NEW DIRECTIONS IN POSITRON MODERATION

S. Chemerisov, C. D. Jonah, W. Gai , J. Long, W. Liu, and H. Wang
Argonne ational Laboratory, Argonne, IL 60439, U.S.
chemerisov@anl.gov

Positron spectroscopies are powerful tools for studying point/structural defects in materials. The development of these methods has been hindered by the low flux available from present positron sources. Using reactors or accelerators, 10^8 positrons/second have been obtained. However, the conversion efficiency of the primary electron- or gamma- particles to slow positrons is low. Here, we present calculations that suggest using a relatively simple deceleration scheme one can achieve two orders of magnitude improvement in moderation efficiency using tungsten foil moderator in transmission or reflection geometry. These calculations use the PARMELA code to describe beam dynamics and EGSnrc code to obtain information about moderation efficiencies.

I. INTRODUCTION

Positrons have tremendous potential in many fields of science, including chemistry, physics, materials science, surface science, biological sciences and nanoscience. However, the utilization of positrons in these fields of research has been strongly inhibited by the inability to get a sufficient flux of positrons to utilize proposed techniques such as positron microprobes [1], positron holography [2], or to carry out gravitation experiments with antimatter [3] or to do antimatter chemistry[4]. Compared to a radioactive-isotope positron source, an accelerator-based positron source can reach much higher intensities. These positrons are produced in the conversion target due to e+/e- pair process when bremsstrahlung photons interact with target atoms. But the spectrum of the positrons is not appropriate for the needed research. Instead of high-energy positrons (energies primarily greater than 150 keV), one needs positrons at thermal energies or at the well-defined energies in the range of several keV.

Present technology uses “moderation” to obtain thermal positrons. Positrons out of the target impinge on a material where they are slowed to thermal energies. These slowed positrons can then be ejected from the surface of the moderator with a few volts of translational energy, if the work function for the surface is appropriate. The efficiency of this process is on the order of 10^{-4} to 10^{-5} low energy positrons per incident positron [5] for 22Na source were energy of the emitted positrons is ranges from 0 to 500 keV with peak around 200 keV. Solid rare-gas moderators may increase this efficiency to greater than 10^{-2}; however, these techniques are still in the early stages of development and are limited by the energy deposited [6]. To use solid rare gas moderator in an accelerator-based positron source, the positrons would have to be separated from high-energy electrons and X-rays.

A slow positron is generated when a positron is thermalized sufficiently close to the surface of the moderator so that the positron can diffuse to the surface without annihilating. Lower energy positrons have greater probability of being stopped near the surface. Experimental data suggest that the moderation of a tungsten foil could reach 0.23 for 1-5keV positrons [7]. In addition, lower energy positrons will deposit less energy in the material and thus reduce radiation damage to single-crystal moderators or decrease thermal load on cryogenic moderators.

Another possible option for producing low-energy positrons is to trap and cool positrons in a high-magnetic-field trap. For this the energy of the positrons has to be decreased below 100 keV. (There are reports that the potential of the gate electrodes on a Penning trap may be as high as 100 kV; however, in this case because of the high velocity of the positrons, the trap would have to be very long to efficiently capture a pulse of positrons that isn’t very short). The positrons will be cooled in the trap by collision with one another and by cyclotron radiation.

Because the present yield of slow positrons from the moderation of high-energy positrons is so low, even moderate success in decreasing the energy of positrons generated by high-energy accelerators could make substantial increase in the generation of slow positrons. Our first goal with this research is to explore the possibility of decelerating high-energy positrons using a relatively simple deceleration scheme. To match with the possible subsequent processes described above we set the goals for this research

1. To determine the efficiency of positron deceleration to energies below 100 keV and with relatively narrow (<20 keV) energy spectrum so that the positrons can then be efficiently decelerated using electrostatic fields and then cooled to thermal energy in a positron trap.

2. To calculate the efficiency of the positron moderation for the case when major fraction of the positrons is decelerated to energies below 200 keV.

All relevant parameters for calculations are based on a 20 MeV high current linac [8] and other available equipment such as a 108 MHz RF source in the Chemistry Div. at Argonne National Lab. If possible, the future experimental work will be carried in this facility.

II. DECELERATOR

Our initial attempts to design the beam line encounter a significant problem. The positrons, which are a product of the electron-positron pair reaction, have a large spread of transverse and longitudinal momenta and little correlation between the transverse and longitudinal momenta. For this reason, it is difficult to define a reference particle. This limits the applicability of one-dimensional modeling and simulations have had to be employed.

Figure 1 is the beam-line schematic that we used for simulation. Between the conversion target and RF cavity, there is an Adiabatic Matching Device (AMD), mainly used for making the transverse phase ellipse of the beam rotate 90 degree. The transverse momentum of the positrons' could be reduced after passing through the AMD.

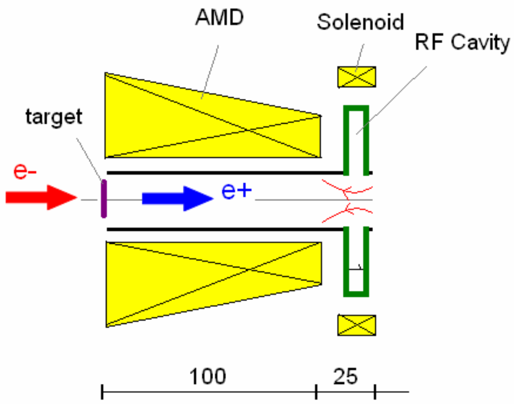


Fig.1 Schematic of the positron deceleration beam-line design, cavity gap=5cm, considering the fringe field, the total length of affected region along z is set 25cm.

In the AMD, magnetic field along z-axis decreases from 10000 Gauss to 720 gauss from entrance to exit (100 centimeters). The field in the AMD satisfies optimized design equation [9].

$$B_z = \frac{10000}{1 + 0.129 \cdot z} \qquad (1)$$

The parameters of the AMD are optimized by adjusting the AMD length, field strength to get a small RMS (root mean square) positron divergence at the AMD while minimizing the loss of positrons. The maximum magnetic field is limited by available conventional magnets.

After the AMD, a pillbox cavity is used to decelerate the positrons. The axis size of the cavity is fixed and its radial size could be adjusted to get different resonant frequencies. The beam pipe radius in the simulation was 7 centimetres. The magnetic field around the cavity is 720 gauss.

III. SIMULATION AND RESULT

A general charged-particle transport code, Parmela [10], is used to simulate positrons movement in the beam-line. The initial positron parameters are from Monte-Carlo simulation code EGSnrc [11] for 15 MeV electrons impinging on a 0.2 cm tungsten target.

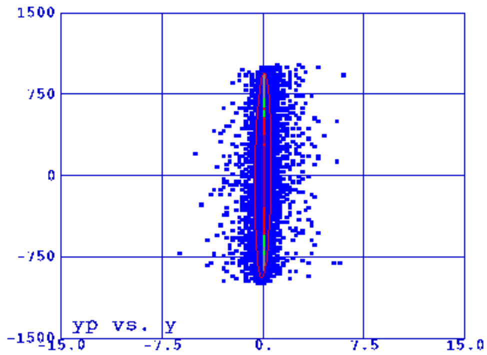
III.A. Transverse ellipse transformation

For positron deceleration, the AMD is very important. Figure 2 shows the transverse phase ellipse transformation of the beam.

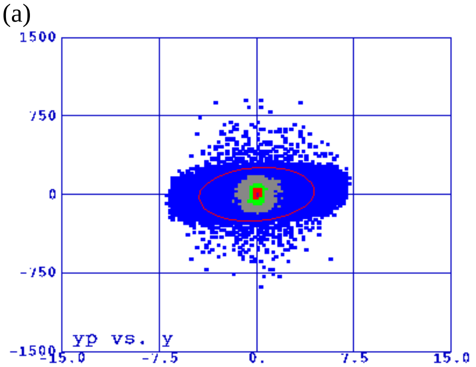
The spectrum of the particles' longitudinal velocity before and after AMD are presented in Figure 3, to give a better understanding of the function of AMD.

III.B. Deceleration calculations

We have simulated two different cases. In case 1 only 108MHz RF field is present in the cavity; in case 2 both 108MHz and 216MHz RF frequencies are present in the cavity to see how much improvement could got. By changing amplitudes and initial phases of its rf field, we could get different result. We try to slow down positrons as much as we can. The best results are showed in Fig.4, the histograms are plotted with 10keV bin. For case 1, the peak value is around 873 positrons out of 59034 within [80keV, 100keV], which means about 1.5% of total positrons in the band. For case 2, the peak location shifts to [40keV, 60keV] while number of the positrons in 20kV band to 1.6% of total number of positrons.



(a)



(b)

Fig. 2 (a) transverse phase ellipse of the beam at the AMD entrance, (b) transverse phase ellipse of the beam at the exit; horizontal coordinator is x axis in cm, vertical coordinator is x prime (Px/Pz) in mrad.

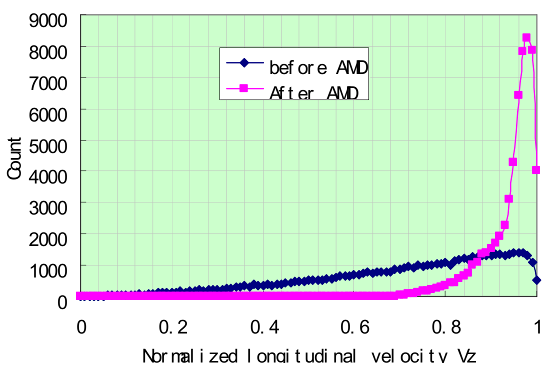


Fig.3. Comparison of longitudinal velocity spectrum before and after AMD, Here, the velocity is normalized by c (light speed in vacuum) and each bin=0.01c

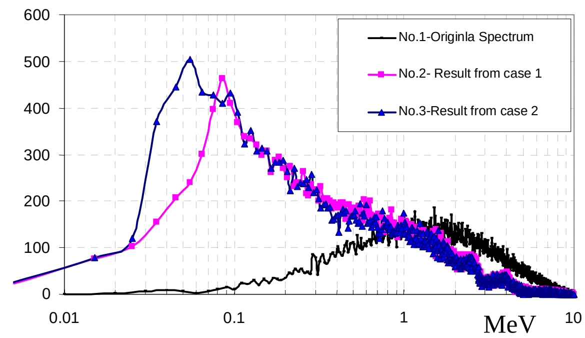


Fig. 4. The energy spectra before and after one/two RF cavities. Case 1 only 108 MHz (amplitude 3.5 MeV/m, phase 0^o) is present in the cavity. Case 2 both 108 MHz and 216 MHz are present (108 MHz, amplitude 3.5 MeV/m, phase 0^o, 216 MHz, amplitude 1.6 MHz, phase 240^o).

In both cases, the average axial electrical fields are less than 5 MV/m in the cavity that corresponds to 2 MW peak RF power. RF sources for that frequency and power are commercially available.

III.C. Relative moderation efficiency

Calculation of the absolute moderation efficiencies would be a very difficult task because it would require energy-loss and scattering cross sections for particle energies less than 1 keV. So instead of trying to calculate absolute moderation efficiencies we decided to calculate relative efficiency of positron moderation for energies from 20 keV to 2 MeV.

For these calculations we used EGSnrc Monte Carlo code [11]. It was assumed that the moderation efficiency would be proportional to the number of positrons that are stopped within a short distance of the surface. For the calculation, it was assumed that the particles were stopped when their energy was reduced below 2 keV. Preliminary calculations suggested that the relative yield was independent of the thickness of the region, as long as the region was small, so a distance of 10^{-6} m was chosen. The geometry used for calculation shown in Fig. 5. The results of these calculations are presented in Fig. 6. Using these data and the spectra in figure 4, both relative reflection moderation efficiency and transmission moderation efficiency were calculated and results are presented on Fig. 7. These values are relative to the yields from the unmodified energy distribution.

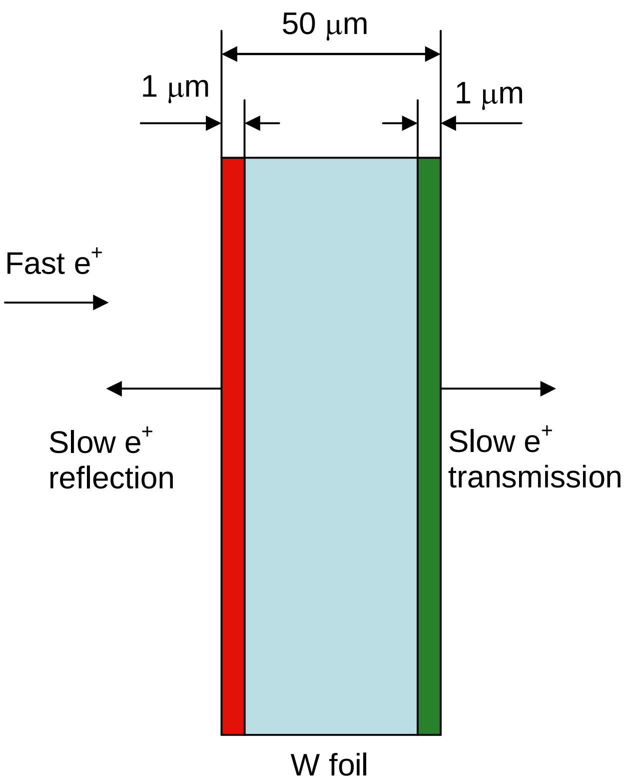


Fig. 5. Geometry of the moderator used for EGSnrc calculations. The thickness of the W foil is 50μm. 1 μm layer at the surfaces was used to calculate relative moderation efficiency for reflection and transmission mode of moderation.

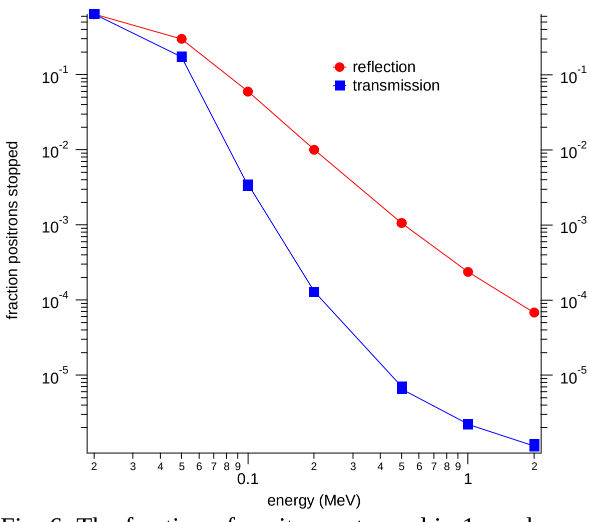


Fig. 6. The fraction of positrons stopped in 1 μm layer of W moderator for reflection and transmission mode as a function of positron energy.

For case 1, a single RF field in the cavity, the largest gain is around 20 times for reflection yield and 30 for transmission yield. For case 2, yields increase approximately by 50% for transmission and 80% for reflection relative to case 1. If we reexamine fig.4, it seems that lower position energy could raise the yield. So we calculated the positron yield that would be expected if we shifted the spectrum down 20 keV. The results are shown in figure 7 as case 3. This energy could be obtained by using a 20kV DC gap downstream from the RF cavity.

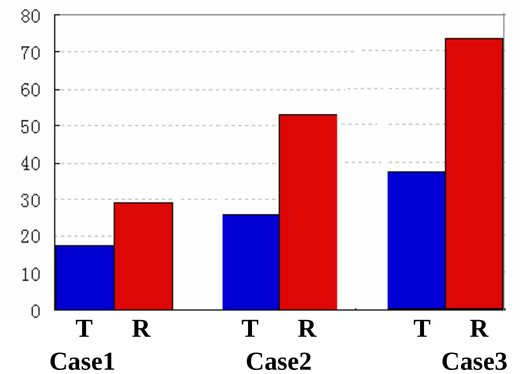


Fig. 7 Histogram of moderation efficiency, here R means reflection and T means transmission

The results, which are shown in case 3,show that even a small shift in energy substantially increased the yields. Thus we believe that an increase in yield of slow positrons by two-orders-of-magnitude is possible.

IV. CONCLUSIONS

In this work, we have shown that it is possible to use RF fields and accelerator techniques to increase the yield of slow positrons from high-energy positrons. These calculations suggest it is possible to increase the yields 2-orders-of-magnitude greater than what is conventionally available by decreasing the energy and increasing the positron thermalization yield in the moderator or decreasing the energy and energy spread and injecting into a trap. However, because most of the positrons are still not utilized, there is still considerable opportunity to increase the yields of slow positrons.

The proposed scheme for efficient positron production based on the results from the presented calculations is depicted in Fig. 8. The total efficiency of high energy electron to positron conversion is on the order of 10^{-5} e^+/e^-.

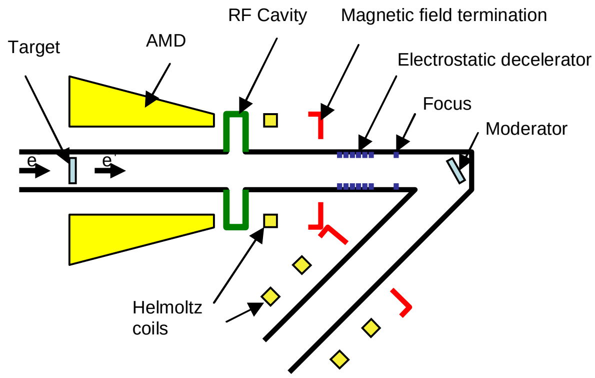


Fig. 8. Proposed simplified positron generation apparatus utilizing one cavity RF decelerator, electrostatic decelerator stage and moderator in reflection mode.

Acknowledgements

We gratefully acknowledge discussions, assistance and help from Palakkal Asoka-Kumar, Hongmin Chen, Ken Edwards, Richard Howell, Alan Hunt, Al Wagner and Lawrence Livermore Laboratory. Work performed under the auspices of the Office of Science, Division of Chemical Science, US-DOE under contract number W-31-109-ENG-38 and NSF (CHE-0439134) and Air Force Research Labs.

REFERENCES

1. A. David, G. Kogel, P. Sperr, and W. Triftshauser. *Phys. Rev. Lett*. 87(6), 6 (2001).
2. Tong, Huang and Guo, *Phys. Pev. Lett.* 69, 3654 (1992).
3. P. Perez and A. Rosowski, *NIM A.* 545 (1-2), 20 (2005)
4. P.J.Schultz and K.G.Lynn, *Rev. Mod. Phys.* 60, 701 (1988).
5. A. Vehanen, K. G. Lynn, and P. J. Schultz, *Appl. Phys. A* 32, 163 (1983).
6. A.P. Mills and E. M. Gullikson, *Appl. Phys. Lett*. 49 (17), 1121 (1986).
7. G. Kogel, G. Dollinger, *Applied Surface Science*, 252 3111 (2006).
8. W. Gallagher, K. Johnson, G. Mavrogenes, and W. Ramler. *Part. Acc. Proceedings.* 584 (1971).
9. R.Chehab. *IEEE Transactions on Nuclear Science*, Vol NS-30, No.4, 28 (1983).
10. L. Young and J. Billen. *Part. Acc. Proceedings*, 3521 (2003).
11. I. Kawrakow. *Med. Phys*. 27 485 (2000).