Simulation of Cluster Counting algorithms efficiency using Garfield waveforms

Outline

Goal: evaluation of CC algorithms efficiency using waveforms similar to those generated from Proto II FE and different SNRs (that is different DCH gas amplification assuming constant FE noise contribution)

1. *Wire current signal waveforms at 0, 2, 4, 6 mm impact point have been generated using Garfield*
2. *Preamplifier response has been parameterized and convolved waveforms have been generated using the Garfield generated current signals (waveform frequencies content similar to the Proto II FE output signals)*
3. *Average single electron peak current has been evaluated over the full data set*
4. *White gaussian noise has been added both to the "pure" Garfield waveforms and to the convolved ones according to the selected SNR*
5. *Three algorithms have been used in our simulation:*
   1. *SC → Simple Comparison*
   2. *SD → Slope Detection*
   3. *DL → Delay Line*
6. *Algorithms efficiency has been separately evaluated for the*
   a. *"pure" Garfield + noise*
   b. *convolved*
   c. *convolved + noise*

$$SNR = \frac{Signal\ amplitude}{RMS\ noise\ amplitude}$$

Single electron cluster amplitude

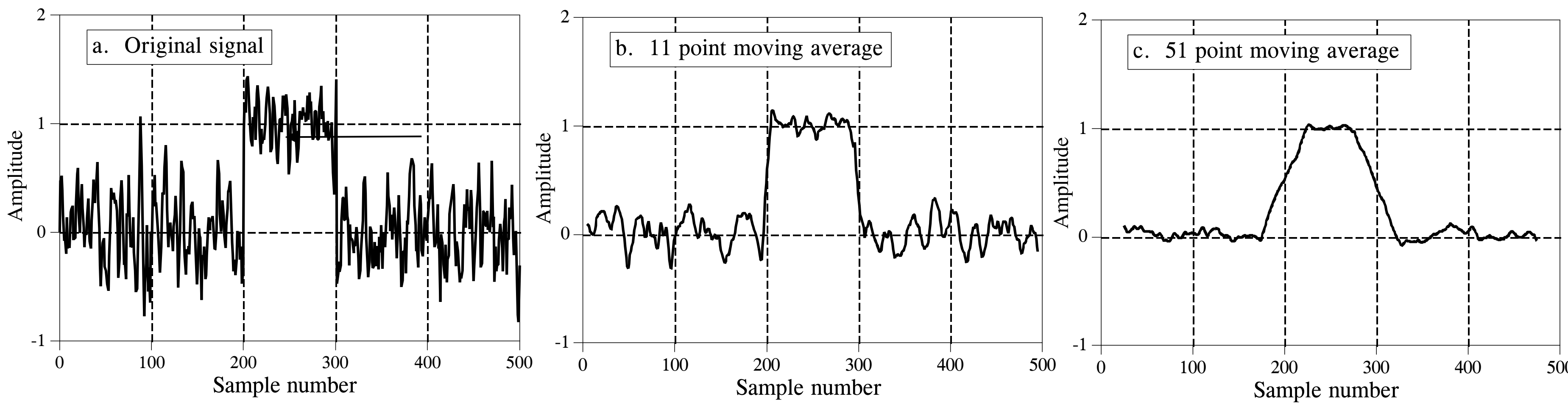
Moving Average Filters

Probably the most common filter used in DSP. Optimal for reducing random noise still maintaining a sharp response for time domain encoded signals (very poor features for frequency domain encoded signals i.e. frequency bands separation)

$$y[i] = \frac{1}{M} \sum_{j=0}^{M-1} x[i+j]$$

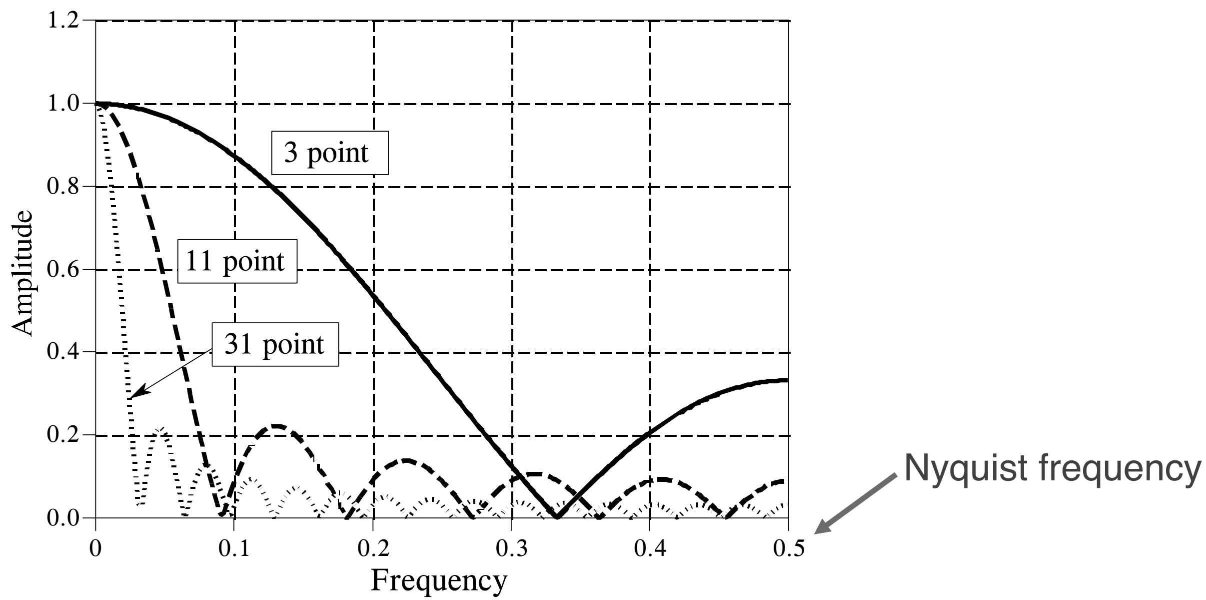
Note: the equation uses points on one side of the output sample (non symmetric)

Examples of moving average filters



Moving Average Filters

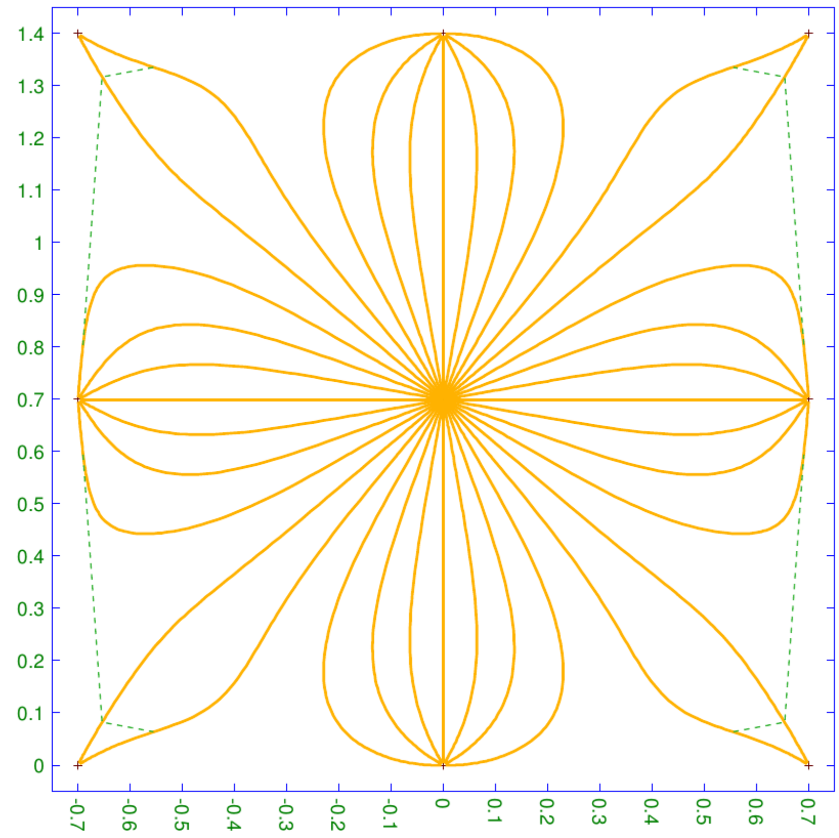
The moving average filter behaves as a very poor low-pass filter (slow roll-off and poor stop-band attenuation)



1: Garfield - simulation (C. Gatti)

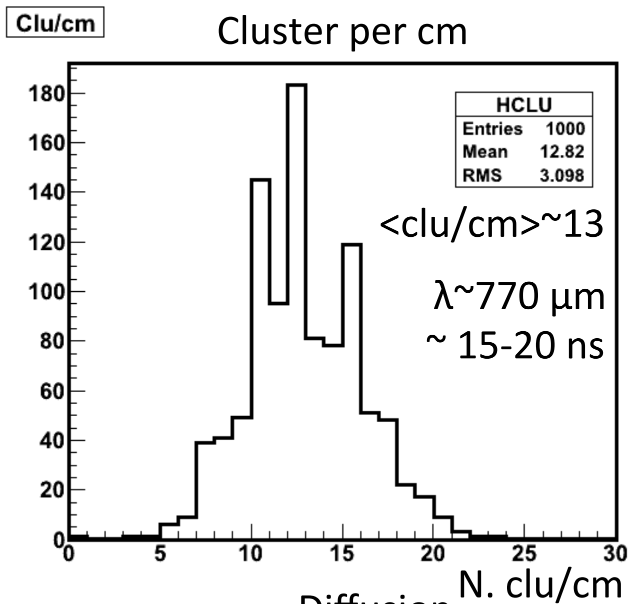
Simulation of electron drift in SB drift chamber using Garfield:

- *Prototype geometry V_s=1850 V*
- *B=0*
- *He 90% $IsoC_4H_{10}$ 10%*
- *Ion mobility 10.4 cm^2/V_s*
- *Gas amplification $18x10^4$ according to Polya distribution with q=0.6*

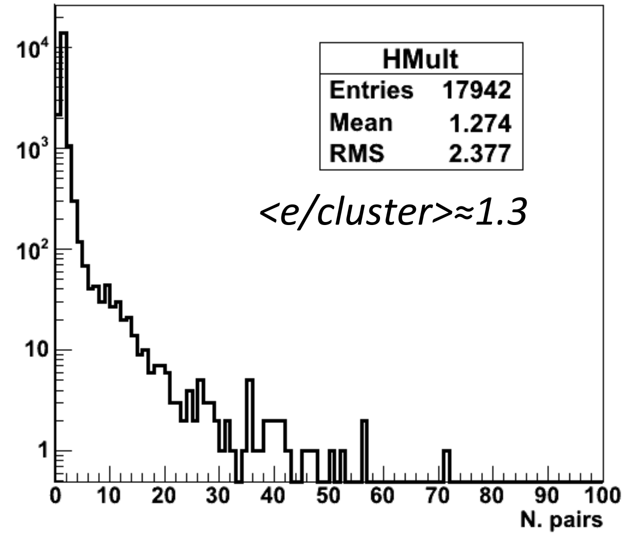


1: Garfield – Gas Properties (C. Gatti)

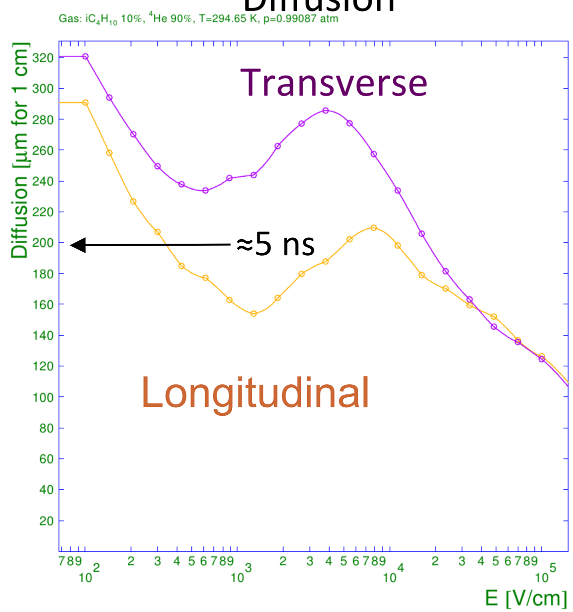
Cluster per cm



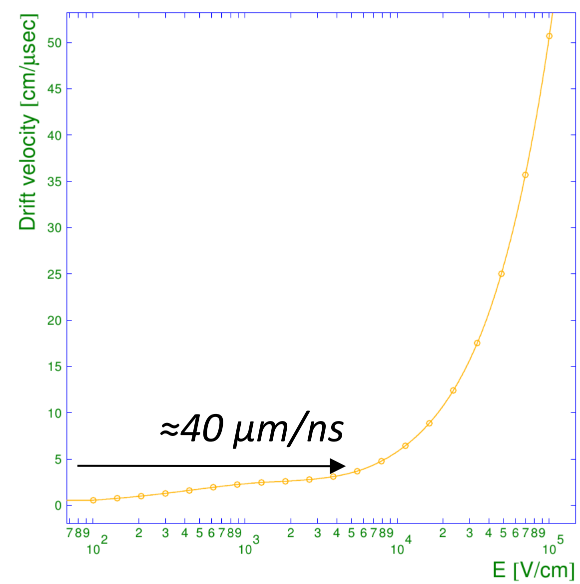
Cluster Size



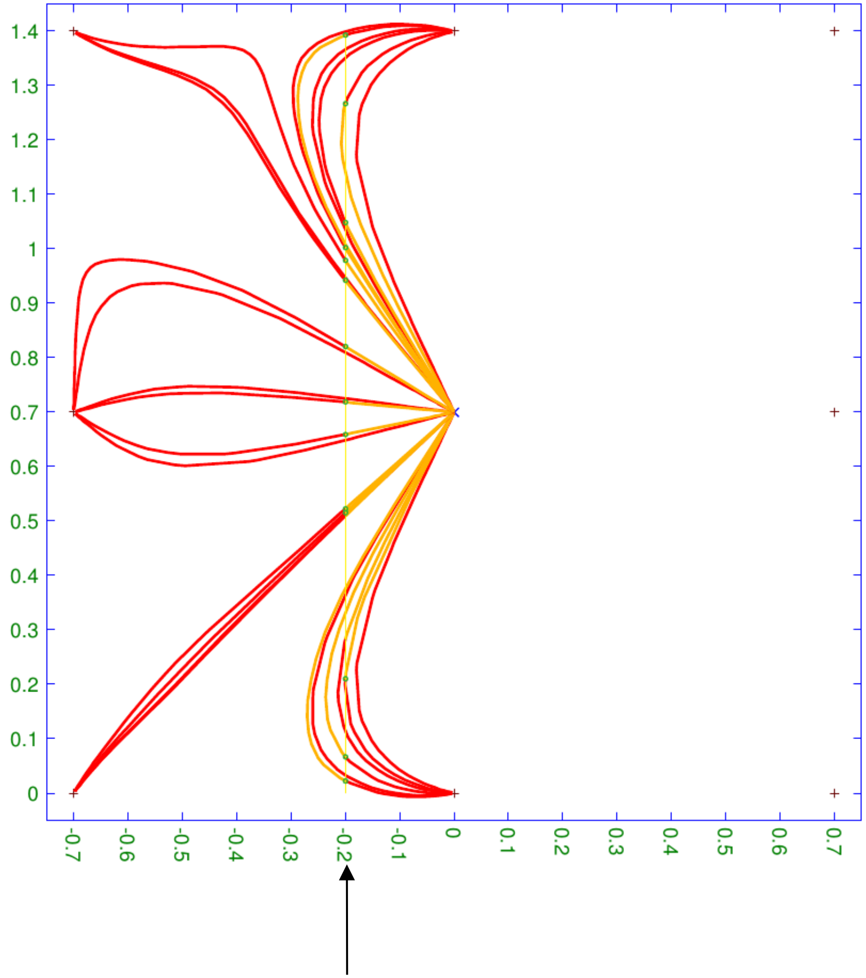
Diffusion

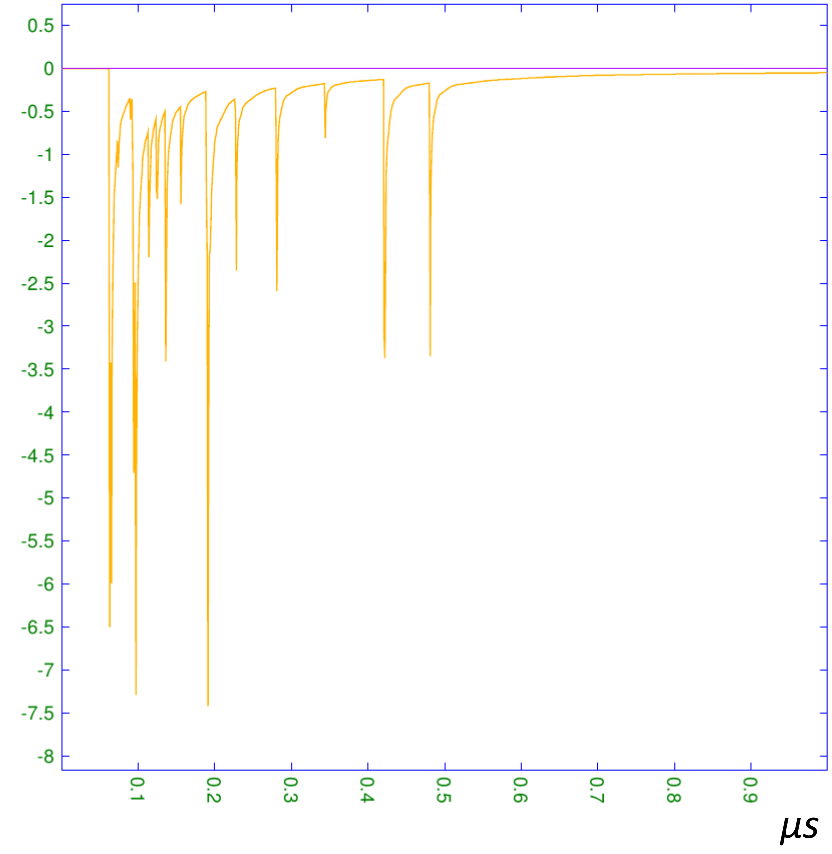


Drift Velocity



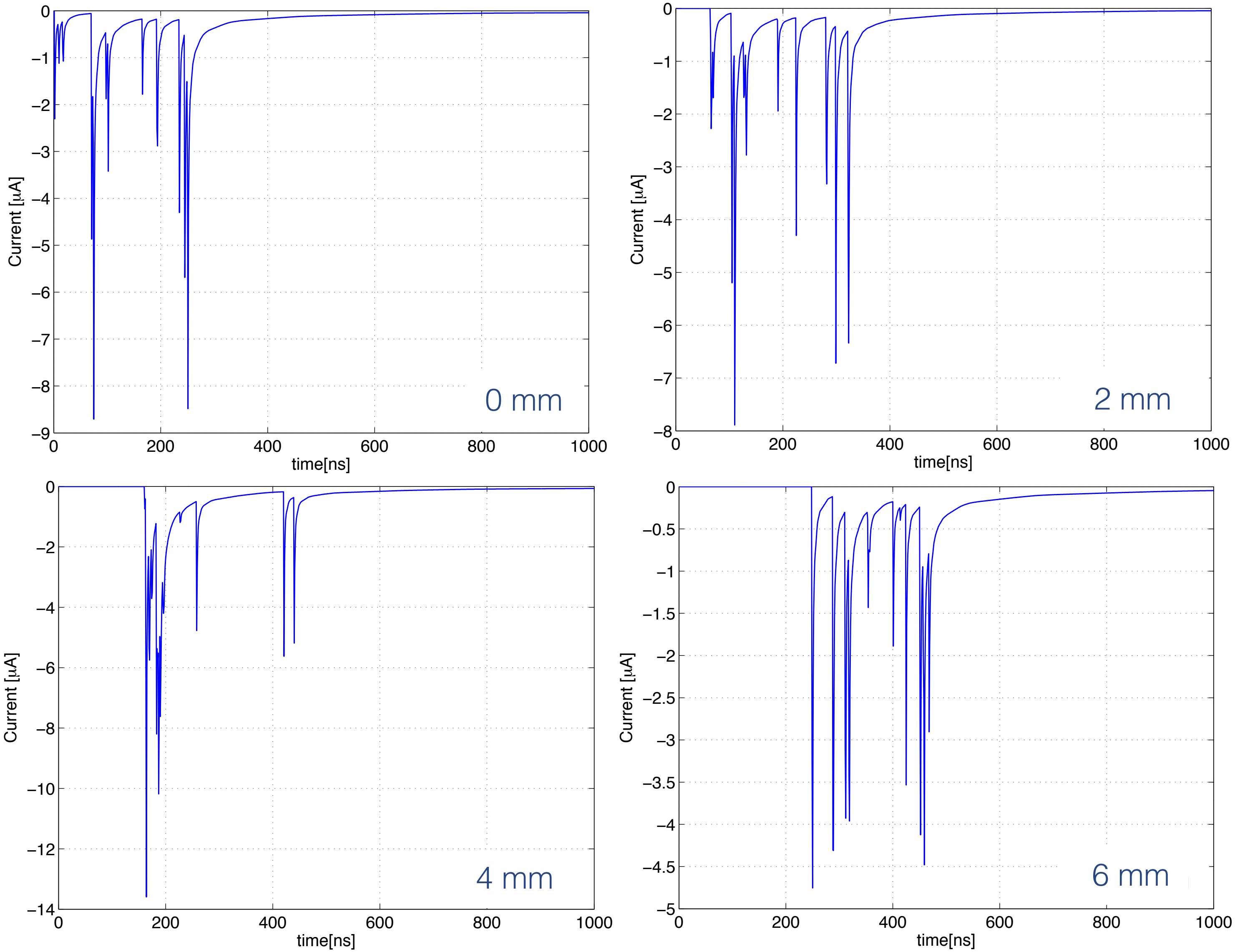
Signal simulated for negative muons with 250 MeV momentum and impact parameters 0, 0.2, 0.4 and 0.6 cm



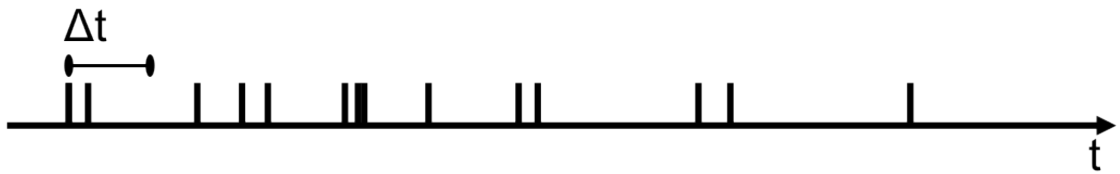


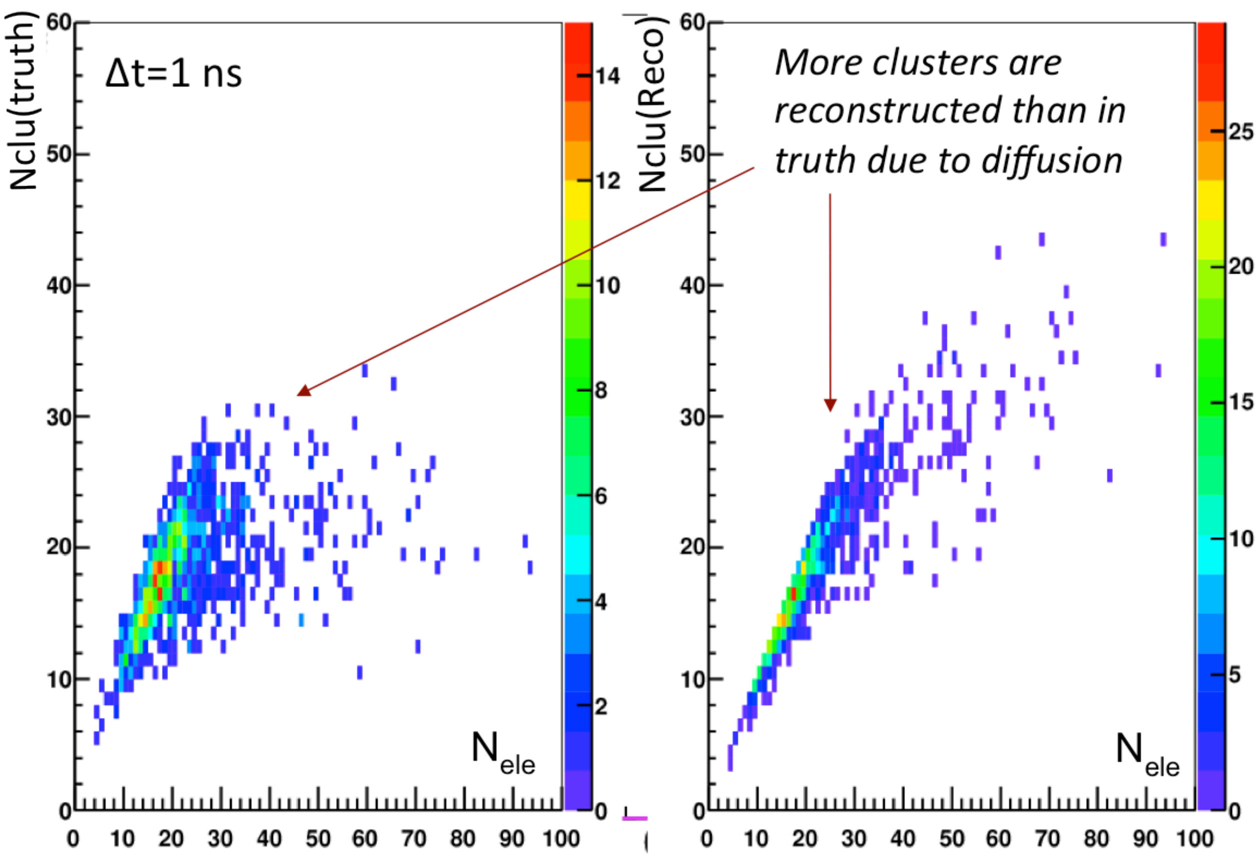
μ- (250 MeV)

1: Garfield - Sense wire current current signals @ 0/2/4/6 mm IP (C. Gatti)

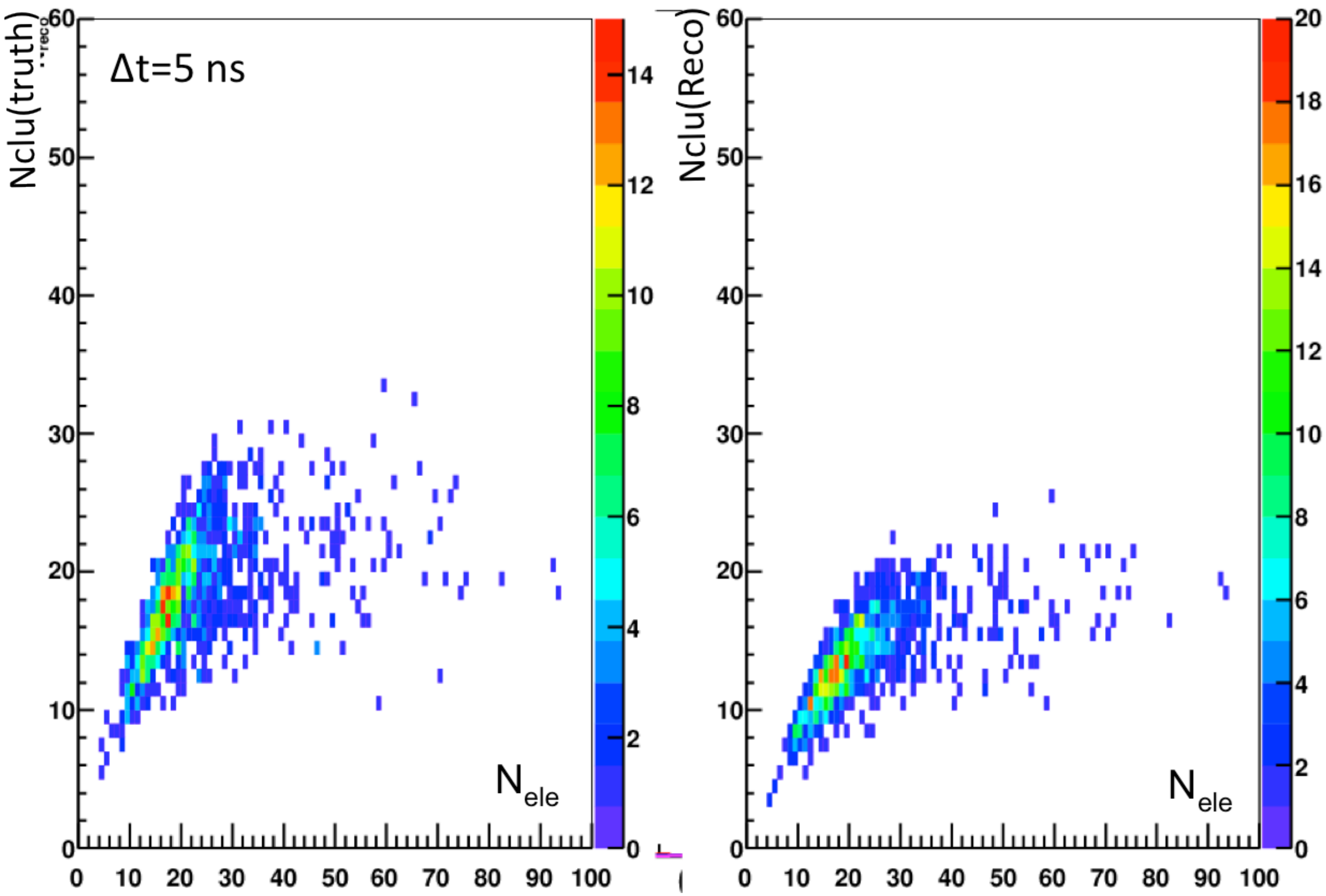


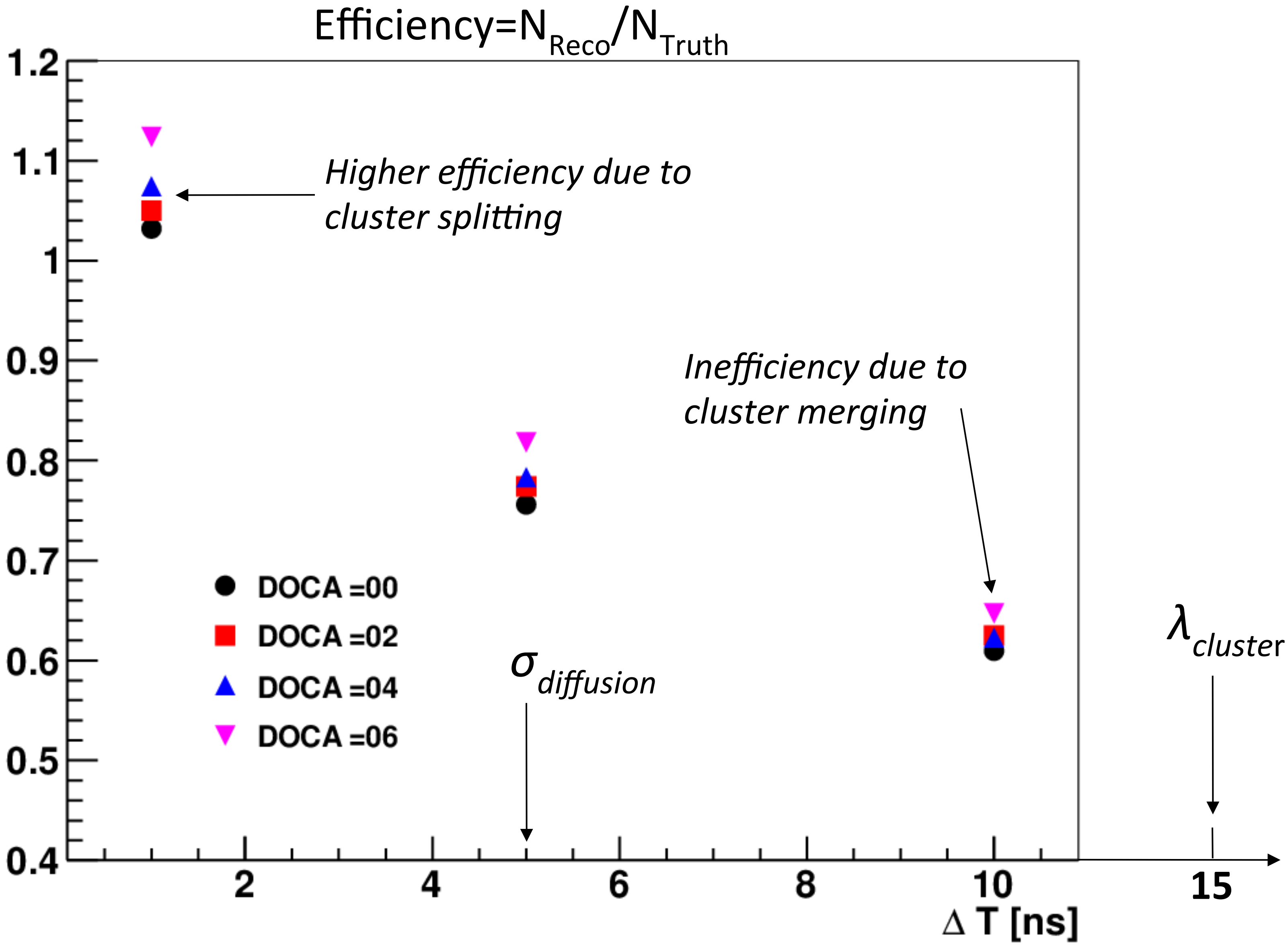
Collect all electrons within a time window Δt in a single cluster, starting from the first electron.





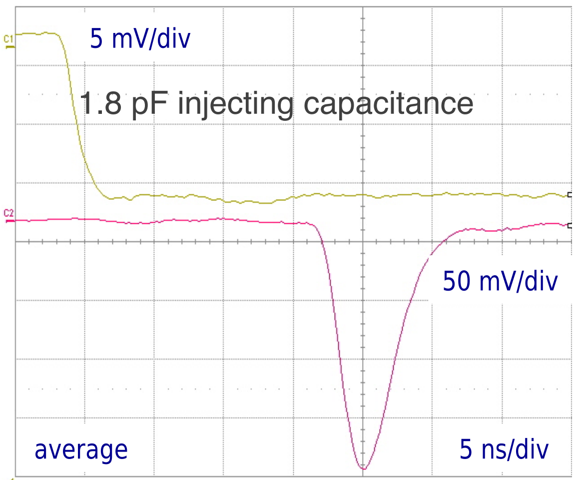
Increasing the "integration time" to 5 ns (comparable to diffusion effects) the number of reconstructed cluster is slightly less than the true one.





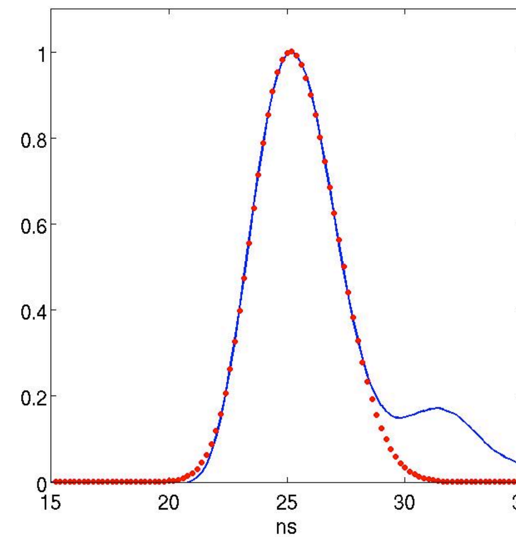
Efficiency=N_Reco/N_Truth
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
Higher efficiency due to cluster splitting
Inefficiency due to cluster merging
DOCA =00
DOCA =02
DOCA =04
DOCA =06
σ diffusion
λ cluster
2
4
6
8
10
15
Δ T [ns]

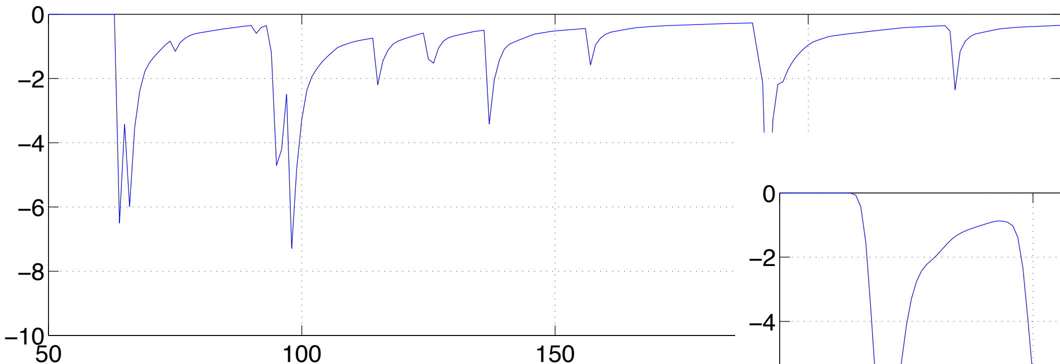
2: Preamplifier response evaluation

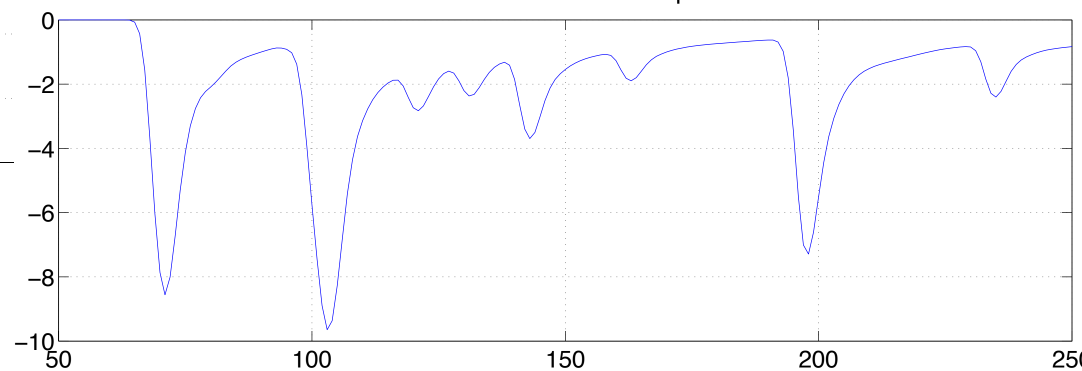


$$h(t) = a_1\ e^{-(\frac{t-b_1}{c_1})^2} + a_2\ e^{-(\frac{t-b_2}{c_2})^2}$$

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

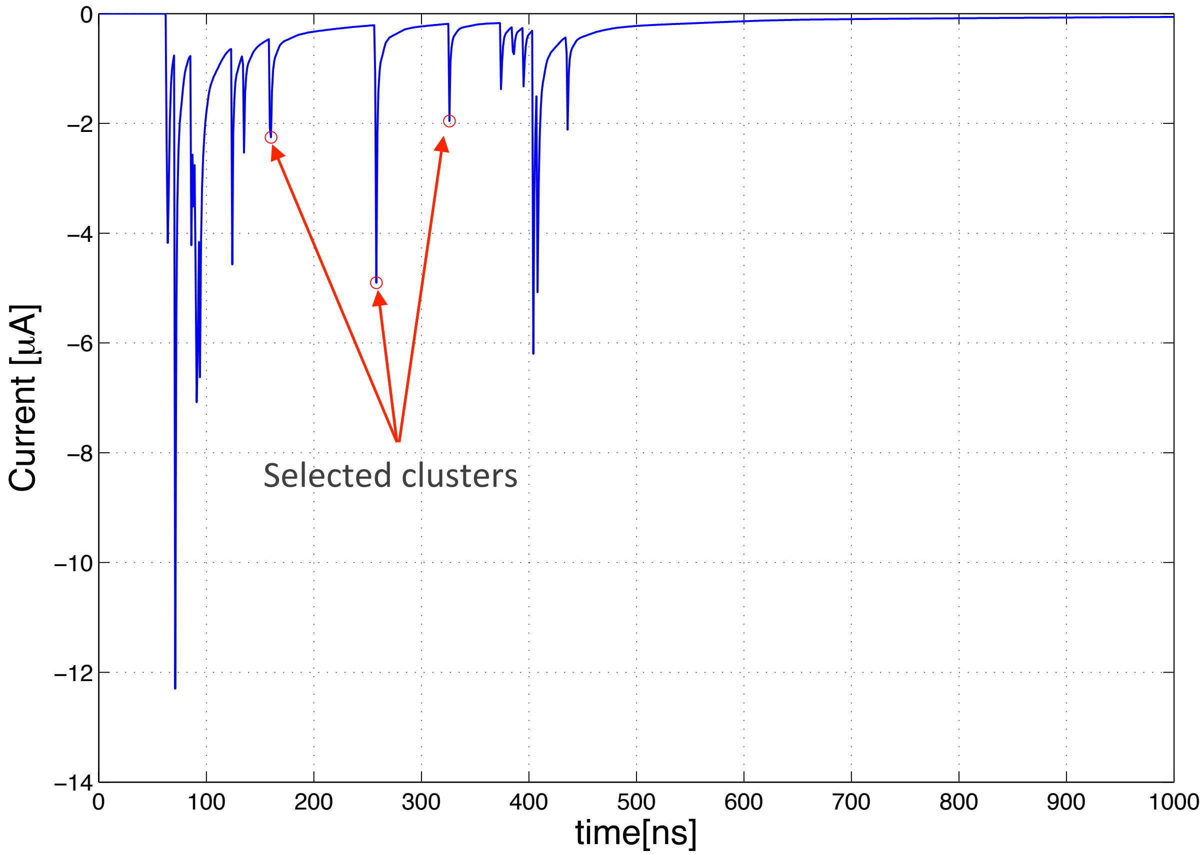






3: Single electron cluster average amplitude evaluation

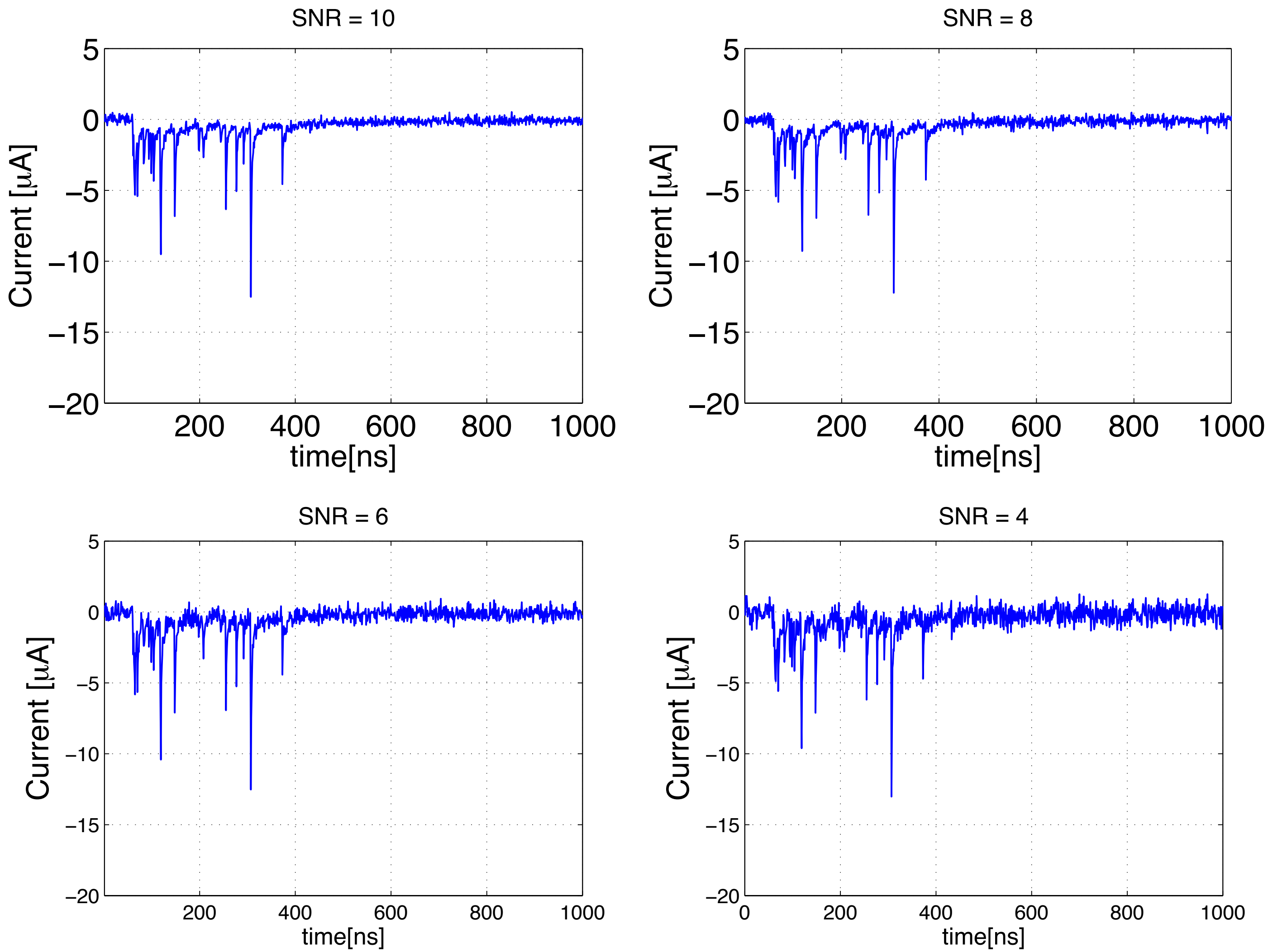
Cluster amplitude evaluation has been carried out looking for isolated clusters (20 ns dead time)



- *Average peak current amplitude ≈ 2.7 μA*
- *He/Iso (90/10) gas mixture average cluster size ≈ 1.33 e*

- *Single electron average peak current ≈ 2 μA*
- *Noise = 2 μA/SNR*

4: Examples of Garfield + noise waveforms



5: Cluster counting algorithms

Simple Comparison (SC)

SC is the simplest and faster CC algorithm. Is is based on neighboring data samples comparison according to

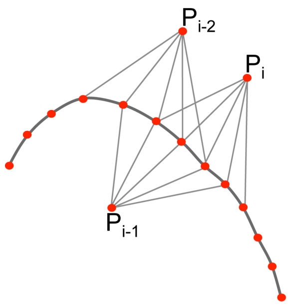
$$| A_n |> (| A_{n-1} | +\sigma) \ \&\& \ | A_n |> (| A_{n+1} | +\sigma)$$

Slope Detection (SD)

SD algorithm is based on signal slope (rising or falling) detection according to

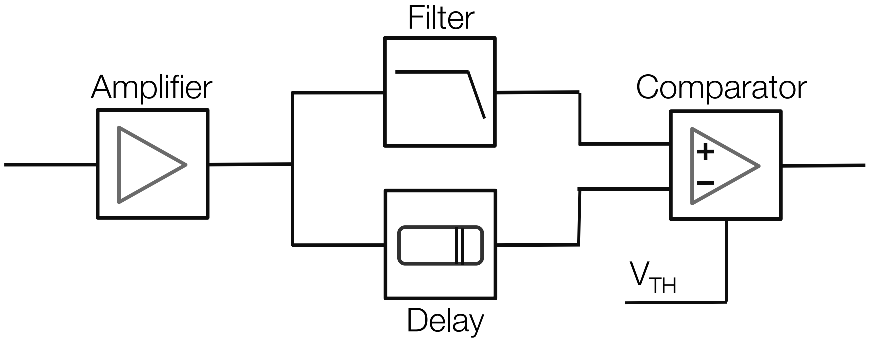
$$P_i = A_i - \frac{\sum_{n=1}^{4} A_{i-n}}{4}$$

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



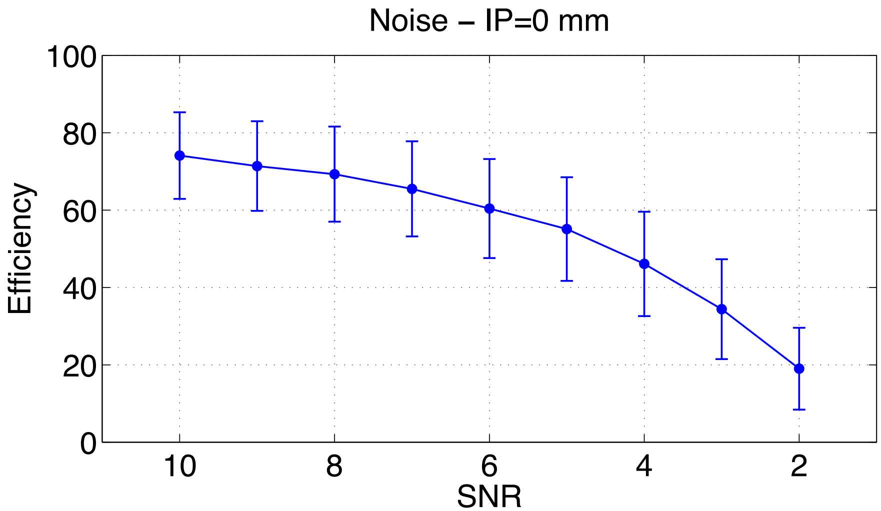
Delay Line (DL)

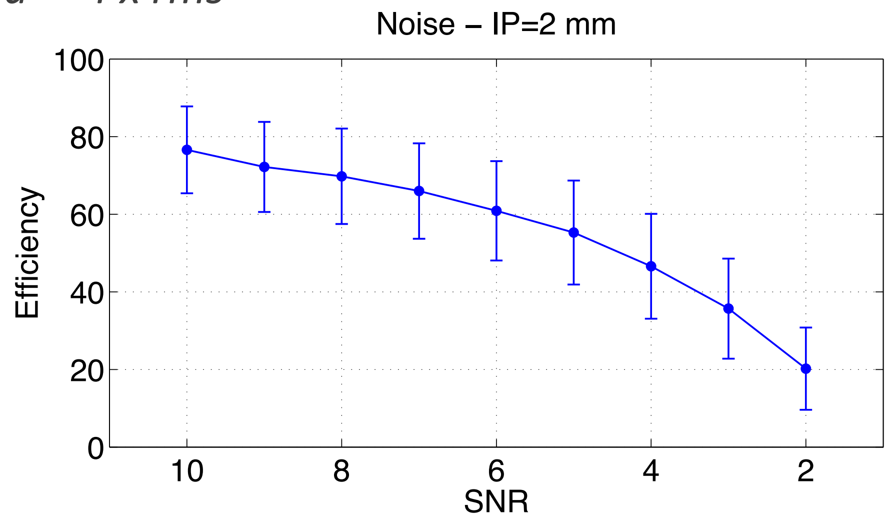
Delay Line approach to CC is a middle ground between SC and SD algorithms.
Most importantly, while SC and SD algorithms require fast (1 GSPS ??!! FADC and the state of art FPGA) digitizers, DL approach can be easily hardware implemented

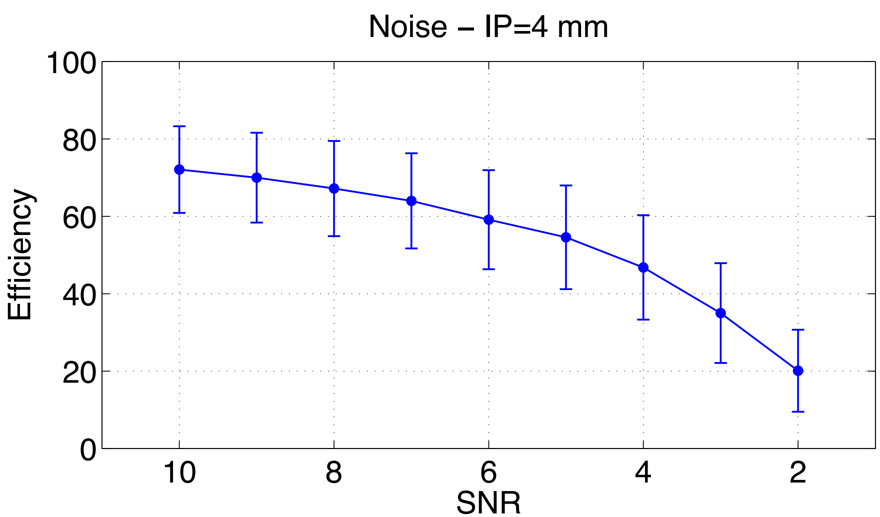


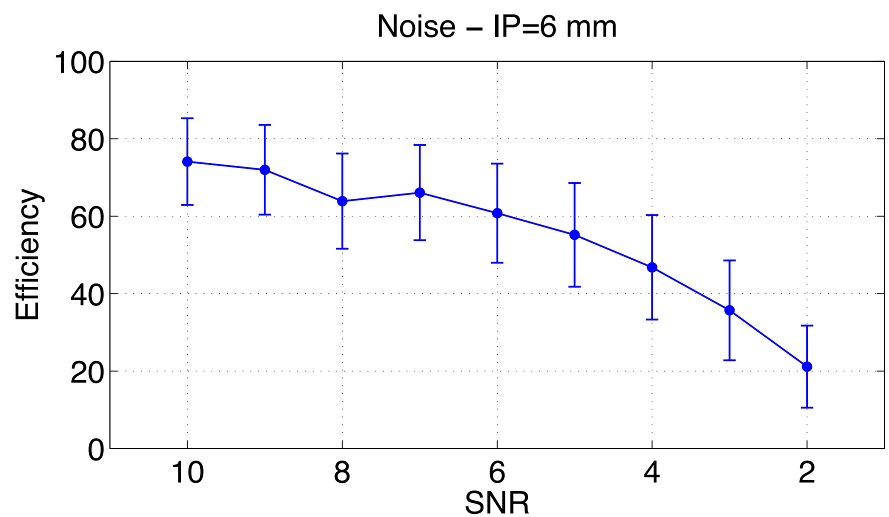
6: SC algorithm efficiency – Noise

Threshold = 4 x rms

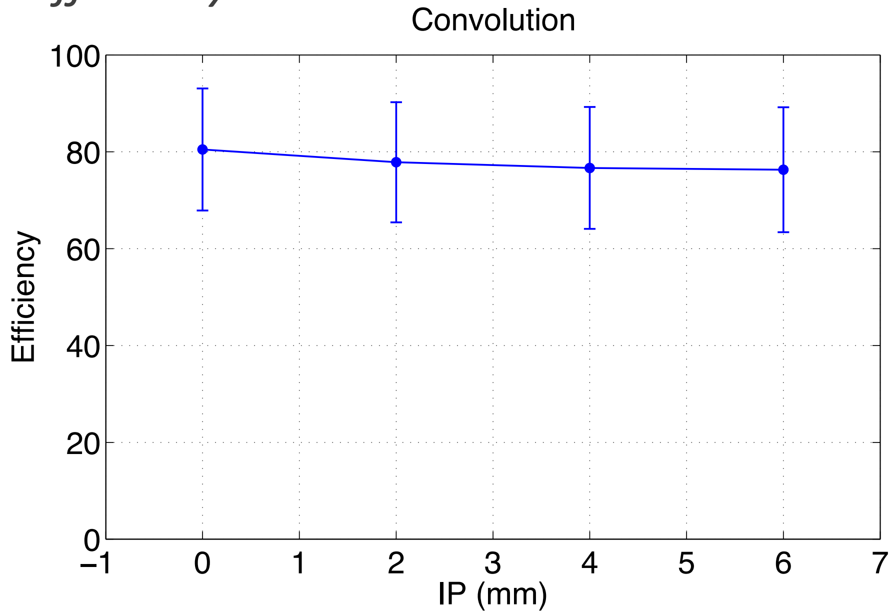




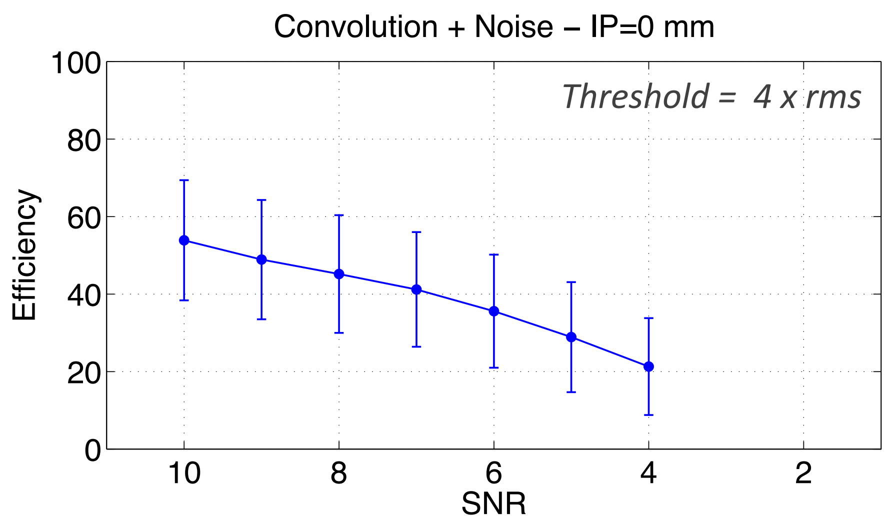




6: SC algorithm efficiency – Convolution

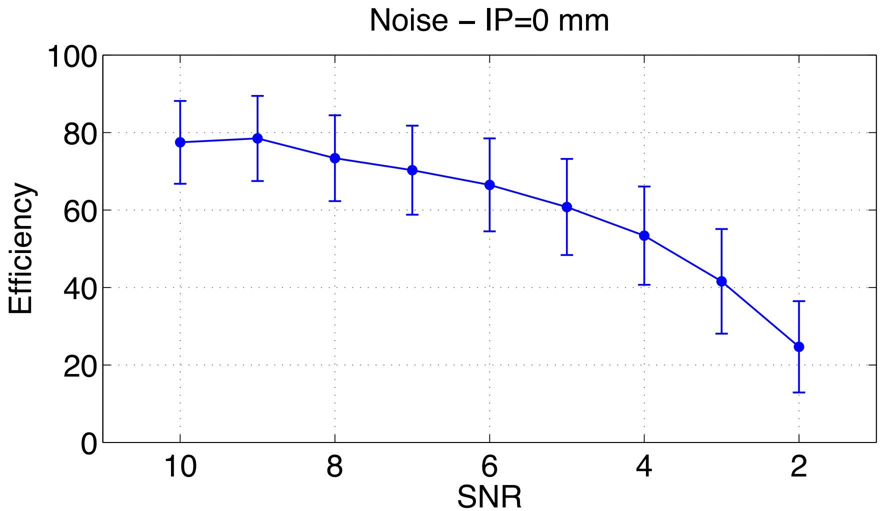


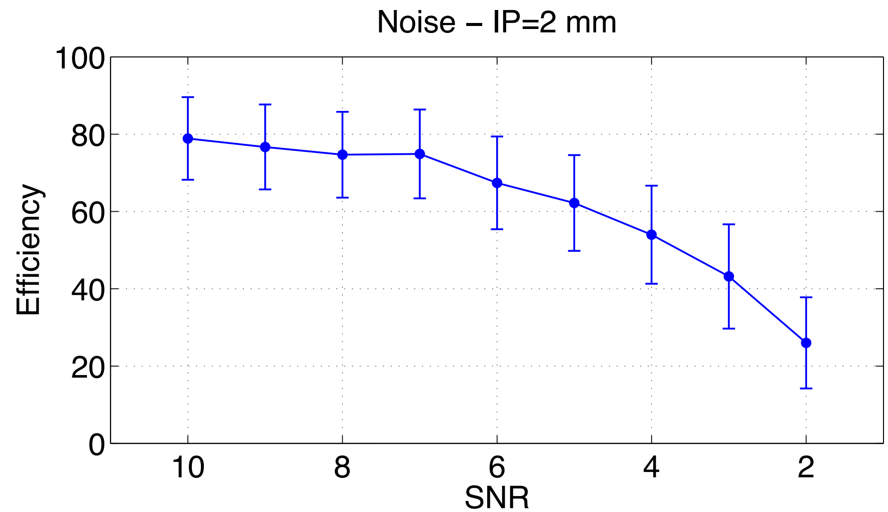
6: SC algorithm efficiency – Convolution + Noise

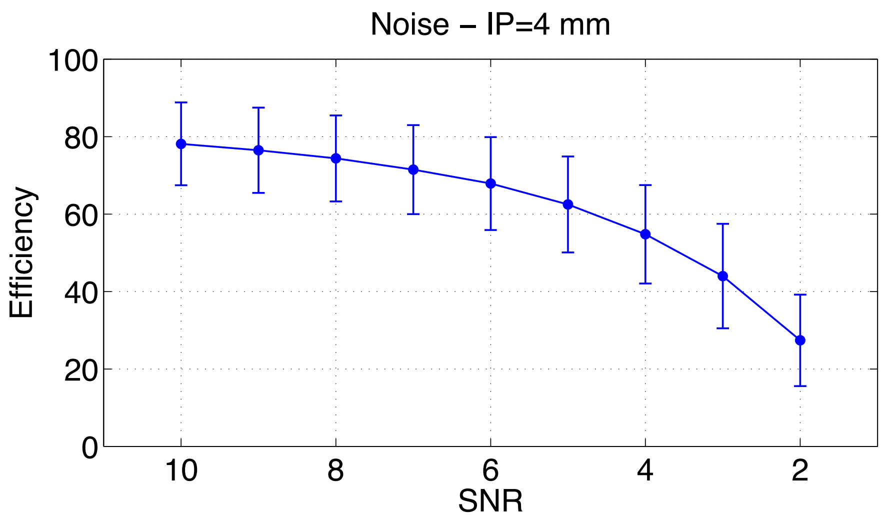


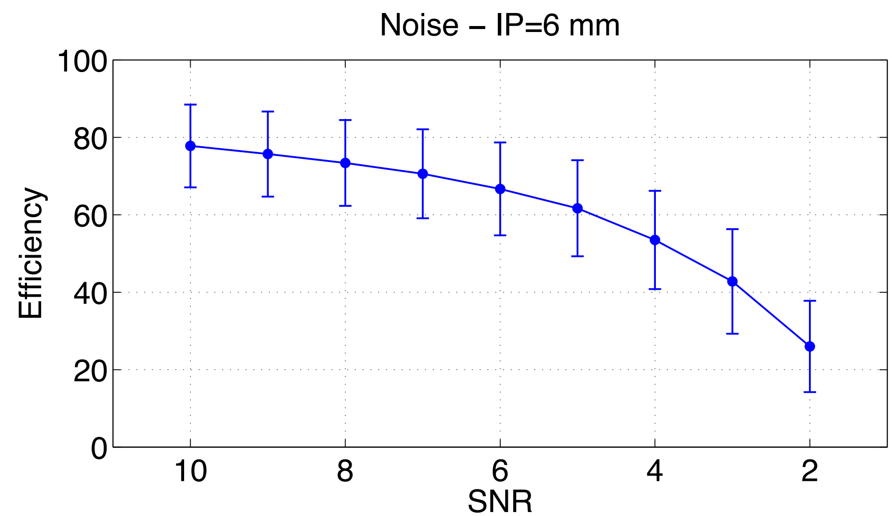
6: SD algorithm efficiency – Noise

Threshold = 4 x rms

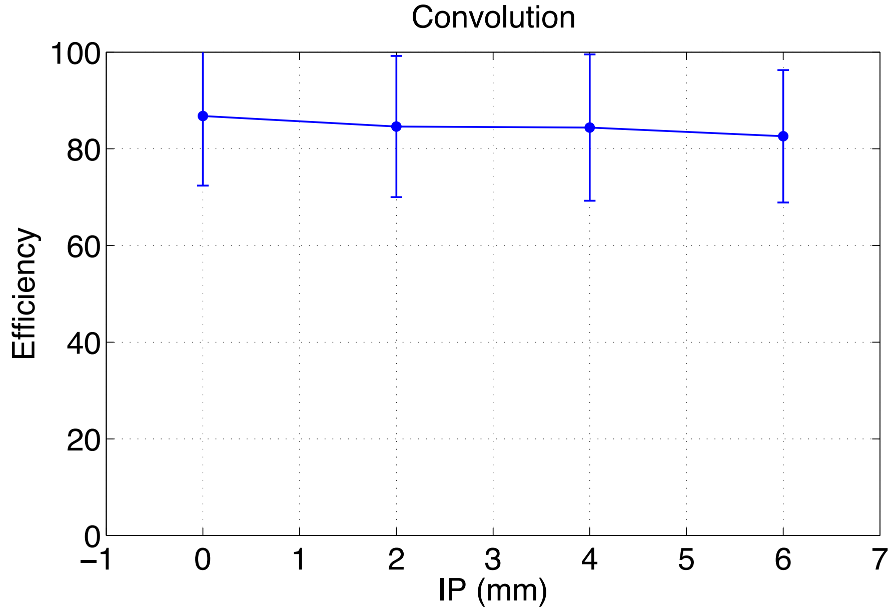




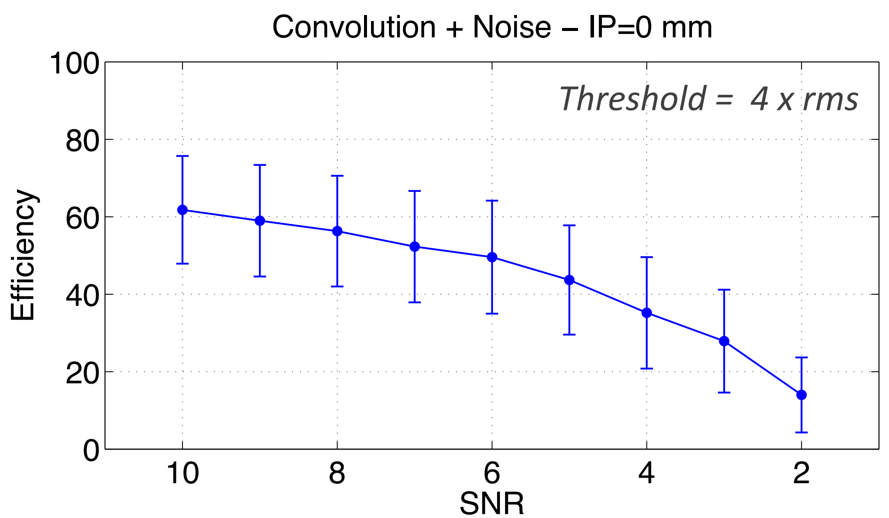




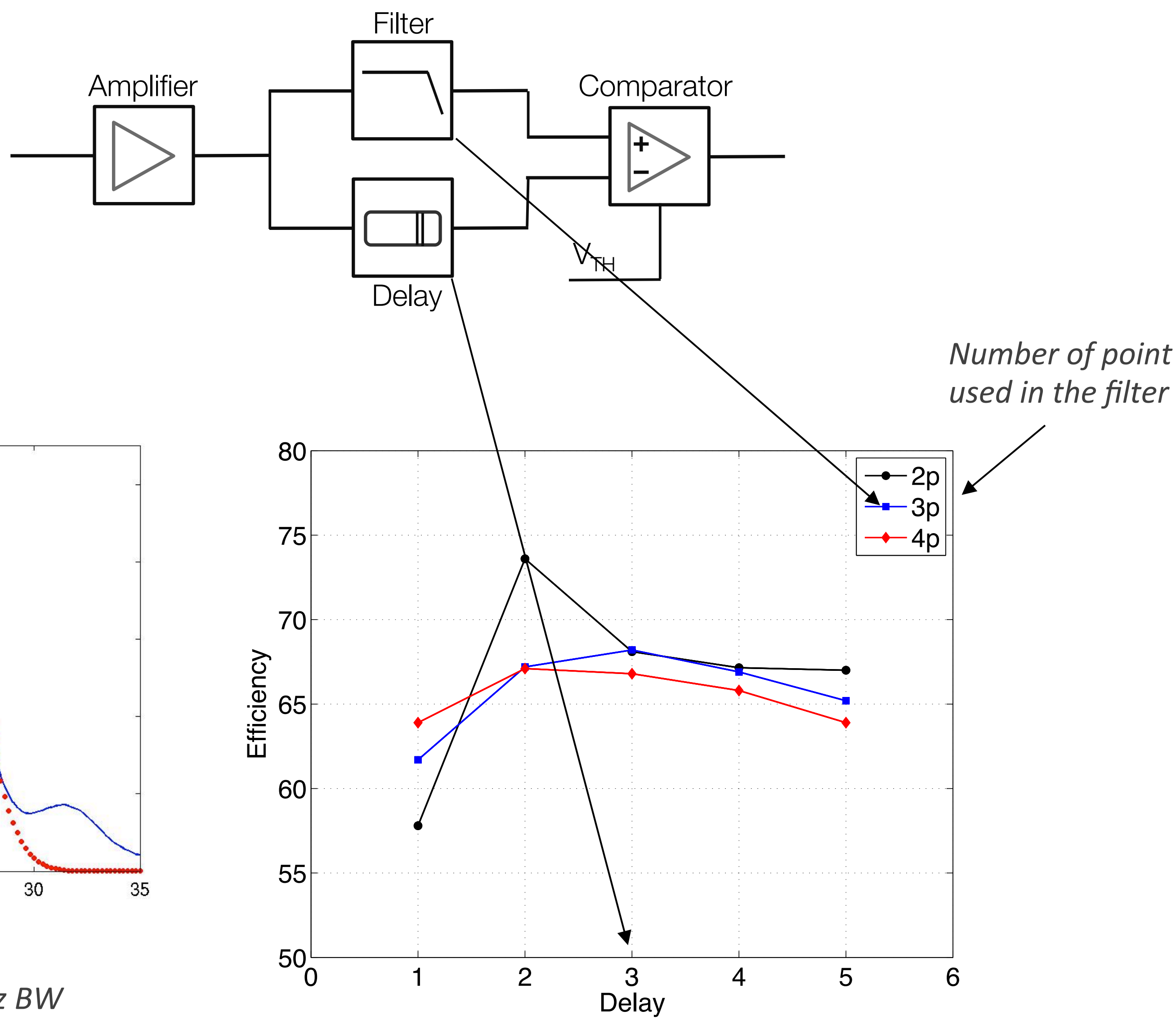
6: SD algorithm efficiency – Convolution

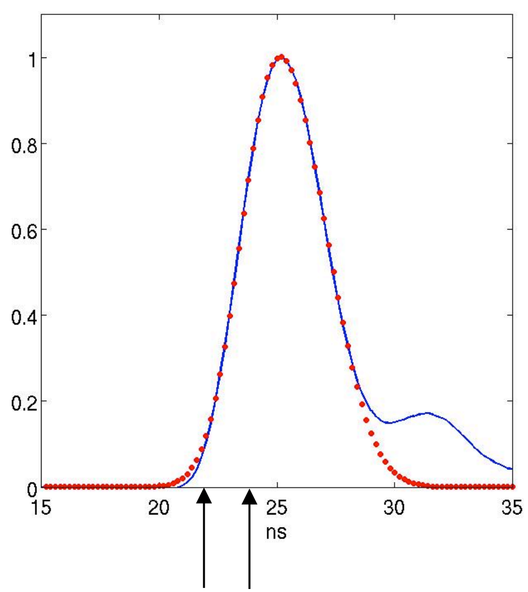


6: SD algorithm efficiency – Convolution + Noise



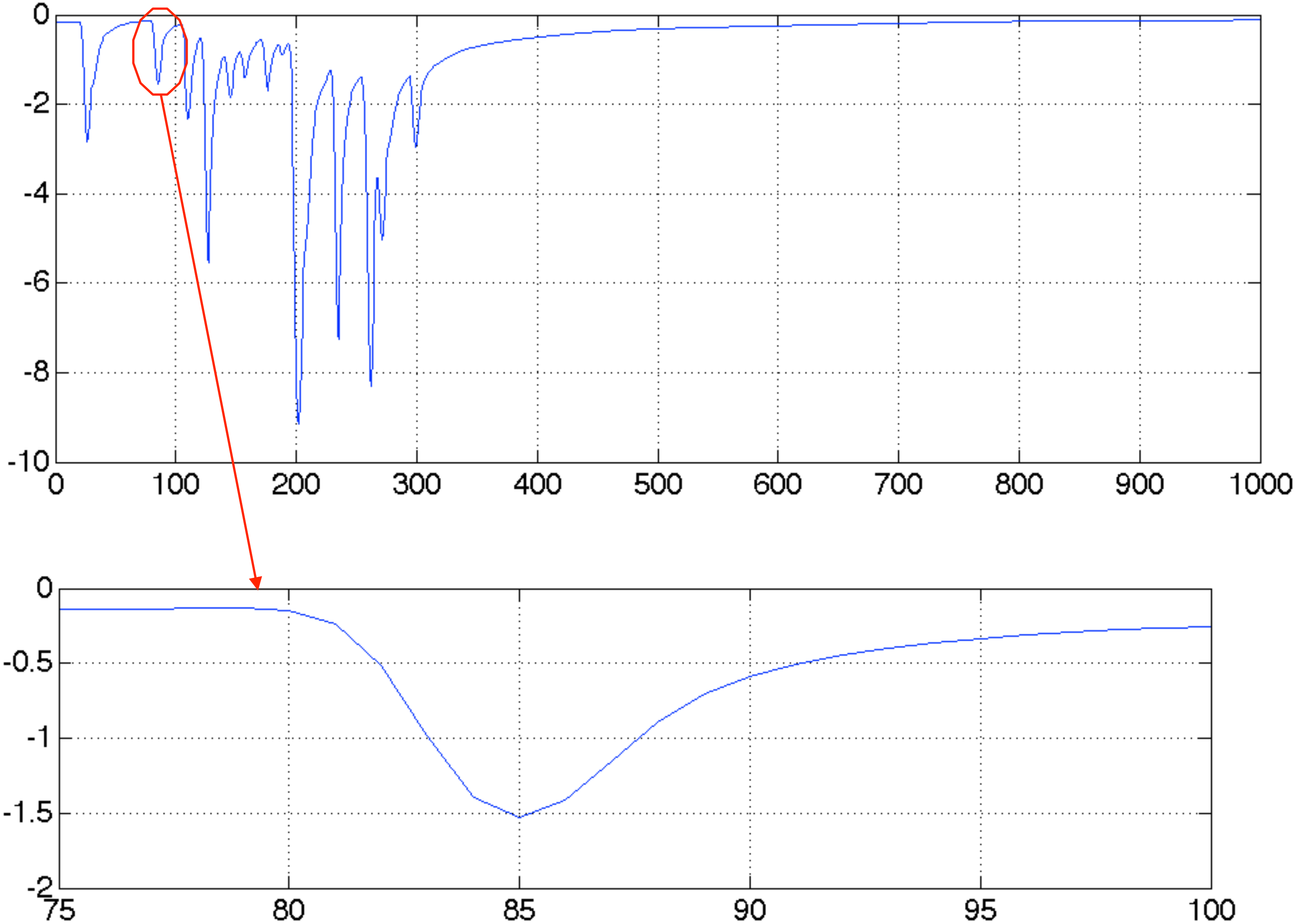
6: DL algorithm - Convolution + Noise - Delay Optimization





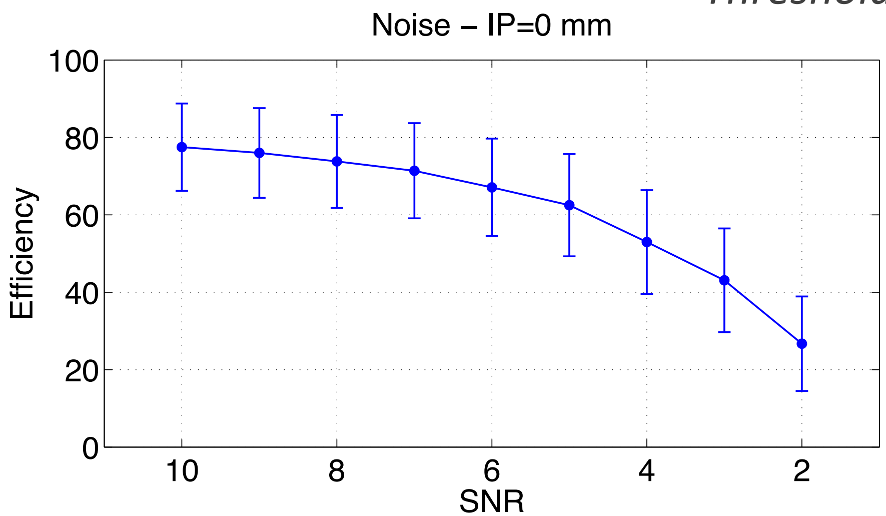
$t_r \approx 2$ ns → ≈ 180 MHz BW

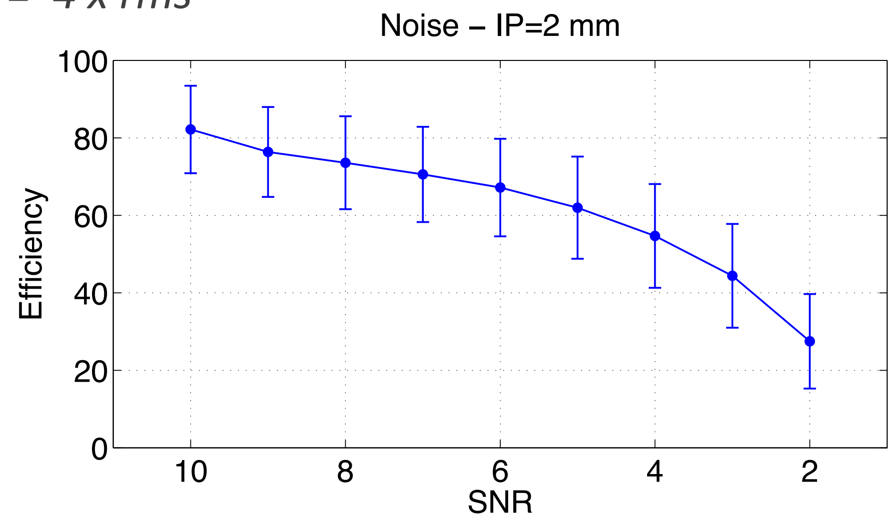
6: DL algorithm - Convolution effect on signal rise time

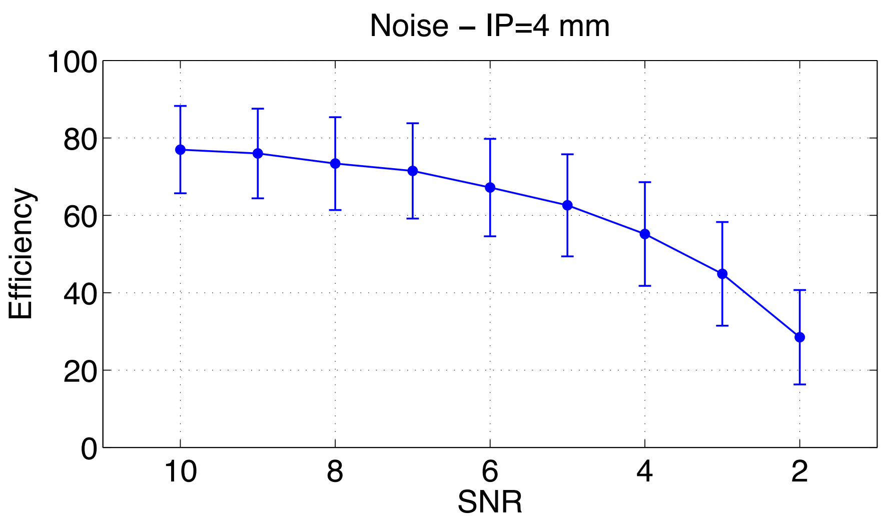


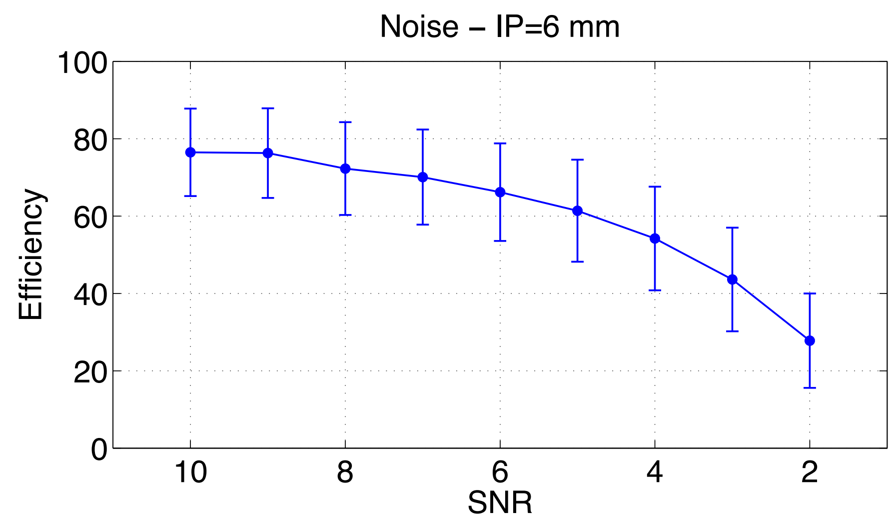
6: DL algorithm efficiency – Garfield + Noise

Threshold = 4 x rms

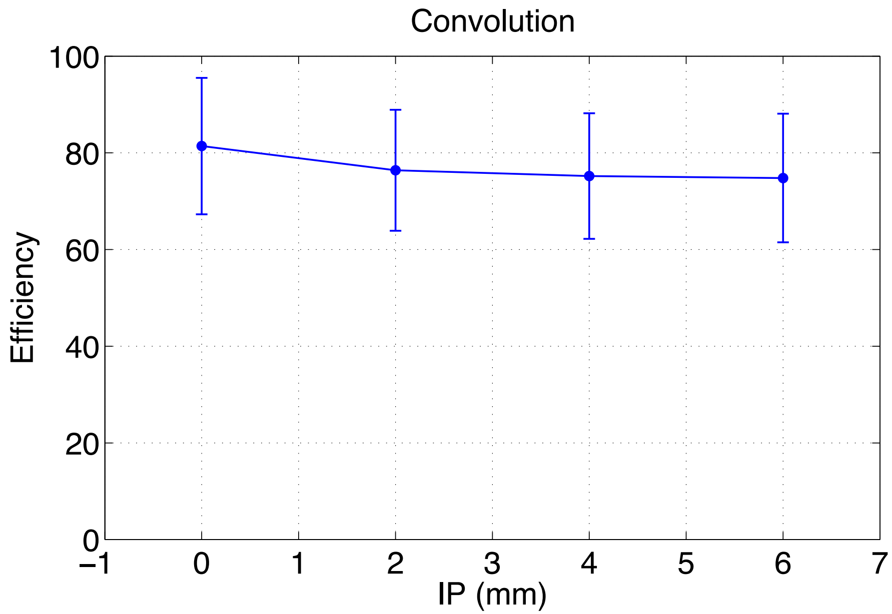




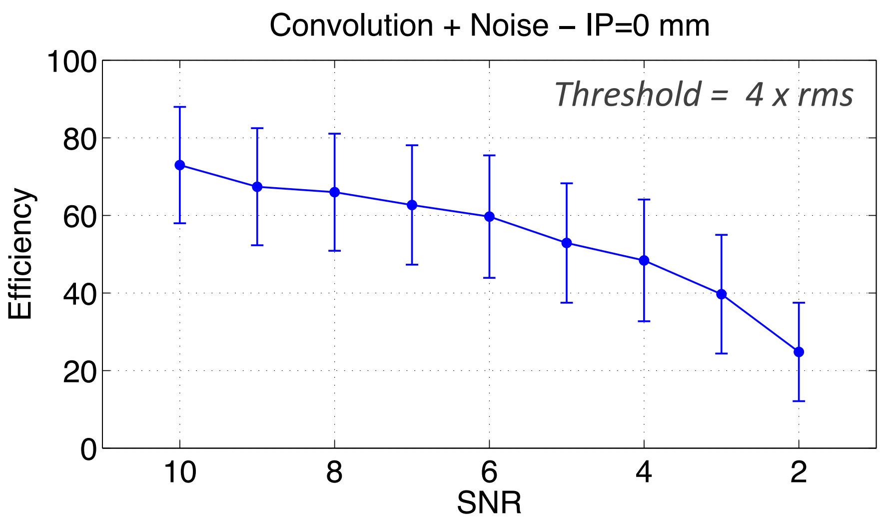




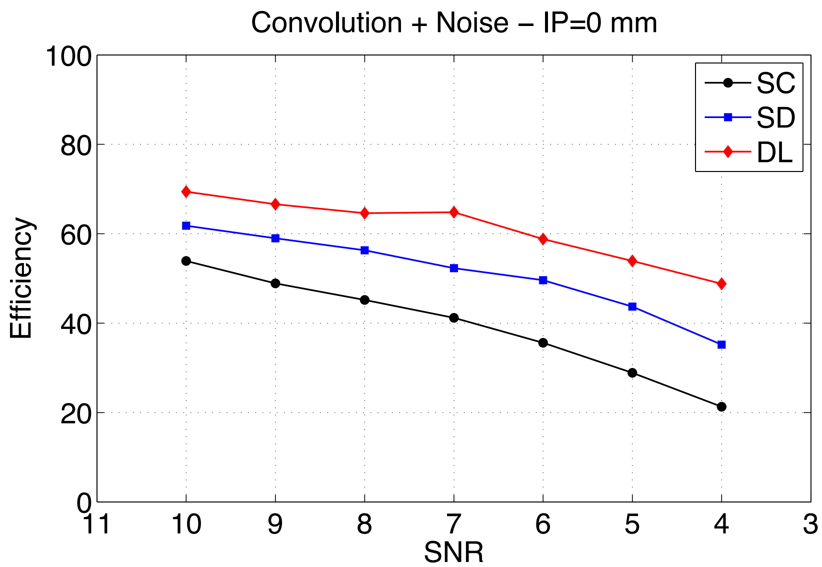
6: DL algorithm efficiency – Convolution

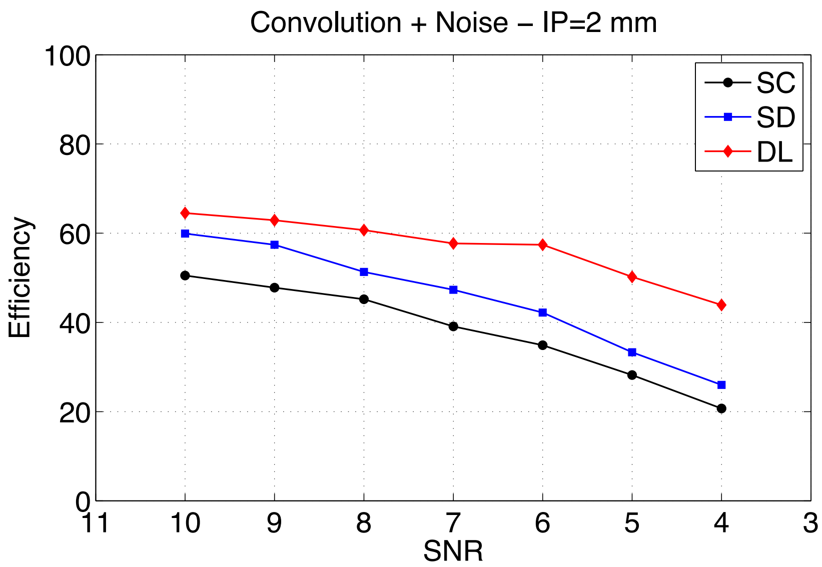


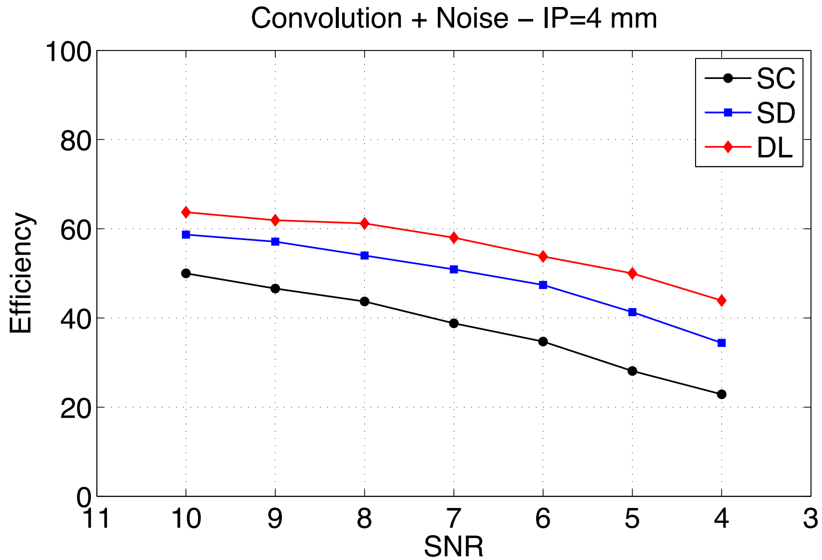
6: DL algorithm efficiency – Convolution + Noise

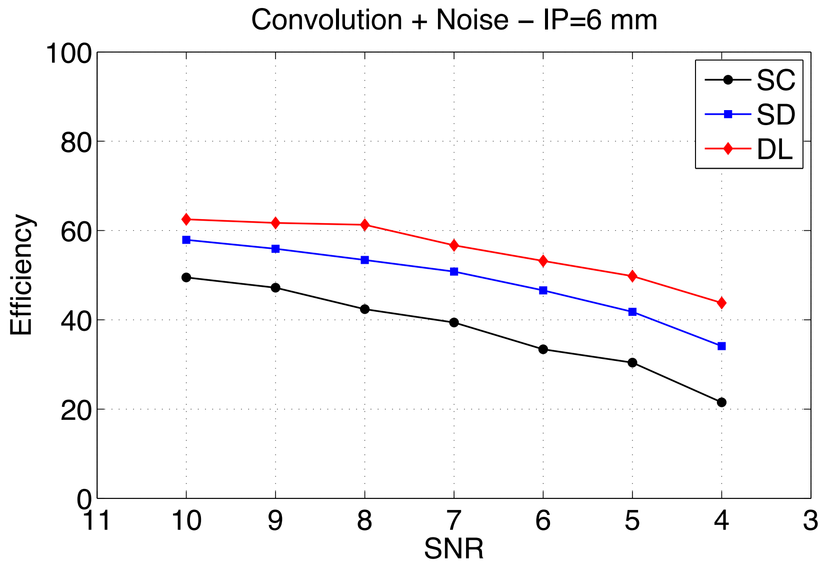


SC, SD and DL algorithms efficiency

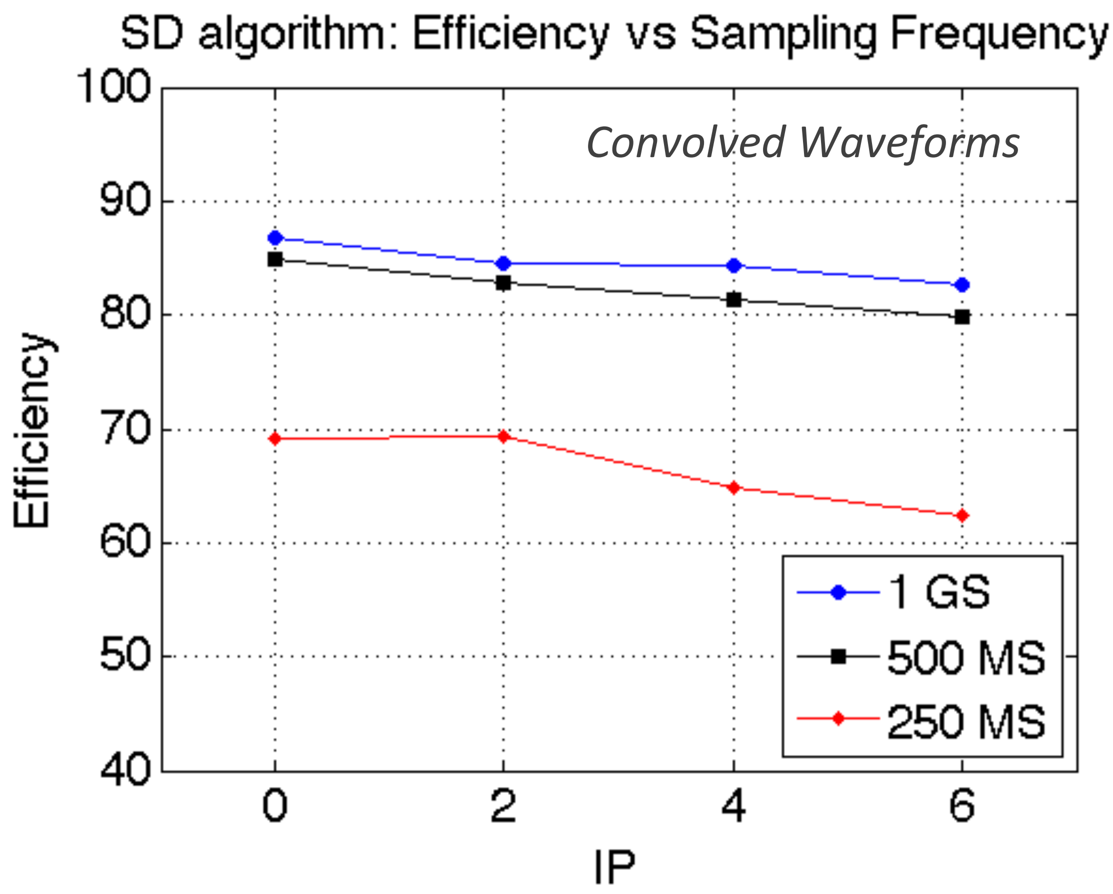








SD: Efficiency vs Sampling Frequency



Conclusions

- *We have evaluated the efficiency of 3 CC algorithms using Garfield waveforms.*
  - *SC → Simple Comparison*
  - *SD → Slope Detection*
  - *DL → Delay Line*

- *For each algorithm the efficiency has been evaluated for the*
  - *"pure" Garfield waveform + noise*
  - *Garfield and FE response convolved waveform*
  - *Garfield and FE convolved waveform + noise*

- *Simulations show that CC efficiency is dominated by SNR*
  - *the use very high BW preamplifiers (> 150 - 200 MHz BW) and GSPS digitizers have a negligible effect on the clusters detection efficiency*

- *No safe operation region (efficiency 'plateau') can be inferred from efficiency plots*
  - *How could we monitor system stability ?*

- *Achievable SNR is bound to the front-end (sense wire termination resistor, sense wire resistance, preamplifier) and picked-up noise*
  - *ProtoII (global) readout noise ≈ 4.5 mV rms ≈ 0.6 fC rms (Pre gain ≈ 7 mV/fC) → SNR = 10 corresponds to a 6 fC single electron cluster collected charge*
  - *6 fC collected charge corresponds to a full delivered charge ≈ 2 (wire charge division) x ≈ 3.3 (assuming a 30% of charge collection) → 6 x 6.6 ≈ 40 fC ≈ 2.5 x 105 (moreover you have to add a safety factor for gas gain fluctuations …)*