

BEAMLINE EXTENSION CONSIDERATIONS FOR AREAL-50 ACCELERATOR

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Abstract

AREAL linear accelerator, presently operating at CANDLE SRI generates 5-MeV ultrashort electron beams for a wide range of applications. The planned upgrade program aims to increase the beam energy up to 50 MeV in order to expand experimental capabilities and enable the generation of THz radiation. For this purpose, two 1.6-m-long accelerating structures are foreseen to be installed. To ensure optimal beam parameters for efficient acceleration and high-quality beam delivery, existing magnetic and diagnostic systems must be modified and supplemented. In this paper, several aspects of the new beamline design are examined, and the corresponding beam dynamics studies for the proposed layout are presented.

INTRODUCTION

The Advanced Research Electron Accelerator Laboratory (AREAL), operated at the CANDLE Synchrotron Research Institute in Yerevan, is a compact linear accelerator generating ultrashort electron beams with energies up to 5 MeV and sub-picosecond bunch durations [1,2]. The facility supports a broad range of scientific experiments, including advanced accelerator and radiation studies, as well as research in materials and life sciences [3]. AREAL is based on a laser-driven RF gun with a 1.5-cell accelerating system operating at a peak gradient of 110 MV/m, providing high-brightness electron beams.

A key objective of the AREAL upgrade program is the increase of the beam energy up to the 20–50 MeV range, enabling the development of an undulator-based THz radiation source and significantly expanding the experimental capabilities of the facility [4,5]. The upgrade foresees the installation of two traveling-wave accelerating structures, each 1.6 m in length, designed for an average accelerating gradient of 15 MV/m [6]. In this context, strict constraints are imposed on the electron beam dynamics, particularly to ensure effective bunch length compression and preservation of low transverse emittance throughout transport.

To meet the beam quality requirements at the entrance of the accelerating structures, the implementation of an optimized magnetic lattice is essential. The present concept includes solenoid-based emittance compensation complemented by quadrupole doublet configurations for transverse matching of the Twiss parameters.

This paper presents a transverse beam dynamics study focusing on the optimal longitudinal placement of the accelerating structures and the corresponding magnetic configuration required for beam matching and emittance

preservation. Attention is devoted to the evolution of the transverse emittance and the Twiss parameter α under the influence of space-charge effects in the low-energy section. The study aims to identify an optimal ‘trade-off’ between low α values and minimal emittance growth through appropriate adjustment of the magnetic optics configuration, including solenoid-based emittance compensation and quadrupole doublet matching.

BEAM MATCHING FOR THE ACCELERATING SECTION

The extension of the AREAL linear accelerator from its current 5 MeV energy to the 20–50 MeV regime requires careful optimization of the transverse beam dynamics. In the low-energy section, the dynamics are dominated by space-charge effects, which critically influence both longitudinal and transverse phase-space evolution. Simulations performed with the ASTRA tracking program show that an initially short laser pulse ($\approx 0.2ps$) generates an electron beam that experiences significant longitudinal broadening, reaching approximately 0.8 ps after 1.5 m of transport through the accelerating lattice.

The transverse beam evolution is described by the RMS envelope equation, accounting for the space-charge-dominated regime [7]:

$$\frac{d^2\sigma}{dz^2} + k(z)\sigma - \frac{\varepsilon_n^2}{\beta^2\gamma^2\sigma^3} - \frac{K}{\sigma} = 0$$

where σ is the RMS beam size, $k(z)$ is the external focusing strength, ε_n is the emittance, and $K = \frac{2I}{I_A\beta^3\gamma^3}$ is the generalized perveance, where I the peak beam current and $I_A = 17 kA$ the Alfvén current. The gun section includes a solenoid magnet located downstream of the RF gun for emittance compensation. In the current setup, the solenoid is positioned at 0.565m. In the proposed configuration, the solenoid is moved closer to the cathode—placed approximately 4 cm downstream—and is mounted directly onto the accelerating structure to achieve more effective emittance compensation (Fig. 1).

The evolution of the transverse emittance along the beamline is characterized by the emittance compensation process induced by the gun solenoid. Analysis indicates that the transverse emittance minimum—reaching a value of $\varepsilon = 1.5 \pi mm mrad$ —occurs at $z = 1.72 m$ downstream of the photocathode with the solenoid field $B = 0.423T$. This longitudinal position is critical, as it defines the optimal location for the entrance of the accelerating

structures to "freeze" the emittance and prevent further growth due to space-charge effects.

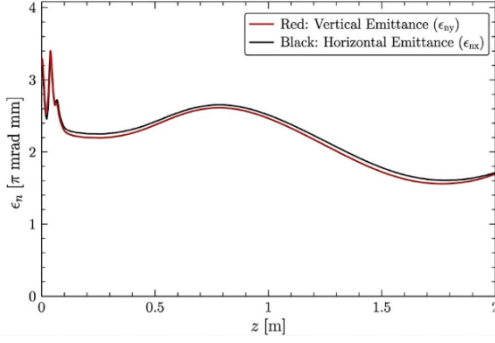


Figure 1: Evolution of the transverse emittance along the AREAL beamline.

However, at this injection point, precise matching of the Twiss parameters is required to avoid downstream betatron oscillations. Improper matching at the transition between the injector and the main accelerating section can lead to beam envelope instability and emittance growth.

At injection point, the matching condition can be obtained from the stationary solution of the envelope equation, where the focusing force precisely counteracts the defocusing effects of space-charge and emittance to establish a stable transverse profile [8].

$$\frac{d^2\sigma}{dz^2} = 0$$

which gives the matched beam size σ_m :

$$k\sigma_m - \frac{\epsilon_n^2}{\beta^2\gamma^2\sigma_m^2} - \frac{k}{\sigma_m} = 0$$

Since a significant contribution to the transverse focusing is provided by the gun solenoid, the matching optics are implemented via a compact quadrupole doublet operating in a relatively weak focusing regime. Considering the upstream solenoidal focusing and the limited drift space toward the accelerating structure, the required quadrupole gradients are optimized to achieve final transverse matching at the injection energy. This doublet provides independent control over the horizontal and vertical phase-space, enabling the formation of the required beam waist near the accelerating structure entrance.

The beam matching condition can be expressed in terms of the Twiss parameters α, β and γ , where the transverse beam matrix is defined as [9]:

$$\Sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

For matched injection into the accelerating structure, the beam Twiss parameters must satisfy:

$$\beta \approx \beta_m, \quad \alpha \approx \alpha_m \approx 0.$$

Physically, achieving $\alpha \approx 0$ corresponds to injection near a beam waist with minimal envelope divergence, allowing the beam to propagate smoothly through the accelerating section without the excitation of strong envelope oscillations.

In the space-charge-dominated regime, the condition $\alpha = 0$ is not fulfilled without additional quadrupole match-

ing. At the position of minimum emittance, the beam exhibits a strong divergence, characterized by an α value of approximately -20 (Fig. 2).

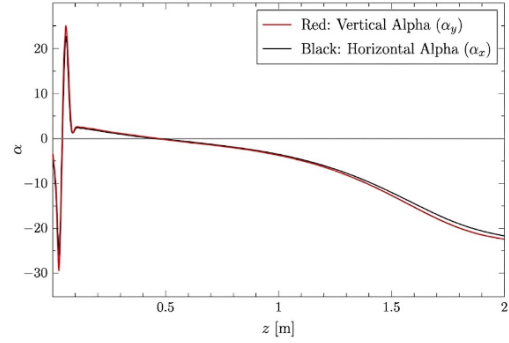


Figure 2: Evolution of the transverse α parameters along the AREAL beamline.

Deviation from the matched solution leads to mismatch-oscillations, commonly referred to as breathing modes. These oscillations are particularly important in the low-energy section where space-charge forces remain significant. The mismatch level can be quantified through the mismatch factor

$$M = \frac{1}{2} \left(\frac{\beta}{\beta_m} + \frac{\beta_m}{\beta} + \frac{(\alpha - \alpha_m)}{\beta\beta_m} \right)$$

where $M = 1$ corresponds to ideal matching. In the mismatched regime, the beam envelope exhibits oscillatory behavior resulting in phase-space filamentation and projected emittance growth [9].

As the beam is accelerated from 5 MeV toward 20 MeV, space-charge forces rapidly decrease according to $K \sim 1/\gamma^3$

leading to gradual adiabatic damping of envelope oscillations and transition toward an emittance-dominated transport regime. Proper optimization of the quadrupole-doublet system therefore allows stable beam transport with suppressed mismatch oscillations and preservation of emittance during acceleration. These conditions are essential for the generation of high-brightness sub-picosecond electron beams required for downstream THz radiation generation in the undulator section.

BEAMLINE OPTIMIZATION AND SIMULATIONS

The optimization procedure was carried out using beam dynamics simulations performed with ASTRA, with particular emphasis on minimizing transverse emittance growth and preserving short bunch duration under space-charge-dominated conditions. For the simulation, the initial beam distribution was generated taking into account the laser spot size ($\sigma_{x,y} = 0.25\text{mm}$) and pulse duration ($\tau = 0.2\text{ps}$), as well as the work function ($\phi_{eff} = 3.993\text{eV}$) and thermal emittance of the Cu cathode. As illustrated in the beam envelope evolution (Fig. 3), the RMS beam size σ reaches a characteristic minimum at $z = 0.45\text{m}$. To effectively capture the beam before significant divergence occurs, the first quadrupole of the matching

doublet was positioned close to this waist point. The quadrupole strengths and their longitudinal positions were then systematically varied to control the Twiss parameters.

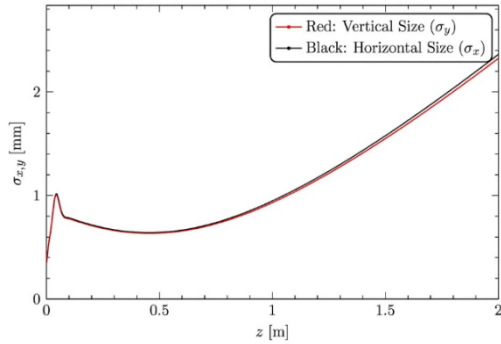


Figure 3: Evolution of the RMS beam sizes along the AREAL beamline.

In the space-charge-dominated regime of the AREAL linear accelerator, achieving an ideal waist where $\alpha \approx 0$ is challenging because the intense quadrupole focusing required to reach that condition simultaneously degrades the beam emittance. Because space-charge forces are highly nonlinear, aggressive focusing leads to phase-space filamentation, which results in irreversible emittance growth. To address this, the optimization for the AREAL 50 MeV upgrade focuses on a strategic ‘trade-off’ between emittance preservation and the Twiss parameters. To avoid the emittance degradation caused by aggressive focusing, the system is tuned to a state where the values for α_x and α_y are less than -5 at the matching point. Consequently, an optimized configuration was identified by placing the quadrupole doublet at $z = 1.15$ m with a 0.15 m longitudinal separation. Shifting the quadrupole doublet further from the optimal waist position results in a marginal increase in the RMS beam size—around 1 mm—which remains within controllable limits (Fig. 3). This configuration provides the opportunity to manipulate the Twiss parameters more smoothly, ensuring the beam reaches the desired balanced emittance state at the matching point after the specified separation. Applying quadrupoles gradients of $k_f = 0.535$ T/m and $k_d = -0.495$ T/m yielded a stable matching region within the 1.6 – 1.7 m interval (Fig. 4).

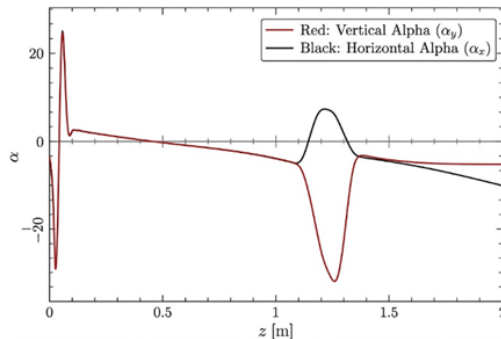


Figure 4: Evolution of the horizontal (black) α_x and α_y vertical (red) along the transport line for the AREAL upgrade beamline.

This configuration effectively balances emittance preservation with the required beam convergence, ensuring stable matching and optimal injection into the subsequent accelerating structures. The evolution of the transverse emittance shown in Fig. 5 illustrates that while emittance increases along the beamline, it remains within a low-emittance region of less than 2π mm mrad near the matching point.

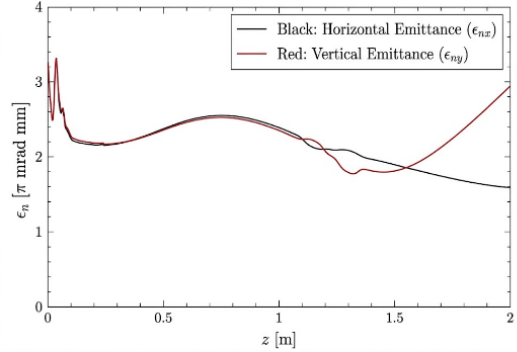


Figure 5: Evolution of the horizontal (black) and vertical (red) transverse emittance for the AREAL upgrade beamline.

In general, the simulation results demonstrate that prioritizing a balanced beam distribution over an absolute waist condition effectively mitigates the impact of space-charge nonlinearities. By maintaining the transverse emittance below 2π mm mrad at the matching point (Fig. 5), the proposed lattice upgrade ensures a high-quality beam with the necessary convergence for efficient injection.

CONCLUSION

This study presents the intermediate results of the transverse beam dynamics analysis for the AREAL linear accelerator upgrade. The results demonstrated that beam matching within the space-charge dominated region necessitates a strategic compromise between minimizing the transverse emittance and achieving a low α parameter. By adjusting the injection to create a beam waist, an operational regime was established that successfully keeps the transverse emittance under 2π mm mrad. However, the current results indicate that further investigation into the emittance compensation configuration is warranted to achieve more rigorous control over beam quality. Furthermore, future efforts will prioritize a refined quadrupole matching scheme to enhance beam transport stability. These developments remain central to the high-brightness beam delivery goals of the AREAL upgrade program, providing a basis for advanced research in higher energy regimes.

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