Status of the IR and THz beamlines at the Metrology Light Source

R Müller¹, A Hoehl¹, A Matschulat¹, A Serdyukov¹, G Ulm¹, J Feikes², M Ries² and G Wüstefeld²

¹ Physikalisch-Technische Bundesanstalt (PTB), Abbestraße 2-12, 10587 Berlin, Germany
² Helmholtz-Zentrum Berlin (HZB), Albert-Einstein-Straße 15, 12489 Berlin, Germany

E-mail: ralph.mueller@ptb.de

Abstract. The low-energy electron storage ring Metrology Light Source (MLS), a dedicated synchrotron radiation source, is in user operation since April 2008 at operating energies ranging from 105 MeV up to 630 MeV. It provides coherent THz radiation when it is operated in a low alpha mode with short electron bunches. At the MLS, two bending magnet beamlines optimized for the MIR and the THz spectral range are operational. We report the status of these two beamlines and present first results of the IR and THz measurements at the MLS.

1. Introduction

For more than a quarter of a century the Physikalisch-Technische Bundesanstalt (PTB) has been performing synchrotron radiation-based radiometry and metrology [1], using various electron storage rings. Since the start of operation of its own electron storage ring, the Metrology Light Source (MLS) [2-4], PTB has at hand an ideal source which can be flexibly operated, e.g. at any electron beam energy between 105 MeV and 630 MeV or at any electron beam current from 1 pA (single electron) up to 200 mA. Additionally, the MLS is the first electron storage ring worldwide designed and prepared for a special machine optical mode, -the low alpha operation mode-, for the production of high power coherent synchrotron radiation (CSR) in the THz spectral range [5]. The high THz power in combination with the high brilliance makes the MLS an interesting radiation source for many THz applications such as exploration of the linearity of THz detectors, microspectroscopy, near field microscopy, THz tomography, or THz electron paramagnetic resonance (THz-EPR) [6]. By tuning the low alpha optics the bunch length can be manipulated to the range of lower than 1 mm (3 ps). This time structure is used for the testing of fast THz detectors. Installed at the MLS are two IR/THz beamlines: (1) an infrared beamline optimized for the MIR, and (2) a dedicated THz beamline.
2. The IR and THz beamlines at the MLS

Typical IR beamlines at electron storage rings 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 1a). After all mirror reflections the σ-polarization of the electrical wave vector of the bending magnet radiation is oriented horizontally. 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 quartz window (Fig. 1b) [7]. Table 1 and 2 show the dimensions of the optical elements in the IR and THz beamline.

![Figure 1. Layout of the IR (a) and THz beamline (b) at the MLS.](image)

| Optical element (mirror) | Distance to source point (mm) | Type       | Dimensions (mm) |
|-------------------------|-------------------------------|------------|-----------------|
| M1                      | 1550                          | planar     | 110 × 110       |
| M2                      | 2450                          | cylindrical| 130 × 240       |
| M3                      | 4450                          | cylindrical| 210 × 150       |
| M4                      | 7050                          | planar     | 40 × 40         |
| Window                  | 7350                          | diamond    | d = 30          |
| M5                      | 8550                          | planar     | 60 × 100        |
Table 2: Optical elements of the MLS THz beamline.

| Optical element (mirror) | Distance to source point (mm) | Type         | Dimensions d (mm) |
|--------------------------|------------------------------|--------------|-------------------|
| M1                       | 1550                         | cylindrical  | 110 x 110         |
| Window                   | 2072                         | z-cut quartz | d = 89            |
| M2                       | 2450                         | cylindrical  | d = 240           |
| M3                       | 4450                         | planar       | d = 240           |
| M4                       | 7050                         | planar       | d = 240           |
| M5                       | 8450                         | planar       | d = 240           |
| M6                       | 9450                         | planar       | d = 240           |
| M7                       | 11850                        | toroidal     | d = 240           |

2.1. IR Beamline

The experimental station at the IR beamline is equipped with an instrumentation for microspectroscopy measurements: a Fourier-transform spectrometer and an IR microscope for life and material science investigations. A state-of-the-art rapid scan FTIR spectrometer Vertex-80v (by Bruker Optics) extended for THz applications and a maximum resolution of 0.06 cm<sup>-1</sup> is now operational. The infrared microscope HYPERION 3000 (Bruker Optics) completes the experimental setup.

The scheme of the optical design concept of the MLS-IR beamline is shown in Fig. 1a. The design is adapted from the concept of the IRIS beamline [8] at BESSY II, a multipurpose beamline which is equipped with two Fourier transform spectrometers, a microscope as well as an ellipsometer and provides useful IR intensities over a broad spectral range. The MLS-IR beamline is located at the bending magnet D6 at the MLS. The plane extraction mirror allows—in combination with a special port of the dipole chamber—a horizontal and vertical collecting angle of 64 mrad (h) x 43 mrad (v). At the maximum ring operating conditions of 630 MeV and 200 mA a mirror heat load of about 16 W is expected. Due to this relatively low heat load and with an additional cooling system, there is no deformation or destruction effects at the first mirror. So there is no need to split the mirror as, for example, at the IRIS beamline [8]. The first optical component M1 is placed at a distance of 1550 mm from the source, the first location possible outside the vacuum chamber of the dipole magnet. M1 deflects the photon beam upwards by 90° to a combination of mirrors which focus the beam outside the radiation shielding wall in the plane of a CVD diamond window. The second mirror M2 and the third mirror M3 focus the IR radiation vertically and horizontally, respectively. Both mirrors are cylindrical and deflect the beam by 90° towards the storage ring (M2) and upwards (M3). The beam passes the tunnel roof at a distance of 700 mm after M3. The fourth optical element M4 is a planar mirror and transports the beam to the parabolic mirror M5. M5 collimates the beam and sends it to the remaining optical system. The IR photon beam has an intermediate focus between M4 and M5 at a distance of 5800 mm from the center of M1. After all these reflections, the polarization is horizontally oriented. Ray-tracing calculations for an energy of 500 cm<sup>-1</sup> indicate a focal spot size of 2.5 mm (h) x 1.0 mm (v) which should easily pass through the diamond window (30 mm opening). This focus serves as a new source point for the remaining optical system. The diamond window separates the UHV of the storage ring from the remainder of the beamline. The subsequent optical elements direct the light to the different experiments. By mounting the optics and experiments on the massive storage
ring tunnel itself, the mechanical stability required for vibration-sensitive IR experiments can be achieved.

The IR beamline is optimized for the MIR spectral region. Figure 2 shows a comparison of the brilliance of the synchrotron light and the internal globar source of the BRUKER80v.

![Figure 2](image)

**Figure 2.** Comparison of the intensity of the internal globar source of the Vertex80v with the synchrotron radiation at the IR beamline after the knife-edge aperture of the IR microscope HYPERION 3000. The intensity was integrated over the wavelength range from 1.5 \( \mu \text{m} \) to 25 \( \mu \text{m} \).

### 2.2 THz beamline

Figure 1b shows the design of the dedicated THz beamline. The beamline is located at the dipole D5. The acceptance of the dipole chamber and the distance between the source point and the mirror M1 are the same as for the IR beamline. The mirrors 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 z-cut quartz window with a diameter of 89 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 focuses the beam and directs it to the experiment. Radiation safety requires this complex optical path. The nominal diameter of the beamline tube is 250 mm throughout the THz beamline.

After mirror M7 the beam will lead to two different experimental stations: Station 1 is equipped with an FTIR spectrometer for spectroscopy and station 2 is used for the tests of THz detectors. Figure 3 shows the focus of the THz radiation (all radiation with a wavelength longer than 100 \( \mu \text{m} \)) in the low-alpha mode at 630 MeV at the THz beamline. Its FWHM size is approximately 1.7 mm in diameter and lies directly on the focus of the visible and near infrared light.
The wavelength range at MLS, where the coherent radiation has more intensity compared to the incoherent THz spectrum, is 1.4 cm$^{-1}$ to about 50 cm$^{-1}$ [6]. This corresponds to a frequency range from 0.05 THz to 1.5 THz. The power gain compared to the normal operation mode is up to 4 orders of magnitude. At the IR beamline the measured power is in the range of a few hundred micro-watts. The highest measured average THz power of about 60 mW gives with the machine parameters of the MLS a peak power of about 35 W [6].

3. THz measurements

The Metrology Light Source (MLS) is the first electron storage ring worldwide designed and prepared for generation of THz radiation by applying a special machine optical mode (low-α operation mode) [5]. In this mode high power coherent synchrotron radiation (CSR) in the THz spectral range can be produced. Under normal operation of the MLS at 630 MeV, high ring currents, and bunches of about 7 mm length (1 σ bunch length) the measured far IR power is temporally smooth and varies linearly with beam current, as expected for incoherent synchrotron radiation. When the bunch length is shortened, bursts of radiation are emitted. The time structure is rather complex and varies with operating conditions. At MLS the bunch length can be adjusted by varying different parameters like α value, ring current, and cavity voltage [5]. For a fixed rf-voltage the bunch length is proportional to α$^{-1/2}$, where α is the momentum compaction factor. By lowering α, the bunches become shorter. The MLS has a unique possibility, to control the higher orders of α and to achieve bunch length reductions by more than a factor 10 in the sub-mm range. The higher orders of α are controlled by suitably placed sextupoles and octupoles. In the following we show two examples of our current THz work: (1) A comparison of different low-alpha optical modes, and (2) first results from our water absorption measurements.

3.1 Low-alpha modes for 450 MeV and 630 MeV electron energy

At the MLS two low-α operation optic modes for different ring energies, 450 MeV and 630 MeV were prepared. We measured the absolute average CSR THz power for the low-α modes at 450 MeV and 630 MeV in the focus of the THz beamline using a Thomas Keating power meter. Figure 4 shows that the CSR THz power for both low-α modes is nearly identical.
Figure 4. Comparison of the average CSR THz power measured in the focus of the THz beamline for the low-α modes at 630 MeV (squares) and 450 MeV (circles).

Figure 5 compares low-alpha spectra for 450 MeV and 630 MeV for two different electron beam currents. For both low-alpha modes the behavior is as expected: the waist and the intensity of the spectra grow with increasing electron beam current. The shape of the spectra for the different electron beam energies is comparable. From theory it is predicted that the THz radiation at the MLS is independent from the electron energy. At the MLS we find that at 105 MeV the CSR is strongly suppressed and at 250 MeV we derived a more intricate picture [9], where we saw an unexpected suppression of CSR THz signals at short bunches and high rf-voltage. So, at the MLS the low-α optics for lower electron energies is still under investigation.

Figure 5. FTIR CSR THz spectra for the two low-α modes at 450 MeV and 630 MeV for two different electron beam currents.
3.2 THz absorption of water

The FIR or THz absorption spectrum (5 cm\(^{-1}\) to 220 cm\(^{-1}\)) of liquid water is characterized by a broad peak at 170 cm\(^{-1}\) and possibly a shoulder at 80 cm\(^{-1}\) [10, 11]. Thus it came as a surprise that a recent publication [12] of the temperature dependance of liquid water optical constants in 2009 in the temperature range of 10 °C to 50 °C (see Fig 7 of ref [12]) showed the existence of an “isosbestic point” near 12 cm\(^{-1}\) (0.36 THz) without any further discussions. An isosbestic point refers to the frequency at which a series of absorption spectra cross i.e. frequency where the absorbance is a constant. The earlier studies reported by Afsar [10] and Hasted [11] did not indicate the presence of an isosbestic point near 12 cm\(^{-1}\) contrary to the spectra published by J.H. Son in 2009 [12]. Also the recent studies on water with the time-domain THz spectroscopy did not indicate the presence of the isosbestic point [13]. The presence of an isosbestic point in the absorption spectrum, if verified, is generally understood as the result of inter-converting distinct chemical or structural species. Alternatively, an isosbestic point in the absorption spectrum can also result from a single solute species in a fluctuating environment. In the present study, we report on absolute measurements of the liquid water transmission in the temperature range of 5 °C to 45 °C using several photon sources (coherent synchrotron radiation, incoherent synchrotron radiation, mercury-vapor lamp and globar source) to verify the existence or the non-existence of an isosbestic point near 12 cm\(^{-1}\). We show the data “as is” without any corrections and processing. For each line we performed 15 measurements each with 128 scans and averaged on all measurements. We performed two sets of measurements: (i) with the mercury-vapor lamp in the spectral region from 5 cm\(^{-1}\) to 25 cm\(^{-1}\) and (ii) with coherent synchrotron radiation (CSR) from 3 cm\(^{-1}\) to 15 cm\(^{-1}\). Due to the specifics of the FTIR measurements with respect to the beamsplitter transmission profile, and spectral intensity profiles of the light sources, we define the reliable spectral range for the mercury-vapor lamp from 9 cm\(^{-1}\) to 22 cm\(^{-1}\) and for CSR from 5 cm\(^{-1}\) to 13 cm\(^{-1}\). Good agreement between the two data sets is obtained in the spectral range from 9 cm\(^{-1}\) to 13 cm\(^{-1}\) (see Fig. 6). The transmission curves for different temperatures are well separated in intensity over the whole measured spectral range, which disproves the isosbestic point existence at 12 cm\(^{-1}\). One can see the wiggles in the spectra, which are mainly caused by the interference on the Si windows. Below circa 8 cm\(^{-1}\) the wiggles are not uniform, which lets conclude, that these structures have also another origin than the interference. Despite these disturbing effects the stability of our measurements is significantly better than ±0.3% (Fig. 6).

**Figure 6.** Left: Spectrum of the 100 µm water layer in the liquid cell (with 2 mm thick Si windows and 100 µm thick Teflon spacer), measured at different temperatures (\(T = 5\) °C, 25 °C and 45 °C measured during warming up cycle) with the internal Hg lamp (red) and the coherent synchrotron radiation source (CSR–black). The dashed line indicates the position of the supposed isosbestic point.
at 12 cm$^{-1}$. The measurements were performed with the FTIR spectrometer (Bruker Optics Vertex-80v) with 0.5 cm$^{-1}$ spectral resolution.

Right: Stability measurements of the CSR source through the fluid cell with 100 µm water sample at 15 mA ring current. To obtain this line, we took the ratio of two sequentially measured spectra (128 scans each) and calculated the average of all the measurements in the temperature series.

4. Summary and outlook

The MLS as one of the few low-energy electron storage rings worldwide is an ideal IR synchrotron radiation source. A special mode of operation allows the production of CSR and thus the production of far-IR/THz radiation with enhanced power making the MLS a promising radiation source for all types of THz applications. All beamlines are operational and equipped with a dedicated experimental set-up.

The low-$\alpha$ mode is prepared for two different ring energies. For 450 MeV and 630 MeV THz power and spectral behavior are nearly identical and ready for user operation. Additionally, we compared the spectra of liquid water in the spectral range from 5 cm$^{-1}$ to 22 cm$^{-1}$ measured with two light sources – mercury-vapor lamp and CSR. Our goals for the near future are to improve the stability of the light source (CSR), and to expand the spectral region toward long wavelengths ideally down to 2 cm$^{-1}$.

References

[1] Beckhoff B et al 2009 Phys. Status Solidi B 246 1415
[2] Klein R et al 2008 Phys. Rev. ST Accel. Beams 11 110701
[3] Klein R, Brandt G, Fliegauf R, Hoehl A, Muller R, Thorngal R and Ulm G 2009 Metrologia 46 266
[4] Klein R, Thornagel R, Ulm G, Feikes J, Wustefeld G 2011 J. Electron Spectr. Relat. Phenomena 184 331
[5] Feikes J, Hartrott M v, Ries M, Schmidt P, Wustefeld G, Hoehl A, Klein R, Muller R and Ulm G 2011 Phys. Rev. ST Accel. Beams 14 030705
[6] Muller R, Hoehl A, Serdyukov A, Ulm G, Feikes J, Wustefeld G 2011 Journal of Infrared Millimeter and Terahertz Waves 32 742
[7] Muller R, Hoehl A, Klein R, Schade U, Ulm G , Holldack K, Wuestefeld G 2006 Infrared Physics & Technology 49 161
[8] Schade U et al 2001 Rev. Sci. Instrum. 73 1568
[9] Wuestefeld G et al 2010 Proc. of IPAC2010, Kyoto (Japan) 2508
[10] Afsar M N, Hasted J B 1978 Infrared Phys 18 835
[11] Hasted J B, Husain S K, Frescura F, Birch J R 1987 Infrared Phys 27 11
[12] Son J H J. Appl. Phys. 2009 105 102033
[13] Ronne C et al J. Chem. Phys. 1997 107 5319