

# Ultrahigh spatiotemporal Resolution Beam Signal Reconstruction with bunch phase compensation

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## Abstract

Various electromagnetic signals are excited by the beam in the acceleration and beam-diagnostic elements of a particle accelerator. It is important to obtain time-domain waveforms of these signals with high temporal resolution for research, such as the study of beam-cavity interactions and bunch-by-bunch parameter measurements. Therefore, a signal reconstruction algorithm with ultrahigh spatiotemporal resolution and bunch phase compensation based on equivalent sampling is proposed in this paper. Compared with traditional equivalent sampling, the use of phase compensation and setting the bunch signal zero-crossing point as the time reference can construct a more accurate reconstructed signal. The basic principles of the method, simulation, and experimental comparison are also introduced. Based on the beam test platform of the Shanghai Synchrotron Radiation Facility (SSRF) and the method of experimental verification, the factors that affect the reconstructed signal quality are analyzed and discussed, including the depth of the sampled data, quantization noise of analog-to-digital converter (ADC), beam transverse oscillation, and longitudinal oscillation. The results of the beam experiments show that under the user operation conditions of the Shanghai Synchrotron Radiation Facility (SSRF), a beam excitation signal with an amplitude uncertainty of 2% can be reconstructed.

## Full Text

### Ultrahigh Spatiotemporal Resolution Beam Signal Reconstruction with Bunch Phase Compensation

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Various electromagnetic signals are excited by the beam in the acceleration and beam-diagnostic elements of a particle accelerator. Obtaining time-domain waveforms of these signals with high temporal resolution is important for research areas such as beam-cavity interactions and bunch-by-bunch parameter measurements. Therefore, this paper proposes a signal reconstruction algorithm with ultrahigh spatiotemporal resolution and bunch phase compensation based on equivalent sampling. Compared with traditional equivalent sampling, the use of phase compensation and setting the bunch signal zero-crossing point as the time reference enables construction of a more accurate reconstructed signal. This paper introduces the basic principles of the method, simulation results, and experimental comparisons. Based on beam test platforms at the Shanghai Synchrotron Radiation Facility (SSRF) and experimental verification methods, we analyze and discuss factors affecting reconstructed signal quality, including sampled data depth, analog-to-digital converter (ADC) quantization noise, beam transverse oscillation, and longitudinal oscillation. Beam experiment results demonstrate that under SSRF user operation conditions, a beam excitation signal with amplitude uncertainty of 2% can be reconstructed.

**Keywords:** turn-by-turn bunch phase compensation technique; equivalent sampling; signal reconstruction algorithm; ultrahigh spatio-temporal resolution; SSRF

## INTRODUCTION

Many electromagnetic signals are excited by electron beams in beam pipes, accelerators, and beam diagnostic elements of particle accelerators [?, ?]. These signals typically consist of a mixture of various oscillating modes and change rapidly with time [?, ?]. Therefore, obtaining time-domain waveforms of these signals with high temporal resolution is crucial for studying related problems such as beam-cavity interactions and bunch-by-bunch beam parameter measurements.

These signals can be calculated using analytical or numerical simulation methods [?]. However, such calculations become difficult when the beam vacuum chamber structure is complex, and it is challenging to determine whether the results are sufficiently accurate. Consequently, it is necessary to explore experimental methods for measuring these signals with high temporal resolution. Additionally, high-precision bunch-by-bunch measurements have become a focus of accelerator

research worldwide in recent years due to advancements in electronic technology and requirements for accelerator machine research [?].

However, the time resolution (sampling rate) and voltage resolution (effective number of bits) of actual sampling equipment are constrained by various conditions [?]. In beam measurement, the excitation signal from the electrode is often very narrow in the time domain. Taking the Shanghai Synchrotron Radiation Facility (SSRF) as an example, the pulse signal from single-bunch excitation has a width of less than 500 ps in the time domain, and the wakefield signal has a width of hundreds of ps [?]. Furthermore, the amplitude of the wakefield signal is relatively small compared to the bunch signal, requiring higher voltage resolution for effective measurement [?, ?]. Therefore, there is high demand for both time resolution and voltage resolution.

During this research at the Beam Instrumentation (BI) Group of SSRF, we could not find any commercially available sampling equipment that met these requirements. Recently, the BI Group at SSRF developed a set of technologies for 3D bunch-by-bunch position measurements based on a high-sampling-rate oscilloscope [?, ?]. The core algorithm of this technology is the response function projection method for the electrode to bunch signal. To obtain ultrahigh time resolution and ultrahigh voltage resolution response functions based on the equivalent sampling principle and statistical methods, we developed a data processing technique to reconstruct high-resolution periodic beam signals using measured data.

This paper provides a comprehensive introduction to the basic principles, simulations, and experimental comparisons of this method. Through beam experiments, we analyze the relationships between reconstructed signal quality and acquisition system parameters such as sampling rate, sampled data depth, and ADC quantization noise. Additionally, we investigate reconstructed signal quality under different beam conditions and discuss the impact of transverse and longitudinal beam position changes on signal reconstruction.

## II. BASIC PRINCIPLE

### A. Equivalent Sampling

To better match various parameter measurements in beam diagnostics, this study uses the extraction of the zero-crossing point of the pulse signal as the time zero point for the coordinate axis, rather than using the starting sampling point as in traditional equivalent sampling [?]. Moreover, this zero point is used to characterize the phase zero point of the beam bunch.

We assume that the excitation signal of the beam bunch is sufficiently stable and can be considered a periodic signal with a revolution period within a certain time interval. When an ideal data acquisition system digitizes the bunch signal  $s(t)$  with  $2N+1$  sampling points, the result of the  $n$ th sampling can be expressed as  $x(n) = s(T_0 + nT_s)$ , where  $n = -N, -(N-1), \dots, -1, 0, 1, 2, \dots, N$ ,  $T_0$  is the

zero-crossing point of the pulse signal, and  $T_s$  is the sampling period.

Because the signal is considered periodic, it can be expressed as  $s(t) = s(t+kT)$ , where  $k = 0, 1, 2, 3, \dots$  and  $T$  is the signal period.

The same signal is sampled multiple times by adjusting the initial sampling time. For example, by adjusting the initial sampling time step to  $\Delta t$  and performing  $M$  samplings, the sampling result can be expressed as  $x(n, m) = s(T_0 + m\Delta t + nT_s)$ , where  $n = -N, -(N-1), \dots, -1, 0, 1, 2, \dots, N$  and  $m = 1, 2, 3, \dots, M$ .

If the results of multiple samplings are equivalent to the same signal period, the sampling rate can be increased. This is known as the equivalent sampling rate. Theoretically, if there is an integer multiple relationship between  $T_s$  and  $\Delta t$ , the equivalent sampling time interval can be reduced to  $\Delta t$ , which corresponds to increasing the equivalent sampling rate from  $1/T_s$  to  $1/\Delta t$  [?, ?].

Figure 1: see original paper shows a typical waveform of equivalent sampling using a dashed blue line, exhibiting a signal with a period of 2000 ps. To sample this waveform three times using an ideal ADC, 12 points were sampled for each period. Based on the principle of equivalent sampling, mapping the data collected from the three cycles onto a single cycle can achieve a higher relative sampling rate for the sampled signal, as shown in Fig. 1(b). However, the bunch signal is not strictly periodic. The waveform represented by the dashed red line in Fig. 1(a) shows sampling of a bunch signal with longitudinal oscillations. If the waveform is directly reconstructed using the traditional equivalent sampling method, the results are as shown in Fig. 1(c), where blue circles represent equivalent sampling points and the dashed red line represents the original signal waveform. It can be observed from Fig. 1(c) that the sampling points have deviated significantly from the true values. Figure 1(d) shows the reconstruction result after applying the turn-by-turn bunch phase compensation technique. The use of turn-by-turn bunch-phase compensation leads to a reconstructed signal that closely matches the source signal.

## B. Signal Reconstruction

For ideal periodic signals and ADCs, the reconstructed signals should exhibit smooth curves. However, actual bunch signals are not strictly periodic; they exhibit certain longitudinal and transverse oscillations, and the ADC exhibits quantization errors and time jitter. To reduce errors caused by beam oscillations, the voltage and time of each sampling (for each ring of the beam) were corrected by subtracting the calculated transverse and longitudinal oscillations to approximate the real bunch waveform. To reduce random error introduced by the ADC, the reconstructed signal was sliced by time, and the most probable value in each slice was used to represent the value, with the time midpoint used to represent the time.

As shown in Figure 2: see original paper, for a signal with a period of 2000 ps, if an ADC with a time interval of 100 ps (sampling rate of 10 GHz) is

used for digitization, 7000 samplings are performed, with 20 sample points each time and a starting time 3 ps earlier for each sampling. After splitting 7000 sets of sampling data, a set of reconstructed data with an equivalent sampling rate of 70 THz was obtained. The blue waveform represents the reconstructed signal before subtracting the oscillation, and the orange waveform represents the reconstructed signal after subtracting the oscillation. In this case, the beam oscillation was relatively small, and no significant difference was observed, as shown in Fig. 2(a). In subsequent analysis, the impact of beam oscillation on reconstructed signal quality was further discussed and experimentally verified.

The reconstructed signal was divided into 100 time slices, with the midpoint representing the time of each slice. Figures 2(c), (d), (e), and (f) show the frequency distribution histograms of the 21st, 41st, 61st, and 81st slices, respectively. The curves in the figures represent normal distribution fitting curves. The value corresponding to the maximum frequency was considered the value for each slice. Thus, the response function is obtained via spline interpolation as shown in Fig. 2(b).

According to the principle of the equivalent sampling and signal reconstruction method, the sampled signal should satisfy the following conditions: it should be periodic (strictly repetitive) or quasi-periodic (with negligible variation during sampling) and have a high signal-to-noise ratio.

### III. UNCERTAINTY ANALYSIS

In the actual sampling process, the beam signal is not strictly periodic and contains nonrandom disturbances such as longitudinal oscillations. These processes are deterministic and measurable and can be considered during signal reconstruction to refine the beam signal and make it closer to a periodic signal. Additionally, for a non-ideal ADC, the sampled data contain random noise, which can lead to excessive errors in curve fitting or interpolation results.

#### A. Quantizing Noise

During the sampling process, quantization noise can be approximated to follow a uniform distribution. If the quantization step size is  $\delta$ , the quantization noise interval is  $[-\delta/2, +\delta/2]$  [?, ?]. Therefore, the quantization noise can be expressed as:  $n_q(t) \sim U(-\delta/2, +\delta/2)$ , where  $n_q(t)$  is the quantization noise of the sampling point at time  $t$  and  $U(-\delta/2, +\delta/2)$  represents a uniform distribution over the interval  $[-\delta/2, +\delta/2]$ .

Because quantization noise is additive, when only quantization noise is considered, the sampled signal can be expressed as  $x(t) = s(t) + n_q(t)$ , where  $x(t)$  is the sampled signal,  $s(t)$  is the real signal, and  $n_q(t)$  is quantization noise. Therefore, at any time  $t_0$ , the sampled signal satisfies  $x(t_0) \sim U(s(t_0) - \delta/2, s(t_0) + \delta/2)$ . Thus, for time  $t_0$ , the sampled signal follows this probability density distribution, whose mean value is the most probable value of this point.

Based on the above analysis, quantization noise with  $\delta$  equal to 2% of the original signal amplitude was constructed for simulation. The most probable value for each point was considered the result of the reconstructed signal. The relative uncertainty of the reconstructed signal was obtained via point-by-point subtraction of the original and reconstructed signals. The results show that when only quantization noise is present in the system, the uncertainty of the reconstructed signal is randomly distributed over the entire time domain, and the relative uncertainty of the reconstructed signal is less than  $1 \times 10^{-2}$  for quantization noise with  $\delta$  equal to 2% of the signal amplitude.

## B. Time Jitter

Similar to quantization noise, time jitter is a random signal at the sampling time and follows a normal distribution with expectation zero and variance  $\sigma_t$ , which is negatively related to the clock stability of the ADC [?]. Therefore, for any sampling point, the sampling time  $t_0$  meets:  $t_0 \sim N(t_0, \sigma_t)$ .

Assuming that the sampling time  $t_0$  and real signal  $s$  satisfy the mapping relation  $f$ , the probability distribution of the sampled signal at time  $t_0$  is shown in Figure 3: see original paper. According to the probability distribution of the sampled signal, it can be inferred that when the real signal satisfies monotonicity near the sampled point, the sampled signal follows a quasi-normal distribution, with the real value of the point as the most probable value, and the mapping relation  $f$  affects the sparsity of the probability density on both sides of the most probable value. When the real signal has an extreme point near the sampling point, if there exists  $f(t_1) = f(t_2)$  such that  $p(t_1) + p(t_2) > p(t_0)$ , where  $p$  represents the probability density at the corresponding time, then the most probable value is not equal to the value of the real signal at this point. Otherwise, the most likely value of this point is the value of the real signal at this point.

Based on the above analysis, clock jitter with a variance of 1 ps (the period of the original signal was 2000 ps, and the time interval was 0.1 ps) and mean of 0 was constructed. The sample number for each point was 10,000, and the frequency distribution at each point was calculated. Figures 3(b) and (c) show the results. As shown in Figs. 3(b) and (c), the simulation results are similar to those of the uncertainty analysis. At points away from the peak, the sample distribution followed an approximately normal distribution, and the most probable value was approximately the true value. Near the peak point, the frequency distribution of the sample no longer followed a normal distribution; however, the most probable value approximated the value of the peak point. Therefore, the most probable value can also be used to characterize the true value of a point.

The most probable value for each point was considered the result of the reconstructed signal. The relative uncertainty of the signal reconstructed by the proposed method can be obtained by subtracting the reconstructed signal from the most probable distribution of the original signal, as shown in Fig. 3(d). In addition, Fig. 3(d) shows that the effect of time jitter on signal reconstruction

is mainly concentrated away from the peak, and the uncertainty is small near the peak. For a beam signal with a period of 2000 ps and a time interval of 0.1 ps, the relative uncertainty caused by time jitter is less than  $1 \times 10^{-2}$ .

The existing acquisition equipment in our laboratory belongs to Keysight' s Infiniium MXR series, with a clock jitter of approximately 120 fs, which is far less than the ps-level beam longitudinal oscillation during SSRF user operation conditions. Therefore, in actual experiments, the error in the time dimension mainly originates from the beam' s longitudinal oscillation, and the influence of clock jitter on this method can be neglected.

#### IV. EVALUATION METHOD

This paper proposes methods for evaluating the quality of reconstructed signals under different conditions. One method involves calculating the standard deviation between the reconstructed and reference signals, which requires a relatively clear reference signal that may not exist in practical experiments. Therefore, the best measurement result obtained under optimal experimental conditions was selected as the reference signal to evaluate the relative uncertainty.

Another method involves evaluating the local quality of the reconstructed signal by calculating the second-order difference in the signal, which indicates the degree of signal unsmoothness. The standard deviation of the second-order difference of the reconstructed signal was calculated to evaluate the overall quality of the reconstructed signal, which is referred to as relative noise in this study.

#### V. BEAM EXPERIMENT

The Shanghai Synchrotron Radiation Facility (SSRF) is a third-generation synchrotron radiation source with an electron energy of 3.5 GeV, featuring high current intensity, high brightness, high beam stability, and low emittance. For the SSRF storage ring, the RF frequency is 499.654 MHz, and the harmonic number is 720 [?]. Based on these parameters, to analyze the relationship between different acquisition system parameters, different beam conditions, and reconstructed signal quality, a series of beam experiments were designed for verification.

##### A. The SNR of Sampled Data

When SSRF operates under user operation conditions, the filling mode of the bunch in the storage ring is shown in Figure 4: see original paper. There are 720 buckets in total filled with 500 bunches, divided into four bunch trains, each containing 125 bunches with 55 buckets spacing. Each bunch train is nearly uniformly distributed; however, there are bunches with larger or smaller charges at the head and tail of each bunch train. The range is fixed during a single sampling event using an oscilloscope, resulting in different signal-to-noise ratios (SNRs) between bunches with varying charges. Therefore, we evaluated

the impact of SNR on response function quality by comparing the responses of bunches with different charges based on single-sampling data collected by the oscilloscope.

Response functions were constructed separately for bunches with different charges, and the second-order differences of the response functions were then calculated. The standard deviation of the second-order difference over the entire period gives the result shown in Fig. 4(b), where it can be seen that there is an approximately inverse relationship between bunch charge and relative noise for the range of 0.1 pc to 1 pc. Therefore, the SNR of the sampled signal and the quality of the reconstructed signal were approximately inversely proportional within the experimental measurement range.

## B. The Depth of Sampled Data

In this experiment, the effects of different sampling depths were evaluated equivalently by truncating data for different lengths from the same sampling, where data length was measured in the number of beam turns. From a statistical perspective, larger sample sizes yield better expected statistical results. Therefore, in this experiment, the maximum depth of the oscilloscope (approximately 7000 turns) was selected as the benchmark for calculating the relative uncertainty of different sampling depths. The results are presented in Fig. 4(c). It can be observed that the greater the number of sampling groups, the smaller the relative uncertainty and the better the signal reconstruction quality.

## C. Beam Transverse Oscillation

To assess the impact of beam transverse oscillation on reconstructed signal quality, the transient process during storage-ring injection was used as a suitable window because it exhibits strong transverse oscillation. Therefore, the experimental data selected for analysis contained the storage ring injection. As shown in Figure 5: see original paper, injection occurs after approximately 800 turns, resulting in a transverse oscillation of approximately  $\pm 1$  mm. Figure 5(b) shows the normalized amplitudes of the signal peak values obtained by a single electrode for the same bunch at different turns, which were used to characterize beam transverse oscillation. As shown in Fig. 5(b), there was a relative change of 10% after injection.

Signals were reconstructed using data from the first 800 turns during injection. The first 800 turns were not affected by beam injection; therefore, they were used as benchmarks. The relative uncertainty was obtained by subtracting the two reconstructed signals, as shown in Fig. 5(c). From these results, it can be speculated that the relative uncertainty of the reconstructed signal can reach approximately 2% when there is a 10% transverse oscillation in the beam signal. Therefore, under conditions of transverse oscillation, if the required accuracy of the constructed signal is less than 2%, the influence of transverse oscillation can be ignored and the signal can be directly constructed; however, when the

required accuracy is better than 2%, data with small transverse oscillation or refined methods should be selected to construct the reconstructed signal.

#### D. Beam Longitudinal Oscillation

To analyze the influence of longitudinal oscillations on reconstructed signal quality, beam signals containing longitudinal oscillations were selected for evaluation, as shown in Figure 6: see original paper. The longitudinal oscillation ranges from -6 to 2 ps.

Based on the actual longitudinal oscillation, the original data were refined by subtracting the bunch phase caused by the longitudinal oscillation per turn, and the reconstructed signal was constructed based on equivalent sampling. The difference between the refined results and the results of direct signal reconstruction without compensation is the relative uncertainty, as shown in Fig. 6(b). As the reconstructed signal was normalized, the result in Fig. 6(b) can also be viewed as the relative uncertainty from longitudinal oscillation, with the relative uncertainty being better than  $2 \times 10^{-3}$ .

Furthermore, the second-order difference in the reconstructed signal before and after compensation can be calculated as relative noise, as shown in Figs. 6(c) and (d). Compared with the reconstructed signal, it can be seen that the relative noise is larger at points with a larger slope of the reconstructed signal, and this part of the difference can be significantly reduced by refining the original data.

In addition, the storage ring may be in different longitudinal oscillation states according to machine conditions, and another set of data with different oscillation states was selected for experimental analysis. As shown in Fig. 6(e), the longitudinal oscillations range from a few ps to -300 ps. Similarly, the results in Fig. 6(f) can be obtained by reconstructing the original signals before and after compensation and then taking the difference as the relative uncertainty. Clearly, when the amplitude of longitudinal oscillation is large, the uncertainty is very large, and the relative uncertainty reaches 10% under the conditions of this experiment.

In summary, for different acquisition systems, the signal quality cannot be guaranteed. However, for transverse and small longitudinal oscillations, compensation can be selected according to system requirements.

## VI. PERFORMANCE EVALUATION

Based on beam experiments, 200 sets of beam data at different times with maximum sampling depth (7000 turns), maximum sampling signal-to-noise ratio, and negligible transverse and longitudinal oscillations were selected for signal reconstruction. The standard deviations of 200 sets of reconstructed signals were calculated point-by-point after normalization. The relative amplitude uncertainty was characterized by this standard deviation, as shown in [Figure 7: see original paper].

Therefore, for the signal reconstruction method proposed in this study, the relative amplitude uncertainty is better than 2% when the sampling depth is at its maximum, the sampling signal-to-noise ratio is at its maximum, and the lateral and longitudinal oscillations are negligible.

## VII. CONCLUSION

A reconstruction method for periodic beam signals in an electron storage ring was developed based on the principle of equivalent sampling. Compared with traditional equivalent sampling, when constructing reconstructed signals of each bunch, the effect of multiturn bunch instability is reduced by subtracting transverse and longitudinal oscillations. The zero-crossing point of the signal pulse is taken as the time zero point, which facilitates subsequent study of signals such as beam wakefields based on the bunch.

Beam excitation signals with a relative amplitude uncertainty of 2% could fully satisfy the requirements of the response function for the bunch-by-bunch 3D measurement system. The reconstructed signal bandwidth in this paper was 4.2 GHz, and this method has no bandwidth limitations. If the data acquisition equipment and signal transmission networks are upgraded, they can be used to process signals with higher bandwidths. Therefore, this method can be extended to the sampling analysis of wakefield signals with bandwidths of tens of GHz.

The higher the number of ADC sampling bits and the larger the sampling depth, the better the quality of the reconstructed signal. For different beam conditions, longitudinal oscillations with large amplitudes must be compensated before signal reconstruction; otherwise, the authenticity of the reconstructed signal cannot be guaranteed.

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*Note: Figure translations are in progress. See original paper for figures.*

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