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Experimental studies of zonal flows and turbulence in CHS

Theories and simulations have predicted that zonal flows — axisymmetric band-like structures ($m = n = 0$) with a finite radial wavelength — should be present in toroidal plasmas [1]. The zonal flows are driven exclusively by nonlinear interactions with turbulence, and they have an effect on plasma turbulence through time-varying $\boldsymbol{E} \times \boldsymbol{B}$ shearing. Zonal flows work as a reservoir of free energy because the axisymmetric property ($k_\theta = 0$) prevents the zonal flows from contributing to any radial transport across the magnetic flux surfaces. The energy balance between the zonal flow and turbulence should determine transport in a toroidal plasma. Therefore, zonal flows are intimately related to confinement in toroidal devices, and studies of these flows, not only in theory and simulations but also in experiments, are of urgent interest.

Helical devices can provide a unique environment for studying zonal flows, because these devices can produce rather quiet plasmas without MHD instabilities driven by current and plasma pressure. In plasmas with such conditions, zonal flow–related fluctuations can readily be detected, and the interaction processes between zonal flows and turbulence can be investigated more easily. In addition, varieties of helical configurations are available to determine how the magnetic field topology affects energy balance between zonal flow and turbulence. This can contribute to finding experimentally an optimum toroidal configuration for turbulence-driven transport.

In the Compact Helical System (CHS), twin heavy ion beam probes (HIBPs) have been used to study turbulence and zonal flows. Figure 1 shows the location of two HIBPs set at two toroidal sections approximately 90° apart. The HIBPs have almost the same geometrical characteristics. Both are capable of measuring three adjacent positions in the plasma. The HIBPs have been used to clarify the physics of zonal flows. The experiments described here were performed in plasmas produced with ~200 kW of electron cyclotron resonance heating (ECRH). The plasma parameters are magnetic field strength $B = 0.88$ T and density $n_e \sim 5 \times 10^{12} \mathrm{cm}^{-3}$. The necessary beam energy is ~70 keV, using cesium ions at this magnetic field strength, in order to see the plasma center.

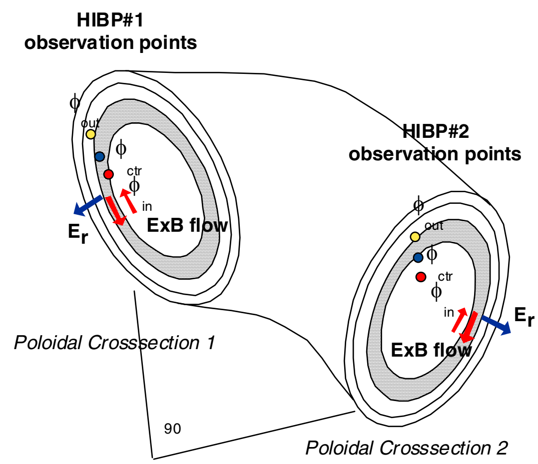

Fig. 1. Schematic view of the geometry of the twin heavy ion beam probes.

In experiments almost two years ago [2], direct measurements of electric field fluctuation using the HIBPs confirmed a long-distance correlation between the radial electric field fluctuations in a low frequency range (<

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Zonal flow is among the central physics issues to be investigated experimentally for the confinement of toroidal plasmas. After the existence of zonal flows was identified in the Compact Helical System (CHS), the relation between zonal flows and turbulence was investigated using twin heavy ion beam probes. Recently, a clear observation was made at the position of an internal transport barrier. This made it possible to show a causal link between zonal flow and turbulence by using time-dependent Fourier (wavelet) analysis. 1

~1 kHz) and proved that the fluctuation in this range is a zonal flow. In addition, the spatio-temporal characteristics of the zonal flows were derived. As shown in Fig. 2, the characteristic radial wavelength of the zonal flow could be ~1.5 cm. Autocorrelation analysis indicates that the lifetime of the zonal flow is about ~1.5 ms. A remaining task of the zonal flow experiments was to prove a causal relationship between turbulence and zonal flow. A recent analysis of turbulence and zonal flows associated with the neoclassical internal transport barrier (N-ITB) [3] indicates that turbulence should be strongly affected by zonal flows.

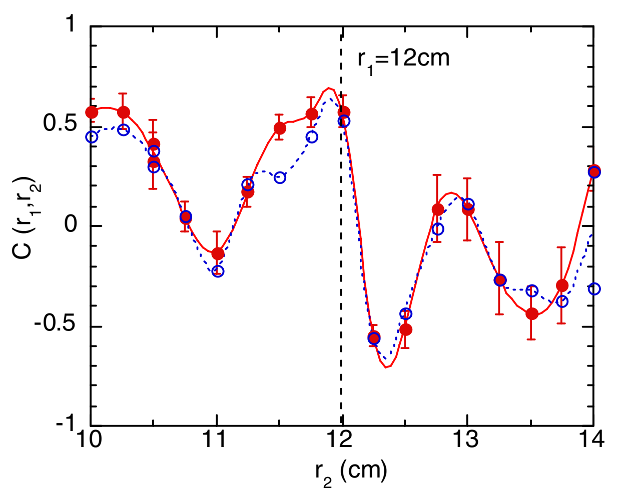

Fig. 2. Radial pattern of the zonal flow, measured with twin HIBPs in CHS.

Figure 3 shows waveforms of potentials and of zonal flows, particle fluxes as a function of frequency, and the total particle flux. One potential signal in Fig. 3(a) (blue line) exhibits a transition (at $t = 71.3$ ms) from the state with a transport barrier to one without a barrier; here we refer to these as H- and L-phase, respectively. The transition occurs on a time scale of less than 100 µs due to neoclassical characteristics. On the other hand, the observation point for the other signal (red line), which shows no significant change in potential, is confirmed to be located precisely at the foot of the barrier ($r = 6.4$ cm, $\rho = 0.34$).

Figure 3(b) shows the evolution of the zonal flow, i.e., the low-pass filtered electric field signal; note that here the signal is measured in V, not in V/m. The real electric field is calculated from the potential difference divided by the channel separation (~5 mm). Here, a positive value means that the zonal flow increases in the ion diamagnetic direction; in other words, total flow intensity increases, since the mean flow is in the ion diamagnetic direction (electric field is positive). One of the findings is that the zonal flow amplitude decreases after the transition.

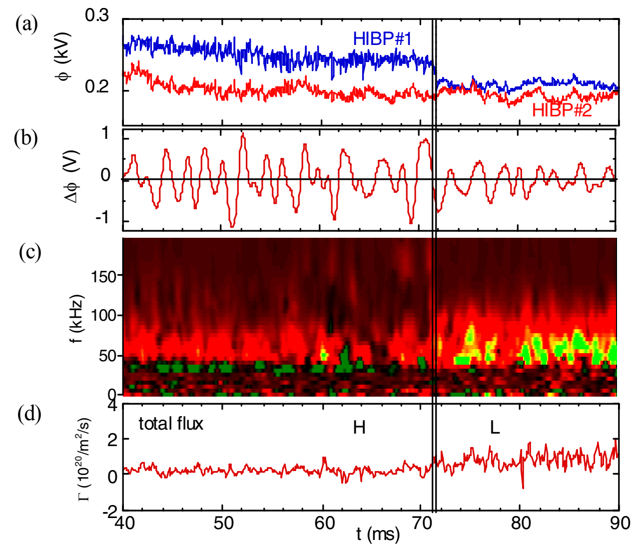

Fig. 3. (a) Waveforms of potentials measured with two HIBPs. A back-transition at $t = 71.3$ ms is clearly indicated in the blue line of potential waveform. (b) Waveforms of zonal flows. (c) Particle flux estimated using an HIBP, as a function of frequency. (d) Total particle flux.

Figures 3(c) and 3(d) show an image plot of evolution of particle flux density, obtained using a wavelet analysis of potential and density fluctuations measured with HIBPs, and the total particle flux, respectively. These signals show intermittent bursts, and the frequency and the averaged height of the bursts increase in the L-phase. In general, these bursts orient radially outward or poloidally in the ion diamagnetic direction, while occasional bursts occur in the opposite direction. The image plot shows that the particle flux density from ~50 kHz to ~100 kHz is the dominant contributor to the particle transport in both L- and H-phases. An important finding for studying zonal flow evolution is that similar activities can be seen in the patterns of zonal flow and in the particle flux density.

In order to confirm this connection between the temporal behavior of turbulence and zonal flow, the power spectra are evaluated during different phases of the zonal flow — maxima, zero, or minima in the amplitude. Figure 4 shows the conditional averaged spectra of the density and potential for the H-phase, since the larger amplitude of zonal flow in this phase makes it easier to recognize. The fluctuation power around ~50 kHz (~120 kHz) is stronger (weaker) in minimum (maximum) zonal flow than that in maximum (minimum) zonal flow, with an intermediate value in the zero phase of the zonal flow. The result, therefore, substantiates a causal relationship between zonal flow and turbulence [4].

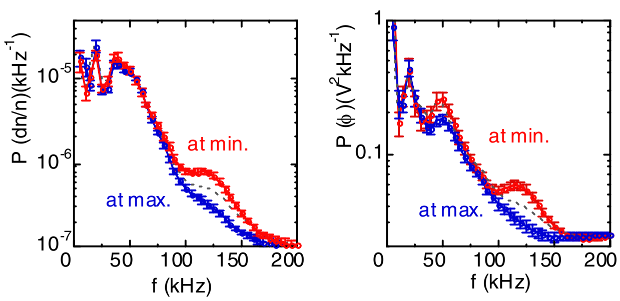

Fig. 4. Conditional averages of the power spectra of density and potential fluctuations for the phases of zonal flow shown in Fig. 3(b). Left: power spectra of normalized density fluctuation; right: power spectra of potential fluctuation.

Several processes may be invoked in the link between the turbulence and zonal flows: i) quasi-energy conservation between turbulence and zonal flow, ii) shearing of zonal flow on the turbulence, and iii) turbulent wave trapping of zonal flows. If the turbulent waves are trapped in a zonal flow valley, the turbulence structure should change in parallel with changes in the local pattern of the zonal flow. The present experimental accuracy, however, cannot distinguish which process is dominant.

The twin HIBP experiments in CHS will be continued to pursue a number of remaining issues for the physics of zonal flows and turbulence. These include, identification of the oscillatory branch of zonal flows (geodesic acoustic modes), radial distribution of zonal flows, dependence of zonal flow characteristics on magnetic field characteristics, relationship between zonal flow and confinement, and so on.

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