

RF design and optimization of the high-energy linac for the FCC-ee injector complex

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The high-energy linac of the Future Circular Collider electron-positron (FCC-ee) injector complex requires high-performance rf accelerating structures to efficiently accelerate beams up to 20 GeV while ensuring operational stability. This study presents an analytical approach to the rf design of traveling-wave structures, incorporating a pulse compression system to enhance power efficiency and meet the demanding FCC-ee specifications. By utilizing lookup tables and analytical models, we systematically explored a broad parameter space to determine the fundamental mode at 2.8 GHz and analyze higher-order mode (HOM) characteristics. The structure's geometry, particularly the iris parameters, was optimized to maximize effective shunt impedance, minimize peak surface fields, and implement HOM detuning for wakefield suppression. Furthermore, a comparative analysis against existing high-gradient S-band linacs was performed, demonstrating the competitive performance and advantages of the proposed design in terms of gradient, efficiency, and wakefield control. Additionally, we investigated the bunch-to-bunch energy spread minimization including the impact of transient beam loading, with a focus on top-up operation, where bunch charges vary dynamically among four bunches. To accommodate these variations, we introduce the concept of the “golden” rf pulse, an optimized input rf waveform that averages the solutions for fully loaded and unloaded conditions. While this method does not eliminate energy deviations entirely, it provides a practical compromise, reducing energy spread across all possible charge distributions. Finally, comprehensive thermal and mechanical simulations were performed to evaluate the structural integrity and operational performance of the HE-linac under 100 Hz repetition frequency, ensuring long-term reliability.

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I. INTRODUCTION

The Future Circular Collider (FCC-ee) is a proposed high-luminosity electron-positron collider designed to enable precision studies of the electroweak sector. As part of the FCC feasibility study, a dedicated injector complex is being developed to deliver high-quality electron and positron beams for both continuous top-up and initial collider filling. The proposed baseline layout of this injector complex [1] includes multiple acceleration stages: an electron linac, a positron linac, a damping ring, a bunch compressor, a high-energy (HE) linac, and transfer lines to the booster synchrotron. Figure 1 shows the current baseline design.

A crucial element of this system is the HE-linac, which accelerates electron and positron beams from 2.86 to 20 GeV

prior to injection into the booster. The HE-linac must meet demanding beam quality requirements to support high-luminosity collider operation, particularly during continuous top-up injection at the Z pole. The design specifies four bunches per rf pulse at a 100 Hz repetition rate, with a bunch charge of 5 nC, 25 ns bunch spacing, and an rms bunch length of 1 mm. The system must tightly control bunch-to-bunch energy spread, wakefield-induced emittance growth, and thermal load at 100 Hz repetition rate.

The choice of accelerating structure technology was driven by both technical performance criteria and practical fabrication considerations. Specifically, the fabrication of the rf structures is planned to utilize the well-established SwissFEL technology [2] developed at PSI, which is optimized for 3 m long accelerating structures. This directly determined the nominal structure length for the FCC-ee injector linacs, ensuring compatibility with proven manufacturing processes and cost-effective large-scale production, given the requirement for several hundred identical structures.

Given this 3 m structure length, traveling-wave (TW) accelerating structures operating at 2.8 GHz were selected

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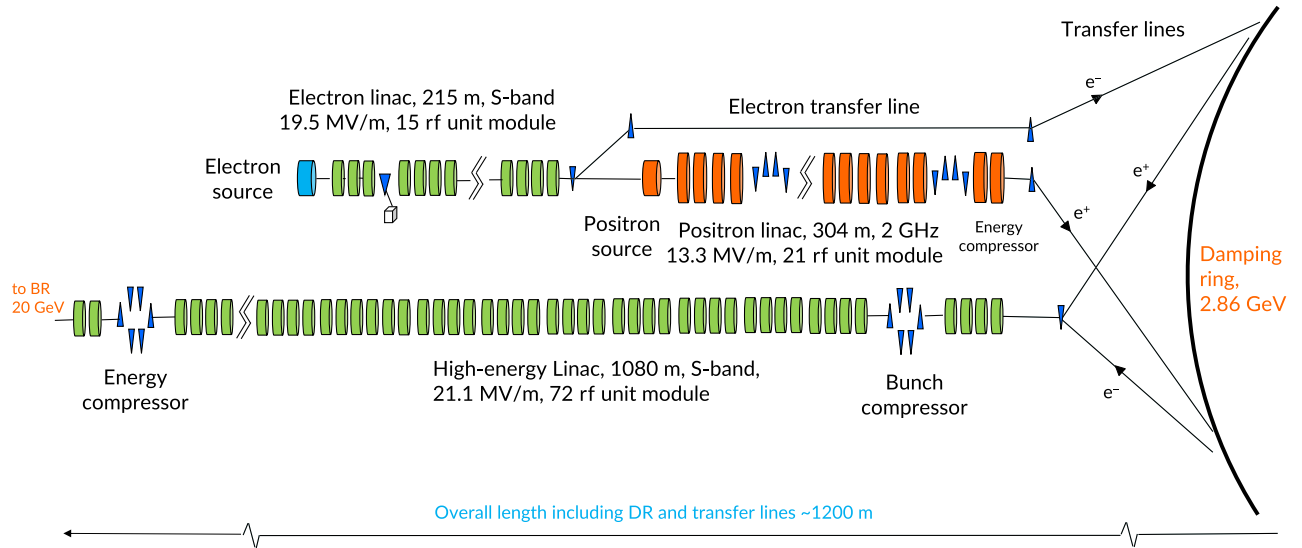


FIG. 1. Latest baseline layout of the preinjector complex, including the high-energy (HE) linac.

over standing-wave designs. TW structures offer significant advantages in rf efficiency, power handling, and accelerating gradient uniformity over longer structures, due to their lower group velocities and more efficient rf power distribution along the structure. Additionally, TW structures inherently simplify rf distribution and minimize reflected power issues in high-repetition-rate operation, making them particularly suitable for the HE-linac's demanding operational regime.

The HE-linac structures, like those of the other injector linacs, employ tapered geometries to balance gradient performance with wakefield suppression. However, the beam dynamics constraints in the HE-linac are notably more stringent due to the higher final energy of 20 GeV and tight emittance preservation requirements. Specifically, the average aperture radius was constrained to remain no smaller than 0.12λ to limit wakefield effects while maintaining high shunt impedance. Additionally, the long-range transverse wakefield amplitudes were required to stay below 0.1 V/pC/mm/m to ensure beam stability in multi-bunch operation. These criteria, driven by FCC-ee's top-up injection scheme at the Z pole, directly shaped the rf optimization process, guiding the selection of iris aperture, iris thickness, and group velocity profiles for effective beam quality preservation and operational reliability.

To achieve this, a comprehensive rf optimization study was performed, focusing on key rf cell parameters such as iris aperture, thickness, phase advance, and group velocity profile. Considering the large number of required accelerating structures and the stringent operational constraints, a systematic multiparameter sweep was initially performed to comprehensively explore the design space and quantify trade-offs between accelerating gradient, shunt impedance, wakefield suppression, and rf efficiency. Although this

method is computationally demanding, it provides a clear and robust means of mapping the multidimensional parameter space, particularly valuable in the early stages of design when identifying feasible and well-balanced configurations.

To further validate the design, we include a benchmarking study comparing the proposed HE-linac structure against several state-of-the-art S-band traveling-wave linacs. These reference structures serve as performance benchmarks due to their proven use in high-gradient applications. The comparative study highlights the HE-linac's strengths in terms of aperture size, rf efficiency, and filling time parameters that are critical for the FCC-ee top-up injection scheme. This benchmarking analysis is presented in Sec. III A and confirms that the HE-linac design offers a well-balanced solution that exceeds key requirements.

To mitigate bunch-to-bunch energy variations in four-bunch operation, we developed a semianalytical optimization model for the input rf pulse shape. By dynamically adjusting the klystron amplitude throughout the pulse duration, the method compensates for beam-loading effects and ensures uniform accelerating voltage across all bunches. This approach improves multibunch energy stability while remaining compatible with the HE-linac's operational constraints.

Finally, detailed thermal and mechanical simulations further confirmed the structure's reliability at 100 Hz operation.

This paper presents the full rf design process for the FCC-ee HE-linac traveling-wave structures, including the design rationale, optimization methodology, beam dynamics constraints, and final performance evaluation, contributing a critical element to the FCC-ee injector complex development.

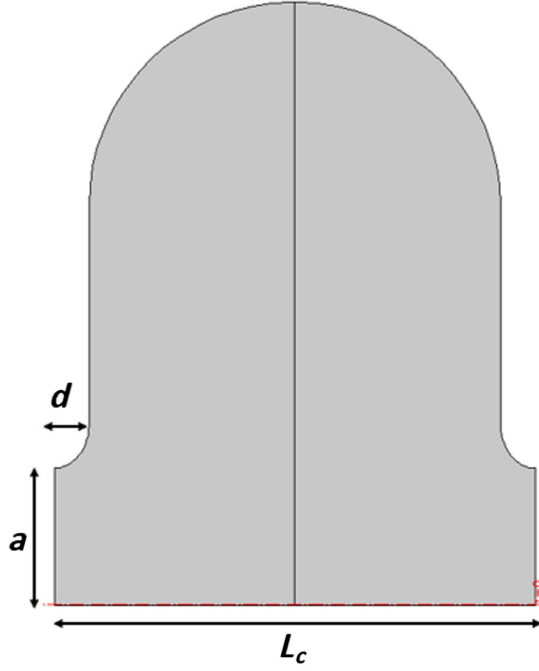


FIG. 2. Basic geometry of the convex cell.

II. RF DESIGN METHODOLOGY

A detailed parametric optimization was carried out to design the accelerator structure for the HE-linac, aiming to maximize the shunt impedance while maintaining a balance between beam dynamics requirements and rf performance, following a similar approach to that employed for the electron and positron linac structures [3]. The design adopts a convex cell geometry (Fig. 2), based on the SwissFEL C-band accelerating structure [4], and is characterized by the aperture radius a , iris thickness d , and synchronous rf phase advance ψ per cell, with the cell length defined as $L_c = \lambda\psi/(2\pi)$, where $f = c/\lambda$ is the operating frequency.

To systematically investigate the design space, a lookup table was generated comprising over 200 reference geometries. For each case, a three-dimensional electromagnetic model of a single accelerating cell was constructed in CST Studio Suite [5], and the fundamental mode properties were computed at 5.712 GHz using the eigenmode solver. The model employed periodic boundary conditions at the cell ends, corresponding to the synchronous phase advance ψ , to simulate an infinitely periodic structure. The table covers a range of geometrical parameters a , d , and L_c , with the iris ellipticity optimized to reduce the modified Poynting vector S_c . For each geometry, the fundamental mode parameters were extracted, including the unloaded quality factor Q , the shunt impedance per unit length to quality factor ratio $\rho = R'/Q$, the group velocity v_g , and the relevant surface field parameters. In addition, the eigenfrequencies and field profiles of the 20 lowest dipole higher-order modes (HOMs) were computed to support subsequent wakefield analysis. These precomputed data

allow for efficient interpolation of rf parameters and their scaling to structures operating at 2.8 GHz.

Based on the selected cell parameters, the time-dependent unloaded accelerating gradient profile for single-bunch operation along the structure was calculated using the formalism described in Ref. [6].

$$G_U(z, t) = A_e[t - \tau(z)]\sqrt{\frac{\omega\rho(0)}{v_g(0)}}g(z), \quad (1)$$

where

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

is the normalized steady-state gradient and A_e , τ denotes the amplitude into the TW structure and signal time delay, respectively.

To achieve higher accelerating gradients for a given klystron rf power, a SLED-type [7] rf pulse compressor is used. It plays a crucial role in shaping the incident rf power to achieve the desired field profile within the structure. By utilizing a storage cavity system, the input rf pulse is temporally compressed, resulting in a higher peak power delivered to the accelerating structure. The transient response of the structure, influenced by this compressed pulse, directly affects the gradient evolution overtime. A key aspect of this process is to determine the average gradient at beam injection $\langle G(t = T_k) \rangle$ for the single-bunch operation, which is essential for evaluating the rf-to-beam energy transfer efficiency. The knowledge of $\langle G(t = T_k) \rangle$ allows for the calculation of the effective shunt impedance R_{eff} , defined as

$$R_{\text{eff}} = \frac{\langle G(t = T_k) \rangle^2 L_s}{P_k}, \quad (3)$$

where (i) L_s is the total length of the accelerator structure, and (ii) P_k is the peak rf power delivered by the klystron to the accelerator structure.

The R_{eff} serves as a key metric for evaluating the overall efficiency of the rf power coupling to the beam, with higher values of R_{eff} indicating better power transfer efficiency and more effective beam acceleration. During the optimization process, several design configurations were tested to maximize R_{eff} while ensuring that other performance constraints were satisfied.

To visualize the impact of rf pulse compression, Fig. 3 presents the temporal evolution of a rectangular klystron amplitude (input rf pulse before compression) of length T_k with a phase reversal at $t = T_k - T_f$, where T_f is the TW structure filling time, the amplitude of the signal entering the TW structure after compression, and the corresponding average gradient overtime. This comparison highlights the

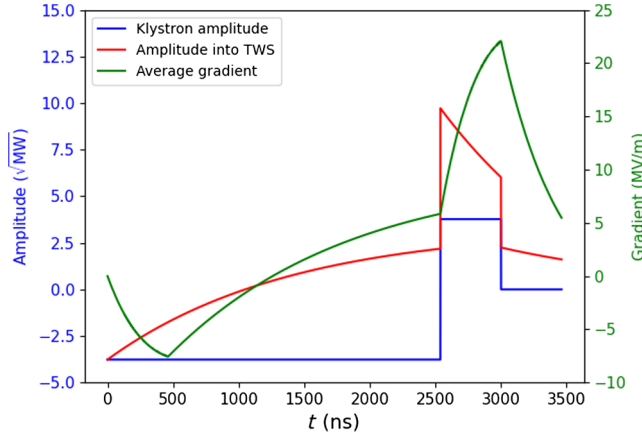


FIG. 3. Temporal evolution of the klystron amplitude, compressed rf pulse entering the TW structure, and the average gradient overtime.

efficiency of the pulse compression system in shaping the rf power distribution to maximize the acceleration process.

While optimizing the rf performance, it is equally crucial to mitigate the effect of the long-range transverse wakefield, which can adversely affect the beam quality by introducing transverse forces that lead to beam emittance growth. To address this issue, a special technique was employed that involves detuning the dipole modes of the accelerator cells. This method effectively suppresses the transverse wakefield without the need for additional external damping elements.

Detuning is achieved by introducing tapering of the aperture radius a and iris thickness d along the structure. This method systematically varies these parameters, allowing for a controlled adjustment of the structure's properties while maintaining a constant average aperture. Consequently, the transverse wakefield potential W_t is kept below a critical threshold within a predefined limit over a certain time span, which is essential for minimizing wakefield-induced beam breakup and ensuring stable beam dynamics.

The long-range transverse wake function generated by the dipole HOMs can be computed in the time domain from the frequency-domain parameters. For an accelerating structure supporting multiple uncoupled dipole modes, the total transverse wake function is given by

$$W_t(s) = 2 \sum_n k_n \exp\left(-\frac{\omega_n s}{2Q_n c}\right) \sin\left(\frac{\omega_n s}{c}\right), \quad (4)$$

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

$$k_n = \left(\frac{R'_x}{Q}\right)_n \frac{\omega_n^2}{4c}. \quad (5)$$

The summation in Eq. (4) accounts for the cumulative effect of all contributing dipole modes across the structure, providing an accurate approximation of the full transverse wake potential. Since all the necessary rf parameters are typically precomputed and stored in a lookup table, this formulation allows for a fast and efficient evaluation of the transverse wake function.

To ensure the robustness of the rf design, the final configuration undergoes thorough validation through numerical simulations and analytical modeling. This process ensures that the design satisfies the necessary criteria for beam dynamics, rf power efficiency, and long-term operational stability. Consideration is also given to external factors, such as temperature variations and mechanical stresses, to ensure reliable performance under realistic operational conditions.

III. OPTIMIZATION OF THE RF STRUCTURE

The optimization of the rf structure for the HE-linac was aimed at maximizing the power transfer efficiency to the beam, while respecting key beam dynamics constraints [8]. An average aperture size of $\langle a \rangle = 0.12\lambda$, corresponding to 12.85 mm (where λ is the rf wavelength), was selected as an optimal compromise. This choice ensures sufficient beam transport through the structure, while simultaneously minimizing rf losses and mitigating wakefield effects. Critical design parameters—including the rf operating frequency, aperture size, iris thickness, and phase advance per cell—were carefully selected to strike a balance between rf performance and beam stability.

The rf operating frequency was fixed at 2.8 GHz, in accordance with system requirements and available rf sources. The phase advance per cell, $\psi = 120^\circ$, was chosen based on its well-established role in traveling-wave accelerating structures, offering an advantageous compromise between shunt impedance, group velocity, and peak surface fields. This phase advance supports efficient acceleration with moderate filling times and helps control peak surface fields that could otherwise increase the risk of rf breakdown. Moreover, the 120° phase advance facilitates favorable beam dynamics by limiting the growth of transverse wakefields, thus enhancing beam stability.

The total accelerator length, $L_s = 3$ m, was dictated by beam dynamics requirements and operational considerations, while also ensuring compatibility with the PSI tune-free assembly process [9], which simplifies fabrication and alignment without the need for postassembly tuning.

To identify the optimal rf structure configuration, a parametric sweep was conducted focusing initially on maximizing the effective shunt impedance R_{eff} under single-bunch operation conditions. Starting from a standard rectangular klystron rf pulse amplitude, the iris thickness was varied systematically from 2.04 to 6.2 mm in 0.2 mm increments, within the limits of the available 2.8 GHz lookup table. The influence of iris thickness on R_{eff} was

evaluated using the analytical expressions derived previously, providing insight into the trade-offs between rf efficiency and beam dynamics constraints.

To investigate the impact of tapering, a delta (Δ) parameter was introduced to modify the apertures of the first and last cells. Positive Δ values correspond to down-tapering, with the first cell aperture being increased by $a_{\text{first cell}} = \langle a \rangle + \Delta$ and the last cell aperture decreased by $a_{\text{last cell}} = \langle a \rangle - \Delta$. Intermediate aperture values are then linearly interpolated between these updated values for the first and last cells along the structure. Negative Δ values result in up-tapering, with the first and last cell apertures being modified in the opposite manner. The Δ parameter was varied from -4 to 4 mm in steps of 0.2 mm. This approach allows fine-tuning of the structure to optimize impedance and beam dynamics. Additionally, wakefield analysis was performed using the frequency-domain parameters of the 20 lowest dipole HOMs. A threshold of 0.1 V/pC/mm/m was imposed [8] to limit wakefields, ensuring transverse stability is maintained. This threshold was chosen to balance wakefield suppression with rf efficiency.

To systematically evaluate the effect of tapering, we performed a 2D scan where each point represents an accelerating structure with different iris thickness tapering levels for a chosen Δ value. The R_{eff} for each structure was calculated and visualized as a color map. During this scan, the coupling factor β of the SLED pulse compressor was optimized for each structure to maximize the R_{eff} . A sweep over 400 values of β in the range of 1 to 200 was performed for each tapering configuration, ensuring that the highest possible R_{eff} was achieved for each case. Structures that satisfied the wakefield constraints were highlighted with white stars. While the structure with the highest R_{eff} without wakefield constraint was marked with a red star, the blue star indicates the structure with the highest R_{eff} where W_t is smaller than 0.1 V/pC/mm/m. Figure 4 illustrates this for a Δ value of 2 mm. This process was repeated for various Δ values, and the final results for all Δ scans are summarized in Fig. 5, where the red traces represent the highest R_{eff} without wakefield constraints, while the blue traces show the performance with the wakefield limit of 0.1 V/pC/mm/m. The highest R_{eff} , with maintaining wakefield constraints, was achieved for Δ of 2 mm. This configuration also exhibited a low surface electric field, indicated by the yellow star in Fig. 5. Given these results, the structure with a Δ of 2 mm emerged as the best candidate for our HE-linac, and thus, it was selected for further optimization and implementation.

After selecting the optimal structure configuration, we calculated the detailed structure parameters for the single-bunch operation, including key characteristics of the SLED-type rf pulse compressor, which has a storage cavity with an unloaded quality factor $Q_0 = 200,000$ and an optimized coupling factor β of 15. The rf module layout consists of four accelerating structures per klystron. The

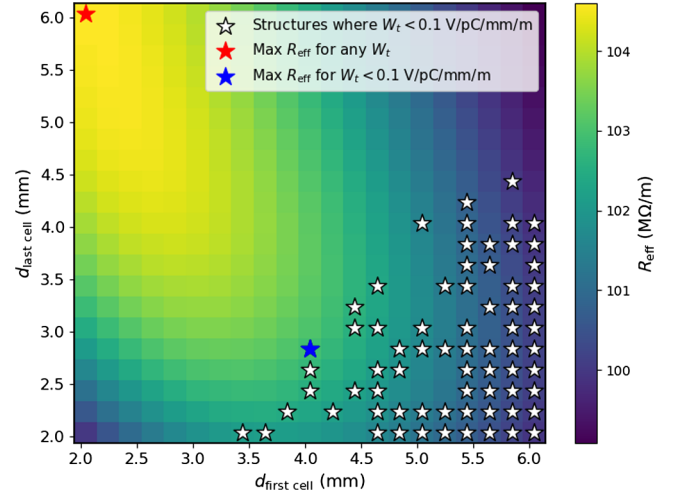


FIG. 4. 2D scan of R_{eff} across varying tapering configurations for $\Delta = 2$ mm, with white stars indicating structures meeting wakefield constraints, a red star marking the highest R_{eff} without wakefield constraints, and a blue star highlighting the structure with the highest R_{eff} where $W_t < 0.1$ V/pC/mm/m.

klystron with maximum power of 80 MW and an rf pulse length of $3 \mu\text{s}$ operates at 64 MW to account for waveguide losses and operating margin, resulting in 14.2 MW of klystron power being delivered to each structure. Based on these parameters, we found the unloaded average gradient to be 22 MV/m, ensuring that the accelerator operates at peak efficiency with the effective shunt impedance to be $102 \text{ M}\Omega/\text{m}$. The detailed structure parameters are presented in Table I. These values are critical in understanding the overall design and performance of the HE-linac.

To provide a comprehensive view of the rf parameters, including the gradient variation along the structure, Fig. 6

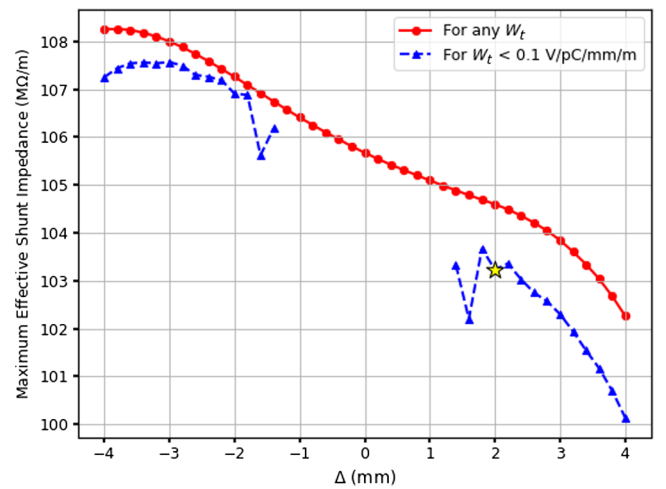


FIG. 5. A parametric sweep was performed as a function of delta Δ . Red traces show results without transverse wakefield constraints, while blue traces indicate conditions with a 0.1 V/pC/mm/m wakefield threshold.

TABLE I. Accelerating structure parameters for the HE-linac.

	HE-linac	Unit
Frequency	2.8	GHz
Structure length	3	m
Average aperture	0.12λ	
Cell aperture: first/last	14.85/10.85	mm
Iris thickness: first/last	2.84/4.04	mm
v_g/c : first/last	3.92/1.25	%
R'/Q : first/last	3.63/4.38	k Ω /m
Q : first/last	16,571/16,039	
Filling time	460	ns
SLED coupling	15	
Repetition rate	100	Hz
Klystron power per structure	14.2	MW
Average power per structure	3.72	kW
Unloaded V_{acc} (single bunch)	66	MV
R_{eff} (single bunch)	102	M Ω /m
Unloaded G_{avg} (single bunch)	22	MV/m
$E_{s,max}$ (instantaneous)	72	MV/m
$S_{c,max}$ (instantaneous)	479	mW/mm ²

illustrates how these key variables evolve along the accelerator structure.

Additionally, to provide a more realistic prediction of wakefield behavior, we employed the ECHO2D time-domain solver [10], which models all 84 cells of the structure and accounts for an infinite number of HOMs, as well as the coupling between the cells. This approach allows for a more accurate prediction of long-range wakefield effects, which are critical for maintaining beam quality throughout the HE-linac. The ECHO2D solver simulates the time evolution of wakefields, capturing the complex interactions within the accelerating structure.

To rigorously assess the worst-case wakefield effects and their impact on the beam, we applied the envelope-of-the-envelope approach to both the wakefield data obtained from

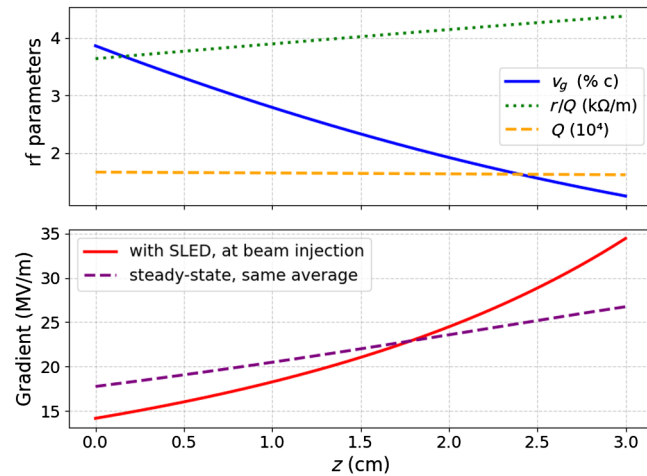


FIG. 6. rf parameters along the structure (top subplot), and the gradient variations along the structure (bottom subplot).

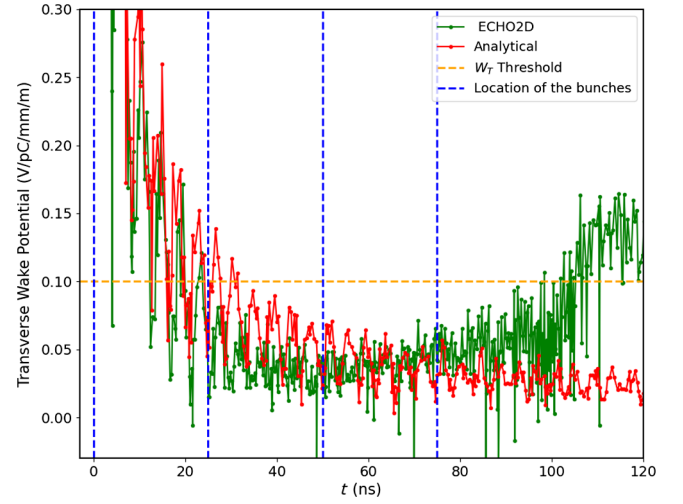


FIG. 7. Comparison of the envelope-of-the-envelope transverse wakefield potentials for the HE-linac structure, calculated over-time using both the analytical formula (red) and the ECHO2D method (green).

the ECHO2D solver and the wakefield data derived from the uncoupled analytical wake function formula, as shown in Eq. (4). We then compared their results in Fig. 7, where the analytical results are presented in red traces, while the ECHO2D results are shown in green traces. Both approaches exhibit good agreement. However, the ECHO2D results show slightly higher wakefield levels for the last bunch and later, probably since it accounts for the infinite number of HOMs and the coupling between cells. Since the accelerator will operate with four bunches, in reality it is crucial to evaluate wakefield levels specifically at the locations where the bunches will be positioned. This ensures that the wakefield effects remain within acceptable limits for the intended beam configuration. The wakefield results indicate that the wakefield levels remain below the specified threshold when the bunch spacing is between 25 and 100 ns. The analysis reveals that a bunch spacing of 25 ns with four bunches is a practical configuration, as the wakefield levels remain well within acceptable limits in this range.

A. Comparison with state-of-the-art S-band structures

To contextualize the performance and design efficiency of the proposed HE-linac, we provide a comparative analysis against several well-established S-band TW structures: those developed at SLAC [11], PAL XFEL [12], and FERMI FEL [13]. These reference linacs are benchmarks in high-gradient accelerator technology and serve as a solid foundation for evaluating the performance of the HE-linac.

Table II presents a side-by-side summary of key rf and geometric parameters, including frequency, structure length, average aperture, iris thickness, shunt impedance (R'),

TABLE II. Comparison of key parameters between the HE-linac and reference S-band structures: SLAC [11], PAL XFEL [12], and FERMI FEL [13].

	HE-linac	SLAC	PAL XFEL	FERMI FEL	Unit
Frequency	2.800	2.856	2.856	2.998	GHz
Structure length	3.00	3.00	2.94	3.18	m
Average aperture	0.12λ	$< 0.12\lambda$	$< 0.12\lambda$	$< 0.12\lambda$	
Cell aperture: first/last	14.85/10.85	13.1/9.6	12.66/9.23	11.38/8.98	mm
Iris thickness: first/last	2.84/4.04	5.8	5.0	2.5	mm
$R'(\text{avg})$: first/last	$\sim 60/70$	$\sim 53/71$	$\sim 55/65$	$\sim 72/81$	MΩ/m
$Q(\text{avg})$	$\sim 16,300$	$\sim 13,000$	$\sim 13,700$	$\sim 15,850$	
v_g/c : first/last	3.92/1.25	2.00/0.65	2.05/0.60	2.21/1.04	%
Filling time	460	830	830	645	ns
Accelerating gradient	22.0	20.0	21.03	24.0	MV/m
rf power per structure	14.2	15.0	20.0	22.5	MW

unloaded quality factor (Q), group velocity, filling time, nominal gradient, and rf power requirements.

The HE-linac design achieves performance that is comparable or superior across several key parameters. In particular, it uniquely satisfies the FCC-ee beam dynamics constraint requiring a minimum average aperture radius of 0.12λ , ensuring effective suppression of short-range transverse wakefields and improved beam quality preservation. In contrast, the SLAC, PAL XFEL, and FERMI FEL designs feature smaller average apertures ($< 0.12\lambda$), which are less suitable for the FCC-ee top-up injection requirements.

Additionally, unlike the reference structures that employ constant iris thickness, the HE-linac incorporates tapered iris thickness and aperture radius, optimizing the trade-off between shunt impedance and wakefield mitigation. This dual-tapering approach helps maintain beam stability in multibunch operation.

The HE-linac also benefits from a higher average unloaded quality factor ($Q \sim 16,300$) and a significantly shorter filling time (460 ns), reducing rf power dissipation and enabling efficient high-repetition-rate operation. The accelerating gradient of 22.0 MV/m is competitive, while the rf power requirement of 14.2 MW per structure remains moderate compared to other high-performance designs.

In summary, the HE-linac demonstrates a well-balanced design tailored to the demanding requirements of the FCC-ee injector linac, offering high rf efficiency, robust beam dynamics performance, and manufacturability advantages over existing S-band TW structures.

IV. BUNCH-TO-BUNCH ENERGY MINIMIZATION

The initial optimization of the accelerating structure geometry was performed using a single-bunch approach, allowing for straightforward and precise tuning of the rf parameters. However, extending the operation to a multi-bunch configuration introduces additional complexities. Specifically, employing the optimized rf input pulse designed for single-bunch operation in a four-bunch

configuration leads to significant bunch-to-bunch energy variations. To address this issue, the input rf signal must be dynamically adjusted to ensure that each bunch experiences an equivalent accelerating voltage.

To achieve uniform energy distribution, we implemented a dynamic rf pulse-shaping technique that involves optimizing both the phase and amplitude of the rf pulse across its duration. A numerical solver was used to determine the optimal klystron drive function, which minimizes the energy spread between the four bunches.

The amplitude modulation of the klystron rf pulse plays a critical role in reducing bunch-to-bunch energy variations. The amplitude function of the klystron, $A_k(t)$, is described as

$$A_k(t) = \begin{cases} 0, & t < 0 \\ -A_{k,ss}, & 0 < t < t_r \\ \kappa A_{k,ss} + (i-1)\Delta A, & t_r + (i-1)\Delta t_b < t < t_r + i\Delta t_b \\ A_{k,ss}, & t_{lb} \leq t \leq T_k \\ 0, & t > T_k, \end{cases} \quad (6)$$

where $A_{k,ss}$ denotes the steady-state klystron amplitude, κ is a scaling factor optimized to minimize the energy spread across the bunches, i represents the index of the discrete modulation steps from 1 to $n_b - 1$, and ΔA is the incremental amplitude adjustment applied during each modulation step.

The times t_r and t_{lb} govern the synchronization of the rf pulse with the bunches. The final bunch arrival time, t_{lb} , is given by

$$t_{lb} = T_k - T_{\text{fill}}. \quad (7)$$

The first bunch arrival time, t_r , is defined by the klystron phase reversal time:

$$t_r = t_{lb} - (n_b - 1)\Delta t_b, \quad (8)$$

where T_k is the total duration of the klystron pulse, T_{fill} is the filling time of the rf structure, $n_b = 4$ is the number of bunches, and $\Delta t_b = 25$ ns is the time interval between successive bunches.

These time definitions establish the precise interaction window between the rf pulse and the bunches, enabling accurate synchronization.

The modulation process is divided into N discrete steps, given by $n_b - 1$ between the times t_r and t_{lb} , each corresponding to a small increment in the klystron amplitude. The incremental change in amplitude, ΔA , is given by

$$\Delta A = \frac{\kappa A_{k-ss}}{N}. \quad (9)$$

This stepwise approach allows for a gradual adjustment in the rf pulse amplitude, thus minimizing voltage variations across the bunches.

To account for the finite response time of the klystron, modulator, and rf electronics, a linear transition is introduced at each discrete modulation step. Rather than instantaneous amplitude jumps, each transition occurs over a finite time interval t_{trans} . The amplitude during a transition from A_i to A_{i+1} is interpolated linearly:

$$A_k(t) = A_i + \frac{(A_{i+1} - A_i)}{t_{\text{trans}}}(t - t_{\text{start}}), \quad (10)$$

where t_{start} is the time at which the transition begins. For this study, $t_{\text{trans}} = 20$ ns was selected to approximate typical klystron and modulator reaction times while preserving compensation effectiveness.

To optimize the amplitude scaling factor κ , we minimize the bunch-to-bunch voltage variation. The optimization criterion is given by

$$\min(\Delta V) = \min[\max(V_n) - \min(V_n)],$$

where V_n represents the accelerating voltage for each bunch. The optimal value of κ is determined by scanning through candidate values and selecting the one that minimizes the voltage spread.

Based on the optimized scaling factor $\kappa = -0.195$, the corresponding klystron amplitude pulse was calculated, as shown in Fig. 8. The modified pulse shape effectively reduces voltage variations across the four bunches. Figure 9 compares the unloaded average gradients before and after the bunch-to-bunch energy spread compensation, clearly illustrating a more uniform gradient distribution (orange traces) compared to the unoptimized case (blue traces).

With the optimized input rf pulse shape, the effective shunt impedance for four-bunch operation was recalculated, resulting in $R_{\text{eff}} = 96$ M Ω /m. This corresponds to a 6.5% reduction compared to the single-bunch value of 102 M Ω /m (Table III). Similarly, the average unloaded accelerating gradient decreased to 21.3 MV/m, which represents a 3.2% reduction compared to the unloaded gradient of

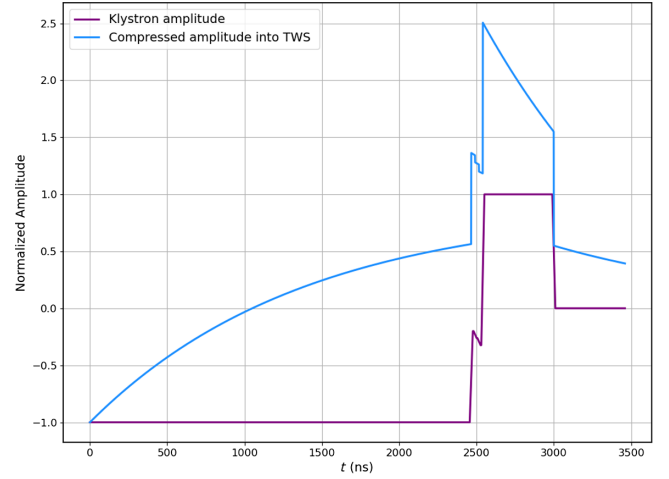


FIG. 8. Normalized klystron amplitude before and after pulse compression. The purple trace shows the optimized amplitude before the rf pulse compressor, and the blue trace shows the amplitude after pulse compressor.

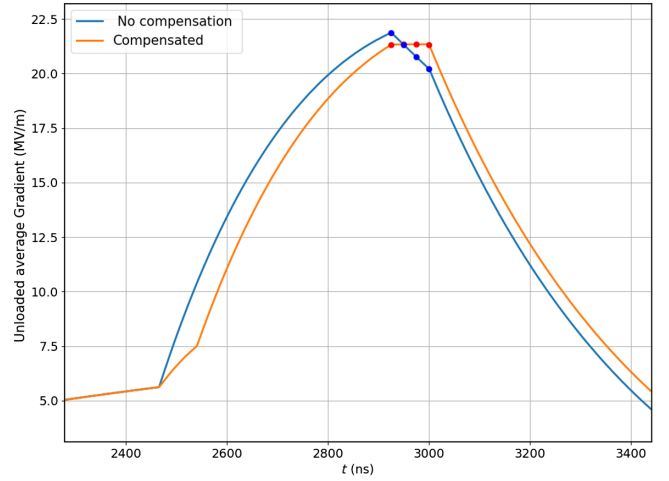


FIG. 9. Unloaded average gradients before and after bunch-to-bunch energy spread compensation. Orange traces show the optimized pulse with uniform gradient distribution, while blue traces represent the unoptimized case.

22 MV/m in single-bunch operation. These reductions are a direct consequence of the lower input power applied during multibunch operation, which is necessary to achieve bunch-to-bunch energy spread minimization.

TABLE III. Four bunch unloaded operation—accelerating structure parameters for the HE-linac.

	HE-linac	Unit
Unloaded V_{acc} (4 bunches)	63.9	MV
R_{eff} (4 bunches)	96	M Ω /m
Unloaded G_{avg} (4 bunches)	21.3	MV/m
$E_{s,\text{max}}$ (instantaneous)	70	MV/m
$S_{c,\text{max}}$ (instantaneous)	452	mW/mm ²

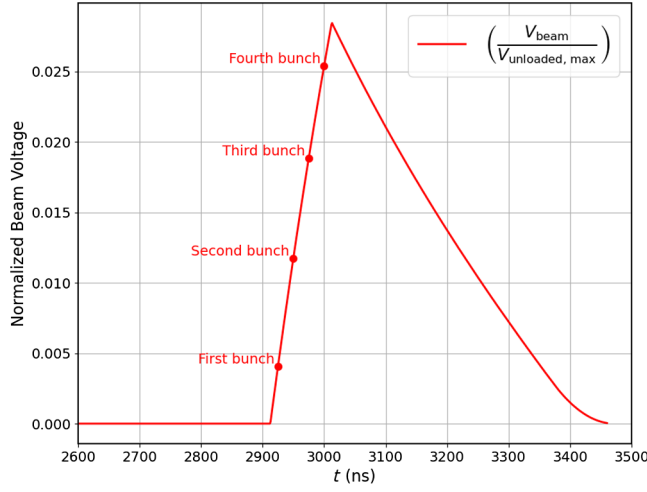


FIG. 10. Distribution of the beam voltage for the four bunches, normalized to the maximum unloaded voltage.

V. BEAM-LOADING STUDIES

Having established the unloaded characteristics of the TW accelerating structure, we now extend the analysis to include beam-loading effects. Beam loading in TW structures causes a time-dependent reduction in the accelerating gradient as the beam extracts energy from the rf fields. The resulting loaded gradient can be described by the following expression [6]:

$$G_L(z, t) = G_U(z, t) - I g(z) \int_0^z \frac{\omega \rho(z')}{g(z') 2 v_g(z')} dz', \quad (11)$$

where $G_U(z, t)$ is the time-dependent unloaded gradient component that is shown in Eq. (1). The second term, known as the beam-induced gradient, describes the reduction in the accelerating gradient due to beam loading, where I is the beam current. This term reflects the difference between the loaded and unloaded gradient profiles.

For the HE-linac, we analyze beam loading under the assumption of a constant beam current of 0.2 A, corresponding to a bunch charge of 5 nC with a bunch separation of 25 ns,

consisting of a total of four bunches. The impact of beam loading is evaluated by normalizing the beam voltage to the maximum unloaded voltage, as shown in Fig. 10. The results indicate that the fourth bunch experiences the highest energy deviation, with an observed variation of 2.42%.

A similar methodology is employed to mitigate both beam-loading effects and bunch-to-bunch energy spread during nominal charge operation by dynamically optimizing the input rf pulse shape. Figure 11 illustrates the optimized rf pulse shape (red trace) with the unloaded and loaded gradients represented by the blue and orange traces, respectively. The four red dots indicate the temporal positions of the bunches. A more detailed view of the unloaded and loaded gradients near the bunch positions is shown in Fig. 12. The computed average loaded accelerating voltage for the four-bunch operation is 63.2 MV, which corresponds to a loaded average gradient of 21.1 MV/m. Finally, these are the values used to define the HE-linac layout, including the number of rf modules required to achieve the final energy.

However, in top-up operation, where bunch charges may vary from 0% to 100% across the four bunches, a single optimal rf pulse must accommodate both extremes. This presents a challenge, as the pulse needs to handle a wide range of conditions without causing large energy variations. To address this, we introduce the “golden pulse,” an rf pulse that averages the optimized pulses for unloaded and loaded voltages. While it does not completely eliminate energy variation, it provides a balanced compromise, minimizing energy spread across all charge variations. As demonstrated in Fig. 13, the golden pulse effectively limits the energy spread to +1.1% and −1.1% for unloaded (small red dots at near-zero bunch charge) and loaded (large red dots at nominal 5 nC intensity) cases, respectively.

VI. THERMO-MECHANICAL STUDIES

A comprehensive steady-state thermal analysis was conducted on both the first and last cells of the HE-linac structure, as the temperature distribution was expected to vary between them due to different power losses. However,

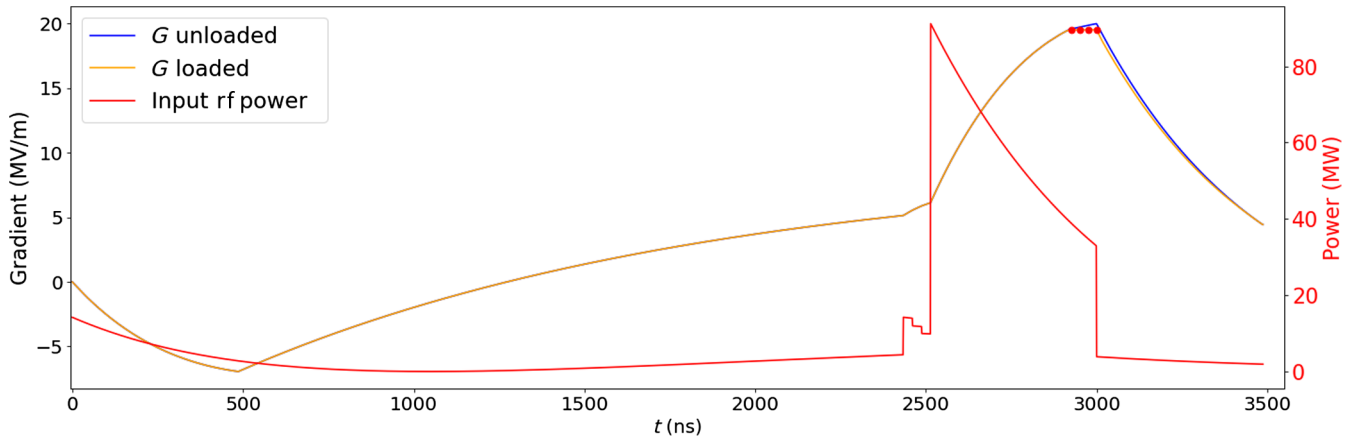


FIG. 11. Loaded input rf power and average gradients versus time for four-bunch operation.

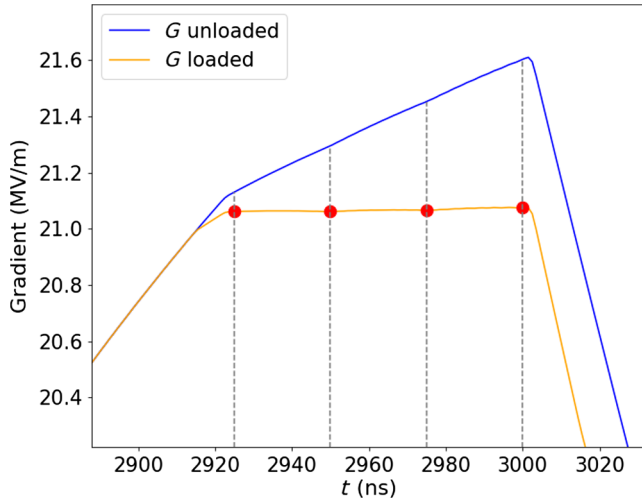


FIG. 12. Nominal charge condition.

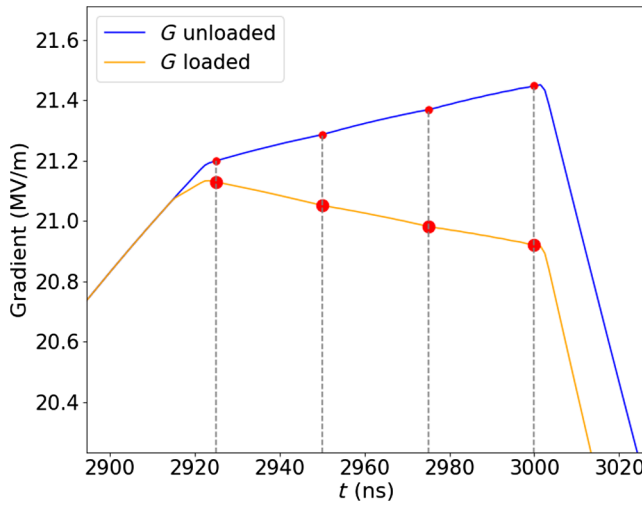


FIG. 13. Top-up operation.

since the last cell exhibits the highest average wall losses, the results presented here focus solely on the last cell. The simulations were performed using the CST Thermal Solver, where surface power dissipation was computed based on the magnetic field distribution obtained from the electromagnetic solver. The dissipated power data was then imported into the thermal model to evaluate the resulting temperature distribution.

The cooling system in the model consists of eight symmetrically placed cooling channels, each with a diameter of 16 mm. A convective heat transfer coefficient of $4000 \text{ W/m}^2/\text{K}$ was applied, corresponding to a water flow rate of 4.4 L/min per channel at an inlet temperature of 293 K [14]. The considered rf power parameters include an average output power of 3.72 kW, assuming a 100 Hz repetition rate with a 3 μs pulse duration and a peak input power of 14.2 MW. The effective power delivered to the accelerating structure accounts for an attenuation factor

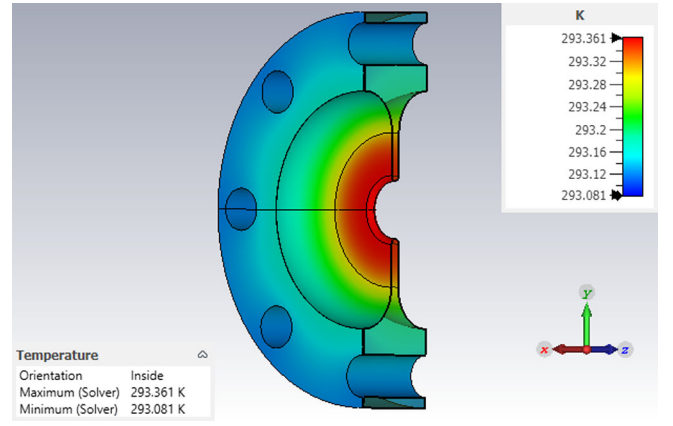


FIG. 14. Steady-state temperature distribution of the last cell in the HE-linac structure. The peak temperature is observed at the iris region.

of 0.87 from the pulse compression system and an additional attenuation factor of 0.61 due to rf propagation along the structure.

The resulting temperature distribution, depicted in Fig. 14, indicates that the peak temperature rise occurs at the iris region, reaching a maximum value of 0.28°C above the initial operating temperature. This localized heating effect is expected due to the concentration of rf-induced wall losses in this region.

Subsequent mechanical analysis was performed using the ANSYS Mechanical Solver [15] to assess the structural deformation induced by thermal expansion. The simulation results revealed a maximum deformation of $0.06 \mu\text{m}$ at the most thermally stressed region of the structure. This level of deformation is negligible and does not impact the electromagnetic performance of the accelerating cavity, ensuring stable operation under the given thermal loading conditions.

VII. CONCLUSIONS

This study presents a comprehensive rf design and optimization of the high-energy (HE) linac for the FCC-ee injector complex, addressing the critical challenges of high-gradient acceleration, beam-loading compensation, wakefield suppression, and operational stability.

A comparative analysis against existing high-gradient S-band linacs was performed to benchmark and validate the design improvements presented here.

The designed TW accelerating structure, operating at 2.8 GHz with a total length of 3 m, meets the stringent requirements for efficient beam acceleration up to 20 GeV. Through meticulous optimization of the iris geometry, phase advance, and rf pulse shaping, we achieved an average loaded gradient of 21.1 MV/m, ensuring high rf-to-beam power transfer efficiency while maintaining a low beam-loading-induced energy spread of less than 2.42% across four bunches.

The implementation of a SLED-type pulse compression system, with an optimized coupling factor of 15, significantly enhances the rf power efficiency. This system, combined with the dynamic modulation of the rf pulse shape, effectively mitigates bunch-to-bunch energy variations, ensuring uniform energy distribution across all bunches. The introduction of the golden pulse further addresses the challenges of top-up operation, where bunch charges vary dynamically. By averaging the optimized rf pulses for unloaded and loaded conditions, the golden pulse limits energy spread to $\pm 1.1\%$, providing a robust solution for maintaining beam quality under varying operational conditions.

Wakefield suppression is achieved by aperture tapering and careful control of the iris radius, resulting in a transverse wakefield potential below 0.1 V/pC/mm/m, essential for preserving beam emittance during top-up injection at the Z pole.

Thermal and mechanical analyses confirm the structural integrity and long-term reliability of the HE-linac. Steady-state thermal simulations reveal a maximum temperature rise of only 0.28 °C at the iris region, with negligible mechanical deformation of 0.06 μm , ensuring stable operation under high rf power and thermal loading conditions. These results underscore the robustness of the design, which is capable of withstanding the demanding operational requirements of the FCC-ee injector complex.

Finally, the choice of TW structures based on proven SwissFEL technology ensures practical feasibility, cost-effective fabrication, and compatibility with the injector complex's operational demands.

In summary, this work demonstrates a successful integration of advanced rf design, beam-loading compensation, wakefield control, and thermal-mechanical optimization, resulting in a high-performance HE-linac that meets the FCC-ee injector complex's stringent requirements. The proposed design not only ensures efficient beam acceleration and minimal energy spread but also provides a scalable and reliable framework for future high-energy linear accelerators.

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DATA AVAILABILITY

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

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