ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPCO22

HEPS BEAM CHARGE MEASUREMENT SYSTEM

Y. Zhao†, Y. Sui, Y. Du, J. He, L. Wang, T. Xu, J. Yue, J. Cao
Institute of High Energy Physics, CAS, Beijing, China

Abstract

HEPS beam charge measurement includes bunch charge measurement system and average current measurement system. The injection scheme of HEPS requires charge monitor with high precision, stability, and a large dynamic range at each phase. This paper introduces the design and commissioning status of HEPS charge measurement system Signal reconstruction method applied in bunch charge measurement is also described in the paper.

INTRODUCTION

The High Energy Photon Source (HEPS) is a fourth geration synchrotron light source based on a 6 GeV diffraction-limited storage ring (SR) [1]. The injector system of HEPS consists of a LINAC a low-energy transport line (LTB), a booster (BST), and two high-energy transport lines (RTB).

Integrated Current Transformer (ICT) is used in LINAC, LTB and RTB for bunch charge measurement. Six ICT sensors are positioned separately at the output of the electron gun and each accelerating section in LINAC, extra two are in the LTB. Additionally, two ICT sensors are positioned at each end of the BTR respectively, and the same sensor arrangement is implemented for RTB. Two DCCTs are used in SR, with one unit serving as a backup for the other. BST follows the same redundancy consideration. All sensors are in-flange type from Bergoz Instrumentation [2]. The details of charge measurement sensor in HEPS are list in Table 1.

Table 1: Charge Sensors in HEPS

Location	Type	Quantities
LINAC	ICT	6
LTB	ICT	2
BST	DCCT	2
RTB	ICT	2
BTR	ICT	2
SR	DCCT	2

SYSTEM DESIGN

LINAC/BTR/RTB Charge

ICT is chosen for LINAC and transport line according to the beam pulse length, for monitoring the bunch charge and injection efficiency. All sensors are 5 V.C/s sensitivity (manufactured), and the diameters are 34.9 mm.

The electronics of ICT (ICT-E) is developed with commercial open-source hardware. The bandwidth of the ICT-E input channel is DC-65 MHz which cover the ICT signal spectrum.The sample rate is 125 MHz, each ICT-E could process 2 channel signals as show in Fig. 1. As the on-axis injection scheme for the booster at 500 MeV, the LINAC must provide an electron pulse with a charge of not less than 6.25 nC [3]. The ICT-E dynamic range of linac and LTB should be 0-10 nC. For RTB and BTR , the dynamic range is 0-5 nC. Trigger from timing system is used to signal synchronous. The ICT-E are in the equipment hall, LMR400 cable is used to transmit ICT output signal. An extra cable connected calibration wire input of the sensor is used to do the calibration and check the sensor function.

The electronic complete the algorithm and integration for each ICT. A self-starting IOC is run on each board to post charge data. The system setting interface is developed by Phoebus, running in the BI station.

Figure 1: HEPS ICT-E.

Signal Reconstruction Algorithm for ICT

ICT signals are susceptible to interference from high-power devices. The bandwidth and sampling rate of ICT-E could suppress most high-frequency noise, but for integral calculations, a sufficient number of data points is still required to ensure accuracy. Therefore, the signal reconstruction method is adopted in ICT-E. The primary objectives are maintaining time-domain smoothness to avoid artifactual oscillation, ensuring accurate waveform representation, and enabling computationally efficient real-time operation.

For choosing a proper function to complete the signal reconstruction, an experiment has been carried out for comparing two regular method: Sinc and Cubic Spline interpolation method. Balance between processing speed and reconstruction accuracy are considered.

In the experiment, original ICT signal was acquired by a high-sampling-rate oscilloscope, then we decimated the original ICT signal with the equivalent sampling rate as ICT-E, applied interpolation algorithms separately to the decimated signal, then compare the results [4]. The basic function is list below in Eqs. (1) and (2). $f_{recon\_sinc/spline}(x)$ is data after interpolation. $f(x_n)$ is the data that being interpolated, T is the sample rate of $f(x_n)$, N is the points of $f(x_n)$. a_i, b_i, c_i, d_i are spline interpolation coefficients need to be solved for each interval.

† zhaoying@ihep.ac.cn

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPCO22

$$f_{recon\_sinc}(x) = \sum_{k=0}^{N-1} f(x_n) g\, sinc(\tfrac{x-x_n}{T}), \quad (1)$$

$$f_{recon\_spline}(x) = a_i + b_i(x-x_i) + c_i(x-x_i)^2 + d_i(x-x_i)^3 \quad x \in [x_i, x_{i+1}]. \quad (2)$$

We respectively apply 16x Sinc and Spline interpolation to the ICT data out of ICT-E, and then compare the results with the high-sampling-rate data from the oscilloscope. The plot and details are shown in Fig. 2. The blue line is data applied Sinc function and red one is Spline. Compare to the origin data in Green dot, the data after reconstruction in two method both show good fitting, except for a loss of the spike at the first falling edge. There is ringing occurred in Sinc interpolated data because of non-ideal truncation in the frequency domain [4]. The zoom-in of the pulse peak shows that the Spline interpolation reduces peak amplitude and smooth the pulse peak. Sinc function can better preserve the information of pulse peak. Based on the results, we applied Sinc function in ICT-E.

For solving the ringing problem, performing interpolation in regions with high-frequency transitions should be avoided. We extract slightly longer segments of ICT output data than strictly required, interpolate this extended segment, and use only the stable portion containing the valid ICT signal. This ensures that ringing artifacts remain confined to the reserved buffer zone and do not affect the core ICT data.

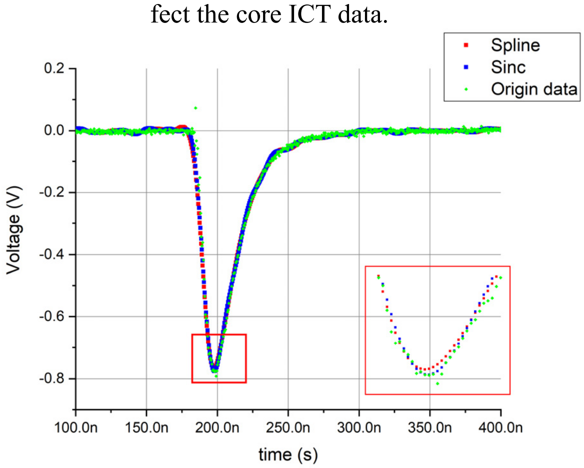

Figure 2: Sinc and Spline interpolation results compared with origin data.

Lab test has been done to evaluate the final algorithm. We use an arbitrary signal generator, simulate a 2 nC pulse and send into ICT sensor with 50 Hz repetition frequency, then ICT-E record about 1000 data. The statistic result shows that the STD is 0.011 nC with mean value -2.005 nC. Figure 3 shows the statistic histograms and distribution curve. The resolution is less than 0.02 nC that meets the requirement.

BST and SR Charge

The SR and BST charge are obtained from DCCTs. BST sensors include BS1 and BS3 DCCT with 30 mm × 36 mm ellipse cross section. SR sensors include R45 and R47 DCCT with 22 mm diameters cross section.

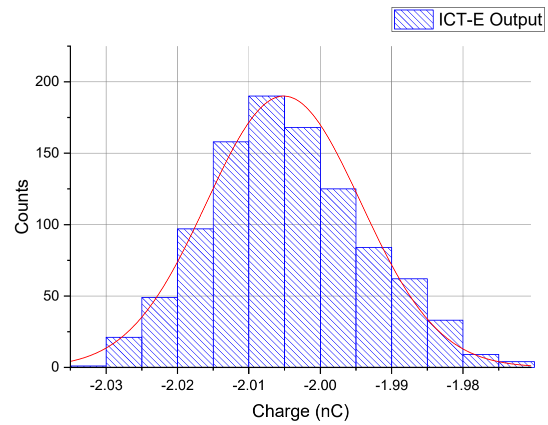

Figure 3: The results of lab test of ICT-E output.

$7^{1/2}$ multimeter from Keithley is selected to digitalize all the DCCT outputs as its low noise and high resolution. The specific requirement and main parameters of DCCT system is in Table 2.

The sample rate of all sensors is set to 1 Hz default. At the first commissioning stage, SR R47 DCCT is set to 50 Hz for monitoring the injection status, R45 DCCT is 2 Hz for beam lifetime calculation as a better resolution. BS3 DCCT is set to 50 Hz for energy ramping and extraction, BS1 DCCT is set to 1 Hz as default. The rate is setting according to the sequency of injection and extaction, as the

The IOC for each DCCT is running on an independent server which is used to transmit data and control the multimeter by LAN port. The system setting interface is developed by Phoebus, running in the BI station. Transmille 3041A precision multi product calibrator is used to complete the calibration and check the system function.

Table 2: Parameters of DCCT

		Requirement	**Parameters**
SR	Non-Linearity error	≤0.1 %	≤0.1 %
	Resolution	≤50 μA @ 0.1-250 mA	≤0.5 μA @ 5/50/500 mA Range
BST	Non-Linearity error	≤0.1 %	≤0.1 %
	Resolution	≤10 μA @ 0-0.1 mA ≤50 μA @ 0.1-15 mA	≤0.5 μA @ 20 mA range

COMMISSIONING RESULTS

HEPS LINAC starts commissioning on March 2023. At the first stage test, we finished the beam tuning and beam parameters measurement at low charge mode [3], then complete the high bunch charge mode. August 6, 2024, the HEPS storage ring successfully storage of a single bunch of electron beams, with a current of approximately 60 μA and a lifetime exceeding one minute. Subsequently, we

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPCO22

start the multi-bunch injection in SR. Figure 4 shows the first storage beam current.

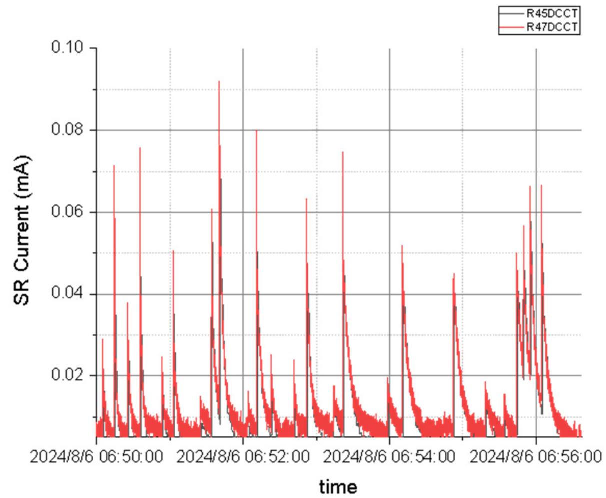

Figure 4: DCCT monitored first storage beam current in HEPS.

Figure 5 shows a top-up commissioning data in January 2025, BST runs at single bunch mode. The green line is the charge data from BS3 DCCT in BST, each pulse represents an injection cycle. The first peak in the pulse corresponds to the bunch injected from the LINAC at a beam energy of 500 MeV. The subsequent change in the pulse shape—characterized by a rapid decrease of the peak immediately followed by a plateau—reflects a sudden charge loss event followed by stabilization. This phase represents the energy ramping process (from 500 MeV to 6 GeV) in the BST. The second peak in the pulse indicates an increase in charge. During this phase, a bunch is extracted from the SR and coalesces with the bunch in the BST. The coalesced bunch is extracted and reinjected to the SR. The entire duration is approximate 1s at that time. The black line is charge data from SR, the declining slope represents the beam decay states, while the periodic gaps representing bunch extraction and the reinjection process.

Red line and green lines are BTR ICT1 and ICT2, the purple and brown lines are RTB ICT1 and ICT2. The steps in the curve is because the data updates are synchronized to the trigger signal. The trigger signal for ICT-E is synchronized with the injection trigger, as the data remains last value until next injection.

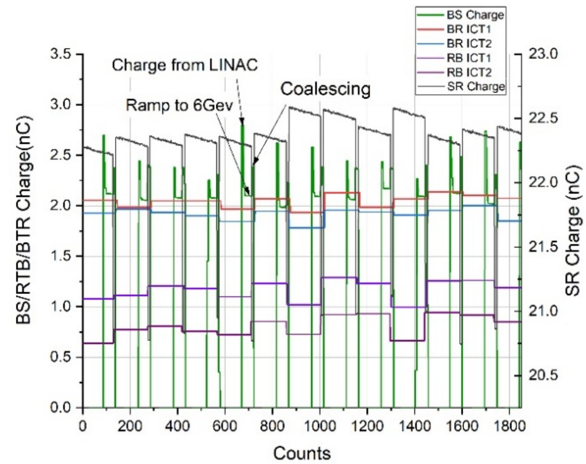

Figure 5: Commissioning charge data at top-up mode.

SUMMARY AND FURTHER WORK

The charge measurement system of HEPS has effectively met the requirements in current stage. Though some issues have been encountered, such as aperiodic offset jumps and baseline fluctuation in the sensor outputs. Besides, the ICT-E also needs further improvements, such as the power supply scheme. In the next phase, we will systematically investigate and resolve these issues in accordance with the updated commissioning requirements.

REFERENCES

[1] Y. Jiao *et al.*, "The HEPS project", *J. Synchrotron Radiat.*, vol. 25, no. 6, pp. 1611–1618, 2018. doi:10.1107/S1600577518012110

[2] Bergoz, https://www.bergoz.com/

[3] Y. M. Peng *et al.*, "Milestone progress of the HEPS booster commissioning", *Nucl. Sci Tech.*., vol. 35, no. 16, 2024. doi:10.1007/s41365-024-01365-w

[4] S. D. Casey, K. A. Okoudjou, M. Robinson, B. M. Sadler, Eds. *Sampling theory and applications*, Birkhäuser Cham, 2020. doi:10.1007/978-3-030-36291-1