Oscillating plasma bubbles. IV. Grids, geometry, and gradients

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Plasma bubbles are created in an ambient plasma. The bubble is formed inside a cavity bounded by a negatively biased grid. Ions are injected through the grid and neutralized by electrons from either the background plasma or an internal electron emitter. The external electron supply is controlled by the grid bias relative to the external plasma potential. When the electron flux is restricted to the ion flux, the sheath of the bubble becomes unstable and causes the plasma potential to oscillate near the ion plasma frequency. The exact frequency depends on the net space charge density in the bubble sheath. The frequency increases with density and grid voltage, provided the grid forms a parallel equipotential surface. The present investigation shows that when the Debye length becomes smaller than the grid openings the electron flux cannot be controlled by the grid voltage. The frequency dependence on grid voltage and density is modified creating frequency and amplitude jumps. Low frequency sheath oscillations modulate the high frequency normal oscillations. Harmonics and subharmonics are excited by electrons in an ion-rich sheath. When the plasma parameters vary over the bubble surface, the sheath may oscillate at different frequencies. A cavity with two isolated grids has been used to investigate anisotropies of the energetic electron flux in a discharge plasma. The frequency dependence on grid voltage is entirely different when the grid controls the energetic electrons or the bulk electrons. These observations are important to several fields of basic plasma physics, such as sheaths, sheath instabilities, diagnostic probes, current, and space charge neutralization of ion beams. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4743022]

I. INTRODUCTION

Plasma sheaths have been first formulated for plane geometries and later expanded to cylindrical and spherical geometries. Sheaths on grids fall between plane and cylindrical cases. For wire spacing small compared to the Debye length, the equipotential surfaces are parallel to the plane of the grid while in the opposite limit a grid forms a two-dimensional array of wires with three-dimensional equipotential surfaces. Grids are of great practical importance for ion beam sources, velocity analyzers, electrostatic confinement schemes, and antennas for electrostatic waves. In the present case, grids are used to enclose a spherical volume in a surrounding plasma to create an oscillating plasma bubble. When the grid is biased negatively ions are injected while neutralizing electrons are supplied from either energetic tail electrons of the ambient plasma or an electron emitter inside the bubble. Three companion papers described the basic properties of the bubble plasma and its instability, pulsed bubbles and time-resolved instability measurements, while the present paper addresses the effect of electron leakage through grids and anisotropic electron flows into grids of different geometries.

It will be shown that electrons of energy \( eV_{el} \) will not reflect from a grid biased at \( -V_{grid} \geq V_{el} \) unless the mesh size is small compared to the Debye length. When electrons leak through the grid, the bias does not effectively control the electron supply, which prevents the formation of a virtual anode and modifies the frequency dependence on \( V_{grid} \). The equipotential surfaces between grid wires become three-dimensional, which may allow new eigenmodes of sheath oscillations. Harmonics, subharmonics, and multiple sidebands are observed.

Bubbles of spherical, cylindrical, and rectangular geometries have been investigated. The sheath instability occurs in all cases but the frequency dependence on grid bias varies greatly. Gradients and anisotropies in the energetic electron flux cause different sheaths properties over the entire bubble surface. The frequency dependence on \( V_{grid} \) depends on whether a grid is exposed to fast or slow electrons.

When a cavity is formed by a solid cylinder with one gridded end face, as is typical in double plasma (DP) devices, the injected ions are absorbed on the solid walls. As in ion sources the backstreaming of ions out of the target chamber is negligible. The density is essentially that of the injected ion beam. But in spherical grids ions are injected over the entire surface, collection on the highly transparent grid is small, and an ion outflow from the bubble is required to achieve steady state. The ion density is enhanced by reflection when ions are obliquely incident on the spherical sheath surface. Thus, geometry is important to the properties of bubbles.

The paper is organized as follows: After briefly reviewing the experimental setup in Sec. II; the observations of leaky grid effects, new low and high frequency sheath instabilities, and anisotropic electron distributions will be presented in Sec. III; and the findings are summarized in Sec. IV.

II. EXPERIMENTAL ARRANGEMENT

A low temperature plasma is produced by a dc discharge in a vacuum chamber of 45 cm diam and 150 cm length shown schematically in Fig. 1(a). The typical parameters are...
an electron density \( n_e \approx 10^9 \text{ cm}^{-3} \), electron temperature \( kT_e \approx 2 \text{ eV} \), Argon pressure \( p \approx 5 \times 10^{-4} \text{ mTorr} \), and a uniform axial magnetic field \( 0 < B_0 < 20 \text{ G} \). Gridded spheres, shown in Fig. 1(b), inset, are inserted into the center of the plasma. The 2.5 cm diam sphere is made of a single sheet of fine grid (mesh size 0.25 mm, 80% transparent). The 3.5 cm diam sphere is made of a coarser grid (mesh size 1 mm, wire diameter 0.2 mm), which was formed by spot welding two hemispheres together. A 2 mm hole allowed the insertion of a ceramic shaft containing a cylindrical Langmuir probe (0.13 mm diam, 3 mm length). Care was taken to avoid any other openings through which electrons could enter the cavity. A larger cavity of rectangular shape has also been used (10 cm x 10 cm). It allows to bias different portions of the grid surface separately so as to investigate gradients in the ambient electron flux.

The grid is biased negatively which attracts ions into the sheath at the Bohm flux. If the plasma potential of the bubble is not above that of the ambient plasma, most ions enter into the cavity. Neutralizing electrons are also supplied from the ambient plasma provided their energy \( \frac{1}{2} m_e v_{\perp}^2 > e|V_{\text{grid}}| \) and the grid forms an equipotential surface at \( V_{\text{grid}} \). When the grid rejects all electrons, the ions build up a large space charge layer (virtual anode) which reflects them back into the ambient plasma and the bubble is empty. Plasma and grid voltage can be pulsed. A broadband rf transformer (100 kHz…100 MHz) in line to the grid is used to measure oscillations in the grid current. The current-voltage (I-V) characteristics of the Langmuir probe have limited value for plasma diagnostics since electron collection perturbs the bubble plasma. All signals are acquired with a 4-channel digital oscilloscope with bandwidth up to 400 MHz and up to \( 2.5 \times 10^6 \) samples stored.

Further details of the experimental setup are presented in the companion papers.10–12

III. EXPERIMENTAL RESULTS

A. Electron leakage through coarse grids

Figure 1(b) demonstrates that the mesh size of the grid plays an important role in determining the electron flux through the grid. The two spheres are located in the same ambient plasma and biased to the same negative voltage well above the discharge voltage or peak electron energy. The Langmuir probe trace in the center of the fine-mesh grid indicates essentially an empty bubble while that of the coarse grid shows that electrons and ions entered the bubble. Since the grid forms a closed surface, the electrons must have entered through the mesh openings. This implies that the equipotential surfaces \( \phi = \text{const} \) are not parallel to the grid and the potential in the center of the mesh openings is insufficient to stop primary electrons of energy \( eV_{\text{dis}} \).

The equipotential surfaces between the grid wires depend on the ratio of the Debye length to the wire spacing. Figure 2 shows the effect of varying the Debye length via the discharge current on the bubble properties. The grid voltage is chosen well above the discharge voltage. For low densities or large Debye lengths, electrons are rejected and the plasma and grid voltage can be pulsed. A broadband rf transformer
frequency of the instability scales like the plasma frequency, \( f \propto f_p \propto I_{\text{dis}}^{1/2} \) as shown earlier in Fig. 7 of Paper I (Ref. 10). Here, the data were taken in uneven current increments and the spectra were not interpolated since the main point is to show that the familiar scaling breaks down at high densities. At \( I_{\text{dis}} = 150 \) mA the frequency drops and at \( I_{\text{dis}} \approx 200 \) mA harmonics appear, which are the signatures of electrons in the sheath. The floating potential drops from near zero to a value of the discharge voltage. Thus, primary electrons have entered the bubble and changed the virtual anode oscillations to a sheath instability with electrons. The mode change also affects the instability amplitude.

Mode changes are also observed as a function of grid voltage. For a plane sheath obeying Child-Langmuir’s law the sheath thickness scales proportional to \( (eV_{\text{grid}}/kT_e)^{1/4} \), but for a coarse grid the equipotential surfaces have a more complicated 3D geometry. A leaky grid does not control the electron flux like a plane sheath; hence, the frequency dependence on grid voltage depends on the grid properties. Figure 3(a) displays \( f(V_{\text{grid}}) \) for the 3.5 cm diam sphere. Over a wide range of \( 0 < |V_{\text{grid}}| < 100 \) V, the grid does not change the frequency, hence has no control of the electron flux. In this regime, the floating potential decreases with grid voltage [Fig. 3(b)]. The plasma potential which is above the floating potential also decreases as \( V_{\text{grid}} \) becomes more negative. The reason is that the plasma potential adjusts itself to maintain charge neutrality. With increasing \( |V_{\text{grid}}| \), the injected electrons have a higher energy and must be slowed down to increase their density which requires a lower plasma potential. At the same time, ions are accelerated which lowers their density by flux conservation. The plasma potential drops until the rising electron density matches the decreasing ion density.

When the potential in the mesh openings exceeds the discharge voltage (\( V_{\text{grid}} \leq -110 \) V), the electron inflow is finally suppressed, the potential rises, the frequency increases with \( |V_{\text{grid}}| \), and the harmonics disappear, all signs that the sheath approaches the state of a virtual anode.

The dependence of the floating/plasma potential on \( V_{\text{grid}} \) is also reflected in the probe current when biased to collect electrons. It has a maximum near or above \( V_{\text{dis}} \), depending on grid leakage. In an afterglow plasma, the peak decreases and shifts to lower voltages as the electron energy decays.
B. Mode jumps and sidebands

The instability has been observed to exhibit a jump in frequency and amplitude as a function of $V_{\text{grid}}$. Frequently, a subharmonic frequency is excited which in rf driven sheaths is explained by a nonlinear sheath capacitance. The jumps could arise from several mechanisms, such as onset of grid leakage, gradients across the bubble creating different sheaths, magnetic field effects, ionization, etc. Here, we focus on the grid mesh size.

Figure 4(a) shows a mode jump observed in a 2.5 cm diam sphere made of fine mesh. The negative grid bias reduces the electron supply which raises the frequency. At $V_{\text{grid}} \approx -60$ V, the frequency suddenly splits from $f$ to $f'/f$ and to $f'/2$. The amplitude also has a discontinuity [Fig. 4(b)]. The new mode $f'$ has created a subharmonic. Multiple harmonics of $f'/2$ are visible and indicate the presence of electrons in the sheath, even when $|V_{\text{grid}}| > V_{\text{dis}}$. Thus, at a high discharge current of 500 mA even a fine mesh grid leaks electrons into the bubble. The mode jump occurs at $B=0$, hence is not due to magnetic field effects. The mode jump also occurs in a 1 cm diam sphere, hence is not a matter of density gradients across the sphere. There is no hysteresis with $V_{\text{grid}}$, hence, it is not an ionization effect.

A second example for mode jumping is shown in Fig. 5(a), which is obtained with the 3.5 cm diam sphere of coarse mesh in a weakly magnetized plasma. The spectrum of grid current oscillations clearly shows a similar frequency jump at $V_{\text{grid}} \approx -90$ V. The presence of harmonics before and after the jump indicates continued electron leakage when $|V_{\text{grid}}| > V_{\text{dis}}$. Just after the mode jump, Fig. 5(b) shows a narrowband spectrum with many harmonics.

A new and interesting feature arises when $|V_{\text{grid}}| \geq 110$ V where a multitude of narrowly spaced sidebands appears on each of the main lines. Figure 5(c) indicates that the sideband spacing is an integral fraction of the fundamental line, typically $\Delta f/f_0 = 1/6$. The spacing is identical for all harmonics; hence, the sidebands cannot be created by amplitude modulation of the fundamental. The grid current has no significant low frequency oscillation at $\Delta f = f_0/6$. In the time domain, the waveform shows a nonsinusoidal fundamental with a nonsinusoidal beat envelope at the sideband frequency. Subharmonic generation also occurs for the sidebands. Figure 5(d) shows that between the first sidebands additional lines with spacing $\Delta f = f_0/12$ have formed.

The reason for a fixed ratio of the modulation frequency to the sheath oscillation frequency still remains to be determined. Sidebands are not caused by acoustic eigenmodes of the sphere since they also occur for different geometries. They are seen with and without external magnetic field, hence are not due to magnetic effects. Sidebands are only seen for the coarse mesh. It happens to have a ratio of wire thickness to mesh opening is $1/6$. The sheath of a coarse grid is rippled and may exhibit normal and transverse oscillations.

**FIG. 5.** (a) Spectrum of a coarse wire sphere with mode jump and formation of multiple sidebands. (a) $I_{\text{grid,rf}}$ vs $f$ and $V_{\text{grid}}$ with subharmonic creation at $V_{\text{grid}} \approx -95$ V. (b-d) Spectra of $I_{\text{grid,rf}}$ at different $V_{\text{grid}}$ showing main instability, sidebands, and sideband subharmonics.
Further characteristics are shown in Fig. 6(b), which is a contour plot of the current spikes vs time and probe voltage. The current spikes arise only when the dc probe voltage is above the ambient plasma potential. The current spikes start with a long delay with respect to the start of the discharge. The time scale (200 µs) is much larger than particle or wave transit times through sheaths or the entire bubble. The delay and repetition time increase with dc probe bias. The spikes are only observed for sufficiently negative grid voltages (|V_{grid}| > V_{dis}), which restrict the electron supply into the bubble.

Based on these observations, the phenomenon may be explained as follows: The coarse grid biased at −100 V allows 50 eV primary electrons to pass through the grid because the equipotential between the wires has a saddle-point with Φ > −50 V. These electrons are collected by the positively biased Langmuir probe whereby the plasma potential is raised. The rising potential in the bubble reduces the potential barrier between both plasmas and allows an avalanche-like electron inflow. The probe current drops when the electron inflow lowers the bubble plasma potential. The ion density changes with plasma potential due to flux conservation, n = const. The time scale for density changes is determined by the electron currents. During the current spike, fewer electrons are available for the ion current closure, hence the ion inflow and ion density drop. With increasing probe voltage or current, the recovery time thereby increases.

The current spikes induced by a positively biased probe also affect the higher frequency ion sheath instability. Several features are displayed in Fig. 7. The probe current I_{probe}(t) is shown for a wide range of probe voltages in a pulsed dc discharge plasma [Fig. 7(a)]. In addition to the above-mentioned current spikes, there are also probe current oscillations observed for negative probe bias |V_{probe}| ≈ V_{dis}. The grid current oscillations, shown in Fig. 7(b), depend on probe bias. In particular, probe induced oscillations strongly modulate the grid sheath oscillations. Frequency pulling and mode changes are also induced by probe currents as shown in Fig. 7(c). For positive probe voltages (>10 V), the rf bursts in I_{grid} produce a broad spectrum since the frequency chirps upward in each pulse. In the regime |V_{probe}| < 10 V, the probe bias has little influence on the instability because the electron supply is large compared to the electron current to the probe. The coarse grid produces no frequency dip at V_{probe} ≈ 0 as seen in Figs. 6 and 9 of Paper III (Ref. 12), where there was an electron source inside a fine-mesh sphere. Finally, at V_{probe} < −50 V, where the probe draws only ions, a mode change occurs which generates a subharmonic with two harmonics.

Figures 7(d) and 7(e) provide a comparison of probe and grid currents at a higher time resolution. For positive probe bias, the oscillations in the grid current coincide with the probe current spikes. Since the probe depletes electrons in the bubble, the decreased electron supply causes the sheath to oscillate. Both grid and probe currents oscillate at the same frequency; hence, the potential in the entire bubble oscillates together. For V_{probe} = −18 V, the probe oscillations start later and have a lower frequency than the grid
oscillations. The grid oscillation is modulated by the probe oscillation, which creates sidebands in the spectrum [Fig. 7(c)]. The higher frequency grid oscillation is not observed on the probe, implying that it is localized near the sheath. On the other hand, the lower frequency must be present from the probe to the sheath since it interacts with the grid oscillation. Both must be instabilities of the sheath. For $V_{\text{probe}} = -46 \text{ V}$, only the grid oscillation is visible. Its time evolution at the beginning of the discharge cannot be seen in the FFT spectrum, which requires a time average. The instability starts with a high frequency burst at a frequency denoted as $f_2$ in the spectrum, followed by a lower frequency denoted as $f_1$. The frequency chirps upward within the initial rf burst, which broadens the spectral line $f_2$. The mode change from $f_2$ to its subharmonic $f_1$ arises only when $|V_{\text{grid}}| > V_{\text{dis}}$. Probe voltage and grid voltage are constant during the mode jump. The ion saturation current to the probe in the center of the bubble is also nearly constant, but the floating potential jumps negative at the onset of oscillations indicating a sudden influx of electrons through the leaky grid. Thus, the mode jump is due to slow changes in bubble parameters at the beginning of the discharge pulse.

D. Gradients and geometry

If there are gradients in plasma parameters on the scale of the bubble, one would expect to find sheath oscillations at different frequencies. However, except for an empty bubble with virtual anode oscillations the oscillations are almost monochromatic. Since the plasma potential of a filled plasma bubble oscillates uniformly, different parts of the sheath are driven by the most unstable sheath region. Nevertheless, gradients can influence the amplitude and frequency dependence on grid voltage.

In a magnetized plasma column, the primary electrons have a radial gradient and an axial anisotropy. When a small bubble is moved radially through the magnetized discharge column, the frequency of the sheath instability decreases due to the ion density gradient and the harmonics vanish since the primary electrons vanish outside the flux tube of the cathode.

Even in the absence of density gradients, there is an anisotropy in the electron distribution since the primary electrons are emitted from a localized source. One side of the bubble may have electrons in the sheath, the other side does not. In order to investigate the effects of electron anisotropies, the wire cage has been segmented which is easier for a rectangular cavity than for a spherical grid. As shown schematically in Fig. 8 (center inset), the cage consists of two plane grids (10 × 10 cm²) of coarse mesh separated by 2 cm wide mica sidewalls. Each grid can be biased separately or both together. When one grid is biased the other one is floating. The grid oscillations of the biased grid are measured.

Figure 8(a) displays the spectrum of $I_{\text{grid1}}$, which faces away from the cathode. The frequency increases when the grid is biased more negative, indicating that it restricts the inflow of low energy electrons. A mode change occurs at $V_{\text{grid1}} = -45 \text{ V}$ which produces a harmonic spectrum with lines at $n \times f_0$ all of which are independent of $V_{\text{grid1}}$, hence are caused by energetic electrons entering through the floating grid on the cathode side.

In Fig. 8(b), the grid 2 facing the cathode is biased while grid 1 floats. Grid 2 controls the inflow of 80 eV primary electrons. For low $|V_{\text{grid2}}| < 30 \text{ V}$, a weak oscillation
at \( f_0 \approx 250 \) kHz with a harmonic is seen. Strong oscillations are excited in the range \( 30 < |V_{\text{grid}}| < 70 \) V. Their frequency decreases from \( 2 \times f_0 \) to \( f_0 \) as the grid becomes more negative. This is contrary to most other observations where a reduced electron supply increases the space charge density in the sheath and thereby raises the frequency to the ion plasma frequency. The reverse behavior may indicate that the ion density is decreased due to a negative plasma potential as shown in Fig. 3(b).

For very negative grid bias, \( |V_{\text{grid}}| > 100 \) V, a monochromatic line at \( \frac{1}{2} f_0 \) is excited. The lack of harmonics indicates that there are few electrons in the sheath, implying that grid 2 is not leaky at high voltages and that no low energy electrons enter from the floating grid side since the plasma potential is negative.

When both grids are biased together, the frequency dependence shows both regimes of increasing and decreasing \( f(V_{\text{grid}}) \), an example of which is shown in Fig. 9(a). At low grid bias, the frequency rises with \( |V_{\text{grid}}| \), dominated by the sheath on grid 1. For \( |V_{\text{grid}}| > 60 \) V, the frequency drops as the case of grid 2 biased alone. Thus, depending on the bias regime different parts of the sheath determine the instability when an electron anisotropy exists.

At a critical bias (\( V_{\text{grid}} \approx -90 \) V), a mode change occurs. The new mode has no harmonics and its frequency increases with \( |V_{\text{grid}}| \) which is typical for virtual anode oscillations. Although a coarse grid was used, it rejects all electrons at sufficiently negative voltages and low discharge currents. Electron leakage always occurs when one grid is floating and the other is biased.

As in Fig. 5, sidebands are created in limited voltage ranges. These are again spaced at about 1/6 of the fundamental frequency which does not depend on the geometry or size of the cavity but on the grid properties [Fig. 9(b)]. In certain voltage ranges (\( 35 < |V_{\text{grid}}| < 50 \) V) the subharmonics vanish, for other voltages (\( 85 < |V_{\text{grid}}| < 95 \) V) the instability has a broad bandwidth or consist of bursty waveforms. Many of these phenomena still need further investigations.

The rectangular box has been rotated such that the magnetic field is tangential to the grid surfaces as shown in the inset of Fig. 10 (center). This arrangement removes the asymmetry of electron flows into the bubble. Consequently, the spectra are identical irrespective of which grid is biased while the other one is floating [Figs. 10(a) and 10(b)]. The frequency gradually increases with \( |V_{\text{grid}}| \) without mode jumps. Harmonics persist at all grid voltages. Thus, the bubble contains electrons which enter mainly through the floating grid since the frequency depends only weakly on the biased grid voltage. Although electrons are collected across \( B_0 \), the cyclotron radius of primary electrons is large (\( r_{ce} \approx 1.6 \) cm) compared to the grid mesh (1 mm) such that they can easily orbit into the bubble. Ions are completely unmagnetized. A weak line at \( f = 0.7 \) MHz with one harmonic is not a sheath oscillation since its frequency is essentially independent of grid voltage. But it is not an external rf signal as at \( f = 1.7 \) MHz in Fig. 10(c), which produces a narrow horizontal line.

When both grids are biased together, the electron flow through a floating grid is eliminated and the spectrum shows
new features. The reduced electron inflow produces a stronger instability. A mode change occurs at $V_{\text{grid}} \approx -100$ V, indicating that primary electrons neutralize ions at large negative grid bias. The broadband spectrum is due to pulsations in time whereby the frequency jumps from one mode to the other. The frequency of the stronger new mode, $f_b$, rises rapidly with $|V_{\text{grid}}|$, but is not a virtual anode oscillation due to its harmonics. The “constant” frequency mode now has a weak dependence on $|V_{\text{grid}}|$. No sideband spectra are observed.

Finally, to compare with previous work on DP devices, a bubble has been constructed in the shape of double plasma devices. It consists of a solid metal cylinder (20 cm diam, 30 cm length) with a coarse mesh on one end as schematically shown in Fig. 11 (bottom). There is no plasma source inside the “target” chamber while the ambient unmagnetized plasma is produced with a steady-state dc discharge. When the entire target chamber is biased negatively, oscillations in the collected ion current are observed. The oscillations frequency decreases when the grid is biased more negatively and can be fitted by a power law $f \propto |V_{\text{grid}}|^{-0.42}$. This is roughly consistent with previous findings of $f \propto |V_{\text{grid}}|^{-1/4}$ (Ref. 19) to $f \propto |V_{\text{grid}}|^{-1/2}$. But Fig. 8 shows that this dependence only holds when the grid controls the flow of primary electrons. Furthermore, coarse grids leak electrons even when $|V_{\text{grid}}| > V_{\text{dis}}$ as is evident from the harmonics in Fig. 11.

The frequency decrease with $|V_{\text{grid}}|$ can simply be explained by the density decrease with $|V_{\text{grid}}|$. There is no ion confinement in DP devices since the injected ions are collected at the solid chamber wall. This implies that the ion density is that of the injected ion flow which decreases with $|V_{\text{grid}}|$, especially when the plasma potential decreases as shown in Fig. 3(b).
IV. CONCLUSION

Oscillating plasma bubbles have been investigated. These are created by leaking ions and electrons from an ambient plasma into a volume bounded by a negatively biased grid. Electrons are also supplied from an emissive filament inside the bubble. The sheath or plasma potential in the bubble develops self-consistently to produce charge neutrality and divergence-free flows. The bubble contains freestreaming and trapped particle populations. When all electrons are reflected, ions form a positive space charge layer (virtual anode) at the inner sheath which reflects them back into the ambient plasma and leaves the bubble volume empty. Time dependent experiments show the trapping of electrons inside the bubble. Inserting probes into a bubble plasma can cause perturbations, especially when collecting electrons whose supply is restricted. The perturbations result in modified \( I-V \) characteristics, which have been shown for Langmuir and emissive probes.

When the electron flux is limited and comparable to the injected ion flux, the bubble plasma becomes unstable. The oscillations arise from an unstable sheath on the inner side of the grid. The instability has been studied for steady state and pulsed conditions. Based on the observations, the following physical picture of the instability emerges: Ions are injected into the bubble. The expanding ion-rich sheath creates a retarding space charge electric field. Due to ion inertia, the sheath can oscillate near the ion plasma frequency. The oscillations become unstable by ion bunching in the oscillating sheath electric field. The space charge electric field of the ion bunches reinforces the oscillations. Oscillations in the space charge density cause the plasma potential of the bubble to oscillate. The instability is driven by the free energy of the injected ions. When the grid voltage is switched off, the instability vanishes within an ion transit time through the sheath. The ambient plasma potential is not oscillating; hence, the outer sheath is stable because the large electron supply neutralizes the ion space charge oscillations. Vice versa, ions cannot neutralize electron space charge fields which exist in electron-rich sheaths and produce the high-frequency sheath-plasma instability due to the electron inertia. The present instability does not require an oscillating grid voltage. The grid current oscillations are mainly displacement currents balancing the injected ion conduction currents into the bubble. The oscillation frequency depends on the space charge density in the sheath, which is determined by both ions and electrons. It scales proportional to the ambient ion plasma frequency but drops below it when electrons are injected into the sheath.

The dependence of the instability frequency on grid voltage is not unique. The frequency depends sensitively on the supply of electrons, which is not only controlled by the grid voltage but also the emission and collection of electrons by probes. In afterglow plasmas, the frequency is independent of the grid potential since it stops the flow of low energy electrons through the grid, provided the grid mesh size is small compared to the Debye length. Coarse grids are leaky to electrons even when the grid potential energy exceeds the electron kinetic energy. If the electron distribution is not
isotropic, different parts of the grid contribute different electrons flows into the bubble which modifies the frequency dependence with grid bias. Multiple sidebands are observed on coarse grids which have 3D equipotential surfaces and could support higher order modes of sheath oscillations.

Mode jumps are commonly observed when the electron supply is decreased. Typically, a half frequency mode with multiple harmonics is excited when $|V_{\text{grid}}| \simeq V_{\text{dis}}$. Harmonics are associated with electrons inside the sheath. Since electrons and ions respond differently to an oscillating sheath electric field, the net current is not sinusoidal or monochromatic. Harmonics vanish in afterglow plasmas, at the edge of a magnetized plasma column and in virtual anode oscillations. Mode jumps are not due to the effects of energetic electrons, magnetic fields, and grid properties. It also occurs when applied voltages are constant while plasma parameters slowly change, e.g., in afterglow plasmas. Fine structure sidebands are predominantly observed with a coarse mesh and occur only in limited ranges of $|V_{\text{grid}}|$. They are beat phenomena with the same period 6:1, which appears to be related to the grid structure. Virtual anode oscillations are typically bursty or broadband since an empty bubble does not couple the locally oscillating sheath regions.

The sheath instability is in many respects similar to that observed in double plasma devices. Here, the explanations for the instability mechanism differ widely. Here, we consider the oscillation frequency of a charge layer in its own space charge electric field. Ion inertia and net space charge density determine the frequency, $\omega^2 = (m_i - n_e) e^2/m_i e^0$. The presence of electrons in the sheath lowers the oscillation frequency below the ion plasma frequency, as observed experimentally. It is controlled by the grid voltage or other electron sources and sinks. In general, a frequency decrease indicates an increased electron supply or a decreased ion supply. Without neutralizing electrons, virtual anode oscillations are observed which have the highest frequency. The strongest instability usually arises for $|V_{\text{grid}}| \simeq V_{\text{dis}}$ where the entire bubble potential oscillates, creating harmonics, subharmonics, and sideband eigenmodes. These global oscillations lock to the most unstable mode producing a fairly monochromatic instability in spite of gradients across the grid. A large electron flux stabilizes the sheath, as in the case of the outer grid sheath. There is no evidence for traveling potential relaxation processes or beam-plasma instabilities.

As regards applications a small bubble could be used for diagnostics of fast electrons, which produce a frequency minimum for $f(V_{\text{grid}})$ at the peak electron energy. In a larger pulsed bubble, the expansion of ions into vacuum can be modeled. Electrostatic confinement has been demonstrated for electrons with energy lower than given by the negative grid voltage. The same holds for ion confinement by a virtual anode on the outside grid when the discharge is produced inside the bubble and no neutralizing electrons are outside the bubble. With neutralization, the setup would become a Kaufman ion source, useful for ion-surface interaction in spherical or cylindrical geometries.

Further experimental research is needed to establish the physics of harmonic and subharmonic generation, sidebands, mode jumps, and instability gaps. Wave propagation in a bubble with trapped particles has not yet been investigated. Bubbles in rf discharges or in dusty plasmas have neither been explored.

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