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Simulations of 3D charge density measurements for commissioning of the PolariX-TDS

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Abstract. The prototype of a novel X-band transverse deflection structure, the Polarizable X-band (PolariX) TDS, is currently being prepared for installation in the FLASHForward beamline at DESY in early 2019. This structure will have the novel feature of variable polarization of the deflecting mode, allowing bunches to be streaked at any transverse angle, rather than at just one angle as in a conventional cavity. By combining screen profiles from several streaking angles using tomographic reconstruction techniques, the full 3D charge density of a bunch can be obtained. It is planned to perform this measurement for the first time during commissioning of the structure. In this paper, simulations of this measurement are presented and the effects of jitter are discussed.

1. Introduction

A transverse deflection structure (TDS) is a diagnostic device for measuring bunch length and investigating the longitudinal dependence of beam properties in electron linacs [1]. The induced EM mode in the structure exerts a time-dependent transverse kick on a bunch, which projects the longitudinal distribution of the bunch onto the transverse axis in which the kick is applied when operated at zero-crossing. From the screen image, the axis in the direction of streaking can be converted to longitudinal position along the bunch by applying an appropriate scaling factor. This not only allows the bunch length to be determined but also gives the longitudinal dependence of the charge density in the axis perpendicular to the streaking direction.

A prototype cavity, based on a new RF design [2], is currently being prepared for installation in the FLASHForward beamline [3] at DESY in early 2019 [4, 5, 6]. Further cavities will be installed subsequently at FLASH2 [7] and SINBAD [8, 9, 10] at DESY, and at the Athos beamline at SwissFEL [11, 12]. The new design for an X-band travelling-wave structure gives control over the polarization of the deflecting mode and therefore the angle at which bunches are streaked. This novel feature opens up the possibility of more complete characterizations of bunch properties, for example reconstrucing the 3D charge density distribution by combining profiles of bunches streaked at several different angles using tomographic reconstruction techniques [13].

FLASHForward is a beamline extension of the FLASH injector at DESY, currently in commissioning [3, 14, 15, 16]. It shares a tunnel with the FLASH2 beamline. The aim of the project is to investigate beam-driven plasma wakefield acceleration and, eventually, to pass the beam through undulators to generate X-rays. Figure 1 shows the layout of the beamline including the TDS. The TDS will allow the characterization of the drive beam, which is key

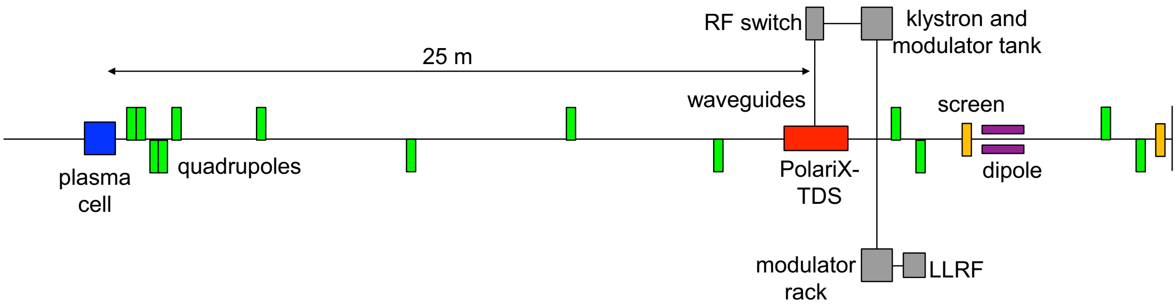

Figure 1. Schematic of the lattice design at FLASHForward, starting from the plasma cell. The electron beam travels from left to right. A SLED will be added at a later date to increase the deflection voltage and the RF switch will allow the power to be switched eventually between the FLASHForward and FLASH2 cavities.

to optimizing the acceleration process. In addition, the longitudinal properties of the witness beam will also be studied, in order to investigate different injection methods and to determine the quality of the beam for X-ray generation [6].

As the prototype cavity will be installed at FLASHForward, this will be the first operation of the PolariX-TDS in a beamline. Commissioning will be therefore a fairly extensive process and involve testing the operation of the TDS in detail, especially the variable polarization feature. The phase jitter and voltage jitter, as well as the accuracy of the rotator, will need to be characterized. Measurements will then be possible, including bunch length measurements and reconstructing the 3D charge density. The cavity at FLASHForward will be operated at a frequency of 11.988 GHz. The maximum deflecting voltage during commissioning will be around 14 MV; a SLED will be installed at a later date, which will approximately double this value.

In the following section, a brief overview of the theory is given and expressions for the longitudinal resolution presented. There follows an explanation of matching considerations for the lattice before the reconstruction is presented and the effects of jitter sources are discussed.

2. Theory

A TDS imparts a time-dependent transverse kick on an electron bunch. The rms spot size on a screen located at longitudinal position s_1 is therefore a combination of the spot size on the screen when the TDS is switched off, σ_y^{off}, and a contribution due to the TDS streaking [9, 10]:

$$\sigma_y(s_1) = \sqrt{(\sigma_y^{\text{off}})^2 + (Sc\sigma_t)^2}. \tag{1}$$

Here, σ_t is the rms bunch length at the TDS in seconds, c is the speed of light and S is the shear parameter, defined as

$$S = M_{1,2}^y \frac{2\pi f e V_0}{c^2|p|}, \tag{2}$$

where M^y is the vertical transfer matrix from the centre of the TDS to the screen, f and V_0 are the cavity frequency and peak voltage respectively, and p is the mean momentum [17]. It is assumed that the TDS is operated at zero-crossing. The shear parameter relates the shift in position of a particle on the screen, Δy, to its position along the bunch relative to the central particle, ζ [17]:

$$\Delta y \approx S\zeta. \tag{3}$$

The temporal resolution is defined here as the bunch length in seconds when the two terms on the right-hand side of Eq. (1) are equal, and therefore can be expressed as

$$R_\mathrm{t} \approx \frac{\sqrt{\epsilon_y}}{\sqrt{\beta_y(s_0)}|\sin(\Delta\phi_y)|}\frac{|p|c}{2\pi f e V_0}, \tag{4}$$

where ϵ_y is the vertical geometric emittance of the bunch. In the case of a drift, the $M^y_{1,2}$ term is simply equal to the length of the drift, L, and so the resolution is

$$R_\mathrm{t} \approx \frac{\sigma_y^\mathrm{off}|p|c}{2\pi f e V_0 L}. \tag{5}$$

This formula assumes the thin-lens approximation and the length L is therefore the length from the centre of the TDS to the screen.

3. Lattice

Figure 1 shows the lattice layout of the FLASHForward beamline starting at the plasma cell, including the 0.8 m TDS cavity. The beam is extracted from the FLASH injector and passes through an extraction arc and then a compression arc before entering the plasma cell. There are several quadrupole magnets upstream of the TDS, which may be used for matching the beam into the TDS. The two quadrupoles between the TDS and the screen are turned off to ensure the beam passes through the same optics with respect to the streaking direction. The reason for this is that higher-order field components will depend on the direction of streaking and may cause unwanted artefacts. The longitudinal resolution of the reconstruction is limited by the streaking direction with the worst longitudinal resolution and so there would only be a benefit from using quadrupoles if the resolution were improved for all streaking directions with respect to what can be achieved using just a drift. In any case, the longitudinal resolution that can be achieved with a drift length is sufficient for a good reconstruction of the features of a drive beam.

The drift length between the end of the TDS and the screen is 7.45 m. From Eq. (5), it can be seen that the only way in which the longitudinal resolution can be improved when using a drift length is by having a smaller unstreaked spot size on the screen. However, if the spot

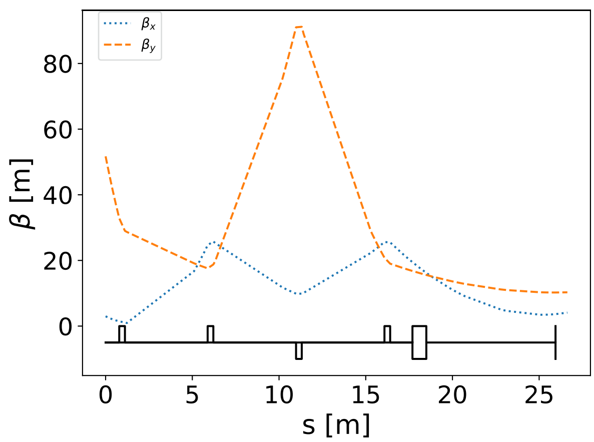

Figure 2. β-functions from the first of the four matching quadrupoles upstream of the TDS to the screen.

size on the screen is too small, the screen's resolution may become a limiting factor in the reconstruction. The screen's resolution is approximately 10 µm to 20 µm. An unstreaked rms spot size of about 80 µm at the screen was found to be a good compromise, as this results in a longitudinal resolution of about 10 fs, assuming a 14 MV kick (this will be the maximum kick before the SLED is added). It is important to note that the beam must be matched in at least two planes to achieve good resolution when streaking at any angle. The four quadrupoles upstream of the TDS were used for matching and the β-functions for this section of the beamline are shown in Figure 2.

4. Reconstruction

Simulations were carried out using *elegant* [18] for particle tracking and a script written in *Python*, using the *scikit-image* package [19], for the tomographic reconstruction (SART algorithm). The bunch used was generated in start-to-end simulations of the FLASHForward beamline. Due to coherent synchrotron radiation (CSR) effects within the magnetic chicanes, the bunches are not symmetric but instead contain correlations [3, 16]. Table 1 shows the properties of the bunch presented in this paper. Wakefields and misalignments (estimated to be less than 100 µm) have not been taken into account in the simulations of the measurement.

Table 1. Bunch Statistical Properties at TDS Entrance (here, x and y correspond to axes with 0 rotation)

Parameter	**Value**
Energy [MeV]	998
Charge [pC]	500
σ_t [fs]	83.7
σ_δ	0.0014
$\sigma_{x/y}$ [mm]	0.184 / 0.103
$\epsilon_{x/y}^{\text{norm}}$ [mm mrad]	3.46 / 1.22
$\beta_{x/y}$ [m]	19.1 / 16.9
$\alpha_{x/y}$	2.12 / 0.82

A phase scan is conducted first to determine the shear parameter. This can be determined from the slope of a plot of mean bunch position against arrival time, as can be seen from Eq. (3). In the case presented here, the shear parameter is approximately 27.7, resulting in a resolution of approximately 10 fs. The initial energy spread of the bunch is small enough that the assumption of a constant shear parameter for the bunch is reasonable.

For the measurement, the beam is streaked at 16 equally-spaced angles between 0 and 180°. Figure 3 shows the original distribution tracked at the screen with the TDS off along with the reconstructed bunch profile. In theory, the longitudinal information is reconstructed from the TDS position whereas the transverse particle distribution is reconstructed from the screen position. However, due to the relativistic energies, the longitudinal mixing within the beam is likely to be very low so the longitudinal distribution should not change much between the TDS and the screen. In general, the more projection angles used in the reconstruction, the more accurate the reconstruction. A fair reconstruction of the overall charge distribution can be obtained with just four projections, although the image is clearly more smeared out than when using more projections.

There are various sources of jitter that could affect this measurement, most notably of the deflecting voltage amplitude and phase, and of the bunch arrival time. All of these sources will

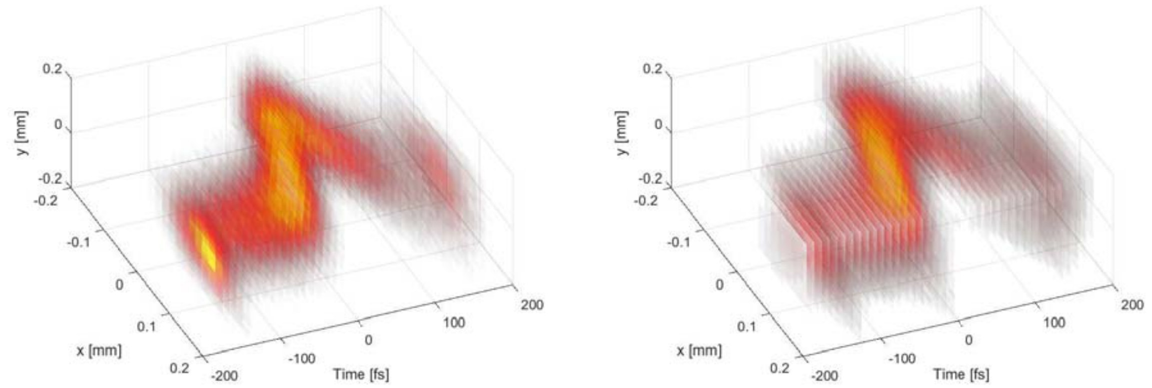

Figure 3. Tracked particle distribution at the screen with the TDS off (top) and reconstructed beam distribution using 16 streaking angles (bottom). The beam is divided into 10 fs temporal slices in accordance with the calculated resolution. The colour map illustrates the charge density profile and has been normalized to the maximum intensity in each plot.

affect both the calibration and the screen images used for the reconstruction. The effect on the calculation of the shear parameter has already been studied [20] so the emphasis here is on how the jitter affects the reconstruction.

Jitter in the voltage amplitude can be detected in principle by comparing bunch length measurements for different shots and scaling if necessary. The jitter in amplitude has been estimated to be of the order of 1%, based on the RF setup. For the drive bunch considered here, the effect of this amplitude jitter falls within the longitudinal resolution and therefore can be neglected.

Jitter in cavity phase and in bunch arrival time both have the same effect on the beam profiles: the centre of the profile on the screen will be shifted. The screen at FLASHForward has dimensions 29 mm by 36.5 mm. Within this range, there is still a linear relationship between position on the screen and phase offset and so the conversion from position offset to time offset should be valid wherever the bunch arrives on the screen. If the complete profile is not visible on the screen, that shot should be neglected.

5. Conclusion

Commissioning of the prototype PolariX-TDS at the FLASHForward facility in early 2019 will be the first time this cavity is used in a beamline. During commissioning, the cavity will be tested extensively and various measurements will be performed, including reconstructing the 3D charge density distribution of bunches. In this paper, a simulation of a reconstruction of a typical FLASHForward drive bunch has been presented. The various sources of jitter have been discussed and it has been shown that they should not cause significant problems for these bunch parameters. Further possible sources of error are the setting of the polarization angle and the shot-to-shot jitter of the bunch distributions. These effects have not yet been quantified and further work is required to estimate their significance. In addition, wakefields and misalignments should be included in simulations to verify that these effects do not affect the reconstruction significantly. Finally, the possibility of changing the correlations in the bunches by manipulating the lattice will be studied.

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