DESIGN OF A COMPACT ENERGY-TUNABLE X-band LINAC FOR FLASH RADIOTHERAPY[*]

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Abstract

FLASH radiotherapy (FLASH-RT) demonstrates the potential to maintain tumor control while reducing normal tissue toxicity through ultra-high dose rates. This paper presents a novel compact X-band (9.3 GHz) accelerating system designed for FLASH-RT applications. The core innovation is a dual-structure common-source architecture: the first structure provides a fixed 6 MeV energy gain, while the second enables independent continuous energy adjustment from 0 to 6 MeV via a tunable microwave network. This design allows a single klystron to drive both structures without mutual interference during energy adjustment. The system length is only approximately 1 meter. The design process integrates radio frequency (RF) simulation and beam dynamics simulation in a coupled manner, with particular focus on the bunching section optimization. This compact system provides a high-performance accelerator solution for next-generation FLASH radiotherapy, especially for intraoperative applications requiring rapid energy adjustment.

INTRODUCTION

FLASH Radiation Therapy (FLASH-RT) employs ultra-high dose rates to reduce normal tissue toxicity while maintaining tumor control compared to conventional radiotherapy [1, 2]. This novel approach has attracted significant interest from the accelerator community, with exploration of various radiation modalities including X-rays, protons, very-high-energy electrons (VHEE), and low-energy electrons for FLASH dose delivery.

X-ray-based systems require high beam currents due to the inefficiency of bremsstrahlung conversion. VHEE offers improved efficiency but still requires high beam power. Intra-operative electron radiation therapy (IOeRT) represents another approach, combining surgical resection with targeted electron irradiation. Clinically applied for decades in cancers such as soft tissue sarcoma, pancreatic, rectal, and breast malignancies, IOeRT can deliver electron beams at dose rates compatible with the FLASH regime [3, 4].

Standing-wave linear accelerators are key enabling technologies for FLASH-RT. X-band accelerators are particularly attractive due to their high accelerating gradients supporting rapid dose delivery and compact, lightweight design enhancing clinical versatility. This work presents a novel X-band microwave system operating at 9.3 GHz, engineered specifically for FLASH-RT applications. The system comprises two accelerating structures integrated into a compact assembly with a total length of only 1 meter. Its key innovation is a dual-tube architecture: the first tube provides fixed acceleration to 6 MeV, while the second enables real-time energy tunability from 0 MeV to 6 MeV. Both tubes are powered by a same klystron, yet the energy adjustment operates independently without interference.

SYSTEM DESIGN

The accelerator system employs a dual-structure common-source architecture to achieve energy tunability from 6–12 MeV. High-energy electron beams are used for deeper tissue penetration, while low-energy beams are suited for superficial treatments. The energy must be adjusted based on tumor thickness and location.

Overall System Architecture

As shown in Fig. 1, microwave power from a single klystron passes through a circulator and a 3 dB power divider, equally distributing power to both acceleration structures. Half the power enters the first structure directly, while the other half passes through a phase shifter and a tunable power divider before entering the second structure. The power divider uses a movable short-circuit plane to continuously adjust output power from 0% to 100%. The 3 dB power divider ensures independence: reflected power from one port cannot enter the other, making the two channels mutually independent.

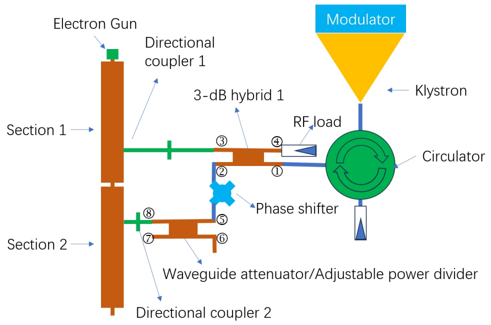

Figure 1: Schematic diagram of the microwave system with dual-structure common-source architecture.

ACCELERATING STRUCTURE DESIGN

This system uses a hot cathode electron gun. Since the electron source produces a DC beam, a bunching section

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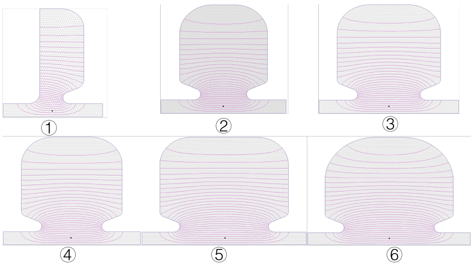


Figure 2: Six types of accelerating cavities.

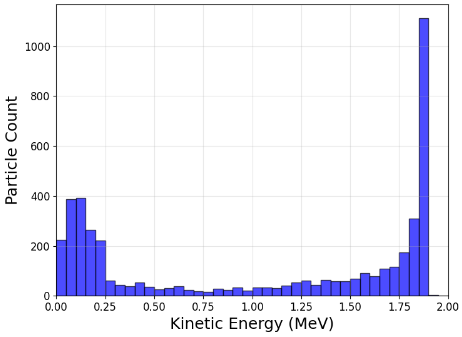


Figure 3: Beam energy spectrum after passing through the bunching section.

is essential to capture and bunch the beam efficiently. The bunching section design is critical for achieving high capture efficiency and good beam quality, requiring careful optimization of both radio frequency (RF) field distribution and beam dynamics performance.

Bunching Section

It was designed through a coupled approach integrating RF simulation and beam dynamics simulation. This iterative process ensures that both electromagnetic field distribution and beam capture efficiency are optimized simultaneously. The design process began with initial single-cavity RF parameters, followed by beam dynamics simulation to evaluate electron capture and bunching performance, and then returned to RF simulation for refinement based on beam dynamics feedback.

The bunching section uses six different cavity types (Fig 2), each optimized for specific phase velocity and accelerating gradient requirements. The cavity parameters were designed with careful attention to the transition from non-relativistic to relativistic beam velocities. Each cavity type was individually tuned to provide the appropriate field distribution for efficient beam capture and acceleration.

The six cavity types are arranged in a specific sequence to optimize the initial acceleration phase. The cavity sequence is [1, 2, 2, 3, 3, 4, 5, 4, 5, 6], carefully designed to provide a smooth acceleration gradient that efficiently captures the injected DC electrons and bunches them for optimal energy gain. This sequence was refined through multiple iterations of RF and beam dynamics simulations, ensuring that the field distribution provides the necessary phase focusing for high capture efficiency. The results are shown in the Fig 3.

Full Structure Design

Following the bunching section optimization, the complete accelerating structures were designed. The system consists of two bi-periodic standing-wave structures operating at 9.3 GHz: First structure complies of 30 accelerating cavities and 29 coupling cavities, providing a fixed energy gain of 6 MeV. Second structure complies of 28 accelerating cavities and 27 coupling cavities, enabling continuous energy adjustment from 0 to 6 MeV

Figure 4 shows the vacuum model of both accelerating structures. The the accelerating cavities in the rear of the first accelerating tube and the second accelerating tube are all light-speed cavities.

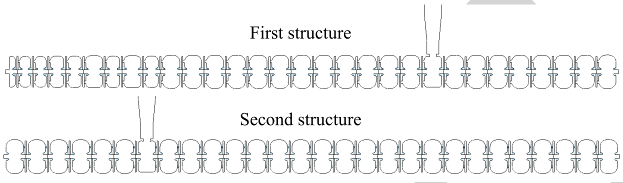


Figure 4: Mechanical models of the two accelerating structures: first structure (top) with 30 accelerating cavities and second structure (bottom) with 28 accelerating cavities.

The complete structure design maintains the field flatness and phase relationship established by the bunching section, ensuring efficient beam acceleration throughout the entire length of both structures.

SIMULATION RESULTS

RF Simulation Results

The structures were designed and tuned using Superfish and CST Studio. Figure 5 shows the S11 curves and axial electric field distribution. The structures are over-coupled to account for beam loading and fabrication tolerances. The field distribution shows characteristic steps at coupling cavity locations, which is the asymmetric effect caused by the coupler.From theoretical analysis, the influence of the stepped light-speed cavity field on the beam can be neglected.

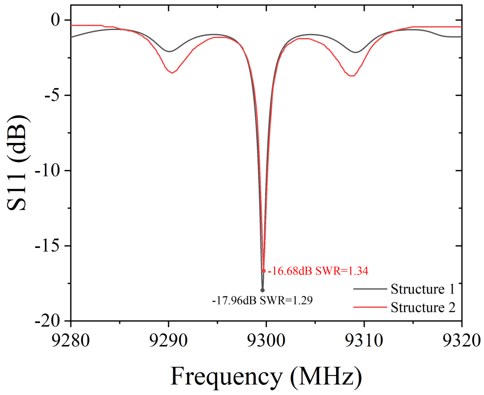
Beam Dynamics Simulation Results

Beam dynamics simulations were performed using RF-Track [5], a tracking code developed at CERN for optimization of low-energy ion linacs with space-charge effects. The code employs C++ for computation with Python interfaces, allowing efficient simulation of both one-dimensional and three-dimensional field effects.

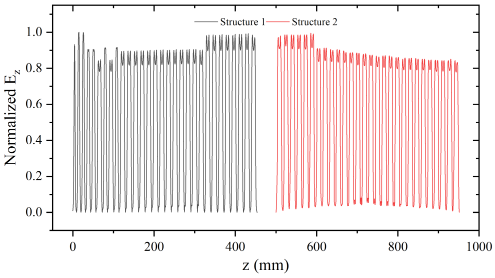
Simulations verified the energy adjustment function with the second structure turned off and at maximum power operation, achieving 6 MeV and 12 MeV respectively. Figure 6 shows the energy spectrum at these two operating modes, demonstrating good beam quality and energy spread characteristics.

CONCLUSION

A compact X-band linear accelerator system with real-time energy adjustability has been designed for FLASH ra-



(a) S11 curves.



(b) Axial electric field.

Figure 5: RF simulation results of the accelerating structures.

diotherapy applications. The dual-structure common-source architecture enables independent energy adjustment from 6–12 MeV using a single klystron. The system length of approximately 1 meter makes it suitable for intraoperative applications.

The design process integrated radio frequency (RF) simulation and beam dynamics simulation in a coupled manner, ensuring optimal performance. The bunching section was carefully designed with a specific cavity sequence to maximize electron capture efficiency. RF simulation results demonstrate proper field distribution, while beam dynamics simulations verify good transmission efficiency and energy spectrum at both 6 MeV and 12 MeV operating modes.

This design provides a practical accelerator solution for next-generation FLASH radiotherapy requiring flexible beam energy and high dose rates, particularly for intraoperative applications where compact size and rapid energy adjustment are critical.

ACKNOWLEDGEMENTS

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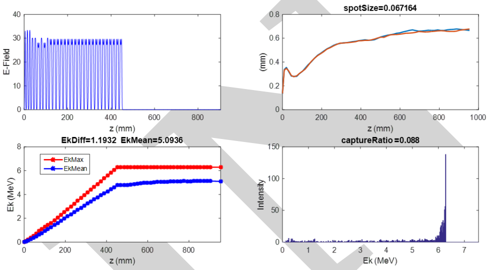
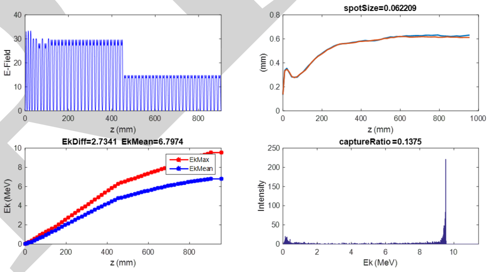
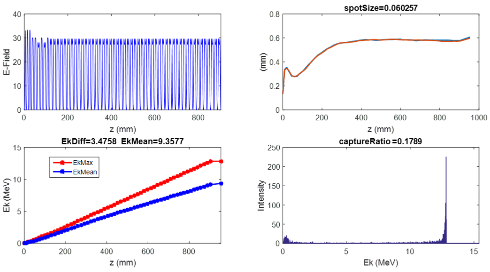


(a) 6 MeV operation.



(b) 9 MeV operation.



(c) 12 MeV operation.

Figure 6: Beam dynamics simulation results showing energy spectrum at different operating modes.