R&D SMALL FOCAL SPOT LINACS FOR INDUSTRIAL AND CARGO SCANNING AT ELEKOM

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Abstract

Electron linear accelerators(linacs) have been widely used in industrial Non-Destructive Testing (NDT) and cargo scanning for decades, exploiting their X-ray radiography features. The focal spot size is a critical parameter of an X-ray source, where a smaller focal spot size generally yields higher image resolution. To enhance system image resolution, Chengdu Elekom Vacuum Electron Technology Co. Ltd has developed a series of small focal spot linacs for industrial and cargo scanning applications. These linacs feature focal spot size bellow 1 mm, with some type achieving sub-0.5 mm performance. After rigorous testing in laboratory and field environments, they have demonstrated high dose rates and extended operational lifetimes. This paper will provide a detailed analysis of these linacs' performance.

INTRODUCTION

The Electron Linear Accelerator (LINAC), an important device for generating high-energy particle beams, has found extensive applications across multiple critical sectors of the national economy, including radiation therapy, irradiation processing, non-destructive testing (NDT), cargo inspection, and agriculture, yielding substantial socio-economic benefits [1-2]. Particularly in the field of industrial non-destructive testing, the electron LINAC serves as an indispensable core equipment for producing high-energy X-ray. Its operational principle involves utilizing high-frequency electromagnetic fields to accelerate electrons emitted from an electron gun along a linear trajectory to high energies. These high-energy electrons are then directed to strike a high-Z (high atomic number) metal target, generating Bremsstrahlung X-ray through the deceleration process.

The focal spot is a key parameter for X-ray source, which is directly related to resolution of the image system. The smaller focal spot size, the higher resolution the image system will have. The linac X-ray source focal spot size in market mostly is about 1.5~2 mm. With development of NDT and cargo inspection system, users demand to have more higher resolution for the image systems.

Elekom was founded in 2018, located in Chengdu city, Sichuan Province, China [3]. Elekom is a high-tech enterprise focusing on design, R & D, manufacturing, sales and service of the S, C and X-band RF electron linear accelerator tubes, accelerators and application systems. In order to meet the demand of small focal spot the high energy X-ray source, Elekom developed a series of small focal spot linac for NDT and cargo inspection and will be introduced in this paper.

LINAC SYSTEM DESIGN

Elekom linac consists modulator, X-ray head, Temperature control unit (TCU) and control console, as shown in Fig. 1. The modulator serves a dual function: it not only supplies the pulsed high voltage required for the radio frequency (RF) power source, but also integrates several critical subsystems, including the control and interlock unit, the automatic frequency control (AFC) unit, the vacuum system unit, and the dose monitoring unit, among others. The X-ray head, serving as the core radiation-generating unit in linear accelerator (linac) systems, is primarily comprised of two key subsystems: the radio frequency (RF) power source and the linear accelerating tube. These components working together to generate high-energy electron beams, which are subsequently converted into a high-intensity X-ray source. The TCU provides constant temperature liquid to maintain parts inside the linac system with normal working temperature.

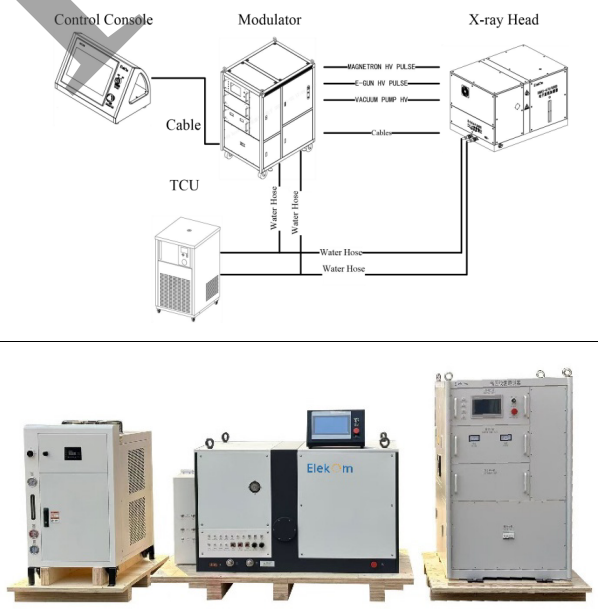

Figure 1: Architecture and layout of Elekom linac.

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SMALL FOCAL SPOT LINAC

Accelerating tube inside X-ray head is the device for accelerating electron beam generated by electron gun to several MeV, which is the most important part of linac. To make the linac system more compact, the small focal spot series linacs adopt a biperiodic standing-wave (SW) accelerating structure operating at 2.998 GHz, with high effective shunt impedance and high stability. Diode electron gun is used as the injector and the ceramic RF window as the vacuum isolator between the linac tube and waveguide side. One ion pump maintaining the vacuum of the accelerating structure. The Fig. 2 shows an S band 9 MeV accelerating tube.

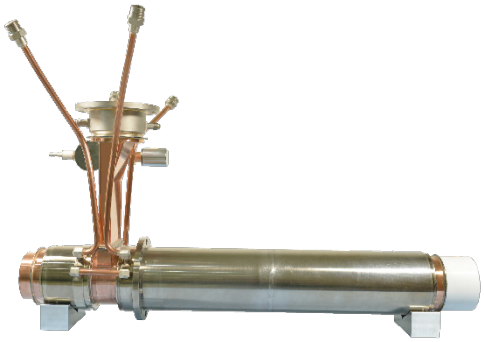

Figure 2: S band 9 MeV accelerating tube.

Based on the comprehensive understanding of linear accelerator principles, precise cavity design, and advanced beam dynamics simulation, Elekom has successfully developed a low-emittance electron gun capable of generating a small, long-range beam waist. This gun provides high-quality initial electron beams that are readily focused by the RF fields within standing wave (SW) cavities. The synergistic optimization of RF cavity geometry and beam dynamics simulation plays a key role in achieving a significantly reduced electron beam focal spot at the target.

Utilizing this integrated design approach, Elekom has engineered a series of S-band linear accelerators (linacs) from 2 MeV to 9 MeV that produce exceptionally small focal spots with a Full Width at Half Maximum (FWHM) of less than 1.0 mm. The key parameters of these linacs are summarized in Table 1. It is noteworthy that these sub-millimeter focal spots are achieved directly through the combination of the low-emittance electron gun and the self-focusing properties of the SW accelerating structure, without requiring any external focusing magnetic fields such as solenoids. This design philosophy aligns with industry trends aimed at reducing system size, weight, and complexity while enhancing image resolution for applications like NDT and cargo inspection. These linacs feature both a small focal spot and a high dose rate, enabling them to serve as high-resolution X-ray sources while maintaining efficient throughput.

Table 1: Parameters of Small Focal Spot Series Linac

Item				
Energy, MeV	2	4	6	9/6
Frequency, MHz	2998	2998	2998	2998
Spot size, mm	0.7	0.7	0.5	0.5/0.8
Dose rate, Gy/min	1.5	4	8	25/10

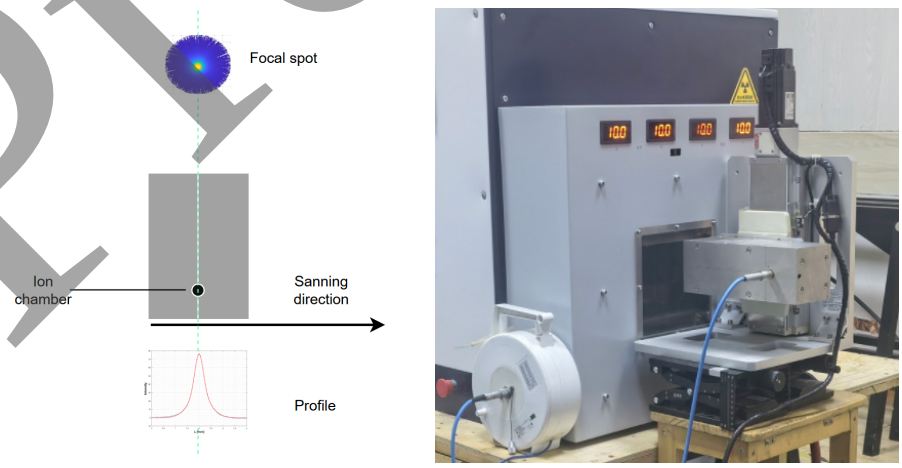

Figure 3: Focal spot measured by slit scanning method.

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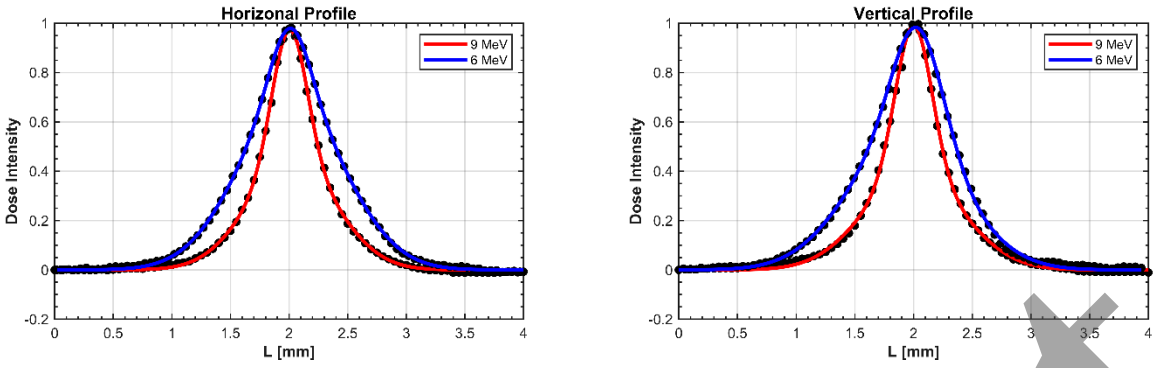

Figure 4: Beam spot profile of 9 MeV (Left: Horizonal, Right: Vertical)

The focal spots were measured by slit scanning method [4-5], as shown in Fig. 3. Two tungsten brick with a slit are moved by step motor scanning in front of linac to acquire the dose profile, and take the Full Width at Half Maximum of profile as the focal spot size.

Figure 4 presents the focal spot profile of a 9/6 MeV linear accelerator (linac). This accelerator can operate at both 9 MeV and 6 MeV energy levels. The full width at half maximum (FWHM) sizes in the horizontal and vertical directions for the 9 MeV setting are 0.47 mm and 0.48 mm, respectively, indicating that the focal spot is nearly circular—a characteristic of critical importance for achieving high-quality imaging in industrial computed tomography (CT) applications. For the 6 MeV operating mode, the corresponding horizontal and vertical FWHM spot sizes are 0.76 mm and 0.78 mm, respectively

CONCLUSION

This paper presents the small-focal-spot linacs developed by Elekom over the past several years. These systems achieve sub-millimeter focal spots and high dose rates, which are key enablers of high-resolution imaging and improved production efficiency. All linacs described herein are commercially mature and have been successfully integrated into industrial non-destructive testing (NDT) and cargo inspection systems.

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