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A positron accumulator

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A design for a two-stage positron accumulator is presented. The first stage employs remoderation cooling of positrons while the second stage utilizes electron cooling. The device is designed to produce intense pulses of positrons at low repetition rates (1–100 Hz). Preliminary results from tests on the first stage are presented.

1. Introduction

Radioisotopes which emit positrons, such as ^{22}Na and ^{58}Co, have been widely used to create cold (< 1 eV energy spread) low energy positron beams [1,2]. However, for many experiments and technological applications the random timing of radiogenic positrons is unsuitable. This article describes progress toward an efficient, inexpensive, and portable positron accumulator capable of producing pulses of positrons for which timing information is available. Such a pulsed beam would be useful in positronium spectroscopy [3] and lifetime [4] measurements, in possible experiments to create Bose-condensed positronium [5], as a positron source for compact positron synchrotron light sources [6], and in experiments to create antihydrogen and measure its hyperfine structure as a test of the CPT theorem [7].

Intense pulsed positron sources based upon e^- bremsstrahlung and subsequent pair production are presently in use [8,9]. These accelerator-based beams suffer from relatively high installation and operating costs and lack portability. This makes them unsuitable for small-scale laboratory use and motivates the search for an inexpensive alternative.

Positrons from radioactive sources are emitted at random times with an energy spread of hundreds of keV. This energy spread can be reduced to a few eV or less through the use of metal moderators [1]. A pulsed beam may be produced by accumulating the positrons in a trap and then ejecting them from the trap suddenly. In addition to the device described in this paper, two types of radioactivity-based positron accumulators have already been built. The first is based upon an rf accumulation and harmonic bunching technique [10]. This approach is unattractive for the above-mentioned applications due to the short trapping times (i.e. high pulse frequencies) which result. The second is based upon positron cooling by residual gases [11]. This requires extensive differential pumping but remains a competitive source of pulsed positrons. A positron accumulator based on a combination of remoderation and electron cooling is described below.

2. The University of Michigan positron accumulator

The device built at the University of Michigan to accumulate positrons is designed to utilize two separate sections (or "stages"). A two-stage device is necessary in order to achieve simultaneously the low pulse frequencies and high efficiencies needed for many applications. Both stages use Penning traps to accumulate positrons. In such traps a magnetic field (~ 130 G in this case) confines the positrons radially while electric fields are used to achieve axial confinement.

Since conservative forces are used to achieve temporal bunching of the positrons, another dimension of phase space must increase (Liouville theorem). In the present case the spread in beam energy expands. This necessitates cooling of the positrons since the applications currently under consideration require beams with narrow energy spreads.

The difference between the two stages of the Michigan positron accumulator lies in the method of application of the required cooling. In both stages the positrons are cooled through immersion in a bath of thermal electrons. In the first stage this is achieved by injecting the positrons into a metal remoderator [12] after the accumulation is complete. The second stage utilizes conventional electron cooling in a merged beam arrangement during the accumulation process. The modes of operation and the merits of both stages are discussed below.

The physical configuration and electrical potentials of the first stage are shown schematically in fig. 1. The axial containment in the first stage is controlled by the voltages applied to the positron moderator (a) on one

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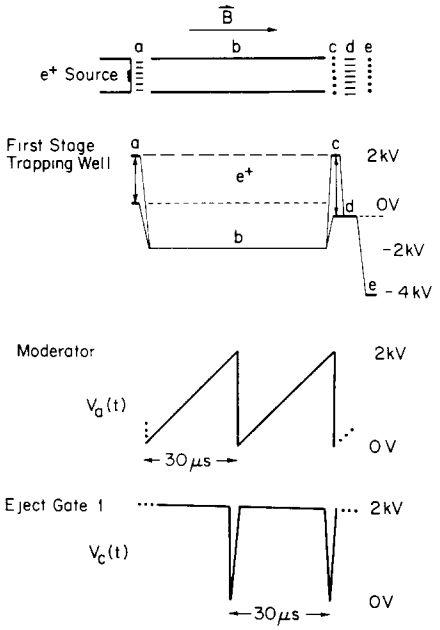

Fig. 1. The first-stage accumulator. The physical configuration of the electrostatic lensing elements (a–e) is shown at the top (see text for discussion). The electric potentials applied to these elements are directly below with arrows indicating voltages which are changing in time. The functional forms of these time-varying voltages are shown at the bottom.

end and to a high transmission, conducting grid (c) on the other. Initially $V_a = 0$ and a positive voltage is applied to grid c. While in the trapping cylinder (b), the kinetic energy of a thermalized positron which has been emitted from the moderator is given by

$$E_K = e(V_a(t) - V_b) - \phi_+, \tag{1}$$

where $\phi_+ \approx -2.8$ eV is the positron work function of the tungsten moderator. These positrons traverse b and are reflected by a potential barrier (V_c) back toward the moderator. The time required for a positron to travel from a to c and back is called the "trap period" and is denoted by

$$\Delta t = 2L/\sqrt{\frac{2E_K}{m}},$$

where L is the length of the trapping well (b). During the trap period V_a is increased by an amount ΔV_a so that the positrons reflected by V_c are not energetic enough to return to the moderator – the positrons are trapped. An advantage of this method of trapping is that the positrons may be trapped very quickly (typically in less than 100 ns).

The value of the moderator voltage at the time of emission ($V_a(t)$) controls the energy of the positrons emitted into the trap. Since $V_a(t)$ is increasing in time, positrons are accumulated in the trap at increasing energies. This process continues until $V_a = V_c$ at which time V_c is suddenly dropped and the accumulated positrons are ejected from the first stage in a pulse (see fig. 1).

The time spread of positrons in the pulse has been greatly decreased since all of the positrons may be retrieved from the trap in one trap period whereas they were stacked in the trap over many trap periods. The energy spread of the accumulated positron pulse is now essentially given by the maximum value of V_a (V_a^{max}). Thus, the time spread of the pulse has been compressed at the expense of an increased energy spread – in accordance with the Liouville theorem. When V_c is dropped to a negative voltage, the accumulated positrons are emitted into a remoderator (d). The positrons are thermalized in the remoderator and re-emitted with a small energy spread. During remoderation the small time spread of the pulse is preserved. Unfortunately, however, 70–80% of the positrons are lost in this process [12].

For reasons of simplicity the preferred form of $V_a(t)$ is a sawtooth wave (see fig. 1). In order to prevent any positrons from returning to the moderator (where they will probably be lost to annihilation) the slope of the ramp must be such that ΔV_a is greater than ΔV_a^{crit} – the critical minimum value. If V_a is increased by ΔV_a^{crit} in one trap period then positrons are just barely able to re-enter the moderator. In practice ΔV_a^{crit} is an experimentally determined parameter which depends on the geometry of the moderator and the trap, but is subject to the constraint $\Delta V_a^{crit} \leq -\phi_+/e$ (see eq. (1)).

The trap period (Δt) is a function of E_K and thus is not constant during the accumulation. In order to use a linear ramp the slope must be chosen to trap those positrons which have the maximum energy, i.e. the minimum trap period:

$$\Delta t^{min} = 2L/\sqrt{\frac{2E_K^{max}}{m}}.$$

The moderator voltage rises ΔV_a^{min} during Δt_a^{min}. If $\Delta V_a^{min} = \Delta V_a^{crit}$ then ~100% accumulation efficiency may be achieved and the slope of $V_a(t)$ is given by

$$\frac{dV_a}{dt} \equiv \frac{V_a^{max} - V_a^{min}}{T_{acc}} = \frac{\Delta V_a^{crit}}{\Delta t^{min}}, \tag{2}$$

where T_{acc} is the duration of the accumulation. Thus, the maximum kinetic energy of positrons which may be efficiently trapped with this ramp is given by

$$E_K^{crit} = \frac{m}{2}\left(\frac{2L}{\Delta V_a^{crit}}\frac{dV_a}{dt}\right)^2 \tag{3}$$

since positrons which are more energetic will traverse the well too quickly and strike the moderator. This

critical energy may be used to determine the optimal period for accumulation:

$$T_{\mathrm{acc}}^{\mathrm{crit}} = \frac{E_{\mathrm{K}}^{\mathrm{crit}} - E_{\mathrm{K}}^{\mathrm{min}}}{e\dfrac{\mathrm{d}V_{\mathrm{a}}}{\mathrm{d}t}}. \tag{4}$$

The optimal design parameters for the first stage trap depend strongly on the details of the solenoid and high voltage pulsers available for use. In the present case, these optimal parameters are $L \approx 80$ cm, $V_{\mathrm{b}} = -2$ kV, and $V_{\mathrm{a}}^{\mathrm{max}} = +2$ kV. The trapping well depth, V_{b}, has been chosen so that the range of trap periods ($\Delta t^{\mathrm{max}} - \Delta t^{\mathrm{min}}$) is not excessive, yet Δt^{min} is still large enough to permit trapping. The resulting minimum trap period is $\Delta t^{\mathrm{min}} \approx 40$ ns so that a slope of

$$\frac{\mathrm{d}V_{\mathrm{a}}}{\mathrm{d}t} \approx 65\ \frac{\mathrm{V}}{\mu\mathrm{s}}$$

should accumulate all moderated positrons during $T_{\mathrm{acc}} \approx 30$ μs.

The width of the positron pulses is given by the trap period of the least energetic positrons in the trap (Δt^{max} which corresponds to $V_{\mathrm{a}} = 0$). Positrons are accumulated for 30 μs and then emitted in $\Delta t^{\mathrm{max}} \approx 60$ ns. The ratio of these time spreads is the time compression factor:

$$\tau \equiv \frac{T_{\mathrm{acc}}^{\mathrm{crit}}}{\Delta t^{\mathrm{max}}} = \frac{E_{\mathrm{K}}^{\mathrm{crit}} - E_{\mathrm{K}}^{\mathrm{min}}}{e\,\Delta V_{\mathrm{a}}^{\mathrm{crit}}} \sqrt{\frac{E_{\mathrm{K}}^{\mathrm{min}}}{E_{\mathrm{K}}^{\mathrm{crit}}}} \approx 500, \tag{5}$$

where the above trap parameters have been used and the assumptions $\Delta V_{\mathrm{a}}^{\mathrm{crit}} = -\phi_{+}/e = 2.8$ V and $E_{\mathrm{K}}^{\mathrm{crit}} = E_{\mathrm{K}}^{\mathrm{max}}$ have been made.

The expected output of the first stage is a series of pulses of positrons (60 ns wide) at a repetition rate of ~ 30 kHz. All of the applications discussed in section 1 require pulsed beams with frequencies in the 1–100 Hz range. Such low pulse rates cannot feasibly be achieved in a single-stage accumulator of the type discussed above since both L and $V_{\mathrm{a}}^{\mathrm{max}}$ would have to be unrealistically high to do so. The positron bunches from the first stage may be accumulated in a second stage resulting in positron pulses of greater intensity emitted at a much lower repetition rate.

The planned second stage of the Michigan positron accumulator uses electron cooling to trap the positrons [13]. The advantage of this scheme over remoderation cooling is that there are virtually no positrons lost during the electron cooling process. Electron cooling circumvents the Liouville theorem by transferring some of the phase space of the positron beam to the electron beam. The total phase space volume is preserved yet the positron phase space decreases. Thus, the energy spread of the positrons is not increased greatly during the second stage accumulation process. Electron cooling cannot be used in the first stage because the time available to cool the positrons (Δt) is not great enough.

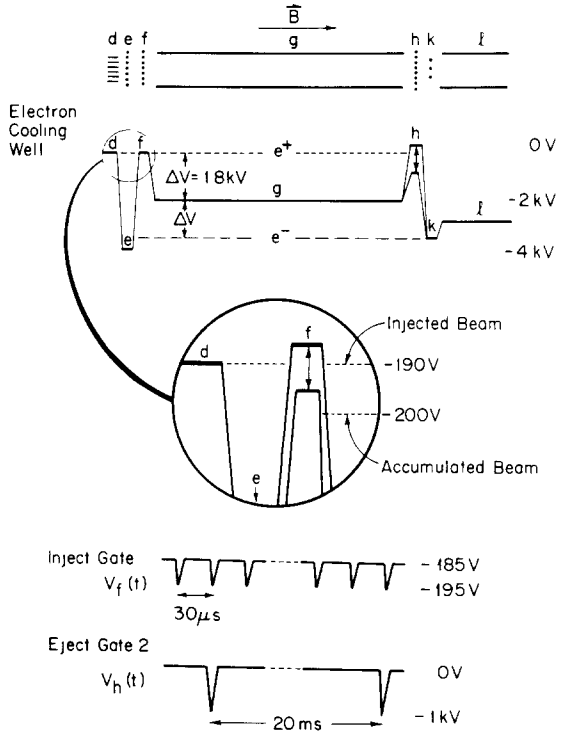

Fig. 2. The second-stage accumulator. The physical configuration of the electrostatic lensing elements (d–k) is shown at the top (see text for discussion). The electric potentials applied to these elements are directly below with arrows indicating voltages which are changing in time. Details of the injection of pulses from the first stage are shown in the inset. The functional forms of the time-varying voltages are shown at the bottom.

The physical configuration and electrical potentials of the second stage are shown schematically in fig. 2. Electrons are emitted from a filament (k), traverse the second trapping well (g) and are reflected by a potential barrier (V_{e}). The kinetic energy of these electrons is given by

$$K_{\mathrm{e}^-} = -e\left(V_{\mathrm{k}} - V_{\mathrm{g}}\right) = e\,\Delta V = 1.8\ \mathrm{keV}. \tag{6}$$

The axial containment of the positron pulses in the second stage is controlled by the voltages applied to grids f and h. When a pulse is emitted from the first stage, V_{f} is lowered enough to allow the pulse to enter the second stage. Once the pulse has entered, V_{f} is raised again and these positrons are trapped between V_{f} and V_{h}. The kinetic energy of the positron pulses injected into well g is given by

$$K_{\mathrm{e}^+} = e\left(V_{\mathrm{d}} - V_{\mathrm{g}}\right) - \phi_{+} \approx 1.81\ \mathrm{keV}. \tag{7}$$

While in this second trap, the kinetic energy of the positrons is reduced to $e\,\Delta V$ through interactions with the electron beam. Thus, a new pulse may be injected

without allowing the previously trapped pulses to escape (see fig. 2 inset). The accumulated pulses are ejected from the accumulator by pulsing V_h at the desired frequency (see fig. 2).

3. Results

The accumulation portion of the first stage is currently operational. The remoderation and the electron cooling stage will be implemented in the near future. At present a small positron source (1.5 mCi of ^{22}Na) is being used to optimize the accumulation technique. The number of positrons available for accumulation may be determined by examining the dc beam of slow positrons produced by the source. This is done by applying electric potentials as in fig. 1 except that $V_c = -200$ V and $V_a = 0$ V. This yields a slow positron beam rate of $R_S = 7200$ cps (the moderation efficiency is 1.4×10^{-4}).

Preliminary tests of the first stage have been run using parameters which were different from those discussed in section 2. Rather than applying the eject pulse to grid c when $V_a(t) = V_a^{max}$ (as in fig. 1) the accumulation period (T_{acc}) was varied by changing the phase between $V_a(t)$ and $V_c(t)$. This was done so that the performance of the accumulator could be examined for different values of E_K^{max} – as summarized in table 1.

The total number of moderated positrons emitted into the trap during one accumulation period is $N_{tot} = R_S T_{acc}$. The efficiency of the accumulator is thus $\eta = N_{obs}/N_{tot}$, where N_{obs} is the number of observed positrons per eject pulse (corrected for detection efficiency and random background). The accumulation efficiency drops off rapidly for $E_K^{max} > E_K^{crit} \approx 250$ eV (see table 1) indicating that the higher energy positrons are not trappable and that $\Delta V_a^{crit} \approx 1.3$ eV (from eq. (3)). As expected the minimum ΔV_a required is comparable to the work function of the moderator ($-\phi_+/e \approx 2.8$ V).

Fig. 3 shows a histogram of detected output positron events versus time after ejection for $T_{acc} = 9 \pm 2$ μs (run number 1 in table 1). The rise time of 60 ns for the first positrons to be ejected is due to the rise time of the eject pulse V_c. The trap period for the most energetic (220 eV) trapped positrons was 70 ns and these events were observed near the peak. The positrons in the tail are those that were trapped at ~ 15 eV kinetic energy ($\Delta t \approx 260$ ns). Approximately 95% of the detected positrons were observed within 260 ns giving $\tau = 35$. Thus, we have demonstrated a considerable time compression at a high efficiency.

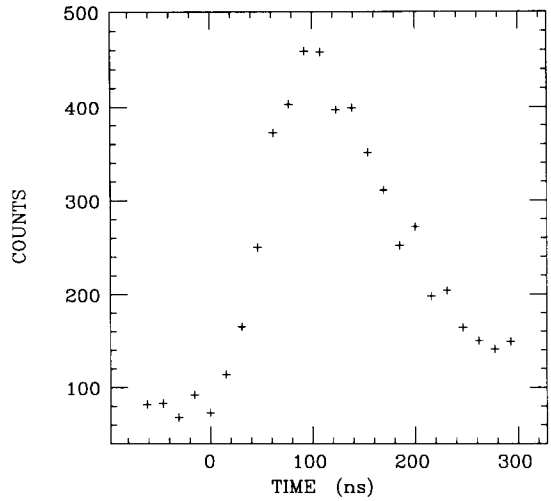

Fig. 3 Histogram of accumulated positrons This histogram shows the counts detected in a NaI crystal (detection efficiency ~ 2%) as a function of time after ejection from the first stage. The data represent a sum of 1.28×10^6 pulses and correspond to run number 1 in table 1.

The main deficiency of this test configuration was the slow ramp rate available on V_a (see table 1). The apparatus has been reconfigured using the parameters from section 2. Tests of this configuration are in progress, and efficient trapping with a time compression factor of 500 is expected. Once this has been achieved the remoderation cooling will be installed. Remodera-

Table 1
Summary of test data. These data were taken with the accumulator in the following configuration: $L = 31$ cm, $dV_a/dt = 19$ V/μs, and $V_b = +200$ V; which implies that $E_K^{min} = 0$ and that accumulation begins when $V_a(t) = +200$ V.

	Run number					
	1	2	3	4	5	6
T_{acc} [μs]	9 ± 2	20 ± 2	33 ± 2	49 ± 2	66 ± 2	82 ± 2
E_K^{max} [eV]	220 ± 40	370 ± 40	620 ± 40	900 ± 40	1250 ± 40	1470 ± 40
Δt^{min} [ns]	70 ± 8	54 ± 4	42 ± 2	34.8 ± 1.5	29.5 ± 1.1	27.2 ± 1.0
ΔV_a^{min} [V]	1.3	1.0	0.8	0.7	0.6	0.5
N_{tot}	0.06 ± 0.01	0.14 ± 0.01	0.24 ± 0.02	0.35 ± 0.02	0.47 ± 0.02	0.59 ± 0.03
N_{obs}	0.089 ± 0.004	0.096 ± 0.004	0.103 ± 0.004	0.105 ± 0.004	0.088 ± 0.004	0.086 ± 0.003
η	1.23 ± 0.28	0.67 ± 0.08	0.43 ± 0.03	0.30 ± 0.02	0 19 ± 0.01	0.15 ± 0.01

tion has become a common technology used in dc slow positron beams, and efficiencies of 20–30% are achieved frequently [12]. Few problems are expected in the adaptation of this technique to pulsed beams. It is anticipated that the installation of the second stage will result in accumulation times in excess of 1 s ($\tau > 10^7$).

4. Applications

The Michigan positron accumulator was primarily designed to provide pulsed positrons for an experiment to measure the fine structure intervals $2^3S_1 \rightarrow 2^3P_J$ ($J = 0, 1, 2$) in positronium. The experiment uses a pulsed excimer laser to photoionize the $n = 2$ level of positronium as a method of detecting the 2^3S_1 state [14]. In order to make efficient use of the laser light, the positrons (and hence the $n = 2$ positronium) must be present when the laser is on. Thus the positrons must also be pulsed.

Assuming the use of a 30 mCi ^{22}Na positron source, the production of 1000 positrons per pulse at 100 Hz is expected. The formation efficiency of 2^3S_1 is 4×10^{-3} of the incident slow positrons, which results in four 2^3S_1 atoms per pulse. Since the detection efficiency using this method is ~ 50% there will be ample numbers of positrons to make measurements of all of the intervals to better than 50 ppm.

Another important application of this accumulator is the formation of antihydrogen ($\bar{H}$) via photorecombination ($\bar{p} + e^+ \rightarrow \bar{H} + \gamma$) in a merged beam arrangement, and the subsequent measurement of the antihydrogen ground state hyperfine structure as a test of the CPT theorem [7]. The repetition rate of the pulsed positron beam shoud be about 1 Hz in order to keep a positron storage ring adequately filled. A very large positron source (60 Ci of ^{58}Co) would provide 10^7 e^+ per pulse which is ample to observe antihydrogen formation and sufficient to measure the hyperfine interval to better than 10 ppm.

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