HIGH ACCURACY CYCLOTRON BEAM ENERGY MEASUREMENT USING CROSS-CORRELATION METHOD

A. Hendy, F. Alrumayan,  
King Faisal Specialist Hospital and Research Centre, Riyadh, Saudi Arabia  
K. Kezzar, H. Kassim, King Saud University, Riyadh, Saudi Arabia

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]

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

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]:

$$E_k = mc^2(\gamma - 1) \quad (1)$$

where:

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

where $v$ is the velocity of the particle and $c$ is the speed of light.
and \( v \) can be estimated using the flight path \( l \) (distance between the two pickups) and the time of flight (TOF) \( t \).

\[
v = \frac{l}{t}
\]

(3)

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

\[
\Delta v = \left| \frac{dl}{dt} \Delta t \right| + \left| \frac{dv}{dt} \Delta l \right|
\]

(4)

Hence

\[
\frac{\Delta v}{v} = \frac{\Delta t}{t} + \frac{\Delta l}{l}
\]

(5)

and worst case error of \( E_k \) resulting from the error of \( v \)

\[
\Delta E_k = \left| \frac{dE_k}{dv} \Delta v \right|
\]

(6)

\[
\frac{\Delta E_k}{E_k} = \left( y + 1 \right) y \frac{\Delta v}{v}
\]

(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 \( y \) 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:

**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 \( \mu \)m 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 \( \mu \)A. 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.
RESULTS AND DISCUSSION

Figure 6 shows the waveforms measured from FCT1 and FCT2. In our experiment, the distance between the two pickups is 2065 cm. Considering the speed of protons as:

\[ v = \sqrt{1 - \left( \frac{1 - \frac{1}{m_o c^2}}{1 + \frac{1}{m_o c^2}} \right)^2} \]  

Hence, for 26.2 MeV proton energy, \( v \) is 6.915 \times 10^8 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 it was 25.9 MeV.

ACKNOWLEDGEMENT

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

REFERENCES