Fluctuations in a Magnetized Toroidal Plasma without Rotational Transform

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An experimental study of low frequency electrostatic fluctuations is presented for a plasma produced by a steady state discharge in a toroidal device. The evolution and propagation of large coherent vortical structures is demonstrated by a conditional sampling technique. The flutelike nature of the structures is explicitly demonstrated.

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A toroidally magnetized, collisionless plasma without a rotational transform does not possess a nontrivial ideal MHD equilibrium [1]. A quasi-steady-state plasma distribution can nevertheless be produced by maintaining a discharge to balance losses of plasma and electric charge. A thorough description and discussion of this type of discharge was given in [1]. It was observed that the plasma state was strongly influenced by the charge injected via the filament cathode. Estimates show that classical transport (in our case dominated by ion-neutral collisions) is not sufficient to provide the cross-field current necessary to compensate the charge injected into the toroidal magnetic flux tube intersecting the filament. It was also shown that classical transport is insufficient to compensate the charge accumulation due to guiding center drift of electron and ions (∇B and curvature drift), although the latter accumulation is small compared to that arising from electron injection. Hence, for nontrivial, inhomogeneous plasma states the radial cross-field current is anomalous in nature. The radial pressure force on the plasma is balanced by the $\mathbf{j}_\theta \times \mathbf{B}$ force which arises from the poloidal diamagnetic current $\mathbf{j}_\theta$, and the radial anomalous current component is balanced by a poloidal anomalous viscous force $\nabla \cdot \mathbf{T}$, where $\mathbf{T} = \overline{\rho_m \mathbf{v}\mathbf{v}}$ is the Reynolds turbulent stress tensor arising from the inclusion of ion inertia in the momentum equation [1]. Here ρ_m is the fluid mass density and $\mathbf{v}$ is the fluid velocity. These ideas were recently formulated into a complete single fluid model for the turbulent state of the axisymmetric torus by Rypdal [2]. Numerical simulations based on this model will be presented in forthcoming papers. Reference [2] also presented a generalization of the proof for nonexistence of an MHD equilibrium given in [3]. Their nonexistence theorem was generalized to a *turbulent equilibrium* and to include plasma source terms. It was shown that, even though turbulence could provide sufficient cross-field current to provide charge balance, a plasma source term would be necessary to maintain such a turbulent equilibrium. An interesting aspect of these developments is that some degree of magnetic confinement is shown to be possible even in the absence of an MHD equilibrium. Although the confinement may be insufficient for fusion applications, we believe that many naturally occurring plasmas belong to this class, and an increasing number of laboratory devices are designed for the study of such plasmas.

In this Letter we describe experimental studies in the Blaamann device at the University of Tromsø, Norway, emphasizing the role of large scale electrostatic vortices in determining the radial plasma transport. Blaamann is a toroidal plasma device with major and minor radii of 651 and 133 mm, respectively [4]. A toroidal magnetic field up to 0.4 T with magnetic ripple ($\delta B/B$) less than 0.01 at the center is generated by 24 coils. The magnetic system also consists of 8 horizontally positioned coils, concentric with the major axis. These coils are used for creating auxiliary radial and/or vertical magnetic fields inside the vacuum chamber. For the experiments described in this paper the plasma is created by 140 eV electrons emitted from a negatively biased hot tungsten filament. These primary electrons flow in both toroidal directions, subject to vertical ∇B and curvature drifts and poloidal $\mathbf{E} \times \mathbf{B}$ drift, ionizing the neutral gas under constant, monitored pressure. A poloidal limiter extending 2 cm inwards from the wall acts as the main anode for the resulting discharge current. There is no transformer action to induce a toroidal electric field, and no externally imposed toroidal electric current, hence there is no poloidal magnetic field except those radial and vertical fields which can be imposed by the auxiliary coils.

The measurements of the time averaged basic parameters shown in Fig. 1 are obtained by using a computer controlled, motor-driven, Langmuir probe with a spherical probe tip of diameter 1 mm. Full Langmuir characteristics

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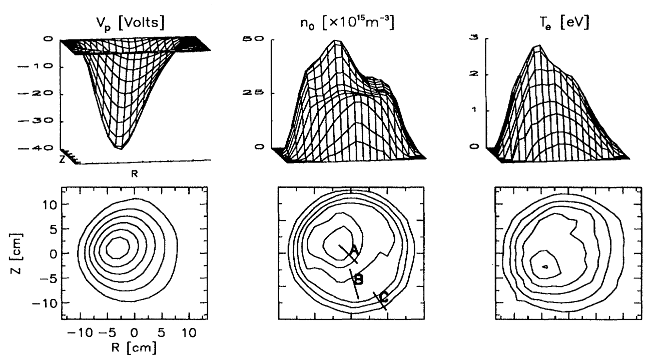

FIG. 1. Plasma potential, density, and electron temperature, for the selected reference plasma parameters. R is the major radius coordinate, and Z is the coordinate along the major axis. The filament is vertical at the position $R = -7$ cm, extending from $z = 8$ to -8 cm, approximately.

were obtained at selected spatial resolution in a cross section of Blaamann. It has been experimentally verified [1] that there is little global perturbation of the plasma by the probe. In Fig. 1 we see plasma potential, electron density, and electron temperature for a selected equilibrium with the following parameters: toroidal magnetic field, $B_0 = 1100$ G, vertical magnetic field, $B_z = 3$ G, primary electron energy $= 140$ eV, and neutral gas pressure $= 8.4 \times 10^{-4}$ mbar. These parameters are selected because the well defined plasma column with closed, almost circular, equipotential contours is obtained, indicating that there is little loss to the walls of the confining vessel due to the mean $\overline{\mathbf{E}} \times \mathbf{B}$ flow. As the following analysis demonstrates, there are nevertheless losses of a "bursty" nature due to fluctuations. The parameters may be varied to obtain different quasiequilibria [1]. It has been verified that these quasiequilibria are highly reproducible.

Coherent vortex structures in the turbulent flow are detected by means of the conditional sampling and averaging method [5,6]. We give here only a brief overview of the method and its interpretation. Time series in floating potential, electron saturation current, or electron temperature all give non-Gaussian amplitude statistics for most of our experiments as evidenced by a nonvanishing skewness, S, and a kurtosis, K, deviating from the value 3 which characterizes a Gaussian. Thus, $S = -0.3$, -0.2, 0, and $K = 3.0$, 2.8, 3.1 for the three regions A, B, and C in Fig. 1, respectively. There are, however, in most cases, some repetitive signatures in the time series deviating from the average background noise. If we assume these signatures to be caused by, or related to, some propagating event in the plasma, the average evolution of such an event can be examined by means of conditional averaging where standard correlation analysis can provide poor information. Conditional averaging as used in the following is based on a two-probe diagnostic. One probe is kept at a fixed reference position measuring a parameter Φ_1, while the other probe scans selected points in a cross section of the plasma column measuring Φ_2. The quantities Φ_1 and Φ_2 can individually represent any measurable parameter.

We use a condition, C, defining time windows of selected size centered around a specific signature at the reference probe, for instance a certain signal amplitude. We define the *conditional time windows* to be the subseries at the movable probe corresponding to a fulfillment of C. At each position of the moving probe we average all acquired conditional time windows, getting the conditional averaged time series

$$\Phi_{ca} = \langle \Phi_2 | C \rangle . \tag{1}$$

In this manner we are able to determine the average time variation of a parameter Φ_2 at any location in the plasma centered around an event at a fixed spatial position. By presenting the results of this analysis as contour or surface plots, we can describe the average time evolution of the structures causing, or being correlated with, the signature selected as our triggering condition. The simplest signature to look for is amplitude levels higher than some critical value, either absolute or relative to the average fluctuation level.

While the conditional averaging method gives the space-time evolution of an *average* structure, it does not give any indication of how individual structures deviate from this average. By defining the *conditional variance* as

$$V_{con} = \frac{\langle (\Phi_2 - \langle \Phi_2 | C \rangle)^2 | C \rangle}{\langle (\Phi_2 | C)^2 \rangle} , \tag{2}$$

where $0 \leq V_{con} \leq 1$, we obtain a measure for the reproducibility of the *entire* event, i.e., the shape and position of a potential structure, and, in particular, also its trajectory. Small values of V_{con} indicate a high degree of reproducibility, and $V_{con} \approx 1$ means little or no reproducibility.

For the selected plasma parameters specified before, we have performed a conditional averaging experiment measuring density fluctuations (obtained by the electron saturation current) on both probes with the results shown in Fig. 2. The fluctuations in density are here normalized in each spatial position by the local average density. The condition used for triggering was in this case

$$\Phi_1 < -1.5\sigma_1 , \tag{3}$$

where σ_1 is the root mean square associated with the time series from the reference probe. Here, $\sigma_1 = 7 \times 10^{-2}$ in terms of the relative density fluctuations. The different frames in Figs. 2 and 3 are obtained by numerical interpolation of measurements performed for probe positions on a grid marked by dots in the figure for $\tau = 0$. The analysis reveals the formation and propagation of a dipole-shaped structure transforming into a monopole while it rotates in $\overline{\mathbf{E}} \times \mathbf{B}$ direction around the density peak shown in the equilibrium measurements. The figures show the fluctuating quantities only. These are to be superimposed on

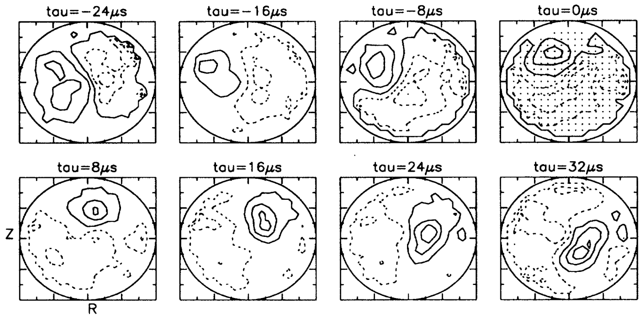

FIG. 2. Temporal variation of the conditionally averaged relative density fluctuations, obtained with the reference probe in the position $(R, Z) = (-2.85, 5.0)$ cm and at the same toroidal position as the movable probe. τ is the relative time from triggering, i.e., $\tau = 0$ corresponds to the time of the triggering event at reference probe. The toroidal magnetic field is into the paper plane. Solid lines denote positive contours, dotted lines negative ones. The separation between contours corresponds to 3% relative density fluctuations. The range of $R-Z$ variations given here applies to the following figures as well.

the dc variations shown in Fig. 1. Calculating the conditional variance (2) we find that the trajectories and the extremum values of the structures are highly reproducible. The statistical uncertainty of the result increases away from the extremum value. At present we cannot distinguish whether this uncertainty represents variations in the structures from one realization to another, or is alternatively a signature of a "flapping" of the edges of the structure as it propagates.

Similar results have been obtained for a wide range of plasma parameters. The signals of the conditionally selected subseries have significantly non-Gaussian characteristics, and the forms and time variations of the conditionally averaged structures depend significantly on the imposed conditions, in particular, their polarity. As large structures appear seldom, they do not give rise to significantly non-Gaussian amplitude distributions for the *entire* time records in the regions where they occur. The observed structures are not to be interpreted as wavelike motion. Charged particles are propagating essentially with the local $\mathbf{E} \times \mathbf{B}/B^2$ velocity along equipotential contours, which have the role of streamlines. Since the structures deform slowly, the streamlines approximate the streaklines for the plasma flow.

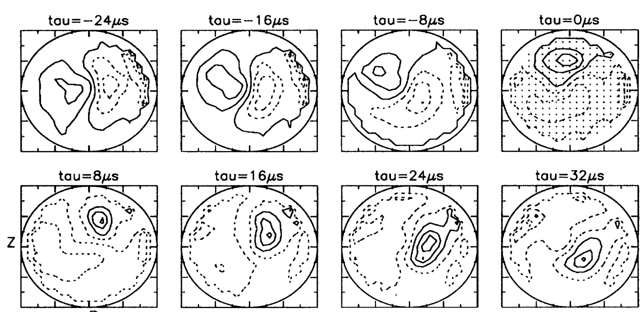

FIG. 3. Conditional averaging with the reference probe displaced 90° toroidally relative to the movable probe. Same triggering condition and contour separations as in Fig. 2.

To get an indication of whether the driving force is drift mode or flute mode instabilities, we repeated the conditional averaging experiment with the reference probe displaced 90° toroidally relative to the previous experiment with the results shown in Fig. 3. Since drift mode waves have a finite **B**-parallel wavelength, while flute modes are strictly parallel to the magnetic field lines, we would expect to see a "phase shift" between the two experiments in the case of drift modes but not for flute modes. By comparing Figs. 2 and 3 we find no such phase shift, indicating flute mode instabilities. Moreover, the drift mode scaling implies $e\Phi/T_e \approx \delta n/n_0$, which is in disagreement with our observations. We find $e\Phi/T_e \approx -3\delta n/n_0$ as an additional support for the interpretation in terms of flute modes. In our measurements we find a density depletion to have a surplus of positive charge, which is not consistent with drift waves but indicates flutelike convective cells. One could suspect that the fluctuations in electron saturation current could in part be due to fluctuations in plasma potential, since the Langmuir characteristic curve is rather inclined in the electron saturation region. Consequently, we repeated the density fluctuation measurements by detecting the ion saturation current with a floating double probe with a fixed bias between the probe tips. The results were similar to those above, possibly with even smaller values of $|\delta n/n_0|$. The Rayleigh-Taylor instability induced by the curvature drifts has been suggested as a possible source for the excitation of the observed fluctuations in this type of device [7].

A local measure of the relative weight of the large amplitude structures compared to the background turbulence can be obtained by a conditional analysis of the signal from the movable probe itself. For this purpose we select a certain length for the time series (here 4096 μs) and count the number of times per second, N_c, that the signal exceeds a value $c\sigma$, where c is a variable coefficient and $\sigma = \sigma(R, Z)$ is now the *local* standard deviation for the signal in the actual position of the movable probe. The value of N_c can then be plotted as a function of c for a given position. The curve is evidently monotonically decreasing. Examples are shown in Fig. 4(a) for the selected probe positions corresponding to the centers of regions A, B, and C in Fig. 1. The higher counts in region B indicate that the large coherent structures have a more dominant role in the turbulence in this region. Similar information is obtained in Fig. 4(b), where N_c is plotted as a function of spatial coordinates for $c = 1.5$. The annular region of maximum counts coincides with region B, and corresponds to the trajectory of the peak amplitude of the conditionally averaged signal, which can be found from

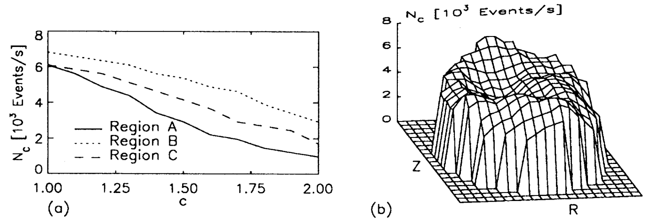

FIG. 4. The number of times per second, N_c, that the signal of the movable probe exceeds $c\sigma$ is shown as a function of c for three different spatial positions (a). In (b) we show N_c as a function of (R, Z) for $c = 1.5$.

Fig. 2. From Fig. 1 it can also be seen that region B has a smaller density gradient than regions A and C. This is displayed even more clearly in Fig. 5, where vertical and horizontal profiles of N_c (for $c = 1.5$) and n are plotted. The density gradient is flattened in regions where the turbulence is dominated by the large amplitude structures (i.e., where N_c is large). Assuming that all the plasma is produced in the vicinity of the filament [1] we can argue that the radial plasma flux is independent of distance from the filament. The anomalous plasma diffusion coefficient will consequently be inversely proportional to the density gradient. This means that the diffusion coefficient is higher in the region dominated by the coherent structures. It is therefore plausible that these structures have a significant role in enhancing the radial plasma transport. Independent experiments in our device based on three probe measurements of the fluctuating electron temperature confirm that the large scale structures give rise to outward bursts of hot electrons originating from the filament region.

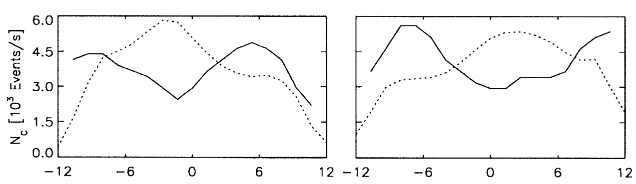

FIG. 5. (a) N_c is shown with a solid line as a function of R for $Z = 0$ and $c = 1.5$. (b) N_c as a function of Z for $R = 0$ and $c = 1.5$. The average density variation is shown with a dotted line for both cases; see Fig. 1 for absolute scale.

The temperature profile shown in Fig. 1 is quite similar to the density profile. The maximum is shifted somewhat downwards as a consequence of the larger downwards curvature drift of the high energy population of electrons. The flat temperature profile in region B can then consistently be viewed as a consequence of the strong "stirring" of the plasma in this region due to the vortex motion.

We find the overall similarity between the present results and those reported in Ref. [8] interesting. The latter experiments were performed in a linear device in a thermally produced plasma. The presence of large vortexlike structures in both experiments indicates that such structures might have some universal properties, and thus be important also, for instance, for confinement in tokamaks or stellarators. Coherent structures have recently been observed in a toroidal device [9]. This and similar studies rely on a biorthogonal decomposition based on the information obtained simultaneously from a large number of spatially distributed detectors or probes. Coherent structures are by this method identified by a constant spatial form, multiplied in each point by a temporally varying function accounting for the time evolution. A biorthogonal decomposition is thus inadequate in representing structures which deform during their temporal evolution. The two-probe method used in the present work does not have this shortcoming.

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