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Title:	**Vortex Dynamics in Externally Driven Flows Studied Using Electron Plasmas**
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Vortex Dynamics in Externally Driven Flows Studied Using Electron Plasmas

N. C. Hurst, J. R. Danielson, P. J. Morrison, and C. M. Surko

INTRODUCTION AND CONTEXT. Ideal (i.e., inviscid, incompressible) 2D fluid flow is arguably among the simplest of fluid systems, one that is Hamiltonian on both the field theory and associated point vortex levels. Consequently, it is an excellent starting point for understanding some properties of the nonlinear terms in the equations of fluid (and also plasma) dynamics [1]. The physics addressed here focuses on such 2D vortex dynamics. Although much theoretical and numerical work exists on this topic, regimes such as those involving long time scales, small spatial scales, or the response to non-perturbative changes are difficult to study without laboratory experiments that realize nearly nondissipative physics. Therefore, understanding the consequences of non-perturbative forcing would benefit greatly by controlled laboratory experiments using electron plasmas. This idea centers on the fact that the Drift-Poisson equations describing the dynamics of single-component electron plasmas in a strong, uniform magnetic field are isomorphic to the Euler equations for the two-dimensional dynamics of the inviscid fluid subject to (idealized) free-slip boundary conditions [2]. Here, the electron density plays the role of fluid vorticity. Thus, for example, a plasma column rotates as a vortex *via* the E x B motion due to its electric self field.

To date, much theoretical and experimental work has been done to study such aspects as the free relaxation of initial states, vortex merger, and vortex crystal formation [2-5]. However, the focus here is on the less well-studied situation where vorticity interacts with externally imposed flow fields. It was recently demonstrated that, by biasing segmented wall electrodes confining the plasma, one can impose strong and precise external E x B flows on the electron fluid [6,7]. This capability creates new opportunities to address key questions in vortex dynamics, as well as in connection with a variety of plasma reduced models that have similar forms of nonlinearity.

RESEARCH FRONTIER AND CHALLENGES. A number of open questions can be addressed using such external flows. Examples include the criteria for, and/or nature of:

- **Vortex destruction**
- **Vortex division**
- **Vortex evolution in flow fields with high azimuthal mode numbers**
- **Nonadiabatic response (i.e., with respect to vortex circulation time)**

We briefly discuss these topics in more detail.

Destruction. While free vorticity in 2D tends to self-organize into coherent vortices, these structures can be destroyed by external forcing. An outstanding objective in the study of vortex dynamics is to determine the conditions necessary for the destruction of a given initial vortex configuration [8-11]. Specific issues include understanding: the critical shear and/or strain required for destruction; the vortex lifetime; and how the critical conditions depend on the initial vortex configuration and vorticity profile.

Division. Although the phenomenon of free vortex merger has been studied in considerable detail [2,12], the reverse process of *vortex division* has received considerably less attention. While it has been observed that a coherent vortex, under external influences, may experience division into a number of daughter vortices [9,13,14], controlled demonstration and study of this process is lacking.

High Azimuthal Mode Number Perturbations. Most studies of forced vortex dynamics to date focus on simple shear and/or strain fields (i.e., azimuthal mode numbers m of 1 or 2); however, flow fields can be much more complicated and, in the extreme, turbulent [8-11]. Beyond understanding the dynamics of a vortex in a strong external flow, such high-mode-number external perturbations can provide information about the influence on a vortex of strong neighboring vortices.

Nonadiabatic Response. This is arguably the most important aspect of the new-found experimental capabilities. Most of the previous work on forced vortex dynamics (e.g., in water-tank experiments) considered external flows that are applied slowly (i.e., generally slow on the timescale of the vortex circulation time), conditions that are not necessarily the case in nature [8,10,15]. While systems undergoing such adiabatic changes are amenable to study with a variety of techniques, investigation of nonadiabatic effects is considerably more challenging. The electron plasma experiments described here are easily capable of studying this nonadiabatic regime by the rapid imposition of an external electric field. One focus of experiments, for example, could be to investigate the recent indication of adiabatic invariance associated with vortex rotation [16].

APPROACH AND REQUIREMENTS. Typical experiments will study the behavior of a single-component electron plasma confined in a Penning-Malmberg trap in a magnetic field several-tesla in strength. The primary diagnostic technique consists of visualizing the areal (2D) electron density, line-integrated along the magnetic field direction. For fixed initial conditions, plasma is created and then ejected at selected times, accelerating the particles onto a phosphor screen and recording the image using a CCD camera. Knowledge of the vorticity field from such images and the boundary conditions permit calculation of the fluid stream function, thus providing a complete, time-resolved description of the dynamics of the fluid flow.

Electron plasma systems exhibit excellent reproducibility, and shot times can be on the order of a few seconds [2], thus allowing researchers to obtain statistically significant data sets regarding vortex behavior in relatively short times. The equipment necessary to conduct such experiments is standard. It would include a tesla-scale magnet, nano-torr vacuum system, sub-μs electronics and ~ 10 megapixel CCD camera system. Thus the requirements for an aggressive program in this area centers on adequate support for a P.I. and a few P.I. driven research programs.

IMPACTS, INCLUDING SOCIETAL BENEFITS. ***Plasma Physics:*** Vortex dynamics plays an important role in many plasma systems, including magnetically confined fusion plasmas [17-19] and space and astrophysical situations including the ionosphere and magnetosphere [20]. Thus the knowledge gained in these precisely controlled experiments can be expected to have considerable impact in understanding important aspects of these and other plasma flow phenomena. ***Other Scientific Areas:*** The studies described here will be applicable to any fluid system that exhibits 2D vortex dynamics. Examples range from engineering-related flows to planetary oceans and atmospheres [21], other stellar systems, and galaxies [22]. ***Societal Benefits:*** Such fluid dynamical phenomena are important in many contexts in modern life. Examples include the drag on vehicles, understanding weather patterns and a wealth of astrophysical phenomena (that capture the public's imagination). Vorticity plays a key role in many of these phenomena, and so understanding, and in some cases controlling, vortex-related fluid dynamics can yield great benefits.

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