

Design and optimization of rf structures for the CLIC main beam injector linacs

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The design of the Compact Linear Collider (CLIC) main beam injector complex linacs necessitates high-gradient, traveling-wave accelerating structures engineered to withstand substantial beam-loading effects due to the elevated beam current and demanding acceleration requirements of CLIC operations. In this work, we present a comprehensive design and optimization study of 2 GHz traveling-wave structures tailored to these stringent requirements. The electron and positron linacs accelerate the beams up to 2.8 GeV with a nominal bunch charge of 1 nC, followed by the booster linac, which increases the energy to 9 GeV with a nominal bunch charge of 0.83 nC. Each bunch train consists of 352 bunches, requiring careful management of beam dynamics and wakefield effects to ensure stable operation. Through detailed analytical modeling and extensive parameter sweeps, we optimized the iris geometry of the accelerating structures to enhance shunt impedance, reduce surface electric fields, and suppress long-range wakefields via detuning strategies, thereby minimizing undesired beam-cavity interactions. Given the high beam current, we analyzed beam-loading effects and implemented compensation techniques to minimize bunch-to-bunch energy spread, supporting reliable, high-efficiency acceleration essential for CLIC operations. This study advances the development of high-performance accelerating structures that operate with high beam currents, which is crucial for achieving CLIC goals.

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I. INTRODUCTION

The Compact Linear Collider (CLIC) is a proposed high-luminosity linear electron-positron (e^-e^+) collider designed [1] to enable precision studies of the Higgs boson and top quark, as well as to search for physics beyond the Standard Model at multi-TeV energies. The accelerator employs high-gradient, normal-conducting accelerating structures powered by a novel two-beam acceleration scheme. CLIC is planned to be implemented in stages, starting with an initial center-of-mass energy of 380 GeV, followed by upgrades up to 1.5 TeV [2].

In the CLIC Conceptual Design Report (CDR) published earlier in 2012 [1], the main beam injector (MBI) complex comprised three linacs: a common injector linac, a positron drive linac, and a booster linac. All were operated at 2 GHz rf frequency and based on 1.5 m-long traveling-wave (TW) accelerating structures powered by 50 MW klystrons with 8 μ s pulse length at a repetition rate of 50 Hz, typically combined with SLED-type [3] pulse compressors. The

common injector linac employed 119 accelerating structures to accelerate electrons and positrons from 200 MeV to 2.86 GeV with a loaded gradient of about 15 MV/m. The positron drive linac used 224 structures with a similar loaded gradient of 15 MV/m to produce a 5 GeV high-current electron beam for positron generation, while the booster linac contained 256 structures to increase both electron and positron beam energies from 2.86 to 9 GeV with a loaded gradient of 16 MV/m. This layout was tailored for the CDR with a 500 GeV entry stage and an ultimate 3 TeV collider.

By contrast, the present study addresses the updated 380 GeV baseline with upgrade potential to 1.5 TeV [2], motivating a re-optimization of the injector linacs to pursue higher rf efficiency for operational power reduction and fewer rf structures and power sources for cost reduction, as well as to facilitate technological compatibility with future 2 GHz rf platforms such as those foreseen for the Future Circular Collider electron-positron (FCC-ee) [4].

In the current baseline [2] of the MBI complex, electron and positron beams are accelerated at a repetition rate of 100 Hz in their injector linacs from their sources to 2.86 GeV, the energy of the damping rings, and then further in the booster linac up to 9 GeV before injection into the main linac. The design specifies bunch charges of 1 nC in the injector linacs and 0.83 nC in the booster linac, with a 0.5 ns bunch spacing and trains of 352 bunches. The electron injector and booster linacs must accelerate two

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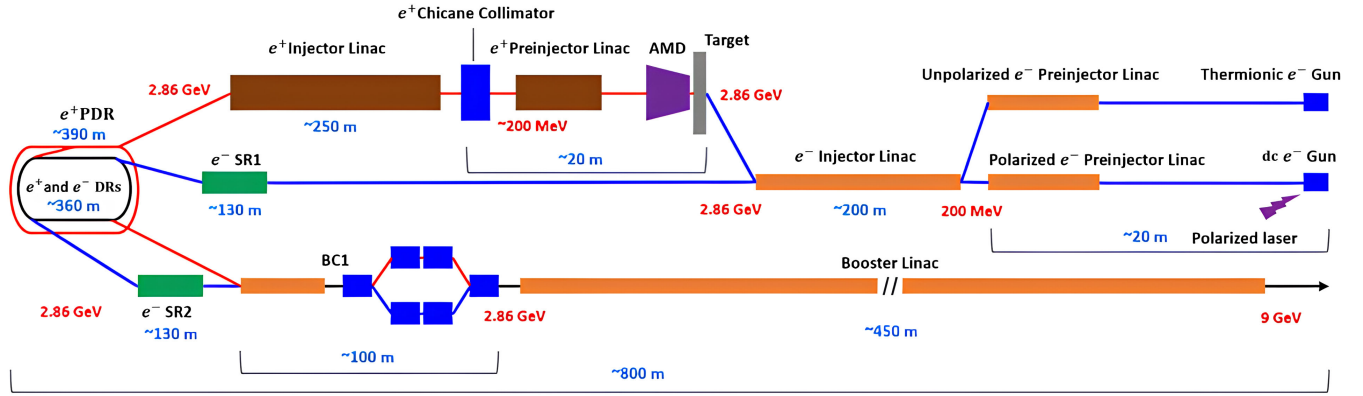


FIG. 1. Layout of the CLIC main beam injector (MBI) complex. The schematic shows the electron (blue) and positron (red) beam paths from their sources to the main linac. Key labeled components include the injector linacs, the adiabatic matching device (AMD), the predamping ring (PDR), the damping ring (DR), and the shared bunch compressor (BC1) and booster linac.

bunch trains per cycle: main beam electrons and positron-production electrons in the electron injector linac, and positrons together with electrons in the booster linac. The positron injector linac accelerates only one positron bunch train per cycle. These parameters impose stringent requirements on the accelerating structures, necessitating high rf-to-beam efficiency, mitigation of cumulative beam-loading, and effective wakefield suppression to preserve beam quality. A schematic view of the updated injector complex layout is shown in Fig. 1.

This work presents the rf design and optimization of 2 GHz TW accelerating structures for the CLIC injector and booster linacs. The study pursues three main objectives: (i) improving accelerating efficiency and reducing operational power under the demanding high-charge, closely spaced bunch train conditions; (ii) reducing the number of rf components and thereby reducing the construction cost of the linacs; and (iii) enhancing technological alignment with FCC-ee [4] by adopting common rf power sources with peak power of 80 MW and pulse length of 5 μ s, pulse compressors, and 3 m-long accelerating structure fabrication technology, with cavity geometries adapted from SwissFEL C-band [5] designs for operation at 2 GHz. The optimization prioritizes the loaded accelerating voltage as the principal figure of merit, combining parametric simulations, analytical modeling, and rf system studies with realistic beam-loading and power-source characteristics.

The resulting structure configurations provide a high-efficiency, beam-loading-compensated solution tailored for the CLIC 380 GeV injector complex, while contributing to a unified rf technology platform for future CERN accelerator facilities.

II. RF DESIGN METHODOLOGY AND ACCELERATING STRUCTURE OPTIMIZATION

The accelerating structures for the CLIC MBI linacs were developed following a systematic design methodology aimed at maximizing rf-to-beam efficiency, mitigating

beam-loading effects, and ensuring compatibility with wakefield suppression requirements under high-current, closely spaced bunch train conditions.

A key design choice was to adopt TW accelerating structures with a length of 3 m for both the injector and booster linacs. This decision aligns with the baseline configuration proposed for the FCC-ee injector linacs [6], enabling the development of a common rf technology platform across CERN's future accelerator projects.

The initial stage of the design process involved establishing a convex cell geometry as the basis for the accelerating structures, as illustrated in Fig. 2. Each cell was defined by

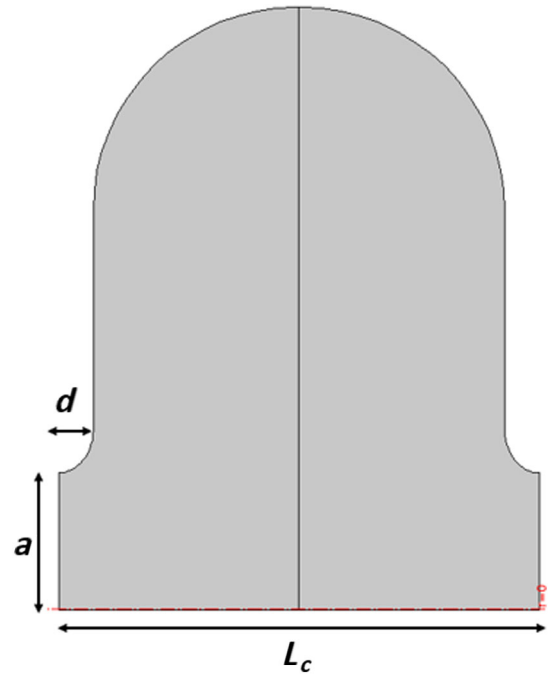


FIG. 2. Basic geometry of a convex TW accelerating cell, showing the primary geometric parameters: aperture radius a , iris thickness d , and cell length L_c .

three primary parameters: the aperture radius a , the iris thickness d , and the rf synchronous phase advance per cell ψ . The corresponding cell length was determined by $L_c = \lambda\psi/(2\pi)$, where λ is the rf wavelength associated with the operating frequency $f = c/\lambda$.

To systematically evaluate the influence of these parameters on rf performance, an rf parameter database was compiled by evaluating over 200 distinct reference geometries. For each configuration, a three-dimensional electromagnetic model of an individual accelerating cell was created using CST Studio Suite [7]. The fundamental mode characteristics were initially evaluated at 5.712 GHz through eigenmode simulations of individual accelerating cells using periodic boundary conditions set to the desired phase advance.

For each simulated geometry, key rf properties were extracted, including the normalized shunt impedance per unit length, ρ (often called R/Q , where R is the shunt impedance per unit length), the unloaded quality factor, Q , the group velocity, v_g , and surface field quantities [8], namely the maximum surface electric field, $E_{s,\max}$, and the maximum Poynting vector, $S_{c,\max}$. In parallel, the 20 lowest dipole higher-order modes (HOMs) were computed for each configuration to support subsequent wakefield analysis.

This reference dataset was subsequently interpolated and scaled to the 2 GHz operating frequency using standard rf scaling relations, providing a flexible parametric model to guide the optimization of the accelerating structures for the specific requirements of the CLIC MBI linacs.

Building upon this foundational dataset, the design and optimization process incorporated beam-loading effects, rf pulse compression modeling, and wakefield mitigation constraints tailored to the specific operational demands of the booster, electron, and positron injector linacs. Due to the significant beam-loading effects inherent in high-current linac operations, achieving a stable and flat accelerating voltage along the bunch train required careful optimization of both the input rf pulse shape and the accelerating structure parameters.

To this end, the temporal profile of the input rf pulse was optimized for each structure by adjusting the coupling coefficient β of the SLED-type pulse compressor. The goal was to produce a high-gain, flat-top compressed rf pulse capable of compensating for beam-induced voltage droop and maintaining stable accelerating conditions throughout the pulse duration. The required pulse duration t_p was defined as the sum of the bunch train duration $t_{\text{bunch train}}$ (176 ns for CLIC) and the structure filling time T_{fill} , which varies depending on the accelerating structure geometry. Figure 3 illustrates the temporal evolution of the klystron amplitude (magenta), which is proportional to the square root of the rf drive power. This amplitude drives the system and is adjusted to produce the desired input profile for the structure, resulting in the compressed rf pulse shown (green).

A systematic scan was then performed as a function of the compressed rf pulse length t_p . Figure 4 shows the

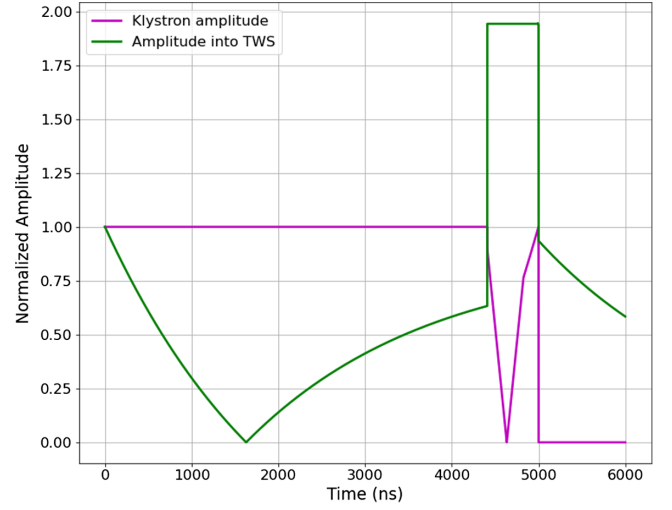


FIG. 3. Example of the temporal evolution of the klystron amplitude and compressed rf pulse from the SLED pulse compressor.

results of the scans: the amplitude gain A_{gain} (blue trace) and the optimal coupling coefficient β values (red trace) as a function of t_p . For each candidate design, the corresponding t_p values were obtained from the rf lookup table. At each scan point, the optimal pulse compressor settings were identified based on the data presented in Fig. 4, and the associated amplitude gain A_{gain} and coupling coefficient β were recorded.

The calculated A_{gain} values were used to compute the rf input power for each candidate structure:

$$P_{\text{in}} = P_k \cdot A_{\text{gain}}^2, \quad (1)$$

where P_k is the peak klystron power. This input power, together with the reference rf parameters from the lookup table $[\rho(z), v_g(z), Q(z)]$, was then used to calculate the steady-state unloaded and loaded accelerating voltages

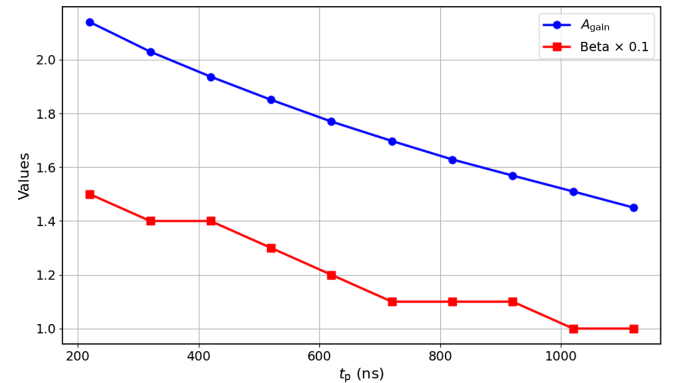


FIG. 4. Dependence of the pulse compressor amplitude gain A_{gain} (blue) and optimal coupling coefficient β (red) on the compressed rf pulse length t_p .

along each structure following the analytical formalism for traveling-wave structures from [9].

The entrance gradient is given by

$$G_0 = \sqrt{\frac{\omega \rho(0) P_{\text{in}}}{v_g(0)}}, \quad (2)$$

and the unloaded gradient profile along the structure is

$$G_{\text{unl}}(z) = G_0 g(z), \quad (3)$$

where:

$$g(z) = \sqrt{\frac{v_g(0)\rho(z)}{v_g(z)\rho(0)}} \exp \left[-\frac{\omega}{2} \int_0^z \frac{dz'}{v_g(z') Q(z')} \right]. \quad (4)$$

The corresponding unloaded accelerating voltage is

$$V_{\text{unl}} = \int_0^L G_{\text{unl}}(z) dz, \quad (5)$$

while the beam-loaded gradient and beam-loaded voltage are

$$G_L(z) = G_{\text{unl}}(z) - g(z) \int_0^z \frac{\omega \rho(z')}{2v_g(z')} g(z') I_b dz', \quad (6)$$

$$V_L = \int_0^L G_L(z) dz, \quad (7)$$

where I_b is the beam current.

For a given average aperture $\langle a \rangle$ defined by beam dynamics constraints, a comprehensive 2D scan over the entrance and exit iris radii ($d_{\text{first cell}}, d_{\text{last cell}}$) was performed. The steady-state loaded voltage formalism was used to evaluate the performance of each candidate design under the actual beam current, directly connecting the results of the A_{gain} vs t_p scan to beam-loaded accelerating voltage. As an example, the outcome of this scan for a structure with an average aperture of 18 mm is shown in Fig. 5.

In parallel, it was essential to address the effect of long-range transverse wakefields, which can degrade beam quality by inducing transverse kicks from preceding to following bunches, potentially leading to emittance growth. This is particularly critical for the booster and electron injector linacs, where beam dynamics constraints require relatively small average apertures.

To mitigate these effects, a detuning strategy was adopted, involving a controlled tapering of the aperture radius a and iris thickness d along the accelerating structure. This introduces a spread in the dipole mode frequencies, thereby suppressing the build-up of coherent transverse wakefields without requiring external damping

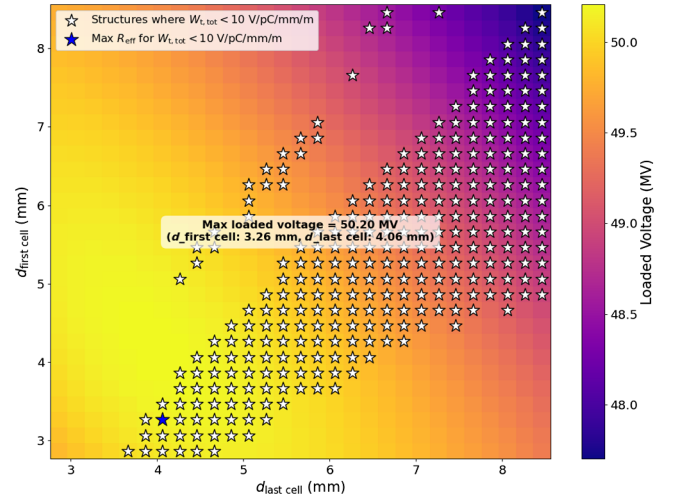


FIG. 5. Beam-loaded accelerating voltage obtained from the two-dimensional iris scan for a structure with an average aperture of 18 mm. White stars indicate configurations satisfying the long-range transverse wakefield requirement $W_{t,\text{tot}} < 10$ V/pC/mm/m, while the blue star marks the configuration providing the highest beam-loaded voltage among the compliant designs.

elements. The tapering is quantified using the taper parameter Δ , which systematically modifies the first and last cell apertures relative to the average aperture: $a_{\text{first}} = \langle a \rangle + \Delta$ and $a_{\text{last}} = \langle a \rangle - \Delta$, with intermediate apertures interpolated linearly. Controlled variation of cell geometries to achieve dipole mode detuning and wakefield suppression has been studied in early accelerator structure research [10].

The long-range transverse wake function, generated by the dipole HOMs, was computed in the time domain from the frequency-domain rf parameters obtained from the eigenmode simulations. For a structure supporting multiple uncoupled dipole modes, the total wake function is expressed as:

$$W_t(s) = 2 \sum_n k_n \exp \left(-\frac{\omega_n s}{2Q_n c} \right) \sin \left(\frac{\omega_n s}{c} \right), \quad (8)$$

where $s = z - ct > 0$ is the longitudinal distance behind the driving bunch, ω_n is the angular frequency, and Q_n is the quality factor of the n th dipole mode. The kick factor k_n , which quantifies the strength of the transverse wakefield contribution of the n th dipole mode, is expressed as

$$k_n = \rho_n \frac{\omega_n^2}{4c}, \quad (9)$$

where ρ_n is the normalized transverse shunt impedance of the mode.

The summation in Eq. (8) accounts for the cumulative contribution of the dominant dipole modes, while the precomputed rf mode parameters from the lookup table

enable fast evaluation of the transverse wake potential across different structure designs. Throughout the optimization, the long-range transverse wakefield is required to satisfy an integrated threshold of $W_{t,\text{tot}} < 10 \text{ V/pC/mm/m}$ over the full 352-bunch train, as imposed by beam dynamics stability considerations. As an example, Fig. 5 highlights with white stars the structures that satisfy this wakefield constraint, while the configuration providing the highest beam-loaded accelerating voltage among the compliant designs is indicated by a blue star.

Together, the steady-state voltage scans, parametric iris optimization, and wakefield mitigation strategy provide a consistent framework for the rf and beam dynamics optimization of all accelerating structures within the CLIC MBI complex. The selected baseline designs, which satisfy both the accelerating efficiency and beam-stability requirements, are then further refined for each linac by applying a transient beam-loading compensation ramp. This final step, discussed in the linac-specific sections that follow, shapes the input rf pulse to achieve a flat accelerating voltage throughout the beam pulse, thereby maximizing performance under actual high-current operating conditions.

III. BOOSTER LINAC AND ELECTRON INJECTOR LINAC

Following the general rf design methodology outlined in the previous section, the accelerating structures for the booster linac and the electron injector linac were optimized to meet their specific operational constraints. While these linacs share the same design of the accelerating structure, they differ in beam charge and performance requirements. This section details the parametric studies, structure selection process, and further optimizations carried out to define the final injector linac structures, addressing stringent beam dynamics requirements driven by the high-brightness main beam and the need for precise emittance preservation within the CLIC injector complex.

Two key beam dynamics constraints shape the design of these structures: (i) The minimum aperture radius must be at least 12 mm to mitigate short-range wakefield effects and meet beam optics and alignment tolerances. (ii) The long-range transverse wakefield must satisfy

$$W_{t,\text{tot}} \equiv \sum_{i=1}^{N_{\text{bunch}}} |W_t(s_i)| < 10 \text{ V/pC/mm/m}, \quad (10)$$

where the summation covers 352 bunches spaced by 0.5 ns.

A parametric scan of the design space was performed to meet these requirements. Configurations were evaluated for average aperture radii starting from the lower bound of 12 mm, increasing in 1 mm increments. For each radius, the taper parameter Δ was varied from zero to its maximum permissible value, as dictated by the minimum physical aperture constraint. The integrated transverse wakefield for each design was then computed and assessed against the long-range tolerance defined in Eq. (10).

This analysis revealed that the wakefield constraint could be satisfied for average radii of 16 mm and greater, provided an appropriate taper Δ was applied. The compliant configurations, specifically within the 16 to 19 mm range, are summarized in Table I along with their corresponding Δ values.

Within this viable parameter space, increasing the average aperture generally improves wakefield suppression, while excessive tapering leads to a reduction in accelerating voltage due to the lower shunt impedance. Among the compliant configurations, the structure with an average aperture of 18 mm and a taper parameter of $\Delta = 3 \text{ mm}$ provides the highest beam-loaded accelerating voltage while maintaining adequate wakefield suppression. This balance between accelerating efficiency and beam stability motivated its selection as the baseline structure. Consequently, the detailed rf and beam-loading parameters of this baseline structure ($\langle a \rangle = 18 \text{ mm}$, $\Delta = 3 \text{ mm}$) for the booster and electron injector linacs are provided in Table II.

The effectiveness of the structure in suppressing long-range transverse wakefields is shown in Fig. 6, which displays the transverse wake potential along the structure as a function of time. The blue curve represents the overall transverse wake potential, while the red dots mark the wakefield amplitudes sampled at the positions of the trailing bunches within the 352-bunch train spaced by 0.5 ns. The total integrated wakefield remains below the beam dynamics constraint of 10 V/pC/m/mm, confirming that the applied detuning strategy effectively controls

TABLE I. Beam-loaded voltage V_L and integrated transverse wake $W_{t,\text{tot}}$ for different average apertures $\langle a \rangle$ and taper parameters Δ .

$\langle a \rangle$ (mm)	$\Delta = 3 \text{ mm}$		$\Delta = 4 \text{ mm}$		$\Delta = 5 \text{ mm}$	
	V_L (MV)	$W_{t,\text{tot}}$ (V/pC/mm/m)	V_L (MV)	$W_{t,\text{tot}}$ (V/pC/mm/m)	V_L (MV)	$W_{t,\text{tot}}$ (V/pC/mm/m)
16	48.31	8.65	...	...	...	...
17	50.15	8.55	49.37	8.61	...	...
18	50.20	9.16	50.17	8.96	47.41	9.22
19	49.39	7.31	49.44	8.54	49.45	9.37

TABLE II. Accelerating structure parameters and beam-loaded performance of the common baseline structure ($\langle a \rangle = 18$ mm, $\Delta = 3$ mm) for the booster and electron injector linacs.

Parameter	Value	Unit
Frequency	2	GHz
Structure length	3	m
Average aperture	18	mm
Cell aperture (first/last)	21/15	mm
Iris thickness (first/last)	3.26/4.06	mm
v_g/c (first/last)	4.21/1.39	%
ρ (first/last)	2.58/3.22	k Ω /m
Q (first/last)	19,799/19,519	...
Filling time	416	ns
SLED coupling	14	...
$W_{t,tot}$	9.15	V/pC/mm/m
Klystron power per structure	31	MW

Parameter	Booster linac	e^- injector linac	Unit
Nominal bunch charge	0.83	1.00	nC
V_L	50.20	46.69	MV
Average G_L	16.73	15.56	MV/m
$E_{s,max}$	96	99	MV/m
$S_{c,max}$	951	976	mW/ μm^2

wakefield growth and ensures transverse beam stability throughout the linac.

Beam loading, which causes a downstream-increasing attenuation of the accelerating field, is examined for the common baseline structure ($\langle a \rangle = 18$ mm, $\Delta = 3$ mm) used in both linacs. Figure 7 presents the on-axis gradient distribution under two conditions: the unloaded profile (orange trace) and the loaded (blue trace) profile for the booster linac. The loaded calculation assumes the booster's nominal operating parameters: a bunch charge of 0.83 nC, 352 bunches, and 0.5 ns spacing. The substantial field tilt

visible in the loaded case demonstrates the clear need for beam-loading compensation to achieve a uniform accelerating gradient and maintain beam quality. When operating with the higher injector charge of 1 nC for the electron linac, this same structure would experience an even more pronounced loading effect.

To counteract the beam-induced field droop and achieve a flat accelerating voltage throughout the beam pulse, a transient beam-loading compensation ramp is applied to the input rf pulse. The compensation profile is computed

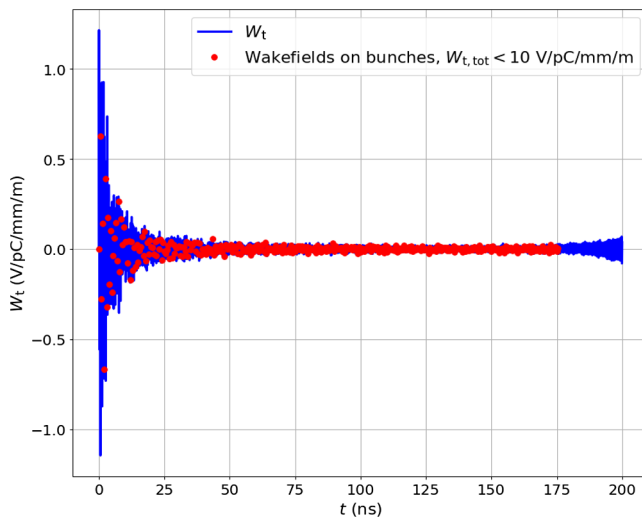


FIG. 6. Transverse wake potential for the 18 mm average aperture structure. Red dots mark bunch positions; integrated wakefield remains below the threshold of 10 V/pC/mm/m.

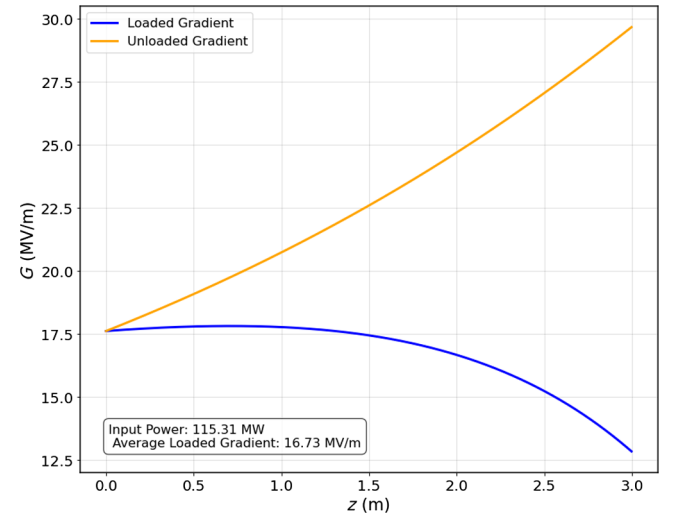


FIG. 7. On-axis accelerating gradients for the selected booster linac structure ($\langle a \rangle = 18$ mm, $\Delta = 3$ mm); unloaded (orange) and loaded (blue) fields. The loaded profile corresponds to nominal operation with 0.83 nC bunch charge without compensation.

using the analytical transient beam-loading formalism for traveling-wave structures described in [9]. In this approach, the time-dependent rf input power is shaped during the structure filling period so that, at the moment of beam injection, the axial gradient distribution matches the steady-state loaded solution, thereby precisely counterbalancing the transient induced by beam injection with the ongoing cavity excitation.

The required instantaneous input rf power $P_0(t)$ during the filling period is given by

$$P_0(t) = P_0(t_f) \left[1 - \sqrt{\frac{v_g(0)\rho(0)P_0(t_f)}{G_0^2}} \times \int_0^{z(t)} \frac{I_b \omega \rho(z')}{2 v_g(z')g(z')} dz' \right]^2, \quad (11)$$

where $P_0(t_f)$ is the steady-state input power after beam injection, G_0 is the entrance gradient, and $g(z)$ is the normalized gradient profile defined in Sec. II. The arrival time $t(z)$ of the rf wavefront at position z is

$$t(z) = \int_z^L \frac{1}{v_g(z')} dz'. \quad (12)$$

This procedure ensures that the loaded accelerating voltage remains flat throughout the beam pulse by precisely compensating the energy extracted by the beam with a shaped rf input.

A. Baseline single-train operation with beam-loading compensation

For the common baseline structure, the compensation profile from Eqs. (11) and (12) was computed for both the booster and the electron injector linacs. This profile shapes the input rf power to maintain a uniform axial field throughout the beam pulse, following established rf pulse shaping techniques for beam-loading compensation in high-gradient linac test facilities [11].

Figure 8 illustrates the compensation scheme for the booster linac. The initially flat input rf pulse (green) is modified into a tailored profile (red) after SLED compression. Additionally, the corresponding klystron amplitude (magenta) is shown, which drives the system and adapts accordingly to achieve the desired input profile. The resulting waveform ensures a constant loaded accelerating voltage throughout the beam pulse, effectively mitigating the beam-induced field droop and improving energy uniformity along the bunch train.

The application of the compensated rf input pulse significantly improved the accelerating gradients in both linacs. For the booster, the average loaded gradient increased by 10.4%, from 16.73 to 18.47 MV/m. The electron injector saw a similar 13.6% gain, from 15.56 to 17.67 MV/m. Figure 9 illustrates this for the booster, plotting the unloaded (green) and compensated beam-loaded (blue) gradients over

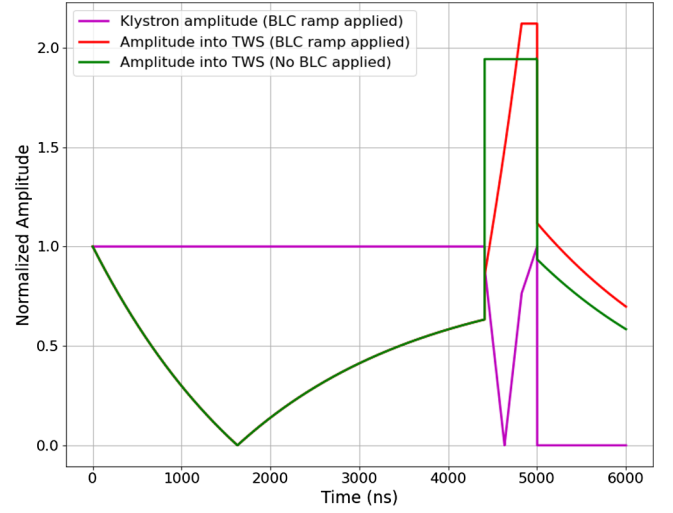


FIG. 8. rf input pulse profiles for the booster linac after SLED compression: without beam-loading compensation ramp (green), with beam-loading compensation ramp (red), and corresponding klystron drive amplitude (magenta).

time. These improvements demonstrate the scheme's effectiveness in mitigating field droop and boosting acceleration efficiency.

Based on these findings, the performance of the selected accelerating structure was re-evaluated for both booster and electron injector linacs. The updated parameters, reflecting the enhanced energy gain and gradient uniformity achieved through the beam-loading compensation ramp, are summarized in Table III.

B. Double-train compressed rf pulse scheme

Following the demonstration of the beam-loading compensation ramp's effectiveness, we now explore an

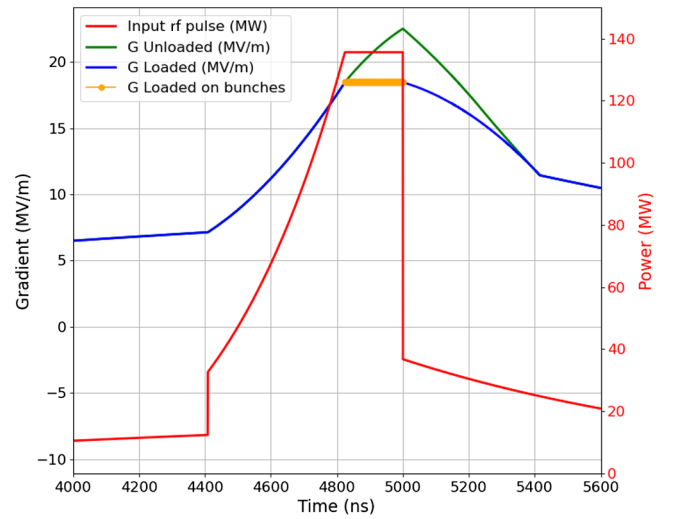


FIG. 9. Calculated accelerating gradients for the booster linac: unloaded (green) and beam-loaded (blue) profiles with beam-loading compensation ramp applied.

TABLE III. Updated performance parameters for the selected 18 mm average aperture structure with $\Delta = 3$ mm after applying the beam-loading compensation ramp.

Parameter	Booster linac	Electron injector linac	Unit
Nominal bunch charge	0.83	1.00	nC
V_L	55.4	53	MV
Average G_L	18.47	17.67	MV/m
$E_{s,\max}$	81	82	MV/m
$S_{c,\max}$	494	509	mW/ μm^2

operational scheme to further optimize linac power efficiency: a double-train compressed rf pulse scheme.

In this study, two rf pulse schemes are examined for the operation of the electron injector and booster linacs. The traditional double rf pulse scheme employs two separate pulses spaced by 5 μs . In this configuration, the electron injector linac accelerates main-beam electrons with the first pulse and positron-generation electrons with the second, while the booster linac accelerates positrons and electrons in separate rf pulses.

However, this traditional double rf pulse scheme effectively doubles the repetition rate of the injector linacs from 100 to 200 Hz, since each beam species requires its own rf pulse. The higher effective repetition rate results in increased average rf power consumption, greater thermal loads on accelerating structures and rf components, and more demanding requirements for the rf power sources.

To overcome these issues, we propose the double-train compressed rf pulse scheme, where two bunch trains are accelerated within a single rf pulse, separated by a short timing offset of about 660 ns due to differences in the path length for electrons and positrons in the booster linac to main linac transfer lines. This timing allows sequential acceleration without overlap within the same rf pulse envelope. Furthermore, this configuration aligns with the nominal repetition rate of 100 Hz in the FCC-ee injector linacs, enabling synergy and cost savings across the future CERN projects. However, accommodating both bunch trains results in a lower peak accelerating gradient, which is a trade-off to consider in the design.

Following the conceptual description of the double-train compressed rf pulse scheme, its practical implementation for the booster linac is illustrated in Fig. 10. This figure shows the rf input pulse profile after SLED compression (red) along with the corresponding klystron amplitude (magenta).

The resulting unloaded and beam-loaded accelerating gradient profiles calculated for the double-train compressed rf pulse input are presented in Fig. 11. As expected, the longer compressed pulse length leads to a reduction in peak accelerating gradient due to the lower rf power gain. The average loaded accelerating gradient achieved for the

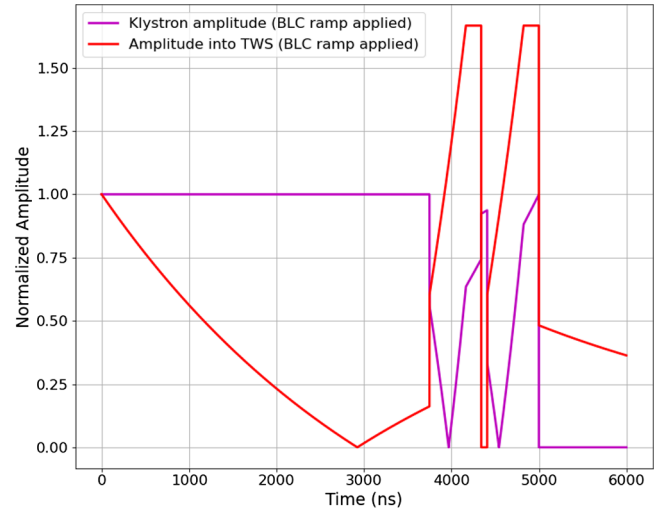


FIG. 10. Double train rf input pulse profile for the booster linac after SLED compression, showing two rf pulses spaced by 5 μs .

booster linac was 13.52 MV/m, and 12.73 MV/m for the electron injector linac. These values represent a decrease of 27% and 28%, respectively, when compared to the corresponding gradients of 18.47 and 17.67 MV/m obtained in the beam-loading compensated case previously shown in Table III.

Despite the longer pulse duration, the bunch-to-bunch energy spread remained well controlled at approximately 0.1% for both linacs, ensuring stable beam quality throughout the acceleration process. These results highlight the inherent trade-off between pulse length and acceleration gradient in the double-train compressed rf pulse scheme while demonstrating its operational viability within beam dynamics constraints. The key rf and beam-loading parameters for this configuration are summarized in Table IV.

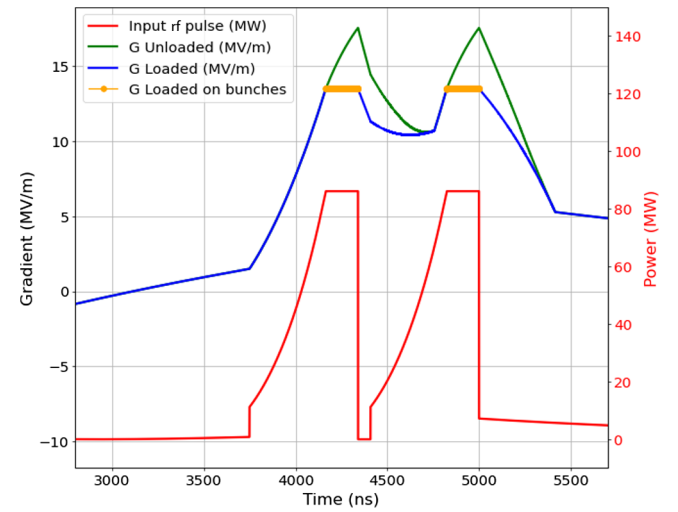


FIG. 11. Unloaded (green) and beam-loaded (blue) accelerating gradients calculated for the booster linac using the double-train compressed rf pulse.

TABLE IV. Key accelerating structure parameters for the booster and electron injector linacs operated with the double-train compressed rf pulse scheme.

Parameter	Booster linac	Electron injector linac	Unit
Nominal bunch charge	0.83	1.00	nC
V_L	40.55	38.18	MV
Average G_L	13.52	12.73	MV/m
$E_{s,\max}$	64	66	MV/m
$S_{c,\max}$	314	326	mW/ μm^2

Finally, the transverse wakefield profiles under the double train pulse configuration are shown in Fig. 12. The plot displays the transverse wake potential with the shaded red areas indicating the positions of the two bunch trains. The integrated transverse wake potentials over the duration of the first and second bunch trains are 9.15 and 7 V/pC/mm/m, respectively. These values remain within the allowable beam dynamics limits, demonstrating effective wakefield control throughout both pulse intervals and ensuring stable beam transport despite the increased pulse length.

In summary, the double-train compressed rf pulse scheme successfully enables the simultaneous acceleration of electron and positron bunch trains within a single rf pulse, maintaining stable beam quality and effective wakefield suppression despite the extended pulse duration. While the scheme entails a reduction in peak accelerating gradient compared to the beam-loading compensated single-pulse case, it offers significant benefits in reducing effective repetition rate and average rf power demands, supporting its adoption for the booster and electron injector linacs.

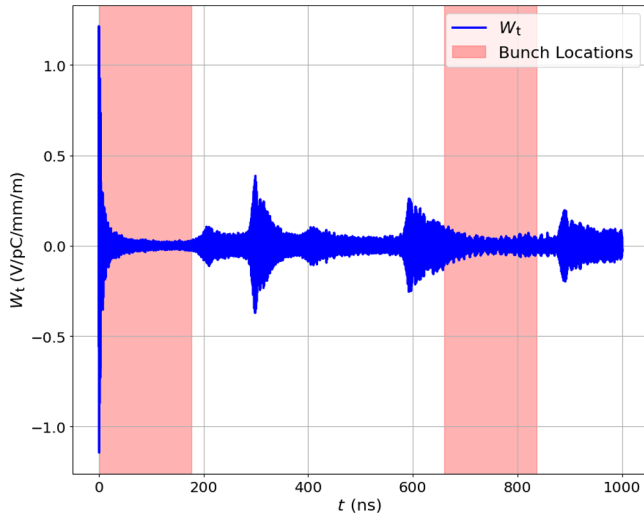


FIG. 12. Transverse wake potential for the double compressed pulse scheme (blue). Red shaded areas indicate the two bunch trains.

IV. POSITRON INJECTOR LINAC

Following the rf design methodology established in the preceding sections, the accelerating structures for the positron injector linac were similarly optimized, while addressing the unique beam dynamics challenges associated with positron beam transport. Compared to the booster and electron injector linacs, the positron injector must accommodate a larger initial beam emittance, greater energy spread, and increased sensitivity to beam loss. Consequently, distinct constraints were applied to the accelerating structure design for this linac.

Two primary considerations guided the design optimization: (i) A minimum aperture radius of 20 mm to ensure sufficient acceptance for the positron beam from the capture section, reduce scraping losses, and accommodate alignment tolerances and energy spread. (ii) Minimization of the integrated long-range transverse wakefield to levels comparable with the booster and electron injector linacs, crucial for preserving transverse stability given the positron beam's larger initial emittance and energy spread.

To address these requirements, a comprehensive parametric scan was conducted. Structures with average aperture radii of 20, 21, and 22 mm were considered, with the taper parameter Δ varied from 0 to its maximum allowable value while maintaining the minimum aperture constraint (yielding $\Delta_{\max} = 0, 1, \text{ and } 2 \text{ mm}$, respectively). For each aperture and Δ combination, three phase advances (120° , 150° , and 162°) were evaluated to assess their influence on both loaded accelerating voltage (V_L) and integrated transverse wakefield ($W_{t,\text{tot}}$).

The complete results are presented in Table V. Analysis reveals that 120° phase advance consistently yields the highest loaded voltages, while tapering dramatically reduces wakefields by up to 91.6% for the 22 mm aperture with only modest voltage penalties (typically less than a 6% reduction compared to the maximum achievable voltage). This clear trade-off between accelerating gradient and wakefield suppression defines the optimization landscape for the positron injector structure.

Based on this trade-off analysis, the 22 mm aperture with $\Delta = 2 \text{ mm}$ at 120° phase advance was selected as the baseline structure for the positron injector. This configuration maintains 95.1% of the maximum achievable voltage while reducing the wakefield to levels comparable with the booster and electron injector linacs, prioritizing transverse beam stability while maintaining competitive accelerating performance.

The parameters for this selected configuration are summarized in Table VI.

The long-range transverse wake potential for this selected baseline structure (22 mm, $\Delta = 2 \text{ mm}$) is shown in Fig. 13, together with the maximum-taper configurations for smaller apertures. The progressive suppression of wakefields with increasing aperture and tapering confirms

TABLE V. Complete parametric scan results for positron injector linac structures showing loaded accelerating voltage (V_L) and integrated transverse wakefield ($W_{t,\text{tot}}$) across different aperture sizes, taper parameters (Δ), and phase advances. Voltage reduction is calculated relative to the maximum voltage configuration (44.98 MV, 20 mm, $\Delta = 0$, 120°). Wakefield reduction is calculated relative to the zero-taper configuration at the same aperture and phase advance.

$\langle a \rangle$ (mm)	Δ (mm)	Phase ($^\circ$)	V_L (MV)	$W_{t,\text{tot}}$ (V/pC/mm/m)	Voltage reduction (%)	Wakefield reduction (%)
20	0	120	44.98	66.92	...	...
		150	43.23	92.80	3.9	...
		162	38.49	72.74	14.4	...
21	0	120	43.95	67.93	2.3	...
		150	42.89	81.08	4.6	...
		162	39.93	64.61	11.2	...
	1	120	44.02	17.17	2.1	74.7
		150	42.89	12.47	4.6	84.6
		162	39.96	10.04	11.2	84.5
22	0	120	42.60	121.58	5.3	...
		150	42.34	50.78	5.9	...
		162	40.46	62.51	10.0	...
	1	120	42.67	15.86	5.1	87.0
		150	42.31	11.03	5.9	78.3
		162	40.50	9.67	10.0	84.5
	2	120	42.79	10.23	4.9	91.6
		150	42.39	7.95	5.8	84.3
		162	40.50	6.22	10.0	90.0

the effectiveness of this combined strategy for transverse wakefield mitigation.

The beam-loading effect for the selected positron injector baseline structure ($\langle a \rangle = 22$ mm, $\Delta = 2$ mm) is shown in Fig. 14. The loaded profile (blue) corresponds to the nominal operating point of 1.00 nC per bunch without any

compensation. The downstream droop in accelerating gradient evident in this profile must be corrected to provide uniform energy gain along the bunch train.

To correct this gradient droop, we applied a beam-loading compensation scheme following the same approach

TABLE VI. Parameters for the selected 22 mm average aperture positron injector linac structure without beam-loading compensation applied.

Parameter	Value	Unit
Frequency	2	GHz
Structure length	3	m
Average aperture	22	mm
Cell aperture (first/last)	24/20	mm
Iris thickness (first/last)	8.46/8.46	mm
v_g/c (first/last)	4.44/2.50	%
ρ (first/last)	2.21/2.57	K Ω /m
Q (first/last)	18619/18490	...
Filling time	300	ns
SLED coupling	14	...
$W_{t,\text{tot}}$	10.13	V/pC/mm/m
Klystron power per structure	31	MW
Nominal bunch charge	1.00	nC
V_L	42.80	MV
Average G_L	14.26	MV/m
$E_{s,\text{max}}$	48	MV/m
$S_{c,\text{max}}$	322	mW/ μm^2

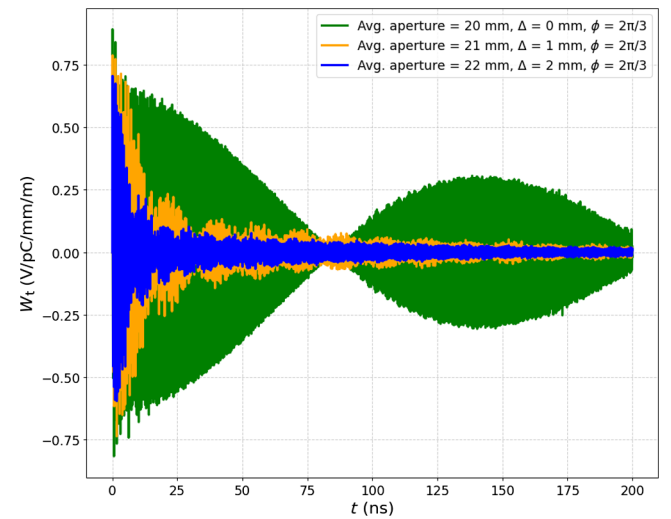


FIG. 13. Long-range transverse wake potentials for linac structures with different average apertures, each shown with its maximum allowable taper parameter: 20 mm ($\Delta = 0$ mm), 21 mm ($\Delta = 1$ mm), and 22 mm ($\Delta = 2$ mm). Increasing both aperture and tapering progressively reduces the transverse wake-field amplitude.

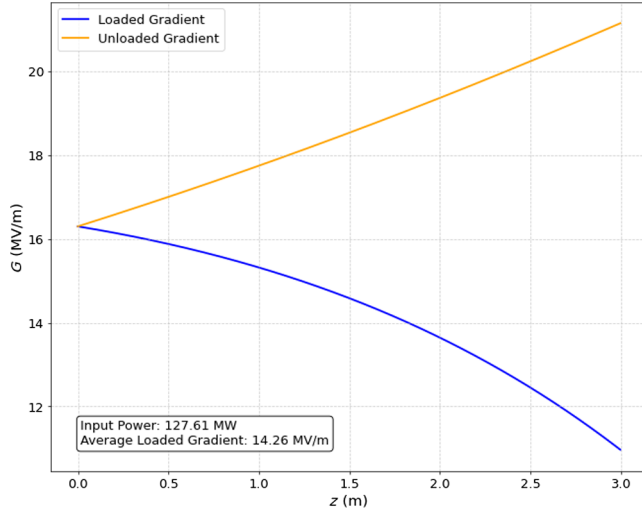


FIG. 14. On-axis accelerating gradients for the selected positron injector linac structure ($\langle a \rangle = 22$ mm, $\Delta = 2$ mm); unloaded (orange) and loaded (blue) fields. The loaded profile corresponds to nominal operation with 1.00 nC bunch charge without compensation.

used for the booster linac, reshaping the rf input pulse with a compensation ramp. As shown in Fig. 15, this compensation effectively flattens the accelerating gradient profile along the bunch train. The improvement yields an approximately 8.1% increase in loaded accelerating voltage and average gradient, from 42.80 to 46.24 MV and 14.26 to 15.41 MV/m, respectively. Concurrently, peak surface electric field and power density decrease by 4.2% and 25% (Table VII), improving operational margins. Most importantly, the final optimized structure achieves a bunch-to-bunch energy spread of only 0.01%, ensuring stable beam transport through the linac.

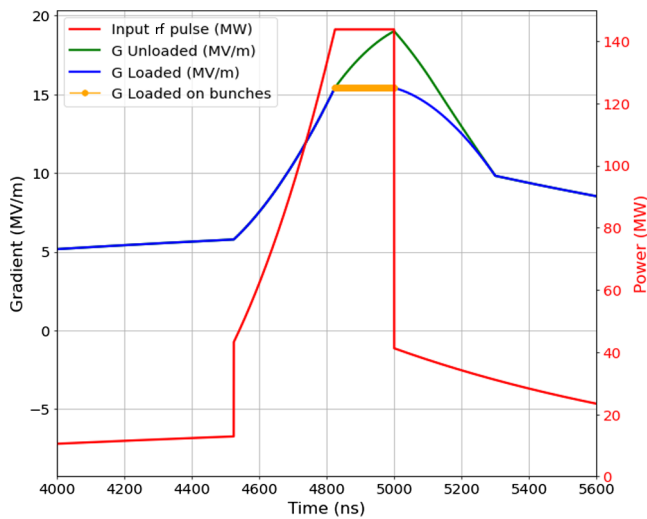


FIG. 15. Calculated accelerating gradients for the positron injector linac: unloaded (green) and beam-loaded (blue) profiles with beam-loading compensation ramp applied.

TABLE VII. Parameters for the selected 22 mm average aperture positron injector linac structure with beam-loading compensation ramp applied.

Parameter	Value	Unit
Nominal bunch charge	1.00	nC
V_L	46.24	MV
Average G_L	15.41	MV/m
$E_{s,max}$	46	MV/m
$S_{c,max}$	240	mW/ μm^2

V. COMPARISON WITH THE CDR DESIGN

The rf structure optimizations detailed in Secs. III–IV, specifically the tapering of iris apertures to suppress long-range transverse wakefields and the shaping of cell geometries to maximize shunt impedance, directly enhance the loaded accelerating gradient and improve transverse beam stability. These improvements in rf performance enable the use of longer structures and higher-power klystrons, which in turn reduce the total number of accelerating structures and rf power sources required for a given energy gain. Consequently, both the peak and average rf power demands of the injector complex are substantially lowered. To quantify these system-level benefits, we compare the updated CLIC injector and booster linac layout with the original 2012 CDR baseline [1], focusing on key metrics such as the number of klystrons and accelerating structures, peak rf power, and average rf power.

The 2012 layout employed 1.5 m-long traveling-wave structures powered by 50 MW klystrons operating at 50 Hz. In the new design, the higher shunt impedance and improved beam-loading tolerance of the optimized 3 m structures allow the use of more powerful 80 MW klystrons at 100 Hz, with two structures powered by each klystron throughout the complex. This consistent powering scheme simplifies the layout and improves overall efficiency.

The hardware counts and power values are derived directly from the energy gain ΔE required for each linac and the loaded gradient G_L achieved by the optimized structures. The number of accelerating structures is obtained from

$$N_s = \frac{\Delta E}{G_L \cdot L_{\text{struct}}}, \quad (13)$$

and the number of klystrons follows from the chosen powering scheme (here, two structures per klystron). Peak rf power per klystron is P_{klystron} , so the total peak power is

$$P_{\text{peak}} = N_k \cdot P_{\text{klystron}}. \quad (14)$$

Average rf power accounts for the repetition rate f_{rep} and pulse length τ_{pulse} :

TABLE VIII. Comparison of the old (CDR, 2012) and new layouts for the linacs. Values are given as energy gain (ΔE), number of klystrons (N_k), number of rf structures (N_s), peak rf power (P_{peak}), and average rf power (P_{avg}). The e^+ injector linac is common to both single- and double-bunch-train configurations.

Linac	ΔE (MeV)	2012 layout				New layout (single-bunch train)				New layout (double-bunch-trains)			
		N_k	N_s	P_{peak} (GW)	P_{avg} (MW)	N_k	N_s	P_{peak} (GW)	P_{avg} (MW)	N_k	N_s	P_{peak} (GW)	P_{avg} (MW)
Common injector	2660	119	119	5.95	2.38	...	...	...	...	...	...	...	...
e^+ drive	5000	112	224	5.60	2.24	...	...	...	...	...	...	...	...
Booster	6140	128	256	6.40	2.56	59	118	4.72	4.72	79	158	6.32	3.16
e^- injector	2660	...	...	...	...	27	54	2.16	2.16	37	74	2.96	1.48
e^+ injector	2660	...	...	...	...	31	62	2.48	1.24	31	62	2.48	1.24
Total	...	359	599	17.95	7.18	117	234	9.36	8.12	147	294	11.76	5.88

$$P_{\text{avg}} = P_{\text{peak}} \cdot f_{\text{rep}} \cdot \tau_{\text{pulse}}. \quad (15)$$

Substituting the corresponding klystron power, repetition rate, and pulse length (50 MW, 50 Hz, 8 μ s for 2012; 80 MW, 100 Hz, 5 μ s for the new design) into Eqs. (13)–(15) gives the hardware and power figures compiled in Table VIII.

From this comparison, the following percentage improvements are highlighted: (i) Reduction in total number of klystrons: The updated layout reduces the klystron count by approximately 67% for the single-bunch-train configuration and 59% for the double-bunch-train configuration. (ii) Reduction in total number of rf structures: The total number of accelerating structures is reduced by about 61% (single train) and 51% (double train), owing to higher gradients, longer structures, and more efficient power coupling. (iii) Reduction in peak rf power: Peak rf power decreases by 48% for the single-bunch-train layout and by 34% for the double-bunch-train layout. (iv) Change in average rf power: Since the 2012 CDR baseline operated at a beam repetition rate of 50 Hz, while the updated design operates at 100 Hz, the average rf power of the CDR layout must be normalized to the equivalent 100 Hz operation for a fair comparison. Under this condition, the updated design achieves a reduction in average rf power of approximately 43% for the single-bunch-train configuration, while the double-bunch-train configuration provides an even larger reduction of about 59%, demonstrating the improved rf efficiency of the proposed dual-train operation scheme.

Overall, the updated injector complex achieves a more compact, cost-effective, and energy-efficient configuration while maintaining beam quality, representing a clear advance over the 2012 CDR baseline and providing a scalable rf platform compatible with future projects such as FCC-ee.

VI. CONCLUSION

This study presents a comprehensive rf design and optimization of 2 GHz traveling-wave accelerating

structures for the CLIC MBI complex, addressing the challenges posed by high-charge, closely spaced bunch trains. The work focused on maximizing rf-to-beam efficiency under strong beam-loading conditions while ensuring compatibility with wakefield suppression and beam dynamics constraints. Through parametric simulations, analytical modeling, and systematic geometry scans, high-performance solutions were developed for the booster, electron, and positron injector linacs, achieving significant improvements in operational stability.

For the booster linac (bunch charge 0.83 nC), the optimized 18 mm aperture structure with $\Delta = 3$ mm tapering achieved a beam-loading-compensated gradient of 18.47 MV/m, while suppressing integrated transverse wakefields below 10 V/pC/m/mm. The electron injector linac (bunch charge 1.00 nC) reached 17.67 MV/m, with the same wakefield constraint. The double-train compressed rf pulse scheme enabled simultaneous acceleration of electron and positron trains within a single rf pulse, reducing the effective repetition rate from 200 to 100 Hz. This reduction lowers the average rf power demand and thermal load, albeit at the cost of gradients reduced to 13.52 MV/m for the booster and 12.73 MV/m for the electron injector. This trade-off supports alignment with FCC-ee operational parameters while improving overall power efficiency.

The positron injector, operating at 1.00 nC bunch charge, achieves a final loaded gradient of 15.41 MV/m with its optimized 22 mm aperture structure featuring $\Delta = 2$ mm tapering. Transverse wakefields are maintained below the 10 V/pC/m/mm stability threshold. Applying the same beam-loading correction scheme as the booster linac improves energy gain by 8.1%, which is particularly important for preserving positron beam quality given its larger initial emittance and greater sensitivity to energy spread.

These rf performance gains translate directly into substantial hardware and power savings. Compared to the 2012 CDR design, the updated layout reduces the total number of klystrons by 59%–67% and the number of accelerating structures by 51%–61%, with peak rf power lowered by

34%–48%. Average rf power remains at a comparable level despite the doubled repetition rate, confirming the improved rf efficiency of the new design.

Beyond CLIC, this work contributes to a unified rf technology platform for future colliders, leveraging shared klystron systems, pulse compressors, and SwissFEL-derived fabrication techniques. The alignment with FCC-ee parameters reduces development costs and fosters synergies across CERN projects.

Overall, this research advances high-efficiency, beam-loading-resilient accelerating structures for CLIC's 380 GeV injector complex and demonstrates that careful system-level optimization can deliver significant hardware, energy, and cost savings, supporting both CLIC's technical readiness and the broader development of next-generation linear colliders.

DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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