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Study of the crosstalk evaluation for cavity BPM

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Abstract In order to pursue high-precision beam position measurements for free-electron laser facilities, a cavity beam position monitor (CBPM) is employed to measure the transverse position that can meet the requirement of position resolution at a sub-micrometer or even nanometer scale. However, for the pill-box cavity BPM, crosstalk between the cavities will have an effect on the accurate measurement of beam position. To reduce the effect of crosstalk on CBPM performance and ease the measurement of the isolation between the cavities, the cavities with a slight difference in resonant frequency were designed and applied in the Dalian coherent light source and Shanghai soft X-ray free-electron laser facilities. Furthermore, two methods, the principal component analysis method and the method of harmonic analysis, are proposed in this paper to evaluate the crosstalk. The results demonstrate that the two methods are feasible in evaluating the crosstalk between the cavities.

Keywords Crosstalk · Pill-box cavity BPM · PCA · Harmonic analysis · Resolution

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1 Introduction

The free-electron laser (FEL), based on the linear accelerator, is a fourth-generation light source, which has characteristics such as high brightness, short wavelength, full coherence, and ultra-fast time resolution. Thus, it has become an extremely important research apparatus to meet the demands of biological, chemical, and material science research [1]. However, for FEL facilities, in order to reduce the gain degradation, the resolution of the transverse position should be less than 1 μm so that the beam position monitor (BPM) can be used for beam alignment in the undulator section, where the electron beams and radiated photon beams can be overlapped precisely. Compared with various types of BPMs such as button and stripline BPM, the cavity BPM adopting a resonant cavity structure, and using the characteristic modes excited by the electron beam to measure the beam position, has the advantage of high resolution and is widely used in FEL facilities [2–4].

For the construction of the Shanghai soft X-ray free-electron laser (SXFEL) facility and Dalian coherent light source (DCLS) facility [5, 6], low-quality (Q) and high-Q cavity BPM prototypes were designed and developed by our research group [7–11]. However, for the cylindrical pill-box cavity BPM (CBPM), because of the inevitable fabrication tolerance that is produced in the actual processing, the cavity has a random deformation that could lead to a change in the polarization direction of the electromagnetic field and has a negative effect on the accurate measurement of the beam position. Therefore, the evaluation of crosstalk between cavities can be used as an acceptance indicator for the CBPM. In turn, the test and analysis process can also provide guidance on the design and processing of the cavity.

However, the evaluation of crosstalk in major laboratories mostly rests on the cold test method that uses a network analyzer to measure the transfer coefficient between ports [12, 13]. Although the benefit of the cold test is its convenience, it also has great significance for exploring ways to evaluate crosstalk under the beam conditions. Then, high energy accelerator research organization (KEK) and Stanford Linear Accelerator Center (SLAC) adopted a method to analyze the crosstalk between the position cavities in the time domain [14, 15]. The beam in the Y-direction was set in the electric center first, and then the beam was adjusted with a larger offset in the X-direction; the output signal of the Y-port was detected and considered the crosstalk from the X cavity. However, this method has two shortcomings and cannot be used as a precise evaluation method. First, the electric center of the cavity is difficult to find because of the existence of beam jitter. Second, if the beam position in the Y-direction also has a slight drift when adjusting the beam position in the X-direction, the output signal of the Y-port will contain a crosstalk signal from the X cavity and a signal from the Y cavity due to the slight drift of the beam position in the Y-direction (it is difficult to ensure that the beam can move strictly in one direction regardless of the platform or kicker motion). These will have a great impact on the evaluation of the crosstalk signals.

To study the effect of crosstalk between cavities for the beam position measurement, the relevant beam experiments were performed at the Shanghai deep ultraviolet free-electron laser (SDUV-FEL) and DCLS facilities. In this paper, the causes of the transverse crosstalk are described and two methods are proposed to evaluate the crosstalk between cavities on the basis of the RF signal of the CBPM probe, which can eliminate the two shortcomings described previously. The specific analytical method is discussed in the following section.

2 Detection principle of the cylindrical CBPM

A cylindrical pill-box CBPM can adopt a resonant cavity structure and use antisymmetric characteristic modes, coupled from the cavity, to measure the beam position. When the beam source runs along the z-axis, the axial electric field component of the TM110 mode in cylindrical coordinates can be expressed by

$$E_z(\rho, \phi, z) = E_0 J_1\left(\frac{\chi_{11}\rho}{r}\right)\cos\phi, \tag{1}$$

where E_0 is the amplitude of the electric field, J_1 is the first-order Bessel function of the first kind, χ_{11} is the first root of $J_1(\rho) = 0$, r is the cavity radius, Φ is the angle between the field of TM110 mode and axial direction, and ρ is the radial coordinate. Because $J_1(\rho)$ is proportional to ρ when $\rho \sim 0$, the excited voltage of the TM110 mode is proportional to the beam offset x and beam charge q, which can be described by

$$V_z = A_0 q x. \tag{2}$$

From Eq. (2), the RF voltage is zero when the beam is at the cavity center and is proportional to the beam offset. Thus, even a tiny variation can be easily detected by using a high-gain amplifier if the beam position is close to the center. However, for the button and stripline BPM, when the electron beam is close to the center, the signals from opposite electrodes must be subtracted, which could result in a significant loss of the effective number of bits. This limits their resolution to only approximately 10 µm. This is the reason why the cavity BPM is capable of high-resolution measurement.

In order to eliminate the variation effect of the beam charge, an additional monopole TM010 mode cavity was also employed. The signal amplitude of the monopole mode is independent of the beam position but is proportional to the beam charge only [16, 17].

3 The causes of transverse crosstalk

Transverse crosstalk of the cavities not only includes the crosstalk between the reference cavity and the position cavities but also includes the horizontal position cavity and the vertical position cavity. For the first case, if the distance between the reference cavity and position cavity is short and the pipe has a large diameter, then the possibility of crosstalk between them would exist. However, this type of crosstalk is easy to avoid in the process of the cavity design. Relatively speaking, the problem of crosstalk between the horizontal and vertical cavities is a more common phenomenon. An ideal cylindrical cavity BPM, as shown in Fig. 1 (left), has resonant modes polarized in the direction of displacement excited by the beam, whose

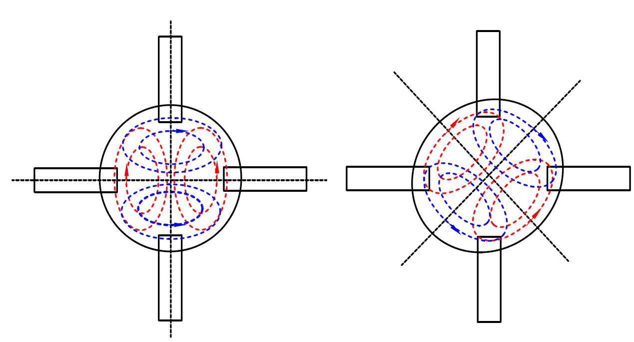

Fig. 1 (Color online) Ideal cavity and coupling (left) and cavity with distortion (right)

offset from the center axis (x, y) is equal to the sum of the two resonant modes polarized in the horizontal and vertical directions by the displacement x and y, respectively. Meanwhile, the waveguides mounted in the horizontal and vertical directions couple the signals so as to measure the corresponding displacement [18].

In reality, there are always some small distortions of the cavity symmetry due to factors such as fabrication tolerance and welding procedure. All these distortions together could be treated as causing a slight elliptical deformation of the cavity, but the cavity distortion caused by fabrication makes the orientation of the axis of the ellipse essentially unpredictable. As shown in Fig. 1 (right), because of the slight distortion in the cavity, the polarization of the two excited dipole modes of the magnetic fields is perpendicular to each other, but the polarization direction of the TM110 modes is no longer consistent with the mounting direction of the waveguide [19]. Under this circumstance, a set of waveguides couples two polarized resonant modes simultaneously to cause crosstalk.

In order to suppress the crosstalk, except by adopting a rectangular cavity structure, an effective approach is to introduce a structure that can fix polarization directions on the X- and Y-axes. Detailed methods can be found in the literature [18, 19]. Although crosstalk can be suppressed by the method described previously, it is still unavoidable for the cylindrical cavity. Thus, it is essential to evaluate the impact of transverse crosstalk on the measurement of the beam position.

4 PCA method

To meet the high-resolution beam position measurement requirement for SXFEL and DCLS, a low-Q CBPM was developed in the exploration process. The parameters of the low-Q CBPM are summarized in Table 1; an evaluation of the cavity performance regarding crosstalk under the beam conditions was performed at the SDUV facility [9].

4.1 System setup

To research the position dependence and the crosstalk of the output signals from the cavities, a two-dimensional motion platform was installed under the cavity that can imitate the beam offset in the both horizontal and vertical directions. A broadband oscilloscope (Tektronix DPO70604) with 6-GHz bandwidth and 25-GHz sampling rate was used as the data acquisition equipment. A diagram of the evaluation system is shown in Fig. 2. With the motion platform, the other direction is set at 0 μm when moving in the one direction. The output signals from the reference cavity and position cavity in every step were recorded in three channels of the oscilloscope simultaneously.

4.2 Principle of the PCA method

Principal component analysis (PCA) is a commonly used method for data analysis that transforms raw data into a set of linearly independent representations of each dimension by linear transformation so that the main characteristic components of the data can be separated and extracted.

The electromagnetic field in a cavity or a signal sampled from the cavity is a linear combination of the orthogonal modes determined by the property of the cavity. The goal of using PCA on the raw signals is to decompose the main mode, the leaked/coupled modes, and stochastic noises. It can be expressed by

$$V(t) = \Sigma_{\mathrm{m,n,p}} C_{\mathrm{m,n,p}} V_{\mathrm{m,n,p}}(t) + C_{\mathrm{noise}} V_{\mathrm{noise}}(t), \tag{3}$$

where the subscript m, n, p indicates the different orthogonal modes such as TM_{010} mode, TM_{110} mode, TM_{020} mode, and so on. The $V_{\mathrm{m,n,p}}(t)$ represents the temporary vectors for various orthogonal modes, so time-related properties such as the resonant frequency and the damping ratio of the modes can be studied separately, and it can confirm the physical source of the modes. The normalized $C_{\mathrm{m,n,p}}$ represents the spatial vectors that indicate the variance of the amplitude during the measurements. The last term is considered a component at the noise level.

From the property of the cavity and a data set of broadband RF signals with different beam positions, the PCA method can be used to evaluate the performance including mode identification and crosstalk evaluation and eliminate unwanted coupling to improve the measurement accuracy, among others [20–23].

Table 1 Parameters of the low-Q CBPM

	Horizontal position cavity	Vertical position cavity	Reference cavity
Resonant frequency (GHz)	4.77	4.77	4.70
Loaded Q factor	73	68	223
Number of ports	2	2	2

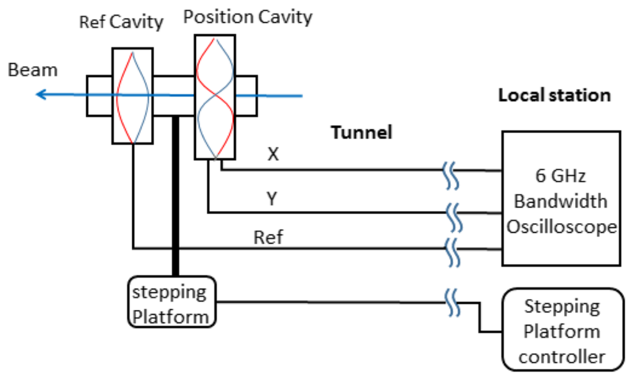

Fig. 2 Diagram of the system

4.3 Mode identification and crosstalk evaluation

For the mode identification and crosstalk evaluation in the vertical position cavity, a signal matrix is formed by moving the cavity vertically and acquiring the signals of the vertical position cavity at every step. By using PCA on the signal matrix, the singular values of the modes were obtained as shown in Fig. 3. As can be seen from the figure, three modes were obviously larger than the others. Therefore, we mainly analyzed the first three modes, and the rest of the model can be considered as the noise floor.

The strength of the first two modes is much higher than that of the other modes. From the spectrum of the temporal vectors, as shown in Fig. 4a (for ease of observation, the amplitude of the modes was not multiplied by the corresponding singular value), the resonant frequency is 4.77 GHz and the Q factor is 68, which are consistent with the design values. At the same time, the mode amplitude of the first two modes has linear correlations with the vertical position of the beam, which can be seen at the spatial vector distribution of the first three modes (Fig. 4b). These indicate that modes 1 and 2 are jointly characterizing the TM110 mode of the position cavity, that is, the main operation mode of the position cavity.

For the third mode, its mode amplitude is independent of the beam position. Combined with the spectrum of the temporal vectors, the mode not only includes the TM010 mode ($f_{\mathrm{pos},010}$ = 3.3 GHz) and the TM020 mode ($f_{\mathrm{pos},020}$ = 6.2 GHz) of the position cavity, but also has a strong mode deriving from the reference cavity ($f_{\mathrm{ref},010}$ = 4.7 GHz, Q = 223).

The existence of the crosstalk between the reference cavity and vertical position cavity was detected using the PCA method. The crosstalk was caused by the short distance between the two cavities (35 mm) so that the damping effect was not sufficient. Because the resonant frequency of the reference cavity is close to that of the position cavity, the effect of the crosstalk should be evaluated carefully.

The intensity of the principal mode signal (4.77 GHz) at different positions was obtained by harmonic analysis, as shown in Fig. 5; the position sensitivity of the principal mode was also obtained by linear fitting. The crosstalk signal from the reference cavity was unrelated to the beam position, so the amplitude was a fixed value that could be obtained by the separated mode. As illustrated in Fig. 6, combined with the position sensitivity, the effect of the crosstalk from the TM010 mode of the reference cavity to the TM110 mode of the vertical position cavity is approximately 4 µm. At the same time, it can also be seen that the spectrum amplitude of the signal crosstalk from the reference cavity has dropped at the resonant frequency point of the vertical position cavity. This is due to the difference in resonant frequency between them, so the effect on the performance of the vertical position cavity is smaller than the condition of the same resonant frequency.

From these analysis results, we verified that the PCA method is a powerful tool to analyze the RF signal of the cavity probe. Moving the position of the probe to construct the data matrix and PCA is a benefit by separating the two types of resonant modes from the original RF signal, that is, the position-independent mode and position-dependent mode. Combined with the information of the signal strength of the mode, resonant frequency, and Q value, we can confirm the source of the main mode, measure the characteristic parameters, and analyze the influence of the mode on position measurement.

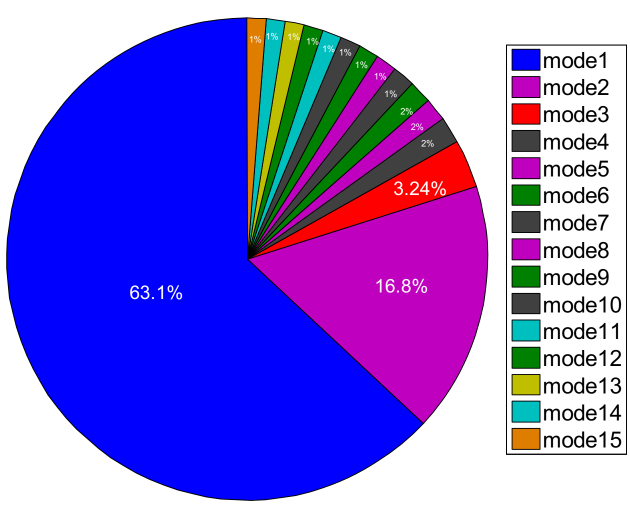

Fig. 3 (Color online) Singular values of the modes

5 Method of harmonic analysis

According to the design experience of the low-Q cavity BPM, a high-Q cavity BPM was redesigned for further study. Among them, the distance between the two cavities

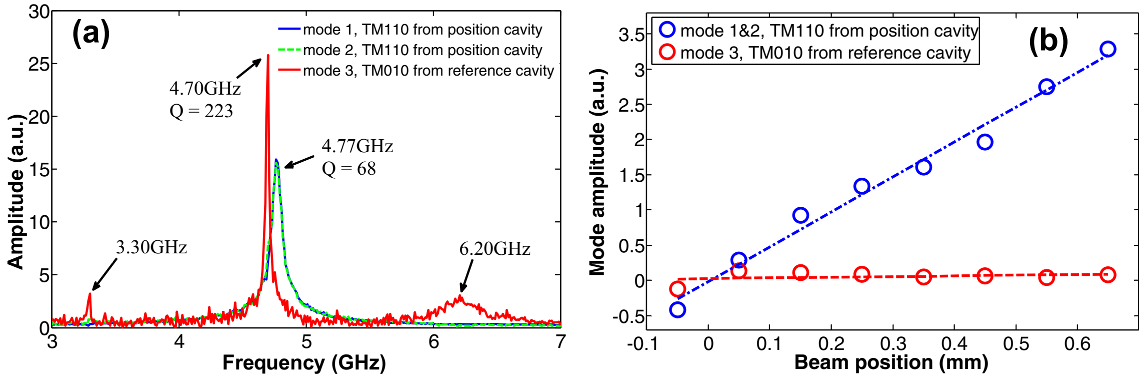

Fig. 4 (Color online) **a** Temporal vector distribution and **b** spatial vector distribution of the first three modes

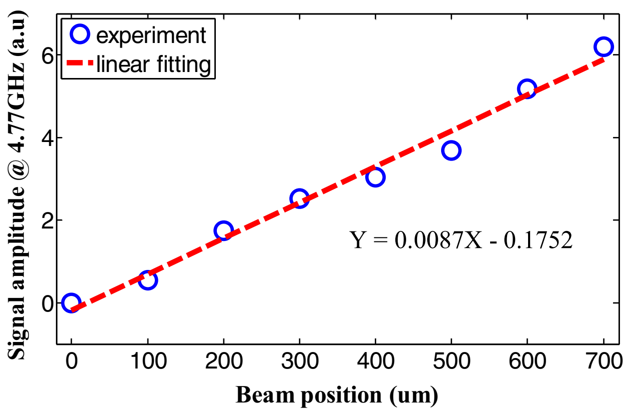

Fig. 5 (Color online) Position sensitivity of the TM110 mode

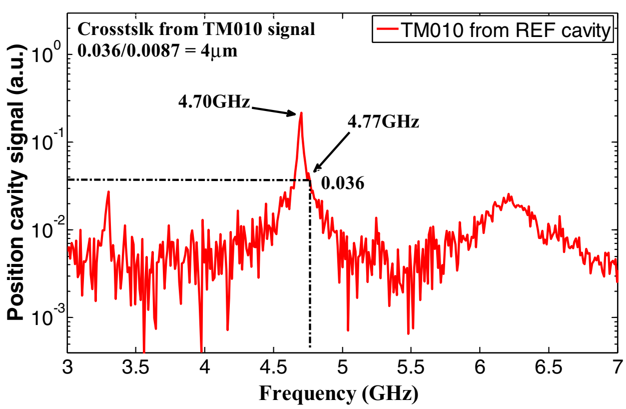

Fig. 6 (Color online) Crosstalk from the TM010 mode of the reference cavity to the vertical position cavity

was increased from 35 to 45 mm so as to reduce the possibility of signal coupling between them. In addition, for the convenience of measuring the isolation between the cavities and reducing the effects on CBPM performance, cavities with a slight difference in resonant frequency were designed purposely. The parameters of the high-Q cavity are shown in Table 2, and a detailed description can be found in Ref. [10].

5.1 System setup

In order to evaluate the transverse crosstalk of the high-Q CBPM with the beam, a tested system was built, similar to the low-Q CBPM, except with a preamplifier front end added in the tunnel, which can minimize the RF signal losses from the long connection cables. The two-dimensional motion platform was also installed under the cavity to imitate the beam offset from − 300 to 300 μm with a step of 100 μm. The diagram of the evaluation system is shown in Fig. 7.

5.2 Principle of the harmonic analysis

In order to separate the crosstalk signal from the interference signal due to the offset and slight drift of the platform, the data processing was performed in the frequency domain. The characteristic of the signal spectrum of the cavity is dependent on the characteristics of the cavity only, such as the resonant frequency and Q value, and independent on the position of the beam. These also can be illustrated by the Fourier transform [24] of the sinusoidal attenuation signals, as shown in

$$F(\omega) = \frac{1}{2\pi} \times \frac{e^{i(\Phi - \omega_0 t_0)}}{\frac{1}{2\tau} + i(\omega - \omega_0)}, \tag{4}$$

where ω is the angular frequency, ω_0 is the resonant angular frequency of the given cavity, τ is the decay time of the cavity, and φ and t_0 are the initial phase and initial time of the excitation of the cavity signal, respectively. The expression of the signal spectrum is taken modulo for Eq. (4), which can be expressed by

$$F = \frac{A}{\sqrt{\left(\frac{1}{2\tau}\right)^2 + 4\pi^2 \times (f - f_0)^2}}, \tag{5}$$

where A is a variable which depends only on the beam offset. τ and f_0 are constants for a given cavity and express the decay time and the resonant frequency of the cavity,

Table 2 Parameters of the high-Q CBPM

	Horizontal position cavity	Vertical position cavity	Reference cavity
Resonant frequency (GHz)	4.680	4.688	4.694
Loaded Q factor	4252	4339	2280
Number of ports	2	2	2

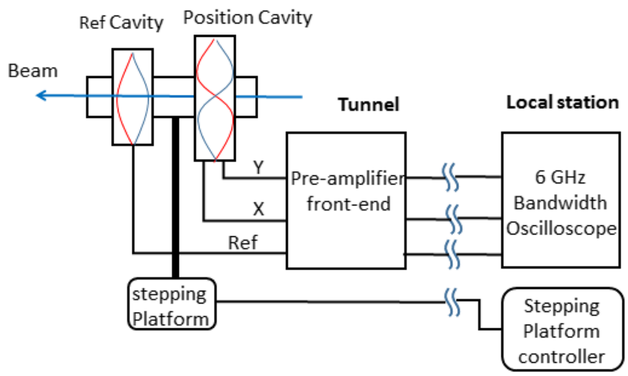

Fig. 7 Diagram of the system

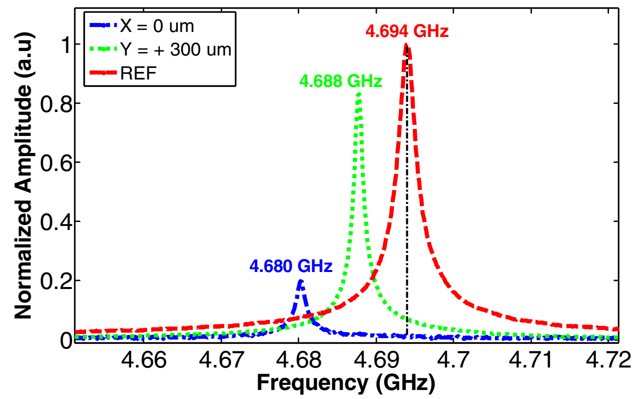

Fig. 8 (Color online) Frequency spectrum of the reference and position cavity

which can be fitted with Eq. (5) on the basis of the data of the cavity. It is better to fit at a larger beam offset so as to diminish the impact of the crosstalk.

When the spectra of the horizontal and vertical directions are fitted, respectively, in the larger offset to obtain the corresponding τ and f_0, then the overall fitting function F_{all} is obtained as shown in

$$F_{\text{all}} = A_x F_x + A_y F_y. \tag{6}$$

A_x and A_y represent the signal magnitude for horizontal and vertical cavities, respectively. F_x and F_y are the corresponding spectral functions. So that the signals of different cavities can be separated for analysis.

5.3 Analysis of the crosstalk

From the experimental data and the method of harmonic analysis, in view of the reference cavity, there is almost no crosstalk to the position cavity, as can be seen in Fig. 8; the research evaluated only the crosstalk of the CBPM between the horizontal and vertical cavities.

The spectra of the horizontal and vertical position cavity were fitted, respectively, in the larger offset to obtain the corresponding τ and f_0; the fitting results were perfect, as shown in Fig. 9.

The cavity was moved horizontally, and the data of the vertical channel were fitted with Eq. (6) at every position. Figure 10b shows the spectrum of overall fitting when the horizontal is located at + 300 µm and the vertical is located at 0 µm; combined with the calibration factor of the vertical direction (Fig. 10a), it can be seen that the crosstalk of the horizontal position cavity to the vertical position cavity was approximately 0.84 µm.

The crosstalk from the horizontal position cavity to the vertical position cavity at different offsets could be obtained, and the degree of crosstalk was obtained by the slope as shown in Fig. 10c, approximately − 52.6 dB.

Similarly, the crosstalk from the vertical position cavity to horizontal position cavity can be handled in the same way. Figure 10d, e illustrates that the crosstalk of the vertical position cavity to the horizontal position cavity is approximately 0.16 µm when the vertical is located at + 300 µm. The degree of the crosstalk was also obtained as shown in Fig. 10f, which is smaller than the crosstalk from the horizontal position cavity to the vertical position cavity, approximately − 71.4 dB. The results show that the isolation between the cavities meets the requirement of less than − 40 dB.

The method of harmonic analysis combined with the motion platform not only can eliminate the problem of finding the electric center of the cavities exactly, but also can exclude the interference of other signals including the mechanical interference from the motion platform. However, when the resonant frequencies of the cavities are closed and the Q value is very low, an accurate fitting and separation of the crosstalk signal cannot be realized because of the large spectral bandwidth. For the PCA method, the crosstalk signal can be separated as long as the data contain different characteristic modes, but the experimental scheme must be designed accordingly to construct the position-independent mode and position-dependent mode. Although the experiment process and data

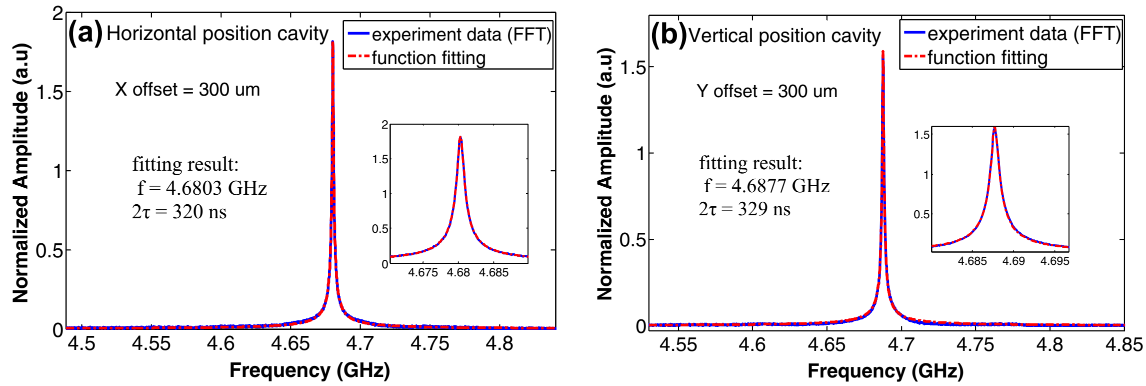

Fig. 9 (Color online) Fitting results of **a** the horizontal position cavity and **b** the vertical position cavity

processing are more complicated, the method is more powerful, which also can eliminate the limits on the method of harmonic analysis mentioned previously.

6 Effects on CBPM performance

From the preceding analysis, the crosstalk was evaluated by the PCA method and harmonic analysis method, but how the performance of the CBPM was affected by the crosstalk must still be analyzed.

6.1 Crosstalk from the reference cavity

For the case of crosstalk from the reference cavity to the position cavity discussed in Sect. 4, because the signal amplitude of the reference cavity is independent of the beam position, it is proportional to the beam charge only. Therefore, it is necessary to consider only the effect of crosstalk from the reference cavity on the precision and resolution of the CBPM when the beam charge is jittered. The effect of the crosstalk signal on the position cavity can be expressed briefly by

$$\begin{aligned}\text{Position}_{\text{measure}} &= \frac{(1+\Delta m)\cdot A_{\text{pos}} + (1+\Delta m)\cdot A_{\text{ref}}\cdot C}{(1+\Delta m)\cdot A_{\text{ref}}}\cdot k_{\text{pos}} \\ &= \frac{A_{\text{pos}}}{A_{\text{ref}}}\cdot k_{\text{pos}} + C\cdot k_{\text{pos}},\end{aligned} \tag{7}$$

where the subscripts ref and pos represent the reference cavity and position cavity, respectively. A_{pos} and A_{ref} represent the signal magnitude for the corresponding cavities. Δm represents the variation of the cavity signal due to the jitter of the beam charge, k_{pos} is the calibration factor of position cavity, and C is the crosstalk factor between the reference cavity and position cavity. From Eq. (7), the first term is the position measured by the position cavity without crosstalk, and the second term represents the contribution of the crosstalk from the reference cavity. Because this contribution is a fixed value that depends on the crosstalk factor and calibration factor, this type of crosstalk affects only the precision of the position measurement and has no effect on the resolution. On the basis of the low-Q CBPM system, the precision of the position measurement is 4 µm.

6.2 Crosstalk between position cavities

For another case of crosstalk between position cavities (the crosstalk was evaluated in Sect. 5), the effects on the performance of the CBPM also should be analyzed by a similar method. Considering the crosstalk from the horizontal cavity to the vertical cavity, the beam charge jitter and the beam position jitter of the X-direction must be taken into account because the signal of the position cavity is mainly related to the beam offset and beam charge. The effect of the crosstalk signal from the horizontal cavity to the vertical cavity can be expressed by

$$\begin{aligned}\text{Position\_}Y_{\text{measure}} &= \frac{(1+\Delta m)\cdot A_y}{(1+\Delta m)\cdot A_{\text{ref}}}\cdot k_y \\ &\quad + \frac{(1+\Delta m)\cdot (A_x+\Delta A_x)}{(1+\Delta m)\cdot A_{\text{ref}}}\cdot k_x\cdot C_{x-y} \\ &= \frac{A_y}{A_{\text{ref}}}\cdot k_y + \frac{A_x}{A_{\text{ref}}}\cdot k_x\cdot C_{x-y} + \frac{\Delta A_x}{A_{\text{ref}}}\cdot k_x\cdot C_{x-y},\end{aligned} \tag{8}$$

where Δm represents the variation of the cavity signal due to the jitter of the beam charge, and C_{x-y} and ΔA_x are the crosstalk factor from the horizontal cavity to the vertical cavity and the beam position jitter of the X-direction, respectively. k_x and k_y represent the calibration factor for the corresponding cavities. From Eq. (8), the first term is the position measured by the vertical position cavity without crosstalk, and the latter two terms represent the contribution of the crosstalk from the beam position jitter of the X-direction. The second term contributed an offset

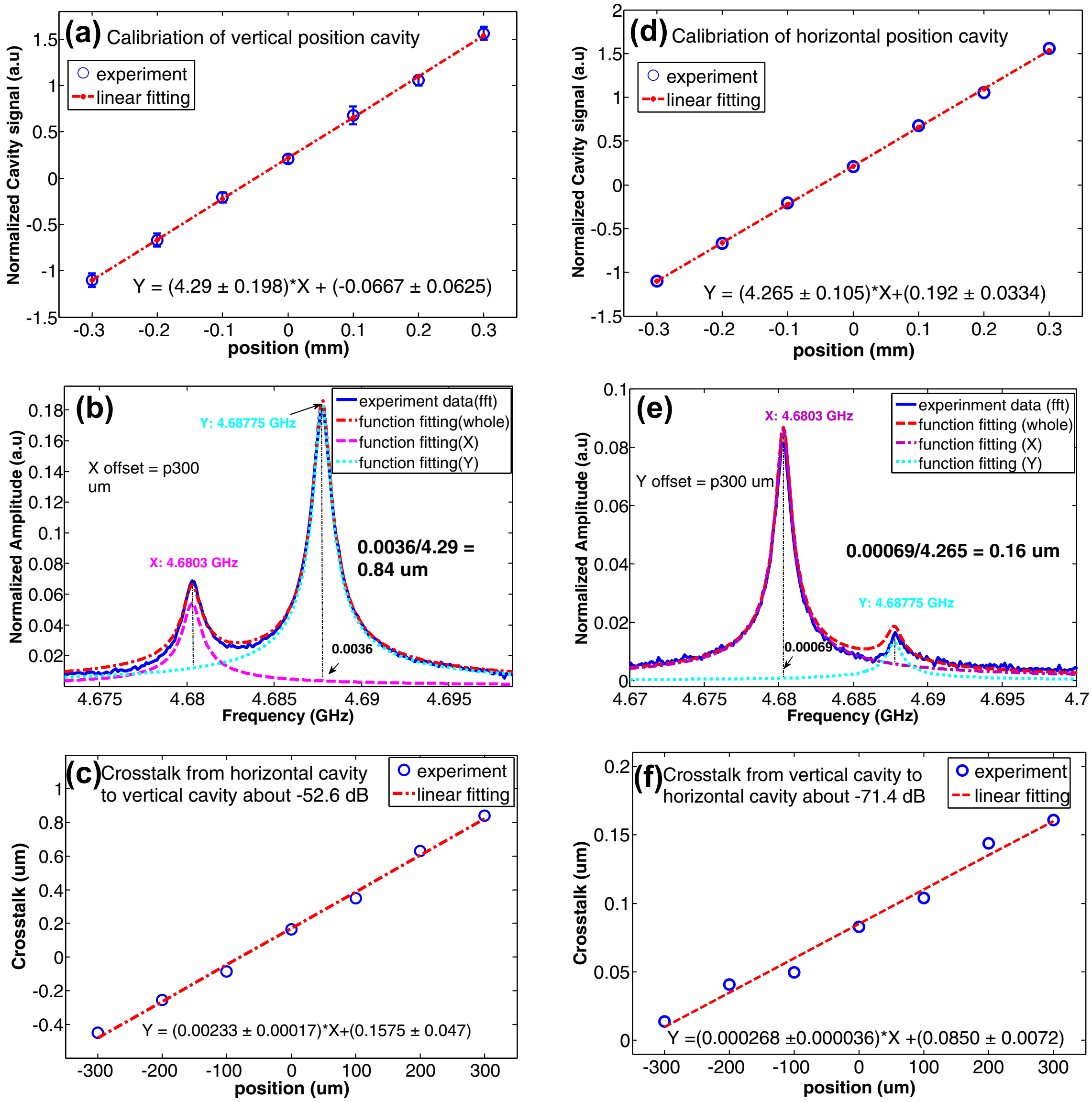

Fig. 10 (Color online) **a** Calibration factor of the vertical position cavity, **b** crosstalk from the horizontal cavity to the vertical cavity when x = p300 μm, and **c** degree of crosstalk from the horizontal position cavity to the vertical position cavity, **d** calibration factor of the horizontal position cavity, **e** crosstalk from the vertical cavity to the horizontal cavity when y = p300 μm, and **f** degree of crosstalk from the vertical position cavity to the horizontal position cavity

related to the beam position of the X-direction, and this term affects the precision of the position measurement and has no effect on the resolution. The third term has an effect on the resolution of the Y-direction when the beam position of the X-direction is jittered.

Taking Fig. 10b as an example, the two-dimensional motion platform was set at + 300 μm (from Fig. 10c, the real beam offset is approximately 360 μm because of the installation error of the motion platform) to imitate the beam offset of the X-direction and assuming the jitter of the beam position is 10%. Therefore, combined with a C_{x-y} of 0.00233, the precision of the vertical position cavity was evaluated as approximately 0.84 μm, and the effect for the resolution was approximately 19.7 nm.

7 Conclusion

In this paper, we described the causes of crosstalk and proposed two methods to evaluate the crosstalk between cavities. The PCA method decomposes the RF signal matrix directly from the cavity, and the position-independent mode and position-dependent mode can be separated; combined with the characteristics of the cavity, the influence of the mode on position measurement can be analyzed. By applying it to the low-Q prototype cavity, the effect of the crosstalk from the reference cavity to the vertical position cavity of approximately 4 μm was evaluated. The method of harmonic analysis by the way of fitting the spectrum of the cavity signal in the frequency domain based on the cavity characteristics can make the object become very intuitive and can exclude the interference of other signals, but it is also limited by the different resonant frequencies of the cavities to be analyzed and better used in the case of a higher Q value. Combined with the experiment performed at DCLS, the crosstalk between the horizontal and vertical position cavities is less than − 50 dB. In addition, the effects of the crosstalk on the performance of the CBPM are discussed. All results show that the two methods are effective and practical to analyze the crosstalk between cavities.

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