Direct Observation of Anomalous Electron Diffusion due to Small-Scale Magnetic Turbulence in a Tokamak

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Nonclassical diffusion of test electrons was directly observed in a tokamak by examination of the radial broadening of their drift orbits. A strong correlation between this enhanced diffusion and small-scale radial magnetic field fluctuations of high poloidal mode number was found. The origin of these magnetic fluctuations is discussed in terms of microtearing mode.

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Fluctuation-induced transport is one of the most attractive and important problems to be solved in plasma physics. Especially, discussion of the anomalous electron transport in tokamaks has been stimulated in connection with magnetic or electrostatic fluctuations in recent years.[1-9] In this Letter we report the direct observation of anomalous electron diffusion due to small-scale magnetic turbulence in a tokamak by use of a technique of electron-beam probing.

Measurements of internal magnetic field fluctuations in tokamaks have been made in Macrotor[3] and TCA[7] devices. But there has been no clear evidence that the magnetic fluctuations really provoke electron transport larger than that predicted by the neoclassical theory, although qualitative correlations between the fluctuation level or the correlation length and the gross confinement time have been claimed.

The tokamak device CSTN-II ($B_t \sim 0.875$ kG, $R = 40$ cm, $a = 8.5$ cm, $V_L < 8$ V, $I_p < 2$ kA, $n_e \sim 1\times10^{12}$ cm^{-3}) allows detailed measurements on the electron motion and the fluctuations inside the tokamak plasma because the high repetition mode, usually ten shots per second, ensures the technique of rapid sampling and averaging for data processing.[10] In addition, detectors can be driven in both the horizontal and the vertical directions with a pulse motor controlled by a microcomputer to obtain two-dimensional profiles of various physical quantities in the poloidal plane. An active method for investigation of the electron diffusion is to inject unidirectionally a monoenergetic test electron beam and to measure the broadening of drift orbits. The energy of the test electrons was chosen so high that we can distinguish them from bulk plasma electrons ($T_e \leq 15$ eV) with a small electrostatic energy analyzer (5 mm in diameter and 5 mm in length). A small hot tungsten filament coil, 3 mm in diameter and 5 mm in length, was inserted into the plasma column. A bias voltage of 400 V in a square-wave pulse form was applied on this filament with respect to the stainless-steel vacuum chamber. This voltage becomes approximately the acceleration energy because the plasma potential is roughly equal to that of the chamber.

The effect of atomic processes on the motion of fast test electrons is small because of low hydrogen pressure ($p \sim 8\times10^{-5}$ Torr). In fact, the test electron can make a hundred turns along the torus before impact ionization of or an elastic collision with a hydrogen atom occurs. This permits the study of orbit broadening, distinguishing it from the scattering due to elastic and inelastic electron-neutral collisions. The smallness of atomic processes was confirmed by the Monte Carlo simulation described below. However, the plasma in the present machine is not assumed to be the same as the hot core of larger tokamaks. It is rather similar to the surface plasma in larger machines. The point is to clarify the effect of magnetic turbulence on the nonclassical electron transport in a tokamak configuration.

The estimation of orbit broadening was done in the outer part of the plasma column as mentioned below to minimize the disturbance to the plasma equilibrium and the interception of the probing electron beam. The rotational transform ensures many toroidal turns of test electrons before they are captured by the energy analyzer, thus permitting study of the orbit broadening. The finite cross section of the energy analyzer, in fact, interrupts a part of the circulating probing beam.

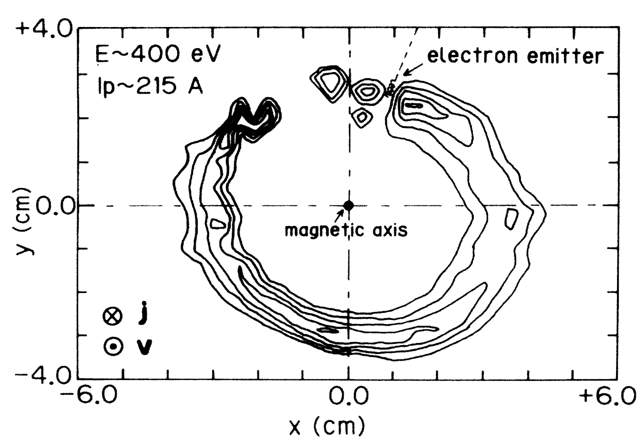

FIG. 1. Contour plot of test-electron flux in the poloidal plane. The electron emitter is located 112.5° away in the toroidal direction from the plane of measurement.

It was thought not to affect the orbit broadening essentially in spite of the diminution of the beam intensity.

A typical contour plot of test-electron flux for so-called counterstreaming electrons is drawn in Fig. 1. The drift orbit thus observed is shifted outward as a result of the toroidal effect as predicted by the drift-orbit theory. The inward shift for costreaming electrons was also confirmed experimentally. The absolute value of the shift does not agree precisely with a simple theoretical prediction (see Fig. 3) probably because of an asymmetrical current distribution in the poloidal plane although the magnetic axis was adjusted to be at the center of the chamber. The breaks of observed drift orbit at the upper left part in Fig. 1 are due to the interruption of primary test electrons by the supporting rod (3 mm in diameter) of the energy analyzer.

The broadening of these drift orbits was found to depend strongly on both the magnitude of the toroidal plasma current and the radial position of the orbit. For example, surface views of these orbits in the outer rectangular area are shown by the insets in Fig. 2 for two different plasma currents. In order to discuss the broadening quantitatively the quasi steady-state FWHM of the drift orbits obtained by averaging of the values at eight different vertical positions are also summarized in Fig. 2 as a function of radial position taking the plasma current as a parameter. The radial position can be changed by movement of the electron emitter. Figure 2 clearly shows that the broadening increases as the plasma current and/or the radial position increases. However, the origin of the broadening should be carefully checked since there are several possibilities to make the drift orbit broad. The most important factor is a finite extent of the electron emitter. As observed in the experiments the minimum width is 5 mm corresponding to the radial length of the emitter. Other possibilities are as follows: (1) electrostatic repulsion of the electron beam, (2) shot-to-shot change of plasma current, and (3) contribution of electrons with different pitch angles and/or initial velocities. The first one can be neglected because the beam electron density is 2 to 3 orders of magnitude smaller than the bulk electron density. The second and third ones were also found to be negligible by examination of the numerical solution of single-particle orbit theory.

We explored a Monte Carlo simulation code for test-electron orbits in the present tokamak configuration, taking electron-neutral as well as electron-electron and electron-ion collisions into account. The inset in Fig. 3 shows a puncture plot of test electrons in a poloidal plane from $t_i = 0$ to $t_f = 0.6\tau_s$, where τ_s is the slowing-down time, and is around 47 μs in the present case. The radial profile shown in Fig. 3 was obtained by plotting the density of puncture points. The broadening is almost unchanged even if t_f is larger than τ_s. Thus it can be said that the profile shown here is the quasi steady-state spatial broadening for flux intensity of test electrons. The radial width is 1 or 2 orders of magnitude smaller than that obtained in the experiments. Moreover, the dependence on

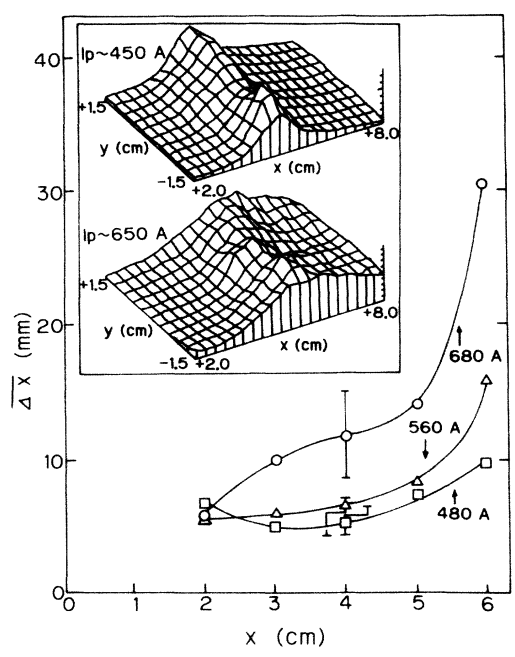

FIG. 2. FWHM of test-electron flux as a function of radial position with the plasma current as a parameter. Inset: surface views of test-electron flux in the outer part of the poloidal plane. The beam energy is 400 eV.

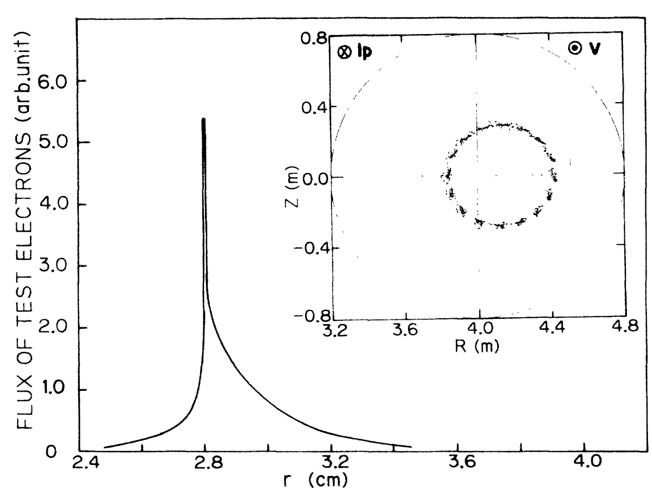

FIG. 3. Results of Monte Carlo simulation. Inset: puncture plot of 45 test electrons in a poloidal plane during $0.6\tau_s$. The curve is a radial profile for the density of puncture points obtained during τ_s. $I_p = 210$ A, $B_t = 0.79$ kG, $E = 400$ eV. Here r is the radial position from the center of the circular drift orbit.

plasma current is opposite for the Pfirsch-Schlüter prediction and the present results because the classical step size for the radial diffusion is the poloidal Larmor radius which decreases as the plasma current increases.

Thus the origin of this anomaly may be brought about by some nonclassical effects, for example, magnetic or electrostatic fluctuations. Figure 4 shows the radial magnetic fluctuations by open circles and the relative density fluctuations by solid triangles as a function of the plasma current at two different frequencies. The latter corresponds to the potential fluctuation divided by the electron temperature. We should note that the electrostatic fluctuation has a very weak dependence on the plasma current. The electron temperature is also almost unchanged in the present range of plasma current while a slow increase of electron density was observed with an increase of plasma current. We can say that the potential fluctuation does not have any strong correlation with the plasma current. In addition, drift waves, typical modes for density fluctuations, are resonant with bulk slow electrons. There are the reasons why we do not consider the electrostatic fluctuations as the origin of anomalous transport for the test electrons.

On the other hand, fast electrons are sensitive to the radial magnetic fluctuations since they tend to run rapidly along the magnetic field line. Therefore, the broadening of orbits increases as the stochastic magnetic fluctuation becomes strong. In the experiment, broad magnetic fluctuation spectra have been actually observed in the frequency range from a few tens to a few hundreds of kilohertz. As shown in Fig. 4 their intensities increase with the plasma current as the orbit broadening does. Two-dimensional profiles of radial magnetic fluctuations in the poloidal plane were examined at two typical frequencies. The fluctuations of higher frequency are strong near the plasma surface, that is, they have *hollow* profiles, while the lower-frequency components have a rather *uniform* distribution. The critical frequency dividing the two frequency domains is around 75 kHz; so there is a strong spatial correspondence between the broadening of drift orbits and the magnetic fluctuations in the higher-frequency domain.

Coherent magnetic fluctuations do not lead to any diffusion. Therefore, the correlation lengths for these fluctuations should be examined. In Fig. 5 the abscissa of each trace shows the cross correlation defined by

$$C_f(\mathbf{r}) = \langle \tilde{B}_f(\mathbf{r}',t)\tilde{B}_f(\mathbf{r},t)\rangle ,$$

where $\mathbf{r}'$ and $\mathbf{r}$ indicate positions of reference and signal probes, respectively. $\tilde{B}_f$ is the frequency component of magnetic fluctuation. The angular brackets mean the average over time and over many shots of tokamak discharge. The reference probe is located at $x = +6.0$ cm, $y = +4.0$ cm. The coordinate employed here is the same as that in Fig. 1. C_f for high-frequency fluctuations approaches zero through fast oscillations as one goes away from the reference probe, while that for the low-frequency component shows slow variation in space. This means that the small-scale high-frequency fluctuations have shorter correlation lengths in both the poloidal and the radial directions than those for the lower-frequency com-

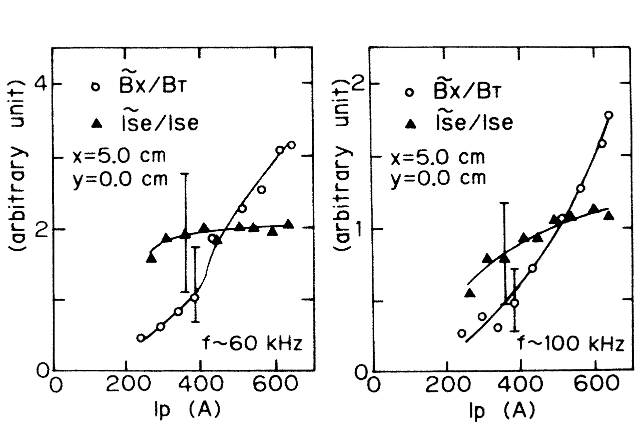

FIG. 4. Relative magnetic and density fluctuations as a function of plasma current for two different frequencies.

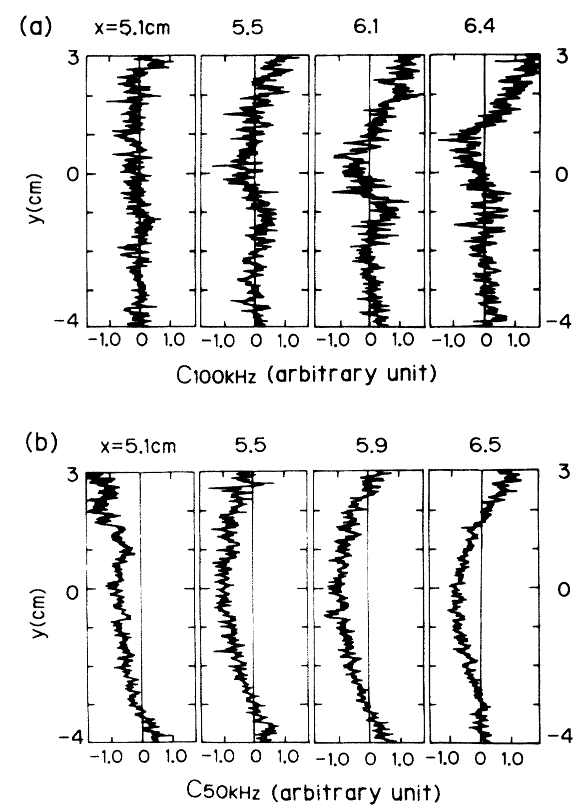

FIG. 5. Cross correlations of (a) high- and (b) low-frequency magnetic fluctuations with the horizontal position of the signal probe as a parameter.

ponents. In Figs. 4 and 5 the data at only two frequencies are represented. But the general trend was confirmed not to be changed at different frequencies in each frequency domain. The lower-frequency global magnetic fluctuations should be excluded as an origin of the anomalous transport from the viewpoints of spatial dependence of orbit broadening and the correlation length. We can say that the most probable candidate for the origin of the anomalous transport of energetic electrons is the higher-frequency, small-scale magnetic turbulence. However, we cannot yet say anything on the transport of bulk slow electrons. The observed positive plasma potential suggests the influence of magnetic turbulence on that.[1,9,11] But further studies are needed.

Now we discuss the nature of the above turbulence. The most possible instability is a microtearing mode driven by the electron temperature gradient in resistive tokamaks.[5] The resistive condition, $\omega_{*n} < \nu_{ei}$, is well satisfied because $\omega_{*n} \sim 3\times 10^5$ Hz, $\nu_{ei} \sim 2\times 10^6$ Hz for the present conditions, where we use the poloidal mode number of ~ 10 obtained by the correlation measurement.[12] The instability frequency was calculated to be 80–90 kHz by use of the observed scale length $L_T \sim 10$ cm, $L_n \sim 4$ cm. It is near the critical frequency obtained in the experiment. The temperature gradient exists only near the plasma surface ($r > 5$ cm) where the magnetic fluctuation is localized. The theory predicts the fluctuation level $\tilde{B}_r/B_t \sim \rho_e/L_T \sim 1\times 10^{-3}$ while the observed relative intensity is from 10^{-4} to 10^{-3}. The comparison between the theory and the experiment in these points seems favorable. But the experiment and theory scaling with the magnitude of the fluctuation do not match up well. It depends on the plasma current and/or the electron density in the experiment while the theory does not predict such dependences when T_e is fixed.

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[12] Notations here and below are the same as in Ref. 5.