NOVEL TIME-OF-FLIGHT MEASUREMENT ON A SHORT BASE

Z. Kormány
HUN-REN Institute for Nuclear Research, Debrecen, Hungary

Abstract

Time-of-flight (TOF) measurements are superior to other methods of measuring beam energy, since the quantity being measured is directly related to the velocity, and therefore the kinetic energy, of the particles. Conventional TOF systems use independent sensors in the beam transport system, each with a separate signal path to the measuring electronics. The unknown difference in signal delay between the paths introduces an absolute error in the measured time. Increasing the flight time can help to reduce the impact of this error. For this reason, a flight path length of several metres is usually applied between the sensors.

A novel method and device have been developed for accurate TOF measurements on a base as short as 20 cm. Two capacitive pickups in a common mechanical structure with an additional electrode are used. The signals from the probes are combined within the vacuum chamber, resulting in a single signal path from the sensor unit to the measuring electronics. Digital signal processing (DSP) is used to determine the distance between the pulses generated by a beam bunch on the probes. The signal processing hardware and software were tested using pulses from a high-precision signal generator. Time measurements with an absolute error of less than 1 ps were achieved. The accuracy of the complete system with beams from a cyclotron was investigated using neutron threshold reactions. The measurement accuracy was found to be at least one order of magnitude better than the accuracy of the energy value calculated from the cyclotron parameter settings.

The prototype unit was developed for the cyclotron at the HUN-REN Institute for Nuclear Research (ATOMKI). Installed in its main beamline, it can continuously monitor the beam energy independently from the beamline in use.

INTRODUCTION

Unlike DC accelerators, the beam energy of cyclic accelerators cannot be determined from the accelerating voltage. When calculating from the machine parameters, values that are not accurately known must also be applied. For circular machines, for example, the radius of the final orbit is required in the formula. Cyclotrons are the worst-case scenario, as this value cannot be determined exactly. Therefore, the nominal extraction radius is used instead, which can lead to significant errors, particularly with multi-particle and variable-energy machines. Therefore, proton therapy cyclotrons, for example, are built as fixed-energy machines, which allow the extracted beam energy to be determined and repeated accurately. The beam is always accelerated to this maximum energy in the cyclotron, and if lower energy is required for treatment, the surplus beam energy is dissipated by a degrader. This has two disadvantages: unwanted extra activation of machine parts and significant electrical energy waste during operation.

At variable-energy machines accurate beam energy is determined by measuring the kinetic energy of the extracted beam in the beam transport system. Of the various measurement methods and systems that have been developed, Time-of-flight (TOF) measurements [1, 2] offer many advantages, including a direct relationship with the energy value, possible non-destructive measurement and low operating costs. However, its large spatial requirement between the probes means it can only be used in dedicated, long beamlines, preventing its use at any accelerator.

At first glance, the flight path length can only be short if the delay difference between the signal paths is extremely small. For instance, the time-of-flight value for a 230 MeV proton beam over 20 cm is approximately 1.12 ns. This means that, to achieve an energy value accuracy of 1×10^{-3}, the absolute time error caused by the delay difference of the signal paths must be smaller than 0.56 ps. Equalising cable and amplifier delays with such accuracy is technically not feasible. However, it is not necessary to equalise the signal path delays perfectly. It is sufficient to know the exact value of the existing difference. The novel device and method ensure that this value is measured with the required accuracy, enabling beam energy measurement on a short base.

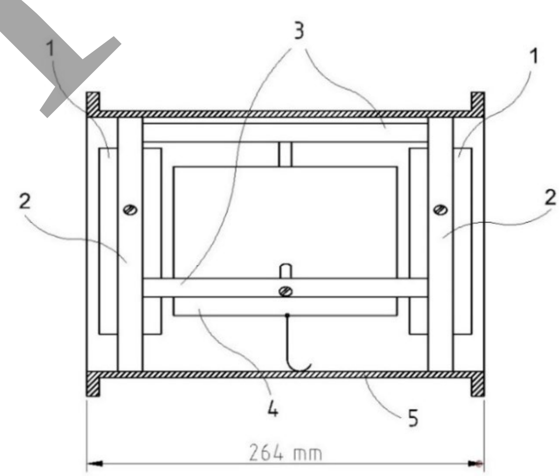

Figure 1: Conceptual structure of the new sensor unit: 1 – capacitive probe, 2 – centring insulator, 3 – spacer, 4 – grounded electrode and 5 – vacuum chamber.

THE NEW DESIGN

Unlike conventional time-of-flight systems, which have two or three probes built independently into the beam transport system at different locations, the novel device uses a special sensor unit comprising two probes and an intermediate electrode. The probes are arranged within a shared mechanical construction ensuring that the distance between them (the flight path length) is fixed and can be accurately measured using a coordinate measuring machine. For example, for a flight length of 20 cm and a coordinate measurement error of 5 µm, the relative path length error is just $\Delta l/l = 2.5 \times 10^{-5}$. This is completely negligible, so velocity error will only depend on the accuracy of the flight time measurement.

Figure 1 shows the conceptual structure of the sensor unit and its main components within the vacuum chamber. The two cylindrical capacitive probes are 5 cm long, with an inner diameter larger than that of the beam pipe. They are mounted on a support structure consisting of MACOR insulators and Invar spacers. The applied materials minimise changes to the flight path length caused by temperature variations. A grounded cylindrical electrode with an inner diameter equal to that of the beam pipe is positioned between the probes. This intermediate electrode plays an important role in the construction, providing longitudinal geometric and electrical symmetry at both ends of the probes. Since the bunches are longer than the probes, charges outside the probes also affect the pickup signals. Without longitudinal symmetry, this would lead to distortion of the pulses and, consequently, false time measurements.


Figure 2: The novel sensor unit with two capacitive probes of shielded construction and an RF power combiner.

The signals from the capacitive probes are added in the unit by a passive RF power combiner (Mini-Circuits ZSC-2-1W+). Since the flight time in the compact unit is shorter than the bunch length, the signal from the second probe is delayed before being added to ensure the generated pulses remain separate. As shown in Fig. 2, this is implemented using an additional piece of coaxial cable. The existing difference in signal delays up to the power combiner can be determined by a calibration measurement. The new construction, with its vacuum chamber, allows the beam to be transported through the device in both directions as the sensor unit can be reversed in the beamline without affecting the flight path or cable length. Thus, the exact delay difference can be determined from the two measured time values using the same energy beam. This value is then subtracted from each measured time difference between the pulses in order to calculate the time of flight of the beam bunches.

Since temperature variation causes a change in the propagation delay of coaxial cables, particular care was taken to control the additional signal delay incorporated into the signal path section prior to the combiner. Good-quality, semi-flexible coaxial cable (FSJ1-50A) with a phase stability value below 10 ppm/°C was used [3]. The temperature of the cable is continuously measured, and any deviations from the value measured during calibration are considered in the additional signal delay.

The single signal path from the sensor unit to the measurement electronics enables modifications to be made freely as no change to this path can affect the time difference between the pulses. Therefore, the sensor unit can easily be relocated and used in another beamline, or even at a different accelerator.

SIGNAL PROCESSING

The signal from the sensor unit is evaluated digitally. The analog probe signal is amplified and acquired by a USB digital oscilloscope (PicoScope 6403C) with a sampling rate of 5 GS/s. As the cyclotron bunches are typically several nanoseconds long, several tens of samples can be obtained from the pulses in real-time sampling (RTS) mode. Of the various signal processing algorithms, the least squares norm (L2Norm) was selected to determine the distance between digitally sampled pulses. This algorithm produces a minimum when the first pulse is shifted towards the second by an amount equal to the exact time difference between them. However, due to the sampled signal, the shifts can only be integral multiples of the sampling distance of 200 ps. To achieve finer resolution, a quadratic function is fitted to the L2Norm points around its minimum, and the minimum's actual position is calculated from the parameters of this curve.

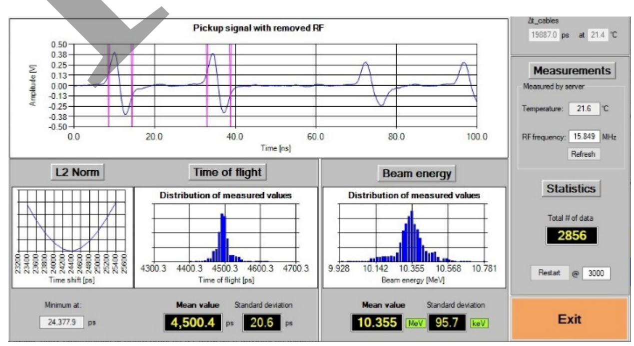

Figure 3: Part of the graphical user interface of the measuring program.

Figure 3 shows this for a proton beam with a nominal beam energy of 10.5 MeV. In the lower left corner of the graphical user interface, the fitted curve to the L2Norm points can be seen. The exact position of its minimum (i.e. the measured distance between the two pulses) is at 24,377.9 ps. This time value incorporates the delay caused by the extra cable length, as determined by a calibration measurement. This value (19,887 ps) can be seen in the top right-hand corner of the figure. Subtracting this value from the measured pulse distance yields a single time-of-flight value of 4490.9 ps corresponding to a beam energy of 10.398 MeV.

Due to quantisation noise in the finite-width analog-to-digital conversion process, the measured time difference between pulses, and consequently the calculated time-of-flight and energy values, fluctuate. This effect can be mitigated by calculating the statistical mean of multiple individual measurements, given that the mean values of thermal and quantisation noise are zero. Numerous tests have shown that averaging around 3,000 individual time measurements suppresses fluctuations below 0.1–0.2 ps. Therefore, the mean of 3,000 individual measurements is considered to be a new beam energy value.

ACCURACY

First the accuracy of the signal processing hardware and software was tested using repetitive 5-ns-long pulses from a high-precision RF signal generator. The unipolar pulses of the generator were differentiated and filtered to produce bipolar pulses similar to those generated by the beam bunches on the probes. The period length of the pulse stream was varied over a broad interval. The average time measurement error was found to be 0.2 ps, with a maximum error value of 0.6 ps. Based on these data, the energy measurement error does not exceed 10^{-3} in any scenario, provided the flight time is longer than 1.2 ns. With the current flight distance of 20 cm, this condition is met up to a proton energy of 190 MeV. For faster beams, the flight path should be increased to maintain this accuracy.

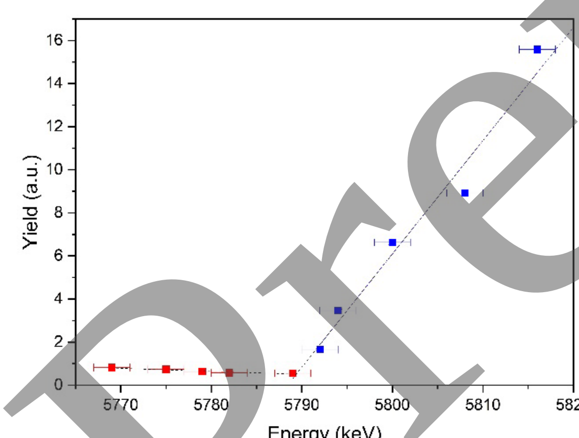

Figure 4: Neutron yield as a function of the projectile energy for the $^{27}Al(p,n)^{27}Si$ reaction.

The accuracy of the entire system in practical operation was tested by comparing the measured energy of the cyclotron beam with a well-known reference value. Specific nuclear reactions can provide such reference energy values. The $^{13}C(p,n)^{13}N$ and $^{27}Al(p,n)^{27}Si$ reactions were used for this purpose; these reactions have neutron threshold energies of 3235.7 ± 0.7 keV and 5804.3 ± 0.2 keV given in the literature, respectively. During these tests, the beam energy was adjusted in small increments around the known threshold energy values. The neutrons emerging from the target atoms were detected by a neutron detector, and the yield was evaluated at each beam energy value measured by the system. Details of the test setup and the measurement results can be found in [4]. Fig. 4 shows the neutron yield as a function of the measured projectile energy for the $^{27}Al(p,n)^{27}Si$ reaction. The inflection point was obtained by fitting the data below and above the threshold energy.

The threshold values for the $^{13}C(p,n)^{13}N$ and $^{27}Al(p,n)^{27}Si$ reactions, as determined from the measured beam energies, differ from the literature values by 2.5 keV and 14.3 keV, respectively, corresponding to relative energy measurement errors of $\Delta E/E = 8.3 \times 10^{-4}$ and 2.5×10^{-3}. These results demonstrate that, despite the short flight path, the new device is capable of determining the kinetic energy of the accelerated beam with an accuracy on the 10^{-3} level.

CONCLUSION

A new beam diagnostic device called the Beam Energy Monitor (BEM) has been created by applying time-of-flight measurement technique on a short base. It comprises a novel sensor unit with two capacitive probes and an intermediate electrode. Combined probe signals result in a single signal path and digital signal processing is used to measure the time between the sampled pulses. The complete system can achieve 10^{-3} level accuracy on a 20 cm base for particle beams with energies of up to 190 MeV/nucleon.

The Beam Energy Monitor has a potentially very broad range of applications. It can be used at any low- and middle-energy accelerators where precise knowledge of the beam energy is important. The compact size of the sensor unit allows it to be installed practically anywhere in the beam transport system. Installing it in the typically short main beamline of the accelerator enables to perform accurate beam energy measurements and monitoring for each beamline and target during irradiation.

The new device is the subject of an international patent application [5]. It has also been commercialised and is available from ionEM Kft. [6].

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