



# Design Studies for Flux and Polarization Measurements of Photons and Positrons for SLAC Proposal E166:

An experiment to test polarized positron production in the FFTB

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We present results from design studies carried out to investigate measurements of the flux, spectrum and polarization of undulator photons for SLAC Proposal E166. A transmission Compton polarimeter is considered for measuring the photon circular polarization. We also present results for measuring the flux and spectrum of positrons produced by the undulator photons in an  $0.5X_0$  Titanium target. And we present some considerations for use of a transmission Compton polarimeter to measure the circular polarization of bremsstrahlung photons emitted by the polarized positrons in a thin radiator.

## **1. Introduction**

SLAC E166 proposes to test polarized positron production utilizing a helical undulator.[1] This experiment would be carried out in the FFTB with SLAC's 50-GeV electron beam. The goal of the experiment is to measure the flux, spectrum and polarization of the undulator photons; and to measure the flux, spectrum and polarization of the positrons that are subsequently produced in the positron target. Measurement accuracies of (5-10)% should be adequate. The positron target will be  $0.5X_0$  Titanium, which is what is currently envisioned as the target for a polarized positron source for NLC. E166, with a 1-meter helical undulator, would be an ~1%-scale version (i.e. ~1% in length of undulator system and yield of positrons) of the polarized positron source for a future Linear Collider (LC).

The design studies reported on here were carried out for developing the E166 proposal. These studies include a detailed description for measurements of the undulator photon flux, spectrum and polarization; and also for the positron flux and spectrum. The photon polarimeter considered is a transmission Compton polarimeter. Some considerations for positron polarimetry, utilizing a transmission Compton polarimeter for bremsstrahlung photons emitted by the positrons in a thin radiator, are also presented.

## 1.1 Motivation for a Polarized Positron Source

Polarized electrons were an essential feature for the SLD physics program at the SLC, and allowed SLD to make many precise measurements of parity-violating asymmetries. The polarized electron beam enabled SLD to make the world's best measurement of the weak mixing angle and to provide key data for predictions of the Higgs mass.[2] At the LC, electron polarization will continue to play a key role. Polarizing the positron beam, in addition, at the LC will provide a significant enhancement to the physics program.[3,4] It can be used to:

- i) increase the effective beam polarization;
- ii) suppress the W-pair background;
- iii) improve the precision electroweak measurements;
- iv) reduce the systematic error on polarimetry; and
- v) improve the deciphering of the origin of new physics signals by measuring their polarization-dependence.

## 1.2 Motivation for an undulator-based positron source

The present positron source design for the Next Linear Collider [5] is similar to the positron source of the SLAC Linear Collider.[6] The NLC source would use a 6.2 GeV electron beam directed onto a  $4X_0$  solid Tungsten Rhenium target to generate positrons. The electron beam spotsize at the target is  $\sim 2$ mm rms and the positron yield is  $\sim 1$  positron per incident electron. The positrons from the target are collected using a flux concentrator and 250-MeV accelerator system embedded in a solenoid field. In order to achieve the required yield, while avoiding damage to the target, three target/accelerator assemblies are required. The positrons are unpolarized.

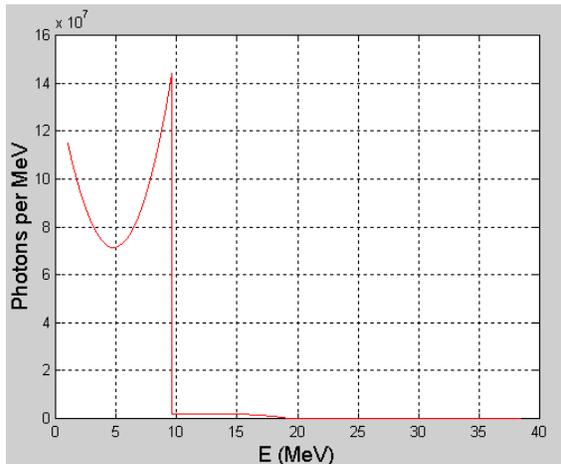
During the past 20 years undulator photon sources have been used to generate intense photon beams at synchrotron light facilities. Recently, helical undulators have also been used to generate intense circularly polarized photon beams. At SLAC's SPEAR facility, circularly polarized photons in the 500-1000 eV energy range with nearly 100% circular polarization, have been generated.[7] And at the VEPP-2M storage ring, a helical undulator has been used to generate 200 eV circularly polarized photons to measure the polarization of the 650 MeV positron beam to an accuracy of 10%.[8]

The possibility to generate a polarized positron beam, utilizing a helical undulator, for the LC was first proposed by Balakin and Mikhailichenko.[9] Photons, with energies of  $\sim 10$ -20 MeV, are radiated from a high energy ( $\sim 150$  GeV) electron beam passing through a helical undulator. They are converted to positrons, which then are collected and accelerated in a system similar to that used for SLC. The current design for the positron source at TESLA is based on a planar undulator and the positrons are unpolarized. However, the TESLA design envisions an upgrade to a

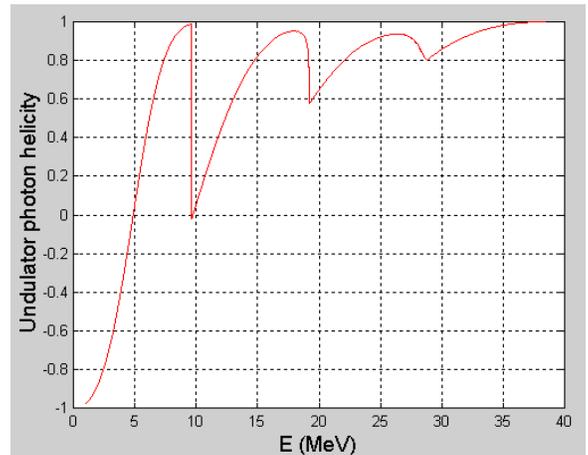
helical undulator to produce polarized positrons. The Positron Source Group for the NLC is also considering a polarized positron source based on helical undulator technology. In addition to providing a possibility for polarized positrons, an undulator-based source can utilize a thinner target, reducing the thermal shock and damage to the target.

### 1.3 Polarized Positron source for E166 [1,10,11]

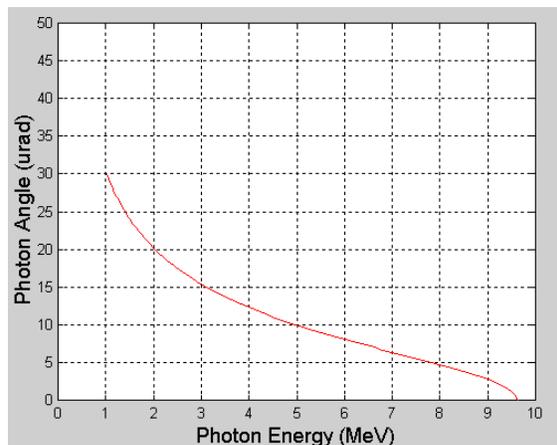
The helical undulator for E166 is proposed to have  $K=0.17$  with a 2.4mm period. The electron beam will be 50 GeV with  $5 \times 10^9$  electrons/pulse. This results in a 1<sup>st</sup> harmonic cutoff energy for the undulator photons of 9.62 MeV. The undulator photon spectrum corresponding to these beam and undulator parameters is shown in Figure 1 for an undulator length of 0.5m. The photon helicity spectrum is shown in Figure 2. The relation between angle and energy for the undulator photons is plotted in Figure 3 (for 1<sup>st</sup> harmonic photons).



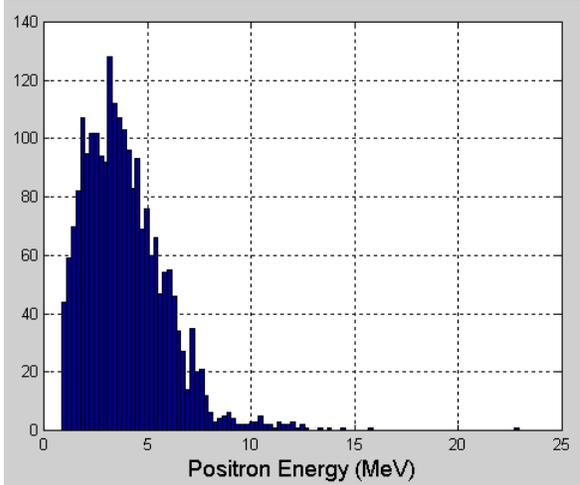
**Figure 1: Undulator Photon spectrum**



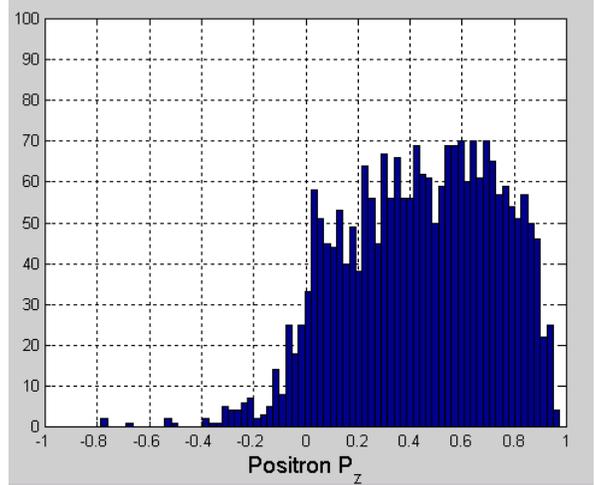
**Figure 2: Undulator Photon Helicity spectrum**



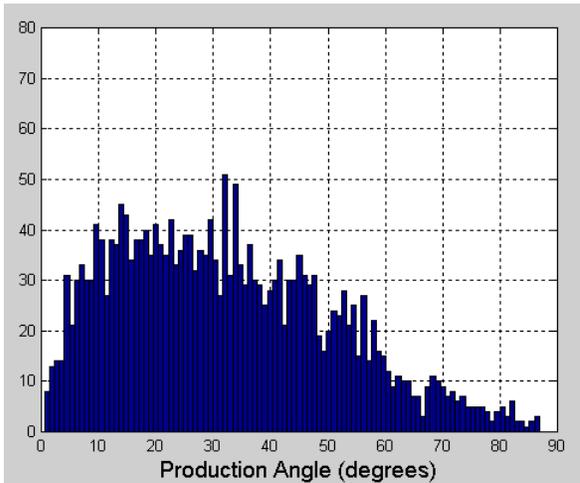
**Figure 3: Production angle of 1<sup>st</sup> harmonic undulator photons versus photon energy**



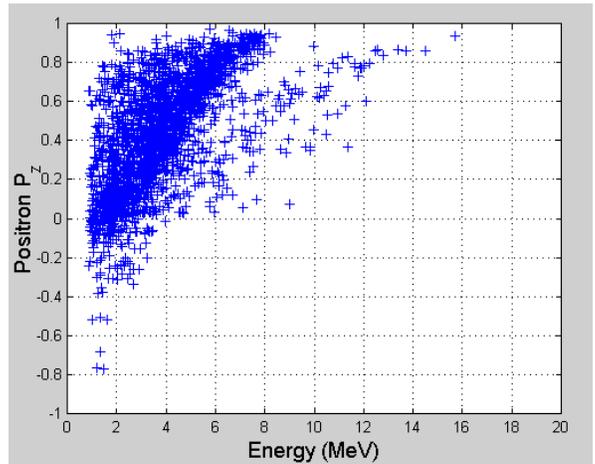
**Figure 4: Positron Energy Distribution after Production Target**



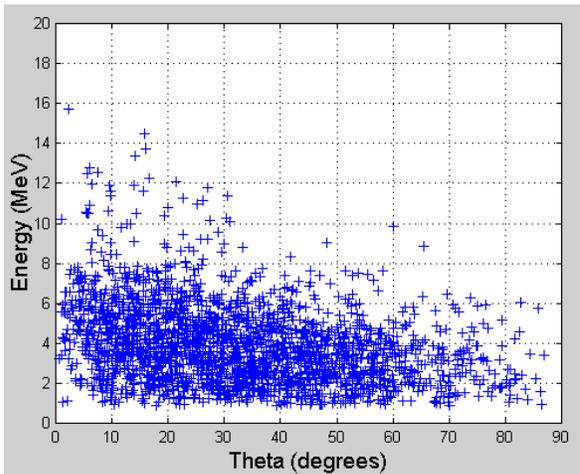
**Figure 5: Positron Polarization projected onto neutral beamline axis**



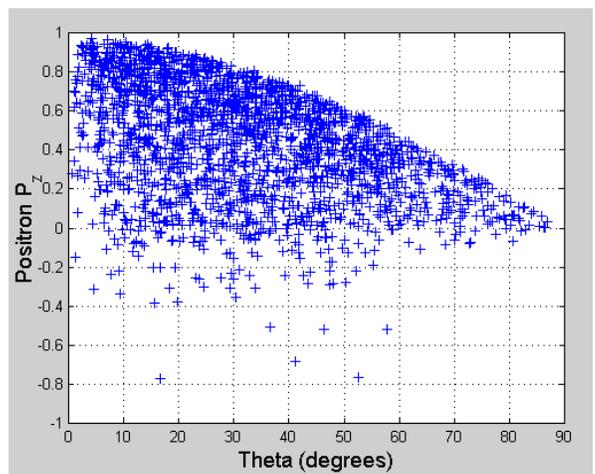
**Figure 6: Positron production angle**



**Figure 7: Scatterplot of Positron P<sub>z</sub> versus Energy**



**Figure 8: Scatterplot of Positron Energy versus Production Angle**



**Figure 9: Scatterplot of Positron P<sub>z</sub> versus Production Angle**

The positron target for E166 is proposed to be  $0.5X_0$  Ti. The energy spectrum of the positrons produced is shown in Figure 4 and their longitudinal polarization (measured in the direction of the incident undulator photons),  $P_z$ , is shown in Figure 5. The positron yield is  $\sim 0.0045$  positrons per incident photon. The energy distribution in Figure 4 is cutoff at 1 MeV, reflecting the energy cutoff used in the EGS4 simulation.[10,12] The positron beam has a large emittance and the production angle of the positron beam with respect to the neutral beamline axis is shown in Figure 6. A scatterplot of  $P_z$  versus positron energy is shown in Figure 7. Lastly, Figures 8 and 9 show scatterplots of positron energy and  $P_z$  versus the production angle. The average energy of all positrons produced is 3.9 MeV, and their average  $P_z$  is 44%. The mean energy and polarization of positrons captured in a real source (and also in the E166 experiment) will be higher than these values because of higher capture efficiencies for positrons with low production angles.

## 1.5 Polarimetry for MeV Photons and Positrons

The energy range of interest for photon and positron measurements in E166 is from 1 MeV to 9.6 MeV. Polarimetry for photons, electrons and positrons in this energy range was extensively explored following the discovery of parity violation in 1957. A recent review of the polarimetry techniques used can be found in Reference [13]. Reviews of some of the early polarization measurements can be found in Reference [14]. All of them utilize the spin-dependent QED scattering cross sections with polarized electrons in a target of magnetized Fe. Photon polarimetry is done with either transmission or scattering Compton polarimeters.[15] In the transmission Compton polarimeter a thick Fe target is used and the transmission asymmetry of the photons is measured. Positron polarimetry can be done with a polarized Fe foil and analyzing either the Bhabha-scatters or annihilation photons. The best polarization measurement for MeV positrons, carried out to date, measured the asymmetry in both Bhabha scatters and annihilation photons using a thin  $500\mu\text{m}$  Fe target.[16] They performed a coincidence counting experiment, analyzing the energy of individual particles, and measured the positron polarization with an accuracy of  $\sim 6\%$ . Another technique for measuring the positron polarization is to have them traverse a thin radiator, transferring their polarization to bremsstrahlung photons, whose polarization is then analyzed in a transmission Compton polarimeter. This technique has been used for electron polarization measurements,[17] and was also used for a positron polarization measurement, which achieved an accuracy of  $\sim 10\%$ .[18]

In this study, we consider a transmission Compton polarimeter for the undulator photons as shown in Figure 10. This is discussed in detail in Section 3.3. Polarimetry using the transmission Compton technique is described by Schopper [15] and has been employed by many experiments for analyzing the circular polarization of MeV

photons. The first experiment to use this technique was carried out by Gunst and Page in 1953.[19] Recently, this technique has been employed in an experiment at the KEK-ATF[20] and is being used at the Bates Lab.[21] For the positron polarimeter, we present only some initial considerations for a transmission Compton polarimeter that analyzes the polarization of bremsstrahlung photons generated by the positrons in a thin radiator. This type of positron polarimeter is similar to the polarimeters described in References [17] and [18], and has also been discussed for the experiment at the KEK-ATF.[20]

## 1.6 Depolarization effects in the Positron Source

Positrons produced in the  $0.5X_0$  Ti production target lose energy due to ionization and to bremsstrahlung. Significant energy loss due to bremsstrahlung results in some depolarization due to spin flips, which has been calculated by Olsen and Maximon[22] and others. (Further discussion of depolarization effects and depolarization measurements made can be found in References [23] - [25]). This depolarization effect is included in the EGS4 simulation done for the E166 proposal.[10,12] As an example, consider the depolarization due to emission of a 5 MeV bremsstrahlung photon by an 8 MeV positron. Using Equation 2 in Reference [23],

$$\frac{\Delta P}{P} = \frac{1}{2} \left( 1 - \frac{1}{3} P_i \right) \frac{\Delta E}{E} \quad (1)$$

one finds for  $P_i=1$  that the depolarization ( $\Delta P/P$ ) is 21%. However, the average depolarization effect for the production target in E166 is expected to be rather small. The dominant energy loss in the target is due to  $dE/dx$  losses from multiple scattering, which are expected to have negligible depolarization effects for relativistic electrons. As an example, one can estimate the average depolarization using Equation 9 in Reference [24],

$$\frac{P}{P_0} = \left( \frac{E_f + dE/dx X_0}{E_0 + dE/dx X_0} \right)^{1/3}, \quad (2)$$

For Titanium,  $X_0$  is 3.6cm and  $dE/dx=23.5\text{MeV}/X_0$ . For  $E_f=3$  MeV and  $E_0=8\text{MeV}$ , one finds that the average depolarization ( $1-P/P_0$ ) is only 6%. But note that the positrons are quickly being stopped in the Ti target. Equation (2) only applies for relativistic electrons, and depolarization of the positrons due to multiple scattering can be significant for energies below 1 MeV.[23, 25] However, this depolarization at low energies below 1 MeV results from scattering that is primarily due to electric fields; this scattering alters the trajectory but not the spin vector. Thus the positron  $P_z$ -component at 1 MeV should be frozen out as the positron continues to degrade in

energy. Above 1 MeV, the spin vector should follow the momentum vector in the scattering processes (due to both electric and magnetic fields). The net effect is that depolarization effects in the positron target are expected to be small and should be accurately modeled in the EGS4 simulation done.

## 2. Electron and Photon Beams

### 2.1 *Left and Right* Helical undulators

E166 proposes to use a pulsed helical undulator [26] to generate circularly polarized photons in the energy range from 1-10 MeV, which then impinge on an  $0.5X_0$  Ti positron target. The 1-meter undulator is pulsed with an  $\sim 30\mu\text{s}$  pulse. For polarimetry it is desirable to be able to flip both the beam helicity and the target helicity to perform cross checks and reduce systematic errors. The target helicity can easily be flipped by reversing the direction of the magnetic field in the Fe target, though this can only be done slowly (perhaps every few minutes). Flipping the beam helicity requires implementing two 0.5-meter undulators with opposite helicity. If this is done, then the positron helicity can be randomly selected on a pulse-by-pulse basis (as is currently done for SLAC's polarized electron beam) by pulsing the *left* undulator on *left* pulses and the *right* undulator on *right* pulses. Pulse-by-pulse control of the beam helicity for E166 is desirable, since such control is not possible for the helicity of the Fe target. Pulse-by-pulse control of the positron helicity is very desirable for the physics program at the LC, where it facilitates minimizing false *left-right* beam asymmetries as well as minimizing effects due to beam jitter, electronics noise and electronics drifts when calculating the *left-right* physics asymmetries,  $A_{LR}$ . For E166, the benefit of implementing pulse-by-pulse helicity control would primarily be to facilitate the positron polarization measurement. The experiment will be able to tolerate higher backgrounds, and the measurement time will be reduced. Lastly, one will also gain experience with this method for helicity control as a possible technique to be implemented at the LC.

The triggers for the undulator current pulses can come from the PMON system. PMON refers to a set of SLAC-built custom electronics, which can be controlled by the accelerator SCP (SLAC Control Program) software. It has been used extensively over the last 10 years at SLAC for many experiments, including SLD and E-158, to control the left-right helicity sequence for the polarized electron beam.[27] For E166 it can be used to generate left (L) or right (R) triggers for the undulators. PMON generates a pseudo-random helicity sequence and imposes a quadruplet structure on this, in which two consecutive pulses have randomly chosen helicities and the subsequent two pulses are chosen to be their complements. For example, a possible sequence could be "LRRL LLRR." In the data analysis, asymmetries can be calculated for pairs of events. Pairs are formed from the first and third members of

the quadruplet, and from the second and fourth members. The pseudo-random sequence used is described in [28]. Observing the helicity state of 33 consecutive pairs allows one to predict the helicity state of future pairs. PMON can be used to generate 20Hz of triggers with a pseudo-random helicity sequence. The remaining 10Hz (assuming the beam is set up for 30Hz operation) can be used for 9Hz of beam pulses with no undulator pulses (for background measurements) and 1 Hz of no beam (for pedestal measurements).

## 2.2 Fast Feedbacks

Two or three fast feedbacks should be used for E166. The 1<sup>st</sup> feedback should stabilize the beam trajectory ( $x, x', y, y'$ ) at the undulator using 4 upstream correctors. The diagnostic measurements would be from 2 beam position monitors near the undulator.

A 2<sup>nd</sup> feedback can be used to zero the left-right flux asymmetry measured by the photon flux counter (see Figure 10). The average synchrotron flux from the *left* undulator,  $F_L$ , and the average flux from the *right* undulator,  $F_R$ , can be measured, and used to compute the flux asymmetry,  $A_F = \frac{F_L - F_R}{F_L + F_R}$ .  $A_F$  can be measured for mini-

runs of  $\sim 2K$  beam pulses, and can be nulled by adjusting the amplitude of the pulsed currents to the *left* and *right* undulators. This feedback is identical to an existing charge asymmetry feedback used by the E-158 experiment. It can be duplicated for E-166, replacing the toroid measurement for charge asymmetry with  $A_F$ .

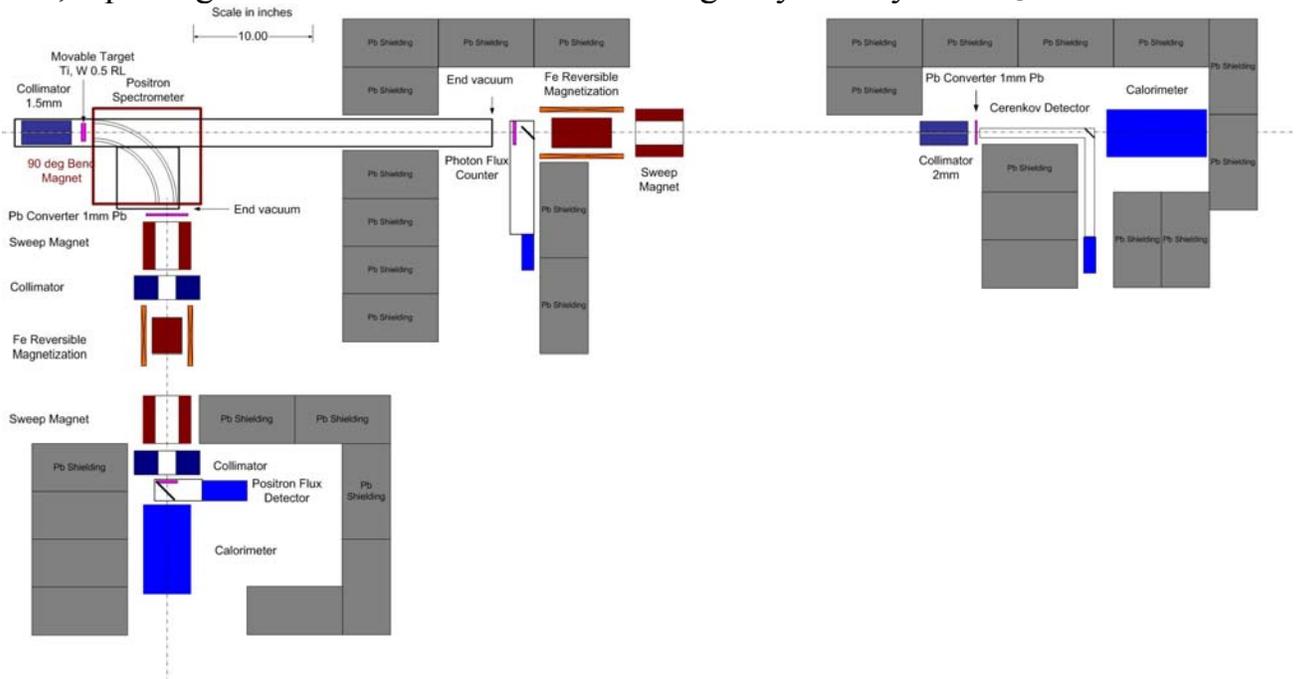


Figure 10: Layout of Apparatus for Photon and Positron Measurements



**Figure 11: Location of Experiment in the Final Focus Test Beam**

A 3<sup>rd</sup> fast feedback may be necessary to accommodate the data acquisition (DAQ) planned for the experiment. The SCP fast feedback software can be used to acquire data from 2 adcs that contain measurements from the photon and positron detectors. This is discussed further in Section 3.5.

### 3. Photon and Positron Measurements

Figure 10 shows the experimental setup we consider, which is located  $\sim 35$  meters downstream of the undulator (see Figure 11). The initial collimator, with an aperture of 1.5mm radius, selects the forward undulator photons and should reject most of the synchrotron radiation from bend magnets near the undulators. This collimator is sized to transmit undulator photons with energies above 1 MeV, while allowing for tolerances in beam targeting and alignment. (1 MeV undulator photons have an angle of  $\sim 30\mu\text{rad}$  and a radius of  $\sim 1\text{mm}$  at this location.)

The undulator photons continue forward for measurements of their flux, circular polarization and total energy. An insertable thin radiator converts a portion of the photons to electron-positron pairs. A dipole magnet is used to sweep charged particles out of the neutral beamline and to select positrons for further analysis (described below). The undeflected photons continue forward, through a thin exit vacuum window to the photon diagnostic hardware. A quartz Cherenkov counter measures the photon flux. The degree of circular polarization of the photons is measured with a transmission Compton polarimeter. The magnetization of the iron target is reversible. Following the magnetized Fe target, charged particles are deflected by a sweep magnet and a subsequent collimator selects the transmitted photons. This collimator has a 2mm radius and is sized to be slightly larger than the 1.5mm collimator further upstream.

The transmitted undulator photons are analyzed in two detectors: a threshold Cherenkov counter, with a thin lead converter before it, followed by a calorimeter. For the threshold Cherenkov counter, data runs with different radiator materials and thresholds can be used to probe the energy and polarization spectra of the undulator radiation. Quartz, aerogel, isobutane and propane are the radiator materials considered in this study. The calorimeter can be either a sampling calorimeter, such as Silicon-Tungsten, or an active calorimeter, such as BaF or NaI.

Positrons are produced in a thin production target and are deflected 90 degrees in a dipole field that selects the desired momentum interval, e.g. 5-7 MeV/c, for

analysis. For polarization analysis, the positrons then pass through a thin radiator to generate polarized bremsstrahlung photons, whose polarization is measured in a transmission Compton polarimeter similar to that described above for the undulator photons. For measurements of the positron flux and energy spectrum, the thin radiator and magnetized Fe target can be removed. The positron flux can be measured, with the threshold Cherenkov and calorimeter detectors shown, in different energy intervals by tuning the field in the 90-degree dipole. A quartz Cherenkov counter can be used for this application. An active calorimeter, such as NaI or BaF, is required because the low energy positrons lose energy very quickly due to ionization losses and stop within 1 or 2  $X_0$ . This setup should provide a good determination of the total positron flux and energy spectrum. Measurements of the average polarization and polarization spectrum are also possible, though this will depend on how well backgrounds can be reduced. The positron flux is significantly lower than the photon flux, making the positron polarization measurement significantly more difficult than that for the photons. If the signal-to-background ratio achieved for the experimental configuration shown in Figure 10 proves too low for positron polarimetry, the configuration can be modified in one of two ways. First, one can compromise on the measurement of the polarization spectrum by having a smaller bend angle and allowing larger apertures to transmit a wider momentum byte of the positrons. This will significantly increase the positron yield for analysis. Second, one can consider the use of a strong solenoid magnet to contain the angular spread of the positrons and/or to transport them a few meters into a new shielded alcove to significantly reduce the background. Ideally one would implement a flux concentrator and short accelerator section to have good collection efficiency for the positrons and make a beam with a reasonable emittance. This would greatly facilitate the polarization measurement and provide a much better mockup of an eventual  $e^+$  source for the linear collider. But it would require a significant investment, which is not yet practical.

### 3.1 Signal Rates; Flux and Spectra Measurements

#### 3.1.1 Undulator Photons

The expected undulator photon spectrum was shown in Figure 1. Integrated over the full spectrum,  $9.3 \times 10^8$  photons are emitted with a mean energy of 4.8 MeV. Over the primary energy region of interest from 1-9.6 MeV, there are  $7.9 \times 10^8$  photons emitted. The total energy per pulse of the undulator photons incident on the Fe target is 4400 TeV. Following the 15-cm Fe target, the energy per pulse is reduced to 120 TeV, with a corresponding flux of  $1.8 \times 10^7$  photons and a mean photon energy of 6.7 MeV. This photon signal at the detectors is very large and backgrounds should not present any problems. Results from the calorimeter and Cherenkov counters will provide a good determination of the total flux and average polarization of the

undulator radiation. Some information on the energy-dependence of the flux and polarization will also be provided from the different energy responses of the detectors.

### 3.1.2 Positrons

The expected energy spectrum for the positrons to be analyzed was shown in Figure 4 and the distribution of production angles was shown in Figure 6. The positron yield for an  $0.5 X_0$  Titanium target is  $\sim 0.0045$  positrons per incident photon for the undulator photons considered in Section 3.1.1. Positrons are momentum-selected with a 90-degree bend as shown in Figure 10. A bend radius of 17cm is chosen, as well as collimation to achieve an effective aperture radius in the bend of 1.75cm. Polarized positron transmission through this geometry was simulated as a function of the bending field.[29] The results are presented in Table 1. The positron flux and energy spectrum are measured by an active calorimeter and a quartz Cherenkov counter. For a B-field of 0.11 Tesla, the expected positron yield is  $6.3 \times 10^4$  per pulse with an average energy of 5.3 MeV, yielding a total energy per pulse of 330 GeV at the detectors. This signal size is expected to be adequate for measurements of the total flux and spectra, though may be marginal for polarimetry.

**Table 1: Simulation results for transmission of polarized positrons, produced by an  $0.5X_0$  Ti target, through a 90-degree bend with 17-cm radius.**

B (Tesla)	Mean Energy (MeV)	Energy spread, $\sigma_E/E$	Transmission (%)	Polarization
0.05	2.8	0.21	0.38	0.28
0.09	4.8	0.17	1.1	0.53
0.11	5.3	0.17	1.5	0.67
0.13	6.5	0.16	1.5	0.76
0.15	7.2	0.13	1.3	0.84
0.17	7.8	0.12	0.97	0.87

## 3.2 Backgrounds

The measurements considered in this study are all integrating flux measurements and do not rely on identifying and measuring single particles in the energy range 1-10 MeV. Though such measurements would be valuable for detailed measurements of the energy-dependent flux and polarization of the photons and positrons, counting measurements seem impractical in this environment. The primary electron beam with  $5 \times 10^9$  50-GeV electrons is only 3 feet below the experimental apparatus. The short pulse structure and low duty factor for the beam make coincident measurements difficult. And there may be considerable backgrounds from the sub-

mm aperture at the undulator, which the neutral beamline has a direct line-of-sight to. There is some guidance for expected backgrounds in E166 from earlier FFTB experiments, but it is difficult to make good predictions. In the laser interferometer spotsize measurement[30], an ethylene threshold Cherenkov counter was used in the neutral beamline. This counter, with a 15-MeV threshold and 1" lead pre-radiator had a measured signal-to-background of ~10:1 for an incident signal flux of ~200 10-GeV photons from Compton backscattering. To achieve this low level of background (~200 GeV per pulse) a significant amount of tuning of upstream collimators in the FFTB and Linac was required, as well as very good beam emittance. The electron beam current was  $5 \times 10^9$  per pulse. In a more recent experiment, E-150, with  $1.3 \times 10^{10}$  electrons per pulse, backgrounds were more typically ~300 TeV per pulse with ~10% pulse-to-pulse fluctuations. This was measured with a similar air Cherenkov counter (25-MeV threshold), using a pre-radiator of  $4X_0$  polyethylene. Fortunately these background levels (and fluctuations) are small compared to the 4400 TeV undulator radiation signal. The transmission Compton detectors for the undulator photons should be easy to shield well, and no difficulty is expected with their signal-to-background ratios. Detectors used after any scattering process (ex. all the positron detectors), require larger apertures and active areas and care is needed to adequately shield them.

A significant source of background can be the small aperture at the undulator itself. The inner radius of the undulator is only 0.45mm, ~10 beam sigma. This is by far the smallest aperture of any element in the FFTB beamline and the neutral beamline for the detector apparatus has a direct line-of-sight to it. Very good beam emittances and primary collimation well upstream of this location are needed to minimize any beam loss at the undulator location. A significant amount of tuning time will likely be needed to achieve acceptable backgrounds.

### 3.3 Photon polarization measurements

In this study, we consider using a transmission Compton polarimeter for the polarization measurement of the undulator photons as shown in Figure 10. The Compton cross section is given by

$$\sigma_C = \sigma_C^0 + fP_e\sigma_e, \quad (1)$$

where  $\sigma_C^0$  is the unpolarized Compton cross section, and  $f$  is the fraction of polarized electrons ( $Zf = \nu = 2.06$  for iron at saturation).  $P_e$  is +1 (-1) for photon and electron spins parallel (anti-parallel).  $\sigma_e$  is the polarized Compton cross section given by

$$\sigma_e = 2\pi r_0^2 \left\{ \frac{1 + 4k_0 + 5k_0^2}{k_0(1 + 2k_0)^2} - \frac{1 + k_0}{2k_0^2} \ln(1 + 2k_0) \right\}, \quad (2)$$

where  $r_0$  is the classical electron radius ( $2\pi r_0^2 = 0.5$  barn) and  $k_0 = E_\gamma / (0.511 \text{ keV})$ .

The polarized Compton cross section for Fe,  $\sigma_e$ , is plotted in Figure 12. The total (unpolarized) photon cross section for Fe,  $\sigma_{\text{tot}}$ , is plotted in Figure 13,[31] together with its contributions from the Compton cross section and the cross section for producing pairs. We use these to calculate the attenuation length in Fe,  $L_0$ , for unpolarized photons, where  $L_0 = \frac{M}{\rho N_A \sigma_{\text{tot}}}$ . ( $M$  is the Molar mass in g/mol;  $\rho$  is the density of Fe in g/cm<sup>3</sup>;  $N_A$  is Avogadro's number (atoms/mol);  $\sigma_{\text{tot}}$  is expressed in cm<sup>2</sup>/atom and  $L_0$  is in cm.) The analyzing power,  $AP$ , for the transmission polarimeter is defined to be

$$AP = \frac{T^+ - T^-}{T^+ + T^-} = \frac{\left( e^{-l/L_0^+} \right) - \left( e^{-l/L_0^-} \right)}{\left( e^{-l/L_0^+} \right) + \left( e^{-l/L_0^-} \right)}, \quad (3)$$

where  $T^+$  ( $T^-$ ) is the transmission for photon and electron spins parallel (anti-parallel),  $L_0^+$  ( $L_0^-$ ) is the attenuation length for spins parallel (anti-parallel), and  $l$  is the length of the magnetized Fe. Figure 14 plots  $L_0$  versus the photon energy in the region of interest for this experiment, from 1-10 MeV.

Figure 15 plots the (unpolarized) transmission,  $T^0$ , versus photon energy for a 15-cm length of magnetized Fe, while Figure 16 plots the analyzing power vs. energy for this target. We can define a figure-of-merit (FOM) to be  $\text{FOM} = (AP)^2 T$  and this is plotted versus  $l$  in Figure 17 for 7.5 MeV  $\gamma$ 's. While this indicates the optimal length to be 8cm, we consider instead a length for this experiment of 15cm. This enhances the measured asymmetry by a factor of  $\sim 2$ , while reducing the measured flux of photons by a factor  $\sim 0.16$ , compared to a 7.5-cm length. Given the large flux of photons, this reduction is not expected to significantly impact the signal-to-background ratio. Significantly larger analyzing powers can be achieved for long Fe targets (see Figure 18) with a corresponding reduction in photon flux.

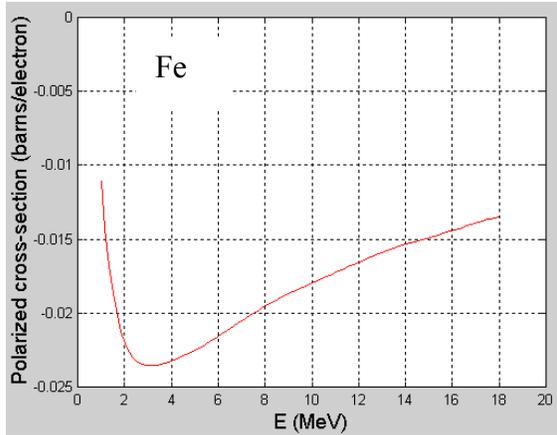


Figure 12: Polarized Compton cross section

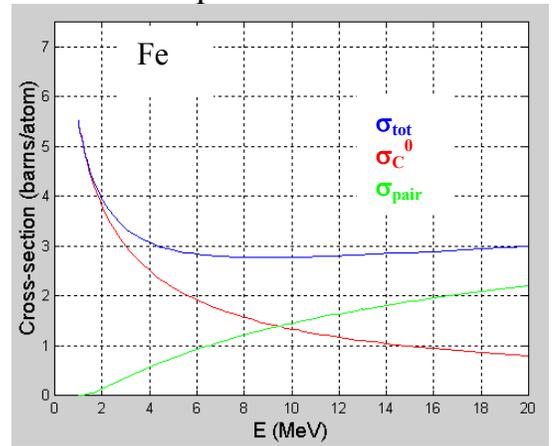
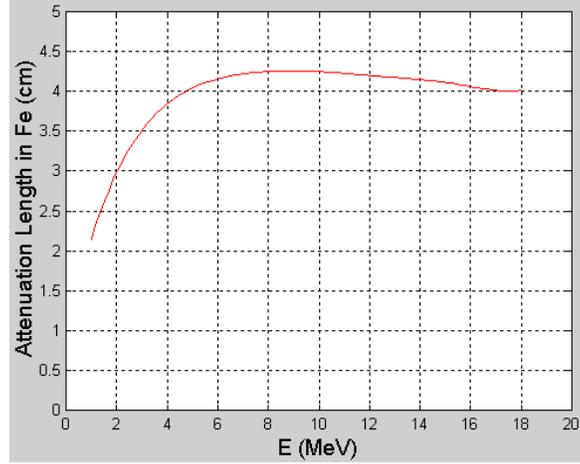


Figure 13: Photon cross sections in Fe



**Figure 14: Photon Attenuation Length vs. Energy in Fe**

The polarized target is a 15-cm length of Fe with radius of 5mm in a field of 2 Tesla. Following the target is a sweep magnet and a collimator with a 2-mm radius. Two types of detectors are used for the polarization measurement: a threshold Cherenkov flux counter, and a calorimeter. We have simulated the expected asymmetry measurements in these detectors. We use as input the undulator photon flux spectrum shown in Figure 1, and the corresponding helicity spectrum shown in Figure 2. The expected photon intensity spectrum after the Fe target is shown in Figure 19, and the corresponding photon asymmetry spectrum is shown in Figure 20. For a 15-cm length of magnetized Fe, the calorimeter should observe an asymmetry of 3.4%. The asymmetry measured by a threshold flux counter is plotted in Figure 21 as a function of the energy threshold.

The detector measurements expected are summarized in Table 2. With measurements from these detectors the predicted photon polarization can be checked with  $\sim 5\%$  (relative) accuracy. The measurements will be quick, with less than one minute required for sub-5% statistical errors. Assuming 10Hz of *left-right* pairs of events, the measurement time can be determined as follows:

$$T(s) = 490s \left[ \frac{\sigma_F/F(\%)}{\text{Pr}(\%)A(\%)} \right]^2 \quad (4),$$

where  $T$  is the required measurement time (in seconds);  $\sigma_F/F$  is the rms uncertainty (in %) per pulse in the signal level at the detector; Pr is the desired relative precision in

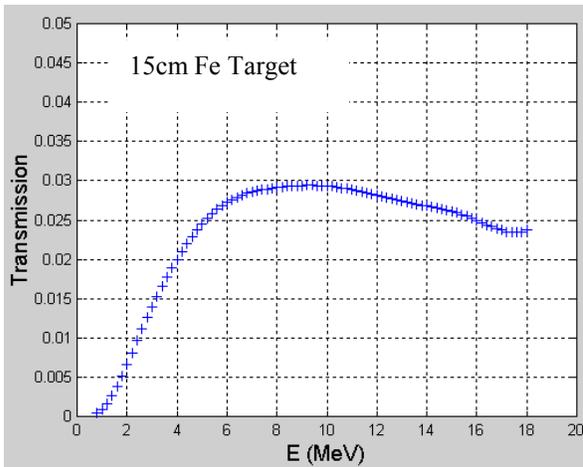


Figure 15: Photon Transmission thru Target

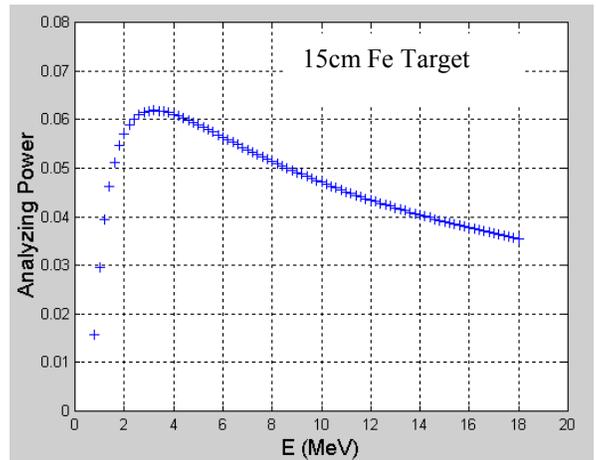


Figure 16: Analyzing Power for Target.

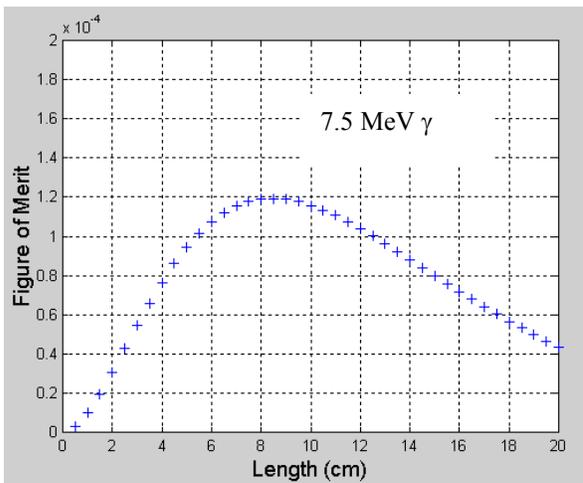


Figure 17: Figure of Merit vs. Length of Fe Target

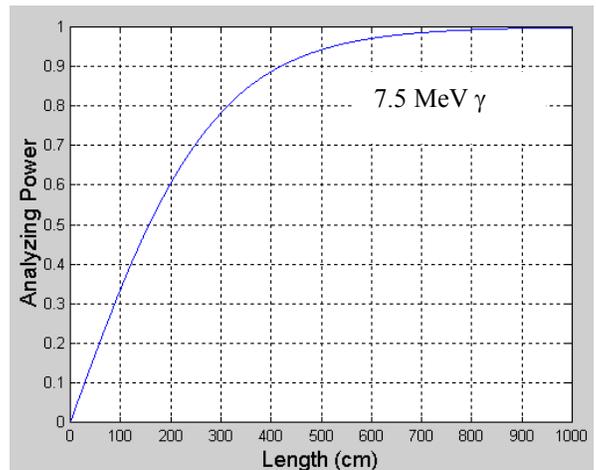


Figure 18: Analyzing Power vs. Length of Fe

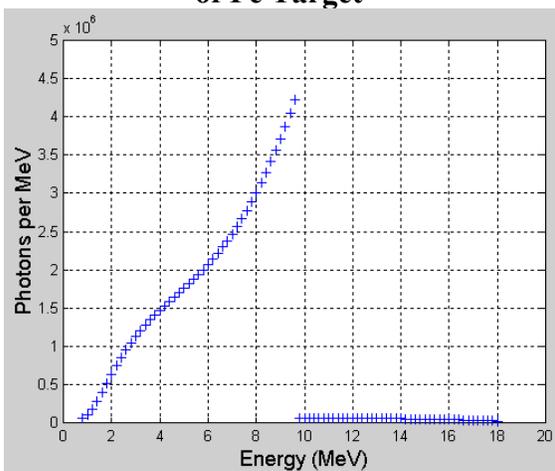


Figure 19: Intensity Spectrum of Undulator Photons after 15-cm Iron Target.

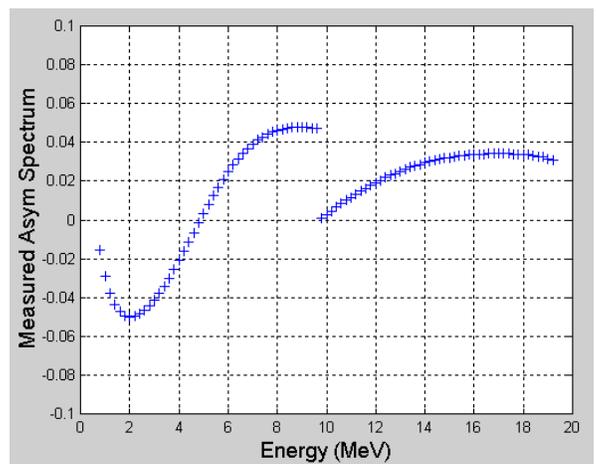
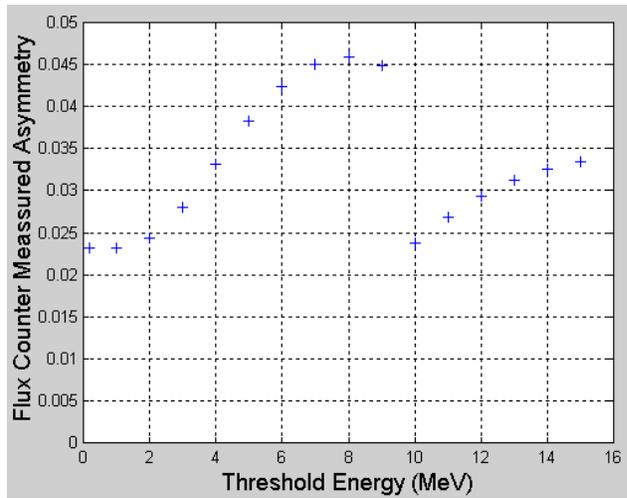


Figure 20: Intensity Asymmetry of Undulator Photons after 15-cm Iron Target.



**Figure 21: Intensity Asymmetry measured by a Threshold Flux Counter.**

the polarization measurement (in percent); and  $A$  is the expected measured asymmetry (in percent). For example: if  $\sigma_F/F=1\%$  (dominated by beam jitter and uncertainty in correcting for this) and  $A=3.4\%$  (for the calorimeter measurement), the time required for 5% precision ( $\text{Pr}=5\%$ ) is found to be 1.7 seconds.

The dominant systematic error for the photon polarization measurement is expected to be due to the target polarization, in particular due to understanding the effective length of the magnetized Fe. This uncertainty has been estimated to be as much as 10% by some groups, though in the experiment of Gunst and Page [19] it was estimated to be only 1% for a 30-cm Fe target. Other systematic errors are expected to be small, though a good simulation of the geometry of the setup and the detector response will be needed. Multiple scattering of photons in the target, for example, should be small given the small acceptance of the detectors. The energy response of the polarimeter should be easy to simulate and be relatively insensitive to beam conditions and alignment errors.

An alternate scheme using a scattering Compton polarimeter for the undulator photons has been suggested for E166 and is described in Reference [32]. It would detect Compton-scattered photons from an 100 $\mu\text{m}$  foil. One advantage to this is a smaller uncertainty in the target polarization, which is estimated to be 3%. However, the signal at the detector is reduced by a factor  $\sim 5000$  and the sensitivity to backgrounds will be larger. Also, the analyzing power of the polarimeter described is sensitive to the collimation angle used for the undulator photons. Understanding this will be sensitive to details of the beam emittance, targeting and alignment.

**Table 2: Summary of Detector Measurements**

Detector*	Threshold Energy	Mean Energy	Asymmetry
Calorimeter	-	7.7 MeV	3.4%
Quartz Cherenkov	0.2 MeV	6.8 MeV	2.3%
Aerogel Cherenkov	3.0 MeV	7.2 MeV	2.8%
Isobutane Cherenkov	8.1 MeV	8.9 MeV	4.7%
Propane Cherenkov	11.0 MeV	14.1 MeV	2.7%

\*These results are for idealized flux counters and calorimeter and will need to be updated with corrections for the energy response of the actual detectors.

\*\*For the calorimeter, the mean energy is determined by weighting by both spectrum and energy. For the threshold Cherenkov counters, the weighting is by the spectrum only.

### 3.4 Positron polarization measurements

The primary goal of E166 is to measure the positron polarization, and so naturally this turns out to be the most difficult measurement. For the geometry shown in Figure 10 and for a 90-degree bend field of 0.13 Tesla, one expects  $6.3 \times 10^4$  positrons per pulse with a mean energy of 6.5 MeV incident on the thin radiator. These positrons were estimated[29] to have a polarization of 76% (see Table 1). The polarimetry technique studied here is based on analyzing the circular polarization of the bremsstrahlung photons emitted. Detailed simulation and optimization of geometry remain to be done, but the expected signal rates at the detectors can be estimated. The radiator should be  $\sim 0.1 X_0$ , which is a compromise to obtain sufficient photon yield while not introducing too much multiple scattering and energy loss. The length of the magnetized Fe target should be chosen to give an average transmission of  $\sim 10\%$  for the photons. The geometry should be optimized to achieve at least 10% acceptance of photons generated in the converter. Thus the photon yield at the detectors is expected to be  $\sim 60$  photons per pulse. The photons will have a  $1/E$  energy spectrum, characteristic of bremsstrahlung, before folding in the transmission function through the Fe, which will preferentially attenuate the low energy photons. Only the higher energy part of the bremsstrahlung spectrum will retain the positron polarization information. An aerogel Cherenkov counter with a 3 MeV threshold may be the most efficient detector for this measurement, though a calorimeter because of its energy weighting may also perform well. However, the yield for this geometry is not very encouraging; backgrounds and large fluctuations from the low photon statistics make this measurement problematic. So to use the technique of analyzing bremsstrahlung photons with a transmission Compton polarimeter, one may only be able to measure the ensemble polarization of the positrons using a smaller bend angle and larger acceptance. For example:[29] if a 20-degree bend is used (again with a 17-cm radius

of curvature), followed by a 0.5 Tesla solenoid field (to transport the positrons away from the neutral beamline) with the transport aperture radius increased to 5cm, then the positron capture efficiency becomes 42%. These positrons have a mean longitudinal polarization (along the solenoid axis) of 64%. This configuration should result in an acceptable measurement for the ensemble positron polarization. Further simulation studies and optimization for this positron polarization measurement are still needed. The measurement time will be significantly longer than that needed for the photons and can be sensitive to beam conditions. The measurement may benefit significantly from the ability to rapidly flip the beam polarization state. If a transmission Compton polarimeter measurement is feasible, the relative uncertainty between the photon and positron polarizations due to the target polarization can be eliminated by performing both measurements with the same target. Because of its large apertures, though, the positron polarimeter will be sensitive to multiple scattering of the photons and this will need to be simulated carefully.

### 3.5 Data Acquisition

The Accelerator SCP (SLAC Control Program) hardware and software can be used for the DAQ. This can be done as part of a fast feedback, as indicated in Section 2.2. The fast feedback can acquire data from ~20 detector channels in 2 adcs at the machine repetition rate of 30Hz. Additionally, the feedback can record the polarization state of the undulator radiation, some beam diagnostics (BPM and toroid information), and also Hall probe readings for the magnetic fields in the detector analyzer magnets. The beam can be run in a mode with 10Hz *left* pulses, 10Hz *right* pulses, 9Hz background (undulator not pulsed), and 1 Hz pedestal (no beam) pulses. The 9Hz background pulses can be used to subtract beam-related background in the detectors not associated with the undulator radiation. A dedicated process will be needed to transfer data accumulated in the fast feedback buffers to a storage disk for offline analysis.

## 4. Summary

We have presented results of design studies carried out to support the E166 proposal for studying polarized positron production in the FFTB. We find that it would be useful to have the ability to flip the positron polarization by implementing two 0.5-meter *left* and *right* helical undulators, rather than a single 1-meter helical undulator. If this is done, then it would be easy to flip the positron (and undulator photon) polarization on a pulse-to-pulse basis by utilizing PMON electronics for triggering the *left* and *right* undulators.

We presented results for how to measure the flux, spectrum and polarization of undulator photons, utilizing a transmission Compton polarimeter for measuring the photon circular polarization. The techniques described should achieve the desired

accuracy of 5-10%. We also presented results for how to measure the flux and spectrum of positrons produced by the undulator photons in an  $0.5X_0$  Titanium target. These measurements should also achieve the desired accuracy of 5-10%. For positron polarimetry, we presented some considerations for use of a transmission Compton polarimeter to measure the circular polarization of bremsstrahlung photons emitted by the polarized positrons in a thin radiator.

## 5. Acknowledgements

Clive Field provided information on backgrounds observed in several previous FFTB experiments. We would also like to acknowledge many useful discussions with members of the E166 collaboration.

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