

Plasma response to a variable electric multipole configuration

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I. Introduction

Charged particle traps are important tools for studying basic properties of atomic systems. Paul and Penning traps, and combinations thereof, can confine small numbers of particles over long timescales, by producing a potential energy minimum in which particles are stably confined [1]. With increasing trapped particle density, space charge can degrade confinement by decreasing the effective potential well depth. The present study explores whether it is possible to improve on the space charge limit in a Paul trap-type device by neutralizing the charge—that is, by loading the trap with quasi-neutral plasma instead of single or multiple species of the same charge. Single species trapping is a well-established and thoroughly investigated topic; the trapping of plasma has rarely been considered, and mostly for specific applications such as antimatter storage [2].

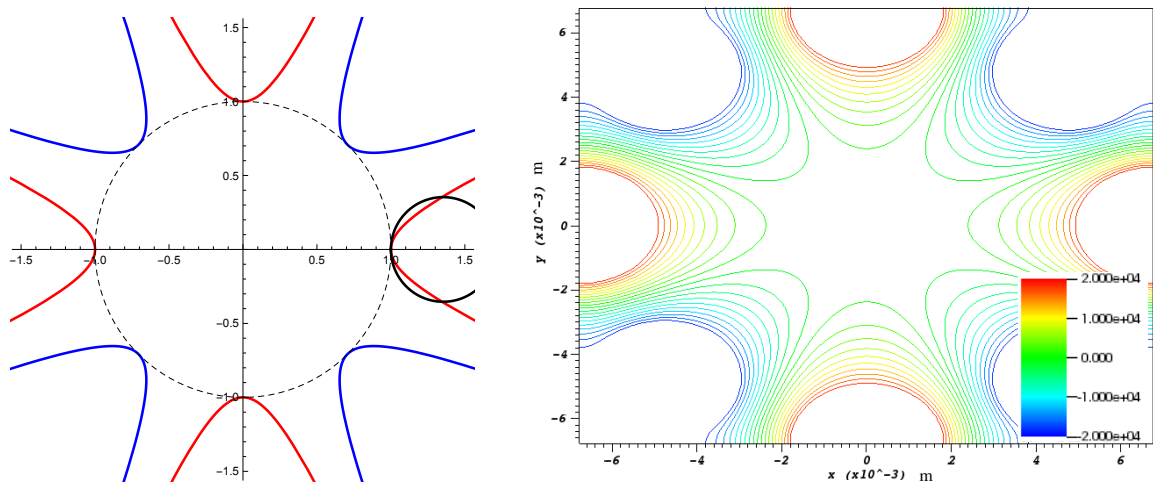


Fig. 1: Transverse cross sections of a linear multipole of order 4 (octupole). Left: Neighboring rods have opposite polarity RF voltage applied. The circular multipole aperture is shown (dashed), with the axes normalized to the aperture radius a_0 . A representation is shown of a circular rod (solid circle) of the type sometimes used for convenience to approximate the ideal hyperbolic equipotentials. Right: The equipotential contours produced by such an octupole, with circular electrodes as in the simulation work to be described; note the relatively large “field-free” region at the center of the trap.

Charged particles cannot be trapped in 3D by a static electric field (Earnshaw’s theorem). However, in a device with a spatially inhomogeneous external electric field that also varies in time, particles can experience a net restoring force toward the center. To achieve this, the equipotential surfaces generally should have a 3D saddle point at the center,

and the time variation repeatedly flips the polarity of the saddle. Charged particles experience alternating focusing and defocusing forces with time. Because the focusing phase results in the particle moving closer to the center of the trap, where the field is weaker, the subsequent defocusing phase is relatively weaker, and the net effect is to restore the particle to the center. This is the principle of *strong focusing*, used also in particle accelerators and quadrupole mass spectroscopy. A quadrupole electrode geometry is often chosen, because it is well-described analytically and has simple periodic particle orbits; however, higher order multipoles—a subject of this study, see Fig. 1—stably trap particles as well, and have the advantage of a larger “field-free” region.

For particles to be stably trapped by a quadrupole field, the trap voltage and driving frequency must be chosen corresponding to the condition on the stability parameter $Q = 2 \frac{qV_0}{ma^2\omega^2} < 1$, where q/m is the particle charge-to-mass ratio, and the other parameters characterize the applied electric field (V_0 is electric quadrupole voltage, a is quadrupole radius, and ω is the field oscillation frequency.) An approximate transverse (radial) potential well depth for a 3D (Paul trap) quadrupole is given by $D = 1/8 Q V_0$, (note this leads to a strong dependence on V_0).

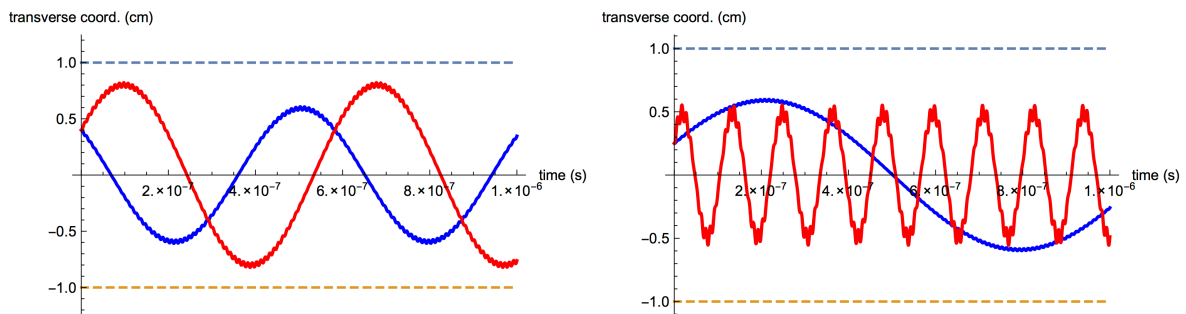


Fig. 2: Left: An RF quadrupole strongly focuses particles within a range of charge-to-mass ratios, irrespective of sign; here, two particles with equal mass but opposite charge, and with the same initial position and velocity, are both stably trapped transverse to the quadrupole axis. The difference in trajectory arises due to the opposite direction of force initially experienced by the particles. The two distinct frequencies of oscillation are observed: high frequency RF jitter superimposed on low frequency “secular” oscillation due to harmonic motion in the effective potential well of the trap. Right: When the particles’ charge-to-mass ratio differs, both particles may still have stable trajectories—here the light particle’s mass has increased by a factor of 5, and the heavy particle’s mass has decreased by a factor of 2. The light particle is more strongly focused, resulting in higher frequency secular motion.

As the trapped particle density increases, space charge repels particles from the trap center, limiting the attainable trapped density. Consideration could be given to neutralizing, for example, a positive ion distribution by adding electrons. But if the trap is stable for the

relatively heavy ions ($0.1 < Q_i < 1.0$), the electrons will be unstable ($Q_e > 100$) and will be immediately ejected from the trap. If, on the other hand, the trap is designed to be stable for electrons, then ions will have $Q_i \approx 0$ —they are too massive to respond on the timescale of the trapping field, and will be neither stabilized nor destabilized by the trap (see Fig. 2). A representative effect of space charge on particle trajectories is shown in Fig. 3.

If the electrons, then, are stably trapped, the positive ions will themselves be confined by the trapped negative space charge. If a trap is loaded with quasi-neutral ion-electron plasma of finite temperature, it is expected that the light species will initially expand faster than the heavy species, and ambipolar diffusion will then occur. The potential in the bulk plasma takes on the sign of the heavy species. The influence of the trap, though, is to restore the light species to the center; when this occurs, the density of the light species will now exceed that of the heavy species in the bulk plasma and a potential well will form. The heavy species becomes trapped by this well. The light species sees the effective trapping potential plus the space charge potential; the heavy species sees only the space charge potential since its inertia reduces its effective trapping potential close to zero.

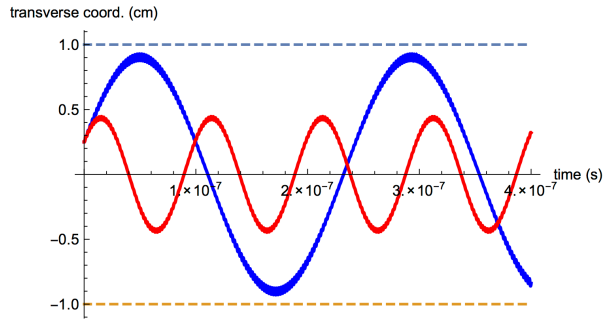


Fig. 3: Space charge due to raising RF quadrupole electron density from zero to $2.1 \times 10^{12} \text{ m}^{-3}$ decreases trapping strength; larger amplitude, lower secular frequency trajectory results.

II. Simulations

To test the hypothesis of the preceding section, particle-in-cell simulation using the VSim 7.2 code from Tech-X Corp. has been performed. A linear RF multipole with $V_0 = 5.0$ kV, $f = 100$ MHz, $a = 0.5$ cm is simulated in 2D, with a time step = 0.5 ns (or 1/20 the RF period), 100 particles per cell, and 250 cells spanning each transverse dimension. The essential points can be investigated in 2D, which makes simulations quick to run for testing various parameters and reduces needed computing resources.

In order to resolve the light species motion without having lengthy simulation runs to capture the heavy species motion, a mass disparity for the simulated plasma of $m/m_+ = 10$ is chosen; this is sufficient to preserve the essential quality that would apply to an ion-electron plasma, i.e. that the heavy species is negligibly focused compared to the light species. A multipole of order 8 (16 electrode poles) is chosen to demonstrate the feasibility of this type of configuration, with the imparted benefit of a larger trap-field-free volume due to the

steeper trap potential well with increasing multipole order. Fig. 4 shows an example of simulation results from this configuration, confirming the ability of the multipole field to stably trap the quasi-neutral plasma of disparate mass. For comparison, with the same configuration but zero RF voltage, the plasma was quickly lost from the trap by ambipolar diffusion (over 50% particle loss by 1.2 μs).

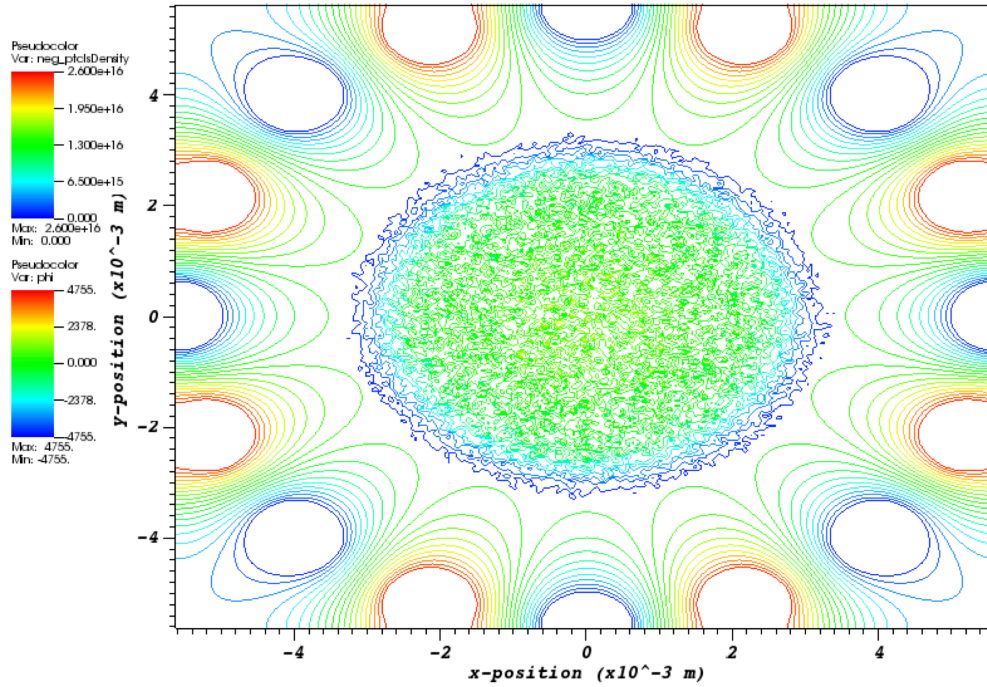


Fig. 4. Simulation results at 17.2 μs (1720 RF periods). Particle density and electric potential contour plots are superimposed showing multipole potential bounding trapped plasma. Initial Gaussian density profile has evolved to be sharply bounded, with nearly uniform density.

III. Discussion

Additional simulations of ion-electron plasma will be performed to explore the trapping effect with even higher mass disparity. Laboratory experiments to test the multipole plasma trap concept are in preparation. An ultra-high vacuum chamber is in place and operational, RF power equipment is on hand, and plasma sources and diagnostics are under construction. The simulation work will guide the choice of experimental trap parameters, such as multipole order, frequency, voltage, aperture radius, and particular 3D geometry. Further simulations will also explore the addition of an external magnetic field, and the transition to higher plasma density such that the driving frequency and plasma frequency become comparable, $f \sim f_p$.

References

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- [2] J. Walz, S.B. Ross, C. Zimmermann, et al., Phys. Rev. Lett. **75**, 3257 (1995)

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