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New Time Pick-Off Algorithm for Time-Of-Flight Measurements with PIN Diodes

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New off-line time pick-off algorithm for time-of-flight measurements of heavy ions with PIN diodes is presented. The digital image of the detector signal obtained in experiment is processed in order to find a real signal start when a particle hits the detector. By this way, so-called plasma delay between the time stamp and a real signal start is taken into account automatically. The algorithm was tested using the data obtained on the ion beams. The algorithm allows to obtain unbiased estimates of the heavy ion velocities and masses in a wide range of these parameters.

INTRODUCTION

To correctly measure heavy ion's time-of-flight (TOF) with PIN diodes, it is necessary to account for the so-called plasma delay effect (PDE) which is due to generation of plasma in a heavy ion track in the PIN diode.

The processes in the ion track at the initial stage of its evolution manifest themselves in such a way that signal from PIN diode could be described as a slowly growing function. This initial part of the signal at least partially lies inside a "noise track". Later the leading edge of the signal becomes almost linear. It is possible to account for PDE by using the method developed in Ref. [1], but this procedure may not correctly work for small masses and energies. We developed an alternative approach aimed at finding an actual start of the signal. It is done by approximating signal's initial part by parabolic curve which vertex coincides with the mean value of the noise track and serves as the "true" signal's start. The first realization of this idea was "Parab" algorithm [2] in which parabolic function was used for interpolation of the signal's noisy region. To increase a robustness of the algorithm against a choice of the region for parabola interpolation, Parab was followed by "Parablin" time pick-off algorithm [3]. Within this algorithm the parabolic function was seamlessly sewed with a linear function which approximated points of the rising edge of the signal lying above the noisy region. Parablin's main drawback was the need to manually choose points for linear function approximation. To further increase robustness of the time pick-off procedure, we propose "Paraspline" algorithm in which the initial part of the signal is described by parabola, seamlessly sewed with a spline that automatically approximates points above the noisy region, without user interference.

PARASPLINE ALGORITHM DESCRIPTION

Let us select the data area ($x_1,\ldots,x_n$, $y_1,\ldots,y_n$), $n \le N$, consisting of points lying to the right of point (x_0, y_0) (Fig 1), which is the border to the right of the "reliable points" of the signal: to the left of this point all points of the signal belongs to the interval [$y_b - 3\sigma$, $y_b + 3\sigma$], where y_b is the mean value of the noise, σ is the noise standard deviation, so it is impossible to reliably distinguish noise from signal. The size n of the area ($x_1,\ldots,x_n$, $y_1,\ldots,y_n$) is chosen large enough, $n \ge 200$.

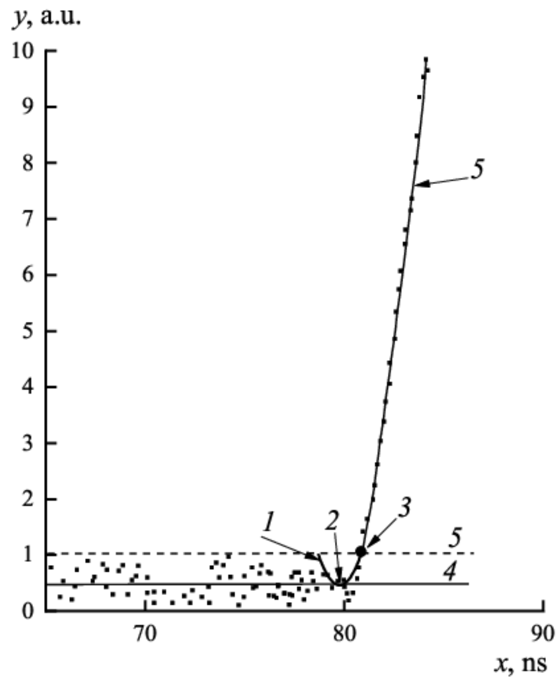


Fig. 1. Waveform from the PIN diode stored with a step 0.2 ns. *1* – parabolic approximation of the initial part of the signal; 2 – the parabola vertex x_p accepted as a time stamp; 3 – sewing point (x_0, y_0); 4 – line corresponded to the mean value of the base-line y_b; *5* – line corresponded to y_b+3σ; *6* – spline approximation of the quasilinear part of the signal.

We define the smoothing spline $s(\cdot)$ [4] of order q as a solution of the following minimum problem:

$$\min\left\{p\int_a^b (s^{(q)}(x))^2 dx + \sum_{j=1}^{n} (s(x_j) - y_j)^2\right\}, \quad (1)$$

Parameter vector of $s(\cdot)$ is varied to rich a minimum of the functional (1) . The smoothness of $s(\cdot)$ increases with increasing order of the spline q and increasing smoothing factor p. Factor p must be known before the minimization of (1). The main idea of the paraspline algorithm is as follows.

1. Fix the value of the smoothing factor p. With this fixed value of the smoothing parameter, we find the smoothing spline $S_p(\cdot)$ of order $q = 2$, which minimize the functional (1) and is the best approximation for signal ($x_1,\ldots,x_n$, $y_1,\ldots,y_n$) (that is, a cubic spline on intervals (x_i, x_{i+1}), $i = 1,\ldots,n-1$, $n \ge 2$).

2. The parabola with a vertex on the mean of the signal's baseline (point (2) in Fig. 1) is defined by the following equation:

$$y = ax^2 + bx + \frac{b^2}{4a} + y_b \tag{2}$$

It is necessary to sew the smoothing spline $S_p(\cdot)$ smoothly (equality of values and derivatives) on its left border x_0 (the sewing point) with the parabola defined by the formula (2). After the smoothing spline $S_p(\cdot)$ is found, we have two equations for finding the parameters a and b of the parabola:

$$\begin{gathered} Ax_s^2 + bx_s + \frac{b^2}{4a} + y_b = S_p(x_s) = g \\ 2ax_s + b = S_P'(x_s) = h \end{gathered} \tag{3}$$

Hence, we find that

$$\begin{gathered} a = \frac{h^2}{4(g - y_b)} \\ b = h - \frac{2x_s h^2}{4(g - y_b)} \end{gathered} \tag{4}$$

As the point of the time stamp, we take the point with the abscissa $x_p = -b/2a$ (i.e., abscissa of the parabola vertex).

Thus, for each value of the smoothing factor p (for example, using the grid $[p_1,\ldots,p_n]$ in increments of 0.1 or 0.01, depending on the software) we find the smoothing spline $S_p(\cdot)$ of order $q = 2$ and the binding point x_p of the parabola, as well as the parameters of the parabola. The value of the smoothing parameter is determined based on article [4] as follows. The smoothing spline $S_p(\cdot)$ can be presented in the form of two terms: the first term is the "smooth" term $\sigma_p(x_i)$, $i = 1,\ldots,n$, estimating the dependence of the signal of interest on time, and the second is the differences $\mu_p(x_i) = y_i - \sigma_p(x_i)$, $i = 1,\ldots,n$, representing the noise dependence on time.

If the smoothing spline (i.e., the smoothing factor p) is selected correctly, then the smooth term should not contain "visible" traces of noise, and the difference should not have "regular" components from the signal. If the smoothing spline σ_p with the "correctly selected" smoothing factor is re-applied to the difference $\mu_p(x_i) = y_i - \sigma_p(x_i)$, $i = 1,\ldots,n$, we get the spline $v_p(x)$, identically equal to zero.

Therefore, to find the "correct" value of the smoothing factor, for each value of the smoothing factor p in some grid $[p_1,\ldots,p_n]$, we calculate the spline $v_p(x)$ and its norm $\|v_p(x)\|^2$. The value of the smoothing factor, at which the norm is minimal, will be considered optimal. Thus, we also find the binding point x_p of the parabola corresponding to this value of the smoothing factor.

EXPERIMENTAL VERIFICATION OF THE PARASPLINE ALGORITHM

A successful time pick-off algorithm should provide both an unbiased time stamp and good time resolution. In order to test the first characteristic, the following series of experiments was performed. Using time-of-flight spectrometer LIS (Fig. 2) with two flight paths, the velocity V of each heavy ion was measured twice, namely estimate V_1 was obtained on the flight path L_1 using two microchannel plates-based detectors St_1 and St_2, and estimate V_2 was obtained on the flight path L_2 with a help of the detector St_2 and PIN diode. Timing detectors St_1 and St_2 are free from the plasma delay effect that is why the value V_1 can be considered "true" velocity. If the plasma delay is taken into account correctly, thanks to Paraspline algorithm, the mean difference $<V_1 – V_2>$ should be close to zero within a change of V_1 when the ion passes through a thin foil 4 in St_2 (Fig. 2). The spectrometer was placed at the beam of heavy ions knocked out from the target foils by the 160 MeV Xe beam of the accelerator IC-100 in FLNR (JINR).

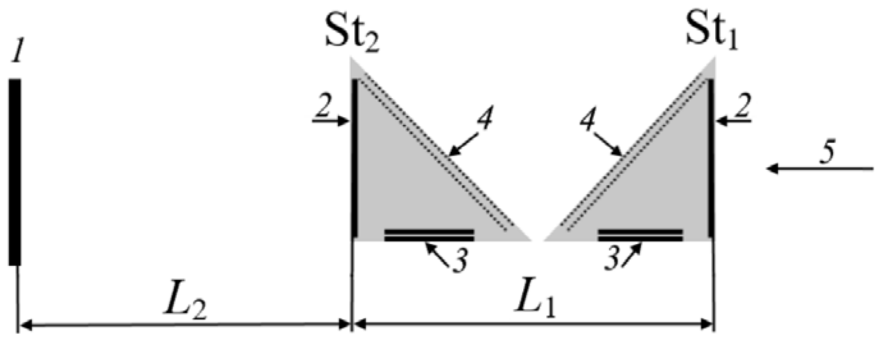


Fig. 2. Layout of LIS spectrometer. St_1, St_2 – microchannel plates-based timing detectors (are shown in gray); *1* – ^{252}Cf source; *2* – emitter-foil; *3* – microchannel plate; *4* – electrostatic mirror; *5* – ion beam; L_1 – 14.2 cm; L_2 – 14.1 cm.

The results of a comparison between V_1 and V_2 for the ions of Cu and Zr are presented in Fig. 3. The difference between the velocities does not exceed 0.4%.

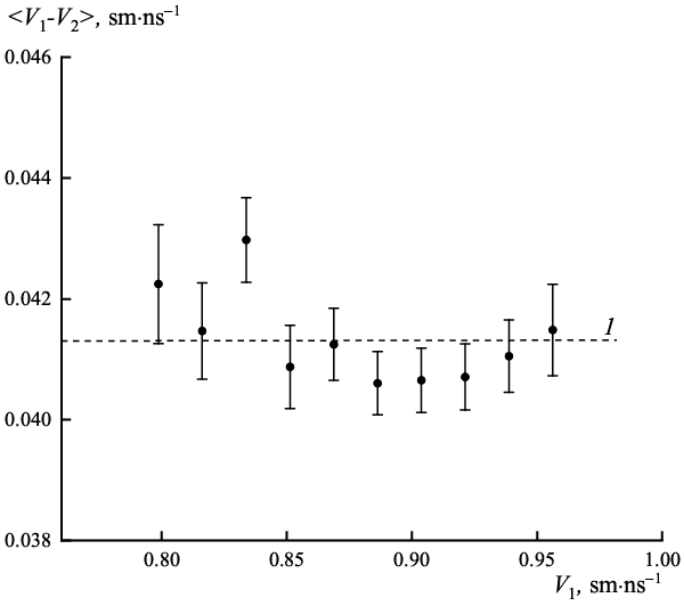
Due to the kinematics of the rare ternary decays in our experiments, the energy of one of the decay products to be detected does not exceed several MeV. To ensure the correct unbiased mass reconstruction especially for the low-energy heavy ions we measured the masses of several different ions in the wide range of energies, using LIS spectrometer (Fig. 2). The values V_2 were used for mass reconstruction, while pulse height defect in the PIN diode was taken into account according the procedure presented in Ref. [5]. The results are shown in Fig. 4.

As can be inferred from Fig. 4, the mass reconstruction procedure involving Paraspline time pick-off algorithm provides quite satisfactory mass spectrometry of heavy ions in the wide range of masses and energies.

Experimental estimate of the time resolution for heavy ions when Paraspline time pick-off algorithm is used are also of interest. It a special methodic task which could be solved accurately only by using the mono energetic ion beams that are inaccessible.

Two main components contribute to a variance of the time stamp for heavy ions. The first one is due to the uncertainly of estimate of the plasma delay, especially for the detector signals in the wide range of amplitudes. The results presented above demonstrate that Paraspline time pick-off algorithm provides unbiased time stamp within the errors of the measurements. The influence of the second factor namely electronic noise we estimated in a following way. By definition, each detector signal could be presented as a sum of its mean shape and a random implementation of noise process. We collected a library of the noise samples $\xi_i(t)$. In fact, each sample is a record of some part of the noise track before the start of detector signal (Fig. 1). Thus, all such samples are statistically independent and represent actual spectrometer noise. The shape of the real detector's signal after strong smoothing could be considered as its mean shape $F(t)$. Then the series of the "quasi-experimental" signals $\phi_i(t)$ can be generated according to the formula:

$$\phi_i(t) = F(t) + \xi_i(t), i = 1 \div 100 \qquad (5)$$



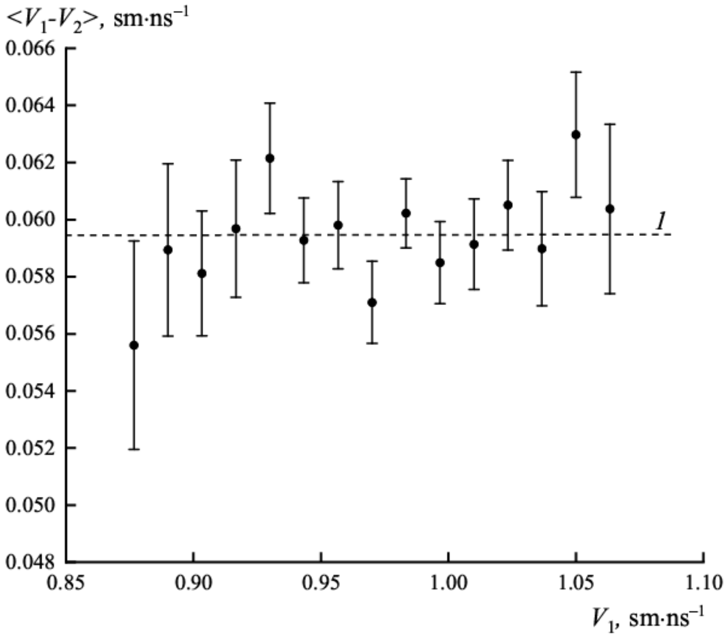


Fig. 3. Mean difference <$V_2 - V_1$> as a function of V_1 for the a) Cu ions, b) Zr ions. The horizontal dashed line *1* – calculated mean value <$V_2 - V_1$>.

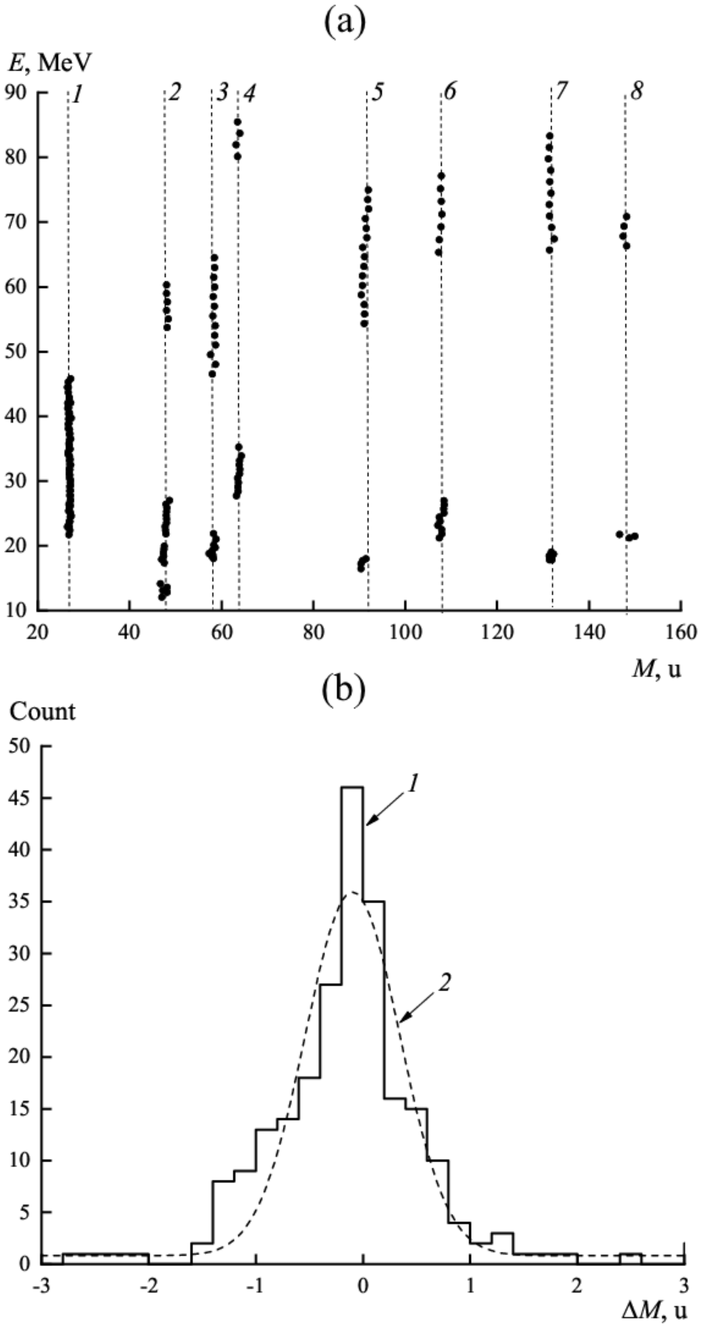


Fig. 4. a) Mass-energy distribution for all ions studied in the experiment. (Uncertainties of *M* are within point's size). The vertical dashed lines corresponded to the ions of Al, Ti, Ni, Cu, Zr, Au respectively are marked by numbers 1÷8. The experimental mass values for the Au ions are shifted in the figure to the left by 50 u. b) Spectrum of ΔM of measured masses for all ions from the known ones. *1* – Experimental spectrum; *2* – Gaussian fit with standard deviation 0.37 u.

For each signal $\phi_i(t)$ a time stamp τ_i is found using Paraspline algorithm. For all the series of quasi-experimental signals the probability distribution $P(\tau)$ is calculated. The $P(\tau)$ function looks like a Gaussian with the FWHM ≈ 200 ps for the signal with an amplitude typical for fission fragments. For the signal with a six times smaller amplitude, the FWHM is about 400 ps. This tendency of time resolution becoming better with increasing steepness of the signal’s leading edge is typical for all known time pick-off algorithms. The obtained values of FWHM are better than that (600 ps) mentioned in Ref. [6] at comparable conditions, but in our case, it is only partial contribution to the full-time resolution.

CONCLUSIONS

Correctness of the new Paraspline time pick-off algorithm was tested in experiment at the accelerator. Heavy ions knocked out from the Al, Ti, Ni, Cu, Zr, Au foils by the 160 MeV ^{132}Xe beam were used. The ion energies lie within the range (12÷87) MeV. It is shown that the algorithm allows obtaining unbiased estimates of the heavy ion velocities and masses of the detected ions. Algorithm provides good noise induced time resolution (200÷400) ps, inversely proportional to the signal amplitude.

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