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# DESIGN AND SIMULATION OF THE COUPLING STRUCTURE FOR SINGLE RESONANT CAVITY BUNCH LENGTH MONITOR*

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*Abstract*

The measurement of the bunch length can better realize the monitoring of the beam, because the bunch length is one of the important longitudinal parameters of the beam. In this paper, a new single-cavity bunch length monitor is proposed, whose coupling structures consist of two kinds of filters. One is a low pass filter, the other is a band pass filter. The coaxial low-pass filter is used to couple out low-frequency signals, and the band-pass filter is used to couple higher-frequency signals. According to the beam characteristics of the National Synchrotron Radiation Laboratory (NSRL)based on the tunable infrared laser energy chemistry research large-scale experimental device (FELiChEM), we perform simulation in CST. The simulation results show that the monitor can measure the bunch length of the FELiChEM device very well, and the simulation measurement error is less than 2%.

## INTRODUCTION

FELiChEM is a large-scale experimental device built by the National Synchrotron Radiation Laboratory of the University of Science and Technology of China. The device has high pulse intensity, continuously adjustable wavelength, and the bunch length is on the order of ps [1]. The bunch length monitor based on the resonant cavity is a non-intercepting measurement and has little effect on beam. Therefore, this measurement method is suitable for measuring the bunch length of FELiChEM. When the beam moves from the beam tube through the resonant cavity, several characteristic modes will be excited in the cavity [2–4]. We extract the desired electromagnetic field, and then process it electronically to get the bunch length information. Compared to conventional double-cavity bunch length monitor, the single-cavity bunch length monitor more compact [5]. In this paper, we designed a single-cavity beam bunch length monitor and its coupling structure based on the beam current parameters of FELiChEM.

## THEORETICAL ANALYSIS

In the resonant cavity, for the Gaussian distributed beam, the Fourier expansion is performed, and the n-th harmonic amplitude is obtained [6] as shown in Eq. (1).

$$I_\text{n} = 2I_0 \exp\left(-\frac{n^2\omega_0^2\sigma_\tau^2}{2}\right) \tag{1}$$

In Eq. (1), $I_0$ denotes the beam fundamental wave amplitude. $\omega_0$ represents the fundamental angular frequency. $n$ denotes the harmonic order and $\sigma_\tau$ is the bunch length.

According to Eq. (1), we can get Eq. (2).

$$V_n = I_n \times Z_n = 2I_0 \exp\left(-\frac{n^2\omega_0^2\sigma_\tau^2}{2}\right) \times Z_n \tag{2}$$

Where $V_n$ represents the voltage value obtained by harmonic detection, and Zn is the shunt impedance of the cavity that can be obtained through actual measurement.

Let $\omega_1 = n_1\omega_0$, $\omega_2 = n_2\omega_0$, then

$$\begin{cases} V_1 = I_1 \times Z_1 = 2I_0 \exp\left(-\frac{\omega_1^2\sigma_\tau^2}{2}\right) \times Z_1 \\ V_2 = I_2 \times Z_2 = 2I_0 \exp\left(-\frac{\omega_2^2\sigma_\tau^2}{2}\right) \times Z_2 \end{cases} \tag{3}$$

where $\omega_1$ and $\omega_2$ are the angular frequencies of multiple harmonics, and $V_1$ and $V_2$ are the corresponding measured harmonic voltage values respectively.

The above term in Eq. (3) is divided by the following term to get Eq. (4).

$$\frac{V_1}{V_2} = \frac{Z_1}{Z_2} \exp\left[\frac{\left(\omega_2^2 - \omega_1^2\right)\sigma_\tau^2}{2}\right] \tag{4}$$

Let $K = \frac{Z_2}{Z_1}$, which can be obtained by actual measurement, then

$$\exp\left[\frac{\left(\omega_2^2 - \omega_1^2\right)\sigma_\tau^2}{2}\right] = K\frac{V_1}{V_2} \tag{5}$$

$$\sigma_\tau = \sqrt{\frac{2}{\left(\omega_2^2 - \omega_1^2\right)} \ln\left(K\frac{V_1}{V_2}\right)} \tag{6}$$

It can be seen from Eq. (6) that is necessary to measure the harmonic voltage values of two different frequency modes to obtain the bunch length.

The beam current parameters of FELiChEM are shown in Table 1. According to Table 1, the designed single-cylindrical resonant cavity needs to resonantly output an electromagnetic field with a multiple frequency mode of 0.476 GHz. Equation (7) represents the resonant frequency formulas of cylindrical resonators [7].

$$\begin{cases} f = \frac{c}{2}\sqrt{\left(\frac{p}{l}\right)^2 + \left(\frac{v_{nm}}{\pi r}\right)^2}, & (TM) \\ f = \frac{c}{2}\sqrt{\left(\frac{p}{l}\right)^2 + \left(\frac{\mu_{mm}}{\pi r}\right)^2}, & (TE) \end{cases} \tag{7}$$

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Where $\upsilon_{nm}$ is the root of the Bessel function and $\mu_{nm}$ is the root of the Neumann function. $r$ denotes the radius of the cylindrical cavity.

Table 1: Electron Beam Parameters of FELiChEM

| Parameter | Specification |
|---|---|
| Energy | 60 MeV |
| Energy spread | <240 KeV |
| Bunch charge | 1.0 nC |
| Bunch length | 5 ps |
| Micro-pulse repetition rate | 0.476 GHz |

In an accelerator, charged particles passing through the center of the cavity will generate an electric field in the longitudinal direction, so it is usually desirable to establish a TM mode in the cavity. In order to make full use of microwave power, $TM_{010}$ mode is generally used [8]. According to Eq. (7), when the radius is same, the modes of two frequencies must be different to couple out two kinds of frequencies, so we choose the other mode as $TM_{030}$. The final mode and frequency are $TM_{010}$ mode resonating at 2.38 GHz, the 5th harmonic of 0.476 GHz, and the $TM_{030}$ mode which resonates at the 18th harmonic of 0.476 GHz at 8.568 GHz. After the mode and frequency are determined, the radius of the resonant cavity is also determined. By adjusting the structure of the single resonant cavity bunch length monitor, the required two modes can be coupled separately at the same time.

## MODEL CONSTRUCTION

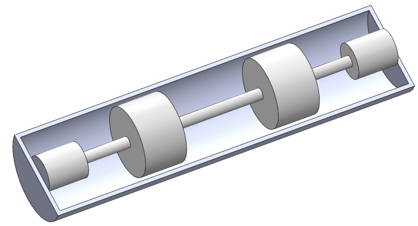
### *Coaxial Low-pass Filter Design*

In order to reduce the interference of other modes on the $TM_{010}$ mode, a coaxial line low-pass filter is designed. High-impedance lines are used to simulate series inductance, and low-impedance lines are used to simulate parallel capacitors. Several high- and low-impedance lines are alternately cascaded to form a low-pass filter [9].

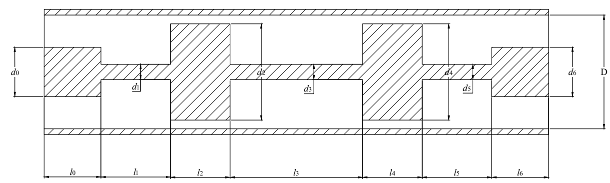
Let $l_0$=$l_6$=5 mm, $l_1$=$l_5$=6.124 mm, $l_2$=$l_4$=5.235 mm, and $l_3$=11.664 mm. $l$ is used to indicate the length, and the subscript indicates the position of the transmission line. The inner diameter of the outer conductor is taken as 10 mm. Look up the table (refer to [9] for details) to get the diameter of each section of transmission line $d_0$=$d_6$=4.343 mm, $d_1$=$d_3$=$d_5$=1.351 mm, $d_2$=$d_4$=8.464 mm. $d$ is used to indicate the diameter, and the subscript indicates the position of the transmission line.

The structure diagram of the filter is shown in Fig. 1. Figure 1(a) is a three-dimensional model diagram, and Fig. 1(b) is a cross-sectional view thereof. In the CST Microwave Studio, the designed model is simulated, and the S parameters of the filter obtained by the simulation are shown in Fig. 2.

Figure 2 shows that the cut-off frequency of the filter obtained by simulation is about 2.62 GHz, which is between $TM_{010}$ mode and $TM_{110}$ mode. By using this filter, the



(a) 3D model of low pass filter



(b) cutaway view of low pass filter

Figure 1: Structure of low pass filter.

interference of other modes on the $TM_{010}$ mode can be removed, and a single mode can be extracted.

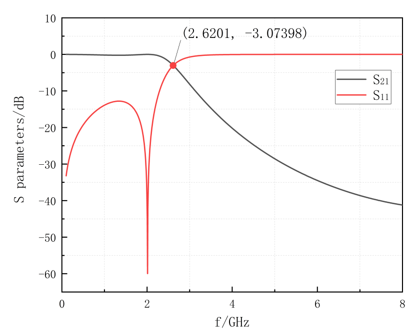



Figure 2: S parameters of low pass filter.

### *Diaphragm Loaded Waveguide Bandpass Filter Design*

From the previous analysis, it can be seen that the measurement of the bunch length requires the simultaneous coupling of two signals of different frequency modes. In order to better couple out the $TM_{030}$ mode, it is proposed to use a diaphragm-loaded waveguide bandpass filter as a coupler for the $TM_{030}$ mode. In high-frequency communications, bandpass filters composed of rectangular waveguides are very common [10] and the diaphragm-loaded waveguide bandpass filter is a typical application. The waveguide section is used as a series resonator, and the parallel inductance formed by the diaphragm is used as the coupling structure between the resonators [11]. The designed filter should be able to conduct and output signal at 8.568 GHz, so the rectangular waveguide model R84 is selected whose main mode frequency range is from 6.57 GHz to 9.99 GHz, and size is a=28.499 mm and b=12.624 mm [12].

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The three-dimensional structure of the waveguide band-pass filter is shown in Figs 3 and 4 is its cross-sectional view. The filter structure is adjusted according to the simulation results in the CST studio, and the final optimized size is shown in Table 2.

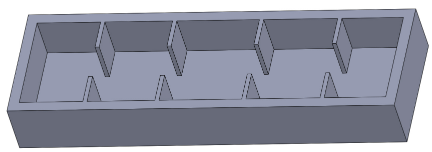

Figure 3: 3D model of band pass filter.

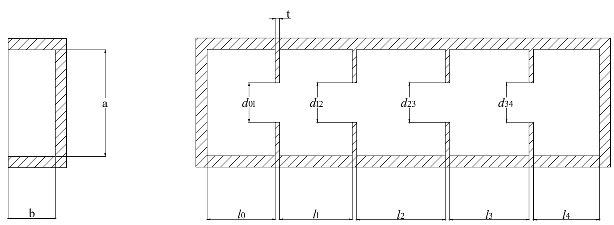


Figure 4: Cutaway view of band pass filter.

Table 2: Parameters of Band Pass Filter

| Parameters | Value/mm |
|---|---|
| $d_{01}$ | 10.54463 |
| $d_{12}$ | 6.26978 |
| $l_0$ | 104.85 |
| $l_1$ | 21.19 |
| $l_2$ | 22.47 |
| t | 1.2 |

The S parameters of the band-pass filter obtained by simulation in CST Microwave Studio are shown in Fig. 5. $S_{11}$ is the return loss of the filter and $S_{21}$ is the insertion loss of the filter. It can be seen from Fig. 5 that the passband bandwidth of the filter is narrow and the return loss is less than -3 dB at 8.568 GHz frequency, which meets the design requirements.

### *Single Resonant Cavity Bunch Length Monitor Design*

When the mode and frequency of the resonant cavity are determined, the radius of the resonant cavity can be calculated by using Eq. (8).

$$r = \frac{c v_{mn}}{2\pi f} \tag{8}$$

Where $r$ denotes the radius of the resonant cavity. c is the speed of light. $\mu_{nm}$ represents the root of the Bessel function, and $f$ is the frequency.

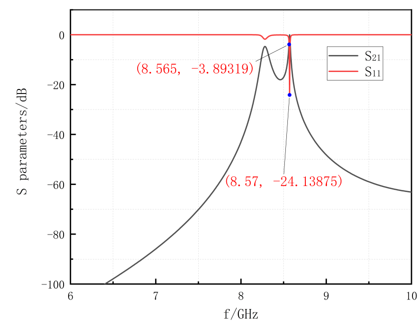


Figure 5: S parameters of band pass filter.

The structure of the finally optimized design of the bunch length monitor is shown in Fig. 6. The center of cylindrical cavity coincides with the center of the beam pipe. The radius of cylindrical cavity is 51.8 mm and the radius of the beam pipe is 17.5 mm. The size in the longitudinal direction has no obvious effect on the frequency of the coupling mode, so the longitudinal length of the resonant cavity is taken as 12 mm. Similarly, the longitudinal length of the beam pipe is taken as 110 mm. The size of the coupling hole is 10.5 mm×0.4 mm×12 mm. The center of the coaxial low-pass filter is offset by 24 mm from the center of the beam pipe and installed symmetrically. At the same time, the waveguide filters are installed symmetrically on the upper and lower coupling holes of the single cylindrical resonant cavity.

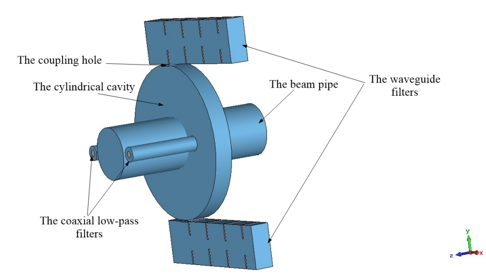


Figure 6: Structure of bunch length monitor.

## SIMULATION

In the CST particle studio, the simulated electron beam is set according to the parameters in Table 1, and the bunch length is set to 5 ps. The simulated electric field mode excited by the monitor is shown in Fig. 7. The field distribution of $TM_{010}$ mode is shown in Fig. 7(a), and the field distribution of $TM_{030}$ mode is shown in Fig. 7(b). The output signal of the port is shown in Fig. 8. Figure 8(a) shows the signal that output from the low-pass filter port, and Fig. 8(b) shows the signal which output from the band-pass filter port.

It can be seen from Fig. 8 that the use of filter to couple the signal can well remove the interference of other modes signals to the desired signal. In the CST particle studio,

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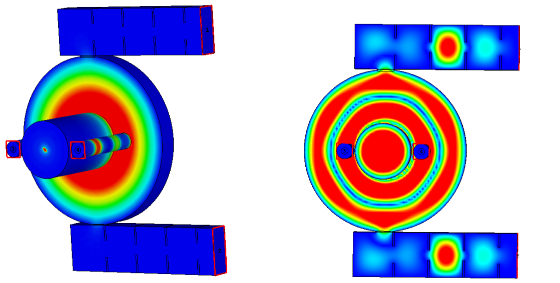
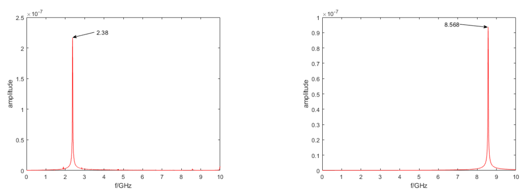


(a) electric field distribution of $TM_{010}$ mode (b) electric field distribution of $TM_{030}$ mode

Figure 7: Electric field distribution of coupling mode.



(a) output signal of low pass filter (b) output signal of band pass filter

Figure 8: Port output signal.

the beam is loaded and the beam length is changed multiple times. The simulation results are shown in Table 3. $V_{TM010}$ represents the spectral amplitude of $TM_{010}$ mode, and $V_{TM030}$ represents the spectral amplitude of $TM_{030}$ mode.

Table 3: Parameters of Band Pass Filter

| Bunch length/(ps) | $\frac{V_{TM010}}{V_{TM030}}$ | Measurements of bunch length/(ps) | Relative error/(%) |
|---|---|---|---|
| 2 | 2.251 | 2.03 | 1.50 |
| 3 | 2.266 | 2.99 | 0.33 |
| 4 | 2.287 | 3.97 | 0.75 |
| 5 | 2.313 | 4.91 | 1.80 |
| 10 | 2.557 | 9.93 | 0.70 |
| 15 | 3.024 | 14.94 | 0.40 |
| 20 | 3.828 | 19.97 | 0.15 |

## CONCLUSION

This paper combines the filters with a single cavity based on the bunch length measurement theory and the filter design principle. By simulation with CST Microwave Studio and Particle Studio, bunch length monitor is designed that can couple output $TM_{010}$ and $TM_{030}$ modes at the same time. The simulation results show that the measurement error of the single-cavity bunch length monitor from 2 to 20 ps is less than 2%, which meet the measurement requirements of FELiChEM bunch length. Compared with a single cavity directly coupled with a probe, the signal interference of the output coupled with the filter is significantly reduced.

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