Plasma Vortices and Their Relation to Cross-Field Diffusion: A Laboratory Study

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Low-frequency, flute-type electrostatic fluctuations propagating across a strong homogeneous magnetic field are studied experimentally. The fluctuations are generated by the Kelvin-Helmholtz instability. The presence of relatively long-lived vortexlike structures in a background of wideband turbulent fluctuations is demonstrated by a conditional sampling technique. It is demonstrated that in spite of the large-scale convection patterns associated with these structures, they can in some cases contribute only modestly to the turbulent plasma flux across the magnetic-field lines.

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Low-frequency, flute-type electrostatic fluctuations propagating across a strong homogeneous magnetic field can be adequately studied by an analysis restricted to the two spatial dimensions in a plane perpendicular to the magnetic-field lines.[1] Steady-state solutions having the form of monopole or multipole vortices (or modons) are readily obtained and it is demonstrated by numerical investigations that these vortices in some cases have solitonlike properties. There is, however, no analog to the inverse scattering transform; i.e., we have no proof that such structures evolve naturally from arbitrary initial conditions. In the present Letter we summarize experimental investigations of the nonlinearly saturated turbulent stage of the Kelvin-Helmholtz instability. The presence of large vortices in the turbulence is demonstrated by a statistical analysis of the fluctuating signals and their contribution to the turbulent plasma flux across magnetic-field lines is clarified.

The experiment was carried out in the residual plasma (or scrape-off layer) of a single-ended Q machine. Typical values for the plasma density were in the range 10^7–10^9 cm^{-3}, the magnetic field was variable in the range 0.2–0.6 T, while plasma temperatures were $T_i \approx T_e = 0.2$ eV. Turbulent electrostatic fluctuations characterized by frequencies well below the ion cyclotron frequency ω_{ci} were generated by a Kelvin-Helmholtz instability[2,3] due to a radially varying electric field $\mathbf{E}_0(\mathbf{r})$ which gave rise to a sheared $\mathbf{E}_0(\mathbf{r})\times\mathbf{B}_0/B_0^2$ azimuthal bulk plasma velocity. Measurements of the steady-state potential $\Phi_0(\mathbf{r})$ and density $n_0(\mathbf{r})$ are reported in Ref. 4. Our measurements were carried out by small spherical 1-mm-diam platinum probes, allowing fluctuations in floating potential and plasma density to be detected. A typical frequency spectrum for the fluctuating potential $\tilde{\Phi}$ is shown in Fig. 1. The characteristics of the turbulent fluctuations were investigated by means of standard correlation measurements.[4] We explicitly verified that the fluctuations were of the flute type (not drift-wave type); i.e., we could not detect any phase change along the $\mathbf{B}_0$ field. This is consistent with the observation that $\tilde{n}/n_0 \approx 0.2e\Phi/T_e$ approximately, where $\tilde{n}/n_0$ is the relative density fluctuation level. The azimuthal velocity of propagation was determined to be $\simeq 200$ m/s, which is close to the local $\mathbf{E}_0\times\mathbf{B}_0$ drift velocity.

Since the characteristic frequency $\langle\omega\rangle$ of the turbulence is much smaller than the ion cyclotron frequency ω_{ci}, we may identify the fluctuating velocity with the $\mathbf{E}\times\mathbf{B}_0/B_0^2$ velocity, where $\mathbf{E}$ denotes the fluctuating electric field. The polarization drift is thus neglected. The relative magnitude of this correction can be estimated as $\langle\omega\rangle/\omega_{ci} \simeq 0.1$. Our estimate for the particle cross-field velocity is thus accurate within 10%. Measuring the azimuthal component $\tilde{E}$ of $\mathbf{E}$ by the potential difference between two closely spaced probes, while the fluctuating density is measured by a fixed third probe, we obtained good estimates for the fluctuating radial plasma flux, $\tilde{\Gamma} = \tilde{n}\tilde{E}/B_0$, at the position of the probes.[4] The azimuthal

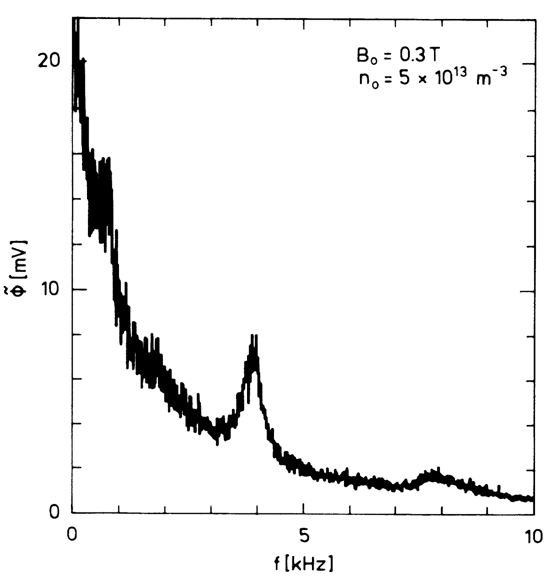

FIG. 1. Frequency spectrum of the fluctuations in potential, obtained at the reference position.

separation of the probes measuring $\tilde{E}$ was much smaller than the azimuthal correlation length measured independently as described in Ref. 4. The average value of the flux, Γ_0, indicated a significant turbulent transport of plasma across the magnetic-field lines, with an effective diffusion coefficient $D \approx 3\times10^{-3}$ $\mathrm{m^2 s^{-1}}$ close to the Bohm value derived for the present parameters.[4] The probability density for the flux signal was notably different from a Gaussian function, with noticeable skewness. It might therefore be that the turbulent transport is caused by sporadic bursts, due to large potential structures in the plasma, rather than by many small random displacements, corresponding to a diffusionlike process. In order to investigate whether large, coherent potential structures were particularly important for the turbulence dynamics, we carried out a detailed statistical analysis of the fluctuations.

It was argued in, e.g., Ref. 5 that a conditional statistical analysis of the turbulence can reveal possible large potential structures, and determine their average properties. For this purpose we choose to consider the electric-field signal $\tilde{E}$ as a reference. The electrostatic potential measured by a movable Langmuir probe is subsequently analyzed subject to certain conditions on the reference signal. In the simplest type of conditional analysis we used sets of time series containing simultaneous records of signals from the reference and the movable probe, high-pass filtered at 800 Hz. The records were obtained with a sampling rate of 50 kHz with an eight-bit resolution and a duration of 500 ms. Choosing a certain prescribed value, E_1, the digitized time series was searched for times where the reference signal takes a value within a narrow interval around E_1 with a positive time derivative of the signal. Each time this condition is satisfied a subseries over a time interval $\{t'-\tau, t'+\tau\}$ is selected from the potential record from the movable probe. The time τ is taken to be larger than the correlation time associated with the turbulent fluctuations. The conditionally chosen time series are then considered as independent realizations for the ensuing statistical analysis. The procedure is repeated for probe positions in a grid of 8×13 positions with 3-mm resolution in the plane perpendicular to the magnetic field. The same analysis is carried out with the fluctuations in plasma *density* being monitored by recording the fluctuating ion current to the movable probe. Conditionally averaged potential and normalized density fluctuations $\tilde{n}/n_0(\mathbf{r})$ ("conditional eddies"), having the form of a double vortex, are shown in Figs. 2(a) and 2(b) for various times with reference to the actual time where the condition on the reference signal is fulfilled. (Note that with full time records available it is possible to investigate the average time evolution before as well as after the reference time.) The formation, propagation, and decay of conditional vortices, or eddies, can be followed and will be discussed in a forthcoming publication. In particular, the breaking

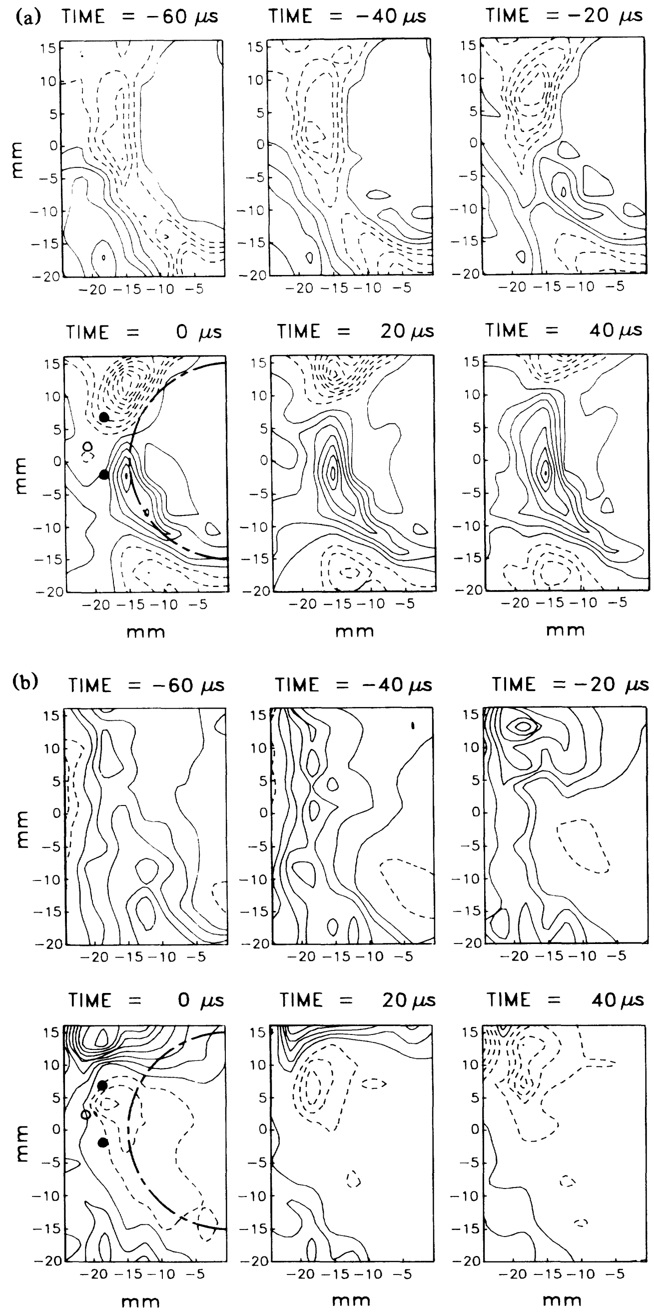

FIG. 2. (a) Conditionally average potential variation and (b) corresponding conditionally averaged relative density fluctuations $\tilde{n}/n_0(\mathbf{r})$, where the imposed condition on the azimuthal electric-field component at the reference position was $E_1 = 1.5\sigma$ and simultaneously $\partial_t \tilde{E} \geq 0$, where σ is the rms value for the fluctuating azimuthal electric-field component. Negative contours in (a) and (b) are given by dashed lines. The zero contour is not shown. The interval between adjacent contours in (a) is $\Delta\tilde{\Phi} = 3$ mV. The maximum amplitude of $\tilde{n}/n_0$ is approximately 20% of the maximum amplitude of $e\tilde{\Phi}/T_e$. The position and size of the reference probes measuring $\tilde{E}$ are marked by solid circles; the one measuring $\tilde{n}$ is marked by an open circle. The dot-dashed semicircle indicates the projection of the hot plate.

and reconnection of equipotential contours (i.e., streamlines) seen in Fig. 2(a) will be important in connection with a detailed understanding of plasma diffusion. We stress that the conditionally averaged potential is obtained from the fluctuating part of the potential, which is superimposed on a steady-state potential gradient giving rise to the bulk $\mathbf{E}_0 \times \mathbf{B}_0$ plasma flow. The conditional vortices are almost stationary in the frame of reference of the plasma flow. Their lifetime is estimated to be at least 100 μs. During that time a particle will be convected by the vortex structure over a distance comparable to the spatial scale size of the vortex in the comoving frame of reference.

We note that an azimuthal shift between the peaks in potential and density variations in Figs. 2(a) and 2(b) is clearly noticeable. This shift, or lack of proportionality, is of central importance for estimating the plasma flux $\tilde{\Gamma}$. Denoting the azimuthal variable by η we have a radial plasma flux across a circularly cylindrical plasma surface of radius R and unit length given by

$$\int_0^{2\pi R} \tilde{\Gamma}(R,t,\eta)d\eta = -\frac{1}{B_0}\int_0^{2\pi R} \tilde{n}(\eta,t)\partial_\eta \tilde{\Phi}(\eta,t)d\eta , \quad (1)$$

where both density and potential are at the same *radial* position R. Clearly, for drift-wave-type fluctuations where $\tilde{n}$ and $\tilde{\Phi}$ are nearly proportional, we have that (1) is very small, while it takes its maximal value when density and azimuthal electric fields, i.e., $\tilde{n}$ and $-\partial_\eta \tilde{\Phi}$, are proportional. According to the results shown in Figs. 2(a) and 2(b) we have a somewhat intermediate case for the present plasma conditions, consistent with the observation $\tilde{n}/n_0 \ll e\tilde{\Phi}/T_e$. (It is not possible to obtain these density and potential variations simultaneously. Small fluctuations in plasma conditions and coating of probes can thus be a source of uncertainty in the comparison of these measurements.) Although large structures with a relatively long lifetime are present in the turbulence, they need not be particularly effective in the anomalous plasma transport across magnetic lines. In order to investigate this problem in more detail we analyzed the (simultaneously obtained) individual electric-field and density fluctuation records which constitute the flux signal at the reference position as discussed before. The conditionally averaged flux $\langle \tilde{\Gamma}(t) \,|\, \tilde{E} \geq \xi\sigma \rangle$ is obtained subject to the imposed condition that $\tilde{E}$ is larger than a certain value $\xi\sigma$ measured in units of the rms value σ for the fluctuating azimuthal electric-field component and simultaneously $\partial_t \tilde{E} \geq 0$. The temporal variation of this averaged flux is shown in Fig. 3(a) for $\xi = 1.5$. The time integral of curves like the one in Fig. 3(a) will thus give

$$\Lambda(\xi) = \frac{N(\xi)}{T}\int_{-\tau}^{\tau} \langle \tilde{\Gamma}(R,t,\eta_0) \,|\, \tilde{E} \geq \xi\sigma \rangle dt , \quad (2)$$

at the reference position (R,η_0), i.e., the time-integrated plasma flux associated with structures having a peak values above $\xi\sigma$, with $N(\xi)$ being the number of oc-

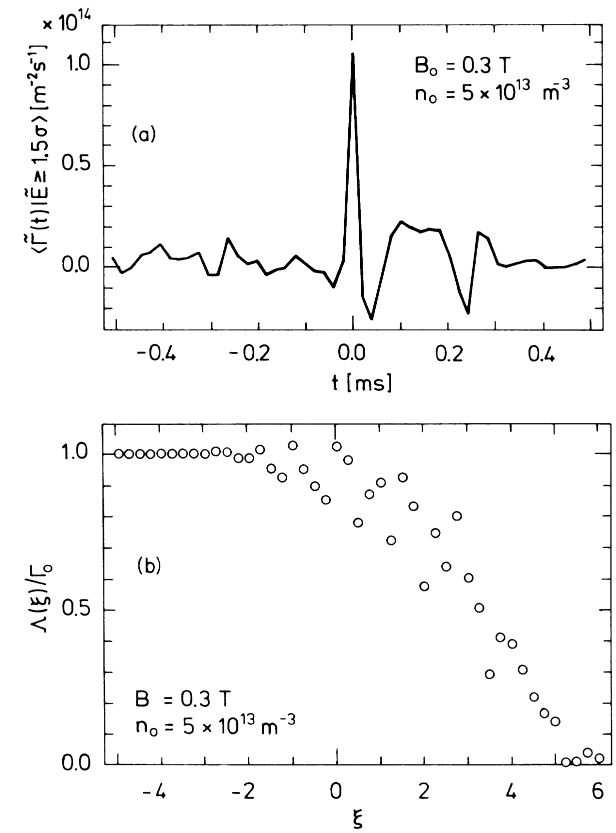

FIG. 3. (a) Conditionally averaged flux $\langle \tilde{\Gamma}(t) \,|\, \tilde{E} \geq \xi\sigma \rangle$ at a reference radial position at $R = 18$ mm subject to the condition $\tilde{E} \geq 1.5\sigma$, i.e., $\xi = 1.5$. (b) The normalized variation with ξ of the time-integrated conditionally averaged flux $\Lambda(\xi)$. The scattering Λ is not systematic and is representative for the uncertainty in the individual points. This uncertainty is increasing with increasing ξ. The normalizing quantity is $\Gamma_0 \approx 3 \times 10^{13}\ \mathrm{m^{-2}s^{-1}}$. The results in this figure are based on extended time series of 2-s duration.

currences of the condition in the records for $\tilde{\Gamma}$. Obviously N is proportional to the record length T. Performing the integration in (2) for various values of ξ we obtain the results shown in Fig. 3(b). Because of the cylindrical symmetry of the problem, all azimuthal positions, η_0, are statistically equivalent[4] for a given R. For large *positive* ξ the quantity $\Lambda(\xi)$ represents that fraction of the average flux which is associated with time intervals where a large structure was present at the reference position. For large *negative* ξ, on the other hand, $\Lambda(\xi)$ is simply a measure for the net total flux across the magnetic-field lines obtained by integrating the entire flux record, i.e., $\Lambda(\xi \to -\infty) \to \Gamma_0$. Evidently, *all* structures contribute to the plasma transport indicating that the very large coherent vortices do not play any *particular* role in the plasma transport. Should this be the case, then Fig. 3(b) would have to reveal a steplike variation at a certain large-ξ value.

Although our results are obtained in a specific plasma device, it should be noted that the basic characteristics of the turbulence described in Ref. 4 are very similar to the results from, e.g., the ISX-B tokamak,[6] indicating that we are dealing with universal phenomena.[7] It is thus expected that the basic properties of vortexlike structures generated by the Kelvin-Helmholtz instability as described in the present paper will be characteristic for other plasma conditions as well.

Investigations like those reported in the present Letter were carried out for varying plasma conditions.[4] The present results are characteristic for spectra having a pronounced peak as in Fig. 1. For very broad-band spectra we found no localized coherent structures. For monochromatic fluctuations having narrow-band spectra, on the other hand, it is the mode structure of the fluctuations which is recovered by the conditional analysis.

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