

Coaxial integrated linear accelerator powered by a high-efficiency and high-power transit-time oscillator

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Integrating a high-power microwave source with an accelerating structure into a single device is a key strategy for developing compact, even portable, high-energy particle accelerators, which hold significant promise for scientific, medical, and industrial applications. To achieve this objective, we propose integrating an X-band coaxial transit-time oscillator (CTTO) microwave source with an X-band accelerating structure, thereby drastically minimizing the total volume of particle accelerators. Leveraging the CTTO's advantages, low operating voltage, stable frequency, high power, and high efficiency, along with the high acceleration gradient of X-band accelerators, our design demonstrates that a CTTO operating at 50 kV (generating 7.8 MW of radio-frequency power at 9.3 GHz) can accelerate an electron beam from 50 keV to 10.96 MeV over a 320 mm length.

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I. INTRODUCTION

The development of high-energy-gain (ΔE) and high-gradient (E_a) normal-conducting radio-frequency linear accelerators (rf linacs) remains a longstanding objective in the accelerator community, with broad implications for scientific, medical, and industrial applications [1]. From a power conversion perspective, both ΔE and E_a scale as $P^{1/2} f^{1/4}$ [2], where P is the available microwave power and f is the operating frequency. This scaling underscores the importance of high-power microwave sources operating at elevated frequencies to realize linacs with simultaneous high-energy gain and high acceleration gradient—a direction reflected in numerous experimental efforts [3–7].

Beyond these fundamental scaling laws, the selection of operating frequency involves practical trade-offs among application requirements, source availability, manufacturing tolerances, and thermal management. In particular, X-band linacs have attracted growing interest as a promising balance among these factors. However, conventional X-band microwave sources face inherent power-scaling limitations due to wavelength-dependent constraints ($P \propto f^{-2}$) [8], which intensify space-charge effects,

breakdown risks, and thermal challenges [8]. For example, commercially available X-band magnetrons typically deliver under 2 MW [9–11], while high-power klystrons require operating voltages exceeding 200 kV, leading to bulky insulation and complex interaction structures that compromise system compactness and efficiency [12–14].

Emerging coaxial microwave sources—such as coaxial backward wave oscillators (CBWOs) [15], coaxial Cherenkov generators (CCGs) [16], coaxial transit-time oscillators (CTTOs) [17], and triaxial klystron amplifiers (TKAs) [18]—overcome these limitations through inherent scalability. By maintaining fixed radial differences while flexibly scaling the average radii of the annular beam, interaction region, and beam dump, these devices preserve frequency-domain characteristics across different power levels. In the past few decades, a large number of experiments have demonstrated their capability to produce high-power, high-frequency microwaves [19–30]. Among these coaxial microwave sources, CTTOs offer distinct advantages: facile mode selection, stable operation, compact structure (compared to TKAs), and reduced magnetic field requirements (compared to CBWOs and CCGs)—making them promising candidates for powering linacs. Their high isolation between sections further reduces the difficulty in designing a device with satisfactory efficiency.

Building on these advantages and leveraging the inherent structural characteristics of the CTTO, this paper proposes a novel linac powered by a high-efficiency and high-power CTTO. Specifically, we further develop the Coaxial Integrated Linac (CI-Linac) concept proposed in our recent work [31], which utilizes a novel layout uniquely adapted

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to the coaxial microwave source. Unlike conventional distributed layouts where components are separate, the CI-Linac embeds the accelerating structure directly within the CTTO's hollow inner conductor, forming a unified device. This design capitalizes on the CTTO's high-frequency, high-power microwave generation capability and allows the accelerator to benefit from shared infrastructure without requiring additional external space. By eliminating spatial redundancies and synergistically combining power generation with acceleration, the CI-Linac paves the way for a new generation of compact, high-power, and high-efficiency accelerator systems.

This work significantly advances the CI-Linac concept beyond its initial proposal. The new design achieves three critical improvements: (1) higher power and efficiency, resulting in greater beam energy gain; (2) enhanced stability through CTTO-based microwave generation; and (3) improved engineering adaptability via a dedicated mode converter with standard waveguide interfaces. These advancements fully demonstrate the CI-Linac's technical advantages and substantially enhance its readiness for practical deployment.

This manuscript is organized as follows. Section II overviews the CI-Linac concept holistically. Sections III–V detail the design and simulation results for the high-efficiency CTTO, mode converter, and accelerating structure, respectively. Conclusions are presented in Sec. VI.

II. MODEL DESCRIPTION

As illustrated in Fig. 1, the proposed CI-Linac comprises four core parts: a coaxial transit-time oscillator (CTTO), a standing-wave accelerating structure, a mode converter, and a shared magnet. The CTTO converts the kinetic energy of an intense annular direct-current (dc) driver electron beam into the energy of X-band microwaves. The generated microwaves finally power the embedded standing-wave accelerating structure to accelerate the witness beam. For convenience of engineering, a mode converter is designed *ad hoc*, which converts the coaxial TEM mode generated by the CTTO into the fundamental

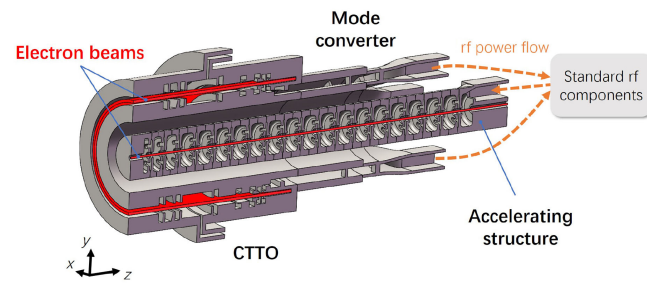


FIG. 1. Schematic of the proposed CI-Linac. The metal blocks are drawn to reveal the approximate size of the final structure, instead of representing the actual engineering design.

mode of standard rectangular waveguides. With such a conversion, microwave transmission, diagnosis, and control can be implemented using existing established techniques. The vacuum models of CTTO and acceleration tube are separated by ~ 19 mm radially, which reserving sufficient space for water cooling and vacuum maintenance.

III. COAXIAL TRANSIT-TIME OSCILLATOR

As illustrated in Fig. 2, the CTTO comprises three core sections: (1) a 5-gap buncher, (2) idle cavities, and (3) a dual-gap extractor. Driven by an annular dc low-voltage intense electron beam (50 kV, 300 A), the device operates under a 0.4 T uniform axial magnetic field for beam confinement, which can be approached by the permanent magnet described in Appendix A. Simulations of beam-wave interactions were performed using the particle-in-cell (PIC) code CHIPIC [32].

The 5-gap buncher provides an initial oscillation at the desired frequency when the dc beam passes through. The dominant mode excited in the buncher is the $TM_{01} \pi/2$ mode, as shown in Fig. 3(a). A “dogleg”-shaped waveguide is loaded on the wall of the longest coupling gap to reduce the external quality factor (Q_e) of the unwanted competitive mode and hence ensures a single-frequency oscillation. Details about the mode selection mechanism are described in Appendix B. This oscillation leads to a modestly modulated beam, as indicated by the growth of the fundamental beam current from 0 to ~ 300 A [Fig. 4(a)].

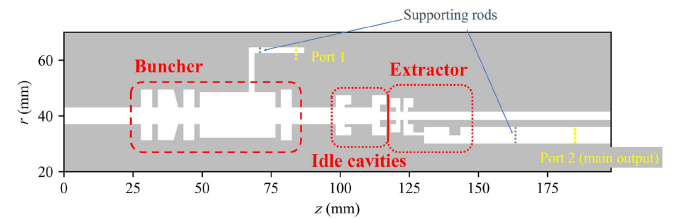


FIG. 2. Geometry of the CTTO.

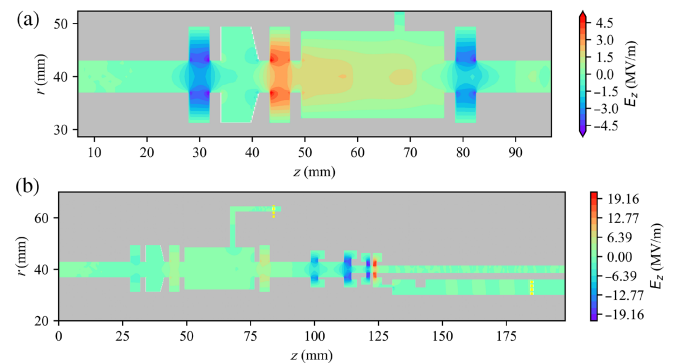


FIG. 3. Typical contour of the longitudinal electric field (E_z) (a) in the 5-gap buncher and (b) in the whole CTTO.

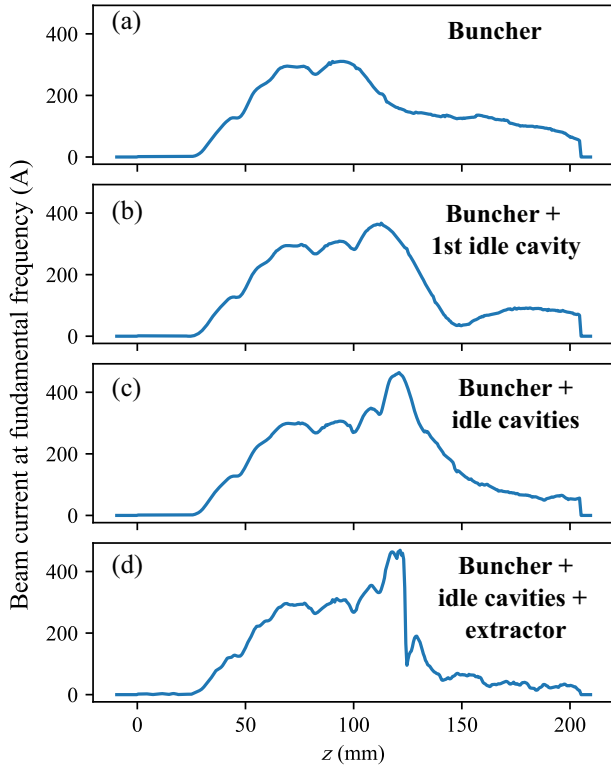


FIG. 4. Evolution of fundamental beam current in the CTTO when adding the sections one by one. (a) Only the buncher. (b) Adding an idle cavity downstream of the buncher. (c) Adding two idle cavities downstream of the buncher. (d) Adding two idle cavities and an extractor downstream of the buncher.

Downstream of the buncher, two idle cavities serve to further improve the bunching. The so-called idle cavity is a cavity with high isolation and a positive beam conductance, so that neither significant power loss nor self-excited oscillation will be introduced. The amplitude and phase of the cavity field are directly determined by the modulated beam, so they can be well predicted with the large-signal theory [33,34]. These features make the idle cavity a proper tool for manipulating the phase space of the beam and improving the modulation. Given an idle cavity, the main parameters that matter in phase space manipulation are the position, the characteristic impedance, and the eigenfrequency. In the present design, these parameters are optimized to maximize the downstream fundamental beam current. The optimization is based on our preliminarily developed large-signal beam-wave interaction code. For the optimal structure, the fundamental beam current reaches a maximum value of ~ 450 A, corresponding to a modulation depth of ~ 1.5 , as shown in Figs. 4(b) and 4(c). This implies that a highly bunched electron beam is produced, as Fig. 5 shows.

The dual-gap extractor, operating in the TM_{01} π -mode [see Fig. 3(b)], is positioned near the location of peak fundamental beam current. A π -mode dual-gap

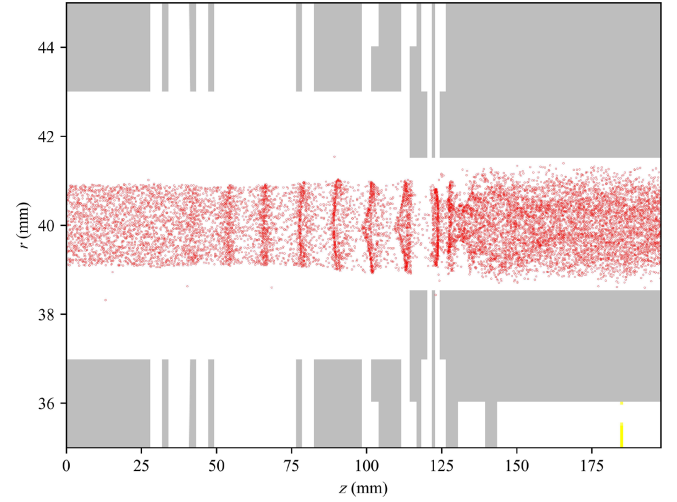


FIG. 5. Typical snapshot of the particle position distribution in the CTTO.

configuration was selected over a conventional single-gap extractor due to its improved power capability and higher theoretical upper limit of extraction efficiency [12,27–30]. Cold test of the dual-gap extractor's PIC model shows that the separation between 0- and π -mode is 175 MHz (0-mode at 9.145 GHz and π -mode at 9.320 GHz), which is sufficient to prevent unstable resonance. The extractor's position, eigenfrequency, and external quality factor were optimized using our large-signal code to maximize extraction efficiency. As the beam is highly bunched, most electrons experience a continuous decelerating field in the optimized extractor. Consequently, the beam kinetic energy decreases sharply after traversal (Fig. 6). A marked reduction in modulation depth is also observed, as evidenced by the rapid decline in fundamental current [Fig. 4(d)] and beam debunching (Fig. 5) downstream of the extractor.

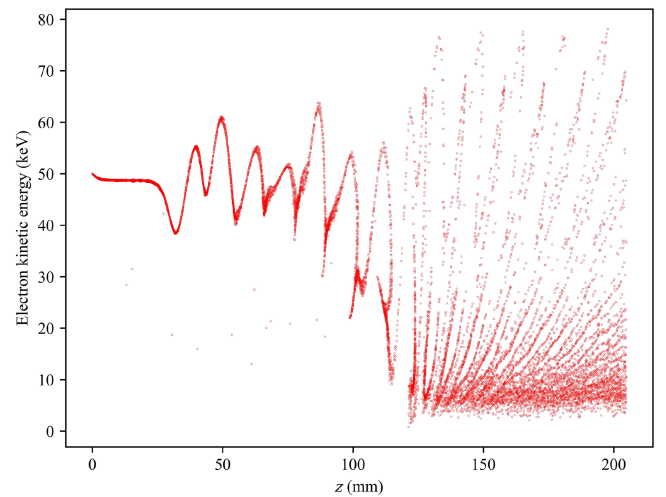


FIG. 6. Energy phase space of the CTTO.

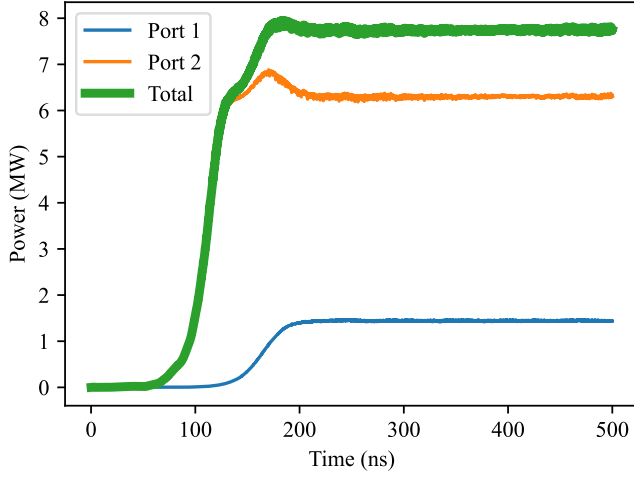


FIG. 7. Cycle-averaged output power of the CTTO as a function of time.

The CTTO delivers a total output power of 7.8 MW (cycle-averaged) at 9.3 GHz, corresponding to a beam-to-wave power conversion efficiency of 52% (see Figs. 7 and 8). Compared to the initial CI-Linac [31], the newly designed one demonstrates significant improvements in both power output and efficiency, better showcasing the superiority of the CI-Linac architecture. The achieved power substantially exceeds the capabilities of conventional low-voltage X-band sources. Moreover, the efficiency remains competitive even when benchmarked against nondedicated microwave sources [35–40]. Fundamentally, this high efficiency originates from the alleviated space-charge effect enabled by the coaxial geometry and the enhanced design flexibility enabled by the high intersection isolation, both of which are inherent to the CTTO structure.

Beyond its higher power and efficiency, the CTTO as a microwave source offers another significant advantage over the CBWO used in the previous CI-Linac [31]: superior

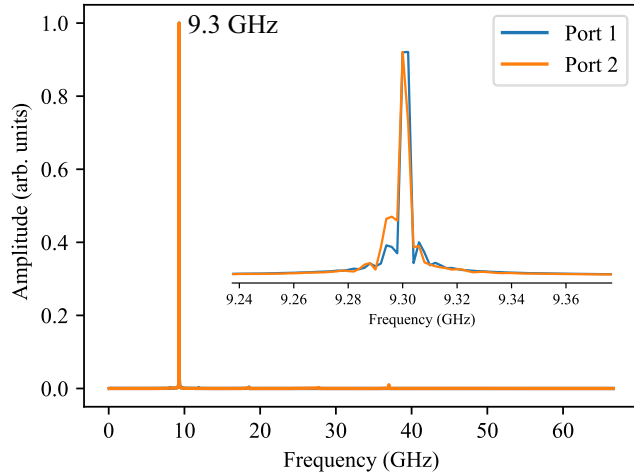


FIG. 8. Fast Fourier transform result of port voltages. The inset is a close-up view near the oscillation frequency.

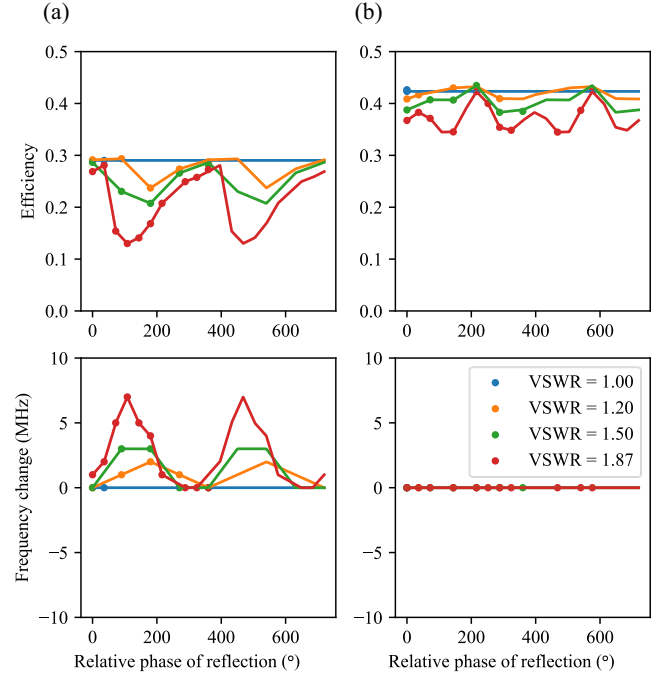


FIG. 9. Comparison of load variation tolerance between different coaxial microwave sources. (a) CBWO in the previous work [31]. (b) CTTO (this work). For the CTTO, the calculation of efficiency only takes the power via port 2 into account.

tolerance to load variations. The standard method for assessing this tolerance involves monitoring changes in output power and frequency across different voltage standing wave ratios (VSWRs) and reflection phases. In our PIC simulations, these parameters were precisely controlled by defining the phase velocity and position of output port (port 2 for the CTTO). The results, shown in Fig. 9(a), reveal that the CBWO in the initial CI-Linac exhibits significant degradation in power efficiency at certain phases when VSWR = 1.87. Additionally, frequency pulling as high as 7 MHz is observed, which even exceeds the bandwidth of the standing-wave accelerating structure. These instabilities in power delivery and spectral characteristics demonstrate the CBWO's high sensitivity to reflections from accelerating structures, thus critically compromising the operational stability of CBWO-powered CI-Linacs. In contrast, as shown in Fig. 9(b), the CTTO maintains < 8% efficiency fluctuations and imperceptible frequency change (below the resolution of the 500-ns simulation), confirming significantly improved robustness. This enhanced operational resilience stems from the CTTO's inherent electromagnetic isolation, which decouples upstream beam bunching dynamics from downstream load variations (as witnessed in Fig. 4). Critically, the result of bunching process—modulation depth that governs extraction efficiency—remains unaffected by such perturbations.

Another factor influencing operational stability is the transient reflection occurring at pulse startup, when the

radiation from the accelerating structure is insufficient to compensate for the strong reflection from its coupling aperture. In the present design, this transient signal can be directed to a dummy load using a commercial circulator installed between the mode converter (Sec. IV) and the accelerating structure—a configuration commonly adopted in standing-wave linac systems. This approach represents a practical improvement over the original design in Ref. [31], where the use of a radial waveguide interface made circulator integration difficult.

In the present design, approximately 1.5 MW of power is extracted through the dogleg waveguide (port 1). As detailed in Appendix B, this configuration is employed to suppress competing modes and enhance single-frequency stability. It should be noted that this distributed power extraction does not compromise the overall efficiency of the CTTO, as the microwave outputs from the two cavities share the same frequency and maintain a fixed phase relationship via the shared electron beam, allowing for coherent combination if required. However, the inclusion of the coaxial output structure around the CTTO introduces challenges for the design and integration of a compact, lightweight focusing magnet. Although the current magnet design (Appendix A) addresses this issue, it does so at the expense of increased weight. Furthermore, reflections from the upstream port 1 can perturb the beam-wave interaction, potentially affecting operational stability—a concern also observed in the earlier BWO-based CI-Linac. To overcome these limitations, future work will focus on developing more robust bunching techniques that eliminate the need for such a coaxial output structure for mode control.

IV. TEM-TE₁₀ MODE CONVERTER

Although directly feeding the accelerating structure with the coaxial TEM mode generated by the CTTO appears straightforward, this approach introduces significant engineering challenges. Since most commercial instrumentation for microwave diagnostics and control is exclusively compatible with standard rectangular waveguides, the coaxial feeding complicates system fabrication, testing, and operation. Additionally, dedicated space must be allocated for cooling and vacuum infrastructure. To resolve these constraints, we designed a dedicated mode converter that transforms the coaxial TEM mode to the TE₁₀ mode for WR90 waveguide interfaces.

Figure 10 shows the vacuum model of the mode converter. There are eight manifolds at the end of the coax. Every two adjacent manifolds are converged to one rectangular waveguide via a transition section. Due to the eightfold symmetry, the first higher-order mode in the coax excited by this geometry is TE₈₁, which is a cut-off mode. Consequently, the conversion efficiency at the operation frequency is mainly influenced by the reflection in the form of TEM mode occurred at the end of the coax. To eliminate

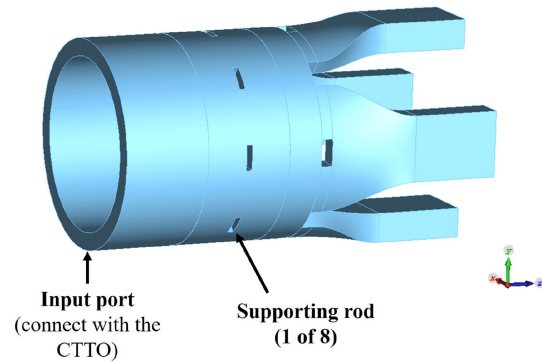


FIG. 10. Vacuum model of the mode converter.

the TEM reflection, an array of supporting rods is introduced. When the TEM reflection from the supporting rods coherently offsets the TEM reflection from the end of coax, the total reflection is minimized and mode conversion efficiency is maximized. Similar to the reason for eight manifolds at the end of coax, eight supporting rods are used to avoid the excitation of transmissible high-order modes.

A cascaded scattering matrix method enabled rapid optimization during design, avoiding computationally intensive full-wave simulations for similar structures. Figure 11 displays the electric field distribution of the optimized converter, demonstrating efficient TEM-TE₁₀ mode conversion with negligible higher-order mode reflection at the coaxial port.

This performance is quantified in Fig. 12. The total reflection of -33 dB corresponds to a mode conversion (power) efficiency of 99.95%, confirming negligible insertion loss.

The four output ports will be combined into a single input for the accelerator using commercially available power combiners. Acknowledging that this approach somewhat compromises system compactness, we plan to investigate more specialized, compact combiners or transition to a single-waveguide output scheme in future studies.

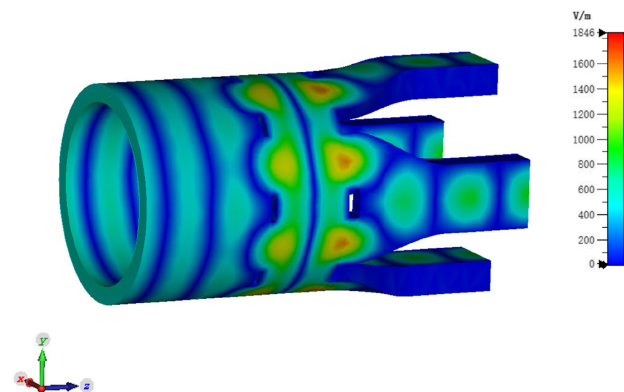


FIG. 11. Electric field distribution of the mode converter when inputting power from the port of coaxial waveguide.

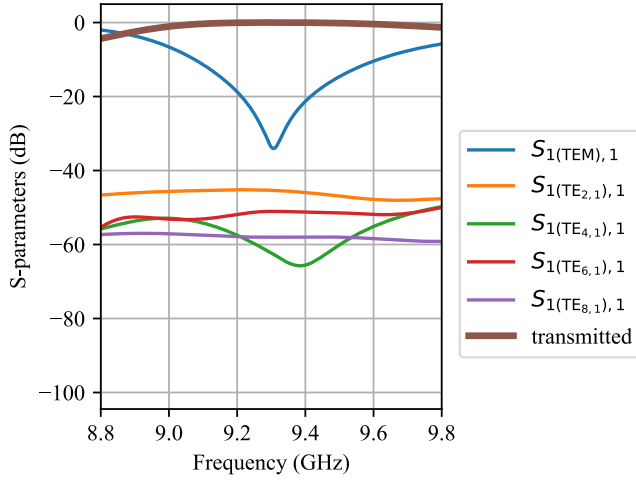


FIG. 12. Scattering parameters of the mode converter. Here, port 1 refers to the input port (see Fig. 10) of the mode converter.

V. ACCELERATING STRUCTURE

A standing-wave accelerating structure nested in the hollowed-out CTTO is used to accelerate the witness beam. It is modified from our previous design [31]. The accelerating structure consists of 3 bunching cells, 16 normal cells, and 1 coupler cell, with a total length of ~ 320 mm.

Figure 13 shows the distribution of rf electric field and the shared magnetic field (generated by the permanent magnet described in Appendix A) on the axis of the accelerating structure. Under these fields, the beam dynamics is simulated with the General Particle Tracer code [41]. In the beam dynamics simulation, a 50-kV, 200-mA dc witness electron beam is uniformly emitted from a circular area with a radius of 0.7 mm.

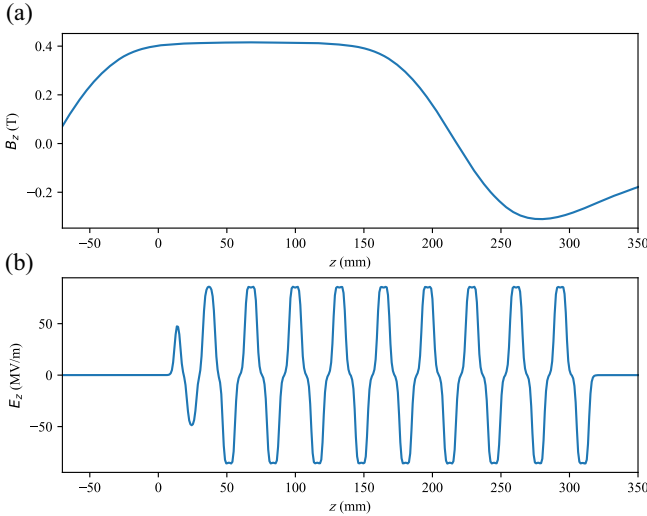


FIG. 13. Field profiles for beam dynamics analysis of the accelerating structure. (a) Magnetic flux density at the axis. (b) Longitudinal electric field E_z on the axis of the accelerating structure at rated input rf power and beam loading.

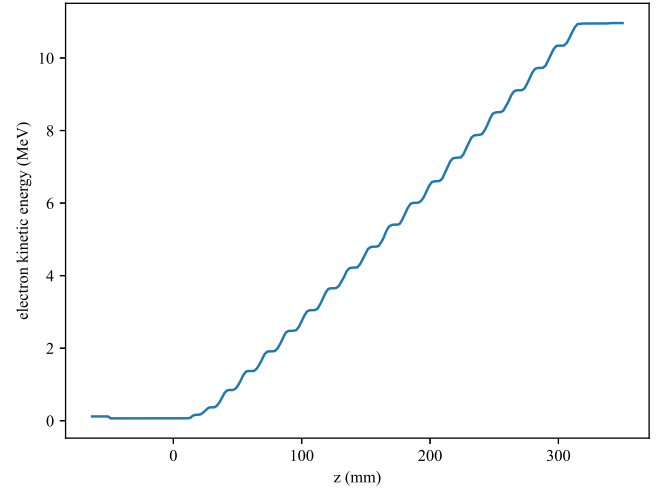


FIG. 14. Mean kinetic energy of the witness beam as a function of longitudinal position (z).

Within the 32-cm-long structure, the witness beam is accelerated to 10.96 MeV, as shown in Fig. 14. The outgoing electrons are 128.2 mA, corresponding to a transmission efficiency of 51.4%. The spectrum shown in Fig. 15 indicates that the energy spread of the transmitted electrons is 2 MeV, and most transmitted electrons have energy exceeding 10.7 MeV. The generated electron beam is sufficient to meet typical requirements in fields such as medical and industrial irradiation.

Based on the equivalent circuit theory and the result of beam dynamics simulation, the power consumption of the accelerating structure can be calculated. The equivalent circuit parameters for the calculation are summarized in Table I, which were obtained with CST Microwave Studio [42]. According to the calculation, the power for building the field and for accelerating the beam is 3.95 and 1.41 MW,

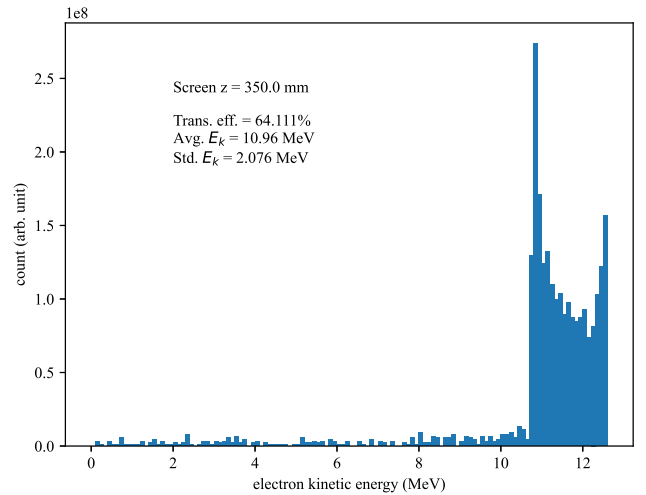


FIG. 15. Energy spectrum of the witness beam at the exit of the accelerating structure.

TABLE I. Primary parameters of the accelerating structure.

Parameter	Value
Operating frequency	9.3 GHz
Operating mode	Bi-periodic $\pi/2$ -mode with magnetic coupling slots
Cell-to-cell coupling coefficient	3.9%
Group velocity ^a	$0.061 c$
Coupler type	Single-feed, aperture coupling
Rated input rf power	5.36 MW
Initial voltage of the beam	50 kV
Emitted beam current	200 mA
Transmission efficiency	64.1%
Number of cells	3 (bunching) + 16 (normal) + 1 (coupler)
Mean kinetic energy at linac exit	10.96 MeV
Total length	~ 320 mm
Effective shunt impedance	125 M Ω /m
Intrinsic quality factor (Q_0)	~ 7000
External coupling strength (β)	1.29

^aHere, c denotes the speed of light in vacuum.

respectively. The total rf power demand of the accelerating structure is hence 5.36 MW, which can be well covered by the output capability of the CTTO main port (the port connected to the CTTO extractor) with appropriate redundancy.

Figure 16 shows the simulated transverse beam profile at the exit of the accelerating structure ($z = 350$ mm). The root-mean-square (rms) beam sizes are $\sigma_x = 0.63$ mm and $\sigma_y = 0.65$ mm, with the beam center displaced by $(\bar{x}, \bar{y}) = (17 \mu\text{m}, -12 \mu\text{m})$ from the axis. This beam quality meets the requirements for typical standing-wave linac applications such as bremsstrahlung-based x-ray generation. The simulated asymmetries originate from the single-feed coupler configuration in the final cell and transverse momentum coupling from the magnetic field. These effects can be mitigated in future designs through coupler geometry optimization or implementation of a multifeed layout, both compatible with the CI-Linac framework. While this study focuses on high-power microwave generation, beam quality optimization will be systematically addressed in subsequent work.

To better highlight the advantages of our design, we have compiled key metrics from recent normal-conducting linac systems operating at similar modulator voltages (below 65 kV, a level typically not requiring bulky oil insulation), as summarized in Table II. Since both the gradient E_a and energy gain ΔE depend on structure length L —following $E_a \approx \sqrt{P_{\text{in}} Z T^2 / L}$ and $\Delta E \approx \sqrt{P_{\text{in}} Z T^2 L}$, where $Z T^2$ is the effective shunt impedance per unit length and P_{in} is the input power—we introduce the product $E_a \Delta E$ as a length-independent figure of merit (FOM). This enables a

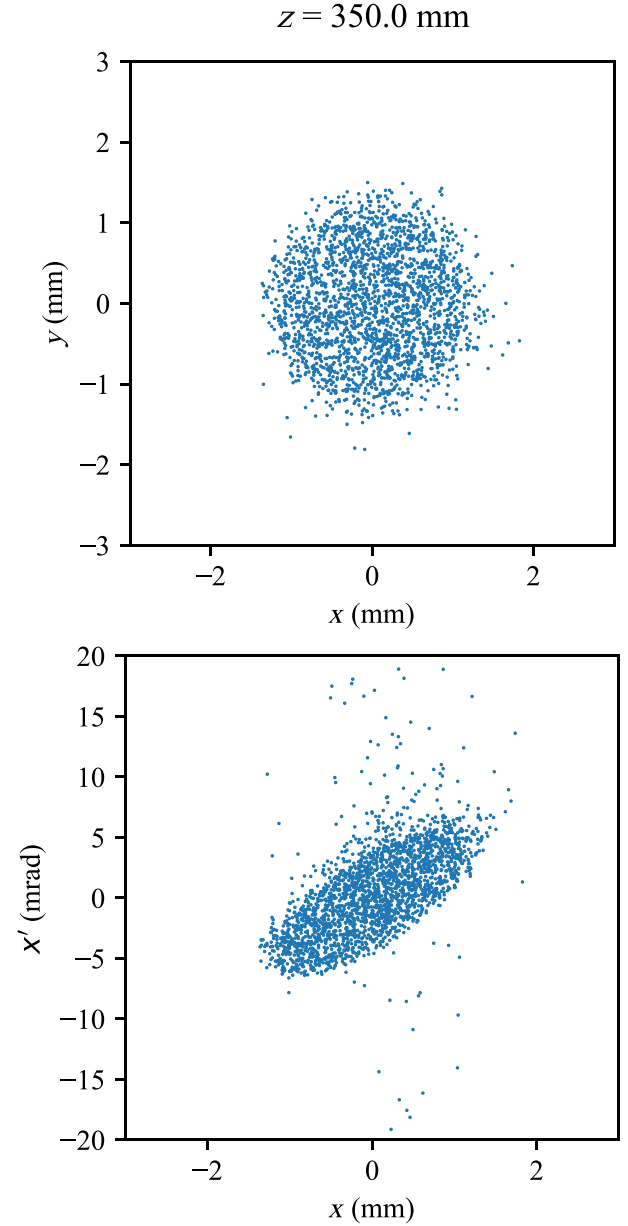


FIG. 16. Beam spot (upper) and transverse phase space (lower) at the linac exit.

meaningful comparison across accelerators designed for different applications.

As shown in the table, the proposed CI-Linac achieves a higher FOM than conventional systems, reflecting its superior overall performance. This advantage originates from the use of a CTTO, which inherently supports intense electron beams and enables higher power generation at high frequencies compared to conventional rf sources. Furthermore, the coaxial integration of the CTTO with the accelerating structure eliminates spatial redundancy, yielding a more compact system than distributed configurations powered by similar high-power coaxial sources.

TABLE II. Comparison of standing-wave linacs powered by microwave sources with similar modulator voltage.

P_{in} (MW)	f (GHz)	ΔE (MeV)	L (mm)	E_a (MV/m)	FOM ($10^{12}\text{eV}^2/\text{m}$)	rf source type	Reference
5.36	9.3	10.96	320	36	375	CTTO	This work
1.58	9.3	6	373	16	97	Magnetron	[43]
0.25	15.14	2	249	8	16	Magnetron	[44]
5.5	2.997	15	1112	13	202	Klystron	[45]
2	2.998	7	520	15	94	Magnetron	[46]
2.2	5.712	6	390	15	92	Magnetron	[47]
1.5	9.3	6	350	17	103	Magnetron	[48]
2.4	9.3	9	500	18	162	Klystron	[49]
5	2.856	15	970	15	232	Magnetron	[50]
1.5	5	4	273	15	59	Magnetron	[51]
1.7	9.3	6	350	17	103	Magnetron	[52]

VI. CONCLUSION

In conclusion, this study addresses the critical need for compact, high-power linear accelerator systems by proposing the integration of a high-power microwave source with an accelerating structure. The proposed design, merging an X-band coaxial transit-time oscillator (CTTO) with an X-band accelerating structure, marks a significant advancement in overcoming conventional linacs' limitations—especially their bulkiness and reliance on high-voltage, space-consuming microwave sources. Leveraging the CTTO's advantages (low operating voltage, stable performance, high power, and high efficiency), the integrated system achieves notable results: a 50 kV CTTO generates 7.8 MW of radio-frequency power at 9.3 GHz (with efficiency over 50%), accelerating an electron beam from 50 keV to 10.96 MeV over just 320 mm. This drastically reduces the accelerator's total volume, establishing it as one of the most compact rf linacs to date. This integration validates coaxial microwave sources, particularly CTTOs, as game-changers in accelerator design. It paves the way for portable, high-energy particle accelerators, unlocking new possibilities in scientific research, medical applications, and industrial processing where compactness and efficiency are critical.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing,

and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: PRELIMINARY DESIGN OF THE SHARED MAGNET

To generate the shared magnetic field that confines both the driver beam in CTTO and the witness beam in accelerating structure, a permanent magnet is designed. The permanent material is sintered NdFeB (N42SH), with a measured remanent flux density of 1.28 T. The geometry and magnetization of the magnet are shown in Fig. 17. The magnet leaves enough space for the installation of the CI-Linac (can be seen in Fig. 1). Figure 18 shows the profile of the magnetic induction intensity (B) along the ideal driver beam path ($r = 40$ mm) and witness beam path ($r = 0$). We have checked that the operation of the CTTO under this magnetic field is very close to the ideal case where a uniform 0.4 T field is applied.

The weight of the magnet is about 138 kg (with the density of 7.6 g/cm^3), which is the main defect of the present device. Fortunately, the weight of the magnet can be

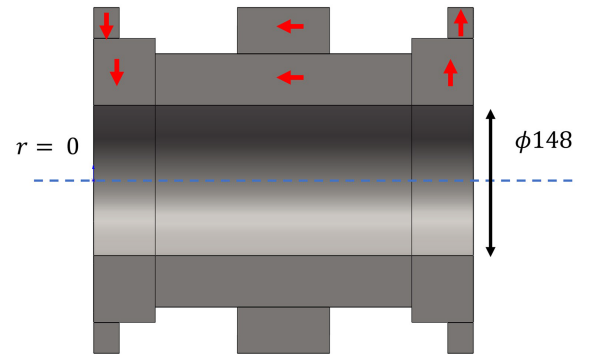


FIG. 17. Geometry and magnetization (indicated by the red arrows) of the shared permanent magnet. The dimensions marked are in millimeters.

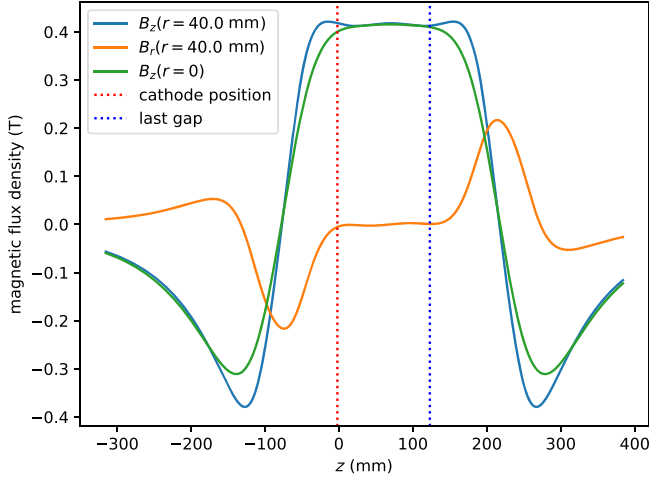


FIG. 18. Magnetic flux density generated by the permanent magnet.

significantly reduced by using the periodic cusped permanent magnet configuration if the gap between the CTTO and the accelerating structure becomes reasonably larger to embed inner magnetic blocks [53,54]. A new CI-Linac compatible with this magnet configuration is currently under design. The design presented in this manuscript will also serve as a benchmark for the future lightweight CI-Linacs.

APPENDIX B: MODEST OSCILLATION INITIALIZED BY THE CTTO BUNCHER

For a CTTO, the monotron oscillation occurring in the buncher determines its operating frequency and strongly influences its ultimate performance. A proper buncher should oscillate at a single frequency to modulate the driver beam, and the amplitude of oscillation should not be too large to overmodulate. Therefore, designing the buncher is one of the most crucial phases when developing a CTTO. Our strategy for designing the buncher is: first, find an appropriate field profile based on analysis of one-dimensional (1D) interaction dynamics; then design geometric structures to match the field distribution of a certain eigenmode with the desired one; and finally verify it through PIC simulation.

To begin with, we consider an E_z profile (i.e., E_z field distribution along $r = 40$ mm, the nominal driver beam path) with two extreme values, as shown in Fig. 19(a), which is commonly used in conventional CTTOs. Based on our self-developed large-signal code PyDISK (grounded in the principles stated in Refs. [33,55]), we can see that, in the steady state, the two-extreme profile causes overmodulation, namely, there is a large energy spread and a low fundamental current downstream of the buncher, as evidenced in the Applegate diagram [Fig. 19(b)], the distribution of modulated beam current [Fig. 19(c)], and the

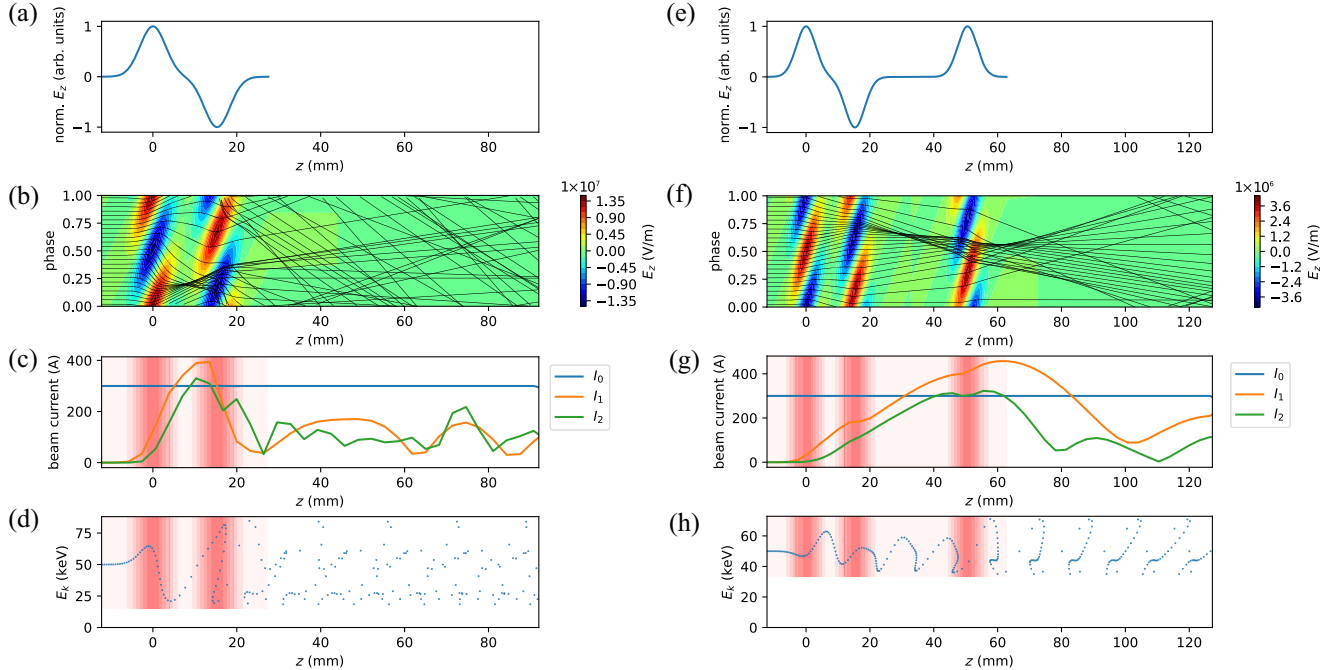


FIG. 19. Two E_z profiles to be considered and their 1D large-signal calculation results. (a)–(d) for the two-extreme case, and (e)–(h) for the three-extreme case. (a) and (e) are the normalized E_z distribution for two-extreme case and three-extreme case, respectively. (b) and (f) are the Applegate diagram for two-extreme case and three-extreme case, respectively. (c) and (g) are the modulated beam current for two-extreme case and three-extreme case, respectively. Here, I_0 , I_1 , and I_2 denote the dc component, fundamental (9.3 GHz), and second harmonic of the beam current, respectively. (d) and (h) are the energy phase space for two-extreme case and three-extreme case, respectively. Here, E_k represents the kinetic energy of electron.

phase space plot [Fig. 19(d)] obtained by PyDISK. Here, the Applegate diagram is a widely used tool for designing O-type microwave sources, which summarizes the spatio-temporal relationship of the electron beam and E_z field at the steady state. The ordinate is $\varphi = f(t - z/v_0)$, where f denotes the operating frequency, t the time, z the longitudinal position, v_0 the reference velocity (typically the velocity of the electron before interaction), respectively. So a trajectory line with positive (or negative) slope in the Applegate diagram means that its represented electrons are accelerated (or decelerated). The convergence and divergence of the Applegate trajectories reflect that the beam is bunched (longitudinally focused) and debunched (longitudinally defocused), respectively. The color map in the Applegate diagram shows the spatiotemporal distribution of the E_z field.

Since the efficiency is positively related to the fundamental beam current at which the extractor is placed, and the large energy spread prevents the beam from being further modulated, it is difficult to achieve high power conversion efficiency with such a buncher. In contrast, the three-extreme profile [Fig. 19(e)], in which an additional extreme is introduced at a proper downstream position of the conventional two-extreme profile, allows a modest

monotron oscillation. As is seen in the Applegate diagram [Fig. 19(f)], the bunch initialized by the first extreme will be overall decelerated in the second extreme, which ensures the eigenmode can obtain energy from the dc beam, so the monotron oscillation still occurs, just like in the only-two-extreme case. The decelerated bunch mainly falls into the bunching phase in the third (the additional) extreme. If the microwave field becomes larger, the deceleration of the second extreme is stronger, and the bunch will fall into the accelerating phase in the third extreme, which offsets the extracted beam energy from the second extreme. This mechanism effectively avoids excessive growth of the microwave field in the buncher, namely, prevents the driver beam from overmodulation [as seen in Figs. 19(f)–19(h)].

Such a three-extreme profile can be approximated by the quasi- $\pi/2$ -mode of a five-gap cavity. Figure 20 shows a candidate buncher's geometry and the E_z -field distribution of the nearby modes. Among them, the mode 3 has an E_z profile similar to the designed one. However, an analysis for these modes based on small-signal theory indicates that the mode 4 is a potential competitor. According to the small-signal theory, the “hot” quality factor Q_{hot} is an indicator for monotron oscillation. A mode with negative $1/Q_{\text{hot}}$ indicates that the mode will obtain energy from a dc

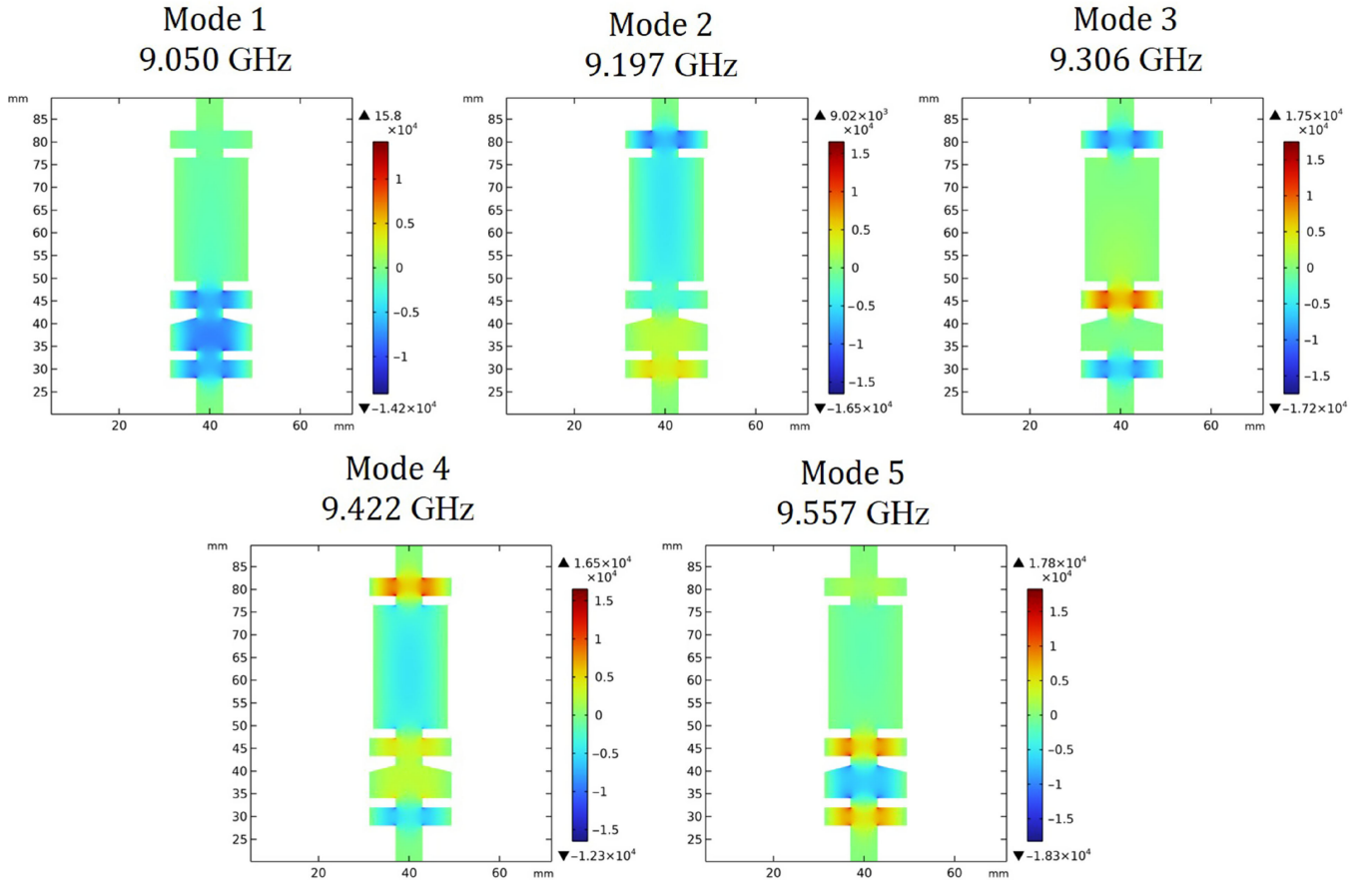


FIG. 20. Longitudinal electric field (E_z) distribution of the eigenmodes in the CTTO buncher (without damping waveguide). The abscissa and ordinate for each subfigure are r and z , respectively.

beam, namely, monotron oscillation occurs, and the mode growth rate scales as $-f/Q_{\text{hot}}$.

The hot quality factor Q_{hot} is defined as

$$\frac{1}{Q_{\text{hot}}} = \frac{1}{Q_0} + \frac{1}{Q_e} + \frac{1}{Q_b}, \quad (\text{B1})$$

where Q_0 , Q_e , and Q_b are the intrinsic quality factor, the external quality factor, and the beam-related quality factor, respectively. The former two can be directly obtained with eigenmode simulation.

$$\frac{1}{Q_b} = \left(\frac{R}{Q}\right) G_b, \quad (\text{B2})$$

where $(\frac{R}{Q})$ is the characteristic impedance of the mode, G_b is the beam conductance.

$$G_b = -\frac{\beta_b I_0}{4 V_0} \frac{\partial |M|^2}{\partial \beta_b}, \quad (\text{B3})$$

$$M = \frac{\int_{-\infty}^{+\infty} E_z(z) e^{i\beta_b z} dz}{\int_{-\infty}^{+\infty} |E_z(z)| dz}, \quad (\text{B4})$$

$$\beta_b = \frac{2\pi f}{v_b}, \quad (\text{B5})$$

where $E_z(z)$ is the complex longitudinal electric field profile, I_0 is the dc component of beam current, V_0 is the dc component of beam voltage, f is the mode frequency, and v_b is the velocity of electron beam.

Figure 21 shows the calculated $1/Q_{\text{hot}}$ of the modes shown in Fig. 20. As is seen, when the electron kinetic energy of the driver beam is 50 keV, only mode 3 has a negative $1/Q_{\text{hot}}$. However, if the kinetic energy is slightly decreased, the $1/Q_{\text{hot}}$ of mode 4 can also be negative enough. Because space-charge effects lower the effective kinetic energy below the applied gun voltage—especially within the coaxial gaps where the beam is farther from the inner and outer conductors (the shielding provided by induced charges on the conductors weakens with increasing beam-conductor separation)—excitation of the unwanted mode 4 becomes possible. This is also demonstrated in the subsequent PIC simulation (see Fig. 22). When the emitting voltage is set to 50 kV, the PIC-simulated spectrum of the microwave field in the buncher shows that it oscillates at two frequencies: 9.31 and 9.48 GHz. The latter is close to the frequency of mode 4 obtained in eigenmode simulation. The oscillation spectrum is purer when appropriately increasing the emitting voltage. However, doing so severely alters the 1D interaction dynamics, ultimately leading to overmodulation again.

Therefore, we adopted another approach: reducing external quality factors of the unwanted modes, as they increase their $1/Q_{\text{hot}}$ according to Eq. (B1). The physical

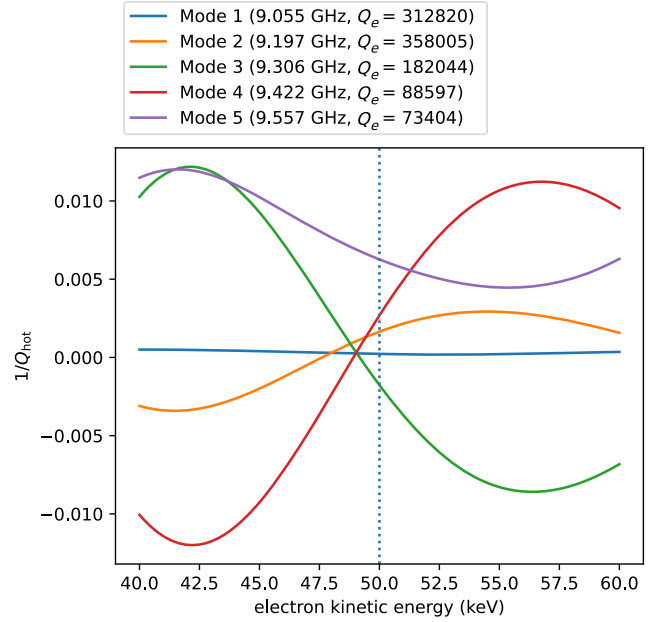


FIG. 21. $(1/Q_{\text{hot}})$ as a function of electron kinetic energy for the buncher without damping waveguide. $Q_0 = \infty$ is assumed in the calculation because it has little impact on the results.

essence of this method is to make the power loss of the undesired modes exceed the power that they obtain from the self-modulated electron beam. As shown in Fig. 20, for the unwanted mode 4, a large amount of rf field energy is stored in the longest gap, while for the desired mode 3, the energy stored in the longest gap is negligible. Hence, a waveguide opening at the wall of the longest gap can significantly damp mode 4 while hardly affecting

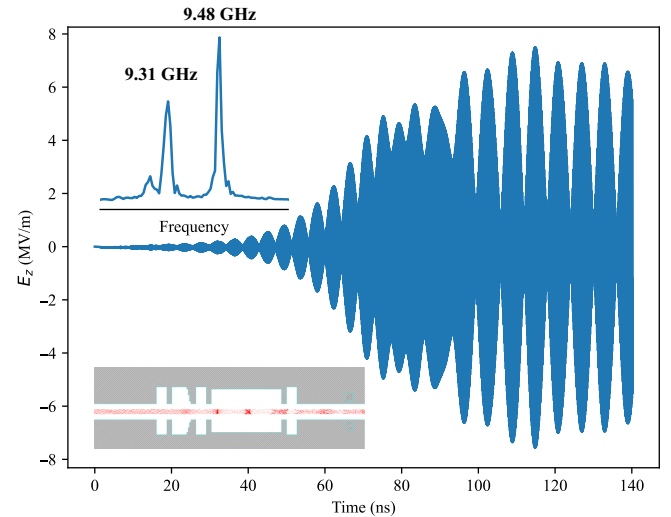


FIG. 22. PIC simulation results of the CTTO buncher without damping waveguide demonstrate mode competition. The time-domain signal is the longitudinal electric field at the first gap. The upper inset is the FFT spectrum of the time-domain signal. The lower inset shows the model for simulation.

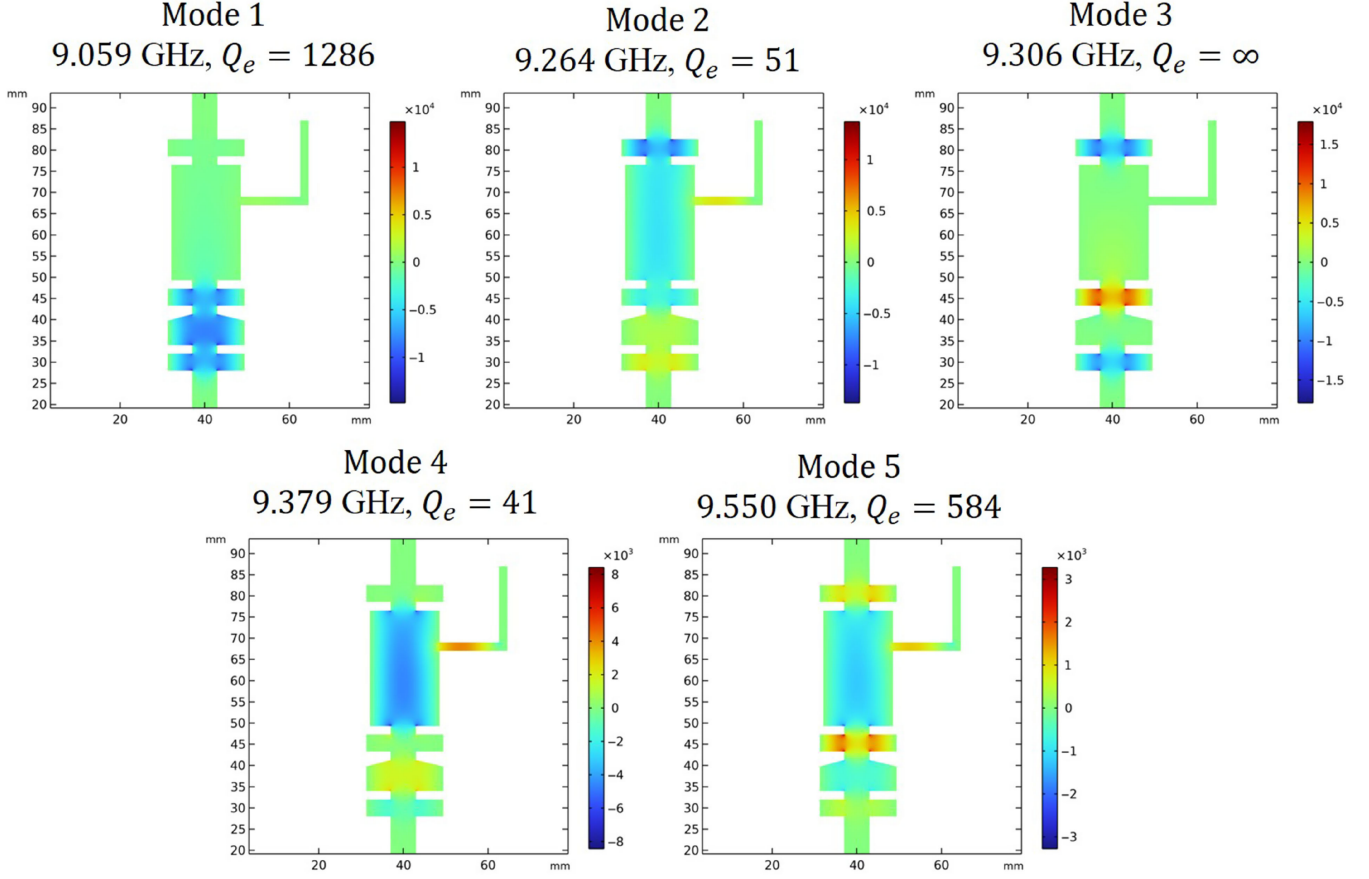


FIG. 23. Longitudinal electric field (E_z) distribution of the eigenmodes in the CTTO buncher with damping waveguide. The abscissa and ordinate for each subfigure are r and z , respectively.

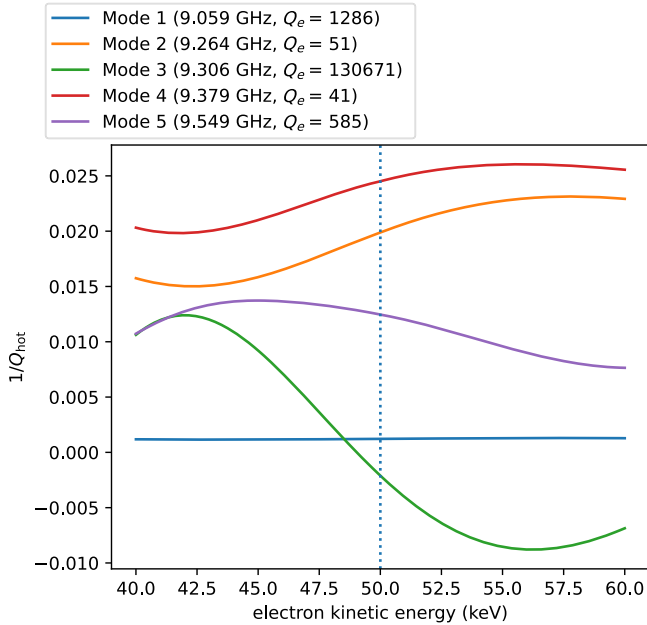


FIG. 24. $(1/Q_{\text{hot}})$ as a function of electron kinetic energy for the buncher with damping waveguide. $Q_0 = \infty$ is assumed in the calculation because it has little impact on the results.

mode 3. Figure 23 shows the E_z -field distribution of the modes of the new buncher with a damping waveguide. The Q_e of the mode 4 in the new buncher is decreased to merely ~ 40 , which results in a positive $1/Q_{\text{hot}}$, as shown in Fig. 24. The PIC simulation results (see Sec. III) demonstrate that overmodulation is well suppressed as expected with the new buncher while no mode competition is observed.

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