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Design and simulation of a C-band SLED with mode converter

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Abstract: The transient response analysis of the SLED based on the equivalent circuit is described. Then, a C-band SLED using $TE_{0,1,15}$ mode cylindrical cavity with TE_{10}-TE_{01} mode converter has been designed. According to the main RF parameters of the accelerator, the coupling coefficient is optimized to obtain the maximum multiplication factor. The key components of the pulse compressor include a 3 dB directional coupler, a TE_{10}-TE_{01}mode converter, and a cylindrical cavity, which are simulated and optimized using 3D electromagnetic field simulation software. In addition, the function defining the relation between the coupling factor and aperture size is derived by a mathematical fitting method.

Key words: pulse compressor, energy multiplication factor, mode converter, 3 dB directional coupler, coupling coefficient

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1 Introduction

An RF pulse compressor, which is a device to convert a long and low energy pulse to a short and high energy one, is an important part of the RF system for a high energy electron linac. It can save huge amounts of investment and improve the reliability of the accelerator. Therefore, it has been used widely in high energy linear accelerators around the world. In the coupled cavity pulse compressor, the cylindrical cavity using $TE_{0,1,15}$ mode was adopted [1]. This paper presents a C-band (5712 MHz) SLED (SLAC Energy Doubler) using $TE_{0,1,15}$ mode cylindrical cavity with a TE_{10}-TE_{01} mode converter. The Q factor is about 190000 and the maximum energy multiplication factor can reach 1.97, analytically.

2 General theory

The SLED is composed of two identical high Q factor cavities attached to a 3 dB coupler, as shown in Fig. 1.

The basic principle of the SLED can be expressed as follows [2]. The high power of a klystron is equally divided by 3 dB directional coupler to feed the two cavities. Then, the field in the cavities is built up and an increasing amplitude wave is radiated from the coupling apertures of each cavity. In addition to the emitted wave, there is another wave reflected from the waveguide-cavity coupling interface, whose amplitude is almost equal to the incident wave's but whose phase is opposite to the incident and emitted wave's. The emitted waves and reflected waves of the two cavities are combined at the accelerator port of a 3 dB directional coupler and they cancel at the input port, respectively. Therefore, the total output wave of the SLED is the sum of the two combined waves. When the remaining length of the input pulse is equal to the filling time of the accelerating structure, the phase of the input pulse is reversed 180° by a phase shifter. At this moment, the combined emitted wave and the combined reflected wave add in phase since the phase of the emitted wave cannot change instantaneously. The amplitude of the total wave increases twice the amplitude of the reflected wave. Afterwards, the output wave decreases rapidly as a result of decreasing stored energy and the opposite charge-up of the cavities.

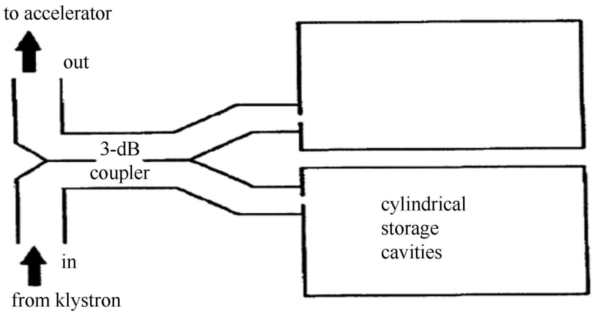

Fig. 1. The SLED schematic diagram.

The equivalent circuit of a cavity-waveguide coupling system is shown in Fig. 2(a). The coupler and cavity are represented by a transformer and a parallel resonant circuit, respectively. The circuit in Fig. 2(a) can be converted to that in Fig. 2(b), where $R = R'/n^2$, $C{=}C'/n^2$, $L{=}n^2L'$.

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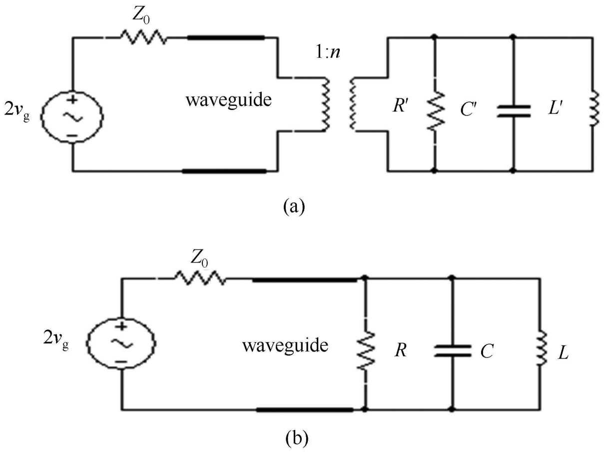

Fig. 2. The equivalent circuit of a cavity-waveguide coupling system.

The characteristic impedance Z_0 for a waveguide can be chosen arbitrarily, which is usually normalized to unity [3]. Then, the general second order differential equation can be derived as follows:

$$\frac{\mathrm{d}^2 v}{\mathrm{d}t^2}+\frac{w_0(1+\beta)}{Q_0}\frac{\mathrm{d}v}{\mathrm{d}t}+w_0^2 v=\frac{2w_0\beta}{Q_0}\frac{\mathrm{d}v_{\mathrm{g}}}{\mathrm{d}t}, \tag{1}$$

where β is the coupling coefficient, Q_0 is the unloaded quality factor, and w_0 is the cavity resonant frequency. Assuming $v(t)=V(t)\mathrm{e}^{\mathrm{j}wt}$, Eq. (1) can be expressed as:

$$\begin{aligned}&\frac{\mathrm{d}^2 V}{\mathrm{d}t^2}+\left(\mathrm{j}2w+\frac{w_0(1+\beta)}{Q_0}\right)\frac{\mathrm{d}V}{\mathrm{d}t}\\&+\left(\frac{\mathrm{j}ww_0(1+\beta)}{Q_0}-w^2+w_0^2\right)V\\&=\frac{2w_0\beta}{Q_0}\frac{\mathrm{d}V_{\mathrm{g}}}{\mathrm{d}t}+\frac{\mathrm{j}2ww_0\beta}{Q_0}V_{\mathrm{g}}.\end{aligned} \tag{2}$$

If the amplitude of the source varies smoothly besides a high Q-value of the cavity, then Eq. (2) can be transformed into Eq. (3).

$$\tau\frac{\mathrm{d}V}{\mathrm{d}t}+V=\alpha V_{\mathrm{g}}, \tag{3}$$

where

$$\tau=\frac{2Q_0}{(1+\beta)w_0},\quad \alpha=\frac{2\beta}{1+\beta}.$$

According to the transmission line theory, the normalized reflected wave can be expressed as [4]:

$$V_{\mathrm{r}}=\frac{1}{2}(V-i)=\frac{1}{2}[V-(2V_{\mathrm{g}}-V)]=V-V_{\mathrm{g}}. \tag{4}$$

Then, the transient response equation of SLED is as follows:

$$\tau\frac{\mathrm{d}V_{\mathrm{r}}}{\mathrm{d}t}+V_{\mathrm{r}}=\mathit{\Gamma} V_{\mathrm{g}}-\tau\frac{\mathrm{d}V_{\mathrm{g}}}{\mathrm{d}t}, \tag{5}$$

where $\mathit{\Gamma}=\frac{\beta-1}{\beta+1}$.

The energy multiplication factor is the most important characteristic parameter of the pulse compressor and it directly influences the beam energy gain. It can be expressed as:

$$M=\gamma\mathrm{e}^{-T_{\mathrm{a}}/T_{\mathrm{c}}}[1-(1-g)^{1+v}][g(1+v)]^{-1}-\alpha+1, \tag{6}$$

where T_{c} is the filling time of the cavity, T_{a} is the filling time of the accelerating structure, and g is the gradient of group velocity variation along the accelerating structure, $v=T_{\mathrm{a}}/T_{\mathrm{c}}[\ln(1-g)]^{-1}$, $\gamma=\alpha(2-\mathrm{e}^{-t/T_{\mathrm{c}}})$.

Figure 3 shows the relation between coupling coefficient β and energy multiplication factor M for $\mathrm{TE}_{0,1,15}$ and $\mathrm{TE}_{0,3,8}$ SLED, which indicates that the higher the unloaded Q, the greater the energy gain will be after the coupling coefficient is optimized. The RF parameters of $\mathrm{TE}_{0,1,15}$ and $\mathrm{TE}_{0,3,8}$ SLED are shown in Table 1. Fig. 4 shows the input and output waveforms of the C-band SLED using $\mathrm{TE}_{0,1,15}$ mode cylindrical cavity.

Table 1. The RF parameters of $\mathrm{TE}_{0,1,15}$ and $\mathrm{TE}_{0,3,8}$ SLED.

operating mode	$\mathrm{TE}_{0,1,15}$	$\mathrm{TE}_{0,3,8}$
frequency/MHz	5712	5712
Q	⩾180000	⩾130000
T_{a}/μs	0.3	0.3
g	0.6	0.6
pulse width/μs	2	2
coupling coefficient	10.32	7.5
M	1.97	1.92

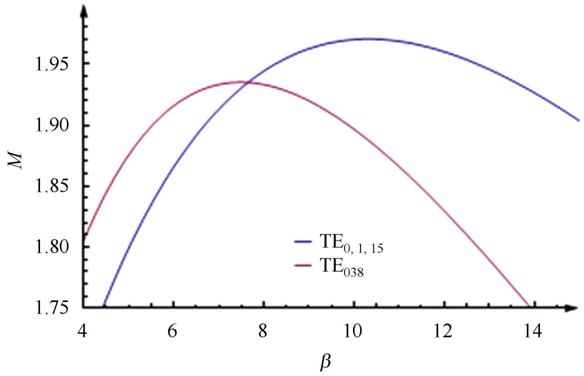

Fig. 3. The relation between coupling coefficient and energy multiplication factor.

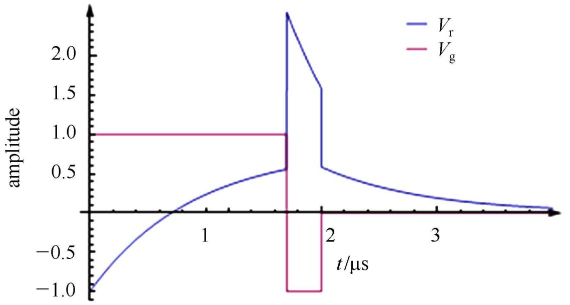

Fig. 4. The input and output waveforms of C band SLED.

3 Simulation results

The key components of the pulse compressor (such as 3 dB directional coupler, mode converter, and cylindrical cavity with mode converter) are simulated and optimized by HFSS and CST.

3.1 TE_{10}-TE_{01} mode converter [5]

The $TM_{1,1,15}$ mode is degenerate with the $TE_{0,1,15}$ mode, which will seriously affect the performance of the cylindrical cavity, so it must be suppressed. According to coupling theory, only the cavity mode, whose electromagnetic field is consistent to the radiation field of the coupler, can be exited. Therefore, the mode converter, translating the rectangular waveguide TE_{10} mode to the circular waveguide TE_{01} mode, is used to suppress the $TM_{1,1,15}$ mode without cutting a groove in one end-plate of the cylindrical cavity. Fig. 5 shows the electric field patterns of a TE_{10}-TE_{01} mode converter. Fig. 6 shows the input reflection and transmission efficiency. At the frequency of 5712 MHz, the input reflection and transmission efficiency are −74.76 dB and 99.35%, respectively.

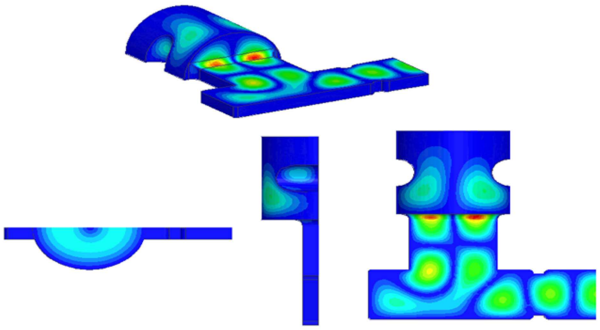

Fig. 5. The electric field patterns of the TE_{10}-TE_{01} mode converter.

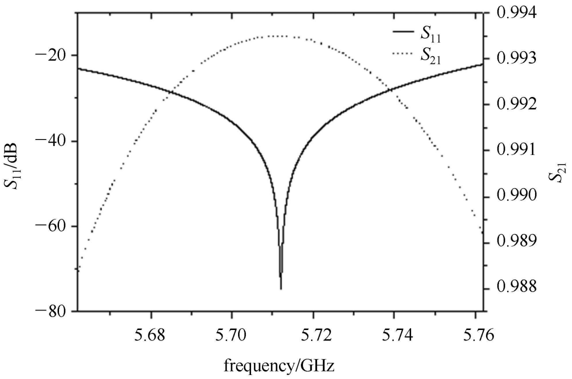

Fig. 6. The input reflection and transmission efficiency of the mode converter.

3.2 The 3 dB directional coupler [6]

The 3 dB directional coupler is an important part of the RF pulse compressor and it plays the role of power distribution and combination. The characteristic parameters, especially the amplitude and phase balance, will influence the output waveform of the pulse compressor [7]. Therefore, it desires a high balance and good impedance match. Fig. 7 and Fig. 8 show the electric and magnetic fields of the 3 dB directional coupler. Fig. 9 shows the Poynting vector. Fig. 10 shows the variation of the characteristic parameters with frequency. The performance of the 3 dB directional coupler at the operating frequency of 5712 MHz is as follows: C=3.02 dB, I=55.44 dB, S_{11}=−54.83 dB, D=52.42 dB, B=−0.005 dB, where C is the coupling factor, I is the isolation, S_{11} is the reflection of input port when the other ports are terminated with matched loads, D is the directivity, and B is the balance.

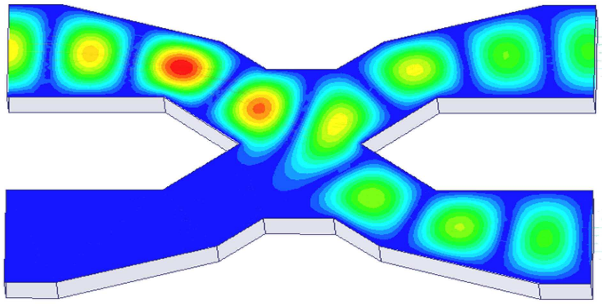

Fig. 7. The electric field pattern of the 3 dB directional coupler.

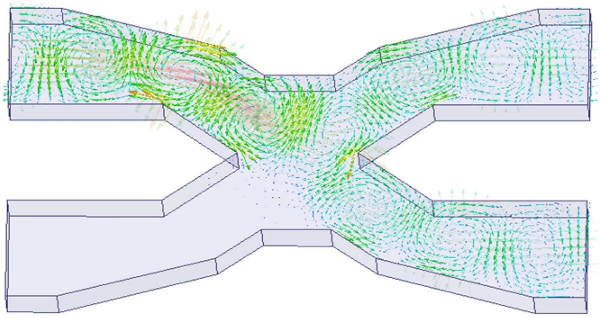

Fig. 8. The magnetic field pattern of the 3 dB directional coupler.

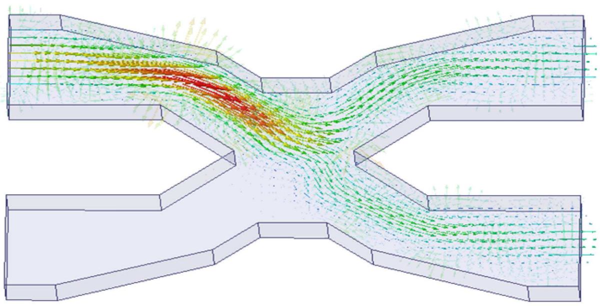

Fig. 9. The Poynting vector.

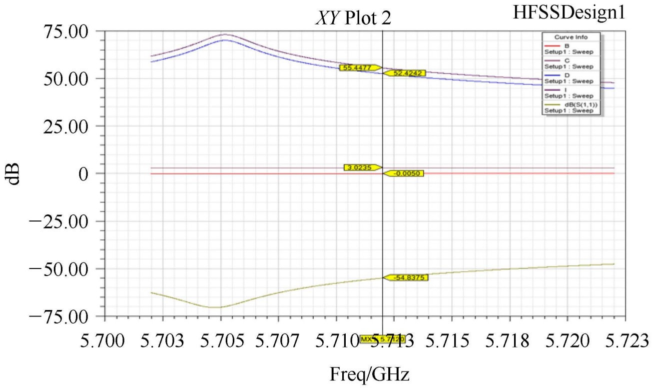

Fig. 10. Variation of the characteristic parameters with frequency.

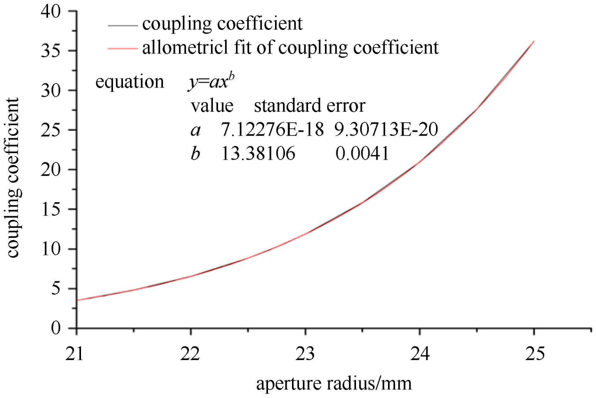

Fig. 11. The relation between β and r.

3.3 Coupling coefficient and cavity mode

The previous theoretical analysis indicate that the optimal coupling factor is 10.32. The coupling coefficient is determined by the aperture size. The relation between the coupling coefficient and aperture size is obtained using the parametric sweep provided by HFSS. The function between the coupling coefficient and aperture size can be expressed as follows:

$$\beta = 7.12\times10^{-18}r^{13.38}, \tag{7}$$

$$\beta = 2.56+29.38\mathrm{e}^{-0.224h}, \tag{8}$$

where r is the aperture radius and h is the aperture height. Fig. 11 and Fig. 12 show the relation between the coupling factor and the aperture size. The electromagnetic field patterns of the RF pulse compressor are simulated by CST, as shown in Fig. 13 and Fig. 14, which indicate that the operating mode is $\mathrm{TE}_{0,1,15}$. The relation between the coupling factor and the frequency is shown in Fig. 15, which indicates that the coupling factor is 10.32 at a resonant frequency of 5711.67 MHz. The coupling holes are usually chamfered in order to reduce the maximum electric field strength at the coupling apertures to prevent breakdown. The chafer radius is 2.5 mm. Then, the diameter and height of coupling aperture are 45.5 mm and 6 mm, respectively. The diameter and height of the cylindrical cavity are 152.6 mm and 433.38 mm, respectively.

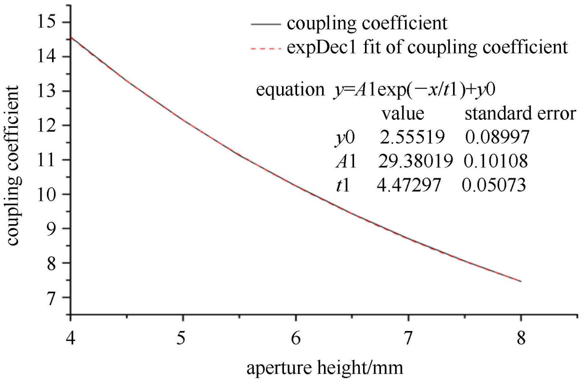

Fig. 12. The relation between β and h.

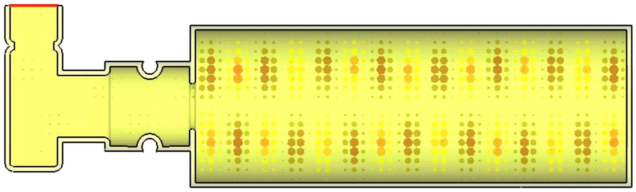

Fig. 13. The electric field of the SLED.

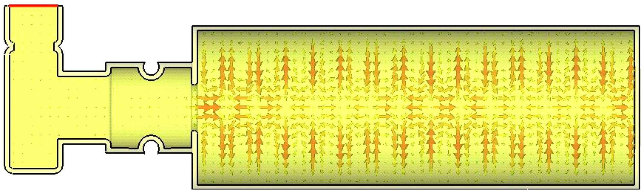

Fig. 14. The magnetic field of the SLED.

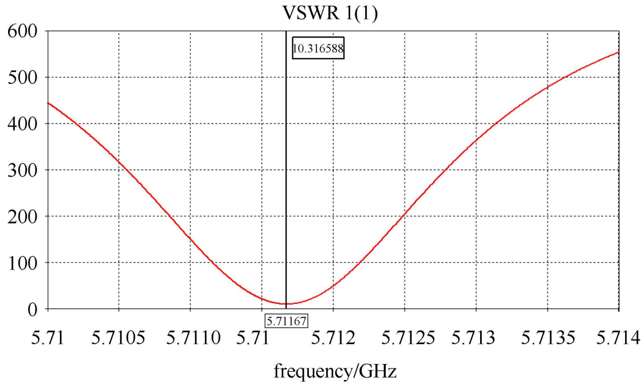

Fig. 15. The relation between coupling factor and frequency.

4 Conclusion

An S band SLED using $TE_{0,1,5}$ mode cylindrical cavity with cutting groove in one end plate has been used in BEPC and BEPCⅡ Linac at the Institute of High Energy Physics. Compared with the S-band accelerator, the C-band accelerator has the advantages of compactness and high accelerating gradient. So, the design frequency of many domestic and foreign accelerators (including SUDV-FEL) will be selected as C-band. As a key component of the RF system of a C-band accelerator, a lot research work on the C-band pulse compressor will be performed at our institute. A C-band SLED using $TE_{0,3,8}$ mode cylindrical cavity with dual side-wall coupling irises has been designed and fabricated, which will be used in the SPARC project of INFN. A C-band SLED using $TE_{0,1,15}$ mode cylindrical cavity with TE_{10}-TE_{01} mode converter can be used as an alternative scheme.

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