

Physical design of a high-charge L-band photoinjector for the next-generation tau-charm factory

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This paper introduces the injector design for the Super Tau-Charm Facility (STCF), addressing the long-standing challenge of generating high-charge (8.5 nC) and high-brightness electron beams. The design pioneers a segmented optimization strategy that effectively decouples the mitigation of space-charge effects from the management of high-energy wakefields. Through multiobjective optimization in the low-energy section and sophisticated beam manipulation in the high-energy section utilizing S/X-band structures and a magnetic compressor, the injector delivers a 2 GeV beam with remarkable properties: a mere 0.22% rms energy spread and transverse normalized emittances of 6.3/5.9 mm mrad. Robustness is demonstrated through error analysis, showing emittance growth is suppressed via orbit correction and stringent alignment tolerances. Its defining innovation is the innate support for both 8.5 nC swap-out and 1.5 nC off-axis injection within a single lattice, seamlessly toggled without hardware intervention. This design provides a versatile and high-performance injection platform ready for the demands of the STCF.

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I. INTRODUCTION

The Super Tau-Charm Facility (STCF) [1] is a proposed next-generation electron-positron collider in China, consisting of three primary subsystems: an injector, a collider ring, and a detector. Designed for center-of-mass energies ranging from 2 to 7 GeV, the STCF requires its injector to deliver both electron and positron bunches that are tunable across the 1–3.5 GeV energy range. Within the injector complex, electrons are first accelerated to 1 GeV in a dedicated linear accelerator (linac) before being transferred to the main linac. Positrons are generated by impinging a high-charge electron bunch onto a target, after which they are captured, damped, and accelerated within the main linac. Both beams are subsequently brought to their final energies for injection into the collider ring.

The injector commissioning will be conducted in two phases, each employing a distinct injection scheme: (i) Phase I (Off-axis injection): continuous top-up operation using low-charge bunches (1.5 nC). (ii) Phase II

(swap-out injection): direct replacement of circulating bunches with high-charge bunches (8.5 nC).

Achieving the high-luminosity goals of STCF phase II demands that the injector deliver electron bunches at a minimum rate of 240 nC/s while simultaneously meeting stringent beam-quality specifications at the injection point. These include a geometric emittance of less than 30 nm rad (horizontal) and 15 nm rad (vertical), along with a root-mean-square (rms) energy spread under 0.5%. These parameters are crucial for ensuring collider stability and maintaining the luminosity necessary for precision physics in the tau-charm energy region.

Meeting these demanding requirements with conventional technologies presents significant challenges. Conventional thermionic-cathode guns, such as those deployed in the Compact Linear Collider [2,3] and the High Energy Photon Source [4,5], are limited by their relatively low accelerating gradients. As a result, beams generated by such sources exhibit large transverse emittance on the order of 100 mm mrad and extended bunch lengths often exceeding 100 ps. These characteristics make it extremely challenging to meet the stringent beam-quality specifications set by the STCF injector.

Alternatively, S-band rf photoinjectors are capable of producing beams with excellent emittance and short bunch lengths, owing to their higher accelerating gradients and the use of photocathode-driven emission. However, they are fundamentally constrained in terms of charge capacity.

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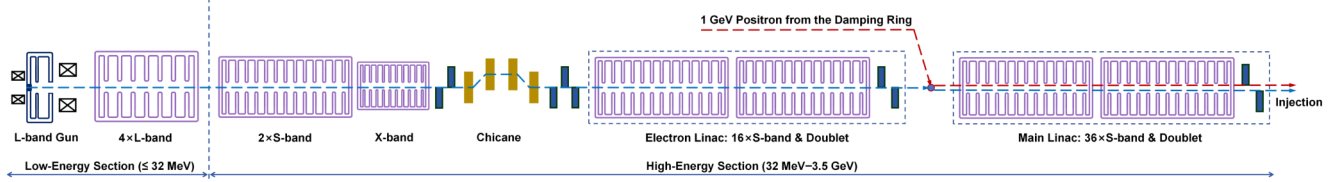


FIG. 1. Schematic layout of the L-band photocathode electron injector. The low-energy section comprises the electron gun, solenoids, and four L-band standing-wave accelerating structures, while the high-energy section includes two S-band traveling-wave accelerating structures, an X-band linearizer, a magnetic bunch compressor, a 1-GeV linac with 16 S-band traveling-wave accelerating structures, and the main linac containing 36 S-band traveling-wave accelerating structures.

In practice, typical S-band photoinjectors operate at bunch charges well below 1 nC, as demonstrated by leading facilities such as the SwissFEL [6] and the Tsinghua Thomson Scattering X-ray Source [7]. Although advanced designs, such as the S-band gun developed for Super-KEKB [8], have successfully pushed bunch charges to 5 nC, scaling up to the 8.5 nC required for the STCF Phase II swap-out injection scheme remains highly challenging. Consequently, S-band devices are deemed unsuitable for fulfilling the extreme high-charge demands of the STCF.

In contrast, L-band photocathode rf guns have emerged as a mature and robust technology for generating high-current, high-brightness electron beams. Developed and extensively validated at institutions like the PITZ facility in Germany [9,10] and Tsinghua University in China [11], these guns integrate high-quantum-efficiency photocathodes with tailored drive lasers to achieve normalized emittance levels approaching 1 mm mrad/nC. This performance has established the L-band gun as a benchmark for modern photoinjectors. Furthermore, the exceptional charge capacity of the L-band architecture has been prominently demonstrated at the Argonne Wakefield Accelerator facility, which successfully operates with extreme bunch charges of up to 100 nC [12,13]. Owing to their proven reliability and scalability, L-band guns have been selected as the core technology for high-charge injectors in next-generation facilities, including the Shanghai High-Repetition-Rate XFEL and Extreme Light Facility [14].

For the STCF, operating at 8.5 nC and 30 Hz translates to a total charge per second exceeding 240 nC/s, thereby meeting and surpassing the injector’s charge rate requirement. Leveraging this established technical foundation, we have designed an injector based on an L-band photocathode rf gun. This injector supports dual operational modes—high-charge (8.5 nC) swap-out injection and low-charge (1.5 nC) off-axis injection—within a unified lattice. This flexible design not only satisfies the stringent demands for beam quality and stability in swap-out injection but also maintains full compatibility with off-axis injection through parameter reoptimization, eliminating the need for hardware modifications during operational transitions.

To mitigate the strong space-charge forces [15,16] at low energies and the significant wakefields [17–19] at high energies—both inherent to high-charge (8.5 nC) operation—the injector is divided into dedicated low-energy and high-energy sections, each optimized with tailored simulation methodologies. Rigorous start-to-end beam dynamics simulations are essential for accurately predicting and optimizing the overall performance of modern accelerator facilities [20]. The schematic of the injector lattice is provided in Fig. 1.

The remainder of this paper is organized as follows: Sec. II presents the multiobjective optimization of the low-energy section and the resulting beam parameters at its exit. Section III discusses the lattice design and optimization of the high-energy section. Section IV provides a comprehensive error analysis, including transverse orbit correction and longitudinal jitter evaluation. Section V introduces the downward-compatible 1.5 nC off-axis injection scheme, derived from the optimized 8.5 nC swap-out injection configuration. Finally, the paper concludes with a summary of key findings and design implications.

II. LOW-ENERGY SECTION

A. Multiobjective optimization

The low-energy section of the L-band injector (schematically depicted in the left portion of Fig. 1) comprises a 1.6-cell L-band photocathode rf gun [11], solenoids, and four L-band standing-wave accelerating structures. The solenoids incorporate a bucking coil and a main coil, meticulously designed to precisely nullify the magnetic field at the cathode surface—a critical feature for minimizing emittance growth [21].

The transverse and longitudinal beam quality emerging from this low-energy section is paramount, as it directly governs bunch evolution in the high-energy section and ultimately dictates the injection performance. To enable optimal downstream acceleration and compression, the electron bunch must exhibit not only minimal transverse emittance but also a short longitudinal length and a nearly linear longitudinal phase-space distribution. These characteristics are essential prerequisites for achieving high-efficiency energy chirping and compression in subsequent accelerator stages.

TABLE I. Multiobjective optimization parameters and their ranges.

Parameters	Ranges	Units
rms drive laser spot size	[1, 3]	mm
Drive laser pulse duration	[10, 35]	ps
Phase of L-band tube $\times 4$	[-50, 50]	degree
Gradient of L-band tube $\times 4$	[10, 30]	MV/m
Position of L-band module	[1, 6]	m
Solenoids field scaling factor	[0.7, 1.5]	

To achieve these goals, we defined the following key optimization targets at the exit of the low-energy section: the bunch length σ_z , the normalized transverse emittance $\epsilon_{n,x}$, and the nonlinearity of the energy spread δ_{NL} . The nonlinearity of the energy spread is quantified by the relation:

$$\delta_{NL} = \frac{1}{\overline{P_{z,i}}} \sqrt{\frac{\sum_{i=1}^N (\Delta P_{z,i} - \overline{\Delta P_{z,i}})^2}{N}}, \quad (1)$$

where N is the number of macroparticles; $P_{z,i}$ is the longitudinal momentum; the overscore notation means the average of a variable; $\Delta P_{z,i}$ is the difference between the momentum and its linear fitting value:

$$\Delta P_{z,i} = P_{z,i} - \hat{P}_{z,i}, \quad (2)$$

Given the strong interdependence of beam parameters in the low-energy section and their nonlinear impact on final bunch properties, we employed the PYTHON-based Geatpy toolbox [22] to perform a multiobjective optimization. To accurately capture the pronounced space-charge effects inherent to an 8.5 nC bunch at low energies, particle-tracking simulations were conducted using ASTRA [23]. The optimization variables and their corresponding ranges are systematically summarized in Table I. The phase and gradient of the four L-band accelerating structures are individually adjustable, but their relative positions are fixed, and the distance between the L-band module and the cathode can be adjusted. In our simulations, the rf phase is defined where 0° corresponds to the maximum on-crest acceleration.

During the optimization, the beam energy was not set as a rigid constraint but was dynamically determined by the multiobjective algorithm to minimize the energy spread and its nonlinearity. The employment of four L-band structures provides a sufficiently large parameter space for the optimizer to find the optimal phase and gradient combinations.

The multiobjective optimization was performed with a population size of 200 and a maximum of 100 generations, balancing computational efficiency with solution diversity. During optimization, the drive laser parameters were fixed

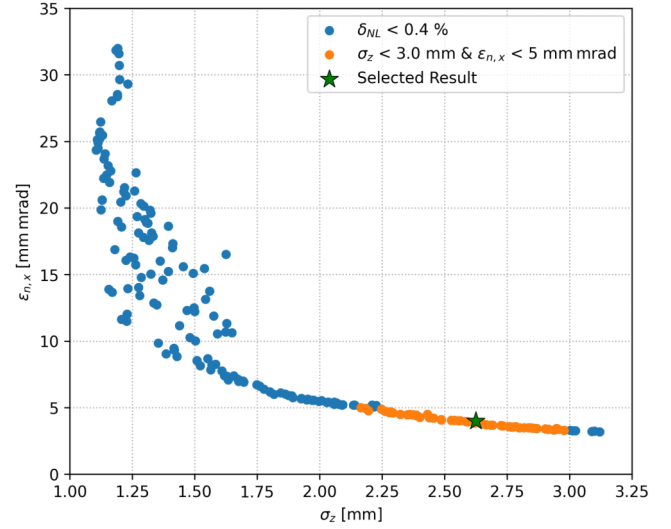


FIG. 2. The Pareto front of the optimization results at the end of the low-energy section. The orange part is the result that meets the expectations, and the green star is the selected result.

to a uniform transverse distribution and a flat-top longitudinal profile, while the bunch charge was maintained at 8.5 nC—matching the operational target.

To accelerate convergence while preserving solution quality, we employed 5000 macroparticles for particle-tracking simulations, significantly reducing the computational cost compared to full-scale tracking. To visually assess trade-offs between transverse emittance ($\epsilon_{n,x}$) and bunch length (σ_z), we extracted optimized solutions where the energy spread nonlinearity (δ_{NL}) was constrained to less than 0.4%, ensuring high-quality longitudinal phase space. The resulting two-dimensional Pareto front (Fig. 2) reveals the fundamental compromise between minimizing emittance and shortening the bunch length.

Despite deviations arising from the 5000-particle approximation, the optimization yielded remarkably competitive results: $\epsilon_{n,x} < 5$ mm mrad and $\sigma_z < 3$ mm. These values align with our design expectations and demonstrate that the low-energy section can deliver beam parameters well suited for downstream acceleration and compression.

B. Results

To validate the optimization outcomes, we selected a representative Pareto-optimal solution and performed a high-fidelity resimulation with 100,000 macroparticles to ensure statistical convergence and parameter accuracy. The simulation parameters for the low-energy section are summarized in Table II.

The longitudinal phase space at the exit of the electron gun is presented in Fig. 3. Under these optimized conditions, the low-energy exit achieved exceptional beam quality: the normalized transverse emittance at the section exit reached 4.3 mm mrad, the rms bunch length was

TABLE II. Simulation settings of the low-energy section.

Parameters	Values
Drive laser length (FWHM)	28 ps
Drive laser radius	2.0 mm
Gun frequency	1300 MHz
Cathode surface gradient	60 MV/m
Gun phase	-2°
Frequency of L-band structures	1300 MHz
Length of L-band structures	1.32 m
Gradient of L-band structures	15.3 MV/m, 13.6 MV/m, 17.8 MV/m, 10.5 MV/m
Phases of L-band structures	20.0° , -47.6° , 24.4° , 49.6°
Position of L-band module	2.516 m
Main solenoid field strength	0.2 T

2.6 mm, and the full bunch length extended to approximately 10 mm (sufficient for generating adequate energy chirp to enable downstream compression). The longitudinal phase space exhibited near-ideal linearity, and the current profile remained highly uniform (Fig. 4), indicating stable and well-controlled beam dynamics. The evolution of key bunch parameters (emittance, bunch length, and energy spread) along the beamline is systematically presented in Fig. 5, while detailed exit parameters are quantitatively summarized in Table III.

It is worth noting that short-range wakefields in the L-band accelerating structures are not included in the simulation. Given the large aperture of L-band structures, the relatively low beam energy and peak current at this stage, the wakefield effects are negligible and do not degrade the beam quality at the low-energy section exit.

III. HIGH-ENERGY SECTION

As the bunch is accelerated to higher energies, wake-field effects become a dominant factor influencing beam

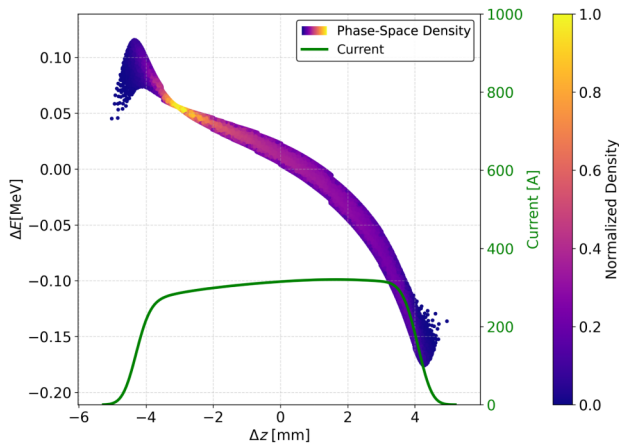


FIG. 3. The longitudinal phase space at the exit of the electron gun, as well as the current density profile.

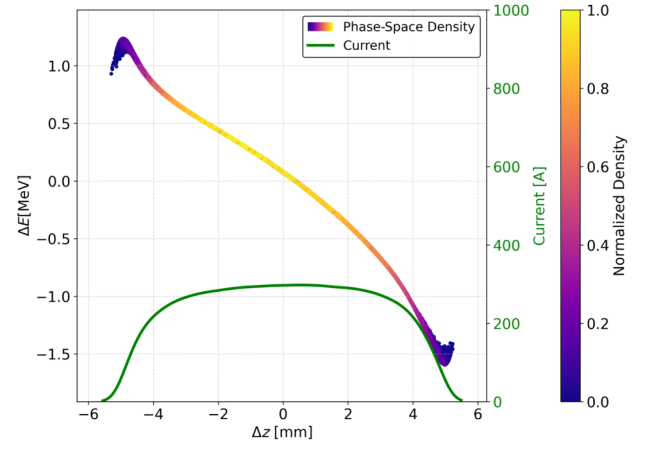


FIG. 4. The longitudinal phase space at the exit of the low-energy section, as well as the current density profile.

quality, particularly under the 8.5 nC high-charge scenario. To accurately model these effects, the longitudinal and transverse single-particle wake functions for both the S-band and X-band accelerating structures were calculated. As illustrated in Fig. 6, the short-range wakefield potentials highlight the varying impact of different structures. Notably, the X-band structure exhibits significantly stronger transverse wakefield kicks due to its smaller aperture compared to the S-band structures. The high-energy section is thus designed to systematically

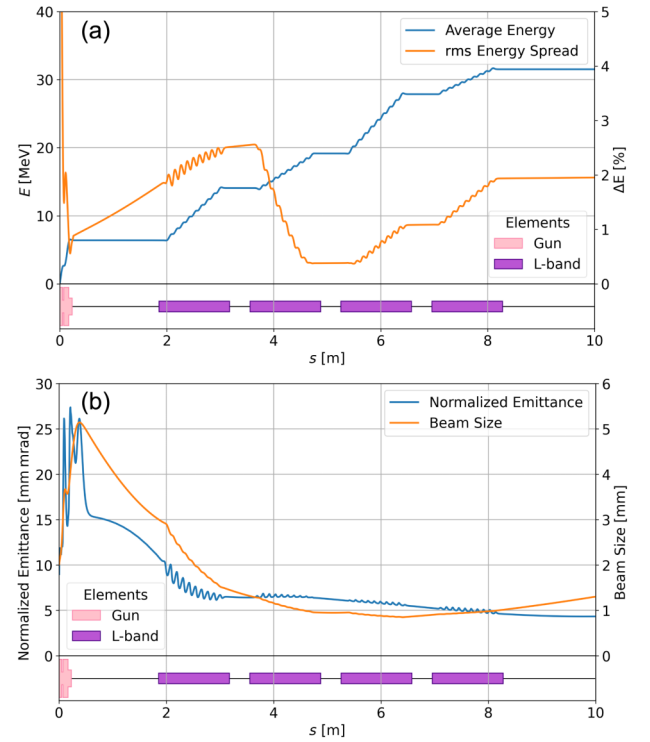


FIG. 5. Beam parameters evolution along the low-energy section. Panel (a): average energy and rms energy spread. Panel (b): normalized emittance and beam size.

TABLE III. Bunch parameters at low-energy section exit.

Parameters	Values	Units
Average energy	32.04	MeV
rms energy spread	1.92	%
rms bunch length	2.60	mm
Normalized emittance (hor/ver)	4.3/4.3	mm mrad
rms beam size (hor/ver)	1.3/1.3	mm
Envelope function β (hor/ver)	23.8/23.8	m

investigate these effects. To evaluate the impact on beam quality, single-bunch dynamics simulations for the high-energy section were performed using ELEGANT [24], which included short-range wakefields, longitudinal space charge, and coherent synchrotron radiation (CSR) [25].

The influence of transverse space charge was specifically examined in the two S-band traveling-wave accelerating structures that boost the beam energy from 32 to 130 MeV. Comparative results indicate that omitting this effect induces a negligible change in the transverse phase space at the injector exit. This result validates the division of the injector into low- and high-energy sections at the 32 MeV interface.

During optimization of the high-energy section, a near-decoupling between transverse and longitudinal bunch parameters was observed. This finding motivated a sequential optimization strategy: longitudinal phase-space evolution was prioritized and refined first, followed by the imposition of constraints on transverse beam dimensions. Iterative coupling between the two domains was introduced only when necessary to meet final performance targets. This hierarchical approach streamlined the design workflow while ensuring simultaneous compliance with stringent transverse and longitudinal beam-quality specifications.

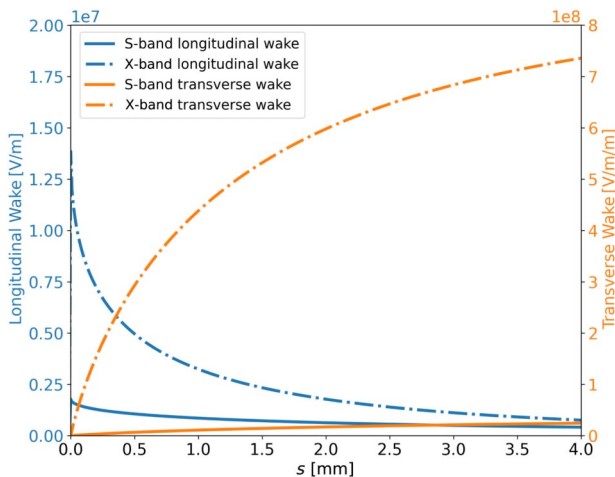


FIG. 6. Longitudinal and transverse single-particle wake function for both the S-band and X-band accelerating structures.

A. Longitudinal considerations

The lattice arrangement of accelerating structures and magnetic bunch compressors has been optimized to satisfy the STCF's stringent longitudinal requirements at the injection point, particularly the sub-0.5% rms energy spread specification, while enabling precise control of the longitudinal phase space. To achieve this, the high-energy section employs a staged strategy: initial bunch compression minimizes the phase extent within the S-band accelerating structures, followed by a progressive reduction in energy spread during acceleration toward the final 2 GeV energy.

As illustrated in the right panel of Fig. 1, the high-energy section integrates two S-band traveling-wave accelerating structures, an X-band linearizer, a magnetic bunch compressor, and 52 S-band accelerating structures. The first two S-band accelerating structures boost the bunch energy from 32 to 130 MeV while imprinting a tailored energy chirp, essential for subsequent compression. In addition to correcting initial nonlinear distortions in the longitudinal phase space, the X-band linearizer is also tuned in phase and amplitude to introduce specific quadratic components. This proactively compensates for longitudinal phase-space distortions induced by longitudinal wakefields in downstream accelerating structures, thereby reducing the bunch energy spread [26]. The magnetic compressor subsequently shortens the rms bunch length from 2.60 to 1.16 mm, resulting in a total bunch length of approximately 5 mm. It should be noted that this specific compressed bunch length (rms 1.16 mm, corresponding to a total length of approximately 5 mm) is not a strict requirement imposed by the main linac. Actually, it is deliberately optimized so that the bunch occupies an appropriate rf phase spread within the S-band accelerating structures, which allows the bunch to leverage the rf curvature, providing the necessary energy variation along the bunch to effectively compensate for the longitudinal phase-space distortions induced by wakefields.

Following compression, the linear accelerator is divided into two functional segments to meet the STCF's requirement for delivering tunable electron and positron bunches across the 1 to 3.5 GeV range, with nominal operation at 2 GeV. The electron linac first accelerates the beam to 1 GeV, after which the main linac alternately accelerates electron and positron bunches to the target injection energies.

The electron linac is equipped with 16 S-band traveling-wave accelerating structures, while the main linac contains 36 such structures. This configuration provides the total gradient required to reach 3.5 GeV, along with sufficient independent control channels—via phase and amplitude adjustments—to compensate for longitudinal wakefield effects along the full linac length [27,28]. The structures are grouped in pairs, each powered by a single rf source. In simulations, the electron linac structures operate with

identical phase and amplitude settings, whereas those in the main linac are individually tuned to meet specific beam-quality and operational requirements.

For the nominal 2 GeV operational scenario, the phases of the accelerating structures in both the electron linac and main linac segments were optimized to compensate for longitudinal phase-space distortions induced by wakefields, while their amplitudes were simultaneously adjusted to achieve target beam energies at critical lattice locations. The downstream tube phases were carefully coordinated with upstream components, including the chirp-producing S-band structures, the X-band linearizer, and the R_{56} parameter of the magnetic chicane.

A hybrid optimization strategy was employed, combining a multiobjective algorithm to explore the correlated parameter space and identify feasible regions, followed by manual fine-tuning to converge on the final operational settings. This approach improved computational efficiency, reduced simulation time, and ensured that all performance criteria were satisfied.

Through this iterative optimization process, the injector achieved an rms energy spread of 0.22% and an average beam energy of 2005.01 MeV at the injection point. To explicitly illustrate the strong impact of longitudinal wakefields on beam parameters, a comparative tracking was performed under the same rf settings by artificially turning off the wakefields. Under this hypothetical condition, the uncompensated rf chirp degrades the rms energy spread to 1.33% and shifts the average energy to 2075.93 MeV. This degradation highlights that the optimized rf chirp offsets the wakefield-induced energy deviations. The simulation parameters for the high-energy section are summarized in Table IV. The evolution of the longitudinal phase space

TABLE IV. Simulation settings of the high-energy section.

Parameters	Values
Frequency of S-band structures	2998 MHz
Length of S-band structures	3 m
Half aperture of S-band structures	13.11 mm
Gradient of S-band chirping structures	20 MV/m
Phase of S-band chirping structures	-25°
Frequency of X-band linearizer	11,424 MHz
Length of X-band linearizer	0.945 m
Half aperture of X-band structures	4.7 mm
Gradient of X-band linearizer	12 MV/m
Phase of X-band linearizer	180°
Gradient of electron linac structures	19.1 MV/m
Phase of electron linac structures	-11°
Gradients of main linac structures	$22.1 \text{ MV/m} \times 16$, $0 \text{ MV/m} \times 20$
Phases of main linac structures	$-8^\circ \times 16$, $0^\circ \times 20$

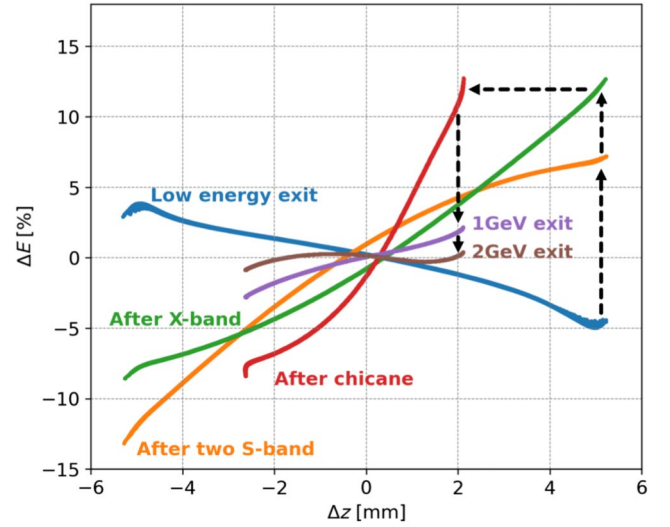


FIG. 7. Evolution of the bunch longitudinal phase space in the high-energy section: sequentially passing through the two S-band chirping structures, the X-band linearizer, the chicane, the 1 GeV exit, and finally to the 2 GeV exit.

along the high-energy section and its final distribution at the injector exit are shown in Figs. 7 and 8, respectively.

B. Transverse beam size constraints

Transverse beam size control is primarily achieved through the optimization of quadrupole magnet design and lattice configuration.

CSR in the bunch compressor can induce substantial beam centroid displacements, which subsequently drive emittance growth through transverse wakefield effects in downstream accelerating structures [29,30]. During lattice optimization, the magnetic compressor configuration was carefully tuned to mitigate these CSR-induced effects. This optimization reduced the CSR-driven emittance

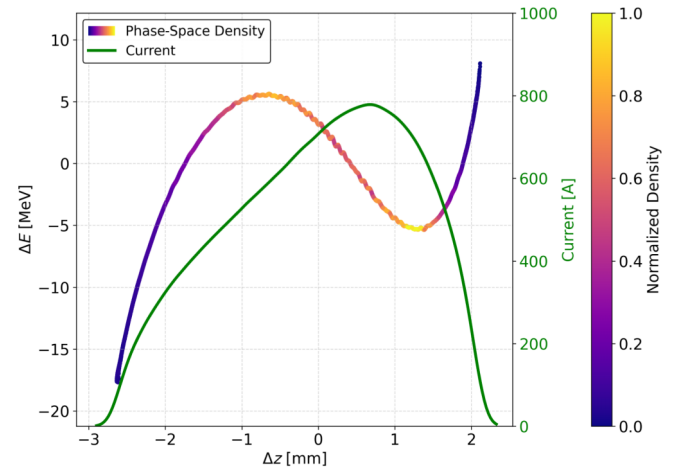


FIG. 8. Longitudinal phase space and current density profile of the bunch at 2 GeV exit.

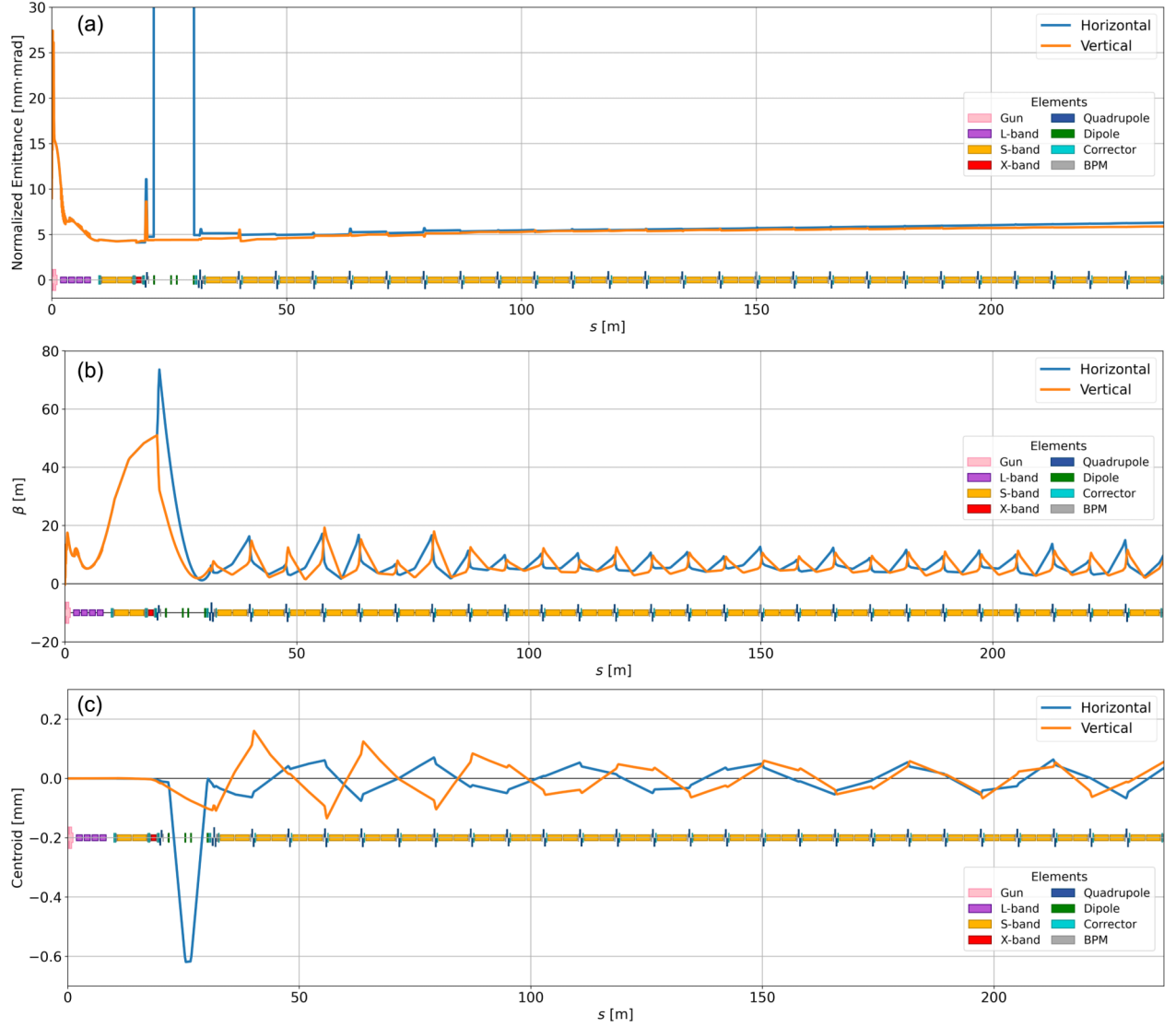


FIG. 9. The evolution of various bunch parameters along the injector beamline. Panel (a): normalized transverse emittance. Panel (b): envelope function β . Panel (c): centroid. The positions of each element are marked below the diagram.

growth from several tens of mm mrad to just a few mm mrad, effectively preserving beam quality throughout the compression process.

Uncontrolled centroid offsets from the bunch compressor can further amplify transverse emittance growth via wakefields in subsequent accelerating sections. Initial designs employing a conventional FODO lattice proved inadequate for simultaneously controlling both the beam envelope and centroid deviation. To overcome this limitation, a specialized lattice configuration was implemented: three matching quadrupoles immediately downstream of the compressor ensure proper envelope matching, followed by a periodic doublet quadrupole arrangement interleaved with the 26 groups of S-band accelerating structures. This design enables simultaneous control of both the beam envelope and centroid trajectory, confines the beam centroid offset to within 0.2 mm along

the electron linac and the main linac, and effectively suppresses emittance growth.

This precise control yields final normalized emittances of $\epsilon_x = 6.3$ mm mrad and $\epsilon_y = 5.9$ mm mrad at the 2 GeV exit, well within the required specifications. The evolution of key beam parameters—including normalized transverse emittance, energy spread, beam envelope, and centroid offset—along the injector is illustrated in Fig. 9, with corresponding injection point parameters summarized in Table V.

IV. ERROR ANALYSIS

A. Transverse error analysis

The beam dynamics discussed in previous sections assume ideal conditions. In practice, however, various beamline errors distort the designed orbit, enlarge the

TABLE V. Bunch parameters at 2 GeV exit.

Parameters	Values	Units
Average energy	2005.01	MeV
rms energy spread	0.22	%
rms bunch length	1.16	mm
Peak current intensity	778.7	A
Normalized emittance (hor/ver)	6.3/5.9	mm mrad
rms beam size (hor/ver)	97/115	μm
rms divergence (hor/ver)	19/35	μrad
Beam centroid	35/56	μm
Envelope function β (hor/ver)	9.47/7.68	m

beam envelope, and degrade emittance. The high beam current associated with the 8.5 nC charge and the short bunch length make the beam particularly susceptible to transverse errors, which can induce significant emittance growth. Our analysis identifies the combined effect of trajectory deviations and short-range transverse wakefields in the high-energy section as the dominant mechanism for transverse emittance increase. In the low-energy section—comprising the L-band electron gun and accelerating structures—the large apertures and relatively weak short-range transverse wakefields result in negligible emittance growth. Therefore, the transverse error analysis focuses exclusively on the high-energy section.

Among all high-energy components, the X-band linearizer is the most critical source of emittance growth. Its small aperture (4.7 mm) generates strong transverse wakefields, and even minor trajectory deviations through it can produce substantial transverse kicks, leading to pronounced emittance degradation—especially at the 8.5 nC bunch charge. Since only one X-band linearizer is present in the lattice, its precise alignment is both technically feasible and cost-effective.

To quantify transverse effects, alignment errors were applied to all accelerating structures, with additional dipole and quadrupole errors included. The specific error settings for each component are summarized in Table VI. All errors follow a truncated Gaussian distribution (cut at 3σ). For the X-band linearizer, the transverse alignment error was conservatively set to 0.05 mm to minimize its contribution

to emittance growth. A detailed analysis of the X-band linearizer alignment tolerance is provided in Sec. IV B.

Emittance distortions were evaluated over 100 random error seeds. Before orbit correction, the maximum rms orbit deviations along the beamline reached approximately 6.4 mm horizontally and 5.0 mm vertically. At the 2 GeV exit, the maximum orbit errors were 13.2 mm (horizontal) and 11.6 mm (vertical), with corresponding rms values of 4.9 and 3.9 mm, as shown in Fig. 10. Without orbit correction, the large trajectory excursions would cause the beam to hit the vacuum chamber walls, leading to partial beam loss, as the deviations exceed physical radial apertures of the S-band and X-band structures. The average normalized emittance at the injection point increased to 1041 mm mrad (horizontal) and 907 mm mrad (vertical), as illustrated in Fig. 11. Such orbit distortions can significantly increase the normalized emittance and degrade overall beam quality, necessitating a robust static beam orbit correction system.

In this work, orbit correction is implemented by measuring distortions with beam position monitors (BPMs) and applying global corrections via corrector magnets to minimize deviations at BPM locations. After extensive simulation studies, an optimized configuration of 35 combined corrector magnets and 35 BPMs was deployed along the 237 m injector lattice.

Following orbit correction, the beam centroid offset was tightly controlled in critical structures. Specifically, the deviations were restricted to below 0.1 mm in the first two S-band structures, below 0.05 mm in the X-band linearizer, and within 2.0 mm (horizontal) and 0.5 mm (vertical) inside the magnetic compressor. In the subsequent electron linac and the main linac, the offsets were maintained below 0.25 mm. This localized, precise control prevents severe short-range wakefield kicks. At the 2 GeV exit, residual orbit errors were on the order of 10^{-5} . Correspondingly, the average normalized emittances at the injection point were reduced to 39.57 mm mrad (horizontal) and 42.00 mm mrad (vertical), fully satisfying the collider injection requirements. These results demonstrate that the orbit correction system suppresses emittance growth due to trajectory distortions by more than an order of magnitude,

TABLE VI. Magnet/accelerator mounting error.

Types of installation errors	Dipole	Quadrupole	S-band accelerator	X-band linearizer
Horizontal mounting error ($\sigma_{\Delta x}$)	0.1 mm	0.1 mm	0.1 mm	0.1 mm
Vertical mounting error ($\sigma_{\Delta y}$)	0.1 mm	0.1 mm	0.1 mm	0.1 mm
Longitudinal mounting error ($\sigma_{\Delta z}$)	0.1 mm	0.1 mm	...	...
Rotational mounting error ($\sigma_{\Delta\theta x}$)	...	0.1 mrad	...	...
Rotational mounting error ($\sigma_{\Delta\theta y}$)	...	0.1 mrad	...	...
Rotational mounting error ($\sigma_{\Delta\theta z}$)	...	0.1 mrad	...	...
Fractional strength error	0.1%	0.1%	...	...

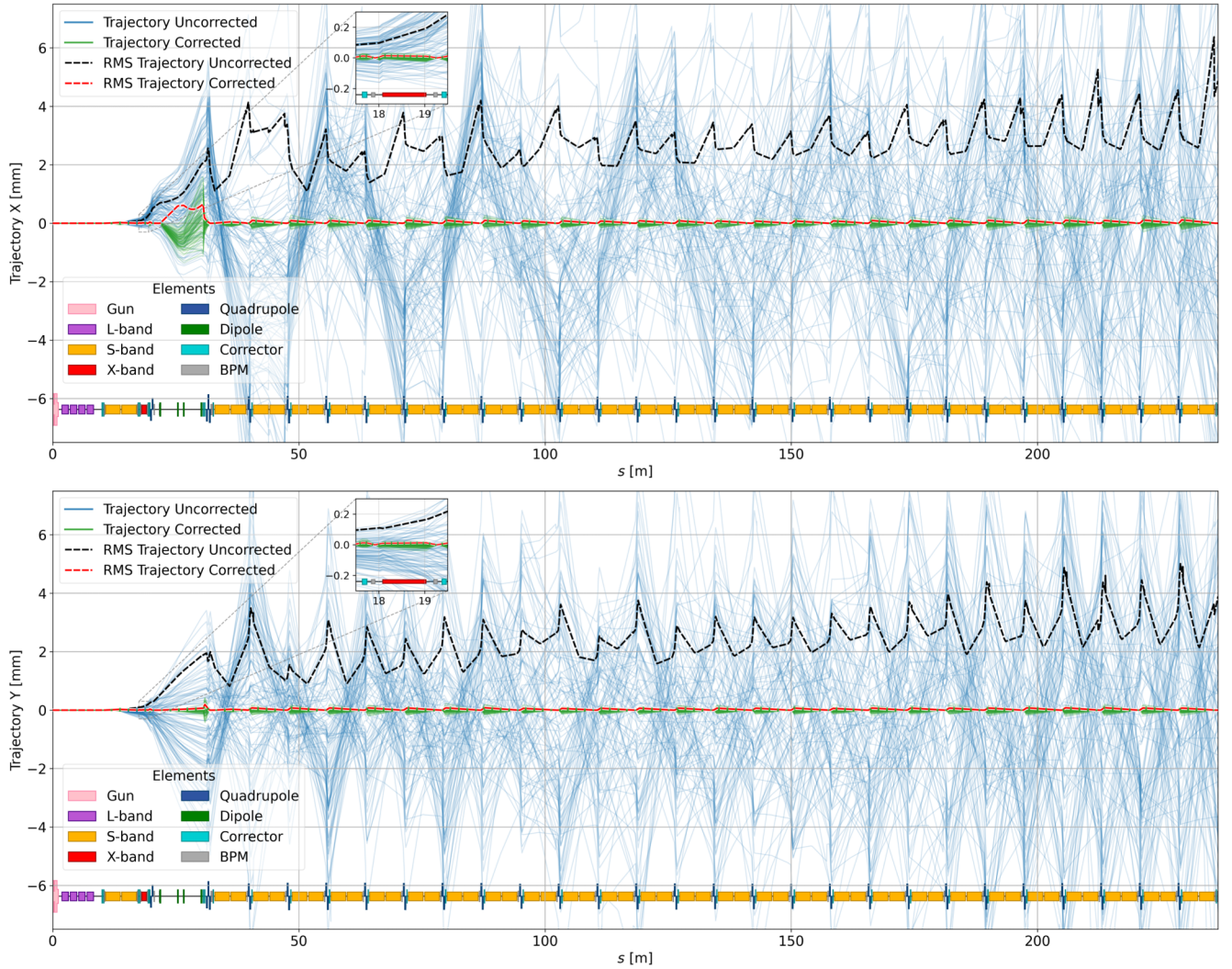


FIG. 10. The orbit distortion and correction results along the high-energy section. Top plot: horizontal. Bottom plot: vertical. The trajectories of the seeds before correction in the figure are marked in blue and those after correction are marked in green. The positions of each element are marked below the diagram.

effectively preserving beam quality and ensuring compliance with stringent injection specifications.

B. X-band linearizer precision alignment requirement

As the emittance growth profile in Fig. 11 indicates, the X-band linearizer is the dominant source of transverse emittance growth along the injector, even under precise alignment. Due to its significantly smaller aperture, even minor orbit deviations of the high-charge bunch can excite strong transverse wakefields and degrade the transverse emittance. Nevertheless, under the current lattice design and orbit correction scheme, this wakefield-induced emittance growth is tightly bounded and fully satisfies the demands imposed by the STCF collider ring. To quantify its precise alignment tolerance, its effect was systematically isolated by performing orbit corrections for 100 error seeds. In this study, only the alignment error of the X-band

linearizer was varied, while the error distributions of all other components remained unchanged.

The dependency of the average normalized emittance at 2 GeV on this misalignment is shown in Fig. 12. The STCF collider ring specifies a stringent geometric emittance limit of 30 nmrad (horizontal) and 15 nmrad (vertical) at 2 GeV, which corresponds to normalized limits of 117.4 and 58.7 mm mrad, respectively. Analysis of the data quadratic fit demonstrates that, despite the strong wakefield impact from the X-band linearizer, an alignment precision better than 70 μm successfully constrains the final emittance well within these allowable bounds. However, to accommodate potential discrepancies between simulation and reality, as well as fitting uncertainties, we imposed a more stringent engineering tolerance of 50 μm . This specification is considered achievable based on current accelerator engineering practices.

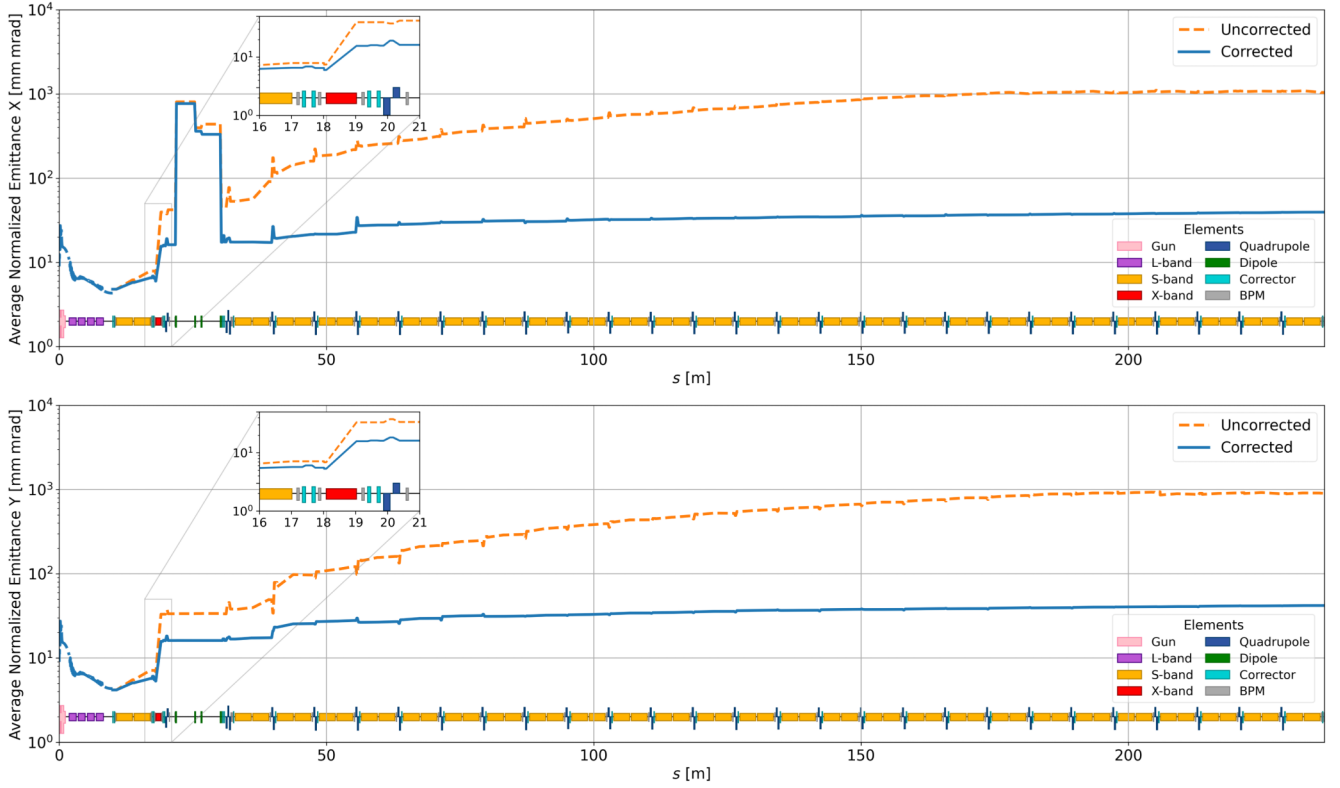


FIG. 11. Evolution of the average normalized emittance along the beamline before and after orbit correction. Top plot: horizontal. Bottom plot: vertical. The positions of each element are marked below the diagram.

C. Longitudinal jitter analysis

In the high-energy section of the STCF, the stability of longitudinal parameters is susceptible to various error sources. These include the charge and arrival time jitter of electron bunches from the low-energy section,

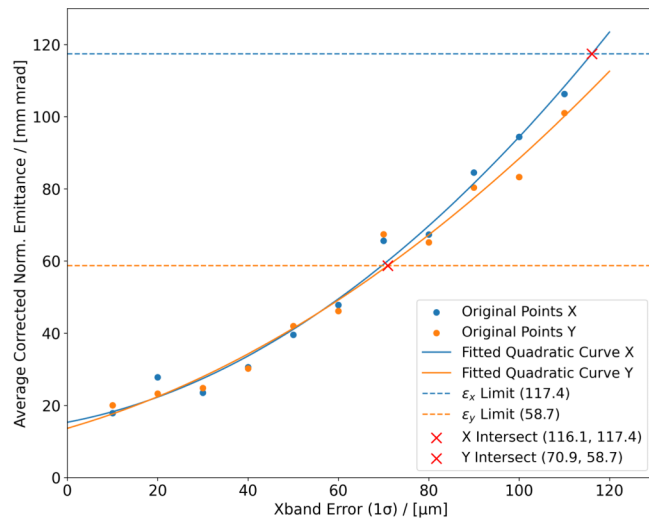


FIG. 12. Dependence of the average normalized emittance at the injection point on X-band linearizer alignment precision (100 seeds).

fluctuations in the rf accelerating fields' phase and amplitude, and the magnetic field jitter in the bunch compressor. Given the multiplicity of these potential error sources and their correlations, a system-level budget allocation is essential, considering the practical error limits of different subsystems. We have therefore conducted a comprehensive jitter analysis for the injector. The individual and aggregated impacts of these errors on the key performance metrics—center energy ($< 0.2\%$), peak current ($< 10\%$), and arrival time (< 100 fs) at the injection point—are summarized in Table VII. The results confirm that the overall jitter at the injector exit complies with the STCF requirements.

V. OFF-AXIS INJECTION SCHEME

To fulfill the dual demands of phase I off-axis injection and ensure compatibility with potential low-charge scenarios at the STCF, the 8.5 nC swap-out injection scheme was successfully scaled down to 1.5 nC through a reoptimization of key parameters. By constraining the reoptimization to nonstructural parameters—specifically, the drive laser settings, rf phase, and amplitude—the original lattice design was kept intact. This enables a hardware-free upgrade path, offering a cost-effective and highly flexible solution for future operational needs.

TABLE VII. Jitter analysis result on the center energy, peak current, and arrival time.

Parameter	Jitter	Unit	ΔE (%)	ΔI (%)	Δt (fs)
Δt from the exit of the low-energy section	0.25	ps	1.47×10^{-2}	0.15	1.12
ΔQ from the exit of the low-energy section	5	%	4.12×10^{-2}	0.77	2.50
Phase of S-band accelerators before bunch compressor	0.1	°	0.28×10^{-2}	0.65	5.14
Amplitude of S-band accelerators before bunch compressor	0.1	%	0.07×10^{-2}	0.48	1.21
Phase of X-band linearizer	0.4	°	0.36×10^{-2}	0.53	5.22
Amplitude of X-band linearizer	0.04	%	0.29×10^{-2}	0.05	0.59
Phase of S-band accelerators in e-linac	0.1	°	0.17×10^{-2}	< 0.01	0.08
Amplitude of S-band accelerators in e-linac	0.1	%	0.02×10^{-2}	< 0.01	0.22
Phase of S-band accelerators in main linac	0.1	°	0.20×10^{-2}	< 0.01	< 0.01
Amplitude of S-band accelerator in main linac	0.1	%	0.02×10^{-2}	< 0.01	0.02
R_{56} of the bunch compressor	0.1	%	< 0.01×10^{-2}	0.08	6.16
Total			4.41×10^{-2}	1.25	10.0

Following the same optimization framework established for the 8.5 nC beam, the beam dynamics for the 1.5 nC case were rigorously simulated. For the low-energy section, multiobjective optimization in ASTRA employing a drive laser with a uniform transverse distribution (1.68 mm radius) and a flat-top longitudinal profile (28 ps FWHM) produced a notably low transverse normalized emittance of 1.8 mm mrad at the exit, which ensures a high-quality input for subsequent high-energy acceleration.

Simulations of the high-energy section, conducted with Elegant, demonstrate that the reduced charge significantly mitigates longitudinal wakefield effects. This suppression yielded a well-linearized longitudinal phase space and a controlled energy spread of only 0.06%. At the 2 GeV injection point, the transverse normalized emittances were measured at 3.5 mm mrad (horizontal) and 4.0 mm mrad (vertical), with a peak current of 439.5 A. All these parameters conclusively meet the STCF requirements for off-axis injection. The corresponding longitudinal phase space is depicted in Fig. 13, and a summary of

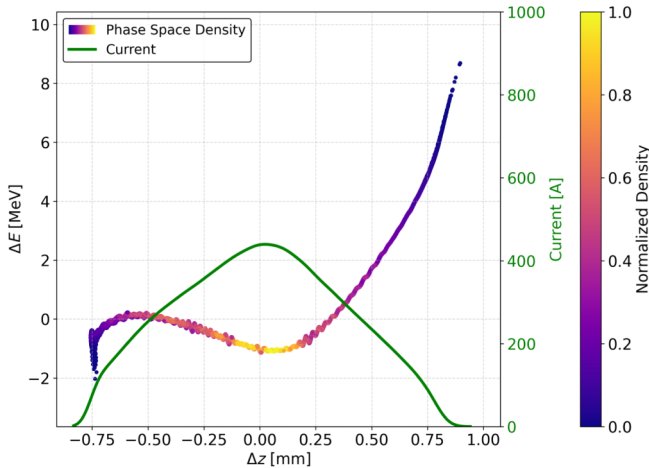


FIG. 13. Longitudinal phase space and current density profile of the bunch at the injection point.

TABLE VIII. Bunch parameters at 2 GeV exit at 1.5 nC.

Parameters	Values	Units
Average energy	2008.81	MeV
rms energy spread	0.06	%
rms bunch length	0.37	mm
Peak current intensity	439.5	A
Normalized emittance (hor/ver)	3.5/4.0	mm mrad
rms beam size (hor/ver)	62/143	μm
rms divergence (hor/ver)	18/39	μrad
Beam centroid	12/14	μm
Envelope function β (hor/ver)	11.67/8.39	m

key input parameters and output results is provided in Table VIII.

These results confirm the dual-mode capability of the proposed injector design, which accommodates both the 8.5 nC swap-out and 1.5 nC off-axis injection modes without hardware modifications, thereby offering substantial cost savings and enhanced operational efficiency for the future STCF upgrade.

VI. CONCLUSION

This study presents the successful design and optimization of a high-charge (8.5 nC), low-emittance electron injector based on an L-band photocathode rf gun, engineered to meet the stringent beam requirements of the STCF. Achieving this performance level posed a significant challenge, primarily due to the strong space-charge and wakefield effects at high charge. These challenges were mitigated through a comprehensive start-to-end physical design that systematically addressed the entire injection process—from bunch generation and compression to final acceleration at the injection point.

A two-stage optimization strategy across the accelerator sections ensures the final beam meets STCF

specifications. In the low-energy section, where space-charge forces dominate, a multiobjective optimization is applied to effectively manage the complex beam dynamics. Consequently, this optimization produces a high-quality beam with a 4.3 mm mrad normalized transverse emittance and a linear longitudinal phase space, which is crucial for subsequent acceleration. In the high-energy section, the beam is manipulated by integrating S-band and X-band accelerating structures with a magnetic bunch compressor. Furthermore, a specialized periodic doublet lattice is employed to constrain the beam centroid, while the phases and amplitudes of the accelerating structures are adjusted. These interventions effectively mitigate the transverse emittance growth induced by CSR and transverse wakefields and compensate for the distortions in the longitudinal phase space caused by longitudinal wakefield effects. Ultimately, the beam achieves an rms energy spread of 0.22% and transverse normalized emittances of 6.3/5.9 mm mrad, thus satisfying the STCF injection requirements.

The robustness of the lattice design is evidenced by two key findings. Comprehensive error analysis indicates that emittance growth is suppressible by more than an order of magnitude through orbit correction and precise alignment of the X-band linearizer within 50 μm . Concurrently, the lattice design enables a fully compatible 1.5 nC off-axis injection mode without hardware modifications, and this dual functionality allows a single setup to meet the distinct operational requirements of both phase I and phase II.

This work proves that L-band photocathode injectors can deliver beams with both extremely high charge and low emittance. This capability provides a robust design framework for next-generation high-luminosity colliders.

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