Extraction of small-diameter beams from single-component plasmas

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A nondestructive technique is described to extract small-diameter beams from single-component plasmas confined in a Penning-Malmberg trap following radial compression using a rotating electric field. Pulsed beams with Gaussian radial profiles and diameters as small as 50 μm are extracted from electron plasmas initially 2 mm in diameter. A simple theory for the beam diameter predicts $4\lambda_D$ (full width to $1/e$), where λ_D is the Debye length, in good agreement with experimental measurements on electron plasmas. Applications and extensions of this technique to create bright, finely focused beams of positrons and other scarce particles are discussed. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2709522]

Low-energy particle beams have wide utility in science and technology, including bright beams for microscopy and scattering experiments and cold beams for spectroscopy.[1–5] While many methods have been developed to create such beams, including passage through small apertures or, in the case of positrons,[6] focusing and rethermalization at material surfaces, these techniques typically involve unavoidable losses of particles. This is disadvantageous when copious particle sources (e.g., of antimatter) are unavailable. Described here is a nondestructive technique to produce a beam with narrow spatial width and enhanced brightness without such particle losses. Applications include the creation of high-quality positron beams for atomic physics studies;[7,8] microbeams for material analysis,[9,10] and the creation of the positronium molecule Ps_2 and Bose-condensed Ps.[11–13]

The beams are formed by extracting particles from a cylindrical, single-component plasma confined in a Penning-Malmberg trap. The technique exploits the fact that the plasma space-charge potential is greatest at the plasma center, so particles from this region escape first when an end confining potential is lowered.[14] To use all of the particles and for increased brightness, the plasma is compressed radially and maintained at constant density using a rotating electric field.[15,16] Using this active-manipulation technique, the plasma can be transformed into a sequence of tailored beam pulses, similar to squeezing small amounts of toothpaste from a tube.[17] Beams with Gaussian radial profiles and diameters as small as $D=50$ μm are extracted from electron plasmas with $D=2$ mm before compression. A simple theory is presented predicting that the beam diameter (full width to $1/e$) is $D \approx 4\lambda_D \propto (T/n)^{1/2}$, where λ_D is the Debye screening length, n the plasma density, and T the temperature. Measurements are presented confirming this prediction. The favorable scaling of D with T and n indicates that further improvements are possible with colder, higher-density plasmas.

The experimental arrangement is shown schematically in Fig. 1 and described in detail in Ref. 16. It consists of a set of cylindrical electrodes 2.5 cm in diameter in a uniform magnetic field, $B=4.8$ T, in the z direction. Confinement voltages, $V_c=-100$ V, are applied to electrodes at the ends of the plasma to provide confinement in the z direction. Plasmas of length of $5 \leq L_p \leq 25$ cm are created using electrodes of different lengths. The trap is filled using an electron gun. Following a brief equilibration period, the plasmas have "flat-top" radial density profiles and constant $\boldsymbol{E}\times\boldsymbol{B}$ rotation frequencies, $f_E \propto n$. For a fill voltage, $V_f=40$ V, and length $L_p=10$ cm, a plasma with $N=4\times10^8$ electrons is created with $n\sim1\times10^9$ cm^{-3} and radius $R_p\sim1$ mm. Plasmas cool to $T\sim0.05$ eV by cyclotron emission in a time $\tau_c\sim0.16$ s.[16] Good plasma-to-plasma reproducibility is observed with $\Delta N/N \leq 1\%$.

Radial, z-integrated, areal density profiles are measured by quickly lowering V_c at one end of the plasma. Escaping electrons are accelerated to 5 keV, then impinge on a phosphor screen, with the light imaged using a digital camera. The parallel plasma temperature $T_\parallel$ is measured from the relationship between V_c and the number of escaping electrons when V_c at one end of the plasma is reduced slowly.[18] The perpendicular-to-parallel equilibration time (<1 ms) and the heat transport time (<10 ms) are rapid compared to τ_c,[19] so that plasmas reach equilibrium rapidly. The temperature is increased by applying 100–1000 cycles of a 10 kHz, 5 V peak-to-peak sine wave (saw tooth for higher T) to an electrode at one end of the plasma,[19] followed by a 50 ms equilibration period.

Plasma density is varied by the application of phased, sine-wave voltages to a four-segment electrode extending over a portion of the plasma [the so-called "rotating wall" (RW) technique].[16] When this RW electric field with azimuthal mode number $m_\theta=1$ rotates in the same direction as the plasma, the plasma spins up to the applied RW frequency, namely $f_E \sim f_{RW}$ ($0.4 \leq f_{RW} \leq 6$ MHz), which sets the value

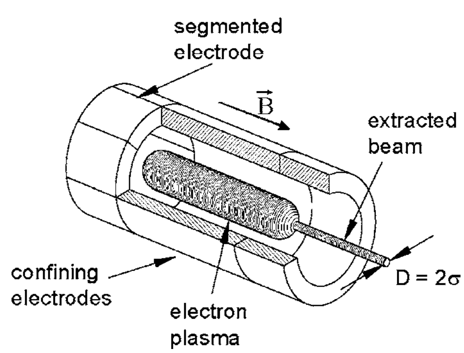

FIG. 1. Schematic diagram of beam extraction from a plasma confined in a Penning-Malmberg trap.

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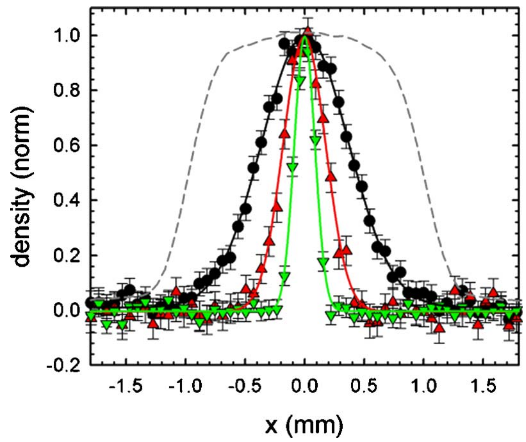

FIG. 2. (Color online) Normalized areal density profiles of beams extracted from an electron plasma with $n=1\times10^{9}$ cm^{-3} at temperatures of (●) 1.0, (△) 0.2, and (▽) 0.04 eV. Solid lines are Gaussian fits, as described by Eq. (2). The dashed line is the areal density of the initial plasma.

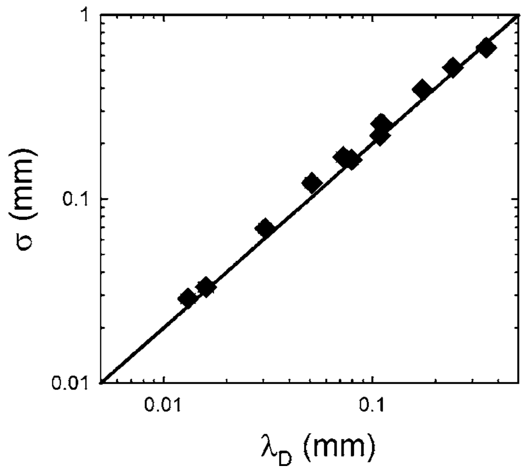

FIG. 3. Log-log plot of the measured beam half width σ from a fit to Eq. (2) as a function of the Debye length λ_D. The solid line corresponds to $\sigma=2\lambda_D$.

of n throughout the plasma.[16] In a given experiment, either the procedure for changing temperature or the procedure for changing density is employed, but not both. The RW compression does produce heating,[16] so in this case, both T and n change.

Beams are extracted using a square-wave voltage pulse V_{ex} to lower the trapping potential at one end of the plasma, thus allowing particles near the (radial) plasma center to exit the trap.[18,20,21] The extraction-pulse duration ($t_{ex}\sim5$ μs) is greater than the axial bounce time (i.e., $\tau_b\sim1.5$ μs),[15] so that all electrons with energies greater than the confinement potential escape, but t_{ex} is kept short enough to avoid radial transport or instabilities during extraction.[22] The number of extracted beam particles N_b is varied by changing V_{ex}. This process of RW compression and extraction can be repeated for efficient use of the plasma. Radial beam profiles are measured using the digital camera, as described above.

Shown in Fig. 2 are areal density profiles for three plasma temperatures. For an equilibrium, single-component plasma with $L_p \gg R_W \gg R_p$, the plasma potential can be written as $\phi(r)=\phi(0)-(T/e)(r/2\lambda_D)^2$. Assuming all particles that can escape do so, the areal density of the ejected beam $n(r)$ can be found by integrating the Maxwellian distribution over energies, $E_{min} \geq -e[V_c-V_{ex}-\phi(r)]$. Defining the scaled confinement potential $A\equiv-(e/T)[V_c-V_{ex}-\phi(0)]$,

$$n(r) = n_0 \,\mathrm{erfc}[A + (r/2\lambda_D)^2]^{1/2}, \tag{1}$$

where erfc is the complimentary error function. For small charge pulses (i.e., $A\geq2$),

$$n(r) \approx n_0 G(A)\exp[-(r/\sigma)^2], \tag{2}$$

where $G(A)=(\pi A)^{-1/2}\exp[-A]$, and $\sigma=2\lambda_D$. Equation (2) is a key result. The radial profile is approximately a Gaussian with half width to $1/e$, $\sigma\approx2\lambda_D$. The beams width is due to the parabolic dependence of $\phi(r)$ on r in the constant-density plasma. For small charge pulses σ is independent of V_{ex}, while the beam intensity can be set by V_{ex} [i.e., through G(A)].

As shown in Fig. 2, the Gaussian radial profiles predicted by Eq. (2) are in good agreement with the data. Shown in Fig. 3 is the measured beam half width σ as a function of λ_D. For these data, T (in eV) was varied from 0.05 to 2.0, and n (in units of 10^{10} cm^{-3}) from 0.06 to 2.2—factors of 40 and 37, respectively. Thus, over a wide range of parameters, σ is proportional to λ_D.

Shown in Fig. 4 is σ as a function of the fraction $\beta=N_b/N$ of the beam extracted for two plasma temperatures. Equation (2) predicts $\sigma\approx2.0\lambda_D$, while direct calculation from Eq. (1) for relevant values of the confinement potential A predicts a $1/e$ half width of $1.9\lambda_D$. The measurements indicate $2.0\leq\sigma/\lambda_D\leq2.1$. The small discrepancy of $\leq0.2\lambda_D$ (i.e., $\leq10\%$) is not understood. The maximum value of β for minimum width (i.e., $\sigma\approx2.0\lambda_D$) is in the range of $0.01\leq\beta_m\leq0.1$ and is smaller at lower T. A plasma with $N=10^9$ could produce a train of $\sim$23, 5 μs duration, 1 μA current pulses (3×10^7 particles per pulse) at a repetition rate of $\sim$100 Hz (i.e., using 70% of the plasma before refilling[17]).

While the beams described here are in a strong magnetic field ($B=4.8$ T), they can be extracted from the field (e.g., for further electrostatic manipulation).[6,23] The beam emittance is given by

$$\varepsilon^* \cong \sigma(\Delta E_\perp/E_0)^{1/2}[1+(\sigma/2\rho_c)], \tag{3}$$

where E_0 and $\Delta E_\perp$ are the beam energy and perpendicular energy spread, respectively, and ρ_c is the cyclotron radius.[23]

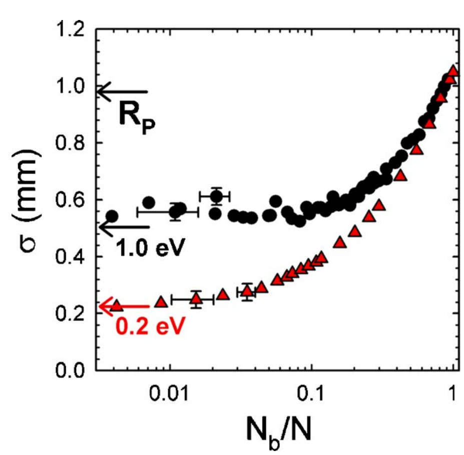

FIG. 4. (Color online) Measured beamwidths σ as a function of the fraction of particles, $\beta=N_b/N$, extracted from a (●) 1 eV and a (△) 0.2 eV plasma with $N=4\times10^8$ electrons. Sample radial profiles are shown in Fig. 2. Arrows mark $\sigma=2\lambda_D$ and the plasma radius.

Starting with a 30 K plasma with $n=3\times10^{10}\ \mathrm{cm}^{-3}$ at $B=4.8$ T, extraction at $B=5\times10^{-4}$ T would result in $\sigma=0.5$ mm, $\Delta E_{\perp}=10$ meV, and a parallel energy spread $\Delta E_{\parallel}\approx3$ meV. This is superb compared to the best electrostatic positron beams in use for atomic physics studies[8] and would admit to further electrostatic brightness enhancement.[6]

In this letter, we have described a nondestructive technique to brightness-enhanced particle beams, particularly useful for scarce particles such as antimatter.[24] Since the ability to create positron plasmas with parameters very similar to those used here has been established,[25] this technique is directly applicable to positrons. The limits of this technique have yet to be established. For example, densities $\sim10^{11}\ \mathrm{cm}^{-3}$ and temperatures $\leqslant10$ K (Refs. 13, 16, and 25) would result in beamwidths $\leqslant1\ \mu$m. Since n is determined by f_{RW}, measurement of σ could also be used to determine plasma temperature. This might be particularly useful at low temperatures where other techniques have limited resolution.[19,25]

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[1]A. David, G. Kogel, P. Sperr, and W. Triftshauser, Phys. Rev. Lett. **87**, 067402 (2001).
[2]C. M. Surko and R. G. Greaves, Phys. Plasmas **11**, 2333 (2004).
[3]Y. Yamazaki, Mater. Sci. Forum **445–446**, 430 (2004).
[4]W. E. King, G. H. Campbell, A. Frank, B. Reed, J. F. Schmerge, B. J. Siwick, B. C. Stuart, and P. M. Weber, J. Appl. Phys. **97**, 111101 (2005).
[5]P. Hommelhoff, Y. Sortais, A. Aghajani-Talesh, and M. A. Kasevich, Phys. Rev. Lett. **96**, 077401 (2006).
[6]A. P. Mills, Jr., Appl. Phys. **23**, 189 (1980).
[7]M. Charlton and J. W. Humberston, *Positron Physics* (Cambridge University Press, Cambridge, 2001).
[8]C. M. Surko, G. F. Gribakin, and S. J. Buckman, J. Phys. B **38**, R57 (2005).
[9]A. P. Mills, Jr., Science **218**, 335 (1982).
[10]P. J. Schultz and K. G. Lynn, Rev. Mod. Phys. **60**, 701 (1988).
[11]A. P. Mills, Jr. and P. M. Platzman, in *New Directions in Antimatter Chemistry and Physics*, edited by C. M. Surko and F. A. Gianturco (Kluwer, Dordrecht, 2001), p. 115.
[12]A. P. Mills, Jr., Nucl. Instrum. Methods Phys. Res. B **192**, 107 (2002).
[13]D. B. Cassidy, S. H. M. Deng, R. G. Greaves, T. Maruo, N. Nishiyama, J. B. Snyder, H. K. Tanaka, and A. P. Mills, Jr., Phys. Rev. Lett. **95**, 195006 (2005).
[14]C. F. Driscoll, Phys. Rev. Lett. **64**, 645 (1990).
[15]J. R. Danielson and C. M. Surko, Phys. Rev. Lett. **95**, 035001 (2005).
[16]J. R. Danielson and C. M. Surko, Phys. Plasmas **13**, 055706 (2006).
[17]For constant beam-pulse characteristics, one would convert most of the plasma (e.g., 70%) into beam pulses, then replenish the plasma.
[18]D. L. Eggleston, C. F. Driscoll, B. R. Beck, A. W. Hyatt, and J. H. Malmberg, Phys. Fluids B **4**, 3432 (1992).
[19]B. R. Beck, J. Fajans, and J. H. Malmberg, Phys. Plasmas **3**, 1250 (1996).
[20]J. Aoki, Y. Kiwamoto, and Y. Kawai, Phys. Plasmas **13**, 112109 (2006).
[21]G. W. Hart and B. G. Peterson, Phys. Plasmas **13**, 022101 (2006).
[22]D. B. Cassidy, S. H. M. Deng, and A. P. Mills, Jr., Nucl. Instrum. Methods Phys. Res. B **248**, 121 (2006).
[23]R. G. Greaves and C. M. Surko, Nucl. Instrum. Methods Phys. Res. B **192**, 90 (2002).
[24]Where copious particle sources exist, sacrificial techniques are available to produce cold bright beams superior to those described here (e.g., for electrons, see Refs. 4 and 5).
[25]L. V. Jorgensen, M. Amoretti, G. Bonomi, P. D. Bowe, C. Canali, C. Carraro, C. L. Cesar, M. Charlton, M. Doser, A. Fontana, M. C. Fujiwara, R. Funakoshi, P. Genova, J. S. Hangst, R. S. Hayano, A. Kellerbauer, V. Lagomarsino, R. Landua, E. Lodi Rizzini, M. Macri, N. Madsen, D. Mitchard, P. Montagna, A. Rotondi, G. Testera, A. Variola, L. Venturelli, D. P. van der Werf, and Y. Yamaz, Phys. Rev. Lett. **95**, 025002 (2005).