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START-TO-END SIMULATION OF THE DRIVE-BEAM LONGITUDINAL DYNAMICS FOR BEAM-DRIVEN WAKEFIELD ACCELERATION*

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Abstract

Collinear beam-driven wakefield acceleration (WFA) relies on shaped driver beam to provide higher accelerating gradient at a smaller cost and physical footprint. This acceleration scheme is currently envisioned to accelerate electron beams capable of driving free-electron laser [1]. Start-to-end simulation of drive-bunch beam dynamics is crucial for the evaluation of the design of accelerators built upon WFA. We report the start-to-end longitudinal beam dynamics simulations of an accelerator beamline capable of producing high charge drive beam. The generated wakefield when it passes through a corrugated waveguide results in a transformer ratio of 5. This paper especially discusses the challenges and criteria associated with the generation of temporally-shaped driver beam, including the beam formation in the photoinjector, and the influence of energy chirp control on beam transport stability.

INTRODUCTION

Collinear beam-driven wakefield acceleration (WFA) schemes, e.g. based on plasmas or structures, strongly benefit from a drive beam with a tailored current distribution. Tailored bunches enhance the efficiency of the acceleration scheme by increasing the transformer ratio $\mathcal{R} = \left|\frac{E_+}{E_-}\right|$, defined as the ratio of the maximum of the accelerating field behind the bunch E_+, to the maximum of the decelerating field within the bunch E_-. Over the years, several beam shaping techniques have been proposed and investigated to enhance the transformer ratio, including photocathode laser shaping techniques [2–4], transverse-to-longitudinal phase-space emittance exchange [5,6], and multi-frequency linacs [7]. In addition to that, similar efforts have been devoted to the practical designs and the study of beam stability in WFA, such as longitudinal-phase-space (LPS) requirements for stability conditions [8], the suppression of transverse wakefields [9], and an overview of WFA development [10]. In this paper, we present our recent efforts in producing the shaped beams required for WFA and addressing beam stability. Building upon efforts in [11], we investigated the generation of required distribution from a low energy electron beam injector, which can be further accelerated and shaped into a drive beam with enhanced transformer ratio ($\mathcal{R} > 5$). The studies were done in beam dynamics simulations where laser profiles and relevant gun parameters were optimized through multi-objective optimization. Consequently, the obtained beam distributions were tracked through longitudinal tracking code TWICE to study the evolution of the associated bunch shapes. Finally, we combined both efforts to perform a start-to-end simulation of drive beam longitudinal dynamics to demonstrate a proof of concept of drive beam generation for WFA.

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BEAM DYNAMICS SIMULATION

Beam Distribution

The target distribution to be produced at the downstream of an injector is shown in Fig. 1, where its beam parameters are shown in Table 1. It was obtained by reverse tracking simulation of a modified doorstep distribution shown in Fig. 2. Additional details, including accelerator parameters and a description of the reverse-tracking technique, were reported on [11].

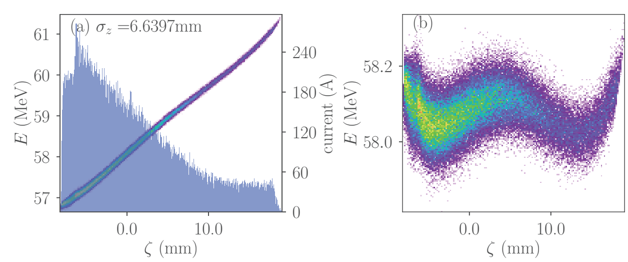

Figure 1: Target bunch LPS to be produced from an electron gun, with its current distribution (a), and its LPS after removing linear chirp (b).

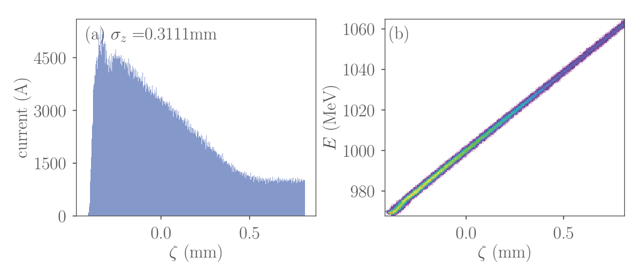

Figure 2: LPS (right) and current (left) distribution used for reverse tracking to obtain target distribution for an injector.

Photoinjector Simulation

In a photoinjector, the laser pulse distribution of a photocathode determines the initial shape of electron bunch

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Table 1: Parameters Associated with the Initial Distribution Required from an Injector

Bunch Property	Value	Value
Charge	10	nC
Reference energy	58	MeV
Rms length	6.6397	mm
Rms fractional energy spread	1.9	%
Rms fractional slice energy spread	0.3	%

distribution generated via photoemission. As the low energy electron beam accelerates through the injector, it is susceptible to space-charge effects which can deteriorate its shape. Hence, accurate modeling of laser profiles is crucial for the generation of shaped beams. In our recent work, we investigated the generation of the required bunch shown in Fig. 1, using an injector consisting of a superconducting radiofrequency (SRF) gun coupled to a SRF linac. For our beam-dynamic investigation, We consider a 200-MHz quarter-wave SRF gun similar to the one originally designed for the WiFEL project [12–14]. The downstream linac consists of five 650-MHz SRF cavities. The SRF gun is surrounded by a solenoid lens for transverse focusing. The simulations were done using Astra [15], a particle-in-cell beam-dynamics program with a built-in quasi-static space charge algorithm. Our simulations assume the beam is cylindrically symmetric. The image charge effects at the cathode are included.

The laser pulse distribution is characterized by $I(t,r) = \rho(t)R(r)$, where $\rho(t)$ and $R(r)$ describe the laser temporal profile and the transverse envelope respectively. In our simulation, we assumed the transverse distribution to be radially symmetric and described by laser spot size. The temporal profile is defined as

$$\rho(t) = Af(t)S(at)S(-b(1-t)), \text{ where} \quad (1)$$

$$f(t) = \begin{cases} h + d(c-t)^{d-1}, & 0 \le t < c \\ h, & c \le t \le 1 \\ 0, & \text{elsewhere} \end{cases},$$

where A is the normalization constant, a, b c, d and h are bunch shaping parameters. The smooth edges at both ends are parameterized by a, b and logistic function $S(t) = 1/(1+e^{-t})$, $1-c$ determine the length of constant laser pulse, in analogy to the length of bunch head of the doorstep distribution, and h determines the relative amplitude of constant laser pulse. An example of the laser pulse distribution is shown in Fig. 3.

The laser profiles, shape parameters and SRF gun settings were optimized using multi-objective optimization framework, Deap [16]. We considered minimizing the second-order LPS correlation coefficient and the Wasserstein distance between output longitudinal distribution from an injector and current distribution from Fig. 1 [**?**]. To speed-up the optimization process, the bunch is represented by 20,000 macroparticles. Subsequently, the optimized accelerator settings were simulated with 100,000 macroparticles. An example of parameters resulting acceptable results is summarized in Table 2 and Fig. 4.

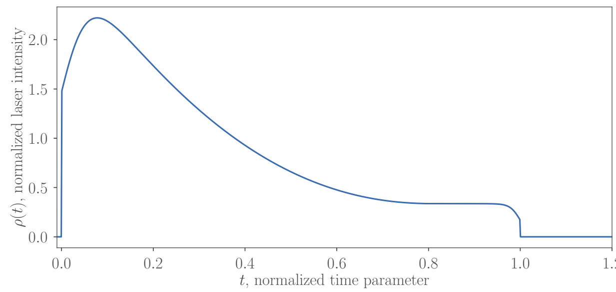

Figure 3: The laser pulse distribution used for the injector simulations (as described by Eq. 1).

Table 2: Optimized Parameters for the Injector and Generated Beam Parameters

Parameter	Value	Unit
Laser spot radius	4.707	mm
Laser duration	86	ps
RF gun peak E-field	40	MV/m
RF gun phase	−11.33	deg
Cavity C1 voltage	32.25	MV
Cavity C1 phase	38.53	deg
Cavity C2 phase	37.86	deg
Cavities C2 to C5 voltage	20	MV
Cavity C3 to C5 phase	0	deg
Solenoid B-field	0.2	T
Shape parameter a	31	-
Shape parameter b	91	-
Shape parameter c	0.1862	-
Shape parameter d	3.1868	-
Shape parameter h	0.2628	-
Final beam energy	64.65	MeV
Final beam bunch length	6.6435	mm
Final beam transverse emittance	19.3	µm

BUNCH SHAPING IN THE LINAC

The optimized accelerator settings and attained beam parameters are shown in Table 2, and the shaped bunch with from injector simulation is shown in Fig. 4. The discrepancies between result here and that of in [11] are due to the differences in LPS and current distribution. While our optimization achieves a good agreement in current distribution, the LPS is different, as shown in Fig. 2 and Fig. 4. Fine-tuning of the LPS can be realized through a passive wakefield from corrugated structures or using high-harmonic RF fields from SRF cavities. While we cannot demonstrate full agreement between results from [11] and here, reverse tracking nevertheless provides a starting point to guide the design of the photoinjector and devise possible photocathode laser

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temporal shape. With the combination of both injector and subsequently a beam-shaping linac, we have demonstrated that the generation and the acceleration of a shaped drive beam are feasible, by manipulating its longitudinal beam dynamics.

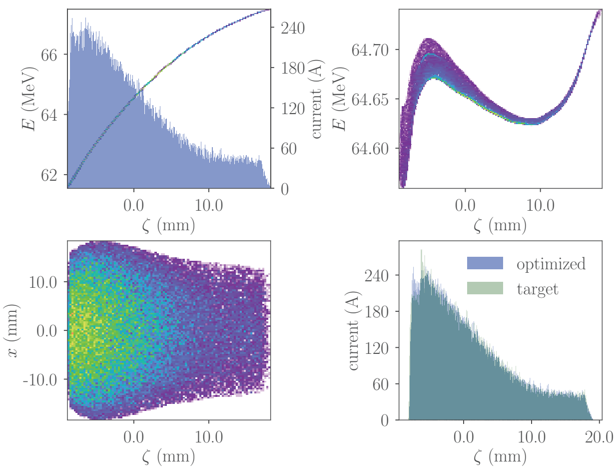

Figure 4: Optimized LPS and current distribution (upper right), and LPS after removing the linear and quadratic chirps (upper left). Transverse versus longitudinal plot (lower left) and overlap plot of optimized and target current distributions (lower right).

Figure 5: Diagram of the photoinjector and linac used in the simulations to produce the tailored bunch. The injector consists of a SRF gun and a 650-MHz linac (C1 to C5). L1 and L2 are 650 MHz linacs, L39 is a 3.9-GHz linac, and BC1 and BC2 are magnetic bunch compressors.

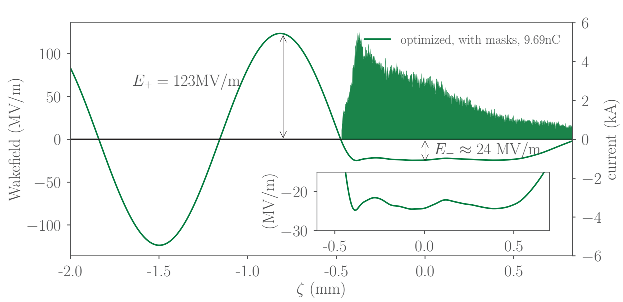

Figure 6: Longitudinal wakefield generated from a a shaped bunch from a start-to-end simulation, the transformer ratio is 5.

The simulation on low energy injector was performed with Astra, and its output was passed to tracking code Twice for longitudinal tracking simulation. Subsequently, we calculated the generated wakefield in a 220-GHz corrugated waveguide from this shaped bunch to quantify the associated transformer ratio and achieved peak accelerating field.

As a proof of concept, we performed a start-to-end simulation of the drive-beam longitudinal dynamics using the simulated LPS distribution obtained from the photoinjector in the beam-shaping linac; see the layout in Fig. 5. The required sinusoidal-like oscillation shown in Fig. 1(b), was introduced using a corrugated structure [18] located downstream of the photoinjector at ~65 MeV. Similarly, we manually removed unwanted macroparticles to further tune the current distribution. The actual process of removing particles through a transverse mask will eventually be investigated. We calculated the transformer ratio of the final bunch from the start-to-end simulation, and obtained a transformer ratio of 5, as shown in the Fig. 6. Accelerator settings for the beam-shaping linac and relevant beam parameters are shown in Table 3.

Table 3: Accelerator Settings for Beam-shaping Linac and Beam Parameters for Final Bunch

Parameter	Value	Unit
Accelerating voltage L1	197.21	MV
Phase L1	15	deg
Frequency L1	650	MHz
Accelerating voltage L39	8.68	MV
Phase L39	200	deg
Frequency L39	3.9	GHz
R_{56} for bunch compressor 1 (BC1)	−0.16	m
T_{566} for bunch compressor 1 (BC1)	0.15	m
Accelerating voltage L2	844.17	MV
Phase L2	28	deg
Frequency L2	650	GHz
R_{56} for bunch compressor 2 (BC2)	−0.134	m
T_{566} for bunch compressor 2 (BC2)	−0.205	m
Final beam energy	992.55	MeV
Final beam bunch length	0.327	mm
Peak accelerating field $\|E_+\|$	123.41	MV/m
Peak decelerating field $\|E_-\|$	24.45	MV/m
Transformer ratio $\mathcal{R}$	5	-

CONCLUSION

Using results from reverse tracking, we obtained an estimated beam distribution needed from a low-energy injector to produce a shaped beam with a high transformer ratio. With that knowledge in hand, we demonstrated that such a distribution can be realized through photocathode laser shaping, and subsequently being tracked through a beam shaping linac to generate drive beam capable of generating high transformer ratio accelerating wakefield. Results here highlight the importance of energy chirp control in achieving the ideal shape, and also provide a starting point for us to study the transverse dynamics.

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