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EFFICIENT 6-DIMENSIONAL PHASE SPACE MEASUREMENTS AND APPLICATIONS TO AUTONOMOUS MONITORING AT LCLS-II

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Abstract

Increasing the performance and capabilities of free electron lasers, such as LCLS-II, hinges on our ability to precisely control and measure the 6-dimensional phase space distribution of the beam. However, conventional tomographic techniques necessitate a substantial number of measurements and computational resources to characterize a single beam distribution, using many hours of valuable beam time. Novel diagnostic techniques are needed to significantly reduce the number of measurements required to reconstruct detailed, 6-dimensional beam features to enable feedback for precision beam shaping for accelerators and characterize unknown physical phenomena. In this work, we present a novel approach to analyzing experimental measurements using differentiable beam dynamics simulations and generative representations of 6-dimensional phase space distributions. We discuss developments in combining this work with advanced accelerator control algorithms and parasitic beam measurements to autonomously monitor the 6-dimensional phase space distribution of the beam at LCLS-II during accelerator operations.

INTRODUCTION

Developing a precise understanding of particles distribution in 6-dimensional position-momentum space in real accelerators is key to maximizing the performance of current accelerator facilities and enabling future accelerators. Current accelerator applications, such as Free Electron Lasers (FELs) require precise control over beam properties in order to maximize FEL pulse intensity, while future accelerators, such as wakefield-based accelerator schemes also benefit from detailed control over the distribution of particles in 6-dimensional phase space [1].

However, currently used techniques for precisely measuring or predicting high-dimensional (> 4 dimensions) beam distributions from experimental data have not been able to adequately address this diagnostic challenge in practical settings. Direct or tomographic measurements of 5- or 6-dimensional phase space distributions have been demonstrated in only a handful of specific situations with specialized diagnostic elements, requiring a substantial number of individual measurements over a large amount of dedicated beam time (> 18 hrs) [2, 3]. On the other hand, using 2-dimensional projections of the beam distribution, such as beam profile monitors, provides substantially more information about the beam distribution than lower dimensional measurements, enabling significantly fewer measurements to reconstruct the beam distribution. Unfortunately, the computational costs of scaling conventional algebraic reconstruction techniques (ART [4], SART [5], MENT [6, 7]) to reconstructing 6-dimensional distributions from 2-dimensional images precludes the use of these algorithms in a practical setting [8].

To address these challenges, we introduced the Generative Phase Space Reconstruction (GPSR) technique [9, 10] to efficiently reconstruct high dimensional beam distribution features from experimental data such that the reconstruction analysis can be performed in an online setting. As a result, we have conducted multiple 6-dimensional phase space measurements at several accelerator facilities, including the Argonne Wakefield Accelerator (AWA) [11] and the Pohang XFEL facility [12]. In this work we describe the GPSR technique as it applies to the parasitic DIAG0 diagnostic line at LCLS-II and describe efforts to enable autonomous monitoring of the 6-dimensional phase space distribution of the beam during normal user operations and machine development time.

GENERATIVE PHASE SPACE RECONSTRUCTION USING THE DIAG0 BEAMLINE

Generative phase space reconstruction is an analysis method that aims to predict the 6-dimensional phase space distribution from tomography-style measurements of the beam distribution. Similar to standard tomography techniques, we rotate the phase space distribution of the beam along multiple axes by using quadrupoles, transverse deflecting cavities, and dipoles while imaging the two dimensional distribution of the beam via a set of diagnostic screens. Instead of reconstructing the beam distribution at a grid of points in phase space by solving a system of linear equations via an iterative solver (e.g. ART/SART), we utilize a machine learning based parameterization of the beam distribution and a differentiable physics simulation to solve for the beam distribution.

GPSR parametrizes a beam distribution in 6-dimensional phase space using a transformer neural network, which transforms particle coordinates drawn from a Multivariate Normal distribution into realistic macro-particle coordinates in position-momentum space. As a result, the structure of the generated macro-particle distribution is governed by the parameters of the neural network, which can efficiently represent arbitrary, high-dimensional features in phase space. To effectively solve for the exact distribution

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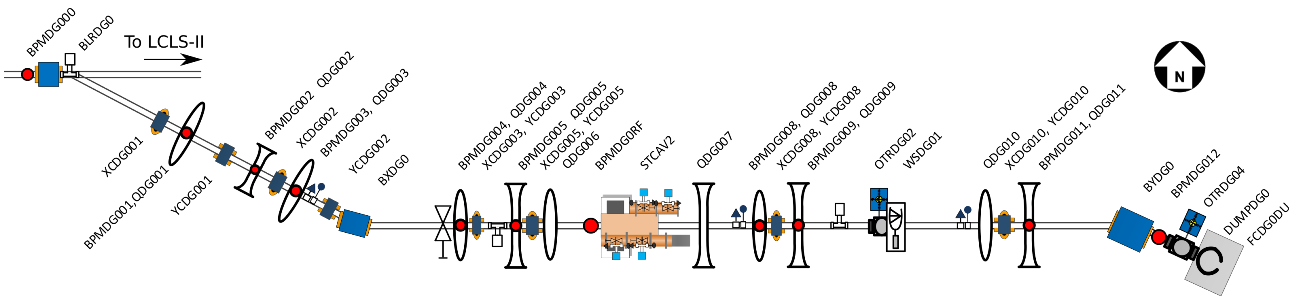

Figure 1: Diagram of DIAG0 lattice at LCLS-II with control elements labeled. GPSR is used to reconstruct the 6-dimensional phase space distribution at BPMDG000 using diagnostic screens OTRDG02 and OTRDG04.

structure that replicates experimental measurements, we utilize fully backwards-differentiable beam dynamics simulations implemented in Cheetah [13], which enables the use of gradient-based optimization algorithms. This enables "from scratch" training of the neural network used to generate the particle beam distribution with as few as 20 individual measurements.

The goal of this work is to conduct autonomous GPSR measurements of the 6-dimensional phase space using the DIAG0 parasitic beamline at LCLS-II, shown in Fig. 1. This beamline uses a fast electrostatic kicker to pick off electron pulses at a nominal 10 Hz rate from the main LCLS-II beamline. The DIAG0 beamline contains multiple diagnostic screens, quadrupole and dipole magnets, and a S-band transverse deflecting cavity (TCAV). The final spectrometer dipole and TCAV kicks are oriented perpendicular to one another (TCAV-horizontal, dipole-vertical), such that the image on the diagnostic screen gives a single shot measurement of the longitudinal phase space. Similar to previous work at AWA, we combine this single shot longitudinal diagnostic with multiple quadrupole scans to characterize the 6-dimensional distribution of the beam, where each quadrupole scan occurs while imaging the beam first at OTRDG02 and then at OTRDG04, both with the TCAV turned on and off, resulting in 4 quadrupole scans. This allows us to reconstruct the beam distribution at the entrance of the DIAG0 line, which is just downstream of the laser heater section of the LCLS-II beamline.

AUTONOMOUS DIAG0 CONFIGURATION AND GPSR MEASUREMENT

Due to the parasitic nature of the DIAG0 beamline, it is possible to utilize this beamline to constantly diagnose and monitor the beam distribution during regular operations. To automate this process, we have developed algorithms that and make control decisions that ensure high-quality measurements of the 6-dimensional distribution. These algorithms reconfigure DIAG0 in response to changes in the incoming beam distribution (either due to time-dependent drifts in the machine or changes in operating modes), while also respecting operational constraints such as maximum beam losses.

We break up the operation of DIAG0 into 4 distinct tasks, which will all be individually handled by Bayesian optimization (BO) algorithms [14] implemented in Xopt [15]. These tasks are completed sequentially by chaining together multiple optimization runs in the pattern shown in Fig. 2. We use a variety of modifications to basic BO algorithms to improve performance and ensure high-quality measurements. With these improvements, the entire DIAG0 beamline configuration and measurement procedure took between 5-10 minutes, depending on how close the DIAG0 beamline was to the optimal configuration at the beginning.

Beam Steering

For this task we aim to minimize the total root mean squared horizontal and vertical distance away from the center of 7 BPMs (BPMDG004-BPMDG012) along the DIAG0 beamline by adjusting the kick strength of 14 individual horizontal and vertical steering magnets, while constraining on a minimum transmission threshold of 90%. To significantly improve convergence speed, we modify the way we model the objective function by leveraging the structure of the objective and known beam dynamics. Instead of modeling the objective function directly with a single Gaussian process (GP) model, we create independent GP models of each BPM signal and combine predictive samples drawn from each of these models to calculate an acquisition function (Expected Improvement) for the total objective. This greatly simplifies the models used, as each BPM signal has a linear response with respect to steering magnet strength, allowing for the use of a linear kernel function, and is independent of downstream steering magnet parameters, which can be specified prior to optimization or learned on the fly.

As a result, convergence speed to an optimal operating condition is greatly enhanced at a cost of additional computational expense needed to utilize and update multiple GP models. We observed that starting from a non-ideal operating condition, this algorithm was often able to reach a sufficient operating point (< 0.5 mm RMS) within 10-15 iterations over the span of approximately one minute, significantly faster than BO when directly modeling the objective function in a 14-dimensional parameter space.

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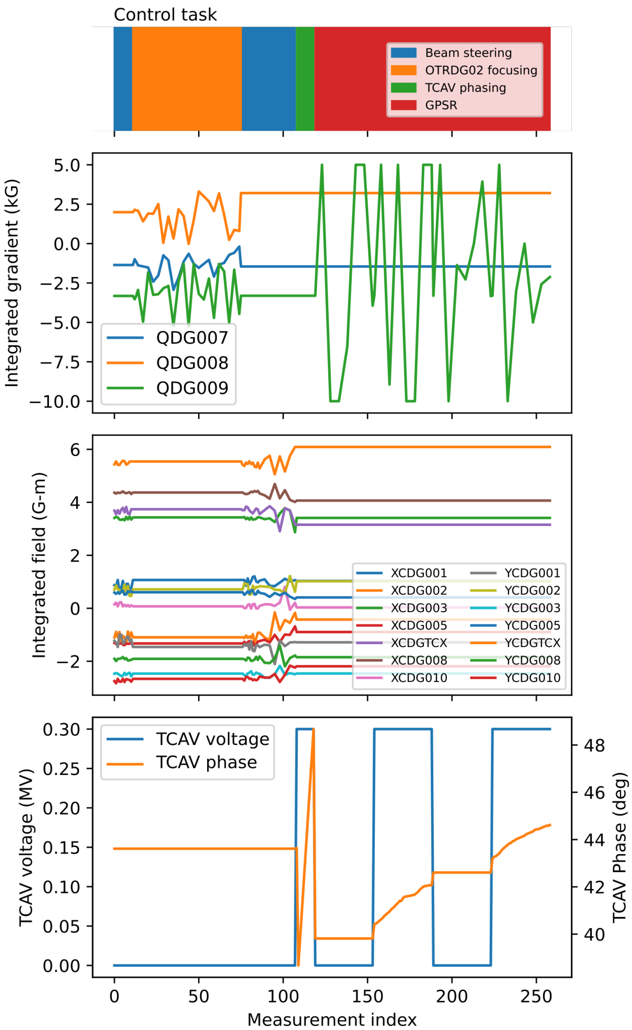

Figure 2: DIAG0 parameter evolution during sequential configuration of magnet / RF parameters and GPSR measurements.

Quadrupole Focusing

For this task, we aim to minimize the beam spot size on OTRDG02 by utilizing three quadrupole magnets, QDG007-QDG009 using constrained BO. To enhance convergence speed in a context where beam size measurements are relatively inexpensive, we utilize sample interpolation (as described in Ref. [14]), which makes multiple intermediate measurements of the objective function in-between the current operating point and the point proposed by the BO algorithm, to improve predictive accuracy while spending less time on algorithmic decision-making.

TCAV Phasing

In this case, we aim to determine the zero-crossing phase of the TCAV by minimizing the beam deflection at a downstream BPM when the TCAV is on and off. Starting with the TCAV off, we measure the transverse beam location and then we optimize the TCAV phase such that when turned on the beam is at the same transverse beam position. In this case, we leverage the sinusoidal dependence of the transverse deflection with respect to the TCAV phase by selecting a periodic kernel function for our GP model.

GPSR Measurements

We conduct the GPSR measurements by repeatedly using the same algorithm used for autonomous emittance measurements [16]. In this case, we utilize a constrained Upper Confidence Bound acquisition function that is heavily weighted towards exploration ($\beta = 10^4$) to efficiently characterize the beam size with respect to the focusing strength of QDG009, while biasing exploration towards the beam size minimum. We repeat BO for both the horizontal and vertical beam sizes (utilizing data collected from the horizontal beam size minimization to warm-start vertical minimization) while constraining on maximum beam size relative to the minimum beam size that has been observed and minimum beam transmission. This effectively finds the quadrupole strengths that achieve enough transverse phase advance to effectively measure the phase space distribution without violating observational constraints that change due to upstream drift or configuration changes. An example dataset collected by this algorithm is shown in Fig. 3. This data was then compressed and transferred to the S3DF computing cluster for performing online phase space reconstruction.

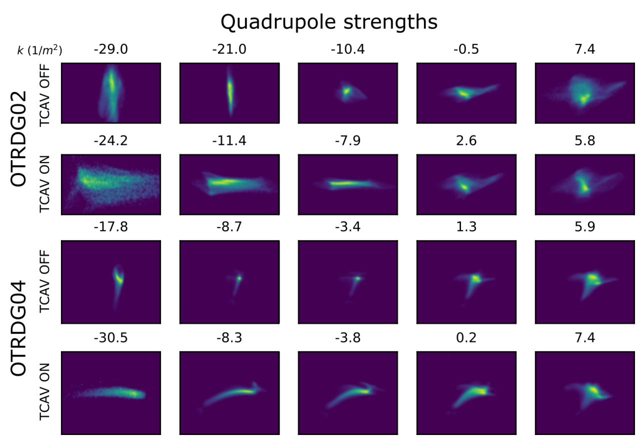

Figure 3: Example dataset acquired by autonomous GPSR control algorithm.

CONCLUSION

In this work, we have described the 6-dimensional phase space reconstruction technique that will be used to reconstruct beam distributions at LCLS-II using the DIAG0 beamline. We have also described initial demonstrations of autonomous configuration and measurement of phase space distributions at DIAG0. Future work will further improve autonomous control algorithm robustness to upstream beamline changes and validate the GPSR workflow for data gathered on DIAG0.

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