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Observation of electron localization and asymmetric frequency sideband generation in bounded microwave-plasma interaction

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Bounded plasmas exhibit many interesting behavior that are not found in plasmas of "infinite" extent such as space and astrophysical plasmas. Our studies have revealed that the dispersion properties of waves in a bounded magnetoplasma deviates considerably from predictions of the Clemmow-Mullaly-Allis (CMA) model for a cold, infinite plasma in the plane wave approximation, giving rise to new regimes of wave propagation and absorption. The article presents some interesting observation on electron localization and asymmetric frequency sideband generation in bounded microwave-plasma interaction, dictated by the medium anisotropy arising from length scales of plasma nonuniformity and magnetostatic field inhomogeneity.

The phenomenon of plasma electron localization or trapping has been studied in large amplitude electrostatic waves (~ 100 V/cm) sustained in uniform subcritical plasma columns [1-3]. Wakeren et. al. studied the trapping of beam electrons in potential well of electrostatic waves resulting from beam-plasma interaction [1]. Franklin et. al. investigated parametric coupling of noise induced sideband frequencies with oscillating plasma electrons trapped in large electrostatic waves [2]. Danielson et. al. observed linear Landau damping and nonlinear wave-particle trapping oscillations with standing plasma waves in a trapped pure electron plasma [3]. However, the possibility of plasma electron localization and oscillations in the intensity minimum of electromagnetic standing waves in the plasma column [4] and the nonlinear interaction with the drive wave, has not been explored. In the current experiment, such a phenomenon is investigated through experiments and Monte Carlo simulations.

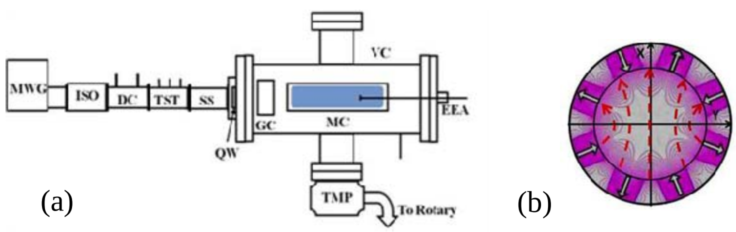

Figure 1 (a): Schematic of the experimental set-up: MWG, microwave generator; ISO, magnetron oscillator; DC, directional coupler; TST, triple-stub tuner; SS, straight section; QW, Quartz window; GC, guiding cylinder; VC, vacuum chamber; MC, multicusp; TMP, turbo molecular pump; EEA, electron energy analyzer or a Langmuir probe or an antenna probe (b) POISSON simulation showing the minimum B magnetic field with the electric field structure of the TE_{11} mode superposed.

A brief schematic of the experimental setup is shown in Fig. 1(a), where argon plasma is generated by continuous mode microwaves (MW) of 2.45 GHz in an octupole MC of radius a = 41 mm and length L = 30 cm [4]. The magnets have a surface magnetic field $B_o \sim 0.4$ T. The resultant field lines in the MC cross section are shown in Fig. 1(b) using POISSON simulation, where the minimum-B structure is clearly demonstrated. The microwaves are launched into MC in the $k \perp B_o$ mode, where k is the wave-vector and B_o is the radially varying magnetostatic field.

Axial measurements of plasma parameters such as plasma (ion) density (N_i), electron temperature (T_e), space potential (V_s), floating potential (V_f), and the wave electric field are carried out by a planar Langmuir probe, and an electric field probe respectively. The wave electric field intensity spectra detected by the antenna probe is recorded by an Agilent E4408B spectrum analyzer (SA) having a bandwidth of ~ 26 GHz [4]. All the measuring equipments are computer interfaced using GPIB protocol in tandem with appropriate LabVIEW programs.

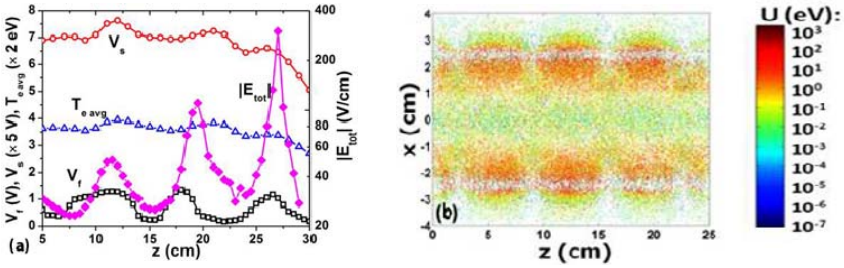

Figure 2 (a) Axial variation of calibrated $|E_{tot}|$ (diamond), V_f (square), V_s (circle), and Te_avg (triangle) with 180 W power, at 0.25 mTorr pressure. (b) Simulation of electron energy in a section parallel to the MC axis.

Figure 2 (a) shows a plot of the electric field versus z along with V_f and V_s. The floating potential V_f follows the wave electric field and has a smaller value in the troughs, indicating larger concentration of electrons in that region. These electrons see a smaller field and are expected to have a lower average temperature Te_avg as compared to those at the crest of the standing waves. This is reflected in the axial profile of Te_avg, which shows that electrons gain more energy at the crests as expected. Figure 2 (b) shows the Monte Carlo simulation of the electrons energy in a section along the MC axis. The existence of electron with higher energy in the standing wave maximas is clearly demonstrated (color coded). Electrons are primarily accelerated by the wave electric field in the transverse direction, however due to the E×B force: $(E_r \times B_\theta)$ and $(E_\theta \times B_r)$ they are pushed in the axial direction and get trapped in the standing wave minimas.

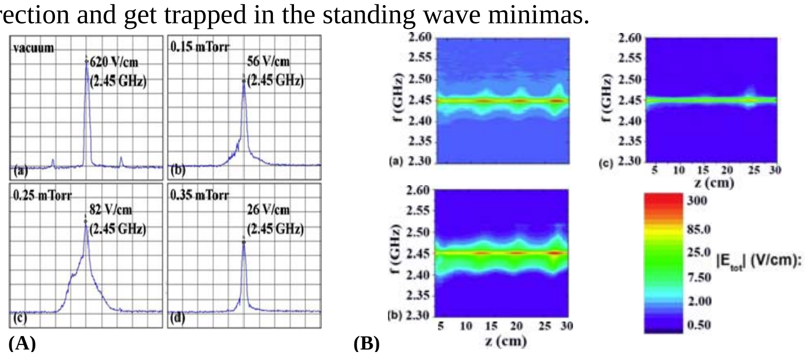

Figure 3: Wave spectrum screenshot at 180 W at different pressures and at *z* = 18 cm. Central frequency = 2.45 GHz, and span = 300 MHz. (b) Asymmetric spectral broadening of central frequency (2.45 GHz) versus z at (a) 0.15 mTorr, (b) 0.25 mTorr, and (c) 0.35 mTorr, at 180 W.

It is expected that the plasma electrons would oscillate in time due to the SW pattern, and couple with the driving frequency and affect the wave spectrum subsequently. Figure 3 (A) shows typical wave spectrum screenshots averaged over 50 acquisitions, taken at z ~ 18 cm (maxima) and 180 W for vacuum and plasma conditions at 0.15, 0.25 and 0.35 mTorr. The axial varation of the spectrum is shown in (Fig. 3 (B) (a)-(c)). With increase in pressure there is an asymmetric broadening towards the lower frequency. The interaction of the trapped electrons with the drive frequency is investigated further.

References

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