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Development of a compact X-band dual-mode medical linac based on a pulse compressor

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Date: 2025-11-17T00:00:00+00:00

Abstract

In this study, a compact X-band dual-mode electron linear accelerator (linac) was developed for medical radiotherapy, which is capable of generating both 100mA/6MeV beams for X-ray radiotherapy (low-energy mode) and 10 mA/13.5MeV beams for electron radiotherapy (high-energy mode). The dual-mode linac leveraged a 3MW multi-beam X-band klystron as the power source, with a total length of 1.5m. A novel spherical SLAC Energy Doubler (SLED pulse compressor) was specially designed for the high-energy mode to achieve flat-top output, with a power gain factor of 2.2. Mode switching is realized through dynamic tuning of the pulse compressor' s resonant frequency. Furthermore, a standing-wave (SW) bi-periodic accelerating structure operating in $\pi/2$ mode was developed, which enables effective bunching and acceleration of electron beams under both modes. A comprehensive experimental platform has been established for the linac, and high-power RF tests have been conducted. The experimental results validate the feasibility of the dual-mode linac, demonstrating its potential for versatile radiotherapy applications with optimized spatial compactness.

Full Text

Preamble

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This study presents the development of a compact X-band dual-mode electron linear accelerator (linac) for medical radiotherapy applications, capable of generating both 100 mA / 6 MeV beams for X-ray radiotherapy (low-energy mode) and 10 mA / 13.5 MeV beams for electron radiotherapy (high-energy mode). The dual-mode linac utilizes a 3 MW multi-beam X-band klystron as its RF power source, achieving a total system length of just 1.5 m. A novel spherical SLAC Energy Doubler (SLED pulse compressor) was specially designed for the high-energy mode to produce flat-top output pulses with a power gain factor of 2.2. Mode switching is accomplished through dynamic tuning of the pulse compressor’ s resonant frequency. Furthermore, a standing-wave (SW) bi-periodic accelerating structure operating in $\pi/2$ mode was developed to enable effective bunching and acceleration of electron beams under both operational modes. A comprehensive experimental platform has been established for the linac, and high-power RF tests have been successfully conducted. The experimental results validate the feasibility of the dual-mode linac concept, demonstrating its potential for versatile radiotherapy applications with optimized spatial compactness.

Keywords: Dual-mode linac, SLED pulse compressor, Standing-wave accelerating structure, High-power RF experiment

Introduction

Cancer remains a pressing global health challenge. According to the 2024 statistical report by the International Agency for Research on Cancer (IARC), 2022 witnessed over 20 million new cancer cases and 9.5 million cancer-related deaths worldwide [1], highlighting the urgent demand for advanced therapeutic modalities. Radiotherapy, employed as either primary treatment or in combination with chemotherapy, surgery, or other modalities for over 60% of cancer patients, contributes to nearly 50% of curative outcomes [2], underscoring its pivotal role in oncology. Innovations in radiotherapy technologies, including improved dose precision [3-7] and multi-mode treatment strategies [8-10], hold profound scientific significance while yielding substantial economic benefits, thus making critical contributions to global health progress.

The 6 MeV low-energy medical electron linac, designed for X-ray radiotherapy, features a compact configuration and low treatment costs, enabling its widespread adoption in public cancer care [11-15]. However, for superficial tumors amenable to electron therapy, such as breast, skin, and thyroid cancers [16, 17], low-energy medical linacs are constrained by their RF power sources, preventing them from producing higher-energy electron beams. Furthermore, most prior medical linacs engineered to generate higher-energy electron beams (10-20 MeV) have relied on higher-power RF sources, resulting in elevated costs, complex system configurations, and stringent maintenance requirements [18-20]. Thus, there exists an urgent demand for medical electron linacs that combine the compactness and cost-effectiveness of low-energy systems with the capability of accelerating higher-energy electron beams, particularly for advancing cancer treatment capabilities in less developed regions.

Since its inception in the 1970s, the pulse compressor has been widely adopted in diverse accelerator applications [21–28]. By compressing pulse width to enhance peak power, it overcomes the power limitations of RF sources, enabling higher-energy electron acceleration. Most pulse compressors feature compact and mechanically simple structures. For example, the SLED pulse compressor comprises only several passive components, such as a resonant cavity and a dual-mode RF polarizer, resulting in low manufacturing costs and high operational reliability. More importantly, leveraging the pulse compression effect can drastically relax the performance requirements for RF sources, including reduced klystron output power, lower modulator voltage, and diminished thermal load on the cooling system, thereby significantly reducing project funding, equipment costs, and long-term operational complexity. Additionally, switching between the low-energy and high-energy modes of the linac can be easily achieved through dynamic tuning of the pulse compressor' s resonant frequency. In summary, compared to developing entirely new higher-power RF sources (including klystrons and magnetrons), the adoption of a pulse compressor provides a more cost-effective and engineering-feasible pathway for medical linacs to achieve high-energy electron acceleration.

Meanwhile, X-band high-gradient technology has progressively matured in recent years, with significant advancements achieved in accelerating structure design, manufacturing, and tuning, as well as in research on beam break-up instability [29–37]. Compared with conventional S-band and C-band systems [38–41], X-band accelerating structures exhibit higher shunt impedance, which facilitates more compact designs of medical linacs with lower spatial requirements. While substantial research has been devoted to the development of X-band medical linacs, existing efforts are predominantly restricted to the design of the accelerating structures themselves [11–15], and no studies have been reported on integrating pulse compressors with X-band accelerating structures for the development of X-band dual-mode medical electron linacs.

Based on the above analysis, we have developed a compact X-band dual-mode medical electron linac integrated with a SLED pulse compressor, enabling seamless switching between X-ray and electron therapy modes. The linac employs a 3 MW multi-beam X-band klystron to accelerate electrons to 6 MeV in low-energy mode and 13.5 MeV in high-energy mode. Table 1 summarizes the physical parameters of the X-band SLED pulse compressor.

II. X-Band SLED Pulse Compressor

A. RF Design and Analysis

The spherical SLED pulse compressor represents an innovative evolution of conventional SLED technology [25, 26]. Its RF characteristics emulate a 3 dB coupler, with two orthogonal TE_{11} modes in a cylindrical port replacing the traditional two ports of the 3 dB coupler, reducing the number of SLED cavities from two to one. Additionally, the butterfly-shaped structure eliminates the symmetric cylindrical waveguide, achieving a 40% reduction in vertical dimension compared to conventional designs. The coupler optimization followed the CERN-proposed Fmax function [44], which has been optimized to -95 dB, ensuring minimal power leakage.

Fabrication of the spherical resonant cavity inevitably introduces deviations in sphericity, leading to resonant frequency detuning between the two orthogonal TE_{114} modes, which significantly affects the S-parameters of the two polarization modes. Therefore, independent measurements and separate tuning of the two polarization modes were critical to ensuring operational consistency. A single-mode RF polarizer dedicated to independently measuring the S-parameters of the two polarization modes was developed. By coupling the single-mode RF polarizer to the spherical resonant cavity at orthogonal orientations, the S-parameters of the two orthogonal TE_{114} modes could be characterized.

The vacuum model and electric field magnitude of the complete pulse compressor are presented in Fig. 1 Figure 1: see original paper, with all simulated RF parameters matching the design specifications. In particular, at an input power of 3 MW, the maximum surface electric field occurring at the coupling aperture was only 19 MV/m. This low-field design significantly reduces the risk of vacuum breakdown and improves the operational robustness of the pulse compressor [45].

B. Lower-Power RF Experiment

Cold testing of the pulse compressor was performed using a Rohde & Schwarz Vector Network Analyzer (VNA). Before welding, the directivity of the dual-mode polarizer was first verified. Within the frequency range of 9.25–9.35 GHz, both S_{11} and S_{22} parameters remained below -30 dB, while S_{12} and S_{21} exceeded -0.15 dB, demonstrating satisfactory performance of the dual-mode RF polarizer. Then, the single-mode RF polarizer was used to measure the frequency separation of the two orthogonal TE_{114} polarization modes in the spherical resonant cavity. The frequency separation between the two modes was finally tuned to less than 100 kHz.

After welding, cold testing and tuning of the complete pulse compressor were conducted, as illustrated in Fig. 2 Figure 2: see original paper. Switching between the low-energy mode and high-energy mode is achieved by adjusting the insertion depth of the top tuning pin to change the resonant frequency of the pulse compressor. When the top tuning rod is fully retracted, the resonant frequency should exactly coincide with the operating frequency, thereby effectively compressing the klystron output power and enabling high-energy electron acceleration. The primary objective of the cold test and tuning is to verify whether the characteristics of the pulse compressor in this state are consistent with design expectations, including resonant frequency f = 9.3 GHz, coupling factor $\beta = 3.2$, and quality factor $Q_0 = 10^5$.

However, the tuning pin has a fragile structure and must be connected to the resonant cavity via a flange to ensure airtightness. Premature installation increases the risk of damage or vacuum leakage during subsequent transportation and installation, so the tuning pin was not installed during the cold test. Instead, direct flange sealing was adopted. Considering that the diameter of the tuning pin hole at the top of the resonant cavity is only 7 mm, corresponding to a cutoff frequency of 25.1 GHz for the dominant TE_{11} mode, the 9.3 GHz microwave undergoes rapid attenuation in the hole. Thus, direct flange sealing yields the same electromagnetic effects as when the tuning pin is fully retracted.

The target operating frequency of the pulse compressor is 9.3 GHz, with an intended operating temperature of 35°C, and an ion pump achieves a high-vacuum environment within the cavity ($< 10^{-6}$ Pa). Thus, the target frequency during cold testing needs to be calculated via Eq. (5) [50]:

$$f_{tun} = f_{tar}\sqrt{\epsilon_r} + \alpha f_{tar}(T_{tar} - T_{tun})$$

where $f_{tar} = 9.3$ GHz is the operating frequency, $\epsilon_r = 1.00059$ is the relative atmospheric dielectric constant, $\alpha = 1.66 \times 10^{-5}/°\text{C}$ is the thermal expansion coefficient of copper, $T_{tar} = 35°\text{C}$ is the target temperature, and T_{tun} is the temperature during cold testing, which was measured to be 22.7°C. The target tuning frequency was calculated as 9.29916 GHz, and the tuning results are presented in Fig. 2(b). At the resonant point, the S_{21} parameter is -5.81 dB, corresponding to a coupling factor of 3.1, which is close to the target coupling factor $\beta = 3.2$. The loaded quality factor of the pulse compressor is measured as 2.40×10^4 using the half-power bandwidth method, corresponding to the intrinsic quality factor $Q_{0pc} = 9.84\times10^4$, which also agrees well with the expected results.

Furthermore, in the low-energy mode, simply inserting the tuning pin to a sufficient depth induces a significant shift in the resonant frequency of the pulse compressor. Under this condition, RF power is reflected at the coupling hole and exits from the dual-mode RF polarizer. The pulse compressor ceases pulse compression functionality, enabling low-energy mode operation. RF simulation demonstrated that a 4 mm-diameter stainless-steel tuning pin inserted to 60 mm achieves a 20 MHz resonant frequency shift, fully meeting the operational requirements. The tuning pin has an actual maximum insertion depth of 100 mm, providing greater tuning margin. In summary, since the low-energy mode only requires full insertion of the tuning pin to detune the pulse compressor, eliminating the need for calibration of insertion depth and resonant frequency offset, specialized cold testing for the detuned state is unnecessary.

Then, leveraging the linear response characteristics of the pulse compressor, a low-power RF experiment was conducted to evaluate its performance, with the experimental setup illustrated in Fig. 3 Figure 3: see original paper and (b). As the power source for the low-power RF experiment, the low-level RF (LLRF) system includes an excitation source, a solid-state amplifier (SSA), a phase inverter, and a trigger source. The excitation source, serving as the primary generator of microwave signals, provides initial RF excitation for the system. The SSA is integrated with the excitation source to amplify the microwave signal, serving as the klystron driving power. It was not activated during the low-power RF experiment. The phase inverter performs dual functions: phase inversion and amplitude modulation of RF signals. The trigger signal source synchronizes the entire LLRF system, ensuring precise timing coordination among components for coherent operation. To maintain consistency with high-power test conditions, the pulse compressor operated under low-vacuum conditions, maintained by a mechanical pump, during the low-power RF experiment. A Rohde & Schwarz NRP-Z81 power meter was employed for measurement of the compressed pulse.

During the low-power RF experiment, the measured temperature of the pulse compressor was 23.5°C. According to Eq. (5), the output frequency of the excitation source was set to 9.30018 GHz to match the resonant frequency of the pulse compressor. The experimental results are shown in Fig. 3(c), with the input pulse consisting of a 4 µs flat-top signal and a 500 ns inverted compensation signal. With an input pulse power of 290 µW, an output pulse power of 660 µW was successfully measured, achieving the predetermined power gain target of 2.2.

However, the phase inverter demonstrated suboptimal performance, with the modulation of the inverted signal exhibiting abrupt transitions. The imperfect performance of the phase inverter directly impacted the output waveforms of the pulse compressor, causing the output waveforms to exhibit ripples. Additionally, at the theoretical phase inversion time of 4 µs, a spike with a pulse width of approximately 100 ns was observed. A potential cause lies in the non-ideal transient response of the phase inverter [46]. Specifically, IQ modulation is adopted to realize phase inversion and amplitude modulation of the RF signal in the LLRF system. A minor timing mismatch may exist between I/Q channels, or there may be overshoot on the edges of control signals. These situations may cause the vector synthesis of phase and amplitude to deviate from ideal conditions at the moment of switching, thereby generating the aforementioned spike. Because of this spike, the measured usable pulse width was only 400 ns, narrower than the designed 500 ns, but still satisfying the high-energy mode operational requirements of the linac.

To improve the output waveform of the pulse compressor, the fundamental approach is to adopt a vector modulator with superior dynamic performance, thereby enhancing the transient response speed of RF signal modulation. In addition, the adoption of predistortion compensation can improve the flatness of the output waveform. Nevertheless, from the perspective of principle feasibility verification, the current experimental results already meet the requirements for high-power RF experiments.

III. X-Band SW Accelerating Structure

In this section, based on a grid-controlled thermionic cathode DC gun, we developed an X-band 9.3 GHz SW accelerating structure operating in $\pi/2$ mode, capable of accelerating both 100 mA / 6 MeV and 10 mA / 13.5 MeV electron beams. The pulse current is adjusted by changing the voltage of the DC gun. The capture ratio and acceleration efficiency of the structure were systematically investigated under different operating modes to optimize its performance.

A. RF Design and Analysis

Structural compactness represents the pivotal advantage of the dual-mode medical linac. The accelerator adopted an X-band 9.3 GHz $\pi/2$ mode bi-periodic SW accelerating structure, which maximizes the frequency separation between adjacent resonant modes while improving acceleration efficiency [35]. In addition, nose-cone structures were incorporated to improve the longitudinal shunt impedance, and magnetic coupling holes were integrated into the cavity chains to enable efficient power transmission. These designs collectively contribute to improving the compactness of the accelerating structure.

The bunching section, consisting of four bunching cavities, was designed through iterative calculations of field distribution and beam dynamics. To maintain structural compactness, the accelerating structure employs a single-feed SW design. However, this introduces an inherent limitation: under the two operating modes with different input powers, the bunching section maintains consistent normalized field distributions while the amplitude scales with the $P \propto E^2$ relationship, leading to significant disparities in bunching efficiency between the two modes. To mitigate this discrepancy, we adjusted the gun voltage and emission current, aiming to identify an appropriate bunching section field distribution that achieves acceptable capture ratios for both modes. Concurrently, the iris radius was increased from 1.5 mm to 2.5 mm to reduce beam transport losses. Distinct from conventional low-energy electron linacs, the high-energy mode represents the key innovation of the new linac, so the bunching section prioritized optimization for 13.5 MeV electron beams, achieving electron capture ratios of 22% in low-energy mode and 35% in high-energy mode. The DC gun parameters were ultimately determined as follows: 8 kV gun voltage and 500 mA emission pulse current for the low-energy mode, and 10 kV gun voltage and 30 mA emission pulse current for the high-energy mode.

The comprehensive vacuum model of the accelerating structure was constructed in Ansys HFSS, with an overall length of 0.33 m, comprising 4 bunching cavities and 18 standard cavities, as shown in Fig. 4 Figure 4: see original paper. The simulation results, including the S_{11} curve, Smith plot, and normalized on-axis electric field distribution, are presented in Figs. 4(b), 4(c), and 4(d), respectively. The longitudinal effective shunt impedance of the standard cavities is 115 MΩ/m.

Combining theoretical analysis and engineering experience, the coupling factor of the accelerating structure was finally determined to be 1.1. For the high-energy mode with 10 mA / 13.5 MeV beams, the beam power is merely 4.80 MW calculated by Eq. (1), and the corresponding theoretically optimal coupling factor is approximately 1.03. However, local temperature rise at the coupling hole during operation causes deformation and a slight decrease in β. Thus, the accelerating structure was designed with $\beta = 1.10$ to ensure optimal power feeding for the high-energy mode. In contrast, for the low-energy mode with 100 mA / 6 MeV beams, the beam power and field-building power are 0.60 MW and 0.95 MW, respectively, corresponding to a matched coupling factor of 1.63. Although $\beta = 1.10$ induces beam load mismatch and power reflection during low-energy mode operation, the power loss is acceptable. The power reflection coefficient in the low-energy mode is 3.43%, calculated via Eq. (6) [43]:

$$P_{ref}/P_{inc} = \left[\frac{\beta - \beta_0}{\beta + \beta_0}\right]^2$$

where $\beta = 1.10$ and $\beta_0 = 1.63$.

In summary, the determination of the coupling factor prioritizes two key considerations. First, the high-energy mode requires 4.94 MW input power. Accounting for -1 dB transmission loss, the total input power reaches 6.22 MW, nearing the power limit of the pulse compressor (6.6 MW). Therefore, power coupling matching of the high-energy mode is the core design objective. Second, the low-energy mode only requires an input power of 1.55 MW. Even accounting for 3.43% reflected power from beam load mismatch and -1 dB transmission loss, the total input power remains 2.02 MW, which can be fully satisfied by the 3 MW multi-beam klystron. Thus, the low-energy mode imposes relatively lenient requirements on coupling matching.

Beam dynamics simulation was conducted using ASTRA. The kinetic energy and pulse beam current of the two operating modes are shown in Figs. 5(a) and 5(b). According to our final design, at an output RF power of 2.0 MW from the klystron, electrons gain 6.0 MeV energy with 100 mA pulse current in low-energy mode operation. For the high-energy mode, the RF power transmission proceeds as follows: The klystron initially outputs 2.8 MW of RF power. After compression by the pulse compressor (with a power gain of 2.2) and accounting for -1 dB of transmission loss, 4.9 MW of RF power is expected to be fed into the accelerating structure, and electrons gain 13.5 MeV energy with 10 mA pulse current. These results are basically consistent with the expected parameters during the pulse compressor design.

The transverse phase space distributions at the exit of the accelerating structure are shown in Figs. 5(c) and 5(d), and the transverse emittance curves are shown in Fig. 5(e). In the high-energy mode, lower pulsed current and higher longitudinal velocity collectively suppress the divergence of electron bunches caused by space charge effects, leading to superior transverse emittance compared to the low-energy mode, characterized by more concentrated position distribution and smaller angular divergence.

The energy spectra for both modes are shown in Fig. 5(f). In the high-energy mode, the RMS energy of 95% of electrons in the bunch is 13.53 MeV, and the relative energy spread is 2.4%, defined as the ratio of RMS energy spread to its RMS energy. The low-energy mode yields an RMS energy of 6.11 MeV with a relative energy spread of 8.3%. The significant discrepancy in relative energy spread between the two modes primarily arises from the longitudinal bunching dynamics, particularly in the bunching section, which was optimized specifically for the high-energy mode. In electron therapy, the dose is deposited directly by the beam, and a larger energy spread directly flattens the dose fall-off at the end of its range, compromising its core advantage of sparing healthy tissues behind superficial tumors. The energy spread design prioritizes the high-energy mode based on the following considerations: For X-ray therapy, the dose distribution results from polyenergetic photons generated by bremsstrahlung, making it less sensitive to the initial electron energy spread. Meanwhile, an integrated design of the bunching and accelerating sections was adopted for structural compactness. This integration leads to reduced field amplitude in the bunching section under low-energy mode, resulting in suboptimal bunching efficiency and a wider phase distribution, thereby inducing a larger relative energy spread.

To further improve the capture ratio and relative energy spread of the low-energy mode, consideration can be given to a scheme where RF power is fed separately to the bunching section and the accelerating section. In this scheme, only the RF power fed to the accelerating section is adjusted across different operating modes to achieve distinct energy gains. Although this approach compromises structural compactness, it maintains a constant bunching field across different modes, thereby preserving bunching efficiency.

B. Cold Test

After fabrication of the accelerating structure, the resonant frequency, quality factor, and coupling coefficient of each cell were examined using the plunger method. Notably, due to the thin wall thickness, traditional tuning mechanisms such as tuning holes or tuning pins could not be incorporated during the manufacturing process. Thus, tuning of each cell was achieved by reprocessing unsatisfactory copper disks with high-precision machine tools. Following two iterative reprocessing cycles, all cavities were tuned into an appropriate range around the operating frequency of 9300 ± 3 MHz, as shown in Fig. 6 Figure 6: see original paper. Deviation of the inter-cavity coupling coefficient from the design values was within 5%, a level of precision that eliminated the need for further adjustments.

Subsequently, the assembled copper disks and waveguide coupler were integrated into a cohesive unit through brazing, utilizing a silver-copper alloy braze. This brazing material was selected for its excellent thermal conductivity, high mechanical strength, and compatibility with copper, ensuring robust bonding and minimal RF loss at the interfaces. The complete accelerating structure is shown in Fig. 6(b). Then, cold testing of the complete accelerating structure was conducted using the VNA. The S_{11} parameter, sampled at 9.3 GHz, exhibited a value of -23.7 dB, corresponding to β cc = 1.14. Q cc was measured to be 3641 using the half-power bandwidth method. From this, τ cc = 125 ns, which is close to the expected value of 120 ns. The on-axis electric field distribution of the accelerating structure was measured by the bead-pull method, showing good agreement with RF simulation results, as illustrated in Fig. 6(c).

IV. High-Power RF Experiment

The pulse compressor has been validated via low-power RF experiment, and cold testing of the SW accelerating structure has been completed. By integrating the SW accelerating structure as the load terminal, configuring high-voltage power for the DC gun, and expanding synchronous trigger settings, we successfully established a high-power RF experimental platform for the X-band dual-mode linac. This section details the construction and configuration of the high-power RF experimental platform, along with the sampling, processing, and analysis of experimental data.

A. High-Power RF Experiment Setup

The photograph of the X-band dual-mode experimental platform is shown in Fig. 7 Figure 7: see original paper. Benefiting from the compact X-band pulse compressor and SW accelerating structure, the main body of the experimental platform has an overall length of only 1.5 m, advancing the path toward commercialization of the linac.

For the RF power section, a 3 MW X-band 9.3 GHz multi-beam klystron served as the primary power source. A phase inverter capable of amplitude modulation was interposed between the LLRF excitation source and the solid-state amplifier (SSA), enabling phase inversion and amplitude modulation of the RF power. The klystron modulator had a maximum high-voltage pulse width of 6 µs, imposing a strict constraint on the RF power pulse width. To protect the klystron from reflected power, a four-port circulator connected with water loads was installed between the klystron and pulse compressor. The resonant frequency of the pulse compressor was tuned via a mechanical tuning pin positioned axially above its cavity. When the pulse compressor was detuned from the operating frequency, it functioned only as a lossy waveguide with measurable power attenuation of approximately -0.2 dB. The pulse compressor maintains a constant cavity temperature of 35°C through four internal water cooling channels, each configured with a flow rate of 10 L/min. Notably, we specifically reinforced the cooling structure near the coupling holes with high surface fields to prevent significant changes in the coupling coefficient due to thermal deformation, thereby ensuring stable operation of the pulse compression system.

In the accelerating section, a directional coupler was installed between the pulse compressor and the SW accelerating structure to enable real-time sampling of incident and reflected RF power, thereby detecting vacuum breakdown in the structure. The grid-controlled thermionic cathode DC gun, serving as the electron source, allowed precise adjustment of emission current by regulating the gun voltage, accommodating the beam current demands for both operation modes. The DC gun had a maximum pulse width of 10 µs, enabling full coverage of the RF power pulse. Electron beams were expected to be bunched and accelerated to 6 MeV and 13.5 MeV by the SW structure in low-energy mode and high-energy mode, respectively. The system was cooled by water through ten 6 mm-diameter internal water channels on copper disks with a flow rate of 3 L/min.

A titanium window or tungsten target was installed at the exit of the SW accelerating structure to extract electron beams or generate X-rays through bremsstrahlung. The linac was sealed using RF windows, and a 4 kV titanium pump maintained a high-vacuum environment with air pressure below 10^{-7} Pa in the accelerator, preventing arcing and ensuring beam stability. Corresponding detectors were installed downstream for beam measurements, and their operational principles were detailed in the measurement results section.

The pulse compressor and SW accelerating structure were conditioned in advance to reduce the breakdown rate (BDR) [47-49]. Breakdown events were identified by abnormal reflected wave signals and transient increases in vacuum pressure. During the conditioning process, RF power injection into the accelerator was gradually increased to avoid any irreversible damage to the structure. After the accelerating structure was fully conditioned with 10^7 RF macro-pulses under each of the two operation modes, the BDR was calculated to be less than 10^{-4}/pulse for both.

B. Low-Energy Mode Measurement Results

When the pulse compressor is detuned, RF power is coupled into the accelerator without pulse compression, thereby enabling low-energy mode operation under a heavy pulse current of 100 mA, as depicted in Fig. 7(b). Measurements in the low-energy mode specifically include the beam energy, pulse current, and X-ray dose rate generated by bremsstrahlung.

An integrated current loop was employed for pulse current measurement. The loop sensitively detects magnetic field variations induced by electron beams and converts such changes into electrical signals that are routed to an oscilloscope via a BNC interface for observation. As shown in Fig. 7(c), the measurement result indicates a pulse current of 116 mA with a pulse width of 5.6 µs, which is shorter than the 6 µs pulse width of the high-voltage modulator. This discrepancy arises from two technical considerations. First, to avoid voltage fluctuations at pulse edges, the pulse width of the klystron drive signal (output from the SSA) was set to approximately 5.8 µs, ensuring operation within the flat-top region of the modulator pulse and thus stable microwave power output. Second, during the initial part of the microwave pulse, the accelerating field has not yet reached steady state, leading to poor electron bunching efficiency. Most electrons in this phase are lost within the accelerating structure, further reducing the effective beam pulse width to the observed 5.6 µs.

The electron energy in the low-energy mode was measured via the current attenuation method, where 0.1 mm steel sheets and a 50 Ω terminated aluminum collector were used to characterize the beam attenuation. By measuring current signals with different numbers of steel sheets and fitting the data to GB/T 25306-2010, the electron energy was determined to be 6.05 MeV, consistent with the designed value.

A water-cooled tungsten target was mounted at the accelerator exit, facilitating X-ray generation through bremsstrahlung. The X-ray dose rate was measured using a Farmer-type ionization chamber positioned 1 m from the tungsten target. At a repetition frequency of 150 Hz and duty factor of 8.4×10^{-4}, the measured dose rate was 720 cGy/min. The experimental results of the low-energy mode are listed in Table 2 .

Table 2. Experimental results of the low-energy mode.

Parameter	Value
Repetition Rate	150 Hz
Pulse Width	5.6 µs
Duty Factor	8.4×10^{-4}
Pulse Current	116 mA
Kinetic Energy	6.05 MeV
Dose Rate	720 cGy/min

C. High-Energy Mode Measurement Results

When the pulse compressor is tuned to the 9.3 GHz operating frequency, the RF power undergoes pulse compression and amplitude modulation, generating a 400 ns flat-top pulse with a gain factor of 2.2, as depicted in Fig. 7(d). This enables the linac to operate in high-energy mode with a pulse current of 10 mA.

Pulse current measurements in the high-energy mode reused the same integrated current loop as in the low-energy mode experiment, as shown in Fig. 7(e). Before activating the phase inverter, the RF power from the klystron failed to undergo effective pulse compression, leading to reduction in field magnitude and phase mismatch in the accelerating structure. This resulted in ineffective electron capture and acceleration, with no noticeable current observed, as indicated by the blue curve. The results confirm that the accelerator fails to produce electron beams without inverse signal excitation, aligning with theoretical predictions.

Following phase inverter activation, an obvious pulse current signal was recorded, as indicated by the red curve. Based on the low-power RF experiment in Section II.B, the pulse compressor can actually output a pulse width of 500 ns, but only 400 ns meets the expected power gain. Thus, the emission duration of the electron gun is set to 400 ns. The rising edge during the initial stage of the pulse current characterizes the process by which the SW electromagnetic field gradually stabilizes within the accelerator and the electron capture ratio increases to the stable value. Consequently, the latter 200 ns of the pulse current reached the expected value, with an average current of 10.3 mA. Additionally, non-zero baseline and crosstalk were noted, though they did not affect the identification of the pulse current. The non-zero baseline is likely caused by imperfect grounding, while crosstalk may arise from electromagnetic interference in the experimental platform or high-voltage line coupling, which requires resolution through shielding optimization or equipment calibration.

The electron energy spectrum was measured using a magnetic analyzer, whose physical image and schematic diagram are shown in Fig. 8 Figure 8: see original paper and (b), respectively. The measurement setup was mainly composed of three parts: the beam transport device, the magnetic analyzer, and the imaging system. The vacuum pump was connected to the magnetic analyzer via a tee joint and a bellows. To improve the energy spectrum resolution, a slit was installed at the entrance of the magnetic analyzer for geometric collimation. By adjusting the excitation current, the deflection magnetic field strength can be precisely regulated, thereby changing the deflection radius of the electron beam. The electron energy formula considering relativistic effects can be expressed as:

$$E = \left[\sqrt{1 + (eBR_e/m_{0c})^2} - 1\right] m_{0c}^2$$

where B is the deflection magnetic field, and R_e is the deflection radius.

The imaging system utilized an optical imaging method. When electrons bombarded the YAG screen, fluorescent material was excited, generating visible light reflected by a 45° mirror and then captured by a CCD camera. By integrating the pre-calibrated correlation between excitation current and magnetic field, the electron energy spectrum was accurately derived through analyzing the spatial distribution and intensity variation of the optical signals. The measured energy spectrum peak is at 13.9 MeV, with a FWHM of 0.43 MeV, as shown in Fig. 8(c). This result slightly exceeds the high-energy mode design target of 13.5 MeV, which is speculated to originate from the actual power attenuation in the high-energy experiment being less than the expected value of -1 dB. The actual power attenuation calculated from the measurement results is -0.73 dB.

Notably, there is a discrepancy in the shape of the energy spectrum between the experiment (Fig. 8(c)) and simulation (Fig. 5(e)), with an isosceles triangle in the experiment versus a right triangle in the simulation. The discrepancy primarily arises from the inconsistency between the ideal conditions adopted in beam dynamics simulations and the actual experimental conditions. In the simulation, the center of the Gaussian bunch is locked at the optimal acceleration phase: the bunch center, with the highest charge density, attains the maximum energy gain, while the head and tail, with lower charge density, experience lower energy gains, resulting in a right triangle with the hypotenuse on the low-energy side. However, in the experiment, limited phase-locking precision prevents the center of the bunch from being accurately aligned with the optimal acceleration phase, leading to slightly higher energy gains for electrons in the head or tail of the bunch. Additionally, a relatively wide collimating slit before the magnetic analyzer may cause some electrons with large transverse velocities to be collected and misidentified as high-energy electrons. Combined with effects from factors such as the initial energy spread of the bunch, non-ideal charge density distribution, and higher-order modes in the cavity, the energy spectrum ultimately exhibits an isosceles triangle shape. The experimental results of the high-energy mode are listed in Table 3 .

Table 3. Experimental results of the high-energy mode.

Parameter	Value
Repetition Rate	20 Hz
Pulse Width	200 ns
Duty Factor	8×10^{-6}
Pulse Current	10.3 mA
Central Energy	13.9 MeV
FWHM	0.43 MeV

Considering the -0.73 dB power attenuation in the transmission, corresponding to an 85% power retention ratio, a correction factor of $1/\sqrt{0.85}$ is induced, yielding an energy of 15.5 MeV under lossless conditions. Further minimizing the power attenuation of RF components would enhance electron energy in the high-energy mode.

V. Conclusion

A compact X-band 9.3 GHz dual-mode medical linac dedicated to radiotherapy applications was first developed in the Accelerator Laboratory of Tsinghua University. The accelerator employs a 3 MW X-band klystron as the power source, coupled with a SLED pulse compressor, enabling dual-mode operation: low-energy mode delivering 100 mA pulse current at 6 MeV for X-ray radiotherapy and high-energy mode delivering 10 mA pulse current at 13.5 MeV for electron radiotherapy. With lower treatment costs and spatial requirements, the linac can significantly facilitate the popularization of cancer therapy.

Design, fabrication, and cold testing of the pulse compressor and accelerating structure have been conducted, alongside the establishment of the high-power

RF experimental platform. Low-energy mode experiments generated 5.6 µs electron beams with 116 mA pulse current and 6.05 MeV energy at 150 Hz repetition rate, demonstrating a dose rate of 720 cGy/min at 1 m from the tungsten target. High-energy mode experiments yielded electron beams featuring 200 ns pulse width, 10.3 mA pulse current, 13.9 MeV central energy, and 0.43 MeV FWHM. The results validated the feasibility of the linac, demonstrating its potential for versatile radiotherapy applications with optimized spatial compactness.

The linac is currently undergoing system integration design, and preparations are underway for subsequent biological experiments in collaboration with hospitals. This compact X-band dual-mode linac provides valuable references for the development of future compact medical linacs.

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