DESIGN AND SIMULATION OF HIGH ORDER MODE CAVITY BUNCH LENGTH MONITOR FOR INFRARED FREE ELECTRON LASER*

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Abstract

A bunch length monitor using resonant cavity has been designed for the NSRL Infrared Free Electron Laser (IR-FEL) facility. To avoid the restriction of working frequency caused by the beam pipe radius, the high order modes of the harmonic cavities are utilized. The position and orientation of coaxial probes are optimized to avoid interference modes which come from the cavity and beam tube according to the analysis formula of electromagnetic field distribution. Based on the parameters of IR-FEL, a simulation is performed to verify the feasibility of the bunch length monitor. The simulation result shows that the design meets the requirements of IR-FEL, and the resolution can be better than 50 fs.

INTRODUCTION

Bunch length is one of the main characteristics of charged particle beam in accelerator. With the development of technology, many bunch length measurement devices have been invented. Bunch length monitor based on cavities has great potential especially for high quality beam sources because of many advantages such as simple structure, wide application rage, and high signal noise ratio. In this paper, the design of a cavity bunch length monitor for the National Synchrotron Radiation Laboratory Infrared Free Electron Laser (IR-FEL) is presented. The beam parameters of IR-FEL are shown in Table 1.

Table 1: Electron Beam Parameters of IR-FEL

Parameter	Value
Beam energy	30~50 MeV
Bunch charge	1 nC
Bunch length, rms	4.5 ps
Bunch repetition rate	476 MHz
Beam pipe radius	17.5 mm
Macro pulse length	13 µs
Macro pulse repetition rate	10 Hz

THEORETICAL BASIS

While passing through the cavity, the bunch will excite different eigenmodes such as TM0n0, which related to bunch length. The electric fields of eigenmodes can be coupled out by the feedthrough with high signal to noise ratio, wide dynamic range and large amplitude. Bunch length can be calculated according to the signals.

Assume a Gaussian distribution in beam direction with beam size σ_τ, RF field is established when the bunch passes through a cavity. The power of the RF field can be expressed as [1]

$$P = [I_0 \exp(-\frac{\omega^2 \sigma_\tau^2}{2})]^2 \bullet R \tag{1}$$

Where I_0 is beam current, ω is resonance frequency of the cavity, and R is cavity shunt impedance. Both I_0 and σ_τ are unknowns while P, R and ω are known quantity measured in actual measurements. So we need two cavities at least and the bunch length can be calculated by solving equation

$$\begin{cases} P_1 = [I_0 \exp(-\frac{\omega_1^2 \sigma_\tau^2}{2})]^2 \bullet R_1 \\ P_2 = [I_0 \exp(-\frac{\omega_2^2 \sigma_\tau^2}{2})]^2 \bullet R_2 \end{cases} \tag{2}$$

It follows that the bunch length can be described as

$$\sigma_\tau = \sqrt{\frac{\ln P_1 R_2 - \ln P_2 R_1}{\omega_2^2 - \omega_1^2}} \tag{3}$$

Further derivation leads to the expression of the cavity bunch length monitor theoretical resolution

$$\Delta\sigma_{\tau r} = \frac{1}{(\omega_2^2 - \omega_1^2) \bullet \sigma_\tau} \bullet (10^{-SNR/20}) \tag{4}$$

Where SNR stands for signal to noise ratio.

In traditional cavity bunch length monitor, both the two cavities' work modes are TM010 [2]. The disadvantage of this type is that the beam pipe radius restricts working frequency of the cavity. On the one hand, we prefer smaller radius of the cavity for higher working frequency, which means high resolution according to Eq. (4). On the other hand, cavity radius must be larger than beam pipe radius, or the device will not work. But it will no longer be a problem in our design, which is able to reach higher frequency with larger cavity radius, for higher order eigenmode TM020 is utilized. It means that this design

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overcome the difficulty of working frequency restriction caused by beam pipe radius and get higher resolution.

PHYSICAL DESIGN

For cylindrical cavity, the electric fields of TM0n0 modes have only an axial component. Radial distribution function of the field can be expressed as

$$E_z = E_0 \bullet J_0(\frac{v_0^n}{a} r) \qquad (5)$$

Where E_0 is a constant, J_0 is the m order Bessel function, and v_0^n is the n^{th} root of the zero order Bessel function.

The signal of electric fields will be extracted from the feedthrough to the post-processing circuit. The schematic diagram of a single cavity is shown in Fig.1.

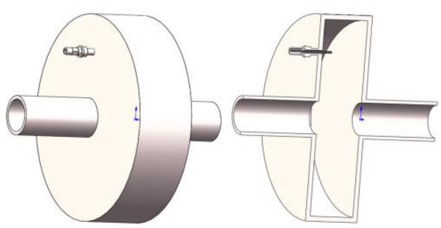

Figure 1: The schematic diagram of a single cavity.

The target frequencies of the two cavities are 0.952GHz and 6.188GHz, respectively, for TM010 mode and TM020 mode. The cavity with lower operating frequency is called the second harmonic cavity, while the other is named as the thirteenth harmonic cavity.

The size of the cavity is shown in Fig. 2 and Fig. 3. Eigenmode frequency is relevant to a_1, l_1, a_2, l_2. The relation between resonant frequency and cavity size can be defined as

$$f = \frac{c}{2} \bullet \sqrt{(\frac{v_m^n}{2\pi a})^2 + (\frac{p}{2l})^2} \qquad (6)$$

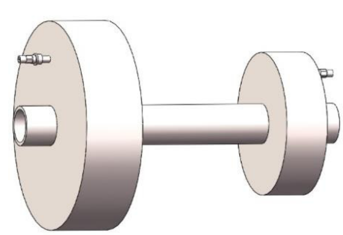

Figure 2: The schematic diagram of double cavity.

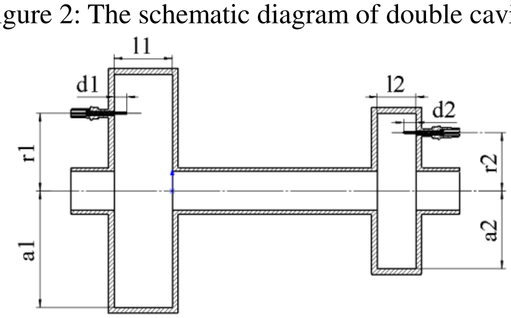

Figure 3: The size of cavity design.

Thus the radiuses of the second harmonic cavity and the thirteenth harmonic cavity, in theory, are 120.62 mm and 42.59 mm, respectively.

Other modes whose resonant frequencies are close to multiple of beam repetition frequency may be excited and they are regarded as interference modes. The modeleak effect is not negligible. Here is how to prevent this trouble. For the second harmonic cavity, TM040 mode whose resonant frequency is 4.67GHz and TM060 mode whose resonant frequency is 7.15GHz are closed to tenfold and fifteenfold beam repetition frequency, respectively. Proper r_1 has to be set to attenuate these modes. According to Eq. (5), the electric field intensity distribution curves of TM010 mode, TM040 mode and TM060 mode along the radial direction are given in Fig. 4. Thus it can be seen that the electric field intensity of TM010 mode reaches the maximal value, while that of TM040 mode and TM060 mode are almost zero when r_1 is equal to about 56 mm. As for the thirteenth harmonic cavity, TM070 mode whose resonant frequency is 23.78GHz may be perceived as interference mode. But the frequency of TM070 mode is so high that its signal has no effect on TM020 mode. As a result, the electric field intensity distribution of TM020 mode is only taken into account and its curve is given in Fig. 5. As can be seen from the Fig. 5, r_2 is preferably equal to about 29.5 mm.

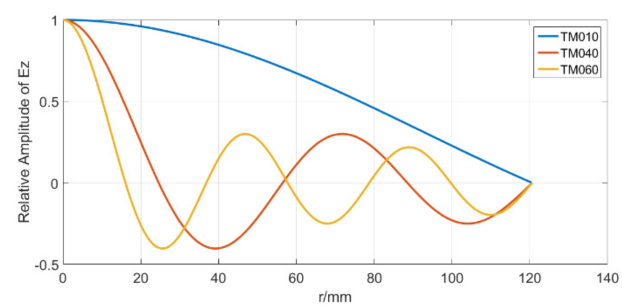

Figure 4: The electric field intensity distribution curves of TM010 mode, TM040 mode and TM060 mode along the radial direction in the second harmonic cavity.

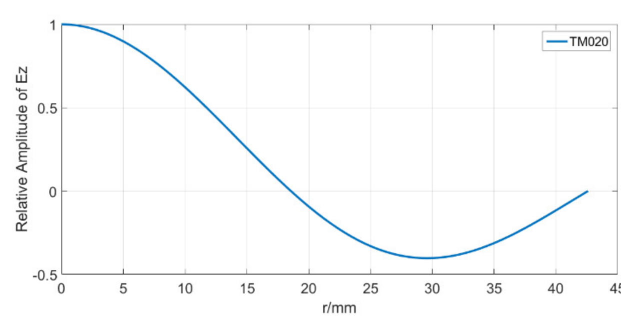

Figure 5: The electric field intensity distribution curves of TM020 mode along the radial direction in the thirteenth harmonic cavity.

The signal intensity also varies with the different depth of penetration d_1 or d_2, which can only be determined by simulation test.

The dimension parameters mentioned above are calculated theoretically. In practice, the field and frequency will be affected by beam pipe and coaxial probe and may be different from their theoretical value slightly. Hence we performed the simulation by using CST Microwave Studio. Finished size of the design is presented in Table 2.

Table 2: Optimized Size of the Design

Parameter	Value
a_1	121.01 mm
l_1	50.00 mm
r_1	56.00 mm
d_1	9.40 mm
a_2	44.10 mm
l_2	20.00 mm
r_2	27.80 mm
d_2	5.00 mm

SIMULATION AND BUNCH LENGTH MEASUREMENT

Q-value

The two cavities were modeled in CST Microwave Studio, and the simulation results are presented in Table 3.

In table 3, Q_0 is intrinsic quality factor, Q_{ext} is single port external quality factor and Q_{load} is loaded quality factor. For the CBLM, higher Q_0 is preferred since it means lower power Loss in the cavity. At the same time, we prefer lower Q_{ext} to get higher output signal voltage and signal to noise ratio [3]. From the form, we can see that our design can meet the requirements mentioned above.

Table 3: Simulation Results

Parameter	The Second Harmonic Cavity	The Thirteenth Harmonic Cavity
Q_0	16722.51	9207.44
Q_{ext}	6743.64	913.27
Q_{load}	4805.67	830.86
R	2580381	8229790

Bunch Length Measurement

According to the beam parameters in Table 1, the cavity bunch length monitor was loaded with virtual beam in CST Particle Studio. The output signals of the second harmonic cavity and the thirteenth harmonic cavity are shown in Fig. 6 and Fig. 7, respectively. For time domain signal, the ascent stage of amplitude means the beam is charging the cavity, and the balancing stage signifies that the field energy is replete in the cavity, while frequency domain signal reflects the different kinds of frequency involved in output signal. It is quite clear that the frequencies of the two output signals exact match the design objectives.

Taking the output power and shunt impedance obtained by simulating into Eq. 3, the simulation results of the bunch length is equal to 4.5486ps, whose relative error is less than 1.1%, which means that the simulation measurement provides a fairly high accuracy.

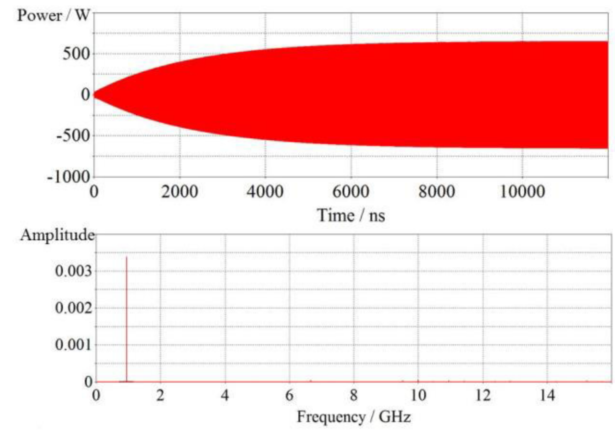

Figure 6: The output signals in time domain and in frequency domain of the second harmonic cavity.

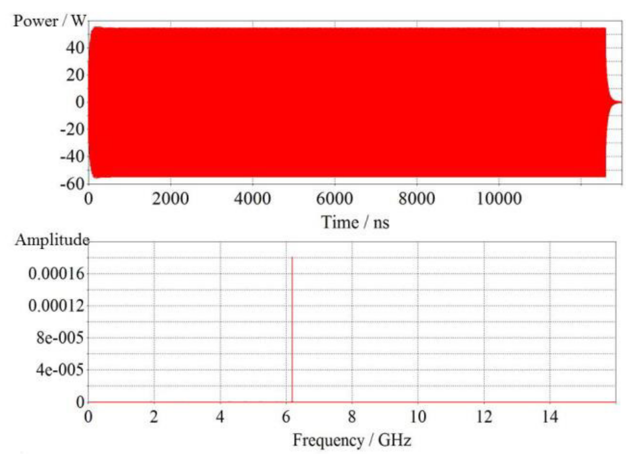

Figure 7: The output signals in time domain and in frequency domain of the thirteenth harmonic cavity.

CONCLUSION

In this paper, the design process of the bunch length monitor based on high order mode cavity is shown, and the simulation results agree with the real bunch length of IR-FEL extremely well. It is probed that high order eigenmode TM020 can also be used to measure bunch length. Furthermore, the limitation that working frequency and resolution are restricted by the radius of beam pipe will no longer be a problem in the high order mode cavity bunch length monitor.

REFERENCES

[1] J. Guo, Z. R. Zhou, Q. Luo, and B. G. Sun, "Design and simulation of TM020 cavity bunch length monitor", *High Power Laser and Particle Beams*, vol. 28, no. 9, p. 095104, Sep. 2016.

[2] Y. Y. Cui *et al.*, "Bunch length measurement in BEPCII linac by harmonic method", *High Power Laser and Particle Beams*, vol. 17, no. 12, pp. 1901-1904, Dec. 2015.

[3] J. H. Su *et al.* "Design and cold test of a rectangular cavity beam position monitor", *Chinese Physics C*, vol. 37, no. 1, p. 017002, Mar. 2012

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