DSP algorithms for fission fragment and prompt fission neutron spectroscopy

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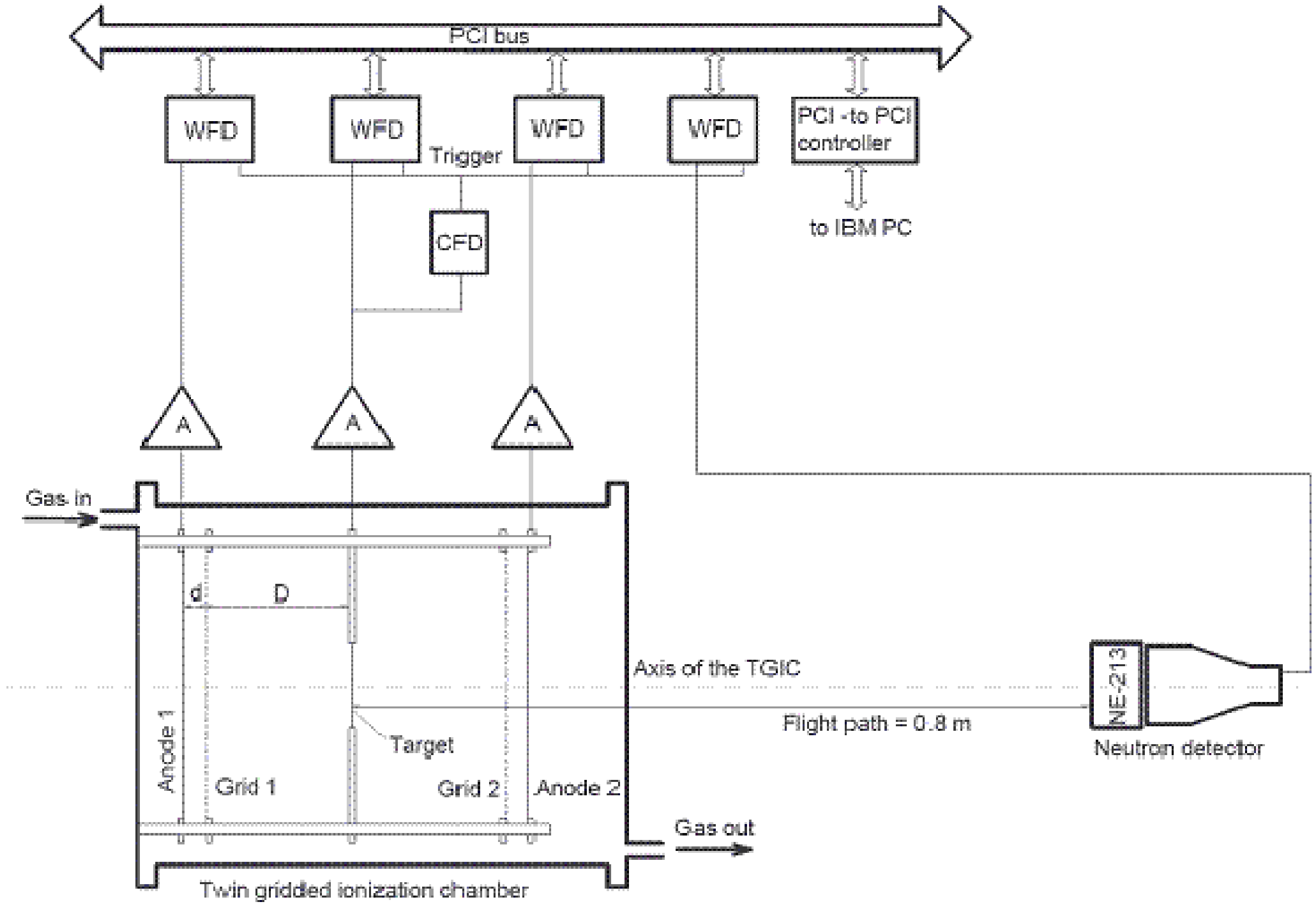
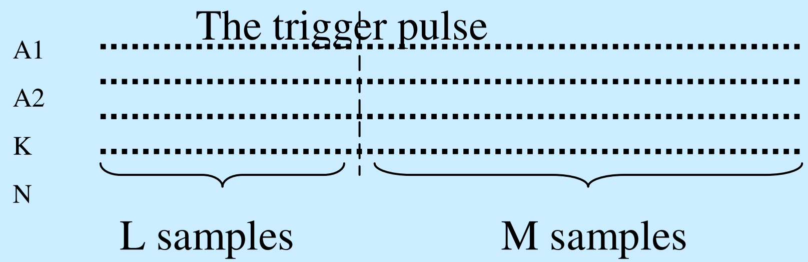
Data acquisition system



Digitized waveforms structure



Waveforms sampled with 100 MHz WFD 12 bit amplitude resolution

Event = {A1, A2, K, N}

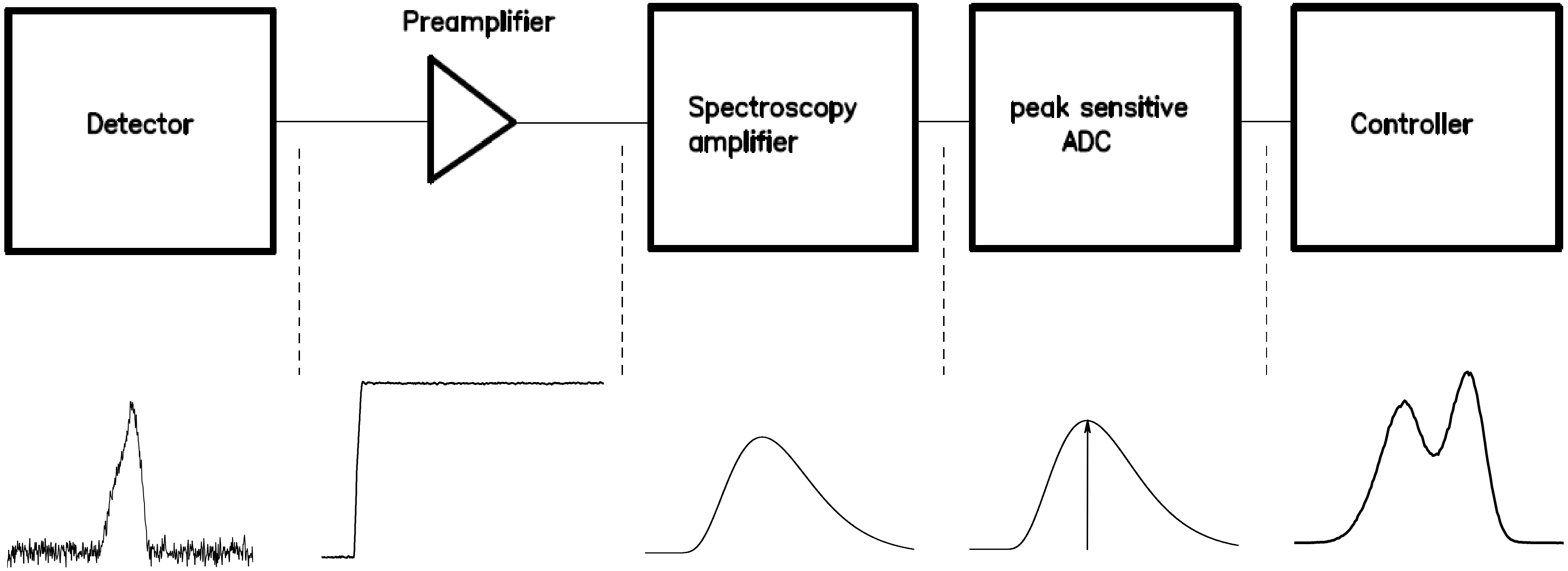
Energy released inside the 1st and the 2nd half of the TGIC

ND signal used for the neutron TOF measurement after pulse shape analysis

Cathode pulse used as a fission event time reference

The actual trigger position L has the mean value $(L-0.5)\Delta$ and the dispersion $\sigma = 0.3\ \Delta$

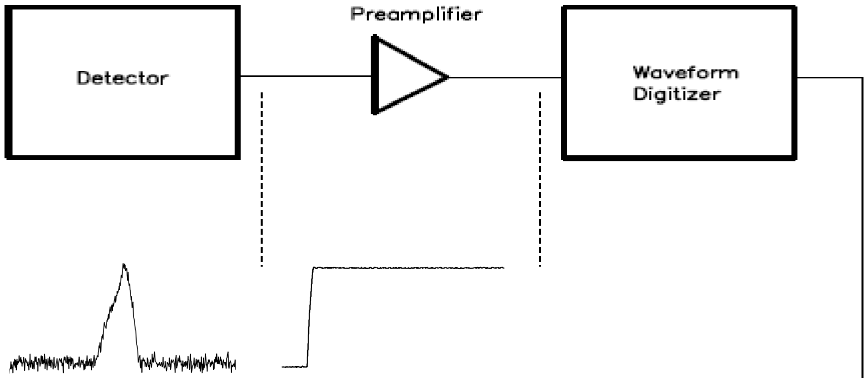
Traditional analogue electronics approach when each module performs a dedicated signal processing.



Detector current is converted into a step pulse in a charge-sensitive preamplifier. The height of the step pulse conveys information on the FF's kinetic energy, released during deceleration in the working gas of the IC. The algorithm for precise pulse height measurement is widely accepted for about 50 y in experimental nuclear physics and it is implemented in a variety of commercially available electronic modules. In a spectroscopy amplifier the pulse undergoes first differentiation, and then the result is integrated by a shaping filter in order to improve the SNR. The peak value of the shaped pulse is measured with the help of an ADC and the numerical value is transferred to the PC, where the desired pulse height distributions can be accumulated and displayed on demand.

DSP approach

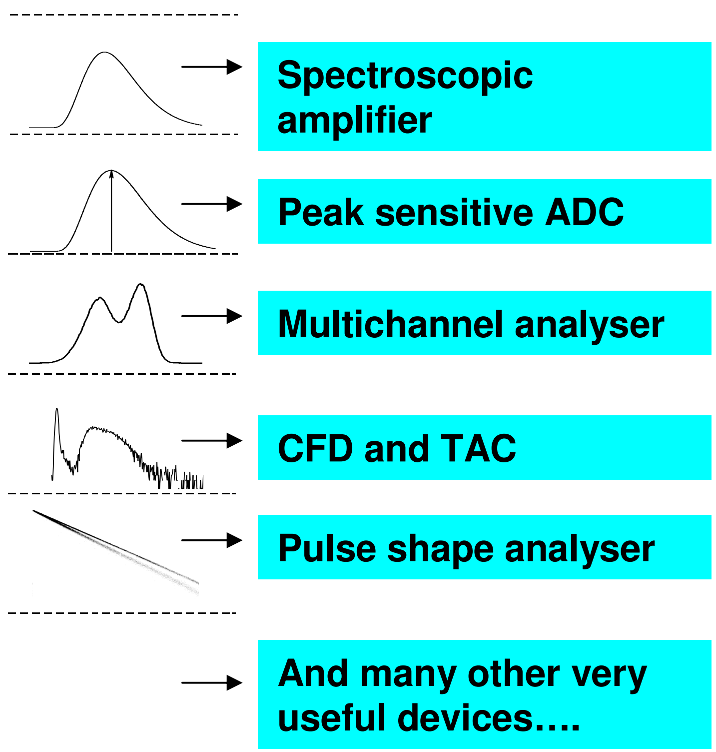
The DSP approach uses a single waveform digitizer module and a variety of software to suit different experimental needs.



Continuous and discrete form relations between the detector current pulse (I_n) and the preamplifier output signal (V_k) are as follows:

$$V(t) = \int_0^\infty I(\tau) h(t-\tau) d\tau$$

$$V(k\Delta) = \sum_{n=0}^{\infty} I(n\Delta) h((k-n)\Delta) \Rightarrow V_k = \sum_{n=0}^{\infty} I_n h_{kn}$$



Basic maths for spectroscopy amplifier

$$V^{Out}(t) = \int_0^t \frac{dV^{In}(\tau)}{d\tau} W(t-\tau)\,d\tau = V^{In}(t)W(0) - \int_0^t V^{In}(\tau)\frac{dW(t-\tau)}{d\tau}\,d\tau \longrightarrow$$ **The differentiating formula**

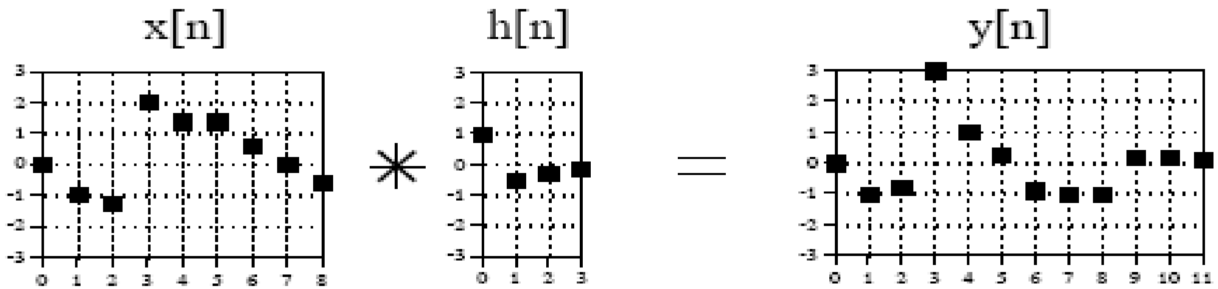
$$W(\tau) = \exp -\frac{\tau}{A}, \quad \frac{dW}{d\tau} = \frac{1}{A} \times \exp(-\frac{\tau}{A}) \longrightarrow$$ **The kernel function describing a signal passing through an RC circuit**

Sampling is the way to convert continuous signal to discrete

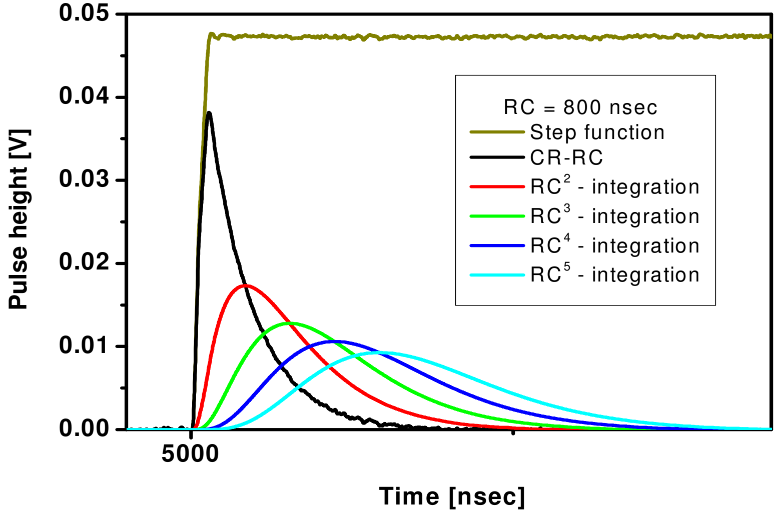
$$V_k^{In} = V^{In}(k\Delta), \quad V_k^{Out} = V^{Out}(k\Delta) \text{ и } V_k^{Int} = \int_0^\infty V^{In}(\tau)\frac{dW(k\Delta-\tau)}{d\tau}\,d\tau,$$

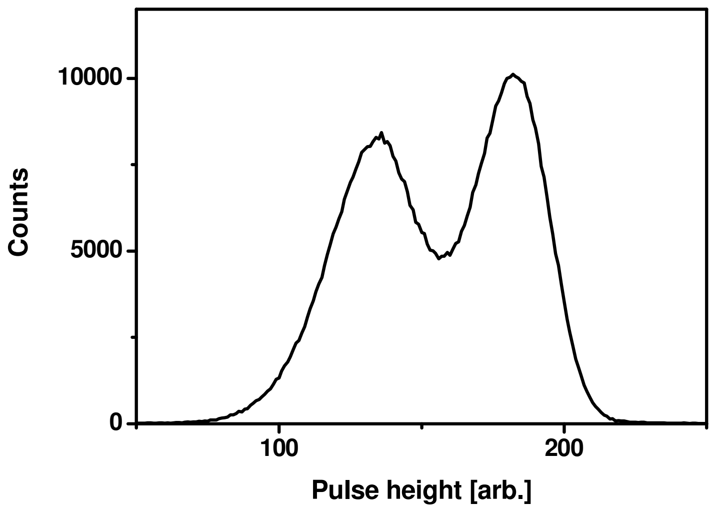
$$V_{k+1}^{Int} = V_k^{Int} \times A + V_k^{In}, \qquad V_k^{Out} = V_k^{Int} - V_k^{In}.$$

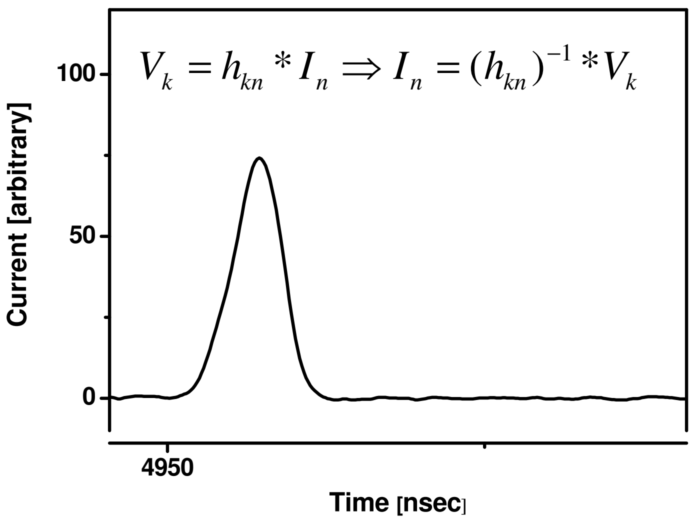
Matrix representation of discrete signals and equations

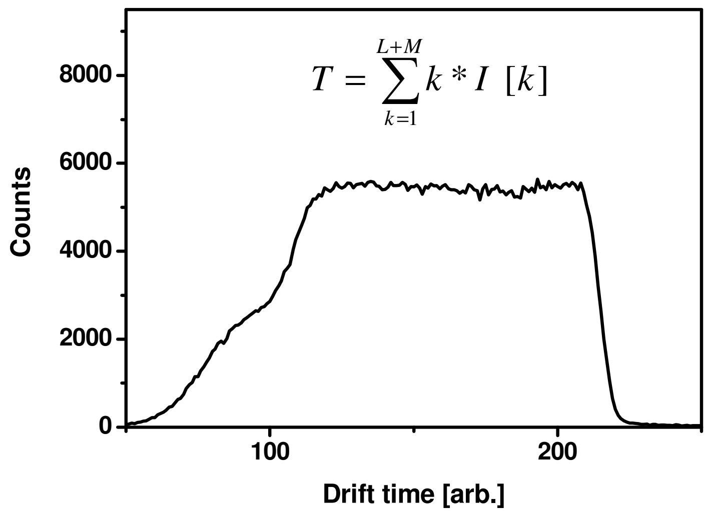


Fission fragment pulse processing

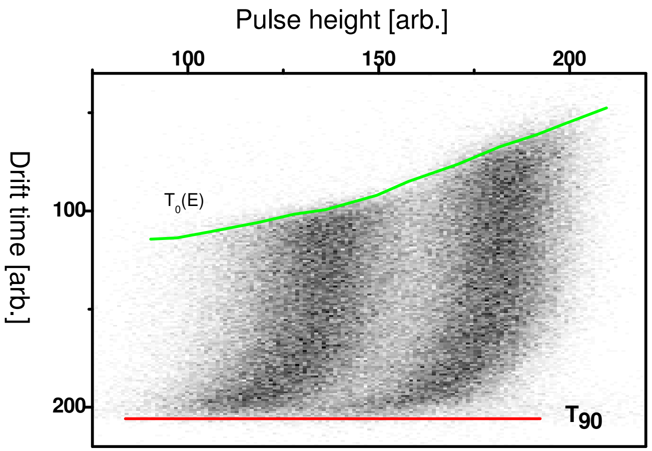


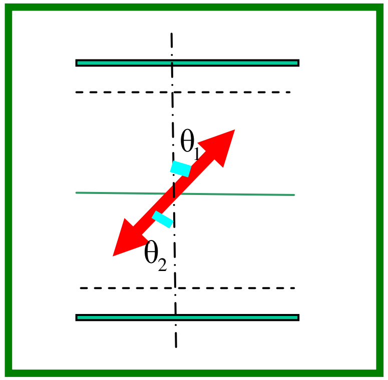


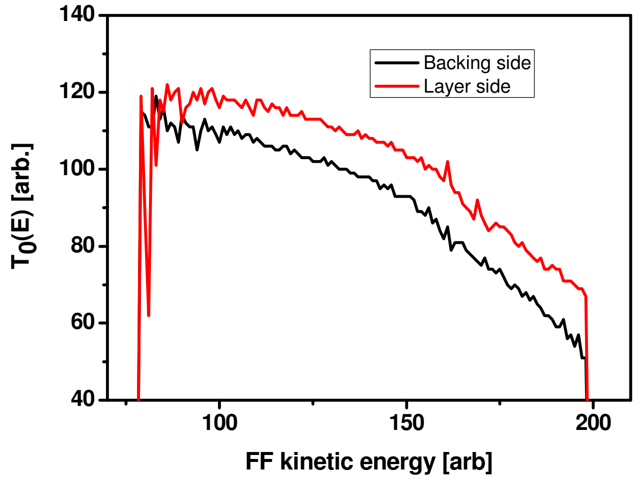


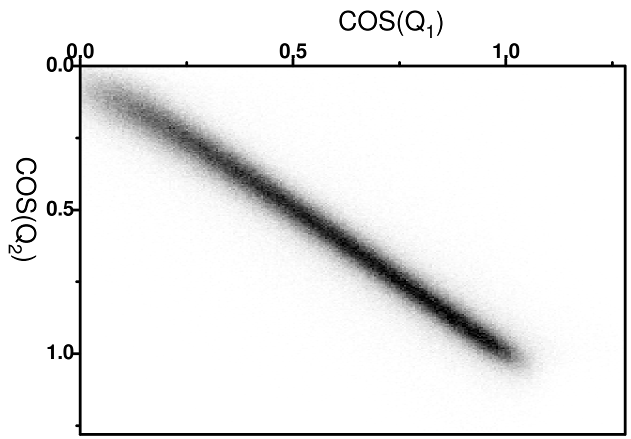


FF angle determination









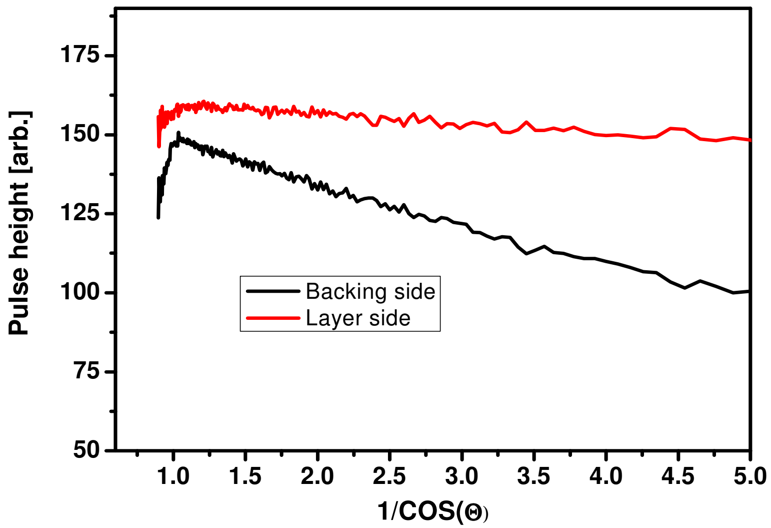
$$T_{90} = \frac{D + 0.5 * d}{W},$$ where D is the C - G and d is the G - A distances; W is the drift velocity

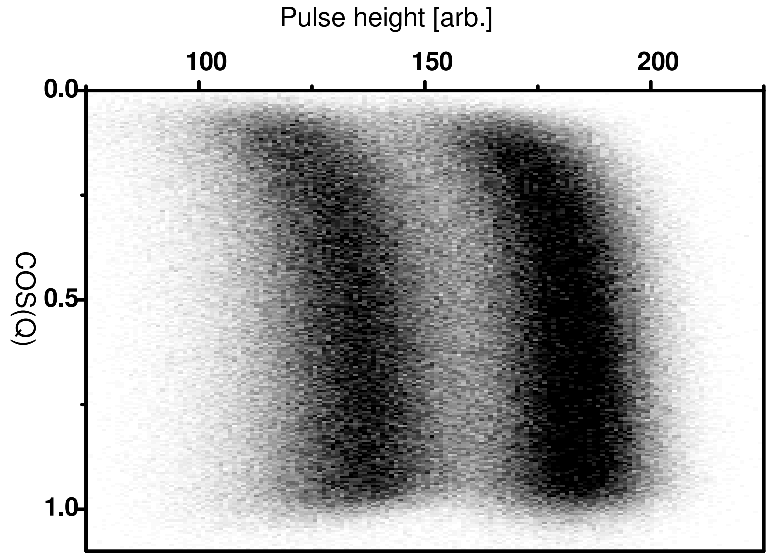
$$T_{90} - T(E) = (T_{90} - T_0(E)) * \cos(\Theta),$$ T_{90}, T_0 - the drift time for 90^o and 0^0 FF

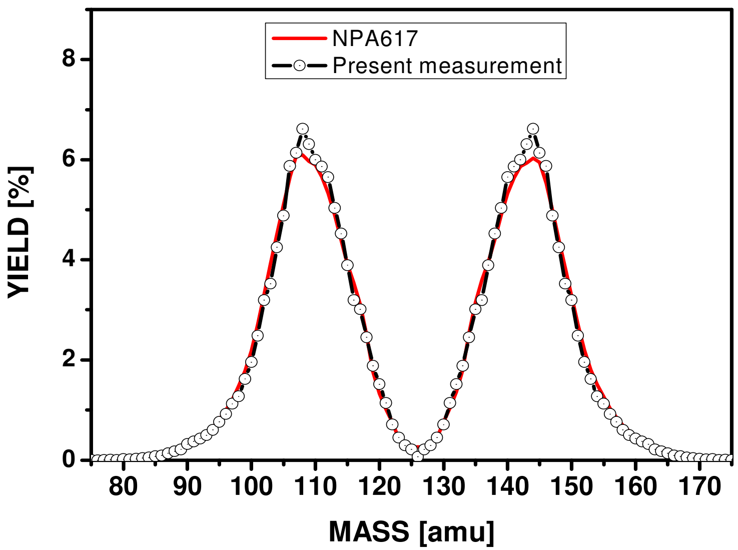
$$P^C = \frac{P^O * T_{90}}{T_{90} + \sigma * T},$$ P^C *and* P^O are corrected and original pulse height values

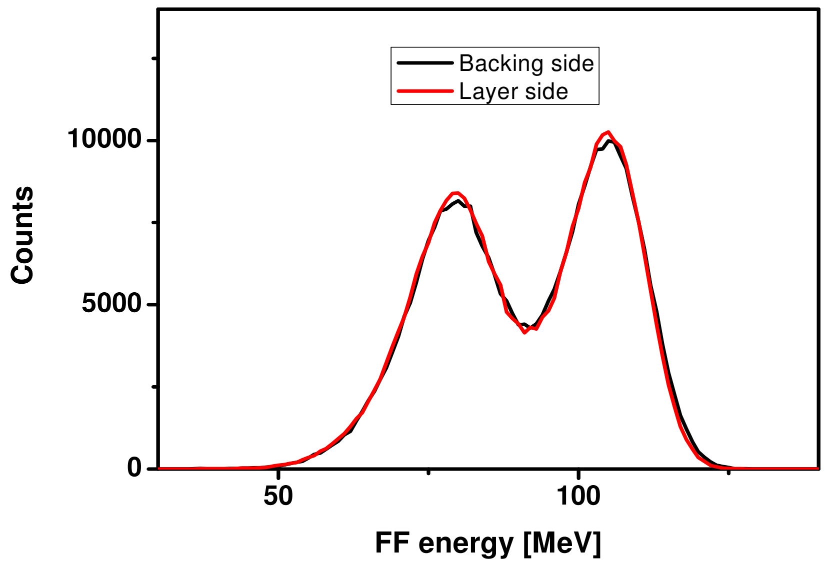
σ is the grid inefficiency factor

FF's energy loss correction

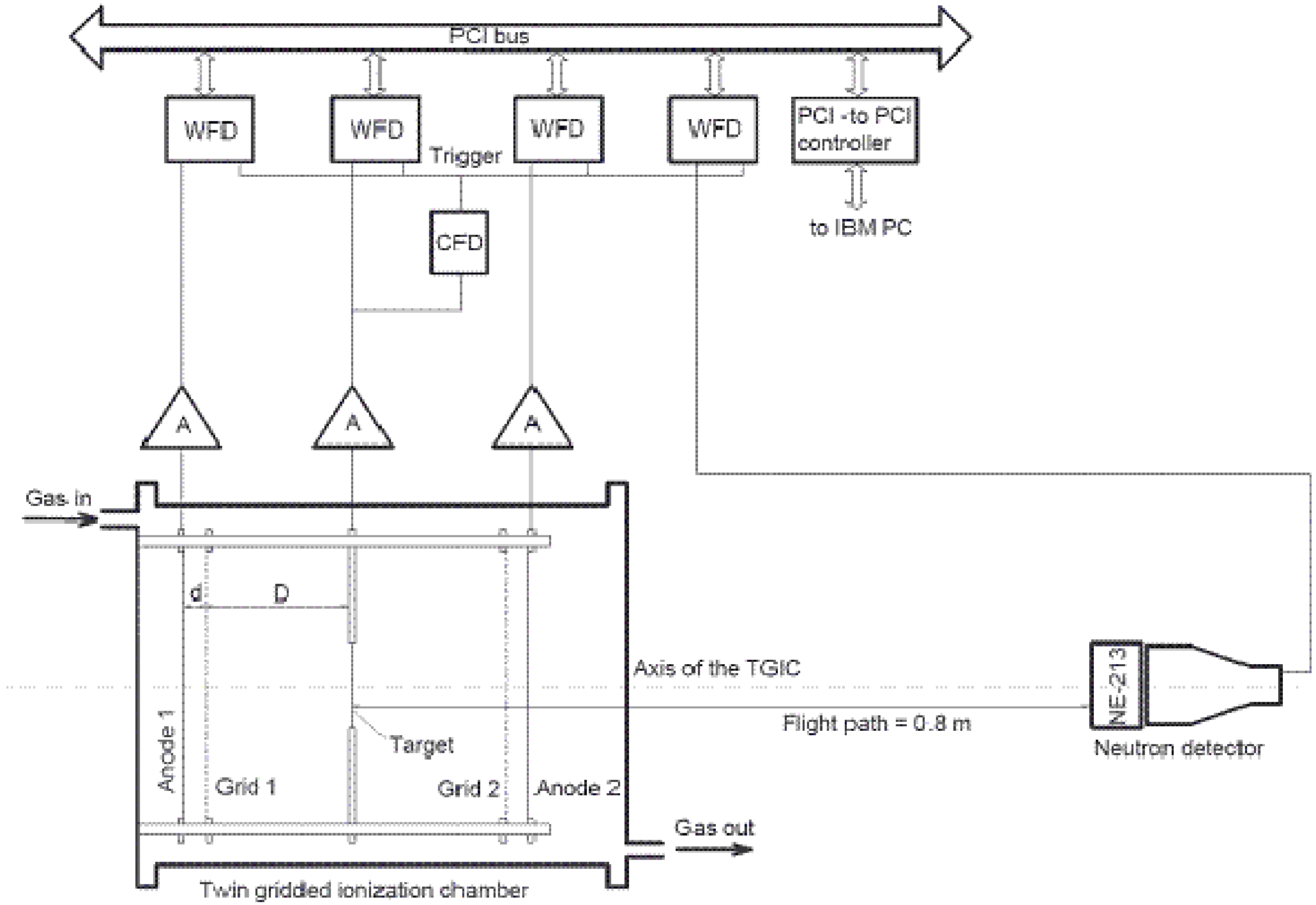








Data acquisition system



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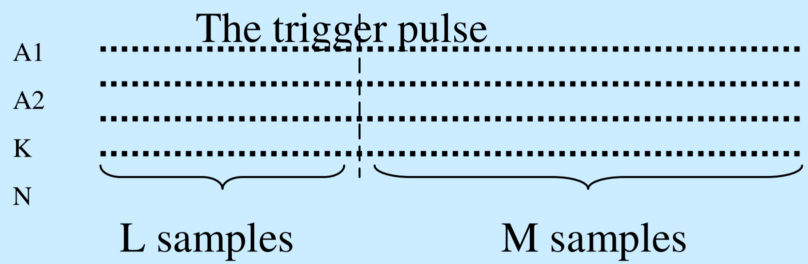

Waveforms sampled with 100 MHz WFD 12 bit amplitude resolution

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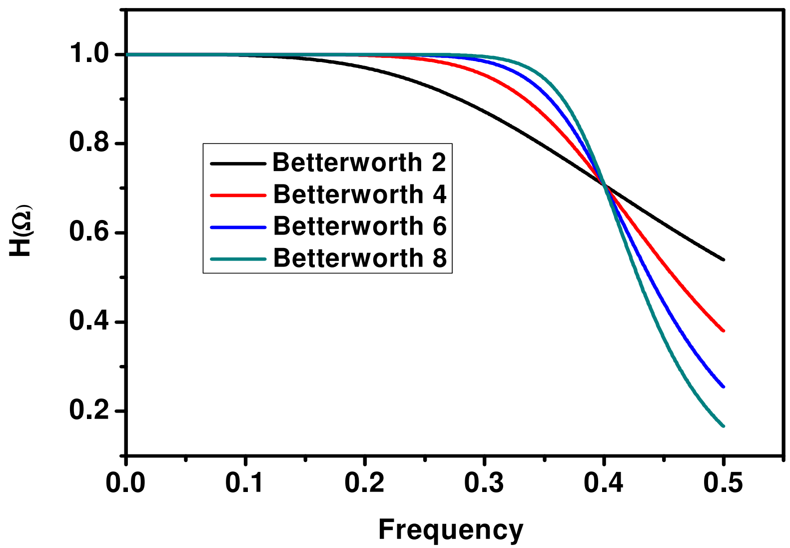
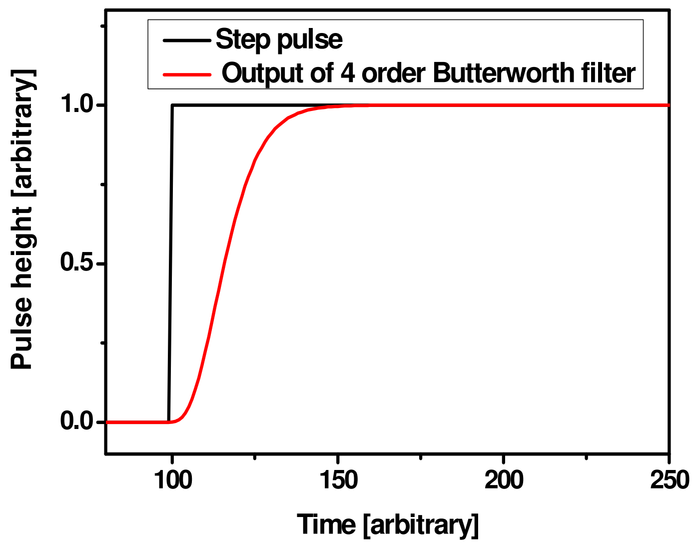
Shannon sampling frequency

The Butterworth filter of 2,4,6,8-th order

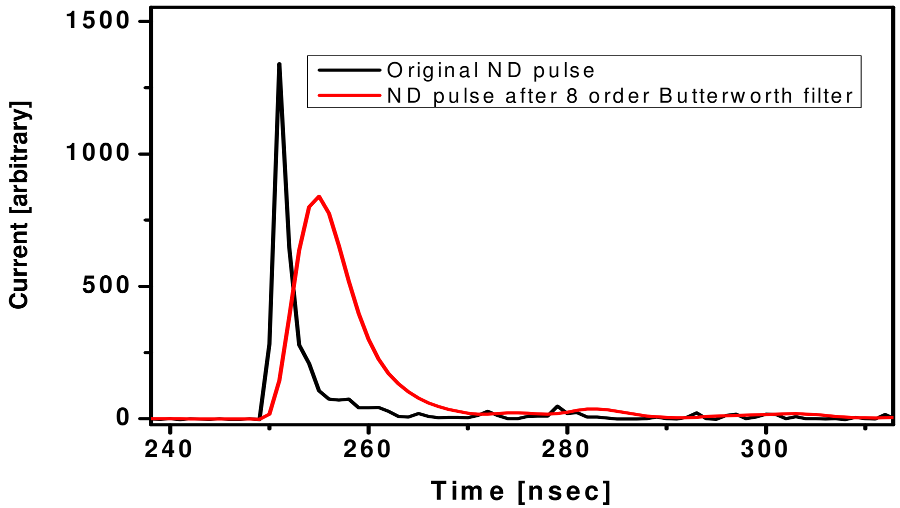
First the DSP signals are passed trough the 8th order Butterworth filter in order to comply to the Nyquist criterion

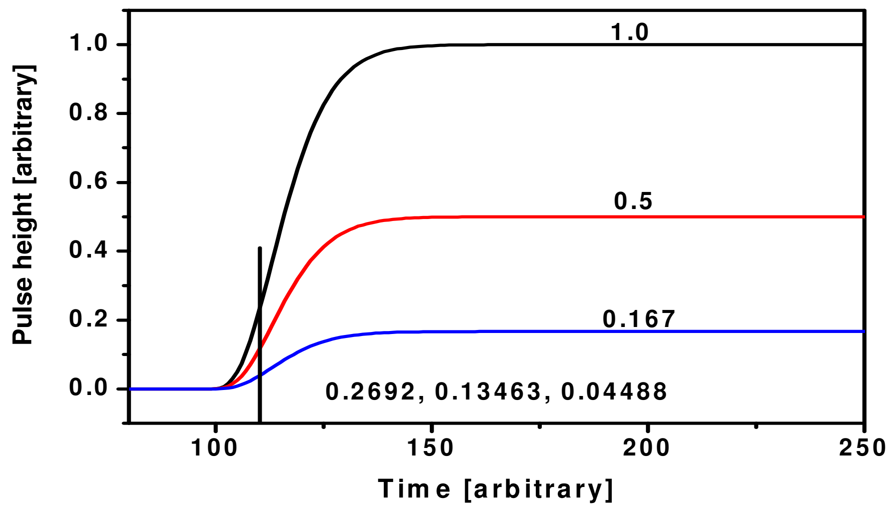




The band-limited continuous-time signal, with bandwidth of B Hz can be recovered from its samples provided that the sampling speed Fs > 2B samples/sec. Thus, to assure a correct signal analysis the bandwidth of the signal should be limited to 50 MHz.

PFN time-of-flight spectroscopy





The left hand figure illustrates how the ND signals are transformed after passing the Butterworth filter. Properly chosen cut-off frequency of the filter guarantees the same rise time for all ND pulses. The right hand figure illustrates how the CFTM algorithm works with pulses having the same rise time, but different pulse heights. Signals are passing the constant fraction of their pulse height at the same time instant. So the simplest digital realisation of the CFTM is to get time instant at the constant fraction of the pulse height

$$B_4(t,\tau) = \frac{1}{\tau * 3!}\left(\frac{t}{\tau}\right)^3 * \exp(-\frac{t}{\tau}) \longrightarrow$$ **4-th order Butterworth filter**

Interpolation formulas:

$$f(t_k + \Delta) = f(t_k) + \Delta * (f(t_{k+1}) - f(t_k)) \longrightarrow$$ **Linear**

$$f(t_k + \Delta) = a * (t_k + \Delta)^2 + b * (t_k + \Delta) + c$$

$$a = (f(t_{k+2}) - 2f(t_k) + f(t_k))/2 \longrightarrow$$ **Parabola**

$$b = f(t_{k+1}) - f(t_k) - a * (2k + 1)$$

$$c = f(t_k) - b * k - a * k^2$$

$$f(t_k + \Delta) = a * (t_k + \Delta)^3 + b * (t_k + \Delta)^2 + c * (t_k + \Delta) + d$$

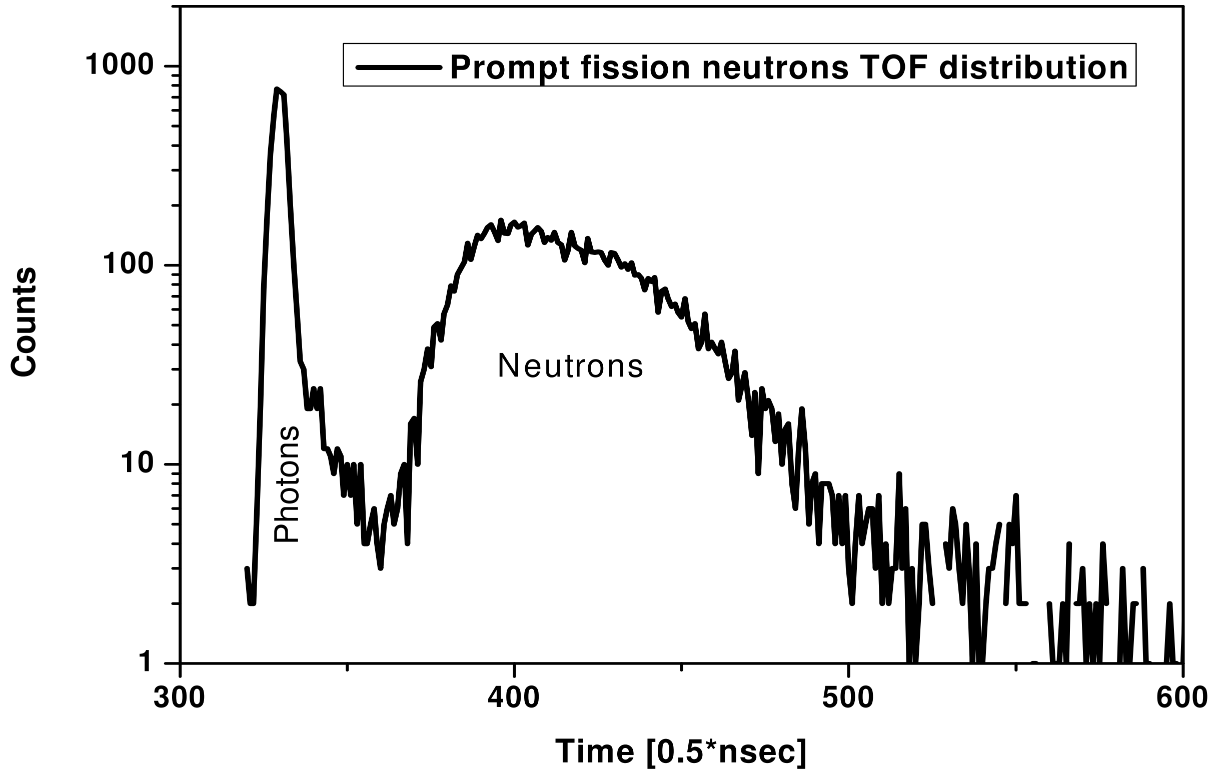
$$a = \frac{f(t_{k+2}) - 3f(t_{k+1}) + 3f(t_k) - f(t_{k-1})}{(k+2)^3 - 3(k+1)^3 + 3k^3 - (k-1)^3}$$

$$b = \frac{f(t_{k+2}) - 2f(t_{k+1}) + f(t_k) - a * ((k+2)^3 - 2 * (k+1)^3 + k^3)}{2} \longrightarrow$$ **Cubic parabola**

$$c = f(t_{k+2}) - f(t_{k+1}) - (2k + 3) * b - a * ((k+2)^3 - (k+1)^3)$$

$$d = f(t_{k+2}) - c * (k+2) - b * (k+2)^2 - a * (k+2)^3$$

Prompt fission neutron TOF distribution obtained using the developed CFTM algorithm with cubic parabola interpolation. The flight path is 0.8 m and the FWHM measured for the photon peak is 1.7 nsec



The pulse shape separation principle

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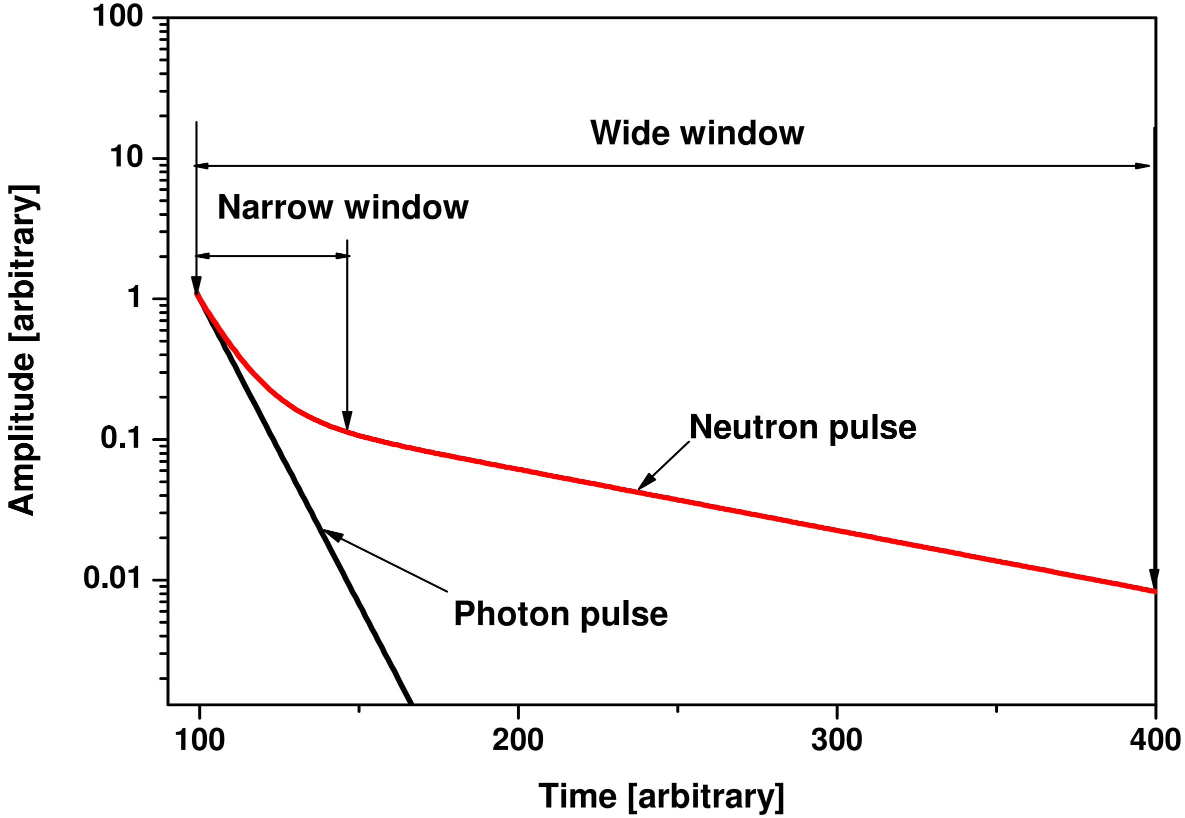
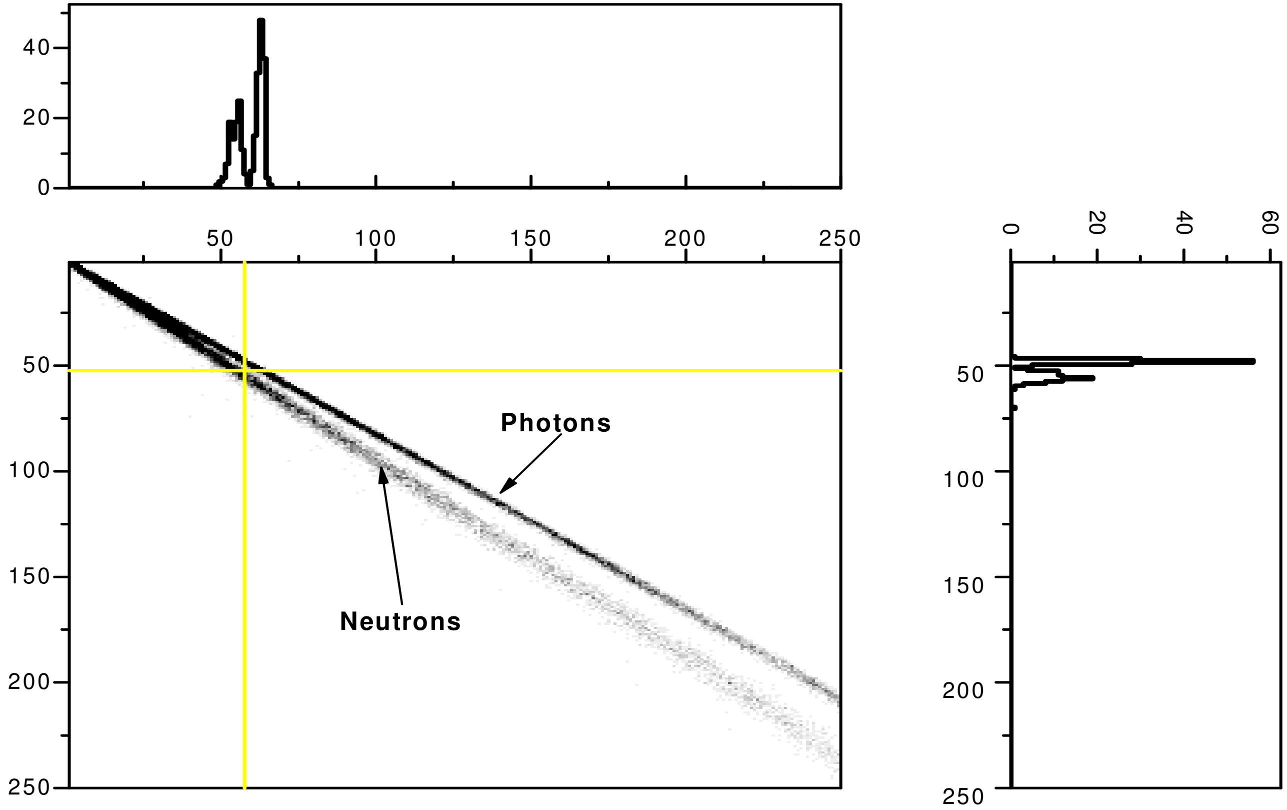


$$x = \int_0^{T_1} I(t)dt, \quad y = \int_0^{T_2} I(t)dt, \quad \text{where } I(t) \text{ - is i-th ND current waveform}$$

Neutron – Gamma separation

Illustration of the neutron – gamma pulse shape separation principle.



Conclusions

- Digital signal processing (DSP) algorithms for FF and PFN spectroscopy have been developed
- The algorithms are applied in an experiment with 252Cf(SF), using a fully digital acquisition system with four 12bit/100 MHz WFD.
- DSP algorithms are developed as recursive procedures performing the signal processing, similar to those available in various nuclear electronic modules such as constant fraction discriminator (CFD), pulse shape discriminator (PSD), peak-sensitive analogue-to-digital converter (pADC), pulse shaping amplifier (PSA).
- To measure the angle between FF and the cathode plane normal of the GTIC a new algorithm is developed, having advantage over the traditional analogue pulse processing schemes.
- Algorithms are tested by comparison of the results of the DSP data analysis for ^{252}Cf(SF) with the data available from literature, demonstrating a superior quality of the DSP technique over traditional analogue signal processing.

Thank you !