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5D TOMOGRAPHY OF ELECTRON BUNCHES AT ARES

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Abstract

The ARES linear accelerator at DESY aims to deliver stable and well-characterized electron bunches with durations down to the sub-fs level. Such bunches are highly sought after to study the injection into novel high-gradient accelerating structures, test diagnostics devices, or perform autonomous accelerator studies. For such applications, it is advantageous to have a complete and detailed knowledge of the beam properties. Tomographic methods have shown to be a key tool to reconstruct the phase space of beams. Based on these techniques, a novel diagnostics method is being developed to resolve the full 5-dimensional phase space (x, x', y, y', z) of bunches including their transverse and longitudinal distributions and correlations. In simulation studies, this method shows an excellent agreement between the reconstructed and the original distribution for all five planes. Here, the 5-dimensional phase space tomography method is presented using a showcase simulation study at ARES.

INTRODUCTION

Advanced accelerator research and development benefits greatly from stable and well-characterized electron bunches. Undesired correlations between the two transverse planes can arise due to unnoticed rotated beamline elements or stray fields on the photocathode and in the gun region and can lead to 2D emittance growth [1, 2]. Longitudinal-transverse correlations are introduced due to space-charge forces [3] in the low energy region, a transverse dependent energy gain which evolves into a longitudinal-transverse correlation over a drift, or coherent-synchrotron radiation in, for example, bunch compressors in the beamline which can introduce longitudinally dependent transverse offsets [4]. In simulations, the full 6-dimensional phase space is available at any location in the beamline and such effects can be monitored and minimized. However, in reality, such diagnostics of the bunch is not as straightforward and requires advanced methods. A measurement of the 6-dimensional charge density has been performed for a H^- beam in a dedicated beamline using slit masks [5]. In operating accelerators, tomographic methods are a useful tool to obtain detailed knowledge of the beam distribution [6–10]. Methods to measure multi-dimensional distributions such as the full transverse phase space [11–14] as well as the 3-dimensional charge-density distribution [15–18] exist. Here, a tomographic method to reconstruct the 5-dimensional charge-density distribution (x, x', y, y', z) of an electron bunch is introduced. It combines a quadrupole-based tomography of the 4-dimensional transverse phase space with the variable streaking direction of a PolariX X-band transverse deflecting structure (TDS) – a device developed in collaboration between CERN, DESY, and PSI [18–20]. The method allows to reconstruct correlations between the horizontal and vertical positions x,y and divergences x',y' as well as the longitudinal position z in the bunch. Such information is useful to identify undesired correlations and therefore enables the optimization and improvement of the accelerator performance and beam quality.

The method is tested on an example case based on the ARES linear accelerator at DESY. ARES [21–23] is a normal conducting S-band linear electron accelerator designed for accelerator research and development. It operates at up to 50 Hz, 155 MeV and charges from 0.05 pC to 200 pC. ARES is designed to produce and measure bunches with sub-fs durations [16, 17, 24–26]. Additionally, it focusses on the study of novel dielectric-based acceleration techniques [27–30] and electron radiotherapy, the development of diagnostics devices and methods [31–34] and the application of machine learning to accelerator operation [35, 36]. Furthermore, it serves as a general test bed for new accelerator components [37]. For the simulations, a Gaussian particle distribution with ARES-compatible beam parameters for a fully on-crest working point is chosen. To demonstrate the potential of the method, an artificial longitudinal sinusoidal oscillation of the transverse beam size and divergence in the x-plane is imprinted on the bunch. The Courant-Snyder parameters [38], the alpha $\alpha_{x,y}$ and beta $\beta_{x,y}$ functions, are kept constant. Together with the geometric emittance $\epsilon_{x,y}$ these functions describe the statistical beam parameters.

The present study aims to demonstrate the working principle of the method by utilizing the ARES beamline. Furthermore, a simulated reconstruction of a particle distribution is presented and compared to the input distribution.

WORKING PRINCIPLE

The 5-dimensional phase space (x, x', y, y', z) of electron bunches is reconstructed using a tomographic method. In general, a tomography uses low-dimensional projections of an object along different angles to reconstruct a higher-dimensional distribution. This can be applied to bunches in an accelerator. The transverse information is obtained by scanning the transverse phase advances $\mu_{x,y}$ with, e.g., quadrupoles. The longitudinal information is obtained by streaking the beam with a TDS. To also resolve the correlations between the two transverse planes, their phase advances are controlled simultaneously. Furthermore, the streaking

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of the bunch at various angles is required. This is due to the overlap of the longitudinal information with the transverse plane parallel to the streaking direction. The streaking at arbitrary angles can be performed with a PolariX TDS. The final transverse distribution is reconstructed upstream of the first quadrupole used for the tomography, the longitudinal information is obtained at the location of the TDS.

The principle of the 5-dimensional phase-space tomography is as follows:

- For a fixed transverse phase advance combination (μ_x, μ_y), the beam is streaked with the TDS, and its projection is recorded on a downstream screen. This is repeated for different streaking angles.
- These screen images are used to reconstruct the 3-dimensional charge-density distribution (x, y, z) of the bunch [15]. The transverse profiles are reconstructed at the location of the screen. The longitudinal information is reconstructed at the TDS center.
- The reconstruction procedure is repeated for all desired phase advance combinations. The final longitudinal resolution is given by the largest unstreaked spot size at the screen in all transverse streaking planes for all phase advance combinations.
- Each 3-dimensional reconstruction can be regarded as the projection of the (x, x', y, y', z) phase space onto (x, y, z) for different transverse rotation angles.
- These rotation angles are given by the phase advance when analyzing the images in normalized phase space [39]. The conversion from real phase space x, y to normalized phase space x_N, y_N is given by $x_N, y_N = x, y/\sqrt{\beta_{x,y}}$.
- Next, the 3-dimensional reconstructions are combined. This is done for each longitudinal slice z_k individually.
- Using the reconstructed sliced projections $(x, y)_{z_k}$, the transverse charge-density distribution $(x, x', y, y')_{z_k}$ can be reconstructed similar to the reconstruction of the 4-dimensional transverse charge density in [11, 12]. This distribution is reconstructed at a chosen location upstream of the TDS and all quadrupoles that are used to scan the phase advance.
- By combining all longitudinal slices, the 5-dimensional charge-density distribution is obtained.

SIMULATION OF 5D TOMOGRAPHY

The section of the ARES linear accelerator used for the tomographic studies contains five quadrupoles and two PolariX transverse deflecting structures (see Fig. 1). Screen images are recorded at the screen station downstream of the TDS. The final distribution is reconstructed at the screen upstream of the first displayed quadrupole. The quadrupoles are used to match the phase advance. Although two PolariX structures are available in the beamline, in these simulations only one structure is used to streak the bunch. The structure is operated at 11.99 GHz. The phase advance is scanned over a range of 180° in 30 steps. The beam is streaked over 180° in 50 steps. For the screen, a size of 2 cm and 1000 pixels

Table 1: Input and Reconstructed Beam Parameters

Parameter	Unit	Input	Reconstruction
E	MeV	155	-
σ_E	%	0.1	-
Q	pC	1	-
σ_τ	fs	200.0	198.9
ϵ_x	m rad	6.12×10^{-9}	5.85×10^{-9}
ϵ_y	m rad	4.66×10^{-9}	4.85×10^{-9}
ϵ_x^{slice}	m rad	5.46×10^{-9}	4.21×10^{-9}
ϵ_y^{slice}	m rad	4.67×10^{-9}	4.79×10^{-9}
α_x / α_y		0.81 / 0.94	0.80 / 0.94
β_x / β_y	m	0.86 / 3.77	0.86 / 3.76

per transverse plane is chosen. This corresponds to a pixel size of 20 µm × 20 µm which is larger than the available resolution at the screen stations at ARES and chosen to reduce computational costs. The longitudinal resolution R is calculated following the definition in [40]. It is defined as $R = \sigma |p| c/(2\pi f eVL)$, where σ is the maximum unstreaked transverse spot size at the screen downstream of the TDS, p is the average momentum of the bunch, c the speed of light, e the elementary charge, f the TDS frequency, V the streaking amplitude and L the drift length between the TDS center and the downstream screen. The beta functions at this screen are matched to obtain an RMS spot size below 0.3 mm in all rotation planes. Together with a 4.79 MV streaking amplitude in the PolariX TDS this results in a longitudinal resolution of 17.81 fs. To reduce computational costs, only 40 slices of 29.8 fs are reconstructed. The amplitude of the TDS at ARES can be increased up to 20 MV. This results in a resolution of 4.3 fs using one TDS. However, to be able to fit a roughly ±3 sigma RMS bunch duration on the screen, the lower amplitude is chosen in the study here. Simulations are performed in OCELOT [41, 42] using second order transfer maps for all elements except the transverse deflecting structure. A particle distribution with 4 000 000 particles is tracked and the beam properties are shown in Table 1, where E is the energy, σ_E the energy spread, Q the charge and σ_t the bunch duration.

All tomographic reconstructions are performed using a python scikit-image [43] implementation of the Simultaneous Algebraic Reconstruction Technique (SART) algorithm [44] with two iterations. The minimum of the reconstructed values is restricted to zero, the maximum to 6000. The reconstructed sliced transverse distributions (x, y) are converted to normalized phase space in a range from $-0.5\,\mathrm{mm}/\sqrt{\mathrm{m}}$ to $0.5\,\mathrm{mm}/\sqrt{\mathrm{m}}$ with 200 bins by using the beta functions obtained from the propagation of the Courant-Snyder parameters through the beamline. The full reconstruction takes less than 2.5 h running in parallel on an AMD EPYC 75F3 on a computing cluster.

A comparison of input and reconstructed beam parameters shows excellent agreement between the input and reconstructed Courant-Snyder parameters and RMS bunch

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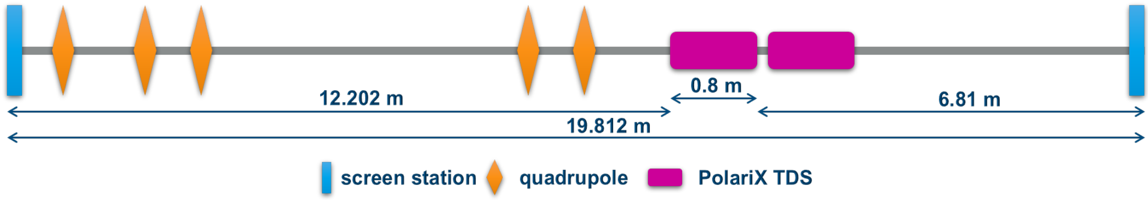

Figure 1: Sketch of the section of the ARES beamline used for the 5D tomography simulations.

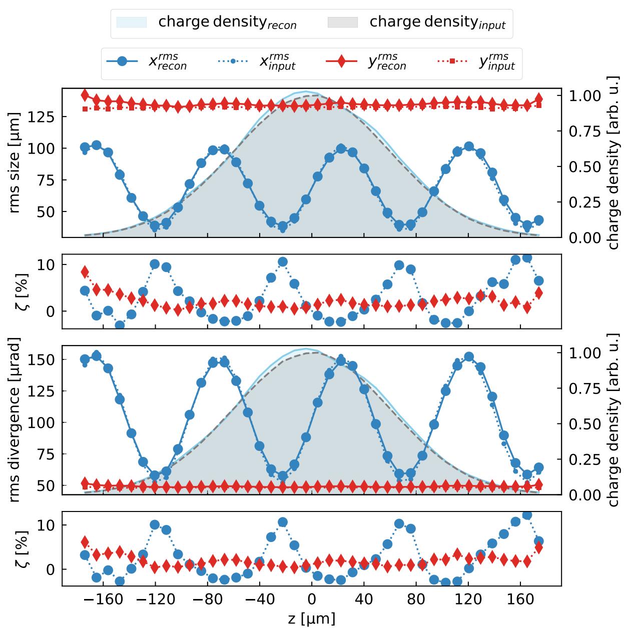

Figure 2: Sliced comparison of the reconstructed (solid line) and input (dotted line) transverse sizes and divergences. A sinusoidal variation is imprinted on the x-plane (blue) to exhibit the ability of the method. The relative discrepancies $\zeta = \frac{(\sigma_{recon}-\sigma_{input})}{\sigma_{input}}$ are shown. The longitudinal charge-density profile of the input (dashed gray) and reconstruction (solid blue) is shown as a reference.

duration (see Table 1). The transverse emittances are reconstructed well with a relative discrepancy of less than 5 % in both planes. The reconstructed emittances are calculated from the standard deviation of the transverse projections of the reconstructed distribution in normalized phase space. The slice emittance is calculated for slice number 19 which ranges from −4.46 µm to 4.46 µm where 0 µm is at the longitudinal center of the bunch. To avoid the influence of artifacts stemming from the tomographic reconstruction, in the transverse planes values outside of a ±3 sigma range from the bunch center are not considered for the emittance and Courant-Snyder parameter analysis.

The reconstructed sliced transverse beam sizes and divergences agree well with the input distribution (see Fig. 2). The imprinted sinusoidal correlation in the x-plane is reconstructed accurately. A slight imprint of the sinusoidal correlation on the y-plane is observed. Since no coupling between the transverse planes is present in the beamline, this possibly stems from the tomographic reconstruction and is subject to further investigations. The relative discrepancies between input and reconstructed distribution of all slices are better than 13 %. For this analysis, the standard deviation of the sliced input distribution is calculated and compared to the RMS value obtained by a Gaussian fit to the reconstructed projection. The input and reconstructed longitudinal charge density agree well and are shown for each longitudinal slice.

CONCLUSION

The presented simulation study based on the ARES beamline with an idealized Gaussian distribution shows that the proposed method accurately reconstructs the 5-dimensional phase-space distribution of the bunch. The results show excellent agreement between the input and reconstructed projected and sliced beam parameters with a relative discrepancy of $\lesssim$ 10 %. Further studies with full start-to-end simulations of an electron bunch at ARES are foreseen.

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