MASKING THE PAUL TRAP SIMULATOR EXPERIMENT (PTSX) ION SOURCE TO MODIFY THE TRANSVERSE DISTRIBUTION FUNCTION AND STUDY BEAM STABILITY AND COLLECTIVE OSCILLATIONS*

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Abstract

A variety of masks were installed on the Paul Trap Simulator Experiment (PTSX) cesium ion source in order to perform experiments with modified transverse distribution functions. Masks were used to block injection of ions into the PTSX chamber, thereby creating injected transverse beam distributions that were either hollow, apertured and centered, apertured and off-center, or comprising five beamlets. Experiments were performed using either trapped plasmas or the single-pass streaming, mode of PTSX. The transverse streaming current profiles clearly demonstrated centroid oscillations. Further analysis of these profiles also shows the presence of certain collective beam modes, such as azimuthally symmetric radial modes. When these plasmas are trapped for thousands of lattice periods, the plasma quickly relaxes to a state with an elevated effective transverse temperature and is subsequently stable. Both sinusoidal and periodic step function waveforms were used.

INTRODUCTION

The Paul Trap Simulator Experiment (PTSX) is a compact and flexible laboratory facility that simulates the propagation of intense charged particle beams over thousands of lattice periods through magnetic alternating-gradient (AG) quadrupole transport systems [1, 2, 3, 4, 5]. The simulation experiments make use of the isomorphism between the transverse equations of motion for particles in the two systems [1, 6, 7]. The PTSX facility has been used to modify the transverse distribution function of the particles to investigate the effects of these modifications on the excitation of beam modes, and their effects on the stability and emittance growth of beams.

The PTSX device is a linear Paul trap confining a one-component plasma of particles with charge e_b, where the $e_b\vec{E}_\perp^{ext}$ force that the PTSX electrodes exert on the trapped particles is analogous to the $e_b\vec{v_z} \times \vec{B}_\perp^{ext}$ force that the AG system exerts on the beam particles in the beam frame, provided that long, coasting beams that are thin relative to the AG system magnet spacing are considered. The amplitude and frequency of the voltage waveform applied to the PTSX electrodes correspond to the quadrupole magnet strength and lattice spacing in the AG system. Further, the self-field forces in both systems can be described by scalar potentials that obey Poisson's equation.

PTSX

The PTSX device is a linear Paul trap constructed from a 2.8 m-long, $r_w = 10$ cm-radius cylinder that is divided into two 40 cm-long end cylinders and a $2L = 2$ m-long central cylinder [3]. All cylinders are azimuthally divided into four $90°$ segments so that when an oscillating voltage $V_0(t)$ is applied with alternating polarity on adjacent segments, the resulting oscillating transverse quadrupole electric field exerts a ponderomotive force that confines the plasma radially. To trap the plasma axially, the two end cylinders are biased to a constant voltage $\hat{V}$. Voltage waveforms with amplitudes up to 400 V and frequencies up to 100 kHz can be used. The trapping voltage is nominally $\hat{V} = 36$ V. The vacuum pressure of 5×10^{-9} Torr prevents neutral collisions from playing an important role in determining the plasma behavior.

A 1.5 cm-diameter aluminosilicate cesium emitter injects 3.1 V singly-charged cesium ions into the machine when a 1 V extraction bias is applied between the emitter and an acceleration grid. The ion source is situated inside of one of the 40 cm-long cylinders, and to inject a pure cesium ion plasma into the trap, the segments on this 40 cm-long cylinder are set to oscillate with the voltage $\pm V_0(t)$.

After trapping the plasma for up to 300 ms, the 40 cm-long cylinder on the opposite end of the PTSX device from the ion source is set to oscillate with voltage $\pm V_0(t)$, and the plasma streams out of the trap. Part of the exiting plasma is collected on a moveable 5 mm-diameter collector disk. The radial density profile is computed using the measured radial charge profile and knowledge of the area of the collector and the length of the plasma column [8]. Since the plasma ions can take several milliseconds to leave the trap, the measurements of trapped plasma transverse density profiles are necessarily averaged over hundreds of lattice periods.

In single-pass, streaming mode, the 40 cm-long electrodes oscillate with the voltage $\pm V_0(t)$ so that ions travel from the ion source directly to the collector disk. Increasing the bias voltage on the emitter surface while keeping

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the extraction voltage fixed allows the transit time $t_{transit}$ of the ions across the machine to be reduced.

Near the axis, the potential is quadrupolar and the average smooth-focusing frequency [9] of particles' transverse oscillations can be expressed for an applied voltage $V(t) = V_{0\ max} \sin(2\pi f t)$ as [1, 9]

$$\omega_q = \frac{8 e_b V_{0\ max}}{m_b r_w^2 \pi f} \xi, \qquad (1)$$

where $m_b = 133$ amu for Cs^+ ions. The factor ξ depends on the shape of the voltage waveform and $\xi = (2\sqrt{2}\pi)^{-1}$ for a sinusoidal waveform, while $\xi = (\eta/4)\sqrt{1 - 2\eta/3}$ for a periodic step function with fill-factor η corresponding to a FODO lattice. The smooth-focusing vacuum phase advance σ_v^{sf} is given by $\sigma_v^{sf} = \omega_q / f$ [3, 9]. The depressed tune is $\nu/\nu_o \sim 0.9$ in the experiments presented herein.

MASKED ION SOURCE EXPERIMENTS

The Paul Trap Simulator Experiment (PTSX) cesium ion source was fitted with a variety of masks (Fig. 1) in order to inject plasmas with transverse density profiles that were either hollow, off-center, or comprising five smaller beamlets [10]. Experiments were performed using both trapped plasmas and the streaming mode of PTSX operation. Transverse profiles of the streaming current were measured and measurements of the peak height and centroid of the current profiles serve as proxies for the behavior of certain beam collective modes, such as azimuthally symmetric radial modes. When plasmas injected from these masked ion sources are trapped for thousands of lattice periods, the plasmas quickly relax with only moderate growth of the effective transverse temperature and are subsequently stable until the end of the experiment.

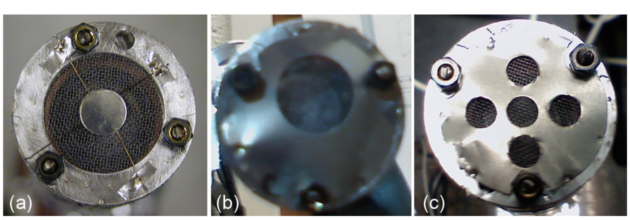

Figure 1: (a) Ion emission is blocked at the center of the ion source to inject hollow beams. (b) A mask with an off-axis aperture creates a beam that is injected off-axis. (c) A mask with five holes arranged in a quincunx pattern is used to study the effects of merging beamlets in a single transport line.

Figure 1 shows the three types of ion source masks that were used. Figure 1a shows a mask that blocks ions at the center of the ion source to create an injected ion distribution that is hollow. The mask shown in Figure 1b was installed to explore machine misalignments that may cause a beam to be injected off-axis. The mask shown in Figure 1c was installed to study the effects of merging multiple beamlets in a single transport line.

When the mask in Figure 1a is used to inject a hollow transverse beam distribution, the beam is hollow immediately after leaving the ion source. However, the individual particles' orbits oscillate back and forth in the transverse plane, across the beamline axis, with an average transverse angular frequency ω_q, or betatron frequency, that is determined by the applied PTSX electrode voltage and frequency. When the product $\omega_q t_{transit}$ is equal to an integer multiple of π then it is expected that the beam should again be hollow and the location of the collector disk.

An example of a hollow transverse beam profile is shown in Figure 2 where periodic step-function waves with amplitude near 90 V and frequency 90 kHz are applied to the PTSX transverse confwinement electrodes. The equivalent vacuum phase advance is 14 degrees, the transit of the beam particles from the ion source to the collector diagnostic occurs over 35.6 lattice periods, and therefore $\omega_q t_{transit} = 2.7\pi$. Although it is not fully understood why this two-peaked distribution does not occur when $\omega_q t_{transit}$ is an integer multiple of π, the data in Figure 3 show that the peak height of the measured transverse profiles has the expected periodicity of π as the PTSX electrode voltage is varied in order to vary the value of $\omega_q t_{transit}$.

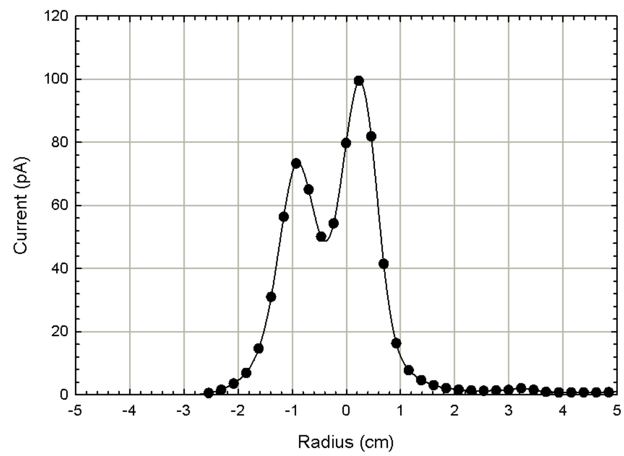

Figure 2: The transverse profile of the streaming ion axial current when an ion source mask hollows out the center of the ion beam during injection. For other system parameters, the measured profiles are broad and single-peaked.

When sinusoidal waves are used to drive the PTSX electrodes instead of periodic step-function waveforms, the experimental results are similar, but the data corresponding to that shown in Figure 3 contain other frequencies, and is thus more complicated to interpret. It is interesting to note that, when trapped, these initially hollow plasmas relax into nearly-gaussian transverse density profiles. Further, after 600 lattice periods, there is no particle loss, and only a 10% increase in the effective transverse temperature.

The mask shown in Figure 1b was used to inject plasmas that were off-axis. In this case, it was expected that the beam centroid should oscillate about the machine axis with

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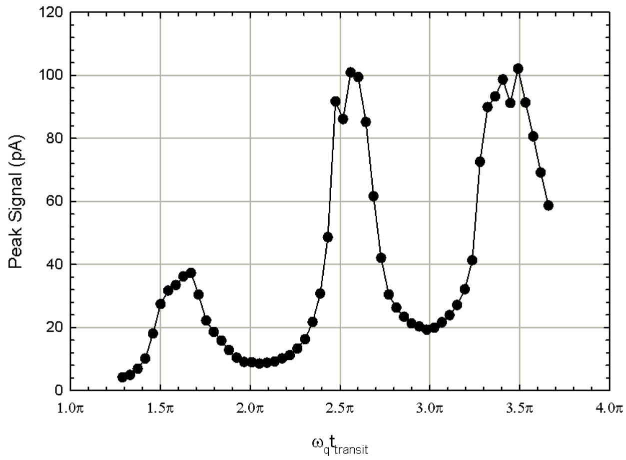

Figure 3: The peak height of the measured streaming current profile varies as the product $\omega_q t_{transit}$ varies. The data have periodicity π, which is expected if the transverse particle motion is described by the average transverse focusing frequency ω_q.

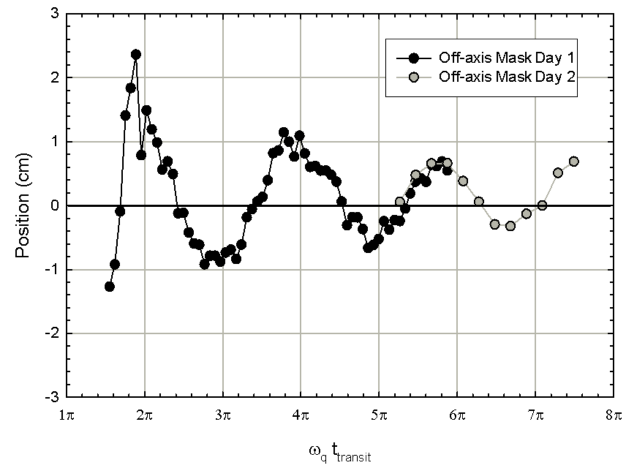

Figure 4: The center of the measured streaming current profile versus $\omega_q t_{transit}$ exhibits oscillations about the center with periodicity 2π.

an angular frequency ω_q. The data in Figure 4 show this effect clearly. For the data in Figure 4, sinusoidal waveforms with frequency 90 kHz were applied to the PTSX transverse confinement electrodes. The applied voltage waveform amplitude was varied from 50 V to 250 V so that $\omega_q t_{transit}$ ranged from 1.5π to 7.5π. The vacuum phase advance was 38 degrees at most. When plasmas were injected using this mask, and held for 6000 lattice periods, there was no particle loss, and a moderate increase in the effective transverse temperature of 38%.

When the mask with the quincunx hole pattern in Figure 1c was used, there was no observed structure in the measured streaming current transverse profiles that was attributable to the mask. Further, when plasmas injected using this mask were trapped for 6000 lattice periods, there was no particle loss, and only a 10% increase in the effective transverse temperature. Thus, for any of the three masks considered in these experiments, the initial plasma distribution is not so radically altered that long equivalent distance beam propagation is prevented. After a sufficiently long time, the trapped plasmas relax to near-gaussian transverse density profiles.

Finally, centroid oscillations similar to those in Figure 4 were observed even when well-centered masks in Figures 1a and 1b were used. In addition, a centered aperture with the same size opening as that in Fig. 1b was used and also resulted in centroid oscillations. This suggests that the PTSX ion source is somewhat misaligned relative to the central axis of the PTSX transverse confinement electrodes.

CONCLUSIONS

The Paul Trap Simulator Experiment (PTSX) cesium ion source was fitted with a variety of masks in order to study the effects of modifying the initial transverse distribution. Transverse profiles of the streaming current were measured and the data from these experiments exhibit centroid oscillations and variations in the peak height showing transverse oscillations with the expected frequencies. When plasmas injected from these masked ion sources are trapped for thousands of lattice periods, the plasmas quickly relax with only moderate temperature increases and are subsequently stable until the end of the experiment.

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