EMITTANCE MEASUREMENT USING UNDULATOR RADIATION

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Abstract

An additional electron beam emittance measurement that uses X-ray radiation from an undulator at the ESRF storage ring is now installed. The method consists in detecting the monochromatic spatial profile of the fifth harmonic of the undulator spectrum at 29.3 keV. The X-rays are converted to visible light using a scintillating screen which is then imaged to a CCD camera. The emittance value is deduced from the image size, the photon beam divergence, the source distance, and the lattice functions at the source point. The direct use of undulator radiation is advantageous in terms of the precise knowledge of the source position and lattice parameters in the straight section. For this reason this device will find its main application as a horizontal emittance monitor with improved absolute precision compared to that of the pinhole cameras which are making use of bending magnet radiation.

MOTIVATION

The electron beam emittance at the ESRF is currently monitored through two different families of devices: Two pinhole cameras [1] and eight so-called In-Air-X-Ray (IAX) detectors [4]. Both kinds of devices use X-rays emitted from dipoles. While the pinhole cameras deliver both, horizontal and vertical emittance values, the IAX detectors allow for precise measurement of the vertical emittance only. Due to the strong gradient of the beta-function along a dipole and difficulties in the precise determination of the X-ray source point position, the beta-value involved in the emittance calculation from the pinhole cameras is prone to errors. In order to cross-check the results with a different method, an emittance measurement using undulator radiation has recently been set up. The advantage of this method, which will be described in detail in the next section, is the very precise knowledge of the lattice parameters in the center of the straight sections in a storage ring.

BACKGROUND

Assuming that the β-function is well known, we can determine the emittance ε from the electron beam size σ and β at a given point in the storage ring. In our case, the point in which we measure ε, is the center of a straight section, where we can ideally suppose β' and η' to be zero. In reality, however, this may not be true, even if, after all, the values will be small, and β' can be neglected without worries. The electron beam size σ and its divergence σ' are then given by

$$\sigma^2 = \varepsilon \cdot \beta + (\eta\delta)^2 \quad , \quad \sigma'^2 = \varepsilon/\beta + (\eta'\delta)^2 \qquad (1)$$

In an ideal storage ring, the dispersion in the vertical plane would be zero, especially in the straight sections. Since, in reality, this may not be the case, we keep the above relations for both, the horizontal and the vertical plane.

Since the parameters β, η, η' and the energy spread δ are a priori known, measuring the emittance is now reduced to the measurement of the electron beam size. This will be done non-intrusively using the X-ray radiation emitted by the electrons traveling through the magnetic field of an undulator. The X-rays emitted by the electrons are freely propagating towards the detector conserving the divergence σ' of the electron beam at the source point. The X-ray beam size on a screen positioned at a distance D downstream the undulator is then given by the convolution of the electron beam size and the angular distribution of electron trajectories, the finite natural divergence of undulator radiation (σ'_{u}), and an image broadening (σ_{opt}) of the optical system. We assume that we have to deal only with Gauß-distributions, such that the rms X-ray spot size measured on the screen can be expressed by:

$$\Sigma^2 = \sigma^2 + (\sigma' D)^2 + (\sigma'_{\mathrm{u}} D)^2 + \sigma^2_{\mathrm{opt}} \quad . \qquad (2)$$

Substituting σ and σ', as given above, allows to calculate ε from the measured beam size Σ:

$$\varepsilon = \frac{\Sigma^2 - (\eta\delta)^2 - (\eta'\delta)^2 \cdot D^2 - \sigma'^2_{\mathrm{u}} \cdot D^2 - \sigma^2_{\mathrm{opt}}}{\beta + \frac{D^2}{\beta}} \quad . \qquad (3)$$

Under the condition that the working point is located at the peak of an odd undulator harmonic, the natural photon beam divergence and the natural source size can be approximated by [3]:

$$\sigma'_{\mathrm{u}} = \sqrt{\frac{\lambda_X}{2L}} \quad , \quad \sigma_{\mathrm{u}} = \frac{\sqrt{2\lambda_X L}}{4\pi} \quad , \qquad (4)$$

with λ_X being the X-ray wavelength of the respective harmonic, and L the undulator length. The natural source size is of the order of 1 μm at about 30 keV, and therefore negligible in our measurements. The above approximation indicates that, in order to keep the photon divergence small, a high X-ray energy is favourable. In general it is desirable not to work at the peak of the harmonics, but at slightly higher energies, in order to minimise the photon divergence. Therefore, σ'_{u} was calculated using the exact expression for the spatial distribution of undulator radiation rather than using the above equation.

EXPERIMENT

On the basis of a previous experiment [2] the setup is implemented in the beamline ID30, the latter being shared

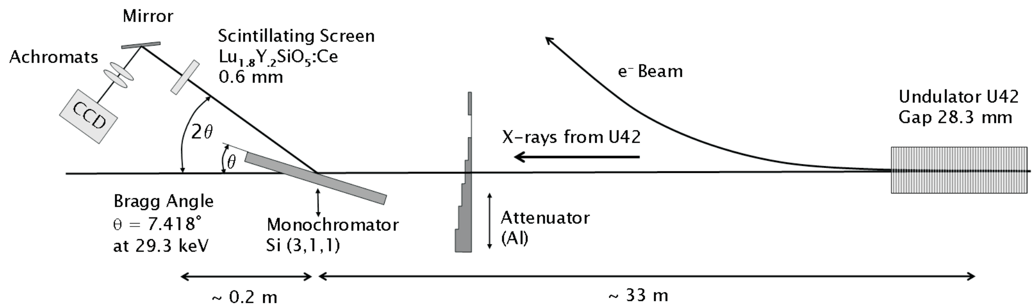

Figure 1: Sketch of the experimental setup seen from the top.

between different groups of the Accelerator and Source Division for testing and development of new equipment for the storage ring. The very compact emittance measurement setup (~50×50 cm) will be permanently installed in this beamline. A sketch of the setup is shown in Fig. 1. In Tab. 1 the storage ring lattice parameters at the source point, the undulator parameters and the geometry of the setup are summarised. For the present measurements at ID30 we use an undulator with 42 mm period (U42). The undulator gap is set to 28.3 mm. At this value the energy of the 5th harmonic is sufficiently high to minimise the contribution of the natural divergence of undulator radiation. Furthermore, the harmonics are widely spaced such that the lower orders can easily be attenuated without affecting the 5th harmonic.

The radiation emitted from the U42 undulator is sent to a monochromator crystal which selects the desired energy. The monochromator is a 0.5 mm thick and 20 mm × 50 mm large single Si(3,1,1) crystal, mounted onto a motorised rotation stage allowing to scan the Bragg angle. The (3,1,1) crystal cut has been chosen in order to produce a reasonable horizontal footprint of the X-ray beam on the crystal surface of about 20 mm (rms) at a Bragg angle of 7.4°. This reduces the X-ray intensity on the surface, and thereby limits effects of lattice deformation due to local heating. A water cooled aluminium attenuator with variable thickness is placed in front of the monochromator in order to reduce the heatload on the crystal. The high energy radiation which is used in the measurement is mainly transmitted while the low energy radiation is absorbed. Without attenuation the radiation power incident on the monochromator crystal is about 30 W in 16-bunch mode at 90 mA electron beam current (measured with a calorimeter). 4 mm of Al have been introduced in order to reduce the power to roughly 2 W. In order to remove any residual heat, the monochromator crystal is mounted on a water cooled copper block, the thermal connection between the crystal and the copper being a highly heat conducting liquid InGa alloy. The energy calibration of the monochromator is done with the K-absorption edge of Sn, which is located at 29.2 keV. For the emittance measurement the energy is fixed at 29.3 keV which corresponds to the narrowest cone of the natural undulator radiation at the gap value of 28.3 keV. At this energy the natural photon divergence of the undulator radiation is $\sigma'_u \approx 3~\mu\mathrm{rad}$. The X-ray energy can be selected with a precision of $\sim 0.01\%$.

Finally, the monochromatic X-ray beam is converted into visible light by a 0.5 mm thick and 15 mm large Cerium doped scintillator crystal $Lu_{1.8}Y_{0.2}SiO_5$:Ce ('Prelude' St. Gobain). A set of achromats is used to image the scintillator onto a digital CCD camera. To avoid radiation damage on both, the lenses and the camera, they are protected with lead and observe the scintillating screen via a mirror. The total blurring induced by the imaging optics is $\sigma_{\mathrm{opt}} \approx 20~\mu$m.

Table 1: Lattice and Undulator Parameters : λ_u...undulator period, L...undulator length, K...undulator K-value at 28.3 mm gap, D...distance to source, E...X-ray energy

Lattice:		Undulator:	
β_x	37.6988 m	λ_u	42 mm
β_z	2.9496 m	L	1.62 m
η	0.1343 m	K	0.895
η'	0	D	33 m
δ	0.106 %	E	29.3 keV

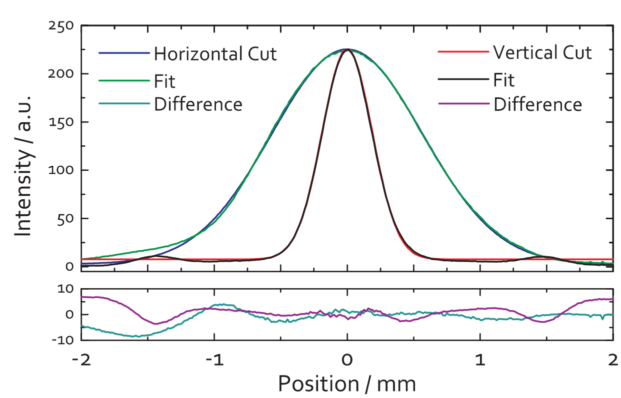

Figure 2: Horizontal and vertical cut through the measured beam profile, the lineouts of the fitted 2-dimensional Gaußian, and their differences.

The images are fitted with a Gaussian intensity profile, from which the rms beam size Σ is extracted. The fit is done on only a small region of the profile of about $1.5 \times \Sigma$. This reduces influences of the background and contributions to the wings of the beam profile which are not coming from the 5th, but higher harmonics. Additionally, the time needed for the fit is strongly reduced if the area is kept small. Therefore the acquisition rate of the system is a few seconds. Fig. 2 illustrates the good agreement between the measured beam profile and the fit.

RESULTS

The emittance value from ID30 is calculated from the measured rms beam sizes on the scintillating screen using Eq. 3. The horizontal and vertical emittances measured in 16-bunch filling at about 70 mA are $\varepsilon_x = 3.9$ nm and $\varepsilon_z = 60$ nm. Tab. 2 compares these values with the other emittance monitoring devices: the pinhole cameras ID25 and D9, and one of the IAX detectors C14. The differences of up to 10% of the vertical emittance values can be explained with the variation of the vertical β-function with respect to the model β due to the coupling around the storage ring. The horizontal emittances measured with ID30 and D9 compare well, while the ID25 value differs considerably.

Table 2: Measured Emittance Values from Undulator Radiation (ID30), the Pinhole Cameras ID25 and D9, and the IAX Detector C14

	ID30	SRW	ID25	D9	C14
horizontal ε_x [nm]	3.9	4.1	6.3	4.1	–
vertical ε_z [pm]	60	55	47	43	53

In order to evaluate the absolute emittance value, the beam size at the position of the scintillating screen was calculated with SRW ('Synchrotron Radiation Workshop' [5]) for different horizontal emittance values and plotted in Fig. 3. To the measured beam size of 540 μm on the screen (corrected for optical blurring), corresponds a calculated emittance value of 4.1 nm. The same calculation is done for different vertical emittance values, keeping the horizontal emittance at 4 nm. The measured beam size of 176 μm corresponds to a vertical emittance of 55 pm. The comparison of the measured emittance values with the calculation clearly shows that the measurements of ID30 and D9 yield the right order of magnitude. The significantly higher horizontal emittance value measured by the pinhole camera ID25 can therefore be doubted, and is most likely due to the uncertainty in the determination of the source distance and horizontal beta value.

As shown in detail in Tab. 3, the uncertainty of the emittance measurement in ID30 is about 2% only in the horizontal plane, but $\sim$13% in the vertical plane. The latter being mainly due to the high uncertainty of the photon divergence. Therefore, the undulator radiation is at the moment not adapted to exploit the very small emittances of less than 20 pm reached in multi-bunch filling modes. The horizontal emittance measurement, however, is very precise and benefits from the well known lattice parameters in the straight section. The undulator radiation can therefore be used to complement the pinhole camera measurements.

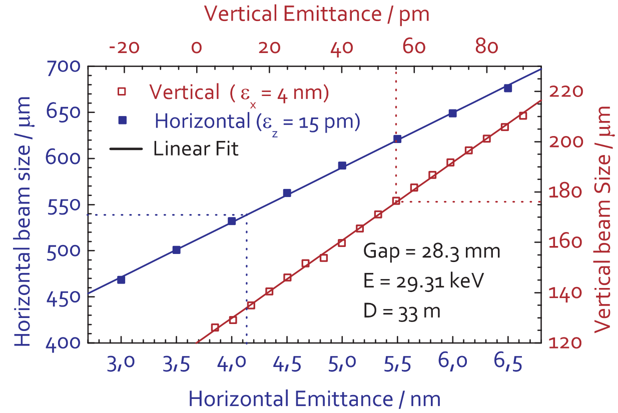

Figure 3: Horizontal and vertical rms beam sizes calculated with SRW for different emittance values.

Table 3: Uncertainties of the Parameters Used to Calculate the Emittance at ID30, and their Influence on the Final Result

	horizontal	**vertical**
3% precision of β_x and β_z	0.5 %	3 %
3% for η_x	0.4 %	–
2% for δ	0.2 %	–
10% uncertainty for σ'_u	0.8 %	9 %
0.2% uncertainty of D	0.15 %	0.5 %
10% image blurring σ_{opt}	< 0.1 %	0.3 %
Total	~ 2 %	~ 13 %

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