Time-of-flight system with a movable ion detector for absolute measurement of cyclotron beam energy

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(Received 16 September 2005; accepted 13 October 2005; published online 21 November 2005)

A time-of-flight system for determining the absolute energy of ion beams has been developed for the azimuthally varying field (AVF) cyclotron at Japan Atomic Energy Agency (JAEA). Ion detectors, a microchannel-plate detector and a plastic scintillation detector, were applied to the system in order to achieve high time resolution measurement of the flight time and to cover a wide range of beam intensity in combination with a beam attenuator. The change of the flight length, performed by moving the plastic scintillation detector with flexible bellows, allows determination of the mean beam energy only from the relative measurement of the flight time and the flight length without knowing their absolute values. A maximum movable distance of 2 m yields the difference in the time of flight from 16 to 94 ns for the energy range of ion beams accelerated by the JAEA AVF cyclotron. The time-of-flight system even with the 2 m change in the flight length achieves accurate energy determination of the order of 0.1%, since the relative measurement has an advantage of elimination of the uncertainties in determination of the time zero and the length zero. The time-of-flight measurement with the relative measurement also allows estimation of the beam energy spread without conventional expensive systems such as a magnetic spectrometer. By comparing the widths of the time-of-flight spectra of ions accumulated at different flight lengths, we have estimated the energy spread. In order to reduce the labor process of the coincidence detection of ions in the time-of-flight measurement, we have also accomplished a simple estimation method for mean beam energy determination with a beam bunch, naturally modulated with the acceleration RF of the cyclotron. The mean beam energy has been obtained from the shift of the beam bunch centroids at different flight lengths in the time-of-flight spectrum. © *2005 American Institute of Physics.* [DOI: 10.1063/1.2135285]

I. INTRODUCTION

The JAEA azimuthally varying field (AVF) cyclotron[1] with a K number of 110 is used for research in biotechnology and materials science in order to broaden the range of ion-beam applications. Various ion beams from proton to gold have been accelerated with a wide rigidity range from 0.46 to 1.5 T m at required beam energies. Determination of the absolute beam energy with an accuracy of better than 1% is required in many applications. The energy spread is also one of the important beam parameters for production of precisely controlled beams[2] in the JAEA AVF cyclotron, such as a microbeam formed with a magnetically focusing system.[3]

The beam energy depends on acceleration parameters of a cyclotron, such as a magnetic field and an extraction radius. It is difficult to estimate the absolute beam energy accurately from the cyclotron parameters because of the uncertainty in determining the real values of the parameters.

For determination of beam energies, various methods, mainly based on resonance or threshold energies in nuclear reactions,[4] crossover techniques,[5–7] and time-of-flight (TOF) techniques,[8–11] have been used in accelerators. The method using resonance or threshold energies can provide accurate calibration values, but the applicable ion beams are restricted only to the particular ions and energies. A crossover technique can be applied to unspecified energies, but the applicable ion beams are also restricted to light ions because of the kinematic limitations. A TOF technique, which is free from these limitations, can be applied to a variety of ion beams accelerated by the JAEA AVF cyclotron with the velocity range of $\beta=0.071-0.41$. This technique also allows to obtain a velocity distribution of ions and to estimate the beam energy spread. Therefore, we have developed an optimum TOF system for the measurement of the mean energy and the energy spread for the beams of the JAEA AVF cyclotron.

Although the accuracy of the energy determination by the TOF technique can be enhanced by increasing the flight length, the length of the TOF system was restricted to a few meters in an experimental room because of the lack of space for installation of additional equipments in the beam transport lines of the cyclotron facility. We, therefore, applied a flight length variation method[11] with a movable ion detector to the TOF measurement in order to achieve an accurate energy determination by a compact system. A flight length variation, 2 m in this case, allows to eliminate the main part of the systematic errors in the TOF measurement. Moreover, this method facilitates the energy spread measurement if sufficient increase of the width of the TOF spectrum with increase of flight length, yielded by the energy spread, is observed.

The mean beam energy determination has been achieved

by two different TOF methods with a flight length variation. The one is the TOF method with the ion coincidence detection. The flight time of ions was obtained from the coincidence detection of the same ions with two detectors including a movable detector. The TOF spectrum with a precise velocity distribution can be obtained by using ion detectors with a high time resolution. The beam energy spread has also been estimated from a significant increase in the width of the TOF spectrum.

On the other hand, the coincidence detection requires complicated procedure, especially in signal processing, and the efficiency of the coincidence detection is not always high depending on the characteristics of the detectors and beam transport between the detectors. Moreover, the energy loss of ions passing through a detector located at the upstream can affect the accuracy of the energy determination, especially for heavy ions. Therefore, we also accomplished the other TOF method with the beam bunch detection for mean beam energy determination. A beam bunch of cyclotrons, naturally modulated with the acceleration RF, has been widely used in various measurements of the beam energy with a TOF technique.[9,10] By applying a flight length variation, we have determined the mean beam energy from the time distributions of the beam bunch measured with only one movable ion detector without the coincidence detection of ions.

II. PRINCIPLE OF THE MEASUREMENT

The kinetic energy of an ion, E, can be obtained from the relation

$$E = E_0\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right), \tag{1}$$

where E_0 is the rest energy and $\beta = v/c$ with c the speed of light and v the speed of the ion. Since the fractional uncertainties in the rest energy E_0 and the speed of light c can be negligible in this measurement, the fractional energy uncertainty is obtained from

$$\begin{aligned}\frac{\Delta E}{E} &= \frac{1+\sqrt{1-\beta^2}}{1-\beta^2}\frac{\Delta\beta}{\beta} \\ &= \frac{1+\sqrt{1-\beta^2}}{1-\beta^2}\sqrt{\left(\frac{\Delta l}{l}\right)^2 + \left(\frac{\Delta t}{t}\right)^2} \\ &= \alpha\sqrt{\left(\frac{\Delta l}{l}\right)^2 + \left(\frac{\Delta t}{t}\right)^2},\end{aligned} \tag{2}$$

where $\Delta l/l$ and $\Delta t/t$ are the fractional uncertainties in the flight length and the flight time, respectively. In case of the 90 MeV proton beam ($\alpha = 2.3$), having the minimum flight time of 16 ns/(2 m) in the JAEA AVF cyclotron beams, the flight time measurement with an accuracy of 5 ps and the flight length measurement with an accuracy of 0.6 mm for the flight length of 2 m are required in order to obtain the accuracy of $\Delta E/E = 0.1\%$.

The energy determination by a TOF method, in general, requires the absolute distance between the detection points of ions and the absolute time interval between the detection times of the ions. The determination of the detection points with an accuracy of less than 1 mm is not always achieved, especially in the case of detectors having a thickness in the traveling direction of ions. The flight time, obtained from the time difference between the start and stop signals in the time analyzer, can include an uncertainty of the order of hundreds of picoseconds in extreme cases because each arrival time of the start and stop signals is affected by inherent factors, such as the individual time delay in the detector, the cable, and the electronics. A reduction of the time uncertainty can be executed by a time calibration, but it is not easy to achieve the overall time accuracy of the order of 1 ps.

The flight length variation method enables a reduction of uncertainties for an accurate determination of the mean beam energy. A microchannel-plate detector, a fixed one, was used at the upstream position, and ions, detected by the microchannel-plate detector, were also detected by a plastic scintillation detector at the downstream. Two measurements of flight time at different flight lengths by moving the plastic scintillation detector provide the differences in the flight time and the flight length without systematic uncertainties yielded in the absolute measurement. Therefore, the mean beam energy can be determined from the direct reading on the measuring instruments with the required accuracies, while the uncertainties caused by the different conditions of the measurements at the different detection points for the plastic scintillation detector have to be considered.

Moreover, the flight length variation method also enables a TOF measurement with a beam bunch for energy determination. Since the beam bunch is accurately synchronized with the acceleration rf, the mean beam energy can be obtained from shifts of the centroids of the beam bunch with respect to the acceleration rf at different flight lengths. While the time structure of the beam bunch for single-turn extraction mode has a narrow peak, the one for multiturn extraction mode, adopted to the JAEA AVF cyclotron, has a widespread distribution with plural peaks in general. The detailed time structure of the beam bunch is obtained by using the plastic scintillation detector and the rf pickup signal. This method, which does not require the coincidence detection of identical ions, enables efficient energy determination, although the detailed time structure of the beam bunch has to be considered. On the other hand, phase stability of the beam in the period of the measurement is essential for accurate time measurement of the beam bunch. Highly stabilized magnetic field with a stability $\Delta B/B$ of within $\pm 5 \times 10^{-6}$ has been achieved in the JAEA AVF cyclotron,[12] and the sufficient phase stability can be confirmed in the TOF measurement by repeating the measurement.

III. EXPERIMENTAL SETUP

A. Arrangement of the devices

A schematic diagram of the experimental setup is shown in Fig. 1. The TOF system was installed in the end of the beam line, located in an experimental room. The beam extracted from the JAEA AVF cyclotron was achromatically transported to the TOF system by using an energy-analyzing magnet and a bending magnet. The beam was aligned on the center axis of the TOF system with a precision of 1 mm by

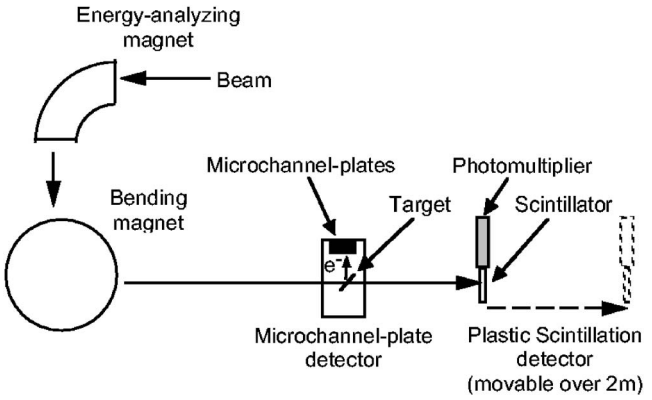

FIG. 1. Schematic diagram of the experimental setup at the JAEA AVF cyclotron facility. The beam extracted from the cyclotron was transported to the TOF system in an experimental room by way of an energy-analyzing magnet. For direct detection of ions, the microchannel-plate detector and the plastic scintillation detector were installed in the vacuum chambers of the TOF system. For the TOF method with the ion coincidence detection, both the detectors were used to measure the flight time of ions; for the TOF method with the beam bunch detection, only the plastic scintillation detector was used to measure the beam phase relative to the rf pickup signal. The vacuum chamber for the plastic scintillation detector can be moved for changing the flight length.

monitoring the scintillation images on fluorescent screens (AF 995R, Desmarquest) placed at the detector positions.

The detectors for the TOF system were mounted on individual vacuum chambers, which were connected to each other through bellows. The microchannel-plate detector was installed in the fixed chamber; the plastic scintillation detector, installed in the movable chamber, can be moved along the beam axis under the high vacuum.

B. Detectors

The microchannel-plate detector has been described in detail in the literature.[13] Secondary electrons, emitted by the target of the detector when ions pass through it, are accelerated to an assembly of microchannel plates to produce detection signals of ions. The target is an aluminum-foil strip, 3 μm thick with a width of 5 mm and a length of 60 mm, which is extended to the vertical direction of the beam axis and tilted at an angle of 45° to the beam axis. Proton beams with the energy of more than 20 MeV can pass through the target with the energy loss of less than 0.1%.

The plastic scintillation detector is composed of a plastic scintillator and a photomultiplier. The plastic scintillator (BC-400, Bicron) has an incidence face of 50 mm long by 50 mm wide with a thickness of 10 mm. The photomultiplier (R4998, Hamamatsu Photonics) was connected to the side of the scintillator from the vertical direction of the beam axis because of a spatial restriction inside the chamber.

The beam intensity from the order of nanoampere to microampere, depending on the variety of the ion beam, was reduced adequately for ion detection by a beam attenuator with metallic meshes installed in the injection line of the JAEA AVF cyclotron. The meshes enable homogeneous beam reduction in space. The counting rate of the detectors was maintained to be less than 10^4 counts/s with a combination of meshes.

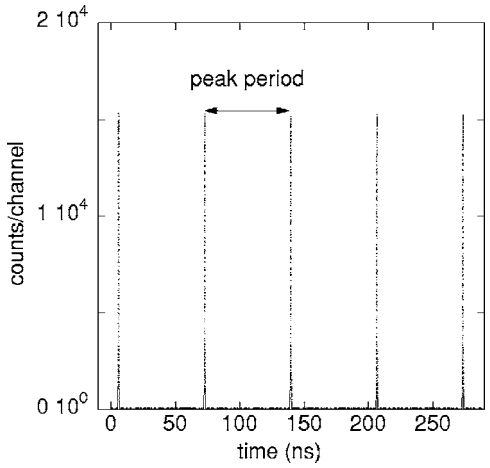

FIG. 2. Time spectrum of the beam bunch including five peaks over the time range of 320 ns for the proton beam with a nominal energy of 10 MeV. The beam bunch measurement was carried out by using the plastic scintillation detector as a start and the rate-divided rf pickup signal as a stop to confirm the timing accuracy of the electronics including the time analyzer.

C. Electronics

The signal from the microchannel-plate detector, amplified with a fast-timing preamplifier (VT120, Ortec), was fed into a constant fraction discriminator (935, Ortec) to provide a fast-timing signal as a start for the TOF measurement with the ion coincidence detection. The signal from the plastic scintillation detector was directly fed into another constant fraction discriminator to provide a fast-timing signal as a stop for the TOF measurement with the ion coincidence detection and as a start for the TOF measurement with the beam bunch detection. The cyclotron rf pickup signal, obtained from the pickup electrode of the rf voltage of the cyclotron, was fed into a discriminator (821, LeCroy) to provide a fast-timing signal as a stop for the TOF measurement with the beam bunch. The time interval between the start and stop signals was measured with a time analyzer (9308, Ortec), which records a time spectrum with picosecond precision by connecting to a personal computer. We used the time range of 80–320 ns (1.221–4.883 ps/ch) in the time analyzer. The time analyzer, based on the coarse counter and interpolation method,[14,15] has an absolute timing accuracy of 100 ppm of the interval because of its crystal-controlled clock, while the interval of the start and the stop has an ambiguity resolution of 5 ns as the delays in each input for the start and the stop. The timing accuracy was confirmed by using accumulated peaks of the beam bunch with an accurate repetition period corresponding to the rf of the cyclotron. The series of peaks of the beam bunch could be obtained by using the rate-divided rf pickup signal as the stop. The rf was measured with a frequency counter (HP53131A, Hewlett-Packard), with an accuracy of $\Delta f/f = \pm 1 \times 10^{-6}$. The time difference between the peak period of the beam bunch and the repetition period of the rf was confirmed to be consistent within 2 ps. For example, Fig. 2 shows the beam bunch spectrum of the proton beam with a nominal energy of 10 MeV. The time differences between the peak period of the beam bunch and the rf repetition period of 66.8003 ns are shown in Fig. 3. The time differences were calculated from the cen-

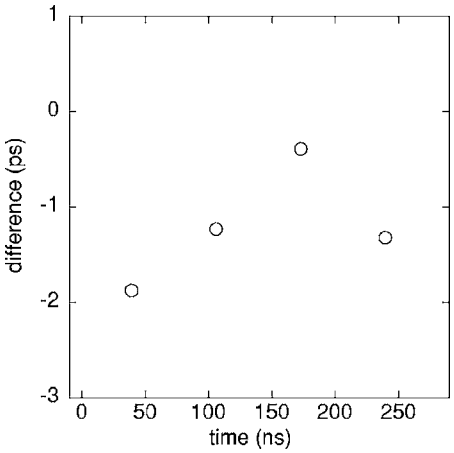

FIG. 3. Time difference between the peak periods of the five peaks, shown in Fig. 2, and the rf repetition period of 66.8003 ns. The centroids of the peaks were determined by computer fit with a Gaussian function. The time means the medium point of the neighboring peaks. The time differences were within 2 ps.

troids of the neighboring peaks of the beam bunch in the time spectrum. From the result of comparing the interval of the beam bunch measured with the TOF system and the repetition period of the rf pickup signal, the overall time accuracy of 100 ppm in the electronics was confirmed.

D. Flight distance variation

While in Ref. 11 the flight length variation was 16 cm for low-energy protons less than 100 keV ($\beta < 0.015$), we have extended the flight length variation to 2 m for higher beam velocity determination ($\beta = 0.1-0.4$) by using a flight length variation mechanism with a series of long bellows. The movable vacuum chamber for the plastic scintillation detector, which was mounted on a linear guide, can be moved through a leadscrew driven with a motor along the beam axis without any changes in the measurement arrangement except the position of the plastic scintillation detector. The distance between the detectors can be varied from 2.4 to 4.4 m. The vacuum in the fixed chamber was 5×10^{-6} Pa and the one in the movable chamber was kept in the order of 1×10^{-5} Pa, while the movable chamber was evacuated by the vacuum pump installed in the fixed chamber.

The traveling distance of the movable chamber was measured with a scale based on the magnetic principle (Magnescale GB-205, Sony Manufacturing Systems). The scale has a thermal coefficient of expansion of $1.1 \times 10^{-5}/°C$ and an accuracy of 0.015 mm at 20 °C for a 2 m distance. We estimated the error of the distance measurement to be ±0.13 mm (maximum temperature variation of ±5 °C), which is sufficient for the desired accuracy of the energy determination.

The incident position of ions on the plastic scintillation detector was maintained within 5 mm from the center axis of the TOF system over the movable length of 2 m by adjusting the beam transport parameters. Since the transit time of light in the scintillator is estimated to be 5 ps/mm, the incident position uncertainty contributes ±25 ps in maximum to the time measurement error. A flight length variation induced by the difference of the incident positions from the beam axis can be negligible because the increase ratio of the flight length is of the order of 10^{-5}.

IV. TIME-OF-FLIGHT MEASUREMENTS

A. Mean beam energy

The mean flight time of ions was calculated from the centroids of the peaks in the time spectra accumulated at two positions of the stop detector with a flight length difference of 2 m. The centroids of the peaks were obtained by a computer fit with Gaussian functions. Although the time spectrum of the beam bunch detection has a more complicated structure than the one of the ion coincidence detection, the computer fit with Gaussian functions can be applied to most of the time spectra of the beam bunch detection.

The mean beam energy, calculated from the interval of the centroids and the flight length variation, involves uncertainties. The dominant systematic error, caused by the uncertainty of the incident position on the plastic scintillation detector, is ±25 ps per flight time of 2 m, while the other systematic errors can be eliminated from the discussion in Secs. II and III. The uncertainty in the estimation of the centroid of the TOF spectrum on the horizontal axis of x is given by the standard deviation of the mean,

$$\sigma_{\bar{x}} = \sigma_x / \sqrt{N}, \tag{3}$$

where σ_x is the standard deviation of the peak and N is the number of the counts in the peak area. This parameter characterizes the uncertainty in the mean value of x. Sufficient counts in the peak area allow us to treat as negligible the uncertainty in the estimation of the centroid.

In case of the proton beam with a nominal energy of 30 MeV, where the energy loss of the beam in the microchannel-plate detector is negligibly small, less than 0.05%, we have measured the beam energy by using both the TOF methods with the ion coincidence detection and with the beam bunch detection. Each time spectrum obtained by the TOF method with the ion coincidence detection at the different flight lengths, as shown in Fig. 4, has a single peak with a Gaussian shape. The standard deviation of the peak σ_x is 80–90 ps and the number of the counts in the peak area N is in the order of 10^5; the uncertainty in the estimation of the centroid is 0.2–0.3 ps. We therefore obtained the beam energy of 28.94±0.06 MeV, the error of which was given by the incident position uncertainty on the plastic scintillation detector. Figure 5 shows the spectra obtained by the TOF method with the beam bunch detection in the same condition as the TOF method with the ion coincidence detection. In each spectrum the centroids of the two peaks could be determined by the computer fit with two Gaussian functions. While the centroids of the two peaks shifted in response to the flight length variation, the other parameters in the both spectra, were constant. The standard deviations of the left and right peaks σ_x are, respectively, 50 and 60 ps and the number of the counts in the left and right peaks area N is, respectively, in the order of 10^6 and 10^5; the uncertainties in the estimation of the centroids of the left and right peaks are, respectively, 0.05 and 0.2 ps. The beam energies of the left

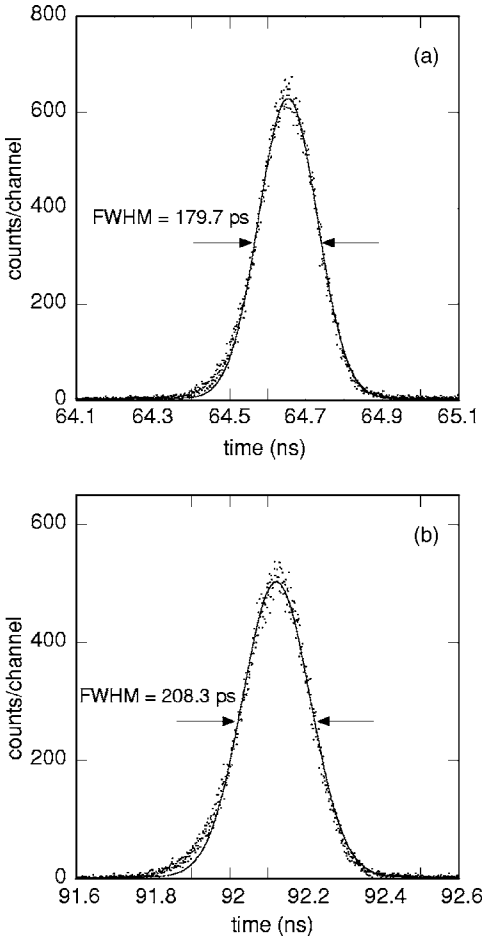

FIG. 4. Time spectra obtained by the TOF method with the ion coincidence detection for the proton beam with a nominal energy of 30 MeV: the flight time distributions for the movable detector position of 0 m (a) and 2 m (b). The centroid of the peak was obtained by computer fit with a Gaussian function. The horizontal axis represents the time scale of the time analyzer.

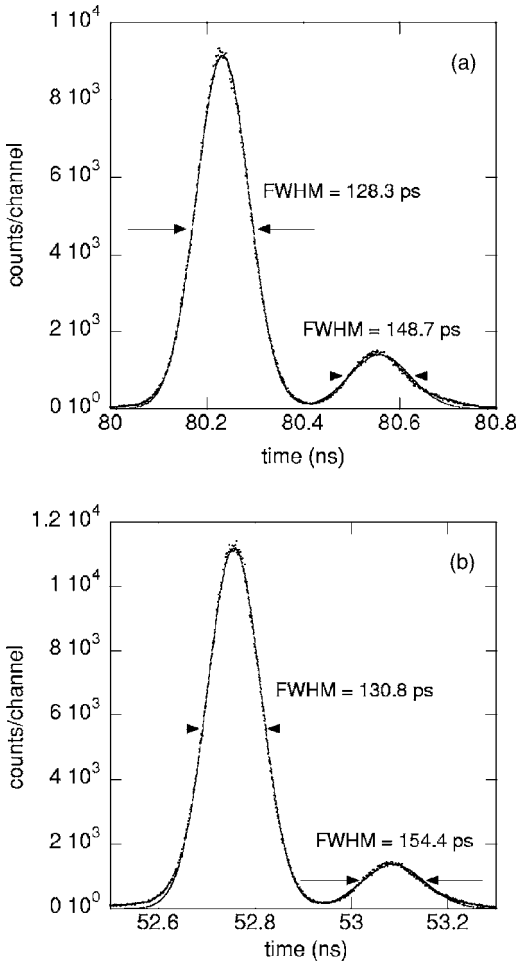

FIG. 5. Time spectra obtained by the TOF method with the beam bunch detection for the proton beam with a nominal energy of 30 MeV: the beam phase distributions for the movable detector position of 0 m (a) and 2 m (b). Each spectrum has two peaks; the centroids of the peaks could be determined by computer fit with two Gaussian functions in this case. The horizontal axis represents the time scale of the time analyzer.

and right peaks were calculated to be, respectively, 28.92±0.06 and 28.93±0.06 MeV, the error of which was given by the incident position uncertainty on the plastic scintillation detector. Since a repeated TOF measurement with the beam bunch provided nearly the same time shift of each corresponding peak with a difference of less than 4 ps in the time of flight of 27.5 ns/(2 m), the stability of the beam phase relative to the rf pickup signal was sufficient for the desired accuracy. The beam energies determined by the two methods agree within the uncertainty of the measurement.

The beam energies, as shown in Table I, were obtained by the TOF method with the ion coincidence detection or by the TOF method with the beam bunch detection in order to calibrate the energy-analyzing magnet over the full rigidity range. From the measured beam energies by the TOF, the rigidities of ions were calculated by using the relation

$$B\rho = \frac{1}{qc}\sqrt{T(T+2E_0)}, \tag{4}$$

where $B\rho$ is the rigidity, q is the charge of the ion, c is the speed of light, T is the kinetic energy of the ion, and E_0 is the rest energy. A relation between the rigidity $B\rho$ and the NMR reading of the energy-analyzing magnet B_{NMR} approximated by applying a third-order polynomial to the measured data is shown in Table I. The functional form, as shown in Fig. 6, is given by

$$B\rho = a_0 + a_1 B_{\mathrm{NMR}} + a_2 B_{\mathrm{NMR}}^2 + a_3 B_{NMR}^3 \tag{5}$$

with

$$a_0 = -1.531 \times 10^{-2}, \quad a_1 = 1.0505,$$
$$a_2 = -4.252 \times 10^{-2}, \quad a_3 = 1.318 \times 10^{-2}.$$

TABLE I. Beam energies obtained by TOF methods and NMR readings of the energy-analyzing magnet.

Ion	Nominal energy (MeV)	Measured energy (MeV)	TOF methods	NMR reading (T)
$^1H^+$	10	10.00±0.01	Bunch	0.458 137
$^1H^+$	20	19.21±0.03	Bunch	0.633 156
$^1H^+$	30	28.94±0.06	Coincidence	0.779 970
$^1H^+$	50	48.10±0.12	Coincidence	1.010 276
$^2D^+$	50	48.64±0.08	Coincidence	1.423 033
$^{12}C^{5+}$	220	226.0±0.3	Bunch	1.499 212

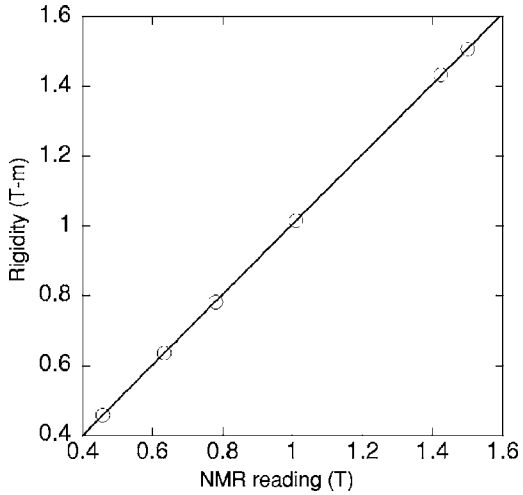

FIG. 6. Relation between the NMR reading of the energy-analyzing magnet B_{NMR} and the rigidity $B\rho$ calculated from the measured beam energies by the TOF methods. The curve was obtained by applying a third-order polynomial to the measured data.

The uncertainty due to the beam position at the object and the image of the energy-analyzing magnet was estimated to be ±0.32% in momentum. The uncertainty in the magnetic field of the energy-analyzing magnet can be estimated to be less than ±0.01% in momentum because of the highly reproducible process with the cycling of the magnet and the high-stable measurement with the NMR probe. The maximum uncertainty due to the beam energy measured by the TOF was ±0.25% in energy at the proton beam with a nominal energy of 50 MeV. Consequently, the beam energy can be calculated with the uncertainty of ±0.7% from the NMR reading by using the energy calibration curve.

B. Beam energy spread

The TOF spectrum obtained by the TOF method with the ion coincidence detection also provides information on the energy distribution of the beam as well as the time distribution. The energy spread of the beam is normally more than 0.1%, because the multiturn extraction mode, in which the beam before extraction from a cyclotron is spread in the radial direction, was adopted to the JAEA AVF cyclotron.

The beam energy spread was estimated from the peak width of the TOF spectrum, which also includes the intrinsic time dispersion of the detectors. Two measurements of flight time at different flight lengths by moving the plastic scintillation detector provide the difference in the peak widths of the TOF spectrum without the intrinsic time dispersion of the detectors. Assuming that the peak width consists of the intrinsic time dispersion of the detectors and the time spread from the beam energy spread, we can estimate the beam energy spread directly from the difference in the peak widths of the TOF spectra.

The peak width measured by the TOF method with the ion coincidence detection, as shown in Fig. 4, increased from 179.7 to 208.3 ps in full width at half maximum (FWHM) by the increase of the flight length of 2 m. The variation of the peak width measured by the TOF method with the beam bunch detection, as shown in Fig. 5, was relatively small, within ±6 ps in FWHM, in the same condition as the TOF method with the ion coincidence detection; significant systematic errors in the peak width variation measurement, such as a spread of the incident position of ions on the plastic scintillation detector, were not observed. This increase of 28.6 ps observed in the measurement by the TOF method with the ion coincidence detection was reconfirmed with a difference of less than 0.1 ps in the repeated measurement. By using Eq. (2), we estimated the energy spread $\Delta E/E$ to be 0.22% in FWHM.

ACKNOWLEDGMENTS

The authors are deeply indebted to the staff of the cyclotron for the excellent and efficient operation of the cyclotron and their assistance in the TOF measurement. We thank Dr. W. Yokota for fruitful comments on the manuscript.

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