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Experimental simulation of beam propagation over long path lengths using radio-frequency and magnetic traps

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ABSTRACT

An overview is given of the novel beam-dynamics experiments based on compact non-neutral plasma traps at Hiroshima University. We have designed and constructed two different classes of trap systems, one of which uses a radio-frequency electric field (Paul trap) and the other uses an axial magnetic field (Penning trap) for transverse plasma confinement. These systems are called "S-POD" (Simulator for Particle Orbit Dynamics). The S-POD systems can approximately reproduce the collective motion of a charged-particle beam propagating through long alternating-gradient (AG) quadrupole focusing channels using the Paul trap and long continuous focusing channels using the Penning trap. This allows us to study various beam-dynamics issues in compact and inexpensive experiments without relying on large-scale accelerators. So far, the linear Paul traps have been applied for the study of resonance-related issues including coherent-resonance-induced stop bands and their dependence on AG lattice structures, resonance crossing in fixed-field AG accelerators, ultralow-emittance beam stability, etc. The Penning trap with multi-ring electrodes has been employed primarily for the study of beam halo formation driven by initial distribution perturbations. In this paper, we briefly overview the S-POD systems, and then summarize recent experimental results on resonance effects and halo formation.

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1. Introduction

There has been an increasing interest in applying high-intensity hadron beams for diverse purposes such as nuclear/particle physics, material sciences, neutron production, beam driven Warm Dense Matter (WDM) and High Energy Density Physics (HEDP), Heavy Ion Fusion (HIF), and other energy sciences [1,2]. Naturally, interparticle interactions are more enhanced as a larger number of charged particles are compressed into a limited space. Since the Coulomb force is long range, particles act in a collective manner influencing each other, and consequently, plasma-like collective modes of a beam become important to understand. Even at low intensity, the Coulomb coupling among particles can be strong when the beam kinetic temperature is small (i.e., "cold") [3]. Advanced cooling techniques are now making it feasible to generate an ultracold (or, in other words, ultralow emittance) ion beam whose temperature is close to the absolute zero [4–6]. In this context, it is increasingly important to understand space-charge driven collective modes in beams to fully ascertain limitations of future accelerator systems.

The origin of collective beam instabilities is the charge of individual particles forming the beam. There are a variety of complex collective phenomena including wake-field instabilities, beam–beam effects, electron cloud instabilities, and so on [7]. Among such collective phenomena, so-called *space-charge effects* (SCEs) induced solely by self-field Coulomb potential are most fundamental [8]. The Hamiltonian describing the SCE can be relatively simple because we need not consider effects such as impedances, wake fields, colliding beams, etc. For instance, the transverse motion of a coasting beam propagating through a linear quadrupole focusing channel obeys the Hamiltonian

$$H=\frac{p_x^2+p_y^2}{2}+\frac{1}{2}K(s)(x^2-y^2)+I\phi(x,y,s). \tag{1}$$

Here, the independent variable s is the axial path length along the design beam orbit, I is a constant associated with the particle species and beam energy, the linear transport lattice determines the focusing function $K(s)$, and the scalar potential ϕ satisfies the Poisson equation. In order to solve the Poisson equation, we need to know the distribution function $f(x,y,p_x,p_y;s)$ in phase space. Neglecting collisions between particles, the time evolution of f is governed by the Vlasov equation that explicitly depends on the Hamiltonian. We must, therefore, solve the Vlasov and Poisson equations simultaneously together with the Hamiltonian to elucidate

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the self-consistent collective behavior of the beam. Generally, this task is extremely difficult to carry out due to the highly nonlinear and finite geometry structure of the system. We are often forced to do numerical simulations with simplifying models, but reliable, high-precision simulations are still time-consuming and difficult to setup even with modern computers and simulation tools.

Systematic experimental studies of collective beam dynamics are also difficult. We always face a contradiction between practical and physical requirements; we are not allowed to lose significant numbers of particles in a high-power intense beam to avoid serious machine damage, but on the other hand, we have to use an intense beam to study SCE and sometimes even intentionally make it unstable and risk large particle losses to identify dangerous parameter ranges. Another problem is that the basic lattice parameters of accelerator transport lines are not very flexible. We cannot typically change the lattice structure once the machine is constructed. It is also difficult to obtain the detailed diagnostic measurements of the collective motion because the beam is traveling through the lattice of the machine in the laboratory frame and typical machines only have limited space for diagnostics. To overcome these difficulties in conventional accelerator-based experiments, an alternative approach was proposed over a decade ago [9]. The experimental method is based on the physical similarity between a charged-particle beam in the center-of-mass frame and a non-neutral plasma in the laboratory frame. It turns out that the transverse collective motion of a non-neutral plasma in a compact trap system is approximately equivalent to the beam–frame transverse motion of a charged-particle beam in an accelerator. Following this idea, we have constructed at Hiroshima University four tabletop systems dedicated to experimental beam-dynamics research [10–12]. Three of them are the linear Paul traps that employ a radio-frequency (rf) electric field to confine a large number of heavy ions [13]. The fourth is a Penning trap where an axial magnetic field is used for transverse particle confinement [14,15]. A second magnetic trap system is presently under construction. These very compact facilities at Hiroshima University are named “S-POD” (Simulator for Particle Orbit Dynamics). Another dedicated Paul trap facility called “PTSX” is being employed for beam-physics purposes at Princeton Plasma Physics Laboratory [16–18]. PTSX has a larger physical scale than the S-POD systems. A unique, compact storage ring “UMER” at Maryland University is an alternative scaled experiment worthy of attention [19]. Although UMER is not a plasma trap, the basic concept behind it is similar to that of S-POD and PTSX; namely, scaling motivates the use of electron ring to carry out relatively compact and low-cost experiments pertinent to the transport of intense hadron beams in large machines.

In this article, we outline the essence of S-POD experiments and briefly report on recent results. In Section 2, we outline the S-POD systems, showing rough sketches of both the rf Paul and magnetic Penning trap systems. Sections 3 and 4 are devoted to a summary of typical S-POD experiments that have been done for the last couple of years using the rf Paul traps and the magnetic Penning trap, respectively. Emphasis is placed in Section 3 on space-charge-induced resonance-related issues, and in Section 4 on mismatch-induced halo formation. Numerical simulation data obtained with the PIC code “Warp” are also given for comparison. Concluding remarks are made in Section 5.

2. S-POD systems

2.1. Radio-frequency confinement (linear Paul trap)

The structure of a typical linear Paul trap is simple. Four rod electrodes are placed symmetrically to produce a transverse electric quadrupole field. The voltages applied to the four rods vary periodically (or sinusoidally in many cases) to achieve strong transverse alternating gradient (AG) focusing of charged particles. An axial potential well is formed by DC voltages applied to separate electrodes sitting at both ends of the quadrupole section to provide axial plasma confinement. The transverse rf quadrupole focusing in the laboratory frame (the time-domain) has the same property as the discrete magnetic AG focusing in the beam frame (the *s*-domain) [9]. In fact, the Hamiltonian for the transverse motion of particles in the trap can be written as

$$H = \frac{p_x^2+p_y^2}{2} + \frac{1}{2}K_{\rm rf}(\tau)(x^2-y^2) + I_c\phi(x,y,\tau) \qquad (2)$$

where the independent variable is $\tau = ct$ with c being the speed of light *in vacuuo*, I_c is a constant, and the periodic function $K_{\rm rf}(\tau)$ is proportional to the quadrupole symmetric rf voltages applied to the rods. This Hamiltonian is identical to Eq. (1) as appropriate for linear quadrupole focusing except for the coefficients. As the Coulomb potential ϕ satisfies the Poisson equation and the plasma distribution function obeys the Vlasov equation analogously to a relativistic beam, we can make use of a non-neutral plasma in the Paul trap to study the nature of the equivalent dynamical system for beam systems governed by the Hamiltonian in Eq. (1).

We have constructed several Paul traps of different designs since the S-POD project was initiated about ten years ago. Unlike large-scale accelerator systems, the linear Paul traps are very compact and inexpensive. We can thus test the performance of one design and, in the event of any issues, slightly modify the electrode geometry or even replace the trap structure by a totally new one. Three Paul trap systems operate side-by-side in our laboratory for different beam-dynamics subjects. The operating rf frequency is typically set at 1 MHz or higher. The transverse clear aperture of the plasma confinement region bounded by the quadrupole rods is 10 mm in diameter. The maximum rf amplitude required for the full survey of the betatron tune space is only less than 100 V when we trap heavy ions as $^{40}\mathrm{Ar}^+$.

Fig. 1 shows a schematic drawing of a “multi-sectioned” Paul trap currently installed in the vacuum chamber of S-POD III. Other Paul traps for S-POD I and II have a similar structure. The quadrupole rods are divided into five axial segments, all of which are electrically isolated. By adding different DC bias voltages to the five segments, we can form several axial potential wells as illustrated in Fig. 1. The total axial length of the trap is about 20 cm and the quadrupole rods are 11.5 mm in diameter. The rod

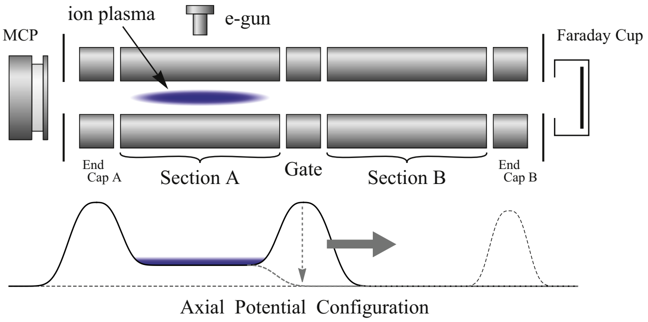

Fig. 1. Schematic of a typical linear Paul trap for S-POD. The quadrupole rods of the multi-sectioned Paul trap for S-POD III are divided into five electrically independent pieces. We can form two axial potential wells simultaneously by applying DC bias voltages to both the “End Caps” and “Gate” quadrupoles. We mostly confine ions in Section A above which an electron gun is installed for ionizing neutral gases. Ion plasmas are eventually detected either by a Faraday cup or by a micro-channel plate sitting on both sides of the trap. In order to use the Faraday cup for ion number measurements, the DC bias voltage on the Gate quadrupole is dropped to release the plasma from Section A. Section A is typically biased with a low DC voltage to accelerate ions toward the detector in the measurement process.

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