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一种新型BEPCII束团电荷测量系统

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A bunch charge measurement system based on Turbo-ICT for BEPCII

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Abstract: A new kind of sensor Turbo-ICT has been applied to accurate bunch charge measurement in BEPCII transportation line. The system improves the resistance ability against external interference and has high signal-to-noise ratio. This paper introduces the principle, the design ideas and the function of the system. Up to now, Turbo-ICT has been used to operate online for electron bunch charge quantity measurements successfully. This paper also presents the experiment results of the sensor.

Key words: bunch； charge measurement； Turbo-ICT； BEPCII

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The BEPCII (Upgrade project of Beijing Electron Positron Collider) injector consists of a linear accelerator (linac) and e^- and e^+ transportation lines. There are 5 Beam Current Monitors (BCTs) installed along the linac, 7 BCTs on each transportation line, which are used for bunch current measurement. These sensors were designed for the early BEPCII, where the rising time was about 300 ps, which was sufficient for 1ns bunch length at that time[1]. In 2009, to get higher efficient injection, a Sub-Harmonic Buncher (SHB) system took the place of the original buncher system, thus bunches are compressed to picosecond at the end of the linac. Although the recalibration of BCTs were done, a relative value could be used to evaluate the injection condition, there were still lack of the accurate charge information from the existing system. Furthermore, the last BCT (BCT7) near the injection point are severely affected by electromagnetic noise during the injection, and it cannot obtain valid data. The sum value of the Beam Position Monitors (BPMs) is available but needs absolute calibration, too. To get accurate bunch charge measurement, especially at top-up mode, the injection should be under good control, a new kind of measurement system with a Turbo-ICT sensor was developed in the summer of 2018.

1 Parameters and installation of the system

The system will be used to monitor bunch charge and calculate injection efficiency in both collide and synchrotron mode. The present main parameters of BEPCII LINAC are listed in Table 1[1].

Table 1 Main parameters of BEPCII LINAC

repetition rate/Hz	frequency/MHz	bunch length/ps(2σ)	energy/GeV
50*	2856	10	1.89—2.5

*It is adjustable, depending on the need of injection.

The charge measurement system includes an Turbo-ICT (Turbo Integrating Current Transformer) sensor, BCM-RF (Beam Charge Monitor-Radio Frequency) electronics, DAQ (Data Acquisition) electronics and an online calibration set. The Turbo-ICT sensor is installed at the end of the e^- transportation line (Fig.1(b)), after dipole TE-B16 along the beam transport direction, about 20 m from the e^- injection point. The main parameters are listed in Table.2. In consideration of proper distance for signal transmission, BCM-RF, DAQ and the online calibration set are located in the transverse feedback station. The schematic of the system and the sensor’s simple layout is shown in Fig.1(a).

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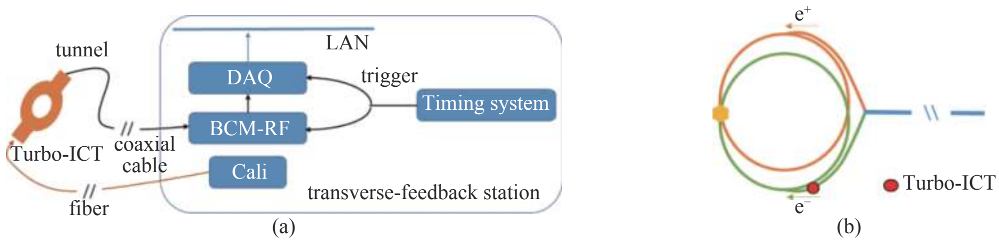


Fig. 1　Schematic of the system (a) and location of Turbo-ICT (b)

Table 2　Parameters of charge measurement system

Turbo-ICT flange	Turbo-ICT length/mm	BCM-RF scale/nC	BCM-RF output/V
DN100	40	0.05—2	+5

2　Measurement principle and function introduction

Turbo-ICT is a commercial current transformer from Bergoz Instrumentation[2], it is designed for ultra-short particle bunch charge measurement. Compared to ICT (Integrating Current Transformer) which is often used for short bunch charge measurement too, Turbo-ICT works with BCM-RF electronics process signals in frequency domain and has higher signal-to-noise ratio (SNR). Turbo-ICT is more efficient than ICT for measuring charges at dozens of picocoulombs, which fully meets BEPCII's needs and demands.

Typical ICT is used for short bunch current measurement. It contains two magnetic cores. A capacitor is put on the sensor's out shell as the first winding, when beam bunch is passing through, the capacitor is charged. A second winding is wounded on only one core with a resistor for readout. When the charged capacitor releases in a slow rate, a signal excited on the second winding will change the resistor's potential. The voltage of the resister is proportional to the charge. The sensor can be seen as a low pass filter for pulse bunch magnetic fields, but the charge value is maintained. The schematic of ICT is shown in Fig.2[3].

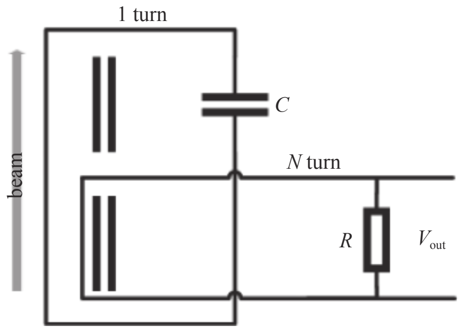


Fig. 2　Schematic of ICT

The ICT 's two-stage windings move the bunch signal to a lower frequency domain close to DC and the charge information is completely saved. In this process, the longitudinal information of the bunch is sacrificed, and the length of the bunch won't influence the measurement, too.

Furthermore, ultra-short single beam bunch down to picosecond can be seen as a Dirac signal[4]. Spectrum of a Dirac function is a constant, it is equally distributed in frequency domain. According to this feature, theoretically, the amplitude of a certain frequency signals could represent the bunch charge, and would have high SNR and resolution in long-distance transmission.

Based on the principle, an FEFA (Front-End Amplifier and Filter) module is applied to the ICT. The module has a band-pass filter to narrow the output signal at around 180 MHz[5]. The Turbo-ICT is shown in Fig.3. The narrowed band signal from the FEFA is sent to BCM-RF for advanced processing. A logarithmic amplifier makes the input signal work at large dynamic range, a sample and peak holding module holds the logarithmic signal and the holding voltage is proportional to the bunch charge. To obtain accurate charge information, the timing sequence of logarithmic bunch signal and holding signal should be set precisely[6].

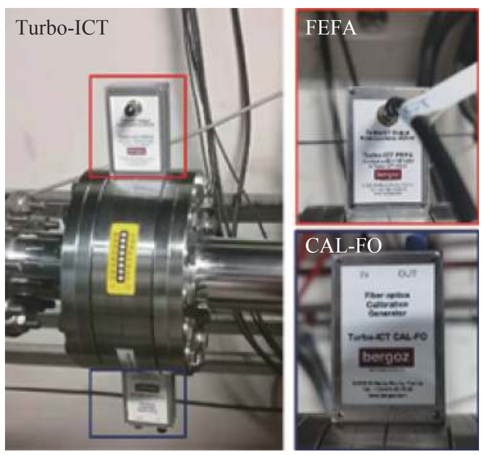
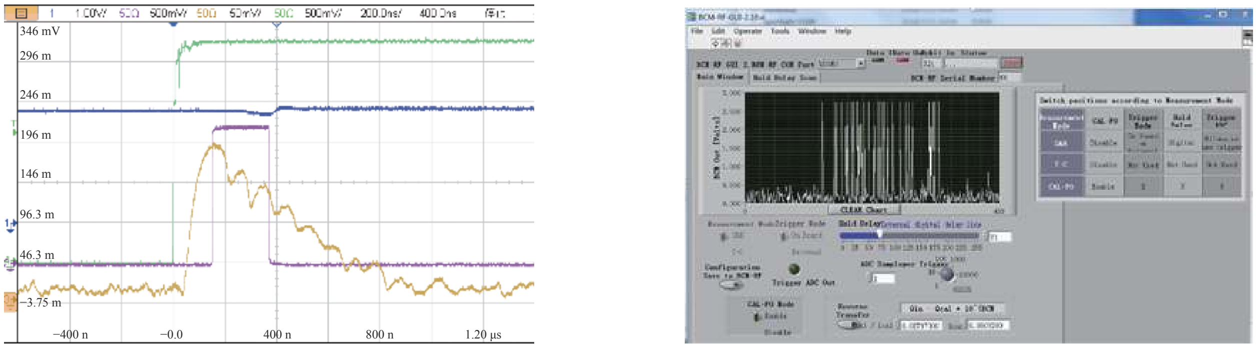


Fig. 3　Turbo-ICT on BEPCII

Fig.4(a) indicates all signals from BCM-RF respectively: logarithmic signal (yellow), hold signal (red), sample and peak



(a) output signal (b) BCM-RF GUI

Fig. 4 BCM-RF output signal view and BCM-RF GUI

holding output signal (blue), the trigger signal (green) from BEPCII timing system which is synchronized with electron gun. By adjusting the delay of the trigger signal (green), the logarithmic signals' peak is set at the rising edge of the hold signal.

A vender-manufactured Labview based GUI (Graphical User Interface) is provided for BCM-RF parameters setting as shown in Fig.4(b). The electronics need enough time to hold single bunch peak value and the hold value is a DC voltage up to 100 ms, the interval of bunches should be longer than 500 ns.

The BCM-RF calibration function is used cooperatively with a CAL-FO module, which is a separate photon-electric conversion module fixed on the Turbo-ICT sensor, as can be seen in Fig.3. A calibrated pulse generator sends out an optical signal manually to the module through an optic fiber, simulating a short beam pulse into the sensor, and the BCM-RF output can be read from the GUI. The waveform in Fig.4. (b) indicates a typical online calibration result, each pulse is one output of the simulated bunch from calibrated-pulse-generator. The calibration result is $U_{\text{BCM-RF}}$ = 2.778 V, which matches the factory setting of the calibrated pulse generator: $Q_{\text{CAL-FO}}$ = (150.5±2.0) pC.

3 Data acquisition and processing

3.1 Data acquisition hardware

RedPitayaSTEMlab 125-14 board from Sloveniais is used for collecting data from BCM-RF. It's a commercial FPGA Xilinx Zynq 7010 based board with various interfaces, whose main features are listed in Table.3[7]. The bandwidth and sample rate are sufficient for a long DC pulse signal.

Table 3 Main features of RedpiataySTEMlab 125-14

RF Input full scale voltage/V	RF Input channels	Sample rate/(MS/s)	ADC resolution/bit	Bandwidth
±20	2	125	14	DC—60 MHz

This kind of board can operate on an OS (Operating System) of Ubuntu 16.04.3. A 16 Gbyte SD card is adopted to complete booting and initialization. A pre-built image can be downloaded from RedPitaya official webserver[8], then burn into the SD card. The obvious advantage is that all programming work could be done in the board and it's easy to transplant, modify and debug.

A crate is designed locally for well shielding and long-term stability. Mingwei AC-DC power supply module is used instead of its original one for reducing the ripple noise.

The BEPCII control system uses EPICS database, which is a set of open source software tools, libraries and applications developed collaboratively[9]. A RedPitaya-EPICS driver is used for Turbo-ICT data processing and storage[10]. This driver is developed by Australian Synchrotron, based on the AsynPortDriver. The main target of AsynDriver is EPICS IOC device support, an open source C++ based class which could simplify the writing work of Asynport drivers[11]. According to the requirement, the driver has been modified and compiled, and Turbo-ICT-IOC is established. The schematic of DAQ is shown in Fig.5.

3.2 Conversion coefficient calibration and data processing

The task of conversion from voltage to charge is accomplished in db (data base) file. The voltage signal from BCM-RF is assigned to a PV, then CALC field is used to complete the voltage-charge transformation.

The real cable's attenuation between Turbo-ICT sensor and BCM-RF-E would affects the conversion coefficient, thus it should be considered. In this case, a 50 m LMR-200 coaxial-cable has 7.2 dB attenuation at 180 MHz, the cable test result by network analyzer is shown in Fig.6.

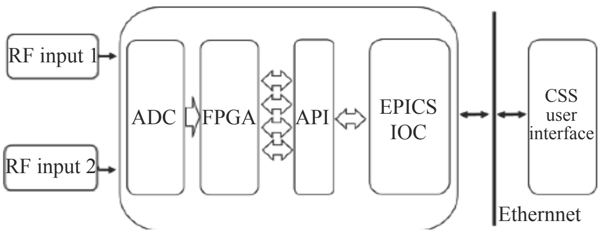


Fig. 5 Schematic of DAQ

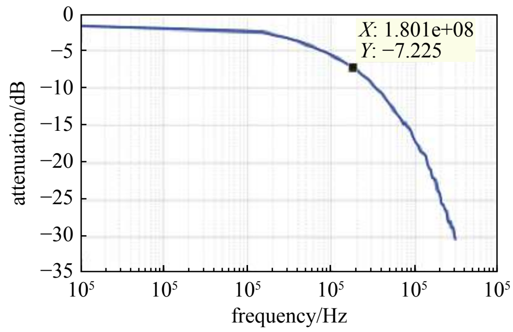


Fig. 6 Attenuation of the LMR-200 cable

The sensitivity of the system can be calculated as

$$U_{\mathrm{BCM-RF}}=U_{\mathrm{cal}}\lg\frac{Q_{\mathrm{in}}\times K\times D}{Q_{\mathrm{cal}}},\quad Q_{\mathrm{in}}=Q_{\mathrm{cal}}\times\frac{1}{K}\times\frac{1}{D}\times 10^{\frac{U_{\mathrm{BCM-RF}}}{U_{\mathrm{cal}}}} \tag{1}$$

where Q_{cal} and U_{cal} are calibration constants, they are factory measured and set in the BCM-RF. K is the transmission coefficient of FEFA and it is a fixed value. The parameter D is the drop at 180 MHz in the cable, it can be calculated as $U_{\mathrm{x}}/U_{\mathrm{Turbo\text{-}ICT}}$, U_{x} is the input at the BCM-RF and $U_{\mathrm{Turbo\text{-}ICT}}$ is the output at the sensor. Hence, for a new cable, the attenuation can be considered as

$$20\lg\frac{U_{\mathrm{x}}}{U_{\mathrm{Turbo\text{-}ICT}}}=\text{cable attenuation} \tag{2}$$

$$S_1=Q_{\mathrm{cal}}\times\frac{1}{K}\times\frac{U_{\mathrm{Turbo\text{-}ICT}}}{U_1}=0.062\,28 \tag{3}$$

$$S_2=Q_{\mathrm{cal}}\times\frac{1}{K}\times\frac{U_{\mathrm{Turbo\text{-}ICT}}}{U_2}=Q_{\mathrm{cal}}\times\frac{1}{K}\times\frac{U_{\mathrm{Turbo\text{-}ict}}}{U_1/1.412}=0.087\,97 \tag{4}$$

assuming U_1 is the input of BCM-RF and $U_{\mathrm{Turbo\text{-}ICT}}$ is Turbo-ICT output. S_1 =0.062 28 is the original coefficient which is provided in the factory calibration report, and the cable's attenuation used for calibration is 4.2 dB. U_2 and S_2 are the BCM-RF input and coefficient at attenuation of 7.2 dB.

The final relation expression is

$$Q(\mathrm{pC})=0.087\,97(\mathrm{pC})\times 10^{\frac{U_{\mathrm{BCM}}(\mathrm{V})}{0.860\,91(\mathrm{V})}} \tag{5}$$

It is noticed that there is a wiggle on the output signal (blue) due to the sample-and-hold circuit as shown in Fig.4(a), effective data acquisition should start after this 200 ns wiggle. For BCM-RF, one bunch's output voltage would maintain still until the next bunch is coming, which will last approximately 200 ms, so the ADC trigger delay could set greater than 200 ns by trigger delay PV, and the data acquired is reliable.

The timing of charge data should be exactly aligned with other parameters of the accelerator, practically the current data in the storage ring (SR). For getting accurate timestamp of data, Network Time Protocol (NTP) client is installed and set to check and correct RP 125-14 system time with BEPCII timing system. A Cron service is used to perform this task hourly.

4 Online measurement results

The charge measurement system has been applied to BEPCII commissioning and it works well. A 10-hours long term data of e^-/e^+ SR beam current from DCCT and injected e^- charge from charge measurement system are shown in Fig.7(a). The accelerator operated on collide mode, and the injection period was about 1 h. The injection would start when the beam current

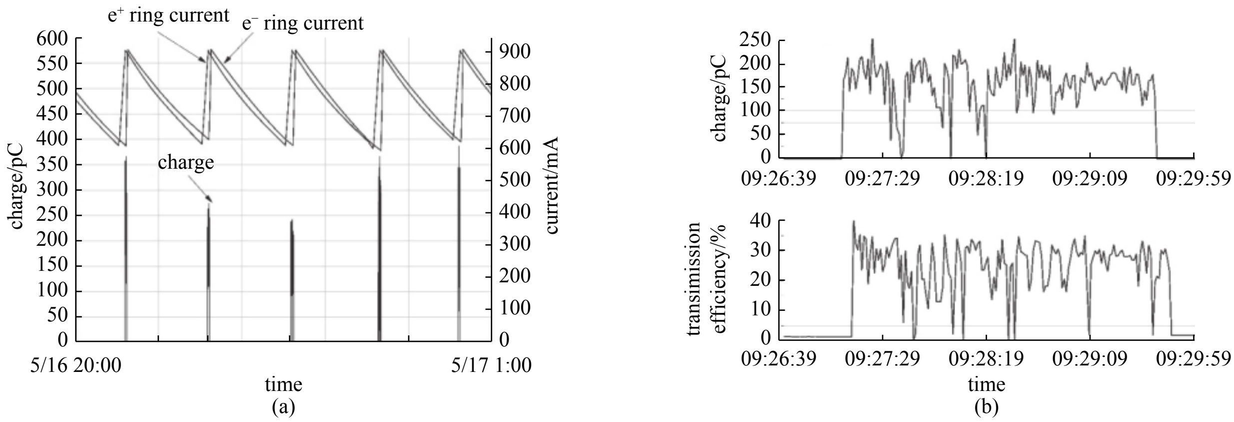


Fig. 7 10 h current/charge curve (a) and charge/transmission efficiency (b)

in the SR was down to 600 mA. The charge curve fits well with the e− beam current accumulating curve. During the non-injection period, the data from charge measurement system showed that the noise signal was close to zero. In a single injection as shown in Fig.7 (b), the charge result (upper) is consistent with the transmission efficiency tendency (down). The transmission efficiency is a relative value, provided by the ratio of two BPM sum data. The first BPM is at the start point of transmission line, the second one is near the e− injection point after the Turbo-ICT sensor. According to the curves, low charge is corresponding to low transfer efficiency. But some spots in the transfer efficiency curve do not match with those in the charge curve, because there is mass beam loss after the first BPM.

4.1 Results in collide mode

During high current collide operation mode, when SR beam current is above 600mA, e− injection frequency is usually set to 50Hz/3 for avoiding over fast filling, which might cause beam instability and loss. Take one shot to evaluate the injection rate: the increment of current per second in the storage ring could transfer to charge value for the SR repetition rate 1.262 MHz, about 792 ns[1], subfigure 3 in Fig.8 (a) indicates the rising of SR current in 2 min injection, subfigure 2 in Fig.8(a) is the corresponding charge value per second from Turbo-ICT, while the charge is around 200 pC. The beam loss from the spot of Turbo-ICT to the injection point along the transportation line is small and ignored in this case. The injection rate equals the increment of injected charge per second/SR charge variation per second, which is indicated in subfigure 1 in Fig.8 (a).

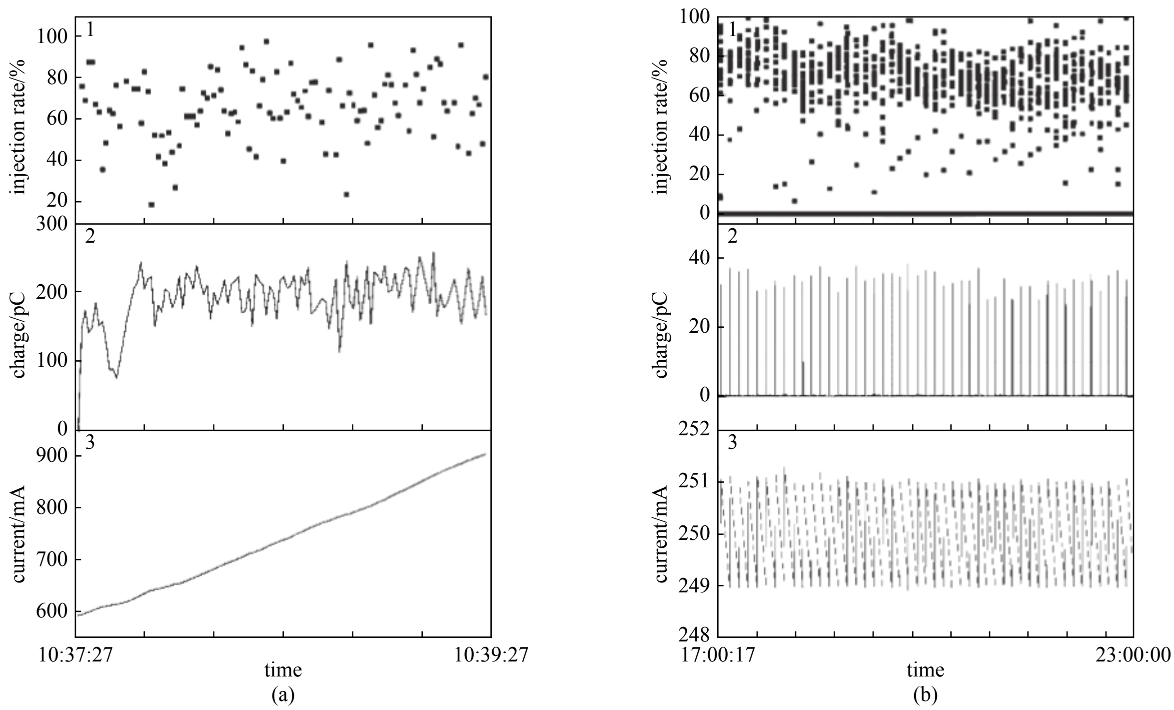


Fig. 8 Large current collide mode (a) and synchrotron top-up mode (b) injection measurement results

4.2 Results in synchrotron mode

In the synchrotron top-up mode, the SR repetition rate is 1.242 MHz, about 805 ns. The injection frequency is 12.5 Hz/3 for avoiding over filling the beam bunches. In subfigure 3 of Fig. 8(b) there is a 7 h long current curve, and the top-up scale is from 249 mA to 251 mA. Subfigure 2 in Fig.8(b) shows the charge curve for each injection variant from 30—40 pC, and subfigure 1 in Fig.8(b) gives the injection rate which is mostly around 60%—90%.

5 Conclusion and outlook

Turbo-ICT shows good performance in BEPCII normal operating modes, especially low charge measurement in top-up mode. The charge measurement system has been operating stably since it was put into use.

But more study and intensive work are necessary for BEPCII now and upgrade project. A Faraday cup is planned to be installed at the start point of the transportation line, so that absolute BPM sum value could be calibrated then. This would supplement the quantitative comparison of charge measurement systems. Although the beam loss can be ignored theoretically in the last section of the transportation line, it still needs experiment to verify. An accurate charge measurement for positron injection is also under consideration for a complete thought. The experience could be a guide for similar system, applied to other kind of accelerators, laser-plasma system or FEL.

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一种新型 BEPCII 束团电荷测量系统

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摘 要: 介绍了一种新型传感器 Turbo-ICT 在 BEPCII 输运线电荷量测量上的应用。 该探测器的电荷测量系统具有强抗干扰能力和较高的信噪比, 能满足各种运行模式, 尤其是 Top-Up 模式时的测量需求。介绍了该系统的工作原理、设计思想和功能。目前, 该系统已在 BEPCII 电子输运线上在线应用于电荷量测量和注入效率的计算, 文中给出了实际测量结果以及该系统进一步优化的方案。

关键词: 束团; 电荷测量; Turbo-ICT; BEPCII