

RECONSTRUCTION OF THE 3D CHARGE DISTRIBUTION OF AN ELECTRON BUNCH USING A NOVEL VARIABLE-POLARIZATION TRANSVERSE DEFLECTING STRUCTURE (TDS)

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Abstract

A TDS is a well-known device for the characterization of the longitudinal properties of an electron bunch in a linear accelerator. So far, the correlation of the slice properties in the horizontal/vertical planes of the electron bunch distribution has been characterized by using a TDS system deflecting in the vertical/horizontal directions respectively and analysing the image on a subsequent screen [1]. Recently, an innovative design for a TDS structure has been proposed, which includes the possibility of continuously varying the angle of the transverse streaking field inside a TDS structure [2, 3]. This allows the beam distribution to be characterized in all transverse directions. By collecting measurements of bunches streaked at different angles and combining them using tomographic techniques, it is possible to retrieve 3D distributions of the charge density. In this paper, a method is proposed and simulation results are presented to show the feasibility of such an approach at the upcoming accelerator R&D facility, SINBAD, at DESY [4].

INTRODUCTION

A TDS is a commonly-used diagnostic device for investigating the longitudinal dependence of beam properties in electron linacs [5]. The induced EM mode in the structure exerts a time-dependent transverse kick on the beam, which converts the longitudinal plane of the bunch into a transverse axis on a screen placed downstream. From the screen image, direct measurements can be made of the bunch length and the charge distribution in the transverse direction perpendicular to the kick. A TDS can also be combined with other components, such as a dipole for slice-by-slice energy spread measurements or a quadrupole for slice-by-slice emittance measurements.

Using recently-designed RF components [2, 3], a new X-band TDS with variable polarization is being developed for use at several DESY facilities and at SwissFEL, allowing the beam to be streaked at any angle in the transverse plane [4]. This opens up the possibility of reconstructing the full 3D charge distribution in a multi-shot measurement by combining profiles of the beam streaked at several different angles using tomographic reconstruction techniques.

At the upcoming SINBAD facility at DESY, short bunches with length ranging from subfemtosecond to a few femtoseconds and charge in the picocoulomb range will be produced

for potential use as a witness beam in laser-driven plasma wake-field acceleration (LWFA) experiments and for testing dielectric accelerating structures [6]. The planned X-band TDS will allow characterization of the 3D charge density profile of the input beam to femtosecond longitudinal resolution. For tests involving dielectric accelerating structures, it is planned to inject asymmetric beams [7]. In this case, characterizing the full profile of the beam can be important for matching and aperture considerations. For LWFA experiments, it may be important to know the transverse beam profile over the length of the beam as the fields in the plasma, and therefore the matching conditions, have longitudinal dependence in certain regimes [8]. The accelerating fields are also influenced by beam offsets, therefore having a complete charge profile reconstruction can help, for instance, in the case of beam loading.

In the following sections, the reconstruction procedure is described and simulation results are presented. Finally, there is a discussion of the limitations of the process and further investigations that could be performed. Other measurements involving the TDS and considerations for a lattice design are presented in a separate contribution [9].

RECONSTRUCTION METHODOLOGY

The aim of this procedure is to combine 2D screen profiles of a bunch streaked at several angles into a 3D charge density profile of the complete bunch. In what follows, a rotating coordinate system is considered with the y -axis defined parallel to the streaking axis and Δy defined relative to the bunch centre at the screen. Each screen profile can therefore be viewed as a projection of the complete charge distribution on the corresponding x -axis.

The first step is to transform the Δy -coordinate into a Δt -coordinate, where Δt is the arrival time normalized to the centre of the bunch. This can be achieved directly using the equation [1]

$$\Delta y(t) \approx S c \Delta t, \quad (1)$$

where the shear parameter, S , is defined as

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

In this equation, M^y is the vertical transfer matrix from the centre of the TDS to the screen, f and V_0 are the frequency and total kicking voltage respectively and p is the particle

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momentum. The shear parameter for each direction of streaking can be determined by scanning over the bunch arrival time at the TDS and measuring the centroid offset at the screen.

The xt profiles for different streaking angles are then combined to reconstruct the complete charge density profile of the bunch using tomographic reconstruction techniques. They are first split into slices in Δt , and the corresponding time slice from each profile is then used as an input to the reconstruction algorithm. In this paper, the Simultaneous Algebraic Reconstruction Technique (SART) [10], using the Kaczmarz iterative solver method [11], has been applied with two iterations. Due to the effects discussed below, the reconstruction does not provide a completely faithful reconstruction of the bunch, however it is observed that the key features are reproduced.

It is clear that the charge density distribution will evolve, both within the TDS and within the following drift section before the screen. The transverse information in the reconstruction pertains to the bunch at the screen position, whereas the longitudinal information pertains to the bunch at the TDS where the bunch is sheared. The bunch length at these two locations may be different in regimes in which velocity bunching or space charge are significant. Although in the ideal case calculations could be performed to transfer the transverse charge distribution back to the TDS, this would require knowledge of the transverse phase space distribution. For this, slice emittance measurements for each streaking angle would be needed, making the measurement much more involved.

SIMULATION RESULTS

Simulations were carried out using *elegant* [12] for particle tracking and a script written in *Python*, using the *scikit-image* package [13], for the tomographic reconstruction. The bunches used were generated in simulations of the SINBAD-ARES linac using the magnetic compression chicane [14]. They are not symmetrical and contain interesting features that make them useful examples to study with this technique. Table 1 shows the properties of the bunch presented in this paper. Space charge effects, wakefields, timing jitter and misalignments have not been taken into account in these simulations (although space charge was included in the generation of the input bunch).

Table 1: Bunch statistical properties at TDS entrance (here, x and y correspond to axes with 0 rotation).

Energy [MeV]	84.2
Charge [pC]	3
σ_t [fs]	5.15
$\sigma_{x/y}$ [μm]	87.9 / 96.8
$\epsilon_{x/y}^{\text{norm}}$ [mm mrad]	0.224 / 0.190
$\beta_{x/y}$ [m]	5.69 / 8.14
$\alpha_{x/y}$	-0.377 / 0.258

The setup used in the simulations comprises two 0.8-metre TDS cavities, each providing a maximum voltage kick of 20 MV^1 , a 5-metre drift space and finally a screen. The resolution of the screen is assumed to be $20\text{ }\mu\text{m}$, which should be achievable with screen stations based on a similar design to those at the European XFEL [15]. The temporal resolution depends on the direction of streaking, as it is a function of the beam size at the screen with the TDS off (σ_y^{off}) [9]:

$$R_t = \frac{\sigma_y^{\text{off}} |p| c}{2\pi f e V_0 L}. \quad (3)$$

Here, L is the length from the centre of the TDS to the screen. In this paper, slice lengths of 0.85 fs have been used – this is just over the largest calculated resolution. The reconstruction has been carried out using profiles from 16 evenly-spaced streaking angles. As the TDS is operated at zero voltage-crossing, the bunches are streaked in both the positive and negative directions.

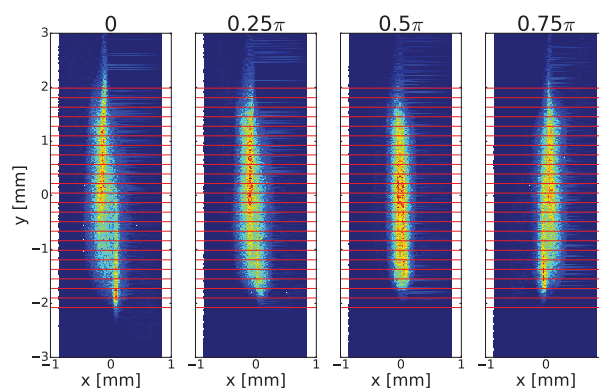


Figure 1: Sample screen images of the streaked bunch with red lines showing the temporal slices. The axes rotate so that y is always in the direction of streaking.

Figure 1 shows sample screen images of the bunch streaked in different planes and the way in which they have been divided up into time slices. Figure 2 shows the 3D charge density profile at the screen obtained by tracking with the TDS off, and the reconstructed profile below. It is clear that the key features, such as the offset in the x distribution, have been successfully reproduced, although the reconstruction is limited by the perturbation of the bunch in the TDS and the inherent inaccuracy of a tomographic reconstruction with a finite number of projections.

There is significant variation in bunch length between the TDS and the screen, as shown in Fig. 3. The reason for the bunch length decrease when the TDS is off is that the initial chirp results in velocity compression in the drift,

¹ For the TDS cavities, the *RFDF* element in *elegant* has been used. The frequency of the structure is 11.9916 GHz. The voltage kick per cavity has been halved for the phase scan to obtain the shear parameters due to the induced energy spread. In order to account for the bunch length change within the TDS cavities due to energy spread (which is not currently accounted for automatically in *elegant*), 100 zero-length *RFDF* elements separated by drift spaces have been used to simulate each cavity.

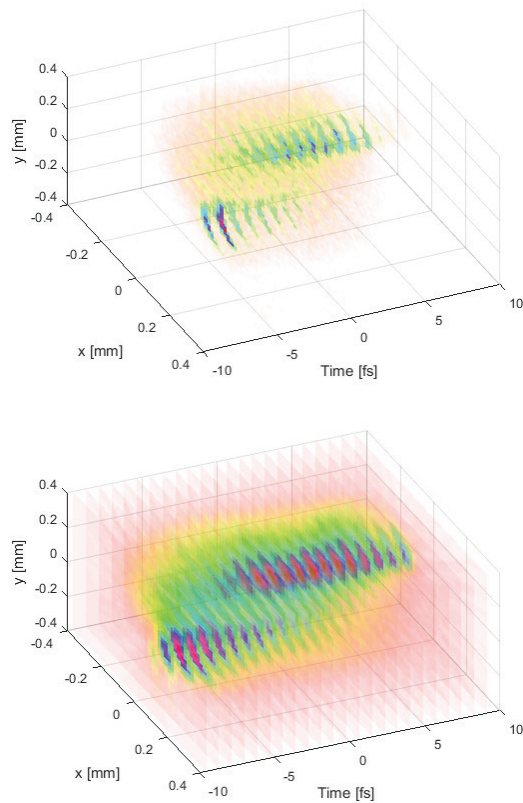


Figure 2: Actual (top) and reconstructed (bottom) view of the beam divided into temporal slices according to the calculated resolution. The colour map illustrates the charge density profile and has been normalized to the maximum intensity in each plot.

as the electrons are not ultrarelativistic. The increase in bunch length when the beam is streaked arises from the induced momentum spread in the TDS, which is illustrated in Fig. 4. This induced momentum spread is a consequence of the Panofsky-Wenzel theorem [16], which states that a transverse deflection is only possible if there is a transverse gradient in the longitudinal electric field. Due to the bunch length decrease between the TDS and screen with the TDS off, the simulated bunch slices at the screen location and the reconstructed slices do not match up.

CONCLUSION & OUTLOOK

A new method for reconstructing the 3D charge density profile using a novel X-band TDS with variable polarization has been described and simulations have been carried out using simulated beams from the SINBAD-ARES linac. This technique reconstructs the transverse beam profile at the screen, although the time slices correspond to the bunch at the TDS. The simulations show that this reconstruction technique can reproduce key features in the slice-by-slice transverse distributions, such as offset from the beam axes and the general shape of the distribution. The induced momentum spread in the TDS perturbs the beam and causes an

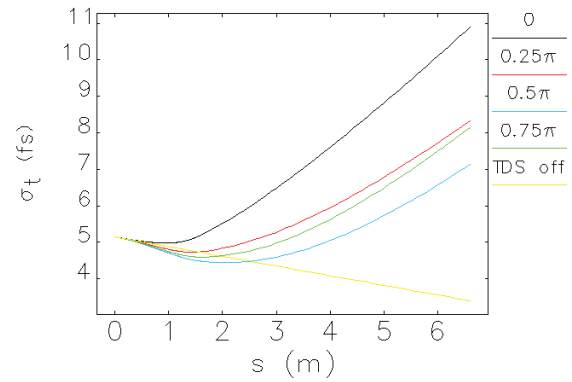


Figure 3: Variation in bunch length from the TDS to the screen for a selection of streaking angles. The exit of the TDS is at $s = 1.6$ m and the screen is at $s = 6.6$ m.

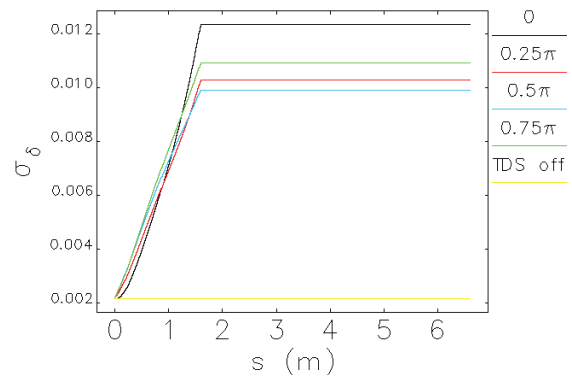


Figure 4: Change in fractional momentum spread from the TDS to the screen for a selection of streaking angles.

increase in bunch length in the drift section preceding the screen.

Although the principle of this reconstruction method has been presented in this paper, further studies are required to investigate space charge effects, wakefields, timing jitter and misalignments, as well as the resolution limit for specific applications.

Possible applications for characterizing the input beam to LWFA and dielectric experiments at the SINBAD facility have been discussed in the introduction. As this reconstruction technique relies on shot-to-shot stability, it would be more difficult to use it to characterize a beam output from an experiment. Nevertheless, by taking many measurements for each streaking direction, it could potentially be possible in some cases to statistically reconstruct a typical bunch. Further tests would be needed to investigate this.

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