OPTICAL DIFFRACTION RADIATION INTERFEROMETRY AS ELECTRON TRANSVERSE DIAGNOSTICS*

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Abstract

The characterization of the transverse phase space for high charge density and high energy electron beams is demanding for the successful development of the next generation light sources and linear colliders.

Due to its non-invasive and non-intercepting features, Optical Diffraction Radiation (ODR) is considered as one of the most promising candidates to measure the transverse beam size and angular divergence.

A thin stainless steel mask has been installed at 45^o with respect to the DR target and normally to the beam propagation to reduce the contribution of synchrotron radiation (SR) background. In addition, interference between the ODR emitted on the shielding mask in the forward direction and the radiation from the DR target in the backward direction is observed. This is what we call Optical Diffraction Interferometry (ODRI) which, better than ODR, allows to separate the intrinsic ambiguity between the radiation produced by a single particle passing through a slit with an offset with respect to its center and a gaussian distributed particle beam with standard deviation of magnitude equal to such offset.

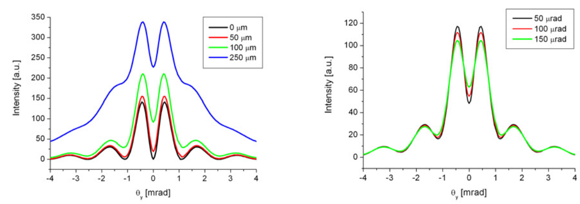
Results of an experiment, based on the detection of the ODRI angular distribution to measure the electron beam transverse parameters and set up at FLASH (DESY, Hamburg) are discussed in this paper.

INTRODUCTION

The development of high energy Linear Colliders (LC) [1] and short wavelength Free-Electron Lasers (FEL) [2, 3, 4] requires high quality electron beams, which means small transverse emittance (< 1 mm mrad) and high peak current (≈ kA). Due to the large power density of this kind of beams, a non-intercepting diagnostics needs to be developed and applied. In 1997 one of the authors suggested a new method for the non-intercepting measurement of transverse beam size [5]. The idea is based on the observation of diffraction radiation (DR) emitted by a charged particle beam going through a slit in a metallic foil due to the interaction of the charge electromagnetic (EM) field with the screen surface. The intensity of the radiation increases linearly with the number of charges and is proportional to $e^{-\frac{2\pi a}{\gamma\lambda}}$, where a is the vertical slit aperture, γ the Lorentz factor and λ the emitted wavelength. The factor $\gamma\lambda/2\pi$, called as DR impact parameter, is the natural size of the radial extension of the EM field, thus when $a \cong \gamma\lambda/2\pi$ DR is emitted.

Since the beam goes through the slit, DR is a non-intercepting diagnostics and, therefore, excellent to be used parasitically without disturbing the electron beam.

The aim of our experiment is measuring the transverse beam size and divergence, in order to calculate the transverse emittance, by studying the angular distribution of Optical Diffraction Radiation (ODR). The DR angular distribution is produced by the interference of radiation from both edges of the slit. The visibility of the interference fringes is correlated to the beam size (see Fig. 1, left).



(a) (b)

Figure 1: Theoretical calculation for the angular distribution of the vertical component of ODR for different transverse beam sizes and vertical angular divergences. The simulation has been performed assuming an electron beam energy of 680 MeV, with interference filter (800 nm) and 0.5 mm slit width.

The effect is also affected, in a slightly different way, by the angular divergence of the beam (Fig. 1, right): the ODR angular distribution becomes wider and the intensity of the minimum higher, when the beam divergence increases.

A dedicated analysis of the radiation angular distribution allows then to separate the two effects. If the beam waist is located in the plane of the DR screen, the transverse emittance can be derived with a single non-intercepting measurement.

EXPERIMENTAL APPARATUS

Our experiment is carried out at FLASH (DESY, Hamburg)[7]. FLASH is an excellent facility for this experiment, since it can drive long bunch trains, up to 800 bunches per macropulse allowing a high charge operation, and it has a good long term stability, a small transverse

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emittance (~ 2 mm mrad), and a high electron beam energy, approaching 1 GeV.

Our experimental set-up is placed in the by-pass beam line (Fig. 2) very far (about 40 m) from the dipole magnets in order to minimize the contribution of synchrotron light coming from them.

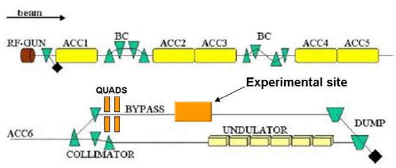


Figure 2: FLASH layout and experimental site.

The experimental set-up consists of two aluminated silicon screens (DR screen), one with the mask the other one without it (cfr. Fig. 5). A motorized actuator allows to insert the desired screen in the vacuum pipe under an angle of 45^o with respect to the beam direction. The target is of fundamental importance for the success of the experiment, since damaged edges and/or an uneven surface may change the interference effects, resulting in a blurred angular distribution.

The DR screen is constructed by lithographic technique starting from a silicon nitride wafer and opening two slits, one of 0.5 mm and the other of 1 mm aperture, by means of chemical etching. The slits on the DR screen are separated by 2 cm, and this space between the slits on the second DR screen without a mask, is used as a standard OTR (Optical Transition Radiation) screen. The main advantage of the silicon nitride with respect to SiO_2 [8] is a much less etching rate which preserves the silicon substrate from damages and makes the surface much more uniform. An aluminum layer is deposited by sputtering on the target to enhance the reflectivity.

ODR MEASUREMENTS

In the first phase of the experiment we had to cope with a very strong background of synchrotron radiation produced not only by the last dipole but also by some strong quadrupoles of the by-pass transport line. Although the distance of these optical elements was more than 40 meters far from our ODR screen, the vacuum pipe acted as an optical guide, producing the pattern shown in Fig. 3. The OTR angular distribution was almost covered and could be distinguished with difficulty.

A big effort, both in beam handling and software development, was required in order to reach a good background subtraction and the elimination of the “salt-and-pepper” noise produced by X-rays. At the end we were able to prove a good qualitative agreement between the experimental data and the simulations, as shown in Fig. 4.

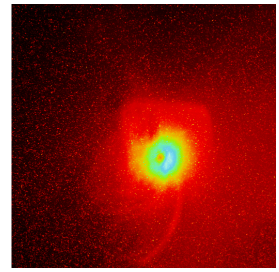


Figure 3: OTR angular distribution covered by the synchrotron radiation background.

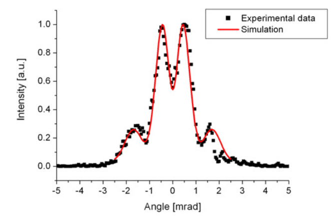


Figure 4: Experimental ODR profile, after background subtraction, and comparison with theory. Beam parameters: 680 MeV, 0.7 nC, 25 pulses, 2 s, 800 nm. Fit parameters: 610 MeV, 0.5 mm, σ_y=80 µm, σ_y'=125 µrad.

OPTICAL DIFFRACTION RADIATION INTERFEROMETRY

To reduce the synchrotron radiation background and to distinguish the effects of rms beam size and beam offset within the slit on the angular distribution, a stainless steel shield with larger cuts (2 mm and 1 mm, respectively) is mounted at 45^o respect to DR target. The electron beam direction is normal to the shield. The sketch of the screen and the shield is in Fig. 5.

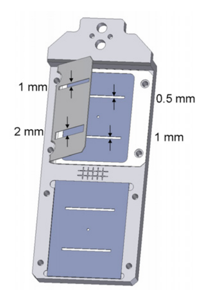
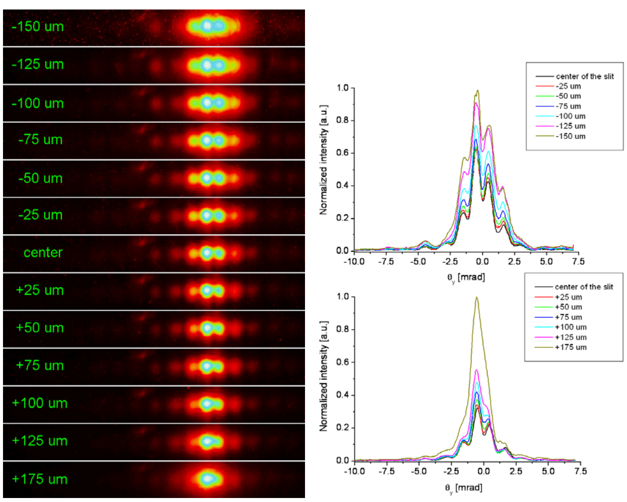


Figure 5: Sketch of the new screen together with its shielding mask.

In our experimental conditions, with an ODR emitted wavelength of 800 nm and 1 GeV electron beam energy, the size of the 1 mm cut on the shield is not large enough to prevent the production of ODR in forward direction. The forward ODR from the shield is then reflected by the DR screen and it interferes with backward ODR produced by the DR screen itself. The amplitudes of the two sources, i.e. forward emitted DR from the 1 mm slit and backward emitted DR from the 0.5 mm slit, are different both in intensity and in angular distribution, thus the interference results in the suppression of the central peaks and the enhancement of the side maxima.

A complete transverse scan of the beam position in the slit aperture has been carried out by moving the slit with respect to the beam position from one edge of the slit to the other edge. The results are shown in Fig. 6: the ODRI angular distribution image for different impact parameters is displayed on the left, the corresponding ODRI angular distribution profile is plotted on the right. We moved in steps of 25 µm around the slit center. Due to the fact that it is very hard to align the two slits with a precision of fractions of the emitted wavelength, a different behavior of the experimental distributions was supposed while going from the center of the slit to one edge or towards the other. For these ODRI measurements, FLASH was operated with 13 bunches per macropulse, 0.8 nC per bunch, 2 s CCD exposure time. Polarizer and interference filter to select the 800 nm wavelength were inserted.



(a) (b)

Figure 6: ODRI angular distribution image (left) and profile (right) for different impact parameters.

Fig. 6 shows strong asymmetrical ODRI angular distributions. This asymmetry can only be explained by assuming that the two half planes of the 0.5 mm slit are parallel but not perfectly coplanar. In this case, the field of a particle incident with angle α (in our case, $\alpha = \pi/4$) will be reflected by one half plane earlier than by the other. The phase difference between the two fields, in the approximation of $d << \gamma\lambda$ and $\beta \approx 1$, is $\phi_0 = 4\pi d/\lambda \cos\alpha$ (d is the longitudinal misalignment). A detailed discussion can be found [9].

The scan has been repeated with a smaller transverse beam size, σ_y=78 µm, in order to observe any slight change of the ODRI angular distribution. Let us now focus the attention on the ODRI angular distribution measured with the beam in the center of the 0.5 mm slit. The ODRI angular distributions for both transverse electron beam sizes (89 µm and 78 µm) are compared in Fig. 7 demonstrating the sensitivity of the experiment even on smallest variations of the transverse beam size in the order of a few micrometer.

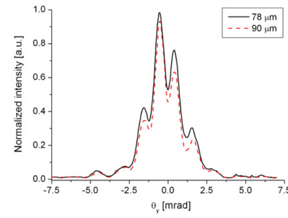
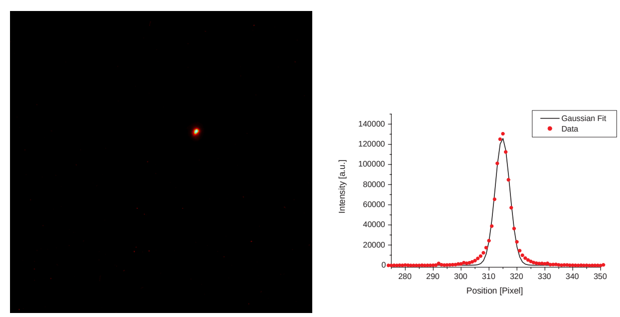


Figure 7: ODRI experimental angular distribution for two different rms vertical beam sizes, σ_y=78 µm and σ_y=89 µm.

The analysis of the Optical Transition Radiation (OTR) in both image and focal plane allowed the estimation of rms electron beam size (Fig. 8), energy and vertical angular divergence. Fig. 9 (left) shows the OTR angular distribution obtained with an integrated charge of 16 nC (4 bunches of 0.8 nC per macropulse with 5 Hz pulse repetition rate and 1 s camera exposure time). The synchrotron radiation back-

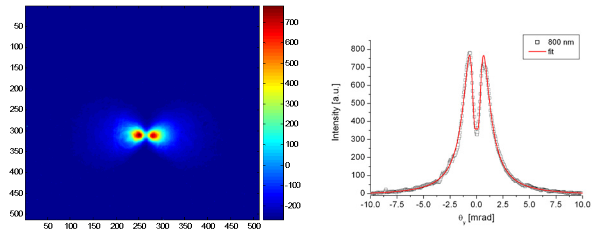


(a) (b)

Figure 8: OTR beam image (left) and its vertical projection (right). The estimated rms beam size is 89 µm.

ground is subtracted. The interference filter to select the 800 nm wavelength and the polarizer to select the vertical component are inserted. From the fit of the OTR angular distribution profile we estimate a beam energy of 870 MeV and a vertical angular divergence of 150 µrad.

In order to validate our experimental results, the fitting function has been modified with respect to the [6] formulas by the introduction of an additional phase term, which takes into account the unavoidable non planarity of the two halves of the slit at the level of fractions of wavelength. Furthermore, since the distance between the two screens is of the order of few centimeters, i.e. much less than the formation zone at this energy and wavelength, interference between the forward DR produced by the first slit and the backward DR coming from the second is observed. Thus, both misalignment and phase difference between the two slits are considered as additional fitting parameters. A



(a) (b)

Figure 9: OTR angular distribution (left) and its vertical profile, fit to retrieve beam energy and beam angular divergence (right). The fit takes into account the contribution of the angular divergence.

Gaussian distributed beam both in transverse beam size and angular divergence is assumed.

The results obtained by the fit are presented in Fig. 10 and Fig. 11 for the two beam sizes considered, showing a very good agreement with experimental data.

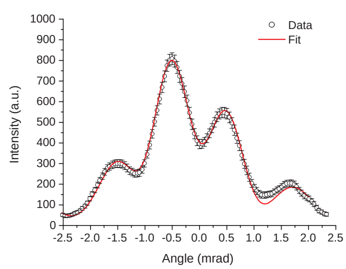


Figure 10: ODRI experimental angular distribution and fit which allows to retrieve beam and geometrical parameters. Fit parameters: 860 MeV, σ_y=83 µm, $\sigma_y^{'}$=200 µrad, Δy=12 µm.

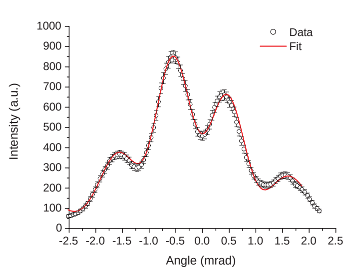


Figure 11: ODRI experimental angular distribution and fit which allows to retrieve beam and geometrical parameters. Fit parameters: 865 MeV, σ_y=70 µm, $\sigma_y^{'}$=263 µrad, Δy=13µm.

CONCLUSIONS

A detailed and quantitative study of the ODRI angular distribution, together with the analysis of the OTR in the image and focal plane, has allowed us to demonstrate the feasibility of a single shot emittance measurement in a phase space waist.

The advantage of using ODRI instead of ODR angular distribution is the chance to distinguish the effect due to the transverse beam size to the one due to the beam offset from center of the slit, which, otherwise, are equivalent. Furthermore, since the visibility of fringes is increased, the sensitivity to the beam dimension is higher.

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