STATUS OF THE COMPTON POLARIMETER PROJECT AT BEPCII

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Abstract

A laser Compton polarimeter is being developed at the Beijing Electron Positron Collider (BEPCII) for non-destructive diagnostics of transverse electron beam polarization. The project reuses a dismantled wiggler beamline and experimental hutch to transport a circularly polarized 532 nm pulsed laser beam to the electron ring and to guide the backscattered photons to a detector in the hutch. This paper summarizes the present project status, including beamline and optical system upgrades, detection of Compton backscattered photon signals, and recent commissioning with the TaichuPix-3 pixel detector.

INTRODUCTION

Polarized lepton beams are an important ingredient of the physics program of future circular and linear colliders [1–4]. Transverse polarization enables precision beam-energy calibration through resonant depolarization [5, 6], while longitudinally polarized beams can enhance the sensitivity of electroweak and beyond-standard-model measurements. These applications require a reliable, non-destructive beam-polarization diagnostic. Compton polarimetry is therefore widely used because it can measure the helicity-dependent asymmetry of photons or electrons produced by Compton scattering between a polarized laser and a high-energy lepton beam [7–11].

BEPCII provides a useful test bench for developing Compton polarimetry for future colliders. The electron-positron double-ring collider operates in the tau-charm energy range and is being upgraded for higher luminosity and a beam energy reach of up to about 2.8 GeV [12]. At a beam energy of 2.35 GeV, the Sokolov–Ternov polarization build-up time is expected to be on the order of 70 min for the electron storage ring, making transverse self-polarization potentially measurable in routine operation. A Compton polarimeter at BEPCII would support resonant-depolarization studies, beam-energy calibration R&D, and polarized-beam studies relevant to future Z-, W- and Higgs factories [13].

This paper summarizes the implemented Compton polarimeter layout, the first observation of laser-electron Compton signals using a scintillator detector [14, 15], and recent work toward a pixel-detector-based transverse polarization measurement.

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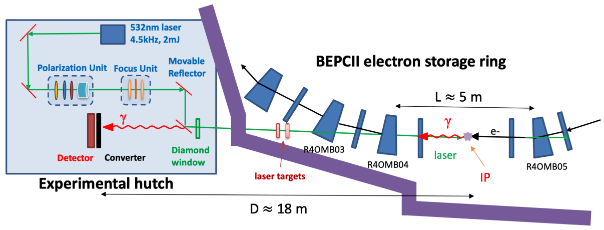

Figure 1: Schematic layout of the BEPCII Compton polarimeter at the 4W2 beamline.

POLARIMETER LAYOUT

The polarimeter is installed at the 4W2 beamline, which originally served a wiggler source and has since been repurposed for the transport of the laser and backscattered photon beams. A circularly polarized laser beam is generated in the experimental hutch, transported through the photon beamline, and brought into collision with the electron beam in a straight section of the electron storage ring. The backscattered photons then propagate through the same beamline and are detected in the hutch. The distance from the nominal interaction point to the detector location is approximately 18 m [15].

The spin-dependent part of the Compton cross section contains a term proportional to the product of the laser circular polarization and the electron polarization. For transverse-polarization measurements, the relevant information is contained in the azimuthal distribution of the scattered particles. A vertically segmented or pixelated detector is therefore required. The TaichuPix-3 CMOS pixel sensor, developed as a CEPC vertex detector prototype, provides a sensitive area of approximately 25.7×15.9 mm^2 and a pixel pitch of 25×25 m^2 [16], in addition to a time resolution of 50 ns. In the BEPCII polarimeter, a high-Z converter is placed upstream of the sensor to convert backscattered photons into charged particles and enhance the detection efficiency.

The laser system is based on a 532 nm pulsed laser with a repetition rate of approximately 4.5 kHz and a maximum pulse energy of 2 mJ. A polarization unit consisting of a linear polarizer, wave plates and a Pockels cell is used to generate switchable circular laser helicity. A three-lens focusing unit transports the laser to the interaction point. In the design estimate, an RMS laser spot size of about 0.5 mm at the interaction point is sufficient for a useful Compton rate, while remaining compatible with the beamline aperture.

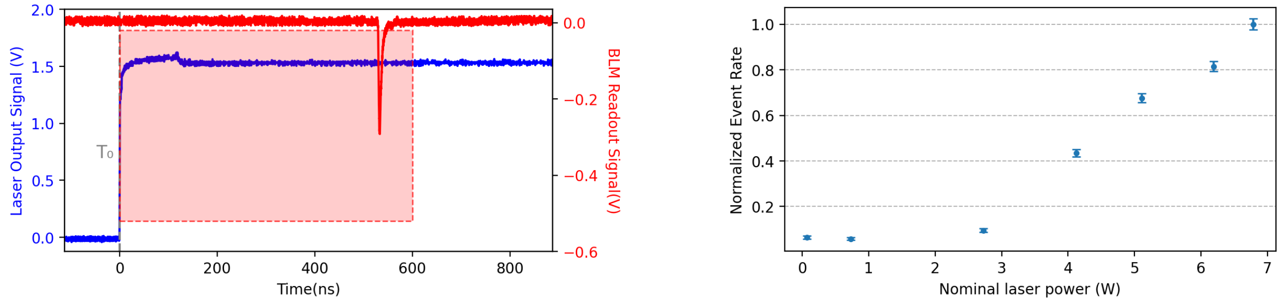

Figure 2: Evidence for laser-correlated Compton signals. Left: representative oscilloscope waveform showing a delayed BLM pulse within the selected time window after the laser trigger T_0. Right: normalized event rate versus nominal laser power.

BEAMLINE AND OPTICAL SYSTEM STATUS

Several modifications were implemented to make the former X-ray beamline compatible with green laser transport and backscattered photon detection. Beamline components opaque to the 532 nm laser, including beryllium and aluminum windows and a carbon filter, were removed or replaced. Additional laser alignment targets were installed to monitor the laser position and transverse distribution inside the beamline. These modifications allowed the laser to be transported from the hutch to the planned interaction region while maintaining acceptable vacuum conditions.

A major limitation identified during the first commissioning campaign was the degradation of the laser wavefront after transmission through the borrowed laser-to-vacuum insertion. The original insertion used an in-vacuum gold-coated copper mirror and had been designed for an infrared laser system rather than the present green laser. Measurements at the laser targets showed significantly distorted laser profiles and larger spot sizes than expected from Gaussian-beam simulations. A replacement scheme based on a water-cooled diamond window and an out-of-vacuum reflector has therefore been pursued. Although the upgraded layout gives a clearer laser profile and improved focusing quality, a residual three-armed structure is still observed on the laser targets. Further beam tests are required to quantify its effect on Compton yield and polarization systematics.

CONFIRMATION OF COMPTON SIGNALS

The first beam commissioning used two plastic scintillator beam loss monitors (BLMs) [17] behind a lead converter as a robust detector for backscattered photons. The BLM system had coarse spatial resolution but sufficient timing response to distinguish laser-correlated signals from the steady beam background. Before searching for laser-electron collisions, the detector and beamline were aligned by scanning closed-orbit bumps and maximizing the beam-induced background rate.

Laser–electron collision tuning was then performed by scanning the remotely controlled reflector that steers the laser toward the interaction point. Events were selected by requiring a BLM pulse above threshold within a fixed time window after the laser trigger. The selected events showed a clear timing correlation with the laser pulse, with a peak delay of about 300 ns. The detected event rate increased with the nominal laser power after the collision was tuned, consistent with the expected dependence of a laser-correlated Compton signal. These observations confirmed detection of Compton backscattered photon signals and established the basic timing and alignment procedure for the next detector stage.

The BEPCII timing system was also configured to trigger the laser externally at a subharmonic of the revolution frequency. By injecting a non-colliding pilot bunch in the abort gap and adjusting the trigger delay, laser pulses were synchronized with a selected electron bunch. This capability is important for polarization measurements of selected bunches and for resonant-depolarization studies based on dedicated pilot bunches.

TAICHUPIX-3 DETECTOR COMMISSIONING

The next stage of the project is the replacement of the scintillator detector with the TaichuPix-3. Compared with the BLM system, TaichuPix-3 provides two-dimensional hit information and can therefore be used to form vertical-position observables sensitive to transverse polarization. Recent commissioning has focused on detector threshold tuning, noise-pixel masking, data-transfer stability, and trigger synchronization.

The TaichuPix-3 detector currently operates in a triggerless mode. Therefore, the laser trigger time must be reconstructed offline in order to separate laser-correlated Compton events from beam-related backgrounds and to improve the signal-to-background ratio. The laser helicity must also be tagged pulse by pulse. For this purpose, a dual-detector scheme has been implemented. A small fraction of the laser beam after the polarization unit is sent through a quarter-wave plate and a polarizing beamsplitter (PBS). With the quarter-wave plate properly oriented, the two circular helicity states σ_+ and σ_- in the standard Jones convention are converted into two orthogonal linear-polarization states and are imaged at two separated positions on Detector A. The reconstructed timing and spot position on Detector A provide the laser-trigger and helicity information, which are

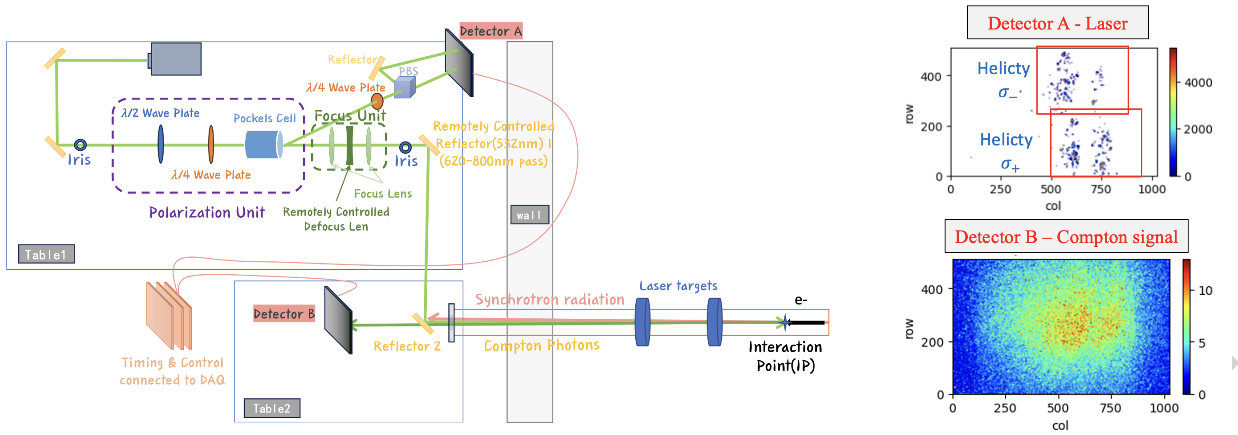

Figure 3: Illustration of the setup of TaichuPix-3 detectors, as well as the measured signals on the two TaichuPix-3 detectors.

then used to sort the photon-induced events recorded by Detector B.

In the present commissioning, to suppress slow drifts of the electron trajectory, laser pointing and detector response in the helicity-odd observable, the Pockels cell is configured to flip the laser helicity at 10 Hz, and preliminary offline analysis has verified the validity of this trigger and helicity-tagging method. This method provides a pulse-by-pulse helicity tag, whereas the absolute circular polarization parameter S_3 at the interaction point must be determined by separate calibration or online polarization monitoring.

For the polarization analysis, the basic observable is a helicity-odd vertical asymmetry or first moment of the photon-induced hit distribution. A simple form used in the ongoing analysis is

$$\Delta\langle y\rangle = \frac{1}{2}\left(\langle y\rangle_+ - \langle y\rangle_-\right), \quad (1)$$

where $\langle y\rangle_+$ and $\langle y\rangle_-$ denote the background-subtracted and acceptance-corrected first moments for the two circular laser helicity states. The electron polarization can then be inferred as

$$P_y = \frac{\Delta\langle y\rangle}{S_3 A_y}, \quad (2)$$

where S_3 is the laser circular polarization parameter at the interaction point and A_y is the vertical analyzing coefficient, with units of length. Ideally $|A_y| \simeq 41\,\mu\text{m}$ for the chosen laser wavelength and IP-to-detector distance of 18 m. In the actual measurement, it will be determined from Monte Carlo simulation and detector calibration. In practice, additional corrections are required for finite detector acceptance, converter thickness, laser position drift, helicity-dependent laser pointing, residual linear polarization, and beam background subtraction.

Data taking aimed at observing the time evolution of the electron-beam self-polarization is now in progress. The expected signature is a helicity-dependent vertical observable that evolves after injection on the Sokolov-Ternov polarization time scale. In principle, we can compare the polarization evolution between a pilot bunch and a colliding bunch. If a non-colliding pilot bunch can be kept without frequent reinjection, its polarization build-up may be observed over a wider dynamic range. By contrast, colliding bunches, regularly refilled at one-hour intervals, are expected to exhibit a smaller polarization variation because each injection partially resets the polarization history. At the time of writing, the analysis has not yet produced a first confirmed polarization evolution measurement.

SUMMARY AND OUTLOOK

A Compton polarimeter is under commissioning at BEPCII to measure transverse electron-beam polarization using laser back-scattering and pixelated photon detection. The 4W2 beamline has been modified for laser and photon transport, and laser-correlated Compton signals have been confirmed with a scintillator-based detector. The project has now advanced to the TaichuPix-3 detector stage. Detector commissioning and helicity-tagged data taking are ongoing, with the goal of observing the time evolution of the self-polarized electron beam. The detector response and vertical analyzing coefficient should be benchmarked with realistic simulations of the converter, sensor geometry, and beamline aperture.

Once beam polarization measurements become routinely available, the BEPCII Compton polarimeter will enable systematic studies of transverse self-polarization, resonant depolarization, and radiative depolarization mechanisms in a collider storage ring. The experience gained from this project is expected to be directly relevant to polarimetry designs for future circular e^+e^- colliders.

ACKNOWLEDGEMENTS

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