Oscillating plasma bubbles

R. L. Stenzel and J. M. Urrutia

University of California, Los Angeles, CA 90095-1547, USA

Plasma bubbles, defined as localized plasma regions within a different ambient plasma are produced in the laboratory. As shown in figure (Fig. 1) a negatively biased spherical grid encloses the bubble in a larger discharge plasma with parameters shown. The highly transparent grid attracts ions and limits the electron flux into the bubble. Bubbles with diameters from 1 cm to 8 cm with mesh from sizes from 0.25 mm to 1 mm have been studied.

In steady state the particle fluxes are divergence free, there is no current flowing into the bubble and the bubble plasma is charge neutral except within the sheath region. The negative grid bias controls the electron inflow while the self-consistently formed plasma potential adjusts the ion flow. When all electrons are reflected by the negative grid the bubble sheath consists of a positive space charge layer ("virtual anode") which reflects all ions such that the bubble is empty. Thus, the bubble density can be adjusted from zero to nearly the ambient plasma density.

Variations of this setup have also been investigated but will be described elsewhere [1]. For example, the injected ions can also be charge neutralized by an electron emitter inside the bubble. The role of the bubble and ambient plasma can be reversed, i.e. a discharge plasma is produced in the bubble and there is no plasma outside. In this case the plasma can be confined electrostatically by reflecting electrons from the negative grid while ions are confined by a self-consistently formed virtual anode.

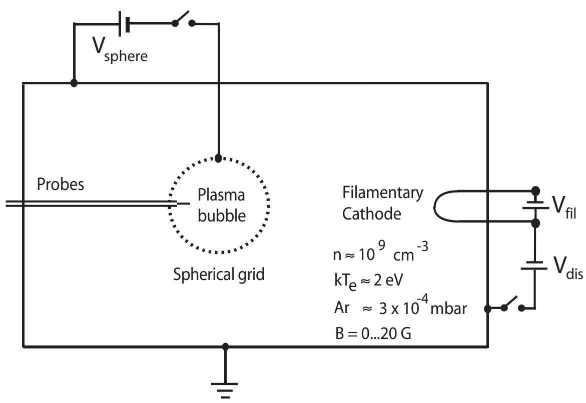

Figure 1: Experimental setup and plasma parameters.

The restricted electron inflow into the bubble complicates the standard probe diagnostics. Langmuir probes modify the plasma properties when biased into the electron collection regime. Emissive probes float when emitted and collected electron and ion currents balance. But the most pronounced effect of the restricted electron supply is an instability of the ion rich bubble sheath. The ions injected from the ambient plasma form a positive space charge layer whose electric field is proportional to the charge density and sheath thickness. Since the force opposes the motion and is proportional to the excursion the equation of motion describes an oscillation at the frequency

$\omega^2 = (n_i - n_e)e^2/(m_i\varepsilon_0)$

Note that electrons in the sheath reduce the space charge so that the sheath oscillates at $\omega = (\omega_{pi}^2 - \omega_{pe}^2 m_e/m_i)^{1/2}$ rather than at the ion plasma frequency ω_{pi}. The oscillation becomes an instability when bunched ions reinforce the oscillating sheath electric field due to their inertia. The ion space charge is cannot be neutralized due to the reduced electron flux into the bubble.

Evidence for the instability is shown in Fig. 2. The grid voltage (top trace) is pulsed negatively so that no electrons can pass through the sheath. The ion saturation current of a small cylindrical Langmuir probe in the center of the bubble (middle trace) is shown to decay to zero while oscillating strongly. The density decay time is determined by the trapping of electrons inside the negatively biased grid. It is much longer than the electron or ion transit times through the bubble. The oscillations on the probe current are not ion density fluctuations but a displacement current due to an oscillating plasma potential inside the bubble. The same oscillations are observed in the grid current, displayed on the bottom trace. However, the grid current continues to oscillate as the density in the bubble vanishes. These are virtual anode oscillations of the bubble sheath which reflects ambient ions. An rf probe outside the bubble shows no oscillations, hence the instability is produced by the inner bubble sheath.

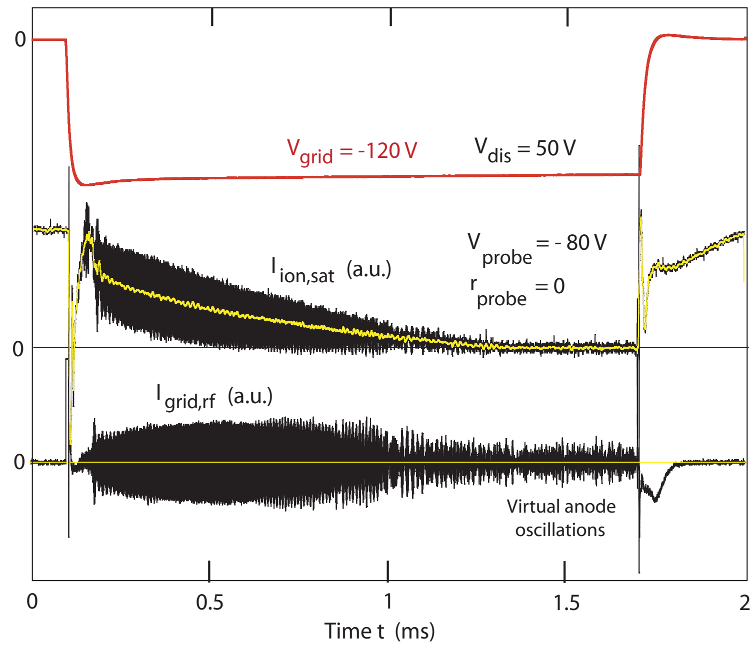

Figure 2: Pulsed negative grid voltage, resulting in the sheath instability and emptying of the plasma bubble.

The frequency of the instability, obtained by a Fast Fourier Transform, depends on density and grid voltage. As observed previously [2, 4, 3], the virtual anode oscillation frequency scales proportional to ion plasma frequency. Fig. 3(a) shows that this finding only holds for low densities where the Debye length is large compared to the grid mesh size and the equipotential surfaces are parallel to the grid. As the density is raised by increasing the discharge current the grid becomes "leaky" to electrons which causes a different mode of oscillations. Electrons in the sheath cause a drop in frequency, a subharmonic and multiple harmonics. The frequency drop is due to the decrease in space charge density of the sheath. The harmonics are thought to arise from two current contributions with different phase shifts, one of the inertial ions and the other of electrons without inertia. In the high density regime the equipotential surfaces meander around the grid wire and exhibit a saddle point in the center of the mesh openings where the potential is not as negative as the applied grid voltage which allows electrons to pass through the grid. Electrons decrease the frequency which modifies the original scaling $f \propto f_{pi}$.

Direct evidence for electron leakage is obtained from the floating potential of a probe inside the bubble displayed in Fig. 3(b). It drops to the discharge voltage which is the energy of the primary electrons in a dc discharge which leak through the grid. The oscillation amplitude, defined by the rms grid current increases for the electron mode with its many harmonics.

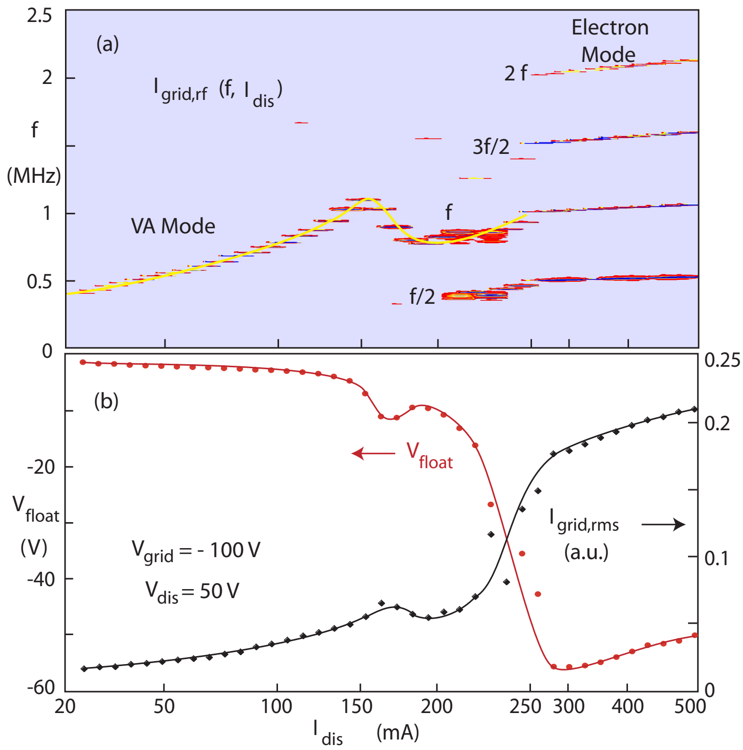

Figure 3: Leaky grid causing a mode jump vs density or discharge current. Grid mesh size 1 mm.

The harmonics are not produced by a nonlinear process of a large fundamental mode but appear to be eigenmodes of the unstable sheath. This conclusion is based on the observation that with a parallel L-C circuit in line with the grid each harmonic can be eliminated without effecting other lines. Furthermore, from the time waveform one can observe that in certain parameter regimes the oscillation switches between the fundamental and its subharmonic, i.e. either is an unstable eigenmode of the sheath.

The three-dimensional equipotential surfaces of a coarse grid create further interesting effects shown in Fig. 4(a). As the grid voltage is raised the frequency increases since the flux of electrons through the grid is reduced although not eliminated as indicated by the harmonics. At $V_{grid} \simeq V_{dis}$ the mode jumps to a slightly lower value and creates a subharmonic with multiple odd-half harmonics. Its line spectrum is displayed in Fig. 4(b). At $V_{grid} \simeq -100$ V Fig. 4(c) shows that a large number of sidebands appear. Their line spacing $(\Delta f/f_(min) = 1/6)$ is the same for all harmonics, hence not a result of a modulation of the fundamental mode. The time waveform shows a low frequency beat of the nonlinear sheath oscillation. At $V_{grid} \simeq -120$ V Fig. 4(d) shows that the sideband oscillation also develops a subharmonic, such that all lines are now spaced apart by $(\Delta f/f_(min) = 1/12$.

Although a description with chaos models is tempting [4] the physical process of nonlinear sheath oscillations remains an open topic. The coarse grid sheath has a 3D structure which can support higher modes of oscillations. The sideband spacing coincides with the ratio of wire thickness to wire spacing suggesting that a transverse oscillation between the wires may determine the sideband frequency. No sidebands are observed for a fine-mesh grid or at low densities ($\lambda_D > d_{mesh}$).

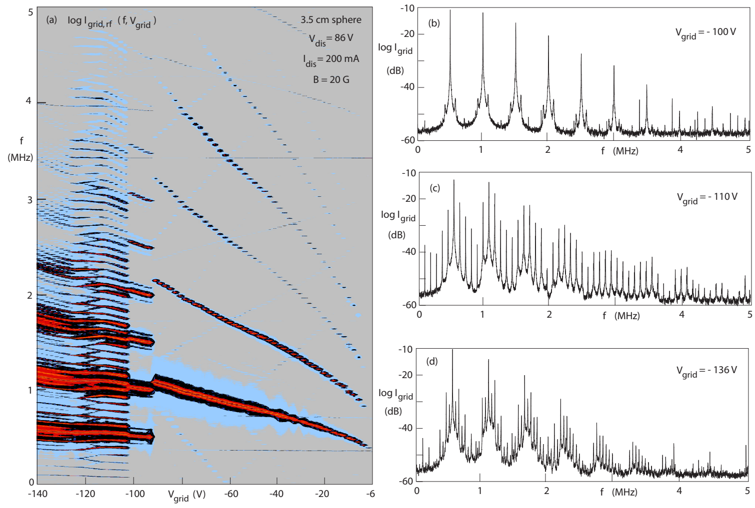

Figure 4: Harmonics, subharmonics and sidebands for a 3D sheath of a coarse grid.

References

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