ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG88

DESIGN OF A CONSTANT-GRADIENT BACKWARD-TRAVELLING-WAVE ACCELERATING STRUCTURE FOR IRRADIATION

Jiaru Shi, Hongbo Yu, Heng Deng, Hao Zha*, Huaibi Chen, Qiang Gao, Focheng Liu
Department of Engineering Physics, Tsinghua University, Beijing, China

Abstract

To develop a high-power, high-efficiency electron irradiation accelerator system with an adjustable electron beam, a novel constant-gradient backward-travelling-wave (BTW) accelerating structure has been designed. This accelerator tube implements a backward-travelling-wave design, which offers the advantages of short filling time and low power reflection, which are characteristic of traveling-wave acceleration structures, and can incorporate a nosecone design to achieve high shunt impedance. The constant-gradient concept is adopted to further enhance the electron beam power and beam efficiency. This paper presents the design of the BTW accelerating structure, encompassing parameter estimation and comprehensive three-dimensional simulations to validate the concept.

INTRODUCTION

The high-energy electron irradiation accelerator system is equipped with a 10 MeV, 20 kW, S-band traveling-wave accelerator structure, complemented by a robust pulsed power modulator and a high-average-power klystron. This configuration is noted for its technical sophistication, exceptional stability, and competitive cost, which has led to a significant market presence in the irradiation industry. [1] Pioneering research in this domain was undertaken by Tsinghua University,[2] where the development of traveling-wave linear accelerator (linac) tubes was initially pursued. As user applications expand and industrial demands evolve, there is an increasing imperative to enhance electron beam efficiency, to increase beam power, and to reduce system energy consumption.

The proposed system for the high-power irradiation accelerator utilizes a backward-travelling-wave (BTW) accelerator tube in conjunction with a high-power solid-state modulator. The BTW design has the benefits of short filling time and low power reflection, inherent to traveling-wave structures, and can apply a nosecone design to enhance the shunt impedance, thereby potentially reducing the length of the structure. These attributes collectively contribute to a significant increase in both electron beam power and power efficiency.

A novel BTW structure has been designed to address the evolving demands of the industry and the detailed design specifications are outlined in the subsequent sections of this document.

SYSTEM DESIGN

The project entails the creation of a high-power irradiation accelerator system utilizing a backward-travelling-wave (BTW) architecture, with a design that includes specifications of 10 MeV and 24 kW. While the system relies on conventional pulsed RF power supply for normal conducting linear accelerators (linacs), it features a BTW accelerating structure as its core component. The facility is also equipped with scanning systems designed to deliver high-energy electron beams to articles undergoing irradiation on the conveyance line.

The electron beams are initially produced by a thermionic cathode electron gun, which employs a 20 kV pulse to emit electrons after preheating the cathode. These electrons are then injected into the accelerating structure, where they are subjected to high-power RF fields that bunch and accelerate the beams along the axis of the electric field. Subsequently, the beams are directed by scanning magnets within a fan-shaped vacuum chamber, passing through a large titanium window.

The high-power solid-state modulator supplies the necessary high-voltage pulse power to the klystron, which in turn generates the RF fields. To manage the heat generated by the high-power operations, a water-cooling system is implemented to cool the accelerator tube, klystron, waveguide, and other associated components.

Table 1: Design Parameters of the High-Power Backward-travelling-wave Irradiation Accelerator System

Parameter	Value
Electron beam energy	10 MeV
Electron beam power	> 24 kW
Average beam current	> 2.4 mA
Pulsed beam current	> 300 mA
Klystron power	5 MW, 45 kW
Modulator Power	100 kW
Surface dose uniformity	⩽ ±5%
Scanning Width	500mm to 800mm
Scanning uniformity	±5%

BACKWARD-TRAVELLING-WAVE ACCELERATING STRUCTURE

In a backward-travelling-wave (BTW) structure, the electromagnetic wave behaves as a traveling wave. The structure features two power coupling ports, one located at

---

[*] zha_hao@mail.tsinghua.edu.cn

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG88

the electron beam input end and the other at the electron beam output end. RF power is fed into the structure through the port nearest to the beam output end and travels as a wave towards the output coupler.

Once the electron beam is emitted from the thermionic electron gun, it is accelerated by the longitudinal electric field along the axis of the structure. The majority of the RF power is effectively transferred to the electron beam, while a portion of the power is dissipated by the copper walls of the structure. Any remaining power is extracted through the coupling port and subsequently absorbed by a high-power water load.

In contrast to traveling wave (forward-travelling-wave) accelerating structures, BTW structures feature cells that are coupled with magnetic field, resulting in phase velocity and group velocity moving in opposite directions. Consequently, the electron beam travels in the direction opposite to the transmission of RF power. With the input coupler located at the end where the electron beam approaches the speed of light, the input coupler is designed as a cell with $\beta = 1$, which corresponds to a "full-length" cell that provides ample space for effective water cooling.

BTW accelerator tubes incorporate a cavity shape with a nose cone and magnetic coupling, reminiscent of standing wave accelerators, to boost the shunt impedance. As a traveling wave structure, they offer the advantages of rapid filling time and minimal power reflection. Additionally, the broader bandwidth of the reflection allows for the absence of a circulator, which is typically used to protect against reflected power during the ramp-up and ramp-down of RF power. This simplifies the design and operation of the accelerator system.

Cell Geometry

Initial simulations using both CST[3] and ANSYS[4] software with single cell models to determine the quality factor (Q-factor) and the shunt impedance. These simulations reveal that with an ideal copper surface, the quality factor can achieve a high of 14,500, while the shunt impedance measures 110 MΩ/m. However, to account for the surface roughness that occurs during the fabrication process, it is prudent to incorporate a safety margin. Consequently, the design should proceed with the more conservative estimates of a quality factor of 13,000 and a shunt impedance of 100 MΩ/m to ensure reliable performance of the accelerator structure.

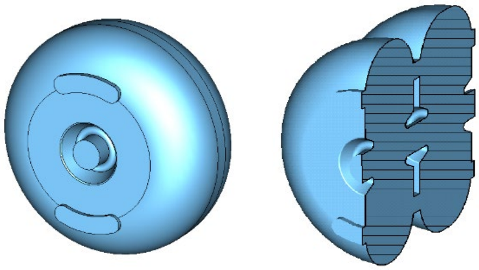

Figure 1: 3D model for calculating single cell parameters (left) and for cell-cell coupling (right)

Parameter Estimation

Since the accelerating structure is a travelling-wave structure, the power attenuates as it propagates through the tube. The attenuation can be calculated using the group velocity and the quality factor. Optimization calculations yield a cavity phase advance of 3π/4, and the length of a cell D is 39.6 mm. Given that the quality factor Q of a cell is 13000, and the average group velocity is 0.016c, where c is the speed of light, it results in an attenuation coefficient of:

$$\alpha = \frac{\omega}{2Qv_g} = 0.144\ \mathrm{m}^{-1}$$

where ω is the angular frequency, and v_g is the group velocity. Given that the shunt impedance Z_s is 100MΩ/m, a total length L of 1.6 meters can meet the requirement of beam energy.

$$E = \sqrt{2P_0 Z_s L}\left(\frac{1-\mathrm{e}^{-\tau}}{\sqrt{\tau}}\right) - I_b Z_s L\left(1 - \frac{1-\mathrm{e}^{-\tau}}{\tau}\right)$$
$$= 11\mathrm{MeV}$$

Where the attenuation constant $\tau = \alpha L = 0.23$, the beam-load I_b of 300mA, RF power input $P_0 = 4.5\mathrm{MW}$. Consequently, the peak beam power is determined to be 3.3MW. Assuming the input RF average power is 45 kW and the electron beam pulse width accounts for 90% of the RF pulse width, the theoretical maximum average beam power can attain 30 kW, and it can stably operate at a beam power of 24kW.

Tapered structure for constant-gradient design

To enhance the stability and efficiency of the linear accelerator (linac), a constant-gradient approach is implemented. This involves tapering the coupling slots between the cells throughout the structure, which causes the group velocity to decrease as the RF power attenuates.

The formula for calculating how the group velocity decreases can be expressed as:

$$v_{\mathrm{g,end}} = v_{\mathrm{g,begin}}\mathrm{e}^{-2\tau}$$

By applying this formula, we can select initial and final group velocities of 0.019c and 0.013c, respectively, where c is the speed of light. The filling time can be calculated by the length and the average group velocity.

$$t_\mathrm{f} = \frac{L}{v_g} \approx 330\ \mathrm{ns}$$

As a summary of the estimation, we list all the parameters in Table 2.

Table 2: Parameters of the Backward-Travelling-Wave accelerating structure

Item	Parameter
Working frequency	2856 MHz
Operating mode	3π/4
Number of cells	44
Group velocity	0.019c~0.013c
Length of the linac	1.6 m
Output beam energy	10 MeV
Input RF power	4.5 MW
Filling time	330 ns

Coupling between adjacent cells

The use of the coupling coefficient (k) simplifies simulation. It can be calculated from the frequency separation while two cells are coupled. Assuming the frequency of first mode (pi-like mode) is f_1 and the second mode (0-like mode) of f_2. The coupling coefficient is calculated as

$$k = \frac{f_2 - f_1}{f_2 + f_1}$$

A two-cell model is constructed to simulate the coupling, as illustrated in the figure to the right of Figure 1. The kidney-shaped coupling slots between adjacent cells are adjusted from 49 degrees at the input side to 42 degrees at the output coupler side, in order to accommodate the transition of the group velocity from 0.019c to 0.013c.

FULL STRUCTURE SIMULATION

The entire structure is designed within ANSYS, as shown in Figure 2. It comprises a bunching section consisting of 5 cells with a relatively low beta (β) value, which is then followed by a section where β=1, also known as the speed-of-light section. The structure is sliced along the symmetric YZ-plane, as indicated in the model, and a perfect magnetic boundary condition is set in the simulation.

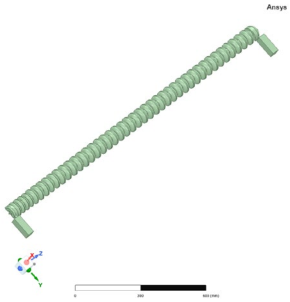

Figure 2: The structure build in ANSYS, with YZ-plane as a symmetric plane. The input and output waveguides are connected.

The input coupler is positioned at the end of the linac tube where the electrons leaves the beampipe, while the output coupler is on the first cell where the electron gun is connected to the linac. The input and output coupler are initially design as single cells to achieve the required external quality factor, Q_{ext}. The external quality factor can be calculted from the group velocity by

$$Q_{ext} = \frac{\omega D}{v_g}$$

The structure is modelled as a parameterized model in ANSYS, allowing for the adjustment of all cell radii within the software. A tuning process similar to that used for tuning a real structure is then applied in simulation.[5] After three iterations of this tuning process, the magnitude of the electric field along the axis within the speed-of-light section is flattened, as shown in Figure 3, and the reflection from the output coupler is significantly reduced. Additionally, as seen in Figure 4, the field phase advance is precisely 3π/4.

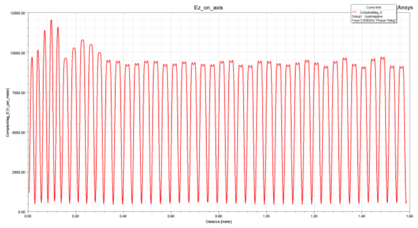

Figure 3: Simulated electric field distribution along axis after fine tuning of cell radii

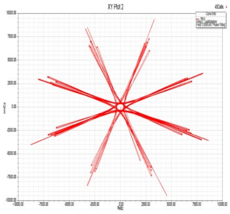

Figure 4: Real-imaginary plot of electric field on axis, showing the phase advance of 3pi/4

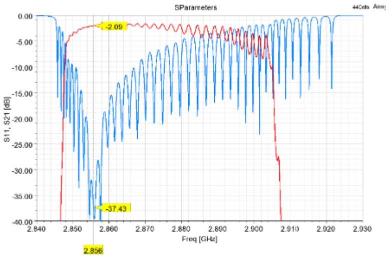

Figure 5: Reflection (S_{11}, blue) and transmission (S_{21}, red) as simulation result plotted

As shown in Figure 5, since the structure is well matched and the frequency of each cell is tuned, the reflection from the input coupler is as small as -37dB. The transmission is -2.09dB, which agrees with 0.23 Nep in previous design.

CONCLUSION

A novel S-band 2856-MHz backward-travelling-wave (BTW) accelerating structure has been successfully designed for irradiation applications. It is designed to provide a 10 MeV electron beam, and the beam power is capable of exceeding 24 kW with the integration of a 5 MW/45 kW klystron, ensuring a robust and efficient performance for irradiation processes.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG88

REFERENCES

[1] Lee Y *et al*, “Performance Qualifications for the Beam in a 10 MeV Electron Accelerator”, *Journal of Radiation Industry*, vol. 13 no. 4, p. 333-338, 2019.

[2] Gong C, “Research on the Tuning Method of Nonuniform Traveling-wave Accelerating Tubes”, Beijing: Tsinghua University, 2012.

[3] CST, `https://www.3ds.com/products/simulia/cst-studio-suite`

[4] ANSYS, `https://www.ansys.com`

[5] J. Shi, A. Grudiev, and W. Wuensch, “Tuning of X-band traveling-wave accelerating structures,” *Nucl. Instrum. Methods Phys. Res.*, Sect. A, vol. 704, pp. 14–18, Mar. 2013. `doi:10.1016/j.nima.2012.11.182`