RF power coupling for the CSNS DTL

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Abstract: The China Spallation Neutron Source (CSNS) drift tube linac (DTL) consists of four tanks and each tank is fed by a 2.5 MW klystron. Accurate predication of RF coupling between the RF cavity and ports is very important for DTL RF coupler design. An iris-type coupler is chosen to couple the RF power to the DTL accelerating cavity. The physical design of the DTL coupler and the calculations of RF coupling between the cavity and coupler are carried out. The results from the numerical simulations are in excellent agreement with the analytical results.

Key words: DTL, RF coupler, coupling coefficient

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1 Introduction

The China Spallation Neutron Source (CSNS) is an accelerator-based multidisciplinary user facility under R&D at the Institute of High Energy Physics (IHEP), Beijing, and is to be constructed in Dongguan, Guangdong Province [1]. The accelerator complex consists of an 81 MeV H^- linear accelerator as the injector and a 1.6 GeV rapid cycling proton synchrotron (RCS). The linear accelerator is composed of a 50 keV H^- Penning surface plasma ion source, a low beam energy transport line (LEBT), a 3.0 MeV Radio Frequency Quadrupole (RFQ) accelerator, a medium energy beam transport line (MEBT), an 81 MeV drift tube linear accelerator (DTL) and a high energy beam transport line (HEBT). The DTL consists of 4 tanks, which are driven by four 2.5 MW klystrons.

The RF power is delivered to each DTL tank through RF couplers. To satisfy the designed accelerating field in the DTL tank, the peak RF power of 2 MW is needed. Therefore, the RF power coupling apparatus should be designed carefully to ensure the total RF power feeding. Coupler performance requirements for CSNS DTL are list in Table 1.

Table 1. Coupler performance requirements.

frequency	324 MHz
peak power	2.0 MW
pulse width	0.6 ms
repetition rate	25 Hz
Max. duty factor	1.5%
average power transmitted	30 kW
coupling coefficient	1.4

Generally, two types of couplers are used in RF power coupling system. One is a coaxial type; the other is an iris type. Their major pros and cons are listed in Table 2 [2].

Table 2. Pros and cons of iris type and coaxial type couplers.

	pros	cons
	simpler design	larger size
iris type	better power handling	more difficult to make
	easier to cool	variable
	more compact	more complicated design
coaxial type	easier to make variable	worse power handling
	easy to modify multipacting power levels	more difficult to cool

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We tend to adopt iris-type couplers with tapered ridge loaded waveguides for the following reasons:

1) Completely satisfy CSNS requirements;
2) Simple structure;
3) Small perturbation in the DTL cavity;
4) Cheaper than coaxial type;
5) Lower risk of RF windows than coaxial type.

In this paper, the ridge profile was designed by using 3D calculations. By introducing analytical and numerical methods to correlate the coupling coefficient with the size of the coupling in a "dog-bone" shaped iris coupler, the coupling coefficient is optimized to deliver the RF power into the DTL tank efficiently.

2 Basic design of the ridge-loaded waveguide

Figure 1(a) shows a drawing of the iris-type input RF coupler connecting the DTL cavity to the RF vacuum window. The tapered ridge-loaded waveguide has the dimensions of the half-height WR2300 at one end, and tapers to only 18 cm×3.2 cm at the interface between the DTL tank and waveguide. It operates in the dominant TE10 mode, the same mode as in the half-height WR2300 waveguide used for the air-side RF waveguide. The length of the tapered ridge-loaded waveguide, about 40 cm, is limited by space restrictions. The waveguide is inserted into the DTL via the "dog-bone" shaped coupler irises in the thick cavity wall. The iris consists of a narrow slot with two cylindrical holes near its ends (Fig. 1(b))

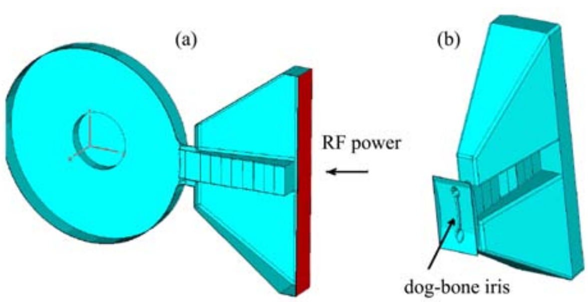

Fig. 1. View of the ridge waveguide (a) and the dog-bone iris shape (b).

The ridge serves to minimize reflections of input RF power due to the waveguide tapering. At first, the ridge width was chosen to be half of the waveguide width along the coupler for an invariable cutoff frequency. However, based on the experience from PEFP RFQ and SNS power couplers, a changed ridge width is more sensitive to multipacting. Therefore, a constant ridge width was adopted, and the ridge width was made as narrow as possible to minimize the possibility of multipacting. In order to keep the same cutoff frequency as the half-height WR2300 waveguide, the end iris slot size is chosen to be approximately 9 cm long and 0.16 cm wide [3].

To couple the RF power into the DTL cavity with the iris slot, the fields are mostly concentrated in the narrow gap between the waveguide ridges. By adjusting the ridge height and the tapered waveguide length (Table 3), the optimized S-parameter of 0.002 is obtained.

Table 3. Parameters of the ridge.

cross-section at RF window side/cm	half height WR-2300, a=58.42, b=14.605
ridge width/cm	9 (keep constant)
gap between ridge/cm	2.365–0.16
ridge length/cm	38.85

3 Analytical coupling coefficient calculation

When the RF power is transmitted through the waveguide and coupled to the DTL tank by an iris coupler, the optimum coupling coefficient with beam loading is given by

$$\beta = 1+\frac{P_b}{P_c}, \tag{1}$$

where P_b is the beam power and P_c is the power dissipation of the DTL cavity.

For an elliptically-shaped iris, the analytical formula for the coupling coefficient established by J. Gao in Ref. [4] is as follows,

$$\beta = \frac{\pi^2 Z_0 k_0 \Gamma_{10} e_0^4 l_1^6}{9ab\left(K(e_0)-E(e_0)\right)^2}\frac{H^2}{P_0}, \tag{2}$$

where Z_0: 370 Ω, free space impedance, a: the width of the rectangular waveguide, b: the height of the rectangular waveguide, H: the magnetic field intensity at the coupling iris position, P_0: the cavity wall loss, K_0: $2\pi/\lambda$, Γ_{10}: $k_0\sqrt{1-(\lambda/2a)^2}$, $K(e_0)$: the first complete elliptic integral, $E(e_0)$: the second complete elliptic integral, l_1: the length of half major axis, l_2: the length of half minor axis, e_0: $\sqrt{1-(l_2/l_1)^2}$.

The expression for the coupling coefficient to account for the "dog-bone" shaped iris has been modified [5], as shown in Fig. 2.

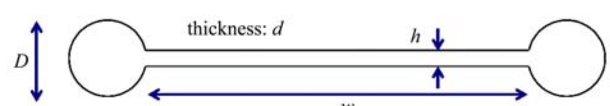

Fig. 2. Geometry of the "dog-bone" shaped iris coupler.

$$\beta = \left(\frac{4\pi^4 Z_0}{9}\right)\left(\frac{1}{\lambda\lambda_g}\right)\left(\frac{1}{wh}\right)\left(\frac{H^2}{P_0}\right)$$
$$\times\left[\frac{\left(\frac{w}{2}+D\right)^3-\left(\frac{w}{2}+D\right)\left(\frac{h}{2}\right)^2}{\ln\left[4\left(w+2D\right)/h\right]-1}\right]^2 \exp(-2d\alpha), \quad (3)$$

where

$$\alpha=\sqrt{\left(\frac{4h\pi}{2wh+\pi D^2\left(D/\lambda\right)^{0.15}}\right)^2-k_0^2}.$$

In Eq. (3), the last exponential term explains the attenuation inside the iris of finite thickness d, and the expression in the square bracket accounts for the dog-bone geometry. The coupling is adjusted by changing the radius of the holes at the end of the coupler slot. With the parameters of the CSNS DTL [6], the required coupling coefficient is 1.4, and the corresponding radius of the hole is 1.275 cm.

4 Numerical coupling coefficient simulation

A simplified model – a short pillbox cavity [7] – is used to study the waveguide-cavity system. As shown in Fig. 3, two identical couplers are used to provide symmetry conditions in order to save computation time, for in this case, only 1/8 model is used in the simulations. It is not necessary to include the tapered waveguide any more because the waveguide has already been adjusted to nearly zero reflection in advance. The pillbox radius is equal to that of the CSNS DTL tank and the inner cylinder radius is the same as that of the drift tube. The gap between the inner cylinders is adjusted to ensure the correct resonant frequency of 324 MHz.

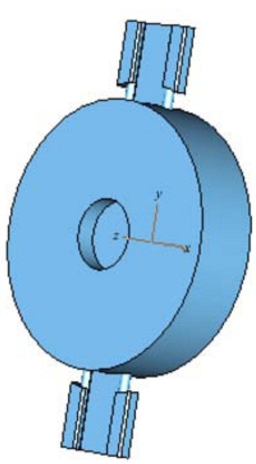

Fig. 3. Model of pillbox cavity with two couplers.

The intrinsic and external quality factors of a resonant cavity are defined as

$$Q_0=\frac{\omega W}{P_W}$$

and

$$Q_{\rm ext}=\frac{\omega W}{P_{\rm ext}},$$

respectively, where ω=2πf with f as the resonant frequency; W the stored energy of the mode in the cavity. $Q_{\rm ext}$ only depends on the coupling while Q_0 depends on the cavity geometry. Obviously, the coupling for the pillbox cavity will be different from that for the DTL tank. The relation between the coupling coefficient of the model and that of the DTL is given by

$$\beta_{\rm DTL}=\frac{W_{\rm mod\ el}}{W_{\rm DTL}}\left(\frac{H_{\rm DTL}}{H_{\rm mod\ el}}\right)^2\frac{Q_{DTL}}{Q_{\rm mod\ el}}\beta_{\rm mod\ el}, \quad (4)$$

where W_i and H_i are the stored energy and magnetic field at the coupler location without the coupler, respectively, and Q is the unloaded quality factor.

Kroll and Yu [8] developed a method in frequency-domain to calculate $Q_{\rm ext}$ indirectly. This works very well for a strong cavity and waveguide coupling system. However, in the case of a weak coupling where Q is high, it could be highly time-consuming for many 3D codes in order to get a very high accurate resonant frequency in the simulations. Here, time-domain simulations are adopted to calculate the coupling directly.

In time domain simulations, the excitation source has to be defined first. The source needs to have the right band-width at the locations where the correct EM modes can be excited. Fig. 4 shows an example of the excitation pulse. Probes placed in the cavity center record the exponential decaying EM fields as a function of time with a pre-defined time step. The excitation pulse lasts for ~140 ns, and the induced fields gradually build up and reach the maximum right before the pulse leaves the cavity. Then the fields in the cavity decay, as shown in Fig. 5, due to radiation through the coupler irises into the open waveguides. This radiation is the only source of energy loss, since all metal surfaces are assumed to be perfectly conducting in the calculation.

The energy decay is expressed in units of dB. A typical energy decay curve obtained from simulations is shown in Fig. 6. The slope of the exponential part of this plot gives $Q_{\rm ext}$ directly [9]

$$Q_{\rm ext}=\frac{20\pi f\,({\rm GHz})}{\ln 10}\frac{\Delta t({\rm ns})}{\Delta E({\rm dB})}. \quad (5)$$

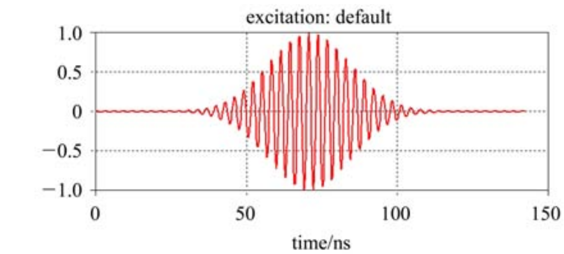

Fig. 4. An excitation signal.

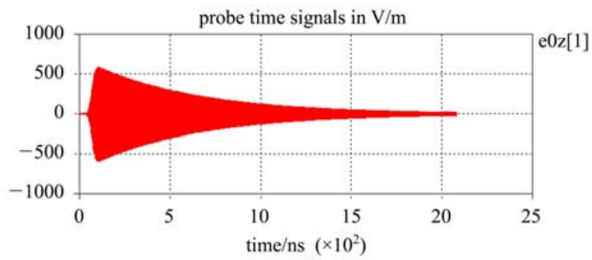

Fig. 5. The electric field decay due to radiation through irises.

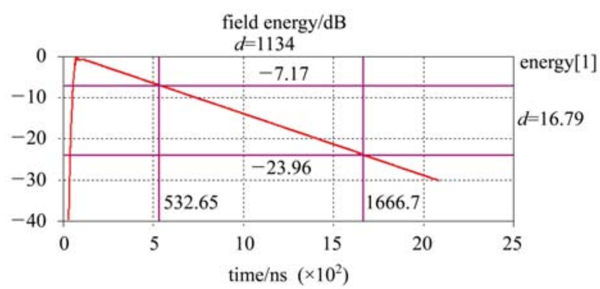

Fig. 6. The field energy decay from time-domain calculations and plot measure lines.

For the particular case shown in Fig. 6, the external quality factor achieved is $Q_{\rm ext}$=537 from Eq. (5) and the corresponding coupling coefficient is 1.36. Therefore, the coupling is a bit low, and the radius of the iris holes should be slightly increased to enhance the coupling. With the iris slot width of 0.16 cm and length of 9 cm as mentioned above, the correct coupling is achieved when the radius of the hole is equal to 1.274 cm, which is consistent with the value obtained by the analytical formula. The calculated coupling coefficients depicted as a function of the size of the coupling hole are shown in Fig. 7. The results from the two calculation methods are in excellent agreement. In addition, the result shows that the coupling coefficient is extremely sensitive to the radius of the hole. Based on the results given in Ref. [5], the coupling coefficient is proportional to the third power of the size of the hole.

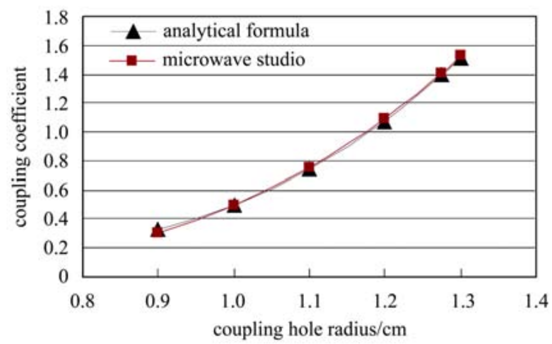

Fig. 7. Dependency of the coupling coefficient on the size of the coupling hole.

5 Conclusion

The CSNS DTL coupler design, including the design of the ridge waveguide and coupling between the waveguide and the DTL tank through the dog-bone iris by using both analytical and numerical methods, has been investigated. As mentioned above, $Q_{\rm e}$ can be determined directly from the computation of the decay time constant through numerical simulation of an iris waveguide coupling system by taking advantage of the time-domain simulation. Moreover, the application of the time domain method seems to be very convenient with the transient solver in 3D EM simulation code. Excellent agreement is achieved between numerical and analytical calculation. Further work remains to be done to study the thermal management issue and cooling of the coupler iris. The final iris dimensions will be determined by experiments during the low power RF tuning process.

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