Baseline recovery method to measure bunch charge under low-current mode of SSRF

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Abstract The top-up injection mode of Shanghai Synchrotron Radiation Facility (SSRF) needs precise measurement of the beam bunch charges. This is performed by an integration current transformer, but the beam current is too low to neglect the background noise. In order to wipe out the noise coming from the ground loops, the adaptable polynomial fitting method is used to extract the baseline, instead of using the constant background or the linear background model. Test results show that the system resolution can be improved to <3%.

Key words Beam diagnostics, ICT, Bunch charge monitor, Top-up, SSRF

1 Introduction

A third generation light sources is capable of running in top-up mode and providing very stable beams for the users[1-4], and Shanghai Synchrotron Radiation Facility (SSRF) has made effort of doing so. The top-up mode requests frequent injection of beam bunches in low but precise charges. The absolute charge of each electron bunch is measured by an in-air integration current transformer (ICT) from Bergoz Instrumentation. When a bunch pulse, in typical width of several dozens of picoseconds, passes through the ICT probe, it generates a signal pulse of about 70-ns. The charge Q can be calculated by Eq.(1)[5,6]:

$$Q = \int i\mathrm{d}t = \int \frac{u_0}{5}\mathrm{d}t \qquad (1)$$

where i is current of the pulse and u_0 is it's voltage which can be measured by an oscilloscope directly. The charge can be calculated correctly when the output signal is noise-free. This was the case for SSRF when it was operated under the conventional mode with a typical beam bunch charge of 1 nC and a system resolution of less than 1%[6].

However, in 2010 when SSRF was preparing to start the new mode operation, an investigation about the required accuracy of the ICT measurements under the top-up mode indicated that the system resolution should not be greater than 10% at the charge of around 50 pC. Unfortunately, the ICT probe located at the transfer line was somehow affected (the modulator could be a major contributor) by the ground loops, and the noises were no longer negligible for injecting the ~50 pC bunch charges with reasonable accuracy.

Figure 1 is a typical waveform of the outputs. The signal is seriously entangled in the noise and the results would not practically be convincing by simply integrating the raw signals. The noise and the true response have to be analyzed individually so that they can be separated from each other.

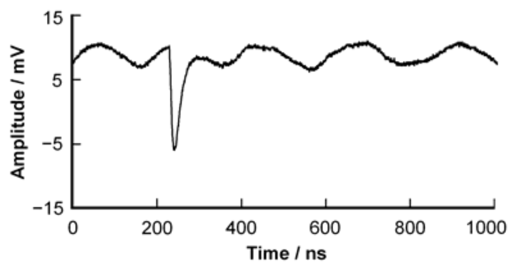

Fig.1 Signal affected horribly by the ground loops.

2 Baseline recovering

Spectral amplitude estimation is a common signal restoration approaches. Assuming that the signal and

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noise are not correlated, the noise signal $y(m)$ can be the sum of the clean signal $x(m)$ and the noise $n(m)$,

$$y(m) = x(m)+n(m) \tag{2}$$

where m is the discrete-time index. The discrete Fourier transforms of Eq.(2) gives the distribution of the noise signal in the frequency domain

$$\begin{aligned} Y(k) &= \mathrm{FT}[y(m)] = \mathrm{FT}[x(m)] + \mathrm{FT}[n(m)] \\ &= X(k)+N(k) \end{aligned} \tag{3}$$

where k is the discrete frequency and corresponds to actual frequency of kFs/N and Fs is the sampling frequency. Therefore the squared spectral amplitude of the raw signal is

$$Y^2(k) = X^2(k)+N^2(k)+2X(k)N(k)\cos\theta \tag{4}$$

where θ is the phase difference between the signal and noise. The clean signal can be obtained by subtracting the estimated spectral amplitude or the power spectral amplitude of the noise from those of the raw signal in the frequency domain, as long as the signal and noise vectors are in the same phase or in a phase difference of $\pi/2$ (perpendicular). Generally, with the knowledge of phase difference, separating the signal from the noise is doable[7].

The phase of instantaneous ground-loop noise is not locked with the phase of beam bunch strictly at the transfer line no matter how much it looks like to be, so any assumption of the phase difference can easily lead to an underestimation or overestimation of the noise. Inaccurate subtraction is not acceptable as the spectra of both the signal and noise are overlapping on the interested and principal components (Fig.2). In spite of the signal and noise cross-product terms, a non- linear mapping of the small-valued spectral estimates can result in more severe distortion problem.

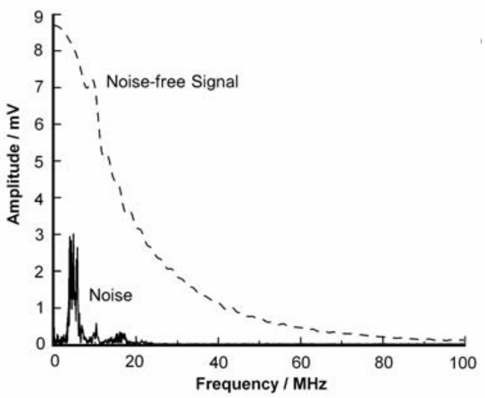

Fig.2 Overlapped signal and noise in the frequency domain.

Another way to reduce the noise is to recover it directly in the time domain. Constant background model is generally used to lessen the electric potential difference between the signals and the ground loops, and linear background is used if the electric potential of the ground is drifting. The noise of SSRF comes from excitations via the ground loops rather than the mere random fluctuations. Amplitude of the oscillating noise is quite comparable to that of the signal which makes no sense to simply do an integral over the region. If there is a slight change of phase between the signal and noise, and the constant/linear background model is used, the integral will differ greatly.

Since the frequency domain solution can hardly be useful, the traditional time domain solution may still make sense if some tweaks are applied. The noise is not trigonometrical (Fig.2). Anyway, a polynomial with a reasonable degree can be found to fit the noise with an acceptable Lagrange remainder term. Based on the shape of raw signal (Fig.1), the highest order should not be less than the ratio between the whole data width and that of the signal. The noise contains only low frequencies and the signal of interest occupies less than one fourth of the critical period of the background, so the baseline extraction can be used to remove most of the noise without sabotaging the actual signal. We actually used a slightly higher order to improve the accuracy and an example is shown in Fig.3.

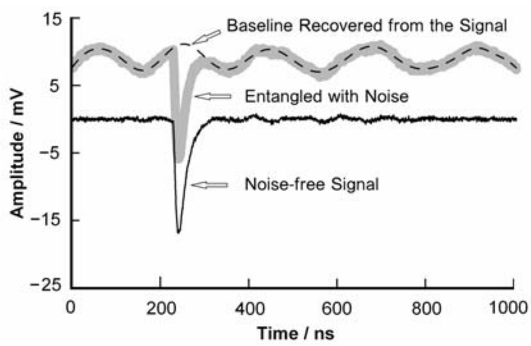

Fig.3 Results by the method of high order polynomial baseline extraction.

3 Performance

1000 sets of data were taken when the bunch charge was kept quasi-stationary at around 150 pC, with the sampling width of 1 μs and the voltage per grid of 5 V.

The constant background model and linear background model gave an average charge of (192.5±14.62) pC and (192.4±14.57) pC, respectively. The standard deviation decreased with the average charge when it was approaching the presumption value (≈150 pC), while degree of the fitting polynomial was increasing. The average charge became (153.7±4.07) pC, with the polynomial order of 18. It is not worthwhile to further increase of the order, because it did not yield a much better result, but consumed unaffordable computer hours, which grow exponentially.

The linear (or constant) baseline method, apparently, does improve the system resolution and the measurement accuracy of each absolute charge, while the high order polynomial baseline method can yield better results. With the traditional baseline extraction method, the standard deviation is one order of magnitude smaller, while with the new extraction method, it is almost two orders of magnitude smaller. Although the average value can be re-demarcated by other means, this new model still gives an elegant outcome of each individual measurement.

Figure 4 shows the results of both algorithms. The major contributor to the poor distribution of the linear fitting is due to that the extracted ground loop noise is not constant, nor linear. Fig.5 shows that both the accuracy and standard deviation are ameliorated as the order increases. Polynomial orders higher than 18 are not necessary, as the decline of standard deviation becomes saturated there.

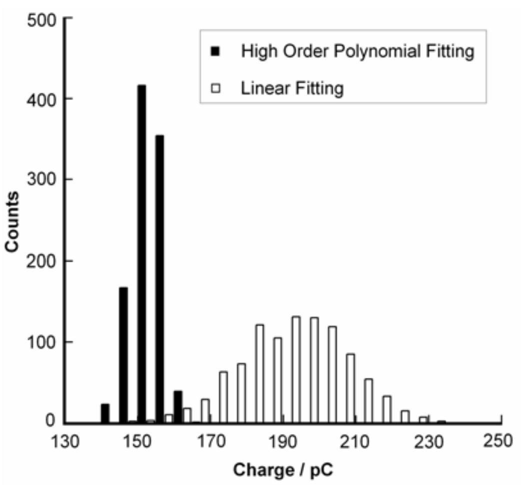

Fig.4 Histograms of the two fitting methods.

When the raw data are mixed with a background having low frequency components, an order number can be decided to estimate for the remainder term if the Taylor approximation is small enough. If the signal is narrow enough (within a half period of the noise), this approximation becomes rather feasible. The phase difference between the signal and noise is quasi-stable in our case, so a well designed program can perform the raw data acquisition and signal extraction simultaneously without any manual interventions. Thus, the requirement of instant bunch charge display with higher precision is met.

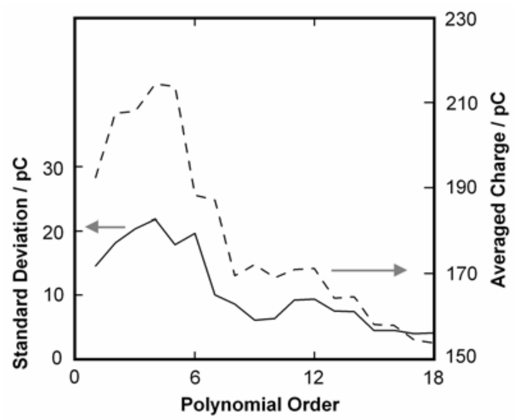

Fig.5 Average charge and standard deviations as function of the polynomial order.

Using the new method, we processed data with sampling width of 0.2, 0.5 and 1 μs. It turned out that the 1-μs results gave the best stability and accuracy, because more noise information could be extracted with greater time scale.

4 Conclusion

The circumstances where the traditional methods usually work under do not coincide with our local situation any more as the noise turns out to be considerably influential when the bunch charge drops under 100 pC. A new polynomial background model is designed to reduce the system deviation affected by the ground loops and enhance the accuracy of the measurement of the bunch charge so as to meet the needs of the top-up mode in SSRF. An experiment confirms that the new background model can make the system resolution drop from nearly 9.7% to less than 3%, comparing to the linear background assumption. The absolute charge that this method obtained is more convincing.

References

1 Tanaka H, Adachi M, Aoki T, *et al.* J. Synchrotron Rad, 2006, **13:** 378–391.

2 Lüdeke A, Muñoz M. Proceedings of EPAC, 2002, 721–723.

3 Ueng T S, Hsu K T, Chen J, *et al.* Proceedings of EPAC, 2000, 1874–1876.

4 Ohkuma H. Proceedings of EPAC, 2008, 36–40.

5 Andras P, Juergen D, Istvan M. Proceedings of EPAC, 2006, 1196–1198.

6 Leng Y B, Chen Z C, Zhou W M, Nuclear Techniques, 2009, **32:** 725–728.

7 Saeed V V, Advanced Digital Signal Processing and Noise Reduction. The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom: John Wiley & Sons, Ltd., 2009.