STUDIES OF SLOW-POSITRON PRODUCTION USING LOW-ENERGY PRIMARY ELECTRON BEAMS

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Abstract

Slow-positron beams produced from negative-work-function solid-state moderators have found numerous applications in condensed matter physics. There are potential advantages in using low-energy primary electron beams for positron production, including reduced radiation damage to single-crystal moderators and reduced activation of nearby components. We present numerical calculations of positron yields and other beam parameters for various target-moderator configurations using the Argonne Wakefield Accelerator (AWA) [1] and Advanced Photon Source (APS) [2] electron linacs [3] as examples of sources for the primary electron beams. The status of experiments at these facilities is reviewed.

1 INTRODUCTION

Slow positrons are valuable tools in atomic physics, materials science, and solid state physics research. They can be used to probe defects in metals, to study Fermi surfaces and material surfaces and interfaces, and to obtain detailed information about the electronic structure of materials. Positrons can be used to gain information complementary to that acquired by other means such as x-ray and neutron scattering. Slow positrons can be obtained either by moderating positrons emitted by some radioactive sources or produced when an accelerated electron beam hits a high-Z target.

In both cases the positron beam occupies a much larger phase-space volume than is useful and some kind of cooling is required. Damping rings can be used at high-energy accelerators, but for the eV-scale positron kinetic energies used in condensed matter physics experiments, a more appropriate technique is the use of solid state moderators. The moderators are typically single-crystal metal films or solid noble gases and are made of materials that possess a negative work function for positrons. Positrons thermalize near the moderator surface and are eventually ejected with a kinetic energy equal to the work function.

The moderation efficiency is low due to competition between the thermalization process and the annihilation of positrons with electrons in the moderator. The geometry of the moderator is relevant as well; a moderator structure with a large surface-to-volume ratio will provide the best chance for the positrons to stop near the surface and be ejected [4]. The moderator material quality is also an issue. Polycrystalline materials contain crystal defects and grain boundaries that can provide potential wells in which positrons can be trapped, thereby further reducing moderation efficiency.

Since the positron production rate is proportional to beam power, the required beam power is generally achieved using high-energy electron beams. There is a possible advantage in using a low-energy, high-intensity primary electron beam for positron production. The raw positron yield decreases with the electron energy. The softer positron energy spectrum should improve the yield of moderated positrons, due to the shorter time required for the positron energy to be reduced by dE/dx losses in the moderator. Additionally, use of low-energy positrons should reduce radiation damage to the moderator crystal lattice, and also result in lower activation of the target, moderator, and nearby beamline materials. At the 14-MeV incident electron beam energy with which we are primarily concerned, photoneutron production rates are very low [5,6].

In this paper we report on a planned experiment to study the efficiency and yield of slow positrons produced by the low-energy intense electron beam from the AWA drive linac. We discuss simulations, experimental configurations, and instrumentation. Possible future directions will also be mentioned.

2 POSITRON YIELD CALCULATIONS

The EGS4 electromagnetic shower Monte-Carlo code [7], together with a C-language user interface code [8], was used to optimize the production target thickness for maximum positron yield. Phase-space coordinates of positrons exiting the target were taken as input to beam optics codes used for design of the spectrometer and detector. The incident electron beam energy was taken as 14 MeV, corresponding to the beam energy from the AWA drive linac. The production target is made of tungsten.

Raw positron yield was studied at various energies as a function of target thickness [9]. The maximum yield of ~0.005 e^+/e^- occurs at around 2.5 mm; this thickness will be used subsequently in this paper. In the simulations, the incoming electron beam energy is represented by a Gaussian distribution whose mean and standard deviation are 14 MeV and 0.7 MeV, corresponding to the measured AWA average beam energy and energy spread. The beam size is similarly represented by a Gaussian distribution of zero mean and standard deviation equal to an rms beam radius of 1.5 mm. The beam is normal to the target. Positrons exiting the target are distributed over a broad range of angles and energies. The positron energy spectrum is shown in Figure 1. The spectrum exhibits a broad peak at an energy of 2 MeV and standard deviation of ~2 MeV. The positron radial distribution right after the target is shown in Figure 2. The positron angular distribution with respect to the z axis is shown in Figure 3, where only the positive angles are plotted. The distribution is peaked around 0°, the small angles correspond to the high-energy particles, and the distribution is symmetric with respect to the z axis. The angular distributions around both the x- and y- axes are uniform. An insert in Figure 3 shows the coordinate system used in the analysis.

Only a small fraction of the positrons produced will actually be transported to the test chamber due to their large angular divergence and energy spread. The PARMELA code [10] was used to calculate the acceptance of the spectrometer and diagnostic chamber. We estimate that 8.75×10^6 positrons per 40 nC of incident 14-MeV electrons will arrive at the test chamber.

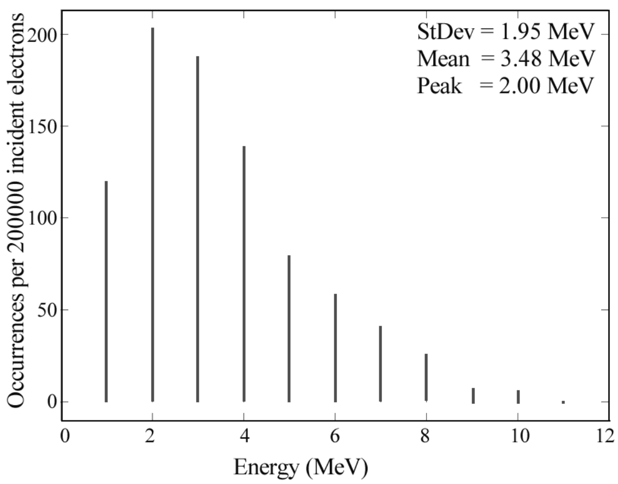

Figure 1: Energy spectrum of positrons from 14-MeV electrons impinging on a 2.5-mm-thick tungsten target.

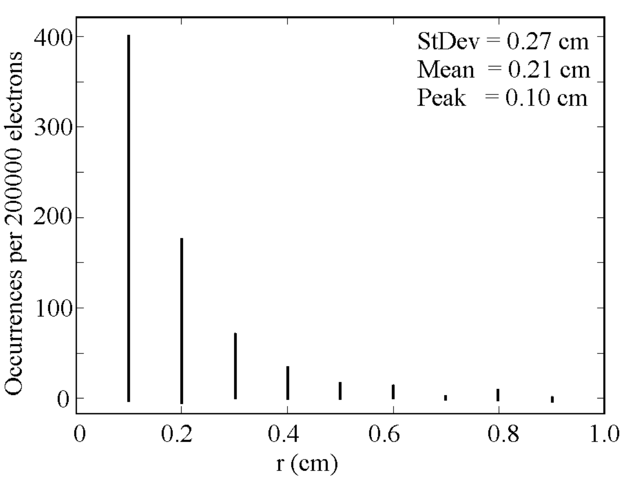

Figure 2: Radial distribution of positrons right after the target from 14-MeV electrons impinging on a 2.5-mm-thick tungsten target.

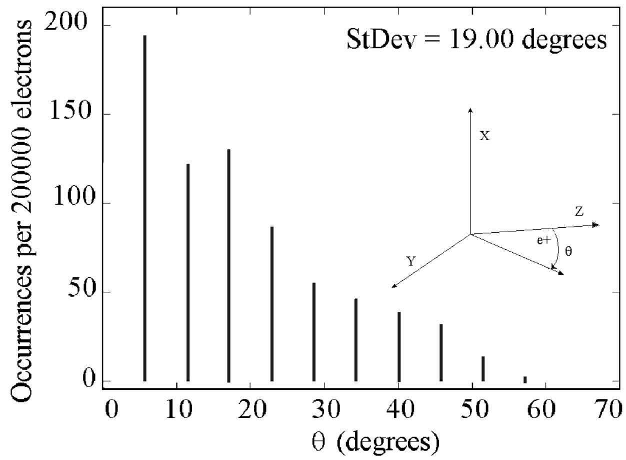

Figure 3: Positron Z angular distribution from 14-MeV electrons impinging on a 2.5-mm-thick tungsten target. The distribution is symmetric with respect to the z axis. Only positive values are shown.

3 EXPERIMENTAL CONFIGURATION

The AWA drive linac is a photoinjector-based machine that can provide 30-ps-long electron pulses containing more than 40 nC/pulse at 14 MeV. The electron beam will be focused to a ≤ 1-cm-diameter spot at the 2.5-mm-thick tungsten target. The target is located directly upstream of a dipole magnet that acts as a spectrometer to measure the positron energies and as a charge separator to dump secondary electrons. The electron (negative bend) side of the vacuum chamber is lined with 2.5 cm of graphite to absorb secondary electrons while minimizing x-ray background due to bremsstrahlung in the chamber walls. Figure 4 is a plan view showing the target, spectrometer, and diagnostics.

Positrons are bent by the spectrometer into a diagnostic chamber. The path of the positrons as they are bent toward the screen is indicated in Figure 4. Initial experiments involve measurement of raw positron yields under various conditions of energy and target thickness in order to calibrate the Monte Carlo calculations. Instrumentation consists of a phosphor screen viewed by a CCD camera and a Faraday cup. A 10-mm-thick (about 3 radiation length) tungsten plate is located upstream of the Faraday cup. The plate has a 1-mm slit to define the momentum slice accessible to the Faraday cup for a given spectrometer field setting. Sweeping the spectrometer current permits a measurement of the positron energy spectrum. Reversing the spectrometer current bends electrons into the diagnostic chamber for tuning and calibration purposes. Construction of the vacuum equipment is nearing completion and we anticipate being able to make measurements shortly.

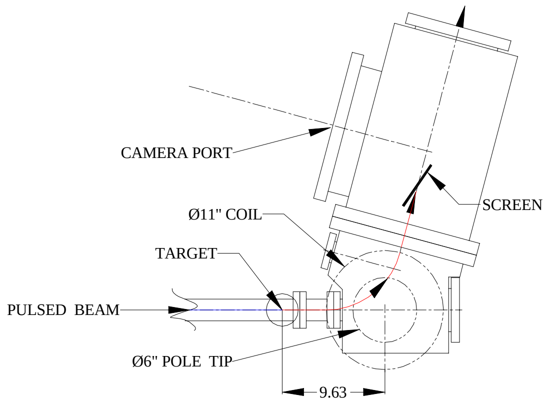

Figure 4: Plan view of the target, spectrometer, and diagnostics, showing the beam path as the positrons are bent toward the screen.

4 FUTURE PLANS

After the positron yield has been fully understood, the Faraday cup/phosphor assembly will be replaced by tungsten sheet moderators and eventually also by thin single-crystal tungsten moderator foils. The moderation efficiency as a function of moderator type and incident beam energy will be studied using a pair of NaI counters to measure the back-to-back 511-keV gamma rays from positron annihilation at rest in the moderator. A solenoid will be installed immediately downstream of the target and tested to assess its effect on capture and transport efficiency as compared to simulation.

A low-field solenoidal beamline will be constructed to transport the slow positrons to a secondary moderator and experimental chamber. Yield from the secondary moderator will be measured using micro-channel plates

Several of the envisaged experiments require short-pulse beams with good timing resolution. A trap capable of collecting positrons from the entire beam macropulse and expelling them as a short pulse will then be required.

The 30-ps pulse length from the AWA photocathode gun can be shortened to several ps using a fairly simple magnetic chicane. The resulting positrons can be energy selected and used to perform positron lifetime studies in bulk materials.

Previously, computer simulations and beam studies were performed using the APS linac and determined that it is well suited as a slow-positron-source driver [11,12]. The APS linac is being reconfigured to drive an FEL in addition to its normal duties as the APS injector. The DC thermionic gun has been replaced by a photoinjector. Spent beam from the FEL is a source of high-energy, few-ps electron pulses that could be directed into a slow-positron target instead of to a beam dump. The DC thermionic gun can then be reconfigured to drive a high-intensity (70nC/30ns pulse), low-energy positron source as well.

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