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Strong drive compression of a gas-cooled positron plasma

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The use of rotating electric fields to control plasmas has found numerous applications in the manipulation and storage of antimatter. When used in strong magnetic fields plasma heating caused by the applied field is mitigated by cyclotron cooling, leading to an efficient broadband mode of compression known as the strong drive regime. We have found that it is possible to access the strong drive regime in a low field trap where cyclotron cooling is negligible and a gas is used for cooling, and we have been able to compress positron plasmas to more than 10% of the Brillouin density limit. © *2010 American Institute of Physics*. [doi:10.1063/1.3354005]

Single component plasmas[1] in Penning–Malmberg (PM) traps have proved to be extremely useful for the storage and manipulation of antimatter.[2] In particular, the excellent confinement properties of PM traps[3] permit large numbers of positrons to be accumulated and stored, which was a key element in experiments to produce molecular positronium.[4]

A plasma of density n_p in a magnetic field of strength B rotates about the magnetic field axis at a frequency

$$f_E = n_p e / 4\pi\varepsilon_0 B, \qquad (1)$$

where e is the positronic charge and ε_0 is the permittivity of free space. There is an upper limit to the density at which such a plasma may be confined, known as the Brillouin limit,[1] $n_B = \varepsilon_0 B^2 / 2m_e$, at which the plasma rotates at half the cyclotron frequency, and is effectively unmagnetized. Achieving densities as close to this limit as possible will help future high-density positronium experiments, and, as discussed below, could also be advantageous in the production of high brightness remoderated pulsed beams.

An important tool for manipulating single component plasmas is the rotating wall (RW) technique, in which a rotating electric field is applied to the plasma[5,6] that produces an inward transport effect, leading to higher density plasmas and greatly improved confinement properties. A significant recent development in the application of the RW is the discovery of a "strong-drive" regime of RW compression by Danielson and Surko.[7] In this strong drive regime plasmas evolve rapidly to a state in which they rotate at the same angular frequency as the applied RW signal f_{RW}, so that one may "dial up" any desired plasma density, in principle up to the Brillouin limit. Application of the RW has a tendency to heat the plasma, however, so some form of cooling is generally required. In a strong magnetic field this may be achieved by the emission of cyclotron radiation,[5] whereas in a weak field it is necessary to introduce a gas.[6]

Cyclotron cooling would be the preferred technique for use with positron plasmas since there is no attendant loss of particles due to annihilation with a cooling gas. However, high-field magnets are expensive to procure, can limit access to the experimental region, and may complicate some experimental procedures (e.g., the use of photo multipliers). Also, if the positrons are to be extracted from the magnetic field entirely, as is the case in the production of intense high-brightness pulses,[8] low fields may be favored. Thus, the ability to access the strong drive regime in a low field gas cooled trap, which we report here, makes it possible to obtain exceptional plasma control in a wider range of systems.

The experimental work was performed in two separate positron traps of similar design. The University of California Riverside (UCR) positron accumulator used in this work has been described in detail elsewhere,[9] as has the trap at First Point Scientific, Inc. (FPSI).[10] Both systems exhibited qualitatively similar results; the main difference between them was that the FPSI trap was able to maintain compression up to higher frequencies (~30 MHz) at a lower, fixed, magnetic field (0.04 T) than the UCR system, which could be varied up to ~0.09 T, but was only effective above ~0.04 T. Figure 1 shows cutaway views of the two traps in which positron plasmas are created by stacking multiple pulses from a two-stage trap. During the stacking a low frequency RW (1–3 MHz) signal is used to maintain confinement, and then when the desired number of particles has been accumulated the plasmas are compressed by the application of a higher frequency RW drive. Positrons are cooled using SF_6 or CF_4 at a pressure of $\sim 10^{-7}$ Torr, for which the

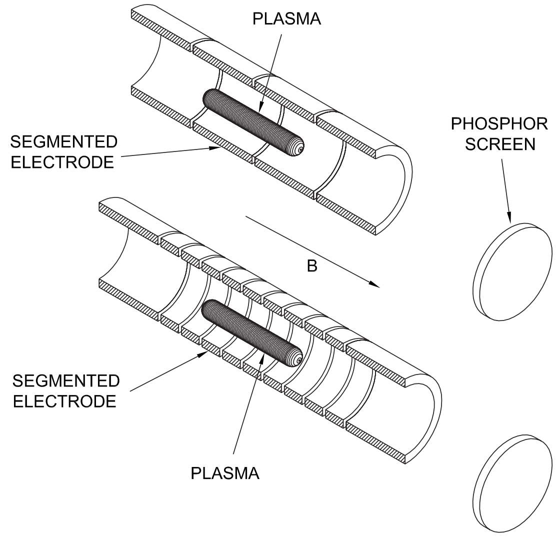

FIG. 1. Cutaway representation of the positron accumulator electrodes and imaging screen. Above: FPSI trap. Below: UCR multiring electrode trap.

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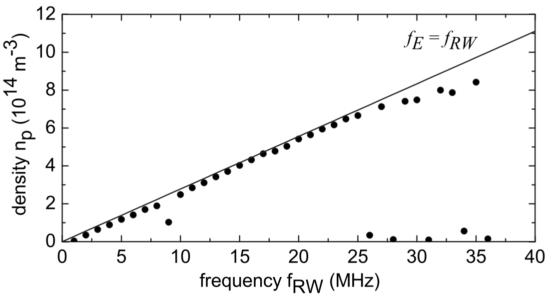

FIG. 2. Plasma density in the FPSI trap as a function of the RW compression frequency at B=0.04 T, for which $n_B \sim 8\times 10^{15}$ m^{-3}. The solid line shows the no slip condition.

annihilation lifetime is several hundred seconds.[6,11] Similar results were obtained with either gas. We note that positron interactions with the cooling gas not only lead to annihilation losses but can also cause outward expansion and thus heating,[12] so that gas cooling is only expected to be effective over a limited plasma density range.[13]

To obtain the plasma densities positrons were ejected from the trap, accelerated to 5 kV and imaged using a phosphor screen and charge coupled device (CCD) camera,[9] as indicated in Fig. 1. Compressed plasma profiles typically have a symmetrical two-dimensional Gaussian density distribution. In the following we refer to the central density $n_p = N/2\pi\sigma^2 L_p$, where σ, N, and L_p, are the Gaussian variance, number of particles and plasma length, respectively. The light output from the CCD camera was calibrated using the dc positron beam, which was itself calibrated using a NaI detector. Plasma densities measured in this way are expected to be accurate to better than 10%.

In order to achieve good confinement properties in PM traps it is necessary to accurately align the trap and magnetic field axes. This may be achieved either by mechanically adjusting the position of the magnetic field coil or by adjusting the currents in two pairs of correction coils with axes perpendicular to the main field. The former method is more suitable for high field traps. The latter method was used in the work described here. We note that without the correction fields we were unable to access the strong drive regime in either the UCR or FPSI devices.

Figure 2 shows the plasma density in the FPSI trap as a function of the applied RW frequency. Also shown in this figure is the "no slip" condition $f_E = f_{RW}$. The plasma density is always slightly lower than this ideal case (possibly due to thermal effects[7]) and eventually the slip increases until the compression fails entirely. However, there is a strong linear dependence of the density on the drive frequency that is characteristic of the strong drive regime that is only observed if the RW amplitude exceeds a critical threshold value; the observed plasma response is therefore qualitatively the same as the strong drive regime of Danielson and Surko, including the presence of frequency-dependent dropouts, which they also observed[7] and ascribed to the presence of static magnetic or electric asymmetries in the trap that propagate in the opposite direction to the rotating plasma. Because the underlying asymmetries are static (in the laboratory frame), this type of mode is referred to as a zero frequency mode (ZFM). At some plasma rotation frequencies these asymmetries can become resonant with (and thus start driving) various plasma modes that cause heating[14] and, in some cases, a loss of confinement.

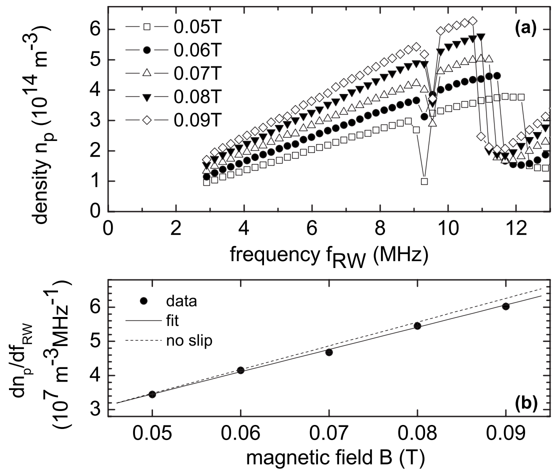

FIG. 3. (a) Plasma density in the UCR trap as a function of RW frequency for a range of values of magnetic field strength, as shown in the legend. (b) Fitted slopes for the data in (a) with $f_{RW} < 8$ MHz as a function of magnetic field (errors bars are smaller than the symbols).

Figure 3(a) shows the plasma density in the UCR trap as a function of the applied RW frequency for different values of the axial magnetic field B. In Fig. 3(b), the slopes of these data (dn_p/df_{RW}) are plotted for each value of B, and show the expected linear dependence. The slope of these data should be equal to $4\pi\varepsilon_0/e = 6.95\times 10^8$ C mF^{-1} [see Eq. (1)]. A fit to the data yields $6.53(0.07)\times 10^8$ C mF^{-1}, which is within the ~10% error expected from calibration uncertainties, and further indicates that we are in the strong drive regime.

In both the UCR and FPSI traps there is a critical frequency above which the strong drive compression fails. For the FPSI trap at 0.04 T, this corresponds to 11% of the Brillouin limit. The highest value obtained in the UCR trap is somewhat lower (<5%) since plasma confinement in this system is less stable below 0.05 T, and the maximum effective drive frequency is also lower. It is not presently understood why the FPSI trap is able to operate at higher frequencies but one possibility is that the magnetic field in this system is more uniform than that in the UCR arrangement. Indeed, we do not yet understand all of the factors that determine why there is an upper limit to the effective RW compression frequency at all. They may include asymmetries driving ZFMs similar to those seen at lower frequencies, but could also be related to the gas heating limit predicted by Surko, or increased radial transport as the plasma becomes progressively less magnetized as it approaches the Brillouin limit.[13]

One of the goals of our research is the production of a Bose–Einstein condensate of positronium,[15] which requires a much higher beam density than we are able to obtain using RW compression alone. For this reason it will be necessary to remoderate the positron beam.[16] This involves extracting the positrons from the magnetic field, which will apply angular momentum to the plasma and increase $\phi_T = \phi_i + \phi_m$, the two-dimensional transverse phase space density of the beam.[17] Here $\phi_i \propto r^2 E_T$ is the intrinsic phase space arising from the transverse energy E_T of the positrons and $\phi_m \propto r^4 B^2 (1 - n_p/n_B)$ is the contribution due to the magnetic field. The magnetic part of ϕ_T typically dominates when r is of the order of a few millimeters or more. For positron plasmas in the strong drive regime that are far from the Brillouin limit, and for which the charge per unit length is constant, we see from Eq. (1) that $\phi_m \propto N^2/f_{\mathrm{RW}}^2 L_p^2$. In principle, one may approach arbitrarily close to the Brillouin limiting density by transporting the beam into a low field. However, since ϕ_m is an invariant with respect to changes in the magnetic field so doing would not affect one's ability to focus the beam. This does mean though that, without deleterious effect, it should be possible to produce a plasma in a high magnetic field, and then reduce the field in order to facilitate extraction of the beam through magnetic shielding material that is only effective in low fields. The important point is that in the strong drive regime, for any plasma with a given number of particles per unit length *the only relevant factor in attaining a high positron density in zero field is* f_{RW}.

In summary, we have demonstrated that it is possible to drive a gas-cooled positron plasma in a low magnetic field into the strong drive regime. Previously this had been demonstrated only in cyclotron radiation cooled electron plasmas in a superconducting magnet. We have utilized this effect to obtain positron plasmas with densities up to $\sim 0.1 n_{\mathrm{B}}$. The ability to use RW compression in the strong drive regime in gas-cooled traps is beneficial for intense pulsed beam experiments since the phase space density of the plasma can be significantly reduced, and a brighter beam produced in zero-field. Strong drive positron plasmas in gas cooled traps may also be useful for the production of high-quality plasma based quasi-dc beams[18] that have a variety of applications, some of which, such as atomic and molecular scattering experiments,[19] may require low magnetic fields.

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[1] R. C. Davidson, *Physics of Non-Neutral Plasmas* (Addison-Wesley, Redwood City, 1990).
[2] R. G. Greaves and C. M. Surko, Phys. Plasmas **4**, 1528 (1997).
[3] T. M. O'Neil, Phys. Fluids **23**, 2216 (1980).
[4] D. B. Cassidy and A. P. Mills, Jr., Nature (London) **449**, 195 (2007).
[5] F. Anderegg, E. M. Hollman, and C. F. Driscoll, Phys. Rev. Lett. **81**, 4875 (1998).
[6] R. G. Greaves and C. M. Surko, Phys. Rev. Lett. **85**, 1883 (2000); C. M. Surko and R. G. Greaves, Phys. Plasmas **11**, 2333 (2004).
[7] J. R. Danielson and C. M. Surko, Phys. Rev. Lett. **94**, 035001 (2005); Phys. Plasmas **13**, 055706 (2006); Phys. Rev. Lett. **99**, 135005 (2007).
[8] D. B. Cassidy, T. H. Hisakado, V. E. Meligne, H. W. K. Tom, and A. P. Mills, Jr., J. Phys.: Conf. Ser. **194**, 012037 (2009).
[9] D. B. Cassidy, S. H. M. Deng, R. G. Greaves, and A. P. Mills, Jr., Rev. Sci. Instrum. **77**, 073106 (2006).
[10] R. G. Greaves, and J. Moxom, AIP Conf. Proc. **692**, 140 (2003).
[11] See, for example, M. Charlton, Rep. Prog. Phys. **48**, 737 (1985); D. A. L. Paul and C. Y. Leung, Can. J. Phys. **46**, 2779 (1968).
[12] M. H. Douglas and T. M. O'Neil, Phys. Fluids **21**, 920 (1978).
[13] C. M. Surko, in Physics with Many Positrons, edited by A. Dupasquier and A. P. Mills, Jr. (IOS, Amsterdam, in press).
[14] Slow dumps indicate that the plasmas usually have a (parallel) temperature of ~0.1 eV [D. L. Eggleston, C. F. Driscoll, B. R. Beck, A. W. Hyatt, and J. H. Malmberg, Phys. Fluids B **4**, 3432 (1992)] but that this rises dramatically near a ZFM resonance. Because these latter plasmas are intrinsically unstable it is not possible to reliably measure their temperatures, but from an inspection of the emission profiles we estimate that it is >1 eV, indicating that the ZFM is a strong source of plasma heating.
[15] P. M. Platzman and A. P. Mills, Jr., Phys. Rev. B **49**, 454 (1994).
[16] Remoderation or brightness enhancement refers to the technique of focussing a beam into a solid material and then extracting some fraction of it with a reduced phase space. A. P. Mills, Jr., Appl. Phys. (Berlin) **23**, 189 (1980).
[17] K. F. Canter, in *Positron Spectroscopy of Solids*, edited by A. Dupasquier and A. P. Mills, Jr. (IOS, Amsterdam, 1995), p. 361. For simplicity we assume here that the plasmas have a flat top distribution and radius *r*. The conclusions drawn are unaffected by making this assumption.
[18] J. R. Danielson, T. R. Weber, and C. M. Surko, Appl. Phys. Lett. **90**, 081503 (2007).
[19] C. M. Surko, G. F. Gribakin, and S. J. Buckman, J. Phys. B **38**, R57 (2005).