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The proton beam energy measurement by a time-of-flight method

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Abstract. A simple TOF equipment for cyclotron protons beam energy measurement was constructed. For short distance of 165 cm between capacitive pick-up probes, the accuracy of proton beam energy is below 1% for mean beam currents above 200 nA and within the energy range 20–30 MeV.

Key words: beam diagnostics • cyclotron • ion beam

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Negative hydrogen ions are accelerated in the proton isochronous cyclotron C-30 of the Andrzej Sołtan Institute for Nuclear Studies (IPJ) at Świerk. Particles are extracted by stripping on a thin Al foil. The extraction radius and magnetic field of 1.7 Tesla give the possibility to obtain the range of proton velocities from 0.2 c to 0.24 c what corresponds to energies from 19 MeV to 28 MeV.

The knowledge of the ion beam energy only from the extraction radius is often insufficient. Thus, other ways of beam energy measurement are needed. One of the ways is the nuclear interaction of beam particles with a nucleus of well known energies of its excited states. For protons from the C-30 cyclotron, it can be scattering by ^{12}C which has a few well defined excited states. From the spectrum of scattered protons, it is very simple to calibrate a spectrometer and define beam energy (Fig. 1). Using well known energies of excited states of ^{12}C from the $^{12}C(p,p')$ reaction, (Q_1 = 4.43 MeV, Q_3 = 9.64 MeV), the energy of the beam is simply defined. Although this method is very useful it has one disadvantage. To check energy stability, the studied target must be replaced by a ^{12}C target.

Therefore, another way giving the possibility to measure beam energy not moving the studied target is needed. The time-of-flight (TOF) method described in this paper has no influence on the beam properties and allows to measure beam energy on-line. A similar method was already described [1].

The C-30 cyclotron uses 52 MHz rf electrical field to accelerate protons. During every rf period, a bunch of protons is injected into the beam line. Subsequent bunches are spatially separated by the distance L

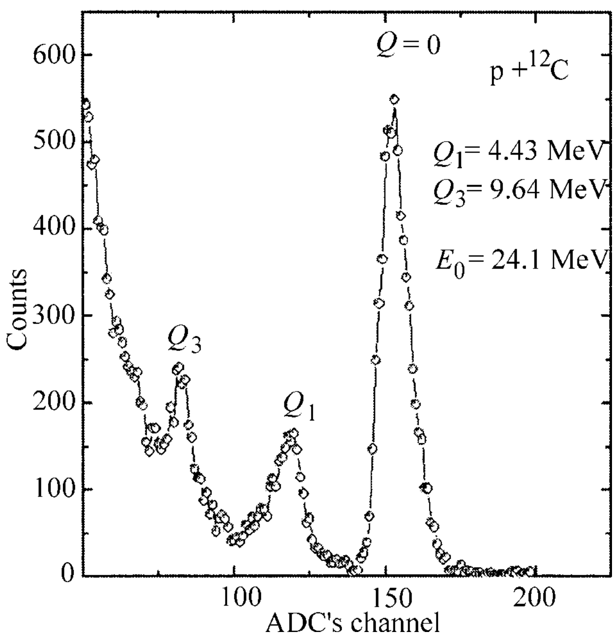

Fig. 1. The energy of proton beam E_0 was obtained from the spectrum of protons scattered on ^{12}C target.

proportional to the proton velocities v, according to the simple formula:

$$L = v^*(1/f) \tag{1}$$

where f is the rf field frequency; and L varies from L_{min} = 110 cm to L_{max} = 140 cm for minimal and maximal proton energies available.

The convenient way to determine proton velocity is to measure the time-of-flight along the well defined base between two probes recording the time of passage of one bunch. If no more than one bunch travels, the base of its recognition is unambiguous. Then, however, the base is short and precision is low. Longer base offers higher accuracy but requires taking into account a number of bunches k. It is easy to show that if the probes are separated by the base D fulfilling relation:

$$(k-1)^*L_{max} < D < k^*L_{min} \tag{2}$$

then, every k-th signal in the second probe, following the signal in the first one, is the true one, i.e. both signals originate from the same bunch. With growing k, the lower and upper limits of D become closer and meet around $k = k_{max}$.

$$k_{max} = L_{max}/(L_{max} - L_{min}) \tag{3}$$

In the C-30 cyclotron k_{max} = 4.

The above reasoning leads to the conclusion that the base should be fixed in the middle of the range (2) i.e.

$$D = \big((k-1)^*L_{max} + k^*L_{min}\big)/2 \tag{4}$$

where $k < k_{max}$.

It was convenient to adjust D = 165 cm with k = 2. Two probes at this distance were introduced into beam line and the used apparatus is sketched in Fig. 2.

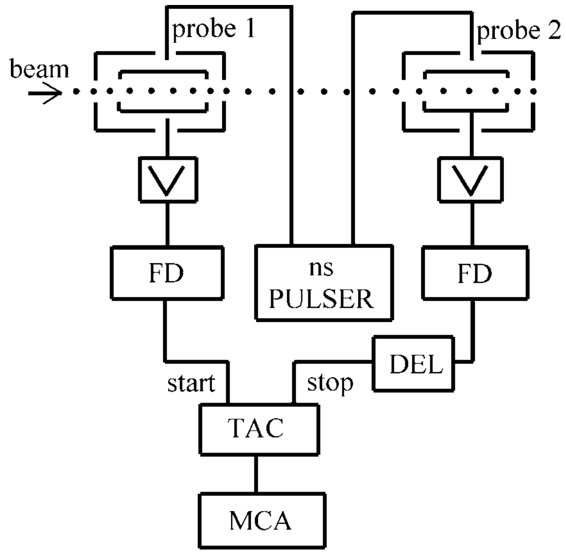

Fig. 2. TOF equipment, abbreviations mean: FD – fast discriminator; TAC – time to amplitude converter; DEL – fixed delay in stop channel; MCA – multichannel analyzer.

The probes have shapes of the cylindrical capacitors 10 cm long with inner and outer diameters of 3 cm and 9 cm, respectively. Their lengths correspond to typical bunch size. The outer cylinders are grounded and signals are picked up from the inner ones. They are closed from both sides by diaphragms with central apertures of 2 cm diameter to stop the beam halo. Their symmetry axis is collinear with the proton beam. Additionally, they are equipped with tiny pin electrodes stimulating response of the probes for capacitively coupled 2 ns wide reference signal. A small mercuric wetted reed relay switches charged small capacitor through tee splitter onto two matched in length transmission cables terminated at probes pin electrodes. These discharging pulses induced simultaneous response of probes relevant to absolute zero time calibration. Signals from the probes are amplified by ac coupled wide-band amplifiers made from two cascaded monolithic chips ERA-3SM, each of 20 dB nominal gain in the dc to 3 GHz range, manufactured by Mini Circuits Inc. The ac coupling 3 dB cutoff frequency was about 15 MHz. In order to improve signal to noise ratio, both amplifiers were installed into the ions guide very closely to the probes.

Next, the amplified signals are sent to fast discriminators built from LeCroy 400 MHz quad comparators type MVL407. The fast NIM logical pulse is triggered at zero crossing of the input signal what corresponds to the crossing the bunch centroid through the middle of the probe. Zero-crossing triggering is activated if the positive and negative parts of bipolar signal cross the predetermined noise level. Since rms signal noise constituent was 5–6 mV, the dc discriminator level was chosen to be 20 mV. It corresponds to about 100 nA mean beam detection level. The intervals between logical pulses from the discriminators are measured with the time to amplitude converter ORTEC TAC 566.

The typical TOF spectrum is shown in Fig. 3. The first peak in the time spectrum originates from the reference pulser. It marks absolute zero time span, within 100 ps. The following peaks originate from

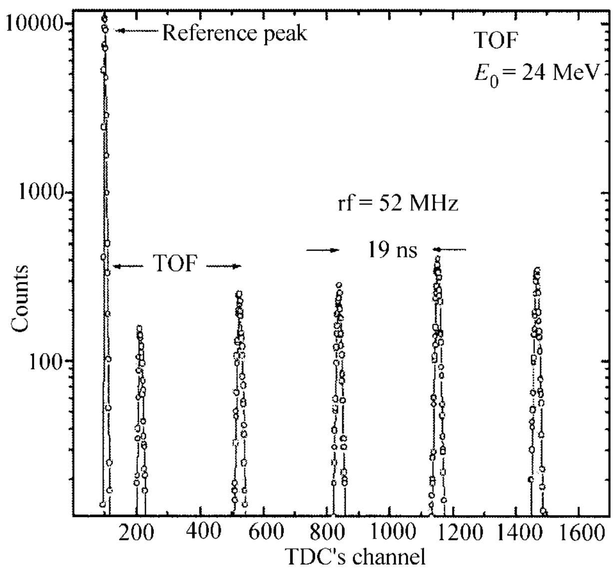

Fig. 3. TOF spectrum. The energy of the proton beam E_0 = 24 MeV was obtained from measured velocity.

protons and the intervals between them correspond to the rf field period known precisely from the frequency synthesizer. These peaks give precise TAC calibration checked earlier for integral nonlinearity to be less than 0.1%. The proton velocity is determined from the separation between the 1st (reference pulser) peak and the 3rd peak (k = 2), in the time spectrum.

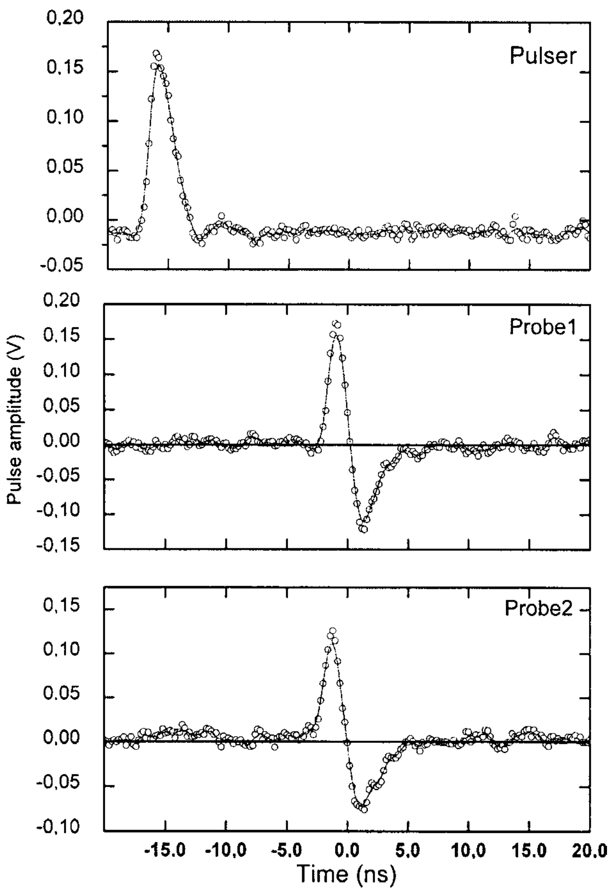

Fig. 4. Pulse shapes of generator and corresponding probe pulse.

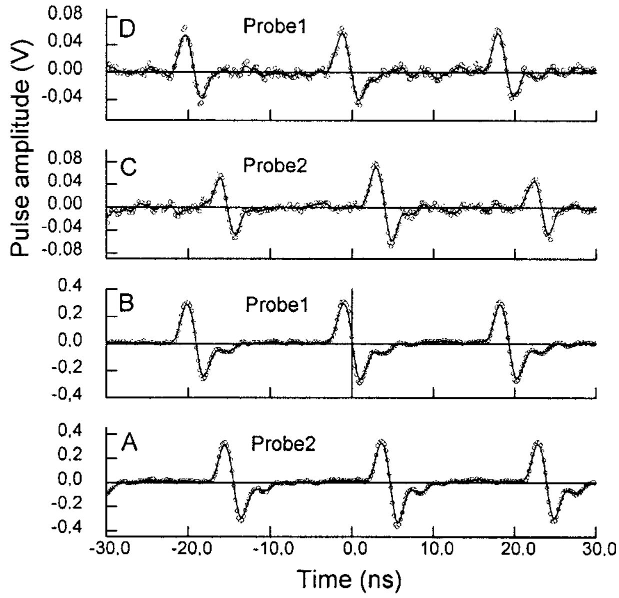

Fig. 5. Probes signals induced by 22 MeV proton beam. A-B – beam current 1.5 μA; C-D – beam current 0.3 μA.

The digital TEK TDS 3054 scope of 500 MHz bandwidth was used to record waveforms of the pulser, responses of the probes and actual probes signals induced by 22 MeV proton beam. The respective oscillograms are shown in Figs. 4 and 5.

The accuracy of the energy measurements depends on the distance and the time-of-flight inaccuracy. The distance is measured with 1 mm precision giving less than 0.1% error. Inaccuracy in the time determination follows from the amplifier noise, time jitter and walk of discriminators. Exchange of reference signal cables produces only 20 ps propagation mismatch which means that the time is measured with good accuracies on both probes simultaneously.

We have checked the time walks with defocusing beam and thus the varying mean beam current from 100 nA to 1.5 μA. In the range 200 nA – 1.5 μA, the walk was below 80 ps giving energy error 0.8% and in 100 – 200 nA deteriorated to about 240 ps resulting in 2% error. Checks with pulser amplitude variation showed a similar behaviour. These numbers should be related to 24 ns time-of-flight value. We estimate the energy accuracy to be less than 0.4 MeV for 20 MeV protons mainly due to the short 165 cm probe distance.

The TOF technique is non invasive and is routinely used for continuous monitoring of the beam energy during long irradiation of samples.

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