Letter of Intent to PAC35

Polarized electrons for polarized positrons:

A proof–of–principle experiment

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Abstract

This letter proposes an experiment at the CEBAF injector to demonstrate and measure the longitudinal polarization transfer from a highly spin polarized electron beam to positrons via the polarized bremsstrahlung and subsequent pair-creation processes in radiator and pair production targets, respectively. A new dedicated injector beam line and experimental apparatus is described. The segmentation of the MeV region of the injector from the remaining CEBAF complex is described as a strategy to perform the experiment during the 6-month shutdown (May-October, 2011) of the 12 GeV Upgrade.

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1 Synopsis

The purpose of this letter is to inform, and seek approval from, the Program Advisory Committee for an experiment we would like to perform during the 6-month shutdown (May-October, 2011) for the 12 GeV Upgrade. The experiment constitutes the Ph.D. Thesis of Jonathan Dumas (LPSC/JLab) and would be the first ever demonstration and measurement for producing polarized positrons using a polarized electron beam. The experiment is proposed to occur in the CEBAF injector using a new dedicated electron beam line and an experimental apparatus successfully applied at the SLAC E166 experiment [1] to demonstrate polarized positrons by an alternative method. The proposed beam energy for the experiment is 3-8 MeV which can be provided by the injector cryounit ($\frac{1}{4}$ cryomodule). The low electron beam current required (1-10 μA) implies a relatively straight-forward and low-power target conversion system and small radiation budget. The positron polarization will be measured by a Compton transmission polarimeter. To perform this experiment during the 6-month shutdown we propose to temporarily segment the lowest MeV energy region of the injector from the remaining CEBAF complex. This configuration and long shutdown provide ample time to install the segmentation, then install, commission and perform the experiment, and finally recover the original injector configuration in advance of restoring the injector for CEBAF operations.

2 Motivation

An efficient scheme for positron production, widely used in particle accelerators, relies on the creation of electron-positron pairs from high energy photons. A significant aspect of the process is the dependence on the polarization, in particular, the circular polarization of the photon transfers to the longitudinal polarization of the positron [2]. This is the basic concept of operation tested for the polarized positron source being developed for the International Linear Collider (ILC). The circularly polarized photons are produced either from the Compton back-scattering of a laser light from high energy electrons [3] or from the synchrotron radiation of very high energy electrons travelling through a helical undulator [1], the latter approach selected for the ILC. This letter of intent proposes an experiment to investigate an alternative scheme based on the polarized bremsstralhung process [4].

Similarly to pair creation, the bremsstrahlung process is a polarization sensitive mechanism. This property has been widely used at un-polarized electron accelerators to produce linearly polarized photon beams. In addition to the intrinsic linear polarization, the photons have a circular component when the incoming electron beam is polarized, such that the bremsstrahlung of polarized electrons most generally lead to elliptically polarized photons [2,5]. This concept is routinely used to obtain a linearly or a circularly polarized photon beam at Hall B [6] at several GeV beam energy.

The production of polarized positrons from polarized bremsstrahlung [7,8] was explored in the ILC context, although not pursued in part because of the requirement of a high intensity polarized electron beam. However, recent advances in high-polarization (85%) and high-current (1 mA) electron sources [9] are encouraging and may offer greater potential for a compact, low energy driver for a polarized positron source [10]. To the best of the authors' knowledge this basic operational concept to transfer the longitudinal polarization of electrons to positrons via polarized bremsstrahlung and subsequent polarized pair-creation has never been experimentally investigated. It is the goal of the present experiment to demonstrate and quantify this concept by measuring the energy distribution of the positron yield and polarization obtained using a highly polarized electron beam of 3-8 MeV.

3 Physics processes

3.1 Polarized bremsstrahlung

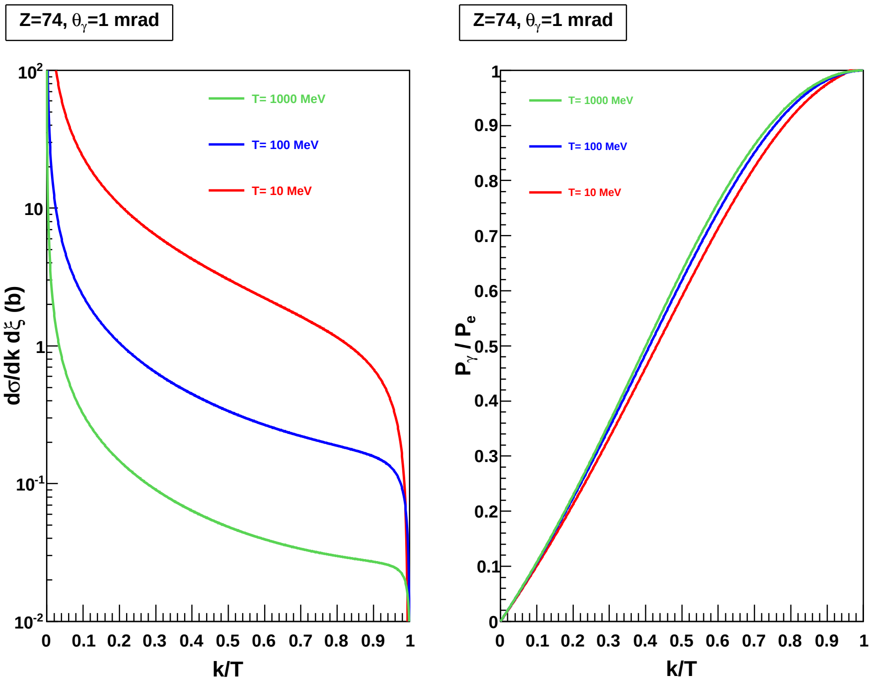

Figure 1. (color) Differential bremsstrahlung cross section ($d\sigma/dkd\xi$) and longitudinal to circular polarization transfer (P_γ/P_e) from electrons (or positrons) to photons with energy (k) expressed as a fraction of the electron beam energy (T), for a tungsten nucleus (Z=74) calculated at a fixed angle θ_γ=1 mrad.

As the essential mechanism for the production of high energy photons, the bremsstrahlung process is a text-book reaction widely investigated theoretically and experimentally. Polarization observables at high energy, including effects of the nuclear field screening and corrections to the Born approximation, were first addressed by H.A. Olsen and L.C. Maximon [2] and are still today the reference calculations implemented in the GEANT4 simulation package [11]. Fig. 1 shows the energy distribution of the differential cross section and of the polarization transfer from longitudinally polarized electrons to circularly polarized photons, as a function of the photon energy for a tungsten nucleus and a fixed photon angle of 1 mrad . The sharp decrease of the cross section in the end-point region is typical of the bremsstrahlung spectra. The polarization transfer is essentially universal, the highest circular polarization being obtained at the highest photon energy.

3.2 Polarized pair-creation

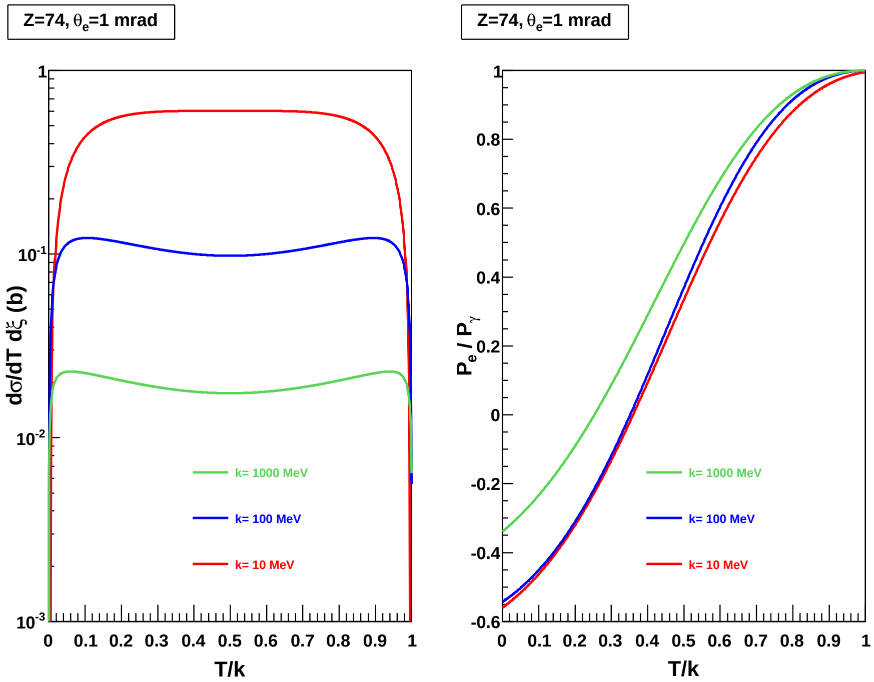

Figure 2. (color) Pair creation differential cross section ($d\sigma/dkd\xi$) and circular to longitudinal polarization transfer (P_e/P_γ) from photons to positrons (or electrons) with energy (T) expressed as a fraction of the photon beam energy (k), for a tungsten nucleus (Z=74) calculated at a fixed angle θ_e=1 mrad.

As the inverse process of the bremsstrahlung reaction, pair production is described by the same matrix elements so that the cross section and polarization transfer relations can be derived from the bremsstrahlung expressions following elementary substitutions [2]. Differential cross sections and polarization transfer are shown in Fig. 2 for a tungsten nucleus and a fixed positron angle of 1 mrad, at typical incoming photon energies. The essentially flat distribution is a direct consequence of the production of two identical mass particles from a massless photon. The polarization transfer shows a shape similar to bremsstrahlung but over a larger range of values, allowing for negative and positive polarization transfer.

Fig. 3 shows the expected positron yield and polarization obtained from a GEANT4 simulation using an 8 MeV electron beam and a 1 mm thick tungsten target. Angular (±10°) and momentum (±5 %) acceptance cuts, reflecting collection and selection magnets, respectively, have been applied to the simulated yield. It is seen that a 2 pA positron current can be obtained with 30-60% longitudinal polarization. Higher polarizations may be obtained at the expense of reduced positron current. Such a configuration should be easy to achieve and improve upon because of the small energy deposited in the target: the beam current can be increased to 10-30 μA without major impact on the target, and possibly more by using a tilted foil [12]. Such a positron current and polarization can be measured rapidly (minutes) as described in Sec. 6.

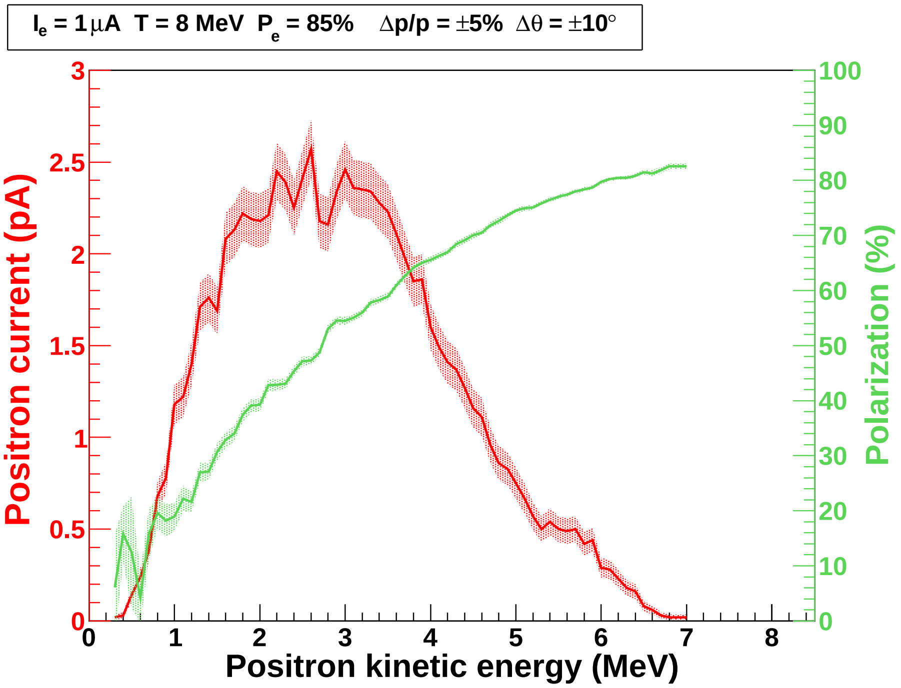

Figure 3. (color) Positron yield and polarization produced from a 1 μA and 85% longitudinally polarized electron beam of 8 MeV striking a 1 mm thick tungsten target.

4 Experiment strategy

The experiment we propose foremost requires a polarized electron beam with energy of at least ∼1 MeV to achieve pair creation. While both the CEBAF and FEL accelerators may in principle provide such a beam, reproducing at the FEL the highly spin polarized electron beam, electron spin manipulators and electron polarimeters that exist at CEBAF is costly and impractical. Consequently, we limited ourselves to the CEBAF complex and evaluated how we might accomplish the experiment at locations defined by typical energy ranges: 1-10 MeV (lowest MeV region) [4], 10-60 MeV (injector full energy) [10] and several GeV (linacs or end stations) [13]. While all cases appear viable, our final choice is guided by practical considerations. For example, photoneutron background radiation yield becomes increasingly a distraction above ∼8 MeV, *green field* designs are less invasive than modifiying existing beam

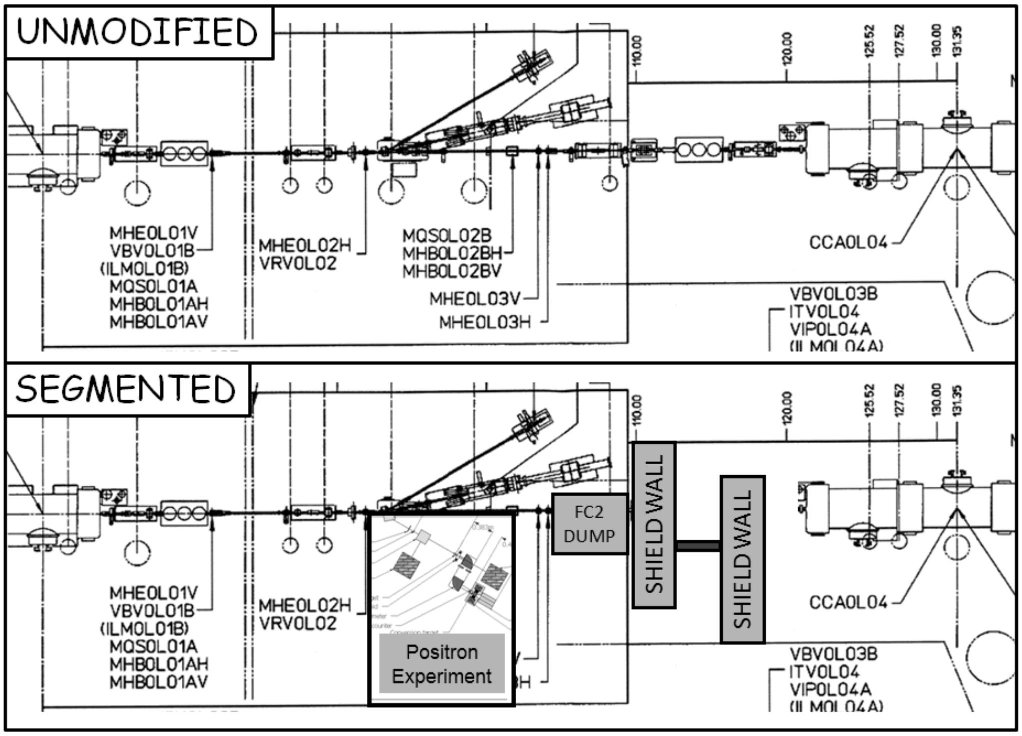

Figure 4. The unmodified (top) and conceptual segmented (bottom) injector layouts are shown together for comparison. In this configuration the segmented injector may operate to deliver a highly polarized (85%) electron beam with energy up to 10 MeV. The beam current may be monitored by both a BCM cavity and a fixed termination Faraday cup (FC2 DUMP) with both operational and hardware limits as routinely used for CEBAF operations.

lines, and the potential availability of experimental equipment (discussed in Sec. 7) significantly reduces cost and overhead. Of all concerns, integration with the CEBAF schedule, dictated by the Nuclear Physics (NP) program, Scheduled Accelerator Down (SAD) periods and the 6-month and 12-month 12 GeV Upgrade shtudowns, is required. Finally, the strategy we propose is to temporarily segment the lowest MeV region of injector following the 10 MeV cryounit from the remainder of the CEBAF complex during the 6-month shutdown May-October, 2011.

Historically, the operation of the electron gun had required for personnel safety purpose that the entire injector and north linac be elevated to a Beam Permit status. However, about 3 years ago an injector segmentation was constructed to allow for operation of the electron gun and warm radio-frequency cavities to accelerate the beam to 500 keV. This was done within constraints set by the Radiological Control (RadCon) and Personnel Safety System (PSS) groups to protect personnel and hardware. This mode has since become routine and proved invaluable for maintenance opportunities and beam operations, particularly while starting the accelerator after a shutdown. The proposed segmentation of the injector for 10 MeV beam energy would offer similar opportunities. In particular the 6-month 12 GeV Upgrade shutdown would provide sufficient opportunity to install, commission and run this experiment. While we may still consider a permanent segmentation, for the purpose of this letter of intent we only request a temporary segmentation, that is, one that would be entirely removed at the end of the shutdown.

The region of the injector intended for segmentation is shown in Fig. 4, where the unmodified (top) and conceptual segmented (bottom) layouts are shown together for comparison. Our plan proposes to reconfigure approximately 5 meters of beam line. All components would be surveyed prior to removal for later re-installation. Two optics girders and one differential pump girder would be removed and stored under vacuum. A fourth girder containing a Faraday cup would move upstream, where installed 10 years ago, to function as a fixed beam dump (rated for 10 MeV and 200 μA); effectively the termination point of the segmented injector. The cleared region would be used to fabricate a temporary shield wall labyrinth consisting primarily of steel shield blocks and re-using the existing PSS personnel gate and egress controls. Downstream of the shield wall the existing cryomodule 0L03 would exist unmodified, never vented. Note the primary entrance of the injector (not shown) provides routine egress and a 2-ton crane/door for moving equipment to the injector. The ultimate configuration would be evaluated by the RadCon and PSS groups and approved by the Director of Operations.

The new electron beam line and experimental apparatus to be installed, occupy a 3×3 m^2 footprint, shown in Fig. 4 and discussed in detail in the next section. The cyrounit, electron spectrometer and electron Mott polarimeter have been previously tested with 2-8 MeV electron beam energy. The proposed experimental collection optics, spectrometer and polarimeter have been previously applied in a comparable energy range [14].

5 Experiment layout

The existing equipment of the injector beam line offer the capabilities of beam energy and polarization measurements, allowing for a precise knowledge of the electron beam. For the production of positrons, a new electron line would be installed on the opposite side of the injector line, with no interference with these beam characterization capabilities. This new line (Fig. 5) would be instrumented with various diagnostic devices and a target ladder supporting a viewer, an empty target, and different production targets.

For example, a 1 μA highly longitudinally polarized electron beam of 3-8 MeV would produce a circularly polarized photon beam within a 1 mm tungsten target (T_1) via polarized bremsstrahlung. The beam power deposited in T_1 has been simulated to be about 4 W, corresponding to half of the total electron beam power. A dipole located after the target would guide the exiting electrons towards a beam dump. At a 1 m distance from the initial production target, the polarized photons would create a longitudinally polarized electron-positron pair in a second tungsten target (T_2), the remaining part of the secondary photon beam being absorbed in an appropriate photon-dump.

Major parts of the characterization equipment of the SLAC E166 experi-

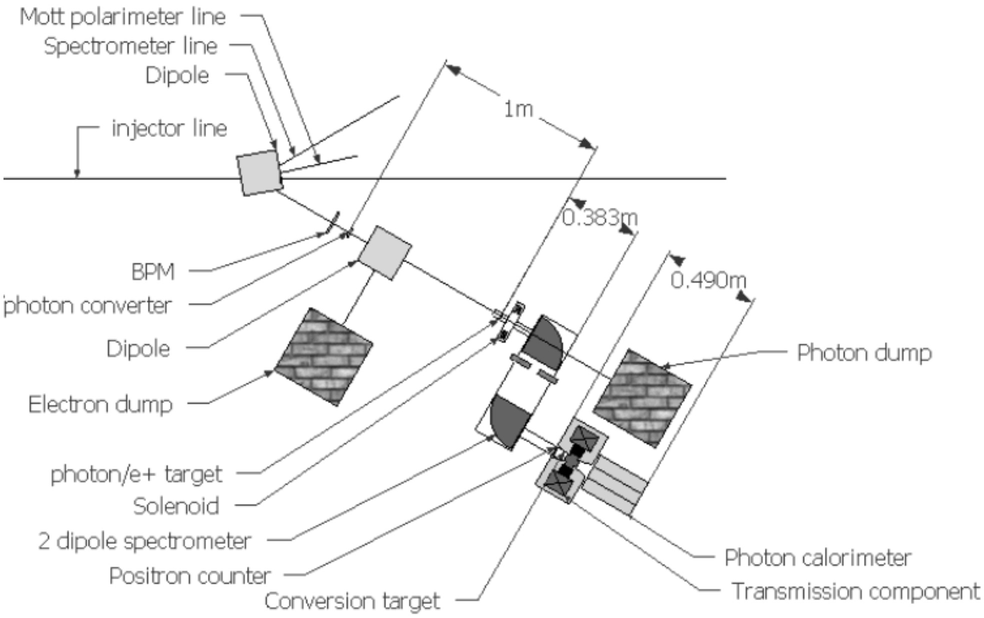

Figure 5. Schematic layout of the experiment.

ment [14] used in a similar energy range would then be installed to measure the positron yield and polarization. A solenoid collects the positrons, a double-dipole spectrometer selects the positron momentum and preserves the longitudinal polarization. In the Compton transmission polarimeter the polarized positrons convert into circularly polarized photons in a third tungsten target (T_3). The Compton absorption of these photons within a polarized iron target is the operationnal principle of the transmission polarimeter: the asymmetry between the number of transmitted photons measured for two opposite target orientations is proportionnal to the positron polarization. In addition, the same experimental asymmetry can also be obtained by reversing the incoming positron polarization (by reversing the electron beam helicity) allowing for the control of systematics. Furthermore, the knowledge of the electron beam polarization from the Mott electron polarimeter allows for a cross calibration of the Compton transmission polarimeter. It is then forseen to firstly commission the new beam line and the Compton transmission polarimeter in electron mode, and secondly perform the positron characterization experiment.

6 Electron and positron polarimetry

6.1 Compton transmission polarimetry

The differential cross section for the Compton scattering of circularly polarized photons (P_γ) from a polarized electron target (P_t) can be written

$$\frac{d^2\sigma}{d\theta d\phi} = \frac{d^2\sigma^0}{d\theta d\phi} \left[1 + P_\gamma P_t A_C(\theta)\right] \tag{1}$$

where $d^2\sigma^0/d\theta d\phi$ is the unpolarized Compton cross section

$$\frac{d^2\sigma^0}{d\theta d\phi} = \frac{1}{2}\left(r_0\,\frac{\omega}{\omega_0}\right)^2 \left[\frac{\omega_0}{\omega} + \frac{\omega}{\omega_0} - \sin^2(\theta)\right]\,\sin(\theta) \tag{2}$$

and $A_C(\theta)$ is the analyzing power of the Compton process

$$A_C(\theta) = \left[\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right]\cos(\theta)\bigg/\left[\frac{\omega_0}{\omega} + \frac{\omega}{\omega_0} - \sin^2(\theta)\right]\,; \tag{3}$$

both quantities depending on the scattered photon energy (ω) and angle (θ), and the incoming photon energy (ω_0).

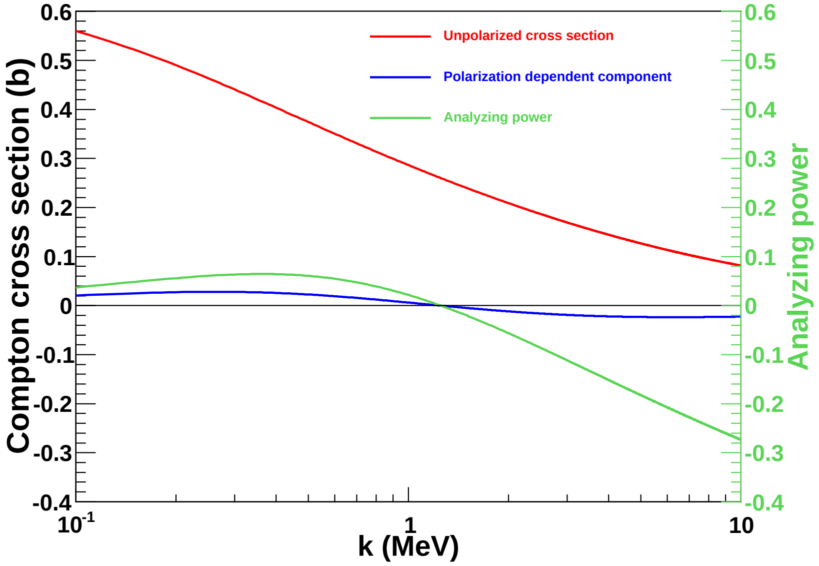

Figure 6. (color) Total Compton cross section components and analyzing power.

Compton transmission polarimetry takes advantage of the sensivity of the Compton process to the absorption of circularly polarized photons in a polarized target. This method, which involves a single detection device matching the size of the incoming beam, is intrinsically easy to implement and has been recently used successfully in experiments similar to the present one [14,15]. Considering the simple case of a monochromatic parallel photon beam scattering off a polarized electron target with length L, the transmission efficiency characterizing the probability that a photon exits the target may be written

$$\varepsilon_T = \exp\left[-(\mu_0 + P_\gamma P_t \mu_1)L\right] \tag{4}$$

which assumes the loss of any photon interacting in the target and the dominance of the Compton process; μ_0 and μ_1 are the unpolarized and polarized Compton absorption coefficients

$$\mu_0 = \rho_e \int d\theta d\phi\,\frac{d^2\sigma^0}{d\theta d\phi}, \qquad \mu_1 = \rho_e \int d\theta d\phi\,\frac{d^2\sigma^0}{d\theta d\phi} A_C(\theta), \tag{5}$$

with ρ_e the electron density of the target. The total unpolarized Compton cross section (μ_0/ρ_e), the polarization dependent part (μ_1/ρ_e) and the Compton analyzing power (μ_1/μ_0) are shown in Fig. 6 as a function of the incoming photon energy. The magnitude of the cross section and of the analyzing power guarantee an efficient polarimeter over the energy range of this experiment. The zero-crossing of the analyzing power at about 1.5 MeV is of particular interest for detector calibration purposes.

The measurement of the circular polarization of the photon beam is obtained from the number of transmitted photons for oppositly polarized target orientations. The corresponding asymmetry is

$$A_T = \frac{N^+ - N^-}{N^+ + N^-} = \tanh(-P_\gamma P_t \mu_1 L) \tag{6}$$

from which the photon circular polarization is inferred according to

$$P_\gamma = -A_T/P_t\mu_1 L\,. \tag{7}$$

The associated statistical uncertainty is

$$\delta P_\gamma = \Big[2N_\gamma\, P_t^2\, \mu_1^2 L^2 \exp\left(-\mu_0 L\right)\Big]^{-1/2}\ , \tag{8}$$

in the case of small asymmetries. In this discussion a single photon energy is assumed, however, in reality the broad photon spectrum must be considered. The resulting experimental asymmetry is then a convolution of this spectrum with the polarized Compton absorption process. This multistep process has been simulated with GEANT4 taking advantage of improvments to include polarized electron, positron and photon interactions [16].

As an example, consider a 7.5 MeV electron beam of 400 μm width illumintating a 1 mm thick tungsten foil. The created photons travel 12 mm to a polarized analyzing target (iron cylinder 75 mm in length and 50 mm in diameter with a 7.4 % polarization). The photon detector is modeled by a 60×60 mm^2 ideal detection surface located 72.5 mm from the exit of the polarized target. This geometrical arrangement corresponds to the E166 experiment [14]. Fig. 7 shows the number of transmitted photons and the expected asymmetry for a measurement lasting about 100 s with a 1 pA electron beam of 85% longitudinal polarization. For each photon energy bin, the electron beam polarization can be inferred from

$$P_e = \frac{A_T}{P_t A_e} \tag{9}$$

where the electron analyzing power A_e is determined either from simulation or experiment with a known polarized beam, varying from -0.08 to 0.34 in the considered energy range. The statistical average over the accepted photon energy yields the absolute statistical uncertainty ±0.03 on the determination of P_e meaning that an accurate measurement may be obtained within a short amount of time due to the high (150 kHz) event rate.

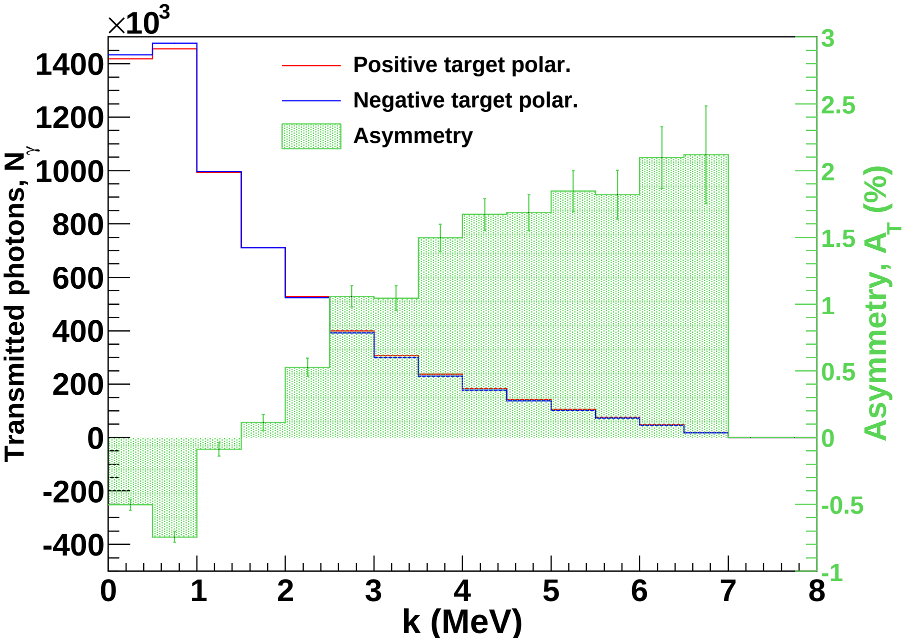

Figure 7. (color) Number of transmitted photons for two opposite target polarizations and expected experimental asymmetry as obtained from GEANT4 simulations. The statistical error bars correspond to a measurement time of 100 s at a 1 pA current.

6.2 Data acquisition

In order to achieve the statistical accuracy in reasonable time, a fast acquisition will be designed for the readout of the photon calorimeter of the Compton transmission polarimeter. Achieving anticipated rates of several hundred kilohertz is possible through the use of Flash Analog to Digitial Converters (Flash ADC), allowing pipe-lining and buffering of the event data. The data acquisition system (DAQ) proposed for this experiment is similar to that presently implemented for the Hall A Compton polarimeter, which demonstrated 100 kHz trigger acquisition already in 1999 [17].

Wireless technology and increased micro-processor speeds with GHz bandwidth have made suitable Flash ADC's both attainable and affordable. The benefit to the DAQ system is that complete pipe-lining of the event data is possible, meaning data is recorded continuously into a large circular memory buffer (access rates from 1.5 μs up to 250 μs). A consequence is the ability to locate events by accessing the memory corresponding to the trigger time thereby eliminating extrinsic dead time as long as events are read before being overwritten by another event. This concept will be the core of the acquisition system of Hall D [20] intended to record and generate the trigger of several thousand calorimeter channels at rates of 160 kHz. Jefferson Laboratory has developed the corresponding Flash ADC with a sampling rate of 250 MHz and is presently commissioning the ADC in the Hall A Moeller DAQ where direct on-board processing of the data using scalers allows for computation of experimental asymmetries and polarization calculations without dead time [18].

As mentioned previously the Hall A Compton polarimeter reached high event rates 10 years ago using a 40 MHz Flash ADC, the state of the art transfer VME protocol available at that time with a speed of 20 MBytes/s, buffering and online histogramming on the VME CPU. A new data acquisition is now being tested in parallel to the *old* DAQ, using a similar 250 MHz Flash ADC to compute the integral of the signal during each helicity period [19]. By using commonly available Field Programmable Gate Arrays (FPGA) one can easily implement integration of the signal or histogramming, completely eliminating the dead time linked to data transfer to the central processor. Depending upon the trigger rate and using new transfer protocols reaching 320 MBytes/s one may also transfer all the events without dead time for offline analysis. It appears reasonable to assert that trigger rates of about 1 MHz are attainable simply by scaling the old DAQ with transfer speeds now 10 times faster. Such performance improvement will soon be confirmed preparing the Hall A Compton DAQ for coming experiments at 6 and 12 GeV in which this system will be fully implemented.

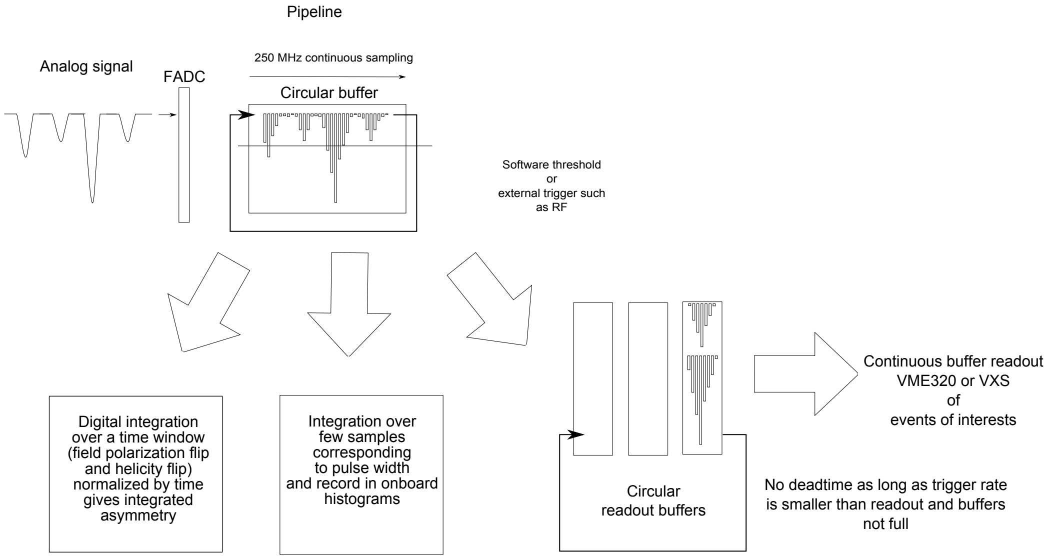

Figure 8. Schematic of the proposed data acquistion system.

As illustrated in Fig. 8, the system will allow several methods of measurement. First, as an integration measurement it has the advantage of being free of threshold effects, insensitive to pile-up and will work at any rate at the expense of energy information. Second, implemented for online histogramming it is also free of dead time and provides the energy dependence of the asymmetry at any rate, although the systematics due to pile up and thresholds must be studied to determine the optimal balance between statistical uncertainty and systematic error. This method should also be able to reach a 1 MHz event rate. Finally, event by event readout provides the greatest quantity of information without dead time provided events are read faster than written. For example, to record 20 samples for each event and transfer 200 MByte/s naively requires a rate of 1 MHz. The challenge is the large amount of data generated, so it may prove more practical to implement this third method with a pre-scaler for systematic studies. Practically, an operational system could be developed in about 6 months taking advantage of existing projects, for example, the Hall A Compton and Moller polarimeter DAQ upgrades and

Hall D is already commissioning a comparable system. The final system will operate simultaneously the three data acquisition methods.

7 Timeline

We propose a 2 year plan to perform this proof-of-principle experiment, complete the Ph.D. Thesis of Jonathan Dumas and publish our results. The following timeline outlines a plan we believe will allow us to successfully perform this experiment.

December, 2009

- Following the 2nd year Ph.D. Thesis Review of Jonthan Dumas we received support by the Accelerator Division Associate Director to proceed and submit a Letter of Intent to PAC35 for this proposed experiment at CEBAF.

January - February, 2010 (Scheduled Accelerator Down)

- Collaborators seek PAC approval so that we may have official support of JLab, and to develop a Memorandum of Understanding (MOU) with DESY (Compton transmission polarimeter) and Princeton University (collection solenoid and spectrometer) to loan hardware for this experiment.
- Survey and assess region for positron experiment and segmentation.

March - June, 2010 (Nuclear Physics Program)

- LPSC to loan Compton transmission polarimeter from DESY, acquire analyzing magnet power supply, develop data acquisition system, test photon calorimeter, integrate systems.
- JLab to loan solenoid and spectrometer from Princeton University, acquire magnet power supplies, make functional, map and/or develop magnetic model for simulation.
- Develop detailed layout to add new electron beam line to injector at 0L02 (lowest MeV) region, with suitable optics and diagnostics to deliver/control beam at conversion target. Fabricate and acquire components for new beam line “spigot”.

July - August, 2010 (Scheduled Accelerator Down)

- Early opportunity to install new beam line “spigot”: new vacuum chamber and isolation valve.
- Perform final measurements to prepare for the injector segmentation.

September 2010 April 2011 (Nuclear Physics Program)

- Complete integrated design of the experiment with full simulations, scattering chamber, targets, collection optics, dumps, detectors and shielding.
- Fabricate and test beam line components.
- Fabricate injector segmentation.

- Transfer Compton transmission polarimeter from LPSC to JLab.
- Prepare for experiment installation.

May - October 2011 (Perform Experiment)

- 1 month to install segmentation, experimental apparatus and commission segmentation.
- 3 months to commission and perform experiment.
- 1 month to un-install segmentation, remove and return experimental apparatus to DESY and Princeton University.
- 1 month advance recovery in preparation of CEBAF operations.

November - December 2011 (Nuclear Physics Program)

- Experiment and analysis are completed.
- Jonathan Dumas to defend Ph.D. Thesis and publish results.

8 Summary

This letter proposes an experiment at the CEBAF injector to demonstrate and measure the longitudinal polarization transfer from a highly spin polarized electron beam to positrons via the polarized bremsstrahlung and subsequent pair-creation processes in radiator and pair production targets, respectively. It requires a new dedicated injector beam line and experimental apparatus. A strategy which implies the segmentation of the MeV region of the injector from the remaining CEBAF complex has been proposed to perform this experiment during the 6-month shutdown (May-October, 2011) of the 12 GeV Upgrade.

This experiment is designed to have a small physical and radiation footprint. By using a 1-10 μA electron beam low power targets and minimal shielding is intended. The positron (and electron beam) polarization will be measured via the Compton transmission method. The expected positron yield is low $\sim$pA but yet demanding in terms of data acquisition performances. We should benefit from the current developments for Hall A and Hall D to guarantee a powerfull operation of this device.

In addition to this unique *proof-of-principle* experiment, this represents the first accelerator physics experiment at Jefferson Lab aimed at a production mechanism for positrons in the CEBAF accelerator. This R&D issue has been discussed for many years and through two workshops, most recently at the International Workshop on Positrons at Jefferson Lab in March, 2009 [21]. The results of this experiment would provide valuable information for the potential development of a higher intensity polarized positron source for CEBAF, and may prove useful for opportunities in the context of the ILC.

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