

# HIGH-PRECISION CURRENT FEEDBACK CONTROL OF A MHz KICKER MAGNET SYSTEM FOR THE SHINE

S. Li<sup>1</sup>, Y. Liu<sup>1</sup>, Y. Jiang<sup>1</sup>, R. Wang<sup>1</sup>, W. Zhang<sup>1</sup>, H. Deng<sup>1</sup>, Q. Yuan<sup>1†</sup>

<sup>1</sup>Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai, China;

## Abstract

A kicker magnet system is under development for the Shanghai High Repetition Rate X-ray Free Electron Laser and Extreme Light Facility (SHINE) at the Shanghai Advanced Research Institute, Chinese Academy of Sciences (SARI, CAS). Mitigating thermal drift during extended operation is essential to maintain the beam distribution stability. A high-precision current feedback control system has been designed to regulate the kicker power supply at 1 MHz with an amplitude stability below 100 ppm. The system integrates a differential amplification circuit using a low-thermal-coefficient resistor network for real-time drift compensation, together with a proportional–integral–derivative (PID) control operating at a response time of ~100 ms to stabilize the output current. This approach supports current measurement resolution on the order of 0.1 mV. Under 1 MHz pulsed operation, the experimental results achieve a pulse-to-pulse amplitude stability of 85 ppm over 30 minutes with closed-loop feedback, and maintain stability around 111 ppm after 8 hours of continuous running. The design, implementation, and tested performance of the system are reported and discussed.

## INTRODUCTION

The Shanghai High Repetition Rate and Extreme Light (SHINE) facility is under construction based on the superconducting linear electron accelerator facility at the Shanghai Advanced Research Institute (SARI), Chinese Academy of Sciences (CAS). It generates a maximum energy up to 8 GeV at a high repetition rate of 1 MHz. A pulsed power system provides the required pulsed excitation current for the kicker magnet (load in this case) to maintain the trajectory variation of the electron beam. The inductively loaded kicker system consists of a charging current power supply (CCPS), an energy storage unit, a pulser unit, a programmable logic controller (PLC) unit, and an inductive magnet.

The kicker system outputs consecutive half quasi-sinusoidal waveforms – with a peak current up to 54 A (convert to a voltage amplitude of 2.7 V at a matched resistance of 50  $\Omega$ ), a width of around 450 ns, and a flat-top width of 10 ns – at a maximum repetition rate up to 1 MHz with a desired stability of less than 100 ppm when loaded with the magnet at an inductance of 1.6  $\mu\text{H}$  [1]. The above requirements have posed a significant challenge to controlling the kicker system in order to fulfill the design criteria of the SHINE facility. In particular, the amplitude stability of the kicker is fundamental for precise beam switching and transport, as thermal drift is expected to occur over extended operation.

Several studies have been carried out to investigate the feasibility of improving the stability of pulsed power supplies [2-7]. At PSI, a balanced measurement scheme comprising balancing, limiter, and amplifier circuits was designed. Digital peak detection was implemented in a field-programmable gate array (FPGA), and the maximum pulse value was sent to a microcontroller system [2]. The peak-to-peak stability was  $\pm 11$  ppm with active feedback control. At SACLA, a feedback control system consisting of a current transducer, an error amplifier, and a proportional-integral-derivative (PID) control circuit was designed to stabilize the output current within 5 mA, and a pulse-width modulation (PWM) module was employed for gate control of the fast switching [3,4]. In reference [5], the measured current was regulated using a reference signal tracking (RST) tri-polynomial form and processed in a digital signal processing controller. A similar control method to that in [2] was applied for the digital control electronics at SOLEIL and HEPS, with closed-loop regulation implemented in an FPGA [6,7]. The control methods mentioned above primarily rely on closed-loop PID control implemented in an FPGA, RST digital control, or a combination thereof. Other more complex control methods, such as model predictive control [8,9], adaptive control [10,11], and analytical model-based optimal control [12], have also been reported.

In this work, a novel continuous chopping amplifier circuit design is proposed to enable high-precision measurement of the kicker’s voltage amplitude, providing an accurate voltage reference at each iteration. While closed-loop control enables consistent pulse-to-pulse correction, minor voltage/current variations of the kicker cannot be submerged from the inherent zero-drift of the amplifier, and flicker noise is also mitigated. Controlling the charging voltage of the CCPS—which is proportional to the excitation pulse current—through a high-speed closed loop helps reduce thermal drift of the overall system during extended operation.

## MATERIALS AND METHODS

### *Current feedback control overview*

The current feedback control system consists of a pulse detection circuit, a 16-bit ADC board, an FPGA core board, and a digital-to-analog converter (DAC) board. The two ADC modules are connected to the FPGA core board, which provides the necessary resources and interfaces for data acquisition, processing, and monitoring. The DAC board supplies analog output channels to close the overall system’s control loop. The 1 MHz quasi-half-sine wave is resistively balanced against a high-stability DC reference to generate a differential signal for further amplification.

A LabVIEW interface (National Instruments, U.S.A.)

<sup>†</sup>yuanyuan@sari.ac.cn

was developed for data monitoring and transfer. The PID control is implemented by configuring several key parameters, as illustrated in Fig. 1, with further details provided in Section FPGA control.

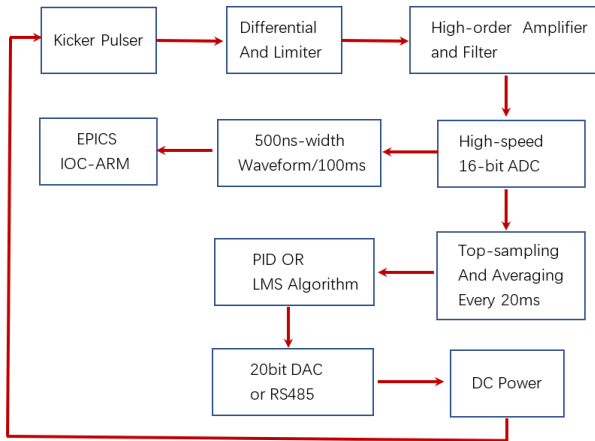


Figure 1: A diagram of the current feedback control for the kicker at SHINE.

### Mechanical design

The current feedback control system is designed as a standard 1U rack (dimensions: 482.6 mm width  $\times$  400 mm depth  $\times$  44 mm height) for ease of maintenance. It is installed in a standard 19-inch cabinet together with a PLC controller to avoid radiation damage. Each board is independently designed to facilitate easy debugging and replacement. An internal layout is shown in Fig. 2 for further clarity.

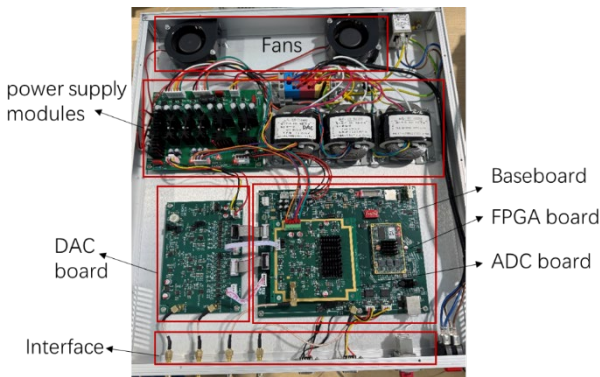


Figure 2: Internal layout of the feedback controller for the kicker.

### Experimental measurements

Measurements were performed to characterize the full and amplified waveforms across a frequency range of 1 Hz to 1 MHz, as well as to evaluate system resolution and pulse-to-pulse stability. Generally, a signal generator (Agilent 33500B Series, 16-bit) was used to directly provide a DC signal, enabling verification of the feedback controller's capability to detect the minimum voltage step change. Pulsed current measurements were carried out using an internal wide-band current transducer (Pearson model 6600, USA) with a sensitivity of 0.1 V/A, a RMS current rating up to 40 A, and a bandwidth of up to 120 MHz.

## RESULTS AND DISCUSSIONS

### Resolution measurement

To distinguish the smallest voltage change, a resolution measurement was carried out using the method described in Section Experimental measurements. A DC voltage ranging from 2.376 V to 2.381 V was fed into the feedback controller with step adjustments of 1 mV to 0.1 mV, and the resulting response curves are shown in Fig. 3. As indicated in the embedded plot of Fig. 4, the 0.1 mV steps are clearly visible during the interval from 800 s to 900 s. In particular, the voltage peak at 2.3798 V confirms that the minimum resolvable voltage increment on the system readout is 0.1 mV.

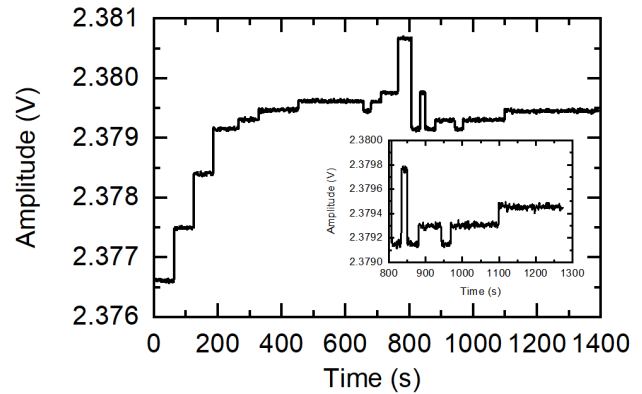


Figure 3: Resolution measurements at a voltage step of 1 mV – 0.1 mV.

### Short-term stability measurement

Figure 4 provides the overall measurement results –including waveform acquisition, PID configuration, and key parameters – obtained at a charging voltage of 800 V<sub>DC</sub> and a repetition rate of 1 MHz with feedback control enabled. Data were recorded every 50 ms for subsequent comparison. The full waveform shows a width of 452 ns and a voltage amplitude of 1.32 V, while the difference between the full-voltage and cut-voltage measurements (denoted  $FulAct\_Lv$  and  $CutAct\_Lv$ , respectively) yields an amplified voltage of 0.15 V. The measured stability is 85 ppm RMS with the designed feedback control based on the amplified-voltage method, representing a significant improvement compared to the open-loop operation [1].

The dynamic process of stability improvement is illustrated as follows: (i) the PID control rapidly suppresses voltage fluctuations during the pulse flat-top, with waveforms settling to the target value within approximately 100 ms; and (ii) the integral (I) term compensates for baseline drift caused by slow variations such as temperature changes and component-parameter shifts from pulse to pulse, thereby ensuring consistent energy per pulse. These results indicate that the kicker system, under closed-loop control, exhibits a response time sufficiently fast to maintain the target value.

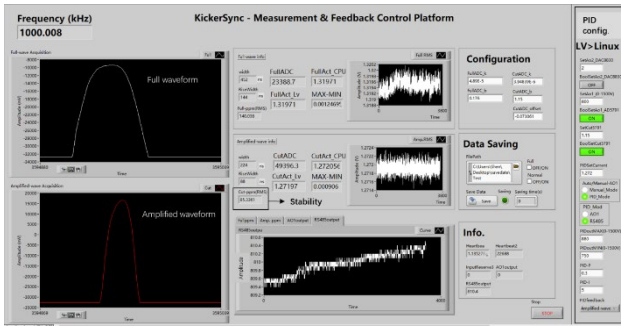


Figure 4: Short-term stability measurement over 30 min with feedback control.

### Long-term stability measurement with feedback

To ensure safe commissioning, the PID output voltage was constrained to the range of 750 V to 850 V. The PID coefficients were set to  $P = 0.8$  and  $I = 2$  for evaluating the closed-loop performance. The closed-loop feedback control is employed to correct amplitude drift and reduce temperature-induced drift through continuous compensation of voltage measurements. The results are plotted in Fig. 5, showing the variation of the DC power-supply output voltage, amplitude, and stability over 8 hours.

As shown in Fig. 5, the stability trend shows a gradual, monotonic drift toward a new equilibrium over the subsequent hours. After 8 hours of continuous operation, the system achieved a stability of approximately 111 ppm RMS, meeting the design requirements outlined in prior work [1].

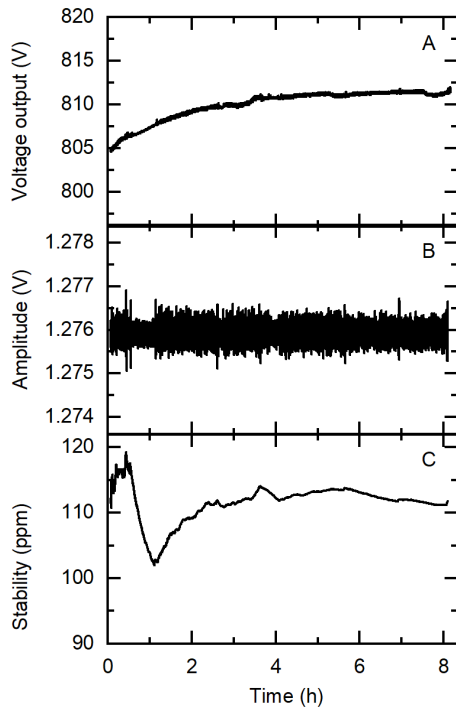


Figure 5: Long-term stability measurements of closed loop, including voltage output (A), amplitude (B), and stability (C).

## CONCLUSIONS

In this work, a prototype of a high-precision current feedback controller for a kicker power supply operating at a repetition rate of 1 MHz was designed. Preliminary results demonstrated a voltage measurement resolution in the sub-ppm level for a 0.1 mV step. Under closed-loop feedback control at 1 MHz repetition rate, pulse-to-pulse amplitude stabilities of 85 ppm over 30 minutes and 110 ppm after 8 hours of continuous operation were achieved. The development of the current feedback controller confirms that the performance meets the design targets and demonstrates the ability to mitigate thermal drift during long-term operation.

Further measures are being implemented to enhance performance, including: (i) adopting master timing for synchronization in subsequent algorithms—once synchronized, a fixed sampling point can serve as a reference, eliminating the need for multi-data averaging in current calculations; and (ii) incorporating fault-diagnosis information such as waveform distortion, jitter, and vibration.

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