Development of a C-band 6 MeV standing-wave linear accelerator

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C-band low-energy electron linear accelerators are preferable for applications which require compact structure and accurate positioning. During the past two years, the accelerator laboratory of Tsinghua University has developed a C-band 6 MeV standing-wave biperiodic on-axis coupled linear accelerator. The weight of the accelerator is 7.4 kg and the length is about 39 cm, which includes the thermal-cathode gun and the flange for tests. High capture ratio, narrow energy spectrum, and small spot size have been achieved in the high power rf test, which shows good performance of this accelerator and its great potential for industrial and medical applications.

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I. INTRODUCTION

Electron radio-frequency (rf) linear accelerators are widely used in industrial and medical applications, such as electron beam processing, nondestructive testing, as well as electron and x-ray therapy [1]. The S-band accelerators (operated at 2.856 or 2.998 GHz) are the most commonly used linear accelerators and the technology has been well developed. However, when space is limited and accurate positioning is required, the C-band (5.712 GHz) and X-band (9.3 GHz) ones are preferable, because these types exhibit smaller volume, higher shunt impedance, and higher acceptable gradient. Compared with X-band accelerators, C-band accelerators require less production precision and are less likely to detune after brazing [2–4]. Recently, the research of low-energy C-band accelerators is of high interest and various institutions around the world are focusing on this topic [5–11].

In the past two years, a C-band standing-wave linear accelerator driven by a domestic magnetron has been designed, fabricated, and subjected to a high power test at the accelerator laboratory of Tsinghua University [12–14]. Because of the usage of magnetron and elaborative optimization, this accelerator is quite compact, thus ideal for compact and movable industrial and medical applications.

In the design stage, the codes SUPERFISH [15] and PARMELA [16] have been applied for cell optimization and beam dynamics study, respectively. Some C codes have also been developed to accelerate the entire process.

In addition, CST MICROWAVE STUDIO [17] has been used to design the coupling slots between cells, as well as the input coupler.

After fabrication by high-precision machine tools, the cells were measured in the cold test for their frequencies and coupling factors. The results were consistent with those obtained from previous simulations.

In the following high power rf test, with 2.07 MW input power, the peak current was 130 mA and the capture ratio was more than 40%. The output kinetic energy was 6.0 MeV with 0.45 MeV full width at half maximum (FWHM) of the spectrum. The root-mean-square (rms) of output spot diameter was about 0.8 mm. These results, including high beam current, narrow energy spectrum, and small spot size, demonstrate that this compact C-band accelerator performs efficiently.

This paper is organized as follows: Sec. II discusses the design process of the accelerator. Section III presents the fabrication and the cold test results. The setup and the results of the high power rf test are provided in Sec. IV. Finally, a summary and future studies are given in Sec. V.

II. DESIGN OF THE ACCELERATOR

A. Optimization of the normal cell

The normal cell is the basic element of a rf linear accelerator. Some important characters of the accelerator, such as total length, power consumed on wall, etc., are strongly dependent on the normal cell. So the normal cell must be carefully optimized as the first stage.

Figure 1 shows the cross section of the normal cell under optimization (excluding the coupling slots). The model consists of an accelerating cell and two half coupling cells, defined by 11 independent parameters.

Normal cell optimization primarily aims to maximize the effective shunt impedance Z_{eff} and maintain the ratio

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FIG. 1. Cross section of the normal cell.

$E_{\max}/E_0$ at a proper value. $E_{\max}$ represents the maximum electric field on the surface and E_0 denotes the average electric field magnitude on the axis.

First, the maximum output energy of a linear accelerating structure is expressed as [18]

$$E = \sqrt{Z_{\text{eff}} P_w L},$$

where P_w is the power consumed on the wall, and L is the length of the structure. When E is fixed at 6 MeV, increasing Z_{eff} can reduce the power with a fixed length or shorten the structure with a fixed input power.

Second, in research involving high-gradient accelerating structures, the breakdown phenomenon of a structure is found to exhibit a strong dependence of the maximum electric field on the surface [19,20]. Kamino has selected 120 MV/m as the maximum electric field on the surface for C-band accelerators [5]. E_0 can be calculated from some parameters of the accelerator, as follows:

$$E_0 = \frac{E}{L} = \frac{E}{E^2/Z_{\text{eff}} P_w} = \frac{Z_{\text{eff}} P_w}{E} = \frac{Z_{\text{eff}} (P - EI)}{E},$$

where P is the total consumed power, and I is the beam current which is designed to be 130 mA. In the design, the maximum output power to the accelerating structure from the magnetron was assumed to be 2.2 MW. In addition, the maximum Z_{eff} was around 130 MΩ/m. Thus, E_0 was restricted under 30 MV/m and an $E_{\max}/E_0$ ratio of about 4 was considered safe.

During optimization, the 11 independent parameters must be subject to the scanning, which is time consuming. To improve efficiency, a C code has been developed to write an input file with different sets of parameters, run the SUPERFISH code, and automatically read out the results. Table I presents the main intrinsic parameters of the normal accelerating cell after careful optimization.

B. Beam dynamics study

The performance of an rf linear accelerator also depends strongly on the beam dynamics design. The

TABLE I. Parameters of the normal cell after optimization.

Parameter	Value
Frequency	5712 MHz
Quality factor	11500
Efficient shunt impedance	130 MΩ/m
$E_{\max}/E_0$	4.1

beam dynamics study aims to develop a compact accelerating structure with a proper capture ratio, a narrow energy spectrum of the output beam, and a small beam spot size.

First, a proper capture ratio is required for high output current and high dose rate because of the limited current emitted from the thermal-cathode gun. In our design, we defined the efficient capture ratio, r_{eff} , as ratio of output current with kinetic energy higher than 6 MeV to the injected current from the thermal-cathode gun. A r_{eff} higher than 30% was set as a criterion during optimization.

Second, narrow energy spectrum is necessary to allow a practical accelerator to increase its dose rate [21]. In addition, a broad spectrum affects the final depth dose curve in medical applications [22]. Thus, the width of the output energy spectrum must also be considered in the beam dynamics design.

Third, a small spot size of the output beam can improve the space resolution, and is often required for x-ray imaging applications such as industrial computed tomography and cargo inspection [23,24]. Without any outside focusing solenoid, a beam spot size with a diameter of less than 1.5 mm root mean square was set as a criterion in our design. The root-mean-square diameter d_{rms} was defined as follows:

$$d_{\text{rms}} = 2r_{\text{rms}} = 2\sqrt{\frac{\sum_i r_i^2}{N}},$$

where r_i is the radius of the i th output electron and N is the total number of the output electron.

In beam dynamics design by PARMELA, combinations of bunching section design such as the field, the gap length, the number of cells, and the choice of E_0 in the following normal cell section were scanned by another C code to obtain a structure that meets all requirements. Table II presents the

TABLE II. Parameters of the designed accelerating structure.

Parameter	Value
Number of accelerating cells	12
Total consumed power	2.16 MW
Accelerating beam current	130 mA
r_{eff}	32.8%
d_{rms}	1.4 mm
Spectrum FWHM of the output beam	0.1 MeV
$E_{\max}$	111 MV/m
Length	<29 cm

parameters of the designed accelerating structure. The high voltage and the emittance of the gun in simulation were assumed to be 10 kV and 60 mm mrad, respectively.

C. Design of coupling slots and coupler

In addition to the previous optimization by two-dimension models and codes, the three-dimension input coupler and the coupling slots were designed by CST MICROWAVE STUDIO.

The dispersion relation of linear accelerating structure is expressed as follows [18]:

$$f_{\theta} = \frac{f_0}{\sqrt{1 + k \cos \theta}},$$

where k is the coupling factor, and θ is the phase advance between cells. In our design, which consists of 12 accelerating cells and 11 coupling cells, k of 2.4% can achieve a frequency separation of 9 MHz between $\pi/2$ mode and its adjacent mode.

For bunching cells, the relationship between stored energy and the coupling factor can be deduced from the circuit model [25]:

$$k_1 \sqrt{U_1} = k_2 \sqrt{U_2},$$

where U_1 and U_2 denote the stored energies of two adjacent accelerating cells, and k_1 and k_2 are their coupling factors with the mutual coupling cell. The electric field pattern in the bunching cells for an appropriate beam bunching, simulated by PARMELA previously, can be realized by adjusting the coupling factor with geometry variation of the coupling slots.

After the coupling slots are machined on the wall, the radius of each cell has to be reduced for tuning. A model consisting of one accelerating cell between two half coupling cells was used to calculate the frequency of the accelerating cell. Another model consisting of one coupling cell between two half accelerating cells was used to calculate the frequency of the coupling cell and the coupling factor [6,26]. By adjusting the geometry of each cell, all cells were tuned to 5712 ± 1 MHz and all the required coupling factors were well satisfied.

The accelerating structure and the waveguide system are connected by the input coupler. To minimize the reflection during the operation, the coupler must be tuned and its external coupling factor must be optimized.

The external coupling of a linear accelerator is given by the following expression [18]:

$$\beta = \frac{Q_0}{Q_e} = \frac{P_{\text{ext}}}{P_w},$$

where Q_0 is the unloaded quality factor, Q_e is the external quality factor, and P_{ext} and P_w represent the consumed power of the outside circuit and wall of the accelerating structure, respectively. To minimize the reflection during operation, the following relationship must be satisfied [25]:

$$P_{\text{ext}} = P_w + P_b,$$

where P_b is the power transfer to the beam. Plugging the parameters of the proposed design into the function above, an optimal external coupling factor became 1.7.

Computing β with the entire structure in the simulation software is a very time-consuming task. Instead, the external coupling factor β_s of the single input coupler can be calculated conveniently using CST MICROWAVE STUDIO in the time domain (TRANSIT SOLVER) [27], and β can be expressed as

$$\beta = \frac{U_s}{U} \beta_s,$$

where U_s and U are the energy stored in the input coupler and the whole structure, respectively. By this method, the input coupler was tuned and the optimal external coupling factor was obtained.

III. FABRICATION AND COLD TEST

A. Fabrication

All cells were machined by high-precision machine tools. The machined cells and the rf components are shown in Fig. 2.

The accelerator is equipped with a 60 mm mrad-emittance thermal-cathode gun. To measure beam properties, the output end is sealed using a titanium window with a thickness of 50 μm instead of a heavy-metal bulk target. The accelerator is cooled by a water jacket. Figure 3 shows the entire structure after fabrication.

B. Cold test

All the cells were initially machined into smaller radii because no tuning holes are present on the cells. Several machining rounds need to be performed toward the final stage to obtain the right frequency and coupling. The frequency, quality factor, and coupling factor of each cell

FIG. 2. Machined cells and rf components.

FIG. 3. Structure after fabrication.

were measured after each round by the plunger method, detuning the adjacent cells by inserting a plunger [18]. The results of the first machining round and the corresponding simulation show good agreement, as shown in Table III.

The main parameters of the accelerating structure after sealing are listed in Table IV.

IV. HIGH POWER RF TEST

A. High power rf test setup

A C-band magnetron, followed by a four-port circulator, provides input power for the accelerating structure. Two matched Agilent 423B low-barrier Schottky diode detectors and two low-loss cables were attached to the directional couplers between the circulator and the accelerator to monitor the incident and reflected power. The detected signals can be used to calculate the reflection and the standing-wave ratio (SWR) of the accelerator after careful calibration.

TABLE III. Results of the cold test and simulation for the first machining round.

Parameter ^a	Cold test	Simulation
f_{an} (MHz)	5722.4	5726.1
f_{cn} (MHz)	5731.1	5725.1
k_n (%)	2.46	2.44

^a a represents accelerating, c coupling, and n normal cell.

TABLE IV. Final parameters of the accelerating structure in cold test.

Parameter	Value
Frequency	5711.1 MHz
Mode separation	9.8 MHz
Quality factor	10500
External coupling factor	1.8
Total length ^a	390 mm
Total weight ^a	7.4 kg

^aThe length and weight include the gun and the flange for high power rf test.

Prior to testing, a high power water load was used for input power calibration. The maximum stable input power was limited to 2.07 MW. Frequent breakdowns of the magnetron occurred when the output power to the accelerating structure was increased to the level higher than 2.07 MW. Therefore, the maximum input power was maintained at 2.07 MW instead of the value in the original design, which was 2.16 MW, to protect the magnetron.

A Faraday cup with integral circuit, consisting of a resistance and a parallel capacitor, was used to measure the capture ratio. The Faraday cup was placed in air instead of in vacuum for convenience and distance from the titanium window to the Faraday cup was about 60 mm. The diameter of the beam hole at the output from the accelerator was 4 mm and the diameter of the Faraday cup was 25 mm. The signals saved by the oscilloscope were filtered to eliminate noise from the imperfect ground.

To measure the output energy spectrum, a magnetic analyzer was connected to the accelerator. By scanning the magnetic field strength, electrons with different energies can sequentially pass through the side way of the magnetic analyzer and hit a fluorescent screen. The energy spectrum can then be calculated by the relative brightness of the screen. In the test, we also installed a 38 mm long, 0.2 mm wide slit at the entrance of the analyzer to increase the energy resolution, which can reach less than 1% [28].

The spot size of the output beam can be measured by the optical transition radiation emitted at the vacuum boundary and the titanium window of the accelerator [29]. Light from the titanium window was reflected by a mirror which positioned at a 45° angle to the beam line. A charge-coupled device (CCD) camera equipped with a focusing lens was used to capture the image and the resolution was about 50 $\mu\text{m}/\text{pixel}$. The root-mean-square diameter of the beam can be easily calculated from the brightness distribution of the image because the brightness of optical transition radiation is proportional to the number of incident particles.

The high power rf test area is shown in Fig. 4 (including only the devices for the measurement of energy spectrum).

Based on the measured emitted current and high voltage of the thermal-cathode gun as well as the input power, the

FIG. 4. High power rf test area.

beam dynamics of the accelerator under each condition has been simulated by PARMELA to compare with the test results. The comparison is also shown in the next subsection.

B. High power rf test results

1. Operating SWR

Figure 5 shows typical waveforms during operating including the anode current of the magnetron, incident wave, and reflected wave. By tuning the magnetron, the SWR could drop lower than 1.2, representing less than 1% of the input power reflected by the accelerating structure. The SWR without beam loading has been measured as 1.7, which is in good agreement with the cold test result and that of our design value.

2. Capture ratio

Figure 6 shows the plot of the capture ratio vs input power. For a different input power, the gun voltage was changed in order to keep accelerating pulse beam current at 130 mA.

FIG. 5. Anode current of the magnetron (green), incident wave (blue), and reflected wave (purple).

FIG. 6. Capture ratio vs input power.

The calculated capture ratios were $\sim 6\%$ higher than the measured ratios. The difference may be attributed to the scatter on the titanium window and loss of electron from the window to the Faraday cup in air. A simulation by FLUKA [30] shows that only 78%–93% output electron, dependent on the energy, can be collected by the Faraday cup because of these effects. Thus, the simulation shows agreement with the experimental results.

3. Energy spectrum

Figure 7 shows the energy spectra of the output beam with different input power given an accelerating pulse beam current of 130 mA. For 2.07 MW input power, the FWHM of the spectrum was about 0.45 MeV.

The kinetic energy at peak intensity of the output beam for different input power can be extracted from Fig. 7, as shown in Fig. 8 (three points are added for lower input power).

FIG. 7. Energy spectrum for a different input power (beam current fixed at 130 mA).

FIG. 8. Energy at peak intensity vs input power (beam current fixed at 130 mA).

FIG. 9. Energy spectrum for different beam current (input power fixed at 2.07 MW).

The pulse beam current was changed from 90 to 140 mA for the maximum stable input power of 2.07 MW. The corresponding energy spectrum is shown in Fig. 9.

The kinetic energy at peak intensity of the output beam for a different pulse beam current can be extracted from Fig. 9, as shown in Fig. 10. The energy at peak intensity drops linearly as a function of beam current.

The measured energies were $\sim 5\%$ higher than those obtained from the simulation. This difference is attributed to several factors, including the misalignment of the magnetic analyzer and the beam, imperfect elimination of the fringing field, etc. [31].

In addition, the FWHM of the spectrum was markedly wider than that in the beam dynamics design, which was only 0.1 MeV. This variation is attributed to the imperfect shape of the input power (see Fig. 5). Unflatness of the peak power has broadened the energy spectrum.

FIG. 10. Energy at peak intensity vs pulse beam current (input power fixed at 2.07 MW).

FIG. 11. Beam spot and distribution along the dashed line.

4. Spot size

Under the condition of a 2.07 MW input power and 130 mA pulse beam current, the beam spot image captured by the CCD camera and its distribution along the red dashed line are shown in Fig. 11. The root-mean-square diameter of the beam spot was about 0.8 mm.

The measured spot size was markedly smaller than the simulated one by PARMELA. In simulation, the spot size was found to be sensitive to the parameters of the thermal-cathode gun (especially the Courant-Snyder transverse ellipse parameters α and β). Thus, we think the occurrence of a smaller spot size is attributed to the difference in the parameters of the gun between the practical one and the one in simulation.

V. CONCLUSION AND FUTURE STUDIES

A C-band 6 MeV standing-wave linear accelerator driven by a magnetron has been developed at the accelerator laboratory of Tsinghua University. This accelerator has a compact size with a narrow spectrum and small spot size that can be used for industrial and medical applications.

The normal cell has been optimized by the SUPERFISH code and the beam dynamics has been carefully studied by the PARMELA code. The coupling slots and the input coupler have been designed by CST MICROWAVE STUDIO. The cold test results show good agreement with the simulation.

High power rf tests after fabrication have also been conducted on this accelerator. In the high power test, the capture ratio, energy spectrum, and beam spot size have been measured. With an input power of 2.07 MW, the peak current was 130 mA and the output spot root-mean-square diameter was about 0.8 mm. The output kinetic energy was 6.0 MeV, with 0.45 MeV FWHM of the spectrum.

The high power rf test shows that this accelerator performs efficiently and can be used for compact and movable industrial and medical applications. However, the performance remains lower than expected because of insufficient input rf power. An improved version was recently designed and fabricated. The modified accelerator has one more normal cell and the total consumed power can be reduced to 1.95 MW. Meanwhile, other critical parameters such as r_{eff} , the spot size, and the FWHM of the spectrum remain nearly the same as Table II presents. This new prototype can readily be subject to high power rf test, and enhanced performance is expected.

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