THE METROLOGY LIGHT SOURCE – AN ELECTRON STORAGE RING DEDICATED TO METROLOGY

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Abstract

PTB, the German National Metrology Institute, in close cooperation with BESSY, is currently setting up a low-energy electron storage ring (200 MeV up to 600 MeV electron energy), the Metrology Light Source MLS, which will be dedicated to metrology and technology development in the UV and EUV spectral range with synchrotron radiation and is ideally suited for the production of IR and FIR/THZ radiation.

The MLS has been designed by BESSY according to PTB specifications and is being built adjacent to the BESSY II facility. Construction started in 2004 and user operation is scheduled to begin in 2008. The storage ring, building is nearly completed by now (June 2006), and all major parts of the storage ring and the injection system have been ordered or have already been delivered.

The MLS will be equipped with all the instrumentation necessary to measure the storage ring parameters needed for the calculation of the spectral photon flux according to the Schwinger theory with low uncertainty, enabling PTB to operate the MLS as a primary source standard. Moreover, calculations show, that the MLS is ideally suited for the production of coherent synchrotron radiation in the far IR and THz region.

INTRODUCTION

For more than 20 years PTB has been using synchrotron radiation from the electron storage rings BESSY I and BESSY II for metrology [1]. At present PTB is operating 10 experimental stations at four bending magnet beamlines and one insertion device beamline in its BESSY II laboratory [2]. Since the shut down of BESSY I a dedicated source and instrumentation for covering the spectral region of the UV and VUV is missing, a lack that will be compensated by the set-up of the MLS [3]. Fig. 1 shows the spectral range covered by the MLS. In comparison to the BESSY II emission spectrum, the lower photon energies are best covered by the MLS radiation. At the MLS also 10 experimental stations are planned, covering the region from the FIR up to the VUV. Fig. 2 gives a rough overview of the MLS experimental stations, a detailed description can be found elsewhere [4]. The status of the storage ring construction can be found in [5]. In this paper we focus on two topics that show the potential of the MLS besides being a normal synchrotron radiation source for the common user community: The first is the operation of the MLS as a primary source standard, that requires the MLS to be operated in a highly stable mode with all storage ring parameters determined to high accuracy and often with reduced electron beam currents down to a few stored electrons. The second topic illustrates the potential of the MLS operated in a super radiant mode for the production of coherent synchrotron radiation or short VUV/soft X-ray pulses. These operation modes are in principle also possible at other storage rings as e.g. BESSY II but at the MLS more beam time can be attributed to these special modes as can be at large user facilities.

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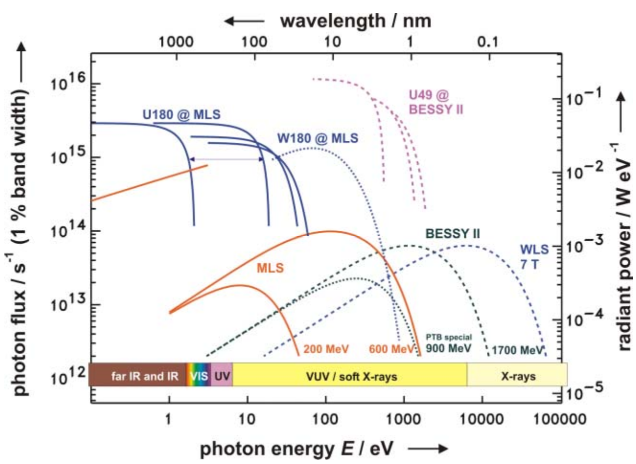
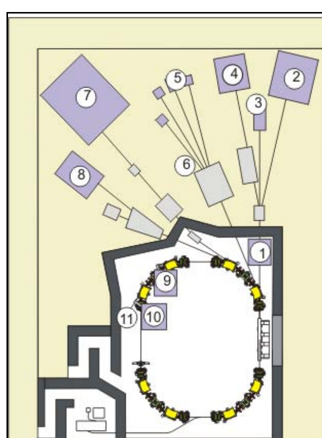


Figure 1: Spectrum of the MLS as compared to BESSY II. With the electron storage rings MLS and BESSY II (including a 7 T WLS), PTB can use synchrotron radiation in the spectral range from the FIR up to the hard X-rays for photon metrology.



	Beamline / Application
1	IR undulator radiation, 2 µm to 20 µm / Compton-backscattering laser
2	deflected undulator radiation
3	direct undulator radiation / Compton-backscattering detector
4	UV/VUV monochromator for undulator radiation, 4 nm to 400 nm
5	direct bending magnet radiation (use of calculable photon flux)
6	UV/VUV monochromator 4 nm to 400 nm (source calibration)
7	EUV plane grating monochromator
8	UV/VUV monochromator
9	FIR/THz beamline, 2 µm to 8 mm
10	IR beamline, 2 µm to 8 mm
11	diagnostics frontend

Figure 2: Planned beamlines and experimental stations at the MLS.

THE MLS AS A PRIMARY SOURCE STANDARD

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 at several national metrology institutes, such as the National Institute of Standards and Technology (at the SURF III electron storage ring, Gaithersburg, USA [6]), the National Metrology Institute of Japan (at the TERAS electron storage ring, Tsukuba, Japan [7]), the Budker Institute of Nuclear Physics (at the VEPP-3 electron storage rings, Novosibirsk, Russia [8]) or PTB (at the BESSY II electron storage ring [9]).

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 [10] $\Phi_E = \Phi_E(E; W, B, I, \Sigma_y; \Psi, d, a, b)$.

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 $\times$ b. The effective vertical divergence is derived from the vertical electron beam size σ_y and beam divergence $\sigma_{y'}$ according to $\Sigma_y = \left(\sigma_y^2/d^2 + \sigma_{y'}^2\right)^{1/2}$.

The calculated, white synchrotron radiation will be used at station 5 (Fig. 2), e.g. for the calibration of energy dispersive detectors [11], spectrometers or filter radiometers. The monochromator-detector system of station #6 can be calibrated in this way and thereafter used for the calibration of radiation sources [12].

At the MLS electron storage ring PTB will install all the equipment for the measurement of the storage ring parameters needed for the calculation of Φ_E with high accuracy. The parameters, e.g. the electron beam current and electron energy can be varied in a wide range and therefore tailor-made conditions for special calibration tasks can be chosen.

The electron energy will be measured by the method of Compton back-scattering of laser photons [13]. For this the beamline for IR undulator radiation (#1 in Fig. 2) will be used in a parasitic mode: A CO_2-laser will be fed in from the end station of this beamline and will be super imposed anti-parallel to the electron beam using the optical components of the beamline. The backscattered photons being in the range from 70 keV to 650 keV, for 200 MeV and 600 MeV operation of the MLS respectively, will be detected with a HPGe detector at station #3. The anticipated relative uncertainty in the determination of the electron energy is $1\cdot10^{-4}$.

The electron beam current, which can be altered from 1 pA (one electron stored) up to 200 mA, will be measured by two commercial DC parametric current transformers for the range above 1 mA, single electron counting for the range below 1 nA, and with filtered photodiodes for the range in-between. The photodiodes will be installed at station 11 (Fig. 2). This approved method is also used at the BESSY II electron storage ring and is described in more detail in [14].

The bending magnet vacuum chamber is designed in such a way that, after a beam dump, a nuclear magnetic resonance probe can be brought to the location of the radiation source point for an accurate determination of the magnetic induction at this point. Therefore, provision has to be taken that the magnetic field map of the bending magnet in the area of the radiation source point is sufficiently flat so as the NMR probe will be functioning and small displacements of the probe position from the actual source point will be tolerable. The port for beamline 5 (Fig. 2) is chosen in such a way, that the radiation source point is located in the center of the bending magnet. The measured relative change of the mag. induction around that point is shown in Fig. 3. This will allow the determination of the magnetic induction at the radiation source point with a relative uncertainty of better than $1\cdot10^{-4}$. A detailed status of the magnet fabrication can be found in [15].

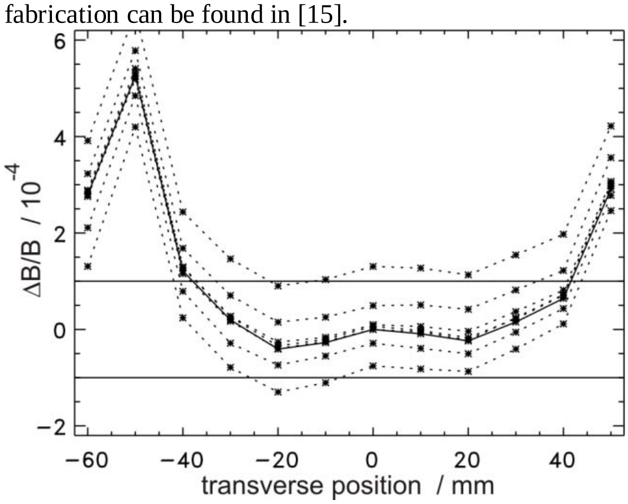


Figure 3: Measured homogeneity of the magnetic field in the central region of the MLS bending magnets according to ref. [16]. The solid line is at the longitudinal center of the magnet, the dotted lines have an offset of 5 mm, 10 mm and 15 mm upstream and downstream, respectively.

The combined vertical source size and the geometrical quantities defining the solid angle will be determined as described in [9]. The anticipated measurement uncertainty in these parameters are summarized in Tab. 1 and will then allow the calculation of the spectral photon flux for photon up to 1 keV with a relative uncertainty below 0.2 % as can be seen in Fig. 4.

THE MLS AS A SOURCE OF COHERENT SYNCHROTRON RADIATION

The optics of the MLS ring is designed for bunch length manipulation ('Low Alpha Optics'). Based on the experiences at BESSY II, 3 ps bunches of rms length are very well suited to generate intense and stable, coherent THz radiation. Following the bursting theory [17],

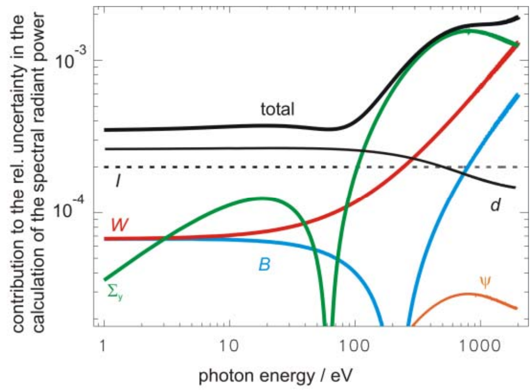


Figure 4: Relative uncertainty in the calculation of the spectral photon flux of the MLS. The uncertainty of the input parameters is according to Tab. 1.

Table 1: Parameters that enter the Schwinger equation with typical values and uncertainty.

		$\Delta\Phi_E(E)/\Phi_E(E)$ (*10^{-3}) at E=		
parameter / typical value		**1 eV**	**100 eV**	**1000 eV**
electron beam current 200.00(4) mA	*I*	0.20	0.20	0.20
electron energy 600.00(6) MeV	**W**	0.07	0.12	0.67
mag. induction 1.30000(13) T	*B*	0.07	0.04	0.27
eff. vertical divergence 44(9) µrad	Σ_y	0.04	0.18	1.52
distance to source point 15000(2) mm	*d*	0.27	0.26	0.17
angle to orbit plane 0.000(5) mrad	ψ	0.0007	0.003	0.03
total		**0.35**	**0.40**	**1.71**

the threshold current per 3 ps bunch can be estimated to 90 µA. Below the threshold the THz emission process is stable, above this threshold there is more THz power but with less spectral and temporal emission stability. We expect an emitted, stable THz power of 12 % compared to BESSY II coherent intensity. The spectral range will be comparable to the BESSY II results, from few wave numbers to 20 wave numbers (see ref. [3], Fig. 3).

At bunches much shorter than 1 mm, the coupling between the longitudinal and horizontal plane could limit the bunch length [18]. To simulate this effect, the MLS ring was tuned to bunches of 0.1 mm length. Tracking results of 800000 turns (10 damping times) were performed at the entrance and exit of the first dipole following the long straight section, Fig. 5. Only at this entrance beam port the full compression of bunch length was achieved. At the exit port the coupling limits the bunches to 0.5 mm. The difference results from the local coupling strength depending on the chromatic H-function. An exit port for the THz beam line was chosen, which preserves the option of ultra short electron bunches.

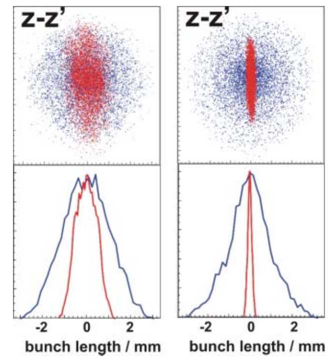


Figure 5: Plot of longitudinal beam phase space (z,z') at two different dipole beam ports of two bunches of different length (red, blue). The lower part shows, that the projected rms bunch length of 1 mm is achieved at both places (blue), 10 times shorter bunches (red) only at beam port #9 (see Fig. 2).

SUMMARY

The MLS, currently being constructed next to BESSY II, will start operation in 2008. PTB will use its synchrotron radiation from the FIR/THz – being produced in a super radiant mode - up to the EUV and VUV spectral range and will therefore complement its measurement potential already existing for the higher photon energy range at the BESSY II electron storage ring. The parameters of the MLS, especially the electron beam current and the electron energy, can be varied in a wide range in order to create measurement conditions that are tailor-made for specific calibration tasks. All storage ring parameters can be precisely measured, which enables PTB to operate the storage ring as a primary radiation source standard of calculable spectral photon flux with low uncertainty.

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