THE DESIGN OF THE QUASI-TRAVELING WAVE PARALLEL-COUPLED STRUCTURE

W. Gu*, Y. Zhao†, H. Chen, J. Shi, H. Zha, Tsinghua University, Beijing, China

Abstract

A quasi-traveling-wave parallel-coupled (TWPC) accelerating structure is proposed for compact linacs requiring both high RF efficiency and improved frequency tolerance. In contrast to conventional standing-wave parallel-coupled structures, the proposed topology enables partial reflected power generated under detuned conditions to be redistributed through the feeding manifold and reabsorbed by downstream cavities. A 12-cell X-band TWPC structure operating in the $5\pi/6$ mode was designed using a cascaded waveguide feeding network. The structure achieves approximately 95% unloaded RF power utilization with a 1.8 MW input power level. Beam dynamics simulations predict a 5 MeV energy gain with a 95%-bandwidth (the frequency range corresponding to a 5% drop in accelerating voltage) of 1.4 MHz.

INTRODUCTION

High-gradient and compact electron linacs are widely required in medical irradiation, industrial processing, and compact radiation-source applications. In these systems, both RF efficiency and operational stability are critical considerations. Conventional traveling-wave accelerating structures generally provide relatively broad operating bandwidth because the microwave power propagates continuously through the structure. However, a considerable fraction of the incident RF power must be dissipated in the output load, which limits the achievable RF utilization efficiency. In contrast, standing-wave accelerating structures can operate with significantly higher efficiency by storing microwave energy inside resonant cavities, but their performance is strongly affected by frequency detuning and fabrication errors.

Parallel-coupled accelerating structures have attracted increasing attention because they distribute microwave power to each cavity through an external feeding manifold rather than through beam-aperture coupling [1]. This configuration provides additional flexibility for cavity optimization and has been investigated in several high-gradient accelerator studies. Nevertheless, conventional standing-wave parallel-coupled structures still operate as resonant systems, where reflected microwave power generated under detuned conditions mainly returns to the input port and contributes little to the accelerating process.

To address this limitation, a quasi-traveling-wave parallel-coupled (TWPC) accelerating structure is proposed in this work. The proposed topology introduces a different microwave power reuse mechanism inside the feeding manifold. Under off-resonance conditions, reflected signals from upstream cavities are redirected through the waveguide network and partially absorbed by downstream cells. Consequently, the reduction of accelerating voltage caused by frequency deviation can be mitigated while maintaining high RF utilization efficiency. The present study mainly focuses on the RF design and dynamics simulation of the TWPC concept. A 12-cell X-band TWPC accelerating structure operating in the $5\pi/6$ mode was designed and optimized.

THEORETICAL ANALYSIS

The TWPC structure can be modeled as a cascaded microwave network composed of multiple waveguide T-junctions and cavity-coupling units, as shown in Fig. 1. Each cavity is independently fed through the external manifold, and the microwave interaction between adjacent cavities mainly occurs through the feeding network rather than through the beam aperture.

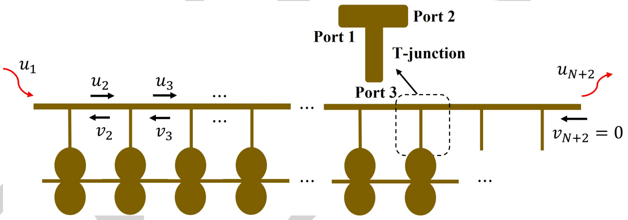

Figure 1: The quasi-traveling wave parallel-coupled structure with one manifold feeding cavities.

Assuming that each T-junction behaves as a lossless and reciprocal three-port microwave network, the electromagnetic response of the TWPC structure can be described by a cascaded scattering-matrix formalism. The relationship between adjacent cavity-coupling units can therefore be expressed as [2]:

$$\frac{1}{2}\begin{bmatrix} s_n - e^{j\theta} & s_n + e^{j\theta} & w_n \\ s_n + e^{j\theta} & s_n - e^{j\theta} & w_n \\ w_n & w_n & -2s_n^*\frac{w_n}{w_n^*} \end{bmatrix} \cdot \begin{bmatrix} u_n \\ v_{n+1} \\ \Gamma x_n \end{bmatrix} = \begin{bmatrix} v_n \\ u_{n+1} \\ x_n \end{bmatrix} \tag{1}$$

where s_n and w_n are undetermined complex numbers in the n-th three-port network, with s_n^* and w_n^* denoting their respective complex conjugates, and $|s_n|^2 + |v_n|^2/2 = 1$. θ is an undetermined degree number. Γ is the reflection coefficient in a resonant-cavity system [3].

When the operating frequency deviates from resonance, reflected signals are generated at each cavity-coupling port. In conventional standing-wave systems, these reflected signals mainly propagate back toward the source. However, when the matrix element S_{33} of the three-port junction is designed as a negative real value, the reflected microwave signals generated by frequency detuning can propagate constructively through the external feeding network and be partially reused by other cavities. As a result, part of the mi-

---

[*] gwh5784@163.com
[†] zhaoyan23@mails.tsinghua.edu.cn

crowave energy that would otherwise return to the source can be reutilized inside the accelerating structure.

Taking a 12-cell constant-impedance TWPC structure as an example, the relative electric-field distributions under resonant and detuned conditions are illustrated in Fig. 2.

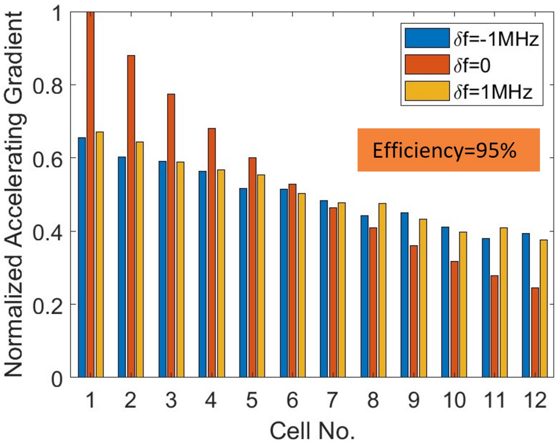

Figure 2: The normalized gradient data of the TWPC structure. It only displays the amplitude of the field but no phase information. The RF power efficiency is 96.5%.

The bandwidth enhancement mechanism originates from this collective response of the coupled microwave network. Although the field amplitudes in upstream cavities decrease under detuned conditions, downstream cavities can maintain relatively stable accelerating fields because they receive additional microwave power originating from reflected signals.

RF DESIGN OF THE TWPC STRUCTURE

The proposed TWPC structure employs a cascaded rectangular-waveguide feeding manifold composed of symmetric T-junctions. Each junction independently couples RF power into a cavity while maintaining the required intercell phase advance. An operating phase advance of $5\pi/6$ was selected because it provided improved shunt impedance during cavity optimization.

To realize arbitrary phase advance within a single feeding network, corrugated waveguides were adopted to reduce the phase velocity in the manifold. The phase shift between adjacent coupling ports was designed to be 150°. Four geometric parameters were independently optimized for each T-junction, including the tap-off width, slot position, slot depth, and coupling-waveguide length. Additional corrugations between neighboring junctions were introduced for fine phase compensation.

The complete 12-cell feeding manifold was optimized using 3D electromagnetic simulations. Since adjacent junctions are electromagnetically coupled through the manifold, the network was optimized globally rather than by independently tuning each T-junction.

To suppress direct cell-to-cell coupling through the beam aperture, a nose-cone cavity geometry with a relatively small beam aperture was adopted. The structure operates at 9300 MHz, and the cavity length was designed as 13.43 mm for the $5\pi/6$ mode. The final 12-cell TWPC structure is shown schematically in Fig. 3. Electromagnetic simulations indicate that approximately 96% of the incident RF power is transferred into the cavities at the operating frequency.

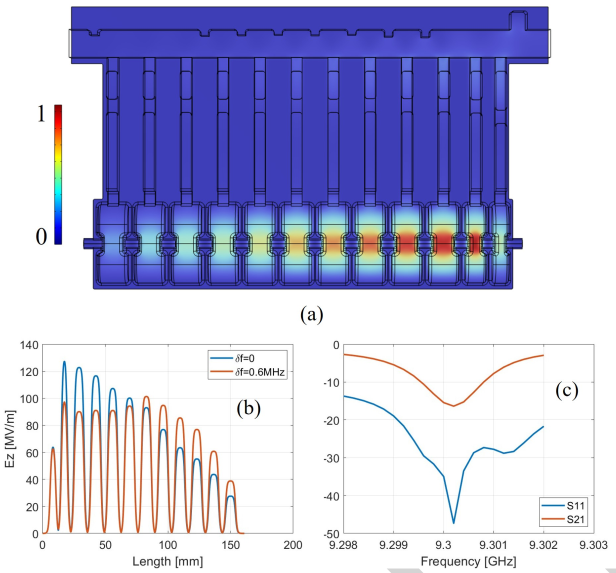

Figure 3: (a) The full design and electric field profile of 12 cells $5\pi/6$-mode TWPC accelerator. (b) The amplitude distribution of on-axis E-field. (c) The simulated S-parameters results.

BEAM DYNAMICS SIMULATION

Beam dynamics simulations were carried out using the ASTRA code for irradiation-oriented applications. The structure was driven by a 2 MW X-band RF source without considering beam loading.

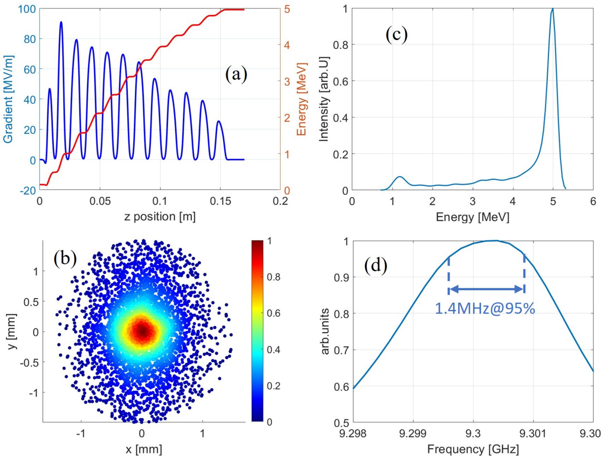

Figure 4: (a) The beam energy gain from the linac input ($z = 0cm$) to the output ($z = 17cm$) and the axial accelerating gradient considering transit time factor; (b) The transverse beam spot at the exit of linac; (c) The energy distributions of the beam at the exit; (d) The frequency-domain data of the accelerating voltage.

A thermionic DC gun with a 12.5 kV extraction voltage and a 1 A emission current was used as the electron source. The buncher section was optimized to improve beam capture and energy distribution. The dynamics results are shown in Fig. 4.

The optimized TWPC structure achieved an output beam energy of approximately 5 MeV. The capture efficiency reached nearly 42%, and the transverse beam size at the linac exit was approximately 3 mm. For the 12-cell TWPC structure, the 95%-value bandwidth is 1.4 MHz and 0.8 MHz for the accelerating voltage and average electron energy, respectively. In the conventional TW structure, the accelerating voltage bandwidth is 1.14 MHz when 95% of the input power is dissipated as loss. Compared with a conventional traveling-wave structure at the same unloaded power efficiency, the TWPC structure exhibited a broader accelerating-voltage bandwidth. The accelerating voltage bandwidth in the conventional SW structure is 0.86 MHz, which is lower than that of the TW and TWPC structures. The improvement originates from the redistribution of reflected microwave power inside the feeding manifold.

CONCLUSION

A quasi-traveling-wave parallel-coupled accelerating structure has been proposed and experimentally investigated. The structure combines high unloaded RF efficiency with improved tolerance to frequency detuning by reusing reflected microwave power through a cascaded feeding manifold. A 12-cell X-band TWPC structure operating in the $5\pi/6$ mode was designed and optimized. The present work establishes the basic design methodology, providing a potential solution for compact and efficient electron linacs.

REFERENCES

[1] Sami Tantawi, Mamdouh Nasr, Zenghai Li, Cecile Limborg, Philipp Borchard, Design and demonstration of a distributed-coupling linear accelerator structure. Phys. Rev. Accel. Beams **23**(9), 092001 (2020). doi:10.1103/PhysRevAccelBeams.23.092001

[2] Y. Jiang, J. Shi, H. Zha, J. Liu, X. Lin, and H. Chen, “Analysis and design of parallel-coupled high-gradient structure for ultrashort input power pulses,” Phys. Rev. Accel. Beams, vol. 24, no. 11, p. 112002, Nov. 2021, doi:10.1103/PhysRevAccelBeams.24.112002.

[3] T. Wangler, Standard Linac Structures, in *RF Linear Accelerators* (John Wiley & Sons, Ltd, New York, 2008), pp. 83–134. doi:10.1002/9783527623426.ch4