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TECHNIQUES FOR STUDYING SYSTEMS CONTAINING MANY POSITRONS

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I INTRODUCTION

We are at the threshold of being able to study systems containing finite amounts of antimatter: the electron-positron plasma, positronium molecules and droplets, and surfaces having comparable electron and positron densities. The necessary ingredients for such studies are well known.[1] One must first obtain 10^{-9} sec bursts containing $\sim 10^7$ slow positrons each either from a pulsed electron accelerator [2-4] or from a strong reactor-produced ^{64}Cu radioactive source [5] combined with time bunching stages. [6] The positron bursts must then be brought to focus on a few hundred angstrom diameter spot on a target surface by means of repeated stages of acceleration, focusing and moderation (brightness enhancement [7]). While no one has made such a positron source, progress is being reported on all aspects of the problem.

The purpose of this workshop and this paper in particular is to stimulate further thought on the subject of intense positron beams. We have been encouraged to think especially about the future development of these beams. The next section gives a brief look at some new areas of study that might become available with advanced beam technology and a discussion of terminology: intensity, flux, brightness, phase space density, fluidity, Debye screening, and space charge limitation. Section III is a brief description of our best radioactive source and moderator. Section IV gives some details about an existing time bunching apparatus and points out a way to bunch bunches. The last section is about obtaining one positron at a time.

II Intensity and Brightness

Beams of monoenergetic low energy positrons have been available for more than a decade. Many interesting experiments have been performed that have increased our understanding of positronium atomic physics, positron-molecule scattering, and positron surface interactions. The understanding gained in the latter studies has enabled us to improve our techniques for making slow positrons. There are now beams in several laboratories that may be termed "intense" because they have passed the threshold at which one should be shielded from the annihilation radiation. These beams with intensities I up to $I = 5 \times 10^6$ slow e^+ $\sec^{-1}$ are the equivalent of a 270μ Ci source of 511 keV γ-rays. In combination with various timing, polarizing, focusing, deflecting, detecting and transporting techniques, these beams have given adequate counting rates in many different investigations. In the near future even more intensity will be available with the perfection of the electron accelerator and nuclear reactor sources. A beam of $I = 10^9$ e^+/sec could be called "very intense" because at any instant there would be typically more than one positron in the target. In this sense the LINAC beams and bunched beams are very intense pulsed sources, since they yield bursts having instantaneous intensities $I > 10e^+$/nsec.

Besides its intensity I, a beam if characterized by its flux or intensity per unit area,

$$\Phi = I/(\pi r^2), \tag{1}$$

where r is the beam radius. A beam may also be characterized by its brightness per unit energy, [8]

$$R = \Phi/(E \sin^2 \theta), \tag{2}$$

where E is the kinetic energy of the beam particles and θ is their angular divergence. One of the most useful parameters describing a swarm of N particles is its density in phase space

$$\rho_\phi = N/\Omega, \tag{3}$$

where Ω is the phase space volume occupied by the swarm. For a beam of particles with energy uniformly distributed between E and E+ΔE, with propagation directions uniformly distributed up to a maximum angle θ with respect to the beam axis and with beam radius r, we have approximately

$$\rho_\phi = R/(2m\Delta E). \tag{4}$$

Liouville's theorem states that ρ_ϕ is constant if the beam is only acted upon by conservative forces. A corollary is that the brightness per unit energy is also conserved if ΔE is a constant. If a beam is focused using a short focal length lens, the maximum obtainable flux satisfies the inequality

$$\Phi_{\max} < ER. \tag{5}$$

For a system of unpolarized Fermions, [9] $\rho_\phi \leq 2/h^3$. A particle beam with ρ_ϕ close to this limit would be called nearly degenerate. A beam with ΔE = 1eV would thus have a brightness per unit energy no greater than

$$R_{max} < 4m\Delta E/h^3 = 3.21 \times 10^{28}\ \mathrm{sec}^{-1}\ \mathrm{cm}^{-2}\mathrm{eV}^{-1}. \tag{6}$$

A 10 keV beam with ΔE = 1eV therefore has a limiting flux of

$$\Phi_{max} < 4mE\Delta E/h^3 = 3.21 \times 10^{32}\ \mathrm{sec}^{-1}\ \mathrm{cm}^{-2}. \tag{7}$$

This means that one could in principle have a 1 mA, 10 keV beam focused to a 1Å spot.

We should now consider thresholds and limits associated with the internal potential energy of the particle swarm. Suppose a beam of energy E and a radius a_o is converging with half angle θ_o towards a focal point. The beam will stop converging at a diameter a such that the potential energy per unit length

$$U = \sigma^2 \ln(\ell/a) \tag{8}$$

equals the initial transverse kinetic energy per unit length

$$T = (\sigma E/q)\sin^2\theta. \tag{9}$$

Here σ is the charge per unit length $\sigma = qI\sqrt{m/2E}$, q is the particle charge, m is the particle mass, I is the beam intensity and ℓ is roughly the length of the beam, $\ell >> a$. Conservation of energy implies

$$\sigma \ln(\ell/a) + (E/q)\sin^2\theta = \mathrm{const.} \tag{10}$$

We thus have [10]

$$a_{min} = a_o \exp\left\{-E\sin^2\theta/\sigma q\right\}. \tag{11}$$

Space charge effects will only show up when focusing a beam having $\sin^2\theta < \sigma q/E$. For $I = 10^7\ e^+$/nsec and E = 2.5 keV this means θ must be greater than about .01 radian. Thus, space charge should not prevent us from focusing even a 1mA beam to a very small diameter.

A fluid threshold [11-14] having to do with the random motion or temperature T of a beam occurs when the inter-particle potential energy $\frac{q^2}{r}$ becomes larger than kT, $\beta^2 \equiv e^2/(kTr) > 1$. Here r is the interparticle spacing. A beam will exhibit plasma effects when the Debye screening length $\lambda_D = r/\beta$ is less than the dimensions of the beam.

Finally we must consider flux, intensity, and brightness thresholds having to do with the special properties of positrons aimed at a solid target surface. The first threshold will be at a brightness and intensity suitable for performing low energy positron diffraction or LEPD experiments [15] in a reasonable time with a resolution comparable to LEED. Taking $E = 50$ eV, $I = 10^6 \mathrm{sec}^{-1}$, $2r = 1$ mm and $\theta = 0.01$ radian we have $R = 2 \times 10^{10}$ sec^{-1} cm^{-2} eV^{-1}. Since LEPD intensities are about 10^{-3}-10^{-4}, such a beam would yield 1% precision at 100 different energies in about an hour. Our present beams have more than the required intensity but a brightness per unit energy of only about 10^7 sec^{-1} cm^{-2} eV^{-1}. A single stage of focusing and remoderation (brightness enhancement [7]) would suffice to make such a LEPD beam. [16] The same beam accelerated to several keV would be suitable for imaging defects on a 1 μm scale.

It is energetically possible to form positronium molecules when two surface positrons interact with each other. By a suitable choice of surfaces, the positronium desorption energy can be obtained from the Ps_2 binding energy, $\Delta E = 0.20$ eV. [17] Using standard thermodynamic arguments [18] it is easy to show that the Ps_2 desorption rate is

$$z_{Ps_2} = (\hbar m n_+/m_+^2)(1-r_{Ps_2})e^{(\Delta E-2E_a)/kT}, \qquad (12)$$

where m_+ is the surface positron effective mass, m is the free electron or positron mass, n_+ is the surface density of positrons, r_{Ps_2} is the thermally averaged Ps_2 reflection coefficient and E_a is the activation energy for thermal desorption of surface positrons to form positronium. Equation 12 was derived using the relations $2\mu_{Ps} = \mu_{Ps_2}$ and $\mu_{Ps} = \mu_{e^+} + \mu_{e^-}$ for the chemical potentials of the constituents: a 2D gas of e^+ and metallic e^- in 3D in equilibrium with a gaseous mixture of Ps and Ps_2. The Ps_2 is taken to have spin zero. The remaining steps in the derivation are identical to Eqs. 8-11 of the paper by Chu et al. [18] The ratio of the number of positrons desorbed from the surface as molecules to the number desorbed as atoms [18] is then

$$z_{Ps_2}/z_{Ps} = (n_+/n_o)(1-r_{Ps_2})/(1-r_{Ps})e^{(\Delta E-E_a)/kT} \qquad (13)$$

where the critical surface density n_o is given by

$$n_o = 2m_+kT/\pi\hbar^2. \qquad (14)$$

At room temperature ($T = 300$ K) and with $m_+ = m$, we have $n_o = 2.5 \times 10^{13}$ cm^{-2}. It is possible to adjust E_a by coating certain surfaces with a partial monolayer of an adsorbate, for instance [19] O_2 on Al or Cs on Ni. If we set $E_a = 0.1$eV, then assuming $r_{Ps_2} = r_{Ps}$, a positron surface density $n_+ = 5 \times 10^9$ cm^{-2} gives us a 1% Ps_2 formation probability relative to thermal Ps. To see Ps_2 molecules we will need a positron flux $\phi = 5 \times 10^{18}$ cm^{-2} sec^{-1} and a brightness per unit energy $R = \phi/E = 5 \times 10^{14}$ $sec^{-1}cm^{-2}$ eV^{-1}. About three stages of brightness enhancement would be required.

Other interesting phenomena will occur when the distance between surface positrons is comparable to a room temperature positron deBroglie wave length (10 Å) and a positronium Bohr radius (1Å). Given a sufficient number of positrons at one time ($\sim 10^6$) we might observe Bose condensation effects and the positron-electron fluid respectively.[20] One and two more stages of brightness enhancement and large e^+ pulses are going to be required to get to this stage. The positron annihilation γ-ray laser [21,22] will be a possibility if we can compress the interparticle spacing by another factor of 100 to less than a Compton wavelength. Entirely new physics may appear if the spacing can be made comparable to the classical electron radius as suggested by Winterberg.[23] These last two regimes require energies much exceeding that which we associate with slow positron beams. Nevertheless, the new techniques for obtaining many positrons with high density and narrowly defined energies may serve as a starting point for bigger accelerators.

Figure 1 summarizes the above. In general it seems that interesting new physics will appear each time the brightness and instantaneous intensity of our beams both increase by several orders of magnitude. We have only begun our journey in this intensity vs. brightness space but the project seems feasible and the motivation is not lacking.

III Single Crystal Tungsten Moderator

The presently most efficient and brightest slow positron sources make use of clean flat single crystal metallic moderators.[24] High energy positrons from β-decay or pair production stop in the moderator and a small fraction of them diffuse to the surface. If the metal has a negative affinity for positrons they can be ejected from the surface. The majority of the positrons are emitted normal to the surface [25] with an essentially thermal energy spread about $-\phi_+$, the negative of the positron workfunction.

Single crystal tungsten has been found to be an excellent positron moderator. [26-28] It can be cleaned by roasting in O_2 to remove carbon followed by gentle heating in vacuum to vaporize the tungsten oxide. A satisfactory moderator surface also can be obtained by heating to white heat in vacuum. Figure 2 shows a mounting arrangement that allows the moderator to be heated by electron bombardment without melting its holder. The moderator was heated with 170 W of electron current several times for 20 sec. each. After several cycles, the pressure in the vacuum vessel (1×10^{-10} torr) rose to no more than 2×10^{-9} torr during the heating Using an emissivity of 0.33, the maximum temperature of the crystal is calculated to be 2900 K. Figure 3 shows how the count rate changes as the moderator was moved toward the source in the back

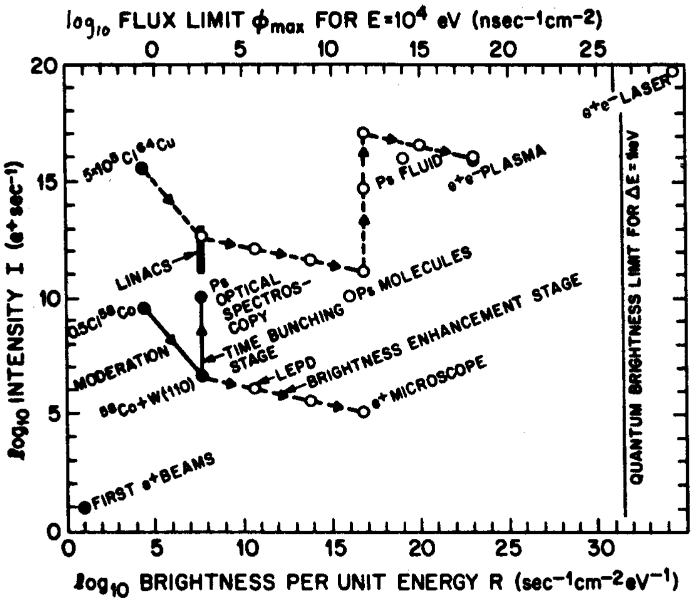

Fig.1 Our present location in e^+ intensity vs. brightness space, some possible goals for future work and some possible paths for getting there through stages of bunching (vertical dashed lines) and brightness enhancement (dashed line sloping down to the right).

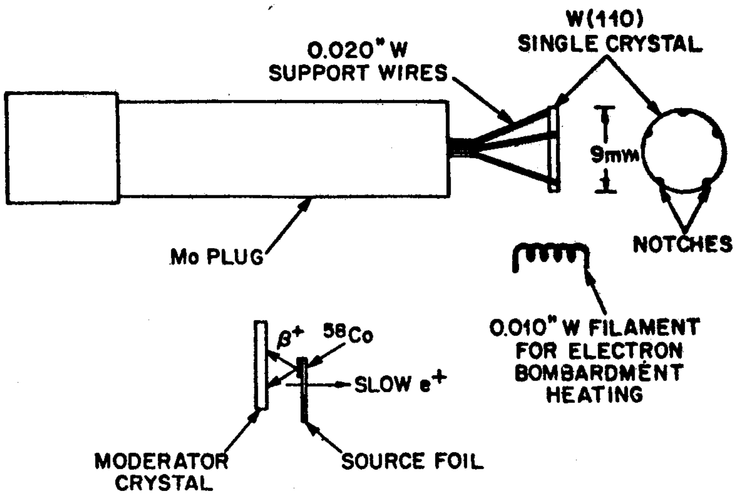

Fig. 2 Mounting arrangements for a tungsten single crystal positron moderator.

scattering geometry [29,30] shown in Figure 2. The source is 310 mCi ^{58}Co plated by New England Nuclear Corp. on a copper plated electro-polished tungsten ribbon 0.005 inches thick by .060 inches wide. This source preparation [24] helps reduce β^+ absorption by keeping the ^{58}Co deposit near the surface of the source foil. The source spot is about 3 mm long. The positron intensity is calculated from the background subtracted count rate of a 3x3 inch NaI(Tl) detector behind a 2 inch thick 8x8" Pb brick with a 1.5 inch hole in the center. The face of the counter is 59 cm from a grounded dirty Si target in the vacuum system. The γ-rays pass through a glass window about 3/16inch thick. The moderator is biased +7 V relative to ground. Using 92% as the detector efficiency for 511 keV γ-rays, the fast positron to slow positron conversion efficiency ε is computed to be $\varepsilon = 0.17\%$ including a 10% absorption in the glass window. Experience has shown that the count rate increases by about 10% when the positrons are driven into the target at keV energies. We infer that $\varepsilon = (0.19 \pm 0.03)\%$. This result is in agreement with that of the Brookhaven group. [31]

Figure 4 shows retarding field energy spectra obtained with the same moderator when attempts were being made to get an improved brightness and yield by coating [28] the W with Cu. The composite moderator does work slightly better than plain Cu, but the clean W moderator is best of all and very easy to prepare. When it is biased to -1.5 V, the positron energy distribution is as narrow as that from the Cu single crystal moderator [24] ($\sim$ 1/4 eV) and the yield is better. The 5 eV spread of longitudinal energies with the moderator at +7 V is the image of the 2.5 eV W work function after the positrons have entered the 150 Gauss transport magnetic field. The field at the source is about 75 Gauss.

IV Time Bunching Accelerators

Given the constraints of Liouville's theorem, it is possible to increase the instantaneous intensity of a slow positron beam by trading energy resolution for spatial density. [6] Figure 5 shows the overall view of a time bunching accelerator for a magnetically transported slow positron beam. The positrons are first trapped in a magnetic bottle by increasing their transverse energy spread. The positrons pass through an rf cavity shown in Figure 6 tuned to the cyclotron resonance frequency, about 408 MHz. The Q of the cavity is $\sim$ 50 and it is typically driven with $\sim$ 50 mW of rf power. The capacitor plates are 1 inch apart and 2.5 inches wide. The parallel inductance is provided by the vertical plates and the 6 inch diameter vacuum can. The input impedance is 50 Ω and no impedance matching element (double stub tuner) is required. It is important that no insulator be used between the plates because they can easily charge up and deflect the beam.

The positrons are dumped out of the magnetic bottle by an accelerator section shown in Figure 5. The accelerator is constructed of reentrant rings (shown in detail in Figure 7) so that

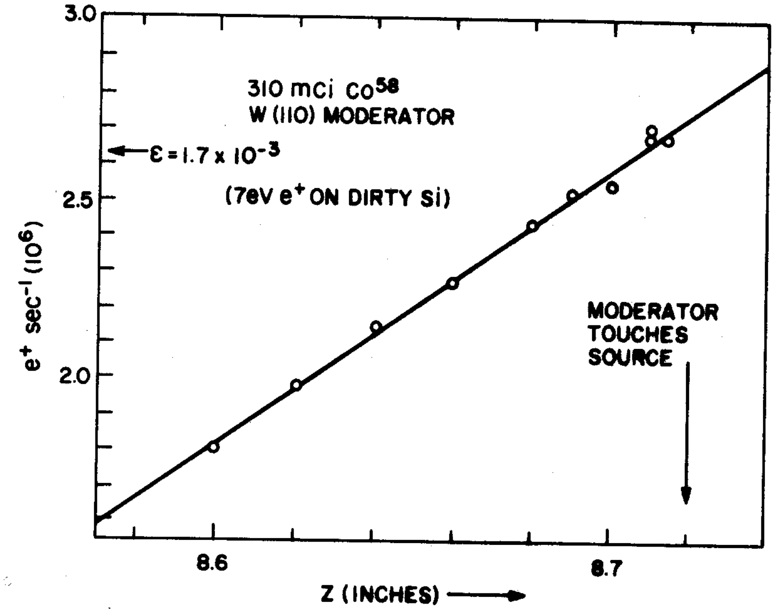

Fig. 3 Slow e^+ count rate vs. moderator position.

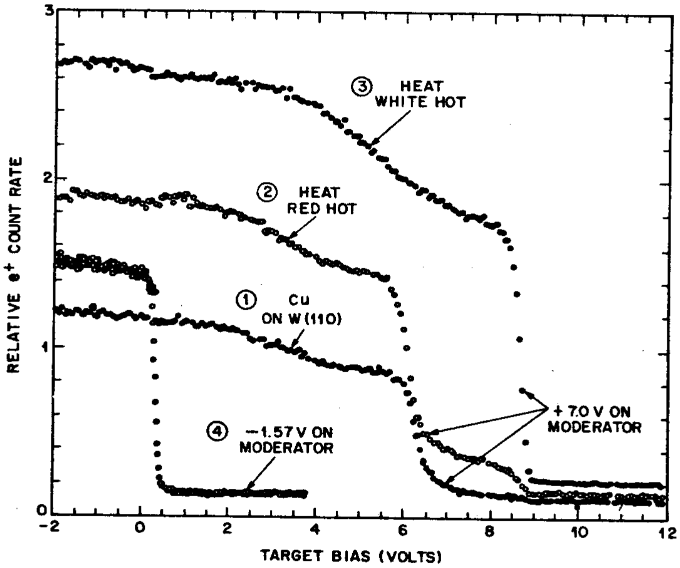

Fig. 4 Slow e^+ energy spectra from 1) W(110) heated to white heat and then coated with Cu; 2) the same heated red hot to anneal the Cu; 3) the same heated white hot to remove the Cu; and 4) the same reverse biased to give a very mono-energetic beam.

the supporting Al_2O_3 rods are not exposed to the positron beam. Between the rings are resistors the values of which are chosen to make a quadratic potential well when a high voltage pulse is applied to one end of the accelerator. The positrons initially have low velocities (< 1eV) in the accelerator and thus all arrive at the minimum of the quadratic potential after one quarter of a simple harmonic oscillator period. The target is placed at this minimum.

The accelerator is divided into two sections, an active part 83 cm long and a passive part 66 cm long, in order to keep the positron pulse from having a wide time spread. Ring S_{53} of Figure 7 is biased slightly positive (about 6 volts) and thus closes one end of the magnetic bottle. The passive part of the accelerator is biased negatively at the Au grid shown in Figure 7. The quadratic potential is established by resistors between accelerator rings $S_{54} - S_{67}$ whose values are R, 3R, 5R, ... 23R with $R = 30$ K Ω. The resistors are ultra high vacuum compatible carbon film resistors with Ni leads.

The active part of the accelerator is designed to continue the quadratic potential and is actually a distributed 50 Ω attenuator. The series resistors between the accelerator rings are parallel combinations of 1/8 watt carbon resistors. The tinned copper leads are spot welded to the stainless rings. Every fifth or tenth ring is connected to ground through a parallel combination of similar resistors. Figure 8 shows the resistor values used. The series resistances are evenly distributed between the accelerator rings. The accelerator matches 50 Ω very well, as demonstrated by Figure 9 which shows the reflections one sees from the high voltage pulse input when a fast rise time pulse from a sampling scope is applied.

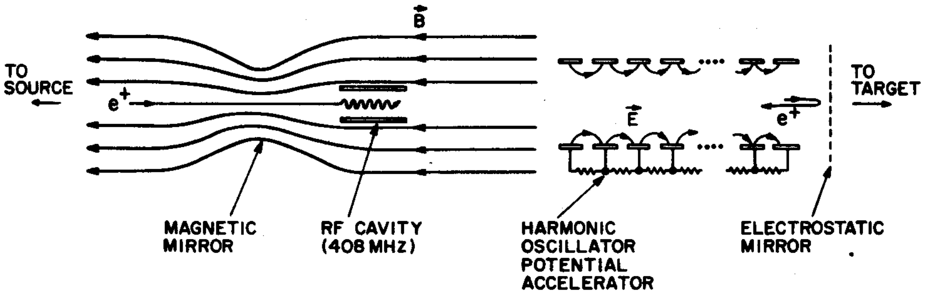

Fig. 5 Time bunching accelerator showing the magnetic bottle and quadratic potential accelerator.

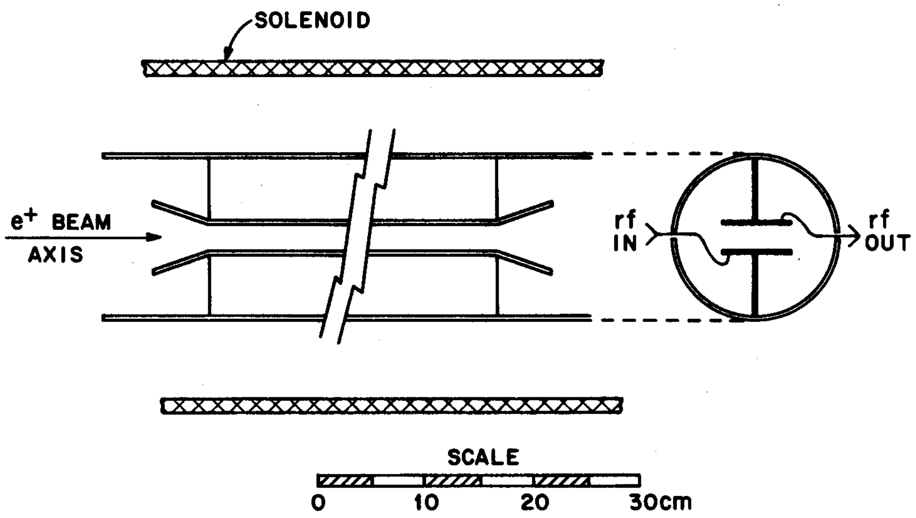

Fig. 6 RF cavity for exciting cyclotron oscillations to trap positrons in the magnetic bottle.

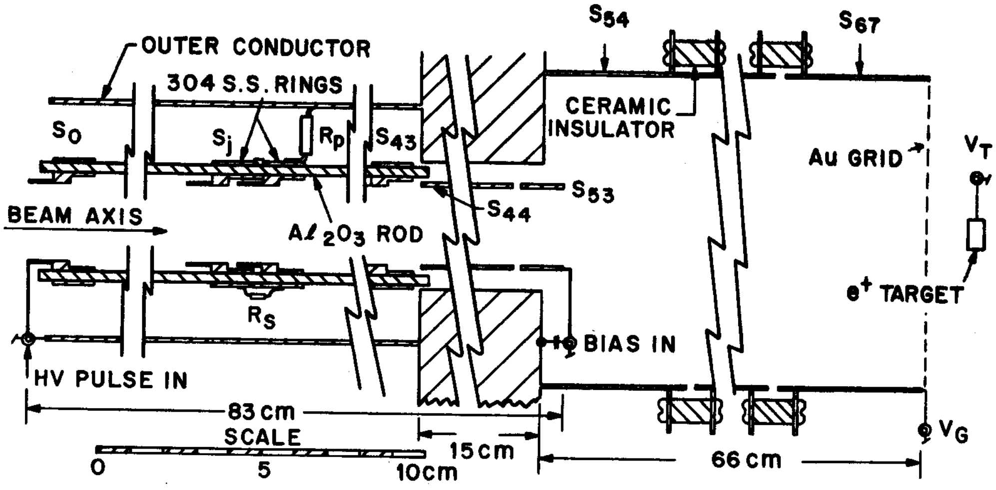

Fig. 7 Quadratic potential accelerator details.

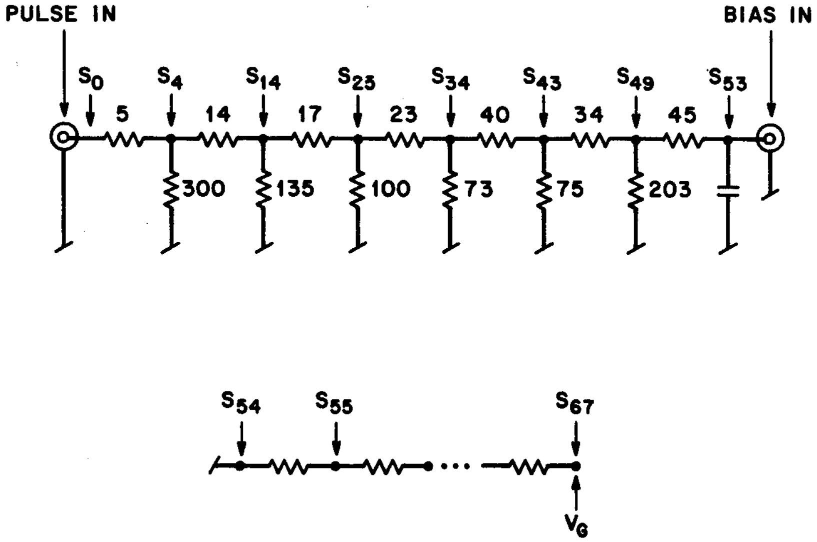

Fig. 8 Resistance values for the quadratic potential accelerator.

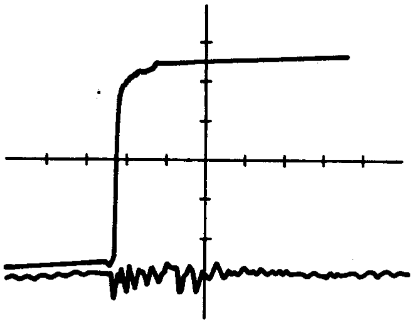

Fig. 9 Reflections (lower trace) observed when a fast pulse (upper trace) is applied to the accelerator input. The time scale (horizontal) is 2nsec/division.

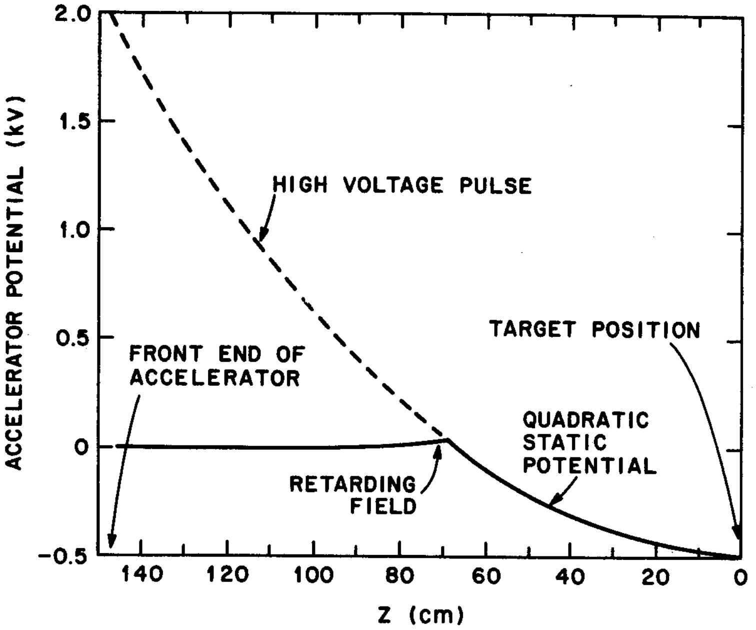

Fig. 10 Potentials on the accelerator. Solid line: accumulation stage; dashed line: acceleration stage.

Figure 10 shows the potentials on the accelerator in the accumulation stage (solid line) and in the bunching stage (dashed line). The high voltage pulse is obtained from an HY2 thyratron operated with a floating cathode and triggered by an avalanche transistor as shown in Figure 11. Filament power is supplied through a high frequency transformer. The output pulse delay time is 50 nsec and its rise time 7 nsec 10%-90%. Using the flux of slow positrons from a 300 mCi^{58}Co source and W(110) moderator we obtain 8 nsec FWHM pulses of 100 ± 20 positrons each at a 1 kHz repetition rate limited by heating of the resistors in vacuum. When the rf trap is turned off the bunches become 32 times less intense.

Figure 12 shows a time spectrum obtained with this accelerator. The Cu target was biased + 100 V relative to the Au grid in Figure 7. Some of the positrons are reemitted from the Cu (∿ 30%), pass through the grid, go up the harmonic oscillator potential, and back to the grid. Evidently a transient associated with the accelerator pulse makes the Cu target potential slightly more negative at the moment of emission so that the returning positrons are repelled back through the Au grid. From the slope of the curve we deduce

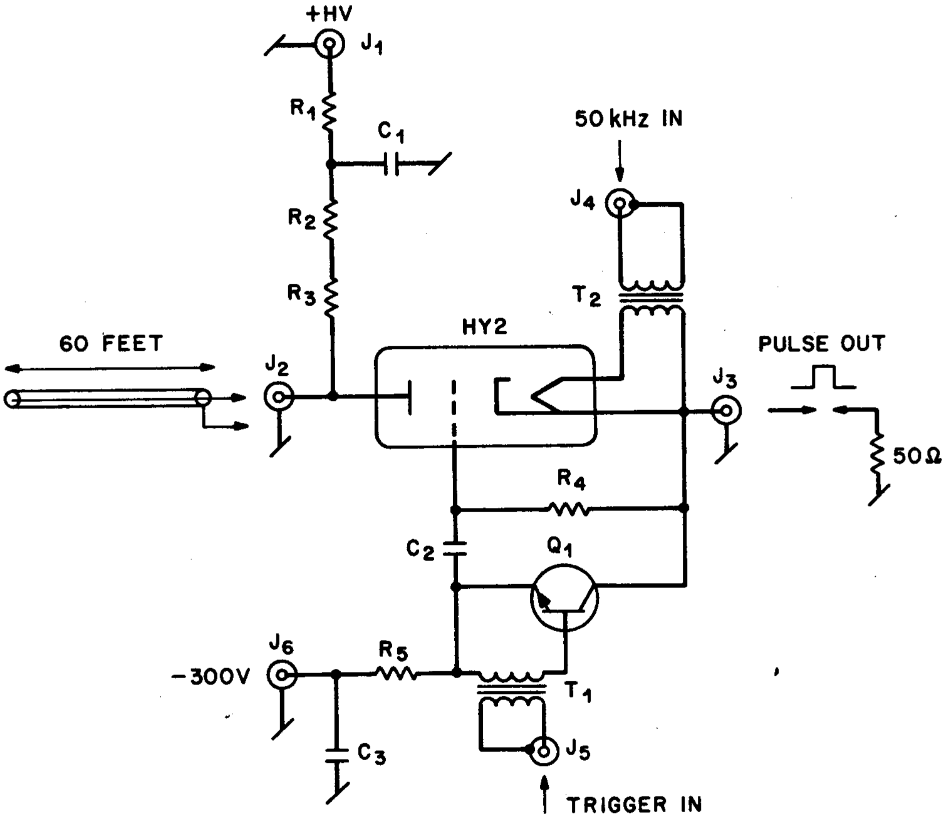

Fig. 11 Circuit diagram for the Thyratron high voltage pulser that drives the accelerator. Q_1 = 2N5271; R_1 = 50kΩ; R_3 = 1.5kΩ; R_4 = 100kΩ. C_1 = 5nF; C_2 = 8.25pF; C_3 = 10nF; T_1 = 5 turns: 10 turns on 3/8" 4C4 ferrite toroid; T_2 = 32 turns no. 22: 9 turns no. 18 on 1/2" 3D3 ferrite toroid. There is a layer of mylar tape insulation between the two windings on the transformers. The 50 kHz rf power supplied to J_4 is adjusted to give 6.3 V across the thyratron filament after it has warmed up.

that about 8% of the positrons annihilate on each pass through the nominally 95% transmitting grid. Since we are able to observe about 40 bounces the positrons must be very mono-energetic or the well quite harmonic.

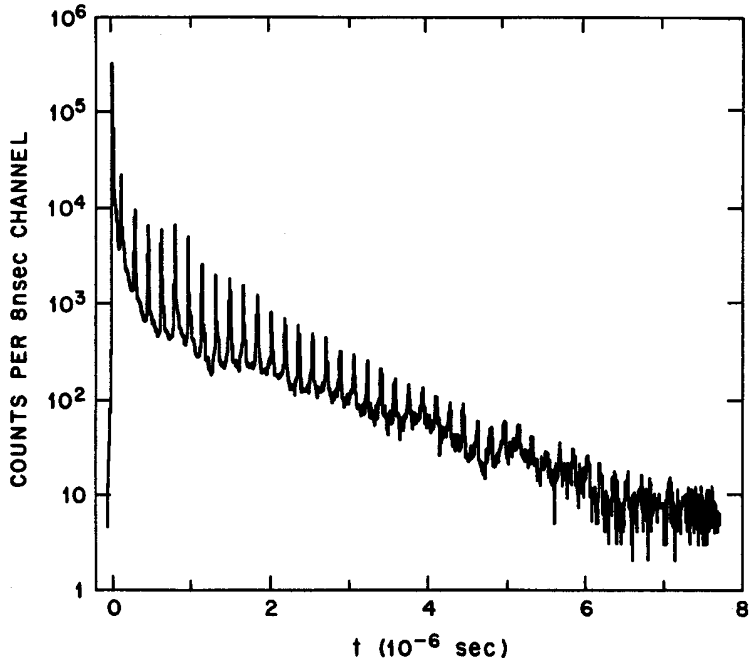

Fig. 12 Annihilation time spectrum obtained with the magnetic bottle and quadratic potential time bunching accelerator.

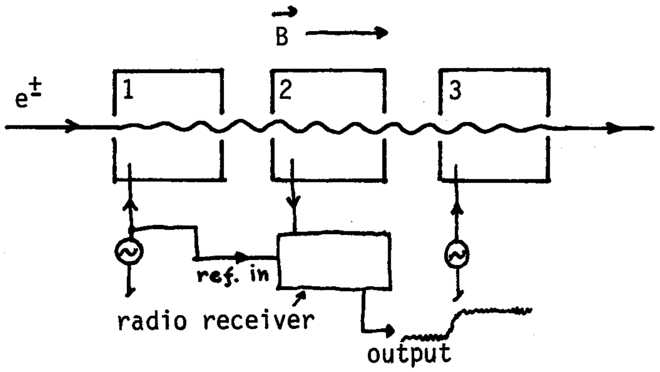

Fig. 13 Non-destructive cyclotron motion detector for slow electrons and positrons.

Figure 12 suggests that we should be able to collect many positron bunches to make a super bunch. Each bunch would be remoderated on a W or Cu single crystal moderator surface and stored in a zero potential region of length ℓ in front of the moderator. We must of course cut a hole in the grid so the positrons will not annihilate. Every time a positron bunch arrives the moderator potential is made to dip a few volts below ground so the reemitted positrons will get trapped in the zero potential region. Only a finite storage efficiency is possible because some of the previously stored positrons will be kicked out of the trap if they are close to the target when its potential dips. If the positrons have a velocity v (6×10^7 cm sec^{-1} for 1 eV e^+) they travel a distance $v\Delta t$ during the pulse of time Δt. For Δt = 10nsec, $v\Delta t$ = 6 mm. Since $v\Delta t/\ell$ of the positrons are eliminated during each pulse, one can store a maximum of $\ell/v\Delta t$ pulses in this way. Setting ℓ = 60 cm we have $\ell/v\Delta t = 100$. When the trap is filled we could transfer the positrons to a second quadratic potential accelerator. We could then expect to obtain 10 super bunches per second, each with more than 10 positrons. It is obvious that pulsed electron accelerators [2-4] provide superior sources of bunched positrons. Nevertheless, when the experiments contemplated in Section II are attempted we may need multiple bunching of even these sources.

V. Single Positron Sources

In beautiful experiments at the University of Washington, Dehmelt, Schwinberg and Van Dyck have captured single electrons and positrons in a Penning trap and cooled them to liquid He temperatures. [32] They have measured precisely the properties of single particles such as their masses and magnetic moments. In a parallel development Malmberg and colleagues at La Jolla have made single component (non neutral) electron plasmas, [33] essentially a many particle version of the Dehmelt et al. Penning trap. Their goal is to observe plasma effects and eventually to observe the liquid and Wigner crystal states at low temperature.[34,35] The Stanford group working with Fairbank has an interest in dropping single electrons and positrons to determine their gravitational interaction. They have suggested [36] a method for cooling positrons to very low temperatures.

As an extension of these ideas, we can think of shrinking Malmberg's plasma to a line with our goal being to obtain a positron beam in which the particles are never closer in time than a certain amount. We could then do experiments free of the effects of pile up. For a random source of intensity I sec^{-1}, the piled up fraction of the count rate is $p = 2I\,\Delta t\,\varepsilon$, where Δt is the pile-up resolution time or the coincidence resolving time and ε is the counter efficiency including solid angle. If p_0 is the maximum acceptable pile up fraction we must have $I < p_0/2\varepsilon\Delta t$. If the counter efficiency is high, $\varepsilon > p_o/2$, the counting rate in an experiment can be improved by a factor of $2\varepsilon/p_o$ and pile up totally eliminated by using a uniform source of intensity $I = 1/\Delta t$. Experiments in which such a source would be useful include lifetime measurements in which p_o is small and ε large, and searches for rare events. [37]

We can think of making a steady beam as follows. Suppose we have a 30 K positron or electron beam confined to a spatial region of radius a = 10 μm by a 100 kG magnetic field B. The beam travels through tiny high Q TE mode microwave cavities tuned to the cyclotron resonance frequency $\omega_c = eB/mc$ and having cold resistive damping elements at a temperature T. Then according to O'Neill [35] the particles lose energy at a maximum rate $\Gamma = (\pi e^2/mNV)^{\frac{1}{2}}$ where N is the number of particles in the cavity of volume V. This expression holds if the collision rate is less than the damping rate ω_c/Q of the cavity mode. At 100 kG, $\omega_c = 2 \times 10^{12}$ $\sec^{-1}$. Using cavities 1mm long and 1mm in diameter and assuming $n = 100\text{cm}^{-1}$ we would have a damping rate of $\Gamma = 3 \times 10^5$ $\sec^{-1}$. The longitudinal motion of the particles is transferred to transverse motion at a similar rate by Rutherford scattering. The whole beam moving with its original mean velocity $v = 3 \times 10^6$ cm $\sec^{-1}$ would thus internally thermalize [38] to a temperature T in a length of a few times $v/\Gamma = 10$cm. If kT is less than $e^2/a = 1$ K the particles will separate longitudinally and can be extracted from the last of the damping cavities one at a time at a rate $nv = 3 \times 10^8$ $\sec^{-1}$. Such a beam of electrons or positrons would have very good energy resolution useful for studying vibrational energy losses, etc.

Simply observing such an "anti-bunched" beam would be of interest. If the little microwave cavities also have a TM mode tuned to the electron spin resonance frequency, the beam will become highly polarized as the spins relax. The relaxation rate is roughly 10^4 $\sec^{-1}$ if $Q = 10^3$. It is interesting to wonder whether the coupling to the cavities will allow the electron string to freeze or possibly exhibit pairing.

Another approach to one-at-a-time slow electrons and positrons is the non-destructive detection of low energy particles. [32] Lynn [39] has suggested that one could use a super-conducting pick up coil and squid detector to observe single slow positrons. He estimates that a 10 μsec averaging time constant would be necessary to eliminate spurious noise events. A second method shown in Fig. 13 would use three microwave cavities: one to excite the cyclotron motion of the particle to an energy E_e, a second to sense the cyclotron motion and a third oscillating out of phase with the first one to take away energy E_e from the cyclotron motion and leave the particle nearly in its ground state again. The signal-to-noise ratio for a TE_{111} detector cavity with noise temperature T, quality factor Q, length d and radius R is

$$S/N = 7.0(E_e/kT)(2\pi Q)^2(r_o/d)(1 + \pi^2R^2/d^2j_{1,1}^2), \qquad (15)$$

where $r_o = e^2/m$ is the classical electron radius and $j_{1,1} = 1.841 \ldots$ is the first zero of $J_1'(x)$. For $Q = 50{,}000$, $\omega/2\pi = 1\mathrm{GHz}$, $d = 2R$ and $T = 300\mathrm{K}$ we have a signal-to-noise ratio of 10 with $E_e = 50\mathrm{eV}$. This amount of energy yields the same S/N independent of ω because $Q \cong \sqrt{\sigma/\omega}$, where σ is the cavity wall conductivity.

Obviously one needs much smaller cyclotron energies E_e for detection of a particle at cryogenic temperatures. It is interesting to think of the possibility of implementing the Fairbank falling positron experiment using this type of non-destructive detector.

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