

GENERATION OF LOW-EMITTANCE BUNCHES WITH SELECTIVE COLLIMATION AT THE ARGONNE WAKEFIELD ACCELERATOR

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Abstract

The Argonne Wakefield Accelerator (AWA) facility's drive-beam linear accelerator can generate electron bunches at a wide range of charge - from 100 pC to 100 nC. This provides a unique opportunity to study selective transverse collimation as a method to increase beam brightness by selecting the core of the beam using various initial bunch charges. This paper presents numerical modeling of the scheme. Simulations were performed to explore the impact of a collimating aperture on emittance, scraping the outermost electrons and retaining only the inner core of the beam with the goal of maximizing the beam brightness for a 100-pC electron beam. An optimization of various beamline parameters, including the initial bunch charge, was done to produce possible operating points that generate the lowest emittance. These simulations inform an experimental campaign that is also discussed.

INTRODUCTION

Bright electron beams have enabled critical developments in accelerator applications, including X-ray free-electron lasers and ultrafast electron microscopy and diffraction. One limiting factor to the generation of high-brightness beams is the beam emittance, with the reduced 5-dimensional brightness given by

$$B_5 \equiv \frac{\hat{I}}{\varepsilon_{\perp}^2}, \quad (1)$$

where \hat{I} represents the beam's peak current and ε_{\perp} represents the beam emittance in the transverse direction [1].

The minimum achievable emittance (sometimes called the intrinsic or thermal emittance) is fundamentally set by the electron source. For photocathodes, it is determined by the mean transverse energy (MTE) of the emitted electrons and the emission area, both of which are governed by the material's intrinsic electronic properties and surface conditions. Generally, due to the disproportionate contribution of halo particles to the transverse phase space, the experimental emittance scales with the fraction of the beam considered. Consequently, removing the outer halo can help reduce the beam emittance. This work investigates the use of a collimating aperture as a method for emittance minimization. The technique was proposed in Ref. [2] as a way to use the beam's peripheral particles to compensate for slice-emittance growth in high brightness photoinjectors. The numerical simulations of this method are presented, as well

as the details of an upcoming experimental campaign guided by the results.

Specifically, we study the generation of a higher-charge initial beam scraped down to 100 pC with the goal of maximizing the beam brightness by emittance reduction using the Argonne Wakefield Accelerator's (AWA) drive-beam linear accelerator. The drive-beam linac operates at a wide range of charge - 100 pC to 100 nC - which enables the exploration of selective collimation for a wide range of initial charge values.

The drive-beam photoinjector consists of a 1.3-GHz $1+\frac{1}{2}$ cells RF cavity with a high-quantum efficiency photocathode; see Fig. 1. The electron bunches are generated via photoemission triggered by 292-nm ultraviolet (UV) laser pulses impinging on a Cs₂Te photocathode. Nominally, the laser is transversely uniform with a 400-fs Gaussian temporal distribution. The Gaussian pulse can be replicated and stacked to produce a plateau-like flat-top distribution with a duration of 6 ps.

As can be seen in Fig. 1, the RF gun is surrounded by three solenoids (LB, LF, and LM) to control the transverse emittance at production and match the beam into the first linear accelerating cavity. Six 1.3-GHz traveling wave linac cavities (C1 - C6) accelerate the beam to energies nearing 70 MeV. Additional solenoids (LS1 - LS3) focus the beam downstream of the gun. Four quadrupoles located just upstream of the aperture can be used for an emittance measurement.

NUMERICAL METHODS

This paper uses multi-objective optimization to investigate the impact of various beamline parameters on minimizing transverse emittance ε_{\perp} and bunch duration σ_t . As a result of the optimization, a Pareto front is generated, which shows the tradeoff between the two objectives by creating a curve composed of the non-dominated solutions; these are solutions where further improvement in one objective degrades another [3]. The optimization framework DEAP [4] is integrated with the particle tracking algorithm ASTRA [5] to generate these tradeoff curves. ASTRA takes as input the on-axis electromagnetic fields and expands them radially, assuming cylindrical symmetry. The beamline parameters varied in the optimization are listed in Table 1, along with their range of values (as a note, the value of the peak B field for the bucking solenoid used in the simulations is calculated by multiplying the setting number with the focusing solenoid peak field value, and taking the opposite). Additionally, the two different laser pulse profiles were studied, as well as

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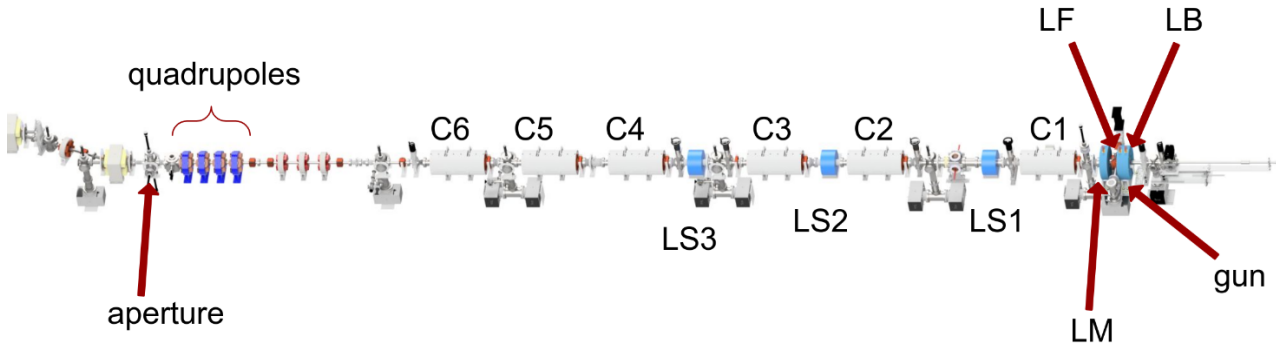


Figure 1: Diagram of AWA's drive-beam linac depicting the RF gun with its surrounding solenoids (LB, LF, and LM), the six accelerating cavities (C1 - C6), and the downstream focusing solenoids (LS1 - LS3). Also depicted is the location of the collimating aperture, located just past four quadrupoles that can be used for emittance measurement.

various initial bunch charge values: 0.25 nC, 0.5 nC, 1 nC, 2 nC, 5 nC, 10 nC, 25 nC, and 50 nC.

Table 1: Parameters Considered During the Optimization, With Their Range of Values

Parameter	Range
Laser spot-size	[0.02,5] mm
RF gun phase	[-40,40]°
RF gun amplitude	[40,80] MV/m
Linac C1 and C2 phase	[-50,50]°
Linac C1 and C2 amplitude	[10,20] MV/m
Solenoid LB peak magnetic field	[0.85,1.15] T
Solenoid LF peak magnetic field	[-0.18,0] T
Solenoid LM peak magnetic field	[-0.4,0] T
Solenoid LS1 peak magnetic field	[0,0.45] T

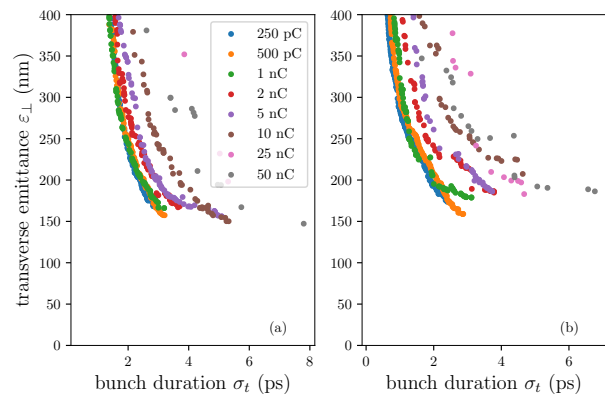


Figure 2: Pareto front showing the tradeoff between the transverse emittance and bunch duration associated with the beam's 100-pC core for the various initial bunch charges (labels). Plots (a) and (b) respectively correspond to the case of a Gaussian and flat-top laser pulse temporal distribution.

SIMULATION RESULTS

Particle distributions of various initial charges were generated and tracked through ASTRA. The 100-pC core of the beam was dynamically selected in each case, and the core's emittance optimized. The Pareto fronts are presented in Fig. 2. The lowest emittance generated by the optimizer is for the case of 10 nC initial bunch charge using the flat-top laser pulse; the emittance in this case is 152 nm. The (x, y) , horizontal (x, p_x) , and longitudinal (z, p_z) phase space distributions for this case are presented in Fig. 3, where the full beam is blue and the beam's core is red. The emittance of the core becomes reduced when the outer halo of the beam is scraped.

Further simulations were performed to take into account various constraints of the experimental campaign. Due to time constraints, the apertures cannot be machined using laser drilling, a technique that would allow a much smaller aperture (50 μm) compared to traditional drilling (300 μm). Therefore, we use the last solenoid on the beamline (LS3) to control the beam size to ensure that 100 pC of charge

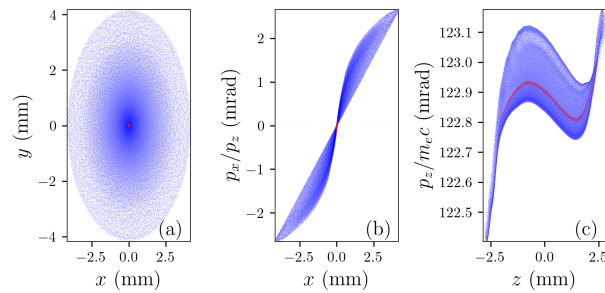


Figure 3: Spatial (x, y) distribution (a), horizontal (x, p_x) distribution (b), and longitudinal (c) phase-space distributions associated with the full beam [blue] and its 100 pC core [red] for the optimized case with the lowest emittance setting.

is scraped using a 300- μm aperture. Ideally, the beam dynamics freeze within the first few linac cavities; therefore,

the emittance should be preserved even with focusing or defocusing from the solenoid.

Performing a scan of the solenoid strength within the range of $[0, 0.4458]$ T using our optimized cases can give us insight into how the emittance degrades from using this technique and check if the solenoid can focus the beam to allow 100 pC to be selected. This scan was performed for the lowest emittance configuration given by every case combination of initial charge and laser distribution type. The lowest emittance achieved after applying this method is 169 nm. Interestingly, this case is not for the low-emittance setting described previously - this emittance was obtained using the configuration of a 500-pC initial bunch charge with the Gaussian laser pulse. The (x, y) and horizontal emittance phase spaces are shown in Fig. 4; again, we can see the reduced emittance of the core. Compared to the nominal case with no extra solenoid focusing, the emittance degrades only by ~ 8 nm (corresponding to a relative growth of $\sim 5\%$).

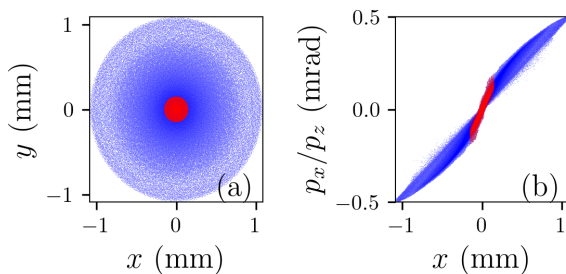


Figure 4: Spatial (x, y) distribution (a) and horizontal emittance (x, p_x) distribution (b) associated with the full beam [blue] and its 100 pC core [red] for the obtained with the lowest emittance after the solenoid scan.

EXPERIMENTAL IMPLEMENTATION

Plans are underway to conduct an experimental campaign to measure the emittance at the Argonne Wakefield Accelerator prior to the accelerator's upcoming upgrade [6]. This campaign aims to provide critical insights into the beam dynamics of the beam's core and provide a path to increasing the beam brightness.

A key component of the experiment involves the installation of a collimating aperture downstream of the linac. The aperture will consist of a 300- μ m-diameter circular hole precisely drilled into a stainless steel plate. The plate will have a thickness of 1.8 mm, which is carefully chosen to introduce sufficient multiple scattering. This scattering ensures that intercepted particles are deflected away from the beam's core, enabling accurate measurements of the beam's emittance and phase space distribution.

The phase-space measurements will be conducted using a quadrupole-scan technique, which is widely used for characterizing beam properties. To enhance the accuracy and efficiency of the analysis, the quadrupole scan will likely be complemented by an AIML-based regenerative reconstruction algorithm similar to the one described in Ref. [7].

CONCLUSION

The simulations presented in this paper confirm that low transverse emittance (< 200 nm) is achievable at the Argonne Wakefield Accelerator's drive-beam accelerator using the selective collimation technique discussed in Ref. [2]. Plans are under way to experimentally demonstrate the method and characterize its performance.

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