Noise lower limit for Cluster Counting front-end electronics

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Update on detection efficiency of cluster counting algorithms using Garfield simulated data sets

Outline

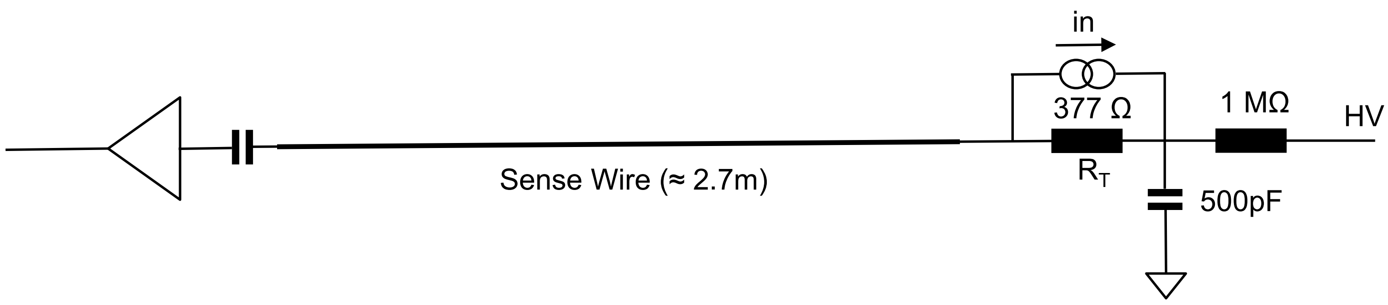
- *Lower limit for front-end noise in Cluster Counting scenario*
- *Efficiency estimation of Cluster Counting algorithms based on GARFIELD simulation*
- *Possible implementation of on-detector/off-detector interconnections*
- *Power supply requirements estimation*

Noise lower limit for Cluster Counting front-end electronics

Cluster Counting technique can improve particles identification in SuperB DCH

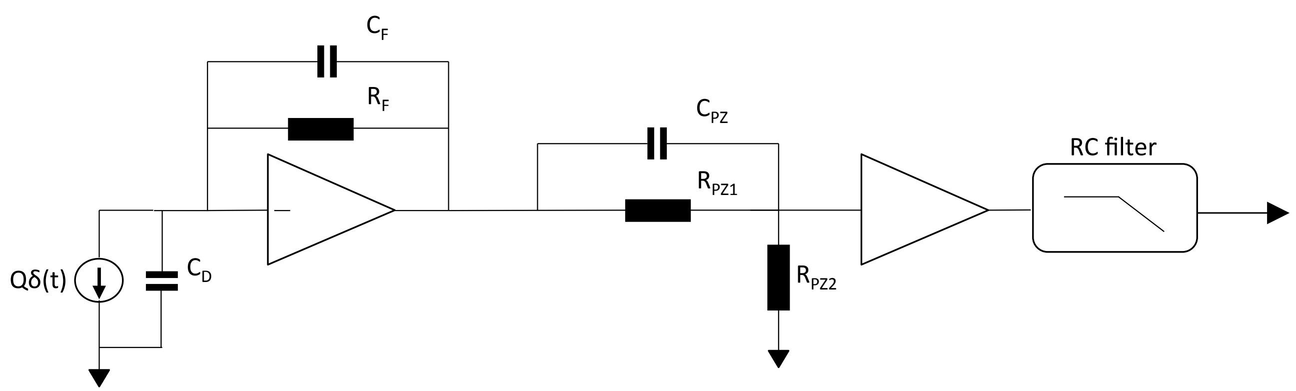
- *The technique is based on primary ionization cluster detection and requires:*
  - *Slow drift velocity gas mixtures (es 90% He – 10% Iso)*
  - *Quite high gas gain (> 10^5)*
  - *Fast amplifiers*
  - *Fast sampling devices (> 1GSPS)*
  - *Correct termination of the sense wire (to avoid signal reflection)*
- *Assuming the chamber sense wire as a lossless transmission line and discarding external noise pick-up the main noise sources are the termination resistor and the preamplifier intrinsic noise*
- *At the moment there is no a definitive decision about the readout chain , nevertheless termination resistor noise contribution can be evaluated by means of the Equivalent Noise Charge (ENC) contribution of a typical readout chain.*

Termination resistor ENC contribution evaluation



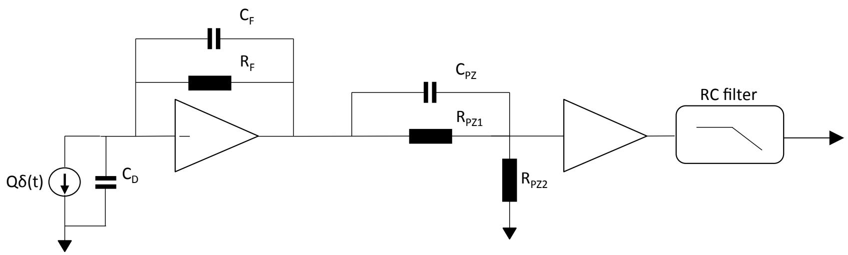
ENC = input signal magnitude that generates a preamplifier output signal equal to the output rms noise

- *Termination resistor noise contribution can be evaluated both in frequency domain (direct transfer function calculation) and in time domain (using system weighting function)*
- *Generic front-end chain made of preamplifier, pole-zero cancellation network and filter has been used*



Termination resistor ENC contribution evaluation – direct transfer function calculation (I)

$$\frac{R_F}{1+sR_FC_F} \qquad \frac{1+sR_{PZ1}C_{PZ}}{1+sR_{PZ}C_{PZ}} \qquad \frac{1}{1+sR_CC_C}$$



$$\begin{cases} H(s) = \dfrac{R_{PZ2}}{R_{PZ1}+R_{PZ2}} \dfrac{R_F}{1+sR_FC_F} \dfrac{1+sR_{PZ1}C_{PZ}}{1+sR_{PZ}C_{PZ}} \dfrac{1}{1+sR_CC_C} \\ R_{PZ} = \dfrac{R_{PZ1}R_{PZ2}}{R_{PZ1}+R_{PZ2}} \end{cases}$$

Assuming $R_FC_F = R_{PZ1}C_{PZ} \longrightarrow H(s) = \dfrac{R_{PZ2}R_F}{R_{PZ1}+R_{PZ2}} \dfrac{1}{1+sR_{PZ}C_{PZ}} \dfrac{1}{1+sR_CC_C}$

Choosing low-pass filter time constant $R_{PZ}C_{PZ} = R_CC_C = \tau \longrightarrow H(s) = \alpha\tau \cdot \dfrac{1}{(1+s\tau)^2}$

Where $\alpha\tau = \dfrac{R_{PZ2}R_F}{R_{PZ1}+R_{PZ2}} = \dfrac{R_{PZ2}R_{PZ1}}{R_{PZ1}+R_{PZ2}} \dfrac{1}{R_{PZ1}} R_F \dfrac{C_{PZ}}{C_{PZ}} = \dfrac{R_F}{R_{PZ}C_{PZ}}\tau$

s=iω $\longrightarrow T(j\omega) = \alpha\tau \cdot \dfrac{1}{(1+j\omega\tau)^2}$

RMS output noise voltage due to termination resistor (noiseless preamplifier) $\longrightarrow V_n^2(rms) = i_n^2\alpha^2\tau^2 \displaystyle\int_0^\infty |T(j\omega)|^2 df \quad \left[i_n = \sqrt{\dfrac{4KT}{R_T}} \right]$

Termination resistor ENC contribution evaluation – direct transfer function calculation (II)

Changing the integration variable → $z = \omega\tau = 2\pi f \tau$ *and extending the integration range to - ∞*

$$V_n^2(rms) = i_n^2 \alpha^2 \tau^2 \frac{1}{4\pi\tau} \boxed{\int_{-\infty}^{\infty} \frac{dz}{(1+z^2)^2}} \rightarrow \boxed{\frac{\pi}{2}}$$

RMS output noise voltage due to termination resistor → $V_n^2(rms) = \frac{4KT}{R_T}\frac{1}{4\pi\tau}\tau^2\alpha^2\frac{\pi}{2} = \frac{4KT}{R_T}\frac{1}{8}\tau\alpha^2$

H(s) Laplace antitransform → $\mathcal{L}^{-1}(\alpha\tau\frac{1}{\tau^2}\frac{1}{(1/\tau+s)^2}) = \alpha\frac{t}{\tau}e^{-t/\tau}$

To evaluate system ENC the square root of rms output voltage must be normalized to the peak output voltage generated by a unit test pulse δ (t) → $V_{peak} = \alpha \cdot \frac{1}{e}$

Assuming a peaking time ≈ 3 ns the ENC due to 377 Ω termination resistor is

$$ENC = e \cdot \sqrt{\frac{kT}{R_T}\frac{1}{2}} \cdot \tau \simeq \ 0.35\ fC \simeq \ 2200\ erms$$

Termination resistor ENC contribution evaluation – time domain calculation (I)

System output noise variance can be estimated starting with noise spectral density and system time response as shown by Radeka thanks to the Parseval's theorem*

Parseval's theorem $\longrightarrow \int_{-\infty}^{\infty} h^2(t)dt = \frac{1}{2\pi}\int_{-\infty}^{\infty}|H(j\omega)|^2 d\omega = 2\int_{0}^{\infty}|H(2\pi jf)|^2 df$

$$\sigma^2 = \frac{1}{2}W_0\int_{-\infty}^{\infty} h^2(t)dt$$

W_0 = input white noise (thermal noise due to resistor connected to the sense wire $\sqrt{\frac{4KT}{R_T}}$ *)*

h(t) = system impulse response ($\mathcal{L}^{-1}(\alpha\tau\frac{1}{\tau^2}\frac{1}{(1/\tau+s)^2}) = \alpha\frac{t}{\tau}e^{-t/\tau}$ *)*

Evaluating the system impulse response for t ≥ 0 $\longrightarrow \sigma^2 = \frac{1}{2}W_0\int_{0}^{\infty}\alpha^2\left(\frac{t}{\tau}\right)^2 e^{-2\frac{t}{\tau}}dt = \frac{1}{2}\frac{4KT}{R_T}\frac{\alpha^2\tau}{4}$

Normalizing to the peak voltage $\longrightarrow ENC^2 = \frac{1}{2}\frac{4kT}{R_T}\frac{e^2}{4}\tau = \frac{1}{2}\frac{kT}{R_T}e^2\tau$ *As shown shown before*

ENC decrease for small peaking times but ……

* *Low Noise Techniques in Detector - Radeka -* Ann. Rev. Nud. Parl. Sci. 1988. 38: 217-77

… the voltage noise contribution

More generally there are 2 basic noise sources: input noise current (i_n) and input noise voltage (v_n)

Time domain → $$ENC^2 = i_n^2 \tau_S F_i + C^2 v_n^2 \frac{F_v}{\tau_S}$$

F_i F_v = form factors (shape of the pulse)
Ts = peaking time
i_n, v_n = noise input current and voltage
C = total input capacitance (detector + preamp + stray)

Termination resistor = noise current source → $$ENC_P^2 = i_n^2 \tau_S F_i$$

F_i = dimensionless parameter function of the CR = nRC filter order → $$F_i = \frac{1}{2T_S} \int_{-\infty}^{\infty} |W(t)|^2 dt$$

Fi (time invariant filters) = normalized system input response
T_S = system shaping factor

General solution for CR-nRC unipolar shaping factor can be found in literature
Es : Blum - Riegler - Rolandi Particle Detection with drift Chamber →

$$F_i = \frac{1}{2}\left(\frac{e}{2n}\right)^{2n}(2n-1)!$$

$$F_v = \frac{1}{2}\left(\frac{e}{2n}\right)^{2n} n^2 (2n-2)!$$

Parallel and series noise contribution

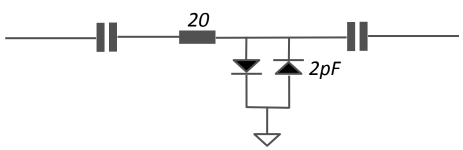
$$ENC_n^2 = i_n^2 \tau_S F_i + v_n^2 F_v \frac{C_T^2}{\tau_S}$$

C_T is the sum of capacitance at the preamplifier input

$$F_i = \frac{1}{2}\left(\frac{e}{2n}\right)^{2n}(2n-1)!$$

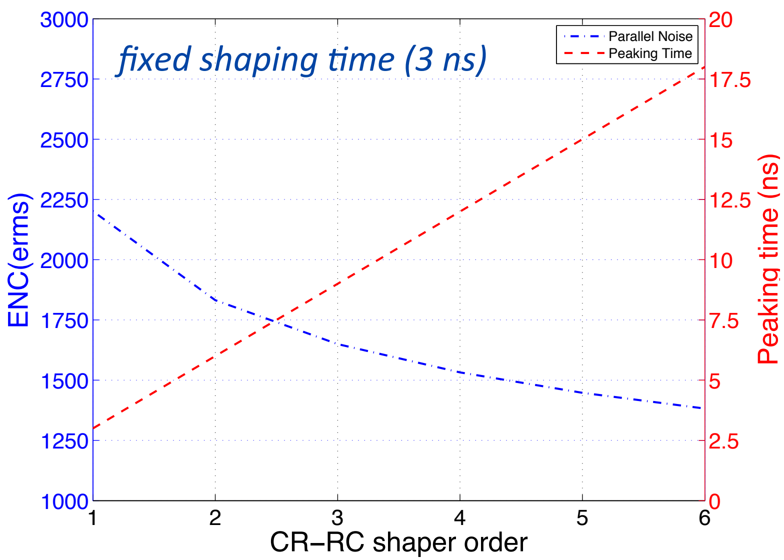
$$F_v = \frac{1}{2}\left(\frac{e}{2n}\right)^{2n} n^2 (2n-2)!$$

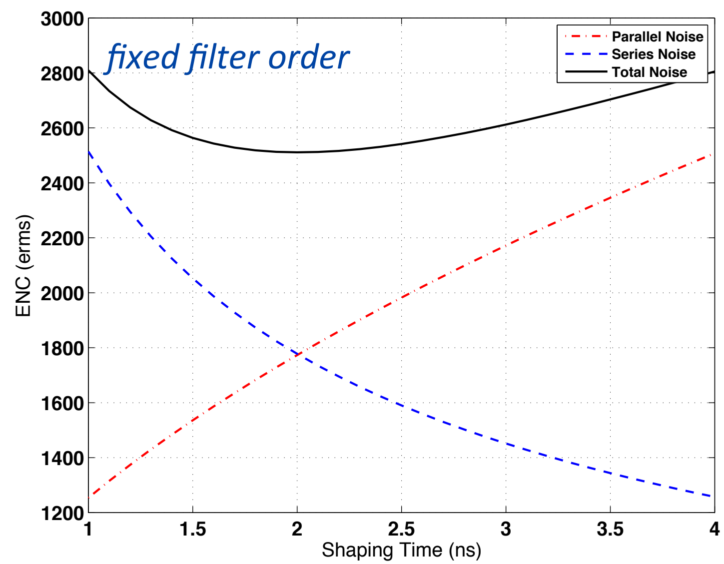
To simplify calculation only preamplifier protection circuit against discharges will be considered



+ 21 pF (wire parasitic capacitance) and $v_n^2 = 4KTR$

noiseless preamplifier





Conclusions (I)

- Wire termination resistor is one of the main noise sources of the system (≈ 2200 erms @ 3ns peaking time)
- An equal amount of noise can be estimated for a high bandwidth preamplifier thus the system total amount of noise is about 3100 erms ≈ 0.5 fC
  ES: LNF proto2 gain ≈ 8 mV/fC (@ 250 MH BW) → Noise ≈ 4 mV rms (≈ 26 mV pp)
- Single electron cluster charge collected on the wire @ nominal gas gain = 10^5

$$10^5 \times 0.5 \times 0.25 \times 1.6\times10^{-19} \approx 2\ fC \rightarrow 1\ fC$$

0.5: charge division due to termination resistor

0.25: charge collected percentage (approximation)

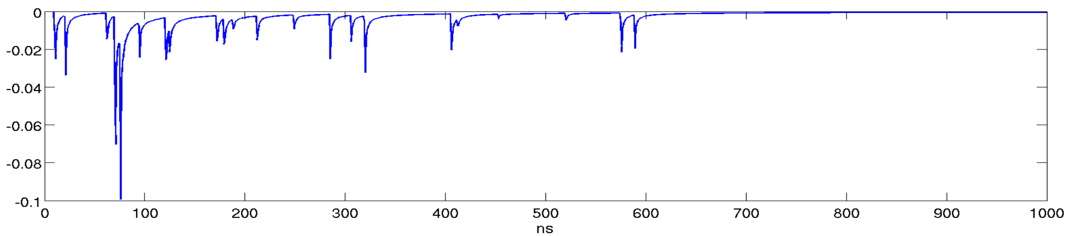
→ 1 fC: gas gain fluctuation (upper limit)

DCH operated @ 10^5 nominal gas gain corresponds to a SNR ≈ 2

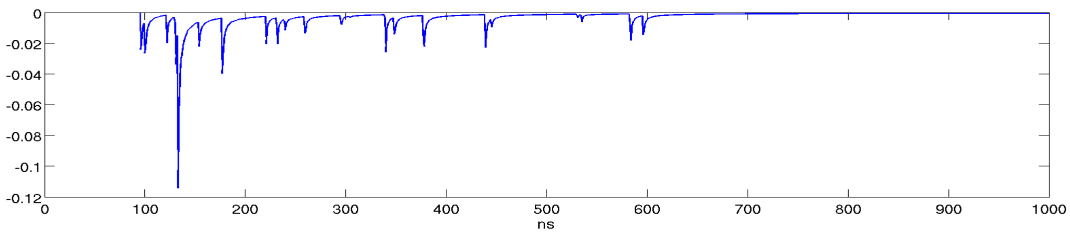
Update on detection efficiency of cluster counting algorithms using Garfield simulated data sets

Remind from Dec 2011 WS: step 1: Garfield Outputs Waveforms samples

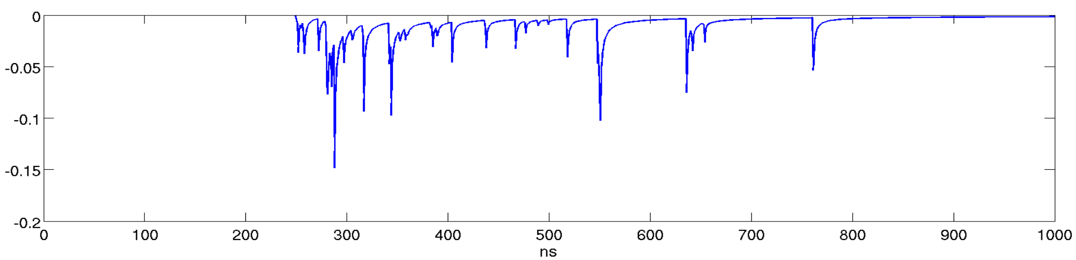
Garfield output (Gas gain $3x10^5$ – preamp gain ≈ 8mV/fC)



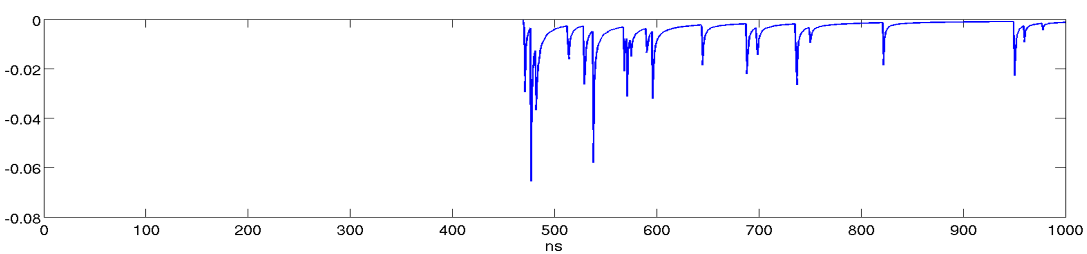
Impact parameter = 0 mm



Impact parameter = 2.5 mm



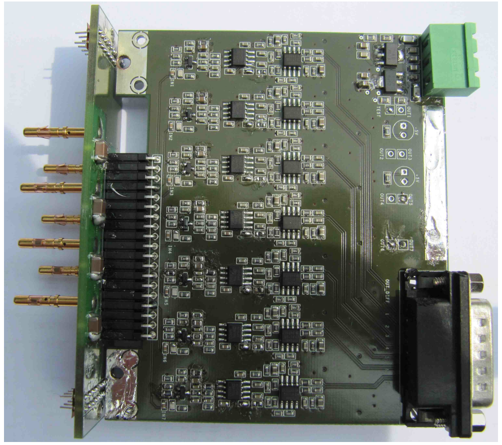
Impact parameter = 5.0 mm

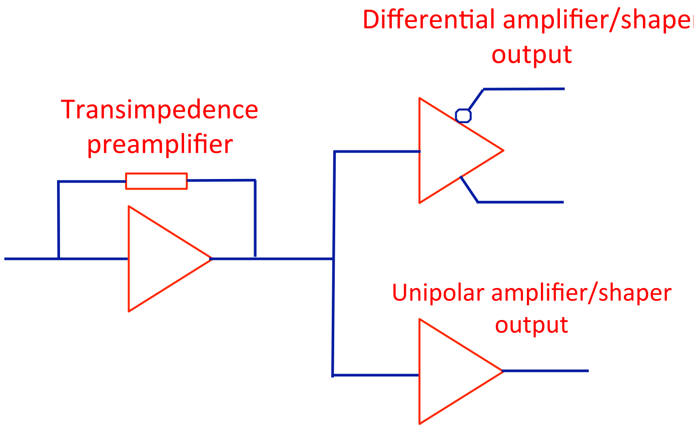


Impact parameter = 7.5 mm

Remind from Dec 2011 WS – step 2: Preamplifier Features

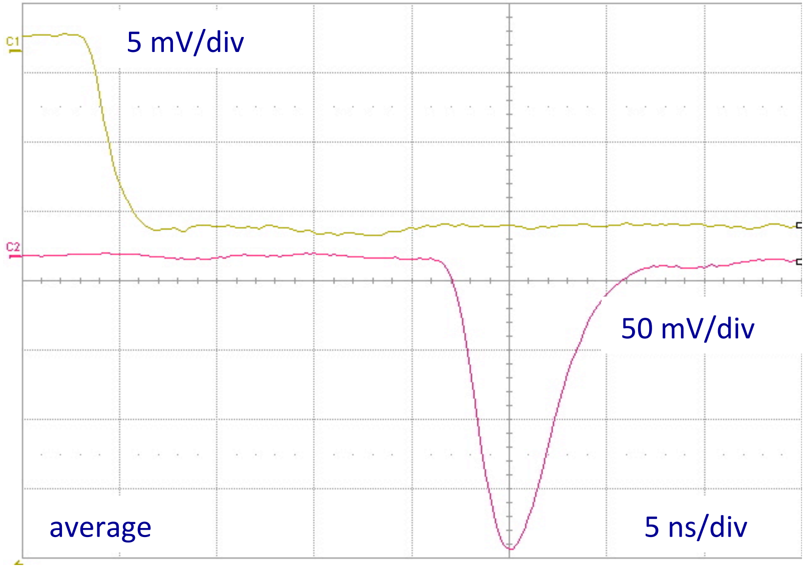
Preamplifier Board





Preamplifier main features

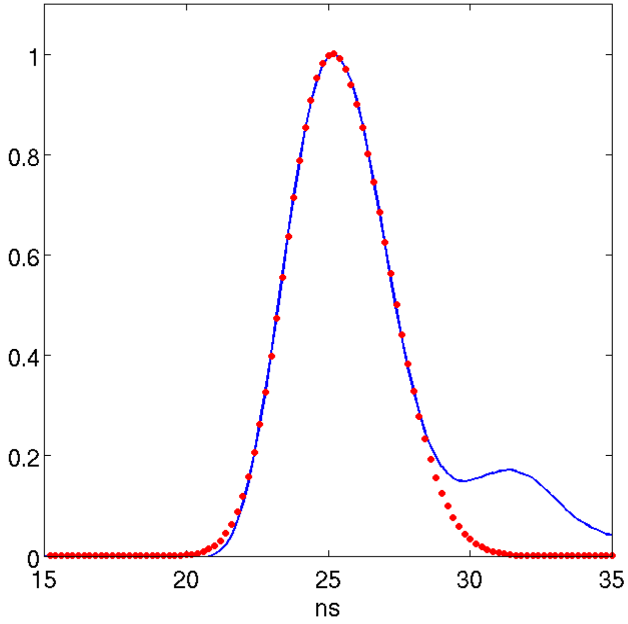
- Number of channels : 7
- Zin ≈ 60 Ω
- Gain ≈ 8.8 mV/fC (C_D= 0 pF)
- Linearity < 1% (1-100 fC)
- Noise ≈ 3000 erms @ 250 MHz BW (C_D=24 pF)
- Rise time ≈ 2.4 ns (C_D=24 pF)
- Fall time ≈ 2.4 ns (C_D=24 pF)
- Unipolar & Differential outputs (50 Ω – 110 Ω)
- Test input
- Supply Voltage : + 7V (310 mA) - 7V (190 mA)
- Power Dissipation : 490 mW/ch



1.8 pF injecting capacitance

Remind from Dec 2011 WS – step 3: Preamplifier Impulse Response Fitting

- Preamplifier board has been connected to the chamber and pulsed through a 1.8 pF internal capacitor.
- Output pulse has been fitted to find out the preamplifier impulse response.



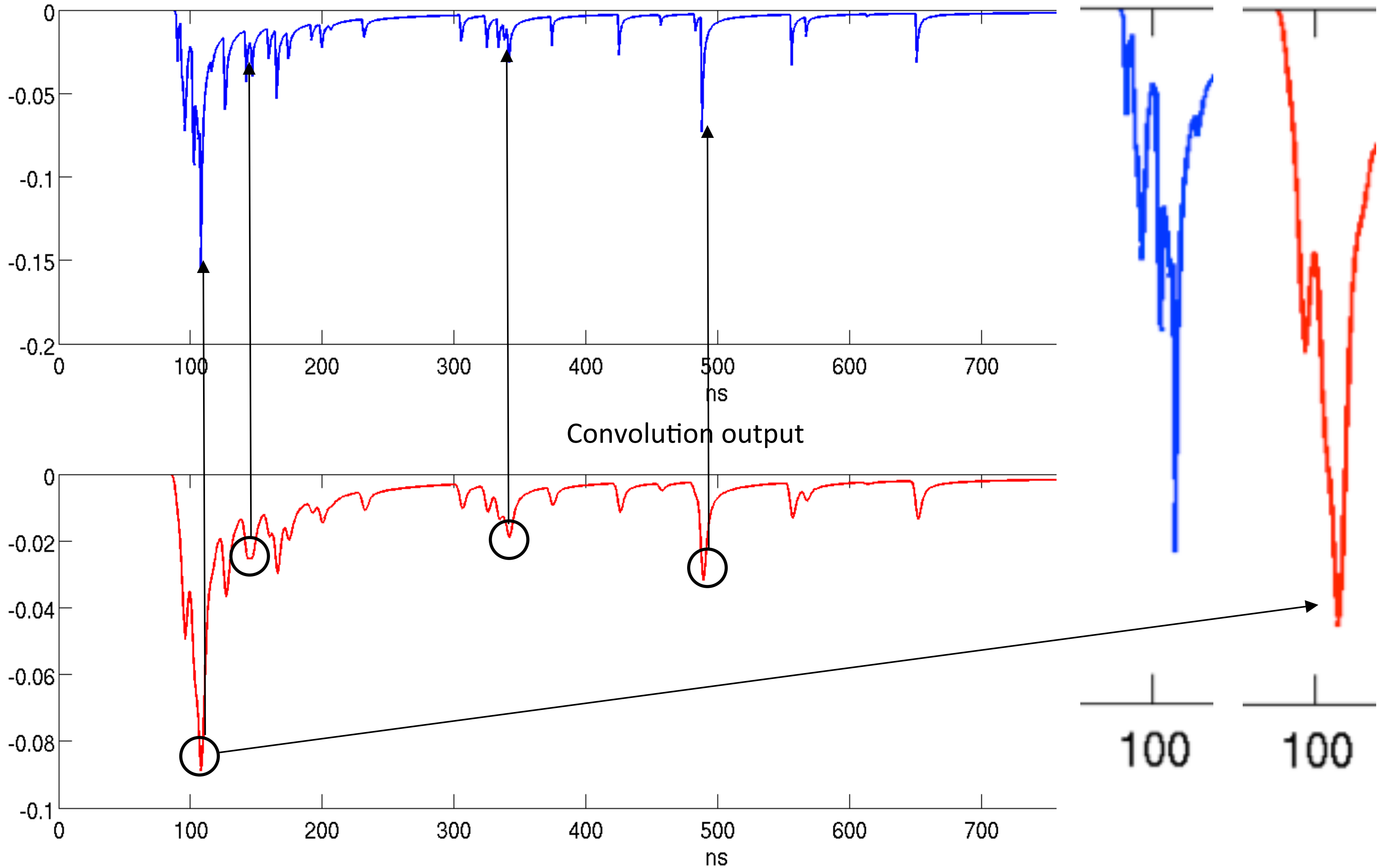
Fitting function:

$$h(t) = a_1\, e^{-\left(\frac{t-b_1}{c_1}\right)^2} + a_2\, e^{-\left(\frac{t-b_2}{c_2}\right)^2}$$

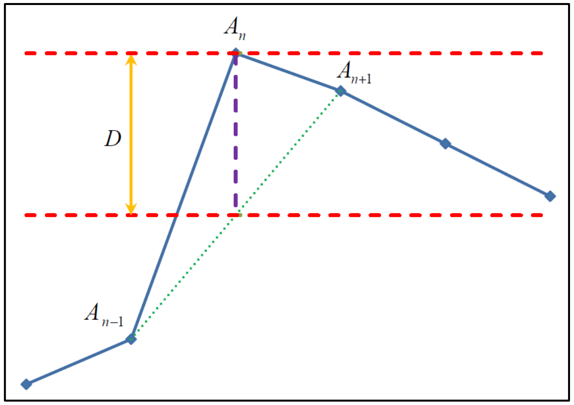
a_1	0.479
b_1	24.367
c_1	1.797
a_2	0.691
b_2	25.983
c_2	2.305

Remind from Dec 2011 WS: Preamplifier response convolution example

Garfield output (Gas gain 3x10^5 – preamp gain ≈ 8mV/fC)



Remind from Dec 2011 WS – step 4: Clusters detecting algorithms

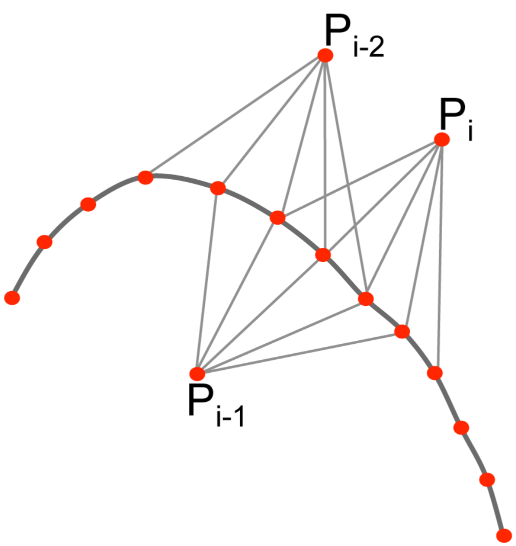


Peak Detecting algorithm

$$D = A_n - \left(\frac{A_{n-1} + A_{n+1}}{2}\right) \geq 3\sigma_d$$ Peak Found Condition

A_{n-1}, A_n, A_{n+1} → consecutive samples
σ_d → rms noise (rms)

Proposed by Luigi Cappelli
on behalf of CLUTIM Group



Slope Detection Algorithm

$$P_i = A_i - \frac{\sum_{n=1}^{4} A_{i-n}}{4}$$

$$C_1 = P_i - P_{i-1} \qquad C_2 = P_{i-1} - P_{i-2} \qquad C_3 = P_i - P_{i-2}$$

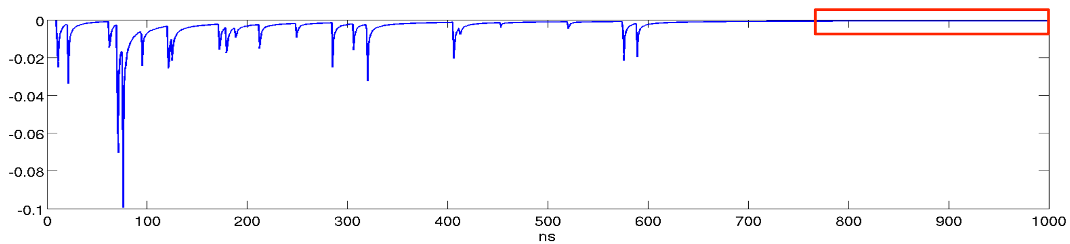
$$(C_1 < -Thr)\ AND\ (C_2 < -Thr)\ AND\ (C_3 < -3Thr)$$

A_i → Data samples Thr → Threshold

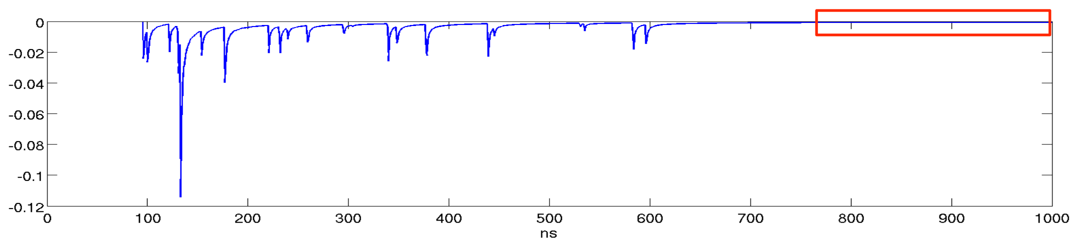
Dead time asserted to avoid extra counting

Remind from Dec 2011 WS – step 5: Noise (rms) evaluation

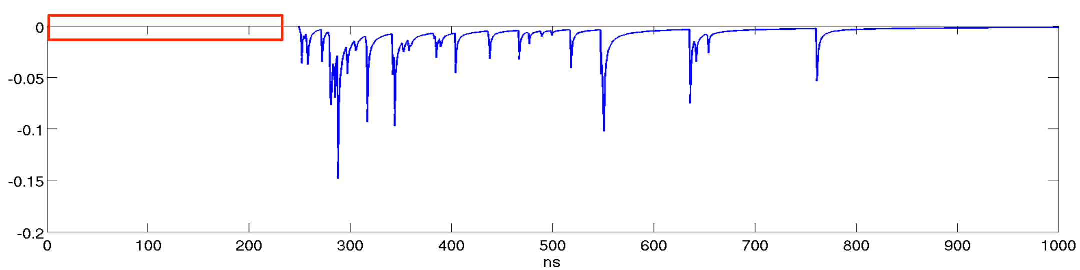
Noise RMS evaluated off-signal



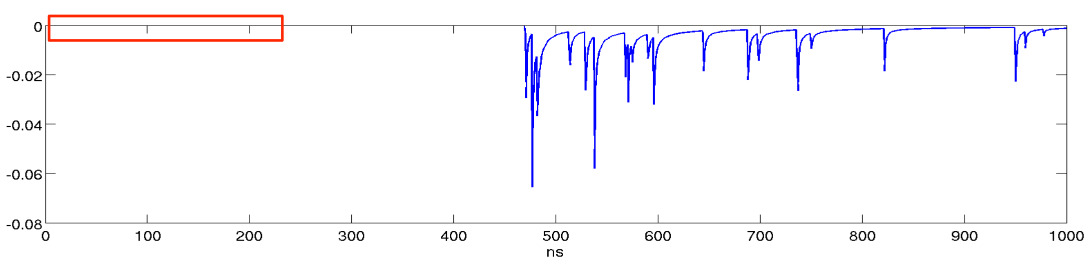
Impact parameter = 0 mm



Impact parameter = 2.5 mm



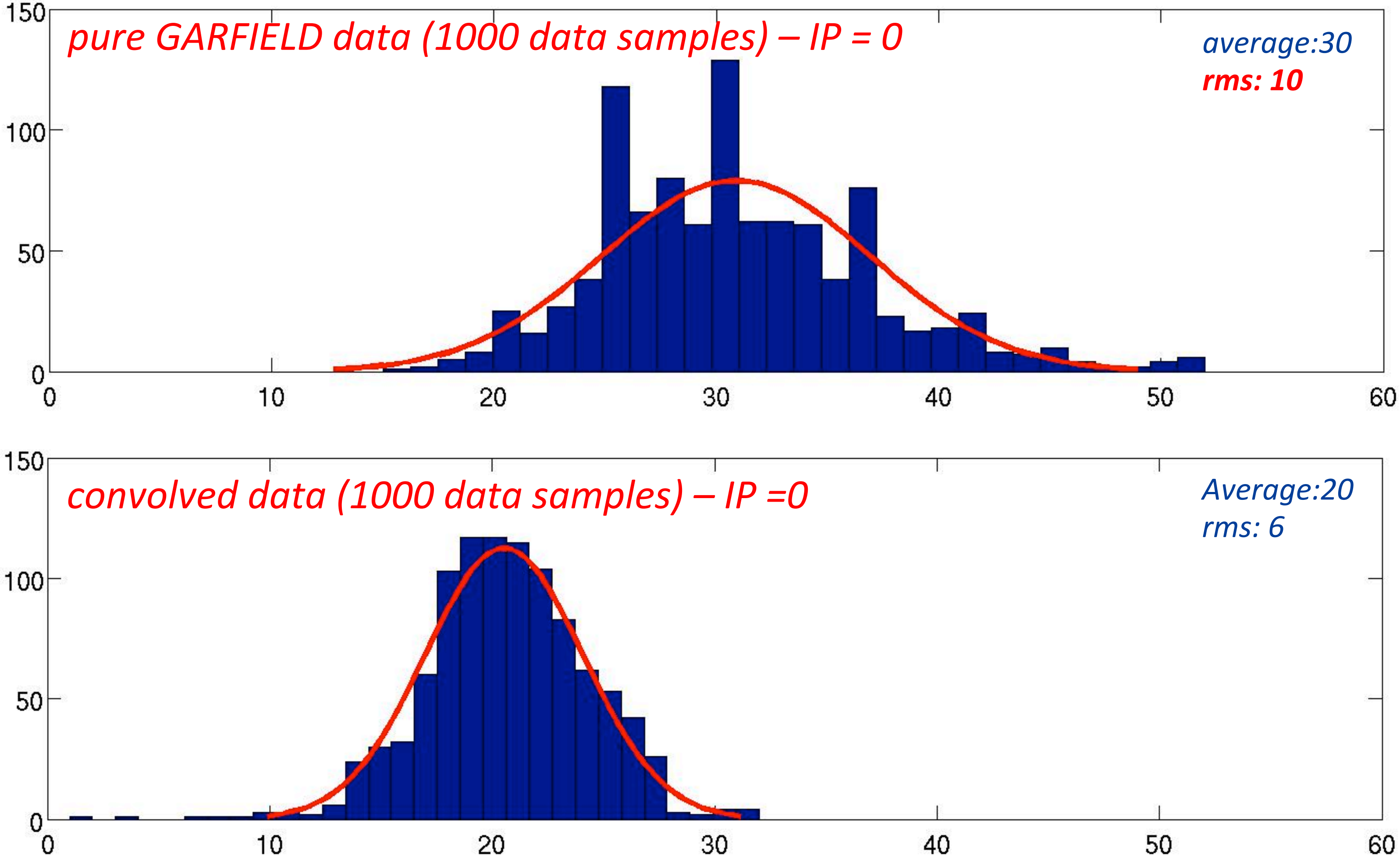
Impact parameter = 5.0 mm



Impact parameter = 7.5 mm

Remind from Dec 2011 WS – step 6: preamplifier convolution effect

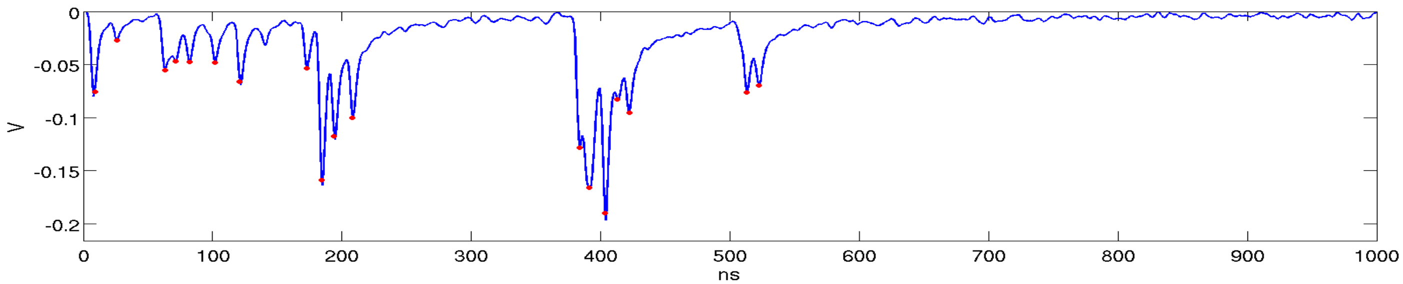
About 30% loss efficiency due to preamplifier response convolution (peak finding method)



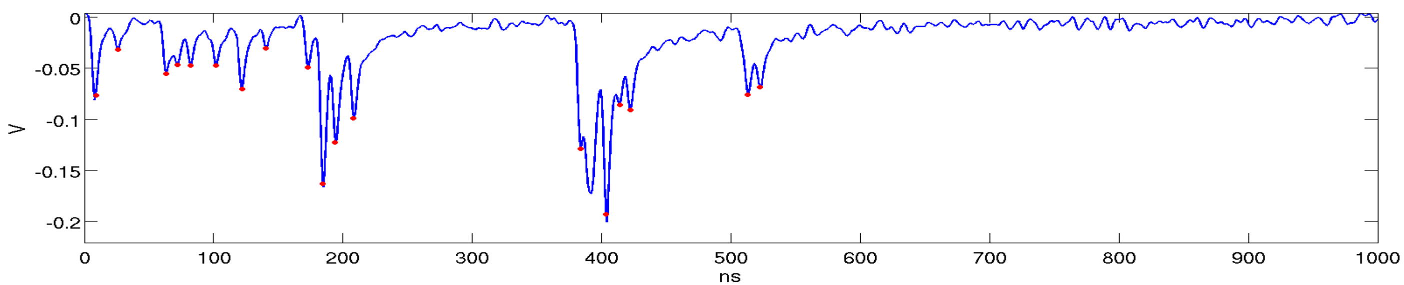
The same result is obtained adding only noise to the pure GARFIELD data

Remind from Dec 2011 WS – step 7: Adding noise and convolution

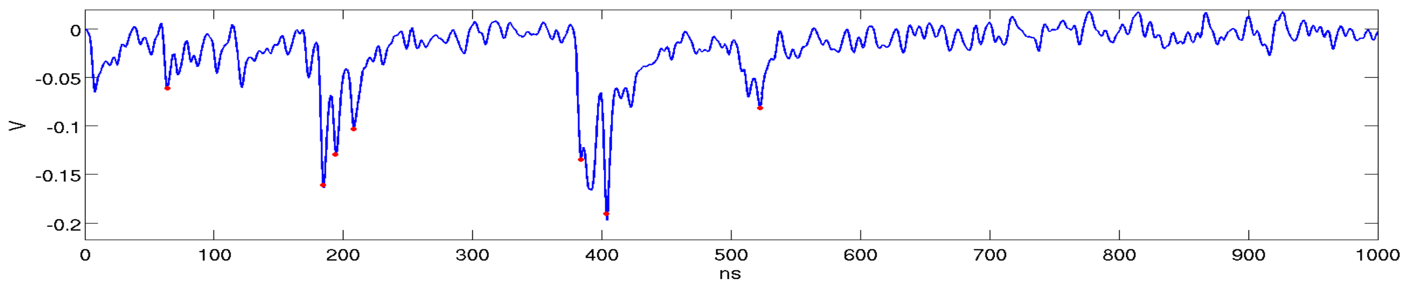
SNR evaluated considering single electron cluster average amplitude (~10mV)



SNR=10



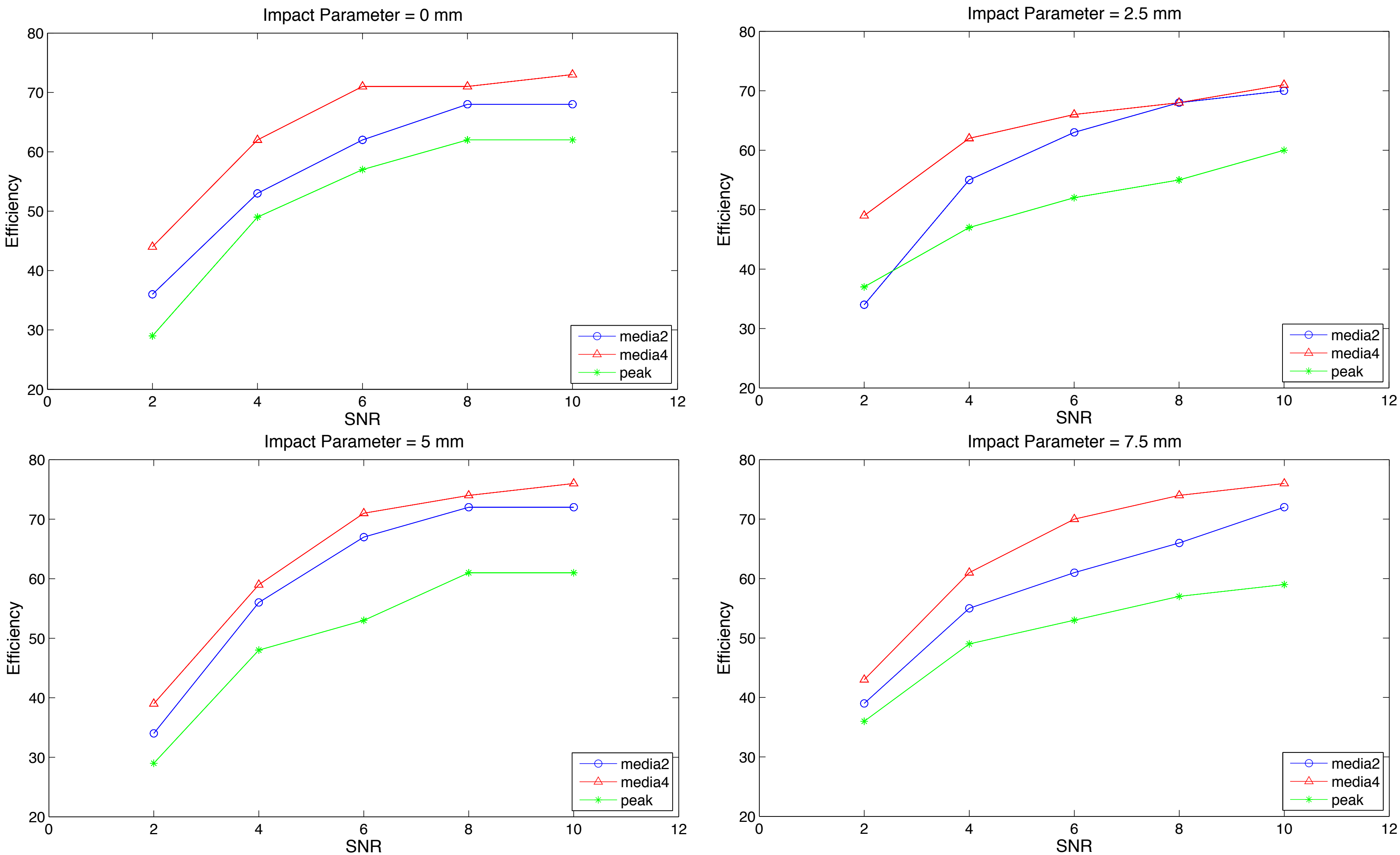
SNR=6



SNR=2

SNR=Signal Amplitude/Noise RMS

Cluster detecting algorithms comparison – Threshold @ 2.5 σ



- *Operating region around SNR = 8 can be inferred*
- *External noise pickup reduces efficiency because higher thresholds must be required*

Conclusions (II)

A cluster counting feasibility study using two algorithms that can be implemented in a FPGA has been carried out.

The analysis have been performed using data sets based on GARFIELD simulations at different impact parameters.

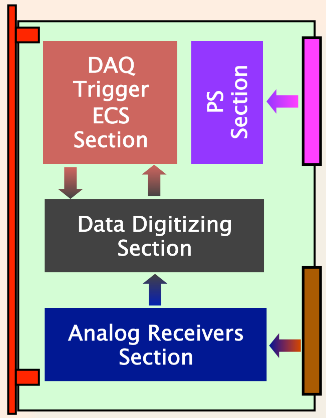
Results show that preamplifier response convolution causes a loss of about 28% in detected clusters for different impact parameters.

The addition of Gaussian noise with different SRN increases the counting inefficiency from 40% (SNR=10) to about 70% (SNR=2) for the peak finding algorithm. Slope detection method is less sensitive to noise, anyway chamber must be operated with high gas gain to guarantee a SNR ≥ 8 (taking into account of external picked-up noise)

Peak detecting algorithm can be easily implemented in a FPGA, but is more sensitive to noise

On/Off detector electronics interconnections (I)

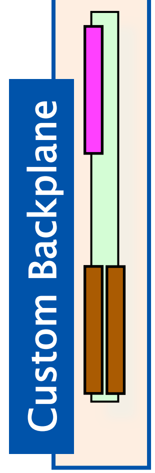
Data Conversion Board



- Power
- System clock
- .....

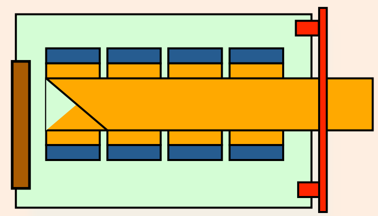
- Inputs (from TB)

EUROCARD 6U



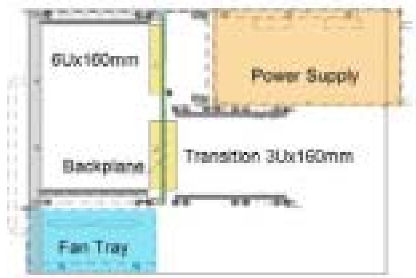
TB I/O signals

- Input Signals (from on-detector)
- On-Detector PS
- Test Pulse (to o-detector)



EUROCARD 3U

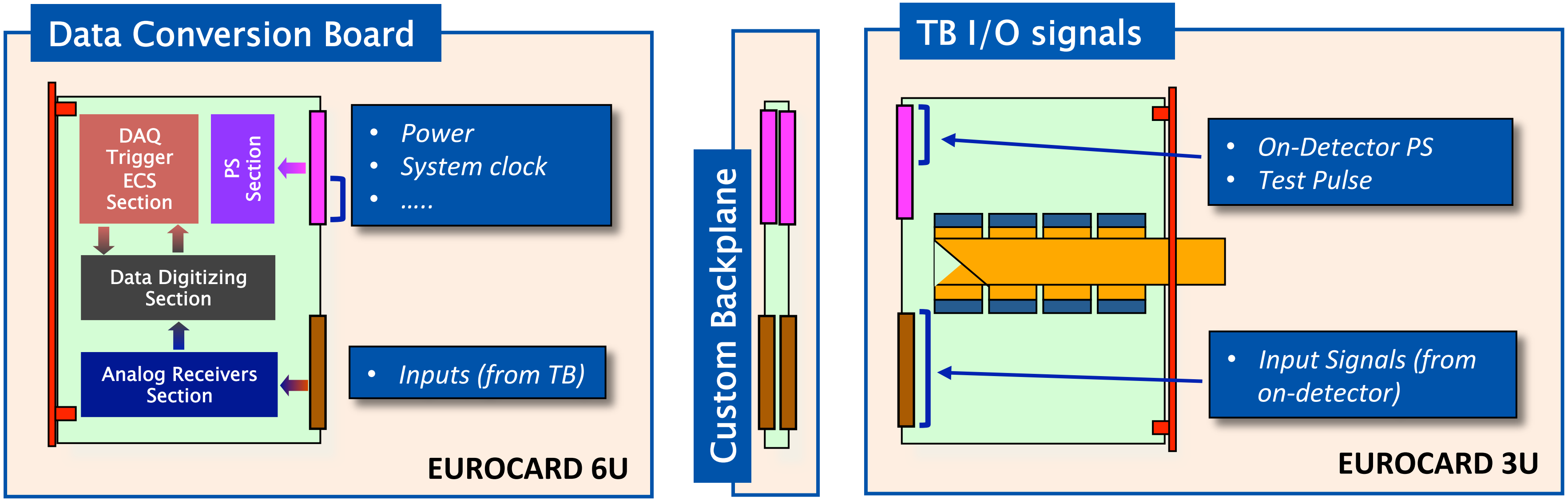
- *Avoid on-detector cables running in front of crates*
- *Avoid disconnecting signal cables to change a readout board*



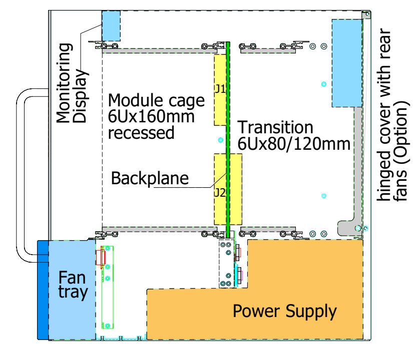
- *96 pin connectors (3 rows x 32 pins) can receive only 32 signals (twisted pairs or coax) (we need spare pins for on-detector PS and pulsing)*
- *NO controlled impedance (OK for charge measurements – Tested in KLOE experiment)*

Crate Version	Backplane	+5V	+12V	-12V
VME 6021-611	VME/VME64	115A	23A	23A
VME 6021-613	VME/VME64	230A	23A	23A
VME 6021-614	VME/VME64	345A	23A	23A
VME 6021-620	VME/VME64	115A	46A	46A
VME 6021-621	VME/VME64	230A	46A	46A
VME 6021-622	VME/VME64	345A	46A	46A

On/Off detector electronics interconnections (II)

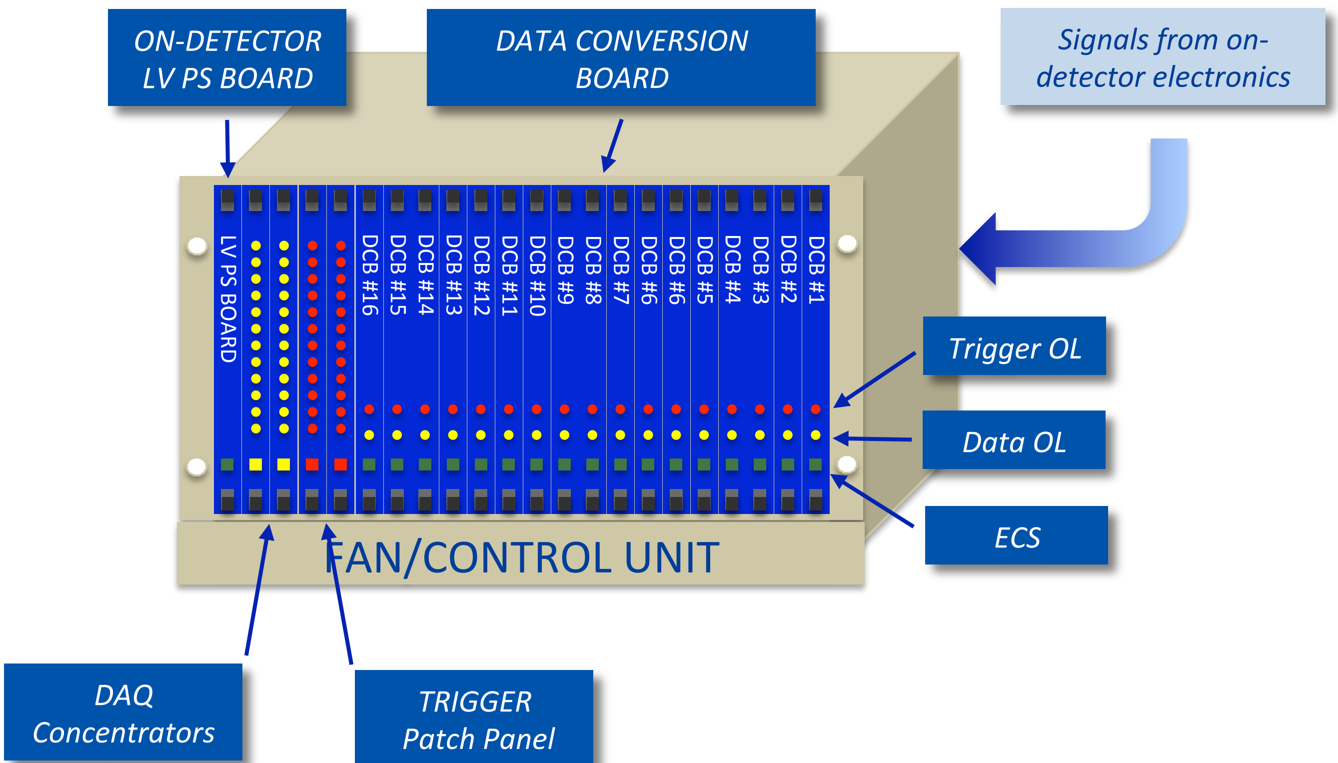


The solution allows to receive up to 64 signals (twisted pairs or coax) but use NON standard PS



Crate Version	Backplane	+5V	+12V	-12V
VME 4503-611	VME/VME64	115A	23A	23A
VME 4503-613	VME/VME64	230A	23A	23A
VME 4503-614	VME/VME64	345A (special)	23A	23A

On/Off detector electronics interconnections (III)



If can use standard VME crates (probably) we do not need external power supply

Power Supply Requirements

Truncated Mean	*Cluster Counting*
Single channel preamplifier	Single channel preamplifier
8 mA @ 4 V	30 mA @ 5 V

Truncated Mean		*Cluster Counting*	
Channels/board	*Number of Crates*	*Channels/board*	*Number of Crates*
64	10	16	40
32	20		

	Truncated Mean (single crate)		*Cluster Counting (single crate)*
	16x32 chs/board RO	16x64 chs/board RO	16x16 chs/board
ON-DETECTOR	512 channels	1024 channels	256 channels
	4.1 A @ 5 V	8.2 A @ 5 V	7.68 A @ 6V
OFF-DETECTOR	16 RO boards + 2 concentrators	16 RO boards + 2 concentrators	16 RO boards + 2 concentrators
	72 A @ 5 V 3.2 A @ 12 V 3.2 A @ 12 V	120 A @ 5 V 3.2 A @ 12 V 3.2 A @ 12 V	120 A @ 5 V 3.2 A @ 12 V 3.2 A @ 12 V