OPTICAL DIFFRACTION RADIATION INTERFERENCE AS A NON-INTERCEPTING EMITTANCE MEASUREMENT FOR HIGH BRIGHTNESS AND HIGH REPETITION RATE ELECTRON BEAM

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Abstract

Conventional intercepting transverse electron beam diagnostics, as the one based on Optical Transition Radiation (OTR), cannot tolerate high power beams without significant mechanical damages of the diagnostics device. Optical Diffraction Radiation (ODR), instead, is an excellent candidate for the measurements of the transverse phase space parameters in a non-intercepting way. One of the main limitations of this method is the low signal to noise ratio, mainly due to the synchrotron radiation background. This problem can be overcome by using ODRI (ODR Interference). In this case the beam goes through slits opened in two metallic foils placed at a distance shorter than the radiation formation zone. Due to the shielding effect of the first screen a nearly background-free ODR interference pattern can be measured allowing the determination of the beam size and the angular divergence. We report here the result of the first measurements of the beam emittance using ODRI carried out at FLASH (DESY). Our result demonstrates the potential of this technique suitable to be used as non-intercepting diagnostic for accelerators operated with high brightness and high repetition rate electron beams.

INTRODUCTION

High brightness or high repetition rate beams can deposit a large amount of energy in the intercepting diagnostic devices, enough to destroy them. Non-intercepting devices are needed in order to avoid such a problem. The laser wire [1] is an attractive option, facing however tight mechanical and optical requirements. The angular distribution of far field Optical Diffraction Radiation (ODR) has been proposed several years ago [2] as non-intercepting device to measure the beam size, which is the fundamental parameter in order to determine the emittance value. In ODR based measurements, the beam goes through a hole in a metallic screen. When the radial extension of the electromagnetic field (in the order of $\gamma\lambda$, being γ the relativistic factor and λ the observed wavelength) is larger than the hole size, it interacts with the screen resulting in the emission of ODR.

The first measurement of the beam size ever using ODR has been realized at KEK [3], showing both the large potential of this technique as well as some unexpected problems. The Synchrotron Radiation (SR) background, produced by magnetic elements upstream the diagnostic station and scattered around the beam pipe, can hide or confuse the signal from ODR. Therefore, in order to avoid a systematic error in beam size measurements [2], ODR based technique requires a complementary diagnostic device to align the beam into the center of the slit.

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ODRI

A detailed description of the ODRI physics, as well as the used formulas and approximations, can be found in [4]. Here we just emphasize the principal features.

We considered the realization of an apparatus that can measure electron beam sizes down to ten of microns at an energy of about 1 GeV using DR emitted at optical wavelengths. All the dimensions in the following description can be rescaled in order to fit different scenarios. To shield the SR we have placed a second metallic screen with an aperture in front of the slit at a distance of a couple of centimeters. A schematic sketch of the layout is shown in Fig. 1.

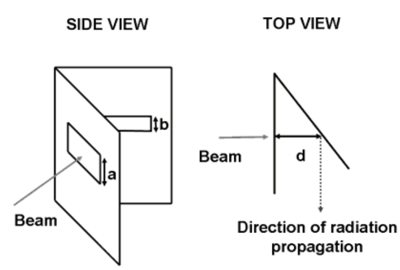

Figure 1: Sketch of the two-slits setup.

At GeV range energy the radiation formation length (L $\approx \gamma^2\lambda$) in the optical wavelength range is of the order of few meters. A metallic screen with 1 mm slit is placed normal to the beam axis. A second 0.5 mm wide slit, opened by means of lithographic technique on a silicon aluminized wafer, is placed at 45 degrees with respect to the beam axis. The distance between the centers of the two apertures is about 2 cm.

When a charge passes through the first aperture forward diffraction radiation (FDR) is emitted. It interferes with the backward diffraction radiation (BDR), produced by the interaction of the EM field with the second screen. The first screen acts also as a mask for the SR background. Although the best choice for SR masking would be the use of two identical slit apertures, the two DR fields would cancel,

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due to the small distance between slits (much smaller than the formation length), each other almost completely in this case. Our setup is a compromise allowing to have a reasonable shield against SR background and in the same time an overall intensity of the emitted radiation large enough to be detected.

The slits are not aligned on the same axis. In fact as pointed out in [4] a small displacement (50 μm) between them is needed in order to clearly distinguish the effect of the beam size and the beam angular divergence in the far field angular distribution.

WAKE FIELDS

To obtain a longitudinal and transverse wakefield for a structure closer to the real one, we have used CST Particle Studio [5]. The code allows us to determine the wake potential of a Gaussian bunch, but not the wakefield of a point charge. However, since we can assume with a very good accuracy that the electron bunch does not change when passing through the slit structure, we can determine the effects of the induced electromagnetic fields on the beam dynamics also by using the wake potential.

Due to the horizontal and vertical asymmetry of our setup, in which the first slit (perpendicular to the electron beam axis) is displaced by 50 μm vertically respect to the second one, we can not obtained the transverse wake potential per unit of displacement (so-called dipole wakefield with an off-axis source and an on-axis test charge [6]), but we have instead simulated an on-axis bunch and have evaluated the transverse electromagnetic fields on the bunch itself.

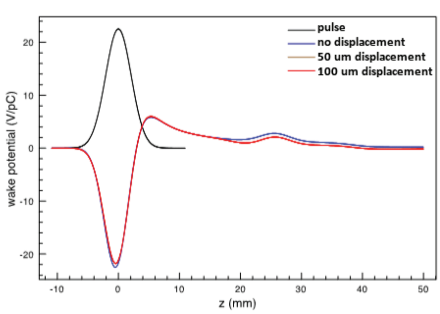

Figure 2: Longitudinal wake potential for different values of slit displacement.

The longitudinal wake potential is shown in the Fig. 2 for different vertical displacement of the first perpendicular slit. As can be seen from the figure, the longitudinal wake potential is independent from the displacement between the two slits. We have also verified that the wake potential does not depend on the assumed length of the beam pipe. The effects of the longitudinal wake potential on the bunch are an energy loss and an induced energy spread. For a charge of 200 pC, they correspond to an energy loss of 2.7 keV resulting in an energy spread of 1.6 keV, which, at 1 GeV, corresponds to a relative energy spread of 1.6 10^{-6}.

The effect of the transverse wake potential is a deflection of the charges inside the bunch. The average value of this deflection, which corresponds to an average kick received by the bunch when it crosses the system of the slits, gives a divergence of 3.6 10^{-7} rad for the horizontal case, and 1.3 10^{-7} rad for the vertical one. The latter is evaluated for a 50 μm slit displacement. Also in the transverse case, there is a spread of the divergence due to the dependence of the transverse wake on the longitudinal position along the bunch being equal to 1.4 10^{-7} rad for the horizontal plane, and 5 10^{-8} rad for the vertical one (50 μm misalignment).

From this wake field study we can conclude that, in all cases in our experimental scenario, the contribution from the longitudinal and transverse wake potentials on the energy spread and beam divergence can be neglected.

EXPERIMENTAL SETUP

In Fig. 3 the target holder is shown. A stainless steel block hosts a 1 mm slit. The complete block can be moved along two rails in front of a silicon aluminated screen with a 0.5 mm slit opened by means of a lithographic technique.

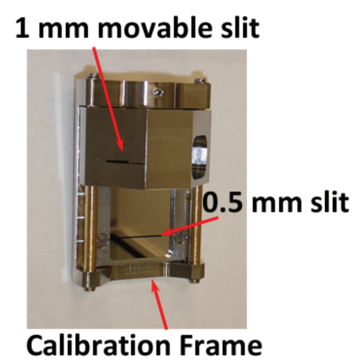

Figure 3: Photo of the target holder. Electron beam comes from the left of the picture. A calibration pattern is placed in the bottom part of the holder.

Radiation from the target is reflected by a mirror and transported through an optical system to the camera.

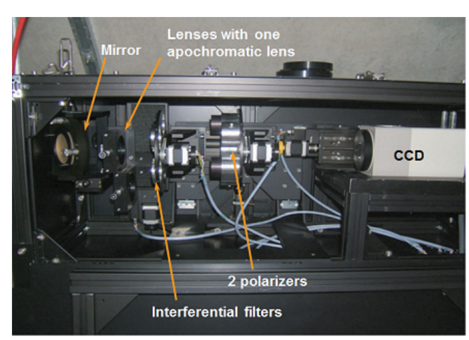

Figure 4: Photo of the optical measurement system. The electron beam line and the target chamber are beyond the system. The emitted radiation is collected by a mirror on the left and transported to the optical axis of the system.

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The optical system is composed by several elements that can be placed remotely on the beam axis. To image the beam we use an achromatic doublet with focal length f=250 mm, while an apochromatic lens (focal f=531 mm), properly designed to reduce the influence of the chromatic aberration, is implemented to obtain the ODRI angular distribution. Two filter wheels can hold several narrow band interference filters and two Glan-Thomson polarizers to select vertical and horizontal polarization. The polarizer lengthens the optical path, thus increasing the focal length. However, this change can be corrected by slightly changing the longitudinal camera position. A cooled, high sensitivity, 16-bit CCD camera (Hamamatsu ORCA II-BT-512G model type C4742-98-26LAG2) is used. The main advantages of such a camera is the very high quantum efficiency, even at 800 nm where it is still 0.8, and the negligible thermal noise.

The measurements have been performed at the FLASH free-electron laser user facility [7] at DESY (Hamburg). FLASH consists of an electron source to produce a high quality electron beam, followed by a superconducting linac with TESLA-type accelerating modules, and an undulator section to produce FEL radiation (see Fig. 5).

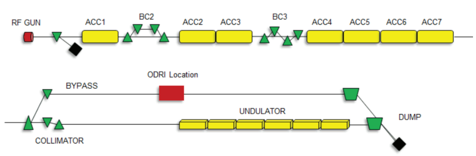

Figure 5: Layout of FLASH linac (not to scale). The location of the ODRI experiment on the bypass line is indicated.

Our experimental station is placed on the bypass line about 40 m away from the last bending dipole. During our measurements the electron beam energy was about 1 GeV and the typical number of bunches per bunch train 20. The bunch train repetition rate was fixed to 10 Hz. In our experiment, we used an electron bunch charge of about 0.2 nC. An integration time of 2 seconds resulted in a total integrated charge of 80 nC. This charge is high enough to damage a conventional aluminized OTR screen. Therefore, we carried out the OTR measurements with one single bunch with 0.2 nC charge.

DATA ANALYSIS

The data analysis has been performed using the Cernlib fitting routine *Minuit* [8] and the algorithm MIGRAD.

The angular distribution of the whole beam is simulated by summing up 5000 distributions produced by a single particle with different vertical positions within the slit as well as different angular divergences, both being Gaussian distributed. Since the resulting expression cannot be solved analytically, a Monte Carlo approach is used instead. The obtained results are entered into the *Minuit* routine. Every time when the fitting procedure changes the starting parameters, new distributions are generated through the Monte Carlo code. Our model makes use of far field approximation that it is consistent only when the slits displacement is very small as in our case. To test the validity of the approximation we collected several angular distributions with different wavelengths and polarizations.

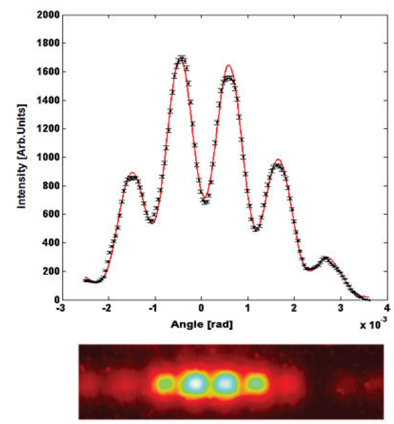

Figure 6: Top: angular distribution of the vertical polarized ODRI radiation at 800 nm with superimposed fit of data points. Bottom: image of the angular distribution on the detector. Fit results:σ_y=77 μm, $\sigma_{y'}$=203 μrad.

In Fig. 6 and Fig. 7 we compared angular distributions at 800 nm but with two different polarizations (vertical and horizontal, respectively).

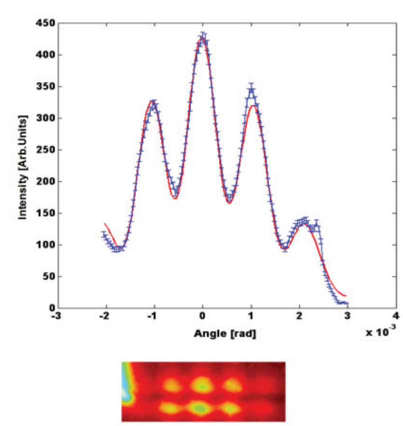

Figure 7: Top: angular distribution of the horizontal polarized ODRI radiation at 800 nm with superimposed fit of data points. Bottom: image of the angular distribution on the detector. Fit results:σ_y=70 μm, $\sigma_{y'}$=211 μrad, $\sigma_{x'}$=122 μrad

The determined values for beam size and divergence in case of both polarizations are consistent with each other confirming the validity of our method. From the horizontal polarization it is also possible to measure the horizon-

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tal angular divergence while the vertical polarization is not sensitive to this parameter.

EMITTANCE MEASUREMENT

The emittance has been measured by means of the quadrupole scan technique [9], using the last quadrupole before the target. Two quadrupole scans have been performed to compare and validate our result.The first one was intercepting, carried out by OTR imaging of a single electron bunch. The second one, totally non-intercepting, has been performed by analysis the ODRI angular distribution, produced by electron bunch trains with 20 bunches each traveling through the slits at 10 Hz repetition rate during a 2 seconds integration time. The large number of bunches was needed to increase the signal to noise ratio. In addition, at each value of the quadrupole current, we recorded two different ODRI angular distribution patterns. Between these two measurements the first slit was moved of about 25 μm with respect to the second one. In this way we obtained two data sets with only one parameter changed, i.e. the offset of the electron beam with respect to the center of the first slit. This constraint on the fit allows to improve the confidence of the measurement result.

The two quadrupole scans show a horizontal shift of about 0.3 A in the quadrupole current. This effect has been observed also in other quadrupole scans performed during this measuring day, resulting in the shift of the whole distribution by a comparable amount. The preliminary analysis of a different data set measured in a different day, does not indicate this problem. One reason might be the hysteresis in the iron yoke of the quadrupole. This artifact affects the emittance slightly (well below 1%), but increases the fit error by a factor of 3, due to a weaker correspondence between data and model. In order to correct that, we have shifted the horizontal axis of the second quadupole scan by 0.3 A. In Fig. 8 we report the result of the analysis.

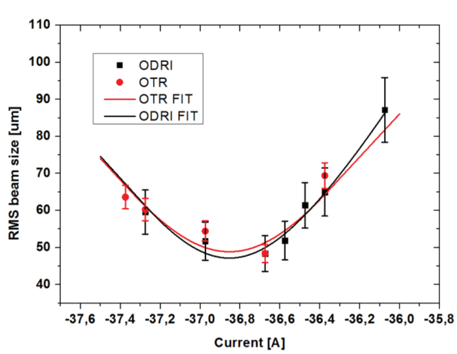

Figure 8: Quadrupole scan results. The beam sizes (rms) determined from ODRI angular distribution (black) and from OTR images (red) are shown as a function of the quadrupole current.

This is the first emittance measurement ever performed with the ODRI non-intercepting method. The ODRI model makes use of a Bi-Gaussian distribution both in position and in angular spread. To be consistent with the two methods, we fit the OTR projection with a Gaussian function and we use as the beam size the rms value of it. When we compare the emittance value determined by quadrupole scan we find that ϵ=3.8 (1.3) mm mrad for the ODRI and ϵ=3.7 (1.2) mm mrad for the OTR based technique. The error on the beam size measured by imaging the OTR corresponds to the standard deviation of the value calculated over 5 images. Unfortunately, due to the random nature of the Monte Carlo model, *Minuit* is not able to produce a fit of the ODRI distribution with error estimation. Therefore we associated at every measurement a 10% error, a value that produces a variation close to one unit in the normalized chi square. Despite of the total measurement error, the agreement between the two methods, both for the emittance values and the shape of the quadrupole scan curves, is very good.

CONCLUSIONS

We have shown that the ODRI effect can be successfully used as reliable non-intercepting technique which is able to measure the beam size with an accuracy sufficient to estimate the emittance by the quadrupole scan technique. We have reported here the first preliminary analysis of the non-intercepting quadrupole scan measurement obtained with such a system. The result has been compared to that retrieved with standard OTR, confirming a very good agreement.

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