ACCURATE MEASUREMENT OF THE MLS ELECTRON STORAGE RING PARAMETERS

R. Klein, G. Brandt, T. Reichel, R. Thornagel,
Physikalisch-Technische Bundesanstalt (PTB), Berlin, Germany
J. Feikes, M. Ries, I. Seiler,
Helmholtz-Zentrum Berlin für Materialien und Energie (HZB), Berlin, Germany

Abstract

The Physikalisch-Technische Bundesanstalt (PTB, the German national metrology institute) uses the Metrology Light Source (MLS) as a primary radiation source standard. This requires the accurate measurement of all storage ring parameters needed for the calculation of the spectral radiant intensity of the synchrotron radiation. Therefore, instrumentation has been installed in the MLS for the measurement of, e.g., the electron beam energy, the electron beam current or the electron beam size that outperforms that usually installed in electron storage rings used as a common synchrotron radiation source.

INTRODUCTION

The PTB, the German metrology institute, utilizes the electron storage ring Metrology Light Source (MLS) [1] in Berlin - Adlershof for the realization of the radiometric units in the near infrared, visible, ultraviolet and vacuum ultraviolet spectral range. For this purpose the MLS can be operated as a primary source standard, i.e. the spectral radiant intensity of the synchrotron radiation (SR) is calculated by means of the Schwinger equation [2]. The primary source can then be used for the calibration of other radiation sources or of wavelength- or energy dispersive instruments [3]. The input parameters for the calculation of the spectral radiant intensity are the electron beam energy, electron beam current, the effective vertical size of the electron beam and the magnetic induction at the source point of the SR. For calibration applications, e.g. the spectral radiant power transmitted through a flux-defining aperture also is of interest. For this, also the geometrical parameters of the experiment have to be measured which are the distance to the source point and the vertical observation angle with respect to the orbital plane. These parameters have to be measured accurately since there measurement uncertainty determines the uncertainty of the calculated spectral radiant intensity. PTB operates equipment for the measurement of the storage ring parameters over a wide range. Especially the electron beam energy and electron beam current can be varied over a wide range (see below) to create tailor-made conditions for various calibration tasks. Table 1 summarizes typical storage ring parameters and the related uncertainties in their determination. The influence of the uncertainty of the measured parameter in the calculation of the spectral power depends on the wavelength. For the uncertainties listed in Table 1 the spectral radiant power can be calculated with a relative uncertainty well below 0.1 % for wavelength longer than 10 nm. In this spectral range the MLS is used for UV and VUV radiometry. The relative uncertainty gradually rises to almost 1 % for a wavelength of 1 nm as can be seen in Fig. 1. In this shorter wavelength range it might sometimes be better to use the neighboring BESSY II electron storage ring, that is operated by PTB in special user shifts as a primary source standard, mainly for the X-ray spectral range [4].

Table 1: Typical Operation Parameters of the MLS as a Primary Source Standard and Related Uncertainty in the Measurement of these Parameters.

Parameter	**Typical value**	**Typical (rel.) uncertainty**
electron energy W	628.5 MeV	$2 \cdot 10^{-4}$
magnetic induction B	1.38 T	$1 \cdot 10^{-4}$
electron beam current I (example)	20 mA	$2 \cdot 10^{-4}$
eff. vert. source size Σ_y	1.5 mm	10 %
vert. observation angle ψ	0 µrad	5 µrad
distance d	20 m	5 mm

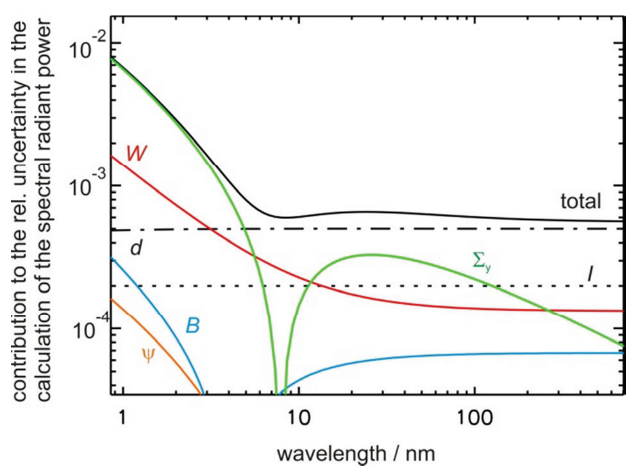

Figure 1: Contribution of the parameters' uncertainties to the calculation of the spectral power. The symbols marking the various lines are explained in Tab. 1, first column; the uncertainty in the parameters is listed in the third column of this table.

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MEASUREMENT OF THE STORAGE RING PARAMETERS

In the following the measurement technique for the storage ring parameters are briefly described, for further details and the description of the measurement of the geometrical parameters please refer to ref. [5].

Electron Beam Energy

The electron energy is used from 105 MeV, the injection energy, up to 630 MeV, the normal operation energy. Performance of the storage ring in terms of beam lifetime and stability is optimized for the range from 150 MeV up to 630 MeV.

Within this large range, the electron energy is measured by the technique of Compton backscattering of laser photons (CBS) [6]. Therefore, a CO_2 laser beam is aligned anti-parallel to the electron beam in the straight section of the undulator and the scattered photons are recorded with an energy-dispersive high purity Germanium detector (HPGe). From the cut-off of the backscattered photon spectrum (see Fig. 2), the electron energy can be calculated. Due to the rather small electron beam energy the technique of resonant spin depolarization (RSD), e.g. also applied by PTB at the BESSY II electron storage ring [7], cannot be applied at the MLS since polarization built-up would take more than 30 hours.

For a validation of the CBS technique and the identification of possible systematic errors, the laser was switched from its normal operation at a CO_2 wavelength (around 10.6 µm) to a CO wavelength (around 5.4 µm). The then measured electron beam energies were 627.78(8) MeV and 627.79(19) MeV, respectively and show a very good agreement (the values in parenthesis show the standard uncertainties). For 150 MeV operation of the MLS the measured energies were 150.38(27) MeV and 149.80(22) MeV, respectively and also agree within the expanded uncertainties.

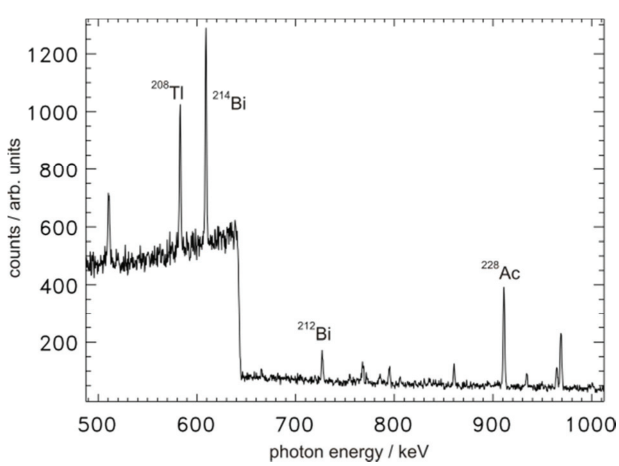

Figure 2: Typical spectrum of back-scattered photons recorded with an HPGe detector, here at 600 MeV electron beam energy. Lines from suitable radio-nuclides used for the energy calibration of the HPGe detector are also shown.

The CBS set-up is also used for general storage ring diagnostics and research. As example Fig. 3 shows the shift of the cut-off of the backscattered photons while the rf frequency is changed by a certain amount. From the related change of the electron beam energy, e.g., the momentum compaction factors can be determined for different operation modes of the MLS [8].

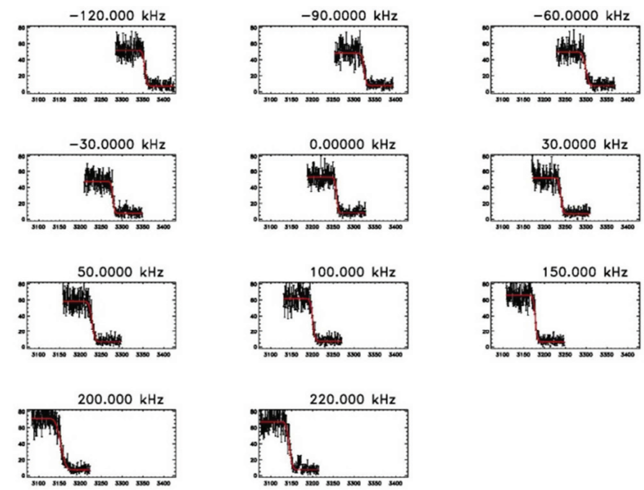

Figure 3: Example for a measurement for general storage ring diagnostics: the radio frequency was shifted and the shift in electron energy was observed by Compton backscattering (x-axis: HPGe detector channel, y-axis: counts).

Magnetic Induction

The synchrotron radiation source point of the beamline using the calculable radiation is located in middle of magnet. 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 dominated by the residual magnetization of the stainless steel tube housing the NMR probe and positioning in accuracy which are estimated to contribute to less than 10^{-4} to the relative uncertainty.

Electron Beam Current

The MLS is operated with electron beam currents between 1 pA (one stored electron) and the maximum allowed beam current of about 200 mA, thus e.g. enabling PTB to match the photon flux to the sensitivity of the devices to be calibrated over a dynamic range of more than 11 decades. Currents in the upper range, i.e. above several mA, are measured with two DC parametric current transformers. Electron currents in the lower range, i.e. below 1 nA, are determined by counting the number

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of stored electrons. For this, the electrons are gradually removed out of the storage ring by a mechanical scraper, which is moved closely to the electron beam, while measuring the step-like drop of the synchrotron radiation intensity by cooled photodiodes. These photodiodes have a 10 mm by 10 mm area and are placed at a distance of about 2.5 m to the source point and are illuminated by the SR. Since they are placed in vacuum, they accept all wavelengths of the synchrotron radiation spectrum.

Electron beam currents in the middle range, i.e. from about 1 nA up to several 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 [9].

The equipment for the electron counting in the lower range was recently improved [9] so that counting even at currents around 1 nA (1000 electrons) is possible at an electron beam energy of 630 MeV. For a special calibration task, i.e. calibration of single photon detectors, the MLS had to be operated at a reduced electron beam energy of 540 MeV in order to reach a wavelength at around 1.5 µm with the existing U125 undulator. But at 540 MeV, one electron only creates about 35 % of the photodiode signal as compared to the 630 MeV operation. Nevertheless, counting of around 500 electrons could be successfully performed as can be seen in Fig. 4.

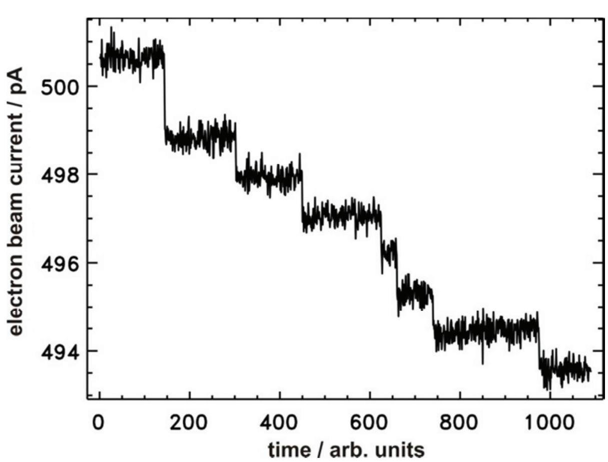

Figure 4: Electron beam current measurement by electron counting for an electron energy of 540 MeV.

Effective Vertical Source Size

Important for most calibration tasks is the so-called effective vertical source size Σ_y, i.e. the influence of the vertical electron beam σ_y size and beam divergence $\sigma_{y'}$ at the distance *d* to the source point at which the calibration is performed:

$$\Sigma_y = \left(\sigma_y^2 + d^2 \sigma_{y'}^2\right)^{1/2}$$

The vertical photon distribution of the synchrotron radiation has to be convoluted with this effective vertical source size. The effective vertical source size can be directly and accurately measured with a Bragg polarimeter [10]. This device measures the vertical distribution of the synchrotron radiation at a photon energy of 1103 eV (Bragg condition for reflection by means of a Beryll crystal) only for the polarization component perpendicular to the orbital plane (by means of the Brewster condition). The measured distribution which shows a distinct drop at the orbital plane is then compared to the theoretical distribution by adjusting the vertical beam size appropriately in order to best fit the measured data.

General Beam Size Diagnostics

For a general diagnostics of the storage ring, e.g. for the investigation of effects influencing the beam size, beam stability diagnostics or the investigation of instability driven by trapped ions, a fast and reliable system for direct observation of the beam size is needed. By knowledge of the optical functions of the storage ring the vertical beam size could be calculated from the measured effective beam size [5], but measurements with the Bragg polarimeter are too complicated for everyday's use. Therefore, two optical imaging systems have been installed at the MLS. One of these is imaging the spot in a ring position with equivalent optical functions as the source point of the beamline using the calculable radiation. This imaging system is furthermore optimized to image the beam if only one electron is stored [11].

For the validation of the beam size measured with this optical imaging system, the beam size was simultaneously measured with a X-ray camera like system. The X-ray camera like system was based on the Bragg polarimeter mentioned above. Additionally, slits with 100 µm in width were introduced into the optical path. E.g. a horizontally orientated slit was used for the measurement of the vertical beam size and a vertically slit for the measurement of the horizontal beam size. The Bragg polarimeter was always operated in such an orientation that the polarization component that is parallel to the orbital plane was observed. The measurements were performed for various operation modes of the MLS, leading to different beam sizes. The result is shown in Fig. 5. The black symbols mark the beam sizes measured for the vertical beam dimension, the red ones that for the horizontal beam dimension. Both values pretty much agree if a resolution limit of approx. 120 µm is assumed for the optical systems. The resolution limit at that time was a bit higher as estimated from diffraction or depth of source effects, but is more than sufficient for typical beam size values at the MLS. The resolution limit has been improved meanwhile to below 80 µm by improved alignment.

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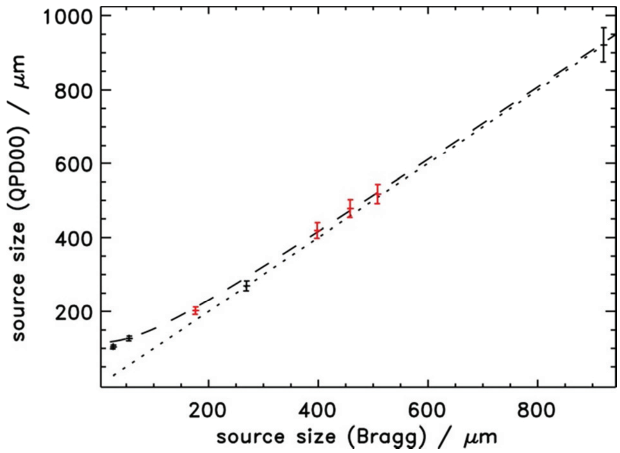

Figure 5: Measured beam sizes in the vertical (black) and horizontal (red) directions for various settings of the MLS. On the x-axis the values measured by the X-ray camera like operation of the Bragg polarimeter, on the y-axis the corresponding values measured with the first optical imaging system are drawn. The dotted line marks the diagonal, i.e. if exactly the same values with both devices would have been measured, the dashed line if a resolution limit of 120 µm for the optical system is assumed.

A similar result for the resolution limit at that time was obtained if the measured values for both systems are observed simultaneously while the beam size is altered by excitation, as is shown, e.g., for the vertical direction in Fig. 6. For larger values the measured beam sizes follow a straight line (dashed red), the slope of which exactly agrees with the square root of the ratio of the ß - functions at the source point positions

$$slope = \sqrt{\beta_y(s_{QPD00}) / \beta_y(s_{QPD01})}$$

imaged by the two devices (measurement: 0.923(1), theory: 0.92). For vertical beam sizes approaching the resolution limit, a deviation from this behaviour is observed. This also indicated to a similar resolution limit at that time.

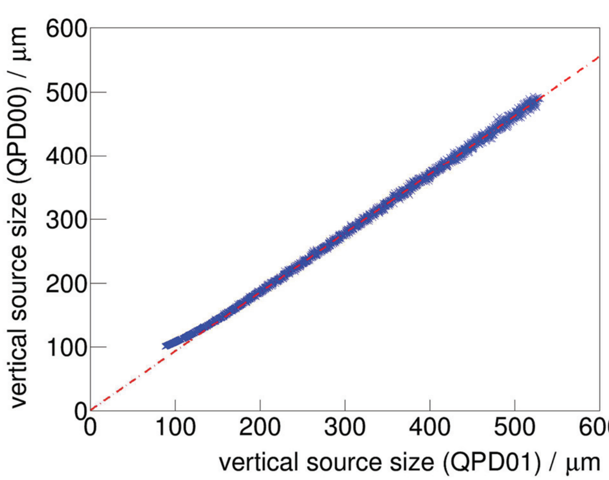

Figure 6: Measured vertical beam size by the two optical imaging systems.

SUMMARY

The PTB is operating the MLS as a primary source standard in the spectral range from the near infrared to the vacuum ultraviolet spectral region. This is possible because all parameters needed to calculate the spectral radiant intensity based on the Schwinger equation are measured with low uncertainty, yielding a relative uncertainty in the spectral radiant power below 0.1% in the spectral region the MLS is optimized for.

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