BESSY II OPERATED AS A PRIMARY SOURCE STANDARD

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Outline

• Introduction to PTB

• BESSY II as a source of calculable synchrotron radiation
  - calibration principle
  - measurement of the storage ring parameters
  - application examples

• Outlook
PTB: German national metrology institute, located in Braunschweig and Berlin

responsible for the realization and dissemination of the legal units in Germany

department „Photon Radiometry“ located at BESSY II in Berlin-Adlershof

tasks: - Realization and dissemination of radiometric units in the UV, VUV, X-ray spectral range by using

  • BESSY II as primary source standard („source-based radiometry“)
  • a primary detector standard („detector-based radiometry“)

- Characterization of optical components, in particular for EUV lithography
- Other applications of quantitative radiation measurements
### PTB Radiometry Laboratory at BESSY II

**1. Plane Grating Monochromator**
- 30 eV to 1800 eV

**2. Four Crystal Monochromator**
- 1.75 keV to 10 keV

**3a. Undispersed Bending Magnet Radiation**

**3b. Normal Incidence Monochromator**
- 3 eV to 35 eV

**3c. Deflected Undispersed Bending Magnet Radiation, EUV Irradiation Test Station**

**4a. Undispersed Undulator Radiation**
- Compton backscattering

**4b. Plane Grating Monochromator at Undulator**
- 20 eV to 1900 eV

**4c. Deflected Undispersed Undulator Radiation**
- EUVL metrology test station

**5. Normal Incidence Monochromator**
- 3 eV to 35 eV
**Source-based radiometry**

**Basis:** Primary source standard electron storage ring BESSY II

- **Task 1:** Calibration of sources
  - Calibration by comparison with a storage ring

- **Task 2:** Calibration of - energy-dispersive detectors (e.g. Si(Li), HPGe, CCD) - monochromator-detector systems

**Important property:** BESSY II has a dynamic range of 12 orders of magnitude in photon flux!

**Requirement for calibration:** Special operation parameters of the storage ring
Planck's Radiation Law:
Temperature, Emissivity
Geometry

Storage ring BESSY II as primary source standard
Storage ring BESSY II as primary source standard

Schwinger Equation:
Storage Ring Parameters
Geometry

Photon Radiometry

Extracted Text:

Schwinger Equation:
Storage Ring Parameters
Geometry
### Storage rings used for radiometry

<table>
<thead>
<tr>
<th>Ring name (Inst.)</th>
<th>Location</th>
<th>Beam energy / GeV</th>
<th>$E_c$ / keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SURF III (NIST)</td>
<td>Gaithersburg, USA</td>
<td>0.4</td>
<td>0.17</td>
</tr>
<tr>
<td>TERAS (NMIJ)</td>
<td>Tsukuba, Japan</td>
<td>0.8</td>
<td>0.57</td>
</tr>
<tr>
<td>VEPP-2M (INP)</td>
<td>Novosibirsk, Russia</td>
<td>0.7</td>
<td>0.62</td>
</tr>
<tr>
<td>BESSY II (PTB)</td>
<td>Berlin, Germany</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td>VEPP-3 (INP)</td>
<td>Novosibirsk, Russia</td>
<td>2.0</td>
<td>4.8</td>
</tr>
</tbody>
</table>
Radiant power of synchrotron radiation is determined by (Schwinger 1949):

(a) storage ring parameters
(b) geometry parameters

Photon flux \( \Phi = \Phi (W, B, I, \sum_y, \psi, d, r) \)

- **Electron beam and storage ring parameters**
  - \( W \): electron energy
  - \( B \): magnetic induction
  - \( I \): electron beam current
  - \( \sum_y \): vertical size and divergence of the electron beam

- **Geometrical quantities**
  - \( d \): distance
  - \( r \): radius of aperture
  - \( \psi \): emission angle
BESSY II as a Primary Source Standard

calculation of the radiant power of synchrotron radiation with a relative uncertainty of < 0.1 %

requires precise determination of the storage ring parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>rel. uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron energy W</td>
<td>1718.60(6) MeV</td>
<td>3.5 \cdot 10^{-5}</td>
</tr>
<tr>
<td>magnetic induction B</td>
<td>1.29932(12) T</td>
<td>1 \cdot 10^{-4}</td>
</tr>
<tr>
<td>electron beam current I (example)</td>
<td>10.000(2) mA</td>
<td>2 \cdot 10^{-4}</td>
</tr>
<tr>
<td>eff. vert. divergence $\Sigma_y$</td>
<td>3.5(7) $\mu$rad</td>
<td>0.2</td>
</tr>
<tr>
<td>vert. emission angle $\psi$</td>
<td>0(2) $\mu$rad</td>
<td>-</td>
</tr>
<tr>
<td>distance d</td>
<td>30 000(2) mm</td>
<td>6.7 \cdot 10^{-5}</td>
</tr>
</tbody>
</table>

Relative uncertainty of the spectral photon flux of BESSY II
Validation of the calculation of spectral power of BESSY:

- Comparison to black body in the IR/visible
- Comparison to radionuclides in the X-ray region
- Comparison of BESSY I and BESSY II
- Total power measured with a primary detector standard
## Measurement of the storage ring parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron energy</td>
<td>resonant spin depolarization and Compton Backscattering</td>
</tr>
<tr>
<td>beam current</td>
<td>two DC PCT, calibrated photodiodes</td>
</tr>
<tr>
<td>magnetic induction</td>
<td>NMR probe movable to source point (modified vacuum chamber)</td>
</tr>
<tr>
<td>source size</td>
<td>negligible influence at BESSY II</td>
</tr>
<tr>
<td>emission angle</td>
<td>during calibration by vertical adjustment</td>
</tr>
<tr>
<td>distance</td>
<td>projection of 5-fold slit to plane at known distance</td>
</tr>
</tbody>
</table>
BESSY II: electron energy measurement

Methods/Equipment

• Resonant spin depolarization for 1.7 GeV: strip-line for depolarization, rf-amplifier loss-detectors
  (see P. Kuske et al. Proc EPAC 2000, 1771)

• Compton Backscattering of laser photons for 900 MeV and 1.7 GeV: CO₂-laser
  HPGe-detector
BESSY II: electron energy measurement

\[ E_{\text{max}} \sim 4 \gamma^2 E_{\text{laser}} \]
BESSY II: electron energy measurement

Compton Backscattering

resonant spin depolarization

Electron beam energy / MeV

No. of measurement

1 2 3 4 5
**Methods/Equipment**

- **currents above 2 mA:**
  two DC Parametric current transformers

- **currents below 2 mA:**
  three sets of N₂-cooled photodiodes with different filters, illuminated by synchrotron radiation

- **currents below 200 pA:**
  single electron counting
BESSY II is a radiation source with a dynamical range of $10^{12}$ in the photon flux.
BESSY II: electron beam current measurement

BESSY II is a radiation source with a dynamical range of $10^{12}$ in the photon flux.
BESSY II: measuring the distance to the source point
BESSY II: effective vertical divergence

Si(Li) detector spectra for different vertical offsets from the orbit plane

Vertical distribution for different photon energies

\[ \Sigma_y = \left( \sigma_y^2 + \sigma_y^2/d^2 \right)^{1/2} \]

= 3.5 (7) \( \mu \text{rad} \) @ d= 30 m

\[ \sigma_r \text{ (8000 eV)} = 100 \, \mu \text{rad} \]
Calibration of energy-dispersive detectors

- Si(Li)-detectors
- HPGe-detectors
- CCD-detectors
- Flow proportional counters

E.g., for astronomy observatories:
- CHANDRA (NASA)
- XMM-Newton (ESA)
Calibration of radiation sources in the UV and VUV

Calibration of deuterium lamps

‘(V)UV Radiometric Scales’
NPL (UK): EUROMET 88/36
BNM (F): EUROMET 539
NIM (VR China)
NIST (USA)
PTB

Calibration of hollow cathode source

‘Solar Observations’
MPAE (D), RAL (UK)
SOHO (ESA), SERTS (NASA)
Solar B (ISAS), EUNIS & SDO (NASA),
SOL-ACES & Solar Orbiter (ESA)
Storage ring BESSY II as primary source standard

Photon Radiometry

wavelength / nm

band width
$\Delta E/E = 10^3$

black body
3000 K

radiant power / W

10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2}

photon energy $E$ / eV

10 100 1000 10000 100000

far IR and IR  VIS  UV  VUV / soft X-rays  X-rays

BESSY II

600 MeV

PTB special
900 MeV

1700 MeV

200 MeV

MLS
PTB in Berlin-Adlershof: Metrology with synchrotron radiation

- 200 MeV to 600 MeV electron energy
- Start of construction: summer 2004
- First beam stored: 2007
- Start of user operation: 2008
• At BESSY II, PTB is operating a radiometry laboratory using synchrotron radiation from the UV to the X-ray range

• Radiometric units are realized and disseminated with high accuracy

• This is e.g. done by utilization of BESSY II as a Primary Source Standard; precise determination of storage ring parameters

• Future: PTB is constructing a 600 MeV electron storage ring, the **Metrology Light Source**, optimized for UV and EUV radiometry