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SELF BUNCHING, RF BUNCHING AND COOLING OF IONS IN AN ELECTROSTATIC ION BEAM TRAP

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Abstract

We describe the beam dynamics in an electrostatic ion beam trap (EIBT). The ion-ion interaction plays a crucial role in governing the beam dynamics in the trap. We show that the EIBT can serve as a unique device for phase space manipulation of the ions. Three important results are presented: 1. Self-bunching of ions where the ion-ion interaction which is a repulsive Coulombic interaction provides the necessary coupling to keep the ions synchronized, 2. RF bunching of ions, where the repulsive ion-ion interaction keeps the ion bunch localized in the RF bucket and suppresses the emittance growth, 3. Auto-resonance cooling of ions, where a slice from phase space is accelerated out and cooled by evaporation.

ELECTROSTATIC ION BEAM TRAP

Electrostatic ion beam trap is a unique and versatile device to store ion beam with no mass limit [1]. A schematic is shown in Fig. 1. The ions are trapped between two sets of mirror electrodes. The motion of ions is detected by the pickup electrode placed at the center of the trap. The inner electrodes for the two mirrors are at the ground which provides a filed free region in the trap. The ions dynamics in the trap are governed by the slip factor η,

$$\eta = -\frac{2E}{f}\frac{df}{dE},$$

where f represents the oscillation frequency of the ion trapped in EIBT with energy E. The trap can be operated in dispersive or self-bunching regime by changing the sign of the slip factor which is decided by the potential profile in the trap. An external time-dependent voltage can be applied to V_5 of the mirror electrode (see in Fig. 1). A bunch of positively charged SF_5^+ ions produced by the Even-Lavie ion source is accelerated to 4.2 keV, focused, and steered using the Einzel lens and XY deflector before being injected into the trap. The density of ions in the trapped can be monitored by adjusting the voltage on the entrance electrode V_P. The time signal obtained from the pick-up electrode is collected by a digitizer and analysed using Fourier transform to obtain the frequency distribution of the ions bunch. This trap is unique and different from the other storage rings or trap devices, since the ion density oscillates in the trap. A typical number of ions in a bunch in the field-free region is $10^5 - 10^7$. The ion density in the turning point can be ~10^3 orders higher than the field-free region. The ion-ion interaction (collisions) is important at the turning point and affects the beam dynamics in the trap. The ion-ion interaction also couples the transverse and longitudinal beam dynamics in the trap. The dynamics of ions in the trap can be simulated with a simulation technique based on particle-in-cell (2DCYLPIC). The simulation can consider the space charge effect and all the experimental results are well reproduced [2].

DISPERSION AND SELF BUNCHING

When a bunch of ions are injected in the EIBT, depending on the potential profile either it will disperse or stay localized in the trap. The dispersion and synchronization of ions in EIBT are studied very well with detail [3, 4]. A

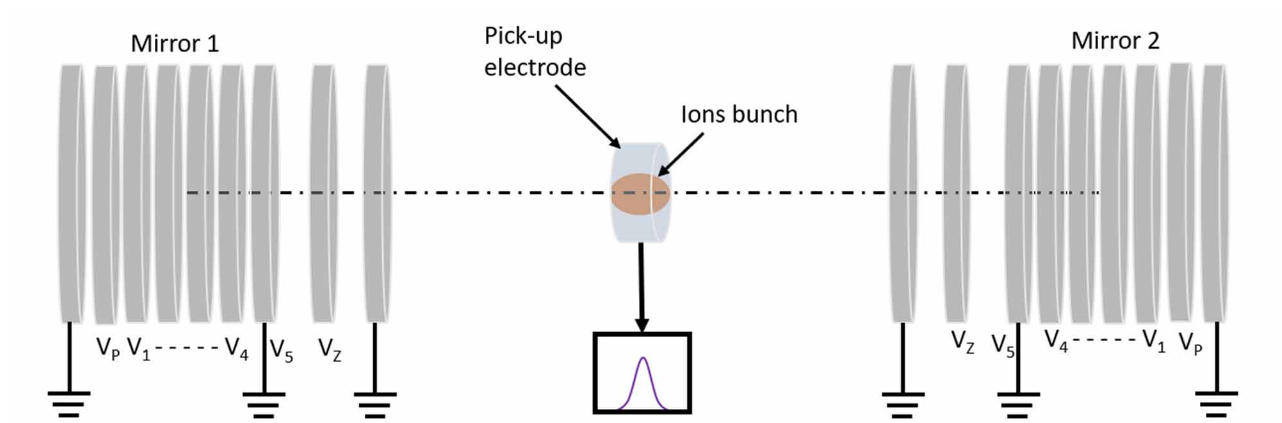

Figure 1: A schematic of electrostatic io beam trap. The ions are trapped between two sets of mirror electrodes and the passage of ions bunch is monitored by pick-up electrode.

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synchronization mode is: (V_P = 5.75 kV, V_1 = 6.5 kV, V_2 = 4.875 kV, V_3 = 3.25 kV, V_4 = 1.625 kV and V_Z = 3.4 kV) and (V_P = 4.05 kV, V_1 = 4.7 kV, V_2 = 4.875 kV, V_3 = 3.25 kV, V_4 = 1.625 kV and V_Z = 4.05 kV). When the trap is operated in the dispersive mode, the ion-ion interaction further increases the dispersion resulting in "enhanced diffusion" of ions. To keep the ions in the bunch, an external time-dependent field can be applied. This is addressed in the next section. The self-bunching of ions can be understood from the synchronization of ions in the EIBT. A non-linear interaction between two periodic systems that are oscillating with nearby frequencies results in synchronization. Inside the trap, the ions have a frequency distribution and strong ion-ion interactions in the mirror region provide the necessary coupling for synchronization. A one-dimensional analytical model for the self-bunching effect is described by Strasser *et al.* [5]. This effect is attributed to negative mass instability. A similar effect is observed in accelerators after the transition energy which results in a change in sign of slip factor.

RF BUNCHING

The most common technique to keep the ions in a bunch is RF bunching. An external time-dependent field is applied with the same frequency or high harmonics as the oscillation frequency of the ions. The synchronous particle is phase-matched (pi or 0) with the external (stationary RF bucket). The high-energy ions will be decelerated and vice versa. The ions will oscillate in the longitudinal phase space around the synchronous ions and stay localized. The separatrix defines the boundary in phase space where the ions with maximum phase offset will stay in closed orbit. The oscillation frequency, commonly known as the synchrotron frequency depends on the phase offset. The oscillation frequency decreases with increased phase offset. This non-linearity results in phase space filamentation. The area occupied by the ions in phase space can be estimated by root mean square (rms) emittance. The filamentation in phase space can be estimated by the increase in rms emittance.

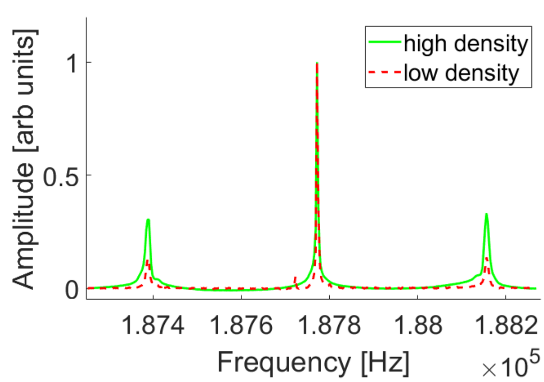

Figure 2: Experimentally observed FT spectrum for two different ion density when external RF field is applied.

When the trap is operated in dispersive mode, an external time-dependent field can be applied to one of the electrodes (V_5 in this case) for the entrance electrode.

The longitudinal motions of ions in the RF bucket result in additional side peaks in the FT spectrum obtained from the time signal from the pick-up detector [6]. If the RF bucket is uniformly filled, the height of the side peaks will be suppressed. The experimental results for RF bunching of ions in EIBT for two different ion densities are shown in Fig. 2. The relative height of side peaks is highly suppressed for low ion density resulting in a uniform distribution of ions in the RF bucket. Figure 3 shows the simulation results for relative emittance growth in the RF bucket for different ion densities. It is very counterintuitive that the emittance growth is suppressed for high ion density. The simulation results support the experimental observation.

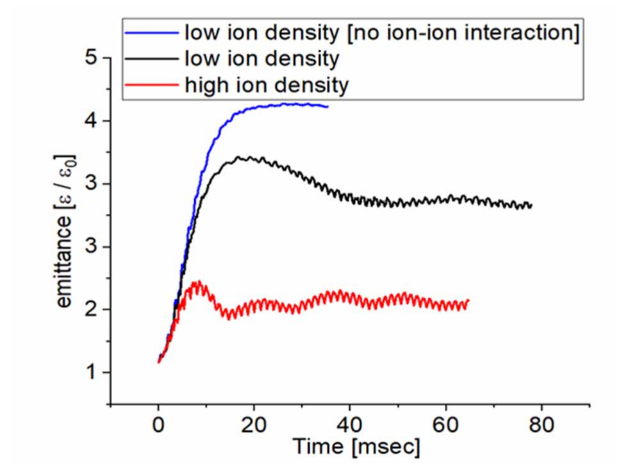

Figure 3: Emittance growth in RF bucket for different ion densities calculated from particle-in-cell (PIC) simulation.

The suppression of emittance growth for high intensity resembles the self-bunching effect in EIBT, the slip factor for the RF bucket has similar sign. A repulsive Coulombic interaction provided the necessary coupling to keep the ions localized in phase space [7].

AUTO-RESONANCE COOLING

In auto-resonance (AR), a periodic nonlinear physical system can be phase-locked with an external chirped driving force if the external force is adiabatic and exceeds a threshold value. An ion bunch injected in the trap will disperse after some time and the Schottky noise gives the initial frequency distribution of ions in the trap (black data point in Fig. 4). The spread in frequency distribution depends on the initial velocity distribution of ions in the trap determine the beam temperature. AR process has been demonstrated in an electrostatic ion beam trap where the beam temperature is reduced to well below 1 K [8].

Instead of applying a constant RF voltage, a chirped sinusoidal voltage is applied on V_5. In this process, a slice of phase space is accelerated out from the initial distribution. Depending on the amplitude and rate of the chirp voltage, one can control the final distribution of the ions. The ions that do not satisfy the AR condition evaporate and transfer momentum for cooling.

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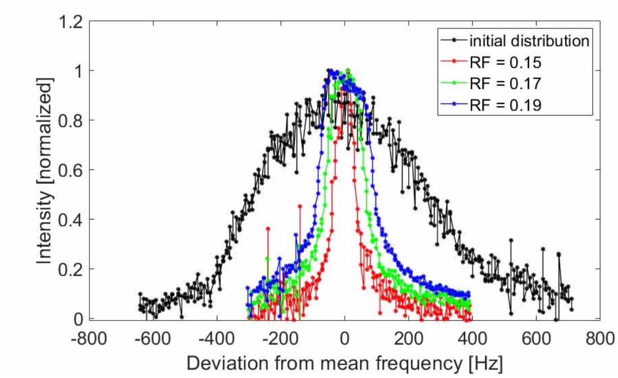

Figure 4: The frequency distribution of SF_5^+ ions in the trap. Black: the initial distribution of the ions. Red, Green, Blue: The distribution of dragged peak for different RF voltages.

Figure 4 shows the distribution of dragged peaks for different dragging voltages. The width of the frequency distribution shows the beam temperature. The sigma of the dragged peak increases linearly with an increase in dragged voltage. The amplitude increases linearly up to a certain voltage and does not change after that, showing that no more ions are lost from the dragged bunch. The dragged ion intensity shows a nonlinear dependence on the initial ion density. The ion-ion interaction strongly influences the AR process and influence the phase space density.

The distribution of the dragged peak on dragging voltage does not conform to the increase in phase space density (cooling). To demonstrate an increase in PSD, the amplitude of external voltage is decreased linearly during the AR process. For a constant sigma, the dragged peak can be increased which shows that more ions can be dragged to the same final position and velocity distribution. Different appsroaches can be used to show an increase in the phase space density along the AR process.

CONCLUSION

In summary, we have demonstrated the beam dynamics in an electrostatic ion beam trap. The ion density in the trap is not constant but keeps oscillating. The enhanced ion-ion interaction in the mirror region strongly influences the beam dynamics. The trap can be operated in diffusive or self-bunching mode. The dynamics of ions under an external time-dependent field are shown. The ions bunch stays localized in the RF bucket for high ion density. The ion temperature in the trap can be reduced to less than 1 K by a novel method of auto-resonance dragging of ions. In general, EIBT can serve as a tool for phase space manipulation of ions beam at low energy.

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