Subnanosecond bunching of a positron beam

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A simple scheme for bunching spatially distributed charged particles is described. In the present application, sub-nanosecond width pulses are obtained from a milliliter volume containing slow ($\leqslant 2$ eV) positrons. The utility of this technique is demonstrated by a qualitative observation of the temperature dependance of the surface state lifetime for positrons on aluminum.

INTRODUCTION

Many experiments in positron physics involve the measurement of the extremely short lifetimes of electron–positron systems. The endpoint of this time interval has a well-defined signature (the appearance of gamma photons), but the starting point of the interaction is rather more challenging to pin down. The difficulty of passive detection of single low-energy positrons leads to the consideration of more creative timing methods. The first measurement of the e^+ surface state lifetime[1] used a start pulse obtained from the secondary electrons produced when positrons enter the sample. Another method, useful when a distribution in energy is tolerable, is to produce a narrow width pulse of positrons at precise intervals.[2] This can be accomplished by bunching with a pulsed electric field.

We begin with an existing beam of axially confined slow positrons.[3] The positrons are allowed to pass into the bunching region, and are then suddenly accelerated in a harmonic potential toward the target. The effectiveness of this method results from the happy circumstance that the frequency and amplitude of a harmonic oscillator are independent. In other words, if charges are initially at rest when such a potential is turned on, they would simultaneously arrive at a target located at the potential minimum, from any initial spatial distribution. To realize such a parabolic potential, one must find a suitable electrode configuration. The design was carried out with a computer model which employed ray tracing,[4] in conjunction with some analytic calculations.

I. THEORY AND MODEL

A. Design considerations

The beam energy, and overall system dimensions were fixed by the characteristics of our tungsten moderated,[5] Co^{58} slow positron source. By reverse biasing the moderator, the beam energy, E_0, was adjusted to be ~ 1 eV, with a FWHM of 1/4 eV. The beam was roughly $\frac{1}{4}$-in. circular diameter with a uniform cross section. A 1-in.-diam AL (111) single crystal served as a target.

We require a quadratic potential on axis, with its minimum positioned at the target. In addition, we must be able to rapidly apply this potential only after the charged particles have been allowed to pass into the bunching region. These requirements give rise to the following primary concerns regarding resolution.

1. Harmonicity

The simplest approximation to a harmonic potential would be obtained from a geometric distortion of the linear potential of a parallel plate capacitor. Our preference for a two-electrode design eliminates the need for resistive elements, and associated construction problems. A closed cylinder geometry was chosen, the aspect ratio of the cylinder being a free parameter. The distribution of equipotentials for this configuration is shown in Fig. 1. The optimum aspect ratio was arrived at by fitting the axial potential to a parabola and minimizing the rms percent deviation. The minimum was later compared with the minimum obtained from computing the rms width of the resulting positron pulse and found to be in agreement. The best fit corresponded to an rms deviation less than 2%, with most of the error in the low field region near the target. A typical result for the axial potential is plotted with the calculated harmonic potential in Fig. 2.

2. Input beam

The finite diameter of the beam was taken into acocunt by doing all ray calculations with off axis particles. The energy spread was approximated with monoenergetic compo-

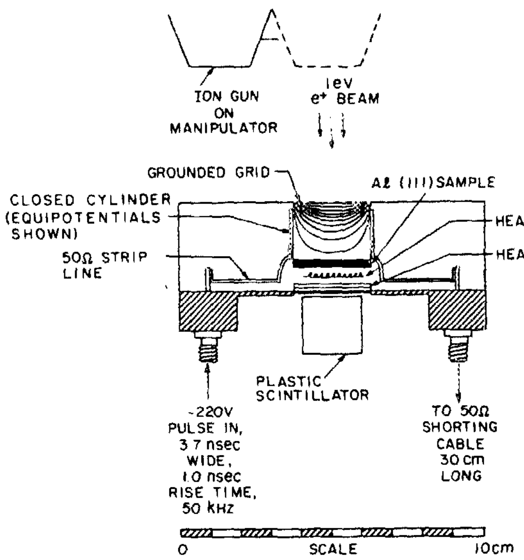

FIG. 1. Experimental arrangement for measuring surface state lifetimes showing equipotential lines of buncher.

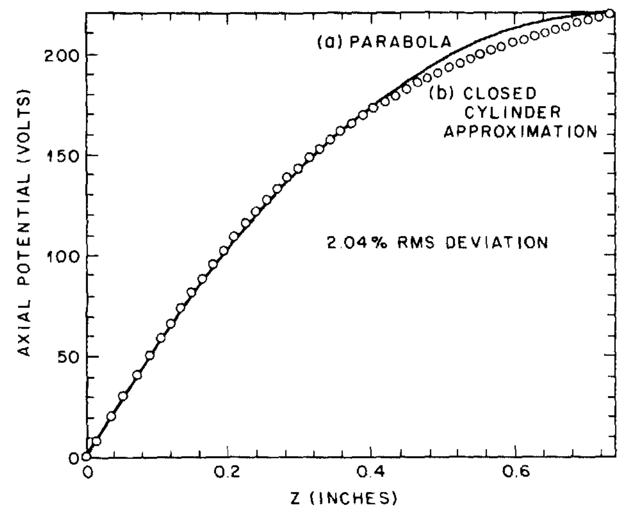

FIG. 2. Axial potentials.

nents at E_0 and $E_0 \pm \Delta E_0/2$. The transverse energy of the beam was not considered.

3. *Rise time*

The effect of the bunching voltage pulse rise time was included via a two step calculation. Since the electron optics program could not handle time varying electric fields, trajectories were analytically obtained for a linearly ramped perfect harmonic potential. This calculation produced starting positions and energies for use in the ray tracing program with the actual, somewhat anharmonic, potential.

B. Mode of operation

Assuming a perfect harmonic potential, a constant initial axial distribution, and a monoenergetic beam, the solution of the equations of motion gives the arrival time as a function of the starting position z,

$$\Delta t(z) = (1/\omega) \tan^{-1}[-\omega(z - l)/v_0],$$

where $\omega^2 = -2qV/ml^2$, V is the voltage pulse height, l is the buncher length, v_0, q, and m are the initial (beam) velocity, charge, and mass of the positron. This reduces to a flat distribution when the beam energy is zero, as expected. The shape of this distribution, particularly the presence of early arriving particles which started close to the target, suggests that a small $(eV_b \gg E_0)$ repulsive bias on the target would immediately improve the time resolution. Although we will now have particles with both positive and negative initial velocities, their magnitudes, on the whole, will be less than the original beam energy, and the early arrivers will have been eliminated.

The ultimate time resolution of the buncher clearly degrades with increasing E_0, all other things being the same, therefore, as a general rule, the input beam energy should be as small as possible, i.e., $E_0 = \Delta E_0/2$ where ΔE_0 is the FWHM beam energy spread. Unfortunately, our data to be presented below was obtained with the less than optimal $E_0 \sim 4\Delta E_0$.

With the target reflecting, the total time that a positron of energy E_0 spends in the buncher is given by $t_c = (2/\kappa)\tanh^{-1}(E_0/qV_b)^{1/2}$. This time, multiplied by the beam current, gives the number of particles in each bunch. In general, the collection time may be increased by decreasing the bias, thereby admitting more positrons. For the case when the bias is at its minimum, $V_b = \Delta E_0$, the maximum counts per pulse are given by $t_c = 30l/V^{1/2}$, where t_c is in nanoseconds and V is in volts. Conversely, the time resolution of the buncher improves with increased reflecting bias. In large part, this is because when the beam is restricted further from the target, the initial energy is a smaller percentage of the accelerating potential. In the closed cylinder approximation, there is an additional benefit since the potential away from the target is more nearly harmonic. The lower limit to resolution is obtained from the approximate formula, $w = 16l/\Delta E_0^{1/2} V$, where w is the width in nanoseconds, l is in centimeters, E_0 is in electron volts, and V is the pulse height in volts. This equality is true for large bias, $V \gg E_0$, and $E_0 = \Delta E_0/2$. This resolution limit is plotted in Fig. 3(d).

Another feature of the reflecting mode is the fact that the between-pulse noise signal is reduced, since the beam does not reach the target unless the pulse is present.

C. Calculations

Ray tracing calculations were performed for various pulse heights and bias conditions. The resulting arrival time curves were distilled by numerical integration into rms pulse widths at the target, and mean arrival times. More specifically, we obtained the distribution of arrival times at the target, $N(t)$, using

$$N(t) = \int dz\, n(z)\delta[\Delta t(z) - t],$$

where $n(z)$ is the distribution of starting positions and energies, and the arrival time curve, $\Delta t(z)$, was procured through ray tracing. As $N(t)$ was, in general, a rather skewed distribution, its first and second moments were then calculated. To evaluate the system resolution, the rms widths thus obtained were converted to equivalent FWHM widths.

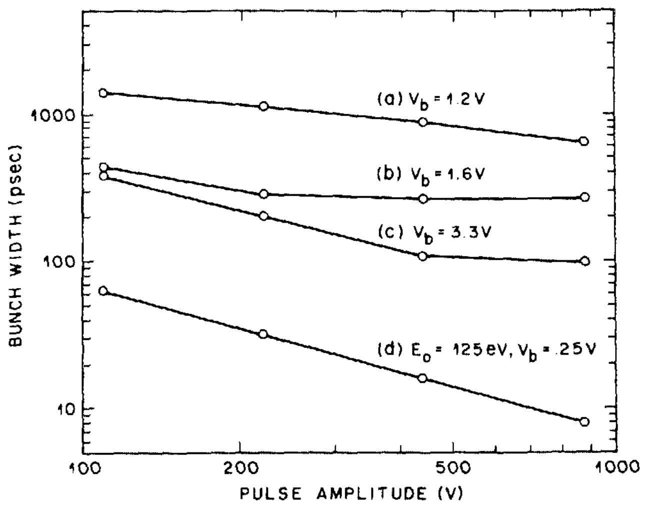

FIG. 3. Calculated equivalent FWHM widths of positron pulses. For (a), (b), and (c), the beam energy is 1 eV and the expected count rates are, respectively, 20%, 50%, and 80% of the optimum rate. Curve (d) is the zero rise-time harmonic limit for a 0.25-eV FWHM beam.

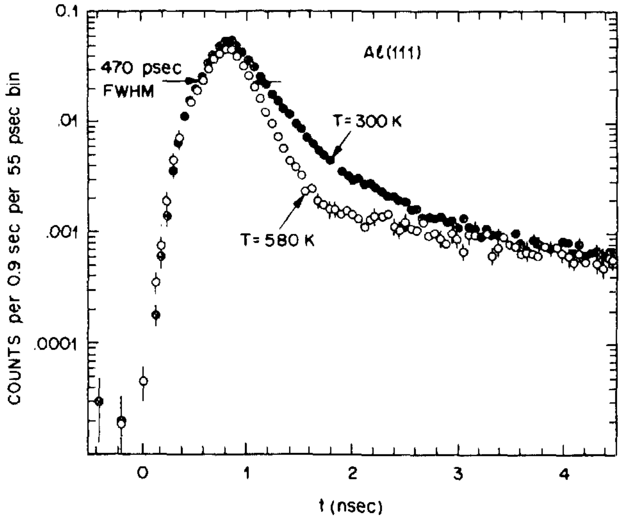

FIG.4. Surface state lifetime decay data.

The calculations in Fig. 3 were performed for an input beam FWHM of 0.25 eV, as was available during the experiment. For curves (a) through (c), the plotted points contain the combined effects of our 1-eV input energy, a finite diameter beam, an anharmonic potential, and a 1-ns pulse rise time. The curves were generated for the various bias conditions indicated. The corresponding count rates are given in percentage of the maximum collection time under these conditions. Curve (d) represents the best attainable resolution given our 0.25-eV energy spread. It was obtained analytically for a 0.125-eV axial input beam in a zero rise-time harmonic potential.

II. EXPERIMENT

The buncher described here was used in an attempt to measure surface state lifetimes for positrons on aluminum. The experimental arrangement we arrived at is shown in Fig. 1. When the positrons from each bunch annihilate with electrons from the surface, the resultant *γ rays* are counted with a plastic scintillator and Hammamatsu R1294 phototube.

The idea in this experiment was to record decay curves with the target surface at two different temperatures. In the higher temperature run, more positrons were expected to be thermally pushed out of the surface well. Thus, a comparison of the two runs would indicate the presence of the surface state and give a measure of its lifetime. Typical data, as in Fig. 4, were obtained over a period of two days for about forty thousand total counts.

The experiment used a magnetically guided positron beam, thus was necessarily immersed in a 150-G axial field. Such a field frustrates the radial motion in the buncher but does not affect the z component of the velocity, whose magnitude defines the time resolution of the system.

Pulses of 220-V amplitude were generated by an avalanche transistor circuit with a 1-ns rise time and 3.7-ns width. These parameters represented the best available compromise between voltage and rise time. A circuit diagram and plot of the output pulse is given in Fig. 5. The width of the pulse was chosen only slightly wider than the longest transit time in the buncher, $T \sim \pi/2\omega$. The pulse was reflected back by a shorted stub to effect a rapid change of sign of the target voltage. This reduced the signal due to reemitted or bounced positrons, which may otherwise be attracted back to the surface. The bias voltage during the experiment, as in curve (b) of Fig. 3, was 1.6 V. For our 1-eV beam, this amounts to sacrificing half of the available counts for improved resolution.

Since the longest lifetime in this experiment is only 1/7 μs, one could, in principle use a high-repetition rate. The rate we used was a moderate 50 kHz, limited by heat dissipation in the avalanche transistors. In a way, the concept of "bunching" is misleading, as during the experiment, the bunches contained, on average, less than one positron. However, the technique was essential in providing uniformity of arrival times from pulse to pulse.

III. CONCLUSIONS

The data in Fig. 4 show a clear difference between the hot and cold runs. In each spectrum, the peak at $t = 0$ is

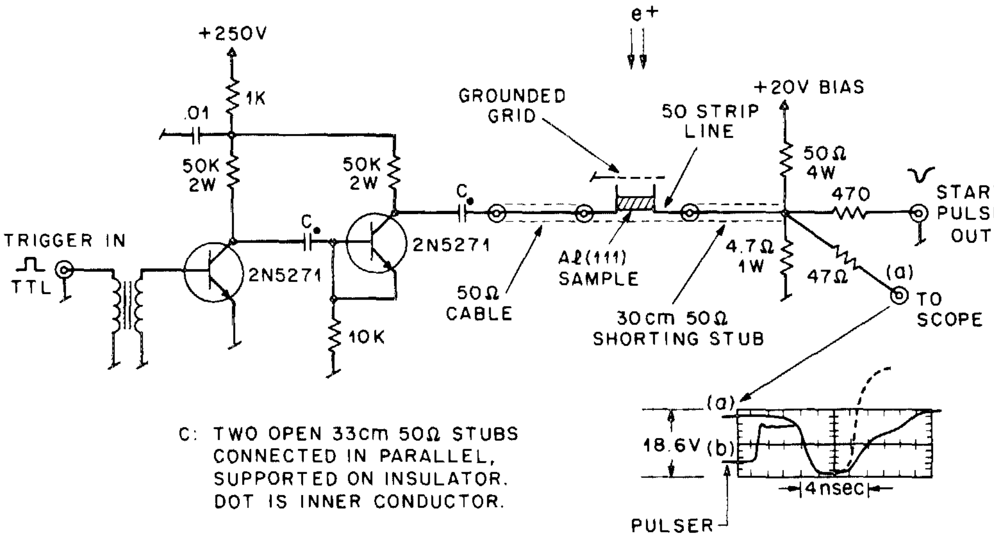

FIG.5. Pulse circuit and output.

predominantly bulk annihilation and singlet *Ps*, and the long tail is due to triplet *Ps*. The sample-cold data, for which the surface state was accessible, contains an extra lifetime component. Thus, the temperature dependence provides confirmation of our present ideas concerning the surface state. Unfortunately, our uncertainty concerning the resolution is too great for a meaningful comparision with the previous measurement by Lynn, *et al.*[1] The 470-ps width is a convolution of the resolution function of our detection apparatus, that of the buncher pulse and the intrinsic width. Thus, we may only assign an experimental upper limit on the performance of the buncher. In future applications, a direct measurement of the experimental resolution could be performed by isolating the buncher from the sample using a grid in its place. With a large negative bias on a noncrystalline sample, defect trapping of the implanted positrons would yield a single lifetime component.[6] This configuration could also be used with a small positive voltage to reduce the resolution degrading effect of bounced positrons.

The potential produced by our simple geometry proved to be adequately parabolic, having no discernable effect on the calculated time resolution. Similarly, a 1-ns pulse rise time was found to have only a small effect. We have found that in optimizing resolution, a trade off can be made between time resolution and particles per pulse, in which one is ultimately limited by the energy width of the input beam. For the present case, this compromise was a secondary effect, since we did not operate our experiment at the lowest possible beam energy. In future operation with $E_0 = \Delta E/2$, we expect a reduction in bunch width by nearly an order of magnitude, with no loss in count rate. The buncher would then be limited by curve (d) of Fig. 3, for a 1/4-eV FWHM beam. However, at this point the experimental resolution would be limited by the $\approx$ 100-ps width obtainable from currently available scintillators and photomultipliers.[7]

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