Abstract

We report on the develop of a partnership between Jefferson Lab's (JLab) Continuous Electron Beam Accelerator Facility (CEBAF) in Newport News, VA and the Idaho Accelerator Center (IAC) at Idaho State University. The partnership will initially be nurtured through a research and development project designed to construct a positron source for the CEBAF. The first year of this proposal will be used to benchmark the predictions of our current simulation with positron production efficiency measurements at the IAC. The second year will use the benchmarked simulation to design a beam line configuration which optimizes positron production efficiency while minimizing radioactive waste. The second year will also be used to design and construct a positron converter capable of sustaining the heat load from high luminosity positron production. The final year will quantify the performance of the positron source and measure the source's radiation footprint. A joint research and development project to construct a positron source for use by the CEBAF will bring together the experiences of both electron accelerator facilities and solidify this partnership for future projects. Our intention is to use the project as a spring board towards developing a program of accelerator based research and education which will train students to meet the needs of both facilities as well as provide a pool of trained scientists.

The Development of a Positron Source for JLab at the IAC

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1 Accomplishments

The performance of a positron source using a quad triplet collection system has been measured using the support from this award. The first year of research accomplished its goal of performing preliminary measurements of positron production and found that efficiency to be $5 \pm 1 \times 10^{-15}$ positrons per incident electron. The second year of work focused on designing an achromat beam line along with a tungsten target to optimize the production of positrons with an energy dispersion ($\Delta E/E$) less than 30 %. The third year measured the performance of a linac based, achromatic positron source and observed a chromaticity of 60% while improving the positron production efficiency measured in year one by more than a factor of two. Based on this work, we believe that the low positron efficiency observed can be greatly improved by placing the production target within a magnetic collection field instead of outside.

1.1 Initial Positron production measurement

The first year of this work focused on performing positron production measurements at the Idaho Accelerator Center (IAC) to evaluate the signal to background level and detector performance. Figure 1 depicts the beam line used for these measurements. A 25 MeV linac, pulsed at 300 Hz, was used to accelerate electrons to 10 MeV. The electrons were bunched into 100 ns wide pulses with a peak current of 40 mA and transported to a 2 mm thick tungsten target located between two dipoles. The second dipole was set to transport 3 MeV electrons or positrons to a shielded cell that housed a high purity germanium (HpGe) and Sodium Iodide (NaI) detector.

A positron transported to the shielded cell would impinge onto a 6mm thick Tantalum foil where it would annihilate and produce two photons. A HpGe detector and a NaI detector were place at 90 degree angles with respect to the Tantalum target in order to detect the characteristic 511 keV photons that would emerge back to back when a positron annihilates after thermalizing in the Tantalum. The analog output of both detectors was measured using a multi-channel analyzer, model MPA-3 manufactured by FAST ComTec Communication Technology GmbH, equipped with a 12 bit ADC.

Figure 2 shows the photon energy spectrum observed by each detector.

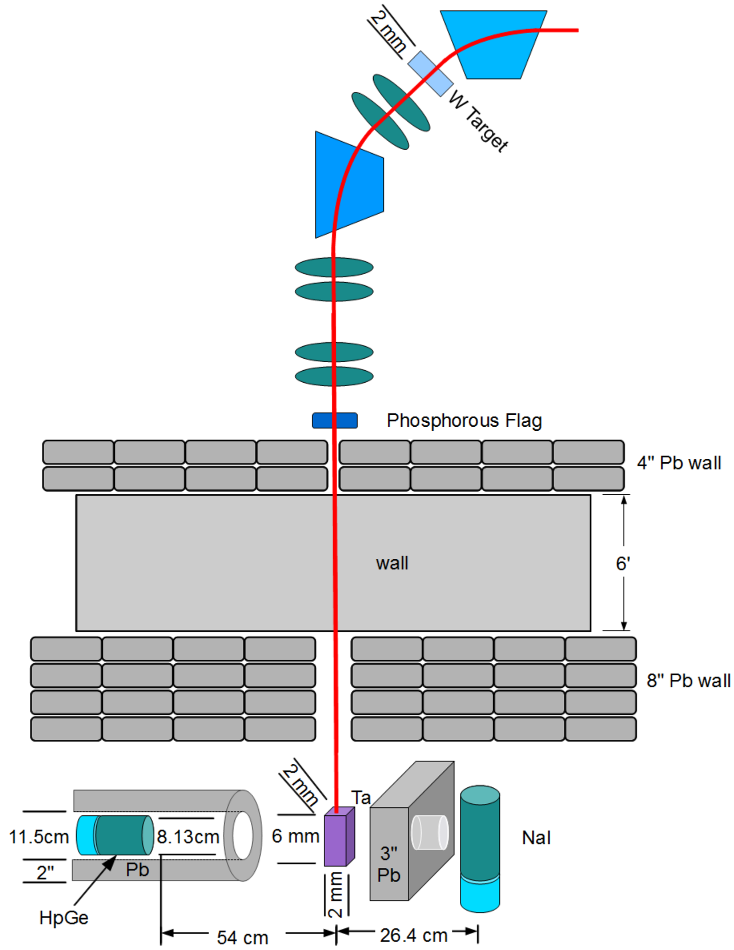


Figure 1: A block diagram of the beam line used for an initial set of positron production measurements

A clear peak at a photon energy of 511 keV was observed using the HpGe detector while the NaI spectrum was less clear. A permanent magnet was inserted to deflect charged particles away from the Tantalum annihilation target. Figure 2 shows the reduction in the 511 keV peak observed by the HpGe detector when the magnet is inserted. Although the HpGe detector calibration was off by 15 keV, the magnet indicated that positively charged particles were being produced and transported to the shielded cell. We did not determine if those particles were from the upstream Tungsten converter target or created somewhere along the beam line. Our next measurement would use retractable targets to determine the origin of the positively charged particles producing the 511 keV photons.

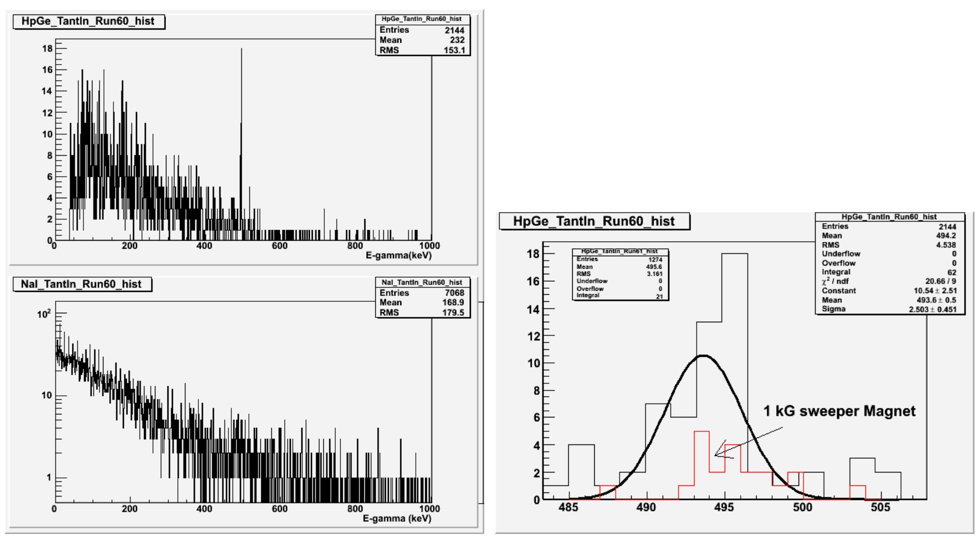


Figure 2: The left figure is the observed photon energy distributions as measured by the HpGe (top) and NaI (bottom) detectors. There was no coincidence requirement using the two detectors. The right figure is the HpGe photon energy distribution before and after a sweep magnet is used to deflect charged particles away from the annihilation target.

2 The design of a linac based positron source

The experience from the first year of research was used in the second year of this work to design and construct a beam line specifically for use as a positron source. The first step was to increase the available space for a beam line by moving the High Repetition Rate Linac (HRRL) cavity from the center of the Physic's beam lab room to a corner and add a system of quads and steering magnets to improve beam transport. The second step was to measure the emittance of the linac and use those measurements as the input parameters of a beam line simulation to optimize positron transport. The installation of a positron production target (T1) and an annihilation target (T2) was done to complete the linac based positron source.

2.1 Beamline Optimization

As shown in the Fig. 3, the HRRL's accelerator cavity was relocated to provide enough space for a beam line that would allow the magnet elements needed to construct an achromat. Quadrupole (Q1-Q9) and dipole magnets (D1 & D2) were added to the new beam line as well as an optical transmission radiator (OTR), labeled S1, to measure the beam emittance and a YAG screen (S2) to locate the beam after it is deflected by the first dipole. Labels FC1, FC2, and FC3 in Figure 3 are Faraday cups installed to measure the electron beam current. Energy slits (EnS) were installed to restrict the beam's energy/momentum spread after the first dipole. A retractable tungsten foil target (T1) was placed between the 1st and 2nd triplets and used to produce positrons from the bremsstrahlung photons emitted by electrons within the Tungsten target. A four foot thick wall separates the accelerator side from the experimental cell. A beam pipe at the end of the 90 degree beam line goes through a hole in this wall and delivers the beam from the accelerator side to the experimental cell. The positron detection system consisting of two NaI detectors was placed at the end of the beam line on the experimental cell side as shown in the Fig. 3.

2.2 HRRL emittance measurements

The accelerator's emittance was measured using an optical transmission radiator (OTR) and one of the quadrupole magnets close to the accelerators exit port. Figure 4 illustrates the components used for the emittance measure-

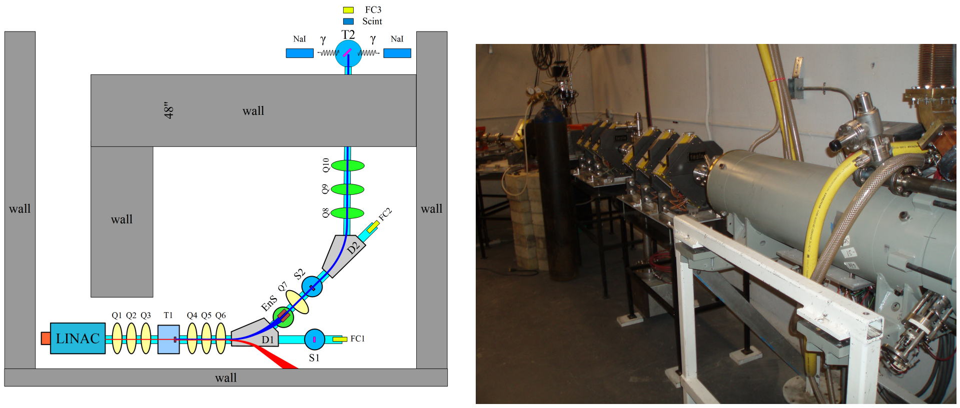
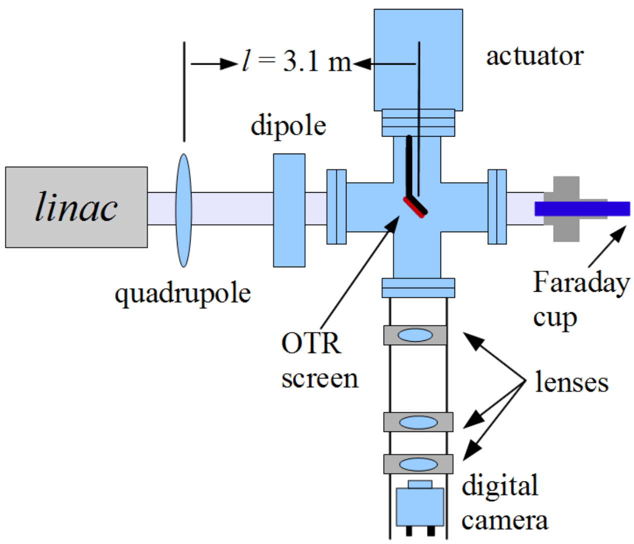


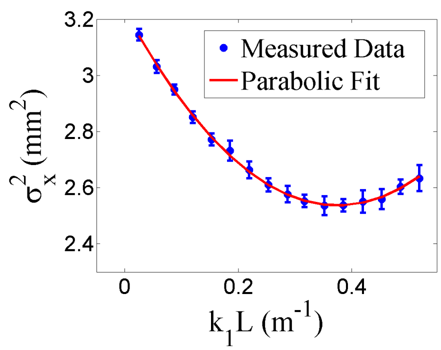
Figure 3: Left: a block diagram describing the new beam line constructed for this project. Right: a picture of the linac and the zero degree line.

ment. The visible radiation produced by the electrons traversing the OTR screen was captured with a JAI digital camera that was calibrated by illuminating the 31.75 mm diameter OTR frame with a light emitting diode. The horizontal and vertical calibration factors of 0.04327 ± 0.00016 mm/pixel and 0.04204 ± 0.00018 mm/pixel, respectively, were determined using image processing software to inscribe a circle around the OTR inner frame in units of pixels. The digital image intensity measured by the JAI camera was recorded in a 2-D matrix format and projections on both axes were taken to perform a Gaussian fit. The observed image profiles were not well described by a single Gaussian distribution. The profiles may be described using a Lorentzian distribution, however, the rms of the Lorentzian function is not defined. The super Gaussian distribution seems to be the best option [11] as rms values may be directly extracted. Figure 4 shows the square of the rms (σ_s^2) vs k_1L for x (horizontal) and y (vertical) beam projections along with the parabolic fits. The emittances and Twiss parameters from these fits are summarized in Table 1. A simulation used these input parameters to optimize positron transport and quantify the expected beam loss.

3 Positron Production Performance

The final year of this work was dedicated to measuring the performance of this linac based positron source. Two NaI detectors were calibrated and





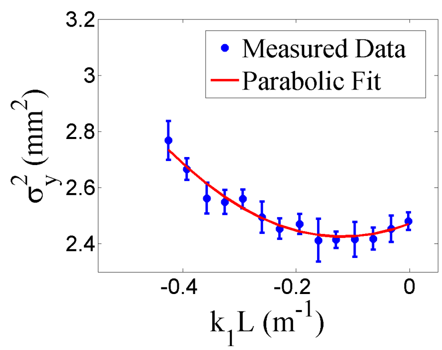


Figure 4: The top figure depicts the OTR apparatus. The bottom left (right) figure represent the measured change in the beam spot size along the vertical (horizontal) direction when the quadrupole field strength changes.

Parameter	Unit	Value
projected emittance ϵ_x	μm	0.37 ± 0.02
projected emittance ϵ_y	μm	0.30 ± 0.04
β_x-function	m	1.40 ± 0.06
β_y-function	m	1.17 ± 0.13
α_x-function	rad	0.97 ± 0.06
α_y-function	rad	0.24 ± 0.07
micro-pulse charge	pC	11
micro-pulse length	ps	35
energy of the beam "E"	MeV	15 ± 1.6
relative energy spread $\Delta E/E$	%	10.4

Table 1: The measured emittance of the high rep rate medical linac.

installed into the experimental side of the HRRL along with several layers of lead shielding to minimize photon contamination. The performance measurements first focused on establishing the veracity that the detected photons were from positrons annihilating in target T2 by using a permanent magnet to deflect positrons on the accelerator side and then by removing the annihilation target T2. The energy distribution of the positrons produced using a 10 MeV electron beam was also measured. The results were compared with a simulation of the beam line to reconcile the observed beam loss.

3.1 Positron Detection

A pair of NaI crystals were used to detect 511 keV photons emitted by positrons annihilating in the target T2. Originally, the NaI detector's output pulse length was around 400 μs. New PMT bases were constructed to shorten the time of this response to less than 1 μs. The NaI detector's PMT base was also altered to include both a dynode and an anode output. The crystal attached to these PMTs is from Saint-Gobain (Model 3M3/3) with a dimension of $3'' \times 3''$. The PMT base HV was set to approximately 1150 V. The anode output pulse was integrated over a time interval of 2 μs and converted to a digital value by a CAEN V792 ADC. The calibrated NaI detector spectrum from Na-22 and Co-60 sources are shown in the Fig. 5. The NaI measurement of the Na-22 511 keV photons has a sigma of about 18 keV.

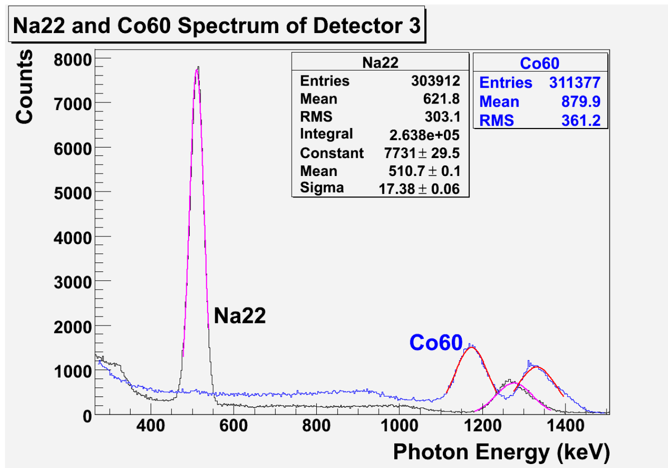


Figure 5: NaI detector calibration using a Na-22 (0.511 & 1.27 MeV lines) and a Co-60 source (1.17 & 1.33 MeV lines).

3.2 Positron Production Efficiency

The NaI detectors were installed in the shielded experimental cell as shown in Figure 3. The annihilation target, shown in Figure 3, intercepted the positron beam causing some of the positrons to annihilate and emit the back-to-back 511 keV photons that characterize the annihilation. Figure 6 represents the photon energy observed by the NaI detectors for three cases. First, a peak in the photon energy spectrum was observed which had an energy consistent with the expected 511 keV annihilation energy when T2 was inserted. Second, a permanent magnet deflected charged particles on the accelerator side of the experiment cell and caused the previously observed 511 keV peak to diminish substantially. Third, the 511 keV signal was also drastically reduced when the annihilation target T2 was removed from the beam line. Removing the production target T1 had the effect of reducing the coincidence rate to zero. We argue, based on these results, that the observed signal is predominantly caused by positrons annihilating in the target with very little signal from positrons that are produced by photon pair production.

The rate of 511 photons detected in coincidence within a 150 keV window was measured for several dipole current settings that would correspond to the transport of positrons having energies between one and five MeV in step of one MeV. Figure 7 illustrates the positron production efficiency observed in this experiment along with the efficiency predicted by a simulation. The

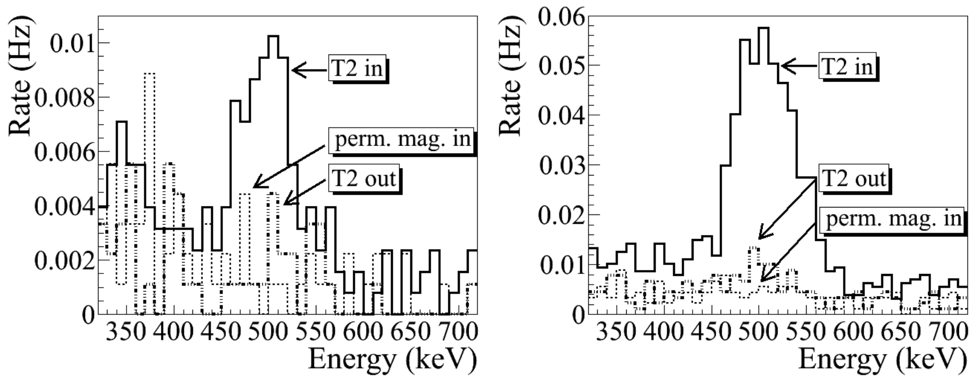


Figure 6: The coincidence signal observed in the beam left and beam right NaI detectors when T2 is in, T2 is in along with a magnet, and when the magnet is removed and T2 is out. The right figure correspond to the beam right detector.

simulation accounted for beam loss, NaI detector efficiency when two are used in coincidence mode, the detector acceptance, and the probability that a positron would annihilate in the annihilation target T2. Although the simulation agrees with experiment for the one, three, and four MeV positron energy bins, the two and five MeV positron bins are not in agreement.

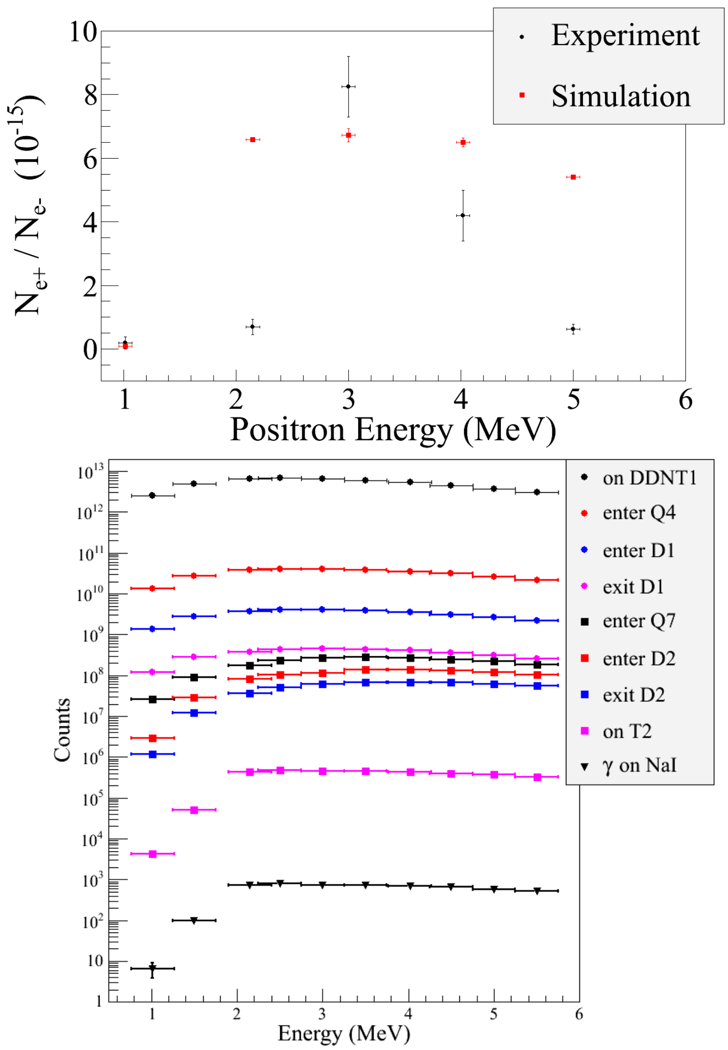


Figure 7: Top: a comparison between the observed positron to electron ratio and a simulation. Bottom: a simulation's beam loss prediction at several locations along the beam line.