Proc. 13th International Beam Instrumentation Conference,Beijing JACoW Publishing
ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-THP72

A PRELIMINARY DESIGN OF A COMPTON POLARIMETER AT BEPCII

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Abstract

BEPCII is a double ring e+ e- collider running in the tau-charm energy region. We propose reusing the beamline of a dismantled wiggler magnet to implement a Compton polarimeter detecting scattered γ photons, to measure the self-polarization of the electron beam at BEPCII. This would enable resonant depolarization, and thus provide precision beam energy calibration for BEPCII, and serves as a testbed for future colliders like the CEPC. In this paper, the preliminary design of this Compton polarimeter is presented, and the tentative plan for the implementation and commissioning in the coming years are shown.

INTRODUCTION

Polarized lepton beams are essential for the physics program of the future colliders like the Circular Electron Positron Collider (CEPC) [1]. The preparation, manipulation and utilization of polarized beams rely on precision measurements of the beam polarization, in particular using Compton polarimeters [2] in the storage rings. As a test bed for this key technology, a Compton polarimeter has been designed for the Beijing Electron-Positron Collider (BEPCII) [3] to measure the self polarization of the electron beam, and the implementation plan has been established. This development will enable resonant depolarization [4] and other beam polarization experiments at BEPCII.

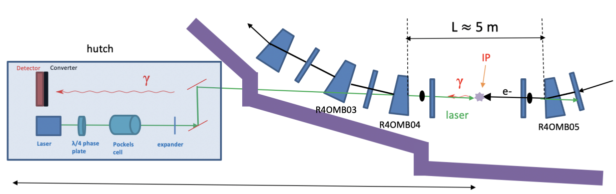

Figure 1: The layout of the Compton polarimeter at the 4W2 beamline of BEPCII.

BEPCII is a double ring e+ e- collider, with a design luminosity of $1 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 1.89 GeV, achieved routinely in operation since 2023. Now BEPCII is under a major upgrade (BEPCII-U) to enable delivering 3 times more luminosity at 2.35 GeV and operating up to 2.8 GeV. 4W2, a wiggler-based X-ray beamline of BEPCII for high pressure studies, has retired from operation. We propose to modify the front end and the hutch of this beamline to implement a Compton polarimeter. As shown in Fig. 1, a laser system in the hutch will shoot a laser through the X-ray beamline and collide at a small vertical crossing angle with the incoming electron beam, inside the straight section where the wiggler occupied before. The backscattered γ photons will be transported back to the hutch through the same beamline, and their spatial distributions are measured by the detector system.

In this paper, we begin with the principle and design parameters of this Compton polarimeter. Next, we describe the detector system and GEANT-4 simulations. Then we discuss the planned hardware modifications, including a laser transportation experiment during this long shutdown of BEPCII. We proceed to present the design of the laser alignment targets and the proof-of-principle experiments.

DESIGN PARAMETERS

Electron beams tend to become vertically polarized in a storage ring due to the Sokolov-Ternov effect. The polarization build-up time is about 75 min at 2.35 GeV for BEPCII. This beam energy is away from first-order spin resonances and the vertical polarization level is expected to be measurable with a Compton polarimeter.

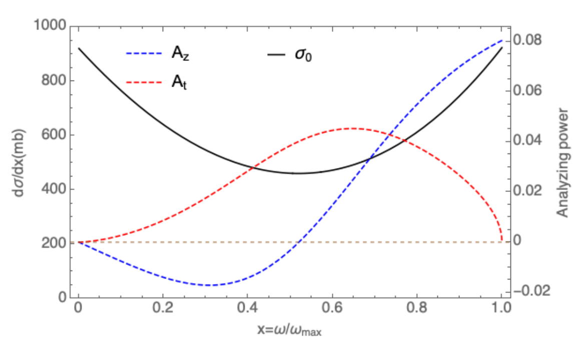

Figure 2: The differential cross section and analyzing powers as a function of the normalized scattered photon energy.

The Compton scatterings between a circularly polarized laser and a vertically polarized electron beam imprint an up-down asymmetry in the spatial distributions in both scattered γ photons and scattered electrons, the differential cross

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section is [5]

$$\frac{d^2\sigma}{dxd\phi} = \sigma_0(1 + f(S_1^L, S_2^L, \phi) - S_3^L\left[P_z^e A_z + P_t^e A_t \cos\phi\right]) \tag{1}$$

where σ_0 is the differential cross section for unpolarized electron beam, x is the ratio between the scattered γ energy and the Compton edge, and ϕ is the azimuthal angle of direction of the outgoing photon with respect to the electron transverse polarization P_t^e, S_3 is the circular polarization of the laser, the analyzing power A_t reflects the sensitivity of the Compton polarimeter. Note that such measurements can be disturbed by the linear polarization of the laser S_1^L, S_2^L and the electron beam longitudinal polarization P_z^e. For an electron beam energy of 2.35 GeV, and a green laser at a wavelength of 532 nm, the Compton edge is at 182 MeV. As shown in Fig. 2, the analyzing power is only a few percent. In order to realize a good signal-noise ratio, a small electron beam divergence and a fine detection resolution are required.

We consider using a pulsed laser to synchronize with a selected electron bunch, to facilitate resonant depolarization measurements. The γ yield rate is the product between the luminosity and the cross section. For a very small crossing angle, necessary to clear the first mirror in the hutch from the path of scattered γ, and considering that the vertical size of the electron beam is much smaller than that of the laser, the luminosity L can be approximately calculated by

$$L \approx \frac{N_e N_{\rm ph} f_{\rm laser}}{2\pi\sqrt{\sigma_{x,e}^2 + \sigma_{x,\rm laser}^2}\,\sigma_{y,\rm laser}} \tag{2}$$

where N_e and $N_{\rm ph}$ are the number of electrons and photons per beam, $f_{\rm laser}$ the repetition rate of the laser, σ the rms beam size at the interaction points for electron and laser beams. Table 1 shows the parameters of the electron beam and the laser, and the calculated luminosity and γ-yield rate.

Table 1: Electron and Laser Beam Parameters

Parameters	Electron	Laser
Energy(eV)	2.35×10^9	2.33
Pulse energy(mJ)	-	0.25
repetition rate(kHz)	1.26×10^3	1
Pulse length(ps)	50	500
Rms emittances(nm)	157/0.53	-
Rms beam size(mm)	1.3/0.05	0.6/0.6
Vertical crossing angle (mrad)	0.8	
Luminosity (barn^{-1}s^{-1})	4.6×10^5	
γ-yield per crossing	283	
γ-yield rate(kHz)	283	

DETECTION SYSTEM AND PERFORMANCE SIMULATION

Since the detection efficiency of leptons are better than those of γ photons, a lead pre-shower is designed to convert γ photons to leptons, which are in turn detected by the "TaichuPix" silicon detectors [6], a CMOS pixel sensor for the CEPC vertex detector, with a pixel size of 25 µm×25 µm. The scattered γ events are recorded and integrated over the horizontal direction, by laser helicity flipping we can obtain an asymmetry as a function of the vertical coordinate, when fitted with the theoretical formula of the asymmetry, the beam polarization is obtained.

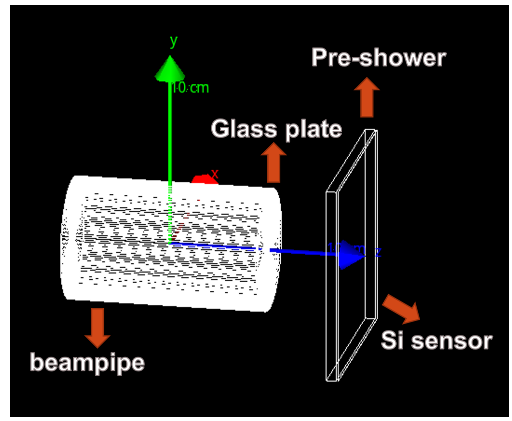

Figure 3: The sketch of the Geant4 model. The vacuum pipe with a one-mm-glass end cap is located on the left. The lead pre-shower and silicon sensor are located on the right.

To investigate the uncertainty of polarization measurement, a Geant4 simulation is performed, including a vacuum pipe with a glass end cover, a lead pre-shower, and a silicon sensor, as shown in Fig. 3. 1×10^8 Compton scattering events are randomly generated, for each laser helicity [7], and the beam polarization is measured according to the asymmetry in the deposited energy in the silicon pixels. For an assumed vertical polarization of 50%, as shown in Fig. 4, the measured polarization is close to the true value for a thickness of the lead pre-shower smaller than 4 mm, while decreases significantly as the thickness increases. This suggests that a thinner-than-4-mm lead pre-shower is suitable. On the other hand, the statistical uncertainty decreases as the thickness increases, at a thickness of 3 mm, the statistical uncertainty is about 0.9%, corresponding to a data taking of 12 min.

PLANNED HARDWARE MODIFICATIONS

During the long shutdown of 2024, we plan to modify the front end and the hutch region, so that the laser beam can be transported into the vacuum chamber of the electron beam. As shown in Fig. 5, one vacuum chamber just upstream of the IP will be replaced, the plan is to shoot a laser from the hutch and transport till this location, to ensure there is no obstacle in the beamline and establish a reference trajectory for the laser. To this end, two new laser alignment targets (green diamond in Fig. 5) will be installed to mark the transverse position of the laser.

During the summer shutdown of 2025, modifications to the timing and synchronization system, the vacuum system, the installation and commissioning of the new laser system and the detector system are planned. In addition, previous

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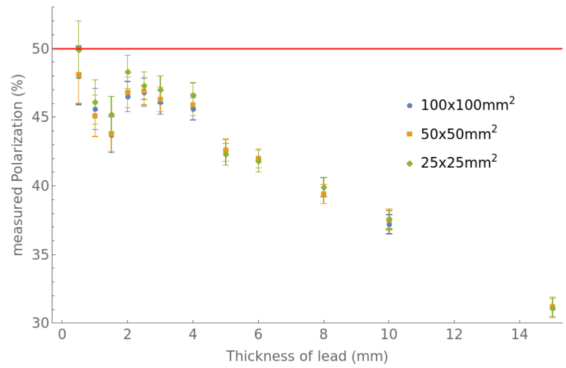


Figure 4: The measured polarization as a function of the thickness of the lead pre-shower and the area of the sensor. The areas of the sensor are 100×100 mm^2, 50×50 mm^2 and 25×25 mm^2. The red line indicates the true value of beam polarization.

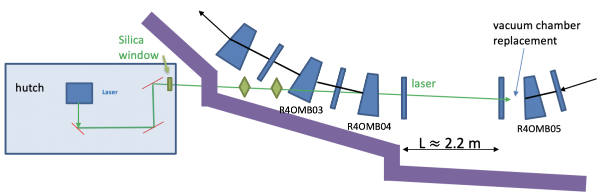


Figure 5: The laser transport experiment.

data taking with detectors indicated that spurious electrons of 10kHz from the ring could arrive at the hutch and disturb the planned Compton polarimeter experiment. To mitigate this, we plan to install a bending magnet in the front end region to deflect these spurious electrons. The synchrotron radiation photons are of less concern since they can be stopped by the lead conversion target.

LASER ALIGNMENT TARGETS

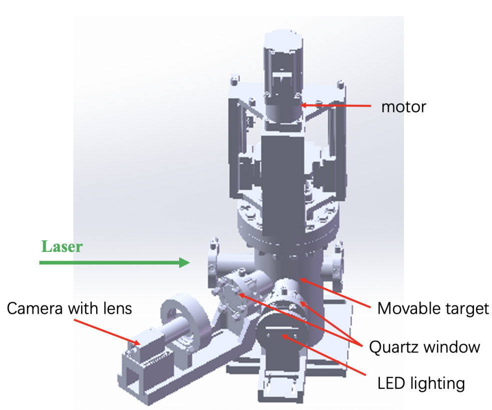


Figure 6: The laser alignment target.

The laser alignment target(see Fig. 6) have a movable ceramic target inside the chamber, when the target is moved in the way of the laser, the diffusely reflected light at about 45 degree is captured by a imaging system followed by a CCD camera. The image of the laser spot on the camera is then fitted with a Gaussian distribution to extract the center position of the laser. Note that the design is also compatible with a mirror reflection approach.

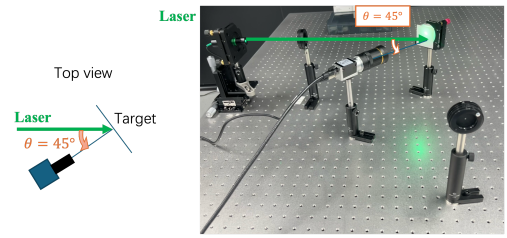
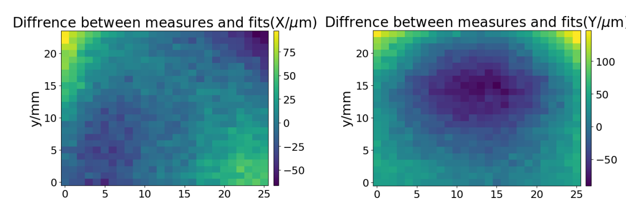


Figure 7: The proof-of-principle experiment for the laser alignment targets.

To address the concern that the diffuse reflection would deteriorate the position resolution of the optics system, a proof-of-principle experiment has been carried out. As shown in Fig. 7, the spot of the laser (cnilaser, TEM-F-520nm) on the target surface is recorded by the CCD camera placed perpendicularly to the target plane. When the transverse position of the laser, denoted by (x, y) are manually adjusted, the center of the laser spot, (X, Y), can be obtained by a Gaussian fit to the image captured by the CCD camera. A linear mapping between (x, y) and (X, Y) is thus deduced. The difference between the measured and the fitted X or Y are shown in Fig. 8. The position RMS uncertainties are 25 µm horizontally and 42 µm vertically, including the fitting error, the measurement reading error and the laser drift error. The repeatability error of the target motor is about 10 µm. Overall, this diffuse reflection alignment method can meet our need.



(a) X (b) Y

Figure 8: Difference between measurement and linear fitting in the X and Y directions.

CONCLUSION

A transverse Compton polarimeter has been designed for BEPCII, reusing the beamline of a dismantled wiggler magnet. Preliminary Monte-Carlo simulations show promising performance. Beamline modifications are planned for the two shutdown periods of BEPCII in 2024 and 2025. The first polarization measurement is scheduled in late 2025.

This work was supported by the France China Particle Physics Network/Laboratory and Youth Innovation Promotion Association CAS (No. 2021012).

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