Experimental Observation of a Periodically Oscillating Plasma Sphere in a Gridded Inertial Electrostatic Confinement Device

J. Park, R. A. Nebel, and S. Stange
Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA

S. Krupakar Murali
University of Wisconsin, Madison, Wisconsin 53706, USA
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The periodically oscillating plasma sphere (POPS) [D. C. Barnes and R. A. Nebel, Phys. Plasmas **5**, 2498 (1998).] oscillation has been observed in a gridded inertial electrostatic confinement device. In these experiments, ions in the virtual cathode exhibit resonant behavior when driven at the POPS frequency. Excellent agreement between the observed POPS resonance frequency and theoretical predictions has been observed for a wide range of potential well depths and for three different ion species. The results provide the first experimental validation of the POPS concept proposed by Barnes and Nebel [R. A. Nebel and D. C. Barnes, Fusion Technol. **34**, 28 (1998).].

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Initially proposed by Elmore *et al.* [1], Farnsworth [2], and Hirsch [3] in the 1950s and 1960s, inertial electrostatic confinement (IEC) is a general term describing plasma confinement devices that use either electrostatic fields [1–4] or a combination of electrostatic and magnetic fields [5–8]. The confining fields can be produced either by grids or by virtual cathodes, typically in spherical geometry. The fields create an effective potential well that confines ions and accelerates them towards the center of the device. In the case where fuseable ions are used, fusion reactions can occur. The ease of accelerating the ions to fusion-relevant energies of 10–150 keV in a tabletop device was the basis for IEC's early success—it produced a steady-state neutron yield of 2×10^{10} neutrons/s in the late 1960s [4].

Though promising as practical neutron sources, existing IEC fusion devices have shown only modest fusion yields, $\sim$0.01% or less of input power. Furthermore, theoretical studies have indicated that such systems either cannot scale to net energy producing devices [9,10] or their fusion power density will be too small for practical use [11]. The high energy cost of maintaining a beamlike ion energy distribution makes it difficult to produce net fusion power and is considered to be a crucial obstacle facing IEC based fusion energy devices.

A new electrostatic plasma equilibrium that should mitigate this problem has been proposed by Barnes and Nebel [12,13]. This concept uses electron injection into a spherical device to produce a virtual cathode with a harmonic oscillator potential (constant electron density). An ion cloud immersed in the virtual cathode [referred to as the periodically oscillating plasma sphere (POPS)] will then undergo a harmonic oscillation where the oscillation frequency is independent of the amplitude. By tuning the external radio-frequency (rf) electric fields to this naturally occurring mode, it is then possible to phase lock the ion motions. This simultaneously produces very high densities and temperatures during the collapse phase of the oscillation, when all ions converge to the center with their maximum kinetic energies.

It has been shown that an analytic solution for the POPS oscillation exists and has the remarkable property that it maintains the ions in local thermodynamic equilibrium at all times [12]. In particular, the equilibrium state survives even though the plasma density and the temperature may vary by several orders of magnitude during the POPS oscillation [12,13]. This is because these solutions are exact solutions of the Vlasov equation, thus they persist independent of the collisionality. A more intuitive explanation is that the POPS oscillation can be described as a rigid rotor rotation in phase space, with the velocity distribution and radial density profiles exchanging places every quarter period [14]. If the radial density profile is Gaussian, the corresponding velocity distribution would be Maxwellian and ion-ion collisions would not cause any further relaxation. This would eliminate most of the energy cost due to Coulomb collisions. In theory, a fusion device utilizing the POPS oscillation could result in the net energy gain required for fusion power generation.

Previous work on the POPS concept has been focused on the dynamics and the stability of the background electrons that are required to form the spherical harmonic potential well [15–19]. Earlier theoretical works using the electron fluid equations showed that a uniform electron density profile for POPS is susceptible to a two-stream instability that is analogous to the Rayleigh-Taylor mode present in fluid mechanics [17]. However, the electron stability improves greatly when electron kinetic effects, such as the spread in the electron angular momentum distribution, are included [16]. These results are consistent with recent experimental results showing that nearly harmonic potential wells with a fractional well depth of $\sim$60% of the applied grid bias can be produced with no sign of instability [16].

In this Letter, we describe the first experimental observations of the POPS oscillation in a gridded (IEC) device. Resonance behavior of the ions in the virtual cathode is clearly observed when an external fluctuation is provided at the POPS frequency. The scaling of the POPS frequency is measured and compared with the theoretical predictions for a wide range of potential well depths and three separate ion species.

The IEC device at Los Alamos National Laboratory, known as the intense neutron source-electrons (INS-e), consists of a 30 cm (o.d.) spherical vacuum vessel containing two concentric, highly transparent wire grids. A schematic diagram of the device is shown in Fig. 1. The electron injection in the INS-e device comes from six thermally emitting electron dispenser cathodes. This eliminates the need for Paschen breakdown and reduces the operating gas pressure. The grids are constructed of 75% tungsten/25% rhenium wires and have a transparency of about 92%. The outer grid is 23 cm in diameter and the inner grid diameter is 12.7 cm. Each of the grids can be biased independently. Because of the presence of electron beams, the interpretation of the Langmuir probe data is questionable, particularly for the plasma potential. Consequently, we have used an emissive probe to measure the plasma potential and its fluctuations. A more detailed description of INS-e operation can be found elsewhere [15,16].

Two experimental modifications were implemented for the current work on POPS resonance measurements. The first was the installation of a new inner grid to improve the spherical symmetry of the plasma potential in the virtual cathode. The grid spacing was reduced from 3.5 to 1.0 cm. In comparison, the estimated Debye length is ~1.8 cm. Radial profile measurements of the plasma potential show that the plasma potential at the midpoint between the grid wires agrees to within 10% of the grid bias voltage using the new grids, compared with a difference of up to 40% before. The second upgrade was the addition of a pulsed power system. In steady-state operation, the ion density in the virtual cathode monotonically increases in time due to the ionization of the background gases and a practically infinite ion confinement time [15]. This ion buildup results in the loss of the virtual cathode on a time scale comparable to the background ionization time, ~1–5 ms. Therefore, the pulsed power system was implemented to operate the device with pulse durations of 0.5–10 ms. The lower bound of the pulse duration was chosen to accommodate the slow temporal response of the emissive probe, and the upper bound was chosen to match the decay of the virtual cathode. The pulse duration is sufficiently long to study the POPS oscillations—since it is many times longer than a POPS period, which is a few microseconds.

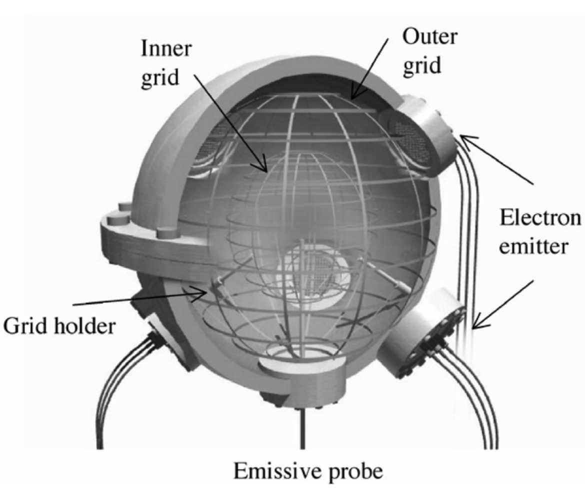

FIG. 1. Schematic of the INS-e device.

In order to measure the POPS oscillation, a virtual cathode is produced using pulsed electron injection. As shown in Fig. 2, a high voltage (HV) pulse is applied to the six electron emitters in order to extract the electrons. The injected electrons are pulled into the grid region by the positive bias on the outer grid. A constant dc bias is used for the outer grid at all times, 300 V in this case. After electron injection starts, a second HV pulse is applied to the inner grid to produce the virtual cathode in the core region. Though the production of a harmonic plasma potential in the virtual cathode is sufficient to cause the ions to undergo POPS oscillation, an external perturbation is required to phase lock the ion motion and to excite a coherent oscillation [12,13]. Therefore, an additional rf modulation of 5–10 V is applied to the inner grid along with the HV pulse. It is noted that the well depth in a virtual

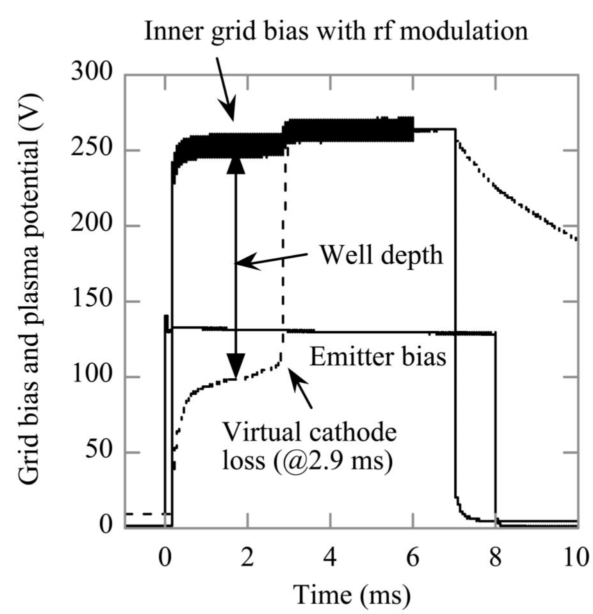

FIG. 2. HV pulse operation for the POPS oscillation measurement. Solid lines indicate the grid bias and the dotted lines indicate the plasma potential measured by the emissive probe at the center of the virtual cathode.

cathode is defined as the difference between the inner grid bias and the measured plasma potential at the center. Since the well depth gradually decreases as the ions accumulate in the virtual cathode, the time average value of the well depth is used.

The ion dynamics in the virtual cathode are those of a driven harmonic oscillator, which is described by the Mathieu equations using two dimensionless numbers: a for the square of the ratio of the oscillator frequency to the driving frequency and q for the strength of the driving perturbation [20].

$$\frac{d^2x}{dt^2} + \omega^2[a - 2q\cos(2\omega t)]x = 0, \quad (1)$$

$$a \equiv \frac{2e\phi_{00}}{r_{\mathrm{VC}}^2 m_i \omega^2} = \left(\frac{2\omega_{\mathrm{POPS}}}{\omega}\right)^2, \quad (2)$$

$$\omega_{\mathrm{POPS}} = \left(\frac{e\phi_{00}}{2r_{\mathrm{VC}}^2 m_i}\right)^{.5}, \quad (3)$$

$$q \equiv \frac{e\delta\phi}{r_{\mathrm{VC}}^2 m_i \omega^2}, \quad (4)$$

where ω is the angular frequency of the external oscillations, ω_{POPS} is the angular frequency of POPS oscillations, r_{VC} is the virtual cathode radius, ϕ_{00} is the absolute value of the zeroth order (i.e., dc component) well depth in the virtual cathode, m_i is the mass of the ion, e is the electrostatic charge on the ion, and $\delta\phi$ is the perturbed potential induced by oscillating the grid voltage. At the fundamental resonance at $a = 1$, even infinitesimal perturbations drive the ion orbits unstable and eventually eject them from the virtual cathode. Concurrently, the ion ejection will limit the ion buildup and slow the loss of the virtual cathode. The resonance can be measured either by directly measuring the ejected ion flux or by monitoring the change in the virtual cathode decay time. The next resonance occurs at $a = 4$, which is the half harmonic of the POPS oscillation.

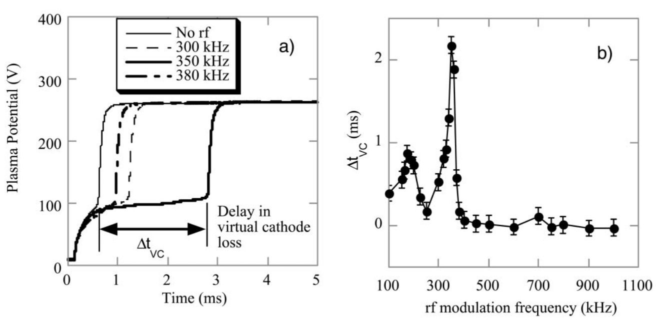

FIG. 3. (a) Temporal evolution of the plasma potential at the center of the virtual cathode with and without rf modulation. (b) Delay in the loss of the virtual cathode due to the rf modulation as a function of the modulation frequency.

In these experiments, an emissive probe is used to measure the temporal variation of the plasma potential at the center of the virtual cathode in order to verify the existence of a resonance. Direct measurements of the ejected ion particle flux using a Langmuir probe proved to be impractical due to the low plasma density and the large disturbance that such a probe makes in the plasma potential structure. There are some drawbacks to using the virtual cathode decay to identify the POPS resonance. For instance, it is not possible to measure the phase change across the resonance or to determine the quality factor of the resonance. In the future, an electron beam will be used to directly measure the plasma compression during the POPS oscillation. However, the observed significant change in the virtual cathode decay time (discussed below) indicates a large quality factor.

Figure 3(a) shows the temporal evolution of the plasma potential as measured by the emissive probe at the center of the device. The dc part of the inner grid bias was 250 V and the average well depth of 148 V was estimated by the difference between the grid bias and the measured plasma potential. A significant delay in the loss of the virtual cathode was observed for a moderate rf modulation amplitude of ~8.0 V at 350 kHz, compared to the case without rf modulation. This demonstrates the strong resonance effect of the driven POPS oscillation. On the other hand, rf modulation of the same amplitude results in only a small delay in the loss of the virtual cathode for frequencies of 300 and 380 kHz. In Fig. 3(b), the change in the virtual cathode loss time due to the rf modulation is plotted as a function of the modulation frequency from 100 kHz to 1 MHz, showing the fundamental resonance at

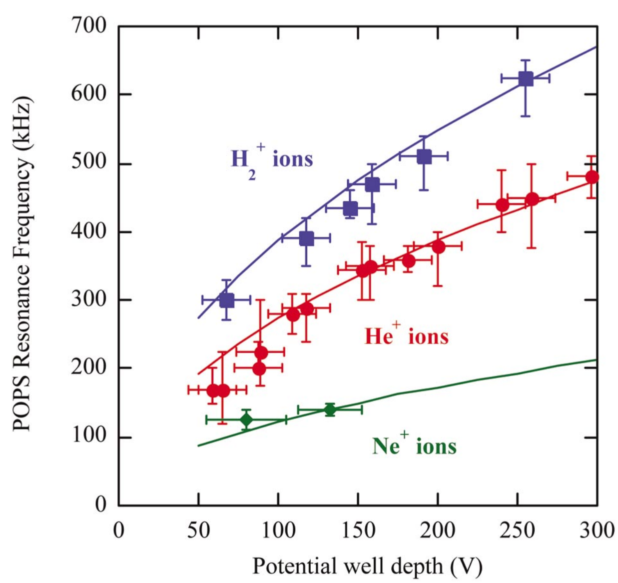

FIG. 4 (color). Comparison between the experimentally measured POPS frequencies (points) and the theoretical calculations (lines) from Eq. (3) as a function of the virtual cathode well depth and the ion mass.

~350 kHz and the much broader half harmonic resonance at ~175 kHz.

The scaling of the fundamental resonance frequency has been measured as a function of the potential well depths and the ion masses. The well depth of the virtual cathode was controlled by varying the amplitude of the inner grid bias pulse. The fill gas was also varied, producing three different ion species, H_2^+, He^+, and Ne^+. At low gas pressures of $\sim 10^{-6}$ torr, the ionization rate of H_2^+ ions greatly exceeds the ionization rate of H^+ due to the much large cross section for H_2^+. From Eq. (3), it is expected that the POPS frequency will scale as the square root of the potential well depth and as the inverse square root of the ion mass. As shown in Fig. 4, the scaling of the measured POPS resonance frequencies agrees with the prediction. Furthermore, the values of the measured POPS resonance frequencies agree with the calculation values from Eq. (3). The virtual cathode radius was estimated as $r_{vc} = r_{grid} + \lambda_{Deff}$, where $\lambda_{Deff} = (\frac{eV_{bias}}{4\pi n_e e^2})^{1/2}$ is the effective Debye length using the electron energy of eV_{bias}. This correction was made in order to ensure that the ion orbits reach the region free from the attractive electrostatic fields of the virtual cathode. It is noted that the λ_{Deff} is nearly constant at ~1.8 cm for all data points in Fig. 4 since the potential well depth is proportional to the bias voltage, $\varphi_0 \sim 0.6 \times V_{bias}$.

In conclusion, the periodically oscillating plasma sphere oscillation has been observed for the first time in a gridded (IEC) device. By exciting the plasma at the POPS frequency, ions are resonantly heated and ejected from the virtual cathode resulting in a significant slowing of the virtual cathode decay. The resonance effect is clearly observed and agrees very well with the theoretical predictions. Both the predicted potential well depth and the ion mass scalings were observed. The results provide critical experimental validation for the POPS-based fusion concept proposed by Barnes and Nebel [12,13].

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