BESSY II OPERATED AS A PRIMARY SOURCE STANDARD

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Abstract

The Physikalisch-Technische Bundesanstalt (PTB) is the German National Metrology Institute and responsible for the realization and dissemination of the legal units in Germany. For the realization of the radiometric units in the visible, UV, VUV and X-ray spectral range PTB has been using calculable synchrotron radiation of bending magnets from the BESSY I and BESSY II electron storage rings for more than 20 years.

The spectral photon flux of synchrotron radiation can be precisely calculated by Schwinger's theory. Therefore, all the storage ring parameters entering the Schwinger equation have to be measured with low uncertainty, which requires a stable and reproducible operation of the storage ring. At BESSY II, PTB has installed all equipment necessary to measure the electron energy, the electron beam current and the magnet induction at the radiation source point as well as all geometrical quantities with low uncertainty. The measurement accuracy for these quantities enables PTB to calculate the spectral photon flux from the visible up to the X-ray range with a relative uncertainty below 0.2 %.

INTRODUCTION

Electron storage rings with calculable bending magnet radiation are used as primary source standards for radiometry in the spectral range from the visible to the X-ray region [1] at several national metrology institutes, such as the National Institute of Standards and Technology (at the SURF III electron storage ring, Gaithersburg, USA [2]), the National Metrology Institute of Japan (at the TERAS electron storage ring, Tsukuba, Japan [3]), the Budker Institute of Nuclear Physics (at the VEPP-2M and VEPP-3 electron storage rings, Novosibirsk, Russia [4]) or PTB (at the BESSY II electron storage ring [5]). Typical radiometric applications are the calibration of radiation sources [6] by comparing their spectral radiance to or the calibration of energy dispersive detectors [7,8,9,10] with a known response function by direct illumination with the primary source standard.

Prerequisite to the operation of an electron storage ring as a primary source standard is – in addition to sufficient stability - the knowledge of the parameters needed for the calculation: The spectral photon flux Φ_E for a photon energy E is given by the Schwinger equation [11] $\Phi_E = \Phi_E\left(E; W, B, I, \Sigma_y; \Psi, d, a, b\right)$.

The parameters are: electron energy W, magnetic induction B at the radiation source point, electron beam current I, effective vertical divergence Σ_y, vertical emission angle ψ, distance d between the radiation source point and a flux-defining aperture of size a × b. The effective vertical divergence is derived from the vertical electron beam size σ_y and beam divergence $\sigma_{y'}$ according to $\Sigma_y = \left(\sigma_y^2/d^2 + \sigma_{y'}^2\right)^{1/2}$.

MEASUREMENT OF THE STORAGE RING PARAMETERS

At the BESSY II electron storage ring PTB has installed all the equipment for the measurement of the storage ring parameters needed for the calculation of Φ_E with high accuracy.

Electron energy

The electron energy is measured with two independent and complementary techniques, i.e. by resonant spin depolarization (RSD) and by Compton backscattering of laser photons (CBS).

The RSD technique requires a spin-polarized electron beam which takes about one hour to build up at BESSY II operated at 1700 MeV. The technique is well established [12] and allows the electron beam energy to be measured with a relative uncertainty of better than $5 \cdot 10^{-5}$. Unfortunately, it is not applicable when the storage ring is operated at a reduced electron energy of 900 MeV in special PTB calibration shifts, since at that electron energy, polarization built-up would take more than 30 hours. Therefore, the alternative method of CBS is also applied at BESSY II [13] (Fig. 1), giving a relative uncertainty of better than 10^{-4}. For 1700 MeV operation of BESSY II both methods have been applied simultaneously and an excellent agreement was found [13].

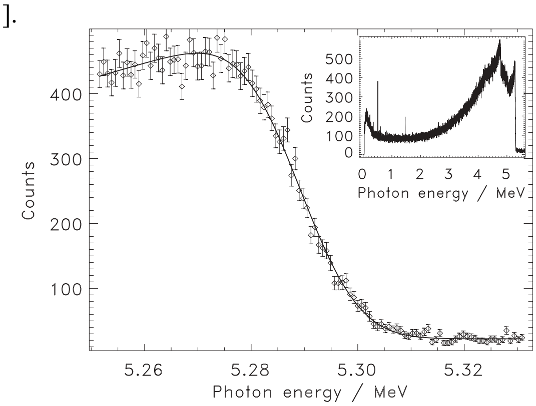


Figure 1: Spectrum of Compton backscattered photons for the measurement of the electron energy: The photons of a CO_2-laser are scattered from the electrons in a forward direction and the resulting γ spectrum is measured with an HPGe-detector (inlay). The main figure shows an enlargement of the high energy cutoff of the spectrum, from which the electron energy can be determined (see [13] for details).

Magnetic induction

A specially designed bending magnet vacuum chamber allows a nuclear magnetic resonance probe to be brought to the source point of the radiation after a beam dump has been performed. The source point lies in a region of the bending magnet with very low field gradients which has been checked by a field mapping of the bending magnet before installation. The relative uncertainty for the determination of the magnetic induction at the radiation source point is better than 10^{-4}.

Electron beam current

BESSY II is operated for special PTB shifts with electron beam currents between 0.2 pA (one stored electron) and normal current of about 250 mA, thus enabling PTB to match the photon flux to the sensitivity of the devices to be calibrated over a dynamic range of more than 12 decades [5]. Currents in the upper range, i.e. above 2 mA, are measured with two DC parametric current transformers. Electron currents in the lower range, i.e. below 40 pA, are determined by counting the number of stored electrons. For this, the electrons are gradually kicked out of the storage ring by a mechanical scrapper that can be moved closely to the beam while measuring the step-like drop of the synchrotron radiation intensity by cooled photodiodes (see Fig. 2). Electron beam currents in the middle range, i.e. from about 10 pA up to 2 mA, are determined by three sets of windowless linear Si photodiodes with different filters that are illuminated by synchrotron radiation. The calibration factors of these photodiodes, which relate the photo current to the electron beam current, are determined by comparison with the electron beam current measured at the upper and lower end of the range as described above.

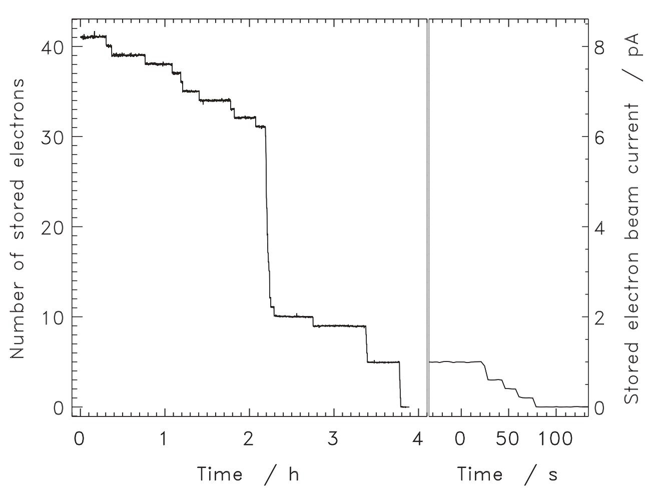
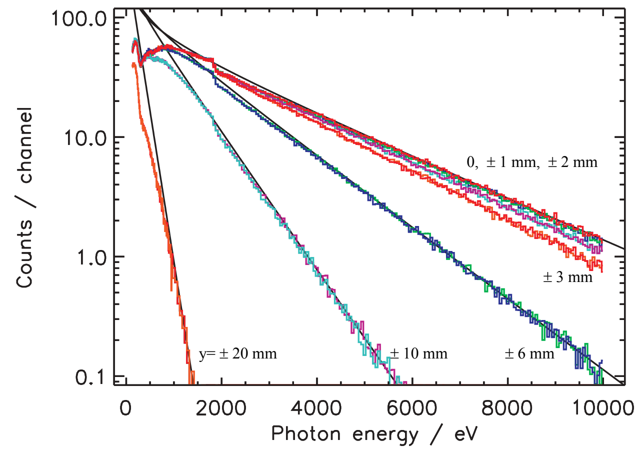


Figure 2: Electron beam current measurement by electron counting.



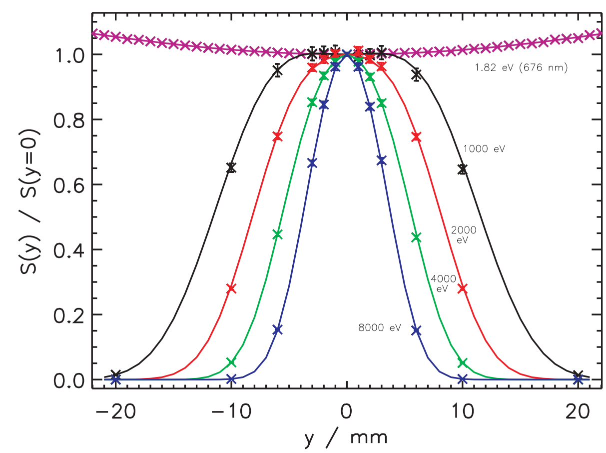


Figure 3: The upper figure shows the spectra measured by means of an energy-dispersive Si(Li) detector with a 1 mm by 1 mm flux-defining aperture for several vertical offsets from the orbit plane at a distance of 30 m from the source point. The change of the electron beam current from 56 electrons to 51 electrons due to the beam lifetime during the measurement is taken into account. By comparison to the corresponding spectra calculated by the Schwinger equation (solid lines) the detector efficiency and other detector parameters could be determined. This is outside of the scope of this paper and presented elsewhere [15]. Nevertheless, in the high energy region of the spectrum where the detector efficiency is about unity and other detector effects have little influence, a very good agreement is shown. The lower picture shows the normalized vertical distribution at some specific photon energies as derived from the upper picture (marks). The error bars are determined by errors in the determination of the detector response function and statistics. Also included in the lower figure is the vertical distribution measured with a filter radiometer at 676 nm (1.82 eV). The solid lines show the corresponding vertical distributions calculated from the Schwinger equation which are in very good agreement. The small effective source divergence of typically 3.5 µrad has no influence on the vertical distribution for the photon energies shown above and is therefore not included.

Effective Vertical Divergence

The effective vertical source divergence of 3.5 µrad is very small at BESSY II compared to the vertical opening angle of the synchrotron radiation at the photon energies of interest and has therefore very little influence on the vertical distribution (fig 3, see figure caption for explanation). Therefore, we normally rely on the value given by the machine operators which has a relative uncertainty of about 20%. The influence of this rather high uncertainty on the uncertainty in the calculation of the spectral photon flux is small, as is shown in fig. 4. At BESSY I, where the effective source size had a non-negligible effect, a Bragg polarimeter-monochromator was developed for the precise measurement of the vertical angular distribution at different energies [14].

Distance from the source point and other geometrical quantities

The distance to the source point is measured by projecting a fivefold slit into the detection plane [5]. The distance between the slit and the detection plane is precisely known from an interferometric measurement. The distance from the projection plane to the radiation source point at the location of the electron beam can then be calculated from the distance of the projected slits at the detector plane. An accuracy of about 2 mm in the determination of the distance to the radiation source point is reached. Typically, a detector to be calibrated is placed about 30 m from the radiation source point, which gives a relative uncertainty of about 7 10^{-5} in the determination of the distance. The vertical emission angle is normally chosen to be zero (measurement in the orbit plane) by adjusting the detector to maximum signal. A typical uncertainty is 2 µrad for a calibration at 30 m distance.

The size a × b of a flux-defining aperture is normally a detector property and not a property of the primary source standard and therefore not included in this discussion.

Calculation uncertainty

Table 1 summarizes the parameters needed for the calculation of the spectral photon flux according to Schwinger. The uncertainty of these parameters leads to a relative uncertainty in the calculation of the spectral photon flux which is shown in figure 4. For low photon energies the measurement uncertainty of the distance d and the electron beam current I are the limiting factors, whereas for high photon energies the storage ring parameters W and B are limiting.

CONCLUSION

BESSY II is established as a European primary source standard from the visible to the X-ray range with relative uncertainties in the realization of the spectral photon flux of 0.03 % (for photons below 3 keV) to 0.2 % (for 50 keV photons). Nevertheless, for many radiometric applications in the lower photon range up to the VUV spectral region, the BESSY II spectrum often has a characteristic energy which is too high. This is one of the reasons why PTB is setting up a dedicated UV/VUV electron storage ring, the so-called Metrology Light Source (MLS), in the close vicinity of BESSY II [16].

Table 1: Summary of the parameters needed for the calculation of the spectral photon flux (example)

parameter	**value**	**rel. uncertainty**
electron energy W	1718.60(6) MeV	$3.5 \cdot 10^{-5}$
magnetic induction B	1.29932(12) T	$1 \cdot 10^{-4}$
electron beam current I (example)	10.000(2) mA	$2 \cdot 10^{-4}$
eff. vert. divergence Σ_y	3.5(7) µrad	0.2
vert. emission angle ψ	0(2) µrad	-
distance d	30 000(2) mm	$6.7 \cdot 10^{-5}$

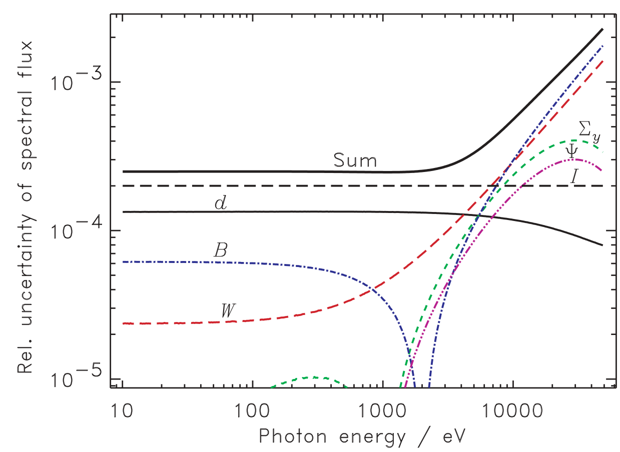


Figure 4: Relative uncertainty in the calculation of the spectral photon flux for the parameters given in table 1, calculated for an aperture of 5 mm × 5 mm size.

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