Doppler Velocimetry of Cryogenic Ion Plasmas

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***Abstract*—We describe a technique and present results for imaging wakes and modes excited in a laser-cooled plasma of $^9Be^+$ ions in a cylindrical Penning trap. Wakes are created by an off-axis laser "push" beam, while individual modes are excited by sinusoidally time-varying potentials applied to the trap endcaps. Variations in ion velocities are imaged by changes in the ion fluorescence due to Doppler shifts. A comparison between theory and experiment shows good agreement.**

***Index Terms*—Doppler measurements, fluorescence spectroscopy, laser cooling, plasmas, waves.**

NONNEUTRAL plasmas consisting exclusively of particles of a single sign of charge can be confined by static electric and magnetic fields and can also be in a state of global thermal equilibrium. A particularly simple confinement geometry is the quadratic Penning trap, which uses a strong uniform magnetic field superimposed on an electrostatic potential produced by biasing a central ring to V_0. For sufficiently low temperatures, the plasma takes on the simple shape of a uniform density spheroid. The plasma density and spheroid aspect ratio ($\alpha \equiv$ axial extent/diameter) are set by the frequency ω_r of the plasma rotation about the trap axis. An interesting result is that all of the electrostatic modes of a magnetized, uniform-density spheroidal plasma can be calculated analytically [1]. This allows us to easily calculate the response of the plasma to perturbations.

Fig. 1 shows the geometry of the experiment and its optical diagnostics. An axial laser beam at wavelength $\lambda \approx 313$ nm laser cools the $^9Be^+$ ions to temperatures of $T \leq 10$ mK, and the fluorescence is monitored by sensitive cameras to provide information on the ion density and axial velocity. The frequency of the axial cooling laser is fixed at about one-half of the natural linewidth (~10 MHz) below the resonance frequency. Due to Doppler shifts, ions with axial velocities $v_z < 0$ (toward the laser) fluoresce more strongly than ions with $v_z > 0$, giving us a sensitive diagnostic for coherent axial motion in the plasma [2]. With the resonance transition we use, we estimate that the minimum ion velocities measurable with this technique are ~15 cm/s.

In Fig. 2(a), we plot a top-view image of the differential fluorescence intensity produced by a small push laser beam on a disk-shaped ion plasma with $\omega_r/2\pi = 45$ kHz, radius $r_0 \simeq 0.9$ mm and aspect ratio $\alpha = 0.042$. The radiation pressure of the push beam excites modes that interfere to produce a wake that is well described by analytic theory, as shown in Fig. 2(b) [3].

Fig. 3 shows how Doppler velocimetry can image the eigenfunctions of individual plasma modes. Fig. 3(a) shows a side-view image of the total fluorescence intensity of unperturbed ions, and Fig. 3(b) shows the intensity when the endcaps are driven ($V_{AC} = 35$ mV, $\omega_{drive} = 1.524$ MHz) and the side-view camera is synchronously strobed with a duty cycle of 16%. The odd axial symmetry of the perturbation has excited an axial motion of the entire cloud, known as the (1, 0) mode (where the modes are classified by integers (l, m) [2]), in addition to a higher order (7, 0) mode with a predicted frequency of $\omega_{7,0} = 1.532$ MHz.

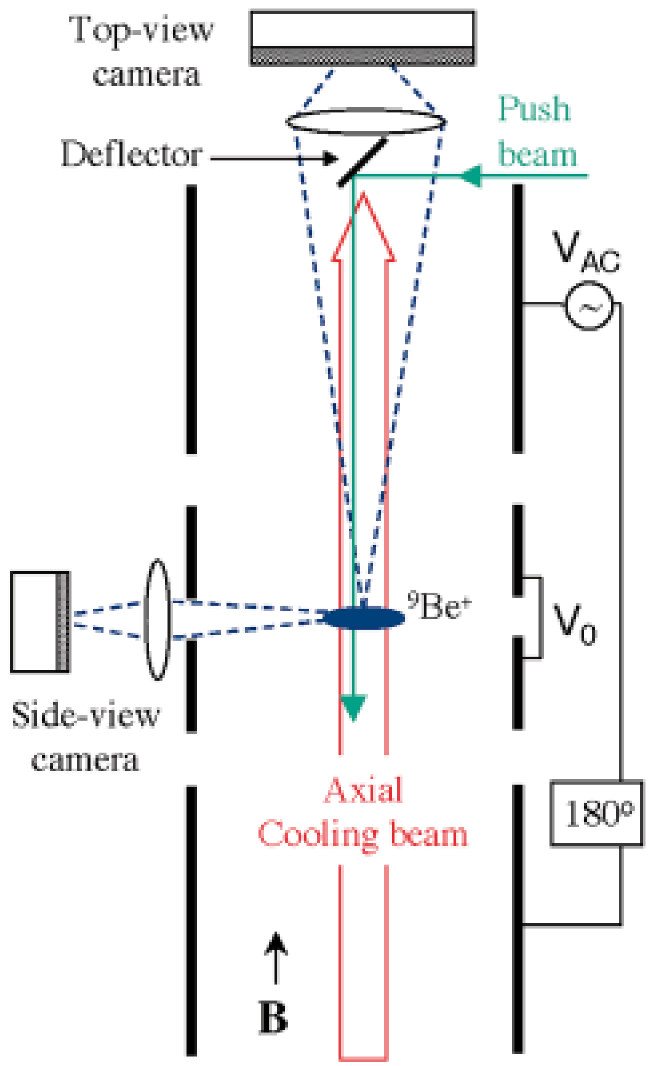

Fig. 1. The cylindrical experimental apparatus and its optical diagnostics. In this work $B = 4.46$ T and V_0 ranged from -1 kV to -2 kV.

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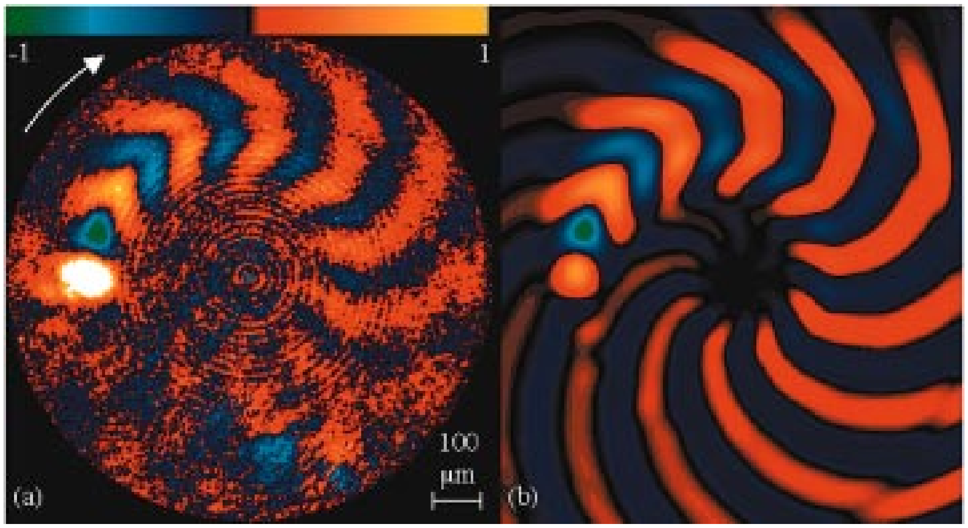

Fig. 2. Top-view images of the differential intensities, proportional to the ion velocities, induced by a laser push beam (white spot) incident on a disk-shaped ion plasma rotating clockwise. (a) shows experimental results while (b) shows the prediction from theory.

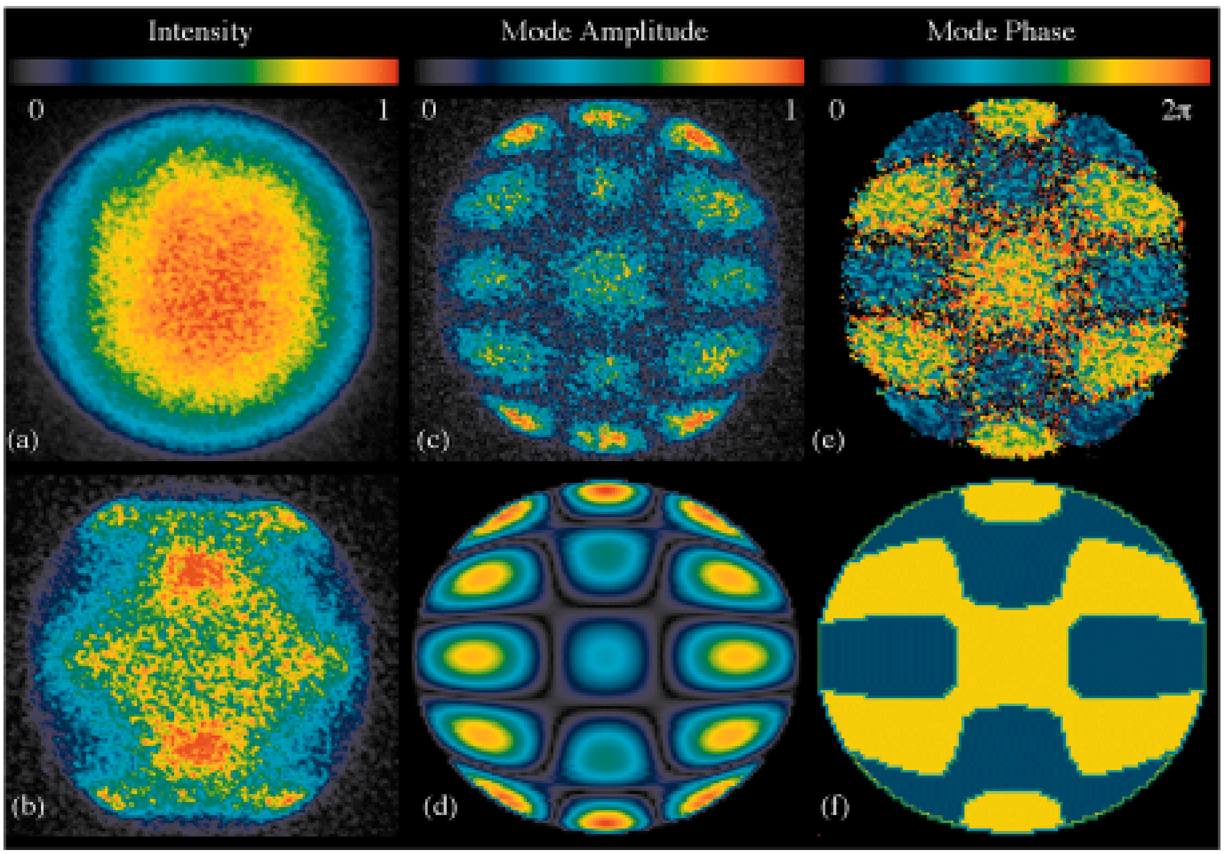

Fig. 3. Side-view images of $\sim$35 000 $^9Be^+$ ions with $\omega_r/2\pi = 240$ kHz, radius $r_0 \simeq 0.23$ mm and aspect ratio $\alpha = 0.91$.

We further analyze the intensity data by subtracting the contributions of the (1, 0) mode and then performing a Fourier analysis of the intensity at each (x, y) point. Figs. 3(c) and (e) are plots of the amplitude and phase of the resonant response, while Figs. 3(d) and (f) are the predictions of theory for the (7, 0) mode eigenfunction. Excellent agreement is observed.

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