LATTICE CONSIDERATIONS FOR THE USE OF AN X-BAND TRANSVERSE DEFLECTING STRUCTURE (TDS) AT SINBAD, DESY

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Abstract

An X-band TDS is a well-known device for the characterization of the longitudinal properties of an electron bunch in a linear accelerator. It is planned that a novel X-band TDS with variable polarization [1, 2] will be installed within the next few years at SINBAD, an upcoming accelerator R&D facility at DESY [3, 4]. There are several measurements that can be performed with the TDS, each with specific optics requirements to reach the highest possible resolution and keep induced energy spread to a tolerable level. Quadrupoles will be installed between the TDS and the screen to help satisfy these conditions. In this paper, the requirements for the bunch length measurements, a novel 3D charge density reconstruction technique and slice energy measurements are discussed and some simulation results for the slice energy measurement using example lattices are presented.

INTRODUCTION

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

Based on novel X-band technology proposed recently [1, 2], a TDS with variable polarization is currently being designed for installation at the FLASH and SINBAD facilities at DESY and the SwissFEL facility at PSI in the next few years [3]. This TDS will allow beams to be streaked at any angle in the transverse plane, thus opening up the possibility of a 3D reconstruction of the charge density distribution, as detailed in a separate contribution [6].

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 in the ARES linac [4, 7]. They will be compressed, either by velocity bunching using the two travelling wave structures or by magnetic compression using a four-dipole chicane further downstream. A likely location for the two 0.8-metre TDS cavities is just after the chicane, and a screen station will be placed a few metres further downstream. There is currently flexibility over the design of the lattice between the TDS and the screen with ongoing studies into the optimal setup. A schematic of the setup being considered is shown in Fig. 1.

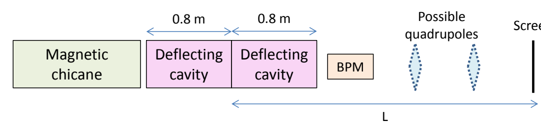

Figure 1: Schematic of beamline setup (not to scale).

Measuring the bunch properties of such short bunches is challenging and proper consideration must be given to the longitudinal resolution, as well as to the resolution of the other quantity being measured, e.g. energy. A key difficulty is that the TDS induces a considerable energy spread, which increases as the longitudinal resolution improves. In the following sections, the optimization of the resolution is discussed for bunch length measurements, a novel 3D charge density reconstruction technique and slice energy measurements.

THEORY

Longitudinal Resolution

A TDS imparts a time-dependent transverse kick on an electron bunch. Assuming the TDS operates at zero voltage crossing, this kick contributes to an increase in the particle spread in the direction of the kick (defined here as the y direction). The RMS spot size on a screen located at s_1 is therefore a combination of the spot size at the screen when the TDS is switched off, σ_y^{off}, and a contribution due to the TDS streaking:

$$\sigma_y(s_1) = \sqrt{(\sigma_y^{\mathrm{off}})^2 + (S\sigma_z)^2}. \tag{1}$$

Here, σ_z is the bunch length at the TDS and S is the shear parameter, defined as

$$S = M^y_{1,2}\frac{2\pi f eV_0}{c^2|p|}, \tag{2}$$

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 [8]. The shear parameter relates the shift in position of a particle on the screen, Δy, to its position along the bunch, ζ [8]:

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

The longitudinal resolution is defined here as the bunch length when the two terms on the right-hand side of Eq. (1) are equal, i.e.

$$|S|\sigma^{\mathrm{long}} = \sigma_y^{\mathrm{off}}. \tag{4}$$

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In general,

$$M^y_{1,2} = \sqrt{\beta_y(s_0)\beta_y(s_1)}\sin\Delta\phi_y, \quad (5)$$

where $\beta_y(s_0)$ and $\beta_y(s_1)$ are the β-functions at the centre of the TDS and the screen respectively, and $\Delta\phi_y$ is the phase advance between these two locations. The temporal resolution can therefore be expressed as

$$R_\mathrm{t} = \frac{\sqrt{\epsilon_y}}{\sqrt{\beta_y(s_0)}|\sin(\Delta\phi_y)|}\frac{|p|c}{2\pi f e V_0}. \quad (6)$$

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

$$R_\mathrm{t} = \frac{\sigma_y^\mathrm{off}|p|c}{2\pi f e V_0 L}. \quad (7)$$

It should be noted that this formula assumes the thin-lens approximation and the length L is therefore the length from the centre of the TDS to the screen.

It is useful to consider the meaning of the resolution defined here. If the time slices are much larger than the resolution, then the contribution to the spot size at the screen from the streaking is much more significant than the contribution from the transverse particle spread before the TDS. It is therefore only possible to resolve differences in features between time slices that are larger than the resolution.

Another important quantity is the minimum measurable bunch length. This can be calculated by considering the bunch length required so that the difference between the streaked and unstreaked bunch is equal to the screen resolution, R_screen. The minimum measurable bunch length in seconds can be expressed as

$$\sigma_t^\mathrm{min} = \frac{\sqrt{R_\mathrm{screen}\left(R_\mathrm{screen} + 2\sigma_y^\mathrm{off}\right)}}{Sc}. \quad (8)$$

Induced Energy Spread

A consequence of the Panofsky-Wenzel theorem [9] is that there must be a transverse gradient in the longitudinal electric field present in any TDS. This has the undesired effect of inducing energy spread in the sheared bunch, which makes measuring the original energy spread challenging, but can also perturb other measurements due to chromatic effects, for instance. It has been shown that there is an inherent limitation in minimizing both the temporal resolution (R_t) and the induced energy spread (σ_δ) [10]:

$$R_t\sigma_\delta > \frac{\epsilon_y}{c\sin(\Delta\phi_y)}. \quad (9)$$

BUNCH LENGTH MEASUREMENT

The bunch length measurement is the simplest measurement involving the TDS. The bunch is streaked onto a screen and the temporal profile can be seen in the direction of streaking. By varying the arrival time of the electrons at the cavity and measuring their mean position on the screen, the shear parameter can be determined from the gradient of a plot of Δy against arrival time [8]. The shear parameter is then used to convert the Δy coordinate on the screen to a longitudinal component, and the RMS spread calculated.

In this case, the aim is to achieve the highest possible longitudinal resolution and so there should be a phase advance of $\pi/2$ (or $3\pi/2$ etc.) in the direction of streaking, as can be seen from Eq. (6). This can be achieved via a drift space of an appropriate length or using one (or multiple) quadrupole(s). In addition, the highest stable voltage should be used, which is taken to be 20 MV per cavity, or 40 MV in total.

Although a drift space can satisfy the phase advance requirement of a given beam in principle, the desired drift length would be different for different beams. In addition, the spot size on the screen cannot be optimized. For the case of a sample working point bunch of length 0.461 fs, charge 2.73 pC and energy 100 MeV, a phase advance of $\pi/2$ can be achieved with a drift space of 3.99 m. Using the definition in the preceding section, the minimum measurable bunch length is calculated to be 0.37 fs for a screen resolution of 20 µm.

An important consideration is that the lattice after the TDS does not cause the beam to evolve in a way that would change the bunch length measurement to a significant extent. Specifically, the mapping from the TDS exit to the screen should be approximately linear in the direction of streaking, otherwise the longitudinal coordinate cannot be reproduced via Eq. (3).

Although a strong focusing quadrupole will reduce the length of drift space required, it will also lead to undesired chromatic and space charge perturbations. The former is especially important given the significant induced energy spread in the TDS.

3D CHARGE DENSITY RECONSTRUCTION

The details of this novel technique to reconstruct the charge density of a bunch are presented in a separate contribution [6]. The principle is that the bunch is streaked at multiple angles and the screen intensity profiles are divided into time slices and combined using tomographic techniques. In order to achieve the highest possible resolution of the reconstruction, the longitudinal resolution should be simultaneously minimized in all directions of streaking. It is also important that the lattice does not distort the bunch in a way that depends on the direction of streaking as the information from different streaking directions needs to be combined. Finally, it is important to limit chromaticity due to the considerable energy spread induced in the TDS.

With these considerations in mind, a drift space between the TDS and the screen has been used in simulations of this measurement. The disadvantage of this approach is that the phase advance cannot be adjusted and so the longitudinal resolution cannot be optimized.

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For the case simulated using a 5-metre drift space, the phase advance in the direction of streaking is approximately 0.5 rad to 0.6 rad between the centre of the TDS and the screen, which is sufficient here. However, this technique will be limited by the longitudinal resolution when probing shorter bunches.

SLICE ENERGY MEASUREMENT

In this measurement, the bunch is first streaked in the y direction using the TDS and then deflected in the x direction using a dipole. The setup consists of the TDS cavities, two quadrupoles, a dipole and a screen placed perpendicular to the beam leaving the dipole. The x coordinate on the screen can be converted to energy whereas the y coordinate can be converted to a longitudinal time coordinate, as in the previous cases.

The theoretical resolution achievable for a dipole spectrometer depends on the emittance, β-function and dispersion at the screen, according to the relation [11]

$$\delta_{\min} \geq 2\frac{\sqrt{\epsilon\beta}}{D}. \tag{10}$$

The temporal information pertains to the bunch at the TDS with the resolution given by Eq. (6). A major difficulty in this measurement is that achieving a high temporal resolution and a low energy spread is not possible due to Eq. (9).

In order to limit the induced energy spread to reasonable levels, a kick of just 2 MV per cavity (4 MV in total) has been used. To maximize the energy resolution, β_x should reach a maximum and then decrease to the screen as the beam is focused. For optimal longitudinal resolution, $|\sin(\Delta\phi_y)|$ should equal 1, and in this case the most appropriate phase advance is $3\pi/2$. The optics design for the lattice used in simulations is shown in Fig 2. The dipole is rectangular with a magnetic length of 0.302 m and the beam enters perpendicular to the edge. The bending angle is set to 0.93 rad.

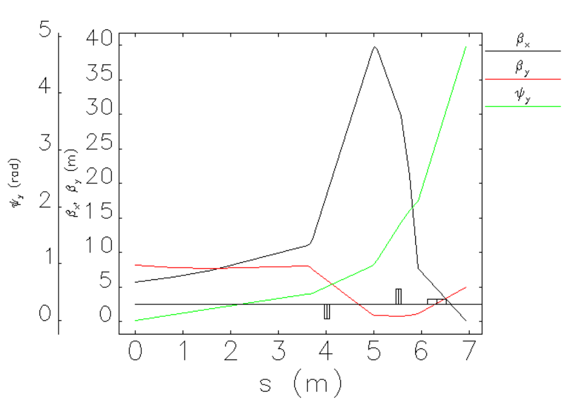

Figure 2: Evolution of β-functions from the TDS entrance to the screen. The positions of the two quadrupoles and dipole are indicated.

Simulations using an input bunch from the SINBAD-ARES linac (parameters given in [6]) were performed in *elegant* [12] and do not include space charge, wakefields, jitter or misalignment errors. Fig 3 shows the energy profile of the incoming 84.2 MeV beam and the reconstruction using this lattice. The induced energy spread is clearly visible, even at these low voltages, however the original correlated energy spread can still be discerned.

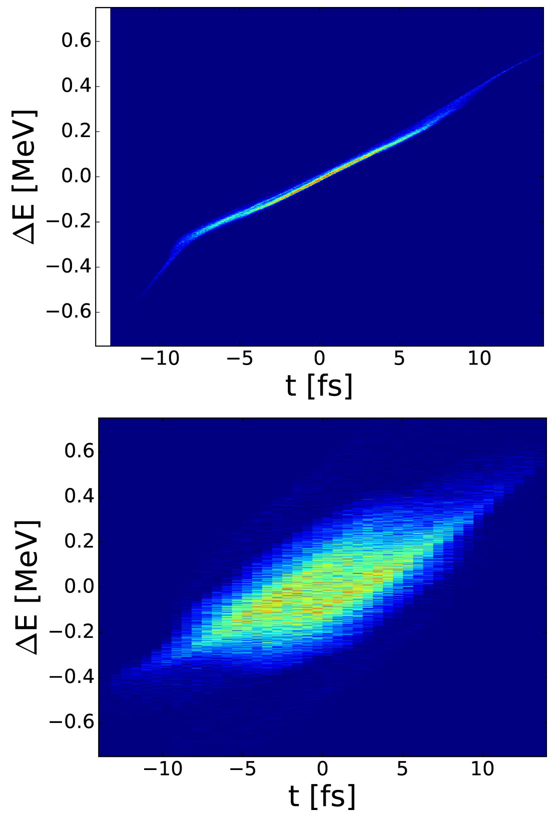

Figure 3: Original (top) and reconstructed (bottom) slice energy spread. There is significant induced energy spread from the TDS visible in the reconstruction.

CONCLUSION

In this paper, some considerations relating to the lattice design for various measurements involving the TDS have been discussed and some preliminary studies presented. Collective effects, timing jitter and misalignments have not been included, although they should be studied in future simulations. Further studies are required, in particular for planned slice emittance measurements and novel 6D beam characterization techniques, which will combine slice emittance measurements on different streaking axes with slice energy measurements. Finally, the best way to combine the requirements of all the different measurements to fix the quadrupole and screen positions must also be considered.

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