ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-WEPMO16

A COMPACT DEVICE FOR MEASURING AND MONITORING THE ENERGY OF ACCELERATED PARTICLE BEAMS

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

Abstract

A Beam Energy Monitor (BEM) using time-of-flight (TOF) measurements on a short flight path was developed for the cyclotron of the HUN-REN Institute for Nuclear Research. The sensor unit comprises two capacitive probes 20 cm apart; the entire geometry is approximately 40 cm long. Its compact size enables the unit to be installed in the main beamline, allowing the beam energy to be measured and monitored independently of the beamline in use.

Probe signals are acquired by a digital oscilloscope, and digital signal processing algorithms determine the time difference between pulses generated by a beam bunch on the probes. The unique design of the sensor unit, together with the signal processing hardware and software, provides accurate beam energy measurement despite the short flight path.

The accuracy of the monitor in practical operation was investigated using neutron threshold reactions. These reactions showed that the measurement accuracy is at least one order of magnitude better than the accuracy of the energy value calculated from the cyclotron settings. The accuracy of the signal processing indicates that the beam energy can be scaled up to several hundred MeV while maintaining measurement accuracy at the tenth of a percent level.

INTRODUCTION

The MGC-20 cyclotron at the HUN-REN Institute for Nuclear Research is a multi-particle, variable-energy machine that accelerates the four lightest ions within a broad energy range, up to 18 MeV for protons and 20 MeV for alpha particles. The cyclotron's beam transport system has nine target locations. The system also contains an analysing magnet (AM), which, in addition to its primary function of reducing the energy spread of the beam, can be used for beam energy measurements. However, this function is only available for dedicated beamlines and targets located behind the magnet. Furthermore, an AM measures beam energy indirectly, meaning the measured quantity (magnetic field strength) is not directly proportional to the kinetic energy of the accelerated particles. Instead, the connection is made with another parameter: the bending radius in the given magnetic field. The accuracy of the measured beam energy value therefore depends on how close the actual bending radius is to the nominal one, which is largely determined by the quality of the beam transport.

From this perspective, TOF measurements are superior to AM energy measurements. They determine quantities, such as flight time and particle velocity, that are directly related to the beam energy. However, they can only be used in dedicated beamlines due to the geometric requirements of the beam path. Conventional TOF systems require a flight path of several metres or even more than 10 metres, which prevents them from being installed in the typically short main beamline of the accelerator. Consequently, when the beam is transported to another beamline, the energy value can only be calculated with limited accuracy from the accelerator settings. For example, the accuracy of such calculations is typically several percent for cyclotrons [1, 2].

DESIGN ASPECTS OF THE BEM

The Beam Energy Monitor was developed to overcome the drawbacks of the above systems. It uses time-of-flight measurement; therefore, the measured value is directly proportional to the kinetic energy of the beam. At the same time, its novel sensor construction makes it possible to achieve high accuracy over a short flight path. To achieve this, the two sensors are arranged within a vacuum chamber in a common geometric construction. In conventional TOF systems, the two (or three) probes are built into the beam transport system independently of each other, which leads to relatively large values of the absolute error in the flight path length and the measured flight time due to the existing differences in the signal paths. That is why the flight length and time cannot be short in these systems. The novel construction of the BEM enables highly accurate distance measurement between the probes, as well as determining the exact delay time difference in the signal paths from the probes. Knowing the existing delay time difference, the measured time difference between the pulses can be corrected to provide an accurate flight time value.

Figure 1 shows the conceptual structure of the sensor unit with the main components inside the vacuum chamber. It has two cylindrical capacitive probes, each 5 cm long, which allow the time of flight of the beam bunches between them to be measured. The inner diameter of the probes is larger than that of the beam pipe preventing beam particles from directly hitting them. The probe-to-probe distance (the flight path length) is defined by 3 spacers with an azimuthal separation of 120 deg. A grounded electrode is placed between the probes. The inner diameter of this cylindrical electrode is equal to that of the beam pipe and its length and position provide longitudinal geometrical and electrical symmetry on both sides of the probes. This special and unique construction [3] makes it possible to measure the time-of-flight value and thus the beam energy with high accuracy despite the applied short probe-to-probe distance of 20 cm and the longer beam bunches (typically around 30 cm at this cyclotron). The length of the vacuum chamber is only 26.4 cm and with connecting flanges and beam pipe sections the entire mechanics occupies less than 40 cm longitudinal space in the beamline. With such a compact size it could be easily installed into the main beamline of the cyclotron. Installation at that location not only enables to measure the beam energy on

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-WEPMO16

demand, but also allows continuous monitoring of the beam energy regardless of the actually used beamline.

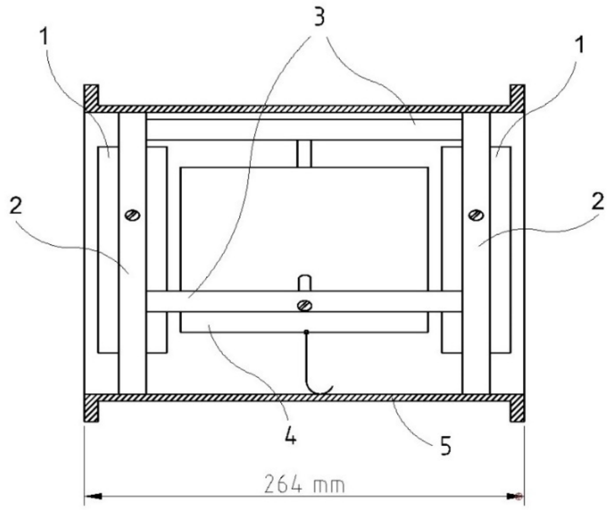

Figure 1: Conceptual structure of the sensor unit: 1 - capacitive probe, 2 - centring insulator, 3 - spacer, 4 - grounded electrode and 5 - vacuum chamber.

Another special feature of the sensor unit is that the signals of the capacitive probes are added in the unit by an RF power combiner. Having both probe signals combined into a single signal provides significant benefits for the system. Firstly, only one electrical feedthrough is required on the vacuum chamber and secondly, only one signal path is needed from the sensor unit to the signal processing electronics. This means that the signal path can be freely modified (e.g. disconnecting and reconnecting or even replacing the cable, or using a new preamplifier) as no change in the single signal path can affect the time difference between the pulses. Therefore, the sensor unit can be easily relocated and used in another beamline or even at another accelerator, too. The output waveform of the added probe signals shows still separated beam pulses as long as the time of flight of the beam bunch is longer the length of the pulse. However, due to the compact size of the unit the time-of-flight value between the probes can be shorter than the length of the pulses generated on the probes by the beam bunches. Therefore, the proper time difference between the pulses is ensured by delaying the signal of the second probe prior to addition. The exact value of this built-in additional signal delay is determined by calibration and then subtracted from each measured time difference between the pulses to calculate the time-of-flight value.

Figure 2 shows the sensor unit and its vacuum chamber. The capacitive probes are designed in 50-ohm geometry. They are fixed together by 3 spacers at a distance of 20 cm. Invar spacers are used to minimize the change in this distance due to temperature variations. The spacers are fixed to the outer electrode of the probes with insulators made of a material with a low linear thermal coefficient (Macor).

The actual distance between the probes was measured with high accuracy on a coordinate measuring machine. The achieved absolute error of 5 µm in the probe-to-probe distance translates into a relative error in the flight path length of 2.5×10^{-5}, which is completely negligible. Therefore, the error in the beam energy measurement depends only on the accuracy of the flight time determination.

Figure 2: Sensor unit with its vacuum chamber.

SIGNAL PROCESSING HARDWARE AND SOFTWARE

BEM applies digital signal processing to determine the time difference between the pulses from the two sensors. The combined probe signal is first amplified by approximately 40 dB and then sampled and converted by a digital oscilloscope. The USB oscilloscope PicoScope 6403C is used, which has a maximum sampling rate of 5 GS/s when only one input channel is in operation. The shortest bunch length of the MGC-20 cyclotron beam is about 4 ns, so this sampling rate provides at least 20 digital samples of the pulses in real-time sampling mode.

The signal processing hardware is located outside the shielding wall of the cyclotron, but far away from the control room. The allowed length of the USB connection required a local controller in the proximity of the oscilloscope. An Intel NUC mini-PC is used with Linux Ubuntu operating system for this. The program controlling the oscilloscope is written as a network server, which sends the waveform data to the connected clients after some preprocessing. Windows PCs on the same network segment can run the measuring client program.

The accuracy of the entire signal processing system was tested using a simulated probe signal. An RF signal generator (Rohde & Schwarz SMB100B type) was used to provide a precisely defined time base for the successive pulses. The shortest pulse length of 5 ns was used, which is very close to the shortest bunch length in the cyclotron. The distance between pulses was increased from a minimum of 20 ns to 100 ns. Figure 3 shows the deviation of the measured time difference between pulses from the preset period length of the generator. The average measured deviation for these 12 pulse period settings was only 0.2 ps, with the largest deviation being 0.6 ps.

Considering a worst-case time measurement error of 0.6 ps, the signal processing system is able to determine the beam energy with an accuracy of at least $\Delta E/E = 10^{-3}$ while the flight time to be measured is not shorter than 1.2 ns. With the current probe-to-probe distance, this requirement can be met up to about 190 MeV proton beam energy. For

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-WEPMO16

faster beams, the flight path has to be increased to maintain this accuracy.

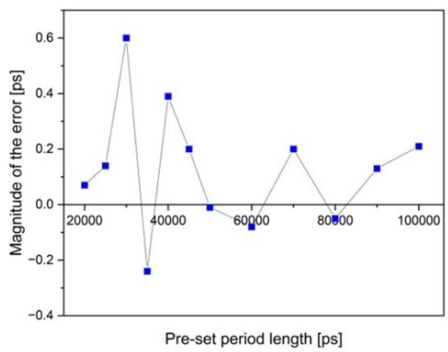

Figure 3: Deviation of the measured time difference between pulses from the pre-set pulse period of the generator signal.

ACCURACY TESTS USING REAL BEAMS

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. Within the cyclotron's energy range, two nuclear threshold reactions were available for this purpose: the ^{13}C(p,n)^{13}N and ^{27}Al(p,n)^{27}Si reactions.

During these tests, the beam energy was adjusted in small increments around the known threshold energy values given in the literature. 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 can be found in [4]. Figure 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.

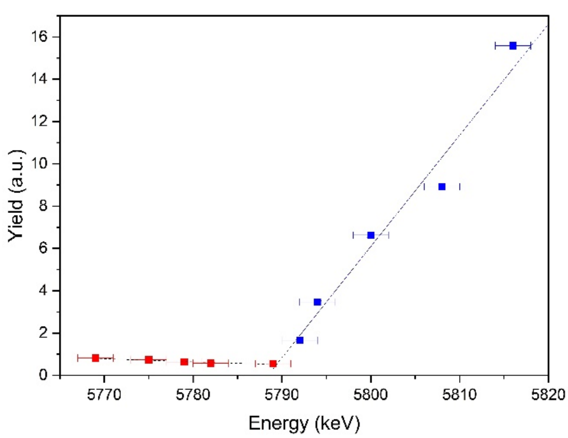

Figure 4: Neutron yield as a function of the projectile energy in the vicinity of E_{proton}= 5800 keV for the ^{27}Al(p,n)^{27}Si reaction. Trend lines are included for guidance only.

Threshold energies of 3233±2 keV and 5790±3 keV were found for the two reactions. Compared to the literature values of 3235.7±0.7 keV and 5804.3±0.2 keV, the relative errors in the energy measurements were found to be $\Delta E/E = 8.3\times10^{-4}$ and 2.5×10^{-3}, respectively. These results demonstrate that the BEM is capable of determining the cyclotron beam's kinetic energy with an accuracy on the 10^{-3} level despite the short flight path.

CONCLUSION

A prototype of a new beam diagnostic device called the Beam Energy Monitor [5] has been developed for the cyclotron at the HUN-REN Institute for Nuclear Research. The innovative design of the sensor unit ensures that the beam energy can be accurately measured despite the applied short flight path. The time difference between the pulses generated by a beam bunch on the probes is determined by digital signal processing.

The accuracy achieved has been verified by neutron threshold reactions. The results show that the system can measure the beam energy with an accuracy close to the lower end of the 10^{-3} range, which is at least one order of magnitude better than the accuracy of the energy value calculated from the cyclotron settings.

The compact size of the sensor unit allowed it to be installed in the main beamline of the cyclotron. In this way, BEM can measure the beam energy independently of the beamline actually used, and with a non-destructive sensor unit, measurements can be made continuously during the irradiation.

REFERENCES

[1] A. M. Hendy *et al.*, "High accuracy cyclotron beam energy measurement using cross-correlation method", in *Proc. Cyclotrons'16*, Zurich, Switzerland, Sep. 2016, pp. 193-195. doi:10.18429/JACoW-Cyclotrons2016-TUP12

[2] J. W. Burrage *et al.*, "A simple method to measure proton beam energy in a standard medical cyclotron", *Australasian Physical & Engineering Sciences in Medicine,* vol. 32, no. 2, pp. 92-97, 2009. doi:10.1007/BF03178634

[3] Z. Kormány, "Method and apparatus for measuring and monitoring the energy of charged particle beams of cyclic accelerators", Hungarian Intellectual Property Office (HIPO), PCT/HU2025/050012, Mar. 4, 2025.

[4] Z. Kormány and L. Csedreki, "Verification of the accuracy of a compact beam energy monitor", *Nucl. Instrum. Methods Phys. Res. A,* vol. 1076, p. 170483, Jul. 2025. doi:10.1016/j.nima.2025.170483

[5] IonEM Kft., www.ionem.hu