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Optical diffraction radiation for position monitoring of charged particle beams

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Abstract

In the framework of the future linear collider collaboration (CLIC, ILC), non-intercepting beam monitoring instruments are under development for very low emittance and high charge density beams. Optical Diffraction Radiation (ODR) was studied and developed during the last years focussing on beam size measurements. We propose in the paper to consider the use of Diffraction radiation for ultra relativistic beams as position monitors with applications for the centering of scrapers, collimators and targets with high resolution. We present the experimental results obtained using small aperture slits on the ATF2 extraction beam line at KEK and on the Cornell Electron Storage Ring with 1.2GeV and 2.1GeV electrons respectively.

Keywords: Optical Diffraction Radiation, non-interceptive beam instruments, Beam position monitor

1. Introduction

Optical transition radiation (OTR) refers to the electromagnetic field emitted by a charged particle when it crosses the boundary between two media of different dielectric constants [1]. Optical diffraction radiation (ODR) is a non-interceptive alternative to OTR, where the particle passes through a narrow aperture, i.e a slit or a hole (see [2] and references therein). The particle Coulomb field generates polarisation currents on the slit edges that in turn give rise to radiation, see Fig. 1.

During the last 20 years, beam size monitors have been developed based on the measurement of the ODR angular distribution [3] [4]. In this context we are performing experimental studies both on the ATF2 electron beam line at KEK [6], and on the Cornell Electron Storage Ring (CESR) [5]. In this paper we discuss the possibility to use diffraction radiation as a way to measure with micron scale resolution beam position in slits or collimators as an alternative to conventional electrostatic beam position monitors [8]. We present then a

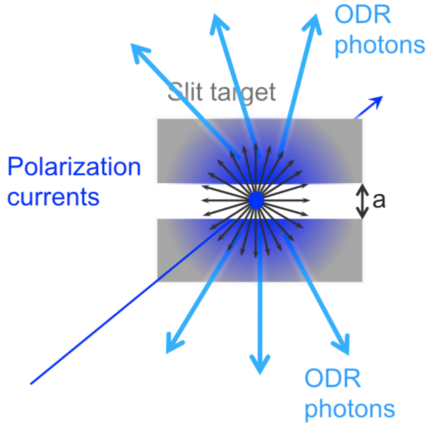

Figure 1: Schematic view of the ODR light production mechanism on the aluminimum target surface. Dark blue: electron beam . Light blue: ODR photons.

set of measurements, performed on the test facilities mentioned previously, showing beam position measurements in small slits using direct imaging of the ODR spatial distribution.

2. Beam position measurement using ODR

The intensity of the ODR light emitted by the edges of a slit depends on the observation wavelength, on the beam energy and on the relative position of the beam with respect to the slit [2]. The best sensitivity for ODR based position measurements is obtained when the slit aperture a is of the order of magnitude of the effective electromagnetic field radius of the charged particle defined by:

$$a \simeq \frac{\gamma\lambda}{2\pi}, \quad \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \tag{1}$$

where λ is the observation wavelength and γ the particle relativistic factor.

The graph, presented on Fig. 2, shows the single electron effective field radius as a function of wavelength both for the beam energy available at ATF2 (red), and CESR (blue). The horizontal lines correspond to the slit sizes we tested. The line crossing points would indicate the most favourable optical wavelength to be chosen in each configuration. This would suggest to work at 800 nm with a 0.5 mm slit on CESR and with 400 nm and 200 nm wavelength on ATF2 with slit apertures of 160 μm and 80 μm respectively. A typical vertically polarised single electron ODR spatial distribution presented on Fig. 3 was simulated using the field described in [7].

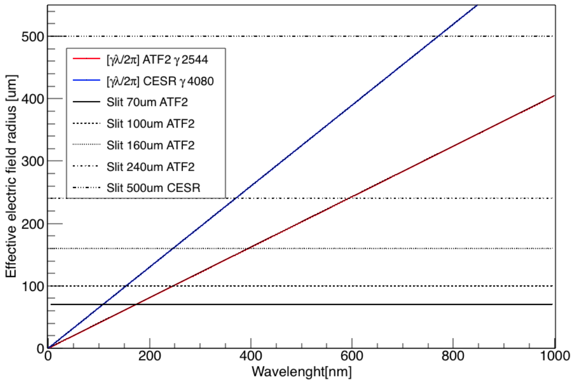

Figure 2: Wavelength versus ODR effective field radius. Used slit sizes are reported as horizontal lines.

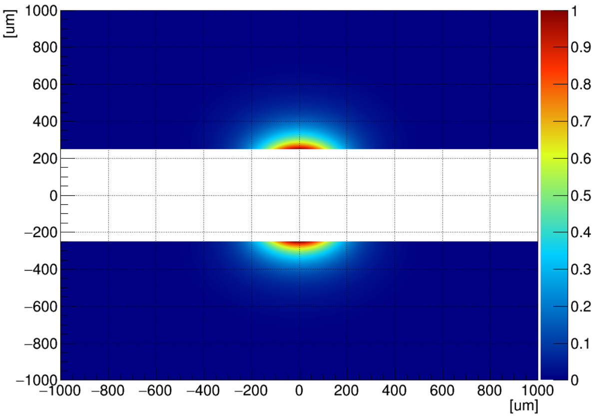

Figure 3: Simulated ODR spatial distribution on the surface of the 0.5 mm slit target at 400 nm wavelength. The 2.1 GeV electron is passing into the slit center.

Since the ODR effective field radius is of the same order of magnitude as the slit aperture, an electron bunch passing off-center will generate more light on one side of the slit than the other. The profiles presented on Fig. 4 are the projection along the vertical axis of the ODR field as shown on Fig. 3 for different beam offsets. The asymmetry between the two peak amplitudes emitted by the top and the bottom edges of the slit can be used to measure the beam position with respect to the slit center. The profiles visible in Fig. 4 are fitted to extract the peak amplitudes A_{top} and A_{bottom}, and the asymmetry is

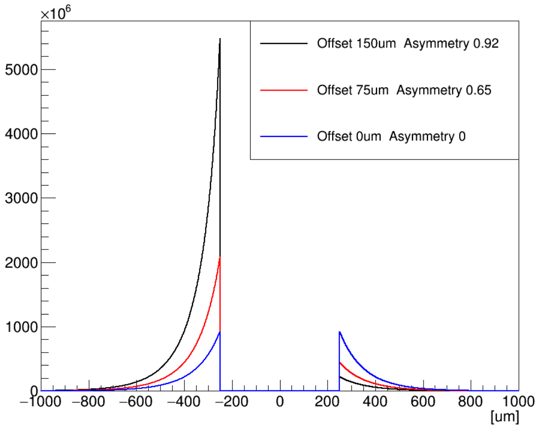

Figure 4: Vertical projections of the ODR spatial distribution simulated for different beam offsets with respect to the slit center.

evaluated using the formula (2).

$$Asym = \frac{A_{top} - A_{bottom}}{A_{top} + A_{bottom}} \qquad (2)$$

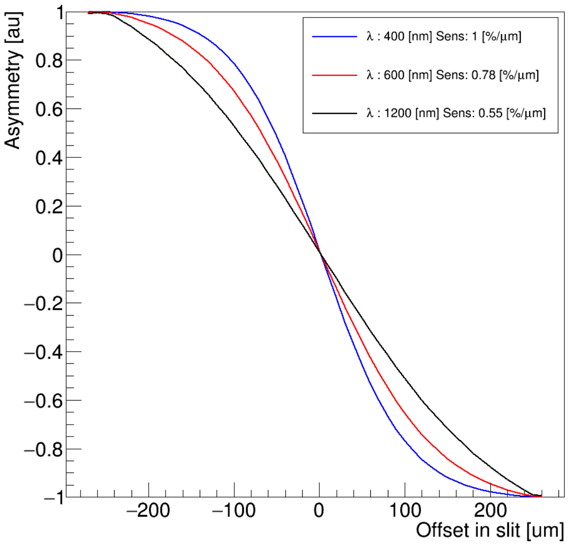

Figure 5: Simulations of the ODR vertical profile peak asymmetry for a 2.1GeV electron beam scanned into a 0.5mm slit (three wavelengths).

For a given beam energy and slit aperture, the choice of the observation wavelength is crucial and the asymmetry curve will change significantly depending on the wavelength in use. As shown on Fig. 5 assuming 2.1 GeV electrons, the response of the ODR BPM for a 1.2 μm wavelength is quite linear almost over the full slit aperture (0.5 mm), and provide a sensitivity of 0.55% asymmetry variation per micron. Using shorter wavelength will provide a higher sensitivity with, for example, 1.0% asymmetry variation per micron at 400 nm. In this case the total ODR photon flux is also smaller which needs to be taken into account when designing the optical line and selecting the imaging camera. When using shorter observation wavelength the linear dynamic range of the measurement will be reduced to a smaller region around the slit center since the photons yield emitted by the closest edge will increase exponentially for large beam offsets, whereas the photon yield emitted by the farthest edge will drop down below noise level. On the other extreme, using longer wavelengths will guarantee a comfortable light yield, a good linearity response to the beam position but a reduced position sensitivity. Thanks to the Fig. 2 and Fig. 5, an optimum wavelength can always be found depending on the beam energy and the target slit aperture.

3. The ODR station experiment in Willson Laboratory Cornell

The first ODR experimental station used for this study was installed in 2013 on the 2.1 GeV electron storage ring at Cornell Univeristy [5]. The 0.5 mm slit target has been designed in a fork shape that is typically inserted after beam injection (see Fig. 6). The vertical beam size can be focussed down to 10 microns at the ODR target location. Since the beam size is only about an order of magnitude smaller than the target slit aperture, scraping occurs and limits the beam life time. When the target is fully inserted the beam lifetime decreases to few minutes. Programmed steering bumps are being used to scan the beam position in the slit aperture keeping the orbit closure properly matched.

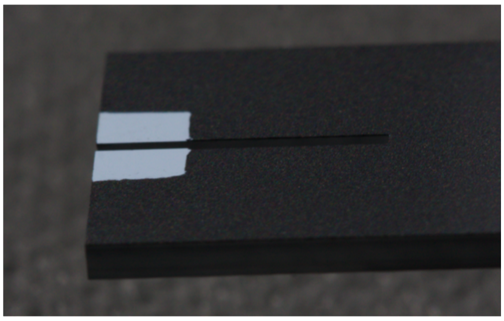

Figure 6: Picture of the ODR 0.5mm slit target used in CESR.

4. The ODR-OTR station experiment in KEK-ATF2

Since February 2016, a new ODR monitor has been installed on the 1.28 *GeV* virtual interaction point of the Accelerator Test Facility 2 (ATF2) at KEK Tsukuba Japan. This instrument was developed for two purposes: the profile measurement of sub-micron beam using the point spread function of optical transition radiation OTR, and the non-interceptive profile measurement of micron scale beams using optical diffraction radiation ODR (for very high beam charges densities) [6].

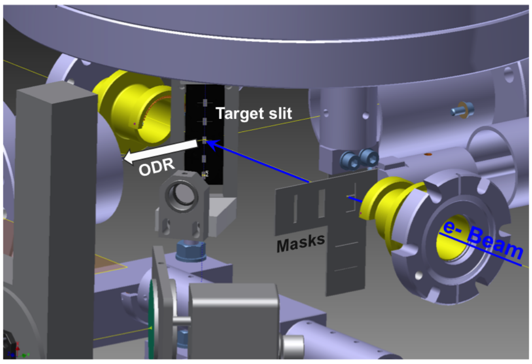

Figure 7: CAD drawing of the OTR-ODR station on ATF2 beam line.

A silicon target substrate has been coated with 30 *nm* of aluminum to improve the surface reflectivity. It features 4 ODR slits [50 − 200 *μm*] and one OTR plain mirrored area imaged by a f:30mm *in vacuum* lens. The target assembly is attached to a remotely controlled 5 axis actuator. Horizontal and vertical slit masks can be inserted upstream the target to shield from the synchrotron radiation background emitted from the ATF2 dipoles, see Fig. 7. When the ODR slits are used the light is extracted perpendicularly to the beam by tilting the target 45°. Two ODR optical lines are available: the first is dedicated to angular pattern observation, the second is a 1:1 imaging line. The measurements that we present into this document where obtained with the imaging line. It is composed of a f : 150 *mm* achromat doublet and a low noise scientific CMOS camera triggered according to the bunch arrival signal. A motorised polariser and a band-pass filter wheel allow to observe the different polarisation components and wavelengths of the ODR emission.

5. Experimental results

The response of the ODR image profile asymmetry was measured scanning the beam inside the slit by means of steering magnets. A typical experimental ODR profile can be seen Fig. 8. The spherical and chromatic aberrations of the optical system, and the quality of the slit edges, lead to a non zero light intensity inside the slit for the recorded experimental profile. The relative position of the beam into the target aperture was extracted from steering magnet's current and compared with the ODR asymmetry ratio. Steering magnet current was calibrated with conventional electrostatic beam position monitors at the beginning of the shift. The zero crossing is found when the two ODR lobes have the exact same amplitude.

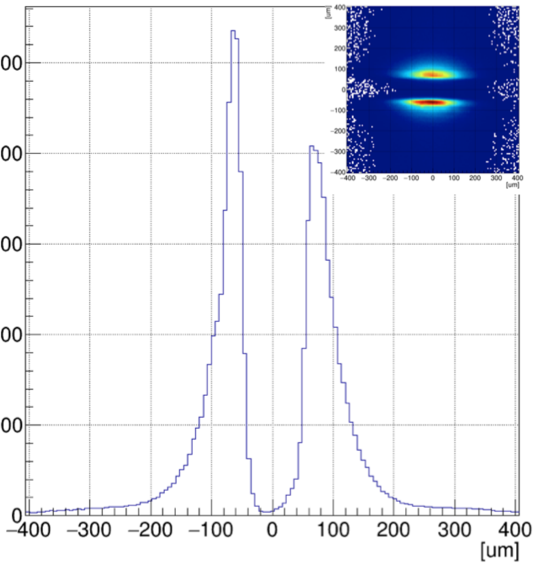

Figure 8: ODR pattern and profile on the ATF2 100 *μm* slit 600 *nm* filter.

5.1. ATF2 measurement

The ATF low emittance damping ring the beam energy is about 1.3GeV so the Lorentz factor of the extracted electrons in ATF2 is $\gamma = 2544$. The beam position dependance presented Fig. 9 was recorded scanning the beam into a 50 *μm* ODR slit, and using a 600 *nm* band-pass filter (BW 40*nm*).

According to the measurement, the asymmetry to position response is quite linear. The sensitivity is about 4% asymmetry variation per micron. The slight deviation from the linear response is due to the hysteresis of the steering magnet since the expected beam position was extracted from the magnet current.

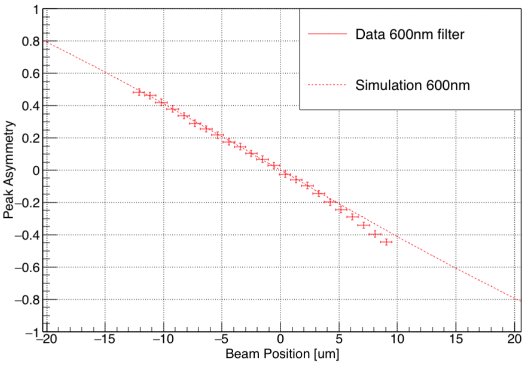

Figure 9: Asymmetry vs beam position for ATF2 50 μm target.

5.2. *CESR measurement*

In the case of the Cornell electron storage ring, the 2.1GeV energy translate into $\gamma = 4080$. The two measurements are presented on Fig. 10, for 600 *nm* and 400 *nm* band-pass filter (BW 40*nm*). In both case we scan the beam in the same 500 μm slit aperture target.

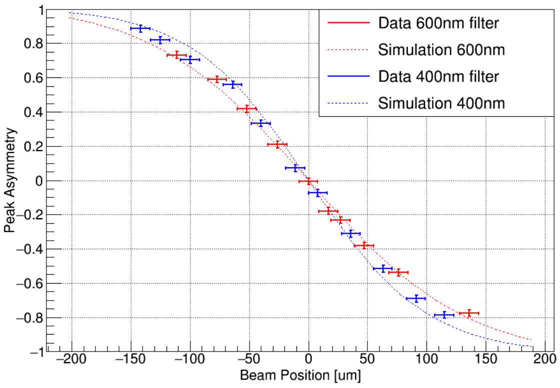

Figure 10: Asymmetry vs beam position for the CESR 500 μm slit target.

Close to the slit center, the sensitivity is found to be 0.78 and 1.0% asymmetry variation per micron, respectively for 600 *nm* and 400 *nm* observation wavelength. The data and simulation are in good agreement and the wavelength dependency on the non linearity response was confirmed. However there is a slight deviation between simulation and experiment which is again due to the hysteresis of the steering magnet used in order to scan beam inside the slit.

6. Conclusions

We have reported the successful operation of optical diffraction radiation slits for beam position monitoring. By carefully selecting the slit aperture and the observation wavelength, one can optimise the beam position monitoring range and sensitivity for possibly any beam energy. When using large slit apertures, detecting in the infrared domain would offer a better sensitivity. In a similar way, studies have been initiated to evaluate the capability of using Cherenkov diffraction radiation instead of diffraction radiation since the expected light yield from longer dielectric material should produce a higher photon flux.

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