FIRST RESULTS OF ENERGY MEASUREMENTS WITH A COMPACT COMPTON BACKSCATTERING SETUP AT ANKA*


Abstract
An electron energy measurement setup based on the detection of Compton backscattered photons, generated by laser light scattered off the relativistic electron beam, has been proposed and developed for operation at the ANKA storage ring of the Karlsruhe Institute of Technology (KIT). In contrast to conventional methods based on head-on collisions, the setup at ANKA is, for the first time, realized in a transverse configuration where the laser beam hits the electron beam at an angle of ~90°. This makes it possible to achieve a relatively low-cost and very compact setup since it only requires a small side-port instead of a straight section. This development could benefit storage rings with restricted space or where no straight sections are available, for example due to interferences with existing beamlines. The setup and the first measurement results are presented in the paper.

MOTIVATION

The ANKA storage ring [1] is operated from 0.5 GeV to 2.5 GeV. In the short bunch operation mode, typically at 1.3 and 1.6 GeV, coherent THz synchrotron radiation is generated [2]. Previously, precise energy calibration at 2.5 GeV was successfully achieved by resonant spin depolarization [3]. For lower energies, however, this technique requires very long measurement times. Here Compton Back-Scattering (CBS) is more suitable as it does not require a polarized electron beam. So far, several facilities have reported energy measurements based on CBS using a head-on collision geometry (φ=π) with relative accuracies reaching 10^-4 to a few 10^-5 [4-9]. Compared to the traditional CBS method, we have for the first time developed and measured with a transverse configuration (φ=π/2). This setup has several advantages: It is very compact and can therefore also be used at rings with restricted space. Furthermore, the transverse setup reduces the energy of Compton edge photons by a factor of two, which either makes measurements and detector calibration much easier, or enlarges the measurable range of a specific setup considerably. The transverse configuration can in principle also be converted easily into a versatile laser wire diagnostics tool.

METHOD PRINCIPLE

If monochromatic (laser) photons (energy $E_L$) scatter off of relativistic electrons (energy $E_e$), the scattered photons with energy $E_s$ follow the kinematics illustrated in Eq. 1 and Fig. 1, where $φ$ is the collision angle between the incoming laser and the electrons and $θ$ is the scattering angle between the scattered photons and the initial electrons. The electron velocity divided by the speed of light is denoted by $β$:

$$E_s = \frac{E_L (1-β\cos φ)}{1-β\cos θ + E_L / [1-\cos(θ-φ)]}. \quad (1)$$

$$E_e \approx \frac{mc^2}{2\sin(φ/2)} \sqrt{\frac{E_{max}}{E_L}}. \quad (2)$$

Its relative uncertainty can be calculated as

$$\frac{σ_{E_e}}{E_e} = \sqrt{\frac{σ_{E_L}^2}{2E_L^2} + \frac{σ_θ^2}{2\tan(φ/2)} + \frac{σ_{E_{max}}^2}{2E_{max}^2}}. \quad (3)$$

Here $σ_{E_e}/E_e$ is the relative uncertainty of the average laser photon energy.

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The angular deviation $\sigma_\phi$ comes from the drifts and measurement uncertainties of both electron beam and laser beam. For the transverse setup, this term has an impact on energy measurement accuracy [10].

The determination of the relative uncertainty of average $E_{\text{max}}$ consists of two parts: systematic uncertainty comes from the energy calibration of the detector; statistical uncertainty is given by fitting the Compton edge.

SETUP AT ANKA

Figure 2 shows the transverse CBS setup for energy measurements currently implemented at ANKA. The interaction point is located at one long straight section. The gamma photons generated by CBS propagate in a narrow cone along the direction of the electron beam. The photons with energy $E_{\text{max}}$ are concentrated on the propagation axis. We use a tungsten collimator in front of the detector to collect these photons and reduce the background level.

Figure 2: The compact CBS setup for energy measurement at ANKA.

The detector is a High Purity Germanium (HPGe) spectrometer (ORTEC GEM-M5970, nominal relative efficiency 38%), as shown in Fig. 3. Its crystal section is shielded by lead blocks in the experimental environment.

Figure 3: Gamma ray detection system.

As shown in Fig. 4, a monochromatic $\mathrm{CO}_2$ laser, on loan from DLR ($\lambda$: 10.2 $\mu$m, ~20 W) covers the detectable range of our HPGe. Its frequency is specially stabilized through a PID loop and a Fabry-Perot interferometer to about $10^{-6}$ ($\sigma_E/E_L$). The laser is tightly focused by a cylindrical lens to $\sim600$ $\mu$m ($4\sigma$) vertically to match the electron beam and maximize the signal rate (Fig. 5). We take advantage of an ion pump port to couple in the laser, therefore it does not require any dedicated section of the storage ring.

Figure 4: Laser and optical system of the CBS setup.

Figure 5: Laser profile at the focal plane with the vertical beam size much smaller than the horizontal one.

MEASUREMENT

Figure 6 shows a typical CBS spectrum with a distinct Compton edge compared to the radiation background. The signal to noise ratio is around 3, which agrees well with the design value [10].

Figure 6: Spectrum at 1.3 GeV for over 120 seconds: (a) radiation background (laser off, e$^-$ beam $\sim10.7$ mA); (b) CBS signal + background (laser on, e$^-$ beam $\sim9.3$ mA).

Collision Angle

We use the mechanical centers of two quadrupoles as a Reference Line (RL) as shown in Fig. 7. We can measure...
the laser direction relative to the RL with a laser tracker (Leica Absolute Tracker AT401) and a camera (Spiricon Pyrocam IV). We also use Beam Position Monitors (BPMs) to monitor the electron orbit orientation relative to the RL. The collision angle $\phi$ can then be determined.

The main part of $\phi$ is between the RL and the vector set by the two camera positions. It is measured as $91.648^\circ$ with the laser tracker. After consideration of the offset of the beam centroid centers shown in Table 1, the laser direction was determined to $91.630^\circ$ relative to the RL.

<table>
<thead>
<tr>
<th>Table 1: Centroid Measurement</th>
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<tr>
<td>X center of 10000 samples (µm)</td>
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<td>$\Delta X$ (4σ) (µm)</td>
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<tr>
<td>Distance between pos. 1 and 2 (m)</td>
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Since the laser tracker is very accurate (maximum permissible error: ±15 µm + 6 µm/m) compared to the beam centroid stability ($\Delta X$ in Table 1), its measurement uncertainty is negligible. If we assume the worst case that $\Delta X$ is solely caused by angular drift rather than parallel beam movement, the angular uncertainty of the laser direction can then be determined as 0.18 mrad = 0.010°. So the laser beam is $91.630^\circ \pm 0.010^\circ$ relative to the RL.

According to the readings from BPM_1 and BPM_2, the electron beam orientation relative to the RL is -0.17 mrad = -0.010°. The uncertainty of this angle mainly comes from: mismatch between the magnetic and mechanical centers of the quadrupoles < 0.05 mrad; electron orbit drift during measurement < 0.01 mrad; calibration of BPM based on beam based alignment < 0.1 mrad/0.006°. The collision angle $\phi$ is $91.620^\circ \pm 0.012^\circ$, which gives $\sigma_\phi/\tan(\phi/2) = 2.0 \times 10^{-4}$.

**Edge Fitting**

According to [7] and [9], the Compton edge curve can be fit by a six-parameter function (similar to a complementary error function, erfc) to determine the average value of $E_{\text{max}}$. For Fig. 6 (b), the edge fitting gives $E_{\text{max}}$ = 1580.44 keV ± 0.28 keV, as shown in Fig. 8. Given that the systematic uncertainty from the detector calibration should be smaller than $10^{-5}$, then the statistical uncertainty dominates $\sigma_{E_{\text{max}}}/E_{\text{max}}$, which is $1.8 \times 10^{-5}$.

**Preliminary Result**

Using $m^2 c^4 = 0.5109989$ MeV, $E_L = 0.1211591$ eV and the measured values $\phi = 91.620^\circ$, $E_{\text{max}} = 1580.44$ MeV, we can calculate $E_e = 1286.95$ MeV using Eq. 2. We can also get $\sigma_{E_e}/E_e = 1.3 \times 10^{-4}$ using Eq. 3. Subsequently, we can determine the energy we measured at 1.3 GeV is $E_e = 1287.0$ MeV ± 0.2 MeV.

**Figure 8**: Zoom into Compton edge of Fig. 6 (b) and curve fitting at 1.3 GeV, $\chi^2/ndf = 524/555$.

**SUMMARY**

Compared to the conventional CBS methods of energy measurement, we have for the first time developed a compact setup based on transverse scheme at ANKA. The signal to noise ratio agrees well with the designed value. Besides the result shown in the paper, measurements around 0.5 GeV, 1.6 GeV and 2.5 GeV also give promising initial results. Furthermore, longer accumulation time has shown the statistical uncertainty of determining $E_{\text{max}}$ can be reduced down to a few $10^{-5}$. Further studies need to be carried out to improve the deviation of the collision angle.

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**REFERENCES**