NON-INTERCEPTING EMITTANCE MEASUREMENTS BY MEANS OF OPTICAL DIFFRACTION RADIATION INTERFERENCE FOR HIGH BRIGHTNESS ELECTRON BEAM

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Abstract

Conventional intercepting transverse electron beam diagnostics, e.g. based on Optical Transition Radiation (OTR), cannot tolerate high power beams without significant mechanical damages of the diagnostics device. Optical Diffraction Radiation (ODR) 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 unavoidable synchrotron radiation background. This problem can be overcome by using ODRI (Optical Diffraction Radiation Interference). In this case the beam goes through two slits opened in 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. Here we report the preliminary result of the first measurements of the beam emittance using ODRI carried out at FLASH (DESY, Germany). Our result demonstrate the unique potential of this technique.

INTRODUCTION

High brightness beams can deposit in the conventional intercepting diagnostic device a large amount of energy, resulting in a damage of it. Optical Diffraction Radiation (ODR) has been proposed already several years ago [1] as non-intercepting device capable to replace standard Optical Transition Radiation (OTR) monitors to measure the beam size and, by varying for instance the current of a quadrupole, also the emittance. In ODR based measurements, the beam goes through a slit or an hole in a metallic screen. If the radial extension of the electromagnetic field (in the order of $\gamma\lambda$) is larger than the hole size, it can interact with the metallic screen producing emission of ODR.

The first measurement of the beam size using ODR [2] has revealed the capability of this technique but also its limitations. The main problem is related with the Synchrotron Radiation (SR) background, produced by magnetic elements upstream the diagnostic station and scattered around the beam pipe. In order to avoid a systematic error in beam size measurements [1], ODR based technique requires a complementary diagnostic device to align the beam into the center of the slit.

ODRI

In our set-up 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.

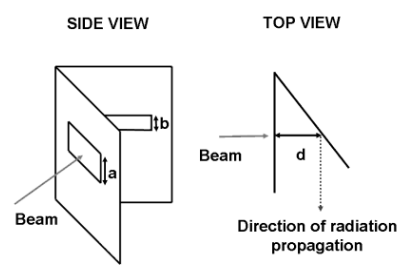

Figure 1: Sketch of the two-slits setup.

This apparatus has been designed for measurements with an electron energy in the range of 1 GeV. At such 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.

Forward diffraction radiation (FDR) is emitted when a charge passes through the first aperture. 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. Up to this point the best choice would be the use of two identical slit apertures. However in this case, due to the small distance between slits, which is much smaller than the formation length, the two DR fields would cancel each other almost completely. Our setup uses 1 mm and 0.5 mm wide slits, and it prevents the cancellation of the fields. This is a compromise allowing to have a reasonable shield against SR background and in the same time large enough total in-

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tensity of the emitted radiation.

A detailed description of the ODRI physics, as well as the used formulas and approximations, can be found in [3]. Here we just like to note one of the most important result addressed in [3]: it is possible to distinguish the contributions due to the beam transverse size σ and the angular divergence σ' in the ODRI angular distribution if the two slits are slightly misaligned with respect to each other (tens of microns). In all of our measurements we took care to fulfill this condition.

EXPERIMENTAL SETUP

The target holder is shown in Fig. 2. The first slit is realized over a stainless steel block. This block can be moved over two rails in vertical direction, spanning a large area over the second screen. The target holder is very compact and can be mounted into different kinds of vacuum chambers designed for beam imaging diagnostics.

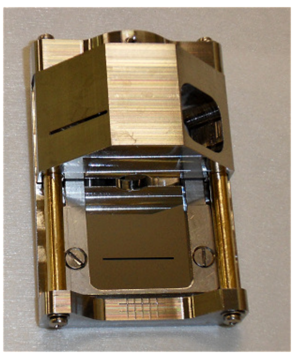

Figure 2: Photo of the target holder. The electron beam enters from left, and the produced radiation leaves the screen from the hole on the right. The first slit can be moved by a stepper motor into different vertical positions. A calibration pattern is visible in the bottom part of the holder.

The measurements reported here have been performed at the FLASH free-electron laser user facility ([4], [5]) 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. 3).

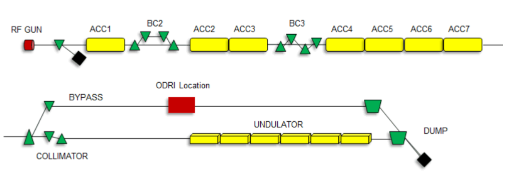

Figure 3: Layout of FLASH linac (not to scale). The location of the ODRI experiment on the bypass line is indicated.

In addition to the main beam line FLASH has a second electron beam line to bypass the undulators. Our experimental station is placed in this line about 40 m away from the last bending dipole. During our measurements the electron beam energy was around 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 only one 0.2 nC bunch charge.

Radiation from the target is reflected by a mirror and transported through an optical system to the camera. The optical system has both an achromatic doublet to image the beam and an apochromatic lens, properly designed to reduce the influence of the chromatic aberration, to obtain the ODRI angular distribution. The lenses have different focal lengths, f=250 mm and f=531 mm. 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 camera main features are the very high quantum efficiency in the whole visible spectrum, that it is still 0.8 at 800 nm, the negligible thermal noise, and therefore the possibility to use the long exposure time.

DATA ANALYSIS

The data analysis has been performed using the Cernlib fitting routine *Minuit* [6] and the algorithm MIGRAD.

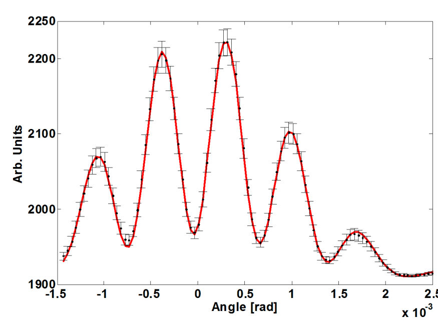

Figure 4: Example of a measured central profile of an ODRI angular distribution. The fit calculated by Minuit is superimposed (red line). The cut on the left of the angular distribution is due to a stray light reaching the camera.

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

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Carlo code. While the fit accuracy is very good (an example is shown in Fig. 4) the error estimation of the single parameter is not performed.

EMITTANCE MEASUREMENT

We have collected data in two separate runs, at observation wavelength of 800 nm and 500 nm. Here we report the first partial analysis of the first run at 800 nm and with the polarization normal to the slit edge.

The emittance has been measured by means of the quadrupole scan technique [7], using the last quadrupole before the target. Two quadrupole scans have been performed to compare and validate our result. The first one was intercepting, by OTR imaging of a single electron bunch, the second one, totally non-intercepting, looking at the ODRI angular distribution, produced by a 2s integration of 20 bunches traveling through the slits at 10Hz. The higher 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 of 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 of the quadrupole. This artifact affects the emittance slightly (well below 1%), but increases the fit error by a factor 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. 5 we report the result of the analysis. 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 we fit the OTR projection with a Gaussian and we plot here the rms of such a Gaussian. When we compare the emittance value determined by quadrupole scan we find that ϵ=3.7 (1.5) mm mrad for the ODRI and ϵ=3.6 (1.2) mm mrad for the OTR. 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 of one unit in the normalized chi square. Despite of the total measurement error, the agreement between the two

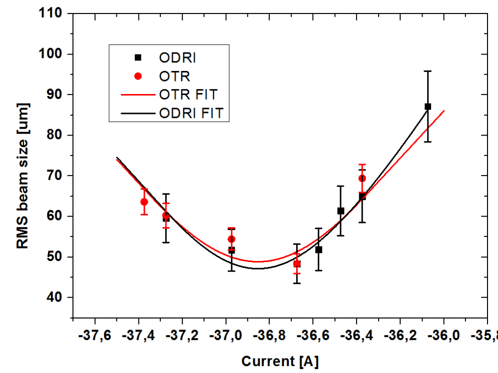

Figure 5: Quadrupole scan results. The beam sizes (rms) determined from ODRI angular distribution (black) and from OTR images (red) are shown as a function of the quadrupole current.

methods, both for the emittance values and the shape of the quadrupole scan curves, is very good

CONCLUSION

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 measurement. We report 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. Further analysis are in progress.

ACKNOWLEDGMENT

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REFERENCES

[1] M.Castellano, Nuc. Instrum. & Methods A 394, 275 (1997).

[2] P. Karataev et al., Physical Review Letters, 93, 244802, (2004).

[3] A. Cianchi et al. Physical Review Special Topics - Accelerators and Beams **14**, 102803 (2011)

[4] Ackermann W et al. 2007 Nat. Photon. **1**, 336

[5] K.Honkavaara et al., "Status of FLASH", IPAC 2012, New Orleans (USA)

[6] James F 1994 Minuit reference manual (Geneva, CERN)

[7] Minty M G, Zimmermann F 2003 Measurement and control of charged particle beams (Berlin, Springer-Verlag)

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