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Design and performance study of an improved cavity bunch length monitor based on an optimized offline test scheme

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A R T I C L E I N F O

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A B S T R A C T

Cavity bunch length monitors (CBLMs) used monopole modes within resonant cavities to obtain the root mean square (rms) electron bunch length. This paper reports the design and performance analysis of a CBLM to be used in FELiChEM, an infrared free-electron laser (FEL) facility in the National Synchrotron Radiation Laboratory (NSRL). Instead of traditional CBLMs which consist of two cavities resonating at TM_{010} mode, the higher-order mode, TM_{020} mode, is utilized to increase the working frequency and improve the resolution. To study the performance of this monitor, an improved offline test scheme using a thin wire to simulate the beam current is proposed and exploited. The influences of the beam transverse offset and the bunch transverse distribution on the bunch length measurement are studied based on the offline test platform, and an error correction methods is put forward. Simulation and experimental results show that the CBLM can measure the bunch length at the picosecond level with very high accuracy. The resolution can reach 50 fs when the signal-to-noise ratio (SNR) is greater than 70 dB.

1. Introduction

Free-electron lasers (FELs) use short bunches to achieve an efficient lasing process in a single pass through an undulator [1]. Therefore, precise measurement methods of the bunch length are required. FELiChEM is a compact infrared FEL. Its beam parameters are listed in Table 1 [2].

Many methods and devices to evaluate the bunch length for FEL have been developed over decades. Streak cameras [3] are widely used, but their resolutions are limited. Although the transverse rf deflecting cavity method [4] and the rf zero phasing method [5] can measure short bunches with high resolutions, both of them are destructive. The electro-optic sampling method [6] and the coherent radiation method [7] are complex and expensive. The cavity monitor has the advantages of high signal-to-noise ratio (SNR), high resolution, and a large dynamic range [8,9]. It is especially applicable for bunch length measurement in the picosecond scale in FEL because of its compactness and noninvasiveness. Moreover, the beam current and the beam position can also be obtained by the cavities simultaneously [10,11]. Instead of traditional cavity bunch length monitors (CBLMs) that consist of two cavities resonating at TM_{010} modes [12,13], in this paper, a CBLM using TM_{020} mode is proposed. This improvement allows the higher frequency mode to be used to measure in a larger cavity, which effectively enhances the resolution. A prototype was manufactured. To estimate the performance of the monitor, an improved test scheme using a thin wire to simulate the beam current was constructed. Two tapered impedance matching with tension devices were exploited to minimize reflections and pull the wire tight. Moreover, the study of the influence of the beam transverse offset and the bunch transverse distribution on the bunch length measurements was performed based on the offline test experiments.

2. Theory of CBLMs

The bunch length is defined as the rms value of the electron longitudinal distribution. Assume that σ_t is the bunch length in units of time, and σ_l is the bunch length in units of length. The relationship can be expressed as

$$\sigma_l = c\sigma_t \quad (1)$$

where c is the speed of light. In this paper, all the longitudinal parameters of the bunch, including the bunch length, are expressed in units of time according to this relationship.

When a bunch distributed between $-\infty$ and ∞ passes through the axis of a cavity, some eigenmodes are excited in the cavity. According to the beam loading theory, the output voltage amplitude of one eigenmode can be represented as [14–16]

$$V_{out} = V_0 q \int_{-\infty}^{\infty} f(t)\exp(j\omega t)\,dt \quad (2)$$

where q is the bunch charge, t is the time, $f(t)$ is the probability density function of the electron longitudinal distribution, and ω is the working

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Table 1
Electron beam parameters of FELiChEM.

Parameter	Value
Beam energy	25–60 MeV
Bunch charge	1.0 nC
Bunch length (rms)	2–5 ps
Bunch repetition rate	476 MHz
Beam pipe radius	17.5 mm

frequency of the eigenmode. In addition, $\square_{\square}$ is a constant determined by the cavity, written as

$$\square_{\square} = \frac{1}{2}\square\sqrt{\frac{\square(\square/\square_0)}{\square_{\square\square\square}}} \tag{3}$$

where $\square$ is the impedance of the detector, $(\square/\square_0)$ is the normalized shunt impedance, and $\square_{\square\square}$ is the external quality factor of the eigenmode. The exponential term in Eq. (2) can be expanded as a Maclaurin series with a Lagrange remainder term, and Eq. (2) can be written as

$$\begin{aligned}\square_{\square\square} &= \square_{\square}\square\int_{-\square}^{\square}\square(\square)[1-\frac{\square^2\square^2}{2_{\square}}+\frac{\exp(\square\square\square\square)}{4!}(\square\square)^4]\,\square\square \\ &= \square_{\square}\square[\int_{-\square}^{\square}\square(\square)\,\square\square-\int_{-\square}^{\square}\square(\square)\frac{\square^2\square^2}{2}\,\square\square \\ &+\int_{-\square}^{\square}\square(\square)\frac{\exp(\square\square\square\square)}{24}(\square\square)^4\,\square\square],\ 0<\square<1.\end{aligned} \tag{4}$$

Since $\square_{\square}$ is also the origin moment, $\square_{\square\square}$ can be approximated as

$$\square_{\square\square\square} \approx \square_{\square}\square(1-\frac{\square^2\square^2_{\square}}{2}). \tag{5}$$

Specifically, for a bunch with a Gaussian distribution, the output amplitude is

$$\square_{\square\square\square} = \square_{\square}\square\exp(-\frac{\square^2\square^2_{\square}}{2}). \tag{6}$$

Because both $\square$ and $\square_{\square}$ in Eq. (6) are unknown quantities, at least two eigenmodes at different frequencies are needed, and a set of simultaneous equations must be established to obtain $\square_{\square}$.

By using the total differentiation method, the resolution of the bunch length measurement can be represented as [13,17]

$$\square\square = \frac{10^{-SNR/20}}{\square_{\square}(\square_2^2-\square_1^2)}. \tag{7}$$

Traditional CBLMs consist of two cavities that resonate at TM_{010} modes. However, according to Eq. (7), the system resolution is restricted because of the low frequencies of TM_{010} modes. If the resonant frequencies are simply increased, the cavity will be too small to work. To solve this problem, a CBLM utilizing the TM_{020} mode is proposed. This improvement allows the higher frequency modes to be used to measure in a larger cavity, which effectively enhances the resolution.

3. Design, manufacture, and installation

3.1. Selection of modes and frequencies

Two cylindrical cavities are used in the design. This method applies to both single-bunch measurement and multi-bunch measurement. The bunch repetition rate of FELiChEM is 476 MHz, which results in a superposition of the bunch signals. Therefore, this CBLM can only be used for the average bunch length measurement of a bunch train, that is, the multi-bunch measurement. When a train of the same bunches passes through a cavity, only the eigenmodes of which the working frequencies are close to an integral multiple of the bunch repetition rate can be excited. According to Eq. (7), to enhance the resolution, $\square_1$ should be as small as possible. Therefore, the first cavity (cavity 1)

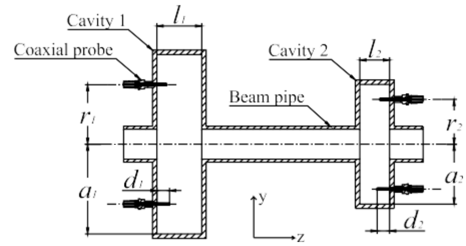

Fig. 1. The cross-section of the cavities.

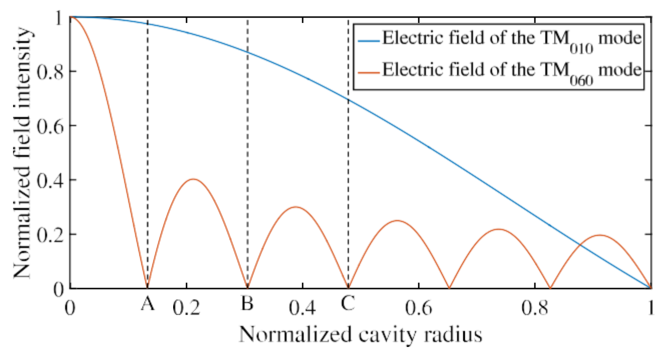

Fig. 2. The field intensity distribution curves of the TM_{010} mode and the TM_{060} mode.

works at TM_{010} mode. The relation between the frequency of $TM_{0\square0}$ mode and the cavity size can be written as

$$\square = \frac{\square_0^{\square}\square}{2\square\square} \tag{8}$$

where $\square^{\square}$ is the $\square$th root of the zero-order Bessel function, and a is the cavity ra^{0}dius. If working at 0.476 GHz, the bunch repetition rate, the cavity will take up many spaces. Therefore, the resonant frequency of cavity 1 is set to 0.952 GHz, twice the bunch repetition rate.

For the second cavity (cavity 2), we aim to choose a higher frequency. Since the cavity directly installs on the beam pipe, the modes within the cavity may leak into the beam pipe. The radius of the beam pipe in FELiChEM is 17.5 mm, so it can be regarded as a cylindrical waveguide with a cut-off frequency of 6.562 GHz. As long as the resonant frequency is less than 6.562 GHz, the mode can be trapped in the cavity for measurement. Therefore, 6.188 GHz, thirteen times the bunch repetition rate, is chosen as the second frequency. However, according to Eq. (7), if cavity 2 operated at TM_{010} mode, its radius would be only 18.56 mm, which means that the coupler could not be installed. To solve this problem, TM_{020} mode is introduced in our design. In this case, the cavity radius increases to 42.6 mm, which is sufficient.

3.2. Couplers

Coaxial probes are used as couplers. Penetrating the pin into the cavity along the electric field direction can couple out the corresponding mode. Since the electric field of $TM_{0\square0}$ modes has only a longitudinal component, coaxial probes are set as shown in Fig. 1.

When the bunches travel along the cavity axis, only the $TM_{0\square0}$ modes can be excited because the integrals for the electric field of the other modes along the beam orbit are zero, which means no energy exchange occurs between the modes and the cavity. However, some unwanted modes may still exist in the cavity. Calculation results show that the TM_{060} mode in cavity 1 may be excited because its frequency is close to fifteen times the bunch repetition rate. The function of the $TM_{0\square0}$ mode electric field can be expressed as

$$\square(\square) = \square\ \square(\frac{\square_0^{\square}}{\square}) \tag{9}$$

Table 2
The final dimensions of the cavities.

Parameter	Value (mm)
$\square_1$	123.3
$\square_1$	5.0
$\square_1$	55.4
$\square_1$	2.4
$\square_2$	46.1
$\square_2$	10.0
$\square_2$	27.0
$\square_2$	2.4

where $\square_0$ is a constant, $\square_0(\square)$ is the zero-order Bessel function, and $\square$ is the radial coordinate. According to Eq. (9), the electric field distributions of the TM_{010} mode and the TM_{060} mode along the radial direction are shown in Fig. 2. To suppress the interference, according to Fig. 2, the coaxial probes are penetrated at position C (approximately 0.48a) because the TM_{010} mode is strong enough and the TM_{060} mode is zero here. To prevent the beam pipe and flanges from disturbing the probe installation, position A and position B are not selected.

3.3. Tuners and Q values

Due to manufacturing imperfections, the resonant frequencies may deviate from the set value. The metal rods are used as tuners to adjust the resonant frequencies, and the depth of tuner penetration can be changed by precession. The tuners are installed at the cavity sidewall. Q value is an important parameter. The bunch repetition rate of FELiChEM is so high that the bunch-by-bunch measurement cannot be achieved. In the case of multi-bunch measurement, the output signal is a superposition of all the previous bunches in the beam train. The superposition leads to saturation of the detecting electronics, narrowing the dynamic range. A high cavity decay rate can effectively reduce the output amplitude. Therefore, lower-Q cavities are preferred. Furthermore, the lower Q values are good for improving the SNR and resolution. In order to retain the function of single-bunch measurement for testing and adjustment of the cavity, the Q value should not be too small, otherwise the output signal will not provide enough sampling points because its attenuation is too fast. Considering the above mentioned, a suitable Q value should be between 100 and 2000.

Since stainless steel has a smaller electric conductivity than copper, the SUS304 stainless steel is used as the cavity material to reduce the Q values. Meanwhile, the $\square_{\square\square}$ decreases with increasing the insertion depth of the coaxial probes. This is another way to adjust the Q value. It should be noted that a deep penetration will destroy the electromagnetic field in the cavity, which is harmful.

By using the 3D electromagnetic field simulation program, CST [18], the materials and dimensions of each cavity were optimized to meet the requirements of the RF parameter. The final dimensions of the cavities are presented in Table 2. The loaded Q values of cavity 1 and cavity 2 obtained by simulations are 290 and 1369, respectively.

3.4. Simulation results of virtual beam

The cavities are modeled in CST Particle Studio and the simulation with a virtual bunch train passing through the CBLM along the cavity axis is performed. The output signals in the frequency domain are shown in Fig. 3.

It can be seen that useful signals are obvious. Some other modes are also excited. There are large frequency differences between the unwanted signals and the useful signals, which means that the interference has little effect on the measurement and can be easily filtered.

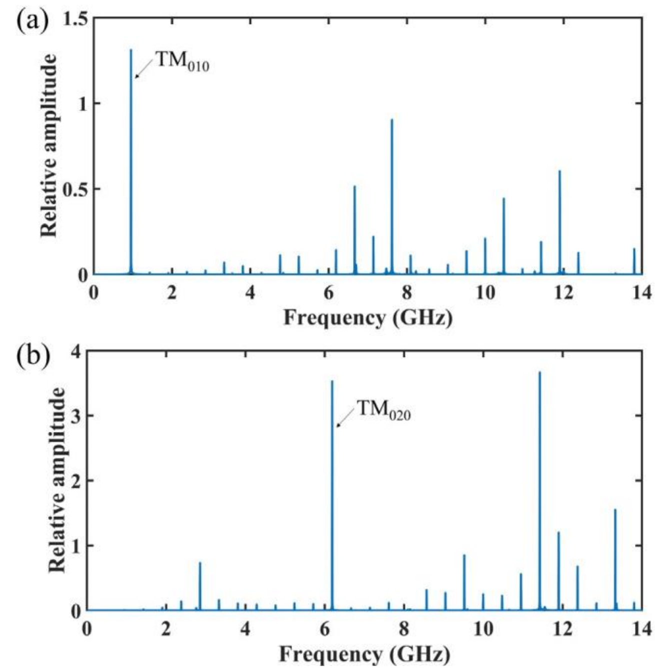

Fig. 3. (a) The output signal of cavity 1. (b) The output signal of cavity 2. The bunch charge is set to 1 nC and the bunch length is 5 ps.

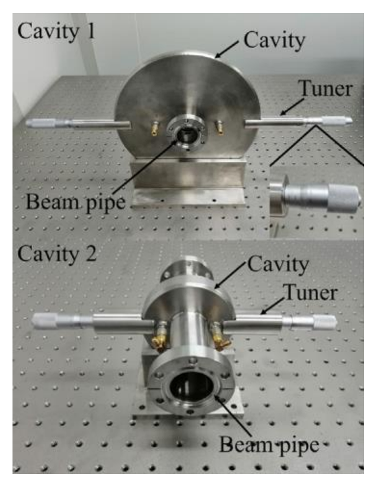

Fig. 4. The prototype.

3.5. Manufacture and installation

The prototype has been manufactured. It is shown in Fig. 4. The material of the cavities is SUS304 stainless steel, associated with a lower Q value. The coaxial probes adopt Hitachi NL-108-546 feedthroughs, and they are welded directly on the cavity wall. The depth of tuner penetration can be estimated by rulers installed onto the screw rod. If the cavities are installed onto the accelerator, the rulers will be removed, and corrugated pipes will cover the tuner to keep the vacuum. Flanges CF35 are employed to connect with the beam pipe. The monitor will be installed in FELiChEM, which is shown in Fig. 5. A four-dipole magnetic chicane that is placed between two accelerating tubes (A1, A2) is utilized to reduce the micropulse length. The CBLM is located in Q19 to diagnose the bunch that is used for the MIR undulator.

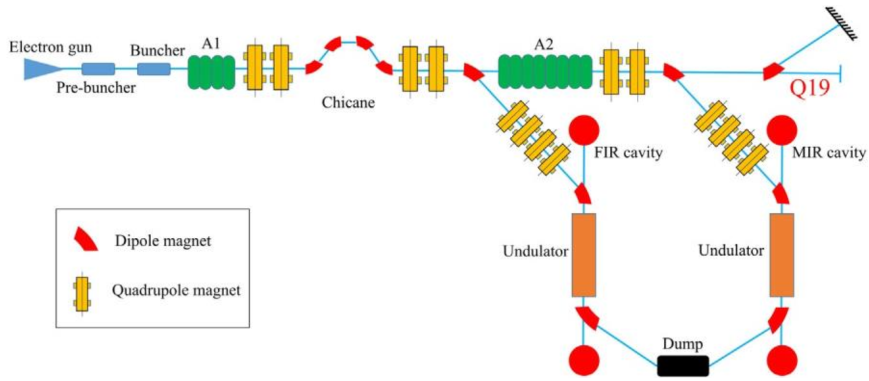

Fig. 5. The layout of FELiChEM and the installation position of the CBLM.

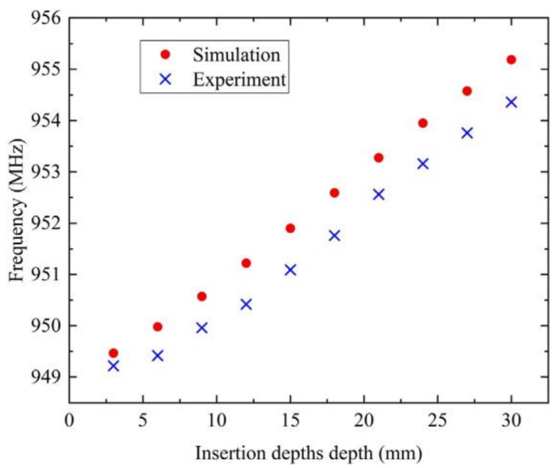

Fig. 6. The insertion depths of the tuner versus the working frequencies in cavity 1.

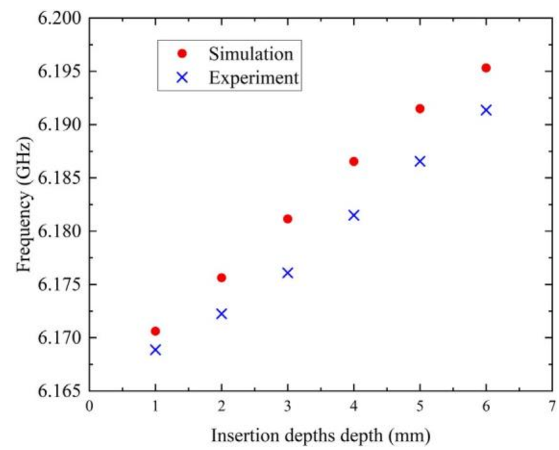

Fig. 7. The insertion depths of the tuner versus the working frequencies in cavity 2.

4. Cold test

4.1. Working frequency

The working frequencies of the cavities are obtained from the S-parameter by using a vector network analyzer (VNA). The experimental results are shown in Figs. 6 and 7. It can be seen that for the TM_{010} mode in cavity 1, the frequency deviation between the design and the prototype is under 1 MHz, while in cavity 2, the frequency deviation of the TM_{020} mode is less than 5 MHz. Therefore, the manufacturing imperfection will bring the error. The tuners are necessary. In this CBLM, the two target frequencies are all in the tuning ranges.

4.2. Offline test platform for CBLM

The layout of the offline test platform is shown in Fig. 8. The signal source is an SML03 sinusoidal signal generator that is used to simulate frequency components in the bunch spectrum. A thin wire passes through the entire structure and the electric signal propagates along the wire. Eigenmodes within the cavity can be excited by the electric signal. Based on the offline calibration test platform for the beam position monitor (BPM) [19], some improvements are made. To reduce the reflection and distortion of the electric signal, two tapered impedance matching sections with tension devices are employed. The impedance matching sections allow the coaxial structure to transition from SMA to the beam pipe smoothly. The tension devices are used to tighten the wire through rotating.

To test the performance of the two impedance matching sections, we connect them with a beam pipe. A wire passes through the entire

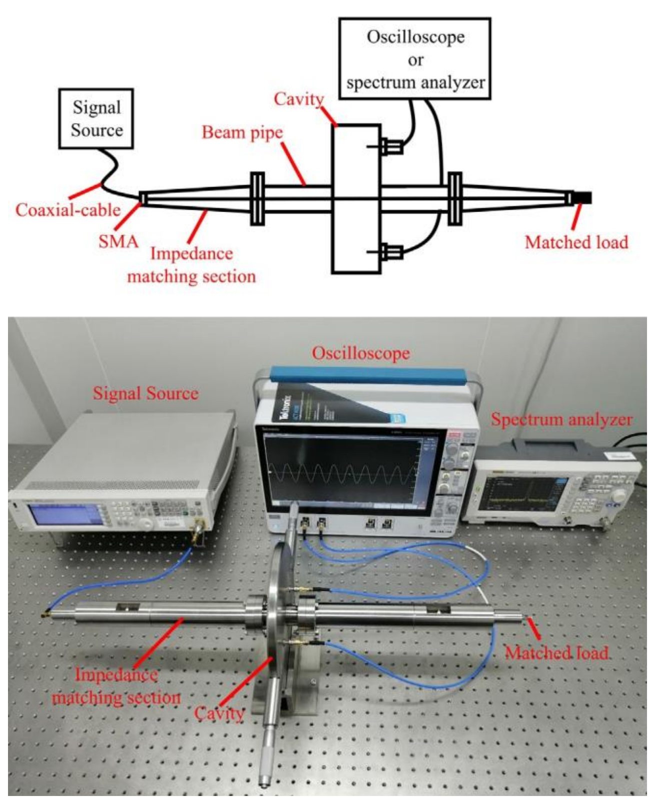

Fig. 8. The layout of the offline test platform.

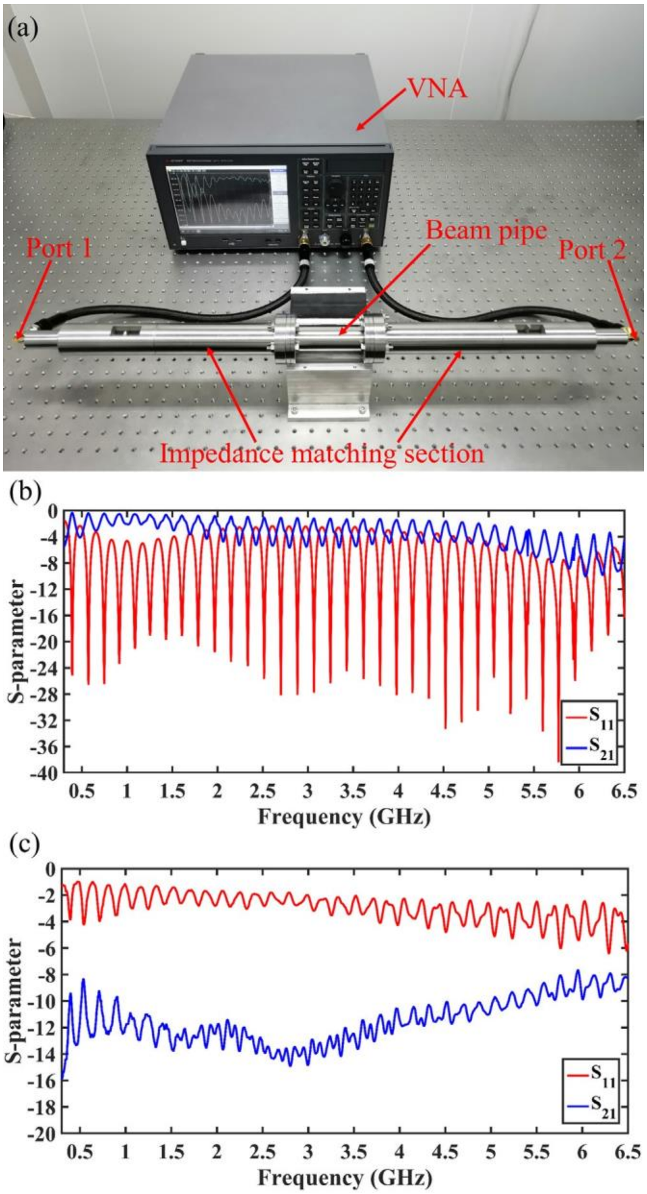

Fig. 9. The test of the impedance matching sections. (a) The layout. (b) The S-parameter of the structure. (c) The S-parameter of the beam pipe when the impedance matching sections are removed.

structure. The S-parameter is measured by using a VNA. The experimental results are shown in Fig. 9. It can be observed that the tapered impedance matching sections are able to reduce the reflection, and the electric signal can propagate along the wire with less loss.

In order to verify the wire excitation, cavity 1 with tapered impedance matching sections and a wire is modeled in CST, and the simulations of wire excitation and beam excitation are performed. The input signal of the wire and the bunch longitudinal distribution are the same. Then, we compared the output signals from the cavity in the frequency domain. Fig. 10 is an example of the output signals from the cavity when both the bunch distribution and the input signal of the wire are Gaussian with rms widths of 5 ps.

A series of simulation results shows that when the input signal of the wire and the bunch longitudinal distribution are the same, they excite similar electromagnetic fields in the cavity. The output signals of the cavity in the frequency domain are also essentially similar. When a wire passes through the entire structure, the beam pipe turns from a cylindrical waveguide into a coaxial line, which means the mode energy

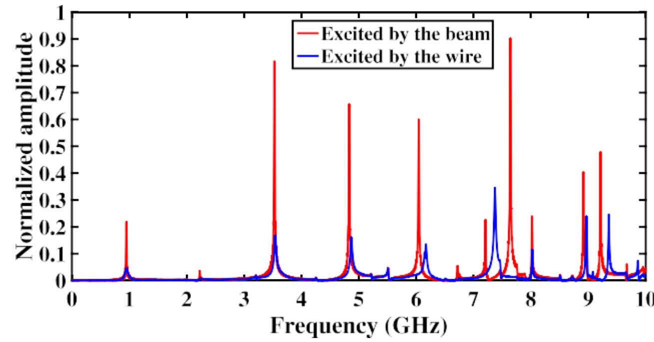

Fig. 10. The output signal of the mode excited by a bunch and the output signal excited by a wire with the same electric signal.

more easily leaks through the beam pipe. Therefore, compared with the signal excited by the beam, the signal excited by the wire has a weaker strength and wider bandwidth, and the mode has a lower Q value. For each frequency component, in spite of wire excitation or beam excitation, there is a stable relationship of amplitude between the input and the output. Thus, the output amplitude of one eigenmode excited by a wire can be written as

$$V_{out} = kA\exp\left(-\frac{\omega^2\sigma_t^2}{2}\right) \tag{10}$$

where k is a constant governed by the wire and cavity. This expression is similar to Eq. (6).

4.3. Bunch length measurement

It can be seen from Section 2 that the output amplitude of a cavity eigenmode reflects the corresponding frequency component of the bunch spectrum. The measurement is to infer the bunch length by at least two frequency components. Because the signal source cannot generate a picosecond pulse in reality, the SML03 sinusoidal signal generator and frequency multipliers are employed to simulate the specified frequency components in the bunch spectrum. For the output amplitudes of the two cavities, simultaneous equations can be established as

$$\begin{cases} V_{out1} = k_1 A\exp\left(-\frac{\omega_1^2\sigma_t^2}{2}\right) \\ V_{out2} = k_2 A\exp\left(-\frac{\omega_2^2\sigma_t^2}{2}\right). \end{cases} \tag{11}$$

It follows that

$$\sigma_t^2 = \frac{2}{\omega_2^2 - \omega_1^2}\ln\left(\frac{k_2 V_{out1}}{k_1 V_{out2}}\right). \tag{12}$$

Then,

$$\exp\left[\frac{(\omega_2^2 - \omega_1^2)\sigma_t^2}{2}\right] = \frac{k_2 V_{out1}}{k_1 V_{out2}}. \tag{13}$$

In practice, instead of Eq. (12), it is convenient to use Eq. (13) to determine σ_t. In order to verify the CBLM's ability to measure bunch length, on the offline test platform, a series of sinusoidal signals with frequencies of 0.952 GHz and 6.188 GHz are input into the wire to simulate the Gaussian bunches with length of 2 to 5 ps, and the bunch length is inferred from the output signals of cavity 1 and cavity 2. The experimental results are illustrated in Fig. 11.

It can be seen that there is a perfect linear relationship between V_{out1}/V_{out2} and $\exp(\sigma_t^2(\omega_2^2-\omega_1^2)/2)$. Because of the stable correspondence between the ratio of output amplitudes and bunch length, the bunch length can be determined as long as the two output amplitudes are obtained. This CBLM is able to measure the bunch length. According to Eq. (13), due to the exponential relationship, a small deviation in the output amplitude has a more serious impact on the measurements of short bunches than long bunches. There is a larger error in the short bunch measurement.

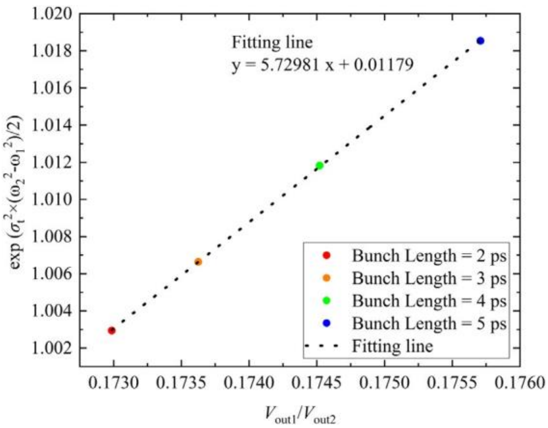

Fig. 11. V_{out1}/V_{out2} versus $\exp(\sigma_t^2(\omega_2^2-\omega_1^2)/2)$.

5. Influence of the beam transverse offset

According to Eqs. (2) and (3), V_{out} is related to (R/Q_0) that can be described as

$$\frac{R}{Q_0} = \frac{|\int E\,dz|^2}{\omega U} \tag{14}$$

where $\int E\,dz$ is the integral for the mode electric field along the beam orbit, and U is the stored energy of the mode in the cavity. When a bunch passes the cavity with a transverse offset, the output amplitude of the mode changes because the integration path is no longer the cavity axis. Since two modes are used to obtain the bunch length, the error caused by the beam transverse offset may be serious. To evaluate the error, a series of experiments is carried out based on the offline test platform. Sinusoidal signals are employed to simulate the frequency components in the bunch spectrum. The thin wire passes through the cavity with different y positions, and cavity responses are obtained and analyzed. The radius of the wire on the offline test platform is 0.1 mm.

From Figs. 12 and 13, it can be observed that the output amplitude variation with offset in the y direction is different between the two symmetric ports. On the one hand, the TM_{0n0} modes are axially symmetric and have a field maximum on the cavity axis, so the energy of the TM_{0n0} modes weaken if the beam moves off axis. On the other hand, (R/Q_0) of the dipole modes is no longer zero, which means that the dipole modes can be excited by the beam with offset. Due to the bandwidth, the dipole modes can affect the monopole modes. In addition, other high-order modes may also have an impact on the monopole modes. Therefore, the output signal is a superposition of all the above. Since cavity 2 resonates at TM_{020} mode, of which amplitude decrease with increasing offset is faster than that of TM_{010} mode, the attenuation of the monopole mode is the main driver of the variation.

Generally, bunch length measurement uses the sum signal of the symmetric ports. The experimental results based on the offline test platform are shown in Fig. 14.

It can be observed that the relative error increases with the offset. The sum signal of the two symmetric ports cannot eliminate the error caused by the monopole modes and higher-order modes. Because the symmetry of the two ports and the uniformity of the cables are imperfect, the error caused by the dipole modes cannot be avoided completely. In accelerators, the beam transverse offset in one direction is generally less than 1 mm. In this case, the relative error caused by the offset is under 4%, which meets the measurement requirements.

Before installation onto the accelerator, the output amplitude of each cavity variation with offset can be determined by using the offline test platform. Then, a series of correction factors are calculated. Since different cavities show different responses to the beam offset, each cavity has its own correction factor. In actual measurements, according to the beam position obtained by BPMs, we can correct the output amplitude and reduce the measurement error by using these correction factors. For this monitor, on the basis of the change rule in Figs. 12 and 13, the fitting curves of the relative change are drawn, and the

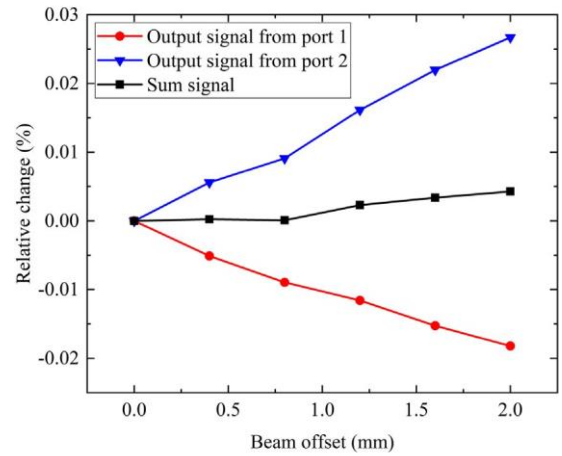

Fig. 12. Relative change in the TM_{010} mode output amplitude versus beam offset in cavity 1.

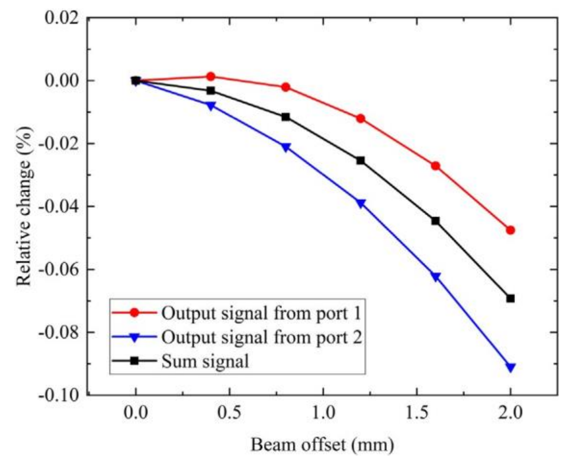

Fig. 13. Relative change in the TM_{020} mode output amplitude versus beam offset in cavity 2.

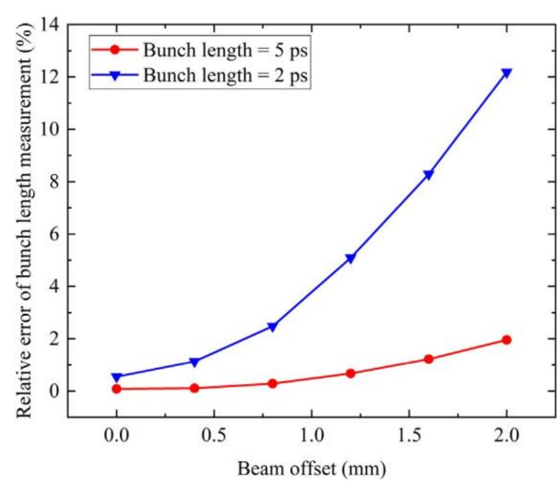

Fig. 14. The relative error of bunch length measurement.

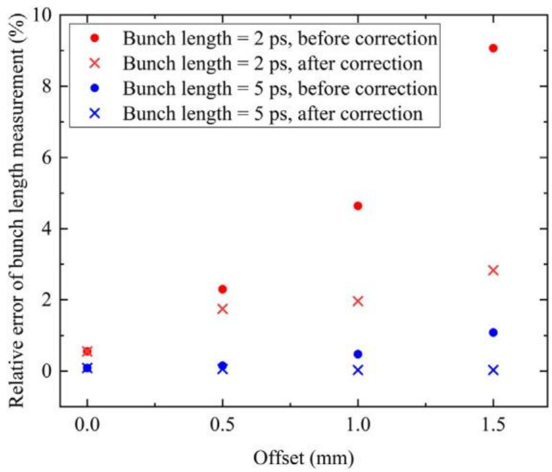

Fig. 15. The relative error of bunch length measurement.

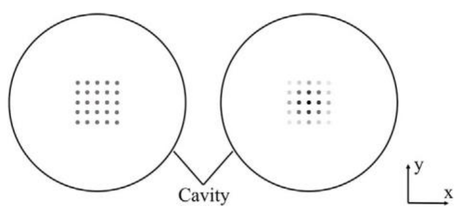

Fig. 16. The simulated schemes used wire for the bunch with a uniform distribution (left) and Gaussian distribution (right) in the transverse direction. The points indicate the position at which the wire passes through the cavity. The deeper the color is, the larger the weight factor is.

corresponding correction factors are taken into account in the bunch length measurement. The results are shown in Fig. 15.

It can be seen that the error caused by beam offset is reduced effectively after using this correction method. However, in the multi-bunch measurement, if there is an inconsistency in the transverse position of a beam train, the correction cannot be achieved. Therefore, this scheme is only applicable for the single-bunch measurement and off-line test.

6. Influence of the bunch transverse distribution

In practice, the bunch has a transverse size. Since the mode energy varied with the bunch transverse positions, the bunch transverse distribution must be taken into account. On the offline test platform, it is difficult for a wire to simulate a bunch with a transverse size. According to the principle of superposition, a weighted method of a two-dimensional grid structure is employed [20,21]. Let the wire pass through the cavity at different transverse positions. The weight factors of all positions are determined in accordance with the transverse distribution function. The weighted sum of all the output signals is regarded as the output signal of the bunch with this transverse distribution. In this way, a two-dimensional grid consisting of the wire at different positions can be used to simulate the bunch with a transverse size. Fig. 16 shows the simulated schemes for the bunch with a uniform distribution and Gaussian distribution in the transverse direction.

In FELiChEM, the transverse distribution range of the bunch reaches about 1 mm. To verify the feasibility of this method, we created a bunch with the same size as the excitation source in CST. On the offline test platform, the wire grids with different densities are utilized to simulate this bunch. The dense grid indicates a small step size. A smaller step size can lead to a better simulation but a longer processing time. Finally, a grid of 11 × 11 and step size of 0.1 mm are adopted. The radius of

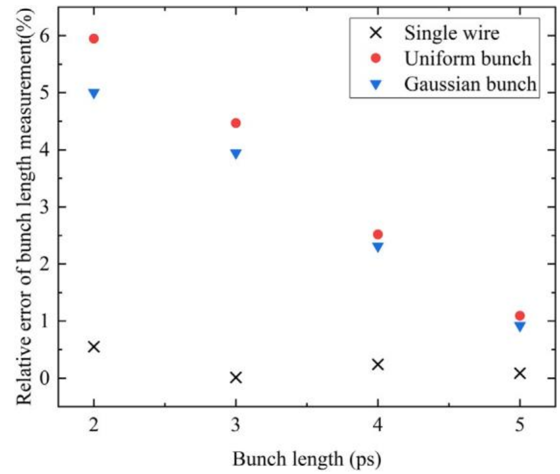

Fig. 17. The relative error of bunch length measurement.

the wire on the offline test platform is 0.1 mm. The experiment results show that the simulation error of the bunch is less than 1.2% in this case.

On the offline test platform, the weighted method is used to simulate the frequency components of a series of bunches with transverse sizes. In the transverse direction, these bunches spread over a circle of radius 0.5 mm, and their distributions are Gaussian with rms widths of 0.1 mm and uniform. Simulated measurement of bunch length is performed on the offline test platform and the experimental results are shown in Fig. 17.

It can be seen that the error caused by the transverse distribution is less than 6%. This is a superposition of the error from the particles in different transverse positions. The shorter the bunch length is, the larger the measuring error will be. Compared with the bunch with the uniform distribution, the error of the Gaussian bunch is smaller, because more particles gather around the axis of the cavity. The correction can be carried out according to the beam spot in actual measurement.

7. Discussion

7.1. Resolution

According to Eq. (7), for this CBLM, the relationship between the SNR and resolution is given in Fig. 18. It can be observed that for the bunch length of 5 ps, the potential resolution of 50 fs can be achieved when the SNR is greater than 70 dB. For a bunch length of 2 ps, the SNR of 77 dB can meet this requirement. The noise of the post-processing electronics is the main reason for SNR limitation. The possible tilt of the bunch and the beam orbit is also a noise source. Moreover, due to the variation of temperature and cavity shape during use, the resonant frequencies may be off target. Cavity detuning leads to a decrease in the output amplitude and the SNR. This requires a real-time frequency feedback and tuning system.

7.2. Measurement of a non-Gaussian bunch

Eq. (5) is applicable to the bunch with an arbitrary longitudinal distribution. The approximate error of Eq. (5) is

$$□ = □_{□}□ \int_{-□}^{□} □(□) \frac{\exp(□□□□)}{24} (□□)^{4} □□, \quad 0 < □ < 1. \tag{15}$$

To evaluate the size of □, a series of derivations is carried out, and

$$\frac{□}{□_{□□□}} < \frac{(□□)^{4}}{24} \exp(-□□□) \tag{16}$$

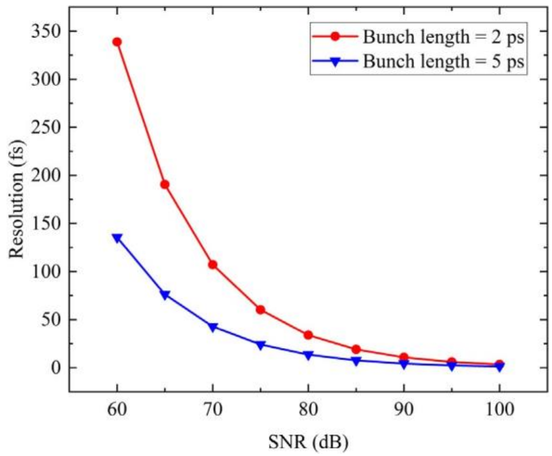

Fig. 18. The relationship between SNR and resolution.

is obtained. It can be observed that the relative approximate error caused by the longitudinal distributions is very small if □□ is small. For FELiChEM, the bunch with a length of 5 ps, □ is 20 ps, and the highest working frequency is 6.188 GHz. According to Eq. (16), the relative approximate error caused by the different longitudinal distributions is approximately 1%. Therefore, all bunches can be regarded as Gaussian bunches in that case.

8. Summary

A cavity is a simple and noninvasive diagnostic device for the bunch length. High accuracy and high resolution can be achieved by using the TM_{020} mode. This paper provides the methods for the design, the performance analysis and the error correction of the improved CBLM. Because the modes excited by a wire and beam are similar, the offline test scheme with a wire can be used to evaluate the monitor performance and analyze the error. An impedance matching section is necessary. The smooth transition structure is a simple method. To eliminate the reflection and increase the coupling between the wire and cavity, the Goubau line will be a more effective selection in the future.

The bunch transverse offset and distribution cause measuring error. In this CBLM, the error is small. However, for the design of other CBLMs, whether the offset and the transverse distribution have serious consequences still needs to be determined by the offline tests. The offline test methods using a wire can be employed to evaluate these errors. The effective way to reduce these errors is to weaken the coupling of the interference mode or to introduce a correction factor.

This CBLM consists of two cavities, which are used to reflect two specified frequency components in the bunch spectrum. There are still some improvements that can be carried out. On the one hand, we can use fewer cavities and more compact structures to generate more monopole modes. It will save space and describe the bunch spectrum more accurately. For the measurement of short bunches, simulations based on this idea have been performed [22]. On the other hand, we aim to couple other kinds of eigenmodes, such as dipole modes and quadrupole modes, to achieve multiparameter measurement.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Qian Wang: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft. **Qing Luo:** Conceptualization, Methodology, Validation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Baogen Sun:** Conceptualization, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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