Achieving pure electric confinement of high-charge-state plasmas

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In this Brief Report, a confinement physics analysis presented previously [D. D. Dolliver and C. A. Ordonez, Phys. Rev. E **59**, 7121 (1999)] is extended to consider three-dimensional electric confinement instead of one-dimensional electric and two-dimensional magnetic confinement for thermal, high-charge-state ion plasmas in nested-well solenoidal traps. Self-consistent numerical results are presented.

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Penning traps are typically used to confine fully non-neutral plasmas with only a single sign of charge [1]. More recently, Penning traps having nested, oppositely signed, electric potential wells have been studied for confining oppositely signed overlapping plasma species [2–4]. One experiment involving electrons and ions has been reported [5]. In a previous analysis, use of a nested Penning trap for confining overlapping electron and high-charge-state ion plasmas was considered [4]. In that analysis, the applied electric potential confined both plasma species axially, and a uniform magnetic field throughout the trap provided radial confinement of each species. The overlap region was considered to be neutral. Here, an extension of that work is presented in which a denser electron plasma creates an overlap region with an overall negative space charge. Ion confinement in both the radial and axial directions is brought about by a three-dimensional electric potential well created by the region of negative space charge together with the applied electric field. It should be noted that radial magnetic confinement is possible only for particles with a cyclotron radius smaller than the trap inner radius. Because they have a smaller cyclotron radius, electrons require a smaller magnetic field for radial confinement than ions of equal temperature. A configuration in which only the electrons need be magnetically confined allows the use of a significantly smaller magnetic field.

The nested Penning trap configuration illustrated in Fig. 1 is considered. The trap consists of five cylindrical electrodes aligned end to end along a uniform magnetic field. The center electrode is grounded, the electrode on either side of it is held at a positive voltage, and the outer pair of electrodes is held at a negative voltage. The central region of the trap bounded on either side by regions of positive potential is referred to as the ‘‘inner well.’’ Each region of positive potential on either side of the inner well is referred to as an ‘‘end well.’’ The entire region in which particles may be confined, including both end wells and the inner well, is referred to as the ‘‘outer well.’’

The outer well provides axial confinement of the electrons. The purpose of the inner well is to confine ions. However, it is possible to have electrons overlap the ions and achieve neutrality or even a negative charge density within the inner well. There are two possible scenarios for a significant overlap if both plasma species follow the Boltzmann density relation axially, and the ions remain adequately confined. A requirement that the magnitude of the change in potential that forms the inner well, $\Delta\phi$, be small enough to allow overlap is satisfied if $\Delta\phi \lesssim T_e/e$, where T_e is the electron temperature in energy units and e is the unit charge. A requirement that the ions be adequately confined axially within the inner well is satisfied if $\Delta\phi \gg T_i/(Ze)$, where T_i is the ion temperature in energy units and Z is the ion charge state. These two conditions can be simultaneously satisfied if either $Z \gg 1$ or $T_e \gg T_i$. While the use of ion and electron plasmas with disparate temperatures could result in overlap, if the two plasmas thermalize the overlap will cease. In the present work, as in Ref. [4], static confinement of high-charge-state ions and equal temperature electrons is considered.

One possible use of the configuration considered in the present work is as a source of high-charge-state ions. In addition, the configuration may be suitable for highly controlled studies of atomic processes that occur in high-charge-state plasmas. By controlling the depth of the three-

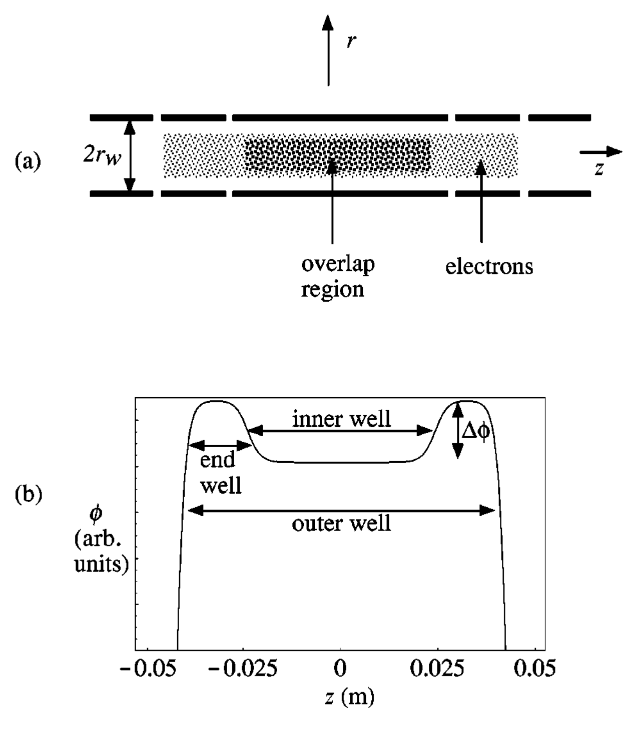

FIG. 1. The electrode configuration of a nested Penning trap (a) and an example of the electric potential along the axis of the trap (b). A solenoidal magnetic field parallel to the z axis provides radial confinement of the electrons.

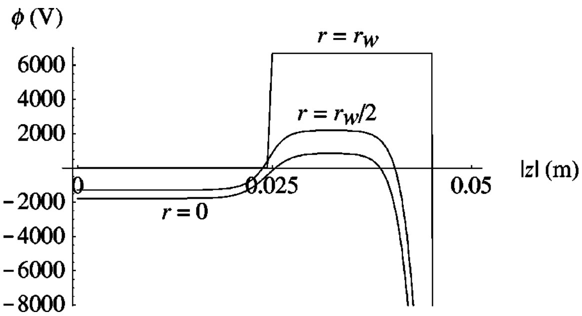

FIG. 2. Self-consistently determined electrostatic potential along $r=0$, $r=r_w/2$, and $r=r_w$. The applied potential is that along $r=r_w$. Parameters used for the computation are provided in the text.

dimensional potential well, near perfect ion confinement can be achieved. Near perfect axial confinement of the electrons is also possible by electrostatic means. Furthermore, it may be possible to achieve near perfect radial confinement for the electrons through the use of a rotating electric field technique [6]. A rotating field could be applied to one of the end well regions, which should provide for radial electron confinement throughout the trap. A constant electron temperature, and consequently a continual overlap of the inner well, could be maintained by external heating of the electrons. Therefore, the overall state of the plasma can be highly static.

The results of a self-consistent two-dimensional computation showing a high-charge-state ion plasma being confined electrostatically are shown in Figs. 2–4. The computation makes use of a finite difference method with simultaneous over-relaxation [3,4,7]. As in Ref. [4], ions with a 3 keV temperature and a density of $1\times10^{14}\,\mathrm{m}^{-3}$ at the geometric center of the trap, $(r,z)=(0,0)$, are considered. The ions are overlapped by an equal temperature electron plasma with a density of $2\times10^{16}\,\mathrm{m}^{-3}$ at (0,0). Argon ions are chosen and at a temperature of 3 keV have a distribution of 24.1% charge state +16, 36.0% charge state +17 and 39.9% charge state +18, according to the corona model of charge state equilibria [8]. Other charge states account for less than 0.1% of the total. For convenience a single species of ions is assumed, having a charge state equal to +17.2, the average charge state determined by the corona model. The electron radial profile is chosen as in Ref. [3] as $h(r)=1-(r/r_w)^\alpha$ at

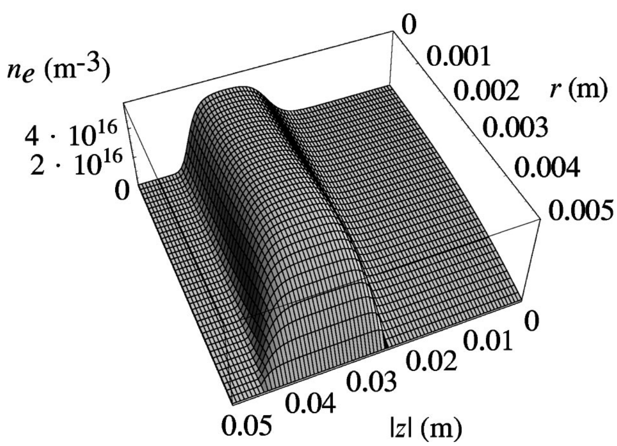

FIG. 3. Self-consistently determined electron density. Parameters used for the computation are provided in the text.

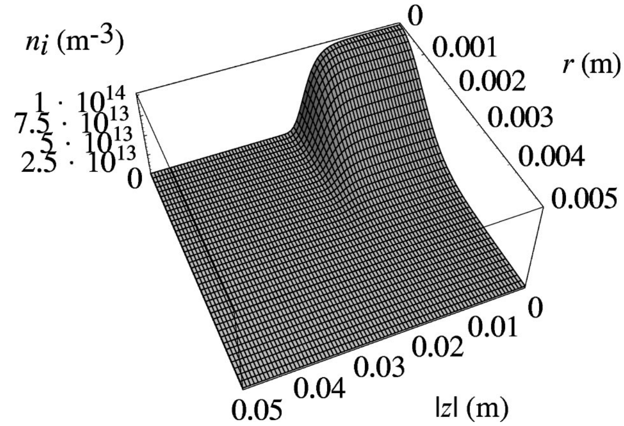

FIG. 4. Self-consistently determined ion density. Parameters used for the computation are provided in the text.

the midplane (at $z=0$), where $\alpha=-2.3/\ln(1-\lambda_D/r_w)$. This type of profile causes the plasma density to decrease near the wall (at $r=r_w$) primarily within one Debye length λ_D [3]. The electron plasma is assumed to follow the Boltzmann relation along each axial magnetic field line. Debye shielding causes the self-consistent value for $\Delta\phi$ to be smaller than the vacuum value. Overlap of the inner well by the electron plasma, which is noticeable in Fig. 3 by looking at the electron density along $r=0$, causes there to be a negative potential within the inner well as shown in Fig. 2. The ions are assumed to follow the Boltzmann relation in three dimensions within the inner well, $n_i(r,z) = n_i(0,0)e^{-Ze[\phi(r,z)-\phi(0,0)]/T_i}$. As is evident in Fig. 4, the ions are confined in all three dimensions. The electrode dimensions and voltages are the same as in Ref. [4]. The central electrode has a length of 5 cm and is held at zero volts. The electrode on either side of the central electrode has a length of 2 cm and is held at 6.7 kV. The outermost electrodes have a length of 0.5 cm each and are held at −82 kV. Each of the electrodes has a radius of 0.5 cm. Considering a magnetic field of 0.2 T, the ion cyclotron radius is 1 cm, and it would not be possible to magnetically confine the ions in the 0.5 cm radius trap. The electrons are magnetically confined, having a cyclotron radius of 0.65 mm.

For a plasma trapped in a potential energy well, if the well depth is much larger than the plasma temperature then the loss regions in velocity space become negligibly small, and the plasma can be reasonably approximated as following a Maxwell-Boltzmann phase-space distribution [see, for example, Eq. (7) of Ref. [4] and the remarks thereafter]. In the self-consistent computation, the potential energy well depth is more than an order of magnitude larger than the plasma temperature both axially for the electrons and in three dimensions for the ions. This is consistent with using the Boltzmann density relation axially for the electrons and axially and radially for the ions and signifies that both plasma species will have essentially full Maxwellian velocity distributions. Consequently, neither plasma species should be affected by the instabilities that arise in magnetic mirrors from the presence of loss cones. However, although the ions do not experience cyclotron orbits and should have no free energy for instabilities themselves, the presence of the ion plasma can be expected to affect radial electron transport and possibly cause some other instability in the electron plasma. Without knowing what effect the ions will have on radial electron transport and what radial profile the electron plasma will relax to, the choice made for the radial electron density profile at the midplane is one similar to profiles commonly observed for relaxed plasmas in Penning traps. It should also be mentioned that, in the self-consistent computation, the ion mass is not a factor and the results also apply to a two-temperature plasma. For example, the results apply to hydrogen ions with a temperature reduced by a factor of 17.2 and a density increased by a factor of 17.2. However, hydrogen ions would gradually be lost from confinement as the ion temperature increases due to electron-ion collisions.

As illustrated with the self-consistent computation, the inner well of a nested Penning trap can have a negative charge density and provide for three-dimensional electric confinement of the ions. Consequently, the Brillouin density limit for non-neutral plasmas in solenoidal fields does not directly apply to the ions in such a configuration. The Brillouin limit is $n_B = \epsilon_0 B^2/2m$, where B is the magnetic field strength, m is the particle mass, and ϵ_0 is the permittivity of free space. Within an end well, where the plasma is completely unneutralized, the electron density $n_{e,ew}$ will be limited. In consideration of this, an expression for the maximum ion density can be obtained. First, assume $n_{e,ew}$ equals the Brillouin electron density limit, $n_{e,ew} = n_{Be}$. If the electrons follow the Boltzmann relation, the electron density within the inner well is given by $n_{e,iw} = n_{Be} e^{-e\Delta\phi/T_e}$. A situation in which a negative charge density exists within the inner well results in an electric field that is directed radially inward and that can serve to keep the ions radially confined. To calculate the maximum ion density that can be confined, consider as a limit the ion density that results in neutrality within the inner well, $n_{i,max} = n_{e,iw}/Z$. Writing the density in terms of the Brillouin ion density limit n_{Bi} yields

$$n_{i,max} = \frac{m_i}{Z m_e} e^{-e\Delta\phi/T_e} n_{Bi}, \tag{1}$$

where m_i and m_e are the ion and electron masses. Note that for overlap to occur $e\Delta\phi/T_e \lesssim 1$ and $e^{-e\Delta\phi/T_e}$ is of order unity. For an argon plasma of average charge state $Z=17$, $m_i/Z m_e \approx 4000$. Due to the large mass difference between electrons and ions, the density of ions can be significantly larger than the Brillouin ion density limit. For the self-consistent results shown in Figs. 2 –4 and a magnetic field of 0.2 T, the maximum argon ion density 1×10^{14} m^{-3} is much larger than the Brillouin ion density limit 2.7×10^{12} m^{-3}.

In previous work, a plasma trap was considered that contained electrons and high-charge-state ions, which were confined axially by electrostatic means and radially by a magnetic field. In the present work, self-consistent results for a high-charge-state ion plasma that is radially and axially confined by an electrostatic potential well are presented. The potential well arises from both the electrode and electron plasma contributions to the potential. Because only the electrons need to be magnetically confined, the required magnetic field does not need to be produced using expensive superconducting magnets. While, in Ref. [4], a magnetic field of 10 T was considered so that adequate radial ion confinement would be possible, in the present work a 0.2 T magnetic field is sufficient because the ions are completely confined by a three-dimensional electric potential well. The trap configuration considered here may be used for ion confinement at densities exceeding the Brillouin limit and should be suitable as a source of high-charge-state ions and as a means to study atomic processes in high-charge-state plasmas.

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