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BEAM PHASE MEASUREMENT SYSTEM IN CSNS LINAC

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Abstract

We developed beam phase measurement system ourselves in CSNS (China Spallation Neutron Source). The resolution of the system is less than 0.1° and the accuracy is less than 1°. It played a key role in CSNS Linac commissioning especially in RFQ and DTL commissioning. Further we measured the beam energy by TOF (Time of Flight) method base on this system. The energy accuracy is less than 0.1 MeV.

INTRODUCTION

The CSNS accelerator consists of an 80MeV H- Linac, a 1.6 GeV Rapid Cycling Synchrotron (RCS) and related beam transport line. There are three beam transport line in Linac: Low Energy Beam Transport line (LEBT) after the 50 keV H- Ion Source, Medium Energy Beam Transport line (MEBT) after the 3MeV Radio Frequency Quadrupole (RFQ), Lianc to Ring Beam Transport line (LRBT) after Drift Tube Linac (DTL). Beam is transported to Target after it be accelerated to 1.6GeV in RCS [1]. The layout of the CSNS Linac is shown in Fig. 1.

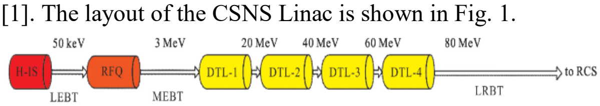

Figure 1. Layout of CSNS Linac.

The repeat period of H- beam macro-pulse is 40ms and pulse width is about 500μs. The radio frequency of beam is 324 MHz and the beam micro-pulse duty ratio is about 30%.

BEAM PHASE MEASUREMENT SYSTEM

FCT sensors are used as beam phase detectors [2] which were produced by Bergoz company. FCT sensor has a rapid signal rise time, which is shorter than 200 ps so it's good for 324 MHz signal's measurement. And the output of FCT sensor signal also has the 324 MHz time structure [3].

The electronics are researched and developed by IHEP and CETC-38 together in China. There are two sets beam phase measurement systems in CSNS Linac and each set has 8 channels for FCT output signals.

Sub-sampling technology has been adopted to realize the electronics. The ADC sample clock is just 100 MHz shown in Fig. 2. Each channel's phase output is the difference between FCT output signal phase and a reference signal phase. The reference signal is a 324 MHz sine wave signal which from the same RF frequency source with beam. Non-coherent digital IQ demodulation technology and CORDIC algorithm are used for phase calculation in FPGA. The schematic is shown in Fig. 3.

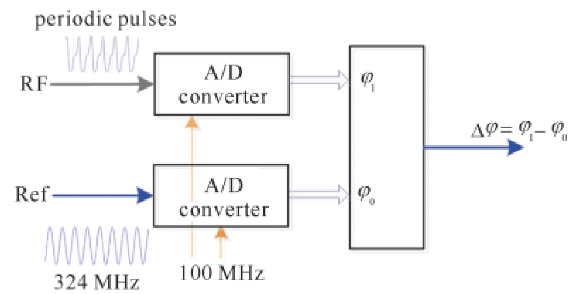

Figure 2. Principle of phase measurement.

The electronics phase resolution is less than 0.1° and the phase non-uniformity between channels limited in ±0.2°. The amplitude accuracy is better than 1% and the phase accuracy is better than 0.3°. We had test the whole system for more than 7 days online with a precise signal generator and find its accuracy is better than 1°.

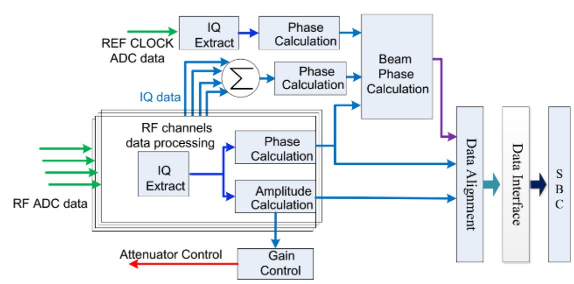

Figure 3: Schematic in FPGA.

The beam phase measurement system played a key role in CSNS Linac commissioning especially in RFQ and DTL commissioning. The RFQ and DTL cavity power phase varied after several days' shutdown or other accident problems. The beam phase measurement system would be running in such a situation.

BEAM ENERGY MEASUREMENT

Beam energy could be calculated by TOF method meanwhile [4]. The distance between FCT sensors are known after they were installed easily. The beam flight time between FCT sensors is computed by phase difference indirectly. Then the beam velocity and energy could be calculated.

There are 5 FCT sensors and 1 set electronics could be used to compute beam energy after beam pass through RFQ, Buncher-1, Buncher-2 in CSNS Linac MEBT. See Fig 4.

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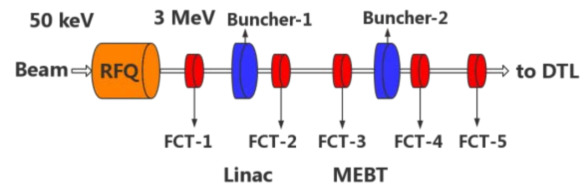

Figure 4: CSNS Linac MEBT layout.

And there are 8 FCT sensors and 1 set electronics be used to compute beam energy after beam pass through 4 DTL cavities and Debuncher. See Fig 5.

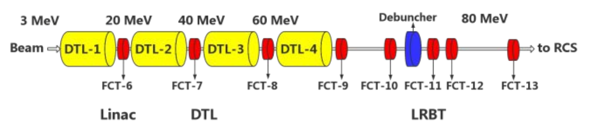

Figure 5: CSNS Linac DTL and LRBT layout.

Due to the distance between FCT sensors and beam theory energy is known. The approximate beam flight time could be estimated. And the exact time is computed by the phase difference:

$$t = \left(\frac{\varphi_2 - \varphi_1}{360} + N\right) \times T \tag{1}$$

T is the RF frequency of beam, here $T = 1/324$ MHz, and the N is the period number estimated by the theory energy. We could adjust it manually in practice. So it is an indirect method to measure beam energy.

Any two FCT sensors could be calculated an energy number using Eq. (1) when you confirm beam was not be accelerated or decelerated between them. Apparently the different combinations would get different results. So how can we know which result is right? I have two principles: 1, each combination should be consistent with others. For example, N is 25 when you choose FCT-1 and FCT-2, N is 20 when you choose FCT-2 and FCT-3, therefore N only could be 45 when you choose FCT-1 and FCT-3. You cannot adjust it to 46 or 44 in calculation even if the result seems closer to theory energy. The all combination results display uniformity once you applied the correct N parameter. 2, The farther of distance between FCTs, the more accurate result you got. The result of FCT-1 and FCT-3 is more accurate than the result of FCT-1 and FCT-2.

Of course, you can measure the time between FCT sensors using a high precision oscilloscope directly. But the error would be very large when flight time is long.

The energy measurement precision of the indirect method in TOF depends on the period number N. The resolution using our beam phase measurement is less than 0.01 MeV, the accuracy is about 0.02 MeV in any fixed combination, and the accuracy is 0.1 MeV after take all combinations into account. One reason is the inconsistency among FCT sensors and according electronics channels were not been completely eliminated. Table 1 list the beam energy measurement result in CSNS Linac experiment.

Table 1: The Beam Energy Measurement Result in CSNS Linac Experiment

Energy[MeV]	Theory	Measured	Deviation
RFQ	3.0258	3.0284	+0.08%
DTL-1	21.67	21.73	+0.28%
DTL-2	41.42	41.54	+0.29%
DTL-3	61.07	61.36	+0.47%
DTL-4	80.09	80.34	+0.31%

CONCLUSION

The beam phase measurement systems have been running well since January 2016. It outputs accurate phase result in RFQ and DTL commissioning. On the other side about beam energy measurement, it takes a long time and many times experiments to ascertain the efficiency of the indirect TOF method. Then I got the two principles to determine the estimated period number N and checked by different FCT sensors' combination. Finally, the measured beam energy result is authentic and helpful for commissioning.

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