The radio-frequency design of an iris-type coupler for the CPHS radio-frequency quadrupole

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Abstract: The Compact Pulsed Hadron Source (CPHS) project is a university-based proton accelerator platform (13 MeV, 16 kW, 50 mA peak current, 0.5 ms pulse width at 50 Hz) for multi-disciplinary neutron and proton applications. The CPHS linac consists of a 3 MeV radio-frequency quadrupole (RFQ) linac and a 13 MeV drift tube linac (DTL). Both the RFQ and DTL share a 325 MHz, 2.1 MW klystron source. A single iris-type radio-frequency (RF) coupler is used to feed 537 kW of RF power to the RFQ cavity. Three-dimensional electromagnetic models of the ridge-loaded tapered waveguide (RLWG) and the coupler-cavity system are presented, and the design process and results of the RLWG and iris plate are described in detail.

Key words: CPHS, RFQ, RF coupler, ridge-loaded tapered waveguide, coupling coefficient

PACS: 29.20.Ej **DOI:** 10.1088/1674-1137/36/1/017

1 Introduction

A 325 MHz radio-frequency quadrupole (RFQ) linac is under construction to produce 50 mA of proton beam at 3 MeV as an injector of the 13 MeV drift tube linac (DTL) for the Compact Pulsed Hadron Source (CPHS) project at Tsinghua University [1]. The RFQ system consists of three four-vane resonant cavity sections, one power coupler, 47 slug tuners, eight dipole-mode stabilizer rods, the radio-frequency (RF) power supply and its low-level control, vacuum, water cooling, resonance control, beam diagnostics, support and alignment systems [2]. In the CPHS RFQ, the cavity cross section and vane-tip geometry are tailored as a function of longitudinal position, and no coupling plate is used between the sections. Fig. 1 shows the 3 m long cavity structure of the CPHS RFQ system, and the main RF parameters are listed in Table 1.

Table 1. The RF properties of the CPHS RFQ.

parameter	value
peak surface field	< 32 MV/m, 1.8 Kilpatrick
peak/average structure power	387/10 kW
peak/average beam power	150/3.75 kW
peak/average total power	537/14 kW
duty factor	2.5%

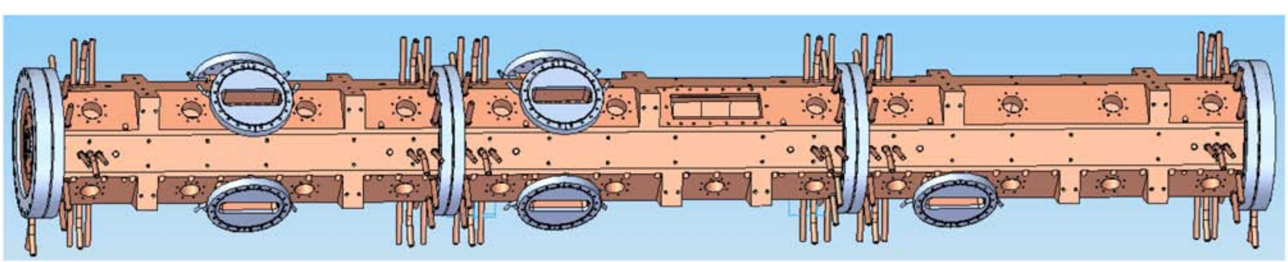

Fig. 1. The cavity structure of the CPHS RFQ.

Received 2 March 2011

The RF coupler is an important component between the input waveguide and the RF cavity. There are two types of couplers commonly used in RF power coupling systems: coaxial and iris. Compared with the coaxial-type coupler, the iris-type coupler has the advantage of a simple structure, good power handing capability, is easy to cool, has small frequency perturbations in the cavity and a low risk of RF window [3]. The LEDA RFQ demonstrated the feasibility of using iris couplers to power RFQs [4]. Since then, iris-type couplers have been used successfully on the SNS DTL, the PEFP RFQ and DTL, and the IPHI RFQ.

The iris-type coupler for the CPHS RFQ consists of a ridge-loaded tapered waveguide (RLWG), an iris plate, a vacuum system, a cooling system and some other components (Fig. 2). The coupling depends on the strength of the magnetic fields in RFQ at the location of the iris, the size of the iris and the strength of the magnetic fields at the end of the ridge-loaded waveguide. In order to power the RFQ efficiently, special care has been taken to design the RLWG and determine the size of the iris.

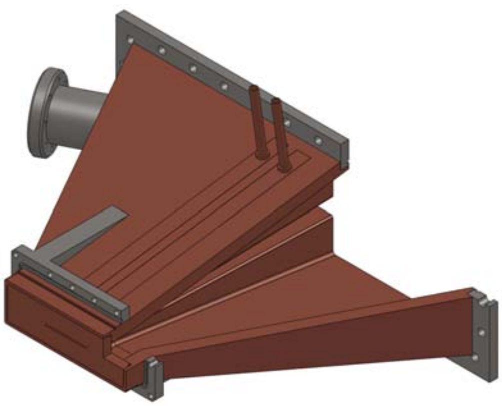

Fig. 2. The iris-type coupler for the CPHS RFQ.

In this paper, the design process of the RLWG and the iris holes are described. Detailed 3D electromagnetic models of the ridge-loaded tapered waveguide and the coupler-cavity system are presented. A simplified short RFQ cavity is introduced to calculate the radius of the iris holes with respect to the desired coupling factor. This method has greatly reduced the amount of calculation needed, and will also be used in the RF coupler design for the CPHS DTL.

2 The design of the ridge-loaded tapered waveguide

The single iris-type coupler will replace one of the tuners on the second section of the CPHS RFQ. The location of the RF coupler represents the midpoint of the power dissipation due to wall loss and beam absorption (Fig. 3). Taking into account the actual structure of the CPHS RFQ cavity, the iris coupler will be set at about 168 cm from the low-energy end of the RFQ; the mounting hole for the RF coupler can be seen in Fig. 1. The strength of the magnetic field at the location of the iris is about 6438 A/m.

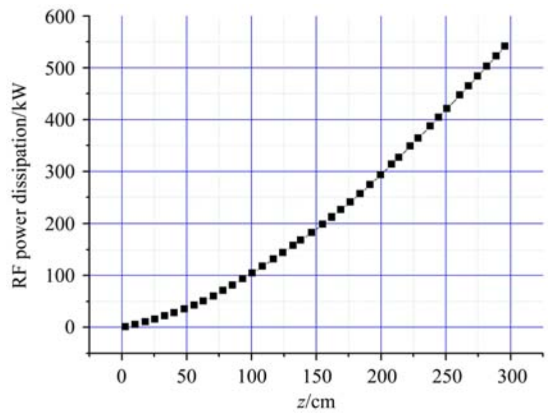

Fig. 3. The RF power dissipation curve of the CPHS RFQ.

For the CPHS RFQ at a frequency of 325 MHz, a half-height WR2300 waveguide will be used. The dimensions of the RLWG are tapered linearly from the half-height WR2300 waveguide to 180 mm×33 mm, which is determined by the space restrictions of the RFQ cavity. Based on the experience from the RF coupler for the LEDA RFQ, the length of the tapered waveguide is approximately one-quarter of a guide wavelength, and the width of the ridge is a constant. These changes will greatly reduce the area where multipacting occurs in the taper and greatly reduce the power level at which multipacting is possible.

A heavily loaded ridged waveguide is at the end of the tapered waveguide, and the heavily loaded ridged waveguide is designed with the same cutoff frequency as a WR2300 waveguide. Based on the transverse resonance method [5], the gap width is 2.1 mm when the width of the ridge is 80 mm.

In our design, the profile of the ridge along the tapered waveguide is a straight line, and this will simplify the design and manufacture. Fig. 4 shows a 3D model of the transition from the half-height WR2300 waveguide to the RLWG, followed by a heavily loaded ridged waveguide. To make sure that the coupler can be manufactured exactly as calculated, the model layout was created by a Solidworks system, and then imported into the calculation code.

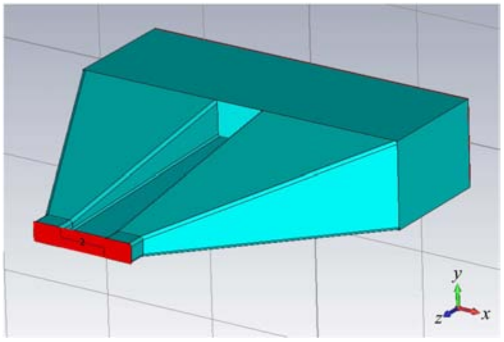

Fig. 4. 3D model of the RLWG for the CPHS RFQ coupler.

The length of the tapered waveguide, l, and the gap width at the beginning of the tapered waveguide, d_0, are optimized to achieve the smallest S_{11} parameter (Fig. 5). When l=397 mm and d_0=27.5 mm, the S_{11} parameter at 325 MHz is about 0.02 and the VSWR is 1.04:1.

The electric fields distribution can also be attained in the calculation (Fig. 6). When the input peak power is 1 W at the port of the half-height WR2300 waveguide, the maximal electric field is about 2005 V/m, at the end of the RLWG. While the input peak power is 537 kW, the maximal electric field will be about 1.5 MV/m, much lower than Kilpatrick's criterion. The fields increase at the end of the tapered waveguide, so that a small iris can feed enough power to the cavity.

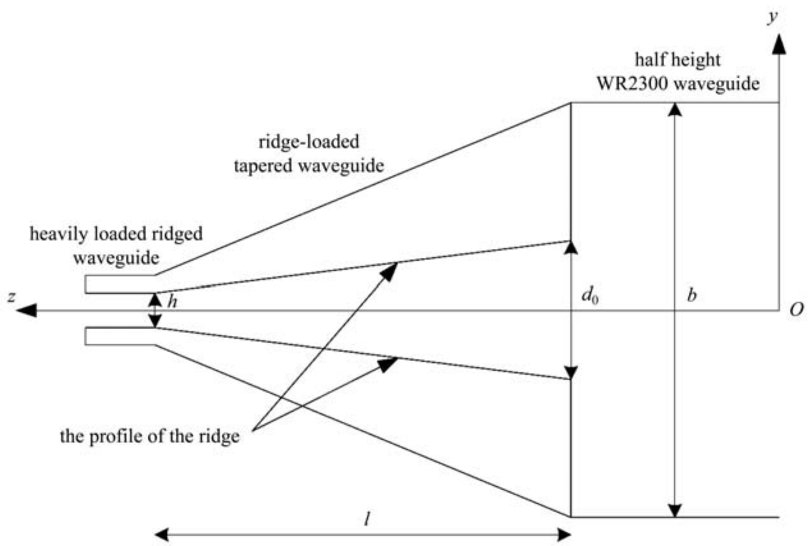

Fig. 5. The cross section of RLWG.

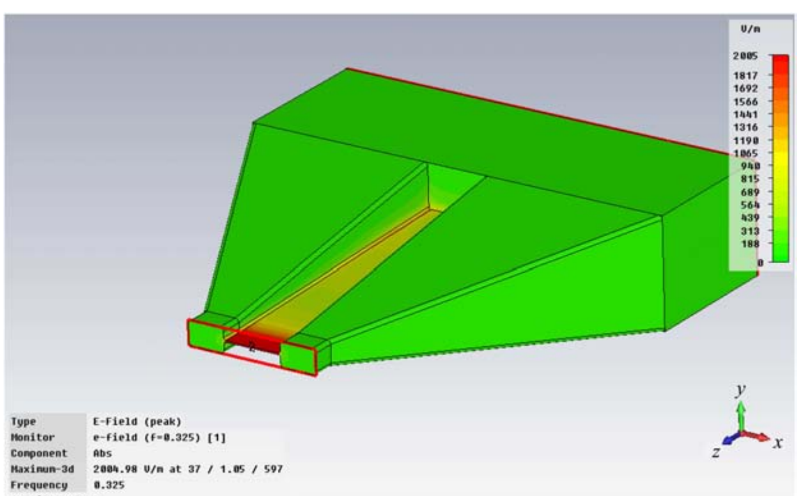

Fig. 6. The electric field distribution in the tapered waveguide.

3 The design of the iris plate

For the iris-type coupler, the coupling is extremely sensitive to the size of the coupling holes at the end of iris [6], so more care is needed to calculate the radius of the iris holes.

For an RF cavity, the coupling coefficient β is defined as:

$$\beta=\frac{Q_0}{Q_{\rm ext}}, \quad (1)$$

where Q_0 is the unloaded quality factor and $Q_{\rm ext}$ is the external quality factor. When the RF power is transmitted through the waveguide to the cavity by a coupler, the optimum coupling coefficient can be given as:

$$\beta_{\rm c}=\frac{P_{\rm w}+P_{\rm b}}{P_{\rm w}}, \quad (2)$$

where $P_{\rm w}$ is the wall power loss and $P_{\rm b}$ is the beam power, For the CPHS RFQ, the required coupling coefficient is about 1.4.

As the calculation of a whole 3 m long RFQ cavity with a single iris coupler will be time-consuming, a simplified short (300 mm) RFQ cavity is used to calculate the coupling instead of the whole cavity. The frequency of the TE_{210} mode of the model cavity is about 324 MHz, the same as the whole RFQ cavity without tuners. Fig. 7 shows the vacuum parts of the model cavity connected to the iris plate and a section of heavily loaded ridged waveguide. The VSWR of the ridge-loaded tapered waveguide is very small, so it has not been taken into account.

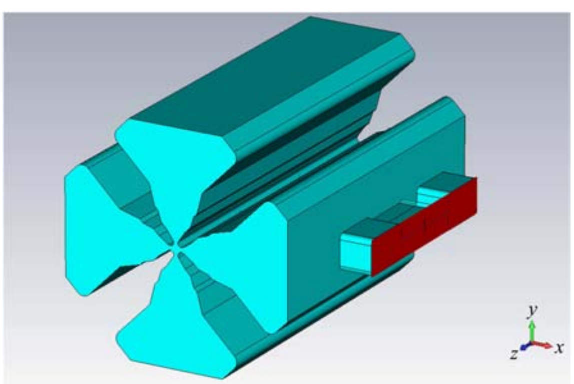

Fig. 7. A model cavity with an iris plate and a section of heavily loaded ridged waveguide.

When the same coupler is connected to the model cavity, the relationship between the coupling coefficient $\beta_{\rm c}$ and $\beta_{\rm m}$ is [7]:

$$\beta_{\rm m}=\beta_{\rm c}\frac{W_{\rm c}}{W_{\rm m}}\left(\frac{H_{\rm m}}{H_{\rm c}}\right)^2\frac{Q_{\rm m0}}{Q_0}, \quad (3)$$

where $W_{\rm m}$, $Q_{\rm m0}$ are the store energy and the unloaded quality factor of the model cavity without coupler, $H_{\rm m}$ is the magnetic field at the iris location and $W_{\rm c}$, $H_{\rm c}$, Q_0 are the corresponding parameters of the whole RFQ cavity. These quantities can be easily attained with the eigensolvers. From Eq. (3), the required value of coupling coefficient $\beta_{\rm m}$ is about 10.6, and the external quality factor of the model cavity $Q_{\rm mext}$ is about 955.

The external quality factor can be calculated directly using the time domain method, and adjusted by changing the radius of the coupling holes to match the required value. In the model of Fig. 8, magnetic boundaries are imposed at z=0 and z=300 mm, and a narrow bandwidth RF pulse is fed through the ridge-loaded waveguide to excite the fields in the model cavity. The field energy decays due to the radiation through the iris into the ridge-loaded waveguide. The time-dependence of the field energy is very convenient in calculating the cavity external quality factor. The slope of the exponential (linear on a dB scale) part of the energy decay curve gives $Q_{\rm ext}$ directly:

$$Q_{\rm ext}=\frac{20\pi f\,({\rm GHz})}{\ln 10}\frac{\Delta t\,({\rm ns})}{\Delta E\,({\rm dB})}. \quad (4)$$

When the radius of the iris hole is 6 mm, the field energy decay is as shown in Fig. 8. When the external quality factor $Q_{\rm mext}$=1525, the coupling is lower than required, so the radius of the iris holes should be increased.

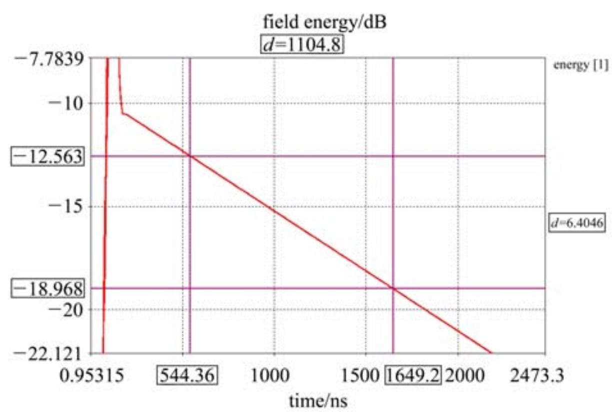

Fig. 8. Field energy decay from the time-domain calculation.

The calculated coupling coefficient versus the radius of iris holes by the 3D simulation code is shown in Fig. 9. When the radius of the iris holes is about 7.7 mm, the required coupling coefficient is achieved.

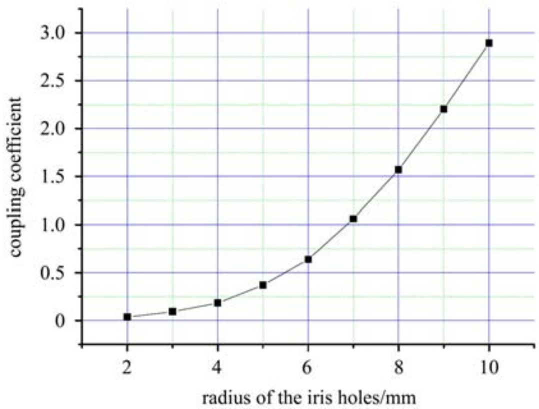

Fig. 9. Dependence of the coupling coefficient on the size of iris holes.

4 Conclusions

An iris-type coupler is designed to feed RF power to the CPHS RFQ cavity. The 3D electromagnetic models of the ridge-loaded tapered waveguide and the coupler-cavity system are described in detail, and a convenient time domain method is applied to calculate the external quality factor and determine the dimension of the iris holes.

The RF coupler for the CPHS RFQ will be machined and fabricated soon, and the RLWG will be manufactured exactly at the design dimensions. The holes at the end of the slot will be machined with a radius of 5 mm. At this size, the waveguide will be under-coupled with respect to the desired coupling coefficient of about 1.4, and the holes will be enlarged during tuning to adjust the coupling coefficient.

We would like to thank Lloyd Young and Liu Hua-Chang for useful discussions.

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