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APPLICATIONS OF THE INTERFEROMETRIC BEAM SIZE MONITOR AT BESSY II*

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Abstract

For the upgrade project of the BESSY II storage ring to BESSY VSR an interferometric beam size monitor was designed and set up. Since this system uses visible light it can be upgraded efficiently to provide bunch resolved measurements. These are required for machine commissioning, development and to ensure long term quality and stability of user operation of BESSY VSR. Various applications of the system are outlined and measurements are presented.

INTRODUCTION

The upgrade project of the BESSY II storage ring towards the variable pulse length storage ring BESSY VSR relies on intense short pulses as well as high average photon flux simultaneously [1, 2]. For this the filling pattern features bunches varying in length, current, and charge density over an order of magnitude. This variation will cause different transverse beam sizes for the various bunch types. Therefore multiple bunch resolved diagnostics are needed for the commissioning and development of BESSY VSR as well as non-invasive diagnostic techniques ensuring long term quality and stability of user operation [3].

To measure the transverse source size an interferometric beam size monitor (IBSM) has been implemented at the BESSY II storage ring [4,5] complementing the two pinhole monitor systems [6], that use direct source point imaging. However, these pinhole monitors cannot be upgraded easily to provide bunch resolved information, since they use X-rays. In contrast the IBSM uses visible light and it is therefore planned to upgrade the IBSM applying gating techniques, e. g. with an ICCD camera, which then allows bunch resolved measurements [3]. This paper shows the improvements and further applications of the IBSM (not yet bunch resolved).

INTERFEROMETER

Theory

The principles are already discussed more detailed in [5,7] and will only be reviewed briefly here. The interference pattern at the detector plane emerging from a double slit interferometer is:

$$I(x) = (I_1 + I_2)\,\mathrm{sinc}^2\left(\frac{\pi a}{\lambda f}x\right)\left[1 + V\cos\left(\frac{2\pi d}{\lambda f}x + \psi\right)\right], \tag{1}$$

where x is the position at the detector, a the full single slit width, d the full slit distance, f the distance between the lens and the detector surface, λ the wavelength, ψ the relative photon phase, I_1 and I_2 the intensities at the slits and V the visibility. The visibility of an interferogram is then defined by the local maximum and minimum intensities of the envelope $I_{\max}$ and $I_{\min}$:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2}|\gamma|, \tag{2}$$

where γ is the complex degree of coherence. So, in case of equal light intensities at the two slits the complex degree of coherence is equal to the visibility.

The complex degree of coherence is given by the van Cittert-Zernike theorem [7]:

$$\gamma = \int \mathrm{d}x\, g(x) \exp\left(-i\frac{2\pi d}{\lambda L}x\right), \tag{3}$$

where L denotes the distance between the source point and the double slit and $g(x)$ is the shape of the source.

For measurements shown in this contribution it is furthermore assumed to observe only Gaussian beams and possible intensity imbalances between or at the two slits are neglected. The Fourier transform can then be performed and solved for the beam size, which can therefore be measured by fitting the visibility of the interferogram:

$$\sigma_x = \frac{\lambda L}{\pi d}\sqrt{\frac{1}{2}\ln\left(\frac{1}{V}\right)}. \tag{4}$$

Setup

A picture of the setup of the IBSM on the optical table at the BESSY II diagnostics beamline can be seen in Fig. 1. A dipole beamline provides synchrotron radiation in the visible region and the light is guided out of plane enabling operation while beam shutters are be closed. At the interferometer a double slit causes a diffraction pattern and the source point is imaged with two lenses onto a CCD camera. In addition the light passes through a polarisation and a bandpass filter to obtain a clear interference pattern from a monochromatic, polarized ray.

An overview of the parameter ranges and relative error contributions, which are important for calculating the beam size from the visibility measurement, is shown in Table 1. The double slits with slit separations from 7.5 mm to 25 mm were produced with a 3D printer. The slit widths and heights are 3 mm for each slit. Bandpass filters from 400 nm to 800 nm with a FWHM bandwidth of 10 nm are available. Together with the restriction of an intended visibility region

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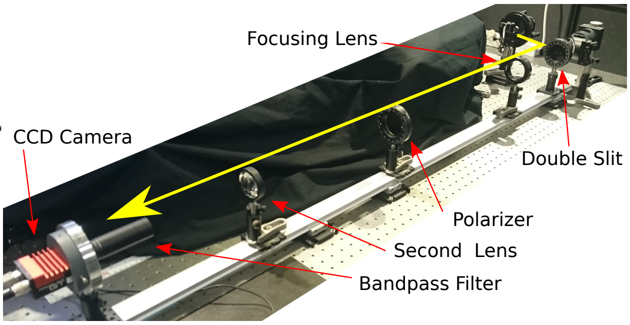

Figure 1: Picture of the interferometric beam size monitor setup at the BESSY II diagnostics beamline.

between 0.3 and 0.9 [4] the reliable region of the beam size measurement ranges from about 20 µm to 420 µm. In addition the impact of an error of the visibility measurement on the computed beam size is shown for an exemplary visibility error of 0.005 for two extreme cases. However, the systematical resolution limit which in first estimations was about 25 µm for a 15 mm double slit separation will increase the measurement error, especially for smaller beam sizes. This resolution limit is caused by a combination of setup and alignment issues of the interferometer components, vibrations of beamline and the setup components and wavefront distortions due to heat load on the extraction mirror.

Table 1: Overview of the parameters ranges, typical total uncertainties, and relative error contributions to the beam size measurement. For comparison the impact of a possible visibility error of 0.005 on the beam size is given.

Parameter	Range	Uncertainty	$(\Delta\sigma)/\sigma$
L	16.09 m	0.84 m	5.2 %
d	7.5 – 25 mm	0.1 mm	1.3 – 0.4 %
λ	400 – 800 nm	1.6 nm	0.4 – 0.2 %
$V(\sigma_{\text{min}})$	0.9	0.005	0.7 %
$V(\sigma_{\text{max}})$	0.3	0.005	2.6 %

APPLICATIONS

Beam Size Measurements

Besides using the IBSM as online monitor, more precise measurements of the beam size are possible recording the visibility for different slit separations [4]. The measurements in standard user mode in vertical and horizontal direction measured at a wavelength of 400 nm are shown in Fig. 2.

The measured visibilities were then fitted to obtain the beam sizes. In the horizontal case the incoherent depth of field effect [8] is considered. The results are shown in Table 2 and are compared with measurements from the pinhole monitors (PINH3 and PINH9) and in the horizontal direction with a lattice model of the storage ring. However, the model does not include any IDs, therefore a combination of the optical functions, not considering the IDs and a lower value for the emittance of 5 nm rad in standard user mode considering superconducting IDs [9], was used to calculate

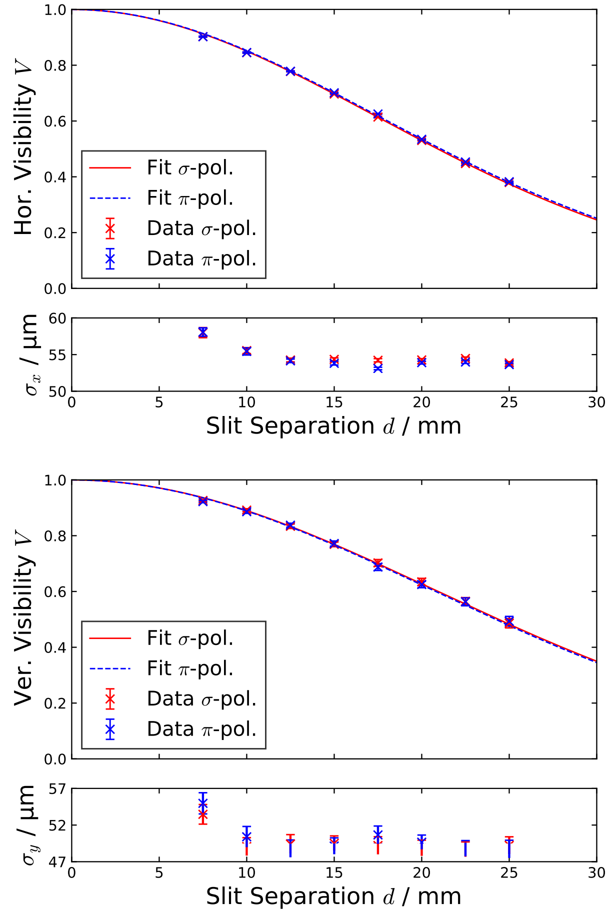

Figure 2: Measured visibility as a function of the double slit separation in the horizontal (top) and in the vertical direction (bottom). The lines show the fits to obtain the beam size.

the horizontal beam size. Compared with measurements the values of the model are smaller which might be caused by the resolution limit of the systems, which are not considered in the results. Because of similar values of the β-function at the source points, similar beam sizes are expected in the vertical case [4]. However, PINH3 measures a much larger beam size in both dimensions which could be caused by a misalignment of the system.

Table 2: Beam sizes from measurements and model. The error of the pinhole measurements is dominated by the resolution limit (about 30 µm)

	PINH3	Interferometer	PINH9
Model σ_x / µm	44.5	44.2	48.1
σ_x / µm	75.0	54.3 ± 2.9	65.9
σ_y / µm	84.4	49.5 ± 2.6	51.3

Energy Ramp

During the last year an energy ramp has been established at BESSY II to ramp the storage ring down to an electron energy of 600 MeV. However, lowering the electron energy also shifts the synchrotron spectrum towards lower photon energies. The pinhole monitors are not suited for any

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measurements since the necessary high energy photons vanish already for energies below approximately 1.6 GeV. Therefore the IBSM gives the only opportunity at BESSY II to measure the beam size for lower energies. Measurements were done for a down and an up ramp with a double slit separation of 25 mm at wavelength of 550 nm at low multibunch currents of 1 mA and 4 mA, respectively, and are shown in Fig. 3.

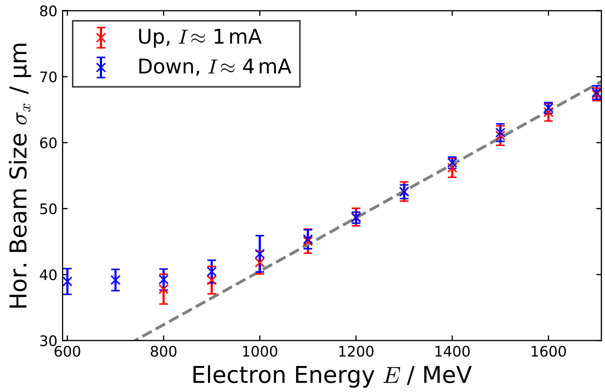

Figure 3: Horizontal beam sizes measured with the IBSM for different beam energies on the up and down ramp for low currents. An auxiliary line through the origin in gray shows the expected linear behavior.

The beam sizes for both measurements are similar for the different energies and follow the expected linear dependence on the energy above 900 MeV. Below 900 MeV the beam size deviates from the theoretical expectation. Here the results are probably dominated by the resolution limit of the interferometer or by nonlinear or collective effects.

Beam Profile Measurement

With an IBSM it is also possible to measure the azimutal beam profile [10]. The measurement was done in standard user mode with a current of 250 mA and with 20 mm slit separation and a wavelength of 400 nm. The visibility was measured by rotating the camera and the double slit starting in the horizontal direction in 5° steps with π-polarisation and in 10° steps with σ-polarisation until the system was again in the horizontal orientation. The incoherent depth of field effect was taken into account by rescaling the horizontal contribution for each angle with the correction factor obtained for the horizontal plane. This assumes a constant horizontal beam size depending on the vertical position. The obtained beam size as a function of the rotation angle and the therefrom calculated beam profile are shown in Fig. 4.

The measured beam profile shows, that the beam is an ellipse with a minor axis length of about 46 µm and a major axis length of about 58 µm and the major axis is rotated by approximately −37.5° from the horizontal orientation. This implies that either the electron beam at the source is tilted or the photon beam is rotated during transport to the interferometer. Further tests concerning coupling conditions and one dimensional blow up of the beam are planned.

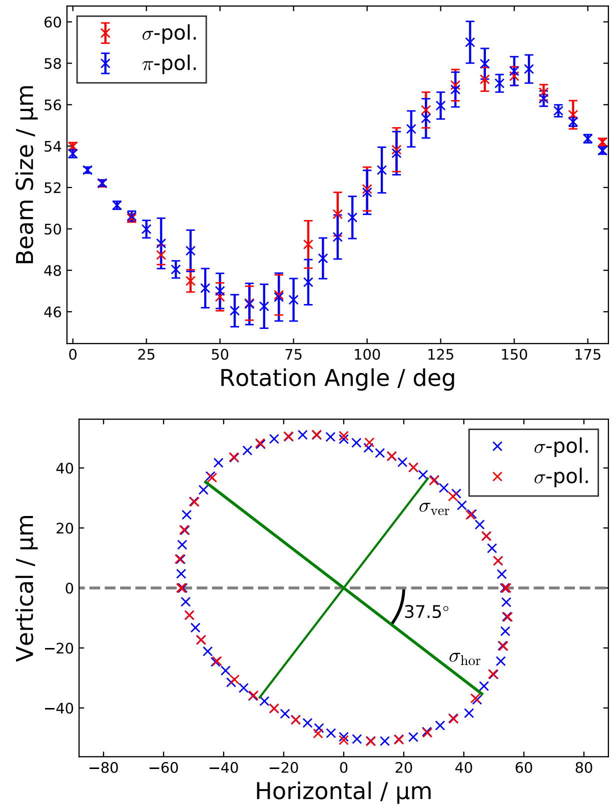

Figure 4: Measured transverse beam size as a function of the rotation angle of the double slit interferometer in standard user operation (top), 0° corresponds to the horizontal orientation and the transverse beam profile calculated from the measurements (bottom).

CONCLUSION

Beam sizes from 30 µm to 250 µm were measured with a statistical uncertainty of about 5 % and the IBSM already has various applications for diagnostics and machine commissioning. It is planned to move the IBSM to the new BESSY VSR diagnostics beamline [3]. The major task will be to investigate and improve the resolution limit of the system with upgrade of IBSM components. Finally an upgrade of the system with a fast ICCD camera is planned enabling bunch resolved measurements.

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