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Design and analysis of a tunable coupler for application to adjustable beam injectors

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Abstract: As a fundamental component of a linac-based beam injector, the rectangular-waveguide coupler is a conventional device for feeding high power, but it will induce field asymmetry and resonant-frequency shifting. Furthermore, it is also difficult to adjust the coupling factor for adjustable beam injectors. In this paper, an equivalent circuit model is established for the coupler with a tuning rod. Based on theoretical analysis, the optimal position for the rod is given. Besides, the frequency shifting is corrected by using another rod inserted to the cavity in the opposite direction. Sizes and adjustment ranges of both rods are given by three-dimensional electromagnetic simulation using CST MICROWAVE STUDIO. Jointly adjusted simulation results show that, critical-coupled states are achieved for different beam intensity while the resonant frequency remains stable, thus the risk of reflected power caused by coupler mismatching can be avoided, and the field asymmetry due to a small coupling hole can be reduced.

Key words: coupling coefficient, resonance tuning, standing-wave cavity, RF accelerator

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The RF electron gun and the RF linac[1-3] are widely applied in high-energy accelerators and storage rings. Since the generation of high-quality electron bunches depends on desired RF fields, a coupler, which is an impedance matching device, is responsible for feeding RF power from RF source into the cavity. In the case of high-gradient acceleration structures especially compact ones, a rectangular waveguide coupler with a hole is commonly adopted to feed high RF power. Besides, the coupling hole must be large enough to achieve sufficient beam power, whereas field asymmetry resonance frequency shifting might be induced inevitably[4]. In other word, the coupler structure will not only affect RF performances of the acceleration system, but also degrade generated beam quality. Furthermore, in the case of adjustable beam injectors for application to free electron lasers, industrial accelerators, etc., it is of great significance to tuning the coupling factor online for an installed acceleration structure. Corresponding advantages of the tunable coupler are summarized as the following.

(1) Avoiding the secondary correction for the mismatching coupling factor induced by machining and construction errors.

(2) Keeping a small coupling hole under the condition of heavy beam-loading, then induced field asymmetry can be reduced.

(3) Making the coupler more flexible for the applications with different beam current, and critical-coupled states can always be achieved to avoid high backward power.

(4) Making the acceleration system more compact without high-power attenuators installed on related RF power transmission waveguides.

Present researches show that the adjustable coupling factor can be realized by adjusting depth of cylindrical regulators Te and Tm which are inserted in the electrical field and magnetic field region of ridge waveguide coupler respectively[5]. However, the design and the fabrication of cylindrical regulators are complicated. It is possible to obtain a wide range of coupling factor

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by rotating the iris between the coupler and the cavity[6] or changing its length and width without adding other components, but this method will destroy the vacuum of the structure. For a waveguide-coaxial coupler, the coupling factor is adjusted by rotating the ring at the end of the coaxial line, but it will destroy the vacuum either[7]. De Jong et al. proposed a feasible solution to connect an exponentially tapered waveguide with an iris to the cavity and adjust the coupling factor through a plunger on the vertebral body[8]. But this exponential tapered waveguide is complicated in design and expensive in manufacture. Furthermore, it is convenient to use a common rectangular contraction waveguide as coupler and apply an inserted tuning rod to adjust the coupling factor, but seeking a suitable position for the tuning rod is much difficult[7-9].

In addition, due to the machining installation errors, the resonant frequency of the actual cavity deviates from the design value. Thus, another tuning rod in the radial direction of the cavity or squeezing adjustment hole[1, 3, 10], is required to tune the acceleration cavity to ensure that it operates at the designed resonant frequency.

All of the above methods are individual adjustments for the coupling factor or the resonant frequency. In this paper, we take a standard standing-wave (SW) cavity with a rectangular waveguide coupler as an example, in which a coupling tuner (T_c) is inserted into the contraction waveguide, and a frequency tuner (T_f) is inserted into the cavity in the opposite direction of the coupling hole, As shown in Fig.1. Firstly, we construct a theoretical tuning model in manner of electrical circuit for such coupling system and analyze it in depth. Secondly, we conduct a 3D electromagnetic simulation to design corresponding structures and verify optimal insertion position for T_c. At last, the joint adjustment of T_c and T_f are performed to obtain the tuning range for the coupling factor and keep resonance frequency stable in the meantime. Therefore, the adjustments of coupling factor and resonant frequency can be achieved simultaneously, which make the coupling factor flexible with the beam intensity while maintaining the cavity resonance frequency stable at the design value. The design results and involved research method can be extended to all RF accelerating structures.

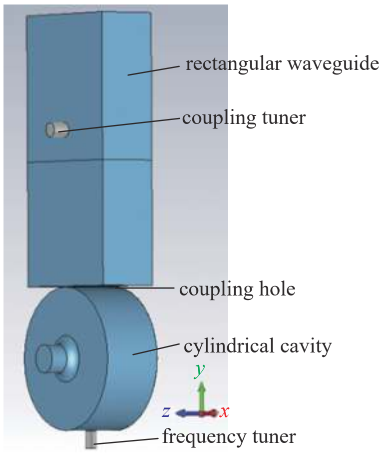

Fig. 1 Simulation model of the coupling system

1 Online tuning methods for the waveguide coupler

1.1 Coupling tuning theory

The microwave equivalent circuit method is used to theoretically analyze the power coupling system between the power source, waveguide coupler and cavity.

When viewed from a plane of detuned short in the input waveguide, a cavity can be equivalent with an R-L-C shunt circuit as illustrated in Fig.2(a), whose resonant frequency is expressed as the following,

$$\omega_0 = 1/\sqrt{LC} \tag{1}$$

As shown in Fig.2(a), the equivalent circuit includes a matching power source, an input waveguide with characteristic impedance $1/G_e$, a coupling hole and an SW cavity. The coupling hole between the cavity and the waveguide can be equivalent to an ideal transformer whose turn-ratio is n. There is a certain conversion relationship between n and the coupling factor β. In the equivalent circuit, assuming that the end of the input waveguide is a detuned short plane, on which the accelerating cavity can be regarded as a parallel R-L-C equivalent circuit[8]. The equivalent circuit of the RF cavity is mapped to the power source and the waveguide side, and the parameters at the source side are labeled by an apostrophe. Then the normalized admittance of the RF cavity mapped to the source can be written as follows[8],

$$y' = \frac{1}{G_e}\left[G' + \mathrm{j}\left(\omega C' - \frac{1}{\omega L'}\right)\right] = \frac{1}{\beta_0}\left[1 + \mathrm{j}Q_0\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)\right] \tag{2}$$

where β_0 and ω_0 are the initial coupling factor and the resonant frequency of the cavity, respectively. ω is the frequency of the

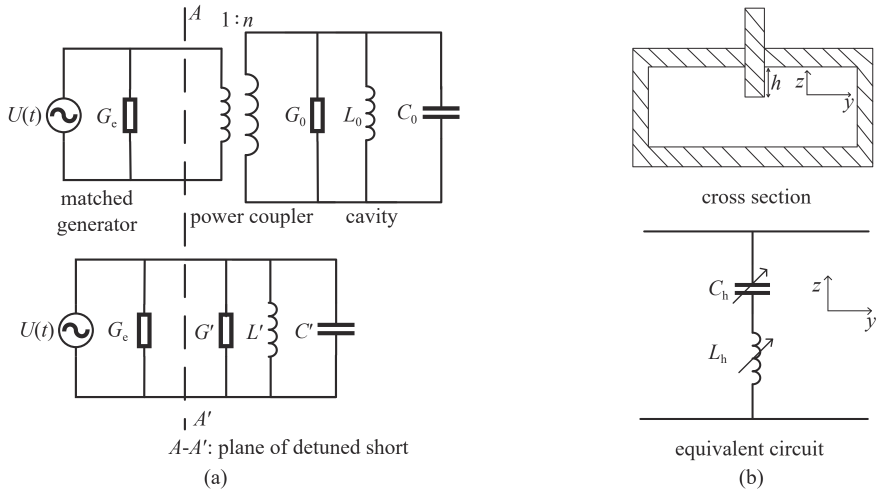

Fig. 2 (a) Equivalent circuit of a one-port-coupled cavity and (b) equivalent circuit of a coupling tuner T_c inserted into the waveguide

RF power source, and Q_0 is the intrinsic quality factor of the cavity. It can be seen that in the case where the parameters of the RF power source and the cavity are well designed, the normalized admittance of the RF cavity mapped to the source is only related to the resonant frequency of the cavity ω_0. A rod (T_c) with axis parallel to the electric field in the waveguide can be treated as an equivalent circuit branch as illustrated in Fig.2(b). The normalized admittance induced by the post changes with the insert depth h, and the variation can be described by the following expression,

$$y_h = \frac{1}{G_e[j\omega L_h + (1/(j\omega C_h))]} = -jb \qquad (3)$$

where $b = \omega C_h/(\omega^2 L_h C_h G_e - 1)$.

The equivalent circuit of the system with T_c is displayed in Fig.2(a), the total input admittance at the insertion plane can be demonstrated by,

$$y = y_h + \frac{y' + j\tan(k_g l)}{1 + jy'\tan(k_g l)} \qquad (4)$$

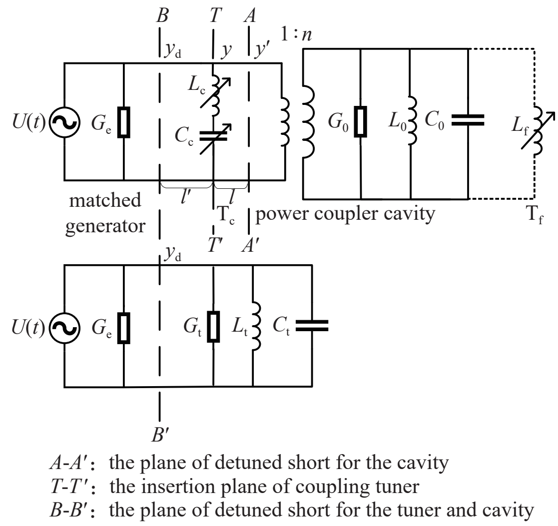

Fig. 3 Equivalent circuit of a tuning system

where K_g is the wave number, l is the distance between the insertion plane of Tc and the plane of detuned short.

As shown in Fig.3, the normalized admittance seen from the plane of B-B' can be expressed as a function of b, which is related to the coupling rod T_c.

$$y_d = \frac{y + j\tan(k_g l')}{1 + jy\tan(k_g l')} = \frac{\tan(k_g l) + b + b^2\tan(k_g l) + j(XQ_0(\tan(k_g l) + b + b^2\tan(k_g l)) - \beta_0(1 + b^2 - b\tan(k_g l))}{XQ_0 + \beta_0\tan(k_g l) - j} \qquad (5)$$

where $X = [(\omega/\omega_0) - (\omega_0/\omega)]$ is only related to ω_0 under the certain RF source. The new coupling factor after inserting T_c is $\beta = 1/y_d$, according to the expresion of coupling coefficient $\beta = \frac{1+\Gamma}{1-\Gamma} = \frac{1 + \frac{Z_L - Z_0}{Z_L + Z_0}}{1 - \frac{Z_L - Z_0}{Z_L + Z_0}} = z_L = 1/y_L$. Eq. (5) shows that the coupling factor changes with the depth and position of T_c. Obviously, the position of T_c can be roughly determined according to Eq. (5). Corresponding theoretical solution are expressed as Eq. (6), when $1/\beta_0 \leqslant \beta \leqslant 1$.

$$\begin{cases} b^2 = \dfrac{\beta_0{}^2 + 1 + \sqrt{5\beta_0{}^2\beta^2 - 2\beta_0(\beta_0{}^2 + 1)\beta + \beta_0{}^4 - 2\beta_0{}^2 + 1}}{2\beta_0\beta} - \dfrac{3}{2} \\ \tan(k_g l) = b + \dfrac{1}{b} - \dfrac{1}{b\beta\beta_0} \end{cases} \qquad (6)$$

1.2 Resonant frequency tuning

The cylindrical cavity working at TM_{010} mode[9, 11-12], whose resonant frequency is only related to radius, is used in the independent tuned RF gun. Therefore, the resonant frequency of the cavity can be adjusted by changing its radius.

Inserting a tuning rod (T_f) in the symmetry direction of the coupler on the cavity, then the frequency can be tuned by adjusting the insertion depth of T_f, which can be explained by the perturbation theory. From the cavity wall perturbation formula[1,10] and the TM_{010} field distribution in the cylindrical cavity (the closer to the cavity wall, the larger the magnetic field; the closer to the axis, the larger the electric field): When the depth of the T_f is small, the magnetic field in the perturbation region is larger than the electric field, and the existence of the metal tuning rod makes the cavity concave. Thereby the resonant frequency of the coupled system increases as the insertion depth of T_f increases. Conversely, when T_f is extended outward, the resonant frequency is reduced.

1.3 Equivalent circuit contains both T_c and T_f

The equivalent circuit of the independently tuned RF gun with T_c and T_f is shown in Fig.3: C_c, L_c and L_f, which are the capacitance and inductance induced by T_c and T_f respectively, are varying with the insertion depth. The total circuit parameters in consideration of T_c and T_f are G_t, L_t and C_t. The normalized admittance of the coupling system on B-B' plane also can be written as Equatiom (5).

Changing the insertion depth of T_f is equivalent to change the inductance and capacitance of the cavity, so that $X = [(\omega/\omega_0) - (\omega_0/\omega)]$ changes with the resonant frequency ω_0 of the cavity from Eq. (2), changing the insertion depth of T_c is equivalent to change the b value. The overall normalized admittance y_d changes with the values of X and b, thereby affecting the coupling factor according to Eq. (5). On the other hand, the total capacitance C_t and inductance L_t alter with the depth of T_c and T_f, which change the total resonant frequency $\omega_t = 1/\sqrt{L_t C_t}$. And from the analysis in section 1.1, the deeper the insertion depth of T_f, the larger the total resonant frequency. In order to achieve a critical-coupled state and maintain the resonant frequency point at the design value at different beam sizes, the joint adjustment of T_c and T_f can be used to tune the coupling system. The 3D simulation model of the entire tuning coupler is shown in Fig.1.

2 Simulation for the tuning system

According to the requirement of the system design, the acceleration structure should be in the over-coupled state without beam loading, and in the best matching state when the beam is turned on. The formula of the optimal coupling factor is given by[12-15]

$$\beta = \left(\frac{I_b}{2} \sqrt{\frac{Z_s L}{P}} + \sqrt{\frac{I_b^2 Z_s L}{4P} + 1} \right)^2 \tag{7}$$

where I_b is the average beam intensity, Z_s is the cavity shunt impedance, L is the effective length of the cavity, P is the incident power of the cavity. Considering most of accelerators with high beam power usually generate mean beam current of several hundred of micro-amperes, corresponding optimal coupling factor calculated by Eq. (7) will be up to over 2. Besides, since the accelerators working at S-band is quite commonly used, a cavity with the resonant frequency 2856 MHz is considered hereafter.

As analyzed in section 1, the coupling rod T_c and the tuning rod T_f can be used to adjust the coupling system to achieve a critical-coupled state under different beam intensity, that is, the coupling factor is adjustable in a wide range, and the resonance frequency is maintained at the design value of 2856 MHz at the same time.

2.1 Simulation results

As illustrated in Fig.1, The coupling system model includes a standard cylindrical acceleration cavity, a contraction waveguide, a cylindrical metal coupling rod (T_c) and a tuning rod (T_f). The coupling system is solved by the frequency domain solver of CST MW studio, then the coupling factor and the resonant frequency of the system are calculated from the S_{11}-parameter curve. The initial coupling system without T_c and T_f is at under coupling state, which decreases the coupling hole size and the asymmetry of the field in cavity. The approximate position of the T_c can be calculated from Eq. (6), and the appropriate position is determined by scanning. A cylindrical metal post (T_c) with a radius of 4 mm is inserted at the center of the waveguide at a distance of 11.5 mm from the short detuned plane. The coupling factor and resonance frequency of coupled

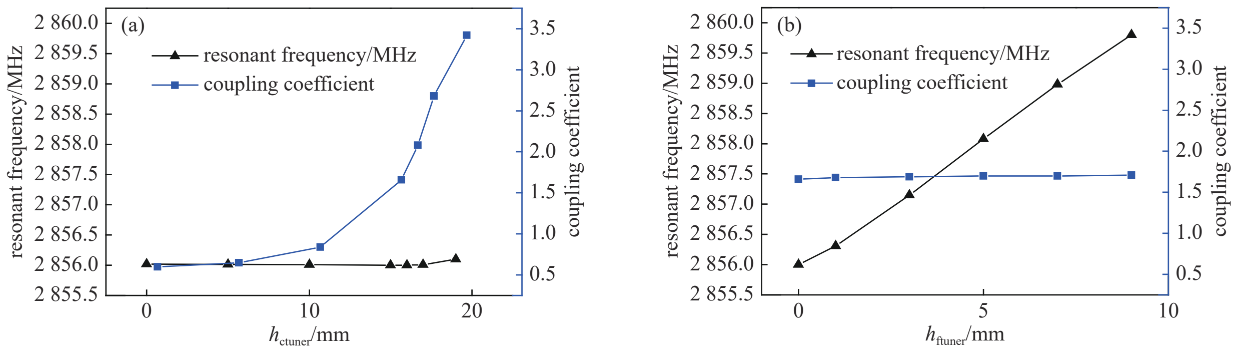

Fig. 4 (a) Resonant frequency and coupling factor at different h_{ctuner} and (b) resonant frequency and coupling factor at different h_{ftuner}

system change with the insertion depth of T_c are shown in Fig.4(a), where h_{ctuner} is the insertion depth of T_c.

From Fig.4(a), T_c has great influence on coupling factor while small influence on resonant frequency. The adjustment range of coupling factor is 0.6—3.42, and the resulting resonance frequency shift is about 0.1 MHz. As the insertion depth of T_c increases gradually from 0 to 19 mm, the coupling factor of the coupling system increases monotonously from 0.6 to 3.42, and the coupling factor is sensitive to h_{ctuner} when h_{ctuner} is from 10 to 19 mm. When h_{ctuner} is fixed at 15 mm, the coupling factor of the coupling system is about 1.66, and the resonance frequency is about 2856 MHz. Then inserting a tuning rod (T_f) in the symmetry direction of the coupler on the cavity. The coupling factor and resonance frequency of coupled system change with the insertion depth of T_f (h_{ftuner}) are shown in Fig.4(b)

From Fig.4(b), T_f has great influence on resonant frequency while small influence on coupling factor. As h_{ctuner} increases from 0 to 9 mm, the resonant frequency gradually increases linearly from 2856 MHz to 2859.8 MHz, and the frequency adjustment range is about 3.8 MHz, which can correct the frequency shift induced by external factors such as T_c and installation. At the same time, the coupling factor increases from 1.66 to 1.71, with no major changes.

The effects of T_c and T_f radius on coupling factor and resonant frequency are displayed in Table 1 and Table 2.

Table 1 Effect of the T_c radius on coupling factor and resonant frequency

radius/m	coupling factor	resonant frequency/MHz
2	0.60–2.70	2856.00–2856.02
4	0.60–3.42	2856.00–2856.10
6	0.60–3.90	2856.00–2856.15

Table 2 Effect of the T_f radius on coupling factor and resonant frequency

radius/mm	coupling factor	resonant frequency/MHz
1	1.66–1.67	2856.00–2856.47
3	1.66–1.71	2856.00–2859.80
5	1.66–1.77	2856.00–2865.79

As can been seen from Table 1 and Table 2, the adjustable range of coupling factor and the resonance frequency as well as the frequency deviation and the coupling factor shift increase with the radii of T_c and T_f. In order to reduce the field asymmetry and fabrication cost, it is necessary to select the minimum radius of T_c and T_f under the conditions that meet the needs according to actual requirements.

2.2 Joint adjustments of T_c and T_f

It can be seen from previous analysis and simulations that the coupling factor of can be flexibly adjusted by changing h_{ctuner}, but correspondingly, the resonant frequency deviates from the ideal value, hence T_f is required to compensate the resonant frequency.

The S_{11}-parameter curves at different h_{ctuner} are shown in Fig.5(a), which indicate that although the coupling factor varies monotonically with h_{ctuner}, the resonance frequency also shifts. Fig.5(b) shows the S_{11}-parameter curves at different h_{ftuner} after T_f pulls the resonant frequency back to the design value. To sum up, under the tuning effects of T_c and T_f, the coupling factor of the coupling structure can be adjusted while ensuring the resonance frequency point is unchanged.

2.3 Effect of T_c on field asymmetry in cavity

Drawing a circle with a radius of 1 mm in the center cross section of the cavity and deriving the dipole electric field distribution along the circumference can represent the field asymmetry of the cavity to a certain extent. Supposing the ideal

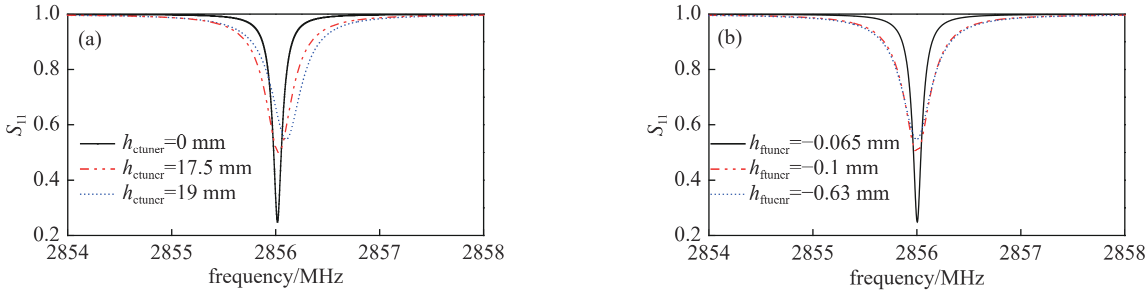

Fig. 5 The S_{11}-parameter curves at different h_{ctuner} (a) and h_{ftuner}(b)

coupling factor is 2, the field asymmetry under three situations: (i) standard cavity without coupler, (ii) cavity with coupler and T_c, (iii) cavity with coupler but without T_c are showed in Fig.6.

The results indicate that using T_c to achieve the ideal coupling factor under a small coupling hole can reduce the field asymmetry of the cavity compared to traditional method that changing the coupling hole size.

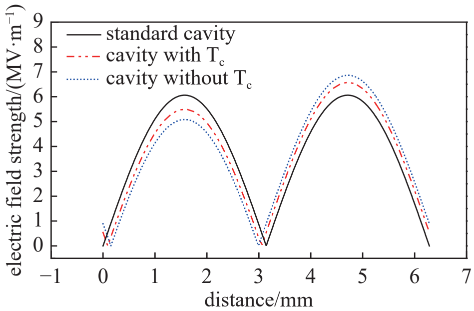

Fig. 6 Electric field distribution of the dipole in the cavity along the circumference

3 Conclusion and perspectives

In this paper, an improved design is proposed for the coupling system of RF acceleration structures with adjustable beam intensity. The coupling factor and resonance frequency of such system can be adjusted by two tuning rods simultaneously. Firstly, the approximate position of T_c is obtained by the equivalent circuit analysis. Then, based on the three-dimensional electromagnetic field simulation, the adjustment range of the coupling factor is obtained, and T_f is used to compensate the shift of the resonance frequency induced by T_c. In addition, the effect of the tuning rod size is analyzed. The final theoretical analysis and simulation results show that the RF gun coupling system can reach the critical coupling state at different beam intensity and keep the resonant frequency unchanged at the same time by joint adjustment of T_c and T_f. Moreover, T_c can reduce the field assymmetry in cavity compared to traditional changing coupling hole method when the ideal coupling factor is large. This tuning method has many advantages such as simple, convenient and low manufacturing cost. Besides, it has good performance on coupling factor and resonant frequency adjustments. Furthermore, it is applicable to most coupling systems. However, in this study, we ignored the effect of vaccum port and there is no experiment to verify this tuning method, which can be researched in the furture.

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可调电子束注入器调配调谐结构的设计及分析

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摘　要：驻波谐振腔是基于直线加速器的束流注入器的基本构造元件，其大功率微波馈入一般选用矩形波导耦合器，但它会引起场不对称和谐振频率的漂移，也难以针对不同流强的束流灵活调节耦合度。建立了带有调配杆的耦合器的等效电路模型，在理论分析的基础上，给出了杆的最佳位置。此外，在耦合器的对称方向插入调谐杆用于补偿结构改变及加工安装等外部因素造成的频率漂移，并使用 CST MICROWAVE STUDIO 的三维电磁仿真给出了两个杆的尺寸和调整范围。联合调整的仿真结果表明，在谐振频率保持稳定的情况下，不同流强的束流均达到临界耦合状态，从而避免了耦合器失配引起的反射功率风险，并减少了由于较小耦合孔引起的场不对称。

关 键 词： 耦合度；调耦调谐；驻波腔；射频加速器