DESIGN OF A COMPACT SETUP TO MEASURE BEAM ENERGY BY DETECTION OF COMPTON BACKSCATTERED PHOTONS AT ANKA* 


Abstract

One of the most important parameters of accelerators is their beam energy. So far, the method of resonant depolarization was used to accurately determine the energy at 2.5 GeV of the ANKA electron storage ring, which, however, becomes cumbersome for lower energies. A good alternative is the detection of Compton backscattered photons, generated by laser light scattered off the relativistic electron beam. To achieve compactness and integration into the storage ring, the setup of transverse scattering is proposed instead of conventional head-on collision. The feasibility has been studied by comparison between simulations of Compton backscattered photons by AT and CAIN 2.35 and actual measurement of background radiation with an HPGe (High Purity Germanium) spectrometer. The layout of the setup is also included in the paper.

INTRODUCTION

Compton backscattering (CBS), sometimes also referred to as laser-Compton scattering or inverse Compton scattering, describes the process of (laser) photons (energy $E_L$) scattering 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 $\phi$ is the collision angle between the incoming laser and the electrons and $\theta$ is the scattering angle between the scattered photons and the initial electrons. The electron velocity divided by the speed of light is denoted by $\beta$.

\[
E_s = \frac{E_e (1-\beta \cos \phi)}{1-\beta \cos \theta + E_e/E_s [1-\cos(\theta-\phi)]}. 
\]  

For typical CBS measurements at storage rings we have $E_e \gg mc^2 >> E_L$ ($mc^2$ is the electron rest energy) and $\phi > 0$. This leads to an approximation for the cut-off energy $E_{max}$ as shown in Eq. 2. The electron beam energy $E_e$ can then be determined from the known values of $mc^2$, $E_L$, $\phi$, and the measured $E_{max}$ using

\[
E_{max} = \frac{E_e^2}{E_e + \frac{mc^4}{4E_L \sin^2 \phi}}. 
\]  

MOTIVATION

The ANKA storage ring [1] operates from 0.5 GeV (injection energy) to 2.5 GeV (normal user operation). Several times a year ANKA offers special user operation at 1.3 and 1.6 GeV, e.g., to generate coherent synchrotron radiation in the THz regime using a low-$\alpha_e$ optics [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 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 ($\phi=\pi$) with relative accuracies reaching $10^{-4}$ to a few $10^{-5}$ [4-9]. Compared to the traditional CBS method, we are currently realizing for the first time a transverse configuration ($\phi=\pi/2$). 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 $E_{max}$ by a factor of two, which makes measurements and especially detector calibration considerably easier because available calibration sources have limited upper energies. The transverse configuration can in principle also be converted easily into a versatile laser wire diagnostics tool.

SETUP AT ANKA

Figure 2 shows the transverse CBS setup for energy measurements currently under construction 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 the maximum (cut-off) energy $E_{max}$ are concentrated on the propagation axis. We therefore plan to use a collimator in front of the HPGe spectrometer to collect these photons and reduce the background level. We chose a laser emitting in the mid-infrared range (CW monochromatic CO$_2$ laser with $E_L=0.117$ eV) to ensure...
that \( E_{\text{max}} \) is within the detectable range of commercially available HPGe spectrometers (up to \( \sim 10 \text{ MeV} \)). The laser can be tightly focused to match the vertical size of the electron beam and therefore maximize the signal rate.

![Figure 2: Energy measurement setup by detection of Compton backscattered photons at ANKA.](image)

**MEASUREMENT ACCURACY**

The relative width of the cut-off edge \( \Delta E_{\text{max}}/E_{\text{max}} \) can be derived from Eq. 2 [10]:

\[
\frac{\Delta E_{\text{max}}}{E_{\text{max}}} = 2 \left( \frac{\Delta E_e}{E_e} + \frac{\Delta E_L}{E_L} + \frac{\Delta R(E_{\text{max}})}{R(E_{\text{max}})} \right) \frac{\Delta \phi}{\tan \phi / 2}. \tag{3}
\]

Here “\( \oplus \)” refers to the square root of the quadratic sum of the individual terms, which are (values are for ANKA):

- \( \Delta E_e/E_e \): energy spread of the electron beam (\( \sim 10^{-4} \text{--} 10^{-3} \));
- \( \Delta E_L/E_L \): relative stability of the laser photon energy and radiation line width (\( \sim 10^{-5} \) for the used laser system);
- \( \Delta R(E_{\text{max}})/R(E_{\text{max}}) \): energy resolution of the HPGe detector at \( E_{\text{max}} \) (\( \sim 10^{-3} \)).

Several sources for \( \Delta \phi \): (1) orbit drift during measurement (<\( 10^{-5} \) rad); (2) horizontal angle of electron beam ~ a few \( 10^{-3} \) rad or less; (3) horizontal angle of laser <\( 10^{-4} \) rad.

Therefore, \( \Delta E_e/E_e \) and \( \Delta R(E_{\text{max}})/R(E_{\text{max}}) \) are the dominant contributions that widen the cut-off edge to \( \sim 10^{-3} \).

Furthermore, to determine the average value of \( E_{\text{max}} \), an erfc-like function [4,7,8,10] can be fit to the edge curve. The statistic relative uncertainty of determining \( E_{\text{max}} \) depends on the photon density at the cut-off edge \( dN_e/dE_e \) (\( E_{\text{max}} \)) and can be estimated as [10]

\[
\frac{\sigma_{E_{\text{max}}}}{E_{\text{max}} \text{ statistic}} \approx \left( \frac{2 \Delta E_{\text{max}}}{E_{\text{max}}} \right)^{1/2} \sqrt{\frac{dN_e}{dE_e}(E_{\text{max}})}. \tag{4}
\]

In our case \( \Delta E_{\text{max}}/E_{\text{max}} \) is around \( 10^{-3} \). The maximum energy \( E_{\text{max}} \) would be around 0.2 MeV, 1.5 MeV, 2.3 MeV and 5.6 MeV for an electron beam energy of 0.5 GeV, 1.3 GeV, 1.6 GeV and 2.5 GeV, respectively. For example, to reduce statistic uncertainty to below \( 10^{-4} \) for a 1.3 GeV beam, \( dN_e/dE_e(E_{\text{max}}) \) must be higher than 100 counts/keV. If it reaches ~1000 counts/keV, the statistic uncertainty can be further reduced to a few \( 10^{-5} \).

The systematic uncertainty of determining \( E_{\text{max}} \) is limited by the accuracy of the energy calibration of the HPGe detector, which can reach a few \( 10^{-5} \) [8]. This is potentially the limit of the traditional head-on collision setup, if enough spectral data has been recorded to reduce the statistic uncertainty.

Once we get the average value of \( E_{\text{max}} \) and its relative uncertainty, we can calculate the electron beam energy using Eq. 2, and its relative uncertainty can be calculated as [10]

\[
\frac{\sigma_{E}}{E} = \frac{\sigma_{E_{\text{max}}}}{2E_{\text{max}}} + \frac{\sigma_{E_L}}{2E_L} + \frac{\sigma_{\phi}}{2 \tan \phi / 2}. \tag{5}
\]

Here \( \sigma_{E_e}/E_e \) is the relative uncertainty of the average laser photon energy, which is in our case much smaller than \( 10^{-5} \).

The angular deviation \( \sigma_\phi \) comes from (1) orbit drift during measurement (<\( 10^{-5} \) rad); (2) measurement error of the electron orbit due to the limited beam position monitor accuracy (on the order of \( 10^{-5} \text{--} 10^{-4} \) rad); and (3) misalignment of the laser (estimated as \( \sim 10^{-5} \) rad). Thus, the total uncertainty can be up to a few \( 10^{-4} \). For traditional head-on collision setups this term can be neglected (second order dependence \( -\sigma_\phi^2/4 \)), since \( \tan(\phi/2)=1 \) for \( \phi=\pi/2 \) and approaches infinity for \( \phi=\pi \). For the transverse setup, however, this term needs to be considered as it has an impact on energy measurement accuracy.

The aim of this project is to achieve an energy measurement of the electron beam with a relative uncertainty of a few\( 10^{-4} \).

**SIGNAL-TO-NOISE RATIO**

Besides the determination of the collision angle, another challenge of the transverse CBS method is the much lower interaction time in contrast to the head-on collision scheme. Therefore a feasibility study has been carried out comparing a simulation of CBS photons with an actual background measurement for the low-\( \alpha_\text{c} \) mode at 1.3 GeV.

The background was measured at the long straight section of the IMAGE beamline, see Fig. 3. The HPGe detector was a Canberra GX3018, with an energy resolution of 1.80 keV (FWHM) at 1.33 MeV and an active volume of 139 cm\(^3\) (diameter 58 mm, length 52.5 mm). The full energy peak efficiency for ~1.5 MeV photons is estimated to be at least several percent. The results are shown in Fig. 4.

If we focus 10 W of laser power to 100 µm rms to...
Figure 4: Results of a background measurement acquired for 2000 s in low-αc mode at 1.3 GeV: (a) using 16 mm² slits with 1.92-1.20 mA electron beam current; (b) using 4 mm² slits with 1.1-0.82 mA electron beam current. The red squares mark the cut-off edge area of CBS photons.

overlap the vertical size of the electron beam in low-αc mode at the interaction point (96 µm rms as simulated by AT) and use a typical 40 mA electron beam current, the spectrum of CBS photons reaching the detector during 20 minutes can be simulated with CAIN 2.35 (Fig. 5). If we assume 5% full energy peak efficiency, the photon density at the edge is found to be \( \sim 4200/\text{keV} \) and \( \sim 2800/\text{keV} \), for 16 mm² and 4 mm² collimators, respectively. Both are enough to reduce the statistic relative uncertainty of determining \( E_{\text{max}} \) to a few \( 10^{-5} \).

Since both the CBS photon and the background radiation level (mainly from gas bremsstrahlung, see Table 1) are proportional to electron beam current and detection time, a signal-to-noise ratio of around 2.5 can be estimated.

<table>
<thead>
<tr>
<th>Slit size/collimator area</th>
<th>16 mm²</th>
<th>4 mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background (measured)</td>
<td>0.779</td>
<td>0.478</td>
</tr>
<tr>
<td>Signal (simulated, ~5% full energy peak efficiency)</td>
<td>1.98</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Table 1: Average Photon Count Rate (photons/mA/s)

at several facilities, a transverse scheme is adopted at ANKA for its high usability. Despite its comparatively low laser-electron interaction time, background measurements and simulations with typical parameters for the low-αc mode have indicated that we can expect a signal to noise ratio exceeding 2.5. Furthermore, the photon density at the spectrum edge is enough to reduce the statistic relative uncertainty of determining \( E_{\text{max}} \) down to a few \( 10^{-5} \). To achieve accurate energy measurements with a transverse setup, a high wavelength stability of the laser, an accurate determination of \( E_{\text{max}} \) and finally a good knowledge of the collision angle are required. For transverse geometries, the collision angle accuracy is most likely the limiting parameter, whereas for head-on collision schemes the absolute energy calibration of the HPGe detector is the most challenging factor finally.

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REFERENCES


SUMMARY

At ANKA, energy measurements by detection of CBS photons are especially useful for energies lower than 2.5 GeV, for example in the low-αc mode. Compared to conventional head-on collision methods previously used