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X-BAND ELECTRON LINEAR ACCELERATOR DESIGN FOR INTRAOPERATIVE RADIOTHERAPY*

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Abstract

In IORT, accelerators typically consist of two or more tubes to achieve adjustable electron energy. To simplify the accelerator structure and meet the demand for convenient adjustment of electron energy, we propose an X-band electron linear accelerator for IORT, composed of 102 cavities. This accelerator can adjust the output electron energy over a large range solely by varying the input power, providing electrons with energy exceeding 13 MeV at maximum and approximately 5.5 MeV at minimum, which satisfies the requirements of electron IORT. We also measured the field distribution and S-parameters at low power, and the energy spectrum distribution also was measured at different input powers. This accelerator design provides a feasible and simple solution for IORT-specific accelerators.

INTRODUCTION

Intraoperative Radiation Therapy (IORT) is a specialized technique used in cancer treatment, whereby a high dose of radiation is delivered to the tumour bed during surgery, while minimizing radiation exposure to surrounding healthy tissues. One of the methods for IORT is the use of electron accelerators, which generate high-energy electrons that can be directed towards the target tissue [1-3]. However, many of the existing electron accelerators used in IORT require two separate sections to adjust the energy, which can be cumbersome and time-consuming for medical personnel. To address this issue, we propose a single-section X-band electron accelerator specifically designed for IORT.

The X-band accelerator we present in this paper is composed of 102 cells operating in $\pi/2$ mode, with a total length of 0.9m. This design allows for the electron energy to be adjusted by changing the input power, with a maximum output energy of over 13 MeV at an input power of 2.2 MW, and a minimum output energy of 5.5 MeV at an input power of 1.39 MW. The dose distribution in water was calculated in Monte Carlo methods. When the electron energy was 12 MeV and the field size was a diameter of 10cm, the dose distribution was shown in Fig. 1. The compact size and energy adjustability of this X-band accelerator make it an attractive option for IORT applications.

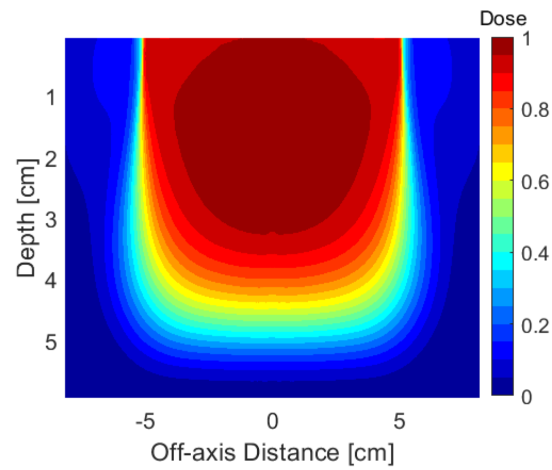

Figure 1: Normalized dose distribution (12MeV, 10cm)

In this paper, we present the design and the test results of our proposed X-band accelerator, including field distribution and S-parameters in low power.

STRUCTURE PRODUCTION

The accelerator operates at a frequency of 9.3 GHz and consists of a total of 102 cells. The focusing section comprises 12 cells, with the remaining cavities being drift-tube cells. The accelerating mode is a standing wave mode, and the coupler cavity is located in the 52nd cavity.

To prevent any issues with single cavities from affecting the overall field or frequency of the entire structure, a segmented welding method is used due to the relatively long length of the accelerator. This allows for replacement of only the affected segment, regardless of which cavity is problematic. As the coupler cavity is prone to frequency errors, other sections are welded first. Figure 2 displays four sections of the accelerator after welding.

Figure 2 : Four parts of welded cells, except for the coupling cavity section.

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LOW POWER MEASUREMENTS

Three rounds of single-cavity frequency measurement and cavity tuning were carried out in order to ensure accurate operating frequency. After the single-cavity frequency met the design requirements, S-parameters were measured and bead-pulling measurement was also performed.

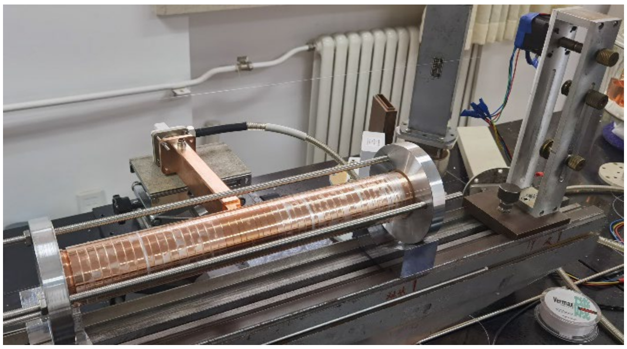

Figure 3: Horizontal bead-pulling measurement of No.1-66 cells. A stepper motor used to control the slow movement of the beads is shown on the right side.

The entire accelerator was horizontally placed, as shown in Fig. 3, and a corresponding work device was made to ensure that the beads did not touch the irises. Figure 4 shows the reflection curve, and the working environment temperature was approximately 15 ℃. Due to multiple cavity tunings, the frequency of the entire accelerator was almost identical to the design frequency.

Since the accelerator is relatively long, if all the cells are assembled for measurement, some cavities may deform due to stress, resulting in frequency deviation. Therefore, the measurement was divided into two sections using the bead-pulling method, and each section had to include a coupler cavity to feed in power. The measurement results of the two sections are shown in Fig. 5. After removing the excess field strength of the coupler cavity, the measured values are in good agreement with the design values (Fig. 6).

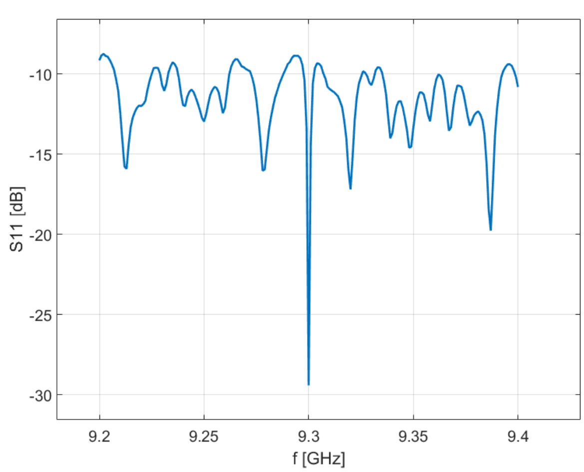

Figure 4: S11 parameter of the whole structure, which is equivalent to -29 dB at the working frequency in vacuum (9.3 GHz)

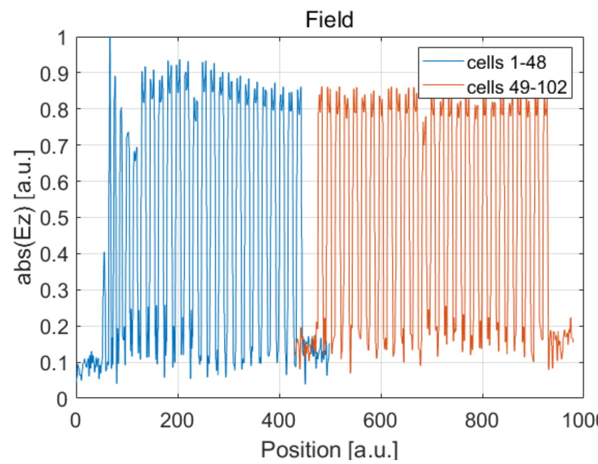

Figure 5: Field distribution (relative values) along the structural axis, where the blue curve on the left represents cavity numbers 1 to 48, and the red curve on the right represents cavity numbers 49 to 102. Each segment requires input power from a coupler cavity.

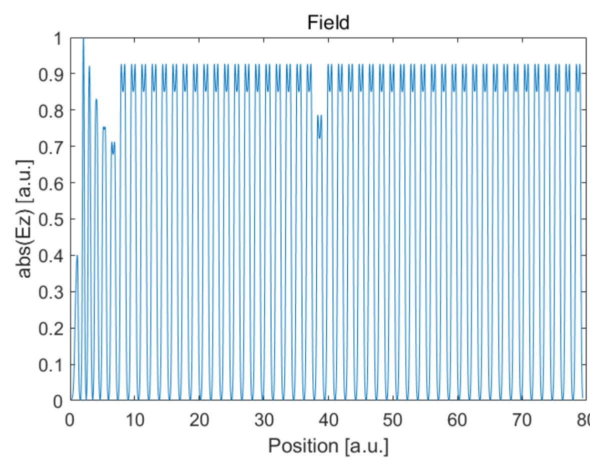

Figure 6: Design values of the field distribution along the axis.

HIGH POWER MEASUREMENTS

After the low-power measurements, the structure was subjected to high-power testing using a 2 MW peak power magnetron. And the electron gun was shown in Fig. 7. We measured the electron energy spectrum generated by the accelerator within the power range of approximately 2.3 MW, achieved by increasing the magnetron current due to the low repetition frequency.

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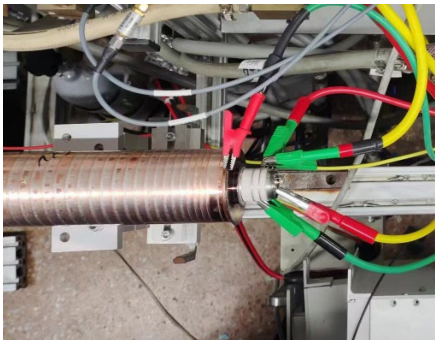

Figure 7: The electron gun used in high power test

The experimental system for measuring the energy spectrum is illustrated in Fig. 8, where the deflection magnet current could be controlled. Seven different input powers were set, and the experimental parameters and results are shown in Table 1.

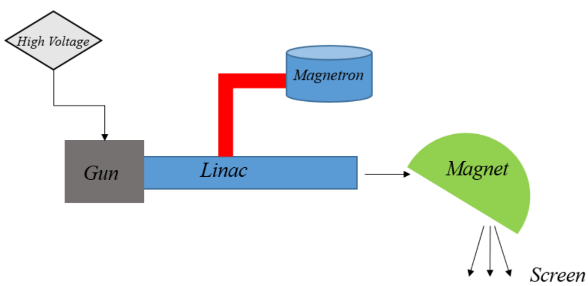

Figure 8: The layout of high-power linac testing system

Table 1: Parameters and results

Input Power [MW]	**Most Probable Energy [MeV]**	**Average Energy [MeV]**
2.28	13.2	13.15
2.2	12.4	12.26
2.08	12.3	11.85
1.78	10.6	10.4
1.67	9.1	9.0
1.56	8	7.78
1.39	5.54	5.83

Figure 9 demonstrates the energy spectra for two of the input powers, corresponding to the maximum and minimum electron energy that can be generated. The spectrum for the lowest energy exhibits a significant distribution in the high-energy region, which may be due to scattering effects during the deflection process, where a portion of the scattered electron spectrum is superimposed onto the high-energy region.

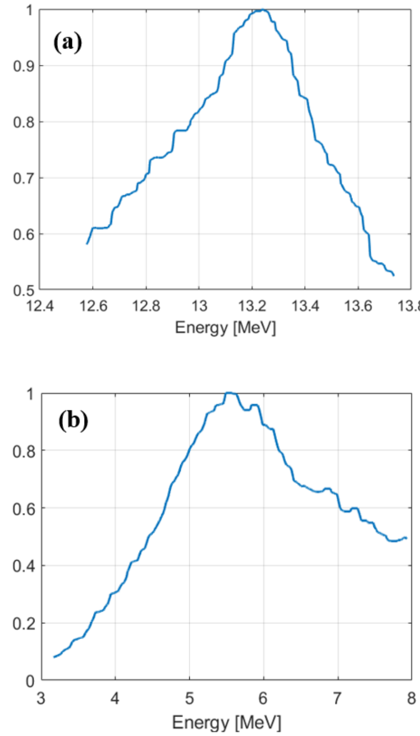

Figure 9: The energy spectra when the input power is 2.28 MW(a) and 1.39 MW(b), the vertical axis represents the normalized relative intensity

CONCLUSION

We described a standing-wave accelerator structure with 102 cells, designed and fabricated this accelerating structure, and obtained results consistent with the design in low-power tests. In high-power experiments, we have achieved an energy adjustment range from 5.5 MeV to 13.2 MeV, equivalent to that of two conventional accelerators, which can meet the requirements of electron energy for intraoperative radiotherapy. Due to equipment limitations, we did not obtain more precise energy spectra, but the excellent performance of this approach has been validated. We expect to further improve the structure and equipment in the future to obtain more accurate experimental results.

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