RADIOMETRY AT THE ELECTRON STORAGE RINGS BESSY I AND BESSY II

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Abstract

The Physikalisch-Technische Bundesanstalt (PTB), Germany's national metrology institute, has been operating a radiometry laboratory at the BESSY I 800 MeV electron storage ring since 1982. BESSY I is used as a primary source standard of calculable spectral photon flux with relative uncertainties below 0.4 % in a broad spectral range from 1 eV to 15 keV. A cryogenic electrical-substitution radiometer is operated as a primary detector standard with a relative uncertainty of less than 0.2 % in the measurement of radiant power. Based on these primary standards, radiation sources, detectors, and optical components are characterized and calibrated at various experimental stations. Currently, PTB is commissioning new experimental stations in its radiometry laboratory at the third generation BESSY II 1.7 GeV electron storage ring to extend the spectral range to the hard X-ray range by using radiation from bending magnets and a superconducting wavelength shifter, and to improve radiometry by using undulator radiation. The current status of radiometry at BESSY I will be reviewed and the new radiometry programs outlined which have been planned for BESSY II.

1. Introduction

Techniques for quantitative measurements of electromagnetic radiation are well established in the visible. The basis of this "optical radiometry" are blackbody radiators acting as primary source standards and laser-operated cryogenic electrical-substitution radiometers used as primary detector standards. In order to extend radiometry into ranges of higher photon energies, continuously from the visible to the hard X-ray region up to photon energies of about 100 keV, electron storage rings are used. They serve as broadband primary source standards for the development of source-based radiometry and as sources of tunable monochromatic photon fluxes for the development of detector-based radiometry in combination with primary detector standards.

Only a few storage rings are used today for radiometry in the vacuum ultraviolet (VUV) and soft X-ray range, mainly at national metrology institutes. A review has been given by Ulm and Wende [1]. We will restrict this short contribution to radiometry performed at the BESSY I 800 MeV electron storage ring and planned for the BESSY II 1.7 GeV storage ring. The primary radiometric standards will be described in some detail, the calibration and reflectometry facilities and examples of recent work will be presented.

2. Radiometry based on electron storage rings as primary source standards

Electron storage rings optimized for radiometry are primary source standards, i.e. their spectral photon flux Φ_E from bending magnets though an aperture can be calculated from storage ring parameters and geometrical quantities.

For a given photon energy E, Φ_E depends on (i) electron beam parameters: the electron energy W, the stored electron current I, the effective vertical beam divergence Σ_y in the observation plane, which results from the vertical extension and divergence of the electron beam, and is taken into account via a convolution of the fundamental Schwinger calculation of synchrotron radiation (SR); (ii) the magnetic induction B at the source point of the radiation; and (iii) geometrical quantities: distance d from the source point, for circular aperture stops the radius r, and the emission angle Ψ with respect to the electron orbit plane:

$$\Phi_E = \Phi_E(E, W, B, I, \Sigma_y, d, r, \Psi).$$

For BESSY I, the measurement of the parameters and their values and uncertainties are presented in various publications [1,2 and references therein]. The total relative uncertainty of the spectral photon flux $\Delta\Phi_E/\Phi_E$, which is increasing with increasing photon energy from about 0.1 % at 1 eV up to 0.4 % at 15 keV, is made up of the uncertainties of the seven parameters involved in the calculation of Φ_E.

Special operation of BESSY I (800 MeV nominal energy) for radiometric purposes at 340 MeV or 850 MeV optimizes the spectrum for the requirements of certain calibrations. Furthermore, the spectral photon flux can be adjusted to the experimental requirements by controlled variation of the stored beam current within a dynamic range of twelve orders of magnitude.

The accurately calculable spectral photon flux of BESSY I (in the future: of BESSY II) is mainly used for two different calibration tasks:

(i) Calibration of energy-dispersive detectors such as Si(Li), high-purity Ge, CCD detectors, or proportional counters [3, 4].

(ii) Calibration of radiation sources by comparing their unknown spectral photon flux with the calculable SR flux. Experimental stations consisting of an imaging mirror, a monochromator, and a detector system are used for this purpose. Recent examples of this kind of work are the calibration of transfer source standards for the calibration of telescopes of the Solar and Heliospheric Observatory (SOHO) [5].

3. Radiometry based on cryogenic electrical-substitution radiometers as primary detector standards

Photon detectors which are not energy-dispersive or have only moderate resolving power, such as photodiodes, cannot be calibrated using the calculable SR continuum. In that case, calibration is performed by comparing the detector response to monochromatized radiation with the response of a primary detector standard at the same radiant flux, exploiting the storage ring as a bright radiation source. PTB has pioneered to adapt cryogenic electrical-substitution radiometers (ESRs), which are well established in the visible as primary detector standards and operated with lasers as sources, to the lower radiant power available behind monochromators at storage rings [6]. We have first demonstrated at BESSY I the extension of an ESR for use in the UV, VUV, and in the soft X-ray spectral ranges. ESRs substitute the radiant power to be measured by the equivalent electrical power, see Fig. 1. The same absorber temperature T_{abs} is obtained either by heating due to the incident radiant power Φ, or without incident radiation, by electrical heating with power P_{el} which can be measured with high accuracy. An absolute measurement of the typically available radiant power of monochromatized SR of about 1 µW to 10 µW is feasible with the PTB's ESR with a relative uncertainty of less than 0.2 %.

For example. Recently, the following detectors were calibrated at BESSY I based on the ESR: semiconductor photodiodes in the UV and VUV [7], and in the soft X-ray region [8], CCD-detectors [9, 10], and superconducting tunnel junctions [11]. Other examples are presented in ref. [12].

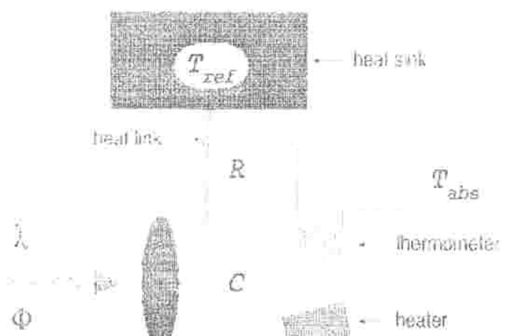

Fig. 1. Schematic drawing of a cryogenic electrical-substitution radiometer used as primary detector standard. T_{ref}, heat-sink reference temperature; R, thermal resistance, T_{abs}, absorber temperature; C, absorber heat capacity, P_{el}, electrical heater power.

4. Reflectometry

The increasing activity in the VUV and X-ray region has led to a corresponding need for facilities for the characterization of optical components such as (multilayer) mirrors, gratings and filters. In response to this, PTB operates two reflectometer facilities which can be installed at the different beamlines depending on the desired spectral range [13]. Due to the low stray light and higher-order harmonic contributions available behind the PTB monochromator beamlines, high-accuracy measurements can be performed. Recent examples cover the characterization of transmission filters for astronomy [14] and the measurement of the diffraction efficiencies of transmission gratings [15].

5. PTB's Radiometry Laboratories at BESSY I and BESSY II

Radiometric applications of SR require experimental stations and beamlines which differ in some respects from the instrumentation commonly available in the basic research areas of SR facilities. Whereas the resolving power of the monochromators may be quite moderate (about 1000 is sufficient in most cases), special emphasis has to be placed on the spectral purity of the monochromatized radiation. Relative contributions of stray light and higher orders to the radiant power must not be higher than 1 %. Furthermore, the reproducibility of the photon flux for a given photon energy must be very good, even after the monochromators have scanned over broad spectral ranges.

At the PTB's BESSY I radiometry laboratory [2] six experimental stations on four bending magnet beamlines optimized for radiometry are in operation. Five of them provide monochromatized SR which covers the photon energy range from 3 eV to 1.8 keV for source calibration and the range from 3 eV to about 1.5 keV for detector calibration. One beamline is intended for use of the direct undispersed calculable SR.

PTB is currently commissioning new experimental stations at its radiometry laboratory at BESSY II [16]. When user operation of BESSY II is started in January 1999, we will have four beamlines ready for radiometric use: Two bending magnet beamlines, one for the use of calculable undispersed SR in an extended spectral range up to about 50 keV, and one equipped with a four-crystal monochromator providing radiation in the range from 1.75 keV to 10 keV. Undulator radiation will be provided behind a plane grating monochromator in the range from 20 eV to about 1.9 keV. The direct undulator radiation beam can be used in addition. Our first source is an undulator built as an electromagnet with a period length of 180 mm and a total of 21 full-field periods [17]. A a second short-period undulator is considered to be installed alternately in the PTB's straight section of BESSY II.

6. Outlook

At present, radiometry is developed by PTB at BESSY I in a broadly extended spectral range from about 1 eV to 15 keV by use of the calculable undispersed SR, and in the range from 3 eV to about 1.8 keV, where monochromatized SR is provided. The higher electron energy of BESSY II will extend the usable range to higher photon energies: about 50 keV when using undispersed SR, and 10 keV in the case of monochromatized SR. Furthermore, the use of undulator radiation will allow radiometric techniques to be improved owing to its superior spectral purity, and it will make new experiments possible where high photon flux is required.

The use of the radiation of a 7 T superconducting wavelength shifter located outside the PTB BESSY II laboratory will soon extend the photon energy range further into the hard X-ray region. Investigations carried out at the wavelength shifter installed at BESSY I proved that this will be possible [18]. Moreover, Compton-backscattered laser photons, currently used for the measurement of the electron energy at BESSY I [19], are considered for use in radiometry in the MeV region.

7. References

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