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Experimental verification of resonance instability bands in quadrupole doublet focusing channels

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ABSTRACT

The tabletop plasma trap experiment named "S-POD" is employed to explore the stability of intense charged-particle beams focused by a series of quadrupole doublet cells. S-POD is a compact linear Paul-trap, where we generate a single-species non-neutral ion plasma that can approximately reproduce the collective motion of an intense beam focused by periodic linear forces. Unlike conventional beam-dynamics experiments relying on large-scale transport channels and accelerators, it is straightforward in S-POD to control the functional form of quadrupole beam focusing over a wide range of variation to explore a variety of quadrupole focusing lattices. We systematically measure the loss rate of trapped particles as a function of bare betatron tune to locate resonance bands in which the plasma becomes unstable. It is confirmed that a few bands of coherent resonances appear depending on the beam intensity. When there is an imbalance between the horizontal and vertical focusing, those instability bands split. Experimental results indicate that the instability band is relatively insensitive to the phase of quadrupole focusing element placement within the doublet configuration over a significant range of parameters. Experimental observations are compared with transverse slice particle-in-cell simulations carried out using the Warp code.

1. Introduction

Almost all modern particle accelerator systems exploit the principle of strong focusing [1]. In strong focusing, both focusing and defocusing forces of the quadrupoles are employed in a manner where one can spatially confine a large number of charged particles more effectively than the case where only focusing forces are used [2–4]. The most standard strong focusing channel is the so-called "doublet lattice" in which the beam receives one linear focusing and one defocusing quadrupole kick alternately within the lattice period [5]. A special case of the doublet with equal length focusing and defocusing quadrupoles axially spaced equidistantly within the lattice period is called a "FODO" lattice. FODO lattices make the most efficient use of the quadrupole focusing strength, but have less free axial drift length within the period for other uses (pumping, diagnostics, etc.). Due to high focusing efficiency, quadrupole doublets are often adopted for beam transport channels and linear accelerators. Applications include a possible driver for Heavy Ion Fusion [6,7], drift tube linacs [8], and a non-scaling fixed field alternating gradient ring also consists of many doublet cells [9]. This widespread use makes it important to understand the collective instabilities of high-quality hadron beams propagating in long doublet channels. While there are a number of numerical and analytic works on this subject in past literature [1,10], little work has been carried out experimentally because of the practical reason of it being difficult to modify the form of the focusing lattice in usual accelerator transport channels. In S-POD, this practical difficulty for accelerator systems is inconsequential since different lattice focusing elements can be synthesized electronically, thereby allowing us to systematically explore a wide variety of changes in lattice focusing functions.

In this paper, we investigate space-charge effects in doublet focusing by employing a compact linear Paul trap system developed at Hiroshima University. Because the transverse collective motion of a non-neutral plasma in the trap is physically almost equivalent (beam–frame correspondence) to that of a charged-particle beam in strong focusing channels, we can use the trap to study transverse effects in beam transport [11]. The dedicated plasma trap system for beam physics applications is called "S-POD (Simulator for Particle Orbit Dynamics)" [12,13]. After outlining S-POD experiments in Section 2, numerical simulation data in which the actual Paul trap configuration has been assumed is presented in Section 3. Experimental results from S-POD are then

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described in Section 4 and compared with the numerical simulations. To systematically explore the stability of ion beams focused by a range of quadrupole focusing doublet lattices, we change the waveform of the plasma confinement field over a wide range. Concluding remarks are made in Section 5.

2. S-POD simulations of doublet focusing

Consider charged particles of mass m and charge state q confined in a linear Paul trap. The transverse collective motion of these particles is governed by the Hamiltonian

$$H=\frac{p_x^2+p_y^2}{2}+\frac{1}{2}K(\tau)(x^2-y^2)+\frac{q}{mc^2}\phi(x,y,\tau), \tag{1}$$

where ϕ is the scalar potential of Coulomb interactions among the particles, the independent variable is $\tau=ct$ with c being the speed of light *in vacuuo*, and $K(\tau)$ is the periodic focusing potential proportional to the radio-frequency (rf) voltages applied to the quadrupole electrodes. Eq. (1) is identical in form to the Hamiltonian for the transverse betatron motion of an intense beam propagating in a linear transport channel, which means that we can make use of a non-neutral plasma in the trap for the study of beam dynamics in alternating-gradient (AG) transport channels.

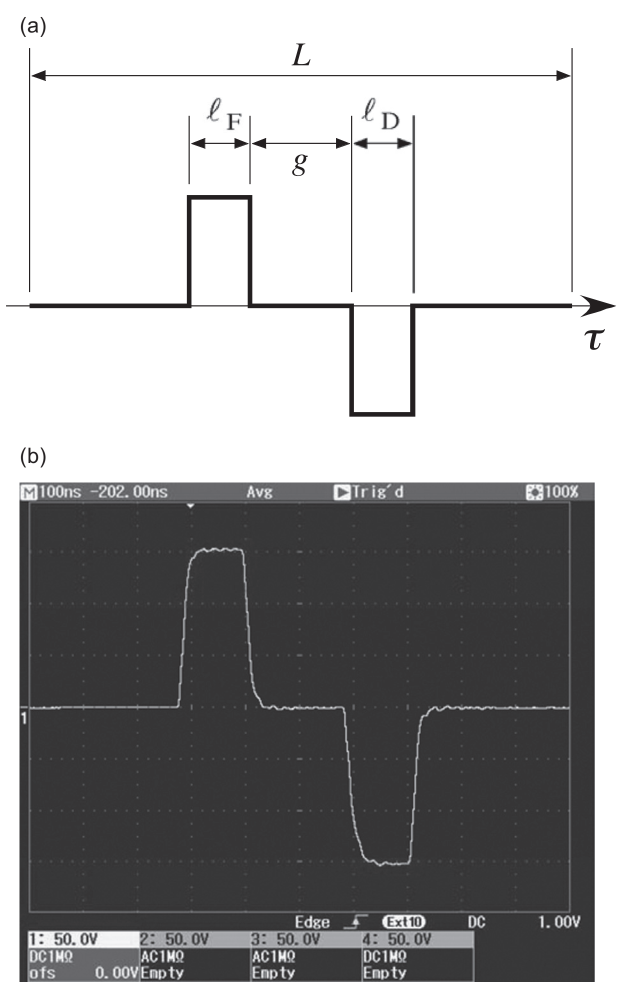

Fig. 1. Doublet waveform for transverse beam focusing. (a) Ideal focusing function $K(\tau)$ for a period L. The amplitudes of the two (focusing and defocusing) pulses are equal. (b) The corresponding measured rf voltage generated by the S-POD rf power supply system. The frequency is set at 1 MHz and the full width is 1μs.

Detailed design considerations of a compact Paul trap for S-POD can be found in previous publications [14,15]. A similar trap system for beam physics applications is also operating at Princeton Plasma Physics Laboratory where Gilson and co-workers have produced many interesting results [16–18].

Ideally, a step-function rf waveform as in Fig. 1(a) is desired to emulate piecewise-constant quadrupole doublet focusing in a Paul trap. Such piecewise constant models for $K(\tau)$ rather than a specific axial fringe function for a magnet focusing technology are often employed in analysis of beam transport in an "equivalent" sense to represent physical magnet lattices [19]. As displayed in Fig. 1(b), it is possible for the rf system of S-POD to approximately generate an rf waveform consistent with piecewise constant $K(\tau)$. We, however, experimentally observe that the maximum number of trappable ions tends to be lower with the step-function voltage, compared to confinement with a sinusoidally varying $K(\tau)$. The reason for this is presently unknown, but we suspect that low-frequency noise included in the applied periodic voltage may be responsible for the observed reduction in plasma density. In addition, the rise (and fall) time of a pulse voltage is limited to 10–20 ns in our rf system while the ideal pulse width for 50% filling is only 250 ns at the nominal operating frequency of 1 MHz. The ratio of the rise (fall) time to the pulse width becomes worse as we reduce the filling factor. Considering these technical issues, we here adopt a sinusoidal model; namely, we extract up to four fundamental Fourier harmonics from the ideal doublet waveform and apply them to the quadrupole electrodes. This model simplification is expected to have little effect on the basic mechanism of coherent resonances because the instability occurs when the frequency of a certain collective mode equals one of the driving harmonic frequencies of the applied focusing forces. It should not matter whether the driving force includes many other harmonics. The use of simple sinusoidal rf waves makes it much easier for us to design the necessary rf power-supply and control systems for systematic experiments.

For later convenience, we introduce several geometric parameters as illustrated in Fig. 1. We denote ℓ_F and ℓ_D as the widths of focusing and defocusing pulses in the horizontal x-direction. The amplitudes of the two square pulses are set equal. The distance between the focusing and defocusing pulses, i.e., the gap width, is denoted as g, and the length of the focusing period as L. The so-called *filling factor* (or *quadrupole occupancy factor*) is given by $\xi=(\ell_F+\ell_D)/L$. Another parameter of interest to us is defined by $\zeta=g/(L-g-\ell_F-\ell_D)$ that we refer to as the *drift ratio*. ζ measures the asymmetry of the gaps in the quadrupole doublet. $\zeta=1$ corresponds to a symmetric FODO. We consider only $\zeta\in[0,1]$ because cases with $\zeta>1$ can be mapped to $\zeta<1$ by simple phase redefinitions in the lattice. Expanding the doublet waveform as in Fig. 1 into Fourier series, we obtain

$$K(\tau)=\sum_{n=1}^{\infty}A_n\sin(2\pi n\tau/L+\alpha_n), \tag{2}$$

where A_n and α_n are the amplitude and phase of nth Fourier harmonic. In the present experiments, we pick a few of the allowed low harmonic Fourier components and apply them simultaneously to the quadrupole electrodes to see if any new stop bands appear depending on which harmonics are chosen. We have so far considered the case where the plasma is focused primarily by the first ($n=1$) harmonic that has the frequency of 1 MHz. The rf amplitude required for the full survey of the tune space set by the single particle (bare) tune ν_0 [1,10] is then less than about 93 V for Ar^+ ions. Other harmonics of higher frequencies are treated as perturbation due to a technical reason that limits the maximum amplitudes of these additional harmonic components [20]. The amplitude of each perturbation harmonic