

Research Article

Design of a 324 MHz 200 kW CW Waveguide-to-Coaxial Adaptor for Radio Frequency Quadrupole Microwave System

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A 324 MHz 200 kW waveguide-to-coaxial adaptor has been designed and fabricated for a microwave coupler in a radio frequency quadrupole system. Optimization of the adaptor is performed by the numerical study and experimental test. High-power measurements show that the reflection coefficient of the adaptor is less than -30 dB at the RFQ operating frequency, and there is no breakdown in the 228 kW pulse test. The measurement results are consistent with the simulation results, indicating that the adaptor has good high-power transmission performance. This work provides theoretical and experimental bases for a rectangular-to-coaxial adaptor design, especially in high-power steady-state operation.

1. Introduction

Linear particle accelerators play an important role in many fields such as radiological medicine and nuclear experiments [1, 2]. The radio frequency quadrupole (RFQ), proposed firstly by Soviet scientists Kapchinskiy and Teplakov in 1969 [3, 4], is an important prefocus accelerating structure [5] in linear accelerators due to its longitudinal and lateral focusing and longitudinal acceleration of the particle bunch [6, 7]. The accelerating energy in the RFQ cavity comes from the coupling loop of the coaxial antenna [8–10]. Thus, a waveguide-to-coaxial adaptor which connects a transmission line with a coaxial antenna is needed to satisfy high-power steady-state operation of the RFQ accelerator.

A rectangular-to-coaxial adaptor for the high-power RFQ system has been studied. It must have small reflection at the operation frequency and must be also capable of handling up to 200 kW. Although studies of a waveguide-to-coaxial adaptor are reported widely for broadband and compact structures, a hundred kW-order high-power adaptor study has uniquely been performed at this RFQ

system. In this study, the requirement for power transition is more stringent. It is getting obvious that higher power needs a bigger coaxial and that it imposes more limitations on the design.

For usual adaptors, Teflon material is often used to fix internal structures. This material limits the power capacity of the adaptor design. In this article, the newly designed adaptor is fixed by a metal strip and matched by a multi-stepped structure. The size of the coaxial waveguide is decided by the coupling antenna of the RFQ cavity. The position and size of each part have been optimized by computer simulation software. Finally, a high-power test was conducted.

2. Structure Design

The schematic diagram of a rectangular-to-coaxial adaptor is shown in Figure 1. A Teflon structure filling the internal and external conductors is used to fix the internal conductor. The inner conductor and waveguide compose an open circuit, which exhibits a capacitive reactance, whereas the section

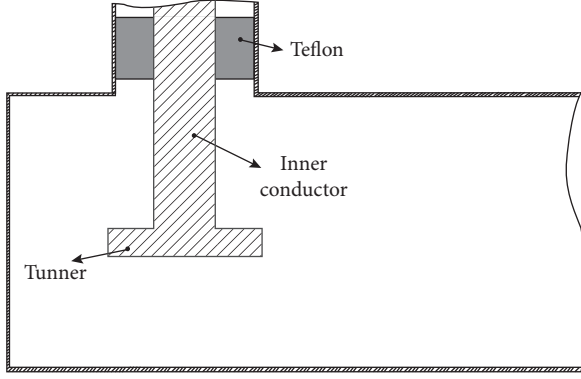


FIGURE 1: Schematic diagram of rectangular-to-coaxial coupling adaptor.

between the short-circuit surface and the inner conductor presents an inductive reactance. In this design, microwave reflection would be reduced by appropriate adjustment of position and depth of the inner conductor. In addition, better impedance matching would be achieved with a tuner at the end of the inner conductor.

In high-power adaptors used in RFQs, power capacity is limited by the Teflon structure. Thus, a redesign with a metal strip used to fix the inner conductor has been realized. The introduction of the metal strip leads to impedance mismatch, and consequently, it is necessary to add an additional matching structure [11], which is used to reduce microwave reflection while avoiding microwave breakdown at high-power input. The new design of the high-power adaptor is presented in Figure 2. The outer diameter of the coaxial inner conductor is 65.3 mm while the inner diameter of the outer conductor is 150 mm. The size of the rectangular waveguide is 584.2 mm \times 292.1 mm. The symbols h and l indicate the depth and distance which determine the position of the inner conductor. The inner conductor is supported by a metal strip in which two ends are connected to the waveguide walls, as depicted in Figure 2(b). Therefore, the size of the wide side is considered as the length of the strip, while w_{st} and h_{st} represent its width and height, respectively.

The microwave performance of the adaptor is affected by the existence of the metal strip, and its dimensions must be optimized to reduce this effect. In order to achieve impedance matching at the frequency of 324 MHz, a multi-stepped pillar structure that consists of two parts is placed on the waveguide wall. The part one is a pillar located in the midline of the wide side with a pillar diameter of 50 mm which is slightly smaller than the coaxial inner conductor. The h_{sc} and p_{sc} represent its height and its distance to the short-circuit surface, respectively. The part two is a multi-stepped pillar and consists of two concentric cylinders with different radius. The height and diameter of these cylinders are h_1 , h_2 and d_1 , d_2 , respectively. As shown in Figure 2(b), the position of part two is indicated by p_x and p_y . The reflection coefficient of the adaptor can be reduced to -40 dB by adjusting the dimensions of the matching structures. In order to avoid high electric field at the tip, all corners are chamfered.

3. Simulation Result and Analysis

3.1. RF Transmission Analysis. The proposed design and its optimization are performed by the finite element method. The reflection coefficients before and after optimization of position and size of the tuning pillars are shown in Figure 3. Curve (a) shows the reflection coefficient of the adaptor without the copper strip and the two matching pillars. The best value at the operating frequency is higher than -15 dB which is too high for microwave transmission. Curve (b) shows the reflection coefficient of the adaptor with copper strip. In curve (a), it can be seen that the optimized copper strip plays the role of fixing the inner conductor and does not significantly affect the reflection coefficient. Curve (c) is obtained after optimization of the matching pillar on the wide waveguide wall, and the minimum value achieved -46.9 dB. In order to achieve impedance matching at 324 MHz, the multistepped pillar is optimized, and the result is shown in curve (d). It is apparent that the designed adaptor shows a good performance with a reflection coefficient lower than -30 dB at a frequency point of 324 MHz. All the optimized parameters are listed in Table 1 in which the units are millimeters.

3.2. Steady-State Thermal Analysis. Thermal stability of the structure is checked up to 200 kW with simulation software. The steady-state thermal analysis is performed with COMSOL Multiphysics (trial version) considering air convection with the environmental temperature of 20°C, and the related results are shown in Figure 4. The maximum reached temperature is 50°C on the surface of the inner conductor when the temperature of the adaptor has stabilized. The thermal deformation of the internal structure is negligible at this temperature. Since the heat generated by the internal structure can be quickly dissipated through the waveguide wall, a newly designed adaptor can be operated stably in high-power input 200 kW.

3.3. Power Capacity Calculation. Calculation of power capacity is needed to prevent microwave breakdown when designing high-power microwave devices. The critical electric field of the air breakdown should be calculated first for the reason that it is the primary factor limiting the power capacity of the adaptor.

The critical breakdown field E_B [12] can be calculated by

$$\left(\frac{E_B}{p^*}\right)_{p^*\lambda \neq 0} = \left(\frac{E_B}{p^*}\right)_{p^*\lambda = 0} - \Delta(p^*\lambda), \quad (1)$$

where p^* and $\Delta(p^*\lambda)$ may be approximated by

$$p^* = \left(\frac{298}{T}\right)(760)\text{Torr}, \quad (2)$$

$$\Delta(p^*\lambda) \approx 6[1 - \exp(-0.75 \times 10^{-3} p^*\lambda)],$$

and $E_B/p^* \approx 30 \text{ V}/(\text{cm}^*\text{Torr})$, which constitutes the attachment controlled breakdown criterion for CW operation,

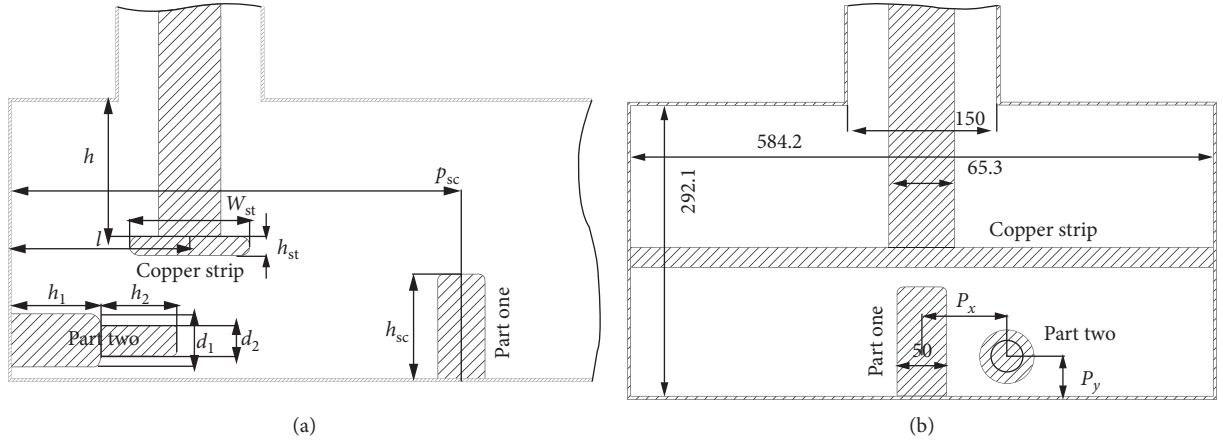


FIGURE 2: Structure with all designed parameters (a) side view and (b) front view.

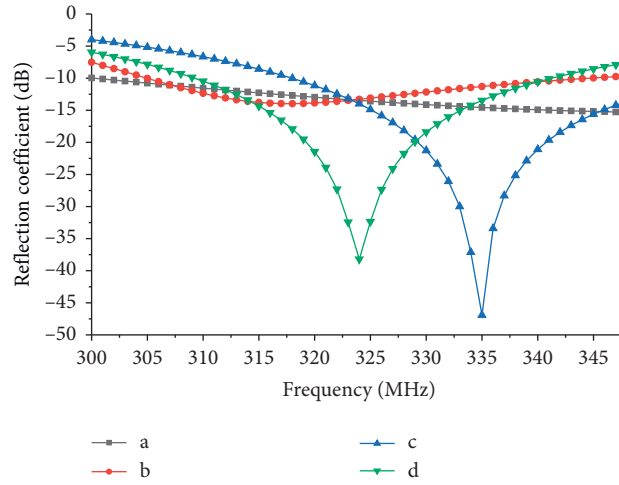


FIGURE 3: Reflection coefficient curve of different matching structures. a, adaptor without the copper strip and two matching pillars; b, adaptor with metal strip structure only; c, adaptor without multisteped pillar; d, adaptor with complete structure.

TABLE 1: Parameters of matching structures.

l (mm)	w_{st} (mm)	p_{sc} (mm)	p_x (mm)	$h_1 h_2$ (mm)	H (mm)	h_{st} (mm)	h_{sc} (mm)	p_y (mm)	$d_1 d_2$ (mm)
142.1	127	475	85	110 95	188.5	20	110	40	50 54

is only valid in the limit of $p^*\lambda = 0$, where λ is the wavelength. The threshold condition for CW operation becomes

$$E_B = p^* \{30 - 6[1 - \exp(-0.75 \times 10^{-3} p^* \lambda)]\}. \quad (3)$$

Thus, the critical electric field for breakdown would be 18.2 kV/cm at 324 MHz when the temperature is 50°C and the atmospheric pressure is 760 Torr (1.01×10^5 Pa).

The simulated electric field amplitude distribution with the maximum electric field of 18.2 kV/cm is shown in Figure 5. The input power to the adaptor in this simulation is 608 kW, and the maximum electric field is located on the top of the multisteped pillar. Considering the working environment of this adaptor, we adopted a safety factor of three as the ratio of power capacity and

transmission power [13], and the above results show that the new adaptor satisfies the demand for high-power microwave transmission.

4. Laboratory Test

4.1. Low Power Test. According to the above analysis, the high-power waveguide-to-coaxial adaptor was fabricated and tested. The photograph of the test system is shown in Figure 6. The coaxial port is connected to the matching load, and the rectangular port is connected to the network analyzer through another coaxial-to-rectangular adaptor. A comparison between measured and simulated results is shown in Figure 7, in which the frequency with a reflection coefficient below -20 dB is

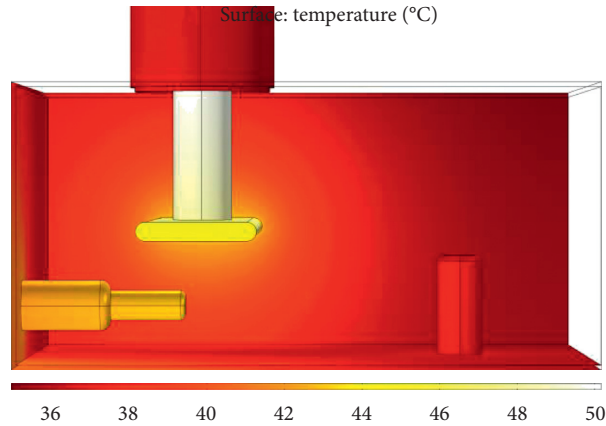


FIGURE 4: Surface temperature of steady-state thermal analysis.

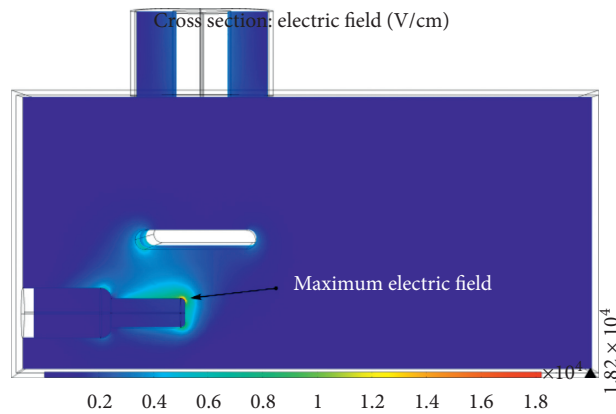


FIGURE 5: Electric field amplitude distribution of electric field with 608 kW input power.

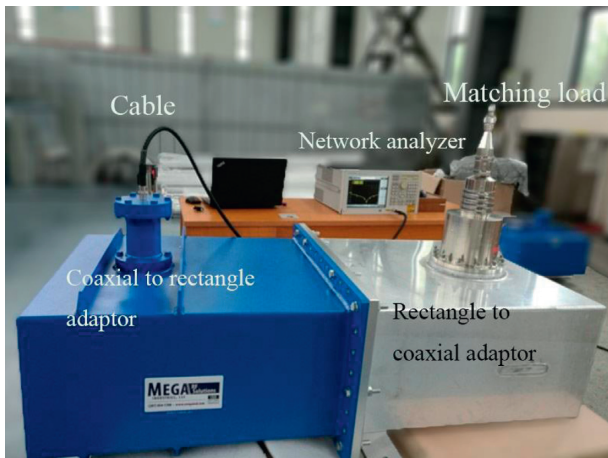


FIGURE 6: Photograph of the test system.

ranging from 316 to 328.8 MHz. Moreover, the reflection coefficient is less than -32 dB at a central frequency point of

324 MHz. The result shows that the adaptor has sufficient performance in the operation frequency of the RFQ microwave system. The measured curve is in rather good agreement with the simulation results. The difference in the frequency of the minimum reflection coefficient is attributed to the fabrication process and measuring accuracy.

4.2. High Power Test. High-power testing is essential to verify the electrical performance of the proposed adaptor. The adaptor was only tested under a pulsed microwave source since there are no CW microwave sources in our laboratory. The pulse width is $500 \mu\text{s}$, and the duty cycle is 1.25%. The test experiment at 2.2 kW and 228 kW was operated, and the results are illustrated in Figure 8. It is observed that no breakdown occurred during the pulse time.

The adaptor can run for a long time under the condition of $500 \mu\text{s}$ pulse width and 1.25% duty cycle. Figure 9 is a photo of 200 ms detection signal when running for a long time. That is to say, there is no breakdown of the adaptor in long time operation.

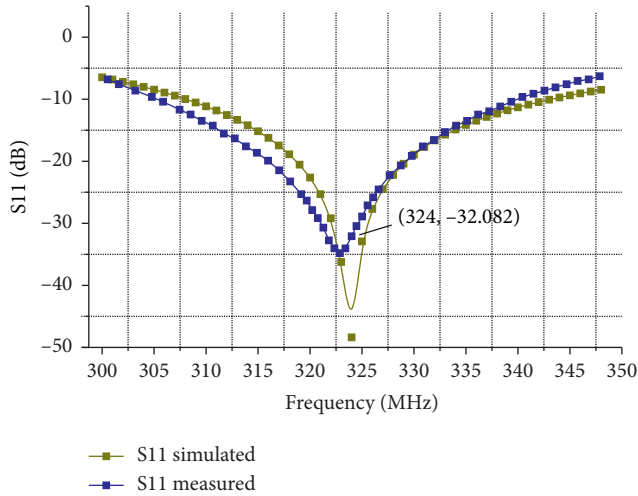


FIGURE 7: Comparison of measured results and simulation results.

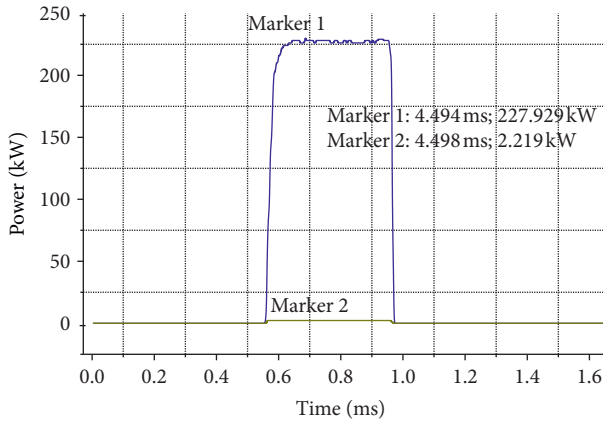


FIGURE 8: High-power pulse experiment results.

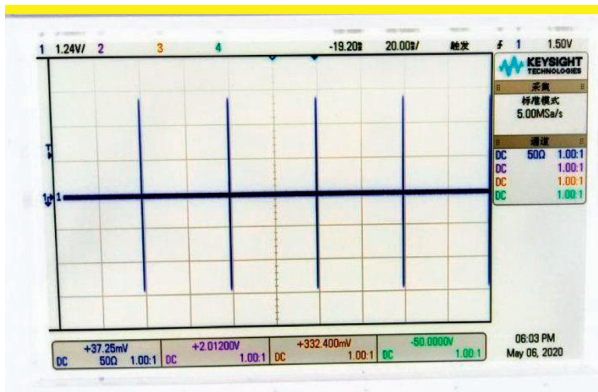


FIGURE 9: Photograph of 200 ms detection signal.

5. Conclusion

In this work, a high-power waveguide-to-coaxial adaptor for a 324 MHz 200 kW RFQ microwave system is designed, fabricated, assembled, and tested. The structures and dimensions are first investigated and optimized through

electromagnetic simulation to reduce microwave reflections. Then, the heat analysis is conducted to ensure that additional water-cooled construction is unnecessary in operation conditions. Finally, the high-power tests show no breakdown generation in long pulsed operation.

The critical breakdown field simulation shows that the design requirement of power capacity can well be met theoretically with the structure that a copper strip could be used instead of Teflon to fix the inner conductor. For the reason that all matching structures are in good contact with the waveguide walls, the maximum temperature of the inner conductor is no more than 50°C under 200 kW power input. Furthermore, the adaptor has been validated with a high-power pulsed source under laboratory conditions. More multifactor analysis and tests have not been carried out, for example, a long-time high-power CW test, which could also limit the working power regime of the adaptor. Synthesizing the simulation analysis and test results, it can be concluded that the performance of the 200 kW CW waveguide adaptor is sufficient to meet the real requirements of the pulsed source microwave transmission system.

Data Availability

The simulation and experimental data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

- [1] H. Li, *Study of APF IH-DTL Proton Accelerating Structure*, Shanghai Institute of Applied Physics, Shanghai, China, 2019.
- [2] G. Xia and Y. Bao, "CIAE heavy ion nuclear research facility," *High Energy Physics and Nuclear Physics*, vol. 30, no. S1, pp. 162–164, 2006.
- [3] I. M. Kapchinsky and V. A. Teplyakov, "Ion linac with a spatially uniform strong focusing," *Pribory i Tekhn. Eksp.*, vol. 2, pp. 19–22, 1970.
- [4] Z. L. Zhang, Y. He, A. M. Shi, and B. Zhang, "Design of a four-vane RFQ for China ADS project," in *Proceedings of LINAC*, Tel Aviv, Israel, September 2012.
- [5] S. Ikeda, T. Kanesue, and M. Okamura, *Design of RFQ LINAC to Accelerate High Current Lithium Ion Beam from Laser Ion Source for Compact Neutron Source*, Brookhaven National Laboratory, Upton, NY, USA, 2016.
- [6] K. D. Wang, *Theoretical and Experimental Study on Compact Heavy-Ion RFQ Linac*, Lanzhou Institute of Modern Physics, Lanzhou, China, 2019.

- [7] X. N. Du, "Dipole field in four vane and four rod RFQ," *Nuclear Physics Review*, vol. 30, p. 420, 2013.
- [8] S. Kazakov, O. Pronitchev, V. Poloubotko, and T. Khabiboulline, "Design of 162.5 MHz CW main coupler for RFQ," in *Proceedings of LINAC*, Geneva, Switzerland, September 2014.
- [9] A. M. Shi, L. P. Sun, Z. L. Zhang, and Y. He, "Design of RF coupler for C-ADS injector II RFQ," *Energy Science and Technology*, vol. 49, p. 539, 2015.
- [10] L. B. Shi, *Research on RF Structure of Window-Coupled RFQ*, Institute of Modern Physics, Lanzhou, China, 2015.
- [11] E. M. Bialkowski, "Analysis of a coaxial-to-waveguide adaptor including a discended probe and a tuning post," *IEEE Transactions on Microwave Theory and Techniques*, vol. 43, no. 2, pp. 344–349, 2002.
- [12] D. Anderson, M. Lisak, and T. Lewin, "Generalized criteria for microwave breakdown in air-filled waveguides," *Journal of Applied Physics*, vol. 65, no. 8, pp. 2935–2945, 1989.
- [13] D. M. Pozar, *Microwave Engineering*, Wiley, New York, NY, USA, 4rd edition, 2005.