

PLASMA TRAPS FOR SPACE-CHARGE STUDIES: STATUS AND PERSPECTIVES*

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Abstract

The beam physics group of Hiroshima University has developed non-neutral plasma traps dedicated solely to a wide range of beam dynamics studies. Those unique experimental tools approximately reproduce, in the laboratory frame, a many-body Coulomb system that is physically equivalent to a charged-particle beam observed from the center-of-mass frame. We have designed and constructed two different types of traps that employ either a radio-frequency (rf) electric quadrupole field or an axial magnetic field for transverse particle confinement. The former type is commonly referred to as a “linear Paul trap (LPT)” and the latter as a “Penning trap”. At present, three LPTs and one Penning trap are operational while a new Penning trap for beam halo experiments is under construction. Each of these compact experimental facilities consists of a trap, many power supplies, a vacuum system, a computer control system, etc., and is called “S-POD (Simulator for Particle Orbit Dynamics)”. S-POD is particularly useful for fundamental studies of high-intensity and high-brightness hadron beams. We here report on the present status of S-POD and also briefly describe some future plans.

INTRODUCTION

Recent worldwide demands for high-intensity and high-brightness hadron beams have made it more crucial to understand the mechanisms of the so-called “space-charge effects (SCEs)”. Naturally, interparticle Coulomb interactions become stronger as the beam density increases in phase space. The simple single-particle picture is no longer applicable, but instead we have to take the coupled motions of all particles carefully into account. The whole beam is then regarded as an extremely complex nonlinear object rather than a group of many independent particles.

There have been a number of theoretical and experimental studies of SCEs in the past [1,2]. A self-consistent analytic treatment of the collective beam behavior is, however, hopelessly difficult without simplifying assumptions and crude mathematical models. Numerical simulations are very popular these days, but we still need long CPU time for high-precision space-charge simulations even with modern parallel computers. Experimentally, poor controllability of lattice and beam parameters limits systematic SCE studies. Besides, high-power beam losses are not allowed in practice to prevent

serious machine damage, while we certainly need intense beams for space-charge experiments and even intentionally make them unstable to identify dangerous parameter ranges. Motivated by these facts, the S-POD project was initiated at Hiroshima University about a decade ago.

S-POD experiments are based on dynamical similarity between non-neutral plasmas in compact electro-magnetic traps and relativistic charged-particle beams in alternating-gradient (AG) focusing channels [3]. Four independent S-POD systems are presently in operation for systematic experimental studies of SCEs. This novel tabletop apparatus enables us to explore diverse beam-physics issues without relying on expensive, large-scale machines. In the following, we outline the recent S-POD status and space-charge experiments in preparation. More detailed information regarding how S-POD works can be found in previous publications [4-6]. Several technical issues required for further improvement of the S-POD performance are also addressed in this paper.

PRESENT STATUS

Paul Traps

S-POD I, II, and III employ LPTs whose typical operating frequency is around 1 MHz. Figure 1 shows the LPT currently installed in the vacuum chamber of S-POD III. Four electrode rods are symmetrically placed around the trap axis to produce an electric quadrupole field for transverse particle confinement. The rods are axially divided into several pieces (five in Fig. 1), so that we can apply different bias voltages to form axial potential wells. The total length of the LPT in Fig. 1 is only about 20 cm and the aperture size is 1 cm ϕ . The other LPTs used for S-POD I and II have roughly the same dimension. As the

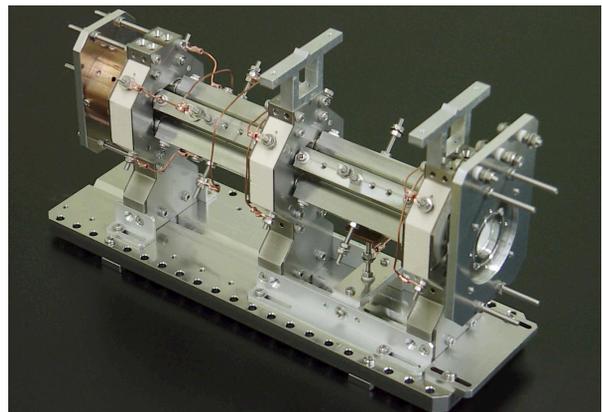


Figure 1: A multi-sectioned LPT for S-POD.

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cost of a Paul trap is very low (say, a few thousand US dollars at most), we have made nearly ten traps, each of which has a mechanical design somewhat different from the others. A research group from the Princeton Plasma Physics Laboratory has also built a beam-physics oriented LPT system where a sector cylinder, instead of quadrupole rods, is adopted for transverse plasma focusing [7,8].

We have usually used $^{40}\text{Ar}^+$ ions generated through electron bombardment processes. Other ion species can also be chosen if necessary. The possible space-charge-induced tune shift reaches 20% of the bare tune without cooling, which is sufficient for various SCE studies. As discussed later, it is even possible to achieve the 100% tune shift, in other words, the tune depression $\eta = 0$, by applying the Doppler laser cooling technique [9]. Another major advantage of S-POD experiments is high flexibility in the external focusing function. The transverse bare tunes are variable over the full range and, furthermore, we can emulate arbitrary periodic lattice structures simply by adjusting the waveform of the rf voltages applied to the quadrupole electrodes. We can thus investigate the collective behavior of an intense hadron beam propagating through a wide variety of AG transport channels. An example of a doublet waveform generated by the rf power source of S-POD II is displayed in Fig. 2. The waveform is easily controlled with the graphical programming tool “LabVIEW” [10].

In most of recent experiments, we have employed the sinusoidal-wave model for simplicity and technical reasons [5,11-13], instead of piecewise-constant rf waveforms as depicted in Fig. 2. The model is actually good enough to clarify the basic feature of collective resonances. So far we have concentrated upon resonance-related issues including collective stop-band excitation and its dependence on AG lattice characteristics, resonance-crossing effects, etc. Typical results of S-POD experiments with the sinusoidal plasma focusing are shown in Fig. 3 where the number of ions surviving after a 10-msec storage in a LPT is plotted as a function of the bare tune ν_0 per single focusing period. The 10-msec

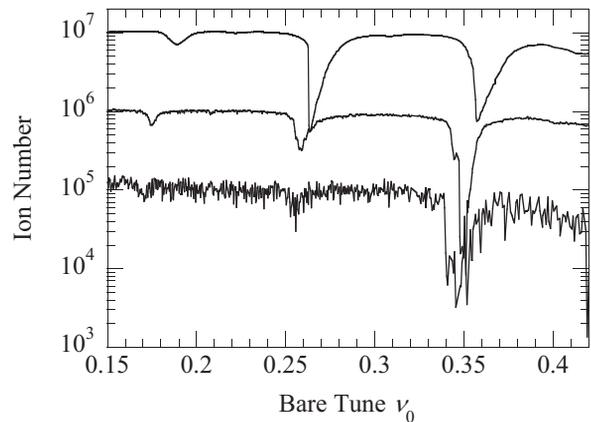


Figure 3: Resonance stop bands measured by S-POD III.

storage in the trap corresponds to beam transport over 10,000 doublet cells. Three different initial ion numbers (i.e., 10^5 , 10^6 , and 10^7) are considered to see density-dependent effects. As we increase the initial ion number, all stop bands shift to the higher tune side due to the space-charge-induced tune shift. This experimental observation agrees with numerical simulation results and can be well explained by a coherent resonance theory [14]. Needless to say, no damage is caused to the trap even if we lose all ions at a time. Note also that each line in Fig. 3 consists of 600 independent data points. The S-POD control system automatically executes a large number of systematic measurements without human intervention to retune fundamental parameters. It took us about 90 min to complete the 600 measurements for one line, which means that a single measurement cycle including data transfer to a PC takes less than 10 seconds.



Figure 4: The Penning trap for S-POD IV.

Penning Traps

S-POD IV exploits a Penning trap as shown in Fig. 4. The transverse linear focusing force is provided by a uniform axial magnetic field, while 45 ring-shaped electrodes aligned along the axis are used to form a longitudinal potential well. All these electrodes have the aperture of 7 cm in diameter and are electrically isolated so that we can put different DC bias voltages on them. Only electron plasmas are confinable for a sufficient period of time because of a limited magnetic-field strength (< 500 G). This Penning trap was originally

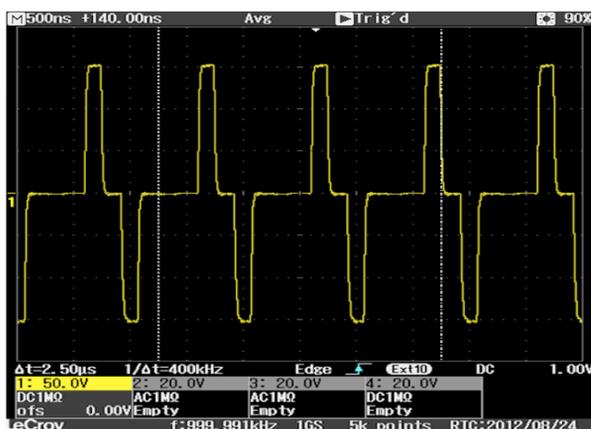


Figure 2: An rf waveform corresponding to a quadrupole doublet lattice.

developed for pure plasma-physics purposes more than ten years ago but is now applied especially for halo formation studies [12]. We have just started the construction of a new Penning trap where a much higher field (> 1 kG) is available for ion confinement.

The transverse spatial profile of a plasma can be measured at high precision with a CCD camera placed behind a phosphor screen. We have succeeded in observing halos produced by sudden disturbance to equilibrium electron plasmas. Figure 5 shows an example of a transverse plasma image on the phosphor screen. A thin but clear halo has been formed around the core exposed to an initial disturbance. Systematic experiments are in progress to reveal the detailed parameter-dependence of halo formation.

Some of the ring electrodes are azimuthally sectored such that we can introduce a periodic driving potential. Low-order resonances can thus be excited under a certain condition satisfied. Since resonance is known as a possible source of halo formation, it might be interesting to carry out similar profile measurements for plasmas on resonance.

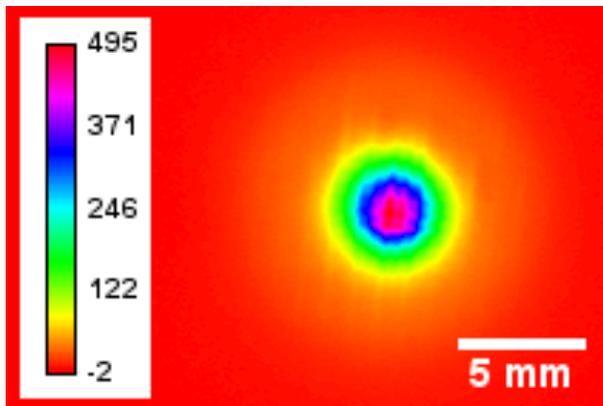


Figure 5: An example of the transverse spatial profile of a perturbed plasma core.

PERSPECTIVES

Possible Near-future Experiments

There are many important remaining issues that can readily be studied with S-PODs. For instance, in the previous resonance-crossing experiments [11], we only briefly investigated the effect from imperfection fields. Since error fields are inevitable in any real machines, accumulating more systematic data on error-induced effects is beneficial to design studies of not only fixed-field AG rings but also other types of accelerators. We are also preparing to excite dipole resonances that do not exist in a regular LPT. Artificial dipole excitation can be done by applying an rf voltage of a proper frequency to one of the four quadrupole electrodes. The LPT in S-POD III is being modified for such experiments.

By DC biasing two of the four electrodes of a LPT, we can realize asymmetric transverse focusing (while the horizontal and vertical bare tunes are equal in the regular operating mode). When the two tunes are different, stop-

band splitting occurs [13]. This is another topic that can be studied with only minor modifications to a LPT. S-POD II will be employed for this experiment to figure out how the distribution of resonance stop bands changes in tune space depending on plasma densities and external AG focusing waveforms.

The spatial configurations of ion plasmas confined in the currently-used LPTs are more or less like a long bunch. Since we are particularly interested in transverse beam dynamics at this early stage of S-POD experiments, all LPTs have been designed such that the longitudinal dynamics does not play an essential role. After on-going and planned experiments as mentioned above are completed, we will proceed to short-bunch experiments in S-POD II and III. The axial length of an initial equilibrium plasma can be reduced simply by replacing the long quadrupole rods by shorter ones. A new multi-sectioned LPT whose electrodes are axially sliced into many pieces just like the ring electrodes in the Penning trap is under consideration for more flexible control of the bunch aspect ratio [15].

The longitudinal plasma confinement is presently achieved with a static potential well formed by DC bias voltages on short quadrupole rods (see Fig. 7). No resonance then occurs in the axial direction. Synchrotron resonances can easily be excited by introducing periodic modulation to the potential well. It should be meaningful to perform all kinds of S-POD experiments with and without the periodic axial driving force.

Danilov and Nagaitsev recently proposed a novel beam-transport technique based on highly nonlinear lattices [16]. Their “integrable” nonlinear optics has a possibility of mitigating collective beam instabilities because of a large artificial tune spread that probably enhances the Landau damping mechanism. A proof-of-principle experiment of this idea may be feasible with a modified LPT that has more than eight electrode rods for nonlinear driving-force excitation [17]. Particle-in-cell simulations are in progress to confirm how much the nonlinear integrable confinement can improve the plasma stability.

As for the Penning-trap experiments, we still need more data to clarify the parameter-dependence of halo formation from a mismatched plasma core. Recent experiments with S-POD IV suggest that the amount of halo particles kicked out of a perturbed core may be dependent on how we trap electrons from an e-gun at the beginning. Those experimental observations will be double-checked soon with the new Penning trap (S-POD V) under construction. It is also practically important to develop a reliable way of estimating the halo intensity. Supporting numerical simulations or high-precision measurements of electron distributions in phase space would be helpful to define a halo.

In a high-intensity linac for heavy-ion inertial fusion, strong longitudinal bunch compression must be done for efficient pellet implosion [18]. A previous numerical study indicates a possible halo formation during the bunch compression process [19]. Our Penning trap is

applicable to this subject because we can quickly compress an electron bunch by controlling the bias voltages on the ring electrodes.

Diagnostic Issues

Each S-POD system is equipped with a Faraday cup and a micro-channel plate (MCP) with a phosphor screen to obtain the information of plasma stability. Although these diagnostic tools suffice for identifying possible instabilities and halo formation at high accuracy, it would certainly be informative if we can measure the momentum (velocity) distribution of particles as well. A couple of new emittance monitors are under consideration. The use of a movable pinhole together with a phosphor screen is probably the easiest way to probe the phase-space configuration of a plasma. Given the size and position of the pinhole, we can deduce the transverse emittance from the plasma image on the screen. Another method more sophisticated than destructive pinhole measurements is the laser-induced fluorescence (LIF) diagnostics. The Doppler laser cooling systems already available in S-POD I and II can be employed for LIF measurements. Our laser systems are designed for $^{40}\text{Ca}^+$ ions whose transition wavelength to an excited state is 397 nm. Fluorescence photons are emitted only from the ions resonant with the laser photons. Since the laser frequency seen from each individual ion depends on the ion's axial velocity due to a finite Doppler shift, we can obtain both spatial and momentum distributions of the ions simultaneously by sweeping the laser frequency.

Unlike $^{40}\text{Ar}^+$ ions, we have to switch on an atomic oven to produce $^{40}\text{Ca}^+$ ions. Neutral Ca atoms from the oven are ionized by low-energy electrons from an e-gun. The number of Ca^+ ions confinable in our current apparatus is not as large as that of Ar^+ ions [20]. $^{40}\text{Ca}^+$ plasmas have, therefore, been employed only for the study of low-intensity but very high-quality (ultralow emittance) beam dynamics. We are planning to test the plasma stacking scheme as explained later, to increase the line density of $^{40}\text{Ca}^+$ ions for high-intensity beam studies. How to estimate the precise axial distribution and tune depression of a short bunch is also an important issue. We currently rely on numerical simulations to obtain these pieces of information.

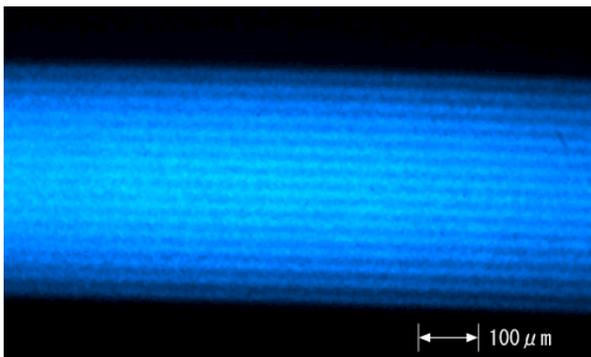


Figure 6: A zero-emittance ion plasma (a Coulomb crystal of $^{40}\text{Ca}^+$ ions) generated in S-POD I.

Plasma Density Control

For future advanced experiments on highly space-charge-dominated hadron beams, it is crucial to establish a supreme controllability of the root-mean-squared (rms) tune depression η . For $^{40}\text{Ar}^+$ plasmas, the lowest η achieved in past experiments is around 0.8. This number can readily be overcome by using the laser cooling technique. The Doppler limit for $^{40}\text{Ca}^+$ ions is below 1 mK, which makes it possible for us to cover the whole range of rms tune depression from 1 (high temperature) to 0 (ultralow emittance limit).

Near the zero-emittance limit where $\eta = 0$, the plasma is Coulomb crystallized; all ions are arranged into a spatially ordered state depending on the line density [21]. Figure 6 is a picture (fluorescence image) of a multi-shell Coulomb crystal generated in S-POD I by Doppler cooling. This result is clear proof that we can actually reduce η to zero in S-POD experiments. A question now is whether we can adjust η to an arbitrary value between 0 and 1. In principle, this task is not too difficult to carry out. The equilibrium temperature of a $^{40}\text{Ca}^+$ plasma after cooling should be controllable by choosing a proper final detuning of the laser frequency. In the experiment of Fig. 6, the laser frequency was fixed near the optimum value required to reach the Doppler limit. For the control of η , we start from a much larger detuning, decrease it gradually, and stop the frequency sweep when the detuning comes to the value corresponding to a specific plasma temperature (higher than the Doppler limit).

Before testing the proposed η -control scheme, it would be necessary to demonstrate that we can confine a very large number of $^{40}\text{Ca}^+$ ions. One of practical solutions to this issue is illustrated in Fig. 7. Since the quadrupole rods of our LPT are axially divided into several pieces (five pieces in the picture), it is straightforward to form a complex potential well as shown in Fig. 7(a) by biasing those quadrupole sections with different DC voltages. In the picture, ions are generated in “Section A” above which an e-gun is placed. In order to increase the line density of a $^{40}\text{Ca}^+$ plasma dramatically, we open the “Gate” dropping the DC potential on it. Ions then flow into “Section B” but are reflected back by the potential barrier at the right end of the trap. While ions go back and forth between the “End Caps”, we keep irradiating a cooling laser to decelerate as many ions as possible. The e-gun is also kept on to continuously generate ions. The laser detuning is repeatedly swept over a proper range or fixed at an optimum value such that the number of coolable ions becomes maximum. Those decelerated ions no longer come back into Section A but are accumulated within Section B. As the ions stored in Section B are colder than those coming in from Section A, we can even anticipate the sympathetic cooling effect that improves the capture efficiency of $^{40}\text{Ca}^+$ ions in Section B. In such a way, the initial line density of $^{40}\text{Ca}^+$ ions could be made much higher than now, which enables us to employ this ion species for a wider range of beam-dynamics studies.

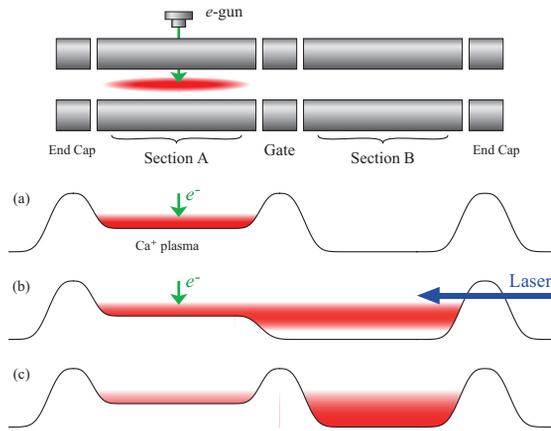


Figure 7: A possible plasma stacking scheme for laser-coolable ion species.

SUMMARY

A unique experimental approach based on non-neutral plasma trapping techniques has been developed at Hiroshima University to study collective effects in high-intensity and high-brightness hadron beams. Unlike any conventional approaches, the new method is totally free from complex large-scale machines and thus provides very compact, flexible experimental environment indispensable for systematic SCE studies. The whole system is named “S-POD” where we can approximately reproduce the collective motion of a space-charge-dominated beam travelling through a long AG transport channel. A series of S-POD measurements are completely automated, which allows extremely fast acquisition of fundamental SCE data. Each measurement procedure typically takes only a few seconds even if beam propagation over millions of AG focusing cells is experimentally simulated. The achievable rms tune depression reaches 0.8 in a LPT without any pre-conditioning of ion plasmas. So far we have applied four independent S-POD systems for diverse SCE studies. S-POD I, II, and III make use of multi-sectioned LPTs to explore resonance-related issues. Since the cost of such a compact LPT is quite low, we can prepare many LPTs of different designs for different purposes, if necessary. A Penning trap with multi-ring electrodes is used for S-POD IV where halo-formation experiments are in progress. S-POD V with a new Penning trap is now under construction.

We are going to test the plasma stacking scheme for the generation of intense $^{40}\text{Ca}^+$ plasmas. The use of $^{40}\text{Ca}^+$ ions will considerably widen the range of possible S-POD experiments due to the applicability of the LIF diagnostics and Doppler laser cooling. We also plan to examine the dependence of SCEs on AG lattice structures in more detail. In particular, we are interested in resonance crossing over dipole and error-induced stop bands.

Although we have presently focused on transverse SCEs expected in intense long bunches, S-PODs can

easily be adapted for short-bunch experiments. We will soon assign one or two of the S-PODs to study SCEs in short bunches with various aspect ratios. Synchrotron resonances, synchro-betaatron coupling, and longitudinal bunch compression are also within the scope of future S-POD experiments.

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