ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-MOOC03

THE REMOVAL OF INTERFERENCE NOISE OF ICT USING PCA METHOD*

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Abstract

The measurement of beam charge is a fundamental requirement to all particle accelerators facility. Shanghai soft X-ray free-electron laser (SXFEL) started construction in 2015 and is now in the commission phase. Although integrated current transformer (ICT) were installed in the entire FEL for the measurement of the absolute beam charge, the accurate measurement becomes difficult in the injector and the main accelerator section due to the noise interference from external factors such as klystron modulator. The evaluation of the source of noise signals and the procession of noise reduction using the principal component analysis (PCA) are proposed in this paper. Experiment results show that PCA method combing with polynomial fitting method can effectively remove the interference noise from the klystron modulator and it can also improve the resolution of the ICT system. Detailed experiment results and data analysis will be mentioned as well.

INTRODUCTION

Beam charge is a fundamental parameter for the particle accelerator facility; therefore, the beam current detector is a very important diagnostic means. Beam charge measurement methods including intercepting measurements such as Faraday cup which often used for LINAC, transfer line and storage ring. Another brunch is the Non-intercepting measurements, DCCT often be used to measure the DC current and the beam lifetime in the booster and storage ring. But for the ultra-fast short pulse charge, since ICT has a time response of the order of ps to ns, it is widely used in LINAC and transfer line for the measurement of bunch charge.

For the ICT, typical usage is the use of Bergoz's ICT probe and BCM-IHR-E processor which can be seen in Fig. 1.

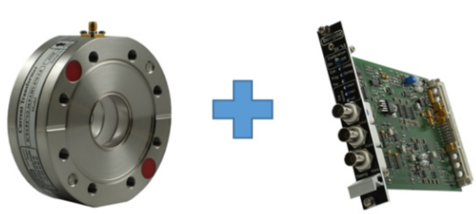
BCM-IHR-E

Figure 1: ICT and BCM processor.

The secondary coil of the transformer coupling electron pulse signal and then be widened through the shaping network, and the integral area of the output pulse is proportional to the amount of charge. The diagram of Bergoz ICT is shown in Fig. 2.

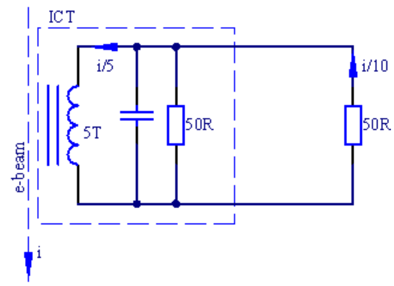

Figure 2: Diagram of Bergoz ICT.

If the input impedance of the external signal processing circuit is also 50 ohms, the Eq.(1) and Eq.(2)are satisfied between the beam charge Q, the bunch current i, and the voltage signal u_0 detected by the signal processing circuit:

$$u_0 = \frac{i}{5} * \frac{1}{2} * 50\Omega . \tag{1}$$

$$Q = \int i dt = \int \frac{5*2*u}{50\Omega} dt \tag{2}$$

Therefore, it is only necessary to measure the integral value of the output voltage pulse signal, the original beam charge can be calculated by combining the probe calibration coefficient. Typical signal processing method like BCM-IHR is to use an analog pulse integrator integrates the output pulse signal of ICT and a level signal which proportional to the integral value can be sampled and quantified by a slow ADC to calculate the beam charge.

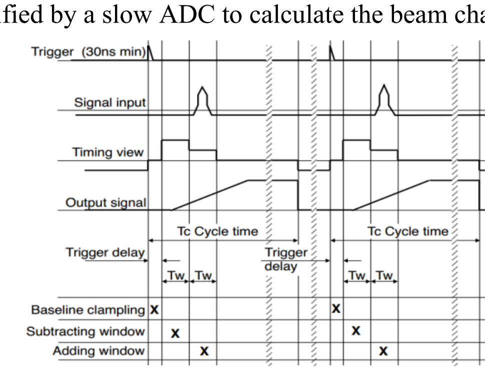

Figure 3: Timing of the BCM-IHR.

Figure 3 show the timing of the BCM-IHR processor. The signal processing is initiated by the external positive-going trigger pulse, then the timer creates three successive time windows: a trigger delay window and two integra-

*Work supported by The National Key Research and Development Program of China (Grant No. 2016YFA0401903, 2016YFA0401900)
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tion windows. One integrator integrates the pulse signal, the other integrates the input noise and baselineoffset. Then the pulse charge is obtained by summing the two integrators: the first with negativesign, the second with positive sign [1].Since the integration window of BCM is in the order of us, if there is an interference signal of the order of MHz and the integration window is not on the integer period, it will easily lead to a large measurement error. So for the typical system, the advantage is that the requirement for DAQ is lower. However, the disadvantage is that the anti-interference ability is poor, external interference signals such as the AC signal comes from the grounded or the modulator noise will be simultaneously integrated and have a big effect on the beam charge measurement.

SCHEME OF SSRF AND SXFEL

Taking into account the above situation, the design of the SSRF beam charge measurement system uses a digital sampling oscilloscope as a data acquisition device to directly quantize the original waveform of the ICT output. If there is an interference signal, it can be processed by the digital filtering algorithm or feed-forward baseline recovery algorithmremove the noise, and then numerical integration can be used to calculate the bunch charge.

For the acquisition of oscilloscope data, the embedded IOC software was developed. The scheme of ICT in SSRF and SXFEL is shown in Fig. 4.

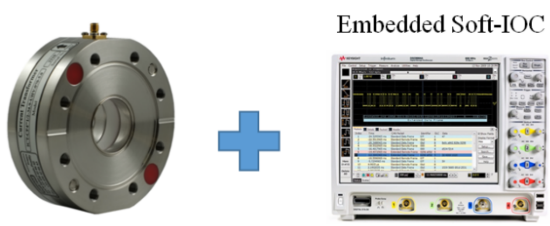

Figure 4: Scheme of ICT in SSRF and SXFEL.

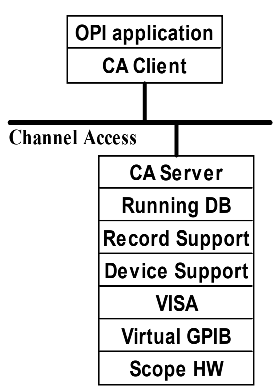

Figure 5: Diagram of embedded IOC.

Taking the oscilloscope as a standard IO device and using the CPU of oscilloscope as the IOC, write the driver to call the VISA Library interference of the machine to obtain the original data. The structure is shown in Fig. 5.

The OPI layer calls the channel access client function (CA Client) to send a data request. When the channel access server (CA Server) in the IOC receives the data request, then using the form of the running database record to obtain the data. After evaluation and test, it can work well under the data refresh rate of 10 Hz [2].

With this scheme, when there is noise crosstalk coming in, it can be processed by digital signal processing algorithm, so the processing method of ICT noise signal needs to be studied.

DATA PROCESSING FOR ICT

Multiple ICTs are used on the whole line of the SXFEL and straight line and transport line in SSRF, the layout can be seen in Fig. 6 and Fig. 7.

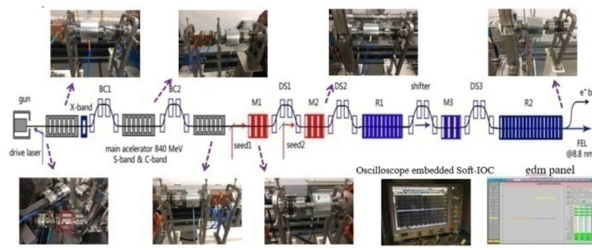

Figure 6: Sensors layout in SXFEL.

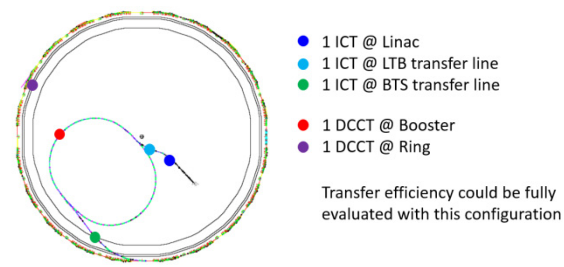

Figure 7: Sensors layout inSSRF.

For the ICTs in SXFEL, the characteristics of the waveform can be divided into three categories, one is only contains thermal noise, which can directly integrate the quantized ICT original waveform, as shown in Fig. 8.

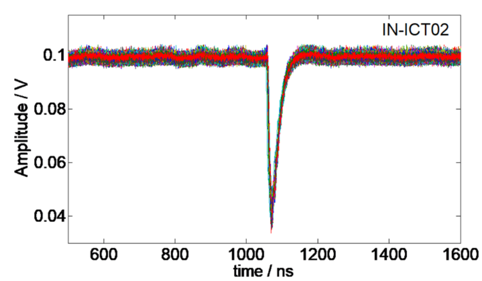

Figure 8: ICT waveform only contains thermal noise.

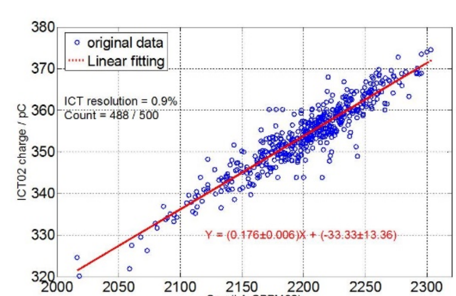

Figure 9: Bunch charge resolution of the ICT.

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For this case, it is usually possible to integrate the quantized waveform directly to calculate the beam charge. But the application of the PCA method can separate the noise, improving the resolution of the ICT system to a certain degreeespecially under the low charge conditions [3].

The other case is thatthe ICT at the exit of the electron gun, the waveform of which is shown in Fig. 10.The reason that the waveform is concave due to the ICT is interfered by the dark current generated by the RF system.In addition, there is also have a modulation effect by high frequency signals.Fig. 11 show the waveform of the dark current when the driving laser is turn off.

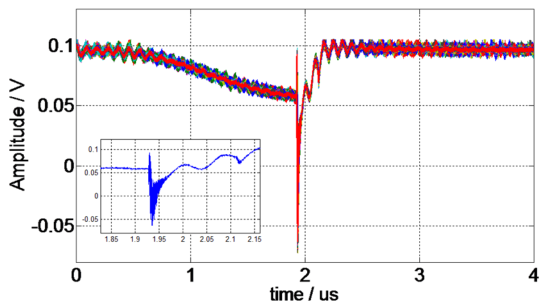

Figure 10: ICT waveform at the exit of the electron gun.

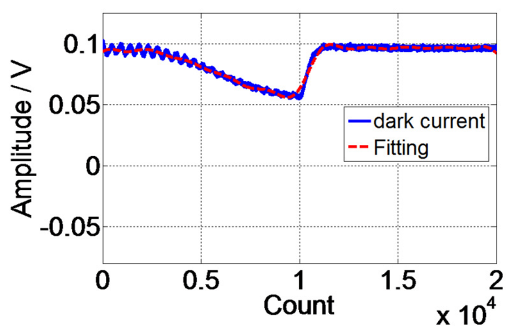

Figure 11: Waveform of dark current.

In this case, due to the existence of dark current, if we use analog integrator like BCM-IHRto set two windows to integrate the area, it will bring a large measurement error to the beam charge. Therefore, we can process the quantized ICT data in the digital domain to remove the effects of interfering signals.

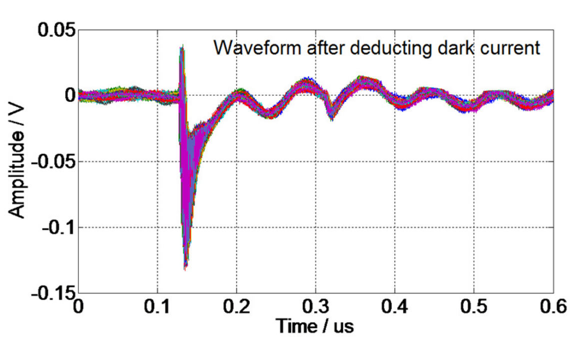

Figure 12: Waveform after subtracting dark current.

Fig.12 show the waveform after subtracting the dark current. But there is also have a modulation effect by high frequency signals.Therefore, we use the PCA method to separate the noise patterns and analyze the noise sources based on the time domain waveform and spectra of the separated noise patterns[4].

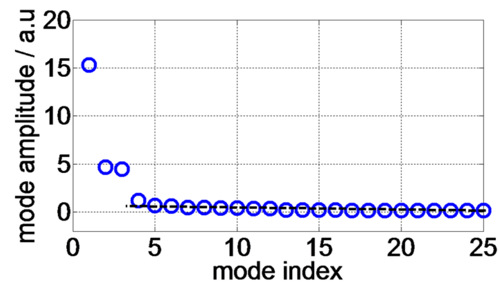

Figure 13: Singular value of IN-ICT01.

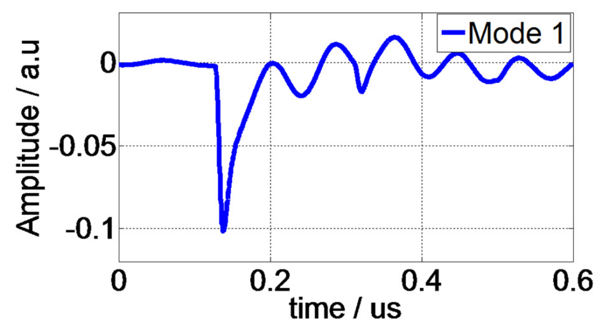

Figure 14: Waveform of mode1.

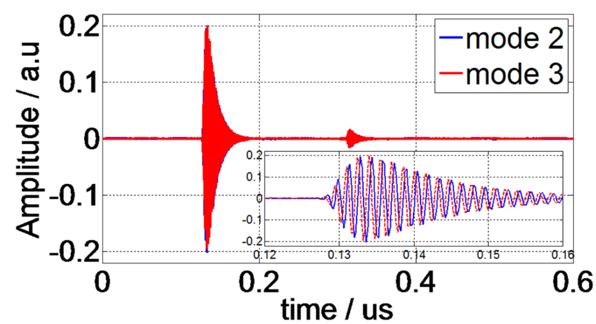

Figure 15: Waveform of mode2 and mode3.

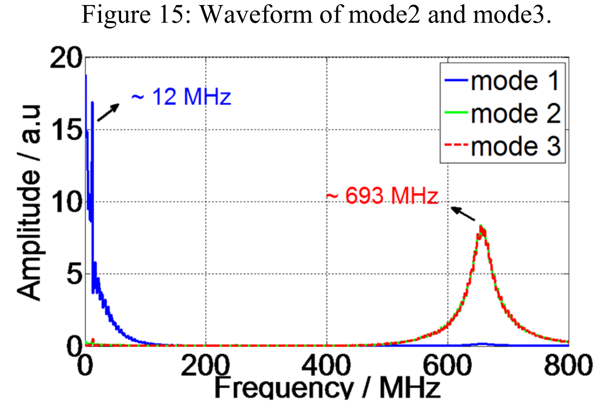

Figure 16: Spectrum of the first four modes.

From the Fig. 13, there has three modes were bigger than the others obviously, so we mainly analyse the first four modes. The waveform of the first mode can be seen in Fig. 14, combine the spectrum of Fig. 16, it can analyse that this is the main mode of the ICT but still have a low

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frequency interference without separation. The waveform of mode2 and mode3 are shown in Fig. 15, it like a signal of a resonant cavity and the resonant frequency at 673 MHz but we have not analyzed the source of this signal now. In order to verify it comes from the algorithm rather than the actual physical quantity, we try to use the digital filtering algorithm to process the original data and the results verifies the conjecture we proposed.

Considering the main mode of the ICT, we only keep the first mode and remove the others mode and then convert back to real space. The waveform after PCA process can be seen in Fig. 17.

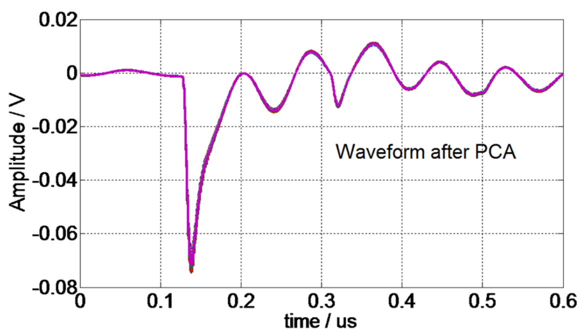

Figure 17: Waveform after PCA processing.

Although the high-frequency interference mode and noise mode are removed, the pattern related to the amount of beam charges still existed. For such interference, the polynomial fitting method is used to fit the interference signal and remove it. The fitting result is shown in Fig. 18.

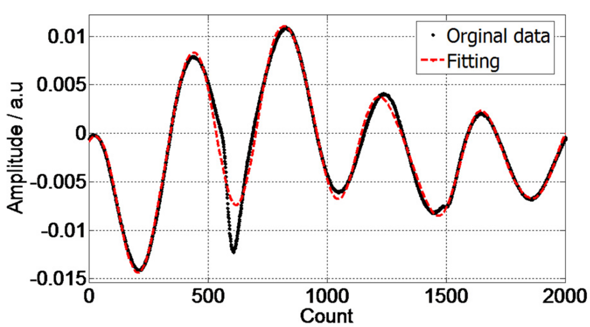

Figure 18: Polynomial fitting for the interference signal.

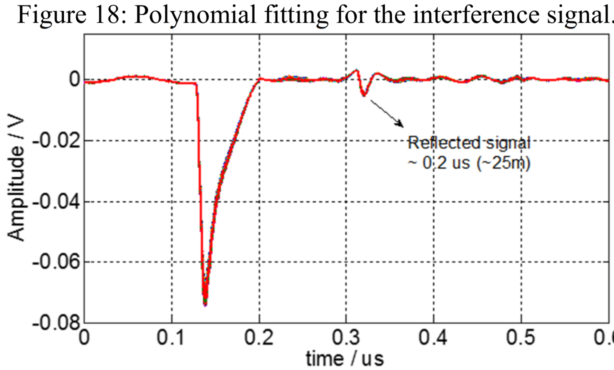

Figure 19: Waveform after deducting the fitting value.

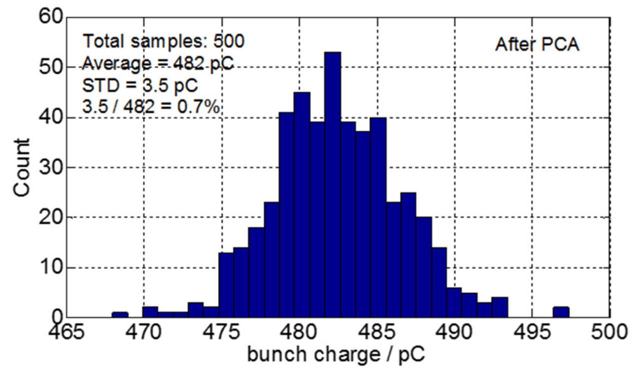

Figure 20: Charge resolution of the ICT.

After deducting the fitting value, the ICT waveform after processing through the digital domain was obtained which is shown in the Fig. 19. We can also find the phenomenon of signal reflection that may be caused by impedance mismatch. The charge resolution of the ICT about 0.7% after PCA method using two ICTs for correlation analysis.

CONCLUSION

In this paper, we introduced the typical usage of ICT and analyzed the advantage of low requirement for DAQ. But it is also susceptible by noise and resulting in incorrect charge measurement.Based on this consideration, SSRF and SXFEL adopts the architecture based on digital oscilloscope and Soft-IOC. The benefit is that quantified ICT signals can be processed in the digital domain to remove the interference signal.Some experiments were performed in SXFEL, due to the presence of dark current and high frequency noise, signal processing can only be performed in the digital domain.The experimental results show that the PCA method combined with the polynomial fitting method can effectively remove the interference of multiple noises.

On the other hand, due to the in-air ICT be used and the external shield is designed by ourselves. There maybe reasons such as unsatisfactory process conditions, resulting in unsatisfactory shielding effect.In the next step, we will purchase in-flange ICT for testing.

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