

# Coupler design for an L-band electron linac

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**Abstract:** The RF coupler is a key component for an accelerating structure which is the most important component for a linac. In order to feed microwave power into the accelerating cavities effectively, the coupler has to be well matched with the feeding waveguide. In this paper, an electron linac coupler was designed, constructed and tested. A numerical simulation method based on the Kyhl's method was employed to search for the optimal dimensions of the coupler. The frequency and the coupling coefficient as a function of the coupler dimensions were also calculated. The results fitted the Kyhl's method simulation results well and gave tolerances of the coupler. The coupler was brazed to the accelerating cavities and it was cold-tested and hot-tested. The experimental results were consistent with the numerical simulation results.

**Key words:** linac, coupler, numerical simulation, Kyhl's method

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## 1 Introduction

An L-band linac is constructed for industrial irradiation. The RF coupler is a key component for the accelerating structure which is the most important component for the linac. It has to be well designed in order to deliver power from the RF source to the disk-loaded accelerating structure efficiently. For a well tuned and matched coupler, it can couple the maximum amount of power into the accelerating structure. It must be tuned to the synchronous frequency of the accelerating cavities and the RF source for the proper phase advance in the accelerating cavities [1].

Before three-dimensional electromagnetic field simulation was available, the coupling cavity for a disk-loaded linac was designed by machine and measurement which needed a sequence of experiments. The whole procedure needed several iterations on prototypes before optimal dimensions could be obtained, so it was very time consuming. After the development of the numerical electromagnetic field simulator, computers were used to design the couplers for the accelerating structure [1–3]. In this paper, we employed a three-dimensional electromagnetic field code which

was based on the Finite Element Method (FEM) to design an L-band linac coupler. The simulation procedures were based on the Kyhl's method [4]. Since the relationship between the microwave parameters and the coupler dimensions has rarely been shown in previous numerical simulation papers based on the Kyhl's method, we also investigated the dependence of the microwave parameters of the coupling cavity on the coupling cavity dimensions. The results fitted the Kyhl's method simulation results well and gave the coupler tolerances.

The L-band linac coupler was fabricated according to the numerical simulation results. It was brazed to the accelerating cavities and the whole accelerating structure was cold-tested and hot-tested. The experimental results were consistent with the numerical simulation results. The present work demonstrates numerical simulation can be helpful for the coupler design.

## 2 The L-band linac

The L-band linac was a constant impedance traveling-wave (TW) structure operating in the  $2\pi/3$

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mode. Its operating frequency was 1.3 GHz. The linac had been conditioned so far. The test results showed that the maximum electron energy was larger than 10 MeV, which meant that the design specification had been satisfied. The average-power of the linac was 50 kW which was larger than the design specification which was 30 kW. A tapered rectangular waveguide was connected to the coupling cavity. The first accelerating cavity was next to the coupling cavity, as shown in Fig. 1. The dimensions of the coupler were the coupler diameter  $2b$ , the iris aperture  $2w$  and its thickness  $t$ . In this paper, the three-dimensional electromagnetic field code was employed to calculate these dimensions when the coupler was matched and tuned.

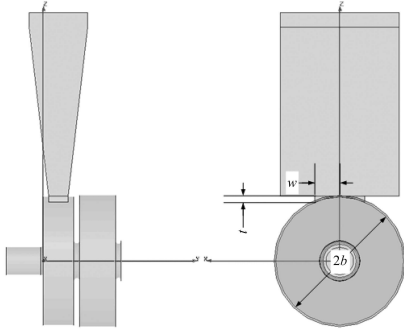


Fig. 1. Schematics of the L-band linac coupler.

### 3 The Kyhl's method

The Kyhl's method is an impedance matching method when a rectangular waveguide is connected to the traveling wave periodic structure[4]. So the method can be used to design the L-band electron linac coupler. In this section, we will describe the measurement procedures and explain the theoretical basics for the method.

First, based on the Kyhl's method, three frequencies are needed to design a coupler for the  $2\pi/3$  mode: the computed frequency of the  $2\pi/3$  mode  $f_{2\pi/3}$ , the computed frequency of the  $\pi/2$  mode  $f_{\pi/2}$  when keeping the coupler dimensions the same and the arithmetic mean of the previous two frequencies  $f_{\text{mean}}$ , respectively. Second, detune the coupler cavity with a copper plunger. The phase of the reflection  $R_1$  in this case is almost independent of the frequency and it should be recorded. Then detune the first accelerating cavity with the copper plunger. The phases of the reflection  $R_2$  must be recorded for the  $f_{2\pi/3}$ ,  $f_{\pi/2}$  and  $f_{\text{mean}}$ . If the diameter of the coupler cavity is correct, then the phase of the reflection  $R_2$  at  $f_{\text{mean}}$  will be different from the phase of the reflection

$R_1$  when the copper plunger is in the coupling cavity by  $180^\circ$ . If this is not true, then the diameter of the coupling iris must change to bring the phase of the reflection to the right value. Next, if the coupling iris aperture is correct, then the reflection points fall on the Smith chart as shown in Fig. 2. If the angle between  $R_2(\pi/2)$  and  $R_2(2\pi/3)$  is larger than  $120^\circ$ , the coupler is undercoupled. The iris aperture must increase to achieve critical coupling. If the angle between  $R_2(\pi/2)$  and  $R_2(2\pi/3)$  is smaller than  $120^\circ$ , then the coupler is overcoupled. The iris aperture must decrease to achieve critical coupling.

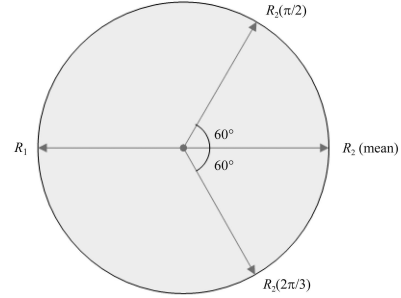


Fig. 2. Smith chart for reflections from the copper plunger.

Now we explain why the previous procedures can be used to match and tune a TW structure coupler [5]. According to the impedance matching, the input coupling network provides critical coupling into  $2\pi/3$  mode accelerating structure. Then the admittance of the coupling network is equal to the admittance of the  $2\pi/3$  mode accelerating structure

$$jY_{\text{in}} = jY_{\infty} \left( \frac{2\pi}{3} \right) = \frac{Y_c}{2\sqrt{3}}. \quad (1)$$

Detuning the coupling cavity is equivalent to disconnecting the whole network from the first capacity on circuit Fig. 3(a). The reflection coefficient of the structure now is equal to

$$R_1 = \frac{jY_{\text{in}} - jY_c/2}{jY_{\text{in}} + jY_c/2} = \frac{1 - j\sqrt{3}}{1 + j\sqrt{3}} = \exp\left(-j\frac{2\pi}{3}\right). \quad (2)$$

Detuning the first accelerating cavity is equivalent to disconnecting the network from the coupling scheme section Fig. 3(b). The reflection coefficient of the structure now will be

$$\begin{aligned} R_2 &= \frac{jY_{\text{in}} - jY_c \left( \frac{1}{2} + \frac{1}{1 - Y_c X_{\text{ser}}} \right)}{jY_{\text{in}} + jY_c \left( \frac{1}{2} + \frac{1}{1 - Y_c X_{\text{ser}}} \right)} \\ &= \frac{1 - j\sqrt{3} \left( 1 + \frac{2}{1 - Y_c X_{\text{ser}}} \right)}{1 + j\sqrt{3} \left( 1 + \frac{2}{1 - Y_c X_{\text{ser}}} \right)}. \end{aligned} \quad (3)$$

Since  $X_{\text{ser}}$  is linear with frequency, and we have

$$\begin{aligned} X_{\text{ser}}(\pi/2) &= 2X_c, \\ X_{\text{ser}}(2\pi/3) &= 3X_c, \\ X_{\text{ser}}(\text{mean}) &= 5X_c/2. \end{aligned} \quad (4)$$

Thus we get

$$\begin{aligned} R_2(\pi/2) &= \exp(j2\pi/3), \\ R_2(2\pi/3) &= 1, \\ R_2(\text{mean}) &= \exp(j\pi/3). \end{aligned} \quad (5)$$

So when the first accelerating cavity is detuned, the phase of the reflection coefficient  $R_2$  of the structure should follow the Smith chart shown in Fig. 2.

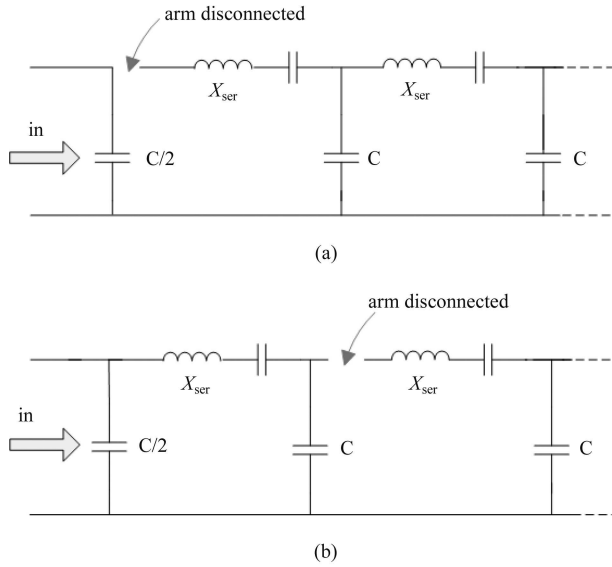


Fig. 3. Equivalent circuit for the accelerator structure (a) with coupler cavity detuned by the plunger, and (b) with the first accelerating cavity detuned by the plunger.

## 4 Simulation

Since the  $\pi/2$  mode frequency  $f_{\pi/2}$  of the structure was requested, the two-dimensional electromagnetic field code SUPERFISH [6] was employed to calculate the frequencies. The calculated frequencies  $f_{\pi/2}$ ,  $f_{\text{mean}}$  and  $f_{2\pi/3}$  were then implemented in the three-dimensional electromagnetic field code which modeled the detuned coupler, shown in Fig. 4. Proper maximum number of passes and maximum delta frequency per pass were set. The tuning and matching procedures were based on the Kyhl's method. The coupler diameter and the iris aperture were changed to make the phase of the reflection coefficient fall on the right value on the Smith chart. Finally, optimal dimensions were found for the coupler.

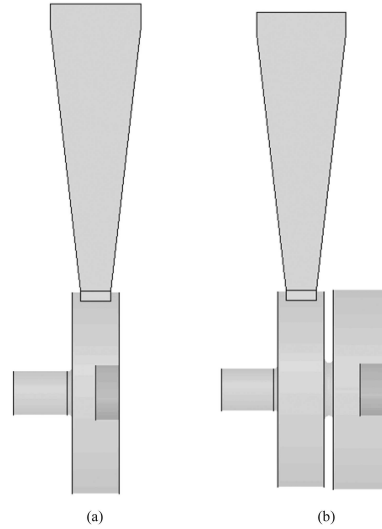


Fig. 4. Coupling structure modeled by the three-dimensional electromagnetic field code (a) coupler cavity detuned and (b) the first accelerating cavity detuned.

Further simulation was done, including the coupler cell's frequency deviation as the cell's dimensions varied from the optimized values when the first accelerating cavity was detuned. The dependence of the cell's frequency on the dimensional deviation was shown in Fig. 5. In both plots we can see that the frequencies were quasi-linear with the coupler dimensions. The frequencies decreased as the coupler dimensions increased which was expected by the theoretical analysis. When the first accelerating cavity was detuned, the frequency of the coupler structure with optimal dimensions was close to the expected value. The discrepancy was most likely attributed to the systematic error between the two-dimensional simulator SUPERFISH and the three-dimensional electromagnetic field code. We also presented the relationship between the coupling coefficient and the iris aperture, as shown in Fig. 6. The coupling coefficient  $\beta$  was calculated by [7]

$$\beta = \frac{1}{\frac{k}{2}\omega_{\pi/2}\sin\theta_0} \frac{\tan\frac{\Delta\phi_1}{2}\tan\frac{\Delta\phi_2}{2}(\omega_1^2 - \omega_2^2)}{\tan\frac{\Delta\phi_2}{2}\omega_1 - \tan\frac{\Delta\phi_1}{2}\omega_2}, \quad (6)$$

where  $\theta_0$  was the operating mode of the accelerator,  $\Delta\phi_1$  and  $\Delta\phi_2$  were the phase differences of the reflection coefficient measured for the two frequencies,  $\omega_1$  and  $\omega_2$ , respectively. Coupling between the rectangular waveguide and the accelerating structure was quite good when the optimal value was achieved. Thus the frequency and the coupling coefficient calculation results fitted the Kyhl's method simulation

results well. Furthermore, Fig. 5 and Fig. 6 could give tolerances of the coupler cell. It could be seen from Fig. 5 that 0.05 mm deviation in  $b$  or 0.5 mm deviation in  $w$  produced almost 2 MHz frequency shift. This meant that the frequency was much more sensitive to the coupler diameter than to the iris aperture. Fig. 6 shows the coupling coefficient changed by about  $\pm 0.03$  when  $w$  had 0.2 mm deviation. The tolerances were required after fabrication.

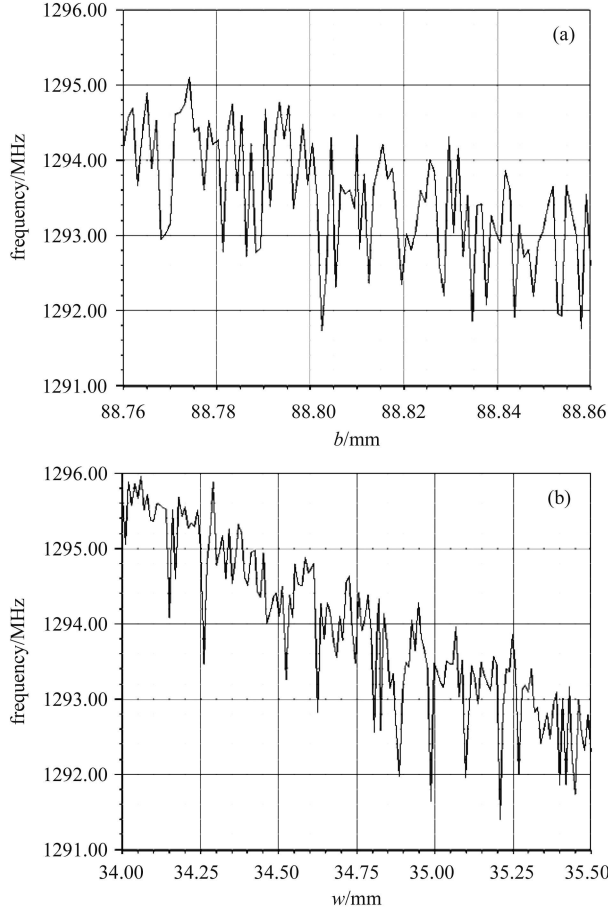


Fig. 5. The dependence of resonant frequency on coupler dimensions (a)  $b$ , (b)  $w$  when the first accelerating cavity is detuned with the plunger.

## 5 Comparison with experiment

The L-band linac coupler was brazed to the accelerating cavities and the whole accelerating struc-

ture was cold-tested and hot-tested. The experimental results were very close to the numerical simulation results. The error of  $w$  was  $\Delta w = w_{\text{sim}} - w_{\text{exp}} = -0.07$  mm, namely the error of the iris aperture was  $-0.14$  mm. This was encouraging because it meant that the proposed design was achieved.

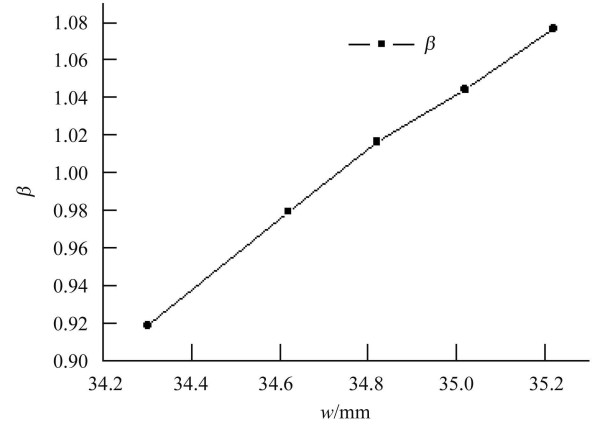


Fig. 6. The dependence of coupling coefficient on iris aperture.

## 6 Conclusion

A coupler was designed, constructed and tested for an L-band linac. The linac was used for industrial irradiation and completed a cold-test and hot-test. Numerical simulation based on the Kyhl's method was employed to find the optimal parameters of the coupler. Further numerical simulation including the frequency and the coupling coefficient calculation were also investigated. The results fitted the Kyhl's simulation results well and gave the coupler tolerances. The coupler was fabricated according to the numerical simulation results. Good agreement was found between numerical simulation results and experimental results. This work demonstrates that the numerical simulation is very useful in coupler design, tuning and matching.

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