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AN ANALYSIS OF A POTENTIAL COMPACT POSITRON BEAM SOURCE

R. M. Hessami*, Department of Physics and Astronomy, UCLA, Los Angeles, USA
S. J. Gessner†, CERN, Geneva, Switzerland

Abstract

For positron studies in plasma wakefield accelerators such as AWAKE, the development of new, cheaper, and compact positron beam sources is necessary. Using an electrostatic trap with parameters similar to other experiments, this paper explores converting that trapped positron plasma into a usable beam. Bunching is initially accomplished by an electrostatic buncher and the beam is accelerated to 148 keV by pulsed electrostatic accelerators. This is necessary for injection into the β-matched rf cavities operating at 600 MHz, which bring the positron beam to a transverse emittance of 1.3 π mrad mm, a longitudinal emittance of 93.3 π keV mm, σ_z of 1.85 mm and an energy of 22 MeV. The beamline used here is far simpler and less expensive than those at many facilities, such as SLAC, allowing for a cheap source of positron beams, potentially opening up positron beam studies to many facilities that could not previously afford such a source.

INTRODUCTION

Plasma wakefield acceleration (PWFA) is a promising way of accelerating charged particles that is far more efficient and compact than traditional radiofrequency (RF) accelerators. However, the acceleration of positron beams in plasma is an unsolved challenge [1–6]. In RF cavities, the phase can simply be changed to account for the different sign of the beam charge, while no such symmetry is easily exploitable in the case of PWFA. One of the greatest barriers to furthering research on this topic is the lack of experimental facilities that can generate the positron beams necessary for these studies. SLAC is the only laboratory that has provided positron beams for PWFA experiments. FACET-II at SLAC is the next facility planning to deliver positron beams and it is over 1 km long [7]. On the other hand, a method of generating a trapped, low-energy positron plasmas with at least 10^8 particles has been developed [8]. The potential exists for this beam to reach 10^{10} particles within a few years [9]. In this paper, the possibility of using this trap as a source for a positron beam is addressed, as well as the small and inexpensive linac needed to compress and accelerate this plasma into a usable beam that can be fed into the AWAKE plasma cell, just as electron beams are currently fed in. While PWFA applications are the primary interest of this paper, such a compact positron source would be of great interest to any facility interested in studying positron physics.

* rafimah@ucla.edu
† spencer.j.gessner@cern.ch

POSITRON BEAM SOURCE

Positron beams may be generated either by using a positron emitter like ^{22}Na or impacting an electron beam on a target, utilizing pair production [9]. The beams generated this way have a wide energy spread, so a moderator is then used to make the beam that will enter into the trap. The potential walls used to trap the beam longitudinally need to be of greater magnitude than the space charge potential, which in this case was about 10 V.

Many of the properties of the beam inside the electrostatic trap can be defined in terms of the trap's parameters. The trap used in the simulations here had the properties defined in Table 1. Note that in this case, the plasma dimensions were defined and trap properties to match it were found from there, but the opposite can also be done using the equations

$$\Omega_C = \frac{qB}{m}, \tag{1}$$

$$\omega_r = \frac{qn}{2\epsilon_0 B}. \tag{2}$$

The cyclotron frequency needed to produce such a beam is given by Eq. (1), where B is the magnetic field strength inside the trap, while the rotational frequency of the trap is given by Eq. (2), where n is the density of the plasma. ω_r is a parameter externally implemented by the rotating wall effect.

Table 1: Parameters Used to Define the Initial Plasma Distribution Inside the Trap

Parameter	Value
Trap radius	0.004 m
Trap length	0.1 m
Magnetic field	1 T
Plasma radius	0.001 m
Plasma length	0.09 m
Temperature	273 K
Number of positrons	10^8 particles
Emittance	0.11 µm

The Debye length for this plasma was found to be 60.6 µm. When the Debye length is much smaller than the plasma radius, the plasma can be considered to be of uniform density up until one Debye length from the edge of the plasma, so this approximation was utilized to generate the initial distribution for the beamline simulation [10].

ANALYTIC EQUATION FOR TRANSVERSE EMITTANCE

From the standard equation for transverse emittance, an analytic equation for the transverse emittance of a plasma

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in a Penning trap was derived, using some assumptions that generally hold well in a Penning trap. The standard equation for emittance is given as

$$\epsilon_n = \frac{1}{mc}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2}. \quad (3)$$

No correlation between x and p_x is anticipated, so the $\langle xp_x\rangle$ term can be ignored.

It was assumed that $k_BT \gg \omega_r r_p$. This implies that the thermal energy is much larger than the rotational energy of the plasma. This was shown to hold extremely well in the electrostatic trap here down to temperatures on the order of 1 K, making this a reasonable assumption. This allows for use of equations relating temperature to kinetic energy and a definition of momentum, given as

$$k_BT = \frac{1}{2}mv^2, \quad (4)$$

$$p_x^2 = mk_BT. \quad (5)$$

To find $\langle x^2\rangle$, Eq. (6) was used under the assumption of constant density, given as

$$\langle x^2\rangle = \frac{\int x^2 n(x,y)dxdy}{\int n(x,y)dxdy}. \quad (6)$$

Since $n(x,y)$ was determined to be constant, it could be pulled out and cancelled. Eq. (6) can then by simplified by using the relation $x = r\cos\phi$, producing Eq. (7), where r_p is the plasma radius, given as

$$\langle x^2\rangle = \frac{\int_0^{2\pi}\int_0^{r_p} r^2\cos^2\phi\, r dr d\phi}{\int_0^{2\pi}\int_0^{r_p} r dr d\phi}. \quad (7)$$

Utilizing the assumption that density is constant to define $n = \frac{N}{\pi r_p^2 L_p}$, where L_p is the length of the plasma and N is the total number of positrons, and Eq. (2), r_p can be defined in terms of the trap parameters, the form of which is

$$r_p = \sqrt{\frac{qN}{2\pi\omega_r\epsilon_0 BL_p}}. \quad (8)$$

Note that here, L_p is considered a trap parameter because it can easily be fixed by choosing the location for the potential wall that longitudinally traps the beam. Evaluating Eq. (7) gives an equation in terms of r_p, which Eq. (8) can be plugged into to get in terms of trap parameters. This is given as

$$\langle x^2\rangle = \frac{qN}{8\pi\epsilon_0 B\omega_r L_p}. \quad (9)$$

Combining Eqs. (9), (5), and (3), an equation for the emittance of the beam in terms of only trap parameters can be derived, given as

$$\epsilon_n = \frac{1}{mc}\sqrt{\frac{qNmk_BT}{8\pi\epsilon_0 B\omega_r L_p}}. \quad (10)$$

This equation was shown to match the transverse emittance found by simulation to within 7%, indicating accuracy.

BEAMLINE DESIGN AND SIMULATION

The simulations for this paper were performed in ASTRA, a space charge tracking algorithm that is useful at low and high energies [11]. Figure 1 visually depicts the beamline designed.

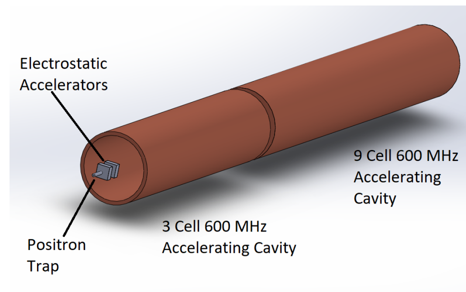

Figure 1: Depicts the beamline design used in the simulation.

To generate the initial beam, a MATLAB script was written to create a plasma distribution inside the trap which was then sampled from to get the 2000 macroparticles that the beam consisted of [12].

Since the beam starts already generated and essentially sitting with a very low initial velocity, the common method of using a 2.5 cell rf gun to quickly bring the beam to relativistic speeds was not an option. Additionally, the beam's initial profile was extremely long with $\sigma_z = 26$ mm when inside the trap. Therefore, the two top priorities at the beginning of the beamline were to compress the bunch in z and accelerate it to $\beta \cong 1$ so that the beam can enter an rf cavity, be much shorter than the associated wavelength, and be fast enough that it does not quickly fall out of phase with the electromagnetic wave.

This was accomplished using three electrostatic devices: A low-field electrostatic buncher inside the trap and two higher field, pulsed electrostatic accelerators powered by 100 kV power supplies. The electrostatic accelerators here are pulsed such that they turn on once the beam is fully contained inside them; that way, when each one turns on, it uniformly accelerates the beam. However, it does not need to be turned off before the beam leaves it, as the extra energy given to the back particles can be used to properly chirp the beam and compress it further, as it was calculated that such devices should bring the beam to $\beta \cong 0.65$, a point where velocity-based bunching is still possible.

The electrostatic buncher inside the trap that initially launches the beam consists of many rings concentric with the beam, where each ring can have its potential set. To kick the beam out of the buncher and get it to focus, a potential corresponding to a linear electric field is created. The buncher runs from 0 cm to 10 cm. Note that the simulation in ASTRA begins at 0 cm, corresponding to the beginning of the buncher.

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Since it would be undesirable for the front of the beam to get a kick the back doesn't, the electrostatic buncher is pulsed and turns on when the beam is at the 14 cm focus point. This corresponds to a time of 9.2 ns. It is placed at 12.7 cm because the furthest back particles of the bunch are at 12.8 cm. This way, there is no charge loss from the device and all particles are accelerated. The electrostatic accelerator is left on once turned on, however, as it can then give a kick to the particles at the back of the bunch, bringing the beam to another focus. After this device, the beam comes to a focus at $z = 0.25$ m with $\sigma_z = 2$ mm.

Initially, only one electrostatic accelerator was used in the simulation, but the beam fell out of phase with the rf cavity too quickly to be of any use. Therefore, two identical electrostatic accelerators were used, with the second being placed slightly behind the focus of the first, so the bunch would be uniformly accelerated to $\gamma = 1.29$, corresponding to $\beta = 0.63$. This was a sufficient speed for the beam to keep up with the rf cavity for at least three cells, meaning that a 600 MHz rf cavity could then be used to bring the beam to ultra-relativistic speeds and $\gamma \cong 6$. After three 600 MHz cells, the beam leaves and then reenters another 600 MHz accelerating cavity, although this one has 9 cells. By changing the rf cavity, the phase that the beam experiences is essentially reset, removing any error that would have been introduced by the beam falling out of phase when it is initially non-relativistic.

Table 2: Beam Values of the Terminal Beam Generated from the Electrostatic Trap Source by this Simulation

Beam parameter	Value
Beam energy	22 MeV
Bunch length (rms)	1.85 mm
Energy spread (rms)	0.38%
Transverse emittance	0.408 µm-rad
Bunch charge	0.016 nC

At the end of the second rf cavity, the beam has an energy of 22.07 MeV and a length of $\sigma_z = 1.85$ mm. This energy is comparable to the electron beam fed into AWAKE [13]. The x and y phase space distributions are quite standard, as shown in Figs. 2 and 3, but the z in Fig. 4 appears unusual due to the electrostatic acceleration and compression from earlier in the beamline. The electrostatic buncher made it so the beam doubles over on itself and here it seems to slightly overshoot so that the beam did not perfectly match with itself. Further work on this could optimize the electrostatic buncher so no trace of the bunching can be seen in the terminal z phase space plot, giving the lowest longitudinal emittance possible. The final properties of the beam are given in Table 2.

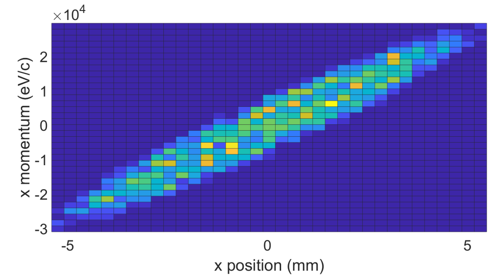

Figure 2: Phase space plot in x for the terminal beam

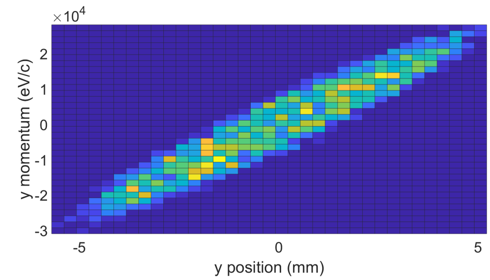

Figure 3: Phase space plot in y for the terminal beam

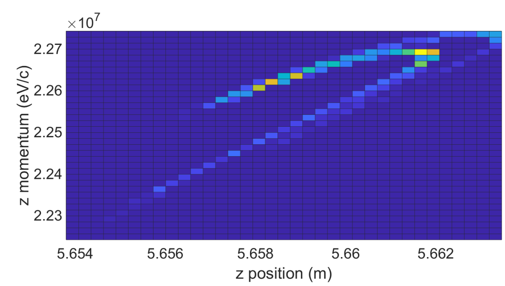

Figure 4: Phase space plot in z for the terminal beam distribution. Note that the two separate curves in the higher energy range were caused by the beam being doubled over for length compression earlier in the beamline.

CONCLUSION AND FURTHER IMPROVEMENTS

The electrostatic trap and beamline described here can produce a positron beam compact enough to be injected into many kinds of accelerators with a very low initial emittance, making this a potentially competitive type of positron source. Further optimization in terms of the electrostatic buncher's functional form may allow for use of only one electrostatic accelerator and a shorter final beam, further improving the beam properties. A major drawback of this method is that the positron trap takes a minute to generate a beam. For AWAKE, this is not a severe problem, since it only runs every thirty seconds, but for other facilities, this could be a major issue. Increasing the rate at which the trap accumulates positrons would reduce this issue and make this method more attractive for a wide range of facilities.

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