New time pick-off algorithm for time-of-flight measurements with PIN diodes

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Introduction:

To correctly measure heavy ion's 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. Because of the PDE, the signal from PIN diode could be described as a slowly growing function of unknown form that changes into a nearly linear function. The start of the signal is also obstructed by background noise. It is possible account for PDE by using method developed in [1], but this procedure may not correctly work for small masses and energies. We developed an alternative method by finding an actual beginning of the signal. It is done by approximating its initial part that lies inside the "noise track" by parabolic curve which vertex lies on the average of the noise and serves as the "true" signal's start. The first realization of this idea was Parab algorithm [2] which used only parabolic function for interpolation of the signal's noisy region. To increase a robustness of the algorithm against a choice of region for parabola interpolation, Parab was followed by Parablin [3] which seamlessly sewed parabola with a linear function that approximated points of the rising edge of the signal lying above the noisy region. Main drawback - the need to manually choose points for linear function approximation. To further increase robustness of the method, we propose Paraspline algorithm which describes the initial part of the signal by parabola, seamlessly sewed with a spline that automatically approximates points above the noisy region, without user interference.

Paraspline description:

To find the best approximation of the signal $f(x_i)= y_i$, $i=1,\dots,N$, by a smoothing spline with the additional condition described above, we will proceed as follows.
Lets select the data area $(x_1,\dots,x_n, y_1,\dots,y_n)$, $n \le N$, for which we will search for a smoothing spline. This area consists of points lying to the right of point (x_0, y_0) (Fig 1), which is the border to the right of "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 dispersion, so it is impossible to reliably distinguish noise from signal. The size n of the area $(x_1,\dots,x_n, y_1,\dots,y_n)$ is chosen large enough, $n \ge 200$.

The main idea of the Paraspline algorithm:
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 $(x_1,\dots,x_n, y_1,\dots,y_n)$ (that is, a cubic spline on intervals (x_i,x_{i+1}), $i=1,\dots,n-1$, $n \ge 2$).
2. The parabola with a vertex on the mean of the signal's baseline (shown as C at Fig.1) is defined by the following equation:
$y=ax^2+bx+b^2/4a +C.$ (2)
3. It is necessary to sew the smoothing spline $S_p(\cdot)$ smoothly (equality of values and derivatives) on its left border x_s (at 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 of the parabola a and b
$Ax_s^2+bx_s+b^2/4a +C = S_p (x_s)=g,$ (3)
$2 ax_s+b= S_p'(x_s)= h.$
Hence we find that
$a=h^2/[4(g-C)],$ (4)
$b=h-2x_sh^2/[4(g-C)].$

As the anchor point, 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 $[p_1,\dots,p_n]$ 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..

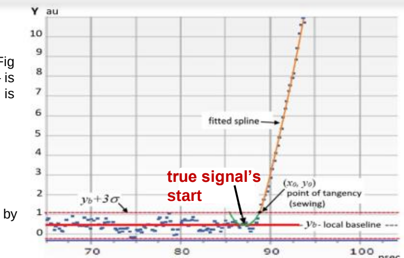

Fig.1 Digital signal with Paraspline pick-off. Red line y_b – mean local baseline; in between dotted red lines $[y_b-3\sigma, y_b+3\sigma]$ – noisy region; orange line – fitted spline; black dot (x_0, y_0) – point of functions' tangency; green curve – parabola with vertex on the signal's start

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

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

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 value of the smoothing parameter is determined based on article [4] (see p. 582). as follows.
The smoothing spline $S_p(\cdot)$can be presented in the form of two terms: the first term is the "smooth" term $\sigma_p(x_i)$, $i=1,\dots,n$, estimating the dependence of the signal of interest on time, and the second is the differences $\mu_p(x_i)=y_i-\sigma_p(x_i)$, $i=1,\dots,n$, 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 to the difference $\mu_p(x_i)=y_i-\sigma_p(x_i)$, $i=1,\dots,n$, re-apply the smoothing spline σ'_p with the "correctly selected" smoothing factor, *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 $[p_1,\dots,p_n]$ 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 found the binding point x_p of the parabola corresponding to this value of the smoothing factor.

Experiment Ex1 to verify Paraspline:

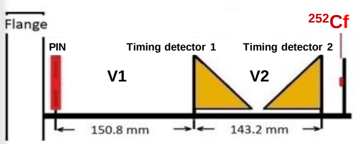

Figure 2. Layout of LIS spectrometer in Ex1.

Ex1 setup (Fig. 2):
- Time-of-flight spectrometer LIS
- ^{252}Cf source
- Two microchannel plate (MCP) timing detectors for time registration (CFD time pick-off)
- PIN diode for both energy and time registration (Paraspline time pick-off)

Paraspline verification:
- event by event comparison of "true" velocity V_1 (calculated using MCP-MCP flight path using SFD) and V_2 (MCP-PIN flight path using Paraspline).

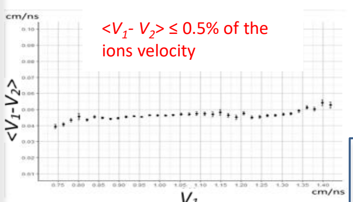

Figure 4. Mean difference $\langle V_2 - V_1\rangle$ as a function of V_1 for the fragments from the ^{252}Cf source in Ex1.

Parasline resolution:

Resolution tested on signals produced by adding various realizations of noise to an expected value of a signal (Table 1).

Resolution is approximately inversely proportional to signal's amplitude.

event №	A (ch)	Fwhm, ps	detector
14	224	395	PIN
819	613	298	---- ----
29	943	179	---- ----
90	1465	204	---- ----
41	112	282	MCP
33	545	53	---- -----

Table 1. Resolution for signals of different amplitude A

Experiment Ex2 to verify Paraspline:

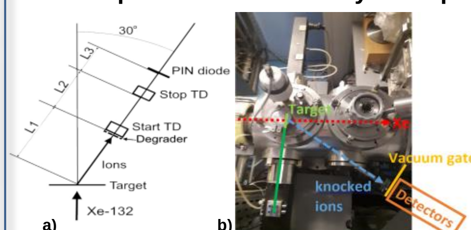

Figure 5. a) Setup of Ex2 at IC-100 accelerator. The flight passes do not exceed correspondingly L1 = 500 mm, L2 = 142 mm, L3 = 141 mm. b) Photo of the target knot at IC-100 accelerator.

Ex2 setup (Fig. 5):
- ^{132}Xe beam of ~ 160 MeV from IC-100 accelerator (FLNR, JINR)
- Target : Al (~5 um thick), Ti (2 um), Cu (~3.6 um), Ag (~0.1 um), Au (~0.1 um), Zr (~2 um) and Ni (~1 um) foils
- Time-of-flight spectrometer set at a 30^0 angle to the beam
- Two MCP timing detectors (START TD and STOP TD for time registration (CFD time pick-off)
- PIN diode for time and energy registration (Paraspline time pick-off)
- Degrader foils of various thickness installed before the START TD detector to ensure a wide range of ions' energies

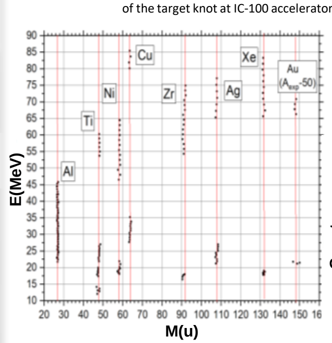

Figure 7. Energy/Mass distribution for all ions in Ex2 (Standard Error of Mean is so small that error bars are omitted in the plot).

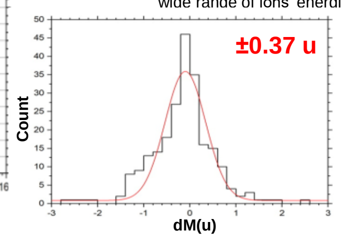

Figure 8. Distribution of derivation of reconstructed masses from the literature data for all ions.

Parasline verification:
- event by event comparison of ions' velocity calculated with PIN diode at Stop TD – PIN flight path with velocity at Start TD –STOP TD path (Fig. 6);
- Reconstruction of ions' masses using their velocities and energies registered by PIN diode (Fig. 7, 8).

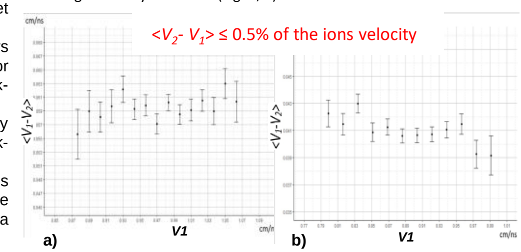

Figure 6. Mean difference $\langle V_2 - V_1\rangle$ as a function of V_1 for a) Cu and b) Zr ions in the experiment at IC-100 accelerator.

Conclusion:

Correctness of Paraspline time pick-off algorithm was tested in two time-of-flight experiments. The results show a good agreement between the experimental velocities as well as unbiased mass reconstructed in a wide range of particle energies. Algorithm provides acceptable resolution inversely proportional to signal's amplitude.

Reference:
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