HIGHLY SENSITIVE BEAM SIZE MONITOR FOR pA CURRENTS AT THE MLS ELECTRON STORAGE RING

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Abstract

For the operation of the Metrology Light Source (MLS) [1], the electron storage ring of the Physikalisch-Technische Bundesanstalt (PTB), as a primary radiation source standard all storage ring parameters have to be known absolutely. For the measurement of the electron beam size and the control of the stability of the orbit location a new imaging system has been set up, that operates at very different intensity levels covering more than 11 decades, given by the variation of the electron beam current. The system uses a commercial zoom lens for the achromatic optical imaging of the electron beam source point onto two different camera systems. One camera system is for life-imaging of the source point at electron beam currents from 200 mA down to some μA. The second system is a cooled CCD-camera that allows imaging of the electron beam source size and location at very low currents, down to only one stored electron.

INTRODUCTION

The spectral and spatial properties of synchrotron radiation (SR) emitted from bending magnets in an electron storage rings can be derived from just a few parameters using classical electro-dynamics [2]. Therefore, electron storage rings can be used as primary source standards for the spectral regions from the IR to X-rays, with the additional advantage that the radiant intensity can be controlled over many decades by adjusting the electron beam current. For more than 25 years PTB has been taking advantage of this [3] at various SR sources (see Fig. 1) for the calibration of radiation sources, many of them for astro physical purposes [4], or for the calibration of energy-dispersive detectors [5] or wavelength dispersive spectrometers. At the MLS, e.g., the electron beam current can be varied from 200 mA down to 1 pA, where the latter value corresponds to a single stored electron. The beam size monitor described in this paper was developed to cover this wide dynamic range for mainly two applications: the measurement of the electron source size is needed for the calculation of the SR properties, monitoring of the stability of the SR source point is indispensable for many radiometric application, especially at low electron beam currents, at which inductive devices, routinely used at storage rings for beam diagnostics suffer from poor signal levels. The MLS can be operated at very different electron beam energies, as can be seen in Tab. 1 which summarizes the main MLS parameters, hence the spectral shape of the SR spectrum can differ largely. The imaging system must be ready for use at each electron energy, which limits the spectral range to the VIS as can be seen from Fig. 1. As SR sources usually emit enough power, it is common to attach a narrow bandwidth filter and strong neutral density filters to optical source monitors (OSM). Since we want to image the source point also for very low electron beam current, we avoid bandpass filters in order to collect as many photons as possible and instead use achromatic optics.

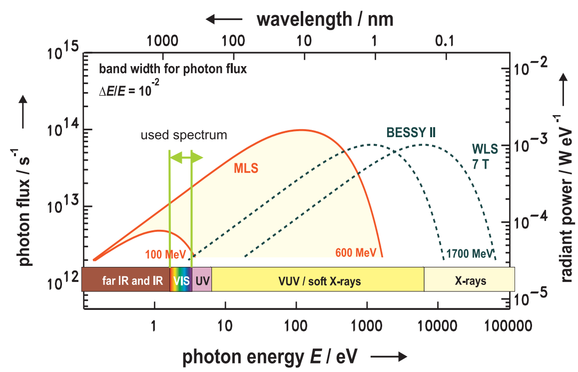

Figure 1: Synchrotron radiation spectra of sources used by PTB

parameter	**specification**
structure	double-bend-achromat
circumference	48 m
straight sections	2×6 m; $2\times$ 2 m
electron beam current	1 pA to 200 mA
electron energy	105 MeV to 630 MeV
injection energy	105 MeV
magnetic induction of the dipoles (600 MeV)	1.3 T
bending radius	1.528 m
nat. emittance (at 630 MeV)	100 nm rad
beam size (1 σ at 630 MeV)	250 μm (h) $\times$ 200 μm (v)
char. photon energy	1.7 eV bis 364 eV

Table 1: Parameters of the MLS.

EXPERIMENTAL SETUP

At a short beamline for diagnostic purposes inside the MLS shielding wall a vacuum chamber is mounted at 3 m distance from the source point, holding a mirror and a view port. The motorized and cooled mirror reflects the VIS part of the spectrum downwards, allowing to mount the optics and cameras off the orbit plane, where the risk of radiation damage is highest. Additionally the optical elements are mounted on a linear stage to center the radiation onto the front lens and to measure the optical magnification. The orbit plane is at a height of 1.4 m from the ground, leaving us 1.2 m for a compact telescope system, that can be set up within one day at the beamline (see Fig. 2). Mirror chamber and optical system are not mechanically connected. Since the lowest electron energy defines the shortest wavelength that can be used (see Fig. 1), we built an optic using the visual spectrum. We could use commercial cameras and camera lenses, which are achromatic corrected. The lens system consists of a 80 mm to 200 mm zoom lens and a 20 mm microscope eyepiece, resulting in magnifications from 0.35 to 1 and giving us a distance of 0.35 m behind the second lens to mount filters, beamsplitters and other optical elements. The image is projected onto two CCD cameras. One is for currents from 200 mA down to some μA and, using 70 % of the intensity, another cooled CCD for operation at currents down to a single stored electron.

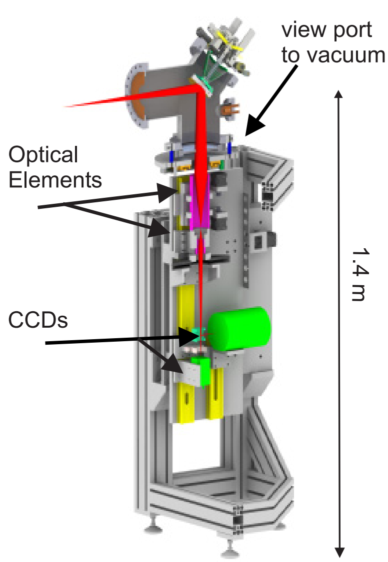

Figure 2: Schematic of the experimental setup

RESOLUTION

When imaging with light emitted into a small solid angle, the resolution limitation due to diffraction is not only limited because of the physical aperture, but as well because of the angular distribution of the emitted light itself. Using an approximation from [6] for the vertical opening angle of the SR and the resolution criteria for imaging behind a slit one can calculate the resolution limitation d to be

$$d \approx 0.3(\lambda^2\rho)^{1/3}, \tag{1}$$

depending on the wavelength λ and the radius of curvature ρ. In more precise theory of diffraction, where diffraction patterns are calculated, one can calculate these patterns for different wavelengths and then apply a weighted mean with respect to the spectral contribution, to expand this theory to polychromatic imaging. The resolution for our system should be about 20 μm but due to lens errors it is higher by approximately a factor of 3. The depth of field effect [7], resulting from imaging of an laterally extended part of the electron arc, is negligible in our case. We recently built a second system with an improved lens module, so that we can hopefully show measurements to resolution theory soon. During user operation the beamsize at the MLS is always larger than 100 μm (σ assuming 2D-Gaussian distribution) and resolution limitation can be neglected.

MEASUREMENTS AT LOW CURRENTS

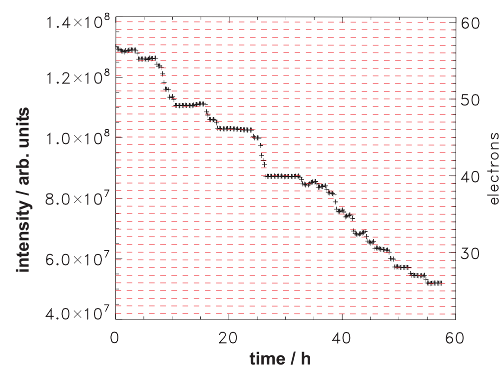

Figure 3: Intensity over time showing the loss of single electrons

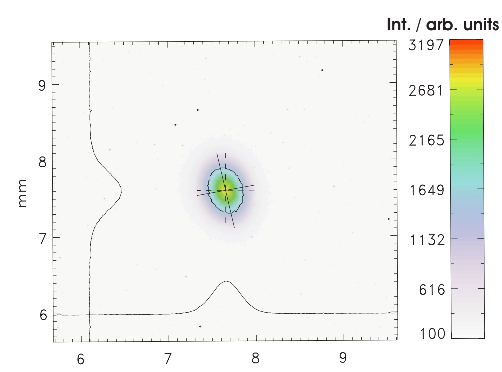

Figure 4: Averaged beam image of a single stored electron measured with a cooled CCD.

Figure 3 shows the integrated CCD signal for 60 h of measurement using exposure times of 30 min and starting with approximately 60 electrons. One can see, that the intensity decreases in discrete steps, which is evidence for the loss of single electrons. With a known underground level one can clearly determine the number of stored electrons. This can also be measured with cooled photo diodes [1] at the electron energy of 630 MeV using the full spectrum to get a more instant signal. The loss rate was raised by reducing the storage ring aperture with a scraper. Figure 4 shows a measurement of the transverse beamsize with a single electron stored using 15 min of exposure time. While reducing the current at 630 MeV (see above) we have measured the beamsize (see Fig. 5), finding that with decreasing current from 5 mA the beamsize does not depend on the current as one would expect from a motion theory free of particle interaction. At the same time, as we increased the exposure time from 2 s to 30 min, we assured that no slow beam instability have to be taken into account, while using long exposure times.

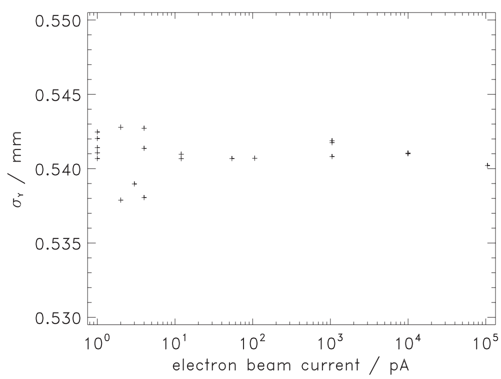

Figure 5: Vertical beamsize as a function of electron beam current.

ENERGY DEPENDENCE OF LOW CURRENT BEAMS

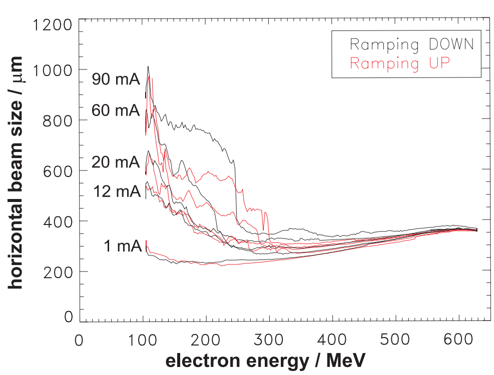

Figure 6: Horizontal beamsize as a function of the electron energy for different electron beam currents.

For a motion theory free of particle interaction, one would expect the horizontal beamsize being proportional to the electron energy. At the MLS it is common technique to vary the electron energy between injection energy of 105 MeV and maximal energy of 630 MeV. This is done by using a setup of tabulated optics and to interpolate in between [8]. Figure 6 shows the horizontal beam size as a function of electron energy for some electron beam currents and Fig. 7 shows the horizontal and vertical beam size measured for a single electron stored. One can state, that at electron energies below 300 MeV the beam becomes dominated by particle interaction if the current is higher than 1 mA. The single electron case is very similar to the 1 mA case, where the horizontal beamsize is proportional to the electron energy and the vertical beamsize remains constant, except for the lowest and highest electron energies. The increase at highest energies is explained by an introduced heavy coupling in the ramping tables, ensuring enhanced lifetime and beam stability at 630 MeV. The effect at lowest electron energies is not yet understood, but could be reproducibly measured also with some μA stored and exposure times of some ms.

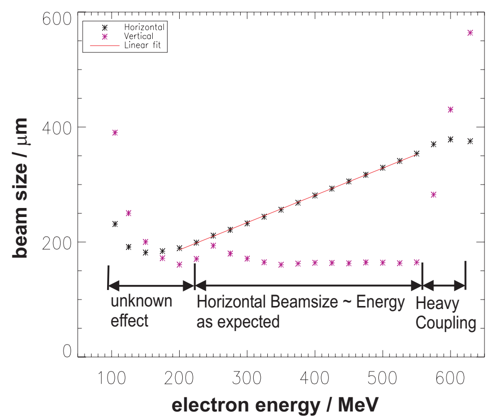

Figure 7: Horizontal and vertical beamsize as a function of electron energy for a single stored electron.

SUMMARY

To the best of our knowledge for the first time, the transverse beam size has been measured in an electron storage ring with only one stored electron. This was achieved by a highly sensitive optical imaging system using broad band VIS light and a cooled CCD camera. This system allows monitoring of the electron beam size and source point stability during calibration task with extremely low electron beam currents. The limited resolution of the present system will be improved by a new system using a high-quality fixed focus lens instead of a zoom.

REFERENCES

[1] R. Klein et al., Phys. Rev. ST Accel. Beams 11, 110701-1, 2008.
[2] J. Schwinger, Phys. Rev. 75, 1912, 1949.
[3] B. Beckhoff et al., Phys. Status Solidi: B246, 1415, 2005.
[4] M. Richter et al., Advances in Space Research 37, 265, 2006.
[5] M. Krumrey et al., Nucl. Instr. Meth. A 568, 364, 2006.
[6] A. Hofman, F. Meot, Nucl. Instr. Meth. A 203, 483, 1982.
[7] A. Anderson, J. Tagger, Nucl. Instr. Meth. A 364, 4, 1995.
[8] T. Birke et al. PAC09, WE1RAC05.