

Compact linear accelerator integrated with a high-power microwave source

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Particle accelerators have played a pivotal role in scientific research, medical applications, and industrial processes. However, conventional radio-frequency accelerators face limitations due to their large size, high cost, and dependence on external microwave sources. This paper presents a novel linear accelerator design that integrates a high-power microwave source directly into the accelerator structure, eliminating the need for external drivers and enabling a more compact, cost-effective, and simplified system. The proposed design employs an X-band backward wave oscillator driven by a 50 keV hollow continuous electron beam. The generated microwave power is coupled into a central X-band standing-wave acceleration structure via a radial coupler. Simulations demonstrate that a witness beam passing through this structure can be accelerated from 50 keV to over 4 MeV across 10 acceleration cells. This work serves as a foundational study on integrated accelerator concepts, offering a pathway toward more efficient, scalable, and versatile particle acceleration systems.

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I. INTRODUCTION

Particle accelerators stand as one of the most remarkable technological advancements of the 20th century, with pivotal roles in the realms of fundamental research, medical and industrial applications [1–3]. Despite their diverse and significant impacts, conventional radio-frequency (rf) particle accelerators come with notable limitations. These systems are characteristically large and expensive, often encompassing extensive facilities to house their vast array of components [4]. A primary contributor to their cost and complexity is the need for outsized external microwave sources [5]. These sources must be finely tuned and matched to the accelerator structure, creating an intricate interdependency that complicates maintenance and scaling.

To address these challenges, researchers have made considerable advancements with novel acceleration schemes [6–19]. Wakefield acceleration in dielectric-lined waveguides, for example, has shown promise in miniaturizing the accelerator footprint by using the wakefields generated by an electron bunch traveling through a medium [6–10]. Similarly, the two-beam acceleration approach

sidesteps the need for an external microwave source by using a driver electron beam to present an acceleration field [11–13]. Both techniques exemplify the shift toward more compact and cost-effective acceleration methods that untangle the complexities associated with external microwave sources. However, they require a well bunched and relativistic driver beam [20]—increasing operational complexity—and demand precise control over the timing between driver and witness beams [21], which is difficult to achieve consistently. Moreover, it is difficult for these accelerators to achieve the efficient acceleration of a continuous electron beam, which limits their applications in many practices, such as medical and industrial treatments.

In light of the challenges of previous accelerator schemes, this paper introduces a novel linear accelerator concept that marries a coaxial microwave source with the accelerator structure. By this merger, our design obviates the need for a separated microwave driver, leading to substantial reductions in size and cost. The integration does not merely improve efficiency; it redefines the paradigm of accelerator designs by embedding the source directly into the accelerating environment, potentially enhancing beam quality and stability. Through our investigation, we aim to establish a new benchmark for compact, cost-effective particle acceleration, bolstering the utility of accelerators across diverse fields.

This paper is organized as follows. Section II describes the key idea of the proposed model and the basic analysis methods of the model. Section III provides details on the design and simulation results of the coaxial microwave

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source. Section IV discusses the design and simulation results of the acceleration structure. Section VI is a conclusion.

II. DESCRIPTION OF THE PROPOSED MODEL

The proposed integrated linear accelerator, illustrated in Fig. 1, consists of two primary components: (i) a coaxial rf source (outer structure) that generates microwave power through self-bunching of an annular driver beam; and (ii) a central rf accelerating structure (inner structure) that receives and utilizes this power to accelerate a witness beam. The system operates by extracting rf power from the annular driver beam in the coaxial source and coupling it radially into the accelerating structure. Both electron beams are confined transversely by a shared quasiuniform guiding magnetic field, ensuring stable transport throughout the system.

This integrated accelerator design offers several key benefits: (i) Mitigation of space-charge effects. The coaxial configuration significantly reduces space-charge limitations, enabling operation with either a higher-current driver beam, a lower driving voltage, or a reduced confining magnetic field [22–24]. (ii) Scalable high-power microwave generation. Increasing the driver beam radius enhances power-handling capability without affecting frequency stability, allowing high-power microwave generation at high frequencies using a single tube [25–27]. (iii) Compact and multifunctional architecture. The embedded accelerating structure adds

TABLE I. Primary parameters of the exemplary integrated linac.

Parameter	Value
(Coaxial rf source)	
Diode voltage	50 kV
Driver beam current	120 A
Power generated by the coaxial rf source	1.8 MW
Guiding magnetic induction intensity	0.35 T
Operation frequency	9.46 GHz
(Accelerating structure)	
Witness beam current	100 mA
Operating mode	Bi-periodic $\pi/2$
Number of accelerating cells	10
Kinetic energy at linac exit	4.38 MeV
Energy spread at linac exit	98.9 keV
Total length	~190 mm
Effective shunt impedance	143.75 M Ω /m
Intrinsic quality factor (Q_0)	7891
Beam transmission efficiency	71%

functionality without requiring additional external space, maintaining an efficient footprint. (iv) Shared infrastructure for reduced complexity. Critical components—such as the guiding magnet, shielding, and pulse modulator—are shared between the coaxial rf source and the accelerating structure, minimizing system size and cost.

A preliminary integrated linac has been designed for principle demonstration. Table I summarizes the primary parameters of the model.

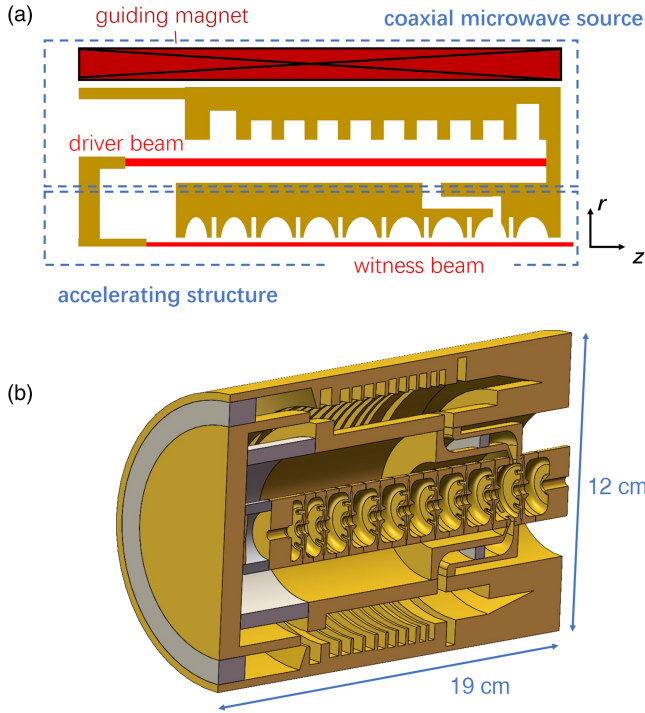


FIG. 1. Proposed integrated linac. (a) Schematic diagram and (b) three-dimensional rendering (the guiding magnet and beams are omitted).

III. COAXIAL MICROWAVE SOURCE

The microwave source is an X-band coaxial backward wave oscillator, as shown in Fig. 2. It is designed to operate under a dc voltage of 50 kV, an emitted beam current of 120 A, and a guiding magnetic induction intensity of 0.35 T. The beam current and voltage correspond to a perveance of $10.7 \mu\text{A V}^{-1.5}$, which is difficult to achieve for those general klystrons using solid beam (typically less

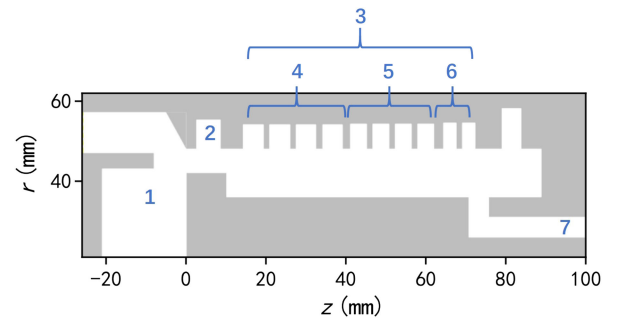


FIG. 2. Structure of the coaxial rf source. 1—diode region; 2—reflector; 3—nonuniform slow wave structures (SWSs), including three uniform SWSs marked 4, 5, and 6, respectively; 7—coaxial output waveguide.

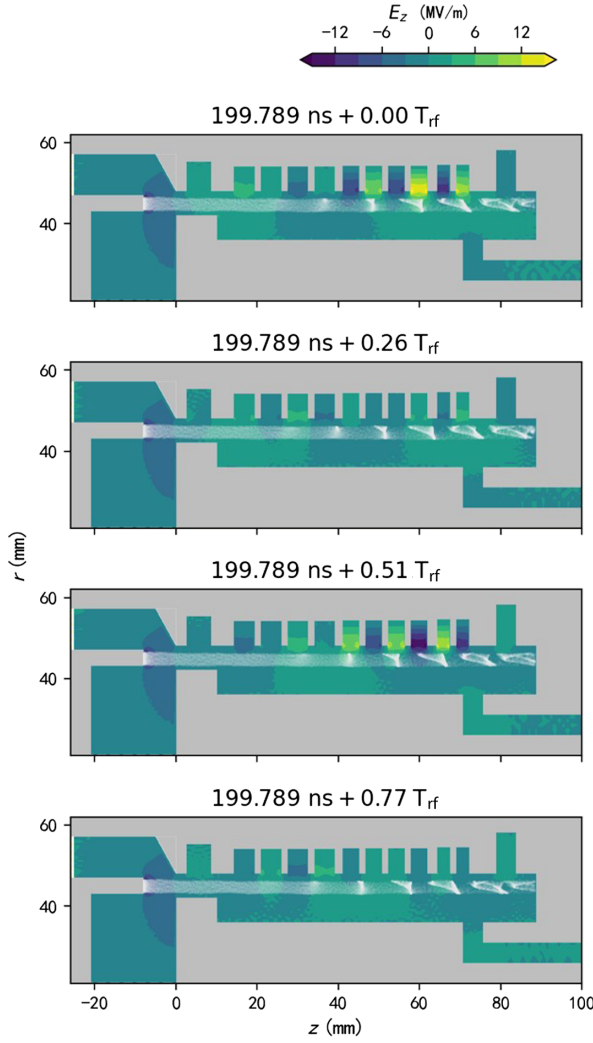


FIG. 3. Snapshots of the longitudinal electric field (E_z) and driver electron positions in the coaxial rf source during one rf period (T_{rf}) when the output power saturates.

than $2 \mu\text{AV}^{-1.5}$ in X-band [28–30]) mainly due to significant space charge effect. The 50-kV voltage typically allows a compact pulse modulator without oil tank [31,32], partly contributing to the reduction of system footprint.

The wave-beam interaction mainly takes place in the nonuniform slow wave structures (SWSs). As shown in Fig. 3, the oscillation mode is a TM_{01} π -like mode. Under this mode, the dc driver beam undergoes a moderate modulation in the first segment of SWS and is then bunched after drifting. The downstream SWSs with step-wise reduced period length ensure a good synchronization with the bunches, contributing to a long-distance deceleration. As a result, the average kinetic energy of the driver beam gradually decreases from ~ 50 to ~ 33 keV (Fig. 4). The broadband reflector in front of the SWSs effectively suppresses undesired coupling between the source and the linac through diode region, so most of the rf power is output through the coaxial port.

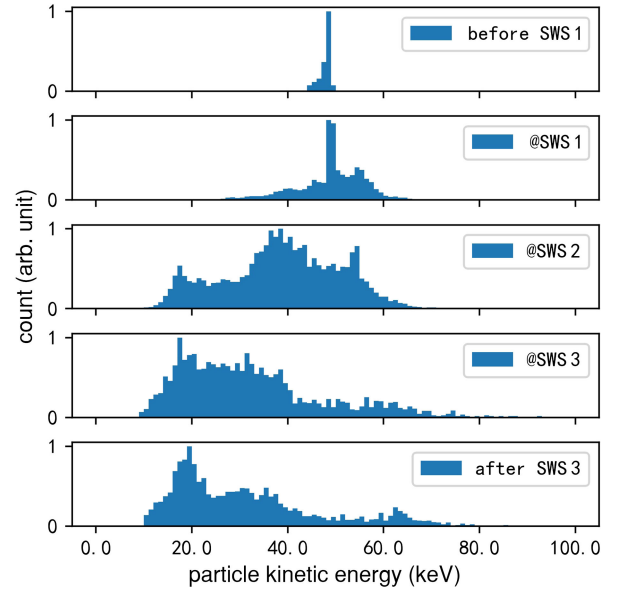


FIG. 4. Histogram of electron kinetic energy of the driver beam at different regions. SWS 1–3 correspond to the regions numbered as 4–6 in Fig. 2.

Figure 5(a) shows the voltage spectrum at the coaxial output port. It shows a high purity, with a dominant frequency of 9.46 GHz and negligible noise frequencies. The average power is 1.8 MW, as shown in Fig. 5(b), indicating a beam-wave power conversion efficiency of $\sim 30\%$.

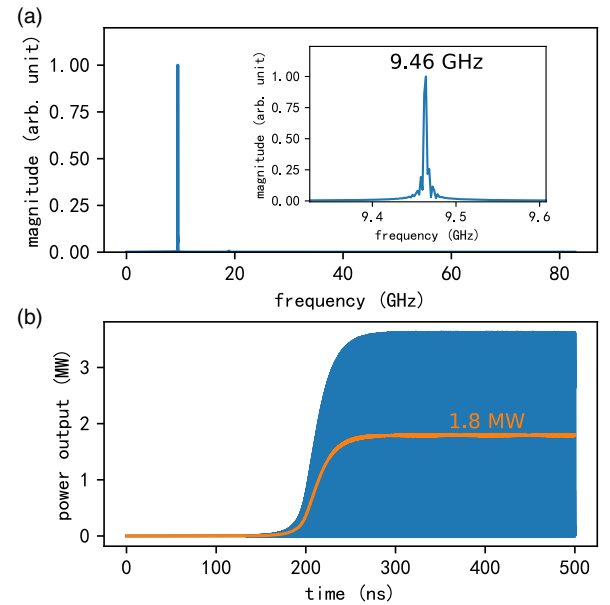


FIG. 5. (a) Spectrum of the voltage at the output port. The inset is an enlarged view of the spectrum near the dominant frequency and (b) output power as the function of time. The blue line is the field oscillations in a continuous buildup of power. The orange line is the periodic average power.

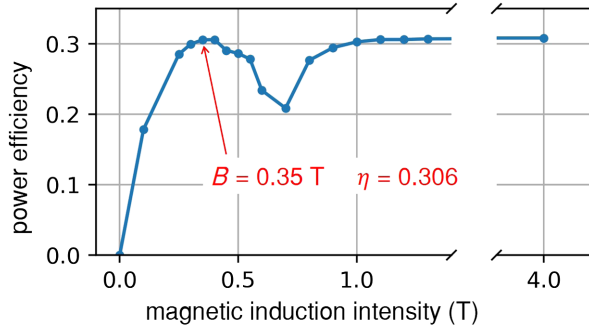


FIG. 6. Power conversion efficiency of the coaxial microwave source as a function of the magnetic induction intensity (B).

A quasiuniform magnetic field is applied for transverse beam focusing. We investigate the output performance of the coaxial source under different guiding magnetic fields, as shown in Fig. 6. A drop in power efficiency occurs at 0.7 T due to absorption from cyclotron resonance [33]. Below the absorption point, the minimum guiding magnetic field to reach the maximum efficiency ($\sim 30\%$) is about 0.35 T, which is close to many commercial products with similar specifications. Also, the magnetic field can be further decreased to 0.25 T if allowing a 2.1% small decline on efficiency, which would be more conducive to the minimization.

IV. ACCELERATING STRUCTURE

A standing-wave, bi-periodic magnetic coupling accelerating structure is designed to accelerate the 50 keV dc witness beam. It operates at 9.46 GHz, consistent with the oscillation frequency of the coaxial rf source. The structure and designing method refers to some published works, such as Refs. [34,35]. Main parameters of the accelerating structure are listed in Table I.

Figure 7 shows the longitudinal electric field distribution along the axis of the accelerating structure in operating mode. To maintain such a field distribution, the power dissipated in the structure is 1.25 MW. The dynamics simulation presented in the following shows that the power consumption of the 100 mA witness beam in this field is 0.31 MW. The total power consumption is not beyond the

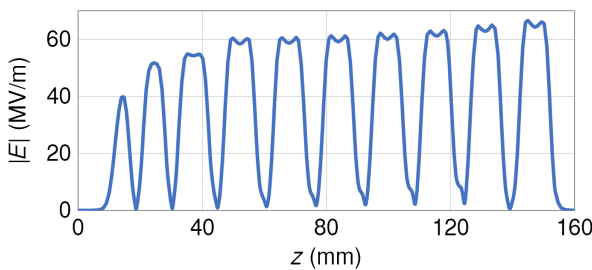


FIG. 7. On axis longitudinal electric field distribution of the accelerating structure.

power generation capability of the coaxial rf source. According to the matching theory of linac [36], the coupling strength between the accelerating structure and the coaxial line is designed to be 1.24, which helps minimize the reflection from the accelerating structure to the rf source at the steady state.

The beam dynamics of the accelerating structure are simulated with CST-PIC. In the simulation, the witness beam is uniformly emitted from a circular area of a simplified Piercelike cathode and accelerated to 50 keV by electrostatic field. The radius of the circular emission area is 0.7 mm. The simplified Piercelike cathode is used to ensure the laminarity of the witness beam when the magnetic field is absent.

Figure 8(a) presents the distribution of witness beam under the optimal guiding magnetic field of the coaxial rf source, 0.35 T. At the linac exit, the witness bunch has a longitudinal length full width at half maximum (FWHM) of about 0.26 mm [see Fig. 8(b)], corresponding to a FWHM temporal length of about 0.9 ps. In the transverse, the beam spot has a root mean square (rms) size of 402 μm in the x direction and 391 μm in the y direction, respectively, as shown in Fig. 8(c). The 3% difference of beamsizes in the two directions is due to simulation accuracy. The mean kinetic energy and rms energy spread of accelerated electrons (i.e., electrons with kinetic energy above 4 MeV) are 4.38 MeV and 98.9 keV, respectively, as Fig. 8(d) shows. At the linac exit, the average beam current is about 71 mA, corresponding to a transmission efficiency of 71%. The power absorbed by the witness beam is therefore 0.31 MW.

It is worth noting that, owing to sharing the guiding magnetic field of the coaxial source, most electrons in the

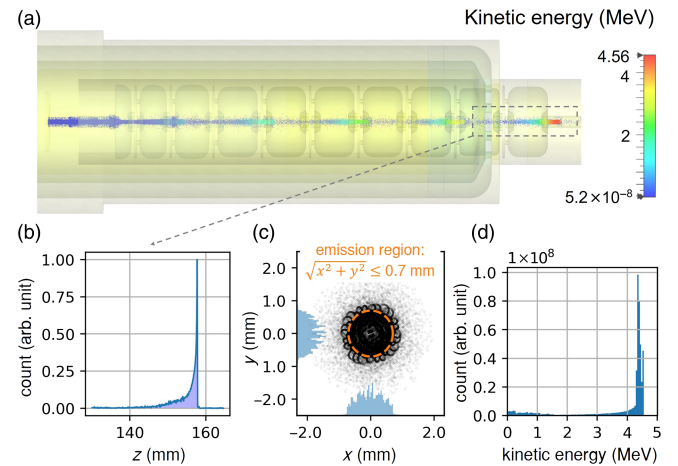


FIG. 8. Particle-in-cell simulation results of beam dynamics inside the accelerating structure at a magnetic induction intensity of 0.35 T. (a) Snapshot of the electron position inside the accelerating structure. The color of the particle represents its kinetic energy, (b) histogram of the axial position of electrons in the rightmost bunch in (a), (c) the beam spot at the linac exit, and (d) the electron kinetic energy spectrum at the linac exit.

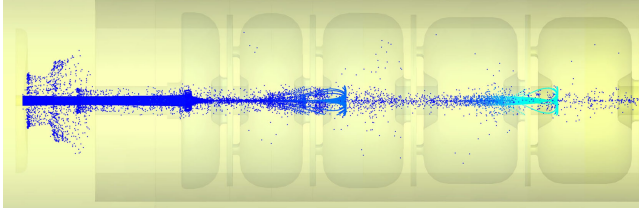


FIG. 9. Typical snapshot of the electron distribution inside the accelerating structure when guiding magnet is absent. The color map is the same as Fig. 8(a).

witness beam are well confined within the circular area with a radius of 0.7 mm [see Fig. 8(c)], i.e., the initial emission area. Hence, electron bombardment on the structure is significantly suppressed [can be evident in Fig. 8(a)]. As a comparison, for conventional medical linacs, this is not the case, since a dedicated magnet is uneconomical. Figure 9

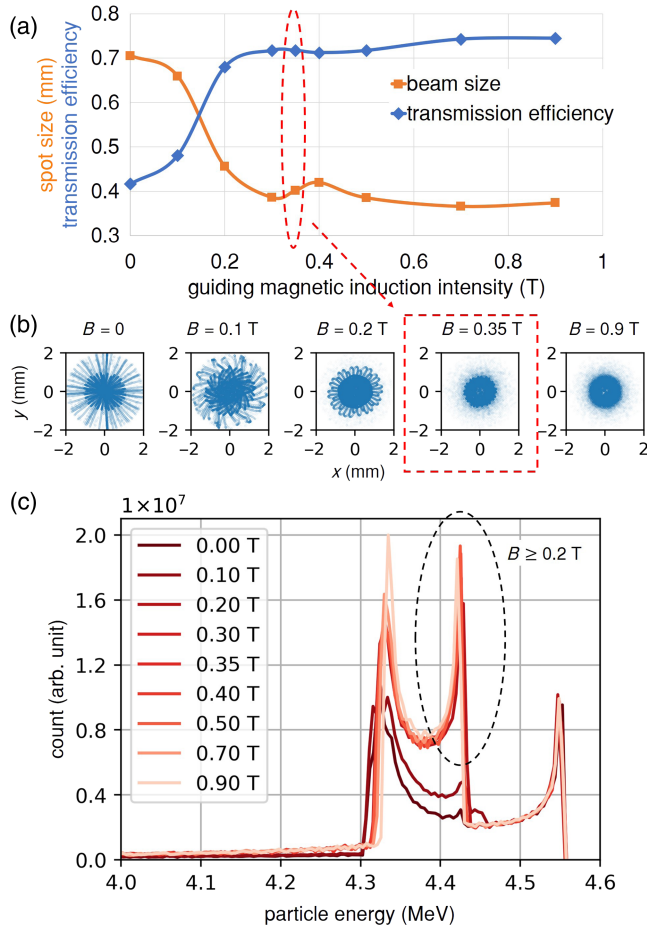


FIG. 10. Guiding magnet of the coaxial source improves the acceleration capability of the accelerating structure. (a) Beam spot size and transmission efficiency as functions of the guiding magnetic field, (b) witness beam spot at the linac exit under different guiding magnetic fields, and (c) energy spectra of the witness beam at the linac exit under different guiding magnetic fields.

shows the simulation result of such a case. Omitting the magnet inevitably sacrifices beam quality, and results in more beam loss on the structure. The average beam transmission efficiency at the linac exit is thus reduced to 41%, similar to most published works on medical linac [37,38], much lower than that of the scheme sharing guiding magnet.

A parametric sweep on the guiding magnetic induction intensity (B) further demonstrates that reusing the coaxial source's guiding magnet significantly improves the acceleration capability of the accelerating structure. Below 0.2 T, the transmission efficiency of the witness beam increases as B increases, as shown in Fig. 10(a). The spot size of the witness beam appears to show an opposite trend, which can also be evidenced in Fig. 10(b). Increasing the magnetic field salvages electrons with energies ranging from 4.3 to 4.45 MeV, as shown in Fig. 10(c). The beam quality does not change significantly when $B > 0.3$ T. Thus, the designed guiding magnetic induction intensity of 0.35 T is sufficient to achieve a noticeable improvement in the quality of the witness beam.

V. DISCUSSION

In this section, we briefly discuss a specific issue regarding the practical implementation of the proposed model. While we present an integrated linac design, including detailed implementation strategies for both the coaxial rf source and accelerating structure, we identify key opportunities for performance enhancement through future research.

The current design utilizes a coaxial waveguide feed to the accelerating structure, which ensures good electromagnetic field symmetry—critical for maintaining beam quality in both the driver and witness beams. However, this integration approach introduces challenges in isolating the rf source from the accelerating structure using

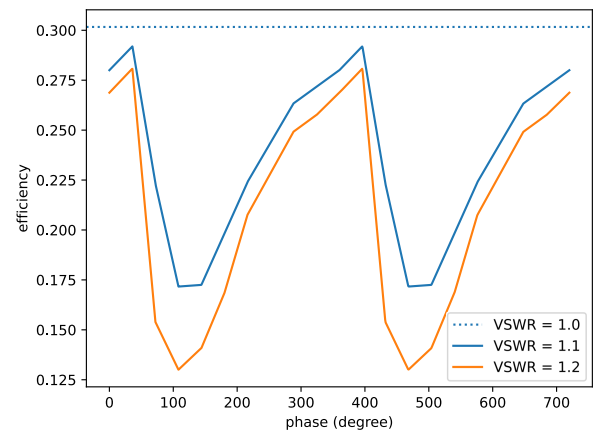


FIG. 11. Power conversion efficiency as function of the relative phase of the reflection due to mismatching at the output port of the coaxial rf source.

conventional circulators. Specifically, impedance mismatch between the rf source and the accelerator can induce power reflections at the rf source output, potentially degrading operational efficiency. To quantify this effect, we performed simulations for different reflection coefficients characterized by voltage standing wave ratio (VSWR) [39]. As shown in Fig. 11, the results demonstrate that the reflected power essentially affects efficiency, which varies periodically with the phase delay at the output port. In certain phase ranges, efficiency decreases by over half, while in others, the reduction is less severe, indicating that partial operation remains feasible under reflection. Integrating rf sources with inherent robustness to power reflections could mitigate this limitation in the proposed scheme, which will be performed in our future research.

VI. CONCLUSION

In conclusion, an innovative linear accelerator integrating a coaxial high-power microwave source was proposed. This microwave source, a coaxial backward wave oscillator, can output 1.8 MW at 9.46 GHz under a dc voltage of 50 kV and beam current of 120 A. Microwave power is fed into the bi-periodic standing-wave magnetic coupling accelerating structure via a radial coupler. Sharing the guiding magnetic field with the microwave source, the designed structure accelerates the 100 mA witness beam from 50 keV to an average of 4.38 MeV, with an rms beam spot of 402 μm (391 μm) in x - (y -) direction. This shared magnetic field significantly enhances acceleration capability, resulting in smaller beam spots and reduced beam loss at the linac exit, reducing radiation protection and cooling requirements. This integrated approach bridges the gap between high-power microwave sources and particle accelerators, paving the way for more efficient, scalable, and versatile accelerator systems.

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