Oscillating plasma bubbles. I. Basic properties and instabilities

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Plasma bubbles are created in an ambient discharge plasma. A bubble is a plasma volume of typically spherical shape, which is separated from the ambient plasma by a negatively biased grid of high transparency. Ions and electrons from the ambient plasma flow into the bubble volume. In steady state the flow of particles and currents is divergence-free, which is established by the plasma potential inside the bubble. The grid has two sheaths, one facing the ambient plasma, the other the bubble plasma. The inner sheath is observed to become unstable, causing the plasma potential in the bubble to oscillate. The instability arises from an excess of ions and a deficiency of electrons. Its frequency is in the range of the ion plasma frequency but depends on all parameters which influence the charge density in the sheath. When the grid voltage is very negative, electrons cannot enter the outer sheath, and the inner sheath becomes a virtual anode which reflects ions such that the bubble interior is empty. When an electron source is placed into the bubble it can neutralize the ions and the bubble refills. Without plasma sources or sinks the bubble plasma is extremely sensitive to perturbations by probes. Modified current-voltage characteristics of Langmuir and emissive probes are demonstrated. A sequence of papers first describes the basic steady-state properties, then the time evolution of bubbles, the effects of electron sources in bubbles, and the role of the grid and bubble geometry. The physics of plasma bubbles is important to several fields of basic plasma physics such as sheaths, sheath instabilities, diagnostic probes, electrostatic confinement, and current and space charge neutralization of beams. © 2012 American Institute of Physics.

I. INTRODUCTION

Plasma sheaths have been studied for a long time since they are relevant to all plasmas encountering a solid object. Double layers are also well known to separate plasmas of different properties. Less common are current-free double sheaths which are addressed in the present work. A grid can separate two plasmas whose properties differ depending on the grid bias. When the grid is biased negatively ions fall into the sheath and may be accelerated if a plasma potential difference exists. Ion beam sources or double-plasma (DP) devices are typical applications. When the grid forms a closed volume free of sources and sinks, the inflow of ions must be balanced by an equal outflow to maintain a constant density in steady-state. The ion-rich double sheath carries two equal and opposing ion and electron flows which do not occur in an ordinary ion-rich sheath on a solid boundary. In addition the electron and ion fluxes must be equal since the current cannot have a divergence in steady state. While the ion influx is nearly independent of the grid bias, the electron flux decreases with negative grid bias. When all electrons are reflected at the outer sheath the inner sheath becomes a “virtual anode” which reflects ions back into the ambient plasma.

As the grid bias is varied the plasma potential adjusts so as to satisfy charge neutrality and current free sheaths. For low and high grid bias it is close to the ambient potential, but in the intermediate regime the bubble potential is negative with respect to the ambient plasma potential. Strong oscillations in the plasma potential are observed inside the bubble but not in the outer plasma. The instability arises when the injected ions are not space charge neutralized by the reduced electron supply through the negative grid. The space charge variations occur on the time scale of the ion transit time through the sheath. Ion bunching creates the oscillating sheath electric field. Ion inertia provides a positive feedback between the field and charge. Electrons in the sheath reduce the space charge and oscillation frequency below the ion plasma frequency, $f_{pi}$. Observationally, they are also associated with formation of harmonics.

Although sheath instabilities have been observed and studied earlier in DP devices, many new results and interpretations are presented in this work. These are the following:

1. The spherical grid geometry which can produce radially converging and counter streaming ion beams which are not present in DP devices.
2. New properties of diagnostic probes have been observed and explained: A negative differential resistance in Langmuir probe traces has been shown and explained. A new current-voltage (I-V) characteristic of an emissive probe has been shown and explained.
3. A clear demonstration of a virtual anode effect has been demonstrated: No ions are observed inside a bubble when all electrons are reflected. In previous double plasma devices, there is usually a plasma in the target chamber which implies that the ions are not reflected by a virtual anode. Under those circumstances theories or simulations of virtual anode oscillations are not appropriate.
4. The sheath instability inside the bubble has been observed only when the electron supply is restricted by
the negative grid bias. Furthermore, it has been clearly shown that only the inner sheath is oscillating, while the outer one is stable. Thus ions do not slosh back and forth between the two sheaths as suggested earlier.

5. It has been shown and explained that electrons inside the sheath influence the oscillation frequency which depends on the net space charge density. This different interpretation explains the observed variety of frequency dependencies on grid voltages. The electron supply depends on the grid voltage, from an internal emissive probe and from electron collection by biased Langmuir probes. In particular, the frequency shifts created by diagnostic tools has been demonstrated which has not been reported earlier.

6. Pulsed experiments have been performed to demonstrate the temporal evolution of the bubble plasma and instability. Transient sheath ringing and growth of the sheath instability have been observed. Trapping of electrons inside a bubble has been demonstrated.

7. The effect of grid mesh size vs Debye length has been investigated. The linear frequency scaling with plasma frequency is violated when the grid “leaks” electrons into the bubble.

8. The formation of harmonics of the fundamental mode at \( f < f_{pi} \) is shown to be due to electrons in the sheath. Virtual anode oscillations are broadband without harmonics.

9. A non-driven subharmonic of the fundamental mode is observed. Harmonics can be larger than the fundamental, even oscillate without it. Multiple sidebands to all lines are observed. These effects cannot be “explained” by a Van der Pol equation model.\(^{11}\)

10. The sheath instability depends on grid geometry and plasma nonuniformities.

The conclusion is that bubbles oscillations are ubiquitous but that their spectrum and amplitudes depend on many parameters and seems far more complicated than previously reported.

The wealth of new results is contained in four companion papers.\(^{12-14}\) The present paper describes the basic bubble properties and is organized as follows: After describing the experimental setup in Sec. II, the observations of basic probe characteristics and instability properties will be presented in Sec. III, and the findings are summarized in the Sec. IV.

II. EXPERIMENTAL ARRANGEMENT

The experiments have been performed in a simple low temperature discharge plasma with parameters of density \( n_e \approx 10^9 \, \text{cm}^{-3} \), electron temperature \( kT_e \approx 2 \, \text{eV} \), and Argon gas pressure \( p \approx 5 \times 10^{-4} \, \text{mTorr} \) in a chamber of dimensions 45 cm in diameter and 100 cm length [Fig. 1(a)]. Such plasmas are nearly collisionless, uniform, quiescent, and well suited for basic studies of waves and instabilities. The discharge can be pulsed so as to obtain a Maxwellian plasma in the afterglow free of energetic electrons. The density is proportional to the discharge current which can be varied by an order of magnitude (50…500 mA). A uniform axial magnetic field of up to 20 G is usually applied which enhances the density by confining the ionizing electrons while leaving the ions unmagnetized. The plasma parameters are measured with Langmuir probes. The signals are acquired with a 4-channel digital oscilloscope with bandwidth up to 400 MHz and storage up to \( 2.5 \times 10^6 \) samples. Gridged spherical cages with diameters between 1 and 8 cm are inserted into the plasma volume. As shown in Fig. 1(b) two types of grids are used, one coarse mesh (1 mm hole size) and a fine mesh (0.25 mm holes). When the mesh size exceeds the Debye length the grids are transparent to electrons even when biased highly negative. The same holds if small openings exist where probes enter the sphere. Electron “leak-tight” spheres were made of a single sheet of fine mesh grid, formed spherically by a mandrill, with the opening tied up against a ceramic tube used to insert probes. These consist of small cylindrical Langmuir probes and/or an emissive probe. The instability is detected with probes and from the oscillations in the grid current. The grid is biased either with dc voltages or pulses. An rf transformer is inserted between power supply and grid to measure ac grid currents. Rectangular boxes (\( 10 \times 10 \times 2 \, \text{cm} \)) have also been investigated. These consist of two electrically insulated grids attached to a mica frame. The purpose was to study sheaths in nonuniform plasmas. One box had also a third large grid in the center.

III. EXPERIMENTAL RESULTS

A. Probe diagnostics

We start by showing basic properties of the wire grid and surrounding plasma. Figure 2 shows the current-voltage (I-V) characteristics of the outer grid of a rectangular box.
Since the grid is usually biased negatively, only the electron retardation regime near the floating potential (−25 V) is shown. For comparison, the upper left insert shows the full I-V trace of a plane Langmuir probe in the outer dc discharge plasma. It shows a tail of “primary” electrons with energy up to the discharge voltage and the bulk of “secondary” electrons produced by ionization. Evaluation of such curves yields the above-mentioned plasma parameters. A negative bias to the outer grid does not significantly affect the outer plasma parameters. When the inner grid is biased negatively the outer grid current remains unchanged. When it is biased positively (+20 V) the outer grid current is slightly modified due to a positive shift in plasma potential. Since the inner plasma is greatly modified by the inner grid bias yet the outer current is unaffected one must conclude that the outer grid current is only supplied by ambient ions. This is obvious for a bubble without inner electrodes where there would be no current closure.

Next we investigate the plasma properties inside a wire cage with a small cylindrical probe. Figure 3 shows current-voltage (I-V) traces in the center of a 2 cm diam. sphere made of a fine mesh grid. As the grid bias becomes negative the electron probe current is reduced. When the grid voltage exceeds the discharge voltage even the most energetic electrons are prevented from entering the bubble. Without neutralizing electrons the ions cannot enter the sphere. They form a positive space charge layer on the inner sheath (“virtual anode”) which reflects them back into the ambient plasma. Electrons reflect at the outer sheath. The bubble is empty. With the grid voltage the density inside the bubble can be adjusted from about the ambient density to zero.

We now turn to the emissive probe properties in a plasma bubble. Figure 4(a) shows I-V traces of a hot probe in the center of a 2 cm spherical grid for different grid biases. When the grid is grounded most ambient electrons can enter the bubble. For positive probe bias the emissive probe collects electrons, for negative bias it emits electrons and floats near the plasma potential. These are the normal properties of emissive probes. However, when the grid is biased negatively the electron collection current nearly vanishes while the emission current shows two levels. The lower level applies to probe voltages between the plasma potential and the grid voltage. In this regime the probe emits a current which equals the injected ion current. The injected ion current must be closed in steady state, and if the outside electrons cannot provide the current closure, electrons must be supplied by the emissive probe. This emission current is space charge limited and does not increase by raising the filament temperature. The electrons are trapped inside the bubble and lost by surface recombination on insulators.

A large increase in emission arises when the emissive probe is more negative than the grid. In this case the grid acts as an anode and the emissive probe as a cathode. The emission current is temperature limited, i.e., increases as the filament temperature is raised and is nearly independent of the potential difference between probe and grid. Figure 4(b) shows that the emitted current partly flows to the grid where it causes the current to drop. From the ratio of collected to
emitted current one can estimate the electrical grid transparency, \( T \approx 1 - (0.2 \text{ mA}/1 \text{ mA}) = 80\% \). Most of the electrons pass through the grid into the ambient plasma. No change in the grid current is seen when the emitted electrons balance the injected ion current of \( I_{\text{ion}} \). A small enhancement occurs when the probe is biased at the ambient plasma potential. It is due to ion reflection since electrons are neither supplied from the probe nor the ambient plasma. This effect could be used for plasma potential measurements.

It should be mentioned that the injected ion current is much smaller than the calculated Bohm current into the bubble. The reason is that most ions entering the sphere also leave the sphere so that the flow is divergence free. The inflow exceeds the outflow because some ions are collected by the grid and some are lost by surface recombination on insulated structures. In an ideal bubble the ion inflow and outflow would exactly balance, hence there would be no need for current neutralization unlike in ion beam sources.\(^5\) Likewise the electron fluxes would balance but still be needed for space charge neutralization.

The floating potential of an emissive probe is normally established when the flux of emitted and collected electrons balance, which neglects the small ion current. In this case the emissive probe floats slightly below the plasma potential. When an ion collection current is added which has the same current sign as the electron emission current a larger electron collection current is required to achieve zero probe current. This shifts the floating potential closer to or above the plasma potential. Without electron collection the probe current can only vanish when it floats above the plasma potential where it can neither emit electrons nor collect ions. All these conditions arise as the negative grid bias is varied.

Figure 5 shows the floating potential of an emissive probe for different grid voltages, measured with a high impedance probe. For comparison the potential of the same probe without heater current is also shown. The plasma potential should lie between these floating voltages for large negative grid biases. When \( |V_{\text{grid}}| > V_{\text{dis}} \) all ambient electrons are reflected at the outer sheath, ions are not neutralized but are reflected at the inner sheath and the bubble center is empty. The floating potential of the hot probe, located in the bubble center, becomes very positive where its emission vanishes. The cold probe potential is close to ground since there are no ion or electron currents to balance and the large but finite external resistance grounds the probe. For \( |V_{\text{grid}}| < V_{\text{dis}} \) electrons enter the sphere and both probe potentials show a minimum near \( V_{\text{grid}} = 30 \text{ V} \). As the grid voltage approaches zero the emissive probe yields appropriately the plasma potential and the cold probe the floating potential. For low grid bias it is reasonable that the bubble plasma approaches the ambient plasma. When electrons are prevented from entering the bubble a high plasma potential is observed as expected. In the intermediate regime the potential turns negative which may be explained as follows:

The plasma potential (or sheath potential drop) develops self consistently so as to maintain charge neutrality in the plasma. As \( V_{\text{grid}} \) becomes more negative the electron flux into the bubble decreases. The ion flux, given by the Bohm current into the sphere, is nearly independent of \( V_{\text{grid}} \). When the plasma potential decreases the ion energy increases while the electrons lose energy. Flux conservation implies that the ion density drops and the electron density increases which maintains charge balance. However, when \( |V_{\text{grid}}| \) approaches \( V_{\text{dis}} \) the reduced electron supply is insufficient to neutralize

![FIG. 4. Emissive probe I-V characteristics (a) inside a plasma bubble for different grid voltages. (b) Emissive probe current and grid current vs probe voltage. When \( V_{\text{probe}} \) is more negative than \( V_{\text{grid}} \) the emitted current flows partly to the grid from which the electrical grid transparency can be derived.](image)

![FIG. 5. Floating potential of an emissive probe in the center of a 2 cm diam sphere vs grid voltage. For comparison, the floating potential of the same probe is measured when emissive (hot) and non emissive (cold). For \( |V_{\text{grid}}| < V_{\text{dis}} \) the emissive probe floats close to the plasma potential.](image)
the constant ion inflow. The potential must rise again so as to reduce the ion inflow. Eventually, without any electron inflow, all ions are reflected by a potential higher than the ambient plasma potential.

The density is not only determined by particle flux but also by particle confinement inside the sphere. In general, most charged particles are scattered from the sheaths. This is evident for the ambient electrons which are Coulomb scattered by the repelling spherical sheath. However, the sheath is not perfectly spherical and charged particles which enter the sphere do not move perpendicular to the sheath at the opposite wall. They cannot escape since their normal energy $m\nu_{perp}^2/2$ is smaller than their total energy. Oblique ions are reflected at the inside sheath, oblique electrons at the repelling outside sheath. Due to multiple bouncing the total density inside the bubble will become much larger than that of the incident fluxes. As in double layers the ion distribution has a population of trapped and free particles. But the potential drop from the ambient plasma to the bubble plasma has a potential well at the grid. Since the bubble plasma floats it would be a current-free double layer.

The plasma potential in the bubble must adjust itself such that particle inflow and outflows produce current and space charge neutralization. If this is not possible it will become unstable. Oscillations and jumps in the sheath potential are readily observed as described below.

### B. Sheath instability

The presence of an instability is readily observed in the probe and grid currents. A few basic properties are shown here, but the instability has many features which will be described in more detail in companion papers. Since most external variables as well as diagnostic probes modify the bubble, the instability becomes a coupled multi-parameter problem. A firm conclusion is that the source of the instability lies in the inner sheath.

Starting with the grid current, Fig. 6(a) depicts the dc and ac current for a range of grid voltages. The grid current oscillation can be fairly monochromatic as shown by the inserted ac waveform and spectrum. The frequency is close to the ambient ion plasma frequency. The ac to dc current ratio can be of order 10%, but this does not represent the fluctuation in the ion density since the ac current is mainly a displacement current, as shown below. Frequency and amplitude depend on grid voltage as shown in Fig. 6(b). The largest amplitude is observed for grid voltages near the discharge voltage, i.e., when energetic electrons are prevented from entering the sphere. In this regime a subharmonic and several harmonics are also observed. For high grid voltages which form a virtual anode the sheath oscillates at the highest frequency and has a relatively broad bandwidth.

It can be seen that the dc current to the grid has no influence on the instability. The instability even exists without dc grid current ($V_{grid} \simeq -48$ V). Thus a floating grid oscillates provided it encloses a bubble. The frequency dependence on grid voltage is not universal and can depend on grid mesh size and geometry as will be shown later.

A basic property of the sheath instability, also observed in most previous double-plasma experiments, is the scaling with density. In discharge devices the density is proportional to the discharge current. Figure 7 shows that within the investigated parameter regime ($n_{max}/n_{min} \simeq 20$) the instability frequency is proportional to the plasma frequency or square-root of the discharge current. The amplitude of the instability rises progressively with density, even when normalized to the density.

The source of the instability has been determined with movable probes. In order to also demonstrate the sheath resonance the instability is triggered with a tone burst whose

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**FIG. 6.** Sheath oscillations at different negative grid voltages. (a) I-V characteristics of the 8 cm diam grid. Insert shows waveform and spectrum of the grid current oscillations at the floating potential ($I_{grid, dc} = 0$). (b) Amplitude (top trace) and frequency of the sheath oscillations vs dc grid voltage.

**FIG. 7.** Instability frequency and rms amplitude vs $l_{dis}^{1/2}$. The frequency is proportional to the plasma frequency.
frequency can be varied. The tone burst is applied to the discharge voltage which changes the energy and density of the energetic electrons that can enter the bubble. The ion density is not changed since $I_{\text{dis}}$ is nearly independent of $V_{\text{dis}}$. The probes are biased in the ion saturation regime. Figures 8(a) and 8(b) show the probe signals observed inside and outside the bubble. The latter, only 5 mm from the grid, shows only the applied tone burst, while the inner probe shows not only a much larger signal but also a long-lasting ringing whose duration depends on frequency. When the frequency is tuned [Figs. 8(c) and 8(d)] the inside oscillations exhibit a pronounced resonance, the outside sheath does not. The resonance frequency is the same as the instability frequency without tone burst. Passive measurements of the oscillation amplitude without tone burst show the same result: It is the inside sheath which oscillates while the outside sheath is stable.

Since probes are frequently used to measure the instability properties it is important to interpret the signals properly. The probe current has a dc and ac component as shown in Fig. 9. The smoothed trace for a negatively biased probe represents the ion saturation current, $I_{\text{ion}}$. Small oscillations around the average are often interpreted as variations in the ion density. However, in the present case the oscillation amplitude exceeds the average ion density and even reverses the current direction. This signal cannot be a particle conduction current since the ion density cannot have a 100% density modulation at the ion plasma frequency over scales of the probe which is several Debye lengths long. Neither can the plasma potential shift on the order of the probe bias (60 V) so as to change ion collection into electron collection. Thus, the ac signal is a capacitive current due to an oscillating space charge potential and the sheath capacitance, $I = C_{\text{sheath}}\frac{dV_{\text{plasma}}}{dt}$.

Since the same signal is observed in the grid current one must conclude that it is also a displacement current and not an ac ion current. Even on a slower time scale the grid current exhibits transients which are clearly displacement currents, an example of which is shown in Fig. 10. When the discharge voltage is pulsed the floating potential rapidly varies at the rise and fall of the discharge current. At a constant grid voltage a jump in plasma potential creates two
capacitive current transients which should not be interpreted as electron or ion current pulses. Note that in the present case the large grid oscillations have been avoided by not biasing the grid negatively.

Using a radially movable Langmuir probe, the spatial properties of plasma parameters and instabilities have been mapped inside the bubbles. However, the potential profile of the sheath cannot be properly resolved since the radial probe length is comparable to the sheath thickness. In order to minimize probe perturbations the probe is either floating or biased to collect ions. The floating potential is found to be highly uniform. The ion saturation current shows a slight enhancement in the center.

Of particular interest is the profile of the rf signal which is addressed in Fig. 11. The rf grid current provides a reference signal for the rf probe current, both of which are measured simultaneously. Their spectra [Fig. 11(a)] are the same but the amplitudes differ. Ideally, the probe movement should have no influence on the grid signal, but the bubble plasma is very sensitive to changing particle losses by inserting a ceramic probe shaft. This creates a small (2%) frequency shift and some amplitude variations. The frequency scan is expanded to compare the lines at each radial position. The ratio of the line amplitudes varies radially as shown in Fig. 11(b). Radial convergence and a density enhancement may explain why the rf amplitude peaks in the center of the bubble. A phase comparison between probe and grid currents is displayed in the form of hodograms at three different positions in Fig. 11(c). The oscillations exhibit no significant radial phase shifts implying that they are global plasma potential oscillations rather than propagating waves. The latter would be unlikely since ion acoustic waves near the ion plasma frequency would have wavelengths comparable to the Debye length and would be strongly Landau damped. On the other hand the plasma potential can change on the electron transit time scale which results in negligible phase shifts.

C. Mode and potential jumps

The instability exhibits predictable scaling only in limited parameter regimes. For example, the density dependence was found to be \( f \propto f_p \), but this result breaks down at high densities where the grid becomes transparent to electrons. Figure 12(a) shows the spectrum of \( I_{\text{grid,rf}} \) vs density which

\[ V_{\text{grid}} = -100 \, \text{V} \]
\[ V_{\text{dis}} = 50 \, \text{V} \]
\[ I_{\text{dis}} = 300 \, \text{mA} \]

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**FIG. 11.** Radial variations of the instability. (a) Spectrum of sheath oscillations for different probe positions in a 3 cm sphere. Probe motion causes small frequency and amplitude variations. Grid oscillations are used as reference signal for phase and amplitude variations. (b) Ratio of probe to grid rf amplitudes vs radius. (c) Hodograms \( I_{\text{probe}} \) vs \( I_{\text{grid,rf}} \) for different \( r \) showing the same phase relation, i.e., no waves and the plasma potential oscillates throughout the bubble.

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**FIG. 12.** Mode change from a virtual anode mode to a bubble volume oscillation. (a) Spectrum of grid oscillations vs density. The grid voltage is much larger than the discharge voltage, hence repels all electrons at low densities. But as the density increases the Debye length becomes smaller than the grid opening and electrons enter into the bubble which changes the spectrum and (b) lowers the potential inside the bubble.
exhibits two distinctly different modes. For low discharge currents or large Debye lengths and a grid voltage sufficiently negative to repel all ambient electrons, the ions are reflected at the inner grid and oscillate in a “virtual anode” mode. Its frequency scales as mentioned earlier. For large discharge currents the 1 mm grid opening [Fig. 1(b), left picture] is too large to form closed equipotential surfaces such that electrons leak into the bubble. This is evident from the drop in floating potential shown in Fig. 12(b). This “electron” mode has a fundamental frequency well below the “virtual anode” mode and a rich spectrum of harmonics whose frequencies rise little with density.

The frequency scaling with grid voltage also exhibits sheath discontinuities. Figure 13(a) shows a set of spectra for $I_{\text{grid,rf}}$ vs $V_{\text{grid,dc}}$ for different densities. The grid voltage is swept slowly (0.5 s) which is essentially the same as steady-state conditions. The sphere is made of fine-mesh grid which avoids the mode jump of Fig. 12. With increasing negative grid voltage the floating potential drops to a minimum and then rises again as all electrons are all repelled [Fig. 13(b)]. The sheath oscillates in the virtual anode mode which exhibits several discrete frequencies that may also appear as a broadband modulation. The frequency assumes a minimum near the potential minimum. All frequencies scale with density as shown earlier [Fig. 13(c)].

The new feature is a gap in emission at $V_{\text{grid,dc}} \approx -35$ V just before the virtual anode is formed. A positive jump in floating/plasma potential coincides with the loss of sheath oscillations [Fig. 13(d)]. No potential changes occur in the ambient plasma. The I-V traces of the grid indicate no density modifications in the ambient plasma. The emission gap narrows as the density increases and eventually vanishes. The potential jump appears to be a nonoscillatory sheath instability. As the potential rises the electron density decreases while the ion density increases ($n_e = \text{const}$), which leads to a further potential rise, i.e., a runaway process whereby a thick virtual anode is produced which cannot oscillate. Further work is needed to understand these sheath phenomena in detail.

The instability has many interesting nonlinear properties. Harmonics are created when electrons are inside the sheath. The penetration of electrons can be controlled by pulsing the discharge. Energetic electrons exist in the discharge but are absent in the afterglow. Figure 14(a) shows discharge voltage, current, and ac grid current at the start of the discharge. The discharge current lags with respect to the discharge voltage since it rises with density. The grid exhibits capacitive transients at the rise of $V_{\text{dis}}$ and the drop in plasma potential at the rise of $I_{\text{dis}}$. The sheath instability starts to oscillate at the second harmonic, then jumps to the fundamental, and alternates between the two modes during the discharge [Figs. 14(b) and 14(c)]. Thus, the second harmonic is an eigenmode of the sheath and not produced by nonlinear effects from the fundamental mode.

![Figure 13](https://example.com/fig13.png)

**FIG. 13.** Bubble and instability properties as density and grid voltage are varied. (a) Spectra of $I_{\text{grid,rf}}$ vs $V_{\text{grid,dc}}$ for different densities. (b) Floating potential and grid current vs $V_{\text{grid,dc}}$ for different densities. (c) Frequency scaling with plasma frequency. (d) Simultaneous single-shot traces of $I_{\text{grid,rf}}$ and $V_{\text{float}}$, showing that a positive potential jump coincides with the loss of oscillations. Both effects are only observed inside the bubble.
When the discharge voltage is slowly turned off the energetic electrons decay with $V_{\text{dis}}$ and only low energy electrons are left in the afterglow. The second harmonic disappears while the fundamental mode persists. The slow electrons cannot enter the sheath of the highly negative grid. Without energetic electrons harmonics vanish.

Further interesting properties will only be described but cannot be all documented with figures due to space limitations. Spherical bubbles with different diameters between 1 cm to 8 cm have been built. All oscillate below the ion plasma frequency but not at exactly the same value. Adjacent bubbles oscillate independently, i.e., when the grids of two bubbles are connected together the spectrum is identical to the linear superposition of the individual bubble spectra. This confirms the fact that the instability is confined to the bubble interior and does not penetrate into the ambient plasma.

It has been mentioned that the grid current can oscillate without drawing a dc current. Thus the grid current can be switched off, and the floating grid continues to oscillate as observed with probes. However, the instability stops within one cycle when the grid voltage is rapidly switched to zero, implying that the injection of ions is crucial.

The instability exists only when there is an insufficient supply of electrons, irrespective of whether they are supplied from the ambient plasma or from an internal electron emitter. Frequency and amplitude can be controlled by the electron supply from an emissive probe inside the bubble. No instabilities are exciting for large emissive probe currents. Likewise collecting electrons with Langmuir probes have profound effects on the bubble sheath instability. Switching emission or collection currents reveals particle confinement times which will be addressed in companion papers.

Plasma nonuniformities should affect the instability frequency. Surprisingly, in spite of density gradients the instability is often highly monochromatic. The plasma potential oscillations throughout the bubble apparently lock the instability to the most unstable sheath condition. On the other hand, the virtual anode type oscillation has a significant frequency spread because the empty bubble lacks the global feedback. Each part of the sheath oscillates separately at the local ion plasma frequency.

Gradients in the electron distribution are particularly important. To assess different electron fluxes into a bubble a rectangular gridded box has been built similar to that shown in Fig. 2 but without inner grid. Each grid can be biased separately to investigate differences in the sheaths facing the energetic electron supply (cathode) or the anode side. When the grid facing the cathode is biased while the other one is floating the frequency decreases with $V_{\text{grid,dc}}$; $j < V_{\text{dis}}$. The frequency is decreased due to lowering the plasma potential by limiting the electron flux as described before. However, when the grid on the anode side is biased while the cathode grid is floating the frequency increases with $V_{\text{grid,dc}}$. Now the floating grid on the cathode side establishes a negative plasma potential while the biased grid raises the plasma potential and thereby the frequency.

The effect of the magnetic field has also been investigated. It increases the frequency since the plasma density increases due to electron confinement. But the basic instability properties remain the same since the ions are unmagnetized.

IV. CONCLUSION

A plasma volume enclosed by a negatively biased grid forms a plasma bubble with interesting properties. Electrons and ions from the ambient plasma leak into the bubble at a rate determined by the grid bias. In steady state charge neutrality and current closure have to be satisfied which are established self consistently by the sheath or plasma potential. Without current sources or sinks the bubble draws no current from the ambient plasma. In this case the ion inflow is balanced by an equal ion outflow which conserves particle continuity or a constant density. The latter is determined by partial trapping of ions which is due to scattering from the sheath for oblique incidence. Neutralizing electrons are
supplied from the ambient plasma at a rate limited by the grid bias. When the electron supply is reduced the plasma potential rises which limits the ion supply correspondingly. When all electrons are prevented from entering the bubble an ion space charge layer or virtual anode forms at the inner sheath which reflects all ions and leaves the bubble empty. Alternatively, neutralizing electrons can be supplied from an internal electron source such as an emissive probe. It supplies an electron current equal to the total ion current flowing into the bubble which balances ion losses by surface recombination. The emission increases from space charge limited to temperature-limited emission when the electron source is biased below the grid potential. The emitted electrons are no longer trapped and the current closes via the ambient plasma to ground.

The plasma potential in the bubble is observed to oscillate at frequencies below but close to the ion plasma frequency, creating displacement currents in the grid and probes with constant bias. The potential oscillates uniformly throughout the bubble; hence, no waves are excited and the potential drop occurs at the inner sheath. The ambient plasma potential does not oscillate; thus, the outer sheath is stable and contains no oscillating ion bunches. The instability frequency scales with the ion plasma frequency of the bubble sheath. The frequency depends on the net charge density in the sheath which includes electrons. Since the grid voltage controls the electron supply it also determines the frequency of oscillations. Furthermore, the grid voltage changes the plasma potential which affects the ion density in the bubble. For increasingly negative grid bias the frequency first decreases with $|V_{\text{grid}}|$ since the ion density drops. It reaches a minimum for $|V_{\text{grid}}| \simeq V_{\text{dis}}$ when energetic electrons stagnate inside the sheath. For larger $|V_{\text{grid}}|$ the frequency rises and finally approaches virtual anode oscillations. Mode jumps, harmonics, and amplitude discontinuities are also observed. The growth and decay of plasma bubbles and other properties will be shown in three companion papers.12–14

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