APPLICATION OF WALL CURRENT MONITOR AT CSNS RAPID CYCLING SYNCHROTRON*

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Abstract

Two sets of Wall Current Monitors (WCMs) have been installed in the Rapid Cycling Synchrotron (RCS) of the China Spallation Neutron Source (CSNS) for longitudinal bunch shape measurement, longitudinal emittance calculation, and beam instability diagnosis. This paper presents the WCM system design (probe and DAQ) and recent beam measurement results, including bunch shape evolution, bunch length measurement, and RF frequency tracking during the acceleration cycle.

INTRODUCTION

The China Spallation Neutron Source (CSNS) is a large-scale scientific facility located in Dongguan, China [1]. Its accelerator complex consists of an 80 MeV H^- linac, a 1.6 GeV Rapid Cycling Synchrotron (RCS), and beam transport lines. The RCS operates at 25 Hz with harmonic number $h = 2$ (double bunches) and a design beam power of 100 kW. The beam is accelerated from 80 MeV to 1.6 GeV in approximately 20 ms.

The Wall Current Monitor (WCM) is a broadband, non-destructive diagnostic device that measures the image current on the vacuum chamber wall with nanosecond-scale time resolution, making it indispensable for longitudinal dynamics studies. Unlike current transformers that only provide slowly varying beam current, the WCM captures the high-frequency bunch structure directly.

Two sets of WCMs are installed in the CSNS-RCS: one dedicated to beam diagnostics and another serving the RF control system. This paper presents the WCM system design, the custom data acquisition system, and recent measurement results.

WCM SYSTEM OVERVIEW

Working Principle

When a charged particle beam travels through the vacuum chamber, it induces an image current (wall current) on the inner surface of the chamber wall. By introducing a ceramic gap to interrupt the wall current path and placing a matched resistor across the gap, the wall current generates a measurable voltage signal proportional to the beam current:

$$V_{\mathrm{WCM}}(t) = R \cdot I_{\mathrm{wall}}(t) \approx R \cdot I_{\mathrm{beam}}(t) \qquad (1)$$

where R is the matching resistance. Ferrite and nanocrystalline magnetic rings are placed around the gap to extend the low-frequency response by increasing the inductance.

Probe Design

The CSNS-RCS WCM probe consists of the following key components [2]:

- **Ceramic gap:** 97-porcelain ring (ID 225 mm, OD 251 mm, thickness 12 mm), $\varepsilon_r = 9.5$, $C_{\mathrm{gap}} \approx 68.1$ pF, $Z_0 = 1.96\,\Omega$.
- **Matching resistors:** Two configurations have been tested: 25 parallel thick-film resistors of 50 Ω each, or 150 parallel metal-film resistors of 300 Ω each. Both yield ∼2 Ω matched to the gap impedance.
- **Magnetic rings:** Four rings symmetrically placed around the gap: two iron-based amorphous rings (1K101, effective from 1 kHz to 100 MHz) and two nanocrystalline rings (1K107B, effective from 1 kHz to 500 kHz). Each ring has dimensions of $\phi 275 \times \phi 330 \times 25$ mm.
- **Signal pickup:** Four symmetric cables combined through a power combiner to cancel position dependence.

The cutoff frequencies are:

$$f_h = \frac{1}{2\pi R C_{\mathrm{gap}}}, \quad f_l = \frac{R}{2\pi L} \qquad (2)$$

Laboratory S21 tests confirmed ±1 dB flatness from 300 kHz to 50 MHz with the upper −3 dB cutoff at ∼500 MHz [2].

Data Acquisition System

A custom NI-PXIe oscilloscope system has been developed for WCM data acquisition [3]. Key specifications are in Table 1.

The 12-bit resolution provides significantly better sensitivity than typical 8-bit oscilloscopes for weak beam signals.

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Table 1: WCM DAQ System Parameters

Parameter	Value
Digitizer	NI PXI-5124
Sampling rate	100 MHz (max 200)
Resolution	12-bit
Storage depth	256 MB
Samples/cycle	2,500,000
Window	25 ms
Bandwidth (probe)	5 kHz – 400 MHz

The 256 MB storage depth captures 2,500,000 data points per cycle, covering the full 20 ms acceleration period. Data is published via EPICS process variables using the LabVIEW DSC module for remote monitoring and integration with the control system.

BEAM MEASUREMENT RESULTS

Measurements were performed during the April 2026 operating period with double-bunch operation ($h = 2$). Three consecutive measurement cycles were recorded at 100 MHz sampling rate, each containing 2,500,000 data points. Representative results are presented below.

Beam Signal Overview

Figure 1 shows the RF reference and WCM signal over one complete acceleration cycle. The RF system is active from approximately 1 ms to 22.5 ms. The WCM signal clearly shows beam injection at ~2.5 ms, progressive amplitude increase during acceleration due to adiabatic bunch compression, and sharp drop at extraction (~22.5 ms).

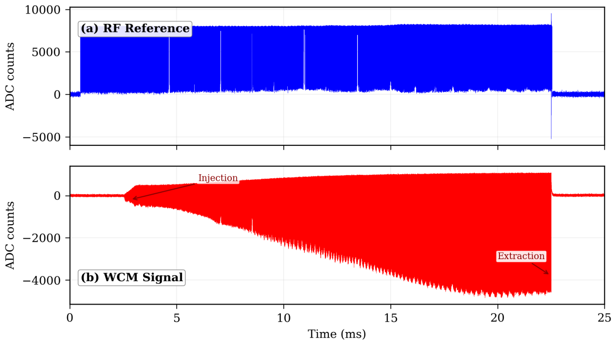

Figure 1: Simultaneously recorded signals over one RCS acceleration cycle: (a) RF reference; (b) WCM beam signal.

The signal envelope (Fig. 2a) reveals the characteristic monotonic increase in peak amplitude as bunches are compressed longitudinally. The negative peak amplitude grows from ~100 ADC counts at injection to ~4800 ADC counts near extraction, while the positive peak remains relatively flat, reflecting the asymmetric WCM waveform due to the high-pass frequency response.

RF Frequency Measurement

By analyzing the rising-edge crossings of the RF reference signal captured simultaneously with the WCM data, the instantaneous RF frequency throughout the acceleration cycle was extracted (Fig. 2b). The measured RF frequency ramps from 1.03 MHz at injection to approximately 2.44 MHz at extraction, corresponding to a revolution frequency range of 0.52–1.22 MHz (with $h = 2$). These values are consistent with the CSNS-RCS design parameters for 80 MeV to 1.6 GeV acceleration [1].

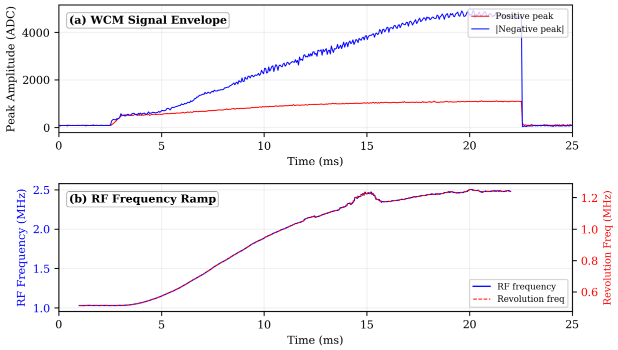

Figure 2: (a) WCM signal envelope. (b) RF frequency and revolution frequency extracted from the RF reference.

Bunch Shape Evolution

Figure 3 shows the WCM signal at three phases: injection ($t = 3$ ms), mid-cycle ($t = 10$ ms), and near extraction ($t = 19$ ms). At injection, the bunches are broad with low amplitude, consistent with the ~500 ns micro-bunches produced by the linac chopper (1 MHz, 50% duty cycle). As acceleration progresses, bunches are adiabatically compressed: amplitude increases while temporal width decreases. Near extraction, the bunches are narrow (~120 ns FWHM) and intense, with the double-bunch structure clearly resolved.

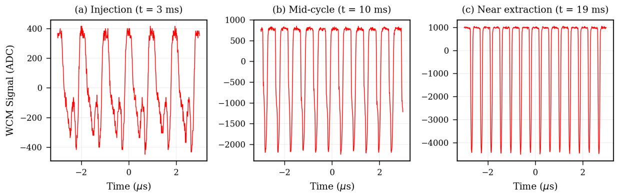

Figure 3: WCM signal at three acceleration phases: (a) injection, (b) mid-cycle, (c) near extraction.

The mountain plot in Fig. 4 illustrates the continuous evolution over the entire cycle. Each trace represents the WCM waveform over one revolution period at a given time. The progressive compression of double bunches from broad profiles at injection to narrow, intense peaks at extraction is clearly visible.

Bunch Length Measurement

The bunch length (FWHM) was measured at successive time intervals throughout the cycle (Fig. 5). The injected beam from the linac has an initial bunch length of ~500 ns determined by the chopper. After RF capture, the bunch length increases to ~290–330 ns during the early acceleration phase (3–7 ms), exhibiting prominent oscillations associated with

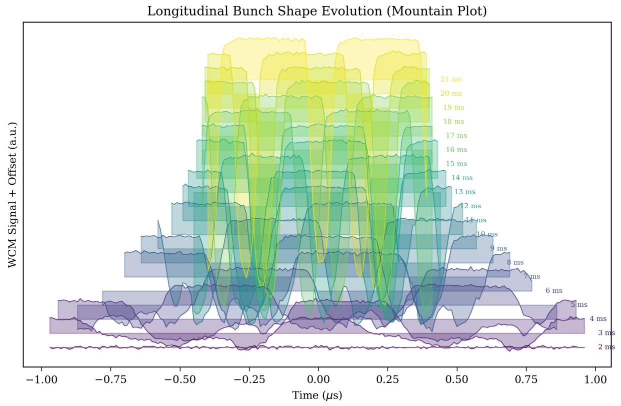

Figure 4: Mountain plot showing bunch shape evolution from injection (bottom) to extraction (top).

synchrotron motion as the bunches undergo longitudinal filamentation. After approximately 8 ms, the bunch length decreases monotonically to ~120 ns near extraction, consistent with the design expectation [4]. The oscillation pattern provides direct information on injection matching quality.

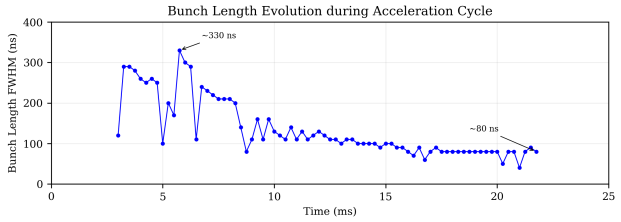

Figure 5: Bunch length (FWHM) evolution during the acceleration cycle.

Measurement Reproducibility

To evaluate measurement stability, three consecutive acceleration cycles were recorded under identical machine conditions. Figure 6 overlays the bunch length curves from three successive cycles. The results show excellent reproducibility: the RMS deviation between cycles is less than 5 ns throughout the acceleration period, confirming that both the beam conditions and the WCM measurement system are highly stable. This cycle-to-cycle consistency validates the WCM as a reliable diagnostic for routine beam monitoring and long-term trend analysis during machine studies.

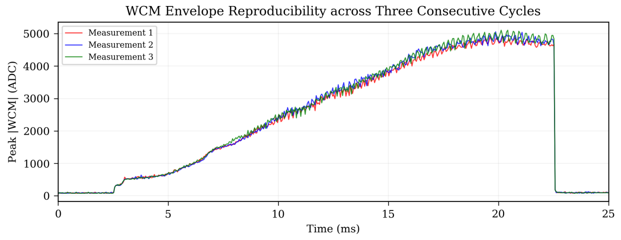

Figure 6: Bunch length measurement from three consecutive acceleration cycles, demonstrating excellent reproducibility.

Double-bunch Phase Measurement

With the harmonic number $h = 2$, two bunches circulate in the RCS, ideally separated by half the revolution period ($T_{\mathrm{rev}}/2$). By locating the centroids of the two bunches within each revolution period, the relative phase deviation was extracted throughout the acceleration cycle (Fig. 7). The measured mean phase offset is ~2° with an RMS fluctuation of ~10°. The oscillatory behavior in the early acceleration phase (3–8 ms) reflects the synchrotron oscillation of the two bunches as they undergo RF capture and phase-space filamentation. After 10 ms the phase difference stabilizes, indicating that both bunches are well centered in their respective RF buckets. This measurement provides a direct diagnostic of double-bunch symmetry and can be used to identify RF imbalance or beam loading effects.

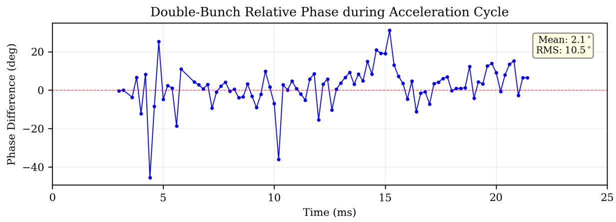

Figure 7: Relative phase difference between the two bunches ($h = 2$) during the acceleration cycle.

SUMMARY AND OUTLOOK

The Wall Current Monitor system at the CSNS Rapid Cycling Synchrotron has been described, covering the probe design, custom DAQ system, and beam measurement applications. The system achieves an effective bandwidth of 5 kHz to 400 MHz with 12-bit resolution at 100 MHz sampling rate, capturing 2,500,000 data points per acceleration cycle.

Recent measurements demonstrate the system's capabilities: tracking bunch shape evolution throughout the 20 ms acceleration cycle, measuring bunch compression from ~500 ns at injection to ~120 ns FWHM at extraction, and extracting the RF frequency ramp (1.03–2.44 MHz) consistent with design values. The WCM data has also been successfully used for synchrotron tune extraction (deviation <0.002 from theory) [4, 5], beam transmission efficiency measurement (~97%, consistent with current transformer readings) [4], and beam instability diagnosis through abnormal envelope pattern identification.

Future upgrades are planned to support the CSNS power upgrade program: increasing the sampling rate to 1 GHz for finer temporal resolution of the bunch microstructure, implementing real-time longitudinal emittance computation, and developing multi-bunch resolved analysis techniques for the power upgrade toward 500 kW.

ACKNOWLEDGMENT

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