HIGH-POWER TEST OF A 40kW INDUSTRIAL ELECTRONIC LINEAR ACCELERATOR

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Abstract

Electron accelerators with high average power output are widely used in radiation processing fields such as material modification, food sterilization, and environmental pollutant treatment. This paper presents a comprehensive high-power test of a 40kW electron accelerator. Key parameters including electron beam energy, average beam current, output power, and pulse characteristics were measured. The results show that the accelerator's electron beam energy, the average beam current, and the effective output power all meet the design specifications. The energy test was performed via the aluminum foil stacking method, ensuring high measurement accuracy. This study validates the reliability and stability of the accelerator, providing technical support for its industrial application.

INTRODUCTION

With the rapid development of advanced manufacturing, new materials, food safety, and environmental protection industries, high-power industrial electron linear accelerators have become core equipment for efficient, clean, and controllable radiation processing [1, 2]. Compared with traditional irradiation sources, MeV-level electron accelerators feature high energy utilization, adjustable beam parameters, good safety, and no radioactive waste, making them widely applied in polymer cross-linking, composite material curing, surface functionalization, food sterilization, medical device disinfection, and industrial wastewater/waste gas treatment.

In recent decades, standing-wave (SW) and traveling-wave (TW) accelerating structures have been the mainstream choices for industrial electron linacs. SW structures offer high shunt impedance and compact size but suffer from poor power efficiency at high repetition rates. TW structures provide high power efficiency and beam stability but require complex focusing systems, increasing equipment complexity and operating costs. These limitations restrict the further improvement of average power, stability, and reliability in high-power industrial irradiation scenarios. The backward-traveling-wave (BTW) accelerating structure, as a magnetically coupled traveling-wave configuration, combines the advantages of both TW and SW structures [3]. It features low power reflection, short filling time, high shunt impedance, and compact structural length, making it highly suitable for high-average-power industrial accelerators. Based on decades of research on BTW structures, Tsinghua University and its industrial partners have developed a 10 MeV 40 kW S-band BTW linear accelerator for industry application.

This paper reports the high-power test of this 40 kW BTW electron accelerator, including RF conditioning, beam energy measurement, average/pulse beam current test, output power verification, and beam scanning uniformity. All tests follow national standards and industrial specifications in China, providing a practical and high-performance solution for high-power industrial irradiation applications.

DESIGN OF THE ACCELERATING STRUCTURE

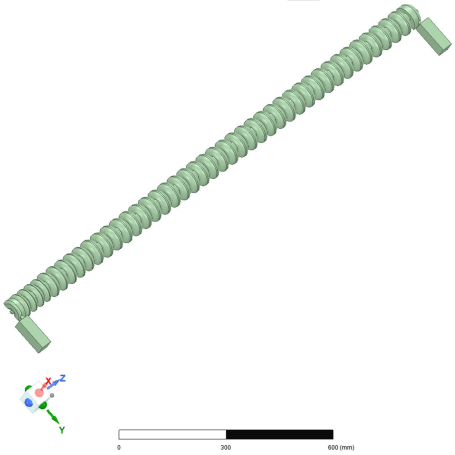

Figure 1: 3D model of the accelerating structure.

First, we briefly introduce the design of the BTW structure. Optimized from the previous design [**?**], it operates stably in the $3\pi/4$ phase advance mode, which is favorable for efficient particle acceleration and transverse beam confinement. As shown in Fig. 1, with a total of 42 accelerating cells and an overall axial length controlled within 1.6 m, the structure realizes a compact accelerator design, enabling an energy gain up to approximately 10 MeV and a peak pulse beam current exceeding 300 mA. To improve beam capture efficiency and initial acceleration stability, a dedicated buncher section is integrated at the front end of the accelerating structure. The main accelerating part adopts a tappered structure to provide stable acceleration field for electrons and boost their energy to the target level continuously. The key radio-frequency (RF) parameters of the BTW accelerating structure are summarized in Table 1. High-power operation of the 40 kW BTW structure causes severe RF power deposition, thermal accumulation, deformation, and frequency detuning. To address this issue, structural and water cooling optimizations are adopted. The coupling aperture and adjacent disks of cells near input coupler were modified: the disk thickness was increased, the aperture opening angle was re-

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duced, and edge fillets were optimized to lower eddy-current loss and improve heat conduction.

Table 1: Key RF Parameters of the BTW Accelerating Structure

Parameter	**Value**
Working frequency	2856 MHz
Operating mode	$3\pi/4$ mode
Number of cells	42
Group velocity	0.013c - 0.019c
Structure length	1.6 m
Shunt impedance	100 MΩ/m
Quality factor	13 000
Filling time	330 ns
Input RF power	4.5 MW

HIGH POWER TEST RESULTS

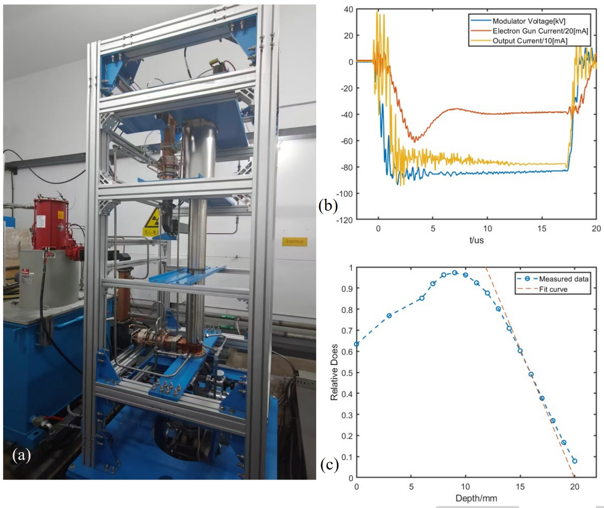

Figure 2: The photograph of the accelerator (a), measured data (b) and depth-dose distribution curve (c).

As shown in Fig. 2 (a), the accelerator comprises a thermionic electron gun, a BTW accelerating structure, a microwave power source (klystron with modulator), and a scanning magnet. key performances of the accelerator under dynamic industrial irradiation conditions, including electron beam energy, output beam energy, scan width, average beam current, and output beam power was test and verified. The average beam current was directly measured as 3800 µA via a milliammeter, shown in Fig. 2 (b). The electron beam energy was measured using the aluminum foil stacking method with CTA dosimeters. A stack of aluminum foils was irradiated dynamically, and the depth–dose distribution was recorded. The practical range R_p was derived by linear fitting, and the most probable energy E_p was calculated according to GB/T 16841-2008:

$$E_p = 0.509R_p + 0.2 \tag{1}$$

The measured energy was 10.36 MeV, meeting the design target, as the depth-dose distribution curve shown in Fig. 2 (c). The effective output power reached 41.44 kW (39.36 kW after loss correction), satisfying the 40 kW high-power irradiation requirement. Scan width and transverse dose uniformity are key performance parameters that directly determine processing quality and product consistency. Experiments were performed at four typical scan currents to reveal the relationship between scan current, effective scan width, and dose uniformity, as shown in Fig. 3 . The relative dose non-uniformity U was calculated using:

$$U = \frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}} \times 100\% \tag{2}$$

At a scan current of 3.34 A, the total scan width reached 80 cm, with a dose non-uniformity of 4.8%. At 3.07 A, the

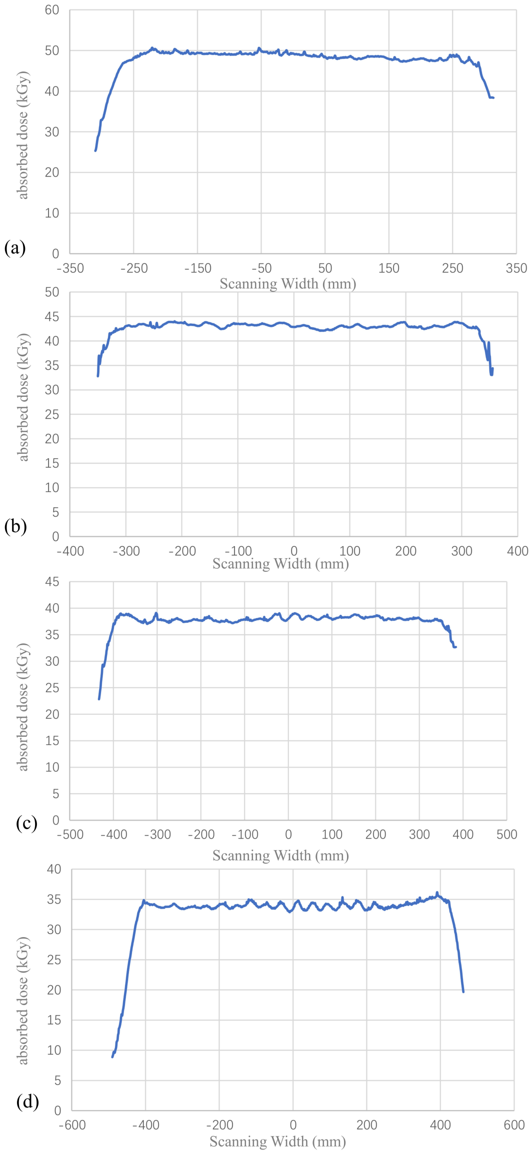

Figure 3: Scanning width at different current: (a) 2.33 A, (b) 2.68 A, (c) 3.07 A, (d) 3.34 A.

scan width was 70 cm, and the non-uniformity improved to 2.7%. At 2.68 A, the scan width was 60 cm, with the lowest non-uniformity of 2.2%. At 2.33 A, the scan width was 50 cm, and the non-uniformity was 3.8%. These results demonstrate that the accelerator can provide adjustable scan widths from 50 cm to 80 cm with excellent dose uniformity, making it adaptable to various industrial processing widths and quality requirements.

CONCLUSION

This paper presents a full high-power test and performance verification of a 10 MeV 40 kW S-band BTW industrial electron linear accelerator. All test results are consistent with simulations and meet national standards and industrial requirements. The BTW structure successfully combines high shunt impedance, high power efficiency, good thermal stability, and compact structure, solving key problems of conventional accelerators. This study validates the reliability, stability, and industrial applicability of the 40 kW BTW electron linac. It provides a domestically independent, high-performance, and cost-effective solution for high-power industrial irradiat ion, and can be widely used in material modification, food sterilization, medical device treatment, and environmental protection. The technology also supports further scaling to higher power levels, promoting the development and upgrading of the global radiation processing industry.

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