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Cyclotron mode frequency shifts in multi-species ion plasmas

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ABSTRACT

In trapped plasmas, electric fields and collective effects shift the cyclotron mode frequencies away from the "bare" cyclotron frequency for each species s. Here, these shifts are measured on a set of cyclotron modes ($m = 0, 1,$ and 2) with $\cos(m\theta)$ azimuthal dependence in near rigid-rotor multi-species ion plasmas. We observe that these frequency shifts are dependent on the plasma density, through the $E \times B$ rotation frequency f_E, and on the "local" charge concentration δ_s of species s, in close agreement with theory.

1. Introduction

Cyclotron mode frequencies are used in a broad range of devices to manipulate and diagnose charged particles. In trapped plasmas with a single sign of charge, collective effects and electric fields shift these cyclotron mode frequencies away from the "bare" cyclotron frequencies $2\pi F_c^{(s)} \equiv (q_s B/M_s c)$ for each species s, and collisions broaden the cyclotron resonances. These electric fields may arise from the trap potentials, from space charge, including collective effects, and from image charge in the trap walls. Modern high-throughput mass spectroscopy devices observe these frequency shifts [1–3], but typically use calibration equations that neglect collective effects [4] or conflate them with amplitude effects [2].

Here, we quantify cyclotron mode frequency shifts in well-controlled, laser-diagnosed, multi-species ion plasmas, with near uniform charge density n_0 characterized by the $E \times B$ rotation frequency $f_E \equiv cen_0/B$. These shifts are measured at small amplitudes for a set of cyclotron modes varying as $\cos(m\theta - 2\pi f_m t)$, including the first quantitative measurements of the rarely observed $m = 0$ cyclotron mode with no azimuthal dependence [5–7].

For radially uniform species densities $n_s(r)$, the measured frequency shifts corroborate a simple theory expression [8–10], in which collective effects enter only through f_E and through the species fractions $\delta_s \equiv n_s/n_0$. Absent laser diagnostics, the measured frequency shifts could then be used to determine f_E and δ_s. At ultra-low temperatures where centrifugal separation of masses becomes significant, we observe large frequency shifts, described by a more general theory involving a radial integral over $n_s(r)$, with a simple asymptote for complete separation.

2. Experimental methods

The cylindrical ion plasmas are confined in a Penning–Malmberg trap with a magnetic field $B = 2.965 \pm 0.002$ Tesla. The ions are predominately Mg^+ resulting from a Magnesium electrode arc, with 5–30% other ions, typically H_3O^+ and O_2^+, arising from ionization of and chemical reactions with the background gas at a pressure $P \leq 10^{-9}$ Torr. Typical isotopic charge fractions are $\delta_{24} = 0.54$, $\delta_{25} = 0.09$, $\delta_{26} = 0.10$, with the remaining 27% a mixture of H_3O^+ and O_2^+.

The ions are confined for days in a near rigid-rotor equilibrium state, by use of a weak applied "rotating wall" (RW) field [11]. Altering the frequency of this RW field, the plasma can be arranged to a desired density and rotation frequency. The ion densities range over $n_0 = (1.8 \to 6.2) \times 10^7\ \mathrm{cm}^{-3}$, with rotation rates $f_E = (9 \to 30)$ kHz, and inversely varying radii $R_p = (6 \to 3)$ mm. The plasma length $L_p \sim 10$ cm and wall radius $R_w = 28.6$ mm remain fixed.

Laser cooling of the $^{24}Mg^+$ enables temperature control from $(10^{-5} \to 1)$ eV. For most measurements, the plasma is laser-cooled to $T \sim 10^{-2}$ eV, giving a small Debye length $\lambda_D \sim R_p/35$ and a near-uniform density profile. At this temperature the ion species are intermixed radially, with inter-species collisionality $\nu_{ii} \sim 10^3$ /s. In contrast, plasmas at $T < 10^{-3}$ eV begin to exhibit

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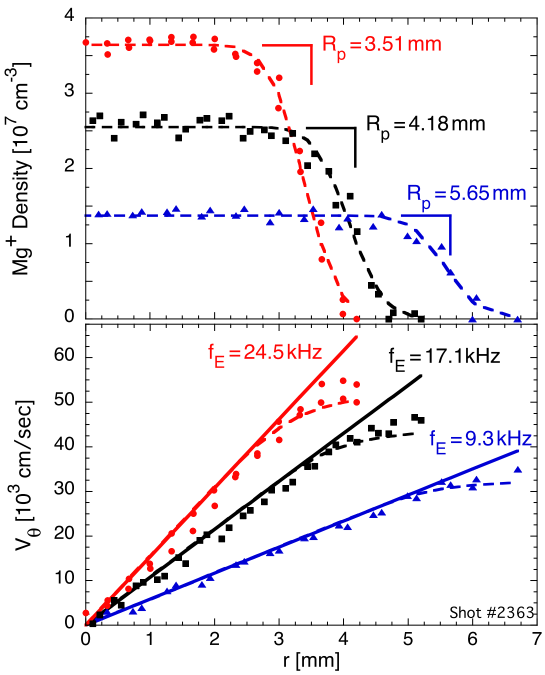

Fig. 1. (Color online.) Radial profiles of Mg^+ density (Top) and rotation velocities (Bottom) at three different rotation rates in the "uniform density" temperature regime $T \sim 10^{-2}$ eV. Symbols are laser-width-averaged data, and dashed curves are fits to the "top-hat" rigid-rotor model (solid lines).

centrifugal separation of species [12–14], with near-complete separation at $T < 10^{-4}$ eV.

Radial profiles of the plasma temperature and velocity distribution $F(v_z)$, total Mg^+ density, and rotation velocities, $v_\theta(r)$, are obtained using Laser Induced Fluorescence (LIF) [15]. Fig. 1 shows measured density and rotation profiles (symbols) at three different rotation rates. These profiles are a convolution of the true "top-hat" plasma profile with the finite size (half-width 0.39 mm) probe laser beam. The profiles are fit assuming a convolved "top-hat" rigid-rotor model with $n(r) = n_0$ and $v_\theta(r) = 2\pi r f_E$ for $r \le R_p$, giving the dashed lines in Fig. 1. The solid lines in Fig. 1 represent the true "top-hat" Mg^+ density and rigid-rotor rotation profiles of the plasma resulting from this fitting process. This rigid-rotor rotation frequency f_E and "top-hat" radius R_p will be used to characterize the cyclotron mode frequency shifts.

The cyclotron resonance frequencies are detected using Thermal Cyclotron Spectroscopy (TCS). A series of RF bursts, scanned over frequency, are applied to azimuthal sections of a confinement ring. Resonant wave absorption causes plasma heating, which is detected as a change in the $^{24}Mg^+$ velocity distribution. The change in the plasma temperature is measured to be $\Delta T \propto \delta_s A_b^2 \tau_b^2 / M_s$; here A_b is the burst amplitude and τ_b is the burst period. These results are for short bursts $\tau_b \nu_{ii} < 1$. The changes in temperature for different excited species can provide a measurement of the charge fractions δ_s.

Here, we are interested in the frequency and natural width of these cyclotron resonances, so long bursts with narrow frequency widths are used. The sine-wave bursts consist of 10^4 cycles at (0.1–3) V_{pp}, with $\pm$ polarity on sectors chosen as to give $\cos(m\theta)$ electric fields. These bursts typically heat the plasma by $\Delta T \lesssim 10^{-2}$ eV. This heating broadens the $^{24}Mg^+$ distribution $F(v_z)$, here causing an increase in the cooling beam fluorescence.

A typical broad $m = 1$ TCS scan is shown in Fig. 2. This TCS scan enables identification of the ion species, but the change in the cooling fluorescence (the height of the peaks in Fig. 2) suggests about 50% more $^{24}Mg^+$ than measured with LIF diagnostics. A possible cause for this discrepancy is that heat is directly removed from the laser cooled $^{24}Mg^+$, but only from the other species through collisions as they equilibrate with the $^{24}Mg^+$ at a rate near ν_{ii}.

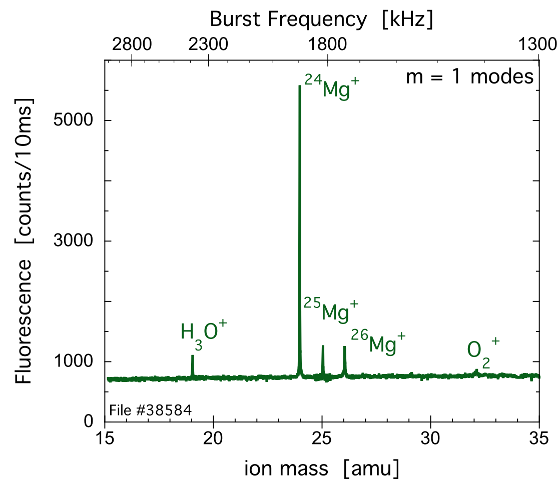

Fig. 2. (Color online.) Mass spectra of a typical plasma containing $^{24}Mg^+$, $^{25}Mg^+$, and $^{26}Mg^+$; with H_3O^+ and O_2^+ impurity ions.

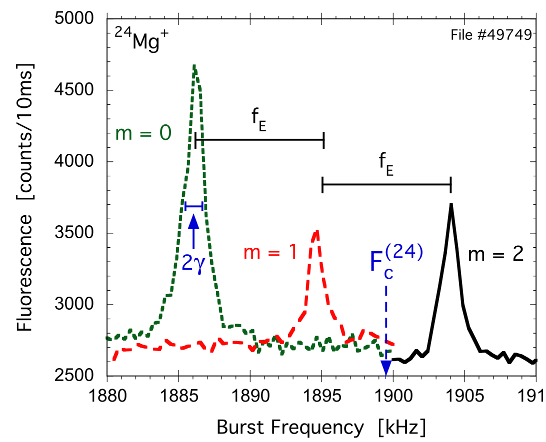

Fig. 3. (Color online.) Measured cyclotron resonances at $T \sim 10^{-2}$ eV for $m = 0, 1$, and 2, shifted away from the "bare" cyclotron frequency $F_c^{(24)}$. These modes have a frequency spacing of approximately the $E \times B$ rotation frequency $f_E = 9.3$ kHz.

3. Results and discussions

The center-of-mass $m = 1$ cyclotron mode is most commonly used for mass measurements, but other cyclotron modes exist and can provide further information on the plasma. Theoretical work [8–10] has predicted a set of cyclotron modes $m = 0, 1, 2, \ldots$ with $f_m^{(s)} \sim F_c^{(s)} + O(f_E)$. The $m = 2$ mode is a rotating elliptical surface perturbation, and the novel $m = 0$ mode is a radial "breathing" mode which generates no external electric field except at the plasma ends.

Fig. 3 shows experimental observation of this set of azimuthal modes for $^{24}Mg^+$. Each mode is driven with the corresponding $\cos(m\theta)$ electric field. These modes are shifted away from the "bare" cyclotron frequency $F_c^{(24)} = 1899.22$ kHz, and have frequency spacing of approximately $f_E = 9.3$ kHz. The cyclotron mode frequencies are measured from the peaks in this heating response, and we note that the width of these resonances is a possible measurement of the mode damping γ.

Compressing the plasma with the RW increases f_E, enabling measurements of the cyclotron resonances under different space