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PRELIMINARY COMPUTATIONAL STUDY ON MINIMIZING LONGITUDINAL EMITTANCE IN PHOTOINJECTOR

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Abstract

Recently, we proposed a novel photoinjector that incorporates an emittance exchange (EEX) beamline. Previous studies demonstrated promising 4D emittance performance of an EEX-based injector, but the beam's longitudinal emittance at the linac exit still limits the final transverse emittance downstream of the EEX stage. We performed a comprehensive scan of injector parameters—including gun phase, laser spot size and pulse length, and solenoid strengths to (1) estimate the minimum achievable longitudinal emittance, (2) identify sources of emittance growth, and (3) explore mitigation strategies. Here, we present the status of this study. Simulations were carried out using General Particle Tracer (GPT) including space-charge effects.

INTRODUCTION

The brightness of most modern accelerators has been tremendously improved over the last several decades. While we achieve sub-micron scale transverse emittance [1] and kilo-Ampere level peak currents [1], longitudinal emittances are often much higher than the transverse emittances. It is obvious that improving the longitudinal emittance will provide significant advantages on a variety of scientific accelerator facilities. Therefore, R&D is required to understand the minimum achievable longitudinal emittance and the mechanism of emittance growth, similar to Ref. [2].

Currently, from the simulations for Argonne Wakefield Accelerator facility [3], we believe the major sources of longitudinal emittance growth are (i) nonlinear correlation from RF curvatures and nonlinear space charge forces and (ii) a large energy spread at the periphery of the beam, which must be originated from space charge effects entangled with RF fields in the cavity. Radial dependency of accelerating fields can also introduce an increase of uncorrelated energy spread.

To explore the opportunity of generating a low longitudinal emittance, resulting in significant boost for 4D emittance, we previously ran simulation with an emittance exchange (EEX) beamline [1]. In this study, we have exchanged the transverse and longitudinal phase spaces via the EEX beamline. Then, the nonlinear correlation now in the transverse phase space was corrected using recently proposed transverse wiggler-based linearization [4]. A large spread at the periphery of the beam was simply blocked using a wide slit. With such treatment, the simulation for 100 pC beam showed promising and exciting results of the final transverse emittance of 0.63 µm and the final longitudinal emittance of 0.4 µm [1].

While the previous study demonstrated the feasibility of achieving low longitudinal emittance, the emission mechanism suggests that the minimum achievable longitudinal emittance seems not inherently larger than that of transverse planes. We conducted injector parameter scan to explore minimum achievable longitudinal emittance using the beamline at the AWA facility. This paper discusses observations from the parameter scan.

PARAMETER SCAN SETUP AND RESULT

For the injector parameter scan, we modeled AWA facility's drive beamline [3] using General Particle Tracer (GPT) code [5]. Scan variables and their scan ranges are summarized in Table 1. The charge of the beam was set to 100 pC, and the beam was accelerated up to 44 MeV to account future experiment using the EEX beamline [1]. The parameter scan results are shown in Fig. 1.

Table 1: Parameters used for the scan. Gun phase scan includes 41°, 42°, 43°, and 44°.

Parameters	Value	Step
Gun phase [deg]	20–50	5°
Matching solenoid ampere [A]	150–270	5 A
Number of α-BBO crystals	0–5	1
Laser radius on cathode [mm]	0.2–0.3	0.01 mm

We also note another important point regarding the linearization. Harmonic cavities are a usual choice to compensate RF curvature from accelerating cavities [6]. However, such compensation mechanism is insufficient to fully linearize the phase space. Among the sources of nonlinear correlations, the second (or at most third order) polynomial components, such as RF curvature, will only be removed. As shown in Fig. 2, longitudinal phase space can easily have remaining nonlinear correlations, which increases the emittance. To address this issue, we assume to use transverse wiggler with EEX beamline [1]. For this process, we apply 20th-order polynomial fit to the phase space and subtract it from the phase space as shown in Fig. 2 (b). Table 2 also shows a significant difference between these two cases. We also apply the periphery cut to further reduce the longitudinal emittance. 20% of outermost particles are removed.

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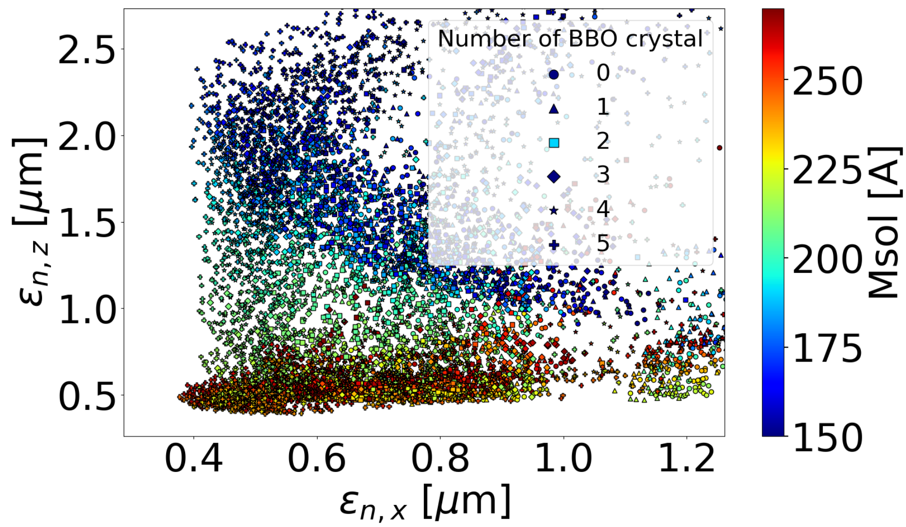

Figure 1: Parameter scan results. Each marker shape corresponds to different number of α-BBO crystals in the laser system. The color represents the matching solenoid strength.

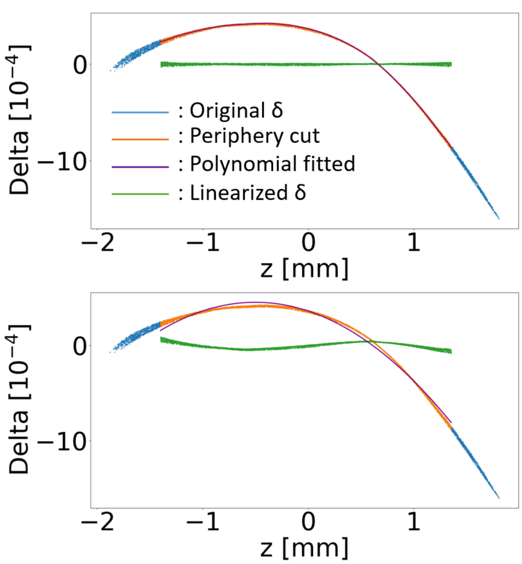

Figure 2: Comparison between 2nd-order and 20th-order linearized phase space. Blue: longitudinal phase space at the end of the linac. Orange: longitudinal phase space with periphery cut. Purple: polynomial fitted curve up to (a) 2nd-order and (b) 20th-order. Green: longitudinal phase space after linearization up to (a) 2nd-order and (b) 20th-order.

OPTIMIZATION TOWARD MINIMUM 4D EMITTANCE

While the scan has somewhat coarse step sizes, the result in Fig. 1 shows minimum achievable emittances in both planes under given parameter range and beamline. If we simply define the 4D emittance as the product of horizontal and longitudinal emittances, the minimum 4D emittance is approximately 0.17 μm^2 ($\varepsilon_{n,x}$ =0.40 μm and $\varepsilon_{n,z}$ =0.43 μm). The corresponding injector parameters were: a gun phase of 44°, a laser radius of 0.22 mm (uniform profile), 5 α-BBO crystals, a matching solenoid current of 230 A. Interestingly, the condition minimizing the longitudinal and transverse emittances was not far from each other while there is a trade-off.

Table 2 provides a summary of emittance changes over the treatments. Case I is the original longitudinal emittance at the end of the linac, which includes nonlinear curvature and spreads at the periphery. Case II shows the emittances with periphery cut. Case III includes both periphery cut and linearization. Case IV shows corresponding 4D emittance. It emphasizes the importance of linearization removing higher order nonlinear terms. After the treatment, the longitudinal emittance actually reached the level of transverse emittance.

Table 2: Longitudinal Emittances for Different Cases

	20th order	**2nd order**
Case I	28 μm	28 μm
Case II	16 μm	16 μm
Case III	0.4 μm	2 μm
Case IV	0.17 μm^2	0.81 μm^2

MATCHING SOLENOID DEPENDENCE OF LONGITUDINAL EMITTANCE

As shown in Fig. 1, the data points form a clear left edge where the longitudinal emittance dramatically changes while the transverse emittance stays around 0.4 μm. Here, the colors are assigned based on Msol strength. Thus, it tells us that longitudinal emittance has a strong dependence on the matching solenoid, hereafter Msol, strength. It is a solenoid near the exit of the gun cavity to provide envelope matching or beam size control.

In terms of the beam propagation, the major difference between strong and weak Msol strengths is the beam envelope

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as shown in Fig. 3. This figure compares beam envelopes in the injector for two different Msol strengths. It is evident that a stronger Msol produces much smaller transverse beam size along the injector. Consequently, such beam could experience less effect from accelerating field's radial dependency. To confirm this, we plotted longitudinal phase spaces of two cases shown in Fig. 3. Then, we applied colors based on particle's radial position. The results shown in Fig. 4 show radial position dependency of uncorrelated energy spread, which will introduce the increase or decrease of the longitudinal emittance.

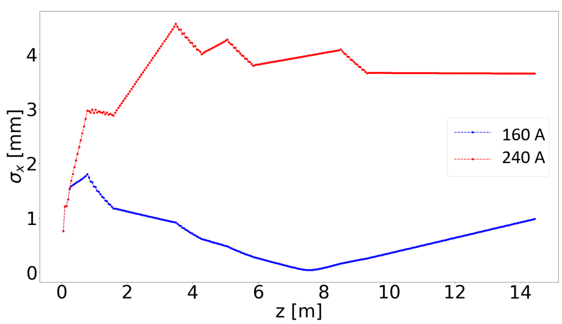

Figure 3: Beam envelope for two different Msol strengths.

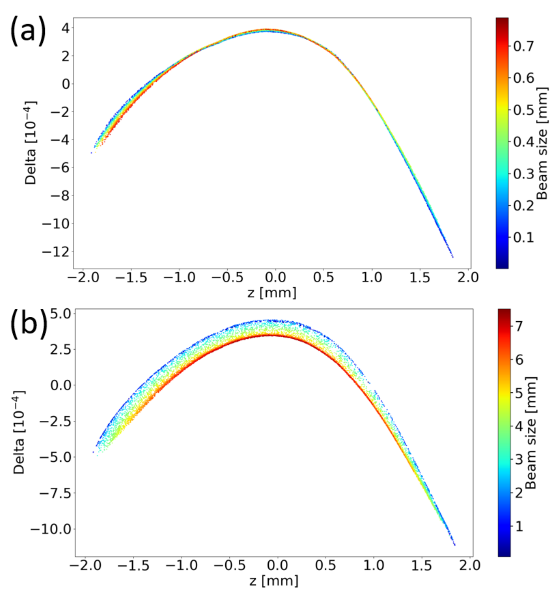

Figure 4: Longitudinal phase spaces for two different Msol strengths. Colors are assigned based on particle's radial position. (a) and (b) corresponds to Msol=240 A and 160 A, respectively.

LIMITATION OF MINIMUM ACHIEVABLE LONGITUDINAL EMITTANCE

Another interesting behavior in Fig. 1 is the bottom edge corresponding to the lowest longitudinal emittance. While the transverse emittance decreased as the laser spot size decreases or laser pulse length increases, the minimum longitudinal emittance always stays within 0.4–0.5 µm range.

We confirmed that such behavior occurs due to the slice mismatch in longitudinal phase space. Similar to the time slice in the transverse space, we can consider radial slices for longitudinal phase spaces. Figure 5 shows the longitudinal phase space corresponding to the minimum longitudinal emittance case. We assigned color based on particle's radial position to distinguish different radial slices. The result shows (i) highly nonlinear correlations and (ii) significant mismatch between correlations of radial slices. This must also be the cause for large energy spread at the periphery.

The source of such nonlinearity and mismatch should be investigated, and its dynamics must be understood to further reduce the achievable minimum longitudinal emittance.

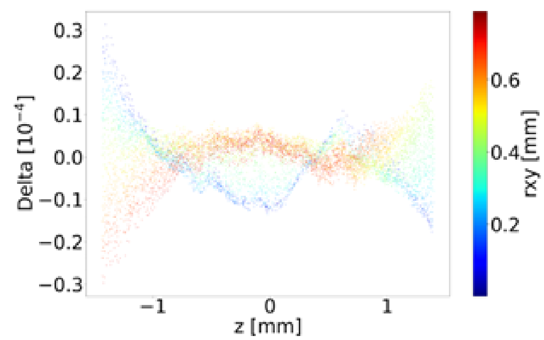

Figure 5: Radial slice emittance seems the source of the limit of longitudinal emittance.

SUMMARY

A parameter scan of the photoinjector was conducted. Several injector parameters—such as gun phase, laser radius, number of α-BBO crystals, and Msol strength—were scanned. From the simulation results, we determined the minimum 4D emittance of the given beamline at the AWA facility. The results indicate that the implementation of transverse wiggler-based linearization with periphery cut to an EEX beamline would offer a promising approach toward a brighter beam generation.

It is also worth noting that the longitudinal emittance is sensitive to focusing solenoid strength due to $E_z(r)$, the radial dependency of the accelerating field. Beam size in the cavity directly affected the uncorrelated energy spread, ultimately causing the growth of longitudinal emittances. In addition, nonlinearity and mismatch of radial slice's longitudinal phase space were another interesting points, which may be the cause of the fundamental limit of the minimum achievable longitudinal emittance.

Further investigation on the source and mechanism would help us to achieve a smaller longitudinal emittance, in turn a lower 4D-emittance.

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