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BEAM CHARGE MEASUREMENT AND SYSTEM CALIBRATION IN CSNS *

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Abstract

In China Spallation Neutron Source (CSNS), the beam charge monitors along the ring to the target beam transport line(RTBT) and the ring to the dump beam transport line(RDBT), are consisted of an ICT and three FCTs manufactured by Bergoz. The electronics includes a set of NI PXIe-5160 oscilloscope digitizer, and a Beam Charge Monitor (BCM) from Bergoz as supplementary. The beam charge monitors provide the following information: a) the quantity of protons bombarding the tungsten target; b) the efficiency of particle transportation; c) a T0 signal to the detectors and spectrometers of the white neutron source. With the calibration with an octopus 50Ω terminator in lab and an onboard 16-turn calibrating coils at the local control room, corrections for the introducing the 16-turn calibrating coils and the long cable were made. An accuracy of ±2% for the beam charge measurement during the machine operation has been achieved with the ICT/FCTs and a PXIe-5160 oscilloscope digitizer.

INTRODUCTION

The accelerator and target layout of CSNS and beam instrumentations distributed on the linac , the RCS ring and beam transport lines are presented in Figure 1. After the 50keV H- source, the 4-tank 324MHz drift tube linac (DTL) is designed to accelerate the H- beam from 3MeV to 81MeV, and the H- ions are injected into the RCS ring. During the injection, H- stripping by a carbon primary stripper foil (100μg/cm^2) and a secondary stripper foil (200μg/cm^2) is adopted for this high intensity proton synchrotron [1], then protons are accelerated to 1.6GeV in 20ms by 8 ferrite-loaded RF cavities before extraction [2]. There is an ICT sensor installed at the beginning of RTBT and RDBT beam line, one FCT sensor just in front of the R-dump, one FCT sensor in the mid of bending magnets RTB1 and RTB2 and the third FCT sensor in front of the tungsten target.

Before the installation, two sets of charge measurement methods were utilized for the sensor calibration. During the machine commissioning, the beam charge measurement was calibrated with the extracted particle numbers derived by the beam current measured by DCCT on the RCS ring and the RF frequency (round about 2.44MHz). Then we made a statistics analysis of the beam charge measurement during machine operation. It is showed that a sensitivity of 1.0×10^{10} protrons/pulse and an accuracy of less than ±2% could be achieved in the beam charge measurement.

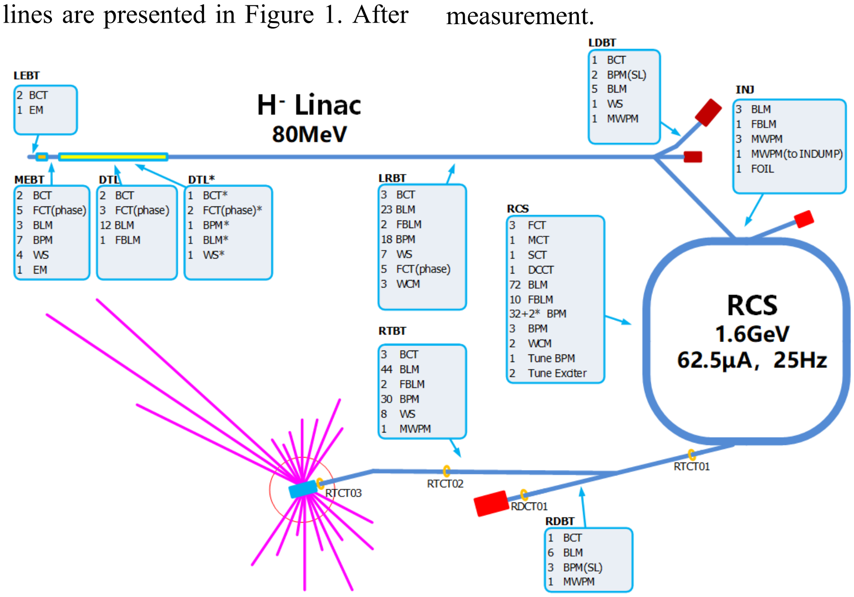

Figure 1: Accelerator and target layout and beam instrumentations of CSNS.

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TIME STRUCTURE AND SPECTRUM OF EXTRACTED PROTON BEAM

The repetition rate of the extraction proton beam is 25Hz in operation, which can be configured as one-shot mode during machine commissioning. The RCS harmonic number is 2, thus there are two bunches accelerated in the ring and extracted simultaneously in a fast extracting time of 600ns. The maximum charge of each bunch is 1.248 µC, corresponding to the beam power of 100kW bombarding the target. The interval of them is 409ns, a reciprocal of f_{rf_high} (2.44MHz). According to the simulation of longitudinal beam dynamics [3], the extracted two bunches are in a kind of dual quasi Gaussian distribution, shown in Figure 2. An FFT analysis to the beam spectrum is performed using LabVIEW, and the result is showed in Figure 3. Above 15MHz, the amplitude of the beam manifests 15dB less than its maximum, and above 30MHz, it has a round about 30dB weaker amplitude.

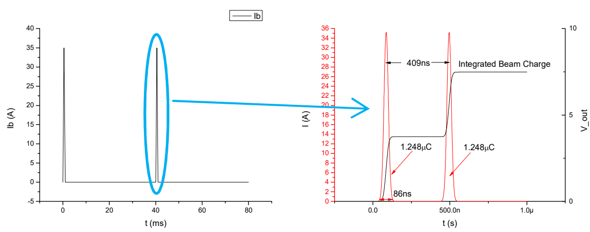

Figure 2: Time structure of the extracted proton beam.

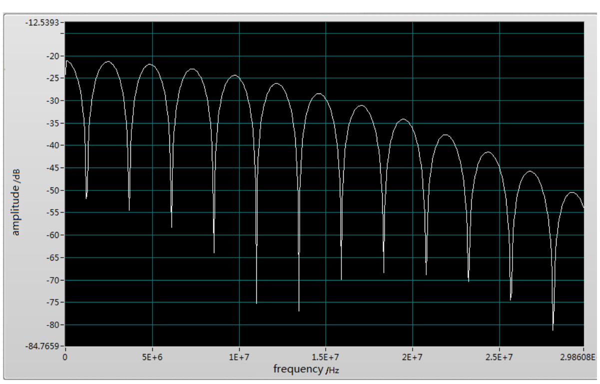

Figure 3: Spectrum of the extracted proton bunches.

Table 1 gives the main parameters of the FCTs installed on the RTBT/RDBT beam line. Thus, all the FCTs have a rise time of less than 500ps, and will response promptly to the extracted beam.

Table 1: Main Parameters of RTCTs/RDCT Sensors [4]

Position	RTCT02	RTCT03	RDCT01
Model	FCT-178-0.5	FCT-302-0.5-H	FCT-302-0.5
f_{low}(-3dB)/Hz	134.5	122.3	149.5
f_{high}(-3dB)/MHz	810	708.8	708.5
Droop/(%/us)	0.08	0.08	0.09
Risetime/ps	432	494ps	494
Pulse Response/ps	413→754	405→551	413→610
Step Response/ps	427→808	410→959	405→824
Differentiation	21.2%/300µs	21.2%/300µs	23.4%/300µs

According to the frequency response measurement of Bergoz FCT, as showN in Figure 4, it's not as flat as that in middle frequency range (1 kHz ~ 1MHz), especially in frequency range of less than 200Hz and higher than 5MHz. Therefore, if we use an oscilloscope digitizer as the electronics of FCT to sample the current waveforms and integrate the pulse area to deduce the beam charge in a time window, the nominal sensitivity of 0.5V/A need specific corrections. Also, considering the long cable connecting the sensor and the electronics in local control room (60m~120m long separately), the signal attenuation and distortion due to the cable should be measured and corrected.

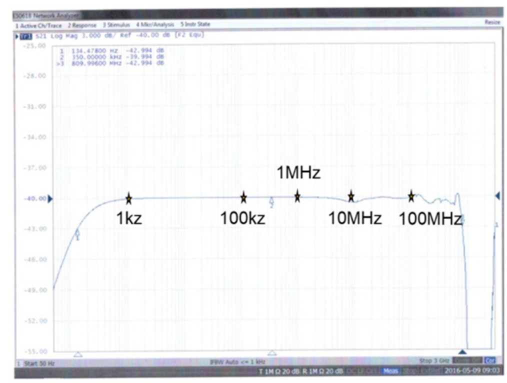

Figure 4: Frequency response of a Bergoz FCT (RTCT02).

CALIBRATION IN THE LAB

The number of the protons hitting the target will be 1.56×10^{13}/pulse in design, and one tenth of that in the acceptance test. We designed a 16-turn 8-direction coil with a 50Ω PCB board to realize the on-line calibration, showed in Figure 5.

Figure 5: FCTs and ICT tied up to a 16-turn 8-direction coil with a 50Ω PCB board.

In order to evaluate the influence of the 16-turn coils and a 100m-long cable to the original FCT output, we also designed an octopus 50Ω terminator [5], as showed in Figure 6. It was like a single turn calibration coil which was used in a single pulse beam charge monitor [6], but an isotropous calibration current was fed into the coil. A pulse with a width of 80ns and a leading/trailing time of 30ns is generated by a function generator Tektro-

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nix AFG3102 and the signal was fed into an octopus 50Ω terminator. The output of the FCT/ICT was sampled by a Keysight MSO X3034T oscilloscope (2GSa/s, 8bit ADC). Then the pulse area was integrated and noise eliminated by a self-designed LabVIEW code.

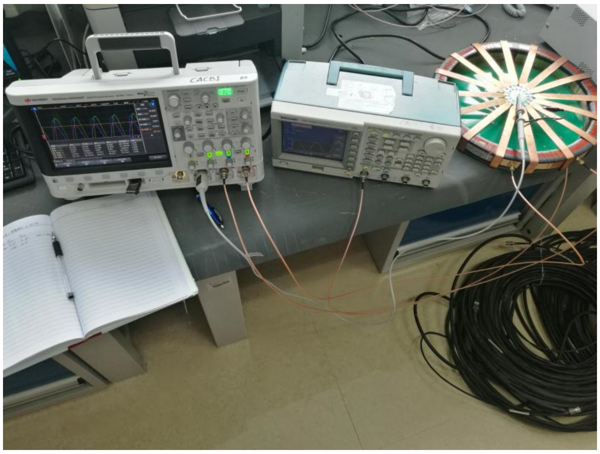

Figure 6: FCTs or ICT calibrated with a 50Ω octopus terminator.

We assume that if there is no calibration coils, but only the octopus as the primary winding (N=1) of the FCT sensor (N_s=50 turns and R_s=50 Ω), the current in the secondary coil should be

$$i_s = \frac{s\tau_s}{1+s\tau_s}\left(\frac{i_b}{N_s}\right) \qquad (1)$$

$$where \quad \tau_s = \frac{L_s}{R_s/2} = \frac{{N_s}^2 L_0}{R_s/2}$$

Here, s is the Laplace operator, and L_0 is the inductance of the core with only one turn winding. Then we have an equivalent circuit of the FCT with both the secondary winding and the calibration winding (here N_c=16 turns), where R_c=R_s=50Ω, but it's in serial to the calibrating inductor (Figure 7). Then, the current in the secondary coil changes to be

$$i_s' = \frac{s\tau_s}{1+s\tau_s+s\tau_c}\left(\frac{i_b}{N_s}\right) \qquad (2)$$

$$where \quad \tau_c = \frac{L_c}{2R_c} = \frac{{N_c}^2 L_0}{2R_c}$$

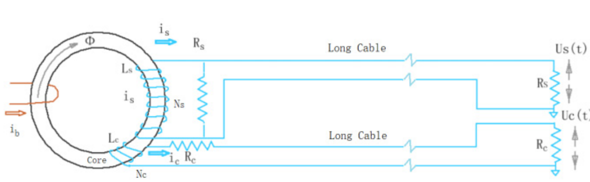

Figure 7: Equivalent circuit of an FCT with calibration coils.

We substituted the actual value into the variants of the above formula (1) and (2), and got the result of i_s'/i_s=100/102.56, for the correction of introducing the calibration coils to the FCT sensor.

Then we did the comparison of the pulse area of the FCT output with/without the calibration coils, and get a correction factor of 100/102.5, which agrees with the equivalent circuit analysis very well.

When the FCTs/ICT were installed in the ring tunnel, we did the calibration with long cables, and got the relation of the integrated pulse area (unit: nVs) with the particle number for each sensor. For example, Figure 8 shows the linearity and the error of the calibration for RTCT03, which is installed in front of the target and involved in the calculation of neutron production efficiency.

Table 2: Calibration Result of RTCTs/RDCT

Senor ID	Particle Number (1E+10)	Error(%)
RTCT01	1.3083 * Area + 0.020	±2
RTCT02	1.4013 * Area + 0.606	±2
RTCT03	1.3755 * Area + 0.850	±1
RDCT01	1.3329 * Area + 0.191	±2

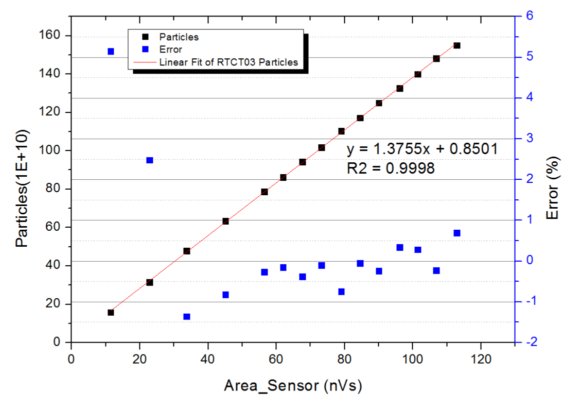

Figure 8: Calibration result of the RTCT03.

BEAM CHARGE MEASUREMENT IN MACHINE OPERATION

Along with the commissioning of RTBT beam line, we did the calibration of RTCT01, RTCT02 and RTCT03 with the DCCT on the ring, when there is no obvious beam loss along the extraction and RTBT beam transport line. Figure 9 shows the two extracted proton bunches detected by the 3 CT sensors. At the end of RTCT02 cable, we used a power splitter for T0 signal of Back-n beam line, and an -6dB attenuator at the end of RTCT03 cable to avoid the CT output amplitude overload as the beam power increasing. The corrections of the power splitter and the attenuator were measured and taken into account of the pulse area integration. The proton number per pulse (two bunches) is 1.56×10^{12}, corresponding to the beam power of 10kW bombarding the target.

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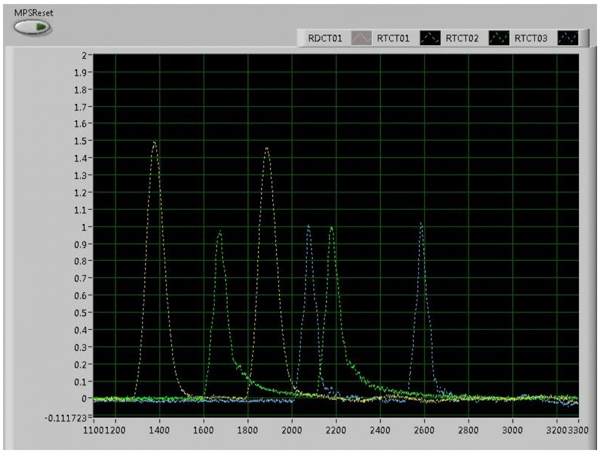

Figure 9: Two extracted proton bunches detected by the 3 RTCT sensors.

For the DCCT on the RCS ring, it measures the average current of the circulating beam, the relation of the beam charge Q and the revolution frequency f_{rev} or the RF frequency f_{rf} (harmonics number h=2) is

$$Q = \frac{I_{beam}}{f_{rev}} = h\frac{I_{beam}}{f_{rf}} \tag{3}$$

At the extraction time, Q_{ext} can be derived by the beam current measured by DCCT and the RF frequency measured by WCM (or just the RF frequency configured by the LLRF code).

Figure 10 shows a statistic result of the RTCTs, which gives a standard deviation of ±2%. During the past 6 months' running, the beam charge measurement system worked very well, and were programmed (EPICS) into the MPS system to inform the operator immediately when there was big beam losses happened along the RTBT beam line.

CONCLUSION

It became complicate when we introduced the 16-turn calibration coils into the beam charge measurement. Corrections including the calibration coils and the long cables were done in the lab and at the local control room. Finally, we obtained an accuracy of ±2% with the 3 Bergoz FCTs, one ICT and an NI PXIe-5160 oscilloscope digitizer as the electronics. Up to last machine running in July, 2018, the maximum hitting-target proton number per pulse has achieved to 3.6×10^{12}, which means the beam power went up to 23kW, almost a quarter of the designed value 100kW.

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REFERENCES

[1] L. Kang *et al.* "Introduction about Key Techniques of Critical Equipment in CSNS", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, paper THPVA049, pp.4548-4550.

[2] H. Sun *et al.* "RF System of the CSNS Synchrotron", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper WEPFI028, pp. 2765-2767.

[3] N. Wang *et al.* "The Design Study on the Longitudinal Beam Dynamics for CSNS/RCS", in *Proc. HB2012*, Beijing, China, Sep. 2012, paper MOP216, pp. 89-92.

[4] Bergoz Instruments Certificate of Calibration FCT#3350, #3351, #3477", unpublished, 2016 and 2017.

[5] J. Bergoz and H. Bayle, private communication, May 2016

[6] B. Vojnovic, "A Sensitive Single-pulse Beam Charge Monitor for Use with Charged Particle Accelerators", *Radiat. Phys. Chem.* vol. 24, pp. 517-522, 1985.

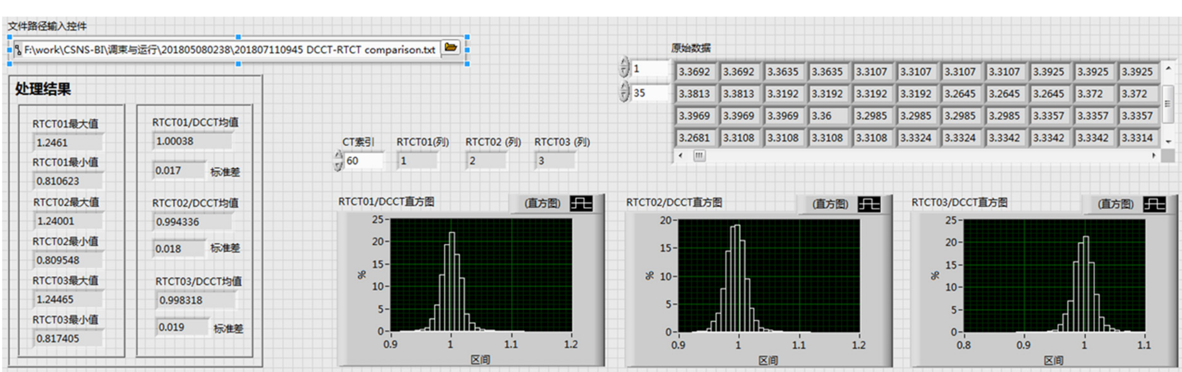

Figure 10: Statistics result of the comparison of RTCT and DCCT (No obvious beam loss along the extraction and RTBT beam line).