HIGH ACCURACY CYCLOTRON BEAM ENERGY MEASUREMENT USING CROSS-CORRELATION METHOD

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Abstract

This paper propose a method to measure the proton beam energy of the CS-30 cyclotron by using two fast current transformer (FCT) and accurately estimate THE TIME OF FLIGHT (TOF) using windowed cross-correlation method. Currently available techniques use pulse width or edge delay measurement to get the TOF. However, the accuracy of these methods are limited by sampling rate, signal level, noise, and distortion. By using Cross-Correlation and interpolation, we can get a fractional delay measurement, and the system works with low level signals (low beam current) and it is robust in the presence of noise and distortion.

INTRODUCTION

The CS-30 cyclotron is 30-inch AVF cyclotron requires a high energy gain per turn and a fixed frequency RF system. It was assembled and tested at TCC in USA before being shipped to Saudi Arabia [1-3]. The CS-30 can accelerate four different particles with different energy levels. Table 1 gives more details about the CS30 specifications and Figure 1 is a photo of the accelerator and its vault.

Beam energy is very important parameters in beam diagnostic process either for radioisotope production or proton therapy. Cyclotrons is known to produce bunches of protons with nanosecond duration and repetition frequency the same as the RF of the Dee voltage. Beam energy can be estimated using Time of Flight (TOF) method while using either single pickup or dual pickups and the pickup can be capacitive or inductive [4, 5]. In single pickup, ToF is estimated by measuring the pulse width of the pickup output and in dual pickups ToF is estimated by measuring the delay between the two waveforms output from the pickups. The two pickups of inductive type is the method of choice in this paper; in this case ToF is obtained by measuring the delay between the two waveforms output from two fast current transformer (FCT) separated by a suitable distance. The FCT converts the beam current bunches into voltage pulses waveform that can be acquired using Analog to Digital Converter (ADC) and send to the PC for digital signal processing.

Delay measurement usually done using edge to edge delay measurement [4, 5], in this case the accuracy is limited by the ADC sampling rate, signal level, noise, and distortion. However, the proposed method calculates the cross-correlation of the two FCT outputs and interpolates the result to get the time of the peak value, which represents the delay between the two waveforms. In this case the delay accuracy is a fraction of the sampling rate which means very high accuracy and the system works with low level signals (low beam current) and high noise levels. Further accuracy improvement is obtained by measuring the temperature and compensate for dimensions change of the FCT fixture due to thermal expansion.

Table 1: Main Specifications of CS-30 [2]

Parameter	Value
Proton Energy	26.2 MeV
Deuteron Energy	15.0 MeV
Helium-3 Energy	38.0 MeV
Helium-4 Energy	30.0 MeV
External Beam Power	2000 Watts
Pole Diameter	38 inch
Number of Sectors	3
Weight	22 T
Number of Dees	2
Acceleration Mode	Fundamental
Voltage Gain per Turn	100 kV

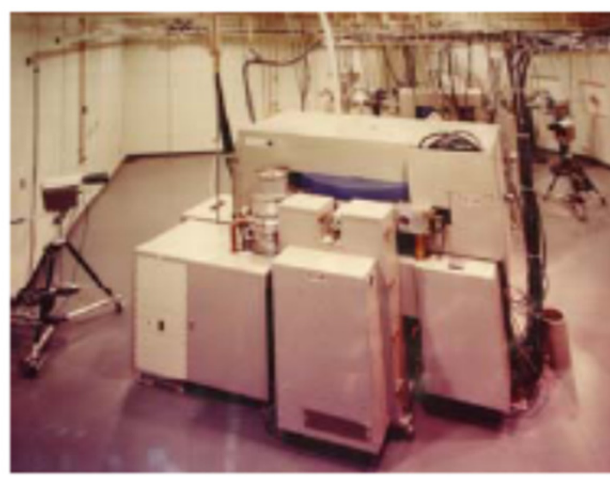

Figure 1: A Photo of the CS30 Cyclotron.

TIME OF FLIGHT (TOF) BASED ENERGY MEASUREMENT

For fast proton, the relativistic kinetic energy E_k can be calculated from [6]:

$$E_k = mc^2(\gamma - 1) \tag{1}$$

where:

$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} \tag{2}$$

ISBN 978-3-95450-167-0

and v can be estimated using the flight path l (distance between the two pickups) and the time of flight (TOF) t.

$$v = \frac{l}{t} \tag{3}$$

Worst case error of v due to measurement errors of l and t is given by

$$\Delta v = \left|\frac{dv}{dt}\,\Delta t\right| + \left|\frac{dv}{dl}\,\Delta l\right| \tag{4}$$

Hence

$$\frac{\Delta v}{v} = \left|\frac{\Delta t}{t}\right| + \left|\frac{\Delta l}{l}\right| \tag{5}$$

and worst case error of E_k resulting from the error of v

$$\Delta E_k = \left|\frac{dE_k}{dv}\,\Delta v\right| \tag{6}$$

$$\frac{\Delta E_k}{E_k} = \left|(\gamma + 1)\gamma\frac{\Delta v}{v}\right| \tag{7}$$

The above equation gives a clear idea about how the energy estimation affected by the measurement errors of either l or t. If assumed that the γ is near 1 then 1 percent error of l measurement will result in 2 percent error of E_k estimation, also 1 percent error of t measurement results in 2 percent error of E_k estimation. This explains the importance of accurately measuring the TOF and the distance between the two pickups.

To keep the error of energy measurement, due to the error of t, below 1% then the error of time measurement should be less than 0.5% or 0.047 ns. And also for l the error should be less than 0.5% or 3.25 mm.

CROSS-CORRELATION METHOD

Cross-correlation method is commonly used to measure the delay between two signals. In this case, delay can be estimated by finding the peak of the cross-correlation between the two signals. It is required to interpolate the points at the peak in order to improve the delay estimation accuracy. We used two simulated signals with arbitrary delay to find the best interpolation method. We try linear interpolation, and cubic spline in which the later gives more accurate results. Also Hanning window is used before the cross-correlation to force the ends to zero to prevent the error due to phase rotation. By using such a method, it's not required to acquire the signal starting from a certain point (trigger point) and this make the acquisition easier.

A LabVIEW program was developed to determine accurately the time difference between two collected signals as shown in the schematic diagram in Figure 2. To ensure highly accurate results, the software was tested using two simulated signals with a known time delay. It was able to determine the delay value accurately. An example of simulated signal is shown in Figure 3:

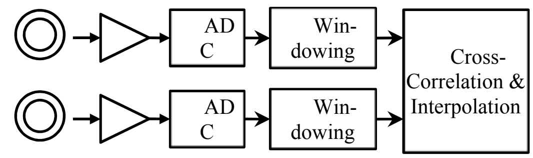

Figure 2: Cross-Correlation method either hardware of software.

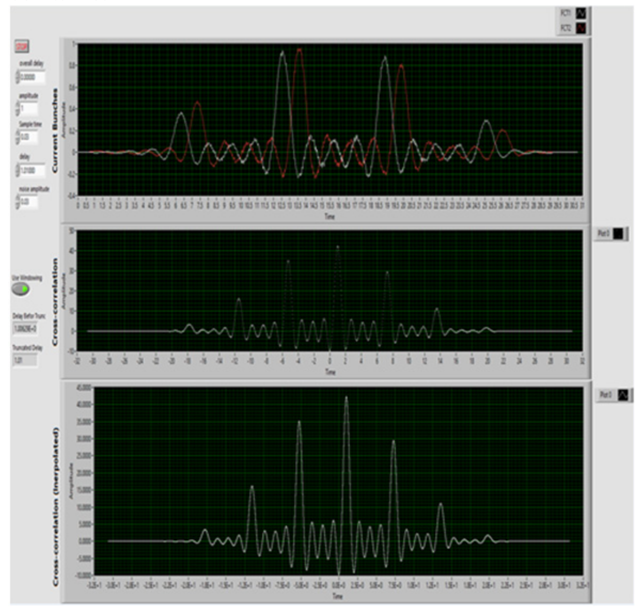

Figure 3: A simulated signal was created using Labview.

EXPERIMENTS AND TOF MEASUREMENT

Figure 4 shows the setup made inside one of cyclotron beamlines, to measure the delay between two bunches. The main detectors in our experiment were two FCT detectors made by Bergoz. These were passive devices with a rise time of 1 ns. They contained no electronics, making them suitable for use in a radiation area. They were installed around an acrylic-made cylinder attached to the beamline. The cylinder's other end was capped by 50 µm of Havar foil. The distance between the two FCTs is 65 cm.

The calibration of the hardware was performed as shown in Figure 5. A signal generator was used to produce an arbitrary signal at a frequency of 26.8 MHz (cyclotron frequency), which was allowed to pass through the two FCTs along identical BNC cables of the same length. Initially, the delay between the two values was 2 ns due to mismatch between the cables and amplifier. Therefore, a delay line was added to one side of the circuitry, reducing the delay to 50 ps. During experiments, the cyclotron was operated to produce 1 µA. The output from the FCT was amplified Equivalent output voltage was approximately 5 mV measured we used a Digital Storage Oscilloscope (DSO) for data acquisition, and data processed offline on the PC using LabVIEW software.

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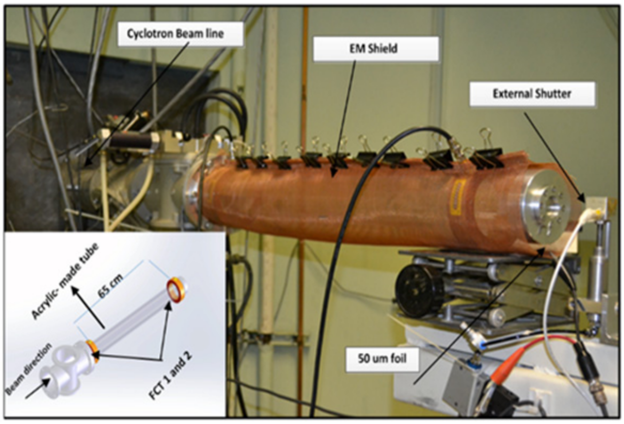

Figure 4: Experimental setup for energy measurement. The two FCT can be seen under the copper mesh. The distance between them is 65 cm. the purpose of the EM shield is to reduce electromagnetic noise.

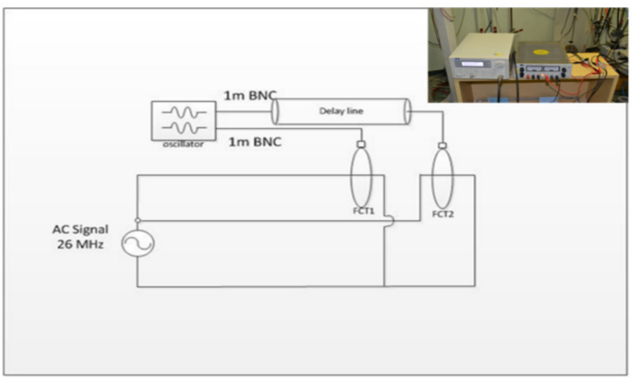

Figure 5: Arrangement of capacitive pickup to perform calibration of the experiment setup.

Measurement of the time delay takes place between one edge of the 1st pickup (FCT) output and the next edge, of same polarity (rising of falling), of the 2nd pickup (FCT) output [3]. In this case the error of time measurement is equals to the sampling interval of the ADC. Sampling can be Real Time Sampling (RTS) or Equivalent Time Sampling (ETS) [7]. Using of RTS cannot be used without interpolation because it will give large error. For example if the sampling rate is 1GSPS (Giga Sample per Second), the sampling interval is 1ns and time measurement error will be ±1 ns this gives error of measured TOF about 35%. Using ETS, on the other hand, will increase the sampling rate by acquire more cycles but the signal should be stable and has limit noise.

RESULTS AND DISCUSION

Figure 6 shows the waveforms measured from FCT 1 and FCT 2. In our experiment, the distance between the two pickups is 2065 cm. considering speed of protons as:

$$\frac{v}{c} = \sqrt{1 - \left(\frac{1}{1+\frac{E_k}{m_0 c^2}}\right)^2} \qquad (8)$$

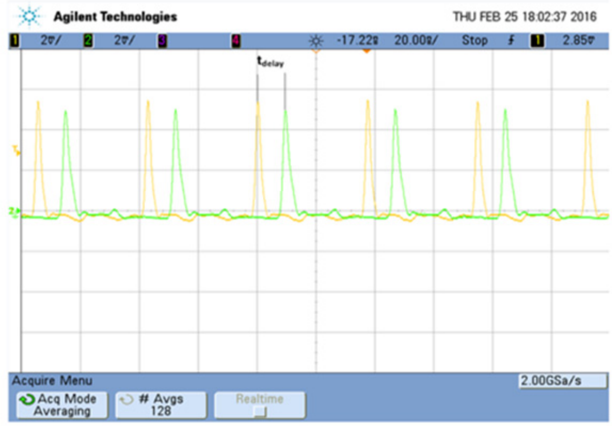

Figure 6: TOF measurement from FCT1 and FCT 2.

Hence, for 26.2 MeV proton energy, v is 6.915x10 m/s. With length of 65 cm, the measured time delay between the two signals was 9.4023 ns. Cyclotron energy was calculated to be 25.99 MeV. As the value of cyclotron energy given in the CS-30 manual is 26.2 MeV for protons, the difference between actual and calculated energy was <2.0%.

CONCLUSION

In this paper, beam energy of the CS30 cyclotron has been determined using cross correlation technique. Time of flight is a method of choice in this experiment due to its high accuracy and less exposure to radiations. Energy measured with TOF and Cross correlation showed that its 25.9 MeV.

ACKNOWLEDGEMENT

This project was supported by the NSTIP strategic technologies program in the kingdom. Award No. (14-MAT-1233-20).

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ISBN 978-3-95450-167-0