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Conditions for minimization of halo particle production during transverse compression of intense ion charge bunches in the Paul Trap Simulator Experiment (PTSX)

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Abstract

The Paul Trap Simulator Experiment (PTSX) is a compact laboratory Paul trap that simulates propagation of a long, thin charged-particle bunch coasting through a multi-kilometer-long magnetic alternating-gradient (AG) transport system by putting the physicist in the frame-of-reference of the beam. The transverse dynamics of particles in both systems are described by the same sets of equations—including all nonlinear space-charge effects. The time-dependent quadrupolar voltages applied to the PTSX confinement electrodes correspond to the axially dependent magnetic fields applied in the AG system. This paper presents the results of experiments in which the amplitude of the applied confining voltage is changed over the course of the experiment in order to transversely compress a beam with an initial depressed tune $v/v_0 \sim 0.9$. Both instantaneous and smooth changes are considered. Particular emphasis is placed on determining the conditions that minimize the emittance growth and, generally, the number of particles that are found at large radius (so-called halo particles) after the beam compression. The experimental data are also compared with the results of particle-in-cell (PIC) simulations performed with the WARP code.

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1. Introduction

It is important to develop an improved fundamental understanding of the influence of collective processes and self-field effects on the long-distance propagation of intense charged-particle beams through magnetic alternating-gradient (AG) transport systems [1–6]. This is motivated by the high beam intensities envisioned in present and next-generation facilities in fields such as heavy ion fusion, spallation neutron sources, high energy and nuclear physics, and ion-beam-driven high-energy density physics [7]. There is interest in fields such as fundamental nonlinear dynamics. The Paul Trap Simulator Experiment (PTSX) is an experimental facility that allows the propagation of intense charged particle beams over large distances to be studied in a compact and flexible laboratory experiment. Important scientific topics such as: beam mismatch and the dynamics of halo particles, conditions for quiescent propagation, collective mode excitation and control, and distribution function effects can be studied in PTSX [8–12].

In an intense charged particle beam, the effect of the beam's self-electric and self-magnetic fields cannot be neglected. The relative importance of these self-fields is described by the normalized intensity parameter $s = \omega_p^2/2\omega_q^2$, where $\omega_p^2 = n_b e_b^2/m_b\varepsilon_0$ is the plasma frequency-squared, which characterizes the strength of the self-fields, and ω_q is the average smooth-focusing frequency of the beam particles' transverse oscillations in the applied focusing field. Here, n_b, e_b, and m_b are the beam density,

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particle charge, and particle mass, respectively. When $s \ll 1$, the beam is emittance dominated, while $s \rightarrow 1$ implies that the beam is space-charge dominated. For a flat-top density profile, the normalized intensity s and the depressed tune ν/ν_0 are related by $\nu/\nu_0 = (1-s)^{1/2}$.

A linear Paul trap [13] confining a one-component plasma can be used to simulate the fully self-consistent transverse dynamics of a long, thin, charge bunch in the beam frame of an AG system because the particles' equations of motion are the same [14,15]. In the beam frame of the AG system, the spatially oscillating magnetic quadrupole fields become transformed into temporally oscillating electric quadrupole fields that have the same form as the oscillating electric fields applied in a linear Paul trap. The self-electric and self-magnetic fields of a long thin beam bunch can be described by a single scalar potential that obeys Poisson's equation, while the self-electric field of a trapped plasma naturally obeys Poisson's equation. The single-particle Hamiltonians, and therefore the resulting Vlasov equations for the two systems also have similar forms.

The voltage waveform amplitude and frequency applied to the electrodes of PTSX therefore correspond to the magnet strength and lattice spacing in an AG system. The long confinement times of plasmas in PTSX and the arbitrary form of the computer-generated voltage waveform make PTSX a flexible facility for studying intense beam propagation.

A brief description of the PTSX facility is given in Section 2. Section 3 discusses the minimization of halo particles that are produced by the mismatch between the ion source and the transverse confinement lattice. Further optimization of the injected plasma is described in Section 4. In Section 5, the results of experiments are presented in which the applied voltage waveform amplitude is changed in order to intentionally create a mismatch. Throughout this paper, comparisons are made with particle-in-cell (PIC) simulations using the WARP code [16].

2. Paul Trap Simulator Experiment

Fig. 1 shows a sketch of PTSX. The PTSX device [17–21] is a linear Paul trap constructed from a 2.8-m-long,

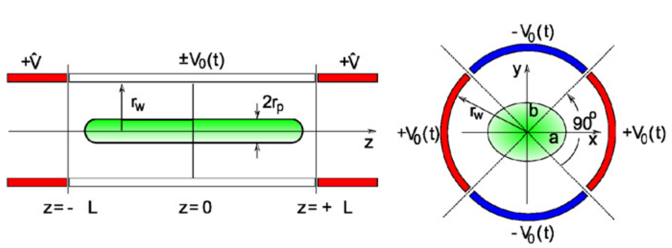

Fig. 1. PTSX is a cylindrical Paul trap that consists of a central confinement cylinder and a pair of shorter axial-trapping electrodes. The oscillating voltage applied to the four 90° segments creates a ponderomotive force that transversely confines the one-component cesium ion plasma.

$r_w = 10$-cm-radius cylinder. The cylinder is divided into two 40-cm-long end cylinders and a $2L = 2$-m-long central cylinder. 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 the plasma behavior.

The plasma source is a 1.5-cm-diameter aluminosilicate cesium emitter. Singly charged cesium ions are extracted by applying a bias of less than 10 V between the emitter and an "acceleration" grid. The ions then pass through a separately biased "deceleration" grid. The ion source is situated in the middle 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 temporarily set to oscillate with the voltage $\pm V_0(t)$. The injection time t_i is several milliseconds in order to allow cesium ions with several eV of kinetic energy to fill the trap.

After being trapped for a time t_t, that can be up to 300 ms, the 40-cm-long cylinder on the opposite end of PTSX 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 inject–trap–dump cycle is repeated to reduce the uncertainty in the data. The collector is moved in the transverse plane in order to collect a radial density profile of the trapped plasma. Note that since the plasma ions can take several milliseconds to leave the trap, the measurements are necessarily averaged over hundreds of lattice periods.

The circular cross-section of the PTSX electrodes allows the time-dependent electric potential to be calculated analytically [14]. Near the axis, the potential is quadrupolar and the average smooth focusing frequency of particles' transverse oscillations can be expressed for an applied voltage $V_0(t) = V_{0\max} \sin(2\pi f t)$ as

$$\omega_q = \frac{8 e_b V_{0\max}}{m_b r_w^2 \pi^2 f 2^{3/2}}. \tag{1}$$

The confining force must balance both the thermal pressure force of the charge bunch and its space-charge force. For a Maxwellian thermal equilibrium distribution, the global force balance equation can be written as [1]

$$m_b \omega_q^2 R_b^2 = 2kT + \frac{N_b e_b^2}{4\pi\varepsilon_0}, \tag{2}$$

where R_b is the root-mean-squared (rms) radius of the charge bunch, kT is the transverse temperature, and N_b is the line density.