Subpicosecond beam length measurement study based on the TM_{010} mode

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This article discusses a beam length measurement technique based on the TM_{010} modes of two cavities in frequency domain. Since the TM_{010} pickup monitor has a much better signal-to-noise ratio (SNR) than the other monitors, it can improve the measuring range and resolution limit of the beam length measurement in the frequency domain to achieve the real-time measurement of the pulse duration of the order of 1 ps or less with the resolution of about 10 fs. The root-mean-square length of a beam—which does not necessarily have a Gaussian distribution—can be obtained by choosing the working frequency of the cavity to be much less than the critical frequency of the beam. The modeling and analysis of the above theory were also made simultaneously. The resulting resolution was about 100 fs when the step size was chosen to be 200 fs in this simulation after the higher order mode coupling effect was eliminated and the beam offset was corrected by using the Bessel function. An efficient algorithm was also provided in case the measurement system would achieve the SNR of 112 dB when there could be some issue in signal processing. This algorithm can still provide the length result with the resolution of 3.5 μm for a beam duration of 0.1 ps when the SNR of the difference signal is as low as 10 dB.

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I. INTRODUCTION

With the development of the free-electron laser (FEL), the basic requirement of the bunch length measurement has been upgraded to be competent to handle the beam that is less than 1 ps. The favorite design would be nondestructive, and the ability to do real-time or bunch-by-bunch measurement with the resolution not worse than 10 fs is preferable.

There have been some methods to get the length of the beam, which has the pulse duration of the order of only 1 ps or less, in an FEL facility, such as optical transition radiation method [1] and zero phasing method [2,3]. There are already comparisons between the femtosecond streak camera, the interferometer and the polychromator which detect the reflective optics, the coherent transition radiation (CTR) and the spectrum of CTR and coherent diffraction radiation, respectively [4]. But all of these methods will either cost a lot of time to process or it is difficult to get the beam length in less than 1 μs, and few methods are nondestructive. The electro-optic technique does achieve the above purposes, but it requires a very complex optical circuit design and it is not easy to be implemented [5–11]. The traditional measurement technique in frequency domain can get the beam length of the order of 10 ps, but the resolution is strictly limited by both the system signal-to-noise ratio (SNR) and the beam length to be measured. Typically, the beam length of about 10 ps with the resolution of about 1 ps can be obtained by using this technique when the signals from button or stripline beam position monitors (BPM) are used [12], which makes it unwise to adopt this method directly in FEL.

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II. BACKGROUND

Beam length measurement in frequency domain is an ancient technique which started half a century ago [13]. A series of researches [14–17] have been done later that were based on the measurement of the power spectrum in SLAC. A waveguide was used under that circumstance to extract the power spectrum of the beam; hence, the band which was lower than its cutoff frequency was blocked. Considering the effect of the propagation in the waveguide, the beam spectrum higher than 10 GHz was finally formed by using the Fourier transform spectrometer (FTS) [15]. The beam length was then obtained by applying an inverse Fourier transform. This technique can be used to measure the beam longer than 1 ps with the resolution of the order of 100 fs. The FTS is not fast enough and the measurement of a single macropulse is hard to implement.

Another bunch length measurement has been made in KEK that used the signals of two different frequencies from striplines or BPMs and was able to do bunch-by-bunch measurement in broadband mode. It was able to get the beam length of 10 ps with the time resolution of about 1 ps [18]. This would still be incompetent in FEL because of the low SNR of the pickups.

Two critical factors, which contradict each other in some way, have been restricting the traditional measurement in frequency domain in FEL: (i) the beam is too short for such resolution requirements; (ii) the temporal profile of the beam is not Gaussian so that the spectrum distribution—especially the high frequency parts—is unknown.

To improve the traditional power spectrum method, one can measure enough signals at high frequencies, e.g., of the order of 10 GHz, with higher measurement accuracy, or measure the signals at lower frequencies to enlarge the measurement interval and get a larger Δf^2. But the signal distortion at high frequencies would surpass the measurement SNR when the distribution of the beam has changed, or the measurement accuracy would not be guaranteed when more and more higher order modes have been mixed in with the decrease of the measured signals' frequencies.

The beam length could not be obtained directly with the information of only a few frequencies if the spatial distribution is unknown. The only way that makes sense is to measure the signals at a series of frequencies and the beam length could be calculated by using an inverse Fourier transform which is almost identical to the power spectrum method mentioned above, and hence it has the same difficulty in applying it to the FEL field.

The length of the beam with an arbitrary shape can still be obtained by measuring the signals at two low frequencies [17,19]. But further analysis showed that Δf^2 would be bounded (the frequencies should be less than 10 GHz) so the resolution requirement of FEL would not be satisfied [the relation between Δf^2 and the resolution will be shown in (8)]. If the frequency difference is set large enough, the signal distortion mentioned above will cancel the benefit of the enlarged squared frequency difference.

It seems that the frequency measurement would be valid only when the signals in the low frequency band are measured with great accuracy in FEL where the beam length is limited to the order of 100 fs and the resolution is required to be about 10 fs. Considering the critical factors previously mentioned, a series of improvements have to be done to achieve the measurement ability of the electro-optic method in frequency domain.

Because of the characteristics of FEL, an SNR up to 100 dB is a decisive factor for the beam length measurement in the frequency domain. The cavity BPM can achieve the position measurement with the resolution of about 10 nm for the signal of the TM_{110} mode has a very high normalized shunt impedance R/Q. The amplitude ratio of the TM_{010} mode and the TM_{110} mode of the same cavity can be written as [20,21]

$$K_r = \sqrt{\frac{(R/Q)_{010}}{(R/Q)_{110}}} = \sqrt{\frac{2f_{110}}{f_{010}}}\frac{J_0(rk_{010})J_0(R_c k_{011})}{J_1(rk_{011})J_1(R_c k_{010})}, \qquad (1)$$

where f is the harmonic frequency of the TM_{010} mode or the TM_{110} mode, J_0 and J_1 is the 0-order and 1-order Bessel function, respectively, r is the beam position from the cavity center, R_c is the cavity's radius, and k is the wave number of the TM_{010} mode or the TM_{110} mode. It is verified that the resolution of the cavity BPM can achieve 0.05 μm when the beam charge is 1 nC [22,23]. It means that the measurement system noise equals to the output TM_{110} mode signal with beam condition 0.05 μm at 1 nC. In this case, K_r is up to 4×10^5, so the realizable system SNR of TM_{010} mode can be inferred up to 112 dB.

The traditional measurement in frequency domain requires the longitudinal beam profile to be Gaussian—or at least its spectrum is known—so that the characteristic length of the distribution could be calculated by measuring the amplitudes of two or more frequencies on its spectrum. The evaluation of the influence of the uncertainty of the distribution is needed in case the real shape of the beam in FEL could be more daedal.

When the trigonometric function term in the Fourier transformation is expanded in Taylor's series, the beam spectrum can be written as the following form [12,19]:

$$\begin{aligned} F(\omega) &= \int_{-\infty}^{\infty} f(t)\cos(\omega t)\mathrm{d}t \\ &= \int_{-t_{\min}}^{t_{\max}} f(t)\left(1 - \frac{\omega^2 t^2}{2} + \frac{\omega^4 t^4}{24} + O(\omega^6 t^6)\right)\mathrm{d}t \\ &\lesssim q\left(1 - \frac{1}{2}\omega^2\sigma_{\mathrm{rms}}^2 + \frac{\beta_2}{24}\omega^4\sigma_{\mathrm{rms}}^4\right), \end{aligned} \qquad (2)$$

where $f(t)$ is the beam's longitudinal distribution in time domain and its integral is the beam charge q. $\beta_2 \geq 1$ is the historical kurtosis and it is 3 if the distribution is Gaussian. The odd functions are trivial and have already been omitted. The beam distribution is bounded and tends to be platykurtic rather than leptokurtic in FEL, thus β_2 will not be intolerantly high. The third term can be used to determine the deviation between the real spectrum and its approximation when only the first two terms are considered in Eq. (2). The beam duration is of the order of 1 ps or shorter in FEL, so the relative difference will be less than 10^{-6} when the detection frequency is less than 10 GHz, regardless of the beam distribution. The difference increases with the beam length and the detection frequency, but it will be acceptably small enough when the detection frequency is not too high—e.g., less than 10 GHz—in FEL. Hence, this rms length measurement in frequency domain can be considered reliable, theoretically.

The amplitude of the signal of TM_{010} mode can be written as the following formula when a beam passes the cavity:

$$V = \pi q f_{010}\sqrt{\frac{Z}{Q_L}\left(\frac{R}{Q}\right)_{010}}\left(1 - \frac{2\pi^2 f_{010}^2 \sigma_L^2}{c_0^2}\right), \qquad (3)$$

where q is the total charge of the beam, f is the working frequency, Z is output impedance, Q_L is the quality factor, σ_L is the beam length, and $(R/Q)_{010}$ is the normalized shunt impedance of TM_{010} mode. If two cavities were used to be working at TM_{010} mode at different frequencies, the output signals would be

$$V_1 = \pi q \rho_1 \left(1 - \frac{2\pi^2 f_{010,1}^2 \sigma_L^2}{c_0^2}\right), \tag{4}$$

$$V_2 = \pi q \rho_2 \left(1 - \frac{2\pi^2 f_{010,2}^2 \sigma_L^2}{c_0^2}\right), \tag{5}$$

where

$$\rho_i = f_{010,i} \sqrt{\frac{Z}{Q_{L,i}} \left(\frac{R}{Q}\right)_{010,i}} \tag{6}$$

denotes the signal detection ability of the ith cavity. Thus, the formula of the beam length is visible:

$$\sigma_L^2 = \frac{c_0^2}{2\pi^2} \frac{V_2\rho_1 - V_1\rho_2}{V_2\rho_1 f_1^2 - V_1\rho_2 f_2^2}. \tag{7}$$

The resolution can be written as the following form since the beam length is much shorter than c/f_{010}:

$$\Delta\sigma_L \simeq \frac{c_0^2}{2\pi^2(f_{010,2}^2 - f_{010,1}^2)} \frac{\mathrm{SNR}_V}{\sigma_L}, \tag{8}$$

where SNR_V is the SNR of the TM_{010} mode. The resolution of the beam length measurement is strictly proportional to the SNR of the diagnostic system and varies inversely with the beam length itself, as shown in Eq. (8). It can be seen that the resolution can achieve 3.5 μm at 1 nC even if the beam length is only 0.1 ps when $f_{010,1}$ and $f_{010,2}$ are chosen to be 3 and 8 GHz, respectively, and the SNR is 112 dB, as shown in Fig. 1.

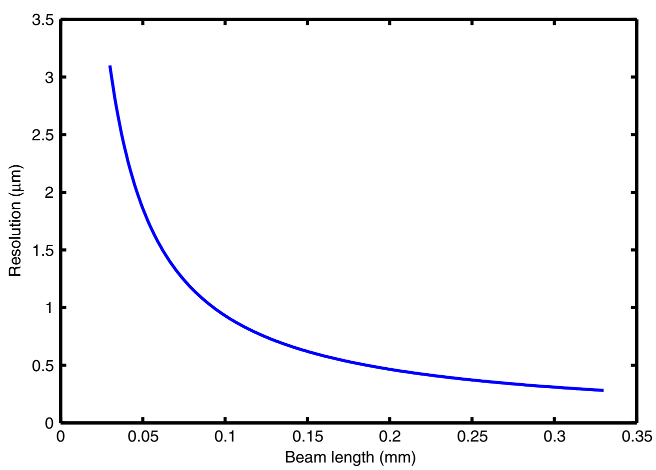

FIG. 1. Relation between the resolution and bunch length.

III. MODELING AND SIMULATING

A. Simulation targetting the local parameters

Simulations based on the above theoretical analysis were required to evaluate the effect of a variety of other modes propagating through the cavity and interference signals from some unknown physical phenomenon. MAFIA was used and the parameters from Shanghai deep ultraviolet (SDUV) FEL were picked in these simulations. The working frequency of the cavity BPM of the SDUV-FEL is designed to be 4.7 GHz, and the TM_{010} mode of the position cavity works at 3.6 GHz. Figures 2 and 3 are the waveforms from the reference cavity with beam charge of 1 nC and beam length of 10 ps in time domain and frequency domain, respectively. The beam charge is set to be 1 nC while the beam position takes the values of 0.25, 1.25, and 5.3 mm. Figure 4 shows the output amplitudes of the TM_{010} mode of beams with different lengths and different transverse locations. Although the amplitude of the signal of the TM_{010} mode is insensible to the beam offset,

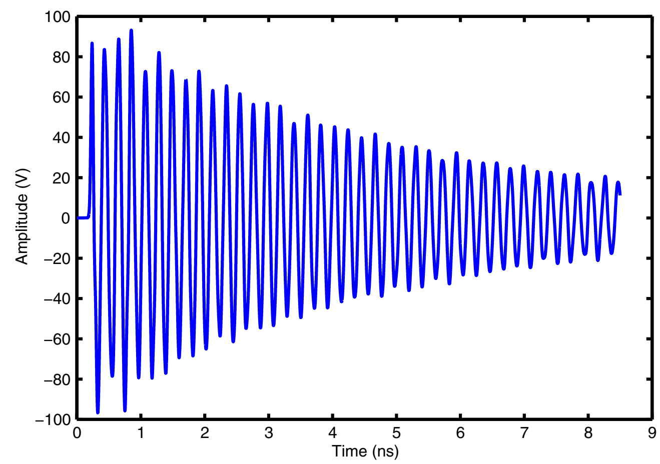

FIG. 2. Output signal of the TM_{010} mode from the reference cavity.

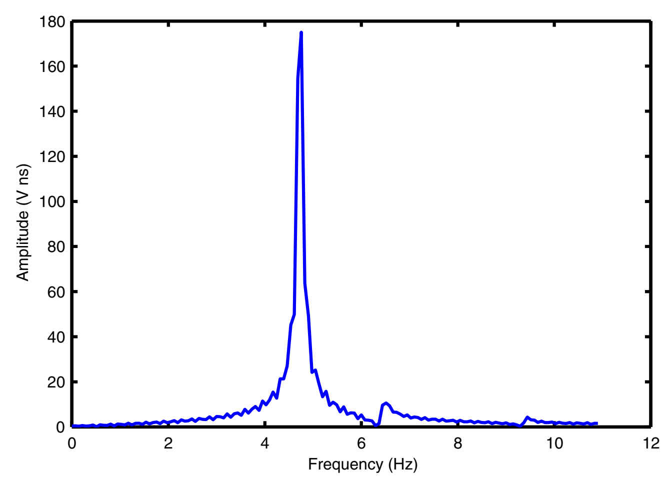

FIG. 3. Spectrum of the TM_{010} mode from the reference cavity.

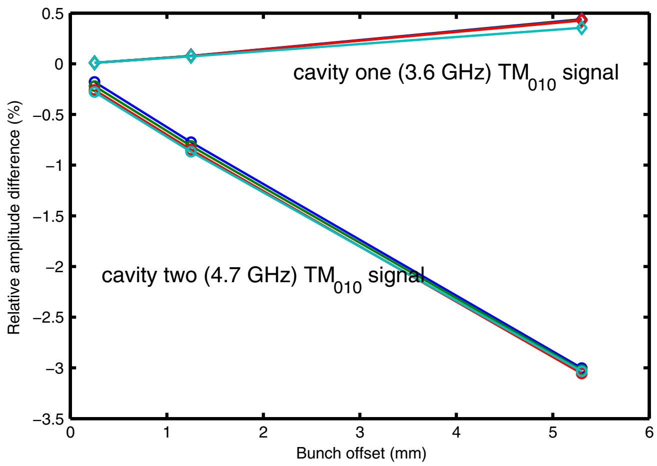

FIG. 4. Amplitude deviations when beam position changes. The beams with bunch length of 3, 5, 7.5, and 10 mm are marked in blue, green, red, and cyan lines, respectively.

TABLE I. Deviations of the beam length results of the measurement of the beams with different bunch lengths and transverse offsets.

Transverse offset (mm)	Initial bunch length (mm)	Calculated length deviation (mm)
0.25	3.0	+0.354
	5.0	−0.125
	7.5	−0.001
	10.0	+0.011
1.25	3.0	+0.795
	5.0	+0.190
	7.5	+0.208
	10.0	+0.170
5.30	3.0	+2.140
	5.0	+1.284
	7.5	+0.986
	10.0	+0.777

it is still changing with the position. The SNR will drop to about 40 dB if the deviation of the output amplitudes is considered as part of the diagnostic noise. The results of the bunch length measurement in frequency domain in this simulation could be seen in Fig. 5 or Table I.

B. Decoupling optimization

The TM_{010} mode is supposed to be an invariant of the beam position but the position correlation has been detected during the previous simulation, thus some position mode signal, such as TM_{110} mode, is assumed to be coupled into the output signal. The output structure has been redesigned to be symmetric to overcome the coupling (as shown in Fig. 6). Figure 7 shows the output results before and after the coupling structure is improved when the transverse offset of the beam center is 5.3 mm. Figure 8 and Table II show the output signals and beam length measurement results after this improvement. The SNR then increases to 60 dB and the resolution is about 0.3 ps when beam length is 10 ps.

C. Enlarge the squared frequency difference

Since the resolution of the measurement is inversely proportional to the squared difference between the working frequencies [as shown in Eq. (8)], it would decrease while the squared difference increases. Another simulation has been made when the working frequencies were changed to be 4.3 and 5.8 GHz. The output amplitudes and beam length results are shown in Fig. 9 and Table III.

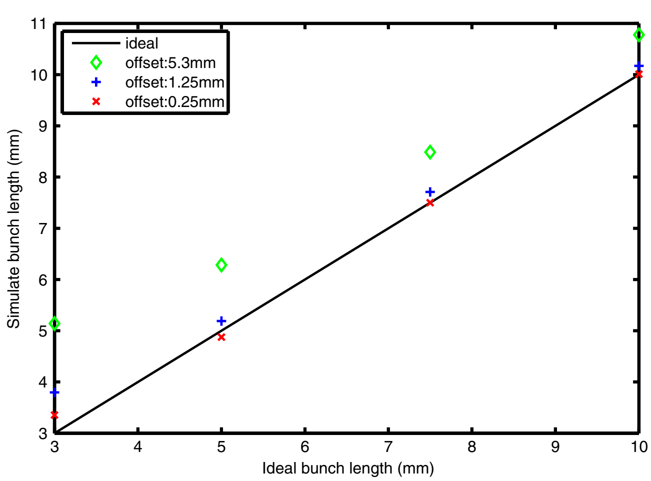

FIG. 5. Beam length simulation results of the measurement of the beams with different bunch lengths and transverse offsets.

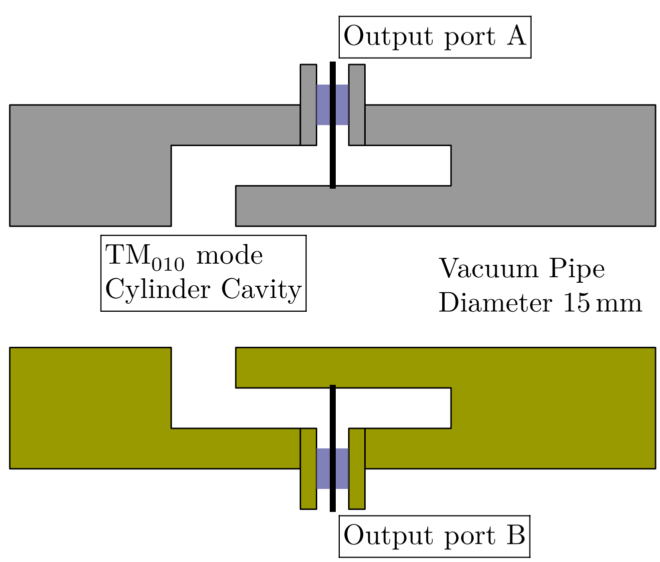

FIG. 6. Sketch of the final structure. Output port B, a completely symmetric output port of port A, was added to overcome the effect of TM_{110} mode.

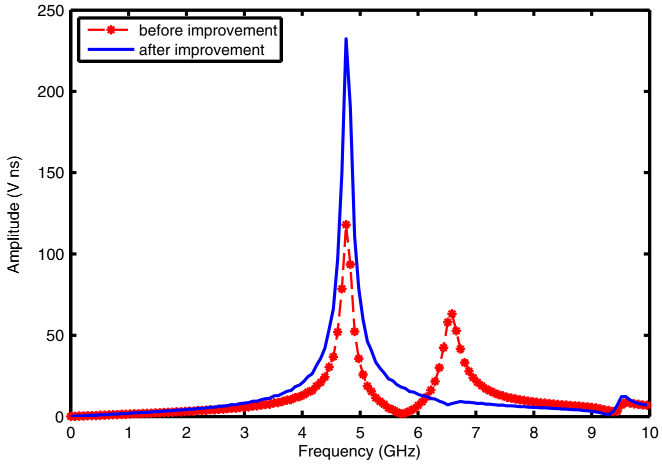

FIG. 7. The signals before and after the coupling structure between the TM_{010} mode and the TM_{110} mode was optimized.

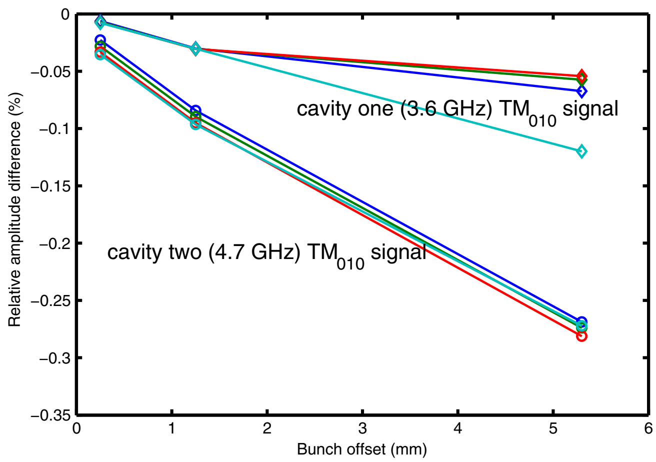

FIG. 8. Amplitude deviations when beam position changes after the coupling structure between the TM_{010} mode and the TM_{110} mode was optimized. The beams with bunch length of 3, 5, 7.5, and 10 mm are marked in blue, green, red, and cyan lines, respectively.

The frequency difference has not changed significantly, but the resolution is less than 0.3 ps now.

D. Other adjustments

From Figs. 8 and 9, it can also be seen that the absolute amplitude deviation of the output signal is proportional to the working frequency. This means that the amplitude of the TM_{010} mode's output is affected by a coefficient which is proportional to the frequency. Hence, the effects of (R/Q) which is determined by the Bessel term $J_0(rk_{010})$ has to be taken into account in Eq. (3). Figure 10 and Table IV have shown the improved simulation results of Fig. 9 and Table III after the adjustment of the $J_0(rk_{010})$ term. The deviation of the output amplitude has decreased

TABLE II. Deviations of the beam length results of the measurement of the beams with different bunch lengths and transverse offsets after the coupling structure between the TM_{010} mode and the TM_{110} mode was optimized.

Transverse offset (mm)	Initial bunch length (mm)	Calculated length deviation (mm)
0.25	3.0	+0.210
	5.0	−0.106
	7.5	+0.005
	10.0	−0.006
1.25	3.0	+0.239
	5.0	−0.087
	7.5	+0.017
	10.0	+0.004
5.30	3.0	+0.303
	5.0	−0.007
	7.5	+0.068
	10.0	+0.039

to 0.1%, and the corresponding resolution has been improved to be less than 100 fs. Since the minimum time step was set to be about 200 fs during the simulation in MAFIA, the beam length measurement with the resolution of 100 fs should be attainable when the bunch offset is reasonably small, i.e., 3 mm or less.

The results can be further improved if a linear adjustment to the transverse offset of the bunch is applied to the output signals since the amplitude difference of the output signal varies with the bunch offset linearly when the bunch is not severely deflected from the center of the vacuum chamber, e.g., the bunch offset is less than 3 mm, as shown in Figs. 4 and 8–10. It is still clueless whether this phenomena is a side effect of the simulation, e.g., the

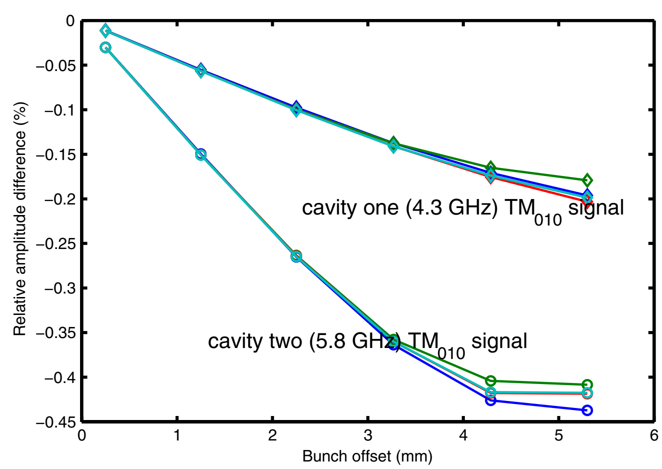

FIG. 9. Amplitude deviations when beam position changes after the working frequencies changed. The beams with bunch length of 1.5, 3, 5, and 7.5 mm are marked in blue, green, red, and cyan lines, respectively.

TABLE III. Beam length simulation results of the measurement of the beams with different bunch lengths and transverse offsets after the working frequencies changed.

Transverse offset (mm)	Initial bunch length (mm)	Calculated length deviation (mm)
0.250	1.5	+0.0280
	3.0	−0.0686
	5.0	−0.0027
	7.5	−0.0214
1.250	1.5	+0.1021
	3.0	−0.0293
	5.0	+0.0204
	7.5	−0.0059
2.250	1.5	+0.1711
	3.0	+0.0065
	5.0	+0.0418
	7.5	+0.0084
3.269	1.5	+0.2244
	3.0	+0.0352
	5.0	+0.0587
	7.5	+0.0196
4.288	1.5	+0.2502
	3.0	+0.0449
	5.0	+0.0657
	7.5	+0.0246
5.300	1.5	+0.2377
	3.0	+0.0400
	5.0	+0.0575
	7.5	+0.0197

computational accuracy, or due to some physical mechanism which has not been revealed yet. A proposal has been made to add two cavity BPMs to the booster-to-storage-ring transfer line of Shanghai synchrotron radiation facility to verify this phenomena as well as the validity of this method. But by now, no adjustments have been applied other than the Bessel one.

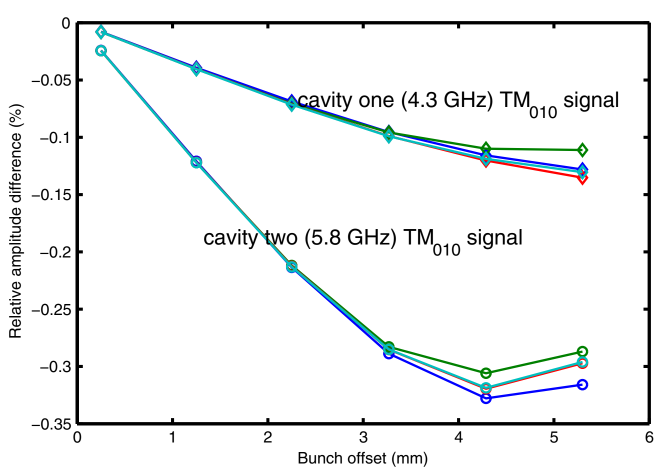

FIG. 10. Amplitude deviations after adjusting the $J_0(rk)$ term.

TABLE IV. Measurement deviations after the $J_0(rk)$ term adjusted.

Transverse offset (mm)	Initial bunch length (mm)	Calculated length deviation (mm)
0.250	1.5	+0.0255
	3.0	−0.0700
	5.0	−0.0035
	7.5	−0.0219
1.250	1.5	+0.0899
	3.0	−0.0359
	5.0	+0.0166
	7.5	−0.0085
2.250	1.5	+0.1500
	3.0	−0.0051
	5.0	+0.0349
	7.5	+0.0038
3.269	1.5	+0.1946
	3.0	+0.0184
	5.0	+0.0486
	7.5	+0.0129
4.288	1.5	+0.2116
	3.0	+0.0229
	5.0	+0.0525
	7.5	+0.0157
5.300	1.5	+0.1896
	3.0	+0.0127
	5.0	+0.0412
	7.5	+0.0087

E. Signal processing and error analysis

The loaded shunt impedance is larger than 100 Ω in the FWHM bandwidth in Fig. 2. The bandwidth in bunch-by-bunch beam length diagnostics is about 500 MHz. The amplitude of the signal in the bandwidth is about 70 V in this simulation. On the other hand, the amplitude of the thermal noise in the bandwidth is only about 20 μV. This means that the system SNR will be up to 130 dB when only the thermal noise has been taken into account.

It is obvious that the system resolution depends on the very high system SNR which is up to 112 dB. A realistic difficulty is to find an analog-to-digital converter (ADC) with effective number of bits (ENOB) of 21 bits which has both the dynamic range of 112 dB and the sampling speed of 10 MHz simultaneously, so the output signals from the two TM$_{010}$ modes have to be mixed to the same frequency. The signals can be input to a hybrid net after which the signals $\Sigma_V = V_1 + V_2$ and $\Delta_V = V_1 - V_2$ will be generated, as shown in Fig. 11. Then Eq. (7) can be written as

$$\sigma_L = \frac{c_0}{\sqrt{2}\pi}\sqrt{\frac{K_\rho - (1 + 2\Delta_V/\Sigma_V)}{K_\rho f_1^2 - (1 + 2\Delta_V/\Sigma_V) f_2^2}}, \tag{9}$$

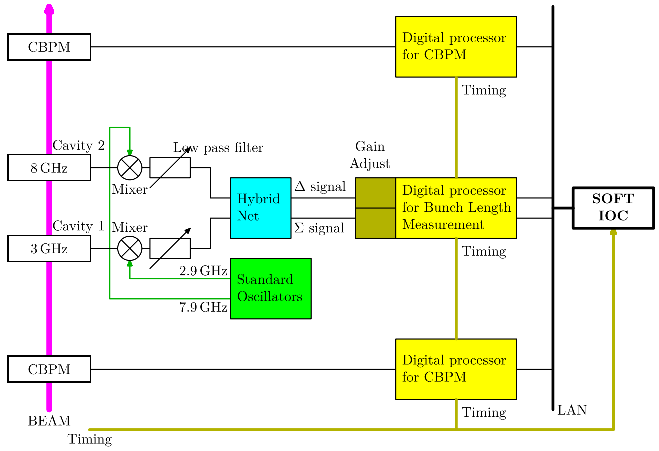

FIG. 11. Block diagram of the signal processing progress. Signals were mixed through a hybrid net to make full use of the ADCs.

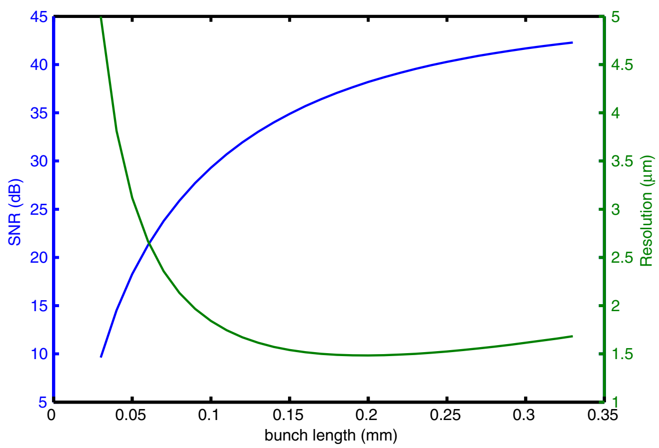

FIG. 12. SNR of the difference signal.

where K_ρ is the ratio of ρ_1 and ρ_2. When the system gains of V_1 and V_2 have been carefully adjusted to make sure that the value of Δ_V/Σ_V is about 50 dB, so that Δ_V and Σ_V can fit the full dynamic range of the ADCs, e.g., 60 dB for an ADC with ENOB of 10 bits. Then the resolution can be written as

$$\Delta\sigma_L \simeq \frac{c_0^2}{2\pi^2(f_{010,2}^2 - f_{010,1}^2)} \frac{1}{\sigma_L} \frac{2\Delta_V}{\Sigma_V} \left(\frac{n_{\Delta_V}}{\Delta_V} + \frac{2n_V}{\Sigma_V}\right), \quad (10)$$

where n_V and n_{Δ_V} consist of the signal noise from TM_{010} mode as well as the ADC noise. Figure 12 shows the SNR of the measurement system and the corresponding resolution when the signals of Δ_V and Σ_V are tuned and measured by ADCs with ENOB of 10 bits. It can be seen that the resolution curve is close to the one in Fig. 1.

IV. CONCLUSIONS

The authors have overcome the major shortcomings of the beam length measurement technique in frequency domain with a comprehensive improvement. The modified, yet still simple, scheme would achieve the measurement ability and resolution of the electro-optic method. Meanwhile, the undestructive and bunch-by-bunch features were reserved.

The beam length measurement in frequency domain based on TM_{010} mode has a very high SNR. This method enables the measurement of the beam length as short as 100 fs with the resolution of about 10 fs and the longitudinal beam distribution does not need to be Gaussian which is a prerequisite in traditional frequency domain measurement. Besides, the structure is compact and it is a noninterceptive device which can do real-time single shot measurement. Simulations—including mode decoupling, transverse offset dependency, working frequency tuning, and Bessel function adjustment—with MAFIA and the error analysis have also been done to calculate the beam length resolution and it is proved that the attainable resolution is close to the predicted one.

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