First results in the IR and THz spectral range at the Metrology Light Source

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1 Introduction

Electron storage rings are nearly ideal radiation sources for metrology over a broad spectral range from the IR/THz to the X-ray region. Over the past two decades, the use of synchrotron radiation (SR) in the fields of physics, chemistry, biology, medicine and elsewhere has expanded rapidly. The number of synchrotron radiation sources currently worldwide in operation is about 60, and about 10 new facilities are under construction or being planned. Some national metrology institutes make extensive use of synchrotron radiation for metrology, especially radiometry [1]. The PTB, the German national metrology institute, has been using synchrotron radiation for photon metrology at the electron storage rings BESSY I and BESSY II for about 25 years. At present PTB operates a laboratory at BESSY II with main emphasis on the EUV and X-ray region [2]. In April 2008, the PTB's new electron storage ring, the Metrology Light Source (MLS), went into user operation [3-6].
In recent years, the strength of electron storage rings as unique sources of IR radiation has also become apparent and is increasingly being exploited around the world [7]. In particular, IR radiation in the mid infrared wavelength region is used in research by means of Fourier transform spectroscopy on biological tissues down to single cells, high-pressure and micro-sample measurements and in investigations on surfaces and thin films applying IR ellipsometry with a high lateral resolution [7, 8]. A rapidly growing number of IR beamlines at several storage rings has been realized or is planned taking advantage of this unique IR light sources. Synchrotron radiation sources have major advantages in the IR range compared to conventional thermal sources: (1) a broader spectral range (continuous from the far-IR to the visible), (2) higher photon flux in the far-IR, (3) higher brilliance (as it is almost a point source the light can be focused down to the diffraction limited size), (4) pulsed radiation in the ps range (the light is emitted from electron bunches which allows fast time-resolved measurements), (5) polarized radiation, and at a few storage rings [9, 10] (6) intense coherent synchrotron radiation (CSR) in the lower energy part of the far-IR (sub-THz to THz) with gain up to 6 to 9 orders of magnitude compared to conventional synchrotron radiation emission.

2 MLS – parameter and beamlines

The new dedicated low-energy storage ring MLS which is located in the close vicinity of BESSY II in Berlin-Adlershof will serve PTB as a radiation source for the THz, IR, visible to the soft X-ray range with special flexibility in its operation parameters [3-6]. The electron energy of the MLS can be tuned to any value from 105 MeV up to 630 MeV and the electron beam current can be adjusted in the range from one stored electron (1 pA) up to 200 mA [3-6]. The MLS can be operated with parameters optimized for special calibration tasks, which, at a multi-user facility such as BESSY II, is only rarely possible. Additionally, the MLS is the first electron storage worldwide designed and prepared for low-α operation mode based on the octupole correction scheme, for the production of CSR in the far-IR and THz region. This option strengthens the MLS as a strong THz radiation source [3-6]. CSR from storage rings could bridge the gap between the microwaves and the black body radiation since it offers powerful broadband radiation in the frequency range below 1.5 THz and allows imaging at the diffraction limit, ellipsometry and time-resolved spectroscopy including pump-probe experiments [11, 12].

At the MLS, the instrumentation will cover the spectral range from the far-IR (with maximum wavelength of 8 mm) up to the EUV region (with minimum wavelength of 4 nm) [3-6]. The radiation from four bending magnets—each of which can be equipped with a maximum of two front-end systems—and from one undulator will be used. Eight stations will be set up on the experimental floor for the coverage of the UV

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up to the EUV spectral range, and on the top of the storage ring bunker, a FIR/THz and two IR stations are under commissioning [13]. Another four bending magnets and an undulator straight-section are available for a future upgrade.

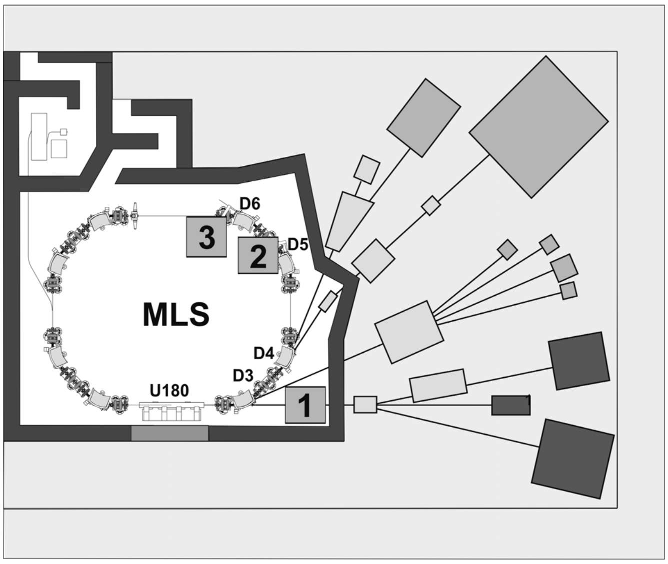


Figure 1: Layout of the MLS with the IR/THz beamlines: (1) Undulator IR, (2) THz beamline, (3) IR beamline.

3 IR and THz radiation at the MLS

The aim is to develop IR experimental stations at the MLS for the near, mid and far IR wavelength region and to make it accessible to the PTB and to an interested scientific community for a broad field of applications. The experimental stations should be equipped with an optimal instrumentation for micro spectroscopy measurements: a Fourier transform spectrometer and an IR microscope as well for life and material science investigations.
There are two major applications for CSR at storage rings. First of all the broadband emission spectrum combined with the high brilliance and with high stable average output power makes CSR an ideal source for Fourier transform micro-spectroscopy [7, 8, 11, 12]. Experiments in THz imaging with near field microscopy as well as superconductor and semiconductor spectroscopy have been demonstrated [8, 11]. The second application is beam diagnostics at the electron storage ring. This is based on the fact that the CSR spectrum depends on the shape of the electron bunches from which the THz radiation is emitted. Basically the bunch shape in the time domain can be retrieved from the CSR spectrum by means of Fourier transformation [14]. So the THz diagnostic will help us to further improve the performance of the MLS.

At the MLS two bending magnet beamlines dedicated to the use of IR and THz synchrotron radiation are under commissioning respectively operational: (1) the MLS-IR beamline optimized for the MIR to FIR [7], and a dedicated THz beamline optimized for the FIR/THz spectral range. The commissioning of the IR beamline started in April 2008. The construction of the THz beamline was finished in the end of 2008. Additionally we have the possibility to produce high power infrared radiation in the MIR at the IR undulator beamline which is now also under commissioning (see Fig. 1).
The IR beamline and THz beamline consist of an arrangement of mirrors which allows - in combination with a special port of the dipole chamber – the transport of the beam to the experiment (see Fig. 2). After all mirror reflections the σ-polarization of the electrical wave vector of the radiation is horizontally oriented. The propagation of sub-terahertz electromagnetic waves from the source point to the experiment through a typical IR beamline is strongly affected by diffraction. This is why we decided to build a dedicated THz beamline with large extraction optics and a larger window.

The first optical component mirror M1 is placed at a distance of 1550 mm from the source, the first position possible outside the vacuum chamber of the dipole magnet. M1 and M2 collimate the THz radiation horizontally and vertically, respectively. Both mirrors are cylindrical and deflect the beam by 90° upwards (M1) and towards (M2) the storage ring. A quartz window with a diameter of 130 mm after the first mirror M1 separates the UHV of the storage ring from the rest of the beamline. The following optical elements M3 to M6 are planar mirrors and transport the beam to the toroidal mirror M7. M7 collimates the beam and sends it to the experiment. Radiation safety requires this complex optical path (see Fig. 2). The nominal diameter of the beamline tube is 250 mm throughout the THz beamline.

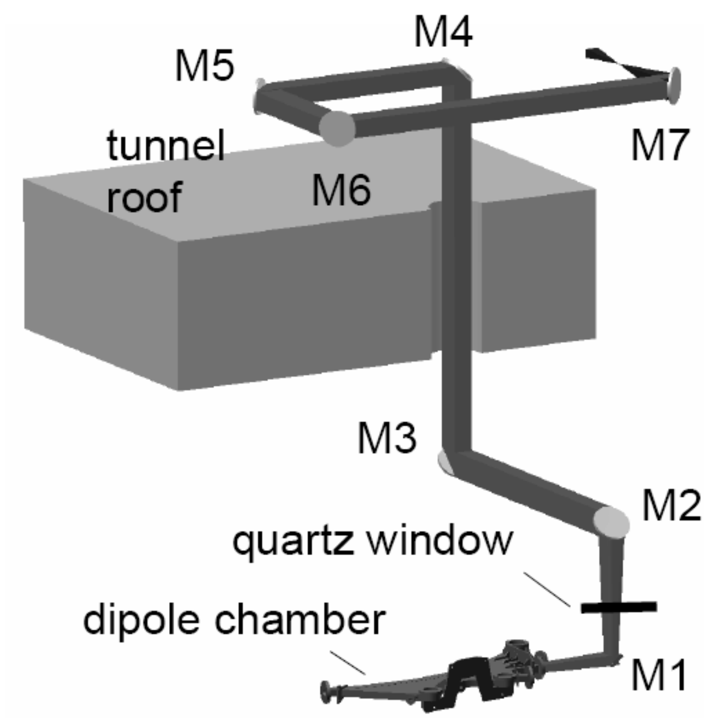
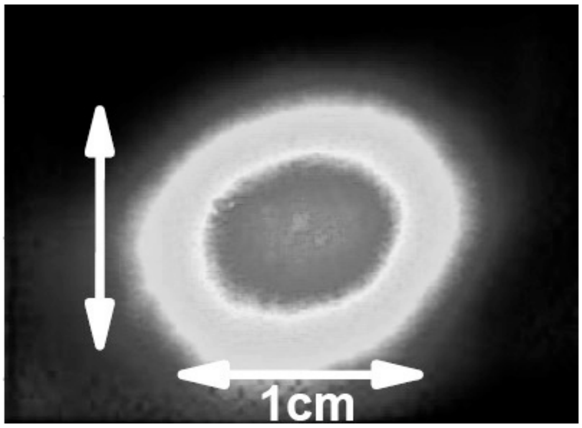


Figure 2: Layout of the THz beamline at the MLS. For details see the text.

4 First Results

First measurements with calibrated filter radiometers and an IR-camera in the visible and near infrared spectral range reveal the very good adjustment of the optical path of the IR and THz beamline. All the flux expected from theoretical calculations is measured at the experiment. The shape and size of the focus is also as good as expected. With the adjusted IR beamline we were able to make first measurements in the THz spectral range [15]. Fig. 3 shows the focus of the THz radiation (all radiation with a wavelength longer than 500 μm) in the low α mode at the THz beamline. Its FWHM size is approximately 4 mm in diameter and is located at the same position as the focus of the visible and near infrared light.



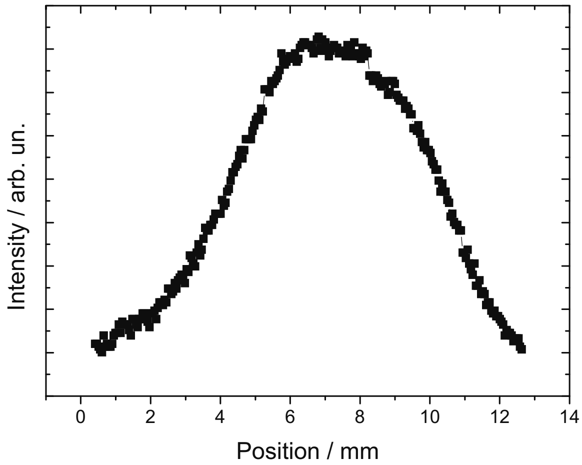


Figure 3: Left: Focus of the THz beamline after mirrror M7 (see Fig. 3). Right: Beam profile of the THz radiation.

Additionally we measured the absolute average THz power in the focus of the IR and THz beamline. Our measurements were done with a set of filters blocking the visible, NIR and MIR radiation using a Thomas Keating power meter [16].

At the IR beamline the measured power is depending on the chosen α in the range of a few hundred micro-watts. At the THz beamline with larger optical elements and different transmission windows compared to the IR beamlinemore than two orders of magnitude more power was measured in the THz range compared to the results at the IR beamline (see Fig. 4). The average power of about 60 mW gives with the machine parameters of the MLS [3-6] a peak power of about 35 W.

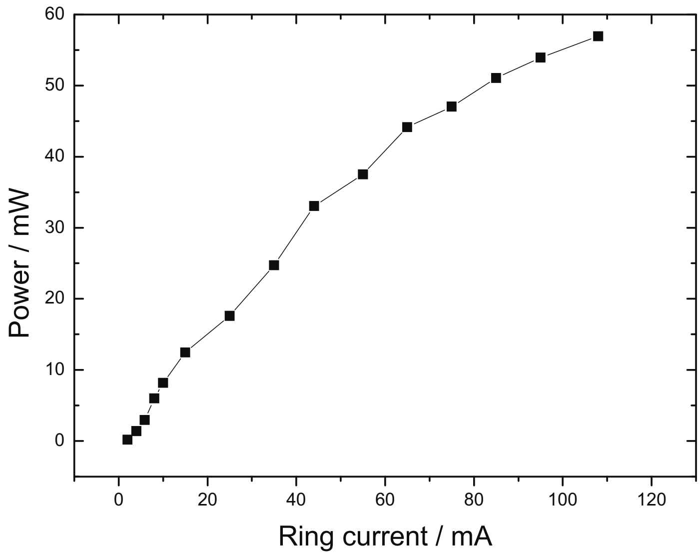


Figure 4: Averaged THz power measured in the focus of the THz beamline. Data were taken in low α operation at an electron energy of 630 MeV.

First experiments are planned to evaluate the potential of the MLS for the measurement of absolute material properties: spectrally resolved reflectance and transmittance with FTIR micro spectroscopy in order to complement the measurements with blackbody-based setups at the PTB [17]. Additionally, we plan to contribute to the development of THz metrology for the characterization of radiation sources, detectors and optical components. All these experiments will strongly benefit from the use of PTB-“in house” calibrated detectors [18, 19].

5 Summary

In summary, the project Metrology Light Source is well under way. The MLS as one of the few low-energy storage rings worldwide is expected to be an ideal IR synchrotron radiation source. 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 measurement tasks. A special mode of operation allows the production of coherent synchrotron radiation and thus the production of THz/FIR radiation with enhanced intensity making the MLS an promising radiation source for THz metrology. A dedicated beamline provides this radiation at the experiments. PTB will continue to optimize the MLS as an IR and THz radiation source in a systematic and quantitative way based on well characterized optical components and calibrated detectors. Radiometry, spectroscopy and microspectroscopy will be performed after setting up dedicated experimental stations and typical instrumentation (FTIR spectrometers, microscopes, bolometers) at the beamlines.

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