Undulator-Based Production of Polarized Positrons
(SLAC Experiment E-166)

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Summary

Princeton University is participating in SLAC experiment E-166 [1], an international accelerator-physics project involving 15 institutions to demonstrate undulator-based production of polarized positrons for a linear collider. This effort, and that of U. Tennessee, forms LCRD 2.37 of the Linear Collider Accelerator Physics R&D Program [2].

The full exploitation of the physics potential of future linear colliders such as the JLC, NLC, and TESLA will require the development of polarized positron beams. In the scheme under study in experiment E-166, a helical undulator is employed to generate photons of several MeV with circular polarization which are then converted in a relatively thin target to generate longitudinally polarized positrons.

To characterize the success of this technique, the experiment includes diagnostics of the polarization of both the MeV-scale photons and positrons, based on the polarization dependence of the rate of transmission of photons through magnetized iron. Princeton University has responsibility for construction of a magnetic spectrometer for the positrons, and also for construction of a pair of silica aerogel counters for use in the polarimeter to diagnose the undulator photons.

All of the hardware construction for experiment E-166 is now complete. In addition, Princeton has purchased tungsten shielding for the positron spectrometer, a waveform generator to control the reversal of magnetic field of the photon polarimeters, a 4-channel digital oscilloscope for use with the 3 Faraday cup diagnostics of the positron spectrometer, and two PC’s for use in the E-166 data acquisition system.

The LCRD budget award for Princeton was $30k in FY05, with the anticipation of a renewal of $40k in FY06. Because the experiment is to run in FY05, it has been necessary to spend about $60k to date, with another $10k needed to cover travel expenses for the coming run of the experiment.

Experiment E-166 had taken two days of beam at SLAC in October 2004, before the lab was shut down due to an electrical accident. As of today, we believe the experiment can run again from May 15-June 4, 2005, and for an additional 3 weeks around Sept. 1, 2005.
Section 1 presents some relevant extracts from the E-166 proposal [1]. Section 2 reviews the Princeton effort on E-166.

1 Introduction

The full exploitation of the physics potential of future linear colliders such as the JLC, NLC, and TESLA will require the development of polarized positron beams.

In the proposed scheme of Balakin and Mikhailichenko [3] a helical undulator is employed to generate photons of several MeV with circular polarization which are then converted in a relatively thin target to generate longitudinally polarized positrons.

To advance progress in this field, a new experiment, SLAC E-166 [1, 4] (approved June 30, 2003), will test this scheme to determine whether such a technique can produce polarized positron beams of sufficient quality for use in future Linear Colliders. The experiment will install a 1-meter-long, short-period ($\lambda_u = 2.4$ mm, $K = 0.17$), pulsed helical undulator in the Final Focus Test Beam (FFTB) at SLAC. A low-emittance 50-GeV electron beam passing through this undulator will generate circularly polarized photons with energies up to a cutoff energy of about 10 MeV. These polarized photons are then converted to polarized positrons via pair production in thin targets.

1.1 Undulator Based Production of Polarized Positrons

A polarized positron source for a Linear Collider was first proposed by Balakin and Mikhailichenko in 1979 in the framework of the VLEPP project [3]. The concept, schematically sketched in Fig. 1, sends the high energy ($\geq 150$ GeV) electron beam of a Linear Collider through a ($\sim 200$ m-long) helical undulator to produce circularly polarized photons with energies of about 11 MeV. While the electrons are further accelerated and brought into collision after passing through the undulator, the photons are converted in a thin target into electron-positron pairs. Here the polarization state of the photons is transferred to the positrons and electrons. Only the on-axis photons of the helical undulator radiation are completely circularly polarized; the degree of polarization is decreasing with increasing emission angle. Hence, the polarization of the photons and of the generated positrons can be increased at the expense of the total number of positrons by collimation. The positrons are captured behind the target similarly to the case of a conventional positron source [5, 6], and fed into a linac.

This undulator-based positron source concept offers the additional advantage that the heat load on the target is less than that of a conventional source, and so the former is very well suited for the production of high intensity positron beams [7]. An undulator-based polarized positron source can in principle be realized independently of the linac technology, i.e., independently of the details of the required pulse structure, because the number of produced positrons scales with the number of the electrons in the drive linac, and the pulse structure of the electrons is directly copied to that of the positrons. In this sense it is an option for all Linear Collider projects.
1.2 Physics Opportunities at a Linear Collider with Polarized Electrons and Polarized Positrons

Polarized electrons have been a part of each of the different Linear Collider proposals for a long time. Recently much scrutiny has been given to the case for polarized positrons in addition to polarized electrons. A consensus has emerged that polarized positrons are a highly desirable option for a Linear Collider.

The importance of beam polarization in general was demonstrated e.g., at the SLAC Linear Collider (SLC). Because of the high degree of electron polarization (during its last run in 1997/98, an average longitudinal beam polarization $P_{e^-} = 74\%$ was reached [8]) one of the world’s most precise measurements of the weak mixing angle at $Z$-pole energies was performed.

Having both beams polarized offers a number of advantages:

- Higher effective polarization.
- Increased signal to background in studies of Standard Model Physics.
- Enhancement of the effective luminosity.
- Precise analysis of many kinds of non-standard couplings.
- The option to use transversely polarized beams.
- Improved accuracy in measuring the polarization.

1.3 The Need for a Demonstration Experiment

The aim of the proposed experiment E-166 is to test the fundamental process of polarization transfer in an electromagnetic cascade. For this, a simplified version of the scheme shown in Fig. 1 will be used, in which a 50-GeV electron beam passes through a 1-m-long undulator as shown in Fig. 2. The resulting photon beam of MeV energy is converted to positrons (and electrons) in a thin target, after which the polarization of the positrons (and photons) is analyzed.
Figure 2: Conceptual layout (not to scale) of the experiment to demonstrate the production of polarized positrons in the SLAC FFTB. 50-GeV electrons enter from the left and pass through an undulator to produce a beam of circularly polarized photons of MeV energy. The electrons are deflected away from the photons by the D$_1$ magnet. The photons are converted to electrons and positrons in a thin target. The polarization of the positrons, and of the photons, are measured in polarimeters based on Compton scattering of electrons in magnetized iron. BPM$_i$ = beam-position monitor; HSB$_i$ = “hard” soft bend; OTR = optical-transition-radiation beam-profile monitor; Toro = beam-current toroid; WS = wire scanner; A$_i$ = aperture limiting collimators; Hcor = horizontal steering magnet; D$_1$ = FFTB primary beam dump bend-magnet string; PR$_d$ = dumpline beam-profile monitor; PR$_{t}$ = e$^+$ target beam-profile monitor; D$_2$ = analyzing magnet.

While the basic cross sections for the QED processes relevant to polarization transfer were derived in the late 1950’s, experimental verification of the polarization development in an electromagnetic cascade is still missing. From this point of view, the proposed experiment has some general scientific aspects in addition to its importance for Linear Colliders.

Each approximation in the modeling of electromagnetic cascades seems to be well justified in itself, but the complexity of polarization transfer in cascades makes the comparison with an experiment desirable, so that the decision whether a Linear Collider should be built with or without a polarized positron source can be based on solid grounds. The achievable precision of the proposed transmission polarimetry of 5-10% is sufficient for this purpose. This experiment, however, will not address detailed systems issues related to polarized positron production for a Collider, such as capture efficiency, target thermal hydrodynamics, radiation damage in the target, or an undulator prototype suitable for use at a Linear Collider; such issues are well within the scope of R&D by a Linear Collider project that chooses to implement a polarized positron source based on a helical undulator.

### 1.4 Overview of Experiment E-166

The goal of the experiment is

- To measure the yield and polarization of the photons produced by passing an electron
beam through a helical undulator.

- To measure the yield and polarization of the positrons produced by conversion of undulator photons in a thin target.

- To compare the results to simulations.

A schematic layout of the experiment is shown in Fig. 2 with emphasis on the particle beams, while Fig. 3 shows the layout of the detectors to measure the flux and polarization of the photons and positrons.

The experiment uses a low-emittance, 50-GeV electron beam in the SLAC Final Focus Test Beam (FFTB) plus a 1-meter-long, short-period ($\lambda_u = 2.4$-mm, $K=0.17$), pulsed helical undulator, to produce circularly polarized photons of energies up to 10 MeV. These polarized photons are then converted to polarized positrons through pair production in a Ti target which has a nominal thickness of 0.5 rad. len. The polarizations of the photons and positrons are measured by the Compton transmission method using a magnetized iron absorber [9].

This experiment is a demonstration of undulator-based production of polarized positrons for Linear Colliders at a scale of 1% in length and intensity:

- Photons are produced in the same energy range and polarization as in a Linear Collider;

- The same target thickness and material are used as in the Linear Collider;
• The polarization of the produced positrons is expected to be in the same range as in a Linear Collider.

• The simulation tools being used to model the experiment are the same as those being used to design the polarized positron system for a Linear Collider: EGS4 [10] and GEANT3, both modified to include spin effects for polarized $e^+$ production, and BEAMPATH [11] for collection and transport.

1.5 The Photon Polarimeter

Measurements of the circular polarization of energetic photons are most commonly based on the spin dependence of Compton scattering off atomic electrons [12, 13]. One can either observe the scattered electrons and/or photons emerging from a thin, magnetized iron foil [14], or measure the transmission of unscattered photons through a thick, magnetized iron absorber [9, 15, 16]. Experiment E-166 uses the latter technique, which is sketched in Fig. 4. The basic components are a magnetized iron absorber and a detector that measures the photons that penetrate through the absorber.

![Figure 4: The concept of transmission polarimetry, in which the survival rate is measured for photons that pass through a magnetized iron absorber.](image)

On reversing the sign of the magnetization of the absorber, an asymmetry $\delta = P_\gamma P_{e^-} A_\gamma$ is measured in the rate of transmitted photons, where $P_\gamma$ is the photon polarization, $P_{e^-}$ is the polarization of the electrons in the iron, and $A_\gamma$ is the so-called analyzing power which is proportional to the spin-dependent part of the Compton scattering cross section [1].

The implementation of the photon polarimeter for E-166 is sketched in Fig. 3. The photon polarimeter will include two types of photon detectors, a total absorption calorimeter and a Čerenkov detector.

1.5.1 Silicon-Tungsten Calorimeter

The total absorption calorimeter for the transmitted photons is a silicon-tungsten sampling calorimeter, similar to that employed in SLAC experiment E-144 [18]. As shown in Fig. 5, this device consists of 20 plates of tungsten, each 1 rad. len. thick, separated by silicon detectors in the form of a $4 \times 4$ array of pads, each $1.6 \times 1.6 \text{ cm}^2$ in area. The pads are read out in longitudinal groups of 5, for a total of 64 readout channels. The resulting transverse
and longitudinal segmentation of the calorimeter will permit confirmation that the energy deposited in the calorimeter has the profile expected from the signal of undulator photons, rather than that of possible backgrounds of scattered electrons and photons.

Figure 5: a) The silicon tungsten calorimeter consists of 20 longitudinal samples of $1 \times X_0$ each, grouped into 4 segments of $5 \times X_0$ each. The transverse sampling is via a $4 \times 4$ array of pads, each $1.6 \times 1.6 \text{ cm}^2$ each. b) View of E-166/T-467 test apparatus in the FFTB: the silicon tungsten calorimeter is the small object (with cabling) at the right; a CsI counter is under the lead brick shield in the center; the aerogel flux counters are at the top center.

The resolution of a similar sampling calorimeter has been measured to be [18]

$$\sigma^2 = (0.19)^2 E + (0.4)^2,$$

where $E$ is the electron energy in GeV. For a pulse of $10^{10}$ electrons, some $4 \times 10^7$ photons of average energy 5 MeV reach the calorimeter, depositing about 200 TeV. Hence, the relative error on that energy of only 0.06%.

1.5.2 Aerogel Flux Counters

A complementary measurement of the transmitted photon flux will be made with a pair of aerogel Čerenkov counters with index of refraction $n = 1.009$ [19]. This extremely low-index material is available from the BELLE experiment. The two flux counters are deployed before and after the magnetized iron absorber, as shown in Fig. 3.

The signal in the aerogel flux counter is generated by conversion of undulator photons in the aerogel, after which electrons and positrons of energy greater than 4.3 MeV will emit Čerenkov light. This light is observed in a photomultiplier that views the aerogel through an air light pipe, as shown in Fig. 6.

Because of their threshold energy of 4.3 MeV, the aerogel flux counters are insensitive to synchrotron radiation in the beam. Hence, a pair of aerogel flux counters that are placed upstream and downstream of the magnetized iron absorber, as shown in Fig. 3, can confirm
Figure 6: a) Sketch of the photon flux counter, consisting of a 2-cm-thick block of aerogel of index \( n = 1.009 \), viewed by a photomultiplier tube at the end of an air light pipe. b) Photograph of the two aerogel flux counters. c) A block of aerogel mounted in a Michelson interferometer in order to measure its index of refraction [19].

The attenuation of this absorber on photons of energy above 5 MeV, independent of possible backgrounds of lower-energy photons.

The conversion probability of an undulator photon in the 1-mm-thick Al cover plate of the detector will yield about 1 electron or positron per 300 photons, but only 1/3 of these will have energy above Čerenkov threshold. The number of photons of energy that penetrate the iron absorber is about \( 4 \times 10^{7} \) per pulse of \( 10^{10} \) electrons, so the number of useful conversions is about \( 4 \times 10^{4} \). There will be about \( 50 \theta_{C}^{2} \approx 5 \) optical Čerenkov photons per conversion, leading to about 1/2 photoelectron per conversion in a photomultiplier whose photon collection efficiency times quantum efficiency is 10%. Hence, the expected signal in the Čerenkov counter downstream of the magnetized iron absorber is about \( 2 \times 10^{4} \) photoelectron per electron beam pulse.

1.6 The Positron Polarimeter

The measurement of positron polarization is to be made by first transferring the polarization to photons, and then using a photon-transmission polarimeter [17]. Measurements of the asymmetry \( \delta = P_{e^{+}}P_{e^{-}}A_{e^{+}} \) in the rate of transmitted photons can be related to the positron polarization \( P_{e^{+}} \) and the polarization \( P_{e^{-}} \) of the electrons in the magnetized iron absorber via a calculable analyzing power \( A_{e^{+}} \) [1].

The layout of the positron polarimeter has been shown in Fig. 3, and is shown again in Fig. 7. A double 90°-bend magnet transports a ±20% momentum bite of the positron spectrum to the reconversion target (0.5 rad. len. of tungsten). The photons that emerge from the target are then incident on an 7.5-cm-long magnetized iron absorber. The photons that are transmitted through the absorber (\( \approx 10^{3} \) per pulse) are detected in a CsI array. The latter device was chosen, rather than a Si-W calorimeter, because the typical energy of...
photons reaching the detector in the positron polarimeter is only about 1 MeV; the energy resolution of a CsI calorimeter for such energies is about 2.5%, compared to 20% for a Si-W device.

Figure 7: Layout of the positron polarimeter.
2 Princeton Activities on E-166

1. K. McDonald is Co-Spokesperson of E-166 (along with J. Sheppard of SLAC).

2. The solenoid and dipole pair for the positron spectrometer were fabricated at Princeton, and are now installed in the FFTB tunnel (Fig. 8).

![Figure 8: The positron spectrometer in the FFTB tunnel.](image)

3. Princeton participated in the mechanical design of the vacuum chamber for the positron spectrometer (Fig. 9).

4. Princeton participated in the mechanical design of the Faraday “cup” at the end of the positron spectrometer (Fig. 10).

5. Princeton participated in the design and fabrication of the temporary articulated bellows system that permits use of two parallel beam pipes at the location of the unulator (Fig. 11).

6. Princeton fabricated a pair of silica aerogel detectors (index of refraction $n = 1.09$) for use with the undulator photon polarimeter (Fig. 12).
Figure 9: The half of the vacuum chamber that fits inside the first dipole of the positron spectrometer. The tungsten jaws of the momentum slit are visible.

Figure 10: The Faraday cup and associated motion control, to be placed at the downbeam end of the positron spectrometer.

Figure 11: The temporary articulated bellows system at the eventual location of the undulator in the FFTB tunnel.
7. Princeton purchased 3 sets of tungsten (heavimet) shielding of various geometries for use in and around the positron spectrometer.

8. Princeton purchased an Agilent 33220A arbitrary function generator to control the ramping of the iron-core solenoids, when their field directions are reversed during the polarimetry measurements.

9. Princeton purchased a Tektronix TDS5504N 4-channel digital oscilloscope for use with the 3 Faraday cup diagnostics of the positron spectrometer.


3 References

[1] G. Alexander et al., Undulator-Based Production of Polarized Positrons. A Proposal for the 50-GeV Beam in the FFTB (June 7, 2003; approved as SLAC E-166 on June 30, 2003),
http://www-project.slac.stanford.edu/lc/local/PolarizedPositrons/E-166bis.pdf


