Inward Turbulent Transport Produced by Positively Sheared Radial Electric Field in Stellarators

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Inward turbulent particle transport observed in the rf heated plasma of the H-1 toroidal heliac is reproduced in the CHS heliotron/torsatron by generating a region of positive radial electric field shear ($E_r' > 0$) using electron cyclotron resonance heating of the plasma edge. Empirical condition of the radial reversal of the turbulent flux derived from two experiments indicates that the shear electric field might be universally responsible for the recorrelation of the density and plasma potential fluctuations leading to the inward transport.

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Turbulent transport in toroidal plasmas is affected by the $\mathbf{E} \times \mathbf{B}$ sheared flows [1,2]. Understanding this effect is crucial for the physics of the transport barriers and improved confinement regimes. Though most of the theoretical and experimental works have been concentrated on the shear flow turbulence suppression model (for review see [2]), it becomes more evident that the radial electric field may also affect the fluctuation cross phase, so that the turbulent-driven transport can change without the fluctuation suppression. For example, the phase shift between density $\tilde{n}$ and poloidal electric field $\tilde{E}_p$ fluctuations can produce a fluctuation-driven particle flux:

$$\Gamma_{\mathrm{fl}} = \langle \tilde{n} \tilde{V}_r \rangle = \langle \tilde{n} \tilde{E}_p \rangle / B_t \,, \tag{1}$$

where $\tilde{V}_r$ is the fluctuating component of the particle radial velocity and B_t is the toroidal component of the magnetic field. In the spectral domain the fluctuation-induced flux can be expressed as [3]

$$\Gamma_{\mathrm{fl}} = \frac{2}{B} \int_0^\infty k(\omega) \times |\gamma_{n\varphi}(\omega)| \times \sin[\alpha_{n\varphi}(\omega)] \times [P_n(\omega) P_\varphi(\omega)]^{1/2} \times d\omega \,, \tag{2}$$

where $k(\omega)$ is the poloidal wave number of the fluctuations, $0 \leq |\gamma_{n\varphi}(\omega)| \leq 1$ and $\alpha_{n\varphi}(\omega)$ are the coherence and the phase shift between density n and plasma potential φ fluctuations correspondingly, and $P_{n,\varphi}$ are the auto power densities of the fluctuations. Equation (2) shows that the particle flux can be reduced by suppressing the turbulence ($P_{n,\varphi}$ reduction), by decorrelating density and potential fluctuations ($\gamma_{n\varphi} \rightarrow 0$), or by changing the relative phase $\alpha_{n\varphi}$ between them. All three scenarios have been observed in toroidal experiments. Turbulent fluctuation levels are often found to be reduced during transport barrier formation [1,2], though the turbulent transport reduction by the $\tilde{n}$-$\tilde{\varphi}$ cross-phase modifications have also been observed during $L-H$ transitions in the PBX-M [4] and DIII-D [5] tokamaks. It has also been shown in [5] that the cross-phase modifications were correlated with changes in the radial electric field shear $E_r' = dE_r/dr$. This result has been supported by the theoretical work of Ware *et al.* [6,7] who have shown that the $\mathbf{E} \times \mathbf{B}$ shear flow can reduce the transport through the changes in the fluctuation cross phase. The turbulent transport reduction due to the decorrelation of the $\tilde{n}$-$\tilde{\varphi}$ fluctuations has been observed in the velocity shear layer of the TEXT tokamak [8] and has been found to be consistent with the shear flow decorrelation model.

Changes in the cross phase can lead to a radial reversal of the fluctuation-driven particle flux from outward to inward. Roth *et al.* have reported the first observation of the inward turbulent transport from the NASA Lewis bumpy torus facility [9]. The inward turbulent transport has also been observed in the inner plasma regions of the H-1 heliac [10] and at the periphery of the electrode-biased plasma in the TEXTOR-94 tokamak [11]. The inward fluctuation-driven transport has been suggested as a candidate to explain a convective inward particle transport in the W7-AS stellarator [12]. It could also be responsible for sustaining high confinement in other experiments. There have been no systematic studies into the cause of the radially inward transport and its relation to the shear flow.

In this Letter we report new results suggesting that the radial reversal of the turbulence-driven particle flux can be externally controlled by generating regions in the plasma where the radial electric field shear is positive ($E_r' > 0$). An empirical condition of the flux reversal is derived from the comparative analysis of two stellarator experiments: the H-1 heliac and the CHS stellarator.

Fluctuation-produced particle flux is studied in the H-1 toroidal heliac [13] having a major radius of $R_0 = 1.0$ m and a mean minor radius $\langle a \rangle \approx 0.2$ m which is operated at low magnetic fields (<0.15 T), with a low electron

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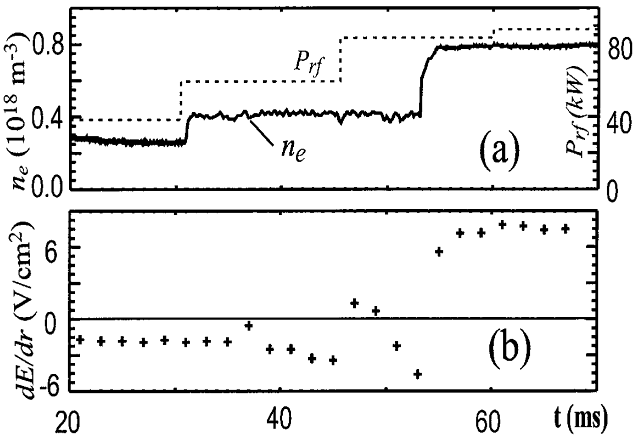

FIG. 1. Time evolution of the rf power, line-average electron density (a) and of the radial electric shear at $r/a = 0.75$ (b) during the power step discharge in H-1.

temperature (<30 eV) plasma produced by the pulsed rf power of less than 100 kW at 7 MHz in argon. Several combinations of the triple probes described in [14,15] are used for the plasma parameter characterization. The effect of the sheared electric field on the fluctuation-produced transport is studied during the rf power step discharges described in [14,16]. The rf power is increased during the discharge in four steps from ~40 to ~90 kW as shown in Fig. 1(a). The first rf power step at $t \sim 30$ ms leads to an increase in the electron density due to the increased ionization. At $t \sim 54$ ms a sudden transition to improved confinement nearly doubles the density. The radial electric field shear [Fig. 1(b)] becomes positive after the transition to the high confinement mode. Before the transition, plasma in H-1 is dominated by the low frequency (3–12 kHz) low poloidal mode number ($m = 1, 2$) fluctuations of the plasma density, plasma potential, and magnetic field [16]. These fluctuations produce considerable outward particle flux. The local time-resolved fluctuation-produced flux $\Gamma_{\mathrm{fl}} = \langle \tilde{n}\tilde{E}_{\mathrm{pol}}/B \rangle$ is shown in Fig. 2 for two time intervals (each 4 ms long) before and after the transition of the discharge of Fig. 1. The time-average flux is outward before the transition [Fig. 2(a)] and it becomes negative (inward) after the transition [Fig. 2(b)]. This reversal of Γ_{fl} is correlated with the formation of the $E_r' > 0$ region in the plasma. The reversal is due to the change in the fluctuation cross phase and is symmetric in the flux surface, as discussed in [10]. Radial profiles of the radial electric field and of the time-average flux $\langle \Gamma_{\mathrm{fl}} \rangle$ are shown in Fig. 3. The flux reverses when the region of the sufficiently strong $E_r' > 0$ appears in the plasma. Analysis of the large number of discharges in H-1 indicates that the cross phase is rather sensitive to even moderately positive shear of about $E_r' \sim 4$ V/cm^2. The formation of the $E_r' > 0$ region simultaneously with the Γ_{fl} reversal (Fig. 3) has also been confirmed in a single shot measurement using three radially separated probes [16].

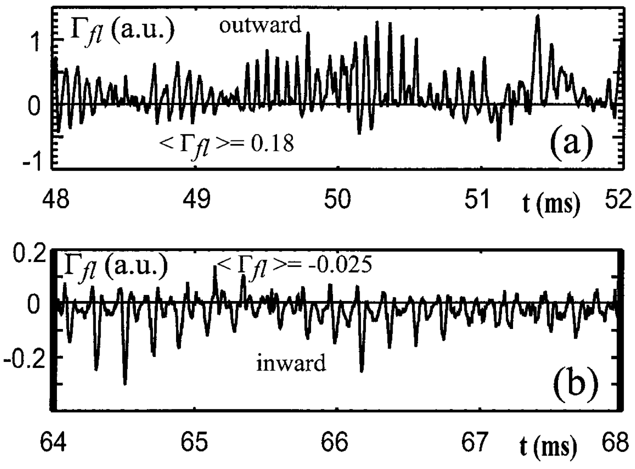

FIG. 2. Time-resolved fluctuation-driven particle flux at $r/a = 0.68$ during the power step discharge of Fig. 1.

Based on this result, we attempt to effect local turbulent transport by generating positive E_r' region in the Compact Helical System (CHS). CHS is a heliotron/torsatron device having a major radius of $R_0 = 1.0$ m and an averaged minor radius $\langle a \rangle \sim 0.2$ m [17]. A radial array consisting of four triple probes (separated typically by $\Delta r/a \sim 0.02$ at $\rho = r/\langle a \rangle = 0.9$ to 1.2) has been used in the edge region of CHS [18].

Fluctuations in the edge region of CHS exhibit broadband frequency spectra extending up to 50 kHz deeper inside the plasma ($\rho \sim 0.92$) and limited to <20 kHz at

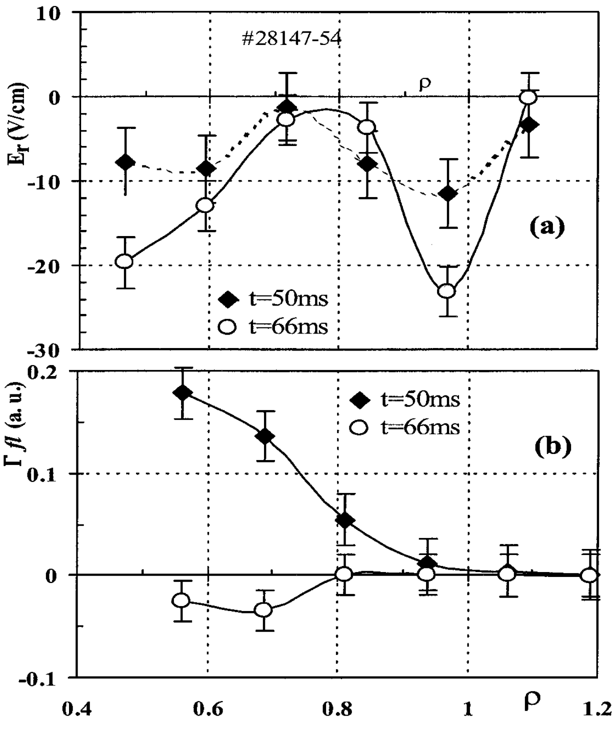

FIG. 3. Plasma parameter profiles in H-1 before (solid diamonds) and after (open circles) the confinement transition: radial electric field (a); fluctuation-driven flux (b).

$\rho \approx 0.99$. The level of the density fluctuations can be as high as $\tilde{n}/n \sim 25\%$. In the lab frame fluctuations propagate in the ion diamagnetic direction which coincides with the direction of the $\mathbf{E} \times \mathbf{B}$ drift velocity. The poloidal fluctuation phase velocity was found to be of the order of ~2 km/s, which is a factor of 2 lower than the local $\mathbf{E} \times \mathbf{B}$ drift velocity. Thus in the plasma frame fluctuations propagate in the electron diamagnetic direction with the velocity of $V_{\mathrm{pl}} = V_{\mathrm{lab}} - V_{\mathbf{E}\times\mathbf{B}} \approx 2$ km/s.

In the described experiments plasma is heated using electron cyclotron resonance heating (ECRH) and neutral beam injection (NBI). The magnetic field in the machine ($B = 1.35$–1.4 T) is chosen such that the ECR layer appears just inside the last flux surface affecting plasma edge parameters. The ECRH power of about 100 kW at $f = 53$ GHz is pulsed several times during NBI-sustained discharges. The duration of each ECRH pulse is about 10 ms, as shown in Fig. 4. The ECRH pulses modulate the edge electron temperature [Fig. 4(a)], and change local radial electric field. An ECRH enhanced electron loss [19] as well as increased electron-temperature-gradient driven neoclassical flux is thought to be responsible for the modification in the radial electric field. The radial electric field shear is also affected as shown in Fig. 4(b): E_r' becomes considerably more positive at $\rho \approx 0.95$ during ECRH pulses. The modulation in E_r' affects the fluctuation-produced particle flux as shown in Fig. 4(b). The flux is characterized by positive and negative bursts corresponding to the outward and inward directed "transport events." Time average (over 2 ms) of this flux is used in Fig. 4(b) to illustrate its time evolution. The time resolved flux Γ_{fl} is shown in Fig. 5 for the time intervals before [Fig. 5(a)], during [Fig. 5(b)], and after [Fig. 5(c)] the ECRH pulse is applied to the plasma edge. The flux is outward before the ECRH pulse and is nearly symmetric (zero average) after the pulse. When the edge ECRH is applied, the fluctuation-driven flux becomes inward directed in the radial region where the radial electric field shear is positive. The time-resolved flux is dominated in this case by the negative (inward) transport events seen in Fig. 5(b). The correlation between Γ_{fl} (or the fluctuation cross phase) and positive E_r' is observed in both hydrogen and deuterium plasmas in CHS. A statistically averaged value of the positive E_r', which noticeably affects the fluctuation-driven flux, is found to be about 50 V/cm^2.

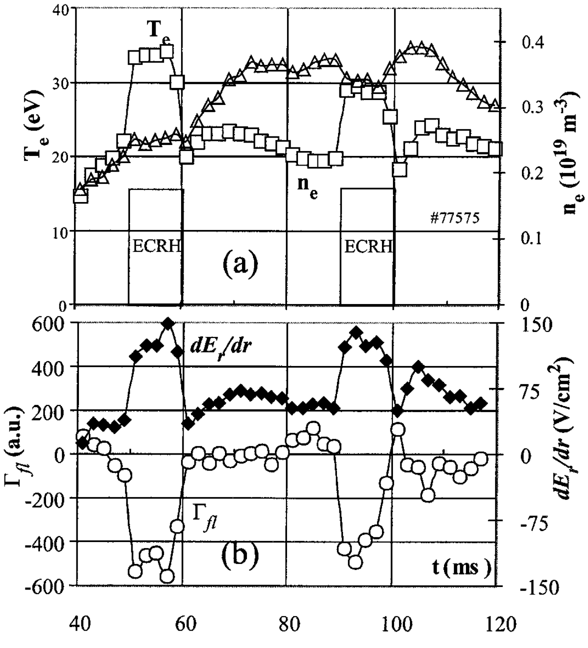

FIG. 4. Time evolution of the electron temperature (squares) and density (triangles) (a), fluctuation-produced particle flux (circles) and of the radial electric shear (diamonds) (b) at $r/a = 0.95$ during the edge ECRH discharge in CHS.

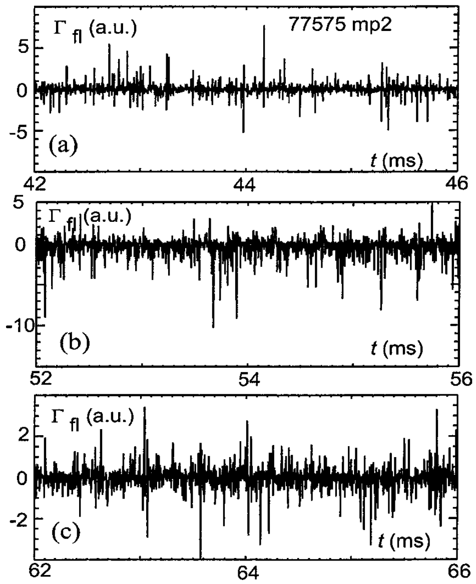

FIG. 5. Time-resolved fluctuation-produced flux at $r/a = 0.95$ during the CHS discharge of Fig. 4 before (a), during (b), and after (c) the ECRH pulse.

We now compare the conditions at which the inward turbulent transport is observed in these two experiments. In both machines the change in the sign of the fluctuation cross phase is correlated with a formation of the positive E_r'. The plasma parameters and conditions at which the effect is observed are summarized in Table I. Some plasma parameters, e.g., electron temperature and density are similar in both machines, while most of them, such as the magnetic field, the magnetic shear, the fluctuation phase velocity, and the radial correlation length as well as the electric field shear differ by an order of magnitude or more. The sign of the radial electric field E_r is different in H-1 and in CHS. However, an empirical criterion for the sheared electric field to affect the fluctuation cross phase has been found as a combination of the above mentioned parameters: Γ_{fl} is inward when

$$\Delta_\rho (dV_{\mathbf{E}\times\mathbf{B}}/dr) > V_{\mathrm{ph}}^{\mathrm{lab}}, \qquad (3)$$

where Δ_ρ is the fluctuation radial correlation length, $V_{\mathbf{E}\times\mathbf{B}} = E_r/B_t$ and $V_{\mathrm{ph}}^{\mathrm{lab}}$ is the fluctuation propagation

TABLE I. Plasma parameters and fluctuation characteristics in CHS and H-1.

Parameter	CHS	H-1
Gas	H, D	Ar, He
$n_e (10^{18}\ \mathrm{m}^{-3})$	1–3	0.5–2
T_e(eV)	20–40	10–20
T_i(eV)	20–50	40–60
Magnetic field (T)	1.0	0.08
Ion gyroradius (m)	<0.001	0.04–0.05
Magnetic shear $\hat{s} = (\rho/\iota\!\!\!-)(d\iota\!\!\!-/d\rho)$	2.0	0.0055
Radial correlation length Δ_ρ (m)	<0.005	0.05
Poloidal phase velocity (m/s)	$(1-2) \times 10^3$	$(1-2) \times 10^4$
Radial electric field E_r (V/cm)	+(40–80)	−(20–0)
Critical shear (dE_r/dr) (V/cm^2)	50	5

velocity in the lab frame. The condition Eq. (3) is satisfied for both H-1 and CHS. The term $\Delta_\rho(dV_{\mathbf{E}\times\mathbf{B}}/dr)$ can be interpreted as the drop of the $V_{\mathbf{E}\times\mathbf{B}}$ drift velocity across the radial width of the fluctuations. The effect of $E_r' > 0$ on the cross phase in the reported experiments becomes noticeable when $\Delta_\rho(dV_{\mathbf{E}\times\mathbf{B}}/dr) \geq V_{\mathrm{ph}}^{\mathrm{lab}}$. The fluctuation-induced flux is radially reversed [like in Figs. 2(b) and 5(b)] when $\Delta_\rho(dV_{\mathbf{E}\times\mathbf{B}}/dr) \gg V_{\mathrm{ph}}^{\mathrm{lab}}$.

The left-hand side of the condition (3) is similar to the condition of the nonrigid body plasma rotation in the shear flow suppression model in cylindrical geometry [20,21].

The correlation between $E_r' > 0$ and $\Gamma_{\mathrm{fl}} < 0$ observed in H-1 [16] has been successfully reproduced in CHS by actively modifying the radial electric field using edge ECRH. In both experiments it is the $E_r' > 0$ that is correlated with $\Gamma_{\mathrm{fl}} > 0$. Both the sign of the electric field E_r and its curvature E_r'' differ in H-1 and CHS when $\Gamma_{\mathrm{fl}} > 0$ is observed.

Turbulent fluxes exhibit bursts in both tokamaks and stellarators [22–24]. It has also been found that statistical properties of turbulence in different toroidal experiments are consistent with the hypothesis of the universality of turbulence [23,25]. We may speculate that the radial reversal of the particle flux reported here is universal since the same behavior is observed for the transport driven by the quasicoherent fluctuations in H-1 and a broadband turbulence in CHS.

The modifications in the turbulent transport discussed above have a different effect on the net particle confinement in H-1 and CHS. In the case of the H-1 heliac particle confinement dramatically improves [10], while the reversal of the local turbulent particle transport in CHS does not noticeably affect the net particle transport. There may be several reasons for this. For example, the relative contribution to the net particle flux of its fluctuation-driven component may be different in two experiments. Also the radial region of the positive E_r' (and reversed Γ_{fl} region) in H-1 extends over nearly one-third of a plasma radius, while in CHS it is generated in a narrow radial region of $r/a \sim 0.03$. Further analysis of the local particle transport in both machines is necessary to clarify this. Also, we cannot completely exclude possibly different effects of the spatial asymmetry of the turbulent flux on the particle confinement in two machines.

In conclusion, we describe first experiment on the controllable reversal of the fluctuation-driven transport by generating the region of positive electric field shear in the stellarator plasma. If proven universal, the effect can be practically used to control the turbulent particle transport in magnetically confined plasmas.

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