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A STUDY ON THE RESOLUTION OF BUNCH LENGTH MEASUREMENT SYSTEM USING HARMONIC METHOD*

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Abstract

Harmonic method is very useful when we try to obtain the bunch length, while its resolution is always influenced by many factors. In this paper, the relations between resolution and working frequencies of two cavities are given by mathematical deduction. The laws of resolution change caused by some decisive factors such as beam position, working frequency, electromagnetic mode and probe position are obtained through simulation on computer. An improved measurement method utilizing TM020 mode is presented based on the theory above. The simulation results show that the improved method can enhance the resolution capability of the bunch length monitor and these analyses can provide references for the design of cavity bunch length monitor.

INTRODUCTION

Harmonic method is used to quantify the bunch length with RF pick-up. The RF pick-ups for linacs are usually cavities. The monitors consisting of the cavities have been constructed to measure the bunch length in the CLIC (Compact Linear Collider) Test Facility (CTF) at CERN [1] and the BEPCII [2]. The electromagnetic fields can be induced when the beam passes through the cavity, and the monitor achieves its function by picking up information about bunch length contained in the electromagnetic fields. It has many advantages such as simple structure, wide application rage, and high signal-to-noise ratio. But the resolution of the cavity bunch length monitor is seriously limited by the system signal-to-noise ratio (SNR) [3, 4]. In this paper, the relationship between resolution and SNR is deduced primarily and then the factors which make an impact on the system SNR is analyzed. Finally, an improved measurement method utilizing TM020 mode is proposed.

THEORETICAL ANALYSIS

Cavity bunch length monitor is usually composed of two cavities with different working frequencies. The schematic is shown in Fig. 1.

When a Gaussian bunch passed through the center of the vacuum chamber, the oscillating electromagnetic fields could be excited in the cavities. The power of the field can be written as [2]

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

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. I_0 is eliminated and the equation is derived as follows

$$\sigma_\tau{}^2 = \frac{1}{\omega_2^2 - \omega_1^2} \ln \frac{P_1 R_2}{P_2 R_1} \quad (2)$$

Take the derivative of both sides,

$$2\sigma_\tau \Delta\sigma_\tau = \frac{1}{\omega_2^2 - \omega_1^2} (\frac{\Delta P_1}{P_1} - \frac{\Delta P_2}{P_2}) \quad (3)$$

is easily shown. The resolution of the system can be expressed as

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

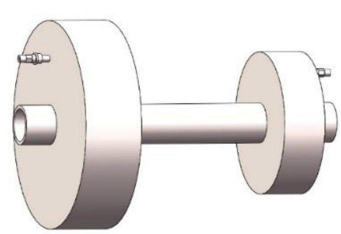

Figure 1: The schematic diagram of cavity bunch length monitor.

From the Eq. (4), it can be seen that the resolution depends on the system SNR and the difference of the square of working frequencies. 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

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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. 2 and Fig. 3, respectively.

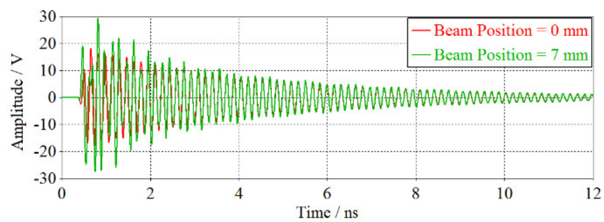

Figure 2: The output signal in time domain.

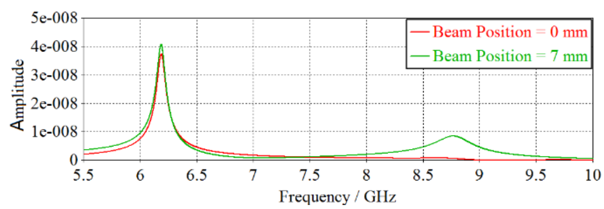

Figure 3: The output signal in frequency domain.

It can be seen that the position offset leads to amplitude changing of the output signal. In the following sections, the amplitude deviation owing to the position offset is regarded as noise. Based on this description, the system SNR and resolution are analyzed.

SIMULATION

The Influence of Beam Position

The cavity bunch length monitor is modeled and loaded with virtual beam in CST. The bunch length is 10 ps and the beam position ranges from 0 mm to 7 mm. The device consists of two cavities. The first one is the reference cavity that works at TM010 mode with 0.476 GHz. The second one is the main bunch length cavity that works at TM010 mode as well. The simulations are performed using main cavities with different working frequencies. Figure 4 shows how the relative errors of the output amplitudes vary with beam positions. In accordance with the amplitudes, the SNR and the resolutions are calculated. They are shown in Fig. 5 and Fig. 6.

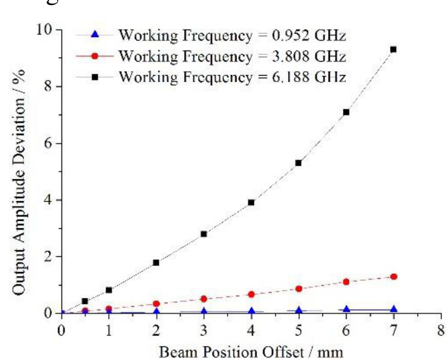

Figure 4: Output amplitude deviations vary with beam position offsets.

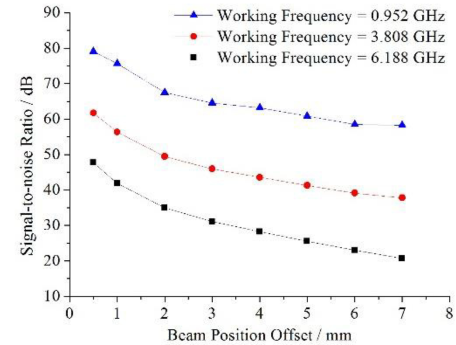

Figure 5: SNRs vary with beam position offsets.

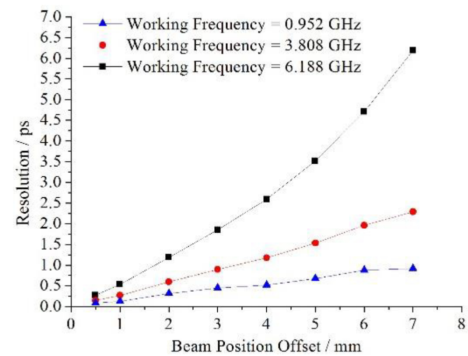

Figure 6: Resolutions vary with beam position offsets.

From the above diagrams, we can clearly figure out that the father away the beam sets from the axis of the cavity, the greater the deviation is. It follows that the SNR and the resolution decline. In the actual accelerator, the beam position is about 1 mm generally, and it will have a negative effect on the resolution. Therefore, the situation still needs optimization.

The Influence of Working Frequency

The extent of the output amplitude deviation due to the beam position also depends on the working frequency of the main cavity. A series of simulations in CST are performed. Keep the reference cavity resonating at 0.476 GHz and change the working frequency of main cavity. The simulation results of output amplitude deviation, SNR and resolution are shown in Fig. 7, Fig. 8 and Fig. 9.

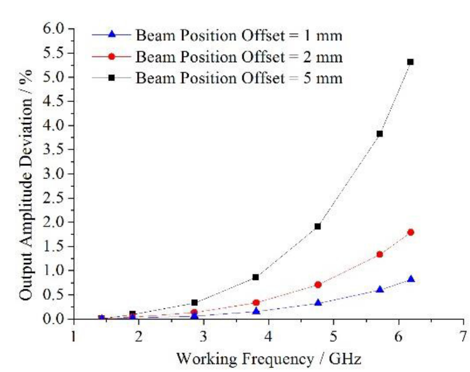

Figure 7: Output amplitude deviations vary with working frequencies.

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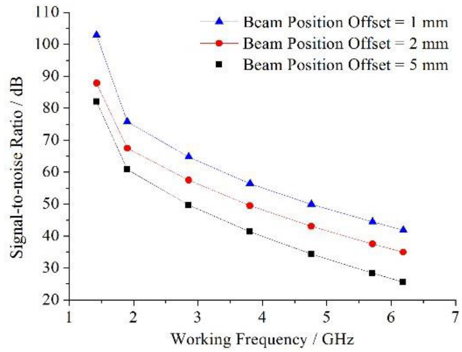

Figure 8: SNRs vary with working frequencies.

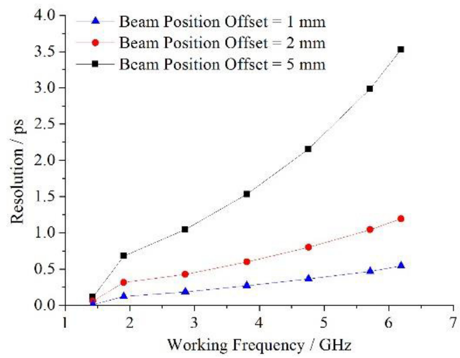

Figure 9: Resolutions vary with working frequencies.

The graphs indicate that the same beam position will introduce greater noise if working frequency is higher. According to the Eq. (4), although increase f_2 can enlarge the difference of the square of working frequencies, the SNR will decline sharply. The situation also needs optimization.

Improved Method and Simulation

To solve the above problems, an improved bunch length measurement method based on TM020 mode cavity is proposed. Comparing with TM010 mode, TM020 mode can be excited in larger cavity whose quality factor Q is higher. In frequency domain, the signal bandwidth Δf can be described as [5]

$$\Delta f = \frac{f_0}{Q_0} \tag{10}$$

Where f_0 is the resonant frequency. Smaller Δf is preferred because it means the interference from dipole modes existing in the cavity such as TM110 can be reduced.

The cavities which resonate at 3.808 GHz and 6.188 GHz with TM020 mode and TM010 mode are designed respectively in CST. The bunch with different position are loaded and the simulation results are shown in Fig. 10, Fig. 11 and Fig. 12.

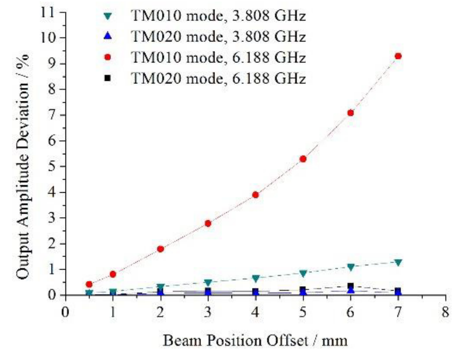

Figure 10: Output amplitude deviations vary with beam position offsets.

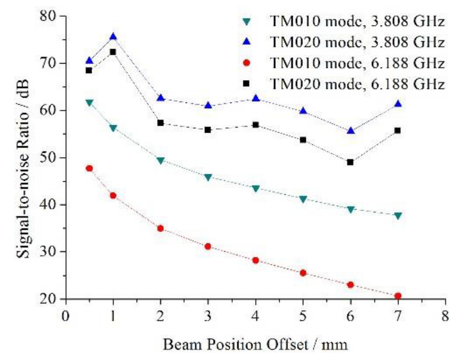

Figure 11: SNRs vary with beam position offsets.

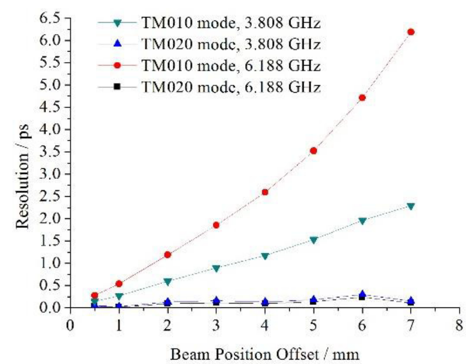

Figure 12: Resolutions vary with beam position offsets.

According to the graphs, it can be seen that using TM020 mode is able to obtain the high SNR and the high resolution compared with the traditional cavity with TM010 mode.

CONCLUSION

In this paper, the main influencing factors of cavity bunch length monitor resolution are analyzed. A series of simulations based on CST have been done and we can find that the SNR depends on the beam position and the working frequency of the eigenmode. To further optimize the performance of the device, an improved method using the cavity that resonates with TM020 mode is proposed. The simulation results prove that this improved method enhances the resolution capability effectively.

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