DETAILED CHARACTERIZATION OF COHERENT SYNCHROTRON RADIATION EFFECTS USING GENERATIVE PHASE SPACE RECONSTRUCTION*

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Abstract

Coherent synchrotron radiation (CSR) in linear accelerators is detrimental to applications that require highly compressed beams, such as FELs and wakefield accelerators. However, traditional measurement techniques lack the ability to fully reconstruct intricate, multi-dimensional aspects of beam structure created by CSR, particularly the varying rotation of transverse phase space slices along the longitudinal coordinate of the bunch. This study explores the effectiveness of our generative-model-based high-dimensional phase space reconstruction method in characterizing CSR effects at the Argonne Wakefield Accelerator Facility (AWA). We demonstrate that the reconstruction algorithm can successfully reconstruct beams that are affected by CSR.

INTRODUCTION

Accelerator applications, such as free electron lasers, need compressed beams in the longitudinal dimension to produce short radiation pulses. Achieving extreme compression is challenging due to the synchrotron radiation emitted by the electron bunches within the dipole magnets [1]. When the spectrum of the radiation contains wavelengths greater than the bunch length, photon emission becomes coherent, increasing its power. This effect is called coherent synchrotron radiation (CSR). The emitted radiation from the particles at the back of the bunch kicks the particles at the front, which results in projected transverse emittance growth [2].

CSR-induced projected emittance growth is caused by the different rotations and offsets of transverse phase space slices along the longitudinal coordinate due to non-linear correlations between particle energy and longitudinal position. This effect has been studied for single dipoles and chicanes, and various CSR suppression schemes have been proposed and implemented [1, 3, 4]. Recent studies on emittance exchange (EEX) lattices have shown that the exchange process introduces difficulties to suppress CSR effects due to longitudinal and transverse coupling [5–10]. However, experimental measurements have been limited to scalar macro-particle metrics of the beam distribution, namely the projected horizontal emittance growth, instead of a more complete description of the dynamic effects, i.e., the rotations and centroid shifts of horizontal phase space slices as a function of the longitudinal coordinate. Measuring these multi-dimensional effects of CSR on beam distributions could uncover which approximations of CSR models are valid and lead to improved suppression schemes.

Recent developments in a generative-model-based phase space diagnostics method have enabled detailed high-dimensional reconstructions [11, 12] by making use of differentiable particle tracking simulations [13]. This method, known as generative phase space reconstruction method (GPSR), allows the measurement of the six-dimensional phase space distribution with a simple diagnostic lattice (consisting of a quadrupole, a transverse deflecting cavity and a dipole), and twenty beam profile images from two YAG screens. The goal of this work is to evaluate if GPSR can be used for the detailed characterization of CSR effects at the Argonne Wakefield Accelerator Facility (AWA).

CSR EFFECTS AT THE AWA DOUBLE DOGLEG

AWA is a high-charge electron accelerator with single and double EEX beamlines for phase space manipulation [14, 15]. Due to the high charge, presence of multiple dipoles, and coupling between transverse and longitudinal coordinates, CSR-induced projected emittance growth is an important limiting factor for precisely controlling the phase space distribution of beams using emittance exchange [7]. The effect of these beam dynamics on the beam distribution can be characterized by the beam diagnostics previously used by GPSR to reconstruct the six-dimensional phase space distribution of a beam [12], namely a quadrupole, a transverse deflecting cavity and a dipole spectrometer. As a result, AWA is ideal to study CSR-induced projected emittance growth using the state-of-the-art GPSR method.

Figure 1 shows a cartoon of AWA up to the first EEX beamline [16]. The drive linac can deliver high-charge and low-emittance electron beams, which can then be used in driving wakefields in structures [17] or plasmas [18]. Dipole bends B1, B2, B3 and B4 compose the double dogleg used for this study (with the transverse deflecting cavity TDC1 turned off). Table 1 summarizes the beam parameters used for the simulation studies.

We simulated the effects of CSR in the double dogleg using the OPAL beam dynamics code [19]. Figure 2 shows the initial (before double dogleg) and final (after double dogleg) longitudinal and horizontal phase spaces. The CSR wakefield causes a negative energy kick at the middle of the beam and a positive one at the front of the beam. There is also a

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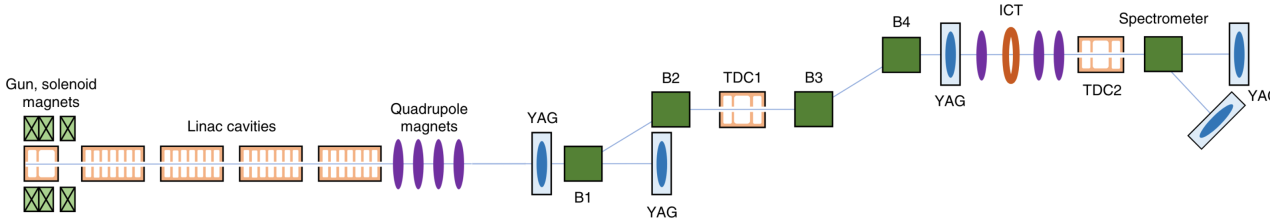

Figure 1: Cartoon of AWA up to first EEX beamline (adapted from [16]). B stands for bend and TDC stands for transverse deflecting cavity. CSR effects produced at double dogleg can be measured using 6D GPSR [12] with the quadrupole, transverse deflective cavity (TDC2) and dipole spectrometer diagnostics.

Table 1: Beam Parameters After Linac

Parameter	Value	Unit
Charge	1.0	nC
Energy	43.4	MeV
Energy spread	0.1	%
ε_x (normalized)	25.5	mm mrad
rms beam size	3.0	mm
rms bunch length	3.0	mm

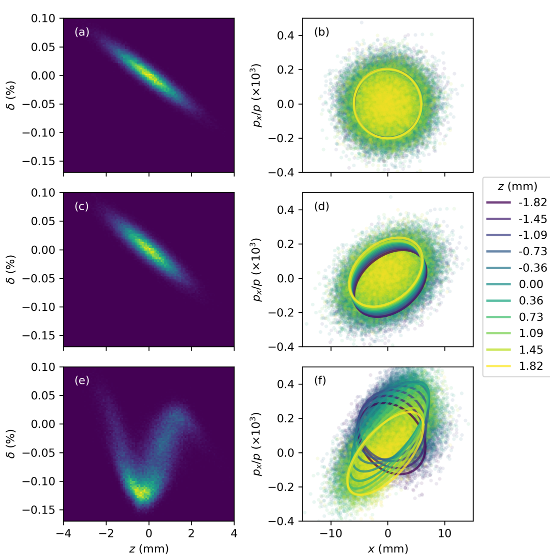

Figure 2: Simulated longitudinal and transverse phase spaces before double dogleg (a-b), after double dogleg with CSR off (c-d), and after double dogleg with CSR on (e-f). Horizontal phase spaces show ellipses for different longitudinal slices.

clear rotation of horizontal phase space slices as a function of z. Even though the normalized slice emittance is unchanged along z ($\varepsilon_{x,\text{ slice}} = 25.5$ mm mrad), the normalized projected horizontal emittance grows to $\varepsilon_x = 32.6$ mm mrad when CSR effects are turned on.

PHASE SPACE RECONSTRUCTION RESULTS

The GPSR algorithm [11, 12] was used to reconstruct the beam distribution after the double dogleg. A simulated quadrupole scan was done for each on/off combination of the transverse deflecting cavity and dipole spectrometer shown downstream in Fig. 1. Figure 3 shows the scan data corresponding to 20 15×15 mm^2 simulated screens. This data was then used to train the GPSR model on an NVIDIA A100 GPU. The training required around 15 GB of GPU RAM and 10 minutes to complete. Results of the reconstruction are summarized in Figs. 4 and 5.

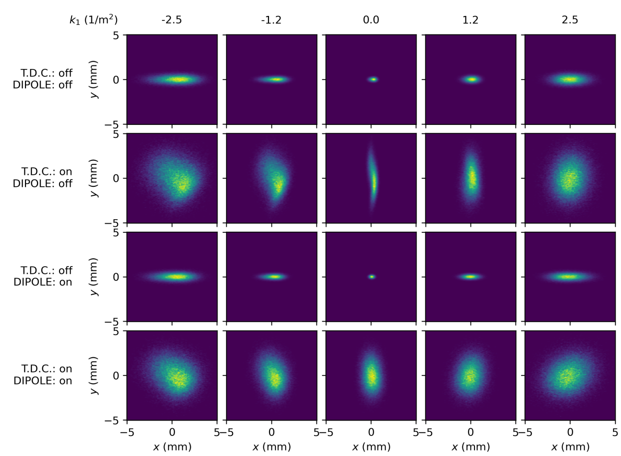

Figure 3: x-y training images. A quadrupole scan is done for each combination of TDC and dipole on and off.

Figure 4 shows the one and two-dimensional projections of the reconstructed beam distribution along the horizontal and longitudinal phase space coordinates. Qualitatively, the projections are in good agreement except for the longitudinal phase space. The normalized projected horizontal emittance of the reconstructed beam is $\varepsilon_{x,\text{rec}} = 33.3$ mm mrad, which is in good agreement with the ground truth value of $\varepsilon_x = 32.6$ mm mrad.

Even though the emittances and two-dimensional projections are in good agreement, this information is not enough to describe the structure of this particular beam. Figure 5 shows three-dimensional x, p_x, z information, necessary to see the structure of CSR effects, namely the rotations and shifts of horizontal phase space slices as a function of z. The agreement of the horizontal phase space slices suggest that GPSR is able to resolve the structure of this effect. Nevertheless, there are some discrepancies on the ellipses corresponding to the tail and front of the beam. This is consistent with the discrepancies in the z-p_z projected phase space in Fig. 4. From Fig. 3, we can see that turning the dipole on only causes small changes in the screen images, which could be limiting the resolution for the p_z coordinates.

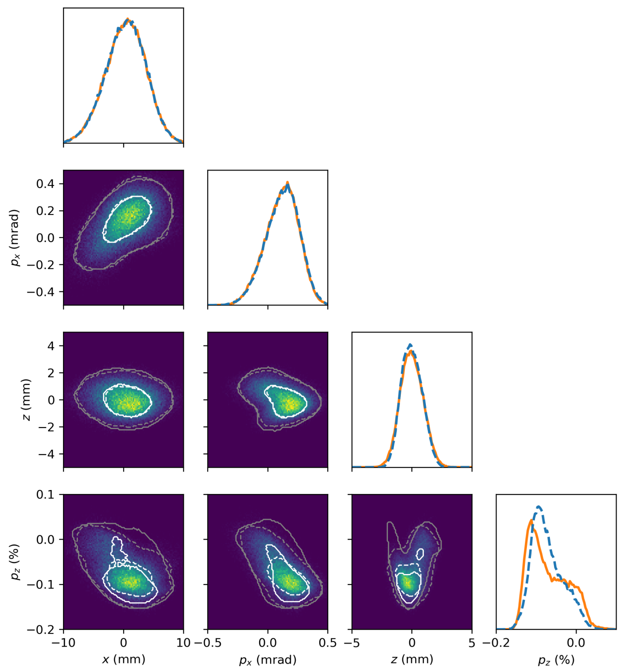

Figure 4: Corner plot of reconstructed beam distribution along the longitudinal and horizontal coordinates. Dashed (solid) contours represent 50th and 95th percentiles of the two-dimensional projections of the reconstruction (ground truth) distribution. Blue (orange) lines show one-dimensional projections of the reconstruction (ground truth) distribution.

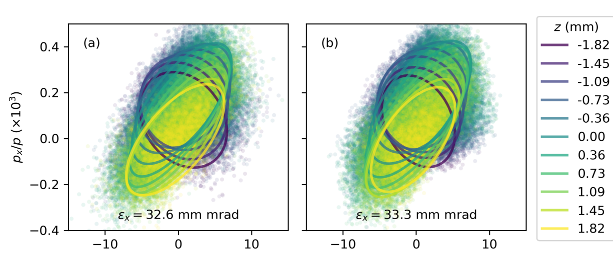

Figure 5: Ground truth (a) versus reconstructed (b) horizontal phase spaces with measurements of the projected emittance. Ellipses for different longitudinal slices are shown.

CONCLUSION

In this work, we have tested the capability of the GPSR method to reconstruct a beam affected by CSR effects at AWA. Simulations show that the first double dogleg at AWA can generate significant CSR-induced effects in the beam distribution, causing a rotation of horizontal phase space slices as a function of the longitudinal coordinate. Our results suggest that the GPSR method is able to resolve the rotation of horizontal phase space slices induced by CSR with as few as 20 beam profile measurements and 10 minutes of computation time. In future work, the accuracy of the measurement could potentially be improved by introducing slits to increase energy resolution, or by adding more phase space rotations to the scan. An experimental demonstration of CSR effects characterization at AWA using this method will be preformed soon.

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