R&D OF THE BUNCH-BY-BUNCH FEEDBACK PROCESSOR PROTOTYPE FOR HALF*

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Abstract

The Hefei Advanced Light Facility (HALF) is designed to generate and operate with a beam current of up to 350 mA while maintaining the beam emittance at the diffraction-limited level. The bunch-by-bunch feedback system serves as a critical tool for suppressing beam instabilities, requiring feedback control targeting the position oscillations of each bunch. To meet this demand, the engineering team has independently developed a bunch-by-bunch feedback system, fabricated a prototype, and conducted relevant tests. Through high-precision phase alignment, the analog front-end conditions the original signals into high-precision and wide-dynamic-range sum-and-difference signals. Utilizing the phase-splitting and time-delaying method, the processor can measure the high-precision three-dimensional (3D) position of each bunch and implement feedback control accordingly. This paper presents the design of the system as well as the details of the prototype development and testing.

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During the construction of HALF, we made the decision to independently develop the bunch-by-bunch feedback processor [1]. Based on the team's previous technical accumulation in bunch-by-bunch parameter measurement [2, 3], we decided to adopt a FPGA-based direct radio frequency (RF) sampling processor scheme for data acquisition. Compared with the bunch-by-bunch parameter diagnostic system, the bunch-by-bunch feedback system needs to acquire 3D position information in the shortest possible time and generate feedback signals, which are then amplified to drive the kickers for trajectory control of the bunches. Meanwhile, the bunch-by-bunch feedback process does not focus on the absolute position of the beam, but only on the relative position change of the beam within a certain time period, and it is necessary to maximize the resolution of relative changes.

Integrating the above basic requirements with mature bunch-by-bunch feedback schemes from other facilities [4], we designed a complete set of analog front-ends for the bunch-by-bunch feedback system. It can realize closed orbit subtraction in the analog circuit and provide amplitude-matched synthesized signals for the processor. In this way, the processor can directly obtain the 3D position changes of the bunches through the variation of signal amplitudes without performing the delta-over-sum operation. Compared with conventional schemes, this front-end eliminates frequency mixing, which simplifies the front-end structure, reduces interference, and correspondingly improves the 3D position resolution of the feedback processor.

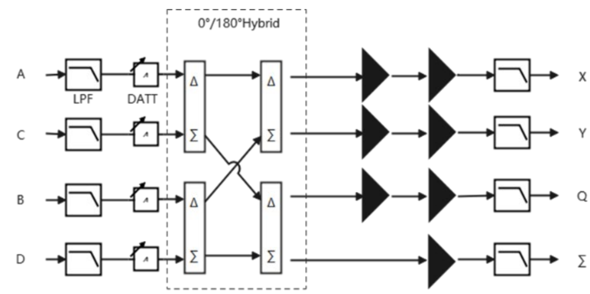

Figure 1: The layout of Front-End.

After prototype fabrication and testing, our current scheme, as shown in Fig. 1, implements filtering, phase shifting, delta-over-sum calculation, and amplitude matching of the input signals. This paper details the research and development of this front-end prototype, including the key issues encountered during the design process and the signal transformations within the system.

SCHEME DESIGN

In the direct RF sampling scheme, to obtain the synthesized signals that accurately reflect the bunch position changes, careful conditioning of the beam position monitor (BPM) signals is required before performing analog sum-and-difference calculations. In practice, even the four signals derived from the same BPM exhibit subtle differences. Direct synthesis would lead to severe signal distortion and degraded resolution, and even result in erroneous measurement results. We plan to solve this problem in two parts.

The first issue is the difference in response functions. Ideally, when the same bunch passes through a perfectly symmetric BPM probe, only signals with different amplitudes induced by the transverse position difference are generated on the probe. Other properties of the signals, especially the response functions, should be consistent. However, in practice, due to factors such as process precision, slight inconsistencies exist among different channels. For example, the gaps between the BPM electrodes and the vacuum chamber introduce different beam impedances, which cause unexpected changes in the bunch signal waveforms. Figure 2 shows a typical set of response functions and their original spectra, where slight differences can be observed among the four channels.

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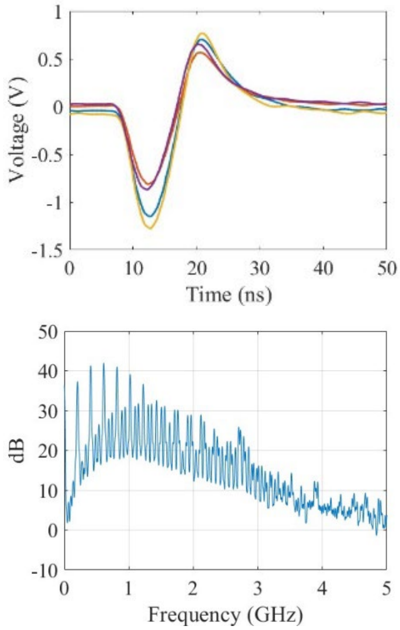

Figure 2: A typical set of response functions and spectra.

Considering that these differences are mainly manifested in the relatively high frequency range, combined with the design of the bunch-by-bunch feedback processor, we choose to filter out all frequency components above 2 GHz. This makes the bunch signal wider in the time domain but smoother, and suppresses the signal distortion caused by impedance mismatch to an acceptable range. Figure 3 shows the response functions and the original spectra of the sampling results after filtering.

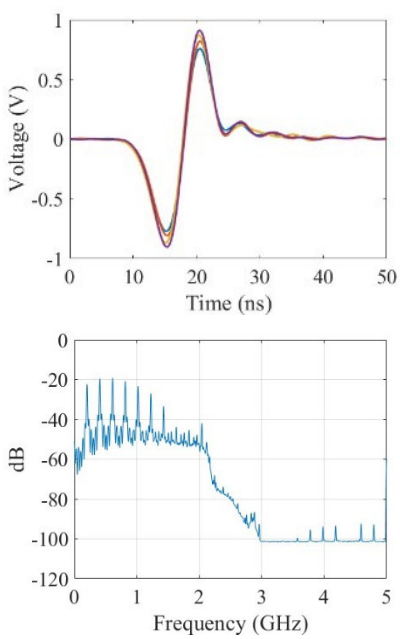

Figure 3: A typical set of response functions and spectra after LPF.

The second issue is the difference in signal arrival times. Ideally, the signals induced by the four probes should arrive simultaneously after passing through equal-length cables. However, it is obvious that cable length equality is not absolute, but an approximation within a certain tolerance range. In general data measurements, this error can be accepted at the level of tens of picoseconds. Nevertheless, in the sum-and-difference calculation of analog signals for the bunch-by-bunch feedback system, this problem also causes signal distortion during the sum-and-difference process, which affects the measurement accuracy of the feedback processor. Therefore, we need to finely compensate for this error. Figure 4 shows the waveforms of the ideal difference signals before and after compensation, and for this set of probes, the optimization is mainly for the Y-direction measurement.

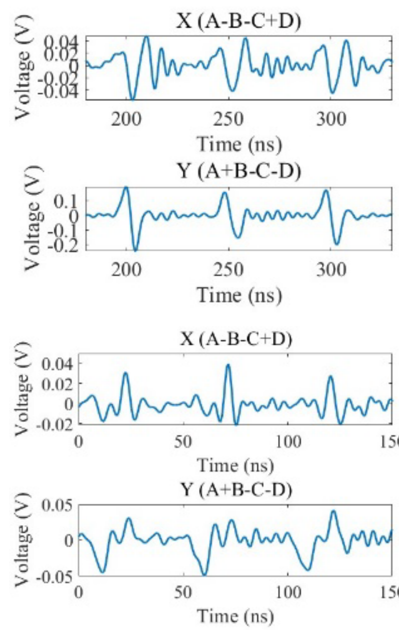

Figure 4: X\Y response before and after phase shifting.

When the transverse position of the bunch itself changes and its centroid deviates from the geometric center of the vacuum chamber, the signal also takes different propagation times to reach the probes in the vacuum chamber, affecting the signal arrival time. After comprehensively evaluating the measurement accuracy of the entire feedback processor and the possible transverse position offset of the bunches, we set the target to compensate for this difference to at least below 5 ps.

For the experimental processes of the above two issues, the former requires reconstructing the complete response of the signal on the probe under the reality of limited sampling frequency, while the latter requires achieving picosecond-level measurement of signal arrival times. Here, we utilized the technical accumulation of the research group—a software processing method based on the random sampling scheme, HOTCAP [5]. This software package can quickly obtain response functions with an ultra-high equivalent sampling rate under existing experimental conditions, and simultaneously obtain the signal arrival time differences between different channels.

The acquisition of synthesized signals adopts a classic scheme. Considering the insertion loss and spurious signals introduced by the calculation process, we added high-quality RF amplifiers and filters at the end of the front-end to achieve amplitude matching and further conditioning of the signals.

BEAM EXPERIMENTS

HALF is still under intensive construction and does not yet have experimental conditions. The beam experiments of this prototype were carried out on Hefei Light Source II (HLSII), another facility of the National Synchrotron Radiation Laboratory. The parameter comparison of the two facilities is in Table 1.

Table 1: HLSII and HALF

Parameter	HLSII	HALF
RF frequency	204.03 MHz	499.8 MHz
Harmonic Number	45	800
Current	500 mA	>100 mA
Energy	800 MeV	2.2 GeV

As a second-generation light source that has been in operation for many years, HLSII exhibits strong instabilities. Therefore, our experimental objective was mainly functional verification. Its strong longitudinal instabilities and the presence of interference signals pose significant challenges to bunch-by-bunch measurements. We collected and recorded the original unconditioned signals and the conditioned synthesized signals during injection in top-up mode, and performed simple transverse position extraction.

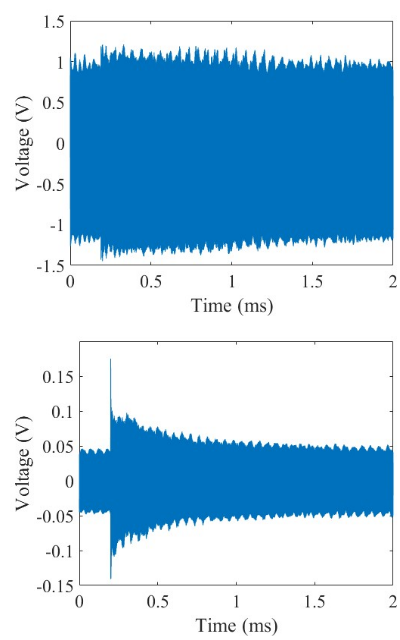

Figure 5: The sampling results in 2 ms.

For a storage ring operating in top-up mode, injection is the most common, stably reproducible, and highly disruptive instability factor. From the measurement results shown in Fig. 5, it can be clearly seen that when the disturbance occurs, the front-end significantly amplifies the effect of the disturbance process on the signal amplitude, improving the utilization of the processor's dynamic range.

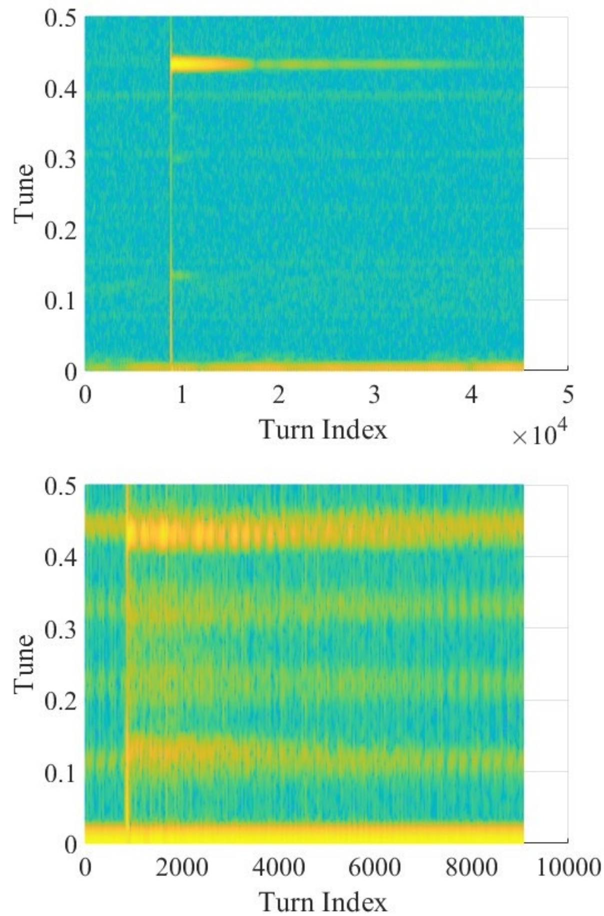

Figure 6: Spectrogram of the bunch X position.

Figure 6 shows the spectra under the two conditions. The X-direction tune can be clearly observed in both spectra. However, in the measurement results after front-end conditioning, the steady-state tune captured can be seen, and it differs from the tune during injection, which is consistent with our previous research results.

CONCLUSIONS AND FUTURE PLANS

The experiments on HLSII demonstrate that the prototype of the bunch-by-bunch feedback front-end basically achieves the expected functions. It significantly amplifies the effect of disturbances on signal amplitude and improves the utilization of the measurement range of the bunch-by-bunch feedback processor. The formal front-end with remote-controlled closed orbit subtraction capability is already under fabrication.

After the completion of HALF, further commissioning and optimization will be required during its operation. Meanwhile, a simplified version of this system is planned to be used for the development of future bunch-by-bunch parameter diagnostic technologies.

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