RECENT RESULTS FROM THE PAUL TRAP SIMULATOR EXPERIMENT

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Abstract

The Paul Trap Simulator Experiment (PTSX) is a compact laboratory facility whose purpose is to simulate the nonlinear dynamics of intense charged particle beam propagation over large distances through an alternating-gradient transport system. The simulation is possible because the quadrupole electric fields of the cylindrical Paul trap exert radial forces on the charged particles that are analogous to the radial forces that a periodic focusing quadrupole magnetic field exert on the beam particles in the beam frame. Initial experiments clearly demonstrate the loss of confinement when the vacuum phase advance σ_v of the system exceeds 90°. Recent experiments show that PTSX is able to successfully trap plasmas of moderate intensity for thousands of equivalent lattice periods.

INTRODUCTION

The Paul Trap Simulator Experiment (PTSX) is a cylindrical Paul trap whose purpose is to simulate the dynamics of charged particle beams in alternating-gradient (AG) magnetic transport systems [1]. The transverse electrostatic forces that PTSX exerts on the plasma are of the same form as the transverse forces that the quadrupole magnets exert on a beam in an AG system [1, 2]. Moreover, the self-fields can be expressed in analogous forms so that the transverse dynamics of both systems are described by a similar set of equations. Because of the long confinement times of ions in PTSX relative to the oscillation frequency of the trap voltage, PTSX is capable of simulating the beam dynamics over equivalent propagation distances of many kilometers. The waveform of the trap voltage is controlled by an arbitrary function generator so that the waveform can be varied in order to study a wide variety of beam physics topics.

The PTSX device is able to study intense beams in which the space-charge is non-negligible and the normalized intensity parameter $s = \omega_p^2/2\omega_q^2$ (where ω_p is the plasma frequency, and ω_q is the smooth focusing applied betatron frequency) approaches unity. Such intense beams are of increasing interest due to their relevance to high-energy physics, heavy ion fusion, spallation neutron sources, tritium production, and nuclear waste transmutation [3, 4]. Our goal is to study the properties of high-intensity beams where the self-field effects can significantly alter beam equilibrium, stability and transport properties.

In this paper, a brief description of the machine is presented, including several modifications to the original design. Then, the operating parameter regimes of the ion source and the trap itself are discussed. Finally, recent experimental results on the loading and trapping of emittance-dominated one-component plasmas are shown.

APPARATUS

Details of the PTSX apparatus appear in Ref. [5] and so only a brief description is given here. The PTSX device consists of three cylindrical electrodes of radius $r_w = 10$ cm that are sliced into four 90° sectors as shown in Fig. 1. The central electrode has length $2L = 2$ m while the end electrodes are each 40 cm long. The trap confines charged particles (presently cesium ions) radially by applying a periodic voltage $\pm V_0(t)$ to the four sectors. In the limit of high frequency, this creates a ponderomotive force that points radially inwards; note, however, that the trap need not operate in this limit to effectively confine particles. A dc voltage, $+\hat{V}$, applied to the end electrodes confines the ions axially. The ratio L/r_w is large in order to minimize the effects of the ions bouncing off of the dc end-potentials as these effects are outside of the analogy. If the plasma radius r_p is small compared to r_w, then the fields from the walls are almost purely quadrupolar with corrections on the order of $(r_p/r_w)^4$. For PTSX, $V_{0\ \max} \leq 400$ V,

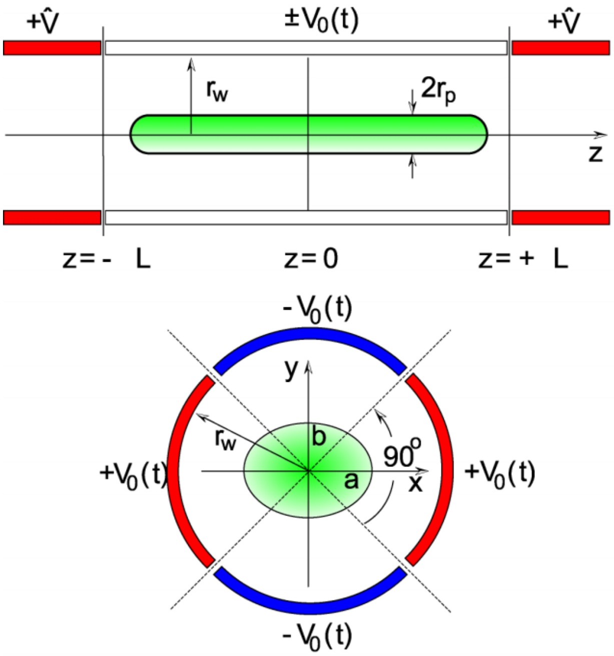

Figure 1: The PTSX device consists of three of cylindrical electrodes, each sliced into four 90° sectors. An oscillating voltage, $\pm V_0(t)$, confines the plasma radially to a radius r_p. Static voltages, $+\hat{V}$ confine the ions axially.

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$\hat{V} = 150$ V, and the frequency f of the oscillating voltage is less than 150 kHz.

For the sinusoidal oscillations used to date, $\omega_q = 4eV_{0\,\max}/\sqrt{2}m\pi^2 r_w^2 f$. Values of the vacuum phase advance ($\sigma_v = \omega_q/f$) from $0°$ to beyond $90°$ are easily accessible by the proper choice of $V_{0\,\max}$ and f as demonstrated in Fig. 2. For the experiments presented here, $V_{0\,\max} = 235$ V and $f = 75$ kHz, so that $\omega_q = 6.51 \times 10^4$ s^{-1} and $\sigma_v = 49.7°$.

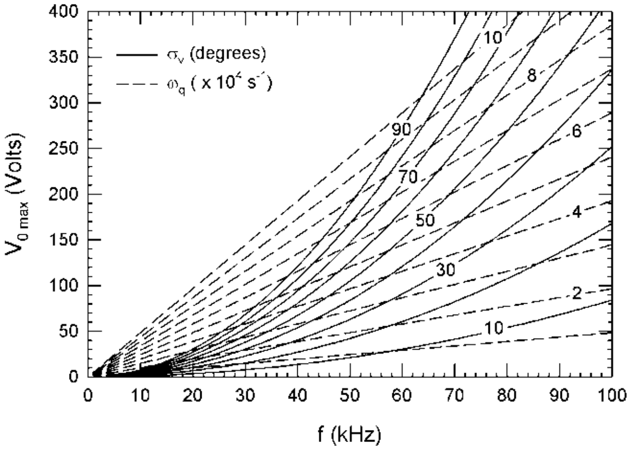

Figure 2: In the $(V_{0\,\max}, f)$ parameter space, curves of constant σ_v are parabolae, while the curves of constant ω_q are straight lines.

The PTSX device normally operates in a load—trap—dump cycle. During loading(dumping), the short electrodes on the source(diagnostic) end of the machine are made to oscillate with the same voltages, $\pm V_0(t)$, as the long electrodes, which allows the ions to pass. When dumped, the ions strike a Faraday cup that has a collection aperture with a diameter, $2r_{ap} = 1$ cm [Fig. 3(b)]. Either the charge or the average current can be measured with an electrometer to determine the radial plasma density profile.

There have been two modifications to PTSX since the device was described in Ref. [5]: the ion source has been improved, and the Faraday cup enclosure has been enlarged. A Pierce electrode has been added to the ion source assembly that employs an aluminosilicate cesium source, an acceleration grid, and a deceleration grid to provide the ions [Fig. 3(a)]. Adjusting the biases on the grids allows the current I_s that streams into the trap,and the ion energy E to be varied independently. The Faraday cup enclosure now shields the top, bottom, left, and right sides of the Faraday cup from stray ions[Fig. 3(b)].

EXPERIMENTAL RESULTS

We expect that I_s should follow the Child-Langmuir $V_e^{3/2}$ scaling with the extraction voltage V_e. The current I_s is measured by allowing the ions to "free stream" directly from the ion source to the Faraday cup where they are collected on the shield enclosure itself rather than through the aperture. There is no axial trapping in this mode of operation. The data in Fig. 4 shows that I_s is linear for small V_e and even sub-linear at larger V_e. Despite the departure from Child-Langmuir, this control gives us a wide range of currents to use for loading the trap.

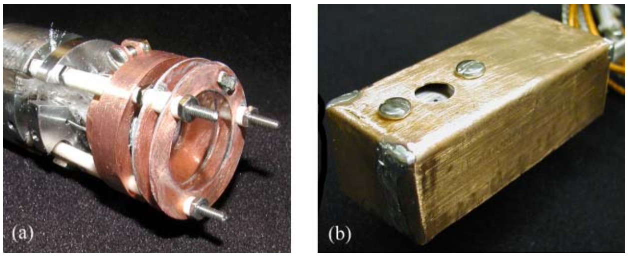

Figure 3: (a) A Pierce electrode has been added to the cesium ion source. (b) The Faraday cup shield has been extended to more completely block stray ions.

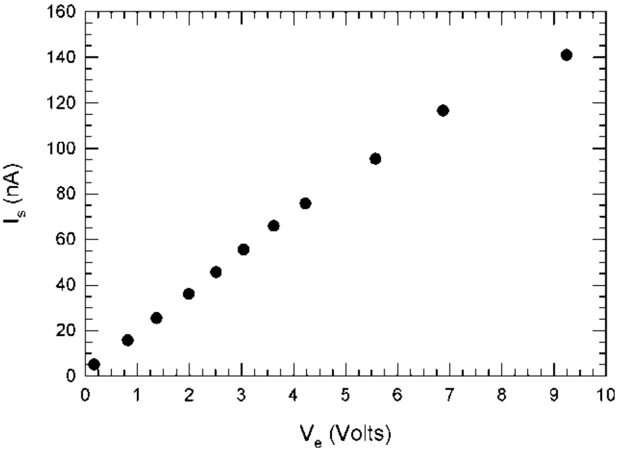

Figure 4: Rather than the $V_e^{3/2}$ scaling of the Child-Langmuir law, the current extracted from the ion source depends linearly on the extraction voltage.

Initial PTSX results confirmed the existence of the envelope instability and loss of confinement for $\sigma_v = 90°$ [6]. This measurement was made with the ions "free streaming". In the absence of space-charge effects, the transverse orbits are governed by Matthieu's equation, and the system parameters must be chosen so that the single-particle orbits are stable. Indeed, if system parameters are chosen so that the vacuum phase advance is greater than $90°$, no ions survive the 2.6 m transit from the ion source to the Faraday cup.

Subsequent experiments investigated properties of trapped plasmas, such as loading time effects, radial profiles, and lifetimes. A radial profile is shown in Fig. 5 for which the ions were loaded for 5 ms, trapped for 1 ms, and then dumped. This trapped plasma corresponds to parameters for which $I_s = 5$ nA. Because the transit time of an ion along the PTSX device is on the order of milliseconds, a loading time of 1 ms is inadequate to fully load the trap. We observe that the amplitude of the radial profile nearly doubles if we allow loading to occur for more than two transit times. The profile is Gaussian in shape, consistent with one-component plasmas that are relatively hot, or emittance-dominated. In thermal equilibrium, the average density profile is proportional to $\exp[(-e\phi - m\omega_q^2 r^2/2)/kT]$. Therefore, if the space charge is negligible, so that ϕ can be ignored, then the radial profile will be nearly Gaussian. For a space-charge-dominated beam, the radial profile will approach a flat-top distribution [3]. It is not known whether the 0.7 cm offset is due to electrode asymmetries, distortion of the ion trajectories due to the Faraday cup, or to misalignment of the Faraday cup.

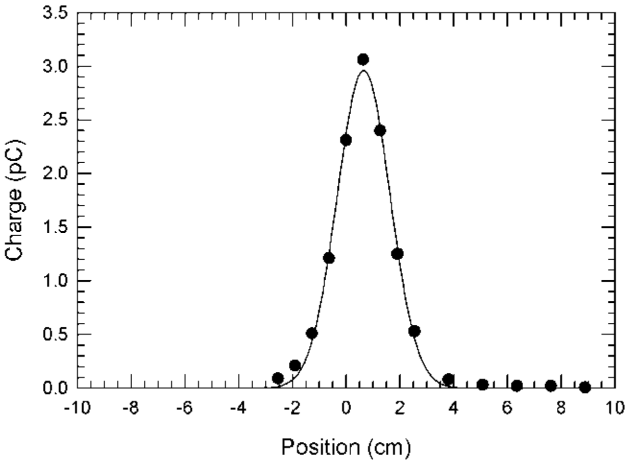

Figure 5: The charge collected in the Faraday cup through the 1 cm aperture. The trap walls are at $r_w = \pm 10$ cm.

It is assumed that the number density $n(r)$ is given by the total charge $Q(r)$ collected through the 1 cm aperture divided by the volume $\pi r_{ap}^2 2L$. The line density, $N = \int n(r) 2\pi r\, dr$, can be measured in two complementary ways: by using I_s and E, or by using $n(r)$. Having measured I_s and E previously, the line density is given by $N = 2 \times 5.2 \times 10^7\ I(\mu\mathrm{A})/\sqrt{E(\mathrm{eV})}\ \mathrm{cm}^{-1}$. The factor of two is a phenomenological factor that accounts for the ions that bounce and travel back towards the ions source during a loading that is longer than twice the transit time. Alternatively, $n(r)$ can be integrated numerically. In the present case, where $n(r)$ is Gaussian, the fit parameters of the Gaussian fit are used. These methods agree to within a factor of 3. The difference could arise because the ultimate energy of the injected ions may not be given simply by the grid biases, but rather influenced by space-charge effects such as the formation of a virtual cathode, or perhaps because the influence of the trapping voltage $\hat{V}$ causes the plasma to have a length shorter than $2L$. For the data in Fig. 5, the Gaussian fit gives $n(0) = 1.2 \times 10^5\ \mathrm{cm}^{-3}$, which implies that $s = 0.18$ and $N = 7.1 \times 10^5\ \mathrm{cm}^{-1}$.

The reproducibility of the system allows us to measure the time evolution of the plasma by measuring the radial profiles of plasmas held for different times. Figure 6 shows that for a plasma corresponding to an initial intensity parameter $s = 0.13$, N decays slowly with time. As 1 s is the approximate timescale for ion-ion and ion-neutral collisions, it suggests that confinement is otherwise quite good until collisions cause transport and plasma loss. Even so, a plasma lifetime of one second allows for approximately 10^5 oscillation periods, and this would correspond to an AG system that is 100 km long if the magnet period is 1 m.

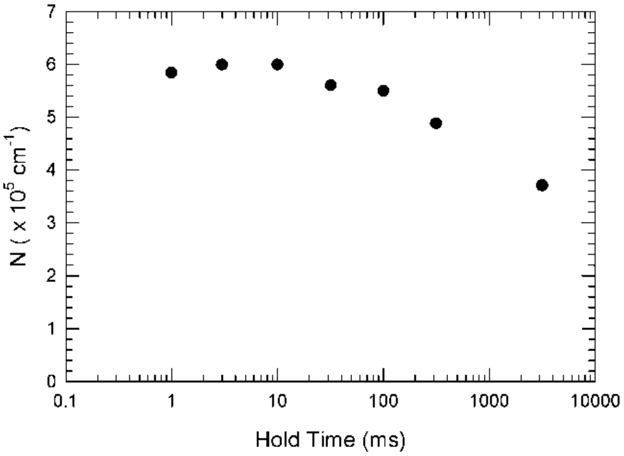

Figure 6: The line density, N, stays relatively steady for several hundred milliseconds before charge is gradually lost from the trap.

CONCLUSIONS

By demonstrating that PTSX can create and trap plasmas that are well-behaved for hundreds of milliseconds, even for $s = 0.13$, the opportunity exists to perform experiments in which the intensity parameter s is extended towards unity, and in which the oscillating voltage waveform on the trap walls is varied in order to simulate various beam physics phenomena.

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