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CHARACTERIZATION OF THE FULL TRANSVERSE PHASE SPACE OF ELECTRON BUNCHES AT ARES

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Abstract

The ARES linear accelerator at the SINBAD facility (DESY) is dedicated to perform accelerator R&D studies with sub-fs short electron bunches to test novel acceleration techniques and diagnostics devices. Currently, the commissioning of the linac is ongoing and first experiments are being performed. For this, the knowledge of the full phase space of the particle beams is of high interest to, for example, optimize the accelerator performance and identify possible errors in the beam line. Tomographic methods can be used to gain insight into the full 4D transverse phase space and its correlations. Here, simulation results and first experimental preparations of a 4D transverse phase-space tomography of electron bunches at ARES are presented and discussed.

INTRODUCTION

The ARES (Accelerator Research Experiment at SINBAD) linear electron accelerator [1] is hosted at the SINBAD (Short Innovative Bunches and Accelerators at DESY) facility [2] at DESY and is dedicated to perform accelerator R&D studies. It aims to deliver well-characterized and reliable bunches with sub-fs duration, up to 155 MeV energy and charges in the pC-range. Due to their short durations, such bunches are well suited, for example, to study the injection into novel high-gradient acceleration structures [3–6] or to test and develop novel diagnostics methods and devices [7, 8]. Furthermore, ARES is an interesting candidate for autonomous accelerator studies [9]. To improve the performance of such applications and better understand the accelerator itself, it is advantageous to have a full and detailed knowledge of the beam properties.

To meet this demand, dedicated beam diagnostics sections in the low-energy (below 6 MeV/c) gun region and high-energy part of ARES have been foreseen and are shown in Fig. 1. The final components are installed at the time of writing and include two PolariX transverse deflecting structures [10, 11]. These structures will be operational in the beginning of 2022 and will enable the characterization of the longitudinal profile of the ultra-short bunches [12, 13] aimed to be produced at ARES.

To gain even deeper insight into the phase space of the bunches, a novel tomographic beam diagnostics method is being developed to reconstruct the 5D phase space of the bunches. This includes the measurement of the full 4D transverse phase space distribution as well as its longitudinal profile and correlations. The latter will be accessible thanks to the variable streaking angle of the PolariX transverse deflecting structures. Since, however, these structures are not yet available for use at ARES, first studies investigating solely the transverse phase space were performed. The transverse phase space can be characterized using 4D phase-space tomography [14]. Here, the application of this method to the ARES linac, measurement preparations and simulation results are presented and discussed.

TRANSVERSE PHASE-SPACE TOMOGRAPHY AT ARES

The 4D transverse phase space of a bunch can be measured using phase-space tomography [14]. This tomographic method is based on rotating the horizontal ($x - x'$) and vertical ($y - y'$) phase spaces by changing the phase advance $\mu_{x,y}(s) = \int_0^s \frac{1}{\beta_{x,y}(s)}\, ds$. Here, x, y and x', y' are, respectively, the horizontal and vertical particle position and divergence, while $\beta_{x,y}$ is the beta function, which together with $\alpha_{x,y}$ and the emittance ϵ describe the statistical parameters of a beam. The rotation of the phase spaces results in different $x - y$ projections, which are recorded at a fixed location by, for example, a screen. From these projections the phase space can be reconstructed using tomographic methods. To access the full 4D phase space, the phase advance in one plane is kept constant while changing it in the other plane. This procedure is repeated until a sufficiently high range of phase advances is covered for both planes. The method of full 4D transverse phase space tomography was originally developed in [14] and was first experimentally demonstrated in [15].

At ARES, the 4D phase-space tomography was performed using the high-energy matching region. This section includes four quadrupoles for phase advance matching as well as screen stations at the entrance and end. A sketch of this part of the beam line is shown in Fig. 2. To set up the ARES beam line for measurements, the beam was first centered in all the used magnets as well as the upstream accelerating structures using the available steerers. To prepare for the phase-space tomography, knowledge of the beam parameters is needed to match the beam line accordingly. Of special interest are the Courant-Snyder parameters α and β in both transverse planes, which were measured by performing a quadrupole scan upstream of the matching region. The results of this measurement are listed in Table 1 together with other relevant parameters. The quadrupoles were matched using OCELOT [16] simulations to achieve the desired phase

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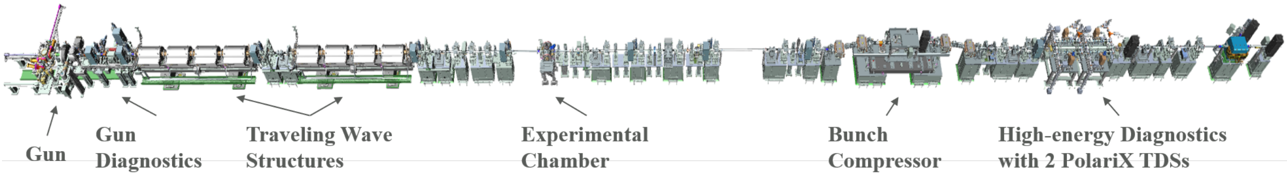

Figure 1: Current layout of the ARES beam line.

Table 1: ARES Beam Parameters for the 4D Tomography

Parameter	Unit	Value
Momentum	MeV/c	155.54 ± 0.01
Momentum spread (FWHM)	MeV/c	0.1
Charge	pC	0.28 ± 0.01
Normalized emittance x	µm	1.06 ± 0.01
Normalized emittance y	µm	0.425 ± 0.008
β_x (at screen 1)	m	6.61 ± 0.15
β_y (at screen 1)	m	17.83 ± 0.42
α_x (at screen 1)		-1.31 ± 0.05
α_y (at screen 1)		-3.06 ± 0.1

advance in each plane (between 180° and 360°). In the following, a specific combination of phase advances in the horizontal and vertical plane will be referred to as a scan point. An example of the evolution of the phase advances and beta functions along the beam line for a subset of scan points is shown in Fig. 3. In total, 20 projections per transverse plane were used. This corresponds to a total of 400 scan points.

Two datasets for the 4D tomography were collected at ARES using a partially automated script. For one dataset the quadrupole strengths for each scan point were set without cycling the magnets in between scan points. For the second dataset the quadrupole magnets were cycled whenever the ramping direction for one of the quadrupoles had to be changed. The RF amplitudes of the gun and the two accelerating structures were monitored during all measurements to ensure a stable beam. In addition, reference images of the beam were recorded at the beginning and end of each measurement at screen 1. Finally, for each scan point the camera gain was adjusted and the beam was re-centered on the measurement screen 2 to compensate for any remaining misalignments in the beam line. In total, this data taking procedure took 6 hours for the not-cycled and 31 hours for the cycled case.

In addition to the experimental data, simulation studies were performed based on the measured beam parameters and matched quadrupole strengths. A simulated dataset was obtained using OCELOT. A pixel size of 11 µm × 11 µm was used which corresponds to the upper resolution of screen 2. This simulated dataset was used to test the reconstruction method as well as the ideal result expected from this beam line setup. The tomographic reconstruction was

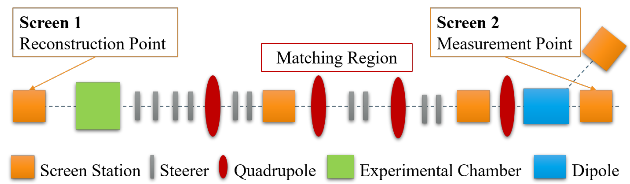

Figure 2: Sketch of the ARES beam line as it was installed until April 2021 and used for the 4D tomographic measurements. The phase advance of the beam is changed by varying the strength of the four quadrupoles. Projections of the beam are recorded on screen 2 (measurement point) and the phase spaces are reconstructed at screen 1 (reconstruction point).

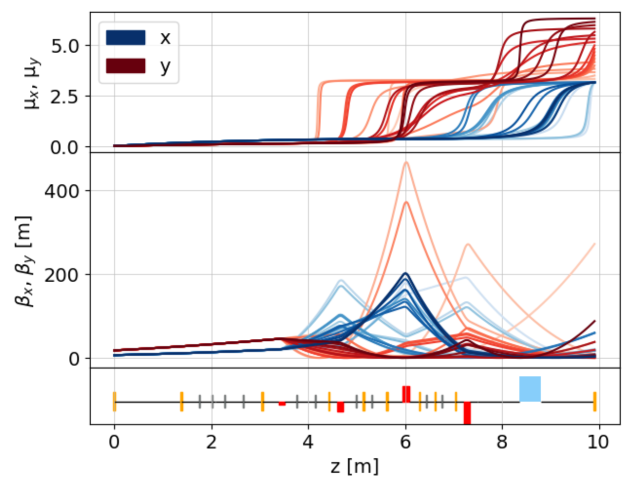

Figure 3: Example of the evolution of the phase advances (top) and beta functions (bottom) for a subset of matched scan points for the 4D tomography measurement. The phase advance in x is kept constant while varying the phase advance in y over a range of 180°. Each shade of the colors corresponds to a different scan point.

performed using the Simultaneous Algebraic Reconstruction Technique (SART) [17] with two iterations implemented in the python scikit-image [18] package. The reconstruction was performed in normalized phase space [19] using a resolution of 100 bins for each of the four dimensions. Negative charge density values in the reconstruction, which can arise due to reconstruction artefacts, were set to zero. The results from the simulation study are presented in the following section. The analysis of the experimental data is still ongoing.

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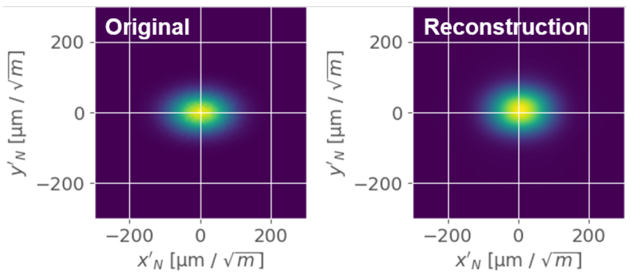

Figure 4: Projection onto the $x' - y'$ phase space at screen 1 of the original (left) and reconstructed (right) normalized 4D phase space obtained from simulations.

RECONSTRUCTIONS OF THE SIMULATED DATASET

The 4D phase space of the simulated electron beam was reconstructed at screen 1 as indicated in Fig. 2. In order to estimate the performance of the reconstruction, the reconstructed phase space can be compared to the original input distribution of the beam. For this, the projections of the reconstructed 4D transverse phase space onto the 2-dimensional planes were analyzed and compared to the original beam. As an example, the comparison of the $x' - y'$ phase space is shown in Fig. 4. A slight blurring of the reconstructed phase space in the y' dimension can be seen, but overall good agreement between the original and reconstruction for all projection planes was observed. This can also be seen when comparing the 1-dimensional projections of the original and reconstructed 4D phase spaces. The standard deviations of a Gaussian fit to these projections in normalized phase space are compared in Table 2. A maximum relative discrepancy of the fitted standard deviation between the original and reconstructed phase spaces of 17% is observed for the y' projection. The relative discrepancies for the other projections lie below 4%. These discrepancies can be reduced by increasing the number of projection angles. Since this would increase the required time for data taking in an experiment, this option is not further explored here. Alternatively, a threshold-cut can be applied to the 4D charge density reconstruction. Values below this threshold are set to zero and thereby the impact of reconstruction artefacts can be reduced. This threshold can be chosen such that the overall charge of the reconstructed distribution is equivalent to the charge of the original input distribution. This results in a relative discrepancy below 12% for y' and 3% for the other projections. The reason for the larger discrepancy in the y' projection is not yet fully understood but could be due to the chosen pixel size of the screen. Simulations with a reduced pixel size of 3 μm × 3 μm and an applied threshold-cut to the reconstructed charge density to obtain the initial charge of the input distribution were performed. These simulations show a reduction of the relative discrepancy to below 4% for the y' projection.

Table 2: Standard Deviations of the 1D-Projections of the Original and Reconstructed 4D Phase Spaces

Parameter	Original	Reconstruction
σ_{x_N} [μm/$\sqrt{\text{m}}$]	59.58 ± 0.05	60.41 ± 0.37
$\sigma_{x'_N}$ [μm/$\sqrt{\text{m}}$]	59.57 ± 0.04	60.63 ± 0.11
σ_{y_N} [μm/$\sqrt{\text{m}}$]	37.74 ± 0.02	39.14 ± 0.14
$\sigma_{y'_N}$ [μm/$\sqrt{\text{m}}$]	37.82 ± 0.02	44.25 ± 0.16

CONCLUSION

The ARES linear accelerator aims at producing reliable and well-characterized electron beams with sub-fs duration. To study such bunches, first measurements and simulation studies to investigate the 4D transverse phase space have been carried out. Good agreement between original and reconstructed phase spaces for a simulated dataset was observed. The analysis of the measured data is still ongoing. For this, the main focus lies on verifying the exact evolution of the phase advance in the beam line section used for the measurement. As a next step, to advance the phase space characterization further, the feasibility of expanding these tomographic techniques to 5D is being explored.

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