

TUNING OF A TAPERED RIDGE-LOADED WAVEGUIDE COUPLER FOR A DRIFT TUBE LINAC OF THE COMPACT PULSED HADRON SOURCE

Y. Lei^{1,2}, S. X. Zheng^{1,2}, Q. Z. Xing^{1,2,*}, R. Tang^{1,2}, C. T. Du^{1,2}, X. L. Guan^{1,2}, X. W. Wang^{1,2}

Key Lab. of Particle & Radiation Imaging (Tsinghua Univ.), Ministry of Education, Beijing, China

¹ also at Lab. for Advanced Radiation Sources and Application, Tsinghua Univ., Beijing, China

²also at Department of Engineering Physics, Tsinghua Univ., Beijing, China

Abstract

This paper presents the tuning result of a tapered ridge-loaded waveguide coupler for the drift tube linac (DTL) of the compact pulsed hadron source (CPHS) at Tsinghua University. The coupler has been designed, manufactured, and mounted on the DTL cavity for the cold measurement and tuning. The iris diameter of the coupler which is related to the coupling coefficient needs to be determined in the tuning experiment, due to the difference between the designed and measured quality factors. Meanwhile, we found that the relationship between the coupling coefficient and iris diameter from the traditional analytical design method is not applicable when the iris diameter is relatively large. In this paper, the target coupling coefficient is analyzed, and the limit of the original analytical design is presented. The measurement method is introduced to improve the measurement efficiency and the tuning process of the coupling coefficient to the target value is described. After several iterations, the coupling coefficient is tuned to 1.54 which is close to the desired value of 1.56.

INTRODUCTION

The compact pulsed hadron source (CPHS) is a multi-purpose scientific research platform designed and constructed in the past 10 years at Tsinghua University [1]. It consists of an ECR ion source (IS), a low energy beam transport section (LEBT), a radio frequency quadrupole (RFQ) linac, a drift tube linac (DTL), a high energy beam transport section (HEBT), a neutron target station and four neutron beam lines. The proton beam is accelerated from 50 keV to 13 MeV by the RFQ and DTL. The radio frequency (RF) power is generated by a klystron-based RF power source and fed into the RFQ and DTL through a tapered ridge-loaded waveguide coupler respectively. The coupler was designed by the analytic calculation and verified by the 3D electromagnetic field simulation [2]. The tuning and cold test of the waveguide coupler for the RFQ was carried out in 2013 [3]. The iris diameter was tuned to acquire an appropriate coupling efficiency. After tuning, the iris diameter was set to 12 mm while the designed value was 14 mm.

However, researchers from CSNS pointed out that the analytic theory does not work when the iris diameter is larger than 15 mm, and the simple simulation model is not accurate enough [4]. We also met this problem during the coupler of

the DTL was tuned. This paper presents the tuning process and result of the DTL coupler.

TARGET COUPLING COEFFICIENT

The coupling coefficient β is defined as

$$\beta = \frac{Q_0}{Q_e} = \frac{P_e}{P_0} \quad (1)$$

where Q_0 and Q_e are the unloaded and external quality factors of the DTL, P_0 and P_e are the inside-cavity power loss and external power loss, respectively [5]. To ensure that the coupling status is critical coupling, the relationship between the power losses should satisfy

$$P_e = P_0 = P_b + P_c \quad (2)$$

where P_b is the beam power, and P_c is the wall power loss of the cavity.

In other words, the unloaded coupling coefficient should be adjusted to

$$\beta' = \frac{P_b + P_c}{P_c} \quad (3)$$

During the design process, the target coupling coefficient β is approximately 1.72 in the condition $Q_0 = 43\,000$, $P_c = 694$ kW and $P_b = 500$ kW. Nevertheless, the measured Q'_0 is about 34 000 after all the aluminum components were replaced by copper ones and all the RF seals were strengthened [6]. Suppose that the stored energies in two same structures are equal, the experimental wall power loss P'_c can be estimated by:

$$P'_c = \frac{Q_0}{Q'_0} P_c \quad (4)$$

where $Q_0 = \omega U/P_c$, U is the stored energy, and ω is the resonant angular frequency.

From Eq. (3) the target coupling coefficient for the tuning is obtained to be 1.56.

MEASURING METHOD WITH $\lambda_g/4$ WAVEGUIDE

During the measurement process, the coaxial-waveguide converter (CWC) was adopted, because the vector network analyser (VNA) measurement port is coaxial.

Since it would be time-consuming if the self-reflection vector of the CWC and the port-reflection vector of the coupler were measured each time when the iris was enlarged. Therefore, a measurement method with $\lambda_g/4$ waveguide was proposed.

* xqz@tsinghua.edu.cn

Approximate Calculation

The coupling coefficient β of the tapered ridged-loaded waveguide coupler can be obtained through the measurement of the voltage standing wave ratio (VSWR) at the iris. In the condition of over-coupling, $\beta = \text{VSWR} = (1 + |\Gamma|)/(1 - |\Gamma|)$, where Γ is the reflection coefficient at the iris.

The measurement of Γ at the iris cannot be measured by a radio frequency two-port network directly, because the measuring port consists of one coaxial-waveguide converter which has reflection itself. Two steps should be carried out to ensure the measuring accuracy. First the self-reflection should be adjusted down to smaller than 0.1. Second a $\lambda_g/4$ waveguide can be employed to offset the self-reflection. Fig. 1 shows the schematic diagram of the measurement with the $\lambda_g/4$ waveguide. The half-height WR2300 waveguide was inserted between the coaxial-waveguide converter and the iris coupler.

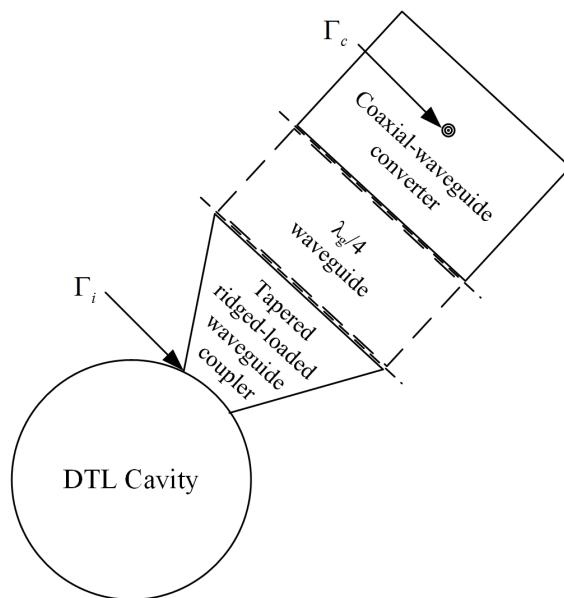


Figure 1: Schematic diagram offset the coaxial-waveguide convert reflection with $\lambda_g/4$.

The reflection coefficient Γ of the port of coaxial-waveguide converter is the superposition of the reflection of iris section Γ_i and the self-reflection of coaxial-waveguide converter Γ_c . The magnitude of measured reflection coefficient $|\Gamma'|$ and $|\Gamma|$ (with and without $\lambda_g/4$ half-height WR2300 waveguide respectively) can be written as Eq. 5 when $|\Gamma_c|$ is less than 0.1:

$$\begin{cases} |\Gamma| = |\Gamma_i| \pm |\Delta\Gamma| \\ |\Gamma'| = |\Gamma_i| \mp |\Delta\Gamma| \end{cases} \quad (5)$$

where $|\Delta\Gamma| = |\Gamma_c| \cos(\phi_c - \phi_i)$, and ϕ_c, ϕ_i is the argument of the Γ_c and Γ_i , respectively.

During the measuring process, the measuring coupling coefficient β' and β (with and without $\lambda_g/4$ half-height WR2300 waveguide) can be obtained by VNA and expressed

as

$$\begin{cases} \beta = \frac{1 + |\Gamma|}{1 - |\Gamma|} \\ \beta' = \frac{1 + |\Gamma'|}{1 - |\Gamma'|} \end{cases} \quad (6)$$

Substituting Eq. (5) to the Eq. (6), the Eq. (7) can be obtained:

$$\frac{\beta + \beta'}{2} = \frac{1 + |\Gamma_i| - |\Delta\Gamma|^2}{1 - |\Gamma_i|} \quad (7)$$

Neglecting the high order small $|\Delta\Gamma|^2$, the Eq. (7) has the same form with the coupling coefficient of the iris section under the overcoupling condition as shown in Eq. (8)

$$\beta_i^o = \frac{1 + |\Gamma_i|}{1 - |\Gamma_i|} \approx \frac{\beta + \beta'}{2} \quad (8)$$

The similar conclusion under the undercoupling can be inferred.

Self-reflection of the CWC

The CWC was built with a half-height WR2300 waveguide. The mutual conversion between the TEM mode in the coaxial transmission line and TE₁₀ mode in the rectangular waveguide was achieved through the CWC. To measure the reflection of the measuring port, a split-type carbon powder load was employed and moved inside the extended waveguide as shown in Fig. 2.

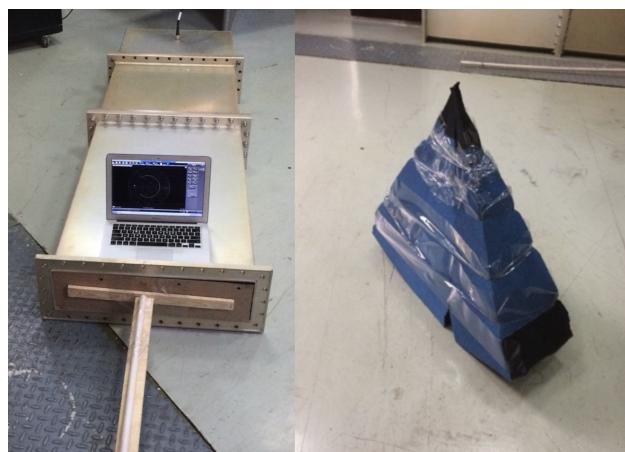


Figure 2: The self-reflection measurement configuration of the coaxial-waveguide converter (left); a kind of split-type carbon powder absorbing load (right).

With three shapes of the split-type carbon powder load, the self-reflection of the coaxial port is obtained as shown in Fig. 3.

TUNING EXPERIMENT

The structure of the coupling iris is shown in Fig. 4. Two holes locate at the two ends of the narrow slit respectively. The diameter of the iris is d .

During the experiment, it was found that the target coupling coefficient cannot be reached with the designed iris

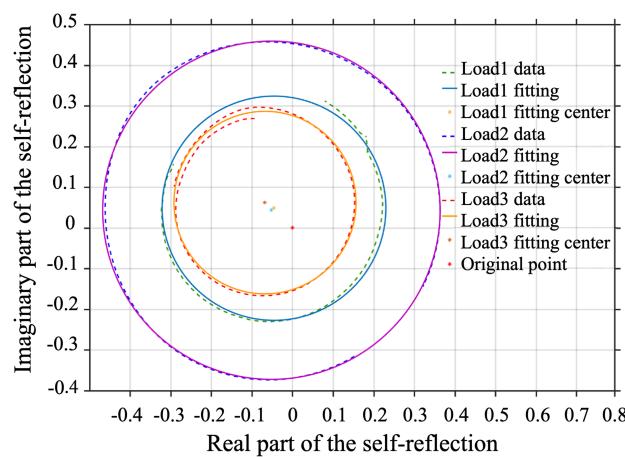


Figure 3: Measurement result of the self-reflection of the coaxial-waveguide converter with three different shape of the split-type carbon powder loads.

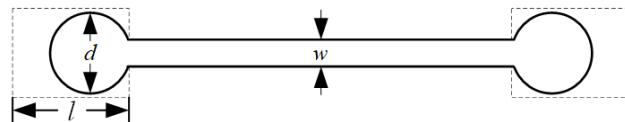


Figure 4: The schematic diagram of the coupling iris.

diameter. Therefore it should be further enlarged. Limited by the mechanical size of the iris section, the shape of the hole was modified to rectangle and only the length

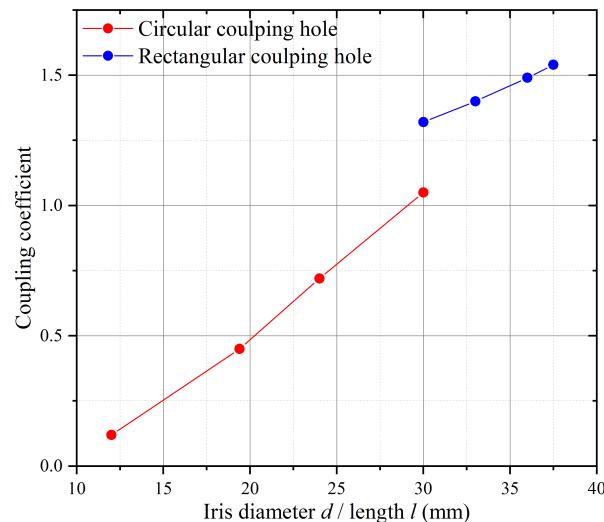


Figure 5: Measured coupling coefficient with the dimension of the iris d and l .

l in the direction paralleling to the iris slit can be altered

in the following tuning process. At the same time, a $\lambda_g/4$ waveguide was adopted to ensure the measuring accuracy. The holes of the iris were enlarged for three times, with the predicted diameter from the linear fitting relationship between the coupling coefficient and iris diameter for the latter two times. The experimental coupling coefficient with d and l is presented in Fig. 5.

After the first two times of enlargement of the iris holes, the linear-fitting equation can be obtained as $\beta = 0.0263l + 0.533$, The estimated coupling coefficient with $l = 36$ mm is 1.480, and the corresponding measured result is 1.496. After the third enlargement and measurement the linear-fitting equation was revised to $\beta = 0.0289l + 0.452$.

CONCLUSION

To properly feed the RF power into the DTL cavity, the coupling coefficient of the tapered ridge-loaded waveguide coupler was tuned. To be more effective, a measurement method with a $\lambda_g/4$ waveguide was proposed, and the self-reflection of the CWC was tuned to be less than 0.1. In our tuning experiment, the analytic prediction result of the iris diameter from the small-hole approximation method is proven to be not applicable when the diameter is larger than 12 mm. To solve this problem the linear-fitting method was adopted. Finally, the coupling coefficient was tuned to 1.54 which is close to the desired value of 1.56.

REFERENCES

- [1] Q. Z. Xing *et al.*, “Development progress of the H⁺/H⁻ linear accelerators at Tsinghua University”, in *Proc. 29th Linear Accelerator Conf. (LINAC'18)*, Beijing, China, Sep. 2018, pp. 732-734. doi:10.18429/JACoW-LINAC2018-thpo022
- [2] Z. F. Xiong *et al.*, “The radio-frequency design of an iris-type coupler for the CPHS radio-frequency quadrupole”, *Chinese Phys. C*, vol. 36, no. 1, pp. 96-100, 2012. doi:10.1088/1674-1137/36/1/017
- [3] Q. Z. Xing *et al.*, “Tuning and cold test of a four-vane RFQ with ramped inter-vane voltage for the compact pulsed hadron source”, *Chin. Phys. Lett.*, vol. 30, no. 5, p. 052901, 2013. doi:10.1088/0256-307X/30/5/052901
- [4] M. X. Fan *et al.*, “Low power RF test and analysis of China Spallation Neutron Source Drift Tube Linac RF power coupler”, *High Power Laser and Particle Beams*, vol. 29, no. 6, p. 065105, 2017. doi:10.11884/HPLPB201729.160491
- [5] T. P. Wangler, “Microwave topics for linac”, in *RF Linear Accelerators*, Berlin, Germany: Wiley-VCH, 2008, pp. 139-144.
- [6] Y. Lei *et al.*, “Radio frequency measurement and tuning of a 13 MeV Alvarez-type drift tube linac for a compact pulsed hadron source”, *Rev. Sci. Instrum.*, vol. 90, p. 013302, 2019. doi:10.1063/1.5064462