ELSEVIER

Applied Surface Science 194 (2002) 56–60

applied surface science

www.elsevier.com/locate/apsusc

Trap-based positron beams

R.G. Greaves[a,*], S.J. Gilbert[b], C.M. Surko[b]

[a]First Point Scientific Inc., 5330 Derry Avenue, Suite J, Agoura Hills, CA 91301, USA
[b]Department of Physics, University of California, San Diego, CA 92093, USA

Abstract

Large numbers of positrons can be accumulated and cooled in a Penning-type trap. These positron clouds can be manipulated and conditioned using plasma physics techniques, before being released from the trap to form high quality positron beams. These techniques offer a qualitatively new method for positron beam formation and manipulation that has significant advantages in efficiency, flexibility, and cost over current beam conditioning techniques. Unique capabilities include the production of ultracold beams, brightness enhancement by radial compression of the plasma prior to extraction, and simple implementation of harmonic potential bunching.

Keywords: Positron trap; Penning trap; Brightness enhancement; Pulsed beams; Positron cooling

1. Introduction

Low energy positron sources have been extensively employed in a variety of areas of science and technology, including atomic physics research [1], plasma physics [2], astrophysical simulations [3], mass spectrometry [4], antihydrogen production [5] and materials science [6,7]. This latter application encompasses the largest body of positron beam users, and is likely to grow as these techniques mature into the commercial arena. Current positron beam systems are based largely on conventional electron beam technology and are now close to their peak of development [8]. Positron traps offer an alternative approach to beam formation that have the potential for using the scarce positron resource more efficiently, in addition to providing some unique capabilities.

While it is commonplace that particle traps can be used as beam sources, (e.g. they have been used for beam conditioning on LINACS for some time [9,10]), the full capabilities of trap-based beam sources have not been widely appreciated. These capabilities arise from the potential for conditioning the particles prior to release from the trap, leading to improved beam quality. For example, positrons may be cooled to much lower temperatures than conventional beams [11], they may be compressed radially [12,13], leading to brighter beams, or they may be bunched using simple techniques. The positrons may be shifted in energy by changing the bias potential on the trap electrodes, enabling systems in which both source and target are at ground potential. Furthermore, because the positrons can be confined for extended periods, they can be used in a more versatile and efficient manner. For example, positrons can be accumulated while systems are off-line, say during cycling of load locks, leading to more efficient usage; and they can be released with a range of different pulse amplitudes and duty cycles, including the production of giant positron pulses.

* Corresponding author. Tel.: +1-818-707-1131;
fax: +1-818-707-2352.
E-mail address: greaves@firstpsi.com (R.G. Greaves).

0169-4332/02/$ – see front matter
PII: S0169-4332(02)00089-2

2. Positron trapping

A variety of techniques have been proposed or developed for accumulating positrons in Penning traps (see, e.g. [14] and references therein). However, the only system that is efficient enough for high throughput systems is the buffer gas technique described below [15].

Positrons are slowed to a few electron volts using a solid neon moderator [16]. They are then injected into the modified Penning–Malmberg trap shown in Fig. 1 in the presence of a buffer gas. A magnetic field ~0.1 tesla is applied along the axis of the trap to provide radial confinement. The accumulator has three stages, each at successively lower gas pressure and electrostatic potential. As many as 30% of the incident positrons become trapped in the third stage of the accumulator by electronic excitations of the N_2 buffer gas and they cool to room temperature in ~0.1 s by vibrational and rotational excitations of the buffer gas [17]. Using this technique, 3×10^8 positrons have been accumulated in 8 min from a 90-mCi ^{22}Na source. Positrons can be cooled to even lower temperatures if they are transferred to a cryogenic environment after they are trapped. A system of this type, using differential pumping to isolate the cryogenic section, is now under construction [18]. Once the positrons have been accumulated, they can be conditioned as described below, and then released to form high-quality beams.

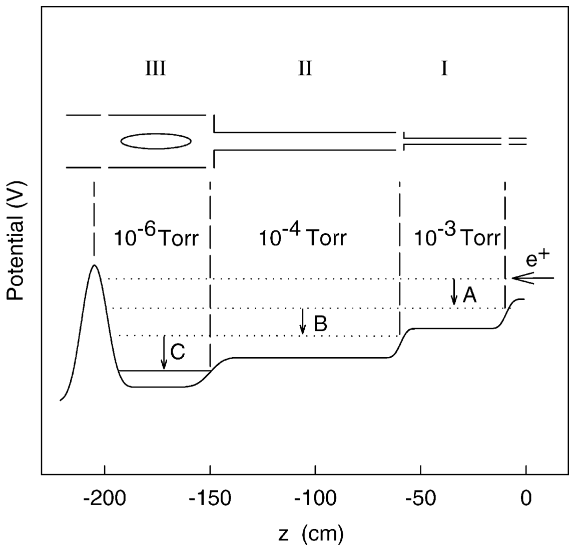

Fig. 1. Schematic diagram of a gas-buffered positron trap, showing the three stages of differential pumping and the electrostatic potential.

3. Beam-formation and bunching

Positron beams can be extracted from traps by reducing the depth of the confining potential. This can be accomplished either by reducing the potential on one of the end confining electrodes, or by increasing the potential on the main electrode surrounding the positrons while maintaining the end potentials fixed. This latter method, which is illustrated in Fig. 2(a), has the advantage that the positron beam has a narrow, fixed beam energy determined by the end electrode potential [11]. As shown in the insert to Fig. 2(a), energy spreads as low as 18 meV can be routinely obtained. These cold beams have already been

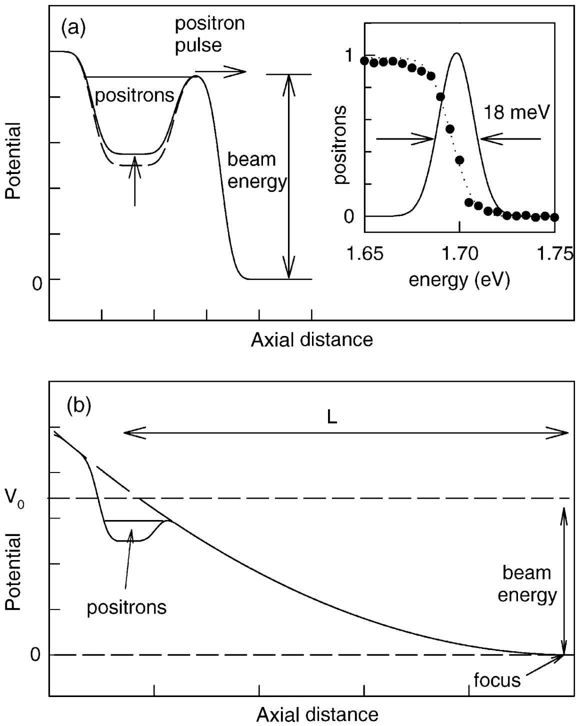

Fig. 2. Electrostatic potential profiles for beam formation using traps: (a) simplest configuration with asymmetrical well and fixed potential exit gate potential. The inset shows a typical parallel energy distribution obtainable using room temperature positrons; (b) the harmonic potential geometry, as described in text.

employed for atomic physics studies in a previously inaccessible low-energy regime [19,20]. The changes in the potential can be made either stepwise or smoothly, leading to pulsed or quasi-steady state ''pulse stretching'' beams, respectively.

Traps are ideal for the implementation of beam bunching by the elegant technique of harmonic potential bunching [21]. This technique, illustrated in Fig. 2(b), imposes a quadratic potential on the flight path of the positrons, leading to a spatial-temporal focusing of the particles at the minimum of the potential. For a flight path of length L, and accelerating potential V_0, and a positron energy spread of ΔE, the duration of the pulse is given by

$$\Delta t = 2\sqrt{\frac{m}{e}}\frac{L\sqrt{\Delta E}}{V_0}. \tag{1}$$

From this equation, it can be seen that harmonic potential bunching benefits significantly from the use of trapped positrons, in that both L and ΔE can be made much smaller than in conventional beam systems, leading to shorter pulses. For example, with $V_0 = 500$ V, $L = 10$ cm, and $\Delta E = 0.025$ eV, one would obtain $\Delta t = 150$ ps, which would be suitable for positron annihilation spectroscopy.

4. Brightness enhancement

Trap-based beam systems have the ability to produce brightness-enhanced beams by compressing the positrons radially prior to release. This is accomplished by applying a rotating electric field to the particles in the presence of a cooling mechanism.

This technique was recently demonstrated for positrons using buffer gas cooling [12,13]. A rotating electric field was applied to clouds of 10–20 million positrons confined in a Penning trap by applying suitably phased sine waves to azimuthally segmented electrodes surrounding the plasma. Cooling was provided by vibrational excitation of polyatomic gases at pressures of $\sim 2\times 10^{-8}$ Torr. The most effective cooling gases for this application were found to be CF_4 and SF_6. At these pressures, positron annihilation is negligible ($\tau_a > 1000$ s). As shown in Fig. 3, in this first proof-of-principle experiment, rapid compression was observed ($\dot{N}/N \sim 15\ \mathrm{s}^{-1}$), with the plasma diameter being reduced from $\sim$3.5 to 0.7 mm in a few seconds. In systems designed for this technique, significantly greater compression is expected.

Another technique for brightness enhancement using trapped positrons becomes possible if a significant amount of positron space charge can be accumulated in the trap. In this case, when the confining voltage is reduced to release the positrons, they are released first from the volume closest to the axis of the charge cloud. Thus, the initial beam is narrower than the charge cloud itself. For this technique to be effectively employed for brightness enhancement, only a small portion of the positrons should be released. The rotating electric field, in combination with natural cross-field transport processes could then

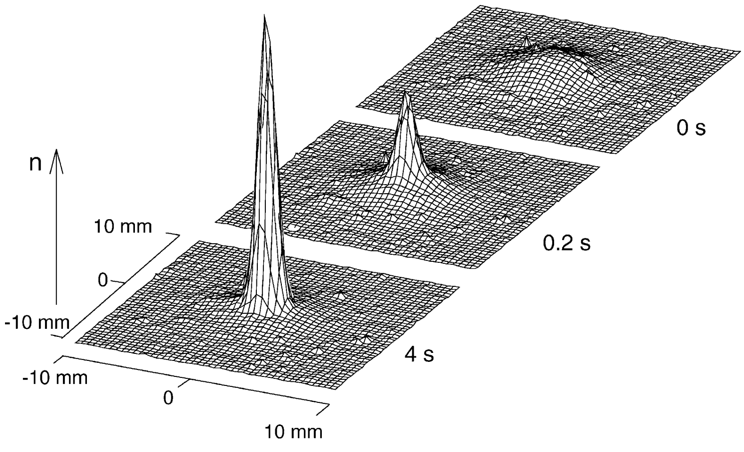

Fig. 3. Radial profiles of a positron plasma following the application of a rotating electric field at $t = 0$. Conditions were: $N_{tot} = 10^7$ positrons, signal frequency, $f_w = 2.5$ MHz, signal amplitude $A_w = 56$ mV. The cooling gas was CF_4 at a pressure of 2×10^{-8} Torr.

be used to replenish the depleted central portion of the plasma. The charge cloud would have to be continuously (or periodically) replenished to maintain the total space charge. The condition for this technique to function correctly is that the space charge potential energy must be much greater than the thermal energy of the positrons. This can be easily arranged in a positron trap because of the low positron temperature. For example, 5 million positrons (amounting to only a few seconds accumulation) in a cloud 1 cm long would have a space charge which modifies the space potential by about 1.5 V, in comparison with the positron energy spread of 0.025 eV.

5. Energy shifting

For many positron-based surface spectroscopy systems, positrons must be injected into the sample at energies of several kilovolts or greater. Since dc accelerating potentials are generally used, either the source or the target must be at high potential. This disadvantage can be overcome in trap-based beams by accumulating the positrons at low potential from a grounded source, and then raising the potential on the trap electrodes so that the positrons can be injected with high energy into a grounded target.

6. Current developments

First Point Scientific Inc. is currently developing trap-based positron beams for commercial applications [22]. Two systems are under development. One is an advanced positron beam source (APBS), featuring a compact, reduced cost, two-stage version of the system described in Section 2, with an integral harmonic potential buncher for producing positron pulses of $\sim$200 ps duration. The second is a positron trap beam source (PTBS) designed to accumulate positrons from the APBS and compress them using a rotating electric field with the goal of producing microbeams. The PTBS can also accommodate cryogenic electrodes for producing ultracold positron beams.

At the University of California, San Diego, a cryogenic UHV trap is currently being constructed [18]. Positrons from a buffer gas trap will be stacked into a UHV trap. This device is expected to enable the accumulation of large numbers of positrons ($>10^{10}$), and the confinement of high density ($>10^{10}$ cm^{-3}) cryogenic plasmas ($T < 10$ K) with long lifetimes (e.g. days to weeks). This device also has the potential to produce very cold positron beams with parallel energy spreads as low as 1 meV, FWHM.

7. Conclusion

A new generation of positron beam systems based on the extraction of positrons from Penning traps is now being developed. The cornerstone of these new beam systems is the exploitation of techniques that have been developed for manipulating single component positron and electron plasmas in traps. Unique capabilities include the ability to supply ultracold positrons, and to implement novel, high-efficiency brightness enhancement schemes. Although these systems are still in the early stages of development, they have already resulted in beams with state-of-the-art performance. When incorporated into surface analysis tools used by industry and in research, these systems offer the potential for substantially improved performance at low cost. For scientific users, they offer new capabilities and the potential to investigate regimes not presently accessible to experiment.

Acknowledgements

The work at University of California, San Diego is supported by the Office of Naval Research, Grant no. N000-14-97-1-0366. The work at First Point Scientific Inc., is supported by the Office of Naval Research, Grant no. N00014-00-C-0710, and the National Science Foundation, Grant no. DMI-0078468.

References

[1] W.E. Kauppila, T.S. Stein, Adv. Atomic Mol. Opt. Phys. 26 (1990) 1.
[2] R.G. Greaves, M.D. Tinkle, C.M. Surko, Phys. Plasmas 1 (1994) 1439.
[3] B.L. Brown, M. Leventhal, A.P. Mills Jr., D.W. Gidley, Phys. Rev. Lett. 53 (1984) 2347.
[4] L.D. Hulett Jr., et al., Chem. Phys. Lett. 216 (1993) 236.

[5] M. Charlton, et al., Phys. Rep. 241 (1994) 65.
[6] P.J. Schultz, K.G. Lynn, Rev. Mod. Phys. 60 (1988) 701.
[7] R.H. Howell, et al., Appl. Surf. Sci. 116 (1997) 7.
[8] A.P. Mills Jr., Exp. Meth. Phys. Sci. 2A9 (1995) 39.
[9] D. Segers, J. Paridaens, M. Dorikens, L. Dorikens-Vanpraet, Nucl. Instrum. Meth. Phys. Res. A337 (1994) 246.
[10] T. Akahane, et al., Appl. Phys. A 51 (1990) 146.
[11] S.J. Gilbert, C. Kurz, R.G. Greaves, C.M. Surko, Appl. Phys. Lett. 70 (1997) 1944.
[12] R.G. Greaves, C.M. Surko, Phys. Rev. Lett. 85 (2000) 1883.
[13] R.G. Greaves, C.M. Surko, Phys. Plasmas 8 (2001) 1879.
[14] R.G. Greaves, C.M. Surko, Phys. Plasmas 4 (1997) 1528.
[15] C.M. Surko, M. Leventhal, A. Passner, Phys. Rev. Lett. 62 (1989) 901.
[16] A.P. Mills Jr., E.M. Gullikson, Appl. Phys. Lett. 49 (1986) 1121.
[17] T.J. Murphy, C.M. Surko, Phys. Rev. A 46 (1992) 5696.
[18] C.M. Surko, S.J. Gilbert, R.G. Greaves, in: J.J. Bollinger, R.L. Spencer, R.C. Davidson (Eds.), Proceedings of the AIP Conference on Non-Neutral Plasma Physics III, Vol. 498, AIP, Melville, New York, 1999, pp. 3–12.
[19] S.J. Gilbert, R.G. Greaves, C.M. Surko, Physical Review Letters 82 (1999) 5032.
[20] J. Sullivan, S.J. Gilbert, C.M. Surko, Phys. Rev. Lett. 86 (2001) 1494.
[21] A.P. Mills Jr., Appl. Phys. 22 (1980) 273.
[22] R.G. Greaves, C.M. Surko, in: J.J. Bollinger, R.L. Spencer, R.C. Davidson (Eds.), Proceedings of the AIP Conference on Non-Neutral Plasma Physics III, Vol. 498, AIP, Melville, New York, 1999, pp. 19–28.