Oscillating plasma bubbles. III. Internal electron sources and sinks

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An internal electron source has been used to neutralize ions injected from an ambient plasma into a spherical grid. The resultant plasma is termed a plasma “bubble.” When the electron supply from the filament is reduced, the sheath inside the bubble becomes unstable. The plasma potential of the bubble oscillates near but below the ion plasma frequency. Different modes of oscillations have been observed as well as a subharmonic and multiple harmonics. The frequency increases with ion density and decreases with electron density. The peak amplitude occurs for an optimum current and the instability is quenched at large electron densities. The frequency also increases if Langmuir probes inside the bubble draw electrons. Allowing electrons from the ambient plasma to enter, the bubble changes the frequency dependence on grid voltage. It is concluded that the net space charge density in the sheath determines the oscillation frequency. It is suggested that the sheath instability is caused by ion inertia in an oscillating sheath electric field which is created by ion bunching. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4743021]

I. INTRODUCTION

The neutralization of dense ion beams is an important topic in ion implantation, plasma thrusters, plasma expansion into wakes, plasma sources, and electrostatic confinement. Neutralization refers to both space charge neutrality and current neutralization if there is no return current. Neutralizing electrons can be supplied by an electron emitter or by the plasma source from which ions are extracted. The simplest ion extraction method is a single grid biased to attract ions from a plasma source and to inject the transmitted ions to a target. A biased grid has two sheaths. In contrast to sheaths on solid bodies, the sheaths on transparent grids can have particle flows in both directions. The stability of the sheaths plays an important role in the properties of the ejected plasma beam.

In the present configuration, the ions are radially injected into a spherical volume forming a plasma bubble. Its density ranges from zero to nearly the ambient density. For low grid bias, electrons are supplied from the ambient plasma, but when ambient electrons are reflected within a plasma source and to inject the transmitted ions to a target. A biased grid has two sheaths. In contrast to sheaths on solid bodies, the sheaths on transparent grids can have particle flows in both directions. The stability of the sheaths plays an important role in the properties of the ejected plasma beam.

When the supply of neutralizing electrons is restricted the bubble sheath becomes unstable and oscillates near the ion plasma frequency. The ion sheath instability has been studied in double-plasma (DP) devices by many authors. In the limiting case of no neutralizing electrons, the ions form a virtual anode analogous to the virtual cathodes for electron beams. The oscillation frequency is approximately the plasma frequency of the injected particles. One model for the instability, based on simulations, suggests that ion bunches oscillate in the two-sided sheath potential well around the grid. Roughly, then, the period will be twice the transit time for an ion bunch through the double-sheath potential well. Harmonics are generated because the well is nonlinear. Our observations do not support this plausible picture since the outer sheath does not oscillate and virtual anode oscillations where a potential well exists exhibit no harmonics.

When electrons are injected into an ion-rich sheath the oscillation frequency of the sheath falls below the ion plasma frequency. The frequency decreases with increasing emissive probe current. The negative grid voltage controls the electron supply which explains the frequency dependence on grid voltage. A strong negative grid potential traps electrons in which case the electron density can be easily perturbed by electron collection from Langmuir probes. The probe bias shifts the plasma potential or charge density in the sheath which changes the oscillation frequency. Thus, the sheath instability presents a multidimensional parameter problem which can result in different modes and frequency dependencies, some of which will be shown. In addition, the sheath is a nonlinear oscillator which produces harmonic and subharmonic frequencies.

The present paper is organized as follows: After briefly describing in Sec. II, the experimental setup, diagnostics and parameters, the observations of bubble parameters, and sheath instabilities with emissive probe neutralization will be presented in Sec. III. The findings are summarized in Sec. IV.
Neutralizing electrons are either supplied from an emissive filament inside the sphere or by tail electrons from the ambient plasma with energy $m v^2_{perp}/2 > e|V_{grid}|$. The bubble plasma is formed by mixing ions with neutralizing electrons rather than by ionization. The emissive probe consists of a 1 cm loop of W wire (0.125 mm diam) heated by a 3 V, 1.8 A dc supply with center tap. Plasma parameters are measured with a radially movable Langmuir probe but electron collection by the probe causes serious plasma perturbations which complicates the interpretation of current-voltage (I-V) characteristics.

All relevant voltages are variable either by slow sweeping or pulsing with a fast transistor switch. Grid current oscillations are measured with an rf broadband transformer (100 kHz–100 MHz) inserted into the bias line feeding of the grid. All signals are acquired with a 4-channel digital oscilloscope with bandwidth up to 400 MHz and storage up to $2.5 \times 10^5$ samples.

### III. EXPERIMENTAL RESULTS

#### A. Filament I-V characteristics

We start by reviewing the characteristics of an emissive probe inside the bubble plasma summarized in Fig. 2. The I-V characteristics in Fig. 2(a) shows that for positive bias the emissive probe collects electrons while for negative bias two regimes of emission are observed. A low space-charge limited emission arises when the emissive probe is biased positive with respect to the grid ($V_{grid} = 18$ V). In this case, the electron emission equals the ion injection into the bubble so as to close the current. No electrons are collected by the grid until $V_{emf} < V_{grid}$. A temperature-limited emission current flows because then the emissive probe behaves as a cathode and the grid as an anode. Ionization is negligible since the emission current ($I_{emf} \approx 1$ mA) is small compared to the discharge current ($I_{dis} = 100-500$ mA). Figure 2(b) shows the current dependence on filament temperature varied by the heater current. The electron collection and the emission current for ion neutralization do not depend on the filament temperature, but the emission current to the grid is clearly temperature dependent.

Figure 2(c) shows I-V characteristics in a pulsed ambient plasma. Prior to the generation of an ambient plasma, there is an emission current from the filament to the grid provided $V_{emf} < V_{grid} \approx -80$ V. Thus, a weak discharge plasma is formed between the emissive probe and the grid.

During the discharge, the space-charge limited emission is controlled by the ion flux into the bubble which does not vary significantly with the emissive probe voltage. But in the afterglow, the emission drops abruptly at a voltage which increases in time and approaches $V_{grid}$. Since emission requires the plasma potential inside the bubble to be above the emissive probe potential the plasma potential must drop and approach $V_{grid}$ in the late afterglow. The negative plasma potential indicates that the ion inflow is smaller than the electron supply which is to be expected as the external plasma decays. Current closure requires that electron emission and ion injection both vanish together. Vice versa, for sufficiently negative $V_{emf}$, when there is electron emission, there must be ion injection since the electrons cannot flow to the grid or the negatively biased probe.

Figure 2(d) shows that the Langmuir probe can affect the emissive probe current. When the probe is grounded ($V_{probe} = 0$), it draws electrons from the emissive probe like an anode. When the Langmuir probe floats ($I_{probe} = 0$), the emission current equals the injected ion current. The difference is the current to the probe. Thus, tracing the I-V curve of a Langmuir probe will modify the plasma parameters in the bubble, in particular when drawing electrons in an afterglow plasma, an example of which is shown next.

Figure 3 displays Langmuir probe traces in a plasma bubble with emissive filament immersed in a pulsed discharge plasma. When the probe is biased positively so as to collect electrons there are large overshoots at the beginning and end of the discharge [Fig. 3(a)] which are not present when the probe collects ions [Fig. 3(b)] or when the emissive probe is cold. By varying the probe, voltage time-resolved I-V characteristics are obtained [Fig. 3(c)] which have to be

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*Fig. 1. Schematic diagram of the experimental setup. An 8 cm diam spherical grid of high transparency is inserted into a discharge plasma of parameters indicated. A plasma bubble is formed inside the sphere by ion injection neutralized either from ambient tail electrons and/or electrons from an emissive probe inside the sphere. For low electron fluxes, the inside sheath of the grid becomes unstable and produces plasma potential oscillations near the ion plasma frequency.*
interpreted carefully since the probe obviously perturbs the electron distribution. Ion collection up to the floating potential usually does not change the sheath instability.

During the steady-state period of the pulsed discharge, the I-V trace indicates a floating potential close to the ground potential. Electrons from the ambient plasma cannot enter

FIG. 2. Emissive probe characteristics in a bubble plasma. (a) I-V curve with different current regimes. (b) Variation of heater current showing the difference between space charge and temperature limited emission regimes. (c) I-V characteristics in a pulsed discharge, showing loss of emission current due to the decay of ion density. (d) Influence of a Langmuir probe on the I-V curve of an emissive probe.

FIG. 3. Probe I-V characteristics in a pulsed discharge with emissive probe inside the bubble. (a) Electron current to a positively biased probe showing a large current overshoot in the afterglow plasma caused by a plasma potential drop. (b) Ion saturation current of the same probe showing a fast ion current drop due to the drop in plasma potential. (c) Langmuir probe traces in the discharge and afterglow showing a drop in floating potential which lasts throughout the afterglow due to trapping of electrons.
the bubble. Electrons are supplied by the emissive filament and collected by the Langmuir probe when its potential is positive with respect to the emissive probe. Ions are injected and maintain a positive plasma potential. The grid is too negative to collect any electrons.

When the ambient plasma decays, the ion influx into the bubble decreases and so must the neutralizing electron current from the emissive probe. For a constant emissive filament bias, the plasma potential must drop close to the emissive probe potential, as indicated in Fig. 3(c) by the I-V traces in the afterglow. The potential drop creates the large electron current to the probe. Ions and electrons decay on the same time scale of \( \tau \approx 1 \text{ ms} \). There are no sheath oscillations in the afterglow since the electron supply is large compared to the ion inflow. When the emissive probe is cold the bubble is empty and virtual anode oscillations are seen in \( I_{\text{grid}} \).

**B. Bubble properties with an internal emissive probe**

In a steady state discharge plasma, an empty bubble has been established by biasing the grid sufficiently negative to exclude all ambient electrons. Then the internal emissive probe is pulsed negatively to study the filling of the bubble by space charge neutralized ions. Figure 4(a) shows the ion saturation current of the Langmuir probe, the emissive probe voltage and the grid current oscillations in time. Within the rise time of \( V_{\text{emfil}} \), the ion current rises with an overshoot and the virtual anode instability is quenched. When \( V_{\text{emfil}} \) is switched off the ion current decays after an initial overshoot and the sheath oscillations start again.

Figure 4(b) shows probe traces for different probe voltages when electrons are collected. The emissive filament is the electron source which supplies the probe current and the injected ion current. The current rises fast but its onset is delayed as shown in the inset of Fig. 4(c). The delay indicates the time of arrival of ions at the center of the bubble since without plasma the electron emission is negligibly small. The rapid rise in electron emission causes a drop in plasma potential which leads to the decrease of ion current during the emissive probe pulse. The I-V trace shows that the potential drops by at least 50 V when the electron current rises after turn-on. At the end of the pulse [Fig. 4(d)], the floating potential rises within the fall time of \( V_{\text{emfil}} \), which increases the ion current until it drops due to the loss of neutralizing electrons. As the bubble empties virtual anode oscillations reappear in the grid current.

![Figure 4](https://example.com/figure4.png)

**FIG. 4.** Change of bubble parameters by a pulsed emissive probe. (a) Ion saturation current of a Langmuir probe, bias voltage of an emissive probe, and grid rf oscillations. The initially empty bubble fills with ions which are neutralized by electrons from the emissive probe. The instability is quenched by a large electron supply. (b) Langmuir probe currents for different probe bias, collecting electrons from the emissive probe. (c) Probe I-V characteristic at the onset of the emissive probe pulse. The peak electron energy is close to the emissive probe voltage. (d) Langmuir probe characteristic after the end of the emissive probe pulse where the energetic electrons are lost to the probe.
The emissive filament current has been varied by changing the heater current. The ion current into the bubble varies proportional to the emitted electron current. When the emission is decreased the potential drop also decreases. The resulting ion current vanishes and so does the appearance of the current overshoots. Furthermore, restricting the electron supply restarts the sheath instability during the pulse. Its frequency is lower than that of virtual anode oscillations, as shown in Fig. 5(d) of Part 2. It lowers the charge density in the sheath which requires the sheath to widen and/or its potential to drop.

For very low emission currents, the bubble density becomes negligibly small and so does the instability amplitude. Thus, there is no optimum emissive probe current producing the largest oscillations. For the same reason, the probe rf current amplitude can exceed the dc ion current from which it is concluded that it is not an ion density oscillation but a displacement current due to the oscillating plasma potential.

C. Spectra with Langmuir and emissive probes

It has been shown in Fig. 2(d) that a positively biased Langmuir probe modifies the emission from an emissive probe inside a bubble. Now we shall show how the instability is affected by sweeping the probe voltage. Figure 6 displays spectra of $I_{\text{grid rf}}$ vs $V_{\text{probe}}$ for different $V_{\text{emf il}}$ in a constant ambient plasma. Since the probe voltage was not a linear function of time the scale of $V_{\text{probe}}$ is nonlinear. The grid voltage is constant and sufficiently negative to keep all external electrons from entering the bubble. Ions enter the bubble with the Bohm flux. The grid also remains negative with respect to the emissive probe so as to reflect all internal electrons. Electrons are lost only by surface recombination with ions on insulators except when the Langmuir probe is biased positive with respect to the emissive probe. The electron confinement is the reason why a probe can easily perturb the electron distribution and modify the sheath instability.

Two modes of oscillations can clearly be distinguished in Fig. 6(a). Mode A arises when the probe collects ions but no electrons. The frequency $f_A$ is independent of $V_{\text{probe}}$ until the probe begins to draw electrons. Then the frequency drops
and the instability is quenched as clearly seen in Fig. 6(b). Mode A has a rich spectrum of harmonics including odd half harmonics, \( n f_{A} / 2 \), where \( n = 1, 2, \ldots, 8 \).

As the probe is biased positively mode B is excited. It has a pronounced frequency minimum when \( V_{\text{probe}} \) is close to the ambient plasma potential. Further increase of \( V_{\text{probe}} \) raises, the frequency toward that of virtual anode oscillations. No dip is seen when \( |V_{\text{grid}}| < |V_{\text{emf fil}}| \) and the emissive filament supplies abundant electrons.

Based on the previous investigations, the probe perturbation can be explained as follows: The emissive probe and the Langmuir probe form an anode-cathode system where the plasma potential is determined by the anode potential. The probe raises the plasma potential when it collects electrons. Mode B is excited because the probe depletes electrons. The temperature-limited emission current is diverted to the probe rather than to neutralize the injected ions.

When the Langmuir probe raises the internal plasma potential close to the external plasma potential the ion influx is reduced. The decrease in the ion flux compared to the electron flux lowers the frequency of the sheath instability. When the bubble plasma potential exceeds the external plasma potential virtual anode oscillations remain.

When the emissive probe potential is reduced [Figs. 6(a)–6(e)], the frequency of mode A and its harmonics is reduced. Figure 2(d) showed that the \( I_{\text{emf fil}} \) decreases with \( V_{\text{emf fil}} \), hence the injected ion current must also decrease. A lower ion density leads to a decrease of the instability frequency.

With decreasing electron energy odd-half harmonics of mode A become abundant. They must be the results of nonlinear sheath oscillations since their harmonics are above the ion plasma frequency where ion acoustic waves are evanescent.

The mechanism of harmonic generation has been investigated by perturbing individual spectral lines. As shown in Fig. 7(a), a parallel L-C resonance circuit has been inserted into the line feeding the grid. When tuned to the frequency of the instability the high impedance (\( Z \approx 10 \, k\Omega \)) highly suppresses the rf grid current. If the harmonics were produced by nonlinear effects of the fundamental grid current, its suppression should eliminate all higher harmonics. Surprisingly, any of the lines of the instability spectrum, shown in Fig. 7(b) can be eliminated without influence on the others. Even the fundamental line can be eliminated and the harmonics continue to oscillate. Thus, each line is an eigenmode of the sheath rather than a nonlinear product of the fundamental mode. This is consistent with observations in pulsed experiments where the instability can start at the second harmonic and later excite the fundamental mode. Furthermore, Fig. 7(b) shows that the harmonics can be larger than the fundamental mode which also excludes harmonic generation by nonlinearity of the fundamental.

While the external high impedance reduces the rf grid current it enhances the rf grid voltage. In order to assess the role of \( V_{\text{grid,rf}} \), the grid is ac shorted via a capacitor to ground (\( C = 0.1 \mu \text{F}, Z \approx 2 \, \Omega \)). The instability is not affected by

![Image](https://example.com/image.png)

**FIG. 7.** Tuning a parallel L-C resonance circuit to harmonic lines of the sheath instability. (a) Schematic diagram. (b) Logarithmic plot of the spectrum of \( I_{\text{grid,rf}} \) with multiple harmonics. Top line is the full spectrum without circuit. Below are spectra where the high impedance circuit tunes out lines of successively higher harmonics without affecting the other lines.
eliminating the grid voltage, hence ion bunching does not arise from oscillations in the grid voltage but in the plasma potential.

The instability depends on many parameters such as $V_{\text{grid}}$, $V_{\text{emf il}}$, $I_{\text{emf il}}$, $V_{\text{dis}}$, and $V_{\text{probe}}$, whose coupling can produce perplexing results. We limit the parameter space by keeping the discharge and $V_{\text{emf il}}$ constant while varying $V_{\text{grid}}$ and $V_{\text{probe}}$. As shown in Figs. 8(a) and 8(b), the frequency dependence on $V_{\text{grid}}$ can be completely changed by a biased Langmuir probe. In order to explain these effects, it is helpful to display the probe I-V characteristics in Fig. 8(c) keeping however in mind that the electron branch has modified the electron distribution.

When the probe is biased negatively [Fig. 8(a)] the lower frequency mode A is excited with harmonics. For $V_{\text{grid}} \leq V_{\text{emf il}}$ its frequency $f_A$ increases with $|V_{\text{grid}}|$. The probe traces of Fig. 8(c) (bottom) show that the ion current, which is not subject to probe errors is nearly independent of $|V_{\text{grid}}|$. Since the emission current equals the injected ion current it must also remain constant requiring a nearly constant plasma potential for space charge limited emission. For constant electron energy and density, the electron density in the sheath must decrease as the grid becomes more negative. Since the net space charge density determines the oscillation frequency it increases with $|V_{\text{grid}}|$.

When $V_{\text{grid}} \simeq V_{\text{emf il}}$ electrons stagnate in the sheath and the oscillation frequency assumes its minimum. When the grid is positive with respect to the emissive probe it collects a larger, temperature limited electron current which usually quenches the sheath instability.

For $V_{\text{probe}} = 0$, the probe collects electron currents which for $V_{\text{grid}} \leq V_{\text{emf il}}$ are supplied by the emissive probe and for $|V_{\text{grid}}| \leq V_{\text{dis}}$ are from the ambient plasma. Mode B is excited whose frequency has a maximum at $V_{\text{grid}} \simeq V_{\text{emf il}}$ which coincides with a minimum in the electron current to the probe. For $V_{\text{grid}} < V_{\text{emf il}}$, the probe electron saturation current increases with lowering $|V_{\text{grid}}|$, hence more energetic electrons are able to penetrate into the sheath which lowers the frequency. The frequency also decreases when $|V_{\text{grid}}| \leq V_{\text{dis}}$ since both Langmuir probe and the grid collect electrons from the ambient plasma and the emissive probe. The penetration of electrons into the sheath lowers the oscillation frequency until the instability is quenched by the abundance of electrons.

An alternative display is the frequency dependence on $V_{\text{probe}}$ for different values of $V_{\text{grid}}$ which reveals further details of the instability. Figure 9(a) displays spectra of $I_{\text{grid rf}}$ vs $V_{\text{probe}}$ for 10 different values of $V_{\text{grid}}$. Mode A is excited for negative probe voltages and mode B when the probe collects electrons. For grid voltages $V_{\text{grid}} < V_{\text{emf il}}$, the conditions are similar to those of Fig. 6: The neutralizing electrons are only supplied by the emissive probe. As long as the probe collects only ions, its bias hardly affects the frequency of mode A. But when the probe starts to collect electrons the frequency of mode A drops and the instability is quenched.

The instability reappears in mode B when the probe voltage is close to the ambient plasma potential. Mode B exhibits a sharp dip in frequency at $V_{\text{probe}} \simeq 0$ irrespective of $V_{\text{grid}}$. Since there is no enhanced electron emission it is

![FIG. 8. Spectrum of grid current oscillations, $I_{\text{grid rf}}$, vs dc grid voltage, $V_{\text{grid}}$, perturbed by Langmuir probe currents when (a) the Langmuir probe draws ions which produces negligible perturbations, and when (b) the Langmuir probe draws electrons, which changes the frequency and its dependence on $V_{\text{grid}}$. (c) Probe I-V characteristics for different $V_{\text{grid}}$. For $|V_{\text{grid}}| > V_{\text{dis}}$ (bottom traces), the electrons are supplied from the emissive probe, for $|V_{\text{grid}}| < V_{\text{dis}}$ (top traces) electrons from the ambient plasma also enter into the bubble. When the Langmuir probe collects electrons the plasma potential rises with increasing probe bias.](image-url)
thought that the ion inflow is reduced when the probe pulls
the plasma potential close to the ambient plasma potential.

Decreasing the grid voltage to $|V_{\text{grid}}| = V_{\text{emf}}$, raises, the
frequency of mode B while lowering that of mode A. The
latter has been explained by the penetration of electrons into
the ion rich sheath as the potential difference between grid
and emissive probe decreases. Electrons lower the charge
density which drops the oscillation frequency. The frequency
increase of mode B indicates a loss of electron flux with
decreasing $|V_{\text{grid}}|$. Figures 6(c) and 8(c) (bottom) show that
the probe current for $V_{\text{grid}} = 0$ decreases with $|V_{\text{grid}}|$, reach-
ing a minimum at $V_{\text{grid}} = V_{\text{emf}}$. While the electron cur-
tent decreases the ion current slightly increases. Thus, the
frequency increase in mode B is due to the increasing ratio
of ion flux to electron flux.

In the regime $|V_{\text{grid}}| > V_{\text{dis}}$, the plasma potential is
determined by the injection of ions through the grid and the
emission of electrons from the hot filament and their respec-
tive loss rates. As shown in Fig. 9(b), the floating potential
becomes increasingly negative with increasing $|V_{\text{grid}}|$ since
the electrons are trapped for $V_{\text{grid}} < V_{\text{emf}}$ while the ion flux
gradually decreases with $|V_{\text{grid}}|$ [Fig. 9(c)]. Measurements of
the floating potential and ion current are non-perturbing. But
for a positive probe bias the probe raises the plasma potential
when it is the only electron sink which is the situation for
mode B. Thus, the frequency increase for mode B is due to
the increased ratio of ion to electron flux [see Fig. 9(d)]
which produces an increasingly positive space charge density
in the sheath and a rising frequency of oscillations up to
$|V_{\text{grid}}| = V_{\text{dis}}$. The sharp frequency dip at $V_{\text{probe}} \approx 0$ occurs
when the probe pulls the plasma potential close to the ambi-
tent plasma potential such that the ion inflow is reduced and
the ion outflow enhanced. No virtual anode is formed since
neutralizing electrons are present. Few harmonics are
observed when the probe and grid collect the electrons.

Mode A is observed when the emitted electrons have no
sink other than surface recombination, provided both grid
and probe are biased below $V_{\text{emf}}$. Although not measurable
the electron flux must decrease with $|V_{\text{grid}}|$ for the following
reason: The emissive probe emits relative to the plasma
potential which must be above but close to the floating
potential. As the plasma potential decreases with $|V_{\text{grid}}|$, the
space charge limited emission also drops [see Fig. 2(a)]. A
dwindling emission and decreasing electron energy increases
the space charge density in the sheath which in turn results
in a high oscillation frequency for large negative grid
voltages.

When the grid voltage is comparable to the emissive
probe voltage the emitted electrons stagnate in the sheath.
Mode A assumes a frequency minimum and produces copi-
ous harmonics and odd half harmonics. Thus, slow electrons
in the sheath appear to be associated with nonlinear oscilla-
tions. Previously, subharmonics have only been observed
when the sheath instability is driven by an oscillating grid

FIG. 9. Bubble plasma parameters and instability properties for different Langmuir probe voltages and grid voltages. (a) Spectrum of $I_{\text{grid}}$ vs $V_{\text{probe}}$ for different $V_{\text{grid}}$ and fixed $V_{\text{emf}} = -50$ V and $V_{\text{dis}} = 35$ V. When $|V_{\text{grid}}| > V_{\text{dis}}$, the electrons in the bubble are supplied by the emissive probe which excites mode A
for negative probe bias and mode B for probe bias $V_{\text{probe}} > V_{\text{emf}}$. For $|V_{\text{grid}}| \leq V_{\text{dis}}$, electrons from the ambient plasma enter the sphere which reverses the fre-
cquency dependence $f(V_{\text{probe}})$. A pronounced frequency dip occurs when the probe is biased close to the ambient plasma potential. Several even and odd-half
harmonics arise when the electrons are neither collected by the grid ($V_{\text{grid}} = V_{\text{emf}}$) or probe ($V_{\text{probe}} = V_{\text{emf}}$). (b) Floating potential of the Langmuir probe vs
grid voltage showing that the emissive probe prevents the formation of a virtual anode. (c) Probe electron and ion saturation currents vs $V_{\text{grid}}$. (d) Ratio of ion
to electron current vs $V_{\text{grid}}$, showing a pronounced maximum when $V_{\text{grid}} = V_{\text{emf}}$ where mode B has a maximum frequency, mode A has a minimum.
bubble when are observed for very positive probe voltages. \[ V_{\text{grid}} \geq V_{\text{emf}} \approx -50 \text{ V}, \] the emitted electrons are collected by the grid and/or the probe whichever is more positive with respect to the emissive probe. Harmonics and odd half harmonics disappear when the plasma potential is tied by electron sinks. When the probe pulls the plasma potential close to the ambient plasma potential the rejection of ions produces the pronounced frequency dip in mode B. There is no enhancement in the electron current at the dip. It is noteworthy that the sheath can oscillate simultaneously at two different frequencies not related as harmonics [see \( V_{\text{grid}} = -50 \text{ or } -35 \text{ V}, \ V_{\text{probe}} < -20 \text{ V}. \) Virtual anode-like oscillations are observed for very positive probe voltages. Energetic electrons from the ambient plasma enter the bubble when \( |V_{\text{grid}}| \leq V_{\text{dis}}. \) As \( |V_{\text{grid}}| \) decreases, the electron supply increases which raises the electron saturation current [Figs. 8(c) (top traces) and Fig. 9(b)] and, at a constant ion flux lowers the oscillation frequency of mode B. The instability vanishes at low \( |V_{\text{grid}}| \) since abundant electrons stabilize the sheath. Mode A reappears when \( |V_{\text{grid}}| \approx V_{\text{dis}}. \) Electrons from the ambient plasma and the emissive probe are mainly lost on the large grid rather than the small Langmuir probe, hence the frequency becomes independent of \( V_{\text{probe}}. \) It slightly increases as \( |V_{\text{grid}}| \) drops before being quenched by the increasing ambient electron flux. Although mode A and its subharmonic fall into the ion acoustic branch they are not unstable sound waves but sheath instabilities. For \( f = 200 \text{ kHz} \) and \( (kT_e/m_i)^{1/2} \approx 2 \times 10^5 \text{ cm/s}, \) the wavelengths would be \( \lambda = 1 \text{ cm} \) which have not been observed in phase measurements. If the oscillations were due to ion transit times through an 8 cm sphere the ion energy would have to be \( > 64 \text{ eV} \) which is not possible for the observed potential drop between ambient and bubble plasmas.

IV. CONCLUSION

Plasma bubbles have been created by leaking ions and electrons from an ambient plasma into a spherical volume bounded by a highly transparent grid. The neutralizing electrons have also been supplied from an emissive probe inside the bubble. For a negative grid bias the ions stream into the bubble while the external electron flow is restricted. The sheath or plasma potential develops self-consistently to produce charge neutrality and current-free conditions. When the bubble potential is lower than the ambient plasma potential an ion beam is injected into the bubble. Without neutralizing electrons 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. Vice versa, electrons inside the bubble can be reflected by a sufficiently negative grid bias. Electron trapping results in long relaxation times for pulsed bubbles. Ion trapping occurs when the plasma potential in the bubble is lower than that of the ambient plasma. Inserting probes into a bubble plasma can cause perturbations, especially when collecting electrons whose flux 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.

Oscillations arise from an unstable sheath on the inner side of the grid. Based on the observations, the following physical picture of the instability emerges: The ion-rich sheath expands into the bubble, which creates a retarding space charge electric field. Due to the ion inertia the sheath oscillates near the ion plasma frequency. The oscillations are maintained by bunching of injected ions in the oscillating sheath. The space charge electric field of ion bunches maintains the oscillations. Oscillations in the space charge density of the sheath create oscillations in the plasma potential of the bubble. No ion acoustic waves or traveling potential oscillations are observed. 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 contains no oscillating space charges due to reflected ions. The grid voltage is constant and not involved in the instability. The grid current oscillates which is mainly a displacement current balancing the injected ion conduction current into the bubble. The frequency of the instability is frequently discussed in terms of the ion transit time through a sheath which does not address the role of electrons in the sheath. Here we take a different approach and consider the basic oscillation frequency of a charge layer in its own space charge electric field. Ion inertia and space charge density determine the frequency, \( \omega^2 = (n_i - n_e) e^2 / m_i \epsilon_0. \) The oscillation frequency depends on the net 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 present in the sheath. The electron supply is controlled by the grid voltage or other electron sources and sinks. A decreasing electron supply raises the frequency which reaches a maximum for virtual anode oscillations, i.e., a pure ion sheath. Vice versa, an increasing electron supply lowers the frequency as well as the amplitude until the instability is quenched.

Pulsed perturbations are used to trigger sheath oscillations. Low frequency transient oscillations are observed when the electron flux is large and the sheath is stable. The ringing frequency is close to the ion beam transit time through the sphere. When the electron flux is restricted the pulse triggers the sheath-plasma instability which oscillates indefinitely. The instability is also affected by grid properties, bubble geometry and plasma gradients which will be addressed in a companion paper.

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