COHERENT SYNCHROTRON RADIATION AT THE METROLOGY LIGHT SOURCE

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Abstract

The Physikalisch-Technische Bundesanstalt (PTB) has set up a low-energy electron storage ring in Berlin-Adlershof in close cooperation with the BESSY GmbH. The new storage ring, named Metrology Light Source (MLS), is mainly dedicated to metrology and technological developments in the EUV, VUV, and IR spectral range. Additionally, the MLS is the first machine designed and prepared for a special machine optics mode (low-alpha operation mode) based on an octupole correction scheme, for the production of coherent synchrotron radiation (CSR) in the FIR and THz region. We report the status of the MLS operated in the normal and low alpha mode and present first results from the commissioning.

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. 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 more than 25 years [1]. Synchrotron radiation sources have major advantages in the IR range compared to conventional thermal sources: (1) higher spectral radiance, also called brilliance or brightness (see Fig. 1), (2) higher photon flux in the far-IR, (3) pulsed radiation in the ps range, and (4) polarized radiation. Additionally, electron storage rings can deliver 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, incoherent synchrotron radiation emission [2, 3, 4].

The MLS is the first electron storage ring 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 [5, 6].

METROLOGY LIGHT SOURCE

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 calculable radiation source from the near infrared to the soft X-ray range with special flexibility in its operation parameters [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 [5, 6, 7].

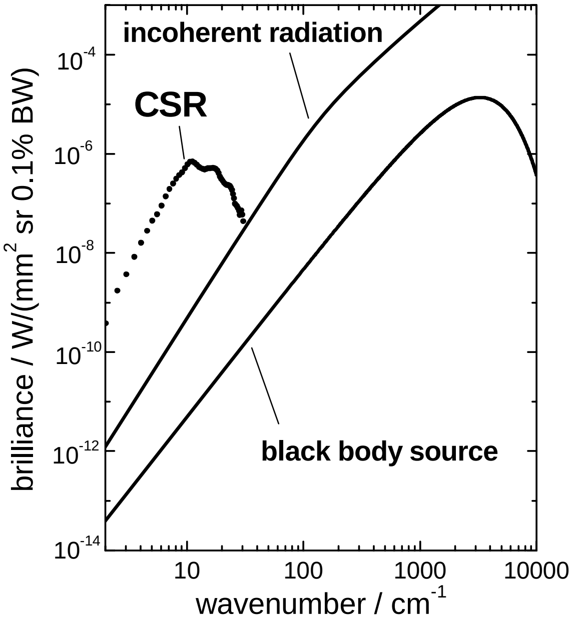

Figure 1: Expected brilliance for stable, coherent synchrotron radiation (CSR) of the MLS (dots) compared with the incoherent MLS radiation and radiation from a black body of 1200 K and 10 mm^2 emitting area. The estimated CSR brillance is scaled from the measurement of CSR at BESSY II.

INFRARED BEAMLINE

At the MLS three beamlines dedicated to the use of IR and THz synchrotron radiation are under construction respectively operational: (1) The undulator IR beamline provides edge radiation from NIR to FIR and with the long period undulator U180 installed, high flux in the MIR spectral range (up to 20 μm) (2) a THz beamline optimized for the FIR/THz spectral range, and (3) the MLS-IR beamline optimized for the MIR to FIR [8]. All results presented here were taken at the MLS-IR beamline.

The design of the beamline is as follows (see Fig. 2): 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) × 43 mrad (v). The first optical component 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 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 bunker 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 σ-polarization of the electrical wave vector of the radiation is horizontally oriented. Ray tracing calculations for an energy of 500 cm^{-1} indicate a focal spot size 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 should direct the light to the different experiments. By mounting the optics and experiments on the massive storage ring bunker itself the mechanical stability required for vibration sensitive IR experiments is achieved.

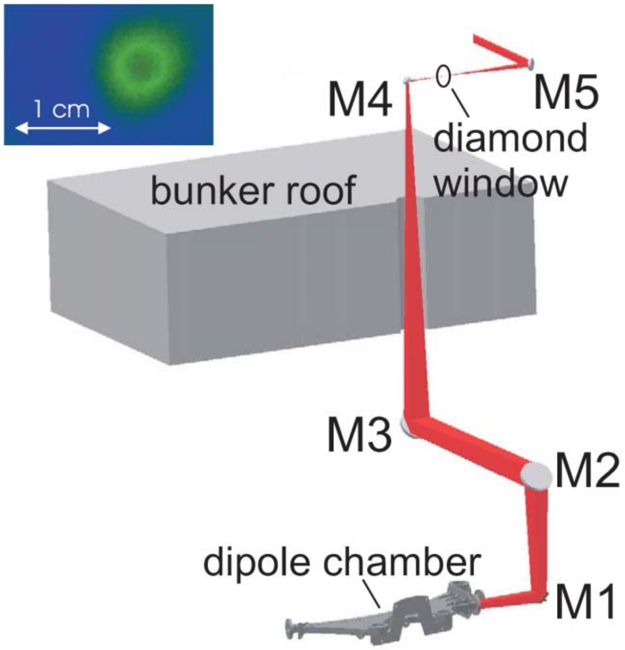

Figure 2: Optical design of the MLS-IR beamline (for details see text). The inset shows the focus of the CSR taken with an infrared camera in the THz spectral range in the low α mode.

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 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 this adjusted beamline we were able to make first measurements in the THz spectral range. The inset of Fig. 2 shows the focus of the THz radiation (all radiation with a wavelength longer than 500 µm) in the low α mode. Its FWHM size is approximately 3 mm in diameter and is located at the same position as the focus of the visible and near infrared light.

COHERENT SYNCHROTRON RADIATION

CSR from storage rings could bridge the gap between microwaves and 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 [2, 3]. Intense CSR can be generated if electron bunches become shorter than the emitted wavelength [4]. Then all the electrons in a bunch emit synchrotron radiation in phase. The CSR intensity is proportional to the square of the number of electrons per bunch in contrast to the linear dependence of the usual incoherent radiation. Since the number of electrons per bunch is typically very large ($\geq 10^8$), the potential intensity gain for a CSR source is huge. During the past few years, at BESSY II a new technique to generate stable, coherent THz radiation from the electron storage ring has been developed [9, 10]. The option to produce CSR is also envisaged for the MLS. Additionally, at the MLS we have the opportunity to produce short bunches in normal operation at lower ring energies and ring currents. Fig. 3 shows calculations for 200 MeV and 600 MeV.

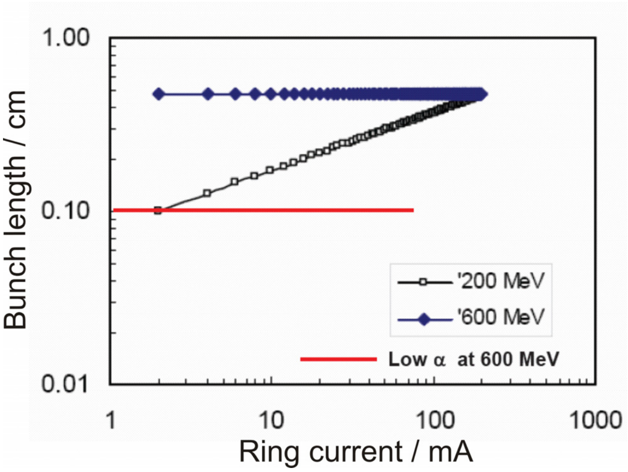

Figure 3: Two ways to short bunches at the MLS: 1. Lower electron energies: as an example the bunch length dependence from the ring current are calculated for 200 MeV and 600 MeV, and 2. Low α mode for 600 MeV.

Coherent Bursting

Under normal operation of the MLS at 630 MeV and high ring currents, and bunches of about 5 mm 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. Typically, bursts occur with varying amplitude and at time intervals ranging from 1 ms to 10 ms. The growth rate and time decay of these bursts is faster than the resolution of our Si-bolometer. Examples of these bursts are shown in Fig. 4. We detected bursts during the ramping of ring energy from 105 MeV to 630 MeV. Our measurements were done at the IR beamline with a set of filters blocking the visible, NIR and MIR light.

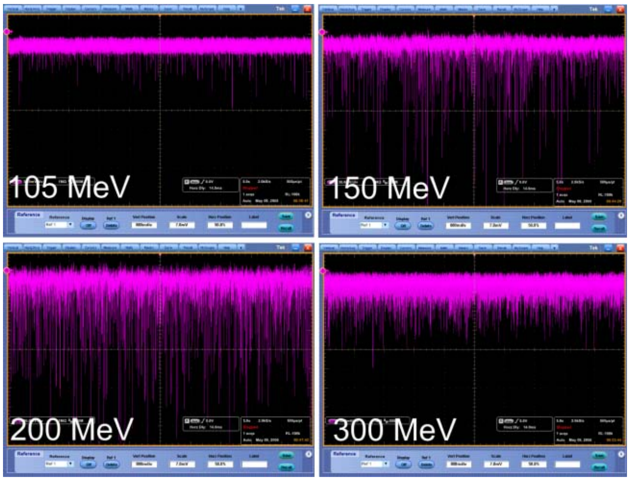

Figure 4: Coherent bursting signal for different electron energies and a ring current of 55 mA.

Figure 5 shows the time-averaged power of the bursts as a function of ring energy in normal operation mode. The bursting power was measured with a Si-bolometer in combination with a lock-in amplifier. The bursting-intensity grows starting from 105 MeV, peaks at about 170 MeV, and is then decreasing for higher electron energies. There are 80 buckets filled with an average current of about 50 mA. From the calculated natural bunch length one would expect the strongest THz signals at injection, when bunches are about 1 mm long. There are several effects leading to bunch lengthening at low energies, such as intra beam scattering or ion trapping. In case of emitted CSR bursts the bunches expand in phase space and suppresses further bursts. The damping of this expansion by synchrotron radiation takes several seconds. This mixture of effects will suppress the THz signals. With increasing energy the relative energy spread increases which further is lengthens the bunches, to 8 mm at 630 MeV, leading finally to incoherent THz signals.

Low α Mode

For a fixed rf-voltage the bunch length is proportional to sqrt(α), 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 a factor 10 in the the sub-mm range. The higher orders of α are controlled by suitably placed sextupoles and octupoles. The bursting power in the low α mode for 630 MeV at MLS is about two orders of magnitude higher than for short bunches in normal operation at 170 MeV. Within the time resolution of an InSb-detector of few milli-seconds we found strong indications for stable CSR.

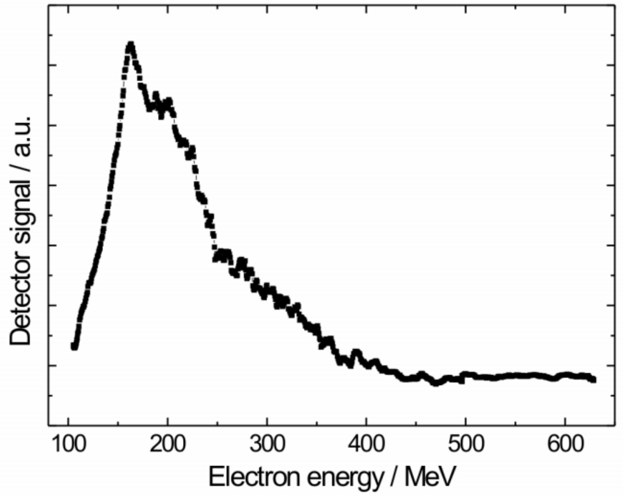

Figure 5: Coherent bursting signal as a function of ring energy at a ring current of about 55 mA.

SUMMARY

In summary, the project MLS is well under way. The MLS-IR beamline is well adjusted and ready for measurements in the infrared and THz spectral range. The machine layout is optimized for the coverage of the IR spectral region and will mainly be used for metrology and technological development. 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 will allow the production of CSR and thus the production of THz/FIR radiation with enhanced intensity.

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