Radial Convection of Plasma Structures in a Turbulent Rotating Magnetized-Plasma Column

Th. Pierre,[1] A. Escarguel,[1] D. Guyomarc'h,[1] R. Barni,[2] and C. Riccardi[2]
[1]*Laboratoire PIIM, UMR 6633 CNRS, Université de Provence, 13397 Marseille CEDEX 20, France*
[2]*Universitá di Milano-Bicocca e INFM, piazza della Scienza, 3 20126 Milano, Italy*
(Received 3 July 2003; published 12 February 2004)

The turbulent regime of a rotating magnetized plasma column has been studied. The detection and the spatiotemporal analysis of structures by means of conditional sampling techniques is performed. Because of the overall rotation and centrifugal effects, the structures inside the turbulence move on average along a spiral trajectory leading to a net radial convection of the charged particles to the walls. The development of a poloidal electric field inside the structures has been measured. It leads to the observed outwards radial $\mathbf{E} \times \mathbf{B}$ drift in agreement with the expectations of recent theoretical works.

DOI: 10.1103/PhysRevLett.92.065004 PACS numbers: 52.35.Ra, 52.25.Xz, 52.55.Dy

The turbulence induced anomalous transport mechanism in magnetized plasmas is a major unsolved problem affecting both our basic plasma physics understanding and the performances of fusion aimed devices. In recent years, a growing consensus is building up in pointing towards the role of burstlike intermittent fluctuations in the transport both in tokamak scrape-off layers (SOL) [1,2] and in other magnetized plasmas, including stellarators [3], simple magnetized tori [4,5], and linear Q machines [6]. Different authors labeled such objects as coherent vortical structures [4], intermittent plasma objects [1], avalanches, or avaloids [2]. The structures seem to be convected due to electric polarization induced by the curvature of the magnetic field lines. These long-lived structures are convected in the background plasma to the walls contributing to a large extent both to particle and to energy transport [1]. In a linear magnetized plasma column, the mean radial electric field induces an $\mathbf{E}\times\mathbf{B}$ poloidal rotation of the column. Without drift induced by the curvature and the gradient of the magnetic field, which is present only in curved devices, other mechanisms should occur in order to drive a radial convection of the structures. In linear devices, it is often assumed that turbulence is maintained by diamagnetic drift wave instability [7] or by Kelvin-Helmholtz shear flow instability [6]. However, numerous studies were devoted also to the centrifugal effects in a rotating plasma [8] in the decade 1970–1980. Only recently, the possible role of the centrifugal force due to the plasma column rotation in anomalous transport [9] was pointed out again. In our plasma device, spiral plasma structures have been recently observed in the regular plasma state [10], closely resembling the form predicted by the theory arising from centrifugal effects [11]. Most of the papers devoted to the centrifugal instability were motivated by the presence of low frequency instabilities in mirror fusion devices and pinches [12]. Recently, centrifugal effects have been used in new confinement concepts in fusion research [13].

In this Letter, we report on an experimental study of the structures and their motion in the turbulent state of the Mistral device. The aim is to investigate the generation of structures in turbulence and their loss processes across the magnetic field. The plasma is produced by a large multipolar source, operating a low pressure ($P =$ 1–5×10^{-2} Pa) argon discharge in the main chamber sustained by hot tungsten filament emission. A floating grid separates the source from the linear plasma column (diameter $D = 40$ cm, $B_{\max} = 0.03$ T). High energy electrons injected from the source produce the magnetized plasma column. The time averaged electron density is longitudinally and poloidally uniform. It peaks radially on the axis, reaching values in the range $n_e = (5 \times 10^8)$–$(2 \times 10^{10})\mathrm{cm}^{-3}$. The averaged electron temperature T_e is about 2–4 eV and ions stay cold ($T_i \leq 0.1$ eV). The injected negative space charge on the axis provides the source for a radial electric field which makes the plasma column rotating at the $\mathbf{E} \times \mathbf{B}$ poloidal velocity [10]. In these experiments, the plasma has been confined to the linear part of the solenoid (length $L = 1.2$ m) by a circular collector. In order to study the different diffusion or convection mechanisms across the magnetic field, the plasma column is restricted to 14 cm in diameter by a metallic diaphragm just behind the grid at the entrance of the column.

With the end plate globally grounded, we have observed that driving the anode potential negative leads to the onset of low frequency unstable regular waves. We have previously reported about an $m = 2$ poloidal mode with a rotating spiral structure [10]. In the present experiments ($B_s = 0.02$ T), the grid is held floating, while the anode potential is kept negative ($V_a = -18$ V). The control parameter was the potential of the collecting plate. Transition from the $m = 2$ mode first goes through an $m = 1$ mode and then reaches a turbulent regime as the potential of the collector is decreased from 30 to 25 and subsequently to 20 V. Similar transitions have been reported in other devices closely resembling our setup [7]. Measurements reported below have been collected in the turbulent regime.

Averaged and fluctuating plasma parameters in the turbulent state have been measured by means of Langmuir probes. Scanning of almost the whole poloidal cross section could be performed through an L-shaped probe moving radially and rotating about its axis, located at a longitudinal position $z = 100$ cm from the grid. A second radially movable probe is used as a reference and has been inserted at different longitudinal positions ($z = 30$–50–80 cm). A time series of the electron saturation current of the reference as well as the scanning probe have been recorded at the same time on a digital scope with a record length of 5×10^4 points. A time series of the floating potential has also been measured. However, in the latter case, in the region outside the plasma column, we observed that the shape of the pulses depends strongly on the impedance of the measurement system. Problems arising in the measurements of the floating potential in the presence of moderately high frequency fluctuations have been anticipated in [14]. More precisely, in floating potential time series, we have detected long decay times after a strong density pulse arrived to the probe. This obviously prevents a direct measurement of the electric field inside the plasma structures by taking the difference of two nearby floating potential measurements, and the local $\mathbf{E} \times \mathbf{B}$ drifts cannot be evaluated in such a way. We have implemented a more accurate set of measurements by recording the full Langmuir characteristic of the probes by slowly sweeping the probe potential (40 V swept within 10 s). Data have been analyzed in order to extract the mean electron temperature and the mean plasma potential.

The conditional sampling technique [15] has been used in order to study the spatiotemporal evolution of the structures. However, we have slightly modified the technique in order to enhance the spatiotemporal resolution. The analysis is performed online on the electron saturation current data, requiring that a particular condition is met in the reference probe time series. A hundred time windows of the electron saturation current, about 500 μs long, have been acquired and averaged for each position in the poloidal cross section, yielding to the reconstruction of the time evolution in the whole plasma section using a grid of 225 positions, with a resolution of 1.5 cm. Contrary to the standard practice [15], in which events are selected requiring simply that the signal crosses a fixed level, we found it necessary to impose a more stringent condition on the shape of the whole selected pulse. This enhanced conditional sampling technique leads to a sharper definition of the structures and to a reduced smearing. In an effort to measure directly the electric field inside the structure, we have also acquired conditionally sampled time windows of the full Langmuir characteristic by performing repeated conditional sampling averages during the slow sweep of the probe potential. We have sampled only a small area of the poloidal section ($5 \times 5\text{cm}^2$), to avoid stability problems of the discharge.

Mean radial profiles of electron density, temperature, and plasma potential have been obtained from averaged Langmuir characteristics. The profile of the electron density is shown in Fig. 1. The main feature is the presence of an annular plateau just outside the limiter surrounding the plasma column. The electron temperature (not displayed) decreases abruptly to almost zero at the limiter. No ionization process could happen in this region and plasma should be continuously transported there due to diffusive or convective flows from the central column. Mean potential profiles are approximately parabolic inside the limiter leading to an almost rigid body $\mathbf{E} \times \mathbf{B}$ rotation of the plasma column. The potential profile flattens behind the limiter and the $\mathbf{E} \times \mathbf{B}$ velocity drops, indicating the existence of a velocity shear behind the limiter.

An inspection of the electron saturation current time series recorded in the region outside the limiter shows the appearance of intermittent pulses very large with respect to the mean values there. On the other hand, in the internal region, fluctuations appear to be smaller ($\sim$30%) and with a more regular oscillating and quasiperiodic pattern. No temporal delay can be detected in the time series of two longitudinally separated probes. This is suggesting that we are observing an almost flutelike structure. The choice of the reference probe location ($r = -6$ cm, $y = 2$ cm) allows us to trigger the rise of the structures propagating in the edge. The results of the conditional sampling analysis, with the triggering condition described hereupon, show a rotating spatiotemporal structure, which is displayed in Fig. 2 for a discharge operated at a pressure of 9.2×10^{-3} Pa. The time step was 2 μs and the space resolution was 1.5 cm. The most striking feature detected in the turbulence is the expulsion of a bent tail of plasma, which we call a plasma burst, from the central column. The burst evolves along a spiral trajectory around the column. This can be understood as

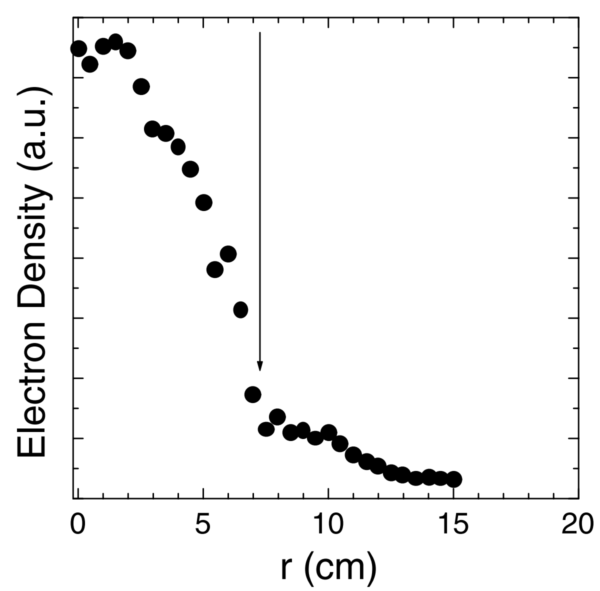

FIG. 1. Mean electron density radial profile measured in the weak turbulence regime. The appearance of a circular corona of plasma around the plasma column is displayed.

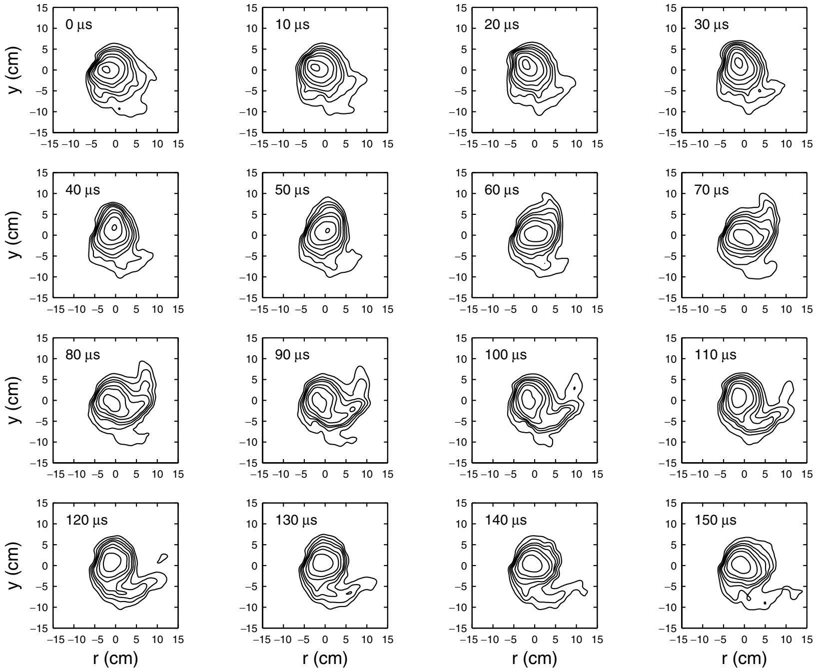

FIG. 2. Electron saturation current contour plot obtained by enhanced conditional sampling technique. Each frame is delayed by 10 μs; lines correspond to values 1.5-2-2.5-3-4-5-7-9 for display purpose. The development of a spiral tail with the radial convection of plasma to walls and its subsequent decay during the column rotation is shown.

due to the rotation velocity decrease along the radius. The winding up of the tail ends when the structure reaches the walls and the plasma gets lost by recombination and parallel collection after about 130 μs. The same kind of spiral structure is recorded changing the size or the shape of the triggering pulses in the reference probe time series. The picture appears more confused and noisy if a traditional 2 standard deviation triggering condition is used.

As already stated, in the region of the poloidal section inside the limiter, the electron saturation current fluctuations are not much skewed and almost symmetric, with both positive and negative pulses. However, these signatures correspond to the same kind of structure. We have selected events in the same discharge conditions triggering on positive pulses and negative events. The obtained conditionally averaged time series appear to be the same in both cases, apart from a fixed time delay corresponding almost exactly to a quarter of the period of the plasma column rotation. This can be understood in terms of the eccentric rotation of the central plasma column.

The conditionally sampled events exhibit the same spiral structure with different radial locations of the reference probe behind the limiter. On the other hand, the event triggered at the center of the column fails to show a spiral tail development, thus suggesting a lack of correlation with the edge of the column. This points out that the structure starts developing from the edge of the plasma column.

In order to study the plasma motion inside the structure, we need information about the local electric field. We have addressed such a problem performing a conditional sampling of the full Langmuir characteristic of the probe, as discussed in the previous section. The measurements have been limited to a small area 5×5 cm^2 of the poloidal section just across the limiter, with a resolution of 0.5 cm. Conditionally sampled time series of electron density, temperature, and plasma potential have been extracted from data taken in experimental conditions similar to the ones reported in Fig. 2. The results for the electron density and the plasma potential are displayed in Fig. 3 at a radial position corresponding to the limiter. The pattern of the electron density structure is similar to that already observed in the electron saturation current. Electron temperature data show that the structure is convecting also energy in the edge of the plasma column. A poloidal electric field inside the structure can be inferred from the pattern of the potential. Indeed, by comparing the time series of electron density and plasma potential at that fixed position, we find that the plasma potential rises as the structure arrives and decreases afterwards. Since both the density and the plasma potential structures appear to be rotating with the whole plasma column, this means that the time variations broadly correspond to the evolution along the poloidal direction. Poloidal and radial components of the instantaneous electric field have been extracted from the plasma potential contour plots. As a result of the structure rotation, a substantial poloidal electric field appears inside the structure ($E_\theta \sim 35$ V/m, while $E_r \sim -60$ V/m at the limiter position), driving the radial convection of plasma outside the limiter and leading to the buildup of the spiral structure. The corresponding $\mathbf{E} \times \mathbf{B}$ drift velocity can be calculated ($v_r \sim 1.7$ km/s at the limiter position) and it is displayed in Fig. 4. Indeed it appears to drive the plasma convection outside the limiter. We point out that such a mechanism is likely to make a substantial contribution to the total transport across the magnetic field lines. These results are very similar to the

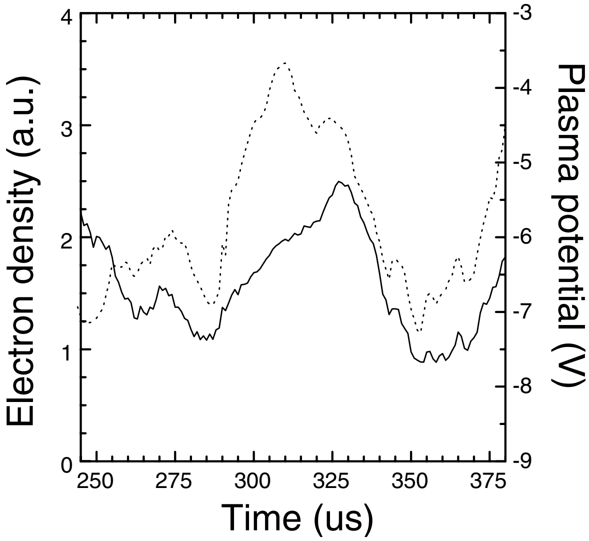

FIG. 3. Conditionally sampled time series of electron density (dot) and plasma potential (full) measured at the radial position corresponding to the limiter edge.

conclusions of the conditional analysis of plasma structures in the SOL of the DIII-D tokamak (see Fig. 7 in [1]). In that case, the polarization in due to the curvature of the *B*-field lines.

In conclusion, we have performed a detailed study of the structures present in the turbulent regime of a rotating magnetized plasma column. A conditional sampling analysis shows that the bursts of plasma are propagated

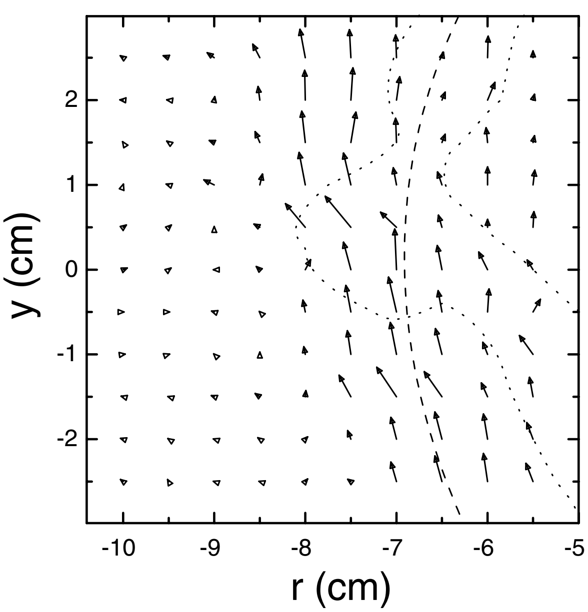

FIG. 4. Vector plot of the $\mathbf{E} \times \mathbf{B}$ drift velocity extracted from the plasma potential space distribution measured at the time the density structure (dot) was passing by the horizontal axis. Limiter position is also shown by the dashed line. A radial drift velocity is clearly seen inside the structure.

radially along a spiral emanating from the plasma column and extending outside the limiter towards the walls. The picture strongly suggests that plasma is radially convected inside such a structure. A simultaneous reconstruction of both the electron density and the plasma potential time series is achieved by conditional sampling of the full Langmuir characteristics. For the first time, radial convection of magnetized plasma in a turbulent regime has been experimentally proven, showing the presence inside the structure of a poloidal electric field inducing an $\mathbf{E} \times \mathbf{B}$ radially outwards motion. Preliminary numerical simulations suggest that in our device centrifugal effects [8,9] can be responsible for the observed behavior. However, more work has to be done before a direct comparison with the experimental data can be performed. This centrifugal effect is rarely taken into account in existing numerical simulations of transport in fusion aimed devices. However, when fast rotating plasma layers exist in the edge of tokamaks, it can be an important contribution for the burst transport phenomenology which was recently so much debated [2].

[1] J. A. Boedo, D. L. Rudakov, R. A. Moyer, S. Krasheninnikov, D. G. Whyte, G. R. McKee, G. R. Tynan, M. J. Schaffer, P. G. Stangeby, W. P. West, S. L. Allen, T. E. Evans, R. J. Fonck, E. M. Hollmann, A.W. Leonard, M. A. Mahdavi, G. D. Porter, M. Tillack, and G. Y. Antar, Phys. Plasmas **8**, 4626 (2001).
[2] G. Y. Antar, G. Counsell, Y. Yu, B. Labombard, and P. Devynck, Phys. Plasmas **10**, 419 (2003)
[3] O. Grulke, T. Klinger, M. Endler, A. Piel, and W7-AS Team, Phys. Plasmas **8**, 5171 (2001).
[4] F. J. Oynes, O. M. Olsen, H. L. Pécseli, A. Fredriksen, and K. Rypdal, Phys. Rev. E **57**, 2242 (1998).
[5] A. Fredriksen, C. Riccardi, L. Cartegni, and H. L. Pécseli, Plasma Phys. Controlled Fusion **45**, 721 (2003).
[6] A. H. Nielsen, H. L. Pécseli, and J. J. Rasmussen, Phys. Plasmas **3**, 1530 (1996).
[7] T. Klinger, A. Latten, A. Piel, G. Bonhomme, Th. Pierre, and T. Dudok de Wit, Phys. Rev. Lett. **79**, 3913 (1997).
[8] B. Lehnert, *Dynamics of Charged Particles* (North-Holland, Amsterdam, 1964); W. Horton and J. Liu, Phys. Fluids **27**, 2067 (1984).
[9] S. I. Krasheninnikov, Phys. Lett. A **283**, 368 (2001).
[10] M. Matsukuma, Th. Pierre, A. Escarguel, D. Guyomarc'h, G. Leclert, F. Brochard, E. Gravier, and Y. Kawai, Phys. Lett. A **314**, 163 (2003).
[11] M. Kono and M. Y. Tanaka, Phys. Rev. Lett. **84**, 4369 (2000).
[12] C. Ekdahl, R. R. Bartsch, R. J. Commisso, R. F. Gribble, K. F. McKenna, G. Miller, and R. E. Siemon, Phys. Fluids **23**, 1832 (1980).
[13] R. F. Ellis, A. B. Hassam, S. Messer, and B. R. Osborn, Phys. Plasmas **8**, 2057 (2001).
[14] M. Light, F. F. Chen, and P. L. Colestock, Phys. Plasmas **8**, 4675 (2001).
[15] H. L. Pécseli and J. Trulsen, Phys. Fluids B **1**, 1616 (1989).