Design, Fabrication and Testing of an X-band 9 MeV Standing Wave Electron Linac

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Abstract

In this study, an X-band standing-wave dual-period linear accelerator for medical radiotherapy was developed, capable of accelerating electrons to 9 MeV using a 2.4 MW klystron. The structure operates in the $\pi/2$ mode with inter-cavity magnetic coupling, producing appropriate adjacent mode separation at a frequency of 10 MHz. The accelerator length is less than 600 mm, consisting of 4 buncher cells and 29 regular cells. Geometric optimization, full-scale radio frequency (RF) simulations, and beam dynamics calculations were performed. The accelerator was manufactured and characterized using low-power RF tests. Cold test results show good agreement with simulations and experimental measurements. In high-power RF tests, the output beam current, energy spectrum, capture ratio, and accelerator exit spot size were measured. With an input power of 2.4 MW and a pulse current of 100 mA, the output spot RMS radius is approximately 0.5 mm. The output kinetic energy is 9.04 MeV with an energy spread of 3.5%, indicating good performance of the accelerator.

Full Text

Preamble

Design, Fabrication and Test of an X-band 9 MeV Standing-Wave Electron Linear Accelerator

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Abstract

An X-band 9 MeV standing-wave (SW) bi-periodic linear accelerator was developed for medical radiotherapy. Electrons can be accelerated to 9 MeV using a 2.4 MW klystron. The structure operates in $\pi/2$ mode and employs magnetic coupling between cavities, generating an appropriate adjacent mode separation of 10 MHz. The accelerator is less than 600 mm long, consisting of 4 bunching cells and 29 normal cells. We conducted geometry optimization, full-scale RF simulation, and beam dynamics calculations. The accelerator was fabricated and measured through low-power RF testing. The cold test results show good agreement between simulation and actual measurement. In the high-power RF test, we measured the output beam current, energy spectrum, capture ratio, and spot size at the accelerator exit. With 2.4 MW input power, the pulse current is 100 mA and the output spot root-mean-square (RMS) radius is about 0.5 mm. The output kinetic energy is 9.04 MeV with a spectrum FWHM of 3.5%, demonstrating good performance of this accelerator.

Keywords: Standing-wave accelerating structure, RF analysis, experiment, thermal DC gun, low-power RF test, high-power

Introduction

Electron linear accelerators are widely used in both industrial and medical applications, including radiotherapy, nondestructive testing, industrial irradiation, and sterilization [1]. Currently, most electron linear accelerators operate at S-band, where the large weight and substantial volume create various difficulties during testing and installation, such as limited space in operating rooms for intraoperative irradiation. Linear accelerators operating at C-band and X-band have been proposed to overcome these problems [2-4].

In recent years, X-band electron linear accelerators have attracted extensive attention worldwide. Compared with S-band and C-band linear accelerators, X-band linear accelerators offer advantages in compact structure, reduced weight, and relatively high accelerating gradient. The accelerator laboratory at Tsinghua University has also conducted research in this field [5]. Over the past ten years, S-band and C-band SW linear accelerators driven by domestic magnetrons have been successfully studied [6-9].

Narrow energy spread is crucial for radiotherapy since it significantly impacts the dose rate. For a linear accelerator, the consumption of RF power follows the relationship described in [10], where the maximum kinetic energy of accelerated electrons and the average energy of accelerated electrons determine the efficiency. For the same input power and beam current, a large energy spread leads to decreasing average energy and increasing maximum energy. This energy spread severely reduces the radiation dose rate, which is unacceptable for radiotherapy. Consequently, medical linear accelerators with narrow energy spread have attracted significant attention.

Using a 2.4 MW input RF power source, we have designed a compact X-band SW linear accelerator at Tsinghua University for medical applications such as X-ray radiotherapy and intraoperative electron beam radiotherapy. The design goal is to achieve a 100 mA pulse current with a kinetic energy of 9.0 MeV, while keeping the accelerating structure length under 600 mm. We selected a standing-wave biperiodic on-axis coupled structure operating in $\pi/2$ mode at 9.3 GHz. RF focusing is introduced through noses in the accelerating cells, eliminating the need for external solenoids. Narrow energy spread has been achieved using a thermal DC gun and specially optimized bunching cells.

The basic components of this linear accelerator are shown in Fig. 1 [Figure 1: see original paper], consisting of an RF power source, circulator, accelerating structure, thermal DC gun, and titanium window. Table 1 presents the critical parameters of the accelerator.

This accelerator was designed, fabricated, and tested at both low and high power in our laboratory. During the cold test, we measured the frequency of each cell, the on-axis electric field distribution, and the coupling coefficient. The cold test results showed good agreement with our previous simulations. The high-power RF test measured the accelerator's performance, including output beam current, capture ratio, energy spectrum, beam spot size, breakdown rate, and other useful data.

This paper presents the RF design, simulation analysis, fabrication, and test results of this SW linear accelerator. The remainder of this paper is organized as follows. Section II illustrates the RF design and analysis of the X-band accelerating structure, along with electron gun simulation and beam dynamics calculation results. Section III introduces the fabrication, tuning, and low-power RF test of the accelerating structure. Section IV presents the setup and detailed results of the high-power RF experiment. Finally, Section V provides conclusions and outlook.

Fig. 1. Schematic diagram of the SW electron linear accelerator.

Table 1. Basic parameters of the X-band SW linear accelerator.

Parameter	Value
Number of accelerating cavities	33

Parameter	Value
Length	0.59 m
Input RF power	2.4 MW
Pulse beam current	100 mA
Capture ratio	32%
RMS beam spot radius	0.5 mm
Energy dispersion	250 keV
Average accelerating gradient	15 MeV/m

II. RF Design and Analysis

A high accelerating gradient is necessary to improve accelerating efficiency and increase output beam energy without excessive length. The longitudinal shunt impedance of the accelerator should be as large as possible within a reasonable RF breakdown rate (BDR) range. Our goal is to find appropriate structural parameters that satisfy these requirements simultaneously. In our design process, we implemented cavity geometry optimization using SUPERFISH, beam dynamics studies using ASTRA, and full-scale RF simulations using CST codes [11-12].

A. Cavity Geometry Optimization

Geometric optimization of normal cells is essential for achieving high accelerating efficiency. In a linear accelerator, the kinetic energy gained by an electron can be expressed as [13]:

$$E = \sqrt{Z_{eff} \cdot P \cdot L}$$

where Z_{eff} refers to the effective shunt impedance, P is the microwave power loss, and L is the longitudinal length. With increased Z_{eff}, the accelerator can be shortened longitudinally. During cavity geometry optimization, we aim to maximize the longitudinal shunt impedance. Fig. 2 [Figure 2: see original paper] shows the two-dimensional model used for geometry optimization, which generates an axisymmetric structure based on 2D models and calculates relevant RF characteristic parameters. This method significantly reduces optimization time and greatly improves efficiency.

Reduced coupling cell length and disk thickness dramatically improve effective shunt impedance, but cavities become prone to deformation during processing. The beam pipe radius and nose radius are also critical to longitudinal shunt impedance. However, a small beam pipe radius and nose radius result in low capture coefficient because more bunches collide with the beam pipe. Moreover, a small nose radius generates high BDR and weakens accelerator stability. These parameters are therefore determined with appropriate values.

We selected $\pi/2$ mode as the operating mode for the electron linear accelerator to achieve maximal adjacent mode separation and frequency robustness during operation. According to bi-periodic structure theory, to maximize longitudinal shunt impedance, the coupling cell should have a small volume and a very weak electromagnetic field inside it. In our model, the coupling cells are only 1.5 mm long longitudinally, so their effective shunt impedance and quality factor can be ignored.

The RF characteristics of the normal cell are presented in Table 2 , where f_a indicates the frequency of accelerating cells, f_c represents the frequency of coupling cells, Z_{eff} is the effective longitudinal shunt impedance, and Q_0 is the unloaded quality factor.

Table 2. RF characteristics of optimized accelerating and coupling cavities

Parameter	Value
f_a	9.3 GHz
f_c	9.3 GHz
Z_{eff}	165 MΩ/m
Q_0	12000

B. Design and Simulation of the Cavity Chain

The nose makes electric coupling through the beam hole rather weak, so magnetic coupling is used instead. We implemented magnetic coupling slots between accelerating cells and coupling cells, as shown in Fig. 3 [Figure 3: see original paper].

First, the coupling coefficient between cavities was determined. To avoid subadjacent coupling effects, adjacent magnetic coupling slots were arranged orthogonally, as shown in Fig. 3. The dispersion equation for the coupled cavity chain can be expressed as [13]:

$$\omega^2 = \omega_0^2(1 + k\cos\phi)$$

where k refers to the magnetic coupling coefficient between cavities and ϕ is the phase shift between cavities. We must consider the separation between adjacent modes of the dominant $\pi/2$ mode to provide sufficient bandwidth between $\pi/2$ mode and its adjacent modes. Meanwhile, a large coupling coefficient k leads to loss of accelerating efficiency. The coupling coefficient should be 2-3% to provide enough bandwidth between $\pi/2$ mode and its adjacent modes [12]. According to our calculation, when k equals 2.7%, an adjacent mode separation of 10 MHz can be obtained. For bunching cavities, the stored power is inversely proportional to their magnetic coupling coefficient [15]. We pre-designed a unique on-axis electric field distribution for bunching cells that had to be formed by modifying the coupling coefficient between bunching cells to obtain a high capture rate as far as feasible. The procedure is the same as that for normal cells described above.

C. Design of the External Coupler and Waveguide Window

To feed RF power into the accelerator, an external coupler consisting of a unique coupler cell and an external coupling hole is connected to the rectangular waveguide. The vacuum model of the accelerator with a coupler was built in CST, as shown in Fig. 4 [Figure 4: see original paper]. The results, including on-axis electric field distribution and S_{11}, are displayed in Fig. 5 [Figure 5: see original paper].

The external coupling coefficient is expressed as [13]:

$$\beta_e = \frac{Q_0}{Q_e}$$

where Q_0 is the unloaded quality factor of the accelerating structure and Q_e is its external quality factor. If the beam current is very weak, the optimal external coupling coefficient is 1. However, if beam loading is non-negligible, the optimum external coupling coefficient should be calculated by [13]:

$$\beta_{opt} = 1 + \frac{I \cdot Z_{eff} \cdot L}{2P_0}$$

where I is the output beam current, P_0 is the input power, and Z_{eff} and L are the effective longitudinal shunt impedance and length of the accelerator, respectively. According to our design, the output beam current is about 100 mA, the average energy is around 9 MeV, and the input RF power is 2.4 MW. Consequently, the optimum external coupling is about 1.96.

Figure 4. Vacuum model of the cavity chain, external coupler, and waveguide for RF simulation in CST.

Fig. 5. (a) Magnitude of on-axis electric field of the accelerating structure. (b) Smith plot of the S_{11} parameter for the accelerating structure.

Waveguide windows are widely used in electric vacuum devices such as klystrons, magnetrons, and accelerators. The waveguide window's function is to transmit RF power with low loss and provide isolation between the vacuum within the accelerator and the SF6 gas inside the waveguide. In this accelerator, we optimized and fabricated a waveguide window based on a 2.4 mm-thick quartz dielectric slice, shown in Fig. 6 [Figure 6: see original paper].

According to classical transmission-line theory, when RF breakdown occurs in the accelerator, the terminal becomes mismatched and the incident wave is fully reflected. The transmission waveguide then contains standing wave components. The RF window should be positioned far from the standing wave's antinode and near the wave node, as indicated in Fig. 7 [Figure 7: see original paper], to reduce the probability of dielectric breakdown on the quartz window surface.

Fig. 6. (a) Components of the waveguide window system: SF6 (green section) in the waveguide close to the power source, high vacuum (blue section) in the external coupler, separated by quartz slice (gray section). (b) Mechanical design of the waveguide window, including copper connector, cooling water pipe, and BJ84 rectangular flange. (c) S parameter plots of this waveguide window, where the blue line represents S_{11} and the orange line is S_{21}. The S_{11} is lower than -20 dB at 9.3 GHz, demonstrating the feasibility of our waveguide window design.

Fig. 7. Magnitude of the standing wave electric field inside the waveguide and coupler when RF breakdown occurs in the accelerator and the input RF power is fully reflected.

D. Accelerating Electric Field Built-up Time

The field built-up time of the RF structure is closely related to its loaded quality factor. The unloaded quality factor Q_0 of the cavity chain is obtained from CST simulation. The loaded quality factor can be directly calculated from the unloaded quality factor Q_0 and external coupling coefficient β.

Based on the RF analysis results, we calculate that Q_L is approximately 3055. During field construction inside the accelerator, basic parameters such as the electromagnetic field and input impedance change exponentially. The amplitude of the electric field in the cavity increases exponentially with time:

$$E(t) = E_{steady}(1 - e^{-\omega_0 t/2Q_L})$$

We calculated that at the end of the transient time $4\tau_F$, the magnitude of the electromagnetic field reaches about 98% of the steady-state value. During electromagnetic field construction, the field distribution is time-varying, reaching 9.0 MeV at steady state. According to theoretical calculation, there exists an optimal injection time that allows the injected electron beam to accelerate stably to 9.0 MeV at and after this time [14]:

$$t_{inj} = \frac{Q_L}{\omega_0} \ln\left(\frac{E_{steady}}{E_{steady} - E_{target}}\right)$$

We obtain $t_{inj} = 0.27\mu s$. Compared with the 10 μs microwave macro pulse width, the transient field built-up time is only 0.27 μs and can be ignored.

III. Simulation of the Thermal DC Gun and Beam Dynamics

A. Thermal DC Gun

We adopted a thermal-cathode DC gun as the electron source, whose components include the cathode, heating filament, focusing electrode, anode, insulating ceramic shell, and connector to the accelerator. The emission model was simulated in the CST particle module. The emission current at 12.5 kV high voltage is 320 mA, and the perveance is 0.23 μP.

The simulation results and basic parameters are shown in Fig. 8 [Figure 8: see original paper], and the DC gun parameters are listed in Table 3 . In the table, V_e refers to the high voltage applied between cathode and anode, I_e is the emission current, P_e indicates the perveance of our electron gun, R_w is the RMS radius at beam waist, L_w is the distance between the beam waist and cathode, and R_h is the beam pipe radius.

Fig. 8. (a) Beam simulation of the thermal DC gun in CST. (b) Mechanical design of the thermal DC gun.

Table 3. Parameters of the thermal-cathode DC gun

Parameter	Value
V_e	12.5 kV
I_e	320 mA
P_e	0.23 μP
R_w	0.316 mm
L_w	13.05 mm
R_h	1.5 mm

B. Beam Dynamics Study

Our design process included a beam dynamics study using ASTRA codes. The apertures were carefully set based on the position of the noses and their radius, allowing us to match the real accelerating structure and achieve accurate beam loss calculation. A 100 mA pulse beam current and a capture ratio of 32% were achieved. Additional beam dynamics calculation results are shown in Fig. 9 [Figure 9: see original paper].

The accelerating structure noses generate weak RF focusing/defocusing for electron beams during transit. Depending on the electric field distribution of a symmetric accelerating cell, electrons experience alternating focusing and defocusing. However, their momentum is greater when focused than when defocused, leading to an overall focusing effect. Along the light-speed section, the energy of accelerating electrons gradually increases while the space charge force decreases. Benefiting from the RF focusing effect, no additional solenoid is necessary in our design, reducing extra space requirements and inconvenience. Fig. 10 [Figure 10: see original paper] shows the beam spot and the transverse and longitudinal phase space distributions at the accelerator exit.

Fig. 9. Statistical results of the beam dynamics simulation. (a) Kinetic energy (blue line) and pulse beam current (orange line) along the accelerating structure longitudinally. (b) RMS beam spot radius (blue line) and transverse beam emittance (orange line) along the accelerating structure longitudinally.

Fig. 10. Beam information at the exit of the accelerator for 10^5 macro particles during beam dynamics calculation. (a) Transverse beam spot (dashed line shows beam pipe radius of 1.5 mm). (b) Transverse phase space.

IV. Low-Power RF Test

Thirty-three pairs of disks were manufactured in total. Four cooling water channels were processed on the copper disks. Due to the thin thickness, all copper disks were fabricated without tuning holes or pins. Each disk was processed with a smaller cavity radius. After each cold test, unsatisfactory copper disks were reprocessed on a high-precision milling machine. The structure was reprocessed for cavities with large deviation from 9.3 GHz to achieve fine-tuning. All RF cavities were tuned to an appropriate range around the operating frequency of (9300 ± 5) MHz. RF cold testing was carried out at each fabrication step. The test results from the final machining round agreed well with simulation results.

Some disks and the low-power RF test setup are displayed in Fig. 11 [Figure 11: see original paper]. We assembled the cavity chain with fixtures, measured the on-axis field distribution using the bead-pull method, and sampled the S_{11} data [15-18]. We also compared these results with our previous simulations, as shown in Fig. 12 [Figure 12: see original paper]. The measured on-axis field distribution can be compared with Fig. 5(a). The cold test results showed good agreement between simulation and actual measurement.

Fig. 11. (a) Copper disks, coupler waveguide, and waveguide after fabrication. (b) Picture of the low-power RF test setup.

Fig. 12. Low-power RF measurement results of the accelerator. (a) Magnitude of the S_{11} parameter: red dashed line shows simulation result, blue line shows cold test result. (b) Relative magnitude of on-axis electric field in cold test.

V. High-Power RF Experiment

A. High-Power Experiment Platform and Conditioning

A silver-based alloy brazed the assembled cavity chain, waveguide coupler, and quartz waveguide window. The cooling water pipe, thermal DC gun, and titanium window were then welded to the accelerator structure using argon arc welding.

After vacuum-leak detection and cathode activation of the thermal DC gun, a complete accelerator was obtained, as shown in Fig. 13 [Figure 13: see original paper]. Through the waveguide and titanium windows, the vacuum inside the accelerator tube is sealed and isolated from SF6 gas in the high-power waveguide transmission system. A CF63 flange was installed to connect with the magnetic spectrometer for measuring the output beam's energy spectrum. A titanium getter pump is welded to the waveguide to maintain low vacuum in the accelerating structure. The vacuum level is kept below 10^{-6} Pa.

With the fixed perveance of the thermal DC gun, we can change the emission current by adjusting the applied high voltage. The emission and pulse beam currents increase when the high voltage is enhanced. Mismatch between the initial kinetic energy and accelerating field causes a drop in capture ratio at excessive voltages (>13 kV). We adjusted the high voltage in the 12-13 kV range for the high-power experiment.

For this completed accelerator, RF characteristics were measured. The reflection coefficient, standing wave ratio, quality factor, and external coupling coefficient were also calculated using an R&S ZVA60 Vector Network Analyzer. No significant frequency shift was observed after brazing. The simulation results are slightly higher than the measured external coupling coefficient of 1.8, possibly due to waveguide port calibration errors before the cold test and unsatisfactory electrical contact between the waveguide window and measurement port.

Fig. 13. Complete accelerator with all components, including thermal DC gun, titanium window, cooling pipes, and ion pump.

Based on studies of RF breakdown phenomena in high-gradient accelerating structures, the RF breakdown rate (BDR) is closely related to accelerating gradient and RF pulse width. The relationship between BDR, accelerating gradient, and pulse width can be expressed as [19-21]:

$$BDR \propto E_{acc}^{\alpha} \cdot \tau_p^{\beta}$$

In our high-power experiment, the klystron pulse is long (up to 10 μs) and the ignition rate is high. The accelerator must be conditioned in advance to reduce BDR and improve stability. The RF power fed into the accelerator was gradually increased while keeping BDR below 10^{-4}/pulse to avoid irreversible damage to the cavity wall. The accelerating structure was fully conditioned to control BDR below 10^{-4}/pulse [22-23] at 2.4 MW input RF power.

We built a high-power experimental platform to obtain the accelerator's high-power performance data. A compact 2.4 MW X-band high-power multi-beam klystron served as the RF power source. A circulator separates the klystron and accelerator, with components connected by waveguide filled with high-pressure SF6 gas. Directional couplers monitor the incident wave into the accelerator and reflected wave from the accelerator. A Faraday cup with integrated circuit measures output beam current at the accelerator's exit.

We used a Tektronix DPO4034 oscilloscope to sample electrical signals, including the klystron's emitting current, thermal DC gun collector current, emission current, high voltage, and output beam current collected by the Faraday cup. De-noising processing was applied to eliminate high-voltage interference from the high-voltage modulator. A Rohde & Schwarz NRP-Z81 power meter measured microwave signals for the accelerator's incident and reflected waves. The beam current waveform, energy spectrum, capture coefficient, and output beam spot size were measured and evaluated during the high-power experiment.

B. Results of the High-Power Experiment

Signals of the output beam current and high voltage applied to the thermal DC gun were sampled by the Tektronix DPO4034 oscilloscope. The best data are displayed in Fig. 14 [Figure 14: see original paper], showing a pulse width of 9.8 μs, pulse beam current of 100 mA, and repetition rate of 50 Hz (operating duty ratio of 0.5‰). Due to some mismatch between the klystron and modulator, the input RF power is not strictly flat and decreases slowly along the pulse time. This imperfect input RF pulse causes a slight decline in the output beam current waveform. We took the ratio between output beam current and emission current from the thermal DC gun as an approximate estimation of the capture ratio. Under the conditions shown in Fig. 14, we measured and calculated a capture ratio of $(31.2 \pm 0.5)\%$, just below the predicted result of 32%, possibly due to processing and measurement errors.

Fig. 14. Signals of output beam current and high voltage applied to the thermal DC gun.

A magnetic spectrometer installed at the linear accelerator exit, shown in Fig. 15 [Figure 15: see original paper], measured the beam energy spread. To reduce beam spot size and improve energy resolution, a slit measuring 38 mm in length and 0.2 mm in width was inserted at the magnetic spectrometer's entry during testing. The slit size significantly affected relative brightness on the screen, greatly impacting energy resolution. By adjusting the magnetic field, electrons with different kinetic energies follow unique drifting trajectories. Based on position and brightness on the YAG screen, we evaluated the beam energy spread. The energy spectra of the output beam corresponding to different input powers are shown in Fig. 16 [Figure 16: see original paper]. At 2.4 MW input power, the output beam kinetic energy is 9.04 MeV and the FWHM of the energy spectrum is about 3.5%.

Fig. 15. (a) Schematic diagram of energy spread measurement experiment. (b) Image of energy spread measurement setup inside shielding room.

Fig. 16. Energy spread measurement results with different input RF power.

A mirror placed at a 45-degree angle to the beam line reflected light from the YAG screen. A CCD camera with focusing lens captured the image with resolution of about 50 μm/pixel. The output beam spot size was estimated from the YAG screen image. The brightness distribution of the images could be used to determine the RMS beam diameter since the brightness of optical transition radiation is proportional to the number of incoming particles. At 2.4 MW input RF power and 100 mA pulse beam current, the beam spot image was captured by the CCD camera and the calculated RMS radius was about 0.5 mm, as shown in Fig. 17 [Figure 17: see original paper].

Fig. 17. (a) Beam spot photo captured by CCD camera. (b) Brightness analysis result in post-processing.

Conclusion

An X-band 9 MeV SW linear accelerator powered by a 2.4 MW klystron has been developed at Tsinghua University. Its advantages include RF focusing without solenoids, low energy spread with a thermal DC gun, and no tuning pins.

During the design process, employing SUPERFISH, CST, and ASTRA codes enabled efficient completion of accelerator RF parameter design, cavity geometry optimization, cavity chain RF simulation, and beam dynamics studies.

We conducted low-power RF tests after fabricating and tuning each copper disk. The cold test results were in good accord with simulation results.

A high-power RF experiment was performed on the accelerator, measuring output beam current, capture ratio, beam energy spectrum, and beam spot size at the linear accelerator exit. With 2.4 MW input RF power, we obtained 100 mA beam current and about 9.8 μs pulse width (under 0.1‰ duty factor). The output RMS spot radius was approximately 0.5 mm, and the output kinetic energy was 9.04 MeV with a 3.5% FWHM spectrum width.

The high-power RF experiment results demonstrated good performance of this accelerator. Future work will examine its performance at a higher duty factor of 1‰, and further explorations will investigate higher-order modes in this linear accelerator.

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Note: Figure translations are in progress. See original paper for figures.