

Fluid V-state dynamics through magnetized electron plasmas

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Nonneutral plasmas (NNPs) are a peculiar example of plasmas with overall charge imbalance, and in the simplest case, just one charged particle species. They occur in natural and laboratory environments [1]. A typical laboratory apparatus used for the confinement and study of NNPs is the Penning-Malmberg (PM) trap, i.e. a magneto-electrostatic device whose confinement principle is based on the superposition of an axial electrostatic potential well and an axial magnetic field [2]. PM-trapped highly-magnetized NNPs have proved to be relevant to the study of nonlinear dynamics in other collective systems. A primary example is the physics of two-dimensional (2D) fluids. Indeed the axial-bounce-averaged dynamics of such plasma is isomorphic to that of a two-dimensional inviscid fluid. In particular, there is an equivalence between plasma density n and fluid vorticity ζ as well as between the two velocity fields. This analogy has motivated a long series of excellent fluid experiments using trapped NNPs [3, 4]. An advantage here is the ability to produce tailored particle density (fluid vorticity) patterns and the ease of manipulation with external electric fields (fluid strains) and diagnosis, while non-idealities of direct fluid experiments (boundary friction, 3D effects) can be removed.

An example of 2D fluid dynamics explored through a trapped, magnetized NNP is the evolution of Kelvin-Helmholtz (KH) perturbations in an electron column of initially circular cross-section (axisymmetric fluid vortex). Such perturbations may be induced by the application of suitable multipolar oscillating or rotating electric fields, which lead to deformed (l -fold symmetric) rotating vortex structures called V-states in the nonlinear regime. Stability of uniform vorticity patches was predicted first by Kirchhoff (in the case of a quadrupolar deformation) and then by Deem and Zabusky (for arbitrary deformation order l) [5].

We present here our observations on the insurgence of KH perturbations, the full development of V-states and their collapse, with a focus on the parameters expected to have a significant influence on the nonlinear dynamics of the vortex. Our experiments have been performed on electron plasmas trapped in the ELTRAP and Eltrappino devices, two conceptually similar PM traps where cylindrical plasma columns of length 100 – 1000 mm and radius ≤ 45 mm can be confined thanks to electrostatic potentials ≈ -100 V applied to the ends of a stack of cylindrical electrodes and to magnetic fields $B \leq 0.88$ T generated by the surrounding solenoid. Azimuthally-split electrodes are used to apply electric field perturbations or to monitor the

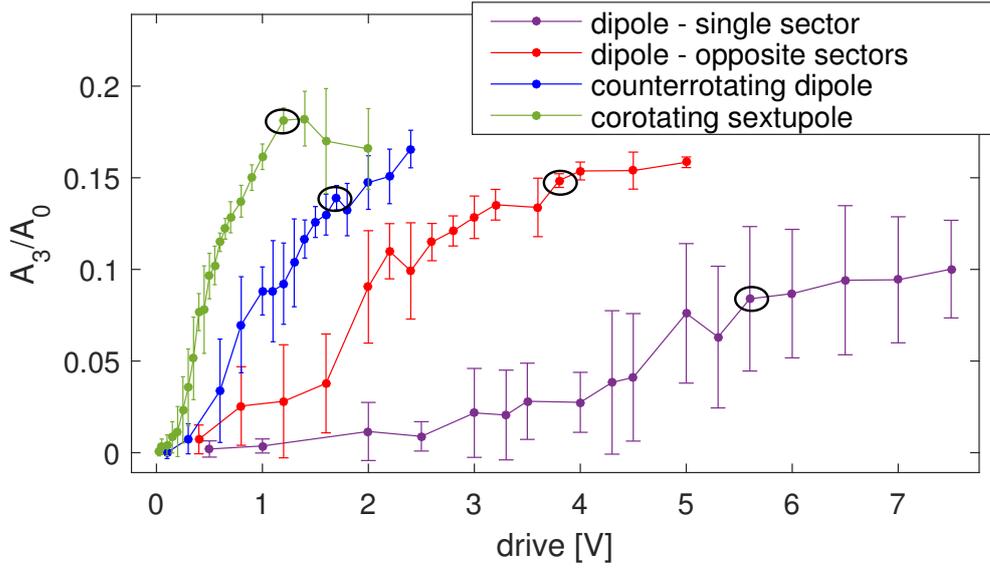


Figure 1: Dependence of mode growth on the perturbation field configuration. Each curve shows the $l = 3$ mode excitation of the same initial state as a function of drive amplitude, using a fourfold-split electrode. Each data point is the average over ten shots of the mode amplitude calculated from the images at plasma dump. Circles indicate the approximate saturation point for each field.

transverse collective motions, e.g., V-state rotation. The axially-integrated transverse density profile is measured at plasma release onto a phosphor screen. Further technical details are given in [6, 7].

The initial state is a cylindrically-symmetric plasma column with core density $10^{12} - 10^{14} \text{ m}^{-3}$ and a tailored radial density profile ranging from quasi-flat to smoothly degrading. The quite unique plasma generation by ionization of the residual gas (mid 10^{-9} to low 10^{-8} mbar) is described elsewhere [6, 8], as is the routine devised to modify the density profile [9]. A single KH mode can hence be excited by an electric field perturbation whose oscillation matches the resonant rotation frequency of the mode itself. As a general feature, growth of the mode well into the nonlinear regime can be achieved within few tens of characteristic mode rotation periods τ_{rot} , but the growth rate and maximum deformation depend on the choice of the field geometry. Indeed, while the simplest and frequently used approach is to apply the forcing on a single azimuthal patch, we have perfected a technique based on both oscillating and rotating fields to maximize the mode growth and achieve a V-state of arbitrary order [10]. Figure 1 shows the results obtained for $l = 3$ using a fourfold-split electrode. One gets comparable results using all sectors for the excitation in the guise of a corotating sextupole or counterrotating dipole field even in a weak perturbation regime (ratio of forcing potential to plasma potential in the 10^{-2}

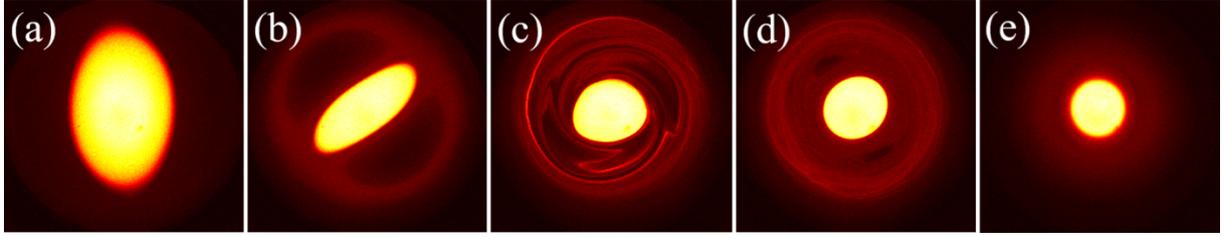


Figure 2: Excitation of an $l = 2$ mode at 155 kHz. Images of the deformed vortex are taken breaking confinement at different times during a continuous quadrupolar excitation. (a) $V_{drive} = 2$ V, 90 ms, no mode collapse; (b) $V_{drive} = 9$ V, 25 ms, before collapse; (c) $V_{drive} = 9$ V, 31 ms, right at collapse; (d) $V_{drive} = 9$ V, 35 ms, after collapse; (e) $V_{drive} = 9$ V, 90 ms, final state.

range). A purely oscillating dipole implemented through one- or two-sector excitation only will be less effective and require stronger amplitude to drive the mode growth, and the drive's effectiveness will anyway saturate at much lower deformation values for the single-sector drive. The reason lies in the drive-vortex interaction being limited to a significantly smaller region, while introducing smearing of the vortex edge through other multipolar field components.

If the forcing is maintained past the point of maximum deformation, we can observe a number of features in the successive vortex dynamics. Stability of the vortex may be observed, but is not guaranteed. One key factor of for survival lies in the strain/vorticity ratio, as seen in experiments with an $l = 2$ mode. Here we excited an $l = 2$ mode at 155 kHz and tracked the mode evolution for increasing confinement times up to 90 ms at different drive amplitudes, acquiring the plasma image at dump. Some of these images are reproduced in Fig. 2. For small drive amplitude and relatively modest stripping of vorticity from the nonlinear structures, we recorded persistence of the V-state over very long times, as much as $10^4 \tau_{rot}$. As the mode frequency is amplitude-dependent, the vortex-drive interaction initially displays strong beatings that are progressively damped as the vortex rotation accommodates to the drive. These beatings increase in frequency as the drive amplitude grows; also, higher stripping is apparent, and the highly deformed core is squeezed. At a critical point the vortex undergoes a sudden collapse accompanied by increased filamentation, resulting in a circular or weakly deformed core in a diffuse vorticity background created by mixing of the filaments stripped from the core. Spatial resonance direct- or beat-wave spatial damping [11] of the excited V-state become more pronounced for higher-order modes as the resonance layer gets closer to the center: in $l = 3$ mode experiments we typically observed catastrophic collapse and cascade to lower modes towards axisymmetry after the first growth stage. This collapse may be followed by repeated stages of growth and decay if the vortex core is left sufficiently intact (modest vorticity is stripped from the vortex and the core couples again

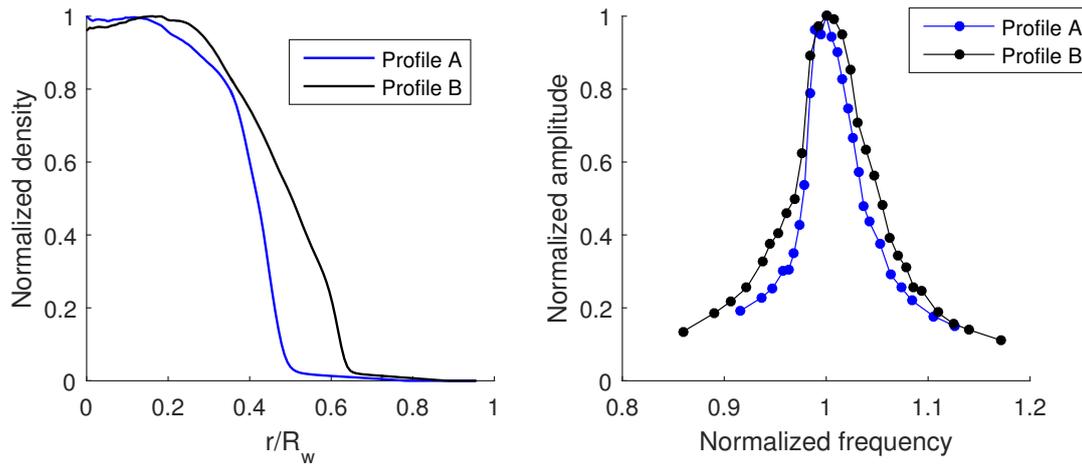


Figure 3: Influence of the vorticity profile on the V-state growth. Left: Two different initial vorticity profiles. Right: The respective $l = 2$ mode excitation normalized resonance curves. Each data point is the average over 10 measurements.

to the forcing). Long-lasting permanent deformation can be attained again over $10^3 - 10^4 \tau_{rot}$.

Coherently with the interpretation of the KH perturbations as a primarily surface interaction, an important factor in the mode-drive coupling is the initial vorticity profile. Indeed a smooth fall-off of the outer region of the vortex is associated to an extended interaction thickness. This in turn results into a higher maximum deformation value with respect to a sharp vortex edge, as well as a broadening of the deformation-vs-excitation frequency resonance curve. An example is shown for the $l = 2$ in Fig. 3, where the two profiles on the left give rise to significantly different resonance curves. Note that the mode amplitude in this case has been extracted from the electrostatic signal picked up by an electrode sector. While the results are qualitatively similar to the optically-diagnosed mode amplitude, this method is more accurate as it can identify the mode's maximum amplitude even in the presence of beatings, which are stronger when the drive is out of resonance and yield images with varying deformation at dump depending on the instantaneous phase. Similar results are obtained for the $l = 3$ mode.

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