are two models related with the stochastic field; one is the tangled discharge model(TDM)[7], another is the resistive evolution model[8]. But recent investigations[9,10] showed that the former is not appropriate for the present RFP, and the latter is closely related with KDT.

The original MHD turbulent dynamo model[11] which is based on an analogy of the geomagnetic dynamo theory, has been developed by a large number of authors[12,13,14,15,16,17,18,19,20] (most of them used the numerical simulation), but they all have the same essence, *i.e.*, assuming an additional electric field induced by fluctuations in the mean Ohm's Law along the mean magnetic field:

$$E_{\parallel} + \left\langle \tilde{\boldsymbol{v}} \times \widetilde{\boldsymbol{B}} \right\rangle_{\parallel} = \eta j_{\parallel} \tag{1}$$

where $E_{\parallel}$ is the externally applied inductive parallel electric field, η the electric resistivity, $j_{\parallel}$ the parallel current, $\tilde{\boldsymbol{v}}$ and $\widetilde{\boldsymbol{B}}$ are fluctuations of the fluid velocity and the magnetic field, respectively. However, the fluctuation-induced electric field $\left\langle \tilde{\boldsymbol{v}} \times \widetilde{\boldsymbol{B}} \right\rangle_{\parallel}$ has never been measured in laboratory, thus the dynamo hypothesis has never been confirmed so far. In this letter, we report the results of fluctuation measurements focusing the fluctuation-induced electric field in $a/2 \lesssim r \leq a$ region of the REPUTE-1[21] RFP plasma, which has a major radius of $R = 82$ cm and a minor radius of $a = 22$ cm. All terms in Eq.(1) including $\left\langle \tilde{\boldsymbol{v}} \times \widetilde{\boldsymbol{B}} \right\rangle_{\parallel}$ are examined experimentally. Some discussions about other possible terms in the parallel Ohm's law, including that originated from current diffusion, are also given.

Because diagnostics used here have been already described in detail in other published works[22,23], we give a brief summary as follows. A triple-probe technique was developed[22] in order to meet the request of measuring mean ($f < 5$ kHz, denoted by overbars) and fluctuation parts (5 kHz $\leq f \leq$ 70 kHz, denoted by tildes) of plasma density n, electron temperature T_e and space potential ϕ_s (with respect to the wall potential) simultaneously in a fluctuating plasma. Effects due to a non-uniform space potential $\tilde{\phi}_s$ between the tips can be reduced sufficiently by using an additional (fourth) tip. The fast electrons also may have effects on the probe measurements, but they are not expected to give significant perturbation to our measurements[22,23].

A complex probe[22], which consists of a triple-probe (measuring n and T_e), a three-components magnetic probe (measuring B_t, B_p and B_r) and three pairs of double probes (measuring electric field E_t, E_p and E_r), has been constructed in order to determine correlations between the fluctuations. All of them are put within a space of 10mm × 10mm × 15mm. Here, we must note that, the electric field $\tilde{E}' \equiv -\nabla\tilde{\phi}_f$($\phi_f$: floating potential) measured by a double-probe is different from $\tilde{E} \equiv -\nabla\tilde{\phi}_s$, due to a finite $\tilde{T}_e$ in the relation of $\tilde{E}' = \tilde{E} + c\nabla\tilde{T}_e$, where c is a constant $\simeq 2.1$[22] in our case.

In order to avoid damages of the inserted probes, discharges were carried out at the relatively low plasma current ($I_p \sim$ 110kA). All measured quantities presented here are taken from the time interval of 0.2ms around the current flattop. The loop voltage V_l, the reversal ratio F, the pinch parameter Θ and the chord-averaged density $\overline{n}_e$ are $V_l \sim$ 220V, $F \sim -0.4$, $\Theta \sim 2.0$ and $\overline{n}_e \sim 4.4 \times 10^{19}\mathrm{m}^{-3}$, respectively.

Radial profiles of the mean values of $\overline{B}_t$ and $\overline{B}_p$ are shown in Fig.1(a), where the error bars indicate the shot-by-shot variation. Polynomial functions are fitted to $\overline{B}_t$ and $\overline{B}_p$ profiles under the constraints that the toroidal and poloidal currents, $\overline{j}_t = (1/\mu_0 r)\partial(r\overline{B}_p)/\partial r$ and $\overline{j}_p = -(1/\mu_0)\partial\overline{B}_t/\partial r$ fall to zero at $r = a$. Figure 1(b) shows the profiles of $\overline{j}_t$, $\overline{j}_p$ and $j_{\parallel} \equiv \overline{\boldsymbol{j}} \cdot \overline{\boldsymbol{B}}/B$ (B is the total field), where the error bar comes from the fitting procedures due to error propagation. Figure 1(c) shows the radial profile of $\eta j_{\|}$ where Spitzer's resistivity η is obtained from the measured profile[23] of $\overline{T}_e$ assuming $Z_{eff} = 1.5$. Parallel component of externally applied toroidal inductive electric field $E_{\|}$ given by $V_l/(2\pi R)\cdot(\overline{B}_t/B)$ in the steady state is also shown. Simple Ohm's law $\eta j_{\|} = E_{\|}$ is not satisfied. Difference between $\eta j_{\|}$ and $E_{\|}$ must be accounted by the fluctuation-induced electric field $\left\langle\tilde{\boldsymbol{v}}\times\widetilde{\boldsymbol{B}}\right\rangle_{\|}$ according to MHD dynamo model in Eq.(1). Note that the assumption of classical resistivity gives the minimum of this difference.

Radial profiles of magnetic fluctuation level had been measured[23]. At $r\sim a$, $|\tilde{B}_t|/B\sim 2\%$ is about twice of $|\tilde{B}_p|/B\simeq|\tilde{B}_r|/B\sim 1\%$, but at $r\sim a/2$, $|\tilde{B}_r|/B\sim 3\%$ is about twice of $|\tilde{B}_t|/B\simeq|\tilde{B}_p|/B\sim 1.5\%$. As the radius decreases to $r\sim a/2$, $|\tilde{E}_t|$(shown in Fig.1(d)), $|\tilde{E}_p|$ and $|\tilde{E}_r|$ measured by the complex probe increase to ~ 0.7kV/m, ~ 0.5kV/m and ~ 0.9kV/m, respectively.

Although a MHD dynamo model usually ignores effects arising from two-fluid treatments, we start from the generalized Ohm's law[24], *i.e.*, $\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}-\nabla P_i/(en) = \eta\boldsymbol{j}$ where $P_i = nT_i$ is the ion pressure. Other terms in the original generalized Ohm's law are examined to be negligible in our case. Then the perpendicular velocity fluctuations become

$$\tilde{\boldsymbol{v}}_\perp = \left[\widetilde{\boldsymbol{E}} - (\nabla\widetilde{P_i/en}) - \widetilde{\eta\boldsymbol{j}} + \tilde{\boldsymbol{v}}\times\widetilde{\boldsymbol{B}}\right]\times\overline{\boldsymbol{B}}/B^2. \tag{2}$$

From the facts that $|\tilde{B}|/B\lesssim 3\%$, $|\tilde{T}_e|/\overline{T}_e\sim 25\%$, $|\tilde{j}|/j\sim 30\%$[25], $\overline{v}\sim E_r/B\sim \phi_s(a/2)/(a/2)/B\sim 2$km/s [23], it is easy to find that 3rd and 4th terms are negligibly small compared the first term in Eq.(2). Because $\left\langle\tilde{\boldsymbol{v}}\times\widetilde{\boldsymbol{B}}\right\rangle_{\|} = \left\langle\tilde{\boldsymbol{v}}_\perp\times\widetilde{\boldsymbol{B}}_\perp\right\rangle = \left\langle\left[\widetilde{\boldsymbol{E}}_\perp + (\nabla_\perp\widetilde{P_i/en})\right]\cdot\widetilde{\boldsymbol{B}}_\perp\right\rangle/B$, the parallel mean Ohm's law becomes

$$\eta j_{\|} - E_{\|} = \left\langle\tilde{\boldsymbol{v}}\times\widetilde{\boldsymbol{B}}\right\rangle_{\|} + \left\langle\tilde{n}\nabla_{\|}\tilde{P}_i\right\rangle/(e\overline{n}^2) - \left\langle\tilde{\eta}\tilde{j}_{\|}\right\rangle$$

$$= \left\langle\left[\widetilde{\boldsymbol{E}}'_\perp - c\boldsymbol{k}_\perp\tilde{T}_e - (\nabla_\perp\widetilde{P_i/en})\right]\cdot\widetilde{\boldsymbol{B}}_\perp\right\rangle/B + k_{\|}\left\langle\tilde{n}\tilde{T}_i\right\rangle/\overline{n}, \tag{3}$$

where $\left\langle\tilde{\eta}\tilde{j}\right\rangle \ll \eta j$. Note that

$$(\nabla_\perp\widetilde{P_i/en}) = (\boldsymbol{k}_\perp - L_n^{-1}\mathrm{e}_r)\tilde{T}_i + (\overline{T}_i/\overline{n})(\boldsymbol{k}_\perp + L_n^{-1}\mathrm{e}_r)\tilde{n},$$

where e_r is the radial unit vector and $L_n \equiv -\overline{n}(\partial\overline{n}/\partial r)^{-1}$. Thus the fluctuation-induced electric fields depend on correlations between electrostatic($\widetilde{\boldsymbol{E}}$, $\tilde{n}$, $\tilde{T}_e$ and $\tilde{T}_i$) and magnetic($\widetilde{\boldsymbol{B}}$) fluctuations.

It is found that the magnetic fluctuations show entirely different behaviors from the electrostatic ones, which are well correlated with each other[23]. For example, squared coherences between $\tilde{T}_e$ and $\tilde{E}'_t$, $\tilde{T}_e$ and $\tilde{B}_t$, $\tilde{B}_t$ and $\tilde{E}'_t$, are shown in Fig.2. The coherences are usually not less than ~ 0.5 in the most frequency range between the electrostatic fluctuations, but below ~ 0.2 between the electrostatic ones and magnetic ones, consistent with MST experiments[26]. It implies that there are almost no correlations between these two types of fluctuations. Indeed, the normalized correlation coefficients $C_{\alpha,\beta} \equiv <\tilde{\alpha}\tilde{\beta}> /|\tilde{\alpha}||\tilde{\beta}|$ $(\alpha = E'_t, E'_p, E'_r, n, T_e; \beta = B_t, B_p, B_r)$ are ~ 0 across the outer half radius. For example, profiles of C_{T_e,B_t} and $C_{E'_t,B_t}$ are shown in Fig.3(a) and (b), respectively. Spatial spread of the complex probe is not expected to bring these decorrelations, because the same type(electrostatic or magnetic) fluctuations are still well correlated with each other even they are measured over a longer distance. Electrostatic fluctuations $\tilde{n}$, $\tilde{T}_e$ and $\widetilde{\boldsymbol{E}}'$ show clear positive or negative correlations[23], as also shown in Fig.3. In Fig.4, the region bounded by lines with open circles shows the measured value of the first term in Eq.(3) including the correlations, and the dotted region shows $\eta j_{\parallel} - E_{\parallel}$ calculated from Fig.2.

The poloidal(toroidal) mode number $m(n)$ spectra of $\widetilde{\boldsymbol{B}}$ were measured by poloidal and toroidal arrays of pick-up coils[22]. It was found that the most fluctuation power concentrates in the modes of $0 \leq m \leq 1$ and $-13 \leq n \leq 13$, therefore, spectral widths are $\Delta m \sim 2$ and $\Delta n \sim 27$ for the magnetic fluctuations. However, spectra for the electrostatic fluctuations are more broad[26] with widths of $\Delta m \sim 3$ and $\Delta n \sim 70$ at the plasma edge where $B_p \gg B_t$. Here we use $|k_{\parallel}| \sim \Delta m/2a \sim 1.5/a$ and $|k_{\perp}| \sim \Delta n/2R \sim 35/R$ as the typical values. The ion temperature T_i at the edge is unmeasured, but an assumption of $T_i \sim 2T_e$ would be reasonable, because $T_i(0) \sim 100$eV at the center measured from the Doppler broadening of OV line, is about twice of $T_e(0) \sim 50$eV measured by a Thomson scattering system. Since $L_n \sim 0.1$m in REPUTE-1 RFP, 2nd $\sim$ 4th terms in Eq.(3) can be evaluated assuming $|C_{T_i,n}| = |C_{T_i,B}| = 1$. These values are also shown in Fig.4. We find that the sum of all possible fluctuation-induced electric fields cannot sustain the parallel equilibrium current in the region, where B_t is reversed($r \gtrsim 17$cm). Even the upper bound values of total fluctuation-induced electric field (when all fluctuations are completely correlated) shown as a dashed line in Fig.4, still cannot account for $\eta j_\parallel - E_\parallel$ near the edge.

Our results do not support the basic hypothesis of MHD dynamo models at least in B_t reversed region. Next let us examine another possible mechanism for sustaining the edge parallel current, *i.e.*, there exists an outward flux of parallel electron current (or momentum) $\Gamma_{total}(r)$ satisfying $\eta j_\parallel - E_\parallel + (1/r)\partial(r\Gamma_{total})/\partial r = 0$ as in Kinetic Dynamo Theory[2]. We have

$$\Gamma_{total}(r) = (a/r)\Gamma_{total}(a) + (1/r)\int_r^a (\eta j_\parallel - E_\parallel) r \mathrm{d}r. \tag{4}$$

Here $\Gamma_{total}(a)$ is the electron-current(momentum) loss to the wall, which has been used to explain the anomalous resistivity observed in RFPs[3]. From the electron drift kinetic equation, radial fluxes of parallel current due to electrostatic and magnetic fluctuations are given by[27]

$$\Gamma_E = \frac{m_e j_\parallel}{e^2 n}\left\langle \frac{\widetilde{\boldsymbol{E}} \times \overline{\boldsymbol{B}}}{B^2} \cdot \mathrm{e}_r \frac{\tilde{j}_\parallel}{j_\parallel} \right\rangle; \qquad \Gamma_B = \frac{T_e}{e}\left\langle \frac{|\tilde{B}_r|}{B}\frac{\tilde{p}_{e\parallel}}{p_{e\parallel}} \right\rangle,$$

respectively. Another expression for the radial flux of parallel current is $\Gamma_{st} = -\lambda_{st}(1/r)\partial(r j_\parallel)/\partial r$, where λ_{st} is a current viscosity[28]. The current-diffusion due to stochastic field[29] is related to electron heat transport[30] by $\lambda_{st} = -\chi_{st} m_e/(e^2 n)$, where the electron thermal diffusivity χ_{st} is $(8/\pi)^{1/2}\ v_{th}^e\ L_\parallel\ (|\tilde{B}_r|/B)^2$, v_{th}^e is the electron thermal velocity, and $L_\parallel \sim 0.35$m in our case[23]. Values of Γ_E, Γ_B and Γ_{st} can be estimated with the use of measured mean quantities and their fluctuation levels, assuming $C_{B_r,p_{e\parallel}} = C_{E,j_\parallel} = 1$ and $p_{e\parallel} = p_e$. However, they all are at least one-order smaller than Γ_{total}. For example, the values at $r = 19$cm are given in the first column in Table 1.

Above estimates are based on the assumption, in which the current is carried by the bulk cold electrons. However, it has been observed that the current is mainly carried by the fast electrons at the edge[4] and even in the core[5] region. If $j_\parallel$ is carried only by the fast electrons with density $n^F \equiv \alpha n$ and temperature $T_e^F = \beta T_e$, we have $\alpha\sqrt{\beta} = j_{\|}/(env_{th}^e)$, with an assumption of a half-Maxwellian velocity distribution[6]. Relations of $\Gamma_E^F = \Gamma_E\alpha^{-1}$, $\Gamma_B^F = \Gamma_B\beta$ and $\Gamma_{st}^F = \Gamma_{st}\alpha^{-1}\sqrt{\beta}$ can be also easily obtained, assuming the same fluctuation levels and correlations. Electric resistivity η^F of the fast electrons are also different from η: $\eta^F/\eta = 3\sqrt{\pi}(2+Z_{eff})/(4Z_{eff})\alpha^{-1}\beta^{-3/2}$, where frictional forces due to the bulk cold electrons and ions are considered. We can obtain Γ_{total}^F replacing η in Eq.(4) by η^F. Table 1 lists the estimated values of radial fluxes of parallel current in the two case of $T_e^F = 50$eV($\sim T_e(0)$) and $T_e^F = 100$eV($\sim 2T_e(0)$) at r =19cm. It can be seen that Γ_B^F or Γ_{st}^F could accounts for Γ_{total}^F while Γ_E^F still does not. This suggests that the magnetic fluctuations may play an important role in sustaining the edge parallel current.

So far studies on stochastic diffusion all based on the prescribed stochastic fields, not self-consistently. A recent self-consistent treatment[31] showed that the current diffusion becomes much smaller than quasilinear result. However, the fast electrons argued here are not affected by self-consistency constraints, since they are enough fast to decouple from the waves.

In conclusion, electrostatic fluctuations($\widetilde{\boldsymbol{E}}, \tilde{n}, \tilde{T}_e$) almost do not correlated with magnetic ones($\widetilde{\boldsymbol{B}}$) in $a/2 \lesssim r \leq a$ region of REPUTE-1 RFP. Fluctuation-induced electric fields, such as $\left\langle \tilde{\boldsymbol{v}} \times \widetilde{\boldsymbol{B}} \right\rangle$, are experimentally examined for the first time. It is found that these fluctuation-induced electric fields are not sufficient to account for $\eta j_{\|} - E_{\|}$ at least in B_t reversed region, not supporting the basic hypothesis of MHD turbulent dynamo models. On the other hand, it is implied that current-diffusions due to magnetic fluctuations, carried by fast electrons rather than bulk cold electrons, sustain the edge parallel equilibrium current.

At the present stage, it is impossible to affirm one and obviate another entirely, between these two classes of models. But our experimental results reported in this letter imply that KDT could be more suitable rather than MHD dynamo models for the actual RFP edge region. For the interior region, it is more difficult to examine these models. Some combination of MHD and kinetic dynamo models may provide a more adequate description. In fact, they both base on the common assumption, *i.e.*, a turbulent state of plasma.

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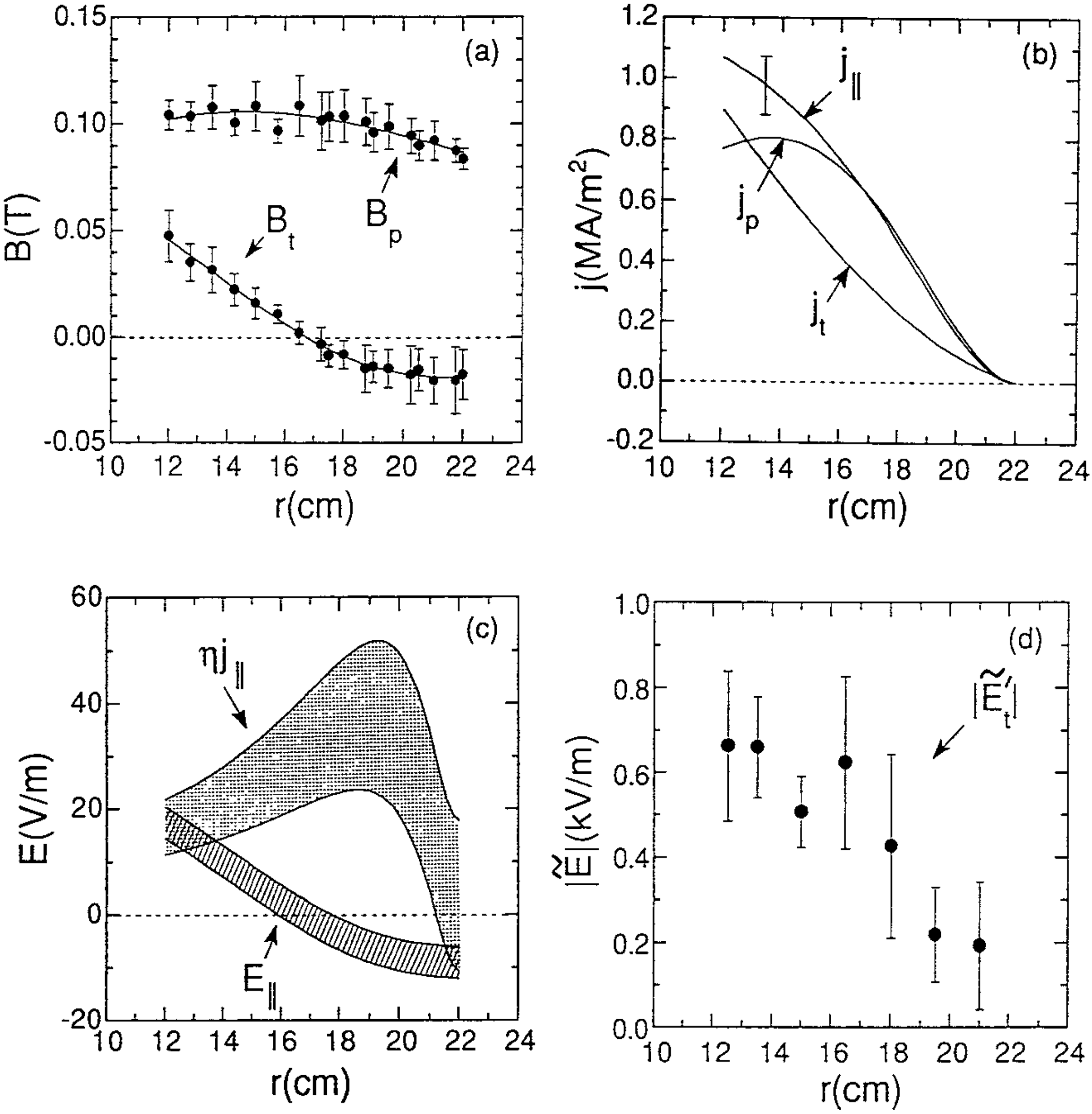

Figure 1 Radial profiles of (a) $\overline{B}_t$ and $\overline{B}_p$; (Fitting curves by polynomial functions under the constraints of $\overline{j}_t(a) = \overline{j}_p(a) = 0$ are also shown.) (b) $\overline{j}_t$, $\overline{j}_p$ and $j_\parallel \equiv \overline{\boldsymbol{j}} \cdot \overline{\boldsymbol{B}}/B$; (c) resistive electric field $\eta j_\parallel$ and externally applied inductive electric field $E_\parallel$; (d) fluctuation level of $\tilde{E}'_t$.

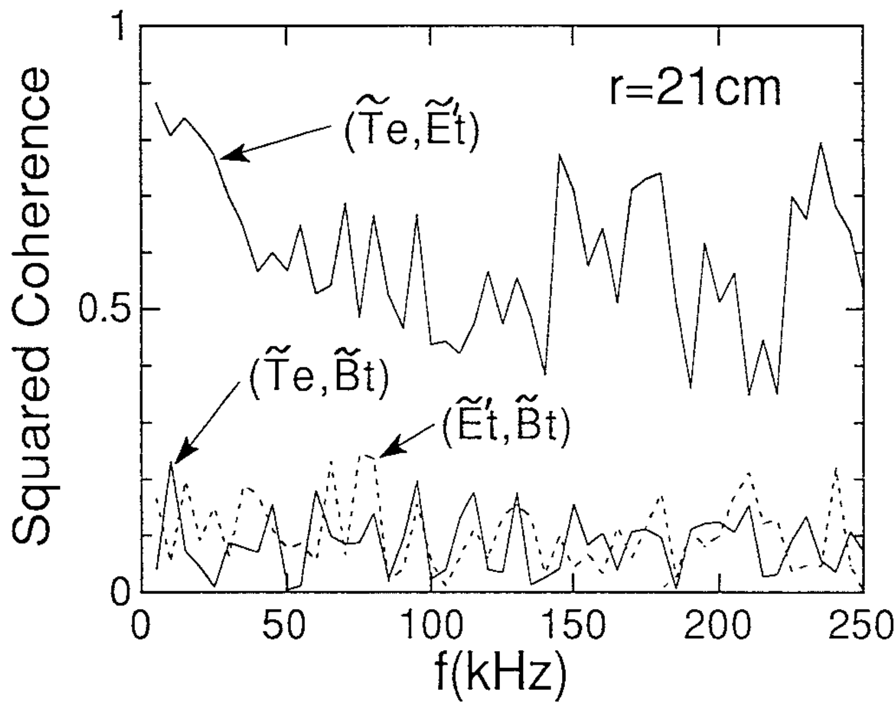

Figure 2 Squared coherence between $\tilde{T}_e$ and $\tilde{E}_t'$, $\tilde{T}_e$ and $\tilde{B}_t$, $\tilde{B}_t$ and $\tilde{E}_t'$ as functions of frequency.

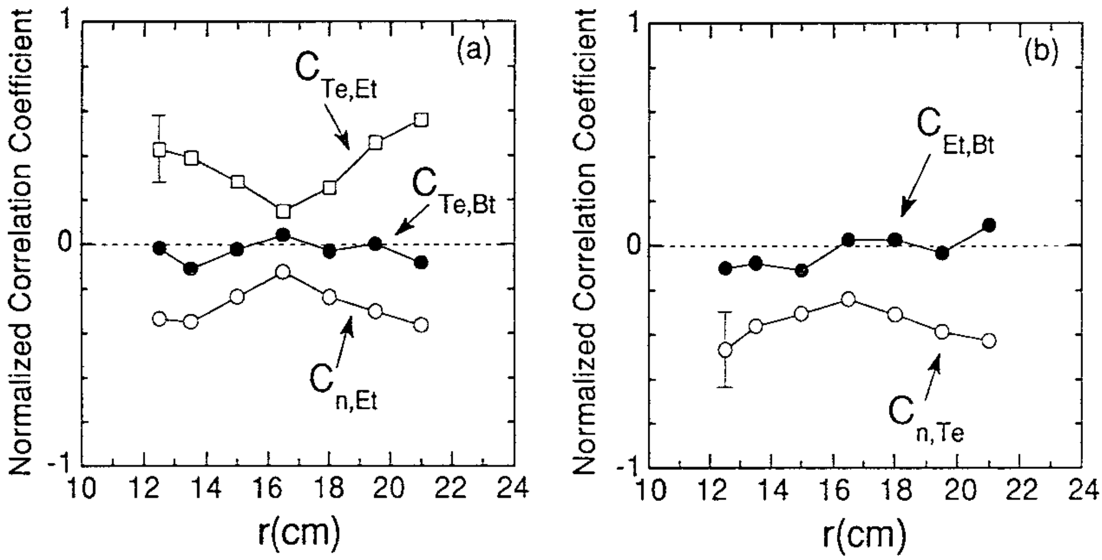

Figure 3 Radial profiles of normalized correlation coefficients (a) C_{T_e,B_t}, $C_{T_e,E_t'}$ and $C_{n,E_t'}$, (b) C_{E_t',B_t} and C_{n,T_e}.

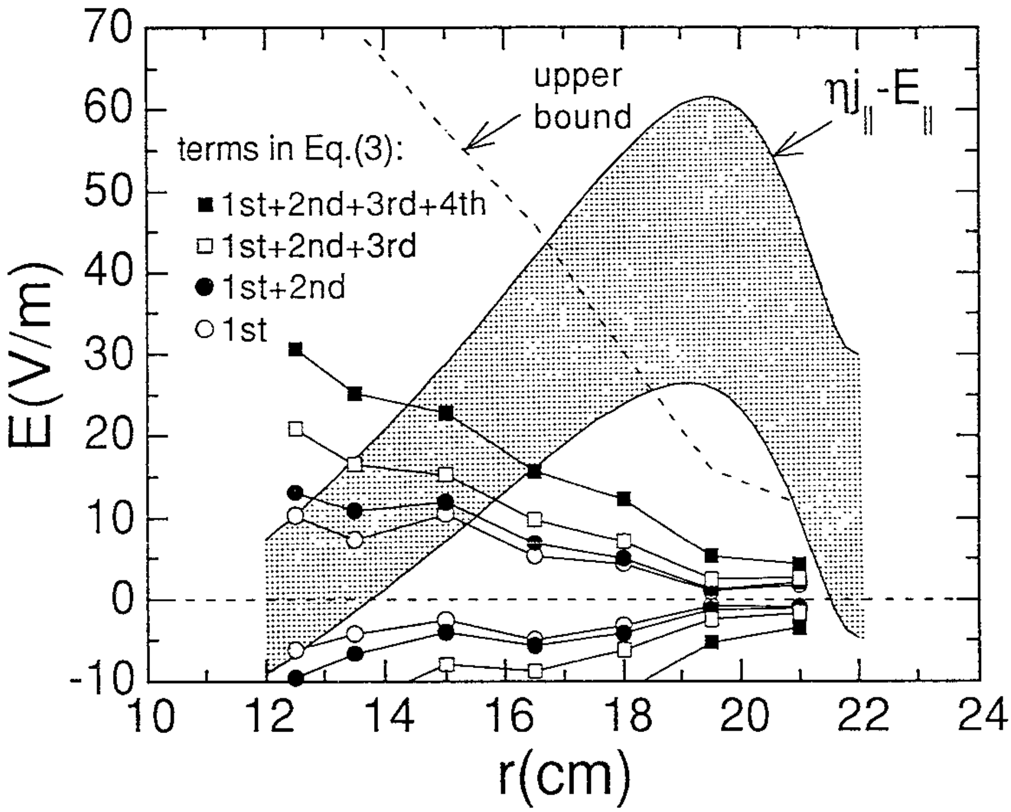

Figure 4 Comparisons between radial profiles of $\eta j_{\|} - E_{\|}$ (shown as the dotted region) and fluctuation-induced electric fields (shown as regions between lines with symbols). Values of 1st $\sim$ 4th terms of Eq.(3), are indicated by different symbols, respectively. Dashed line shows the upper bound of fluctuation-induced electric fields assuming complete correlations.

Table 1: Comparisons between total flux and fluctuation-driven fluxes of electron current at r =19cm in the cases of bulk cold electrons and fast electrons. Here $\Gamma'_{total} \equiv \Gamma_{total}(r) - (a/r)\Gamma_{total}(a)$. Note that $T_e(0) \sim 50$eV.

	bulk cold electrons	fast electrons	
T_e^F[eV]		50	100
T_e^F/T_e		8.6	17.2
n^F/n		13.1%	9.3 %
η^F/η		0.94	0.47
Γ'_{total}[V]	0.22 ± 0.12	0.14 ± 0.06	0.10 ± 0.04
Γ_E[V]	~ 0.001	~ 0.01	~ 0.01
Γ_B[V]	~ 0.008	~ 0.33	~ 0.66
Γ_{st}[V]	~ 0.015	~ 0.34	~ 0.67

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