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Observation of inward turbulent particle transport in edge plasma region of CHS heliotron/torsatron

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Abstract

Reversal of turbulent particle flux near the plasma edge of CHS heliotron/torsatron was observed on various discharge conditions, i.e. during tangential neutral beam injection, electron cyclotron heating at the far edge, and the sawtooth crash. For all cases, the reversal is realized at a narrow particular layer near the plasma edge, when plasma parameters go into low collisionality. The reversal is caused by the change in the cross phase between density (n_e) and poloidal electric field (E_θ) fluctuations. The turbulent flux is always inward when the radial electric field shear (E'_r) exceeds a certain threshold of $\sim 1 \times 10^6\,\mathrm{V\,m^{-2}}$. In the sawtoothing plasmas, the arrival of a heat pulse due to the sawtooth crash enhances both n_e and E_θ fluctuations but changes the cross phase to π in low-frequency range. As a result, a large inward flux is generated by the sawtooth crash. The particle flux reversal in these cases did not lead to obvious confinement improvement.

1. Introduction

Particle and energy transport near the edge in toroidal plasmas always exceeds neoclassical transport. There is a broad consensus that anomalous or turbulent transport is caused by plasma fluctuations. It is well known that electrostatic fluctuations are responsible for turbulent transport in the edge region of tokamak and helical plasmas [1–4]. The turbulent particle flux caused by electrostatic fluctuations is simply expressed by the correlation between density and poloidal electric field fluctuations as follows [5]:

$$\langle\Gamma_{\mathrm{turb}}\rangle = \frac{\langle\tilde{n}_e\tilde{E}_\theta\rangle}{B_\phi} = \frac{2}{B_\phi}\int_0^\infty \gamma_{n_eE_\theta}\cos\alpha_{n_eE_\theta}[P_{n_e}P_{E_\theta}]^{1/2}\,\mathrm{d}f = \int_0^\infty \Gamma_{\mathrm{turb}}(f)\,\mathrm{d}f \quad (1)$$

where B_ϕ is the toroidal magnetic field, and γ_{n_e}, α_{n_e} and P_{n_e} (P_{E_θ}) are respectively the coherence, cross-phase angle, and density (poloidal electric field) fluctuation power. There are three possible cases for the reduction of the turbulent loss flux: (1) reduction of fluctuation amplitudes, (2) reduction of coherence, and (3) change of the cross phase. Spontaneous reduction of these edge fluctuations leads to significant confinement improvement such as H-mode [6]. This transport reduction is mainly caused by the above-mentioned case (1). In case (3), the transport reduction and confinement improvement can be realized, even if the fluctuation amplitudes and the coherence remain unchanged. The transport reduction due to the change in the fluctuation cross phase and confinement improvement are also observed in tokamak H-modes [6, 7] and stellarators [8].

The Langmuir probe is a unique method to measure characteristics of electrostatic fluctuations in the edge region with high time and spatial resolutions, and to derive the turbulent flux. Therefore, this diagnostic tool provides a powerful knob to clarify characteristics of edge turbulence. In this paper, we describe the reversal of the particle flux or inward particle flux, which was derived from edge fluctuation data measured by four sets of triple probe (triple probe array) in CHS heliotron/torsatron [9, 10]. In CHS, the inward particle flux or the reversal of the particle flux was observed on the following conditions:

(a) during tangential neutral beam injection (NBI),
(b) during electron cyclotron heating (ECH) of which ECR layer is in the far edge of the plasma, $\rho_{\mathrm{ECR}} \sim 0.9$–1.0, and
(c) during the arrival of a heat pulse produced by a sawtooth crash.

2. Reversal of turbulent particle flux during tangential NBI and edge ECH

Turbulent particle fluxes in various conditions of NBI-heated plasmas are measured by four sets of triple probes which are arranged radially with a few mm separation [11]. The typical waveform of an NBI-heated plasma in the inward-shifted configuration ($R_{\mathrm{ax}} = 0.92\,\mathrm{m}$) is shown in figure 1, where ECH is also applied in the far edge of the plasma and the toroidal magnetic field is $B_{\mathrm{t}} = 1.4\,\mathrm{T}$. Fluctuations near the edge are simultaneously measured at four radial locations from $r/\langle a\rangle \sim 0.9$ to ~ 1. The time-resolved particle flux as well as the flux expressed by equation (1)

$$\Gamma_{\mathrm{turb}}(t) = \frac{\tilde{n}_{\mathrm{e}}\tilde{E}_\theta}{B_\phi} \qquad (2)$$

was often evaluated in these experiments, except for the case discussing the frequency spectra of the flux. In the shot shown in figure 1, the time-averaged flux at $r/\langle a\rangle = 0.91$ of $\Gamma_{\mathrm{turb}}(t)$ is outward throughout the discharge, but the flux is reversed to inward at the slightly outward position $r/\langle a\rangle = 0.94$. The fluxes evaluated at further outer positions $r/\langle a\rangle > 0.97$ are outward in this shot. The reversal of the particle flux takes place in a narrow layer near the edge, i.e. $r/\langle a\rangle = 0.92$–0.97. In figure 2, we plot edge plasma parameters (electron temperature T_{e} and density n_{e} at $r/\langle a\rangle = 0.94$) of various NBI-heated plasmas, indicating the magnitude and direction of the particle flux at $r/\langle a\rangle = 0.94$. The flux reversal or inward particle flux is observed in the parameter region of $T_{\mathrm{e}} > 15\,\mathrm{eV}$ and $n_{\mathrm{e}} < 3 \times 10^{18}\,\mathrm{m}^{-3}$ at $r/\langle a\rangle = 0.94$. This parameter region corresponds to the plateau or $1/\nu$ regime in the neoclassical transport sense (ν: collision frequency). The radial profiles of plasma parameters including the radial electric field shear and turbulent particle flux are compared for two typical shots in figure 3(*a*). One is a low n_{e} and high T_{e} plasma where the flux reversal takes place, and the other is a high n_{e} and low T_{e} plasma without the flux reversal, where the electron pressure in both shots

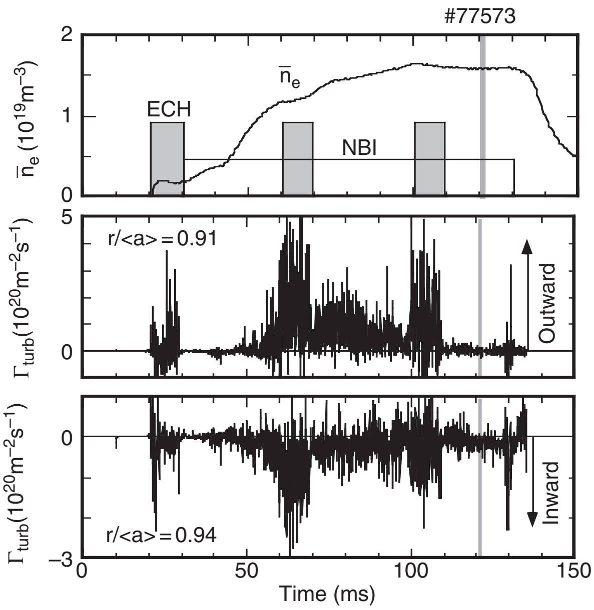


Figure 1. Typical waveforms of the line-averaged electron density and time-resolved turbulent particle flux derived from Langmuir probe data in an NBI-heated plasma, where the toroidal field is $B_t = 1.4$ T.

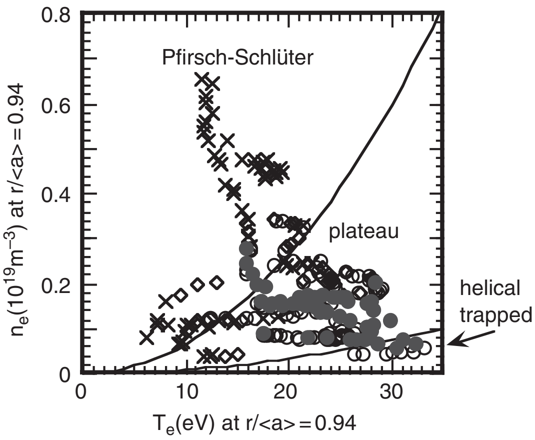
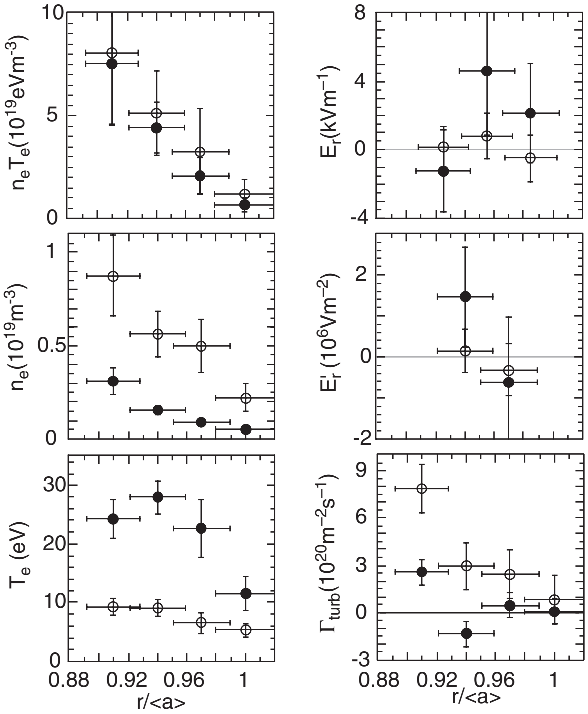


Figure 2. Electron temperature T_e and density n_e at $r/\langle a \rangle = 0.94$ for NBI-heated plasmas. The shots where the turbulent particle flux is outward are shown by crosses. Diamonds and open and solid circles stand for the shots where the flux is inward in the range of 0 to -1×10^{19}, -1 to -3×10^{19}, and less than -3×10^{19} m^{-2} s^{-1}, respectively. Solid curves separate the Pfirsch–Schlülter, plateau and helical ripple trapped regimes (from upper to lower).

is nearly the same. In the former shot, the reversal of the particle flux is observed around $r/\langle a \rangle \sim 0.94$, exhibiting the positive radial electric field shear E_r'. In the latter, the flux is outward in the whole radial range. We studied the correlation between the direction of particle flux at the particular position (i.e. $r/\langle a \rangle = 0.94$) and the radial electric field E_r, the shear E_r',

(a)



(b)

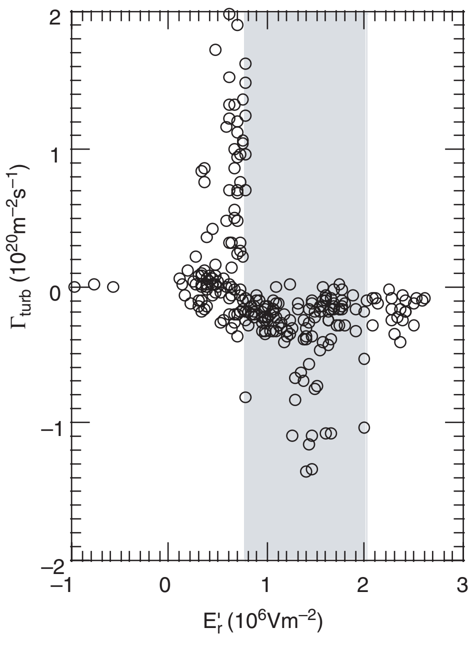


Figure 3. (*a*) Radial profiles of plasma parameters including radial electric field, the shear and turbulent particle flux derived from Langmuir probe data, for two cases: low n_e and high T_e NBI-heated plasma (solid circles) and high n_e and low T_e plasma (open circles). Note that the electron pressure for both cases is nearly the same. (*b*) Dependence of turbulent particle flux on the radial electric field shear for NBI-heated plasmas. The flux is always inward in the range of $E_r' > 0.9 \times 10^6$ V m^{-2}.

and the curvature E_r'' there. The radial electric field was evaluated at three radial positions, from four data points of the plasma potential measured by four sets of triple probes. The shear E_r' was evaluated at two positions from three data points of E_r. The turbulent particle flux data at $r/\langle a\rangle = 0.94$ for many NBI plasmas are shown as a function of the radial electric field shear there (figure 3(*b*)). As seen from this figure, the particle flux always becomes inward in the case that E_r' exceeds $\sim 1 \times 10^6\,\mathrm{V\,m^{-2}}$ (positive shear). The value is comparable to the threshold that fluctuations reduction and confinement improvement were realized in other experiments [12]. However, the flux reversal has no obvious correlation with E_r' or E_r''.

It should be noted that the flux reversal observed in CHS does not lead to obvious confinement improvement [11]. One possible reason may be that the turbulent flux is not uniform along the poloidal circumference on the same magnetic surface. That is, the inward flux is only realized in some fractions of the poloidal circumference, but the outward flux still exists in the remaining poloidal portion. As a result, the net particle flux is still outward, and then the confinement improvement is not achieved. The low-order rational surface may modify the turbulent particle flux in the poloidal circumference, as it was pointed out in TJ-II [13]. In CHS, the rational surface $\iota = 1/1$ exists near the edge ($r/\langle a\rangle \sim 0.95$) in these experimental conditions.

When the ECH is applied to the far edge region ($r/\langle a\rangle = 0.9$–1.0), the inward flux is strongly enhanced, as seen from figure 1. The detailed results are described in [14]. These data also overlap in the parameter space required for the reversal of particle flux, shown in figure 2. Although we did not investigate the threshold in E_r', the threshold of E_r' seems to be about half that shown in figure 3(b) [14]. The reversal of turbulent flux induced by edge ECH did not lead to obvious confinement improvement. One reason is that ECH will induce ECH-driven particle flux comparable to the turbulent flux or even larger than that. In this experimental condition, the role of the low-order rational surface may also be important and should be studied in a future study. The important point of this experiment is that E_r and E_r' can be externally controlled and the direction of the flux can be changed.

3. Enhancement of inward turbulent flux by sawtooth crash

In CHS, so-called sawtooth oscillations are often observed mostly on soft x-ray signals during co-injected neutral beams [15, 16]. The sawtooth crash produces a heat pulse that propagates radially toward the plasma edge. The heat pulse appreciably modifies edge plasma and characteristics of edge fluctuations [17]. In a sawtoothing shot, the turbulent particle flux averaged over 0.5 ms becomes further inward by the arrival of a heat pulse, as shown in figure 4(*a*). In this shot, the sawtooth crash takes place at $t \sim 122.8$ ms and $t \sim 130.3$ ms. We calculated the frequency spectra of edge fluctuations and turbulent particle flux, as shown in figure 4(*b*). Two spectra just before (time window A shown in figure 4(*a*): 118–120 ms; broken curve) and during (time window B: 123–125 ms; solid curve) the sawtooth crash are compared in this figure. It is most significant that the cross phase (in rad) is obviously changed from 0–$\pi/2$ to π in the lower frequency range less than 15 kHz, while both amplitudes of density and poloidal electric field fluctuations are enhanced by the heat pulse and the coherence remains unchanged. This fact leads to the strongly enhanced inward particle flux. In this shot, however, the particle confinement was not improved. This may also be connected with the presence of the low-order rational surface $\iota = 1/1$. That is, the poloidal asymmetry of turbulent flux may still exist and prohibit the net improvement of the confinement. If this asymmetry is removed due to unknown mechanisms, the sawtooth-initiated L–H transition might be achieved in CHS, such as a tokamak plasma.

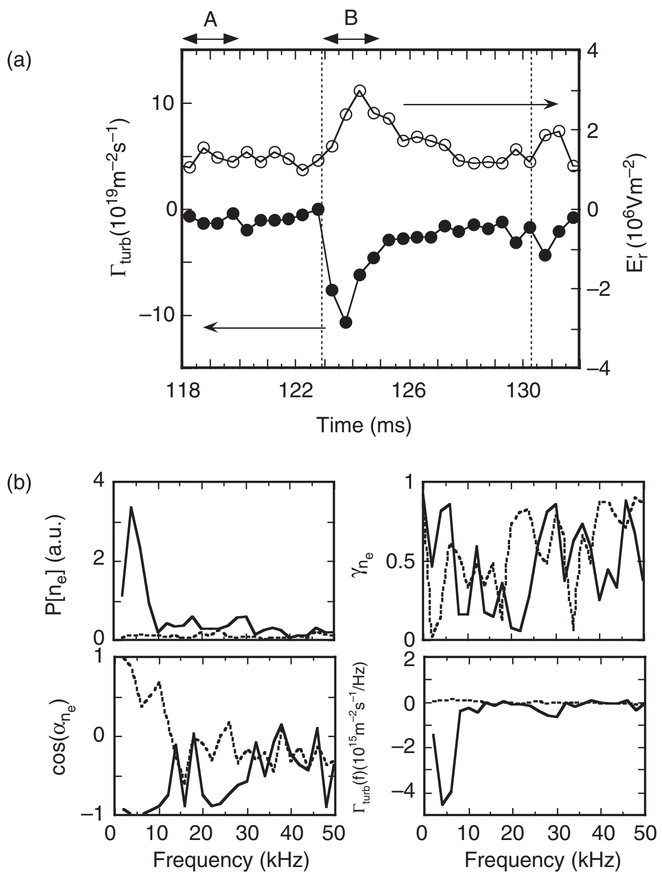


Figure 4. (*a*) Time evolutions of turbulent particle flux averaged over 0.5 ms, and the E_r shear in a sawtoothing plasma. Two sawtooth crashes take place at $t \sim 122.8$ ms and $t \sim 130.3$ ms. (*b*) Frequency spectra of n_e fluctuation level, coherence between n_e and E_θ fluctuations, the cosine of the cross phase, and turbulent particle flux for two time windows before (time window A: $t = 118$–120 ms) and during (time window B: $t = 123$–125 ms) the crash shown in (*a*).

4. Summary

In CHS heliotron/torsatron, the reversal of turbulent particle flux (or inward particle flux) was observed in three discharge conditions: during tangential NBI in the co-direction, ECH applied to the far edge, and the arrival of the heat pulse produced by the sawtooth crash. The reversal regions for three cases are in the edge region of $r/\langle a\rangle = 0.92$–$0.97$. The reversal correlates with the positive radial electric field shear above a certain threshold. So far, the reversal of the particle flux near the edge does not lead to obvious confinement improvement. The role of the rational surface such as $\iota = 1/1$ near the edge, which may induce strong asymmetry of the turbulent flux along the poloidal direction on the magnetic surface, should be investigated in a future study.

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