Determination of Optimal Integration Parameters for Pulse Shape Discrimination in Nuclear Physics Experiments

Matthew Drury

Michael Hall

Justin Proctor

Southern Illinois University Edwardsville
VLSI Design Research Laboratory
ECE552

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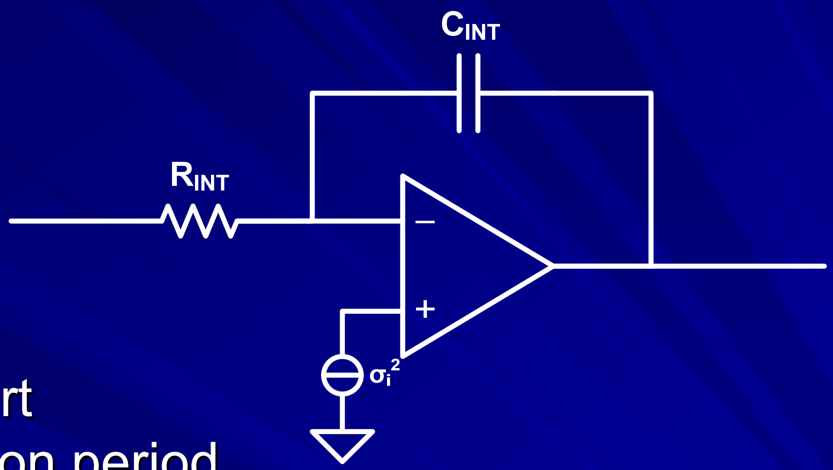
Overview

- Design of a Pulse Shape Discrimination (PSD) IC used in future experiments by Washington University researchers.
- Goal: To discriminate with certainty between multiple particles in a nuclear physics experiment.
- Researchers must choose optimal *delays* and *widths* for the integrators on the PSD IC in order to discriminate the best.

Noise Sources



- ***Poisson*** – noise due to random arrival of discrete electrons
- ***Electronics Noise***
  - ***Jitter*** – noise created by an uncertainty in the integration start time and in the width of integration period
  - ***RI*** – thermal noise from the integrating resistor sampled onto the integrating capacitor
  - ***OTA*** – thermal and 1/f noise of the op amp sampled onto the integrating capacitor
  - ***OTA (+)*** – continuous additive input-referred thermal and 1/f noise of the op amp
- ***ADC*** – quantization noise of a 12-bit converter

Analytical Predictions of Variance of Angular PSD Plots

$$\mathrm{var}(\theta) = \frac{\sin^2 2\theta}{4} \cdot \left[\frac{1}{SNR_A^{\,2}} + \frac{1}{SNR_B^{\,2}} \right]$$

$$FOM = \frac{\left|\theta_1 - \theta_0\right|}{\sqrt{\mathrm{var}(\theta_1) + \mathrm{var}(\theta_0)}}$$

- Variance of angular PSD plot depends on the signal-to-noise ratio of the A (early gate) and B integrators (late gate).
- Small signal-to-noise ratios, which correspond to low-energy particles, results in a larger variance in angle which is consistent with simulation.
- Figure of merit (FOM) is computed as the difference between the means divided by the square root of the sum of the variances.

Optimization

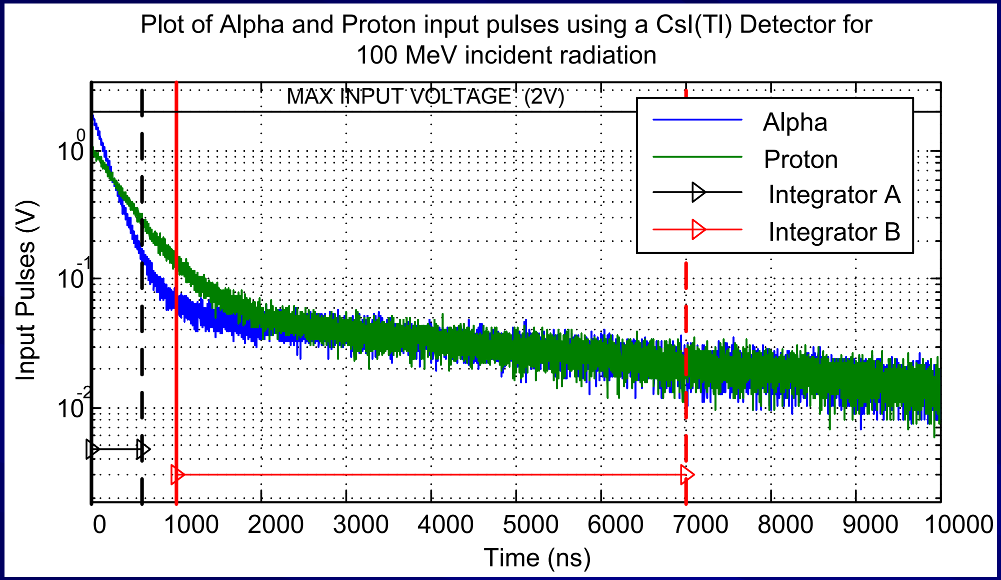
- Naïve Random Optimization
  - Constrained initial guesses for 4 input parameters (DA, WA, DB, WB) so that it would not search unrealistic regions.
  - Randomly pick N guesses.
  - For each guess, find the local maximum of the Figure of Merit (FOM) using MATLAB's *fminsearch* function (unconstrained optimization function).
- Optimized at 1 MeV
- Time constants were chosen for the integrators to ensure that we get as close to 1 V at the output for at least one of the particles
- Chose time constants that ensure we get as close to full scale outputs at 100 MeV for CsI(TI) and 10 MeV for Liquid Scintillator.

Optimization Results

- CsI(Tl)
- Input Parameters
  - Energy = 1 MeV
  - EMax = 100 MeV
  - Guesses = 10,000
  - TauA = 400 ns
  - TauB = 200 ns
- Results
  - FOM = 17.504
  - DA = 0 ns
  - WA = 239 ns
  - DB = 400 ns
  - WB = 857 ns
- Max Voltage at Output
  - VA_{proton} = 0.489 V
  - VB_{proton} = 0.915 V
  - VA_{alpha} = 0.750 V
  - VB_{alpha} = 0.512 V

- Liquid Scintillator
- Input Parameters
  - Energy = 1 MeV
  - EMax = 10 MeV
  - Guesses = 10,000
  - TauA = 20 ns
  - TauB = 4 ns
- Results
  - FOM = 5.304
  - DA = 0 ns
  - WA = 14 ns
  - DB = 44 ns
  - WB = 86 ns
- Max Voltage at Output
  - VA_{gamma} = 0.777 V
  - VB_{gamma} = 0.063 V
  - $VA_{neutron}$ = 0.720 V
  - $VB_{neutron}$ = 0.197 V

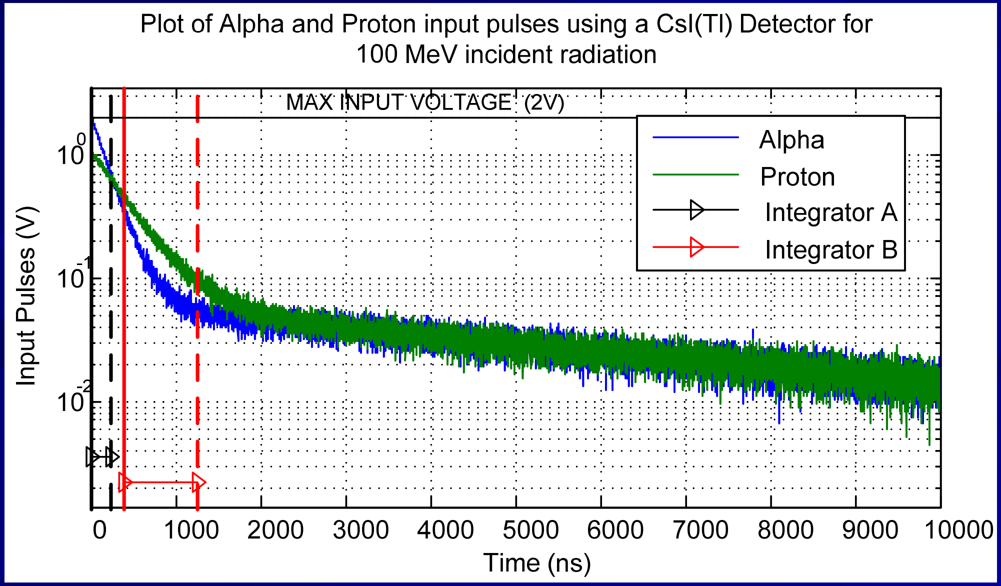
Integration Regions (CsI)



Before Optimization

- Detector: CsI(Tl)
- Integrators:

DA = 0 ns	WA = 600 ns
DB = 1000 ns	WB = 6000 ns
τ_A = 1000 ns	τ_B = 400 ns

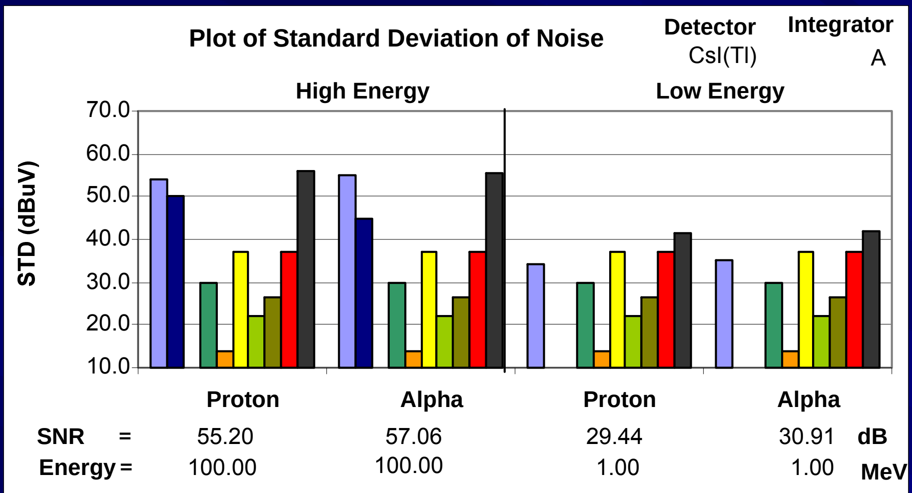


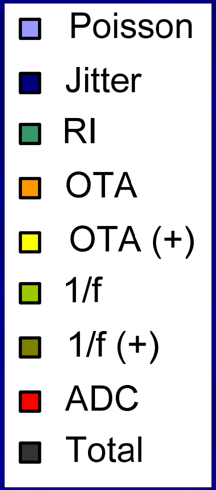
After Optimization

- Detector: CsI(Tl)
- Integrators:

DA = 0 ns	WA = 239 ns
DB = 400 ns	WB = 857 ns
τ_A = 400 ns	τ_B = 200 ns

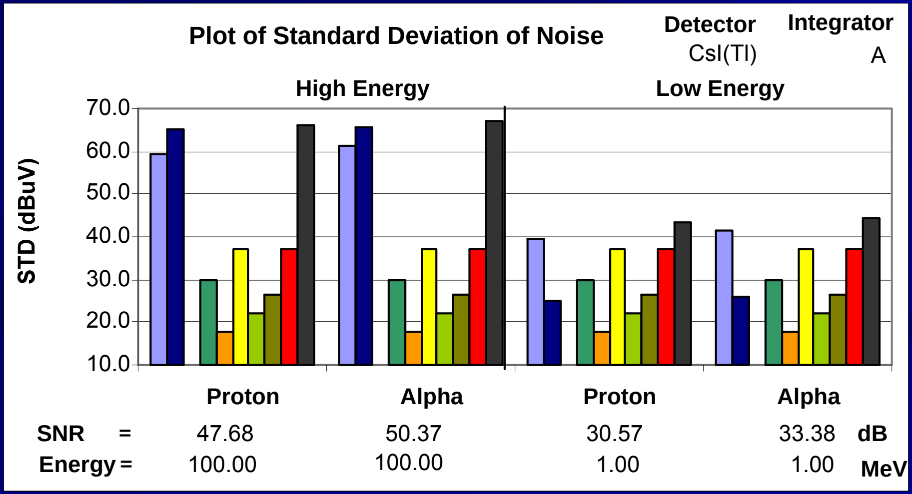
Relative Importance of Noise Sources on Performance for CsI(Tl) Detector





Before Optimization

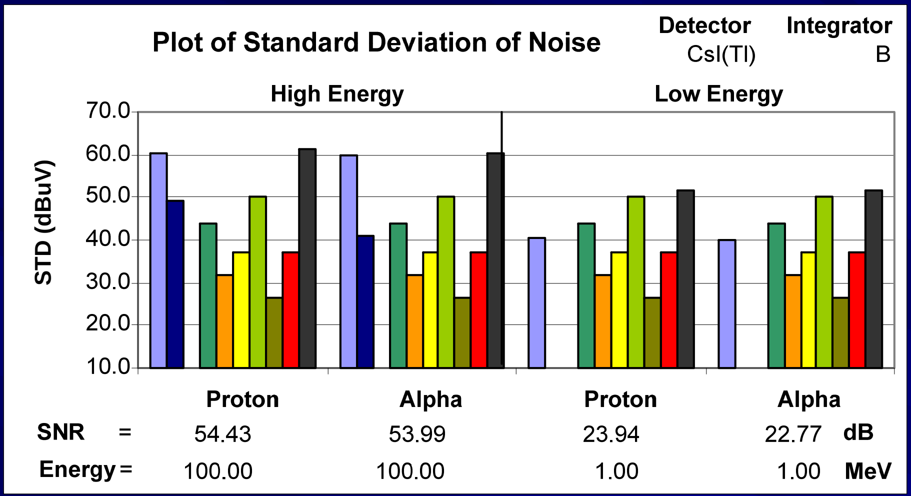
- Detector: CsI(Tl)
- Integrator (A)
  - DA = 0 ns, WA = 600 ns
  - τ_A = 1000 ns
- CI = 10pF
- Jitter
  - Start: 1.00 ns (underestimation)
  - Period: 0.50 ns
- ADC: 12 bit



After Optimization

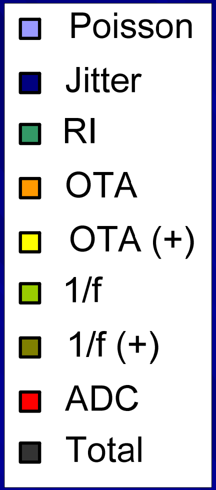
- Detector: CsI(Tl)
- Integrator (A)
  - DA = 0 ns, WA = 239 ns
  - τ_A = 400 ns
- CI = 10pF
- Jitter
  - Start: 1.00 ns
  - Period: 0.50 ns
- ADC: 12 bit

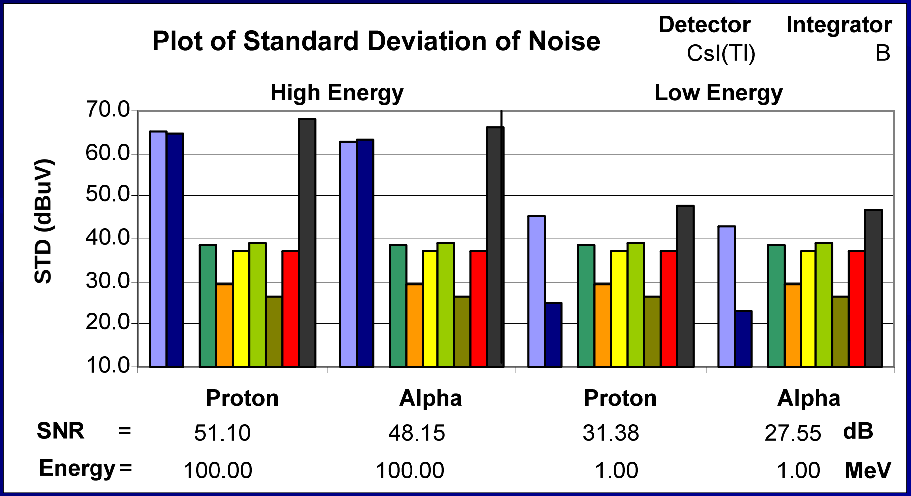
Relative Importance of Noise Sources on Performance for CsI(Tl) Detector



Before Optimization

- Detector: CsI(Tl)
- Integrator (B)
  - DB = 1000 ns, WB = 6000 ns
  - τ_B = 400 ns
- Cl = 10pF
- Jitter
  - Start: 1.00 ns (underestimation)
  - Period: 0.50 ns
- ADC: 12 bit

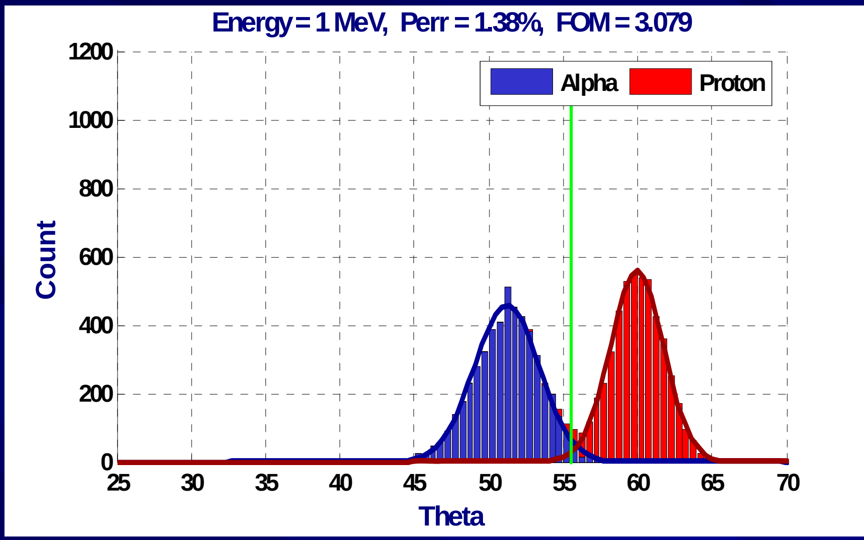


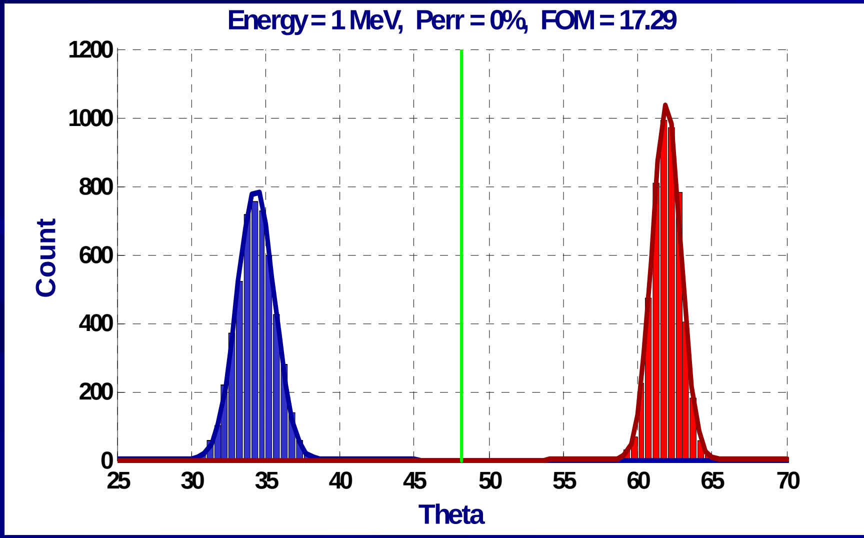


After Optimization

- Detector: CsI(Tl)
- Integrator (B)
  - DB = 400 ns, WB = 857 ns
  - τ_B = 200 ns
- Cl = 10pF
- Jitter
  - Start: 1.00 ns
  - Period: 0.50 ns
- ADC: 12 bit

Angular PSD Plots (CsI)





Before Optimization

- Detector: CsI(Tl)
- Integrators:
  - DA = 0 ns WA = 600 ns
  - DB = 1000 ns WB = 6000 ns
  - τ_A = 1000 ns τ_B = 400 ns
- 5000 realizations
- Includes all noise sources
- FOM = 3.079

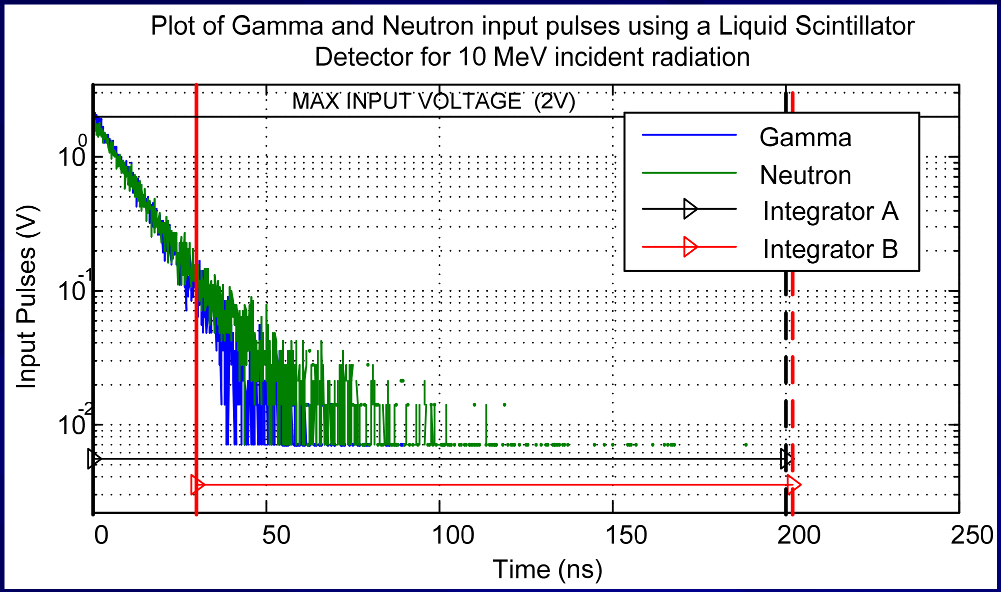
After Optimization

- Detector: CsI(Tl)
- Integrators:
  - DA = 0 ns WA = 239 ns
  - DB = 400 ns WB = 857 ns
  - τ_A = 400 ns τ_B = 200 ns
- 5000 realizations
- Includes all noise sources
- FOM = 17.29

Summary of CsI(Tl) Optimization Results

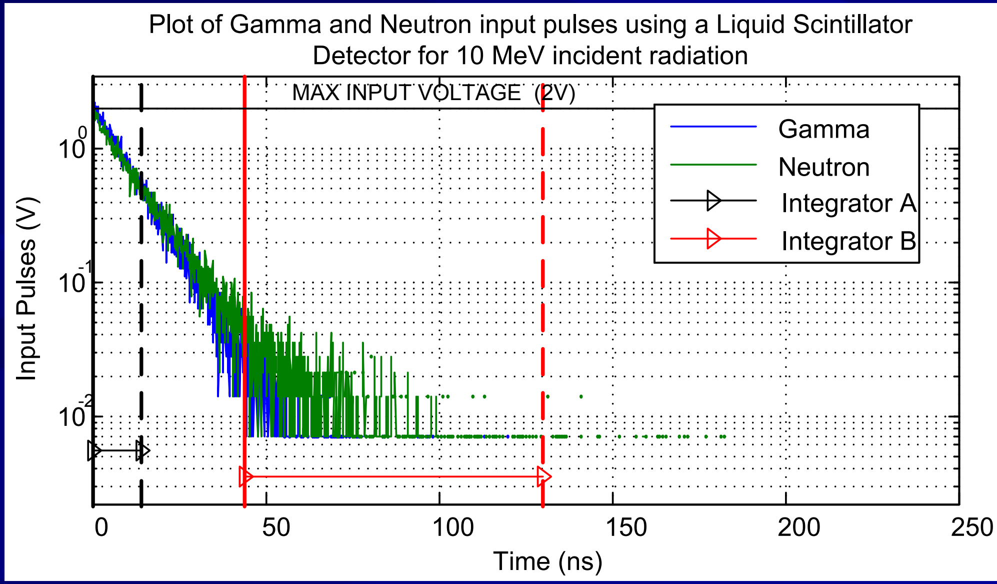
- FOM was improved by the optimizer by
  - Separating the means
  - Narrowing the variances
- This was accomplished by
  - Improving the SNR at low energy while decreasing the SNR at high energy. After optimization the noise is predominantly Poisson. Electronics noise has been made less signifcant.
- Note that jitter related noise was actually increased, but at a rate lower than the signal.
- The optimizer reveals that integrating in the tail region is sub-optimal.
- The energy at which the probability of error is 1%
  - Before optimization: 1.05 MeV
  - After optimization: 145 keV
- SIGNIFICANT IMPROVEMENT IN PERFORMANCE.

Integration Regions (Liquid Scintillator)



Before Optimization

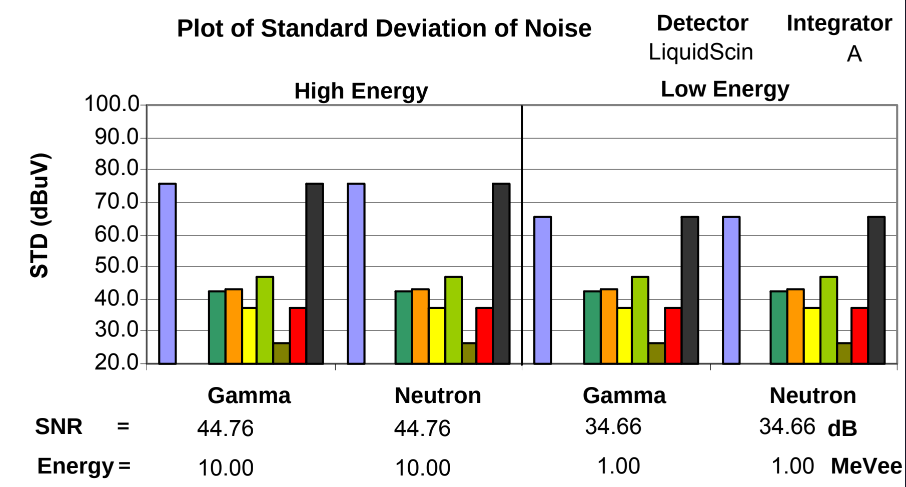
- Detector: Liquid Scintillator
- Integrators:
  - DA = 0 ns WA = 200 ns
  - DB = 30 ns WB = 172 ns
  - τ_A = 20 ns τ_B = 4 ns

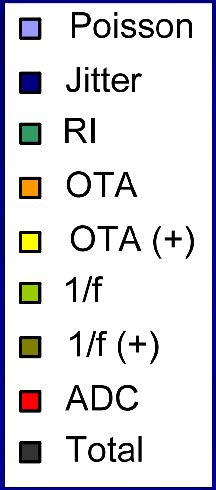


After Optimization

- Detector: Liquid Scintillator
- Integrators:
  - DA = 0 ns WA = 14 ns
  - DB = 44 ns WB = 86 ns
  - τ_A = 20 ns τ_B = 4 ns

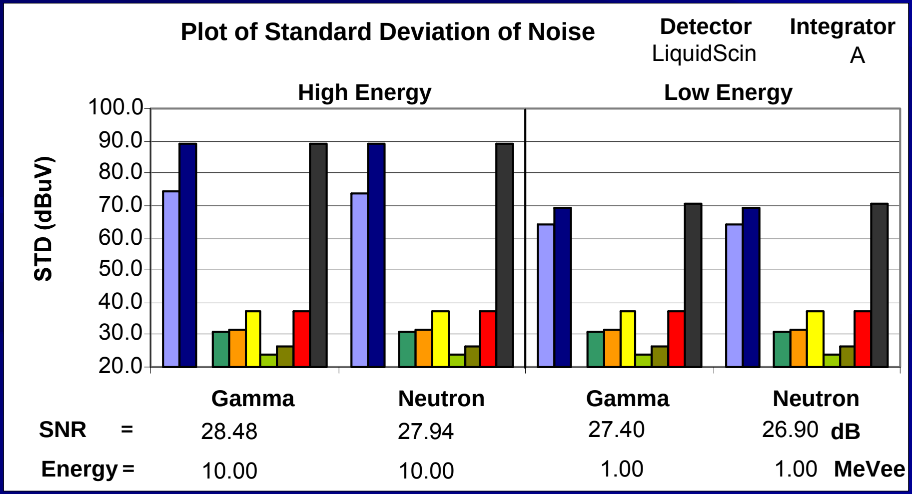
Relative Importance of Noise Sources on Performance for Liquid Scintillator Detector





Before Optimization

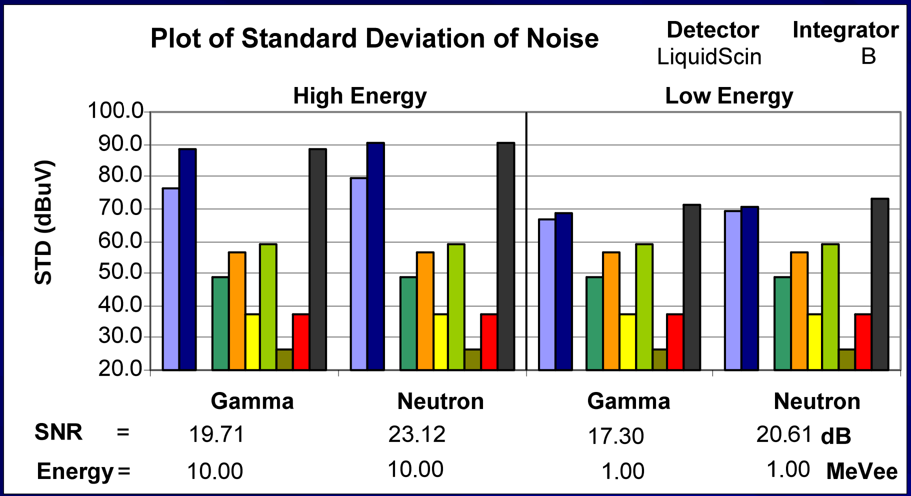
- Detector: Liquid Scintillator
- Integrator (A)
  - DA = 0 ns, WA = 200 ns
  - τ_A = 20 ns
- CI = 10pF
- Jitter
  - Start: 1.00 ns
  - Period: 0.50 ns
- ADC: 12 bit



After Optimization

- Detector: Liquid Scintillator
- Integrator (A)
  - DA = 0 ns, WA = 14 ns
  - τ_A = 20 ns
- CI = 10pF
- Jitter
  - Start: 1.00 ns
  - Period: 0.50 ns
- ADC: 12 bit

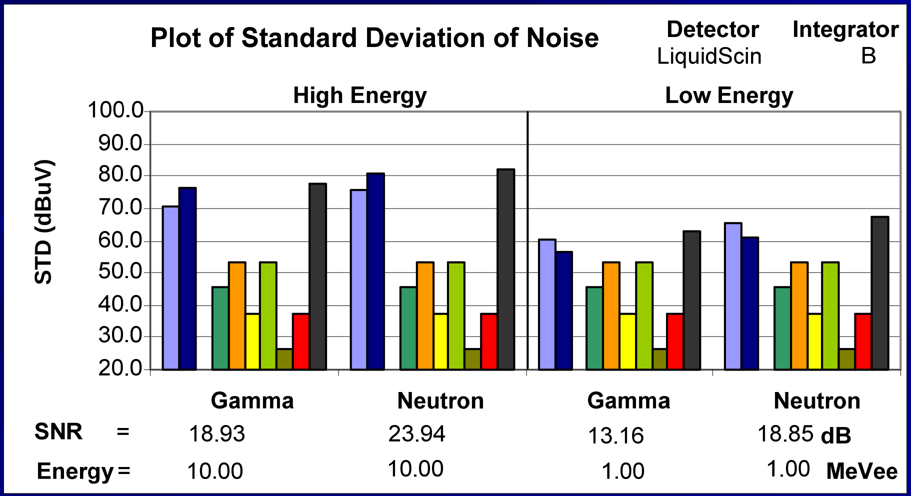
Relative Importance of Noise Sources on Performance for Liquid Scintillator Detector



Before Optimization

- Detector: Liquid Scintillator
- Integrator (B)
  - DB = 30 ns, WB = 172 ns
  - τ_B = 4 ns
- CI = 10pF
- Jitter
  - Start: 1.00 ns
  - Period: 0.50 ns
- ADC: 12 bit

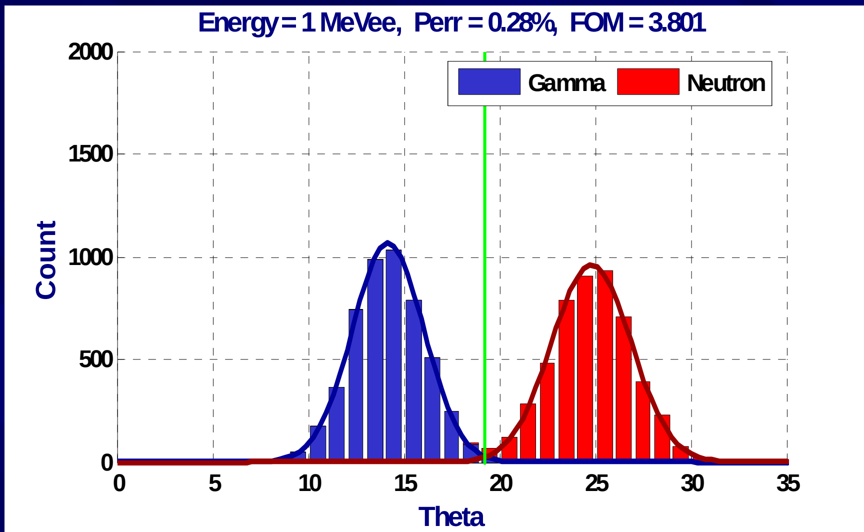
- Poisson
- Jitter
- RI
- OTA
- OTA (+)
- 1/f
- 1/f (+)
- ADC
- Total

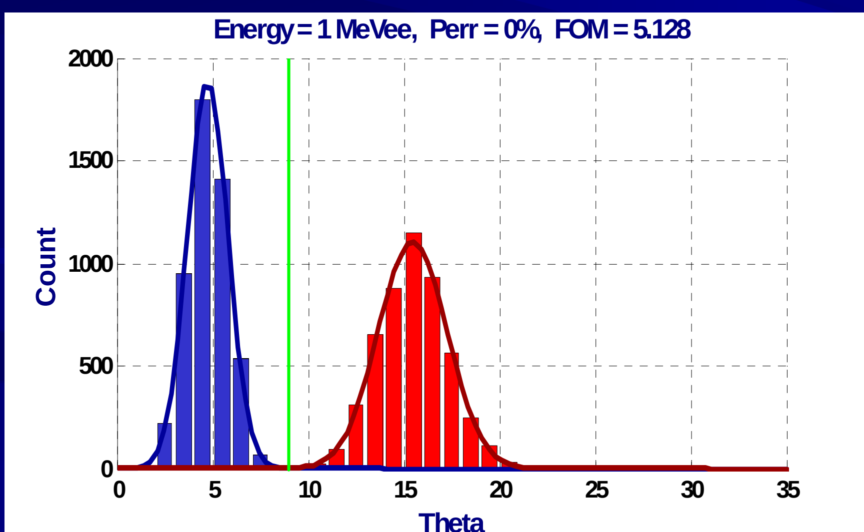


After Optimization

- Detector: Liquid Scintillator
- Integrator (B)
  - DB = 44 ns, WB = 86 ns
  - τ_B = 4 ns
- CI = 10pF
- Jitter
  - Start: 1.00 ns
  - Period: 0.50 ns
- ADC: 12 bit

Angular PSD Plots (Liquid Scintillator)





Before Optimization

- Detector: Liquid Scintillator
- Integrators:
  - DA = 0 ns WA = 200 ns
  - DB = 30 ns WB = 172 ns
  - τ_A = 20 ns τ_B = 4 ns
- 5000 realizations
- Includes all noise sources
- FOM = 3.801

After Optimization

- Detector: Liquid Scintillator
- Integrators:
  - DA = 0 ns WA = 14 ns
  - DB = 44 ns WB = 86 ns
  - τ_A = 20 ns τ_B = 4 ns
- 5000 realizations
- Includes all noise sources
- FOM = 5.128

Summary of Liquid Scintillator Optimization Results

- Unlike with the CsI detector, the optimizer was unable to improve FOM by separating the means and improving SNR.
- SNR decreased slightly even though we saw a decrease in noise.
- FOM was improved by
  - Shifting the means to the left
- This resulted in a decrease in θ for the two particles which gave us a decrease in the variance of θ.
- The energy at which the probability of error is 1%
  - Before optimization: 650 keV
  - After optimization: 400 keV
- In order to get a real improvement, we would need smaller time constants so as to get more gain. This is not feasible on the IC.

- MODEST IMPROVEMENT IN PERFORMANCE.