SIMULATING THE LONG-DISTANCE PROPAGATION OF INTENSE BEAMS IN THE PAUL TRAP SIMULATOR EXPERIMENT*

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Abstract

The Paul Trap Simulator Experiment (PTSX) makes use of a compact Paul trap configuration with quadrupolar oscillating wall voltages to simulate the propagation of intense charged particle beams over distances of many kilometers through magnetic alternating-gradient transport systems. The simulation is possible because of the similarity between the transverse dynamics of particles in the two systems. One-component pure cesium ion plasmas have been trapped that correspond to normalized intensity parameters $\hat{s} < 0.8$, where $\hat{s}$ is the ratio of the square of the on-axis plasma frequency to twice the square of the average transverse focusing frequency. The PTSX device confines the plasma for hundreds of milliseconds, which is equivalent to beam propagation over tens of kilometers. Results are presented for experiments in which the amplitude of the oscillating wall voltage waveform has been modified as a function of time. Changing the amplitude for an integral number N of half-cycles and then restoring the amplitude to its original value affects the plasma in a manner that is non-monotonic with N.

INTRODUCTION

The Paul Trap Simulator Experiment (PTSX) is a compact linear Paul trap, with quadrupolar oscillating wall voltages, that simulates the propagation of long, thin, intense charged particle bunches over distances of many kilometers through magnetic alternating-gradient (AG) transport systems [1]. The simulation is possible because, in the frame of reference of the bunch, the applied magnetic fields of the AG system become Lorentz transformed into the electrostatic fields of PTSX [2, 3]. Moreover, the effects of the self-fields of the charged particle bunch are governed by equations of the same form in both PTSX and AG systems [2]. As AG transport systems are designed to carry increasingly large amounts of space-charge, it is very important to understand the nonlinear dynamics of intense beam propagation over long distances [4–9]. Specifically, the conditions for quiescent beam propagation, collective mode excitation, generation and dynamics of halo particles, and distribution function effects must be studied. These are key issues for applications where intense beams are required, such as ion-beam-driven high energy density physics and fusion, spallation neutron sources, high energy and nuclear physics experiments, and nuclear waste transmutation.

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One-component pure cesium ion plasmas have been trapped in PTSX that correspond to normalized intensity parameters $\hat{s} = \omega_p^2/2\omega_q^2 < 0.8$, where ω_p is the on-axis plasma frequency and ω_q is the average transverse oscillation frequency of particles in the system. To ensure that the plasma is confined radially, $\hat{s} \leq 1$ is required. The PTSX device confines the plasma for hundreds of milliseconds, which is equivalent to beam propagation over tens of kilometers [1]. In this paper, results are presented for experiments in which the amplitude of the oscillating confining voltage waveform has been modified as a function of time. Changing the amplitude for an integral number N of half-cycles and then restoring the amplitude to its original value affects moderately intense plasmas in a manner that is non-monotonic with N.

As shown in Fig. 1, PTSX is a linear Paul trap made from a cylinder that is divided azimuthally into four $90°$ sectors. The cylinder is also divided axially into three shorter cylinders: a two-meter long central electrode, and two 40 cm long end electrodes. An oscillating voltage applied to the central electrodes, with opposite polarity on adjacent sectors, produces a ponderomotive force that confines the plasma radially. Applying DC voltages to the end cylinders confines the plasma axially. The device was made as long as was practical (a total length of approximately 3 m) in order to reduce the number of bounces that plasma particles make off of these axially confining potentials, as such bounces are outside of the analogy between PTSX and AG systems in linear geometry.

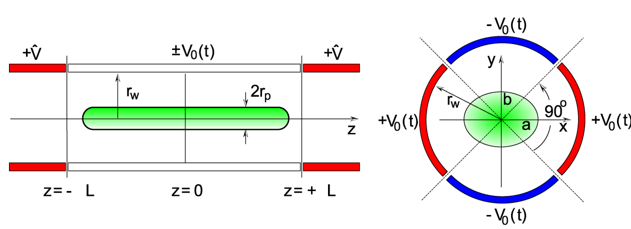

Figure 1: The PTSX device consists of an $r_w = 10$ cm radius cylinder that is divided azimuthally into four $90°$ sectors and axially into three cylinders. A plasma column with radius $r_p \sim 1$ cm and length $2L = 2$ m is confined radially by oscillating voltages $\pm V_0(t)$ applied to the wall electrodes. The plasma is confined axially by bias voltages $\hat{V}$ applied to the end cylinders.

To fill the trap with ions from the steady-state aluminosilicate cesium ion emitter that is centered within one of the 40 cm long electrode sets, that set of electrodes is switched from DC to the same oscillating voltage as the central electrodes. Cesium ions then drift freely into the trap. After trapping the plasma by returning the injection electrodes to their DC voltage, and allowing the plasma to evolve for a given trapping time, the other set of 40 cm long electrodes is switched from its DC voltage to the oscillating voltage to let the plasma exit the trap. The ions then freely stream out of the trap and the injection-trapping-dumping cycle is then repeated with excellent reproducibility.

A computer-controlled arbitrary function generator allows a broad range of waveforms $\pm V_0(t)$ to be considered that describe a variety of AG magnetic lattice configurations. For example, a periodic step-function waveform could be used to simulate transport through a so-called Focusing–Off–Defocussing–Off (FODO) lattice. For the experiments whose results are presented here, a sinusoidal waveform $V_0(t) = V_{0\ \max} \sin(2\pi f t)$ was used for simplicity. The nominal operating parameter are $V_{0\ \max} = 235$ V, $f = 75$ kHz, or equivalently $\omega_q = 6.5 \times 10^4$ s^{-1} and $\sigma_v^{sf} = 49.9°$, where σ_v^{sf} is the smooth-focusing vacuum phase advance.

The primary diagnostic used on PTSX is a 5 mm diameter copper collector disk that is held inside the dumping set of electrodes by a thin arm. The disk can be translated across the diameter of PTSX while always remaining in a null of the fully time-dependent applied potential. Taking advantage of the reproducibility of plasmas in the PTSX device, the collector is repositioned between injection-trapping-dumping cycles and a complete radial charge profile is measured. This is necessarily time-averaged radial profile because of the finite transit time of ions along the length of PTSX. The transit time of a thermal ion is on the order of 1 ms, which corresponds to 75 periods of the applied wall voltage when $f = 75$ kHz. The measured charge is converted into a number density by using the area of the collector and the length of the plasma column as determined by computer simulations [9].

WAVEFORM AMPLITUDE CHANGES

Previous PTSX experiments have explored the effects of adiabatic changes in the amplitude of the applied wall voltage $V_{0\ \max}$ [10]. In contrast, here the results of a set of experiments in which $V_{0\ \max}$ is instantaneously changed from V_1 to V_2 during a zero-crossing of the waveform is presented. After a given number N of half-periods of the sinusoidal voltage, the amplitude is restored to V_1. The nominal PTSX operating parameters are such that both $V_2/V_1 > 1$ and $V_2/V_1 < 1$ can be considered. By holding the frequency f fixed, note that both ω_q and σ_v^{sf} scale linearly with V_2/V_1. The plasma was trapped for 1 ms and the changes in $V_{0\ \max}$ were made at $t = 0.5$ ms. Subsequent experiments (not presented here) demonstrate that increasing the trapping time or altering the time at which $V_{0\ \max}$ is changed do not affect the results.

The expectation is that an abrupt change in $V_{0\ \max}$ will cause a degradation in the transverse confinement of the plasma. Although this expectation is born out in the data, the dependencies of the effect on V_2/V_1 and N are non-trivial, as discussed below. In these initial experiments, a measurement of the time-averaged on-axis plasma density is used as an indicator of the effect of the waveform modification on the plasma.

It might be thought, regardless of whether $V_2/V_1 > 1$ or $V_2/V_1 < 1$, that altering the waveform for a whole-cycle $(N = 2)$ would be more detrimental to plasma confinement than altering the waveform for only a half-cycle $(N = 1)$. However, a scan of V_2/V_1 over the range $0 < V_2/V_1 < 1.6$ shows that for $V_2/V_1 < 1$, changing the waveform amplitude for a whole-cycle is less detrimental to the time-averaged on-axis charge density (see Fig. 2). In all instances, however, the on-axis plasma charge density is reduced from its initial value.

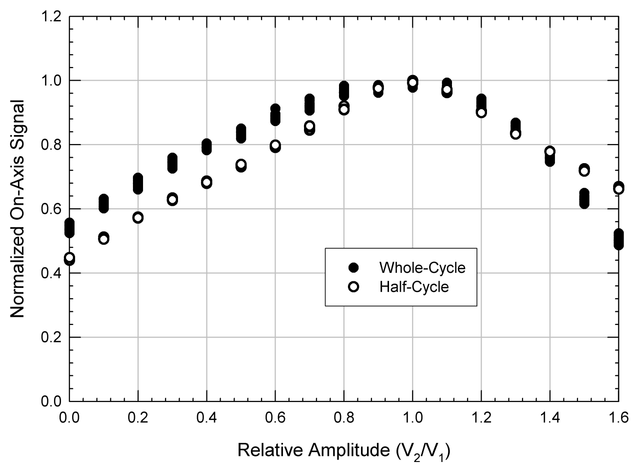

Figure 2: Whether changing the amplitude of the waveform for a half-cycle or for a whole-cycle decreases the on-axis charge density more depends on whether the amplitude is increased or decreased.

Having measured the effects of half-cycle and whole-cycle waveform amplitude changes over a range of values of V_2/V_1, the effect was then measured as a function of N. A discrete set of values for V_2/V_1 was chosen such that $V_2/V_1 = 0, 0.5, 0.7, 0.9, 1.1, 1.3$, or 1.5.

The data in Fig. 3 correspond to the case where $V_2/V_1 > 1$. For a 10% increase in the waveform amplitude, there is little impact on the time-averaged on-axis charge density. Ten whole-cycles with $V_2/V_1 = 1.1$ only decreases the time-averaged on-axis charge density by roughly 10%. Once larger values of V_2/V_1 are considered, it becomes apparent that there is an oscillatory behavior of the time-averaged on-axis charge density with N. For the case of $V_2/V_1 = 1.3$, there is a periodicity of approximately 1.5 cycles. For $V_2/V_1 = 1.5$, the periodicity is less clear. The origin of this oscillatory behavior is not understood.

The behavior for $V_2/V_1 < 1$, shown in Fig. 4, is qualitatively similar to that for $V_2/V_1 > 1$ in that a 10% decrease in V_2/V_1 causes little decrease in the time-averaged on-axis charge density and that larger changes in V_2/V_1

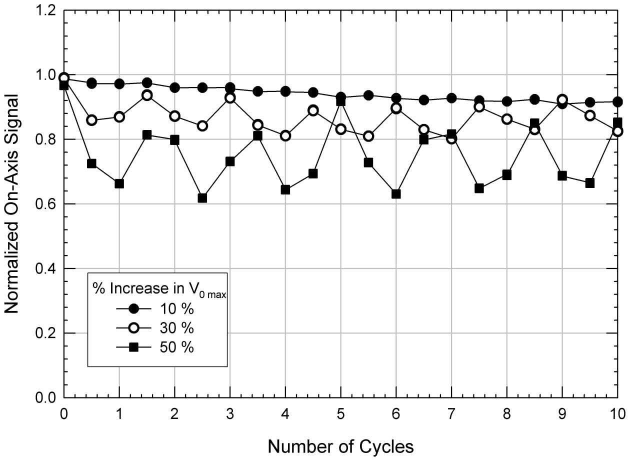

Figure 3: A 10% increase in $V_{0\ \mathrm{max}}$ has only a 10% effect over 10 whole-cycles. The time-averaged on-axis charge density exhibits an oscillation with the number of cycles.

exhibit an oscillatory behavior with N, although the oscillation period is hard to discern from the data. Note that the measurements for one half-cycle and one whole-cycle that are shown in Figs. 3 and 4 are consistent with the data in Fig. 2. Furthermore, note that for a 100% decrease, the applied waveform vanishes altogether and the timescale for the decay of the time-averaged on-axis charge density is consistent with the transit time for a thermal ion to reach the wall. Finally, the on-axis charge density does not completely go to zero even for 10 cycles, where there is no radial confinement at all.

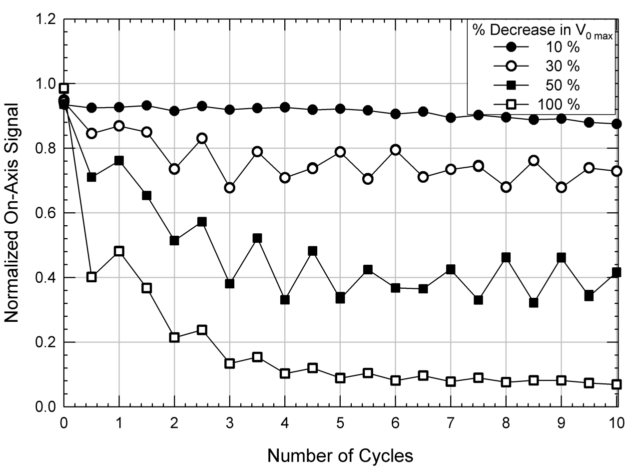

Figure 4: A 10% decrease in $V_{0\ \mathrm{max}}$ has only a 10% effect over 10 whole-cycles. The time-averaged on-axis charge density exhibits an oscillation with the number of cycles.

CONCLUSIONS

The Paul Trap Simulator Experiment provides a compact and flexible laboratory facility in which a wide range of important topics in the physics of intense beam propagation can be explored. Here, the results of a simple set of experiments have been presented in which the amplitude of the confinement waveform $V_{0\ \mathrm{max}}$ was changed for a discrete number of half-cycles of the waveform, and it is found that 10% changes decrease the time-averaged on-axis charge density by about 10% over ten whole-cycles. Larger changes in $V_{0\ \mathrm{max}}$ affect the system more, but not monotonically with the number of half-cycles N during which V_2 is applied. The reason for this oscillatory behavior is not presently understood.

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