UV/X-RAY DIFFRACTION RADIATION FOR NON-INTERCEPTING MICRON-SCALE BEAM SIZE MEASUREMENT

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Abstract

Diffraction radiation (DR) is produced when a relativistic charged particle moves in the vicinity of a medium. The electric field of the charged particle polarizes the target atoms which then oscillate, emitting radiation with a very broad spectrum. The spatial-spectral properties of DR are sensitive to a range of electron beam parameters. Furthermore, the energy loss due to DR is so small that the electron beam parameters are unchanged. Therefore DR can be used to develop non-invasive diagnostic tools. The aim of this project is to measure the transverse (vertical) beam size using incoherent DR. To achieve the micron-scale resolution required by CLIC, DR in UV and X-ray spectral-range must be investigated. During the next few years, experimental validation of such a scheme will be conducted on the CesrTA at Cornell University, USA. Here we present the current status of the experiment preparation.

INTRODUCTION

Over the last 30 years Optical Transition Radiation (OTR) [1] has been widely developed for beam imaging and transverse profile measurement. However OTR based systems are invasive and do not permit the measurement of high charge density beams without risking damage to the instrumentation. Beam diagnostics using Diffraction Radiation [2, 3] has been proposed as an alternative [4, 5].

In the optical wavelength range the use of diffraction radiation (ODR) as a high-resolution non-invasive diagnostic tool for transverse beam size measurement has been widely investigated; at the Advanced Test Facility at KEK in Japan [6], at the FLASH test facility at DESY [7] and at the Advanced Photon Source at Argonne, USA [8]. At ATF2 the achieved beam size sensitivity was as small as 14 µm [9].

For next generation linear colliders such as the Compact Linear Collider (CLIC) [10], transverse beam size measurements must have a resolution on the micron-scale. Currently, laser wire scanners [11] are the main candidate for non-invasive high resolution measurements. However, over a distance of more than 40 km many laser wire monitors would be required. This is both costly and difficult to maintain- DR could offer a simpler and cheaper alternative. However as expected theoretically [12], the DR sensitivity to beam size becomes negligible at extreme beam energies. Our aim is to develop a non-invasive beam size monitor with micrometer resolution for electron and positron beams

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Table 1: Phase 1 Experiment Parameters for CesrTA [13] and Comparison with the CLIC Damping Ring Complex [14]

	E (GeV)	σ_H (µm)	σ_V (µm)
CesrTA	2.1	320	∼9.2
	5.3	2500	∼65
CLIC	2.86	∼10-200	∼1-50

of a few GeV energy. In the CLIC machine layout [15], these devices would then be used both from the Damping ring exit to the entrance of the Main beam linac and in the CLIC Drive beam complex (2.4 GeV).

The Cornell Electron Storage Ring, with beam parameters as shown in Table 1 was primarily reconfigured as a test accelerator (CesrTA) [16] for the investigation of beam physics for the International Linear Collider damping rings. An experimental program was recently proposed to develop and test a Diffraction Radiation monitor to be installed in the straight section of the ring where small beam sizes can be achieved. The sensitivity to beam-size is improved at shorter observation wavelengths, so the experimental program has been divided into two consecutive phases. The first phase, we are currently implementing at the moment aims to measure the beam size in the 20–50 µm range using visible and UV light. If successful a second phase will be launched in order to push the detector sensitivity down to few micrometers using shorter wavelengths in the soft x-ray range. This paper presents the current status of our work.

SIMULATIONS

ODR Model and the PVPC

The ODR model considers the case when a charged particle moves through a slit between two tilted semi-planes i.e. only DR produced from the target is considered. The author of [17] has shown that the vertical polarisation component is sensitive to beam size. In [18], the expression for the ODR vertical polarisation component convoluted with a Gaussian distribution is given and shown here in Eq. 1 where α is the fine structure constant, γ is the Lorentz factor, θ_0 is the target tilt angle, $t_{x,y} = \gamma\theta_{x,y}$ where $\theta_{x,y}$ are the radiation angles measured from the mirror reflection direction, λ is the observation wavelength, σ_y is the rms vertical beam size, a is the target aperture size, $\overline{a_x}$ is the

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offset of the beam centre with respect to the slit centre and $\psi = \arctan\left[\frac{t_y}{\sqrt{1+t_x^2}}\right]$. This model is applicable when the transition radiation contribution from the tails of the Gaussian distribution is negligible- approximately $a \geq 4\sigma_y$.

$$\frac{d^2W_y^{slit}}{d\omega d\Omega} = \frac{\alpha\gamma^2}{2\pi^2}\frac{\exp\left(-\frac{2\pi a\sin\theta_0}{\gamma\lambda}\sqrt{1+t_x^2}\right)}{1+t_x^2+t_y^2}$$
$$\times\left\{\exp\left[\frac{8\pi^2\sigma_y^2}{\lambda^2\gamma^2}(1+t_x^2)\right]\cosh\left[\frac{4\pi\overline{a_x}}{\gamma\lambda}\sqrt{1+t_x^2}\right]\right.$$
$$\left.-\cos\left[\frac{2\pi a\sin\theta_0}{\gamma\lambda}t_y+2\psi\right]\right\} \tag{1}$$

Generally, DR intensity is inversely proportional to the aperture size and the sensitivity to beam size is inversely proportional to the observation wavelength. The sensitivity to beam size is dependent on the visibility (I_{min}/I_{max}) of the DR angular distribution. Therefore the maximum and minimum intensities of the DR angular distribution must be measured accurately. Measuring the maximum intensity (I_{max}) is normally straightforward, however the minimum intensity (I_{min} at $t_y = 0$) measurement is not trivial limited by background and noise. The minimum intensity must be above background and camera noise.

Using Eq. 1, the DR angular distributions (t_x = 0) at observation wavelengths 200 nm and 400 nm with aperture sizes of 0.5 mm and 1.0 mm were plotted for different beam sizes (see Fig. 1). The DR intensity is normalised to the far field transition radiation maximum (TR_{max}) shown in Eq. (2) [2].

From these results it was found the limiting beam sizes at 400 nm and 200 nm observation wavelengths are approximately 25 µm and 15 µm respectively. For the first test of the prototype, the initial experiment set-up using 400 nm observation wavelength, 1.0 mm target aperture size and 50 µm beam size was identified to have measurable visibility.

$$\frac{d^2W_{TR}^{max}}{d\omega d\Omega} = \frac{\alpha\gamma^2}{4\pi^2} \tag{2}$$

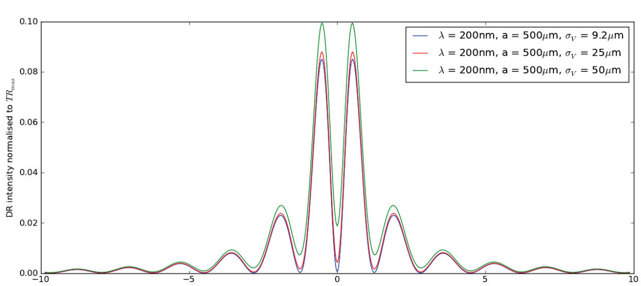

Figure 1: DR angular distributions at different beam sizes for E = 2.1 GeV, a = 0.5 mm and λ = 200 nm.

Generally, increasing the beam energy broadens the angular distribution and increases the peak light intensity. In Fig. 2 it is seen that the sensitivity to beam size decreases with beam energy.

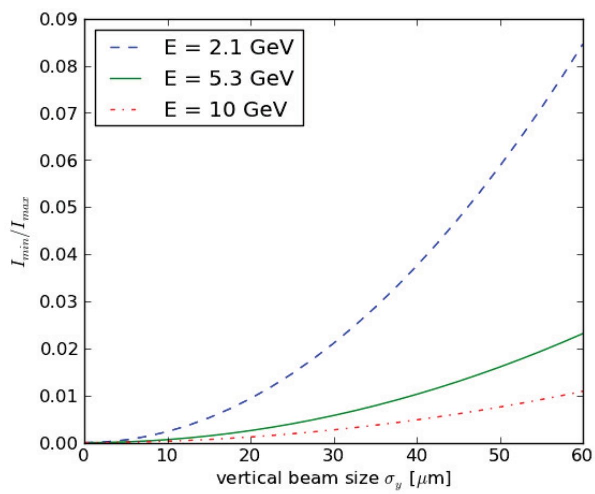

Figure 2: Sensitivity to beam size at different beam energies for λ = 400 nm, a = 1 mm and σ_y = 50 µm.

The projected vertical polarisation component (PVPC) is a technique which takes the vertical (y) projection of the 3-dimensional (θ_x, θ_y, intensity) DR angular distribution. The y-projection is obtained by integrating over the horizontal angle θ_x. The visibility and hence beam size is then measured from the y-projection [18].

The PVPC method collects more DR photons emitted from the target. In turn this improves the sensitivity to beam size since the minimum intensity of the DR angular distribution is further displaced from zero above background.

Synchrotron Radiation

Synchrotron radiation (SR) is the main source of background in DR measurements [19]. A significant proportion of background is stopped by the optical system since a narrow bandwidth and vertical polarisation are selected. Background is further reduced by positioning a mask upstream of the target. Synchrotron Radiation Workshop (SRW) [20] was used to simulate the effectiveness of this mask.

In this simulation, a 0.5 mm target aperture and 2 mm mask aperture were considered. The beam energy was 2.1 GeV at a maximum current of 10 mA. The B48 bending magnet is the nearest principle source of SR upstream of the DR experiment location. It is approximately 10 m upstream of the target and has 0.0498 T magnetic field [13]. The observation wavelength was 400 nm with a 10% bandwidth.

To compare with DR, the y-projection was obtained and normalised to the well understood OTR at similar beam parameters (E = 2 GeV, λ = 390-410 nm) such that the total

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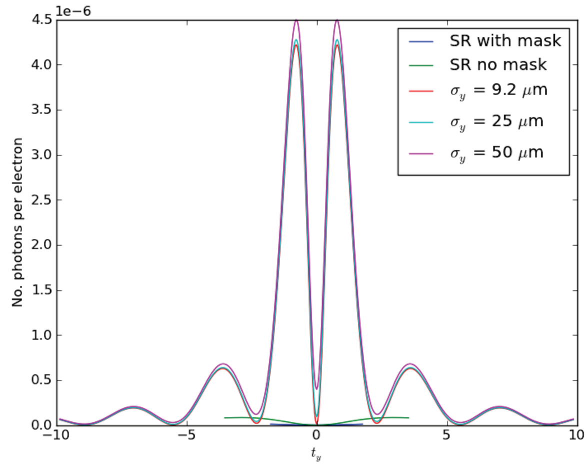

Figure 3: Comparison of DR vertical projections and SR background at E = 2.1 GeV, λ = 400 nm and a = 0.5 mm.

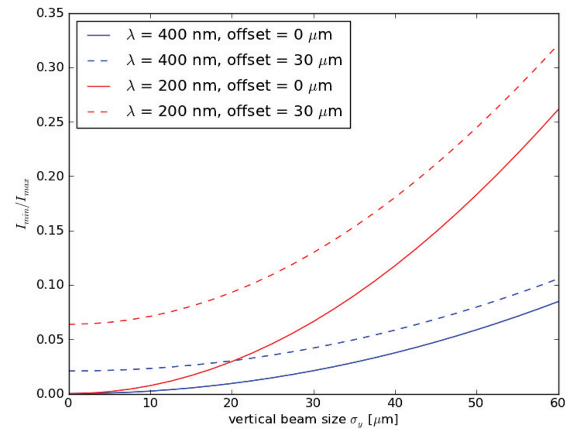

Figure 4: Beam size sensitivity at λ = 200 and 400 nm, E = 2.1 GeV and a = 1.0 mm with and without beam jitter.

photons per electron was 3×10^{-4} [21]. In Fig. 3 the SR background reflected by the target is compared with the y-projections of DR angular distributions. The SR background may be comparable to DR. In [22] it is seen that it is impossible to obtain DR beam size measurements with SR contribution due to interference. Therefore SR must be suppressed and the use of a mask upstream of the target is a common feature in DR experiments.

Beam Jitter

Beam offset from the aperture centre affects the visibility of the angular distribution introducing errors in the DR beam size measurement. Figure 4 shows the sensitivity to beam size for 0 µm and 30 µm beam offset at 200 nm and 400 nm observation wavelengths, 2.1 GeV beam energy and 1.0 mm target aperture size. It is seen that problems arise when the beam offset is unknown and the zero beam offset sensitivity curve is no longer valid. By monitoring the beam position turn-by-turn, the beam offset turn-by-turn can be included in the simulations and data fitting procedure such that the true beam size is obtained.

EXPERIMENTAL SET-UP

The phase 1 experiment will be located in the L3 straight section of CesrTA. The machine parameters at this location are given in Table 1. This experiment will primarily run at an electron beam energy of 2.1 GeV. An overview of the DR tank is shown in Fig. 5. Inside the vacuum chamber there is a section of beam pipe, which is moved out of the way during DR experimental sessions, but which is required during high current operations for CESR to minimize the higher order mode loss for the stored beams.

Target Design

The target and mask assembly are shown in Fig. 6 where the mask is a few centimetres upstream of the target. The

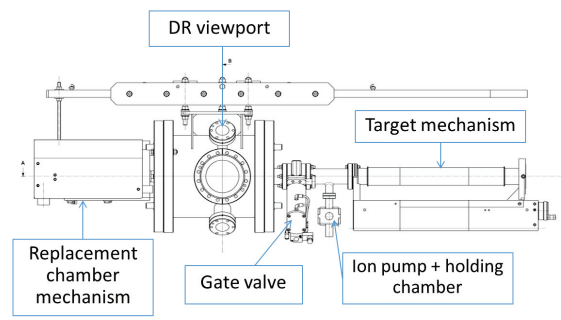

Figure 5: Overview of the DR tank. Electron beam direction is into the page [23].

target will be made out of Silicon with very strict requirements on the surface flatness (20 nm) and roughness (0.3 nm rms). The target tilt angle θ_0 with respect to the electron beam is 70°. This tilt angle has been chosen as the optimal angle to ensure the effective aperture size the beam must pass through is only slightly smaller than the aperture size measured in the plane of the slit. The mask will be based on a similar design but with a relaxed tolerance on the surface quality and will therefore be machined out of Silicon Carbide.

Experimentally, the target aperture size might also limit the beam lifetime and beam scraping must be avoided. The

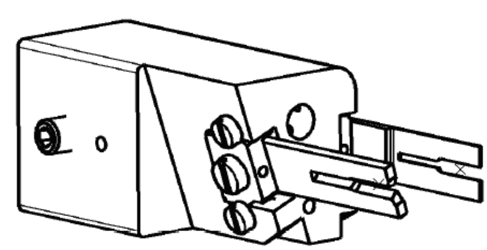

Figure 6: Target and mask assembly [23].

beam lifetime with the target inserted must be long enough for the beam alignment procedure and for the DR beam size measurement. Calculations found the requirement that the aperture size should be at least $7 - 10\sigma_y$ [13] therefore the slit size will range from 0.5-1.0 mm.

Optical System

The optical system must be a dual purpose system, to image the target and also to observe the DR interference pattern. An achromatic lens is used to control the magnification whilst imaging the target. To switch to DR operation, the achromatic lens is removed and replaced by a bi-convex lens (see Fig. 7). A compact system is preferable for alignment and installation although this introduces some complications when imaging the DR angular distribution as the detector will be located within the prewave zone [24]. The system is inside a black box to reduce background.

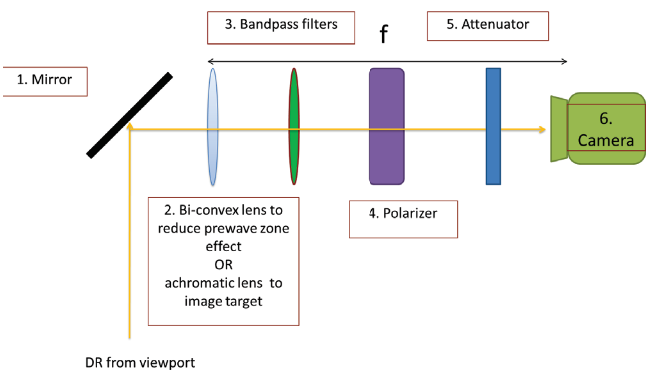

Figure 7: Schematic of optical system.

Figure 7 shows the main optical components. Bandpass filters are used to select the wavelengths of interest. A polariser is required to select the vertical polarization component which carries the vertical transverse beam size information. The same camera will be used for imaging the target and the DR angular distribution. It should be suitable for wavelengths from the UV - visible range. Radiation hardness may be problematic so some shielding should be foreseen.

METHOD OF OPERATION

The positioning of downstream radiation detectors will monitor the particles lost from the beam when the target is inserted. In addition to these Beam Loss Monitors (BLMs), target imaging and a 4-button Beam Position Monitor (BPM) can also be used to initially align the electron beam to pass through the mask and target apertures. Once aligned, the DR measurement will begin. The optical system will be aligned using a laser and mirror upstream of the ODR tank. This laser will send light along the electron beam trajectory. It will then reflect off the target and through the DR viewport to the optical system.

FUTURE WORK

Phase 2 Micron Resolution

The aim of the phase 2 experiment is to measure the vertical beam size on the micron scale using DR at soft X-ray wavelengths. The sensitivity to beam size for 5.3 GeV beam energy is shown in Figure 8 for different wavelengths. At 50 nm beam sizes below 10 μm should be obtainable using a reasonable target aperture.

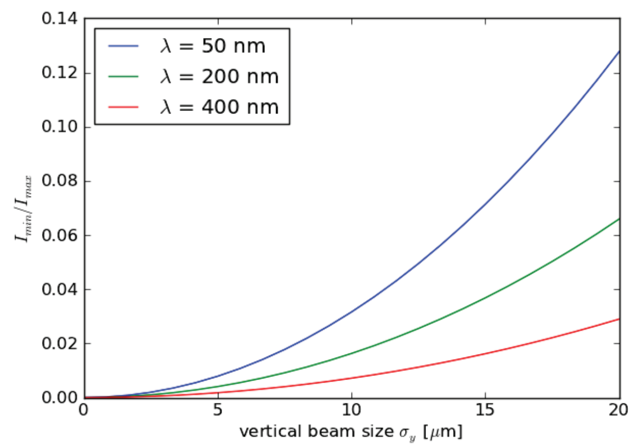

Figure 8: Sensitivity to beam size at λ = 50 nm (phase 2) and λ = 200 nm, 400 nm (phase 1). The target aperture is 0.2 mm.

Feasibility of a Ring Beam Size Monitor

Following the study initiated in this work, DR beam size measurements may also be applicable for protons and ring accelerators assuming that the particles are ultrarelativistic. Here we consider the case for the Large Hadron Collider (LHC) with 4 TeV beam energy. Typically the beam size ranges from 0.2 mm to a few mm. The observation wavelength is in the infra-red spectral range. The sensitivity to beam size for different target aperture sizes is shown in Fig. 9. Using a proton beam also relaxes some of the requirements in the target fabrication and reduces the contribution of synchrotron radiation.

Figure 10 shows the DR angular distributions at various target aperture sizes with 4 TeV protons, 1.0 mm vertical beam size and 10.3 μm observation wavelength. For circular machines, a compromise would have to be met between larger aperture sizes, crucial for circular machines and the corresponding decrease in DR intensity.

SUMMARY AND CONCLUSION

Simulations have demonstrated the feasibility of vertical beam size measurements at CesrTA. The phase 1 experiment is planned for the end of December 2012 for which the design and vacuum assembly are close to completion. The design must also account for the experiment location in a circular machine. This introduces some advantages and

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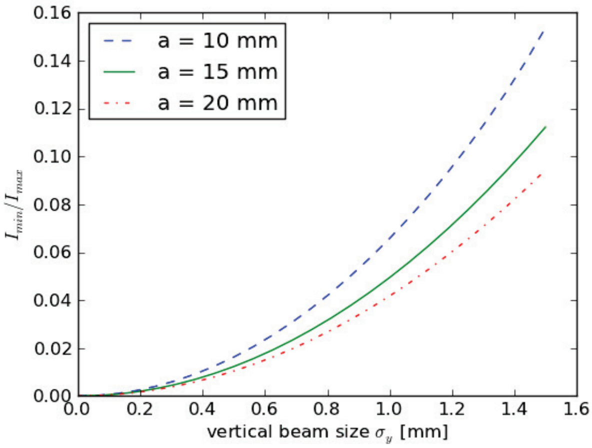

Figure 9: Sensitivity to beam size for the LHC at different target apertures.

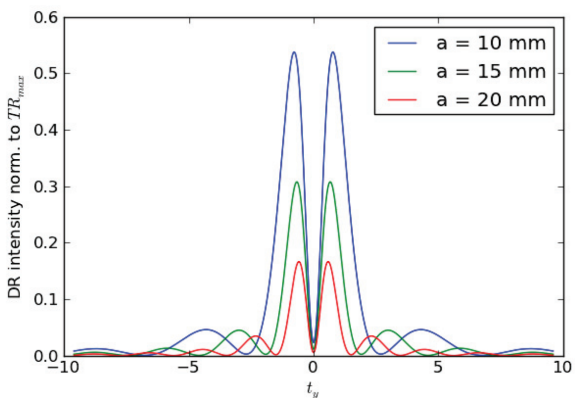

Figure 10: DR angular distributions at different target aperture sizes for the LHC (λ = 10.3 µm, σ_y = 1 mm).

disadvantages not applicable for linacs. Preliminary simulations for the phase 2 test aiming for the soft x-ray spectral range have been presented and show that to achieve micron-scale resolution, wavelengths must be shorter than 50 nm. In addition, the feasibility of DR diagnostics on other accelerators has been considered such as simulations for transverse beam size measurements at the LHC.

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