ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPME112

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

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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 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:

$$E_s = \frac{E_L(1-\beta\cos\varphi)}{1-\beta\cos\theta + E_L/E_e[1-\cos(\theta-\varphi)]}. \quad (1)$$

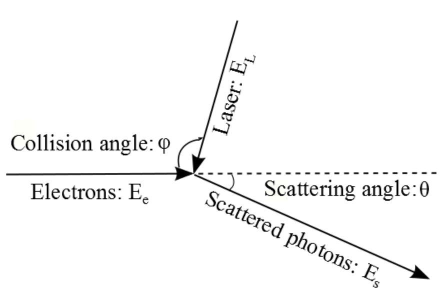

Figure 1: Scheme of CBS.

For θ=0, the energy of the scattered photons reaches its maximum and forms a sharp cut-off edge in the energy spectrum.

For typical CBS measurements at storage rings we have $E_e \gg mc^2 \gg E_L$ (mc^2 is the electron rest energy) and φ>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, φ, and the measured E_{max} using

$$E_{max} \approx \frac{E_e^2}{E_e + \frac{m^2c^4}{4E_L \sin^2\frac{\varphi}{2}}}. \quad (2)$$

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-α_c 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 (φ=π) 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 (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 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

*Work supported by the European Union under contract PITN-GA-2011-289191

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that E_{max} is within the detectable range of commercially available HPGe spectrometers (up to ~10 MeV). The laser can be tightly focused to match the vertical size of the electron beam and therefore maximize the signal rate.

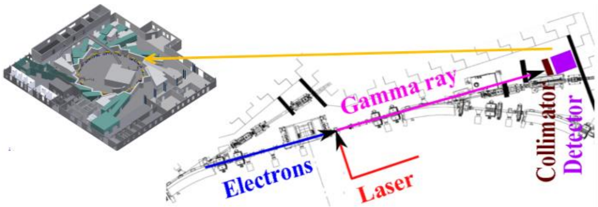

Figure 2: Energy measurement setup by detection of Compton backscattered photons at ANKA.

MEASUREMENT ACCURACY

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

$$\frac{\Delta E_{max}}{E_{max}} \approx 2\frac{\Delta E_e}{E_e} \oplus \frac{\Delta E_L}{E_L} \oplus \frac{\Delta R(E_{max})}{R(E_{max})} \oplus \frac{\Delta\varphi}{\tan\varphi/2}. \quad (3)$$

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 (~10^{-4}–10^{-3});

$\Delta E_L/E_L$: relative stability of the laser photon energy and radiation line width (<10^{-5} for the used laser system);

$\Delta R(E_{max})/R(E_{max})$: energy resolution of the HPGe detector at E_{max} (~10^{-3});

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

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

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

$$\left.\frac{\sigma_{E\,max}}{E_{max}}\right|_{statistic} \approx \sqrt{\frac{2\Delta E_{max}/E_{max}}{E_{max}\frac{dN_\gamma}{dE_s}(E_{max})}}. \quad (4)$$

In our case $\Delta E_{max}/E_{max}$ is around 10^{-3}. The maximum energy E_{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, $dN_\gamma/dE_s(E_{max})$ 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_{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_{max} and its relative uncertainty, we can calculate the electron beam energy using Eq. 2, and its relative uncertainty can be calculated as [10]

$$\frac{\sigma_{Ee}}{E_e} \approx \frac{\sigma_{E\,max}}{2E_{max}} \oplus \frac{\sigma_{EL}}{2E_L} \oplus \frac{\sigma_\varphi}{2\tan\varphi/2}. \quad (5)$$

Here σ_{EL}/E_L is the relative uncertainty of the average laser photon energy, which is in our case much smaller than 10^{-5}.

The angular deviation σ_φ comes from (1) obit 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} -10^{-4} rad), and (3) misalignment of the laser (estimated as ~10^{-4} 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 ~$\sigma_\varphi^2/4$), since $\tan(\varphi/2)=1$ for $\varphi=\pi/2$ and approaches infinity for $\varphi=\pi$. 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 few10^{-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-α_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 showed in Fig. 4.

If we focus 10 W of laser power to 100 μm rms to

Figure 3: Background measurement at IMAGE beamline.

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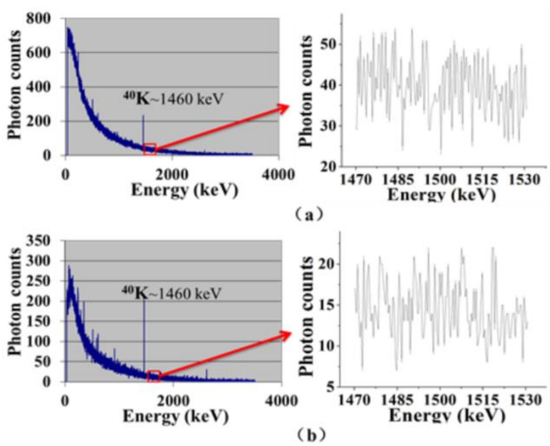

Figure 4: Results of a background measurement acquired for 2000 s in low-αc mode at 1.3 GeV: (a) using 16 mm2 slits with 1.92-1.20 mA electron beam current; (b) using 4 mm2 slits with 1.1-0.82 mA electron beam current. The red squares mark the cut-off edge area of CBS photons.

overlap the vertical size of the electron beam in low-α_c 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 ~4200/keV and ~2800/keV, for 16 mm^2 and 4 mm^2 collimators, respectively. Both are enough to reduce the statistic relative uncertainty of determining E_{max} to a few10^{-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.

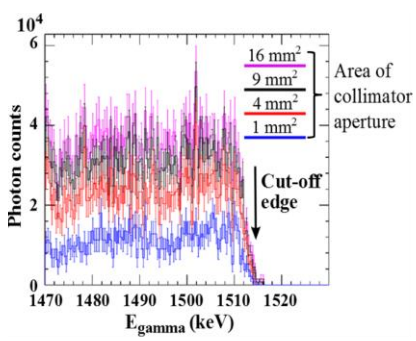

Figure 5: Simulated CBS photon spectrum around the energy edge for a 40 mA electron beam in low-α_c mode at 1.3 GeV, for a 10 W laser and 20 minutes acquisition time. The collimator has the same location as the beamline slits in the background measurement.

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-α_c mode. Compared to conventional head-on collision methods previously used

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

Slit size/collimator area	16 mm^2	4 mm^2
Background (measured)	0.779	0.478
Signal (simulated, ~5% full energy peak efficiency)	1.98	1.32

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-α_c 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_{max} down to a few10^{-5}. To achieve accurate energy measurements with a transverse setup, a high wavelength stability of the laser, an accurate determination of E_{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.

ACKNOWLEDGMENT

Thanks to R. Klein at MLS, Berlin for the inspired discussion. Thanks to C. Wilhelm and S. Kaminski at KSM/KIT for lending us the HPGe detector and a lot of valuable suggestions and instructions. Also thanks to Prof. Hübers from DLR, Berlin, for making the laser available to us. Thanks to E. Bründermann from RUB, Bochum for all the supports. Thanks to S. Bauer, et al. for supporting our measurements at the ANKA IMAGE beamline. Thanks to N.J. Smale for instructive discussions and operating the machine. Thanks to M. Suepfle at the IR beamline for testing our components. Thanks to the entire THz group and all colleagues at ANKA, in particular: M. Hagelstein, A. Voelker and T. Fischboeck.

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