Plasma Blob Generation due to Cooperative Elliptic Instability

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Using fast-camera measurements the generation mechanism of plasma blobs is investigated in the linear device CSDX. During the ejection of plasma blobs the plasma is dominated by an $m = 1$ mode, which is a counterrotating vortex pair. These flows are known to be subject to the cooperative elliptic instability, which is characterized by a cooperative disturbance of the vortex cores and results in a three-dimensional breakdown of two-dimensional flows. The first experimental evidence of a cooperative elliptic instability preceding the blob-ejection is provided in terms of the qualitative evolution of the vortex geometries and internal wave patterns.

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The transport of particles and energy in the plasma edge and in the scrapeoff layer (SOL) of todays magnetic-fusion devices in the low-confinement regime is mostly nondiffusive and occurs in the form of the intermittent convection of coherent mesoscale plasma structures named blobs [1]. There is strong experimental evidence, e.g., from the tokamaks DIII-D and ASDEX Upgrade [2,3], that the blobs are generated in the vicinity of the separatrix. The magnetic field curvature is playing a dominant role in the dynamics of these structures. On the other hand, blob ejection is also observed in plasma discharges performed in linear devices, where the magnetic curvature is absent [4–7]. A general mechanism explaining the intermittent ejection of blobs out of the main plasma region is desirable, which is independent of the magnetic topology and the driving instability.

In linear devices like CSDX, LAPD, and VINETA the blob-ejection process is preceded by an acceleration of an $m = 1$ mode [4–7]. Because of the $E \times B$ drift every perturbation in the potential results in a vortex. An $m = 1$ mode in the potential consists of a negative and positive perturbation, which are vortices rotating in opposite directions and therefore an $m = 1$ mode is a counter-rotating vortex pair. Also in the TORPEX device with a toroidal plasma but open field lines [8] or in the stellarator TJ-K [9], counterrotating vortex pairs, appearing as dipolar patterns in the potential fluctuations, are observed during the blob ejection. Also modes in the plasma edge of large scale fusion devices can be considered as vortex chains which are subject to self interactions. Thus, an instability of vortex pairs or vortex chains in general could also play an important role at the separatrix of these devices.

From fluid mechanics it is known that counter-rotating vortex pairs are subject to the cooperative elliptical instability [10,11] caused by the mutually induced elliptic deformation of the flow within the vortices of a counter-rotating vortex pair. Elliptic flows can be decomposed into a solid body rotation and a potential stagnation point flow giving the strain. Plane wave disturbances, which are advected by the rotating flow can be resonantly amplified if the wave and the straining frequencies match [10]. This matching condition is only fulfilled for one phase difference, which results in the cooperative motion of the vortex cores [10]. It is mainly characterized by the following. (i) An elliptical shape of the vortex centers. (ii) If x is in direction of the line connecting the vortex centers and y perpendicular to it, then the vortex cores are displaced out of phase in the y direction and in phase in the x direction [10]. (iii) The fluid radial motion of vortex cores are in opposite directions than the respective outer layers [10]. Therefore plasma blobs are expected to be ejected when the positive density perturbation in the core moves inward. (iv) It is a three-dimensional instability of a two-dimensional flow, which means it has a finite parallel wave number [10,11]. Indeed, such three-dimensional instability is necessary, since two-dimensional turbulent systems are nonintermittent [12]. In this Letter we give some evidence of the existence of the elliptic instability in magnetized plasmas, providing a general mechanism for the intermittent ejection of turbulent structures.

The characteristic parameters of a vortex pair are the circulations $\Gamma = \iint_D \omega(x, y)dxdy$ [11] of each vortex, their separation length b and their radii defined by $a^2 = \frac{1}{2\Gamma} \iint_D ((x - x_c)^2 + (y - y_c)^2)\omega(x, y)dxdy$, where the integration domain of vortex A is $D_A = \{(x, y)|\omega(x, y) > 0\}$, that of vortex B is $D_B = \{(x, y)|\omega(x, y) < 0\}$, $\omega(x, y)$ is the vorticity and x_c and y_c are the first order vorticity moments. The vortices of a counter-rotating vortex pair have different circulations, which result in a rotation of the vortices around each other with a frequency of $\Omega = (\Gamma_A + \Gamma_B)/(2\pi b^2)$ [11]. There exists a critical Reynolds number $\mathrm{Re}_c > 2^8\pi^3/(9(\lambda/b)^2)$ for the cooperative elliptical instability to develop [10], with λ the parallel wavelength. Each vortex should be delimited and separated from the other vortex giving a breakdown condition of

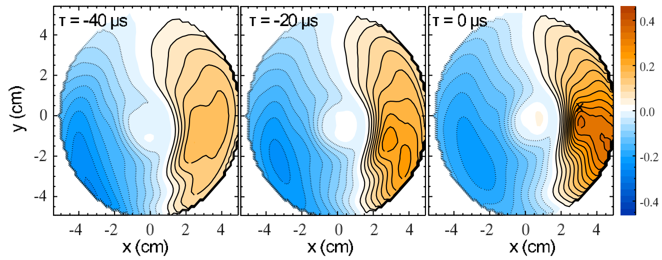

FIG. 1 (color online). Conditional average sequence of fast-camera data, normalized by the background intensity showing the blob ejection. The x marks the reference point for conditional averaging.

the vortex pair $a/b \gtrsim 1/4$, where the value of $1/4$ is a rough estimate and subject to change [11].

Experiments were carried out on the linear cylindrical laboratory plasma device CSDX [13]. The device is 2.8 m long with a vacuum chamber radius of 0.1 m. The plasma ($n \sim 10^{19}$ m^{-3}, $T_e \sim 3$ eV, Argon pressure of 3.2 m Torr, magnetic field strength 0.1 T) is produced by a 13.56 MHz, 1500 W RF helicon source. The typical scale length $\rho_s \approx 1$ cm and speed $c_s = \rho_s \omega_{\mathrm{ci}} \approx 2\pi \times 300$ m/s with the typical ion gyration frequency of 30 kHz give a typical Reynolds number of 10 for CSDX plasmas. The experimental set up is that of [14]. In the present paper fast visible imaging is used to investigate the elliptic instability of the dominant $m = 1$ mode in CSDX. A fast imaging camera was operated behind a 28 cm Schmidt-Cassegrain telescope with 128×64 resolution at 10^5 frames per second. As shown in Fig. 1 the telescope's secondary mirror causes a blind spot in the center of the plasma, where the light intensity is significantly reduced [7]. The camera detects visible light intensity fluctuations, which have been shown to be correlated with the ion saturation current fluctuations from Langmuir probes [5].

Movies captured on CSDX are dominated by a coherent $m = 1$ mode rotating with the frequency of $\Omega = 5.5$ kHz value estimated by time delay estimation [15]. In the following the data set composed of 10^5 frames will be interpolated to polar coordinates and shifted in such a way that the dominant rotation is compensated and that the line connecting the vortex centers is in x-direction. The dynamics of the $m = 1$ mode figures the intermittent excitation of a local density event, defined as an instantaneous local light intensity exceeding 3.5 times the local standard deviation. Over the data set, 116 non time-overlapping events were detected and used to defined the time averaged dynamics of the intermittent event by a conditional averaging technique [16]. Illustration of this averaged dynamic is shown on Fig. 1, where the visible light intensity fluctuations have been normalized to the background intensity. The ejection of the blob is correlated with the appearance of a strong $m = 1$ mode as observed previously in CSDX [5,7]. The density event splits up in two structures, where the outward moving one can be interpreted as a plasma blob. The non-normalized visible light intensity fluctuations will be interpreted as an indicator for vorticity fluctuations ω as done previously [14]. Figure 2 shows the temporal evolution of the conditional averaged data. The vortex cores have an elliptical shape, the vortex centers are displaced horizontally and vertically from a symmetric $m = 1$ mode. The temporal evolution of the spectral power of the symmetric $m = 1$ mode averaged over the radius is shown in Fig. 3(a). It is about 2 orders of magnitude larger than the most unstable drift-mode $m = 3$ [14]. Also a strong $m = 2$ component is observed before the blob ejection $\tau < 0$ μs. Since the horizontal and

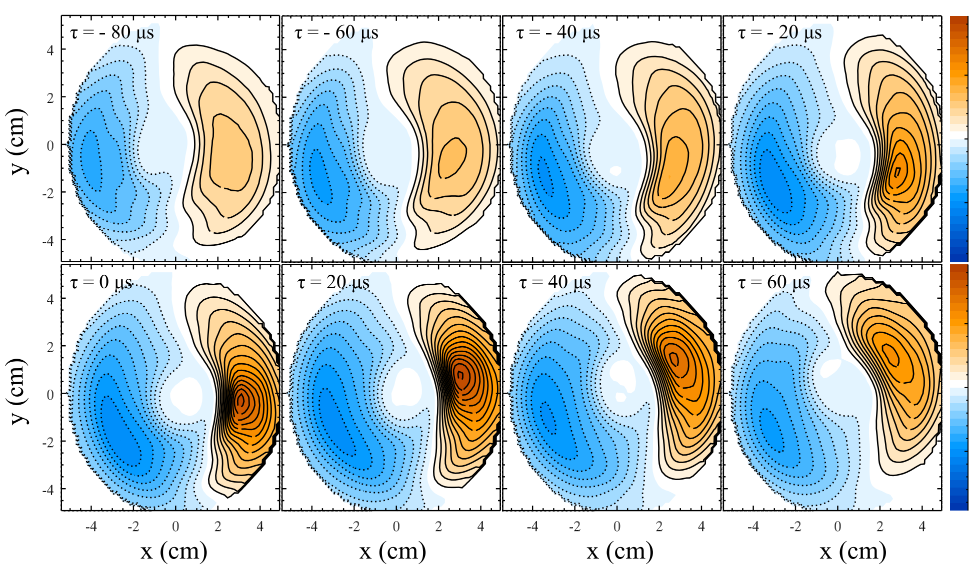

FIG. 2 (color online). Conditional average sequence of fast-camera data during the ejection of a plasma blob showing the evolution of an elliptically shaped vortex pair. The dotted and solid lines indicate negative and positive vorticity, respectively.

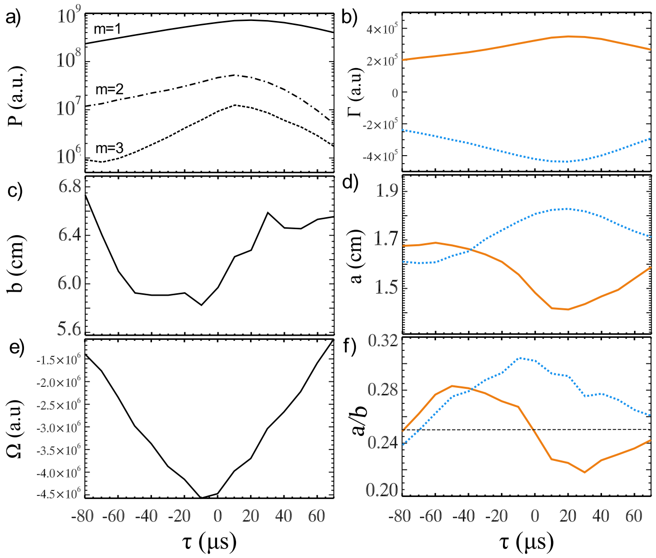

FIG. 3 (color online). Conditional averaged evolution of (a) the spectral power in the $m = 1$, $m = 2$ and $m = 3$ mode averaged over the radius, (b) the circulation Γ of the two vortices, (c) their distance b, (d) their vorticity radii a, (e) the resulting rotation of the vortex pair and (f) the breakdown condition $a/b > 1/4$. Γ, a and a/b are shown for the left (blue, dotted line) and right (orange, solid line) hand side vortex, respectively.

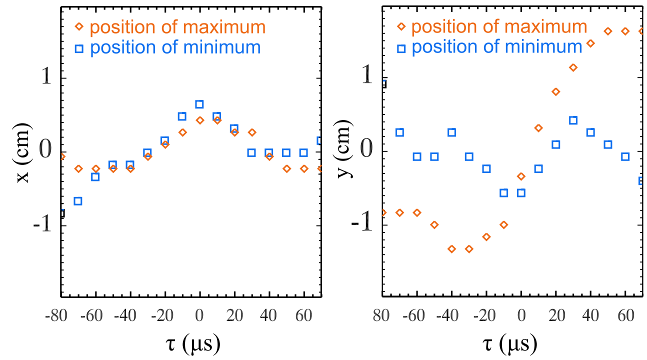

FIG. 4 (color online). Conditional averaged fluctuations of the positions of the maximum and minimum of the vorticity.

vertical displacement from a symmetric $m = 1$ mode directly results in a decrease in the spectral power of the $m = 1$ mode it is more appropriate to consider the circulation of the two vortices Γ_A and Γ_B as shown in Fig. 3(b). They exhibit a very similar behavior as the $m = 1$ mode. As the circulations do not have the same amplitude for the two vortices they rotate around each other with an angular frequency Ω, shown in Fig. 3(e). As observed before [7], the vortex pair accelerates strongly before the blob ejection at $\tau = 0$ μs. Afterward the vortex pair is heavily retarded since the vortex centers move away from each other. The critical Reynolds number gives a condition for the parallel wave length $\lambda \geq 0.5$ m (with $b \approx 6$ cm), which is much larger than the expected $4a \approx 6.5$ cm in the hydrodynamic case [10]. However, a magnetized plasma is nearly incompressible in the plane perpendicular to the magnetic field but compressible in the direction of the magnetic field. Therefore the plasma as a whole is compressible, which is a main difference to the fluid case [10,17]. Therefore, scalings between parallel and perpendicular dynamics are not directly applicable from the fluid theory to the case of magnetized plasmas. Because of parametric resonance the ellipticity of the drift waves can excite drift-sound waves [17], which are in the order of the machine size and fulfill $\lambda \geq 0.5$ m. To investigate the fluctuation of the vortex core positions in detail, Fig. 4 excursions of the maximum and minimum of the light intensity fluctuations from the vortex centers. The maximum and minimum are clearly displaced out of phase (in phase) in y direction (x direction) at $-60 \leq \tau \leq 0$ μs, which breaks the symmetry of the vortex pair in respect to the center plane. Since the interaction of the strain fields of the vortices is responsible for the elliptical instability, it is observed when the two vortices are close together, seen at the distance b between the two vortices in Fig. 3(c) at $-60 \leq \tau \leq 0$ μs. Figure 5 shows the dipole structure in black contour lines and the remaining perturbation field is color scaled. As the elliptical instability develops ($-60 \leq \tau \leq 0$ μs) the $m = 2$ mode is amplified and the phase adjusts in such a way that the fluctuations appear as $m = 1$ internal waves as expected for the elliptical instability [10]. Therefore, the $m = 1$ internal waves, which are expected to result from the shear interaction between the two vortices of the vortex pair (the overall $m = 1$ mode), seems to appear as an overall $m = 2$ mode and the positive perturbation of the right-hand side vortex appears as the blob in Fig. 1. The $m = 2$ perturbation [Fig. 3(a)] give rise to a growth rate of $\gamma \approx 10^5$. To compare this to the strain rate the circulation ($\Gamma \approx 3 \times 10^5$) has to be normalized by the integration domain πa^2 and resolution $\Delta = 1.67 \times 10^{-3}$ (giving $\Gamma \approx 10^3$). The growth rate results in two internal waves resulting in $0.5\gamma/(\Gamma/2\pi b^2) \approx 9/8$ (cf. [10]). This shows that the mutual induced strain is responsible for the $m = 1$ internal wave structures appearing together as an $m = 2$ mode. All of these features are consistent with the investigation of the cooperative elliptical instability of counterrotating vortex pairs in neutral fluids [10].

The presence of background shear modifies the dynamics. For this discharge the azimuthal velocity v_θ is peaked at $r \approx 3.0$ cm, indicating the presence of a plasma shear layer at $r > 3$ cm [14]. This shear interacts differently on the two vortices. Inside the shear layer the background vorticity $\omega = \partial v_\theta/\partial r$ is positive, outside negative, where the negative one is much stronger [14]. As the left-hand side vortex is inside the shear layer ($r > 3.0$ cm, strong negative vorticity) it is prograde. Prograde vortices are stretched by the background shear [18] as observed in Fig. 2 before the blob is ejected $\tau < 0$ μs. Because of this stretching the breakdown condition $a/b > 1/4$ reaches its maximum at $\tau = 0$ μs [Fig. 3(f)]. The center of the

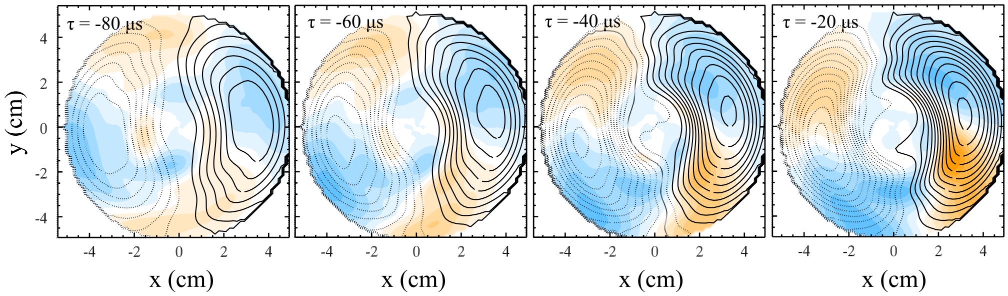

FIG. 5 (color online). Conditional average sequence of internal wave structure.

left-hand side vortex moves outward where the outer layers are brought closer to the stagnation point and the right-hand side vortex. Once the outer layers reach the stagnation point they are wrapped around the primary vortices. Consequently, the $m = 1$ mode loses vorticity and starts to fade away. In the beginning the right-hand side vortex is located at around $r = 3$ cm, where the background vorticity changes its sign and therefore is small. As the negative background shear at $r > 3$ cm is much stronger than the positive shear at $r < 3$ cm, the vorticity of the right-hand side vortex is mainly retrograde. Retrograde vortices are subject to vortex stripping and the vorticity steepens up [19] as seen in Fig. 2 for $\tau < 0$ μs. As the vorticity is steepened up, the vortex is no longer subject to interactions with the background shear as well as with the other vortex. Therefore the vortex is no longer elliptical shaped, the cooperative motion diminishes and the vortex is only convected by the background flow in positive azimuthal direction. Then ($\tau > 0$ μs) the right-hand side vortex moves inwards, where it becomes prograde. Therefore it is stretched and relaxes [Fig. 3(d)].

In summary, first attempts have been made to investigate the elliptic instability in magnetized plasmas. The temporal evolution of vortex cores during the onset of blobs has been investigated using fast visible imaging and compared with flow visualization in neutral fluids [10]. The first experimental evidence of a cooperative elliptic instability in plasmas has been provided by the following observations. During the blob ejection the plasma is dominated by an $m = 1$ mode, which can be interpreted as a counter-rotating vortex pair. The vortex cores have an elliptical shape. The characteristic cooperative oscillation of the vortex cores is observed. During the blob ejection the maximum of vorticity moves toward the plasma center, showing the coupling of the outer layer with the vortex cores [10]. As the minimum of vorticity moves outwards, the outer layer is transported to the stagnation point of the vortex pair resulting in a breakdown of the $m = 1$ mode. The very important three-dimensional dynamics and the nonlinear behavior of shear interactions of the two vortices resulting in the cooperative elliptical instability could not be addressed with the present experimental setup and will be subject of future studies. The cooperative elliptic instability provides a possible mechanism of blob generation at least in magnetized plasmas of linear devices, but the present results may indicate that shear interactions of different vortices within a mode are important for understanding the generation of plasma blobs also in general.

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