Creation of a monoenergetic pulsed positron beam

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We have developed a versatile, pulsed source of cold ($\Delta E = 0.018$ eV), low-energy positrons ($E \approx 0$–9 eV). Multiple pulses of 10^5 positrons, each 10 μs in duration, are extracted from a thermalized, room temperature positron plasma stored in a Penning trap. The frequency, duration, and amplitude of the pulses can be varied over a wide range. © *1997 American Institute of Physics.* [S0003-6951(97)00115-0]

In this letter we describe a new and versatile source of high-intensity, cold, pulsed positrons extracted from a Penning trap. This source unites many of the attractive features not available previously using any single technique. There are numerous potential applications for bright sources of slow and cold positrons. Examples include material surface characterization, such as defect depth profiling, positron and positronium gas scattering, and annihilation studies.[1] Furthermore, many applications of positron beams, such as time-of-flight measurements, positron lifetime experiments, and time tagging, require pulses of positrons. One advantage of pulsed beams, as compared with steady state beams, lies in the potential for greatly enhanced signal-to-noise ratios. Various techniques to create pulsed positron beams have been reported.[2–4] However, many of these techniques have disadvantages, for example the degrading of the perpendicular and/or parallel energy spread in order to achieve pulse compression.

There are several possible approaches to generate slow positron beams.[1,5] The positrons originate from a radioactive source or from a particle accelerator, but in either case they must be slowed from initial energies of several hundred keV to energies in the electron Volt range before beam formation and handling becomes practicable. At present this is accomplished most effectively using a solid-state moderating material.[1,6–8] In general, positrons emerge from the moderator with an energy of several electron Volts and an energy spread in the range 0.3–2 eV, although methods have been described to reduce this energy spread by as much as an order of magnitude in some instances.[9,10]

We have previously developed positron storage and handling techniques, using a Penning trap as a reservoir of thermalized, room-temperature positrons.[11] Figure 1 shows the confinement region and electrode potentials. A more detailed description of the apparatus can be found in Ref. 12. A 40 mCi ^{22}Na source provides a flux of fast positrons, which is slowed by a solid Ne moderator to ≈ 2 eV. The slow positrons are then guided magnetically into a multistage Penning trap, where they cool to room temperature by inelastic collisions with a nitrogen buffer gas. Collisional cooling on nitrogen has the advantage of increasing the particle phase space density without the losses of positrons that use of a remoderation stage[13] would entail. The axial magnetic field in the trap is 1 kG.

The positrons have a lifetime of approximately 30 s in the presence of the buffer gas (10^{-7} Torr), although the lifetime can be as long as 1 hour at the base pressure of the device (5×10^{-10} Torr) when the buffer gas is evacuated. An attractive feature of the positron trap is its ability to capture 30% of the moderated positron beam. For a 40 mCi source, this gives a positron fill rate of $\sim 1 \times 10^6$ s^{-1}. In the experiments described here, positrons were filled for 10 s, resulting in about 10^7 positrons in the trap. Because this fill time is much shorter than the 30 s positron lifetime, the loss of captured positrons during the fill phase is small. The positrons are then dumped in a few milliseconds, so that in this mode of operation the duty cycle for accumulation is close to unity. Hence, the average throughput is about 1×10^6 positrons per second.

After a positron plasma has been accumulated in the trap, pulses are generated by applying incremental voltage steps to the dump electrode (c.f. Fig. 1), with each increase in voltage ejecting a fraction of the stored positrons. During this process the entrance gate is placed 1 V above the exit gate to insure that the positrons leave the trap via the exit gate. The energy of the pulses is defined by the potential of the exit gate electrode. In order to achieve a narrow energy spread, it is important that the steps in the dump voltage be small compared to the plasma space charge. Otherwise, collective phenomena can be excited in the charge cloud, which could degrade the energy resolution.[14,15] By using the central electrode to dump small fractions of the plasma, the energy of the released positrons remains the same for all pulses, determined solely by the potential of the exit gate.

A cylindrically symmetric electrostatic energy analyzer is used to measure the energy distribution of the pulses (see Fig. 1). The positrons are detected with a NaI(Tl) γ-ray detector. Alternatively, the positron plasma can be imaged by a

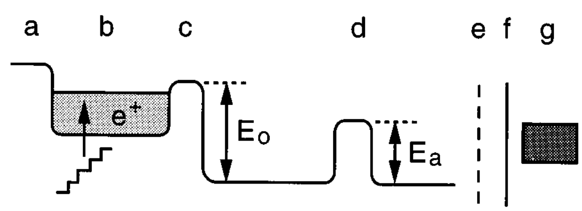

FIG. 1. Schematic diagram of the experiment. The solid line represents the potentials applied to the electrodes; (a) entrance gate, (b) dump electrode, (c) exit gate, (d) energy analyzer, (e) electrostatic grids, (f) phosphor screen, and (g) CCD camera or NaI gamma-ray detector. E_0 and E_a are the electrostatic potentials of the exit gate electrode and the energy analyzer, respectively.

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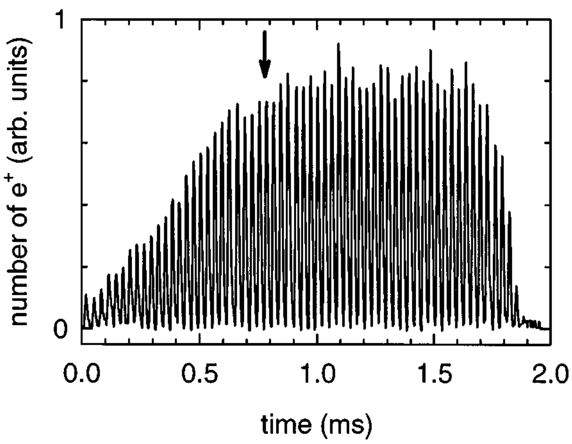

FIG. 2. A pulse train of 60 pulses, each consisting of approximately 10^5 positrons, shows the ramp-up, flat-top, and terminal phases of the pulse envelope, which is independent of the specific number of pulses. The energy distribution shown in Fig. 3 was obtained for a pulse at the beginning of the flat-top portion of an equivalent envelope (see arrow).

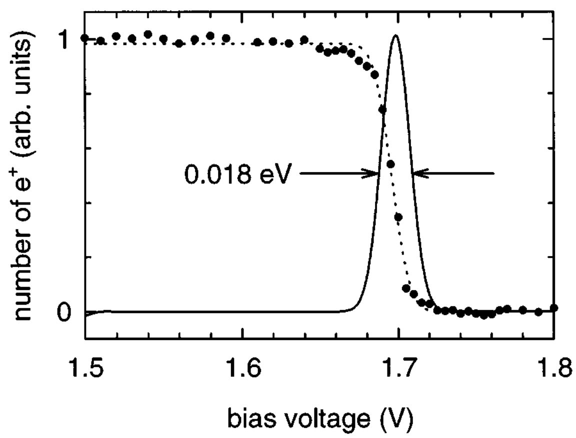

FIG. 3. Energy distribution of a pulse, normalized to unity. Filled circles are the measured data; the dashed line is an error function fit to the data. The solid line, which represents the energy distribution, is the derivative of the fit.

CCD camera, which views a phosphor screen. In this case, an electrostatic grid accelerates the positrons to 8 keV before they reach the phosphor screen.

Figure 2 depicts a train of 60 pulses obtained by applying 60 equal amplitude voltage steps to the dump electrode. For approximately the first 30% of the pulses in the train, the pulse height increases and then stays constant for the remainder of the pulses. We find that the envelope of the pulse train is unaffected by the number of pulses contained in it. Thus, it should be possible to increase the flat-topped portion of the pulse train by adjusting the step size in the dump voltage during the early part of the ramp to compensate for the smaller pulse amplitude there. To ensure that all particles with energies greater than the exit gate potential have sufficient time to leave the trap, we apply each voltage step for 15 μs, which is longer than the axial bounce time in the trap ($\tau_b \approx 6$ μs). Pulse durations less than τ_b can be produced by increasing the dump electrode potential for a time shorter than τ_b before returning it to a lower value. This latter protocol would achieve shorter pulses with a corresponding reduction in the number of positrons per pulse. Spatio-temporal focusing of the beam onto a target[3] could further reduce the pulse duration.

Using a CCD camera, we imaged the radial structure of the pulses, yielding a full-width-at-half-maximum (FWHM) of about 2 cm, which is roughly equal to the measured plasma size. This is representative of the first 75% of the pulse train. Thereafter, the profiles broaden and may become hollow for the last few pulses.

Positron beams with a well defined energy are of primary importance for many applications. A room-temperature plasma will equilibrate to an energy spread corresponding to $\frac{1}{2}kT$ per degree of freedom. In a previous experiment we have shown that the perpendicular energy spread of the plasma is not affected by the dumping process and remains at room temperature.[12]

In the regime where the steps in the potential of the dump electrode are small compared to the plasma space charge, the axial pulse energy spread is not affected strongly by the step size or the position of the pulse in the pulse train. Contributions to the axial energy spread include the radial variation of the exit gate potential across the plasma width, collective plasma effects,[14] and electrical noise on the electrodes. The axial energy spread varies little among pulses in a pulse train.

The axial energy distribution of a pulse taken at the beginning of the flat top portion of the pulse envelope is shown in Fig. 3. The number of positrons reaching the energy analyzer (c.f. Fig. 1) is plotted as a function of analyzer voltage, with the exit gate electrode set at 2 V and a step size of the dump electrode of 37 mV. An error function is fitted to the data and indicates a pulse centroid energy of 1.69 eV, with an energy spread of 0.018 eV FWHM. We attribute the difference of about 0.3 eV between the measured positron energy and the applied exit gate potential to a combination of contact potentials and the radial potential gradient. A lower limit of the beam energy is the axial temperature spread of the beam. The highest beam energy used in this experiment was 9 eV, but this was limited only by the maximum output voltage of the digital-to-analog voltage converters.

We have also created quasi-steady-state positron beams of 0.5 s in duration. This was done by raising the dump voltage continuously over a time scale much longer than the particle bounce time. The beam energy spread in this case was 0.017 eV FWHM.

We are aware of one other report of a Penning trap used as a pulsed source of positrons.[16] Pulses of 1.3×10^5 positrons were derived from a LINAC, and extracted from a Penning trap by applying voltage pulses to the exit gate. However, no attempt was made to achieve a well defined beam energy or narrow energy spread.

Brightness is an important figure of merit for beam sources. Use of the positron trap and a buffer gas to cool the positrons increases their phase space density, and hence the beam brightness, without significant loss of beam intensity. Our pulse brightness is 1×10^9 $\mathrm{s^{-1}\,rad^{-2}\,mm^2\,eV^{-1}}$, which is higher than the brightness achieved using a steady state positron beam with two remoderation stages.[1] In principle, compressing the stored plasma radially by applying an azimuthally rotating electric field to segmented electrodes surrounding the plasma (c.f. Ref. 17) or using source positrons at cryogenic temperature could be means to enhance the brightness even further.

In summary, we have described a new and versatile technique of producing cold and intense positron beams and pulses in a laboratory-scale device. This technique combines advantages that were previously only available in separate devices. A pulsed beam of cold, low energy positrons is extracted from a thermalized, room-temperature plasma and yields high intensity pulses of 10^5 positrons at variable energies and in repeatable pulse trains. The energy spread in the perpendicular degrees of freedom is $\frac{1}{2}kT=0.025$ eV. In the axial direction, we measure energy spreads of about 0.018 eV FWHM. Simple modifications of the method of pulse extraction should produce even narrower energy spreads. It should also be possible to obtain narrower radial beam profiles by compressing the plasma prior to pulse extraction, resulting in a further brightness enhancement. Because the positron pulses generated using this technique are available on demand, with adjustable energies, and at variable intensities, we expect this kind of pulsed beam source to be useful in a wide range of applications.

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[1] P. J. Schultz and K. G. Lynn, Rev. Mod. Phys. **60**, 701 (1988).
[2] R. Suzuki, Y. Kobayashi, T. Mikado, H. Ohgaki, M. Chiwaki, and T. Yamazaki, Hyperfine Interact. **84**, 345 (1994).
[3] W. S. Crane and A. P. Mills, Jr., Rev. Sci. Instrum. **56**, 1723 (1985).
[4] A. P. Mills, Jr., E. D. Shaw, R. Chichester, and D. M. Zuckerman, Rev. Sci. Instrum. **60**, 825 (1989).
[5] E. Ottewitte and A. H. Weiss, editors, *AIP Conference Proceedings 303* (American Institute of Physics, New York, 1992).
[6] M. Charlton and G. Laricchia, Hyperfine Interact. **76**, 97 (1993).
[7] A. P. Mills, Jr. and E. M. Gullikson, Appl. Phys. Lett. **49,** 1121 (1986).
[8] E. M. Gullikson, M. A. P., W. S. Crane, and B. L. Brown, Phys. Rev. B **32**, 5484 (1985).
[9] B. L. Brown, W. S. Crane, and A. P. Mills, Jr., Appl. Phys. Lett. **48**, 739 (1986).
[10] D. A. Fischer, K. G. Lynn, and D. W. Gidley, Phys. Rev. B **33**, 4479 (1986).
[11] C. M. Surko, M. Leventhal, and A. Passner, Phys. Rev. Lett. **62**, 901 (1989).
[12] R. G. Greaves, M. D. Tinkle, and C. M. Surko, Phys. Plasmas **1**, 1439 (1994).
[13] A. P. Mills, Jr., Appl. Phys. **23**, 189 (1980).
[14] G. Hart, J. M. Curtis, and B. G. Peterson, Bull. Am. Phys. Soc. **41**, 1523 (1996).
[15] D. L. Eggleston, C. F. Driscoll, B. R. Beck, A. W. Hyatt, and J. H. Malmberg, Phys. Fluids B **4**, 3432 (1992).
[16] D. Segers, J. Paridaens, M. Dorikens, and L. Dorikens-Vanpraet, Nucl. Instrum. Methods Phys. Res. A **337**, 246 (1994).
[17] X.-P. Huang, F. Anderegg, E. M. Hollmann, C. F. Hollmann, and T. M. O'Neil, Phys. Rev. Lett. (in press).