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DESIGN OF A KU-BAND SIDE-COUPLED STANDING WAVE 2.5 MeV ACCELERATOR

Q. Li*, J. Shi, H. Zha, J. Gao, F. Hu, B. Feng, H. Li, H. Chen

Department of Engineering Physics, Tsinghua University, Beijing, China
and Key Laboratory of Particle and Radiation Imaging of Ministry of Education,
Tsinghua University, Beijing, China

Abstract

Compact accelerator systems are assuming an increasingly significant role within the domain of radiotherapy. As processing technology continues to mature, X-band accelerators have garnered extensive utilization. This study introduces a design for a side-coupled traveling-wave Ku-band accelerator tube, leveraging established processing methodologies. The envisaged particle output energy stands at 2.5 MeV, with a microwave power source requiring a 300 kW input sourced from a magnetron. The microwave design outcomes, derived using ANSYS HFSS, are delineated herein, alongside considerations pertaining to dynamic output and engineering design. Subsequent stages will subject this accelerator tube to processing tests, with the overarching objective of effectively supplanting the natural radiation source Co60 within the realm of radiotherapy.

INTRODUCTION

With the development of processing techniques and complementary power sources, increasingly compact high-frequency accelerators have been continuously advancing. In the medical field, the miniaturization of accelerator tubes is crucial for the broader application of radiotherapy systems. Accelerator tubes operating in the X-band have gained extensive use in today's radiotherapy domain due to their superior acceleration efficiency and compact dimension. Conversely, for many application scenarios requiring more compact accelerator radiotherapy devices, accelerator tubes need to operate in higher frequency bands such as the Ku-band. Accelerator tubes in the Ku-band offer several notable advantages: a more compact size for the same microwave power, higher shunt impedance per unit length, and the ability to withstand higher surface electric fields [1].

However, its technical challenges are also quite apparent. For Ku-band accelerator tubes, the diameter of a single cavity often remains within 1 cm, posing significant challenges for fabrication. Additionally, smaller dimensions imply higher sensitivity to errors, necessitating meticulous design and operation during welding and tuning processes.

In this paper, we propose a linac design operating at the Ku-band (15 GHz). The design objective is to replace natural radiation sources with a small-scale accelerator tube. To achieve the target energy within minimal length possible, we have opted for a standing wave accelerator tube. Concurrently, to circumvent the machining challenges associated with conventional axial coupling structures, particularly concerning the high difficulty in processing small dimensions in the Ku-band range, we have chosen the side-coupled disc structure for its easier tunability. Side-coupled structures offer the advantage of easier adjustment of the coupling cavity while maintaining a high shunt impedance and acceleration efficiency throughout the entire structure. The design goal of the accelerator is to achieve an output beam energy of 2.5 MeV. The power source for the accelerator is a 300 kW 15 GHz magnetron. We perform the RF design using HFSS and subsequently validate the beam dynamics using Astra. Finally, thermal simulation and mechanical design results are provided.

* liqz21@mails.tsinghua.edu.cn

RF DESIGN

We performed a prototype of a 2.5 MeV linac of 15 GHz. Building upon the design of the X-band accelerator, we conducted a design study for the Ku-band accelerator structure. Regarding the single cell, a deeper nose cone structure leads to higher shunt impedance for the accelerator cavity. However, achieving finely detailed deep nose cone structures imposes high manufacturing requirements, especially for the relatively smaller dimensions of the Ku-band. For a standing-wave accelerator tube, the relationship between the final acceleration energy and the beam size is as followed

$$P_{in} = \frac{V^2}{R_S L} + IV$$

Here, we present the relationship between the total effective shunt impedance of the tube and the beam size, accompanied by corresponding figures. Within these, the operational point of the entire tube is selected.

Single Cell

The single-cell unit of the accelerator tube is comprised of an acceleration cavity and a coupling cavity. The design of the acceleration cavity is similar to the traditional axis-coupled structure in the X-band, while the coupling cavities are alternately distributed on both sides of the acceleration cavity. In order to achieve as wide a frequency bandwidth as possible at high frequencies, the accelerator tube adopts a $\frac{\pi}{2}$ operating mode. The length of each acceleration cavity is $D = \frac{\beta\lambda}{2}$, where λ is the microwave wavelength and β is the electron phase velocity. The coupling in the accelerator tube

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introduces two different structural units, namely CAC and ACA structures, where C represents the coupling cavity and A represents the acceleration cavity. These two structural units respectively represent the consideration of the coupling hole structure in the acceleration cavity and the coupling cavity. Based on this, we conducted single-cell tuning.

The coupling between cavities is achieved through coupling apertures between the acceleration cavity and the coupling cavity. For the ACA unit, by determining the operating frequencies of its 0, $\pi/2$, and π modes, the coupling coefficients of the accelerator tube can be obtained:

$$k = \frac{f_\pi - f_0}{f_{\pi/2}}$$

The coupling coefficient between the acceleration cavities can be adjusted by tuning the loading depth of the coupling cavities. Figure 1 illustrates the impact of loading depth variation on the field magnitude between adjacent acceleration cavities and the coupling coefficient. The effective shunt impedance of accelerating cavity is 160 MΩ m^{-1}, and the Q factor of 7300. At the nose cone, the peak surface electric reaches $E_{peak}/E_{average} = 4$, where $E_{average}$ is the average electric field on axis.

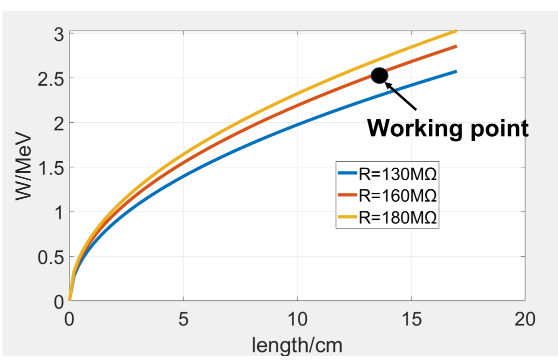
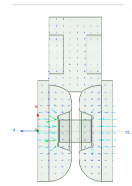


Figure 1: Relationship between the length of the accelerator structure and the output energy under conditions of the same beam current intensity but varying R_{eff}.

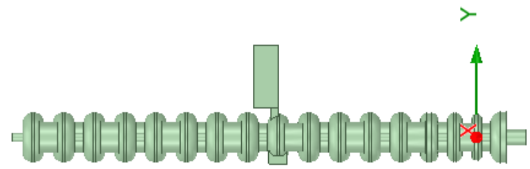
Whole Length

Based on the single-cell design and the target electron energy mentioned above, we present here the microwave design of the entire tube in Fig. 2, which consists of 17 acceleration cavities connected through side-coupling, Among which there are 4 bunching cavities and 13 velocity-matched cells. To achieve a higher capture rate and ensure satisfactory transverse compression results, the design of the first cavity adopts a half-cell configuration.

In conjunction with the target beam size, we have provided a coupling design. Here, we present the distribution of the electric field magnitude across the entire tube and the curve of input reflection coefficient. The average gradient is around 17 MV/m, while peak gradient is 45 MV/m. The input coupling coefficient is set at 1.25, as shown in Fig. 3.



(a) Single cell



(b) Whole length

Figure 2: RF design of the Ku-band linac.

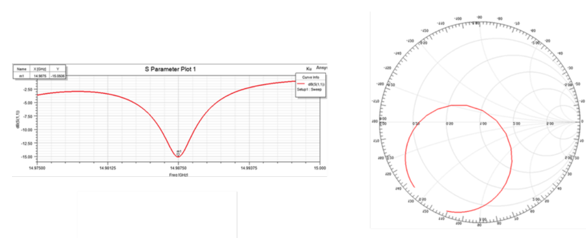
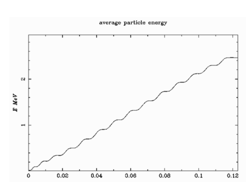


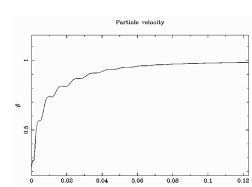
Figure 3: Reflection and coupling coefficient.

BEAM DYNAMICS

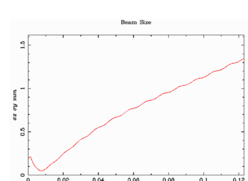
According to the beam parameters commonly used in X-band electron guns, we have set the initial beam distribution for simulation. Conducting beam dynamics simulation in ASTRA, a total of 10000 macroparticles were used for simulation. The electrons were assumed to be generated from a DC e-gun, with initial energy of 12 keV. The transverse distribution was Gaussian with beam spot size of Φ 1.2mm (RMS). We obtained the energy output and transverse-longitudinal distribution results as shown in Fig. 4.



(a) Energy gain of the linac



(b) Particle velocity v.s. length



(c) Transverse beamsize

Figure 4: Beam dynamic results along longitude distance.

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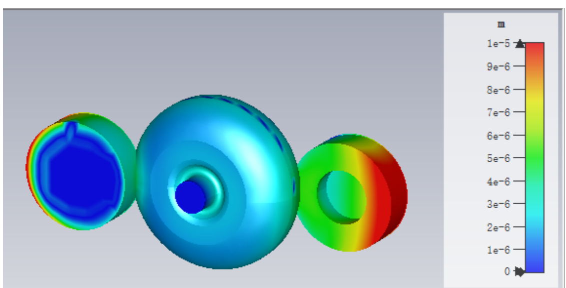
The output energy of particles reaches 2.5 MeV at 3 kW, meeting the design requirements. The transverse beam size at the end of the linac is 1mm, and the beam energy spread is 200 keV.

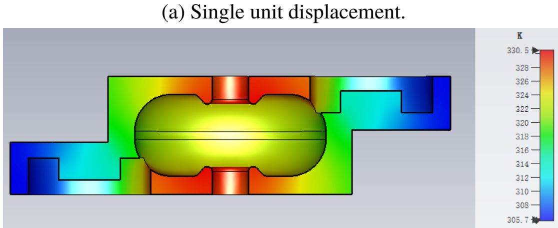
THERMAL AND MECHANICAL DESIGN

Due to the power loss on the cavity wall, the accelerator tube will experience thermal effects and deformation during operation. This has a decisive impact on the formulation of the final production and processing scheme for the accelerator tube.

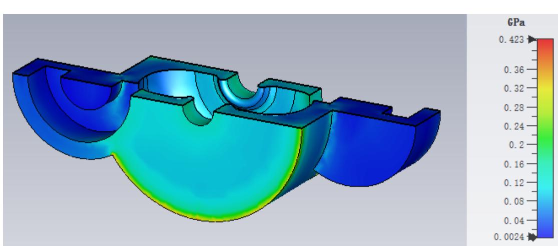
We used CST Studio to calculate the electromagnetic field of a single accelerating unit. Then, we utilized the results from electromagnetic field calculations, combined with the characteristics of the copper cavity wall, to perform simulations of thermal effects and mechanical deformation, as shown in Fig. 5.



(a) Single unit displacement.



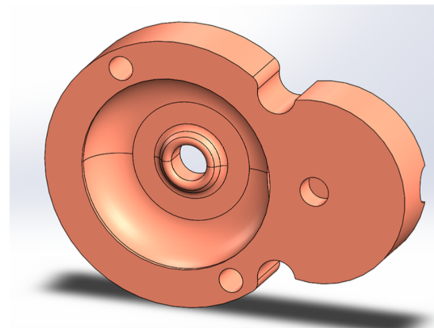
(b) Single unit temperature rise



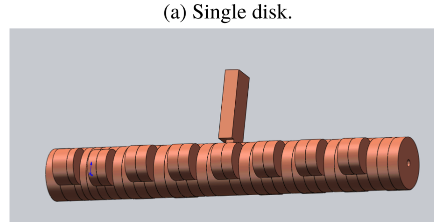
(c) Single unit pressure

Figure 5: Single unit thermal and mechanical analysis.

The thermal simulation results indicate that heat generation concentrates near the nose cone, reaching temperatures as high as 58 degrees Celsius. Due to heat dissipation and mechanical structural constraints, deformation accumulates at the coupling cavity, resulting in localized pressure enhancement. This ultimately leads to a frequency shift of 6 MHz in the single cell. Based on this, we propose a disc design for subsequent processing. The entire disc is composed of half-cycle units, with internal structures milled to form cavities, while external water pipes or water jackets are attached for cooling. The design diagrams of the single-cavity disk and the entire tube body are shown in Fig. 6.



(a) Single disk.



(b) Assembly of the linac

Figure 6: Mechanical design for fabrication.

CONCLUSION

The rf and mechanical design of a single-cell edge-coupled Ku-band standing wave accelerator tube has been accomplished. The design objective of this accelerator tube is to replace natural radiation sources (such as Co60) in radiotherapy with a miniaturized accelerator system. The optimized single-cell structure exhibits high shunt impedance and quality factor. When subjected to an input power of 300 kW, the accelerator tube is capable of delivering an electron energy of 2.5 MeV. The length of the accelerator tube body measures 15 cm, with an overall mechanical structure diameter of Φ 4.5 cm. Both the beam properties and external dimensions conform to the design specifications. The paper further analyzes the thermal and deformation effects of the accelerator tube, upon which cooling and mechanical structure design are predicated. It is projected that this accelerator tube will undergo machining and low-power testing within the current year, with plans for eventual high-power testing.

REFERENCES

[1] A. Yu Smirnov *et al.*, “Cost-efficiency enhancement of X- and Ku-band split waveguides for industrial accelerators.” *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1056, p. 168638, 2023. doi:10.1016/j.nima.2023.168638