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DIFFRACTION RADIATION FOR NON-INVASIVE, HIGH-RESOLUTION BEAM SIZE MEASUREMENTS IN FUTURE LINEAR COLLIDERS

Michele Bergamaschi[1,2], Robert Kieffer[1], Thibaut Lefevre[1], Stefano Mazzoni[1], Pavel Karataev[2], Konstantin Kruchinin[2], Alexander Aryshev[3], Nobuhiro Terunuma[3]

[1]CERN, Geneva, Switzerland
[2]JAI at Royal Holloway University of London, Egham, United Kingdom
[3]High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Abstract

Next generation linear colliders such as the Compact Linear Collider (CLIC) or the International Linear Collider (ILC) will accelerate particle beams with extremely small emittance. The high current and small size of the beam (micron-scale) due to such small emittance require non-invasive, high-resolution techniques for beam diagnostics. Diffraction Radiation (DR), a polarization radiation that appears when a charged particle moves in the vicinity of a medium, is an ideal candidate being non-invasive and allowing beams as small as a few tens of microns to be measured. Since DR is sensitive to beam parameters other than the transverse profile (e.g. its divergence and position), preparatory simulations have been performed with realistic beam parameters. A new dedicated instrument was installed in the KEK-ATF2 beam line in February 2016. At present DR is observed in the visible wavelength range, with an upgrade to the ultraviolet (200nm) planned for spring 2017 to optimize sensitivity to smaller beam sizes. Presented here are the latest results of these DR beam size measurements and simulations.

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M. Bergamaschi†[1], R. Kieffer, T. Lefevre, S. Mazzoni, CERN, Geneva, CH
P. Karataev, K. Kruchinin, JAI at Royal Holloway University of London, Egham, UK
A. Aryshev, N. Terunuma, High Energy Accelerator Research Organization (KEK), Tsukuba, JP
[1]also at JAI at Royal Holloway University of London, Egham, UK

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Next generation linear colliders such as the Compact Linear Collider (CLIC) or the International Linear Collider (ILC) will accelerate particle beams with extremely small emittance. The high current and small size of the beam (micron-scale) due to such small emittance require non-invasive, high-resolution techniques for beam diagnostics. Diffraction Radiation (DR), a polarization radiation that appears when a charged particle moves in the vicinity of a medium, is an ideal candidate being non-invasive and allowing beams as small as a few tens of microns to be measured. Since DR is sensitive to beam parameters other than the transverse profile (e.g. its divergence and position), preparatory simulations have been performed with realistic beam parameters. A new dedicated instrument was installed in the KEK-ATF2 beam line in February 2016. At present DR is observed in the visible wavelength range, with an upgrade to the ultraviolet (200nm) planned for spring 2017 to optimize sensitivity to smaller beam sizes. Presented here are the latest results of these DR beam size measurements and simulations.

INTRODUCTION

Diffraction Radiation (DR) is a polarization radiation that appears when a charged particle moves at near-relativistic speed in the vicinity of a medium [1]. Similarly to the well-known Transition Radiation (TR), DR is emitted in the specular reflection direction of the incident beam with respect to the medium surface (Backward DR - BDR) and in the direction of the beam (Forward DR – FDR). The angular and spectral distributions of DR are also very similar to TR. The main difference between the two is that DR, unlike TR, can be used as a non-invasive beam profile measurement technique as the particles pass through a narrow aperture, i.e. a slit or a hole. In the case of DR the beam size information is obtained from its far-field angular distribution [2]. Furthermore, the possibility to use optical DR imaging as a single shot optical Beam Position Monitor (BPM) with micron-scale resolution has recently been shown [3].

The non-invasive nature of DR makes it an ideal candidate for the measurement of beam profile in future, high intensity linear colliders. Its sensitivity to small (i.e. sub-micron) beam sizes is however still poor if compared to TR. In addition, due to its much lower light yield, any Synchrotron Radiation (SR) emitted upstream and reflected by the DR slit significantly lowers the signal to noise ratio (S/N). To improve S/N and resolution and to understand the technological limitations of DR as a beam size technique a new dedicated monitor has been installed in the Accelerator Test Facility 2 (ATF2) at KEK. This instrument [4] was designed as a combined DR\TR station to explore a wide range of parameters such a beam size from hundreds of nanometres with the TR PSF technique [5-6], to tens of microns through measurements of the DR far-field distribution and conventional TR imaging.

In this paper, the latest results on the beam size measurements obtained using DR are discussed along with comparisons with simulations to understand the limitations of the system. Possible future improvements are also presented.

† michele.bergamaschi@cern.ch

DR/TR MONITOR AT ATF2

The DR/TR monitor is installed in the extraction line of the ATF2. At the experiment location the 1.28 GeV electron beam, extracted from the low-emittance damping ring, can be focused to a vertical size varying from a few hundreds of nanometres to tens of micrometres [7].

Description of the Setup

A Sketch of the in-vacuum part of the DR\TR monitor is shown in Fig. 1. The monitor is composed of a silicon target with a set of four slits of differing sizes. To avoid upstream SR being reflected by the target, two sets of masks (horizontal and vertical) are present 130 mm before the target. As the intensity of BDR and the reflected FTR from the mask are proportional to the target reflectivity, the surface close to the slit edges is coated with aluminium.

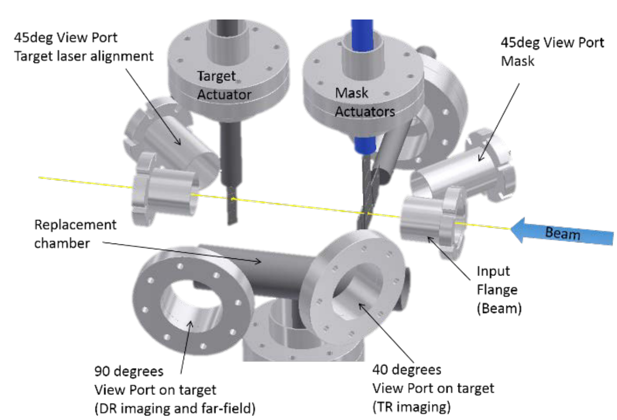

Figure 1: Sketch of the DR\TR monitor inside.

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Target and masks can be inserted and removed independently with micrometre precision actuators. This allows different combinations of target slit and mask sizes to be tested. The emitted DR is observed through two UV-compatible view ports installed at 40 and 90 degrees with respect to the beam axis.

DR optical lines

DR beam size measurements are obtained from the visibility variation of the projected vertical polarization component (PVPC)[2] of the far-field angular distribution of the radiation. The far-field distribution is observed by placing the imaging sensor in the back focal plane of a lens. The light is extracted through the 90 degrees view-port, passes through a polarizer to select the vertical polarization, and, thanks to an optical beam-splitter, is detected by two independent optical lines: one to create an image of the source, the other to observe the angular distribution. This setup allows both imaging and angular profile to be recorded at the same time. The imaging line is used as an optical BPM, with the beam position deduced from the intensity imbalance between the two slit edges.

The imaging optical line consists of a 2-inch diameter achromatic lens with 150 mm focus, giving a ×1.2 magnification on a scientific CMOS camera. A filter wheel with a set of 1 inch band-pass filters, a 2 inch diameter, 150 mm focal length lens and an intensified CCD camera compose the angular distribution optical line.

DR BEAM SIZE MEASUREMENTS

Simulations

A Monte Carlo approach was implemented to simulate the angular distribution given by a Gaussian beam described by its vertical size and divergence. The vertical positions of particles with respect to the centre of the SR mask (z_1) and the DR target (z_2) slits are dictated by the particles trajectory, which in turn is related to the beam divergence and the longitudinal distance between the mask and the target. A sample of 5000 (z_1, z_2) pairs for a given beam emittance were considered to calculate the distribution of the DR pattern in the far-field. The expression used for the vertical polarization electrical field (E_y) of a single electron crossing the mask slit of aperture a_1 and the target slit of aperture a_2, located at distance d, is the following [8]:

$$E_y = \left\{\frac{e^{-[(a_1/2)+z_1](f-ik_y)}}{f-ik_y} - \frac{e^{-[(a_1/2)-z_1](f+ik_y)}}{f+ik_y}\right\} - e^{i\Phi_0}\left\{\frac{e^{-[(a_2/2)+z_2](f-ik_y)}}{f-ik_y} - \frac{e^{-[(a_2/2)-z_2](f+ik_y)}}{f+ik_y}\right\} \quad (1)$$

With γ relativistic factor, λ observation wavelength, β ratio between the particle velocity and the speed of light, $k = (2\pi/\lambda)$, $\eta = (k/\beta\lambda)$, $f = \sqrt{k_x^2 + \eta^2}$, $k_x = k \sin\theta \cos\phi$, $k_y = k \sin\theta \sin\phi$, $\Phi_0 = \eta d(1 - \beta\cos\theta)$, θ and ϕ angular coordinates in the observation plane.

The intensity distribution of the beam is obtained summing the square modulus of the electrical field of all samples.

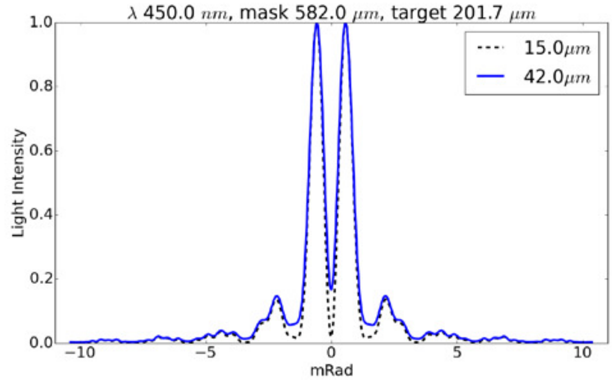

Figure 2: simulated DR angular distribution of Gaussian beams.

Two normalized PVPCs obtained from simulations at λ = 450 nm, target slit = 201.7 µm and mask slit size = 582.0 µm are shown in Fig. 2. These parameter values were chosen because they reproduce the experimental conditions of the set-up. One may notice that two profiles corresponding to different beam sizes at the target (15 and 42 um) and with the same beam divergence present the same angular positions for the peaks but a different visibility, defined as the ratio between the value of the centre of the angular pattern and the value of the main peaks. With this simulation tool we scanned a range of parameters and computed the visibility as a function of the beam size. The value of the visibility for different beam sizes is depicted in Fig. 3 for the usable target slit sizes at the DR/TR monitor at KEK at λ = 450 nm.

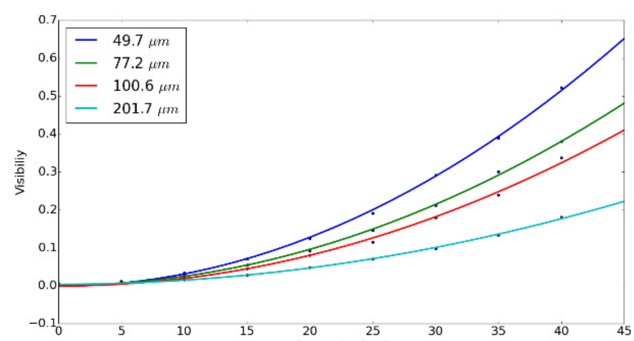

Figure 3: Visibility plot of simulated Gaussian beams.

The points represent simulated values of the visibility and the lines are polynomial fits of second order. It can be seen that the sensitivity increases with decreasing slit size. However, it is also clear that the far-field DR technique has a lower limit of measurable beam size at around 5um.

Results

During 2016 the DR\TR station was succesfully commisioned and far-field DR data were collected during ATF2 operation. As predicted by the simulations, the ATF2 measurements show a dependance of angular distribution visibility on transverse beam size.

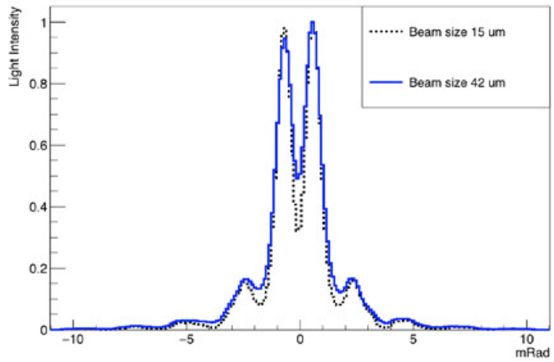

Figure 4: Measured PVPCs of ATF2 beam. at 15 μm and at 42 μm beam size.

Figure 4 shows PVPCs for a 15 um (a) and 42um (b) beam size with a target slit of 201.7 um, a mask slit of 584.0 um and an observation wavelength of 450 nm. These profiles are obtained by averaging 200 images collected in the same beam run. The beam size for each profile is calibrated by measuring the size of the TR profile of the beam under the same conditions. Both profiles in Fig. 4 show a multi-peak structure where the angular peak position is in agreement with the simulations performed with the same parameters (see Fig. 2). The main difference observed is the value of the minimum between the two main peaks. This minimum is higher than predicted by the simulations, which do not take in to account SR reflected by the target and focused by the lens. The SR is still present despite reducing the mask slit-size. This effect can be understood by observing the measured visibility as a function of the beam size for different target and mask slit combinations as shown in Fig. 5.

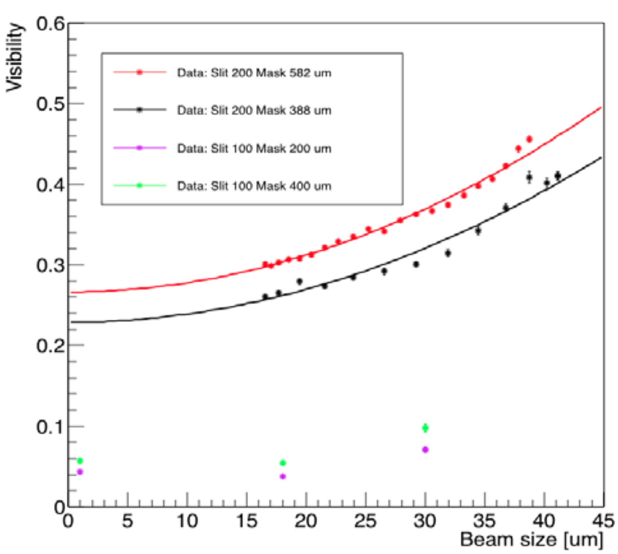

Figure 5: Visibility vs beam size measured.

All combinations tested during ATF2 operation show a quadratic dependence as a function of the beam size as predicted by simulations and shown in Fig. 3. One can notice that using a smaller mask with the same target slit size results in a lower background level since the mask blocks a larger amount of SR. Data collected with a smaller target slit (100 μm) show that the relative SR background level to DR signal can be reduced, as the DR increases exponentially when reducing the target slit size whereas the SR reflected by the target increases linearly.

Synchrotron Radiation Contribution

To measure the beam size using the DR angular distribution technique it is therefore necessary to minimize the SR light present in the system.

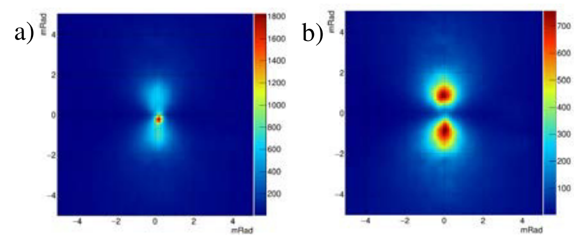

Figure 6: Measured 2D image of the TR far-field distribution without (a) and with mask (b).

The use of the mask removes part of the SR generated upstream in the beam line. Figure 6 compares two 2D images of the vertical polarization of the far-field distribution of TR recorded by the DR/TR station at ATF2. The presence af a spot in the middle of the pattern (focused SR) is clearly visible without the mask, which is removed when the mask is inserted.

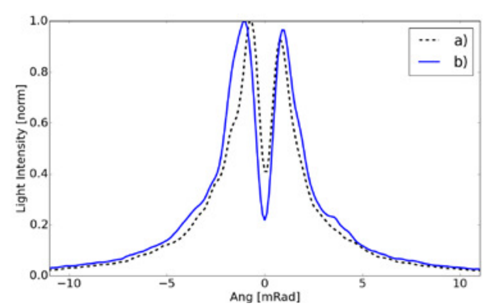

Figure 7: Measured TR far-field profile before (a) and after (b) orbit optimization.

In addition to mask insertion, beam orbit optimization is also necessary to reduce the SR contribution [9]. Figure 7 shows how the minimum in the middle of the angular distribution of TR decreases when the beam orbit is optimized to pass through the centre of the quadrupoles upstream of the DR/TR station.

PERSPECTIVE AND CONCLUSION

The data recorded during 2016 ATF2 operation demonstrate the sensitivity of optical DR to a transverse beam size of 15-40 micrometres. The present limitations of the technique are the wavelength of observation and the presence of a strong SR background. To overcome these limits more studies with smaller slit sizes are foreseen in 2017. These will be performed with an improved version of the optical line that will allow observation of DR in the far-UV down to 200 nm, to optimize the sensitivity to beam sizes around 10 micrometres.

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