IMPROVEMENTS IN LONGITUDINAL PHASE SPACE TOMOGRAPHY AT PITZ


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Abstract

Methodical studies to improve the existing e-beam Longitudinal Phase Space (LPS) tomography were performed at the Photo Injector Test facility at DESY in Zeuthen. Proof-of-principle simulations were done to address some core concerns, e.g., booster phase range, space charge effects and noisy artefacts in results. Phase advance analysis was done with the help of an analytical model that determined the booster phase range and step size. A slit was introduced before the booster to truncate the beam and reduce space charge forces. The reconstruction method adopted was image space reconstruction algorithm owing to its assurance of non-negative solution. An initial scientific presumption of LPS from low energy momentum measurements was established to reduce artefacts in the phase space. This paper will explain the proof-of-principle simulations highlighting the key aspects to obtain accurate results. Reconstructed LPS for different experimental cases will be presented to demonstrate the diagnostic capability.

INTRODUCTION

The Photo Injector Test facility at DESY in Zeuthen (PITZ) is a unique accelerator facility owing to its dynamic parameter space. Initially established to develop and characterize electron guns for FLASH and Eu-XFEL [1], it has now expanded to perform proof-of-principle studies of accelerator-based THz source [2] and to carry out research in state-of-the-art cancer radiation therapy with ultra-high dose rates [3]. Nevertheless, beam dynamics and diagnostic studies remain a crucial part at PITZ to characterize the electron beams, improve beam transport and manipulate phase space.

The electron source in PITZ beamline consists of a normal conducting L-band 1.6-cell copper gun cavity with a Cs2Te photocathode. It can produce up to ~6.5 MeV electron bunches with variable bunch lengths and up to several nC charge. The electron beam is further accelerated by a Cut Disk Structure (CDS) booster cavity to an energy of up to ~22 MeV. Downstream the accelerating structure, the beamline consists of different diagnostics for detailed measurements of the electron beam properties. Figure 1 shows PITZ beamline till the High Energy Dipole Arm1 (HEDA1).

To determine the LPS of the beam before the booster, a tomographic reconstruction technique is applied at PITZ [4].

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Figure 1: PITZ beamline till high energy spectrometer 1.

In this technique, the momentum projections corresponding to different booster phases are fed to a reconstruction algorithm, Algebraic Reconstruction Technique (ART), and the iterations are carried out until the results converge. The results showed many artefacts and hence overestimated the energy spread and bunch length. A hard charge cut was applied on the reconstructed LPS to give reasonable values. Also, the reconstruction results were more accurate for low-charge beams ~ 10 pC since space charge forces are not catered for the algorithm. Typically, 250 pC beams are characterized at PITZ since this is the working point of the Eu-XFEL. Recently, improvements in LPS tomography have been done in terms of optimization of experimental conditions and reconstruction algorithm.

In this paper, proof-of-principle simulations for the case of 250 pC beam will be explained. Phase advance analysis will be discussed with the help of an analytical model as well as the procedure adopted to reduce the space charge effect. Image space reconstruction algorithm will be described and its reconstruction results will be shown with the initial estimate built from the Low Energy Momentum Arm (LEDA) measurements. Finally, the experimental results will be shown for different temporal gaussian beam profiles and for both low and high charge cases.

PROOF-OF-PRINCIPLE SIMULATIONS

Methodical studies were first done on simulated beams generated and tracked by A Space Charge Tracking Algorithm (ASTRA) [5]. The particles were produced by a 6.6 ps FWHM temporal-gaussian laser and a charge of 250 pC was extracted. The beam momentum after the gun was close to 6.3 MeV/c and the gun phase was varied from ~10° to 10° around the Maximum Mean Momentum Gain (MMMG) phase. The mean momentum (p) and the momentum spread pRMS of the projections were calculated and plotted as shown in Fig. 2 (a). The error bars are assumed to be 1 keV/c.
The beam momentum after the booster was close to 17 MeV/c and its phase was varied from $-10^\circ$ to $10^\circ$ w.r.t MMMG phase. The mean momentum and the momentum spread of these particles were also calculated. To estimate these and some other LPS parameters, an analytical model was developed where the first and second order moments of the LPS distribution were calculated by an equivalent ellipse model. This modelling of the LPS properties is done purely from a statistical point of view, without taking space charge effects into account. Therefore, in order to compare this model to simulations, the space charge forces in the booster were turned off while doing the booster phase scan in ASTRA. Figure 2(b) shows the simulated as well as the modelled mean momentum and momentum spread corresponding to each booster phase. Both the first and second order of moments fit reasonably well specially around MMMG phase. The errorbars are assumed to be 2 keV/c.

**Phase Advance Analysis**

The phase advance $\Phi$ of the LPS can be calculated from the bunch length and RMS energy spread which were derived from the analytical model. The expression for the phase advance $\Phi$ is given by:

$$
\Phi = \arctan\left(\frac{k \sigma_{\varphi}}{\sigma_{p_{\text{min}}}}\right)
$$

where, $k$ is the LPS linear chirp that defines the correlation approximated by modelled RMS energy spread, $\sigma_{\varphi}$ is the estimated RMS bunch length and $\sigma_{p_{\text{min}}}$ is the minimum RMS energy spread calculated from simulated data.

Figure 3(a) shows the phase advance corresponding to each booster phase. The phase advance varies significantly around MMMG phase but at the off-crest phases, its change is gradual. This provides the key information to consider the booster phase range and step size for tomography. One can also correlate phase advance with the energy spread as shown in Fig. 3(b). As the booster phase varies, the beam phase advance is significant around the minimum energy spread phase and decreases gradually as the energy spread increases. Thus, the momentum projections for tomography should correspond to the booster phase range which covers the whole LPS phase advance and the step size should be optimized in order to produce a smooth curve.

**Reconstruction Algorithm**

The Image Space Reconstruction Algorithm (ISRA) [6,7] was implemented for LPS reconstruction which showed promising results owing to its assurance of non-negative least-squares solution. The expression for ISRA is shown in Eq. 2. ISRA takes a current estimate $\tilde{x}^k$ of the solution and forward projects it to form a vector $\tilde{A}\tilde{x}^k$. This vector is back projected to form a predicted back projected vector. Similarly, the measured projections $\tilde{m}$ are also back projected using the weight matrix $\tilde{A}$. The ratio of these back projections provides a multiplicative correction vector to update the current estimate. The initial estimate $\tilde{x}^1$ can be taken as a vector of uniform positive values, e.g., 1.

$$
\tilde{x}^{k+1} = \tilde{x}^k \frac{\tilde{A}^T \tilde{m}}{\tilde{A}^T \tilde{A}\tilde{x}^k}
$$

where, $\tilde{x}^k$ is a vector containing the current estimate of the reconstructed phase space and $\tilde{x}^{k+1}$ is the next update, $\tilde{m}$ is a vector that contains simulated or measured projections corresponding to all booster phases and $\tilde{A}$ is a weight matrix built from the analytical mean momentum expression. The weights are distributed in the neighboring pixels by bilinear interpolation to model the signal analogue to discretization conversion effects. Generally, the iterations are continued until the root mean square error between measured and predicted projections converges to $< 0.2 \%$.

**Space Charge Effects**

Next, simulations were carried out on Astra-generated 250 pC beam including booster space charge forces. As LPS analytical model does not include them, a 200 µm-wide slit was inserted before the booster at location 0.8 m from the cathode in the non-dispersive plane of the beam to strongly reduce the space charge effects. LPS before and after the slit insertion is shown in Fig. 4. The energy spread and bunch length are slightly increased after inserting the slit with some kinks at the edges but the overall phase space structure is retained. This can be categorized as a systematic error because of correlation between $p_z$ and radial plane after introduction of the slit [8].
Reconstruction Results

The reconstruction results from ISRA after 50 iterations, starting from an initial estimate \( \vec{x}^1 \) of uniform values, are shown in Fig. 5 (a) and they are comparable to the true LPS shown in Fig. 4 (b). Even the kink on the right side of bunch length profile is reproducible. However, there are noise-like artifacts in the reconstruction area that overestimate the bunch length and energy spread. These artifacts can be removed by incorporating the information that image is 0 outside a certain area i.e by a presumption from LEDA.

Initial Assumption  
An initial educated guess of LPS from LEDA was established to further improve the reconstruction results. Basically, the momentum profile at an off-crest booster phase was used to select the range of gun phase from LEDA scan to be used as an initial matrix. The LPS was modelled by a set of longitudinal slices assuming a Gaussian momentum distribution for every slice. The amplitude of a slice of LPS was taken from the weights of off-crest booster phase momentum profile. The expression for initial guess for LPS can be written as:

\[
LPS(z, p_z) = \sum_{n=1}^{N} G_n(p_z) \Delta_n(z)  
\]

where \( G_n(p_z) \) is the \( p_z \)-distribution for the \( n^{th} \) longitudinal slice within the bunch scanned by the step function \( \Delta_n(z) \). The initial estimate from LEDA removes the noise-like artifacts scattered in the reconstructed LPS. Additionally, it also impacts the overall distribution of particles in the phase space. Being an underdetermined system, the initial guess from LEDA assists the algorithm to achieve a unique result out of infinite many solutions. Therefore, the RMS bunch length and energy spread of reconstructed LPS shown in Fig. 5 (b) are much closer to the true values.

EXPERIMENTAL RESULTS

This section presents results of longitudinal phase space measurements using the tomographic technique for different temporal laser profiles and electron bunch charges.

- Gaussian temporal laser profile, bunch charge 250 pC
- Gaussian temporal laser profile, bunch charge 10 pC
- Modulated gaussian temporal laser profile, bunch charge 10 pC

The steps adopted are the same as explained in the proof-of-principle simulations. Additionally, a few steps were included for experimental data:

- the signal resolution of the projections was improved by careful beta function control at the reference screen of the momentum measurements
- number of pulses were tuned for each measurement to improve the signal to noise ratio

Figure 6 (a) shows reconstructed LPS for 250 pC with and without initial matrix from LEDA. After approximately 50 iterations, the LPS looks reasonable and has negligible artifacts. The bunch length and energy spread values are comparable to simulated case. For 10 pC beam generated from temporal Gaussian laser, there is no space charge and therefore no requirement of slit in the procedure. A more challenging case of modulated beam generated by modulated Gaussian laser was chosen to demonstrate the method capability. Figure 7 shows the reconstructed LPS for both 10 pC cases.

CONCLUSION

LPS in front of the booster was reconstructed by tomography at PITZ. Phase advance analysis was done to select a proper booster phase range and step size. A slit before the booster was used to reduce the space charge effects in case of high charge beam. ISRA used to reconstruct the phase space showed good results and monotonic convergence. The results were further improved by using an initial guess from LEDA. After methodical studies on simulations, the technique was tested on experimental data for 10 pC and 250 pC beam and the results look promising. A combination of improved experimental conditions and optimized reconstruction algorithm yielded reliable LPS tomography results.

REFERENCES


