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Measurement of the electron energy and energy spread at the electron storage ring BESSY I

R. Klein,[a]* T. Mayer,[b] P. Kuske,[b] R. Thornagel[a] and G. Ulm[a]

[a]*Physikalisch-Technische Bundesanstalt, Abbestr. 2-12, D-10587 Berlin, Germany, and* [b]*BESSY GmbH, Lentzeallee 100, D-14195 Berlin, Germany. E-mail: roman.klein@ptb.de*

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Knowledge of the electron energy with a small uncertainty is necessary for the Physikalisch-Technische Bundesanstalt (PTB) to operate the electron storage ring BESSY I, and the future BESSY II, as a primary radiation source standard of calculable synchrotron radiation. At BESSY I the electron energy can now be measured either by the long-established method of resonant spin depolarization or by the newly set up method of Compton backscattering (CBS) of laser photons (CO_2 laser, $\lambda = 10.6$ μm). Results obtained at different electron energies by these two independent methods are presented. They agree within a relative uncertainty of better than 10^{-4}. The advantages and disadvantages of these two complementary techniques are described and applications of CBS for the measurement of other storage-ring parameters, *e.g.* the electron energy spread, are given.

Keywords: metrology; storage rings; gamma-ray spectroscopy; gamma-ray sources; special relativity.

1. Introduction

The spectral photon flux of synchrotron radiation of bending magnets can be calculated with a small uncertainty by Schwinger's theory (Schwinger, 1949), as all storage-ring parameters and geometrical quantities entering the calculation are known with the uncertainty required. For many years, the PTB has exploited this fact extensively and very successfully for the calibration of energy-dispersive detectors and radiation sources in the spectral range of VUV and soft X-rays at the BESSY I electron storage ring (Ulm & Wende, 1995, 1997; Rabus *et al.*, 1996; Arnold & Ulm, 1992; Hollandt *et al.*, 1994).

A condition necessary for the calculation of the spectral photon flux with the required low uncertainty is a knowledge of the electron energy with a relative uncertainty of some 10^{-4}. At the BESSY I storage ring, the electron energy can now be measured with this relative uncertainty by two independent and complementary techniques: resonant spin depolarization and Compton backscattering of laser photons. The former method, which is a well established and precise technique (Derbenev *et al.*, 1980), has the drawback that spin-polarized electrons are needed, a constraint that cannot always be met and that makes measurements very time-consuming. Moreover, at BESSY I, a minimum electron beam current of about 100 mA is needed to achieve a sufficient signal-to-noise ratio. The latter method does not need polarized electrons and can be utilized in a wider dynamic range of the stored electron beam current. Besides this, it allows the determination of further storage-ring parameters, *e.g.* the electron energy spread. This paper focuses on the set-up and description of the CBS technique; details of the technique of resonant spin depolarization and its set-up at BESSY I can be found elsewhere (Thornagel *et al.*, 1994; Arnold & Ulm, 1992).

2. Experimental set-up and measured spectra

Fig. 1 shows a schematic illustration of the experimental set-up for measuring the electron energy by CBS. The technique is based on the determination of the maximum energy of CO_2-laser photons scattered by the electron beam in a head-on collision. The scattered photons are detected behind a lead collimator by an energy-calibrated HPGe detector mounted on a computer-driven *xy*-translation stage for accurate positioning in the forward direction of the scattered photons. The laser photons with energy E_1 scattered in the direction of the electron beam have the maximum energy

$$E_2^{\max} = E_1 4\gamma^2/(1 + 4\gamma E_1/m_e c^2).$$

From this measured maximum energy $E_2^{\max}$, the energy of the electrons $W = \gamma m_e c^2$ can be calculated. A detailed description of the experimental set-up and data evaluation can be found elsewhere (Klein *et al.*, 1997). Fig. 2 shows typical spectra obtained at the three different electron energies (around 340, 800 and 850 MeV) used by PTB for radiometry at the BESSY I storage ring. The cut-off in the Compton spectrum at the corresponding maximum energy can be clearly seen.

Special care must be taken that the detector and collimator are positioned in such a way that the photons scattered in the direction of the electron beam, which have the maximum energy, are accepted. The effect of incorrect positioning of the collimator is illustrated in Fig. 3. A slight difference in the angular acceptance explains the small difference in the shape of the Compton spectra of Fig. 2 near the cut-off energy.

3. Results

The technique of resonant spin depolarization is not applicable to BESSY I operated at 340 MeV, because it takes more than 3 h for the electron polarization to build up. At this energy, only CBS is applicable for an accurate determination of the electron energy. For BESSY I operated at 800 or 850 MeV, we are in the unique position of having two independent techniques for the accurate determination of the electron energy so that stringent cross-

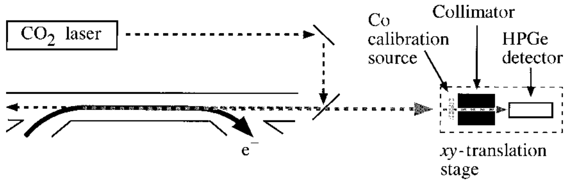

Figure 1
Schematic illustration of the experimental set-up. The photons from a grating-tuned CW CO_2 laser pass through the entrance window into the storage ring and are scattered by the electrons in a head-on collision. Those photons that are scattered in the forward direction of the electron beam are the most energetic and carry information on the electron energy. They pass a thick lead collimator used to absorb the photons scattered off-axis and are then detected with an energy-calibrated HPGe detector. The detector/collimator unit is placed on an *xy*-translation stage for accurate alignment. Co radionuclides are placed in front of the collimator for energy calibration of the detector.

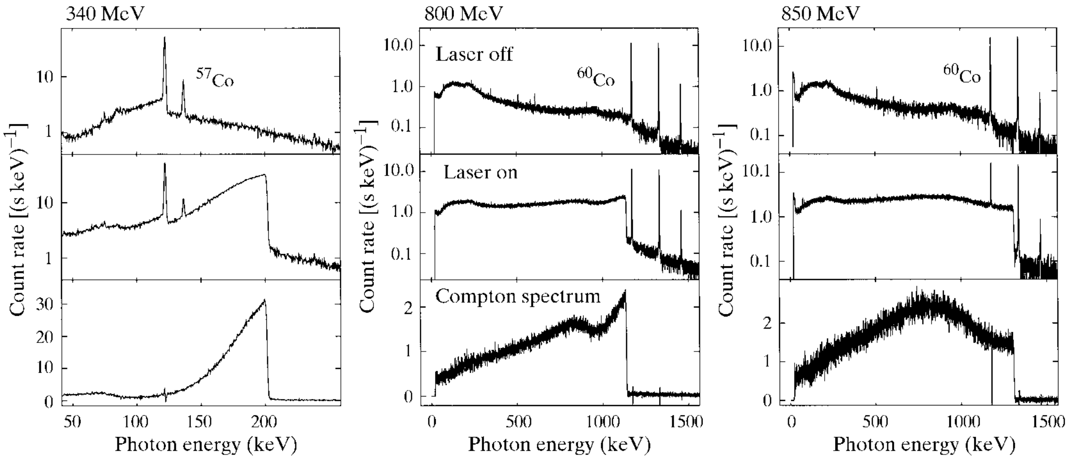

Figure 2
Typical Compton spectra for BESSY I electron energies around 340, 800 and 850 MeV used for special PTB operation of the storage ring. The upper drawings show the background spectra taken with the laser switched off. Only the lines from the calibration source and *bremsstrahlung* background are visible. The spectra in the middle are obtained with the laser switched on. The bottom spectra are the difference between the spectra in the upper and middle rows. The sharp cut-off of the spectra at the high-energy side can be clearly seen. From the energy position of this cut-off the electron energy can then be calculated. The acquisition time was 15 min for each spectrum, the angular acceptance of the collimator was 0.72 mrad.

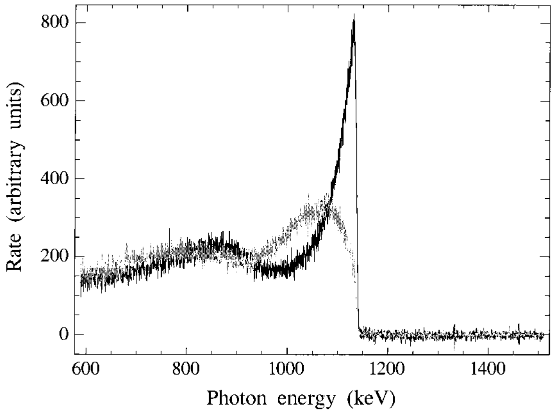

Figure 3
Influence of the collimator/detector alignment. The collimator with an aperture of 2 mm horizontally and 2 mm vertically is placed at a distance of 11 m from the middle of the straight section. With a properly adjusted collimator a sharp peak with quasi-monochromatic γ radiation of 5% bandwidth and a distinct high-energy cut-off is obtained (black spectrum). On the other hand, the broad peak is obtained after displacement of the collimator/detector unit by 2 mm in the vertical direction (gray spectrum). Now only few photons with maximum energy can reach the detector, and the signal at the cut-off energy drops significantly. One can also see that the shape of the signal is a good indicator for proper alignment of the collimator/detector in the forward direction of the electron beam. Nevertheless, the evaluation of the two signals yields electron energies of 796.88 (3) and 796.85 (9) MeV for the properly aligned collimator/detector and shifted collimator/detector, respectively.

checks of the results obtained are possible. Fig. 4 shows the results obtained by spin depolarization and CBS for BESSY I operated at 800 and 850 MeV. The gray bars show the energy interval in which the electron energy can be found with 100% probability by spin depolarization. The different bars relate to measurements at different injections. The data points show the corresponding results of electron energy measurement by CBS for the same injection. The error bars shown are the 1σ confidence level, mainly determined by the combined statistical error on the position of the cut-off energy and of the position of the calibration lines. The results agree very well within the combined relative uncertainties.

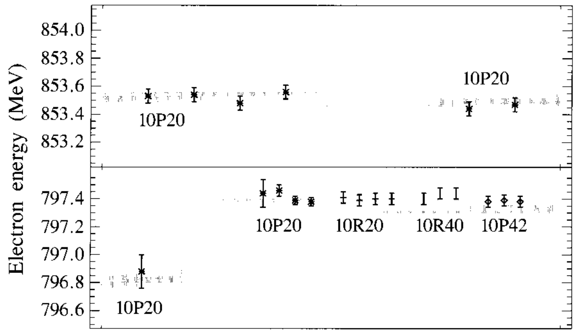

Figure 4
Comparison of the results obtained for the electron energy by the two techniques of resonant spin depolarization and CBS. The gray bars indicate the results of four different measurements of the electron energy by resonant spin depolarization within a period of about 3 months. The width of the bars is related to the energy interval in which the energy can be found with 100% probability. This width is given by the bandwidth of the r.f. frequency applied for depolarization. The data points with error bars are the corresponding results obtained by multiple measurements by CBS for the very same injection. These error bars show the 1σ confidence level. (The different symbols of the data points relate to different laser lines used for the measurements and are of no importance for the comparison.)

For BESSY I operated at 800 MeV, Fig. 5 shows an example of the measurement of the electron energy spread by CBS as a function of the electron beam current. This is possible since, besides the detector resolution, the electron energy spread determines the 'width' of the signal at the cut-off energy. Furthermore, these measurements give an impression of the wide dynamic range of electron beam currents to which the technique is applicable.

4. Conclusions

Results for the electron energy measured by the two independent techniques of resonant spin depolarization and CBS agree well within the combined relative uncertainty of better than 10^{-4}.

Moreover, the technique of CBS is the only means of measuring the electron energy at BESSY I operated at a reduced

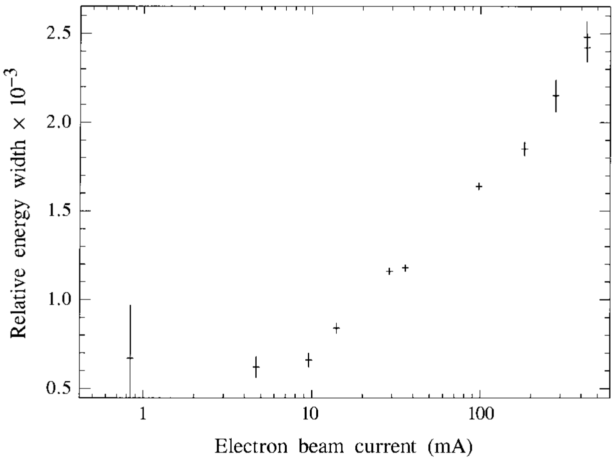

Figure 5

Electron energy spread for the 800 MeV operation of BESSY I as a function of the stored electron beam current measured by CBS.

electron energy of 340 MeV, at which the other technique fails because of very long polarization times. The possibility of a highly accurate measurement of the electron energy at this value considerably improves the operation of BESSY I as a source of calculable spectral output. The same will be the case for the future storage ring BESSY II, when operated for radiometry, at PTB's demand, with a reduced electron energy of 900 MeV instead of its normal 1.7 GeV. Besides this, CBS allows the determination of other storage-ring parameters, as was shown by the example of the electron energy spread.

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