DIFFRACTION RADIATION TEST AT CesrTA 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 polarises 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. DR can therefore be used to develop non-invasive diagnostic tools. To achieve the micron-scale resolution required to measure the transverse (vertical) beam size using incoherent DR in CLIC, DR in UV and X-ray spectral-range must be investigated. Experimental validation of such a scheme is ongoing at CesrTA at Cornell University, USA. Here we report on the test using 0.5 mm and 1 mm target apertures on a 2.1 GeV electron beam and 400 nm wavelength.

INTRODUCTION

Next generation linear colliders such as the Compact Linear Collider (CLIC) [1] typically operate using high charge density beams. Therefore beam size measurement using invasive optical transition radiation (OTR) based systems cannot be used without risking damage to the instrumentation. For this reason, DR is being investigated as a non-invasive alternative [2] [3]. The transverse beam size can be measured by using direct target imaging [4] or the angular distribution of DR [3] [5]. At ATF2 the achieved beam size sensitivity using angular distribution measurements was as small as 14 μm [6].

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

	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

CesrTA with beam parameters as shown in Table 1 was primarily reconfigured as a test accelerator [7] for the investigation of beam physics of the International Linear Collider damping rings. At CesrTA we are conducting the first DR beam size measurement experiment on a circular machine. CesrTA provides a high energy 2-5 GeV electron or positron beam and the possibility to measure small beam sizes. This allows the study of wakefields and synchrotron radiation associated with DR monitors on circular machines. Here we can test the applicability of DR monitors for machines other than CLIC such as the LHC which has a comparable Lorentz factor.

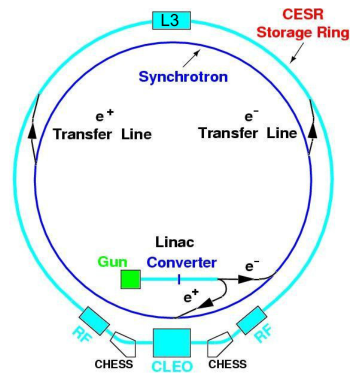

Figure 1: Layout of CesrTA [8].

The DR experiment will run in two phases. In Phase 1 DR is measured in the near optical to UV regime. In Phase 2 the optical system must be redesigned such that DR at X-ray wavelengths can be measured. Over the last year, the first phase of the experimental program has been implemented whereby hardware has been installed and data acquisition is ongoing.

EXPERIMENT SET-UP

The DR experiment is located in the L3 straight section of CesrTA (Fig. 1). Directly attached to the DR vacuum chamber is a 4-button beam position monitor (BPM). This BPM is located approximately 30 cm upstream of the DR target. Another BPM is located 30 cm downstream of the target in the electron beam direction. The X-ray beam size monitor (xBSM) [9] is used to measure the vertical beam size σ_y and is located at the CHESS synchrontron radiation (SR) station (see bottom-left of Fig. 1). The visible beam size monitor (vBSM) [10] is used to measure the horizontal beam size σ_x and is located in L3 approximately 10 m upstream of the DR target.

An overview of the DR tank is shown in Fig. 2. 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 CesrTA to minimize the higher order mode loss

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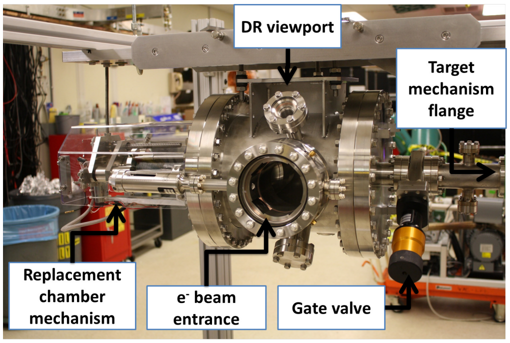

Figure 2: View of the DR target vacuum chamber from the upstream direction.

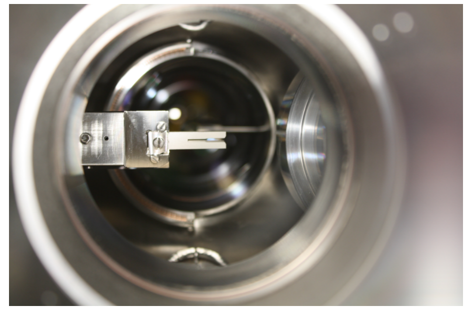

Figure 4: Dummy target in the vacuum chamber viewed from the downstream direction.

for the stored beams. On the opposite side of the chamber the target is attached to a mechanism with two degrees of freedom: translation IN/OUT and rotation about this axis. The compact optical system shown in Fig. 3 consists of an achromat for target imaging, a biconvex lens for imaging the angular distribution in the prewave zone [11], a bandpass filter, a Glan-Laser polariser and an intensified CCD (ICCD) camera .

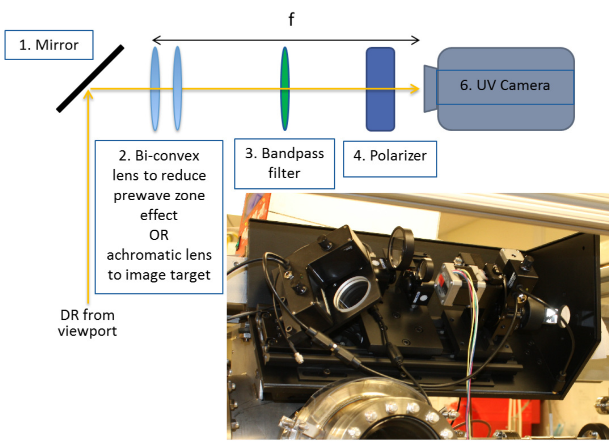

Figure 3: Schematic and image of the optical system.

DIFFRACTION RADIATION TESTS

The first step at CesrTA was to install and test the vacuum chamber, optical system and controls and also to pass a single bunch electron beam through a target aperture. A dummy target was machined from unpolished stainless steel with aperture sizes of 0.5 and 1 mm (see Fig. 4). The apertures were etched. The reflectivity of this target was relatively poor therefore beam size measurements were not possible. However, the aim was to establish a method of beam alignment to pass through the apertures and to observe the beam lifetime.

The beam energy was 2.1 GeV and approximately 1 mA single-bunch beam current. The observation wavelength was 400 nm and the vertical polarisation was selected. The vertical polarisation is preferable to reduce background from synchrotron radiation (SR) which is predominantly horizontally polarised. To align the beam with the target aperture a combination of diagnostic instruments are required, these include: beam loss monitors (BLMs) positioned downstream of the target, beam position monitors (BPMs), beam current/lifetime monitors and direct imaging of the target using the ICCD camera in the DR optical system.

To determine the coarse vertical position of the target aperture the target was rotated such that the incident beam was perpendicular to the target thickness i.e. the largest target surface was parallel to the horizontal plane. A vertical bump was used to pass the beam above the target. The beam was gradually lowered to approach the target. The position at which significant losses were detected on the BLMs was recorded. The target was then retracted and the process repeated from below the target. The centre of rotation of the target is at the aperture centre. Therefore taking the average of these two vertical positions gave a coarse estimate of the vertical position of the target aperture.

The fine vertical position of the target aperture was found by inserting the target to a position at which losses could be detected on the BLMs. The beam was then swept vertically. The vertical position at which the minimum scraping was observed was the central position of the target aperture.

The beam lifetime in the dummy target was 2-3 minutes for the single-bunch beam with both aperture sizes. A 10-bunch train with 1 mA beam current was also tested but no improvement in the beam lifetime was observed indicating the lifetime was not determined by a charge-per-bunch dependent process.

$$E^i_{y_i} = \frac{ie}{2\pi\lambda M\nu}\int d\theta d\phi_l \theta \exp\left[-ik\frac{x_i\theta\cos\phi_l + y_i\theta\sin\phi_l}{M}\right] \times \left[\frac{e^{-kt_1\left(\sqrt{(\theta\cos\phi_l)^2+\gamma^{-2}}-i\theta\sin\phi_l\right)}}{\sqrt{(\theta\cos\phi_l)^2+\gamma^{-2}}-i\theta\sin\phi_l} - \frac{e^{-kt_2\left(\sqrt{(\theta\cos\phi_l)^2+\gamma^{-2}}+i\theta\sin\phi_l\right)}}{\sqrt{(\theta\cos\phi_l)^2+\gamma^{-2}}+i\theta\sin\phi_l}\right] \quad (1)$$

A profile was selected and plotted against the expected intensity distribution using the vertical polarisation com-

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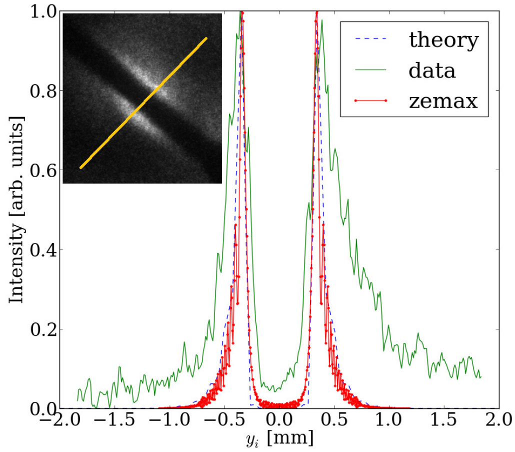

Figure 5: A plot of the intensity profile (solid line) and expected distributions from Eq. 1 (dashed line) and Zemax (dash-dot line).

ponent of the electric field defined in Eq. 1 where x_i, y_i are the horizontal and vertical positions on the detector respectively, $-\frac{ie}{2\pi^2\nu}$ = constant, t_1 and t_2 are the distances of the particle to each aperture edge, using the integration range $[0, \theta_m]$ where θ_m is the maximum acceptance angle of the lens in the optical system and $[0, 2\pi]$ where ϕ_l is the lens polar angle, M is the magnification factor, k is the wavenumber and γ is the Lorentz factor. The intensity is calculated as $I_y(x_i, y_i) \propto \left|E^i_{y_i}\right|^2$ [4].

In Fig. 5 the amplitudes of the data peaks are symmetric indicating the beam was well centred in the aperture. The data is observed to be much broader than expected from the theory. This broadening could be due to the finite beam size used to acquire the data rather than a single particle used in the theoretical model, misalignment of the polariser allowing some horizontal contribution and parasitic light from SR background. The data and theory were also compared to the simulated Zemax output for a single electron which suggests that the broadening is not due to aberrations from the optical system [12]. The exposure time of the camera was 15 ms (CesrTA revolution period T = 2.56 μs), therefore beam jitter although not observed on the BPMs could also contribute. In addition, the bandwidth of the filter was 10 $\pm$ 2 nm which could lead to some smearing of the data from light with wavelength $\lambda \neq$ 400 nm although this effect is presumed to be small.

Two fabrication techniques have been used for the targets: chemical etching and molecular adhesion. The targets are made of polished silicon. In addition to the aperture size, a crucial property of these targets is the coplanarity between the upper and lower tines. The coplanarity δ should be within a fraction of the wavelength λ at which DR is observed i.e. $\delta = 0.1\lambda$. For λ = 400 nm, the coplanarity should $\leq$40 nm. The tines of the target must also be etched such that given a target tilt angle $\theta_0 = 70°$, the effective aperture size should not be further reduced by the 0.3 mm thickness of the target.

Chemical etching is a process where silicon wafers are dipped into an etchant which is traditionally an acidic mixture [13]. Although the 0.5 and 1 mm apertures could be fabricated within tolerance the coplanarity of the tines could not be guaranteed. Therefore an alternative fabrication technique was also investigated.

Bonding by molecular adhesion is a technique that enables two substrates having polished surfaces to adhere to one another, without the application of adhesive [15]. The upper and lower tines of the target are machined separately in sets. The tines are then paired together in all variations to identify which upper/lower pairs result in the best coplanarity. The aperture size was 1 mm only.

Metrology was conducted at CERN to measure the coplanarity of the chemically etched targets. The molecular adhesion targets were measured during manufacture. The coplanarity of the four chemically etched targets showed a wide variation from <0.1 μm to 10 μm. The coplanarity of the best chemically etched target ranged from <0.1 μm at the innermost (0.5 mm) part of the aperture to 0.75 μm at the ends of the tines [14]. The coplanarity of the molecular adhesion target was smaller than the chemically etched target as expected at approximately 60 nm with an rms 20 nm. Although these coplanarity measurements do not meet our requirements for λ = 400 nm they can be accounted for in the data analysis.

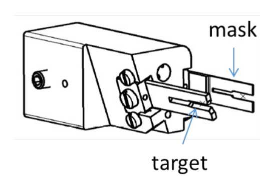

Figure 6: Target holder with mask and target mounted.

A silicon carbide mask is used to reduce the contribution of SR to background and is mounted upstream of the target as shown in Fig. 6. The mask is not etched since it is orientated perpendicular to the beam. The mask aperture size is 4 times larger than the target aperture size to minimise interference effects [3].

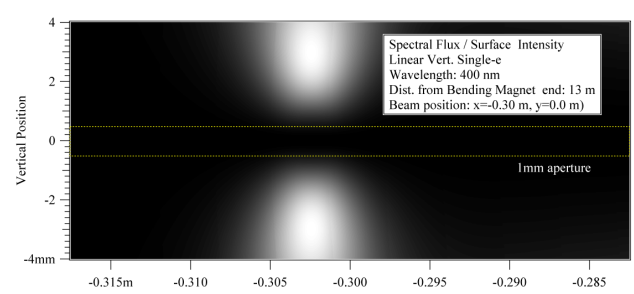

Figure 7: Simulated SR distribution on the target.

Simulations were made using the Synchrotron Radiation Workshop (SRW) [16]. In Fig. 7 the simulated vertically

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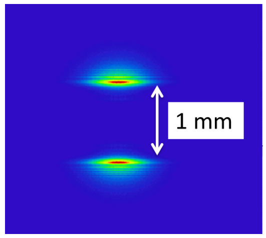

Figure 8: Simulated 400 nm vertically polarised DR distribution on the target using Zemax [12].

polarised SR distribution on the target surface is shown. The 1 mm target aperture is marked by the dashed lines. It is seen that the most intense areas of SR do not occur at the slit edges. Therefore light emitted at the slit edge (see inset Fig. 5 and 8) is from DR, possibly with a small contribution from transition radiation (TR). To verify the signal in the images is DR the intensity profile from the target edge is taken and fitted to an exponential curve. It is known that the DR intensity should decrease exponentially with distance from the slit edge whereas SR is relatively uniform over small regions [4]. Using simulations the DR intensity is found to be approximately 50 times brighter than SR at 400 nm wavelength considering vertically polarised photons only. This difference was found to be a factor of approximately 25 from the chemically etched target images.

From the preliminary test it was noted that 5-10 minutes was lost for each beam injection and manual beam alignment. A program was developed to automate this task, reducing the time taken between data acquisition to a couple of minutes. Initially the same manual beam alignment methods previously descibed were used to establish the route (vertical bump setting and target insertion position) into the target aperture. This route was then used as an input file for the program.

The beam lifetime with the target/mask assembly inserted was 2-3 minutes. This lifetime was the same for the chemically etched and molecular adhesion targets. The vertical beam size was varied from 13-52 μm. The horizontal beam size was approx. 490 μm. The beam lifetime was not affected by the vertical beam size until $\sigma_y = 50\,\mu$m where it could then be regained by manually adjusting the vertical beam position in the slit. It is thought that the beam lifetime is primarily dependent on the roll of the beam and the aspect ratio ($\sigma_y : \sigma_x$) which for this test was 1:38.

CONCLUSION AND OUTLOOK

Over the last year the hardware and instrumentation for the first phase of the DR experimental program have been installed and tested in CesrTA. A method of beam alignment in the target aperture has been established and the typical beam lifetime was 2-3 minutes. DR signals have been identified from SR background in target images.

Recently, improvements were made to the optical system. A plano-convex lens with 500 mm focal length will be used for improved angular resolution. All optical components were also changed for 50 mm clear aperture versions to avoid clipping. The whole system was also dismantled and realigned. As part of the preparations for the next test in the winter of 2013 a machine study is foreseen in the upcoming months to set-up the synchronous single-turn data acquisition and possibly study the beam lifetime. The synchronous trigger will be used for the xBSM, BPM system and DR camera.

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