# Photocathode source for studying two-dimensional fluid phenomena with magnetized electron columns

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Magnetized electron columns are a valuable experimental tool used to study two-dimensional (2D) fluid phenomena. Traditionally, the electrons have been generated with thermionic sources, typically limiting the initial electron distribution to one filled circle and thereby restricting the range of accessible fluid phenomena. Here, we describe a new electron source based on a cesium antimonide photocathode that can generate more complicated initial electron distributions. Experiments so far have focused on the stability of 2D vortex patterns. © *1999 American Institute of Physics.* [S0034-6748(99)02612-X]

## I. INTRODUCTION

Magnetized electron columns are a valuable experimental tool used to study two-dimensional (2D) fluid phenomena. ''Real'' 2D fluids are difficult to manipulate, difficult to diagnose, hindered by three-dimensional boundary effects, and are perturbed by viscosity; therefore, most 2D fluid ''experiments'' have been computational.

Under certain experimental conditions, magnetized electron columns behave two dimensionally, evolving by the interaction of their self-electric field with the imposed magnetic field. This motion is described by the 2D Drift-Poisson equations. Because these equations are identical to the 2D Euler equations describing an ideal 2D fluid, both systems will evolve identically; the magnetized electron system will behave as a 2D fluid.[1–4] The vorticity of the electron ''fluid'' is proportional to the electron density; hence, an electron column is analogous to a fluid vortex. Vorticity is difficult to measure in real fluids, but electron density (and therefore fluid vorticity) can be easily measured by streaming the electrons along the magnetic field, onto a phosphor screen, and imaging them with a charge coupled device (CCD) camera.

Magnetized electron columns can be confined in a Malmberg-Penning trap using static magnetic and electric fields.[5,6] A simple Malmberg-Penning trap, diagrammed in Fig. 1, consists of three coaxial, conducting cylinders contained within a high vacuum chamber. Radial confinement is provided by an axial magnetic field. Axial confinement is provided by negatively biasing the end cylinders with respect to the central one. Electrons are injected from the cathode into the trap by momentarily grounding the cylinder nearest the cathode.

Performing 2D fluid-type experiments with magnetized electron columns requires that the initial 2D electron density (vorticity) distribution be controlled. Traditionally, Malmberg-Penning traps have used a thermionic tungsten filament as the electron source, typically limiting the initial distribution to one filled circle. A circular column can be manipulated into rings,[7,8] two columns,[9] ellipses,[10] or spirals,[11] but injecting more complicated initial distributions necessitates a new electron source.

We developed a new electron source based on a photocathode that provides greater control over the initial electron distribution. To inject a desired distribution, a light image of the distribution is projected onto the photocathode. Because electrons are emitted only where there is light, the initial 2D electron density distribution corresponds to the light image.

## II. THE PHOTOCATHODE

We selected cesium antimonide ($Cs_3Sb$) as the photoemitter because of its fairly strong quantum yield in the visible (1%–5% for a semitransparent photocathode), its reputed ease of fabrication (it involves only two chemicals), and its robustness (it tolerates vacuums below $10^{-6}$ Torr).[12] The fabrication of $Cs_3Sb$ consists of two steps: (1) a layer of antimony (Sb) is deposited onto a substrate; (2) the substrate is exposed to cesium (Cs) vapor while under vacuum and between 120 and 140 °C. Although the initial antimony layer can be exposed to atmosphere, cesium antimonide cannot because of adverse reactions with oxygen and water vapor.

Because of the trap's geometry, we need a semitransparent ''back-illuminated'' photocathode, as opposed to an opaque ''front-illuminated'' one. The fabrication setup is diagrammed in Fig. 1. The substrate is a quartz disk coated with indium tin oxide (ITO), a transparent conductor. The

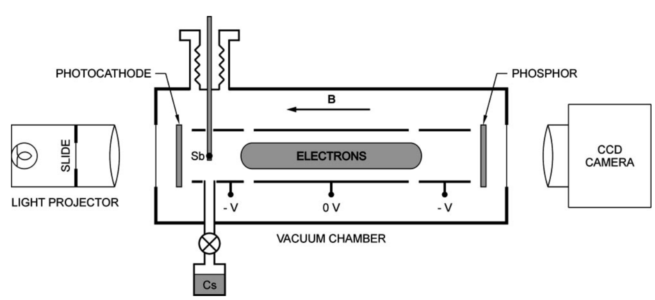


FIG. 1. Geometry of a simple Malmberg-Penning trap with a photocathode electron source and phosphor screen diagnostic. The antimony (Sb) evaporator and cesium (Cs) source are used to fabricate the photocathode.

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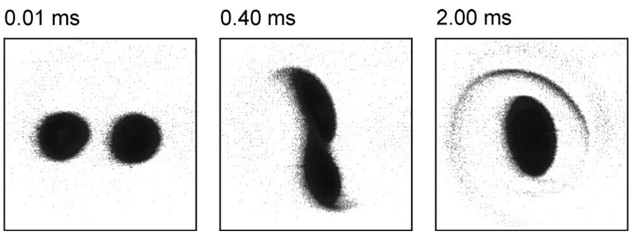


FIG. 2. Evolution of two merging columns.

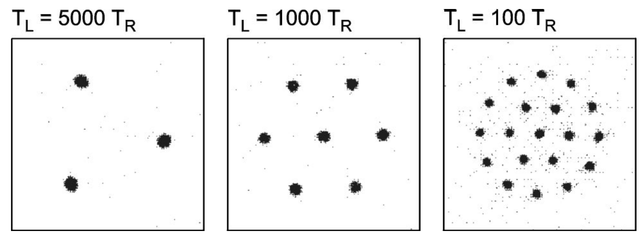


FIG. 4. 2D vortex patterns with their lifetimes ($T_L$) in terms of number of bulk rotations ($T_R$).

antimony evaporator is mounted on a retractable bellows and positioned in front of the substrate only during deposition. The cesium is loaded into a tube and attached to the main chamber via a needle valve. Externally warming the tube above 200 °C releases a sufficient flow of cesium vapor.

The optical system used to project an image onto the photocathode is essentially a common slide projector (from which the heat glass and condenser lens were scavenged) modified to have a magnification of one. The objective consists of two plano-convex lenses, each with a focal length of 125 mm (a cost effective means for achieving decent image quality). A 1 in. diam aperture is used to reduce aberrations. The light source is a halogen slide projector lamp, type EXW, with air cooling. With the lamp running at 40 V (ac), the system projects a luminous flux of approximately 2000 lux to the photocathode, equivalent to approximately $0.3\,\mathrm{mW/cm^2}$ of white light (running at 80 V projects approximately twice as much luminous flux).

## III. PERFORMANCE

The photocathode can inject circular electron columns up to several Debye lengths in radius, with densities of $3\times10^{7}\,\mathrm{cm}^{-3}$ and temperatures of 3 eV, corresponding to Debye lengths of approximately 0.2 cm (these values depend on the light source's intensity, the cathode's voltage, and the photocathode's quantum efficiency). Unlike thermionic sources, it cannot inject columns many Debye lengths in radius. An option to facilitate this is presented in Sec. IV. The photocathode's advantage over thermionic sources is its ability to inject more complicated distributions, as illustrated by the following examples:

(1) Vortex merger: Vortex merger is a good example of a 2D fluid-type phenomenon already studied in a Malmberg-Penning trap, but with a thermionic source.[9] To create two separate electron columns, one column was initially injected, moved off axis, and cut into two; the two columns were dephased and then expanded axially. Here, we simply illuminate the photocathode with two circles of light, thereby injecting two columns of electrons directly (see Fig. 2).

(2) The diocotron instability: The diocotron instability is another phenomenon already studied with a thermionic source.[7] To create a hollow column of electrons, a column was initially injected and then the central electrons were allowed to escape. Here, we illuminate the photocathode with a ring of light, thereby injecting a hollow column of electrons directly (see Fig. 3).

(3) Vortex patterns: Recently, we studied the stability of 2D vortex patterns with our photocathode source.[13,14] Figure 4 shows several examples of 2D vortex patterns injected with the photocathode, all stable for over 100 bulk rotations. These patterns would be extremely difficult to inject without a photocathode.

(4) Go Bears!: The University of California at Berkeley's logo evolves by the Kelvin-Helmholtz instability into vortices (see Fig. 5).

(5) Anchors Away!: We inject an anchor for the Office of Naval Research, our sponsors, demonstrating the capabilities of the photocathode to inject designer distributions (see Fig. 6).

## IV. ELECTRIC POTENTIAL PROFILE CONTROL OPTION

Ideally, the electric potential of the cathode should match the electric potential of the trapped electrons,[15] particularly for the injection of uniform density columns many Debye lengths in radius. If the cathode is an equipotential, the resulting columns may be hollow.[16] However, we find that our equipotential photocathode can inject columns up to several Debye lengths in radius. Even with this restriction, many interesting experiments can be performed, as was discussed in Sec. III. If necessary, the photocathode potential profile can be controlled using the method outlined below.

Substrates for transmission photocathodes are coated with ITO, a transparent conductor. To make an equipotential cathode, we mount the substrate in an electrically isolated holder; the ITO layer makes the cathode potential uniform. Tailoring the cathode potential profile requires electrically

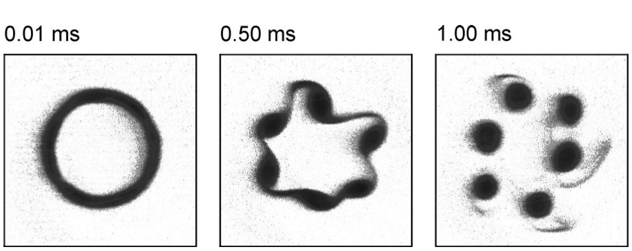


FIG. 3. Evolution of a hollow column by the diocotron instability.

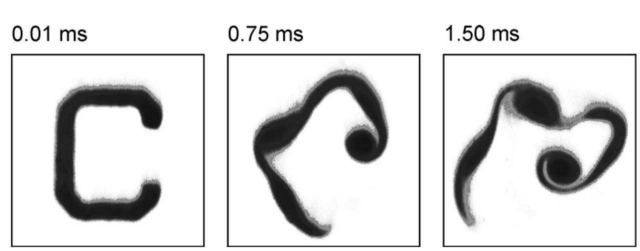


FIG. 5. ''Go Bears!'' evolution.

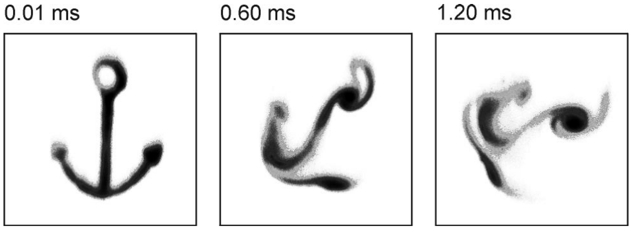


FIG. 6. ‘‘Anchors Away!’’ evolution.

contacting the photocathode at multiple points. One way to accomplish this is diagrammed in Fig. 7. A hole is laser drilled through the quartz substrate and a 100 Ω/square ITO contact pad is deposited about it. Tungsten wire is fed through the hole, knotted, pulled back against the pad's surface, and spring loaded to a vacuum feedthrough. The pattern of the contact pads depends on the symmetry of the electric potential profile: we have developed a square pixelated and a concentric ring version.

Some notes on this method: amorphous quartz is used because of its ability to survive the laser drilling process; the quartz also must be less than 1/16 in. thick to get cleanly drilled holes; the holes are less than 0.010 in. in diameter and the tungsten wire is 0.075 mm in diameter; beryllium copper springs are used because of their low magnetic susceptibility and their ability to withstand a 200 °C vacuum bakeout; care must be taken when spring loading the many tungsten wires. (Too much spring force can have dramatic results, and did!)

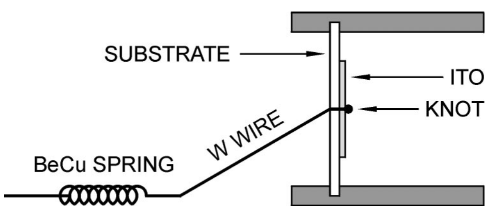


FIG. 7. Simple electric potential control option.

## ACKNOWLEDGMENT

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