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A STUDY ON THE IMPROVED CAVITY BUNCH LENGTH MONITOR FOR FEL*

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Abstract

Bunch length monitors based on cavities have great potential especially for future high quality beam sources because of many advantages such as simple structure, wide application rage, and high signal-to-noise ratio (SNR). The traditional way to measure bunch length needs two cavities at least. One is reference cavity, whose function is to get the beam intensity. The other one is defined as main cavity, which is used to calculate the bunch length. There are some drawbacks. To improve performance, the mode and the cavity shape are changed. At the same time, the position and orientation of coaxial probe are designed to avoid interference modes which come from the cavity and beam tube according to the analytic formula of the electromagnetic field distribution. A series simulation based on CST is performed to verify the feasibility, and the simulation results reveal that the improved monitor shows good performance in bunch length measurement.

INTRODUCTION

Bunch length is one of the main characteristics of charged particle beam in accelerator. There is growing interest in the generation, measurement and application of short electron bunches, so precise bunch length measurement methods are necessary for developing the future light sources. To measure the bunch length, many methods have been developed in the past decades. 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. What's more, the cavities with different modes show the ability of combined measurement of bunch length, beam intensity, position and quadrupole moment so that the whole diagnostic system is simplified and compact. In this paper, a series of studies about improved cavity bunch length monitors for the National Synchrotron Radiation Laboratory Infrared Free Electron Laser (FELiChEM) are presented. The beam parameters, used in the analytical calculation and simulation of this paper, are listed 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	2~5 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

Cavity bunch length monitor is usually composed of two cavities with different working frequencies. When a Gaussian bunch passed through the axis of the vacuum chamber, the symmetric TM0n0 modes could be excited in the cavities. The power of one mode can be written as [1].

$$\begin{cases} P_1 = [I_0 \exp(-\frac{\omega_1^2\sigma_\tau^2}{2})]^2 R_1 \\ P_2 = [I_0 \exp(-\frac{\omega_2^2\sigma_\tau^2}{2})]^2 R_2 \end{cases} \tag{1}$$

Where the subscripts stand for the cavities' serial number, σ_τ is the bunch length, I_0 is pulse current, ω is resonance frequency of the mode, and R is cavity shunt impedance. The σ_τ and I_0 are quantified by solving this two simultaneous power equations.

DESIGN IMPROVEMENTS

Design of the System

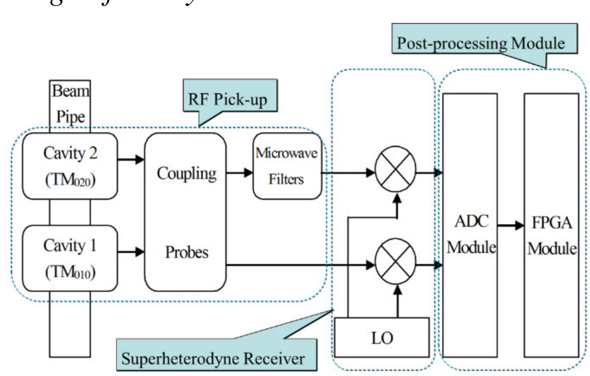

Figure 1: The schematic diagram of a single cavity.

The framework of the whole diagnostic system is shown in Fig. 1. The RF pick-up is composed of two cav-

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ities on the beam pipe and the coupling probes. The microwave filters are needed sometimes. In a general way, the frequencies of the output signals from the RF pick-up are very high. For this reason, the superheterodyne receiver that consists of is introduced in our design to achieve the down-conversion. High speed data acquisition system consists of high speed ADC, high density FPGA and high performance DSP chips is used as signal processing system and the sampling rate can be 1 Gsps.

Cavity Monitors with High Order Modes

Based on Eq. (1), further derivation leads to the expression of the cavity bunch length monitor theoretical resolution

$$\Delta\sigma_{\tau} = \frac{(10^{-SNR/10})}{4\pi^2(f_2^2 - f_1^2)\sigma_{\tau}} \qquad (2)$$

Where SNR stands for signal to noise ratio. From the Eq. (2), it can be seen that the resolution depends on the system SNR and the difference of the square of working frequencies. In traditional cavity bunch length monitor, both the two cavities resonate at TM010 mode [2]. Therefore, working frequency and resolution are restricted by the radius of the cavity and beam pipe. For this reason, the bunch length monitor based on high order mode cavity is proposed. The improved method is able to reach higher frequency with larger cavity radius, for higher order eigenmode TM020 is utilized [3]. It means that this design overcome the difficulty of working frequency restriction caused by beam pipe radius and get higher resolution [4].

The physical design of the improved device has been completed and the simulation measurement has provided a fairly high resolution. The two cavities are modeled in CST Microwave Studio, and the simulation results are presented in Table 2.

Table 2: Simulation Results

Bunch Length (ps)	Simulation Results (ps)	Resolution (when SNR = 70 dB) (ps)
5	5.068	0.0429
4.5	4.570	0.0476
4	4.074	0.0536
3.5	3.582	0.0612
3	3.088	0.0714
2.5	2.596	0.0857
2	2.102	0.1071

It can be seen that high order eigenmode TM020 can also be used to measure bunch length. The improved cavity monitor with high order modes achieves higher resolution than the traditional devices [1]. At the same time, the system is able to show a good performance when the SNR is greater than or equal to 70 dB.

Single Cavity Bunch Length Monitor

Traditional cavity bunch length monitor using two cavities would not only make the configuration complex but also take up too much space. In this section, the design and simulation of a bunch length monitor utilizing only one cavity are presented. Compare with the traditional way, the new method does not need reference cavity. Two eigenmodes of a rectangular cavity, TM310 mode and TM130 mode, are utilized to measure beam current and bunch length，so that the promoted monitor is simplified and compact. To control the working frequencies of the eigenmodes, the tuning screws are introduced in the cavity. Only when the modes' working frequencies are equal to the bunch harmonic frequencies, can the modes resonate at optimum performance. For this reason, we have the TM310 mode resonate at 2.856 GHz and the TM130 mode work at 7.616 GHz in practice. The two probes penetrated to the cavity are used to couple out the two modes' signals, respectively. The positions of the two probes are adjusted to avoid coupling of the other mode. The schematic of the device is shown in Fig. 2.

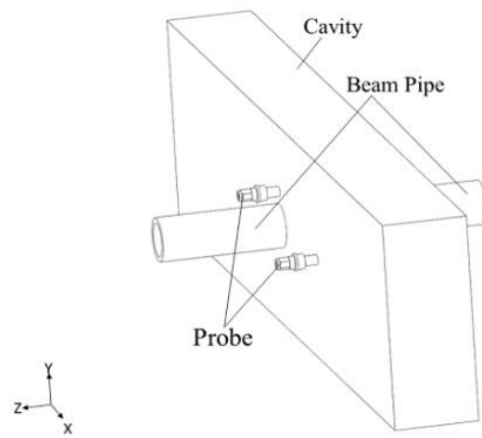

Figure 2: The schematic of the single cavity bunch length cavity.

The physical design of the single cavity bunch length monitor has been completed now [5]. The monitor is modeled in CST Microwave Studio, and the simulation results are presented in Table 3.

Table 3: Simulation Results

Bunch Length (ps)	Simulation Results of Single Cavity (ps)	Relative Error of Single Cavity (%)	Simulation Results of Traditional Double Cavity (ps)	Relative Error of Traditional Double Cavity (%)
5	5.707	1.403	5.068	1.360
4.5	4.572	1.603	4.570	1.556
4	4.075	1.871	4.074	1.841
3.5	3.579	2.245	3.582	2.354
3	3.084	2.806	3.088	2.931
2.5	2.594	3.741	2.596	3.821
2	2.098	4.882	2.102	5.112

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From the diagram it can be seen that the simulation measurement provides a fairly high accuracy. The single cavity monitor is even slightly better than the traditional double cavities monitor when the bunch length is short.

The Influence of Beam Position

As far as actual cavity is concerned, without regard to the electronics noise, the decisive factor affecting the resolution is beam position. When passing through the cavity with a position offset, the bunch will excite dipole modes such as TM110. These modes may make an impact on the output signals and reduce SNR. The output signals in time domain and in frequency domain are shown in Fig. 3 and Fig. 4, respectively. The amplitude deviation owing to the position offset is regarded as noise. Simulations based on the above description were required to evaluate the influence of beam offsets at different working frequencies and different working modes. The results are shown in Fig. 5 to Fig. 10.

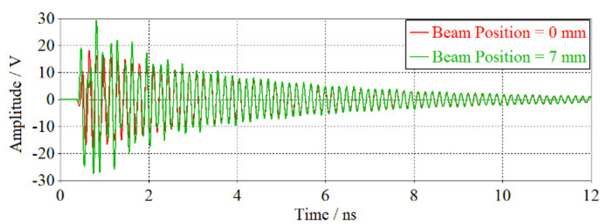

Figure 3: The output signal in time domain.

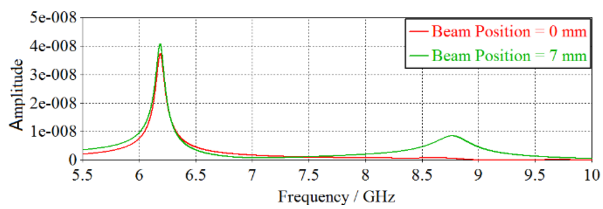

Figure 4: The output signal in frequency domain.

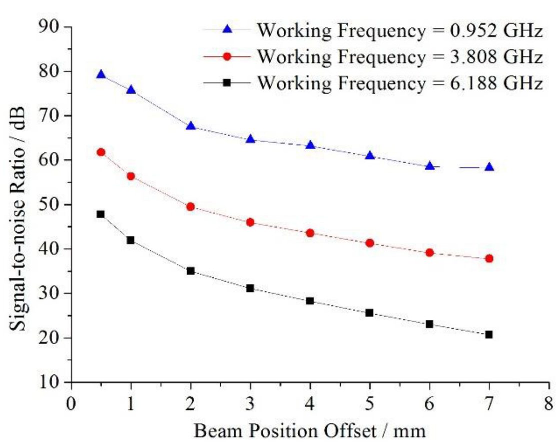

Figure 5: SNRs vary with beam position offsets.

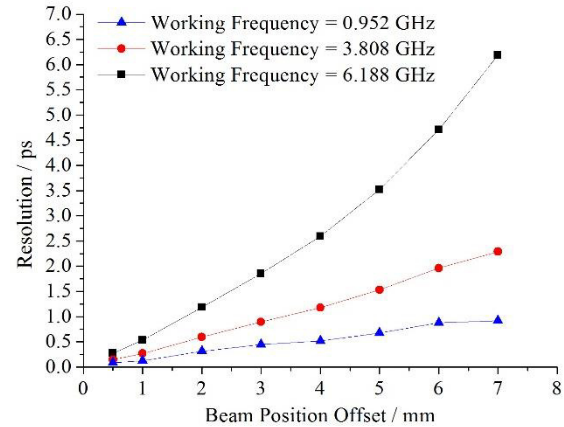

Figure 6: Resolutions vary with beam position offsets.

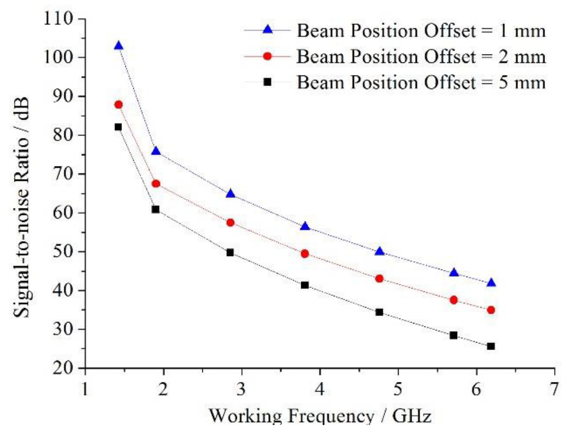

Figure 7: SNRs vary with working frequencies.

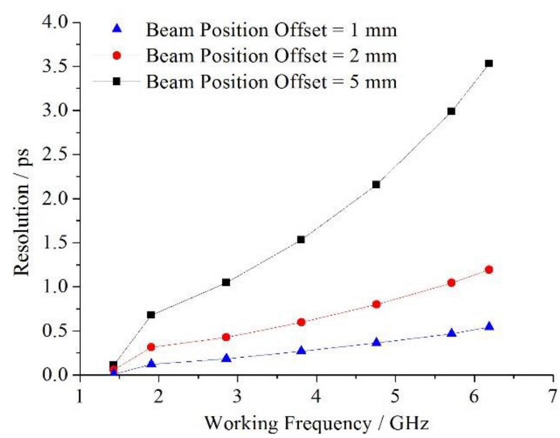

Figure 8: Resolutions vary with working frequencies.

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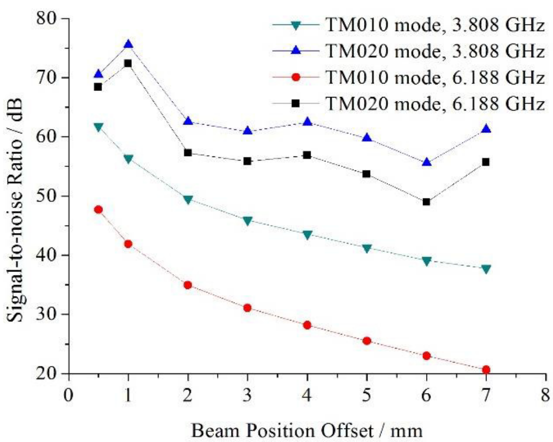

Figure 9: SNRs vary with beam position offsets.

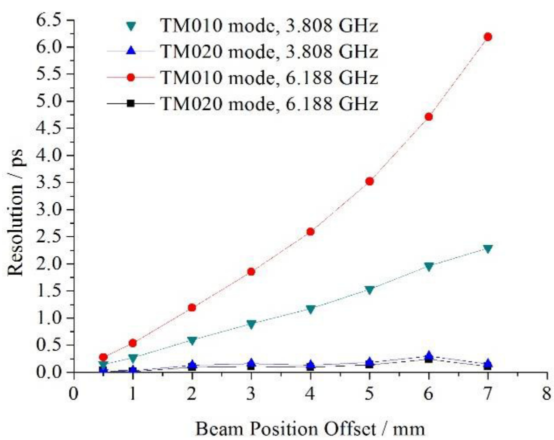

Figure 10: Resolutions vary with beam position offsets.

According to the graphs, it can be seen that the father away the beam sets from the axis of the cavity, the greater the deviation is. At the same time, beam offset will introduce greater noise when working frequency is higher. What's more, using TM020 mode is able to obtain high SNR and high resolution compared with the traditional cavity with TM010 mode.

CONCLUSION

In this paper, a series of studies about improved cavity bunch length monitors for the National Synchrotron Radiation Laboratory Infrared Free Electron Laser (FELiChEM) are presented. Firstly, according to the characteristics of FELiChEM, the framework of the whole diagnostic system is designed. After that, the relationship between resolution and SNR is deduced and the factors which make effect on the system SNR is analyzed. To remove the limitation that working frequency and resolution are restricted by the radius of beam pipe, the bunch length monitor based on high order mode cavity is proposed. And then, a kind of new method to measure bunch length of FEL with single cavity is presented. Finally, the laws of resolution change caused by some decisive factors such as beam position, working frequency and electromagnetic mode are analysed, which offers the theoretical support for the design and application of bunch length monitor in the future light sources.

REFERENCES

[1] 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.

[2] H. H. Braun and C. Martinez, in *Proc. EPAC'1998*, pp. 1559-1561.

[3] 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.

[4] Q. Wang *et al.*, in *Proc. IPAC'17*, pp. 309-311.

[5] Q. Wang, Q. Luo, and B. G. Sun, "Design and simulation of a bunch length monitor for linac based on single cavity", *High Power Laser and Particle Beams*, vol. 29, no. 11, p. 115101, Nov. 2017.