Design Considerations in Systems Employing Multiple Charge Integration for the Detection of Ionizing Radiation

Masters Thesis Defense

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December 13, 2007

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Design Team

Southern Illinois University Edwardsville:

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- Dr. Lee Sobotka (Co-PI)
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- Jon Elson (electronics specialist)

Western Michigan:

- Dr. Mike Famiano (Co-PI)

Research Objective

- Design a custom microchip which can be used by nuclear physicists when they perform experiments.
- In these experiments, physicists use detectors to sense radiation.
- These experiments often require that the physicists identify the type of radiation (α particle, γ-ray, etc) that struck the detector.

NSF Proposal (Funded)

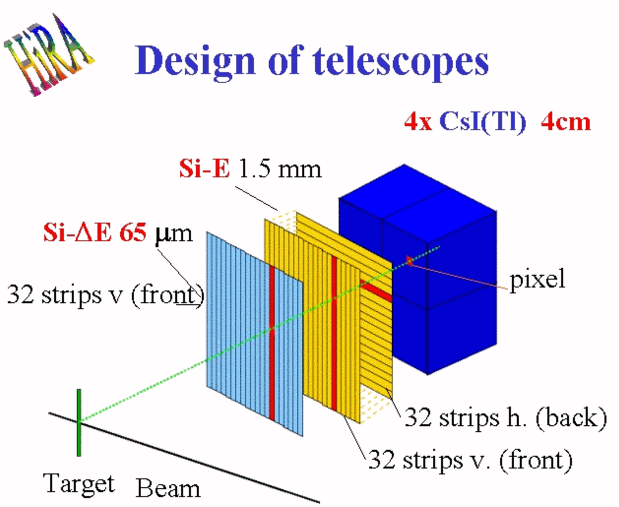
- $200,000 grant funded by NSF from September 2006 to August 2008.
- Design, simulate, and fabricate a custom integrated circuit for particle identification suitable for use with
  - CsI(Tl) (used for charge-particle discrimination)
  - Liquid Scintillator (used for neutron-gamma discrimination)
- 8 channel "prototype" chip
- 16 channel "production" chip
- Funded by NSF grant #06118996.

Intended Applications

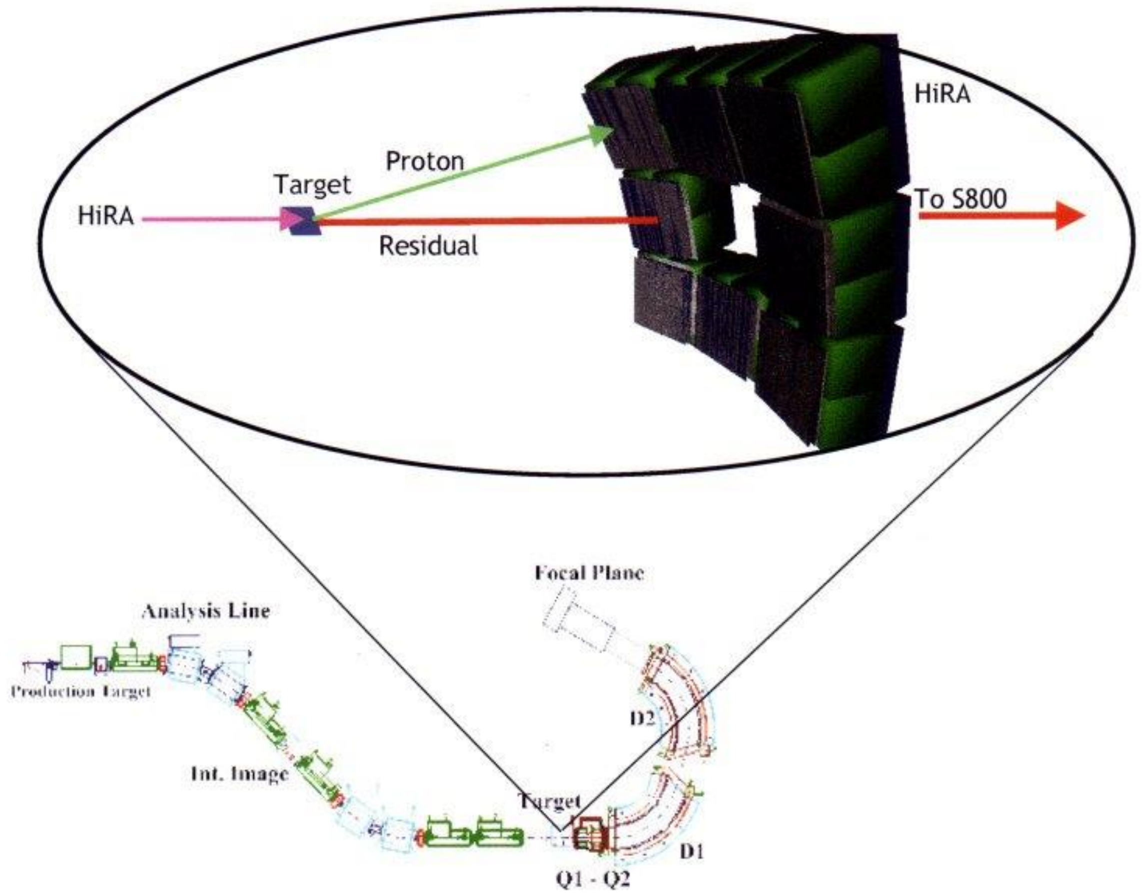
- The chip will be used in an experiment at the National Superconducting Cyclotron Laboratory (NSCL) in Fall 2008 by Washington University collaborators.

- Mass production of PSD technology is actively being sought by our government's Department of Homeland Security.

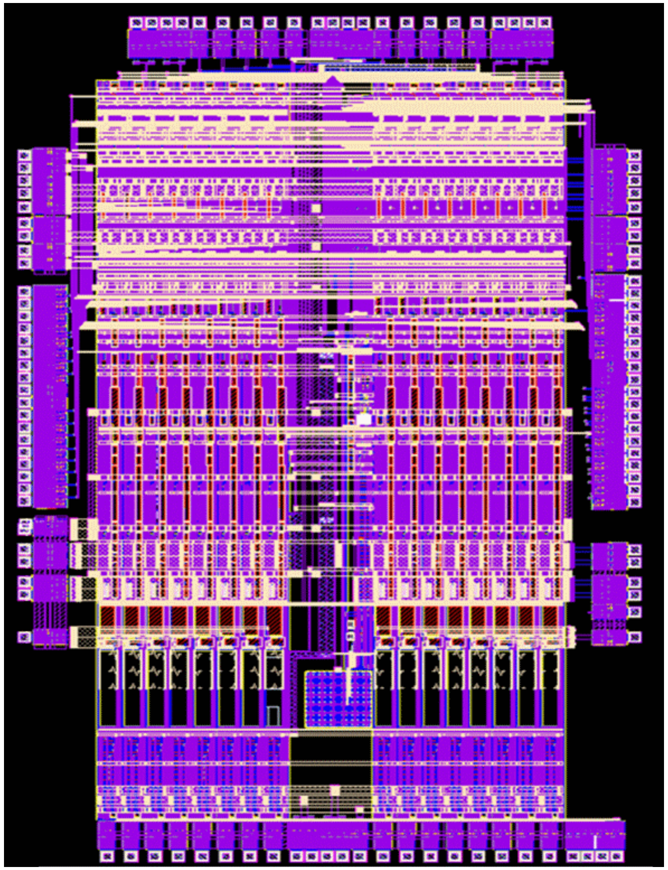
Typical Experiment



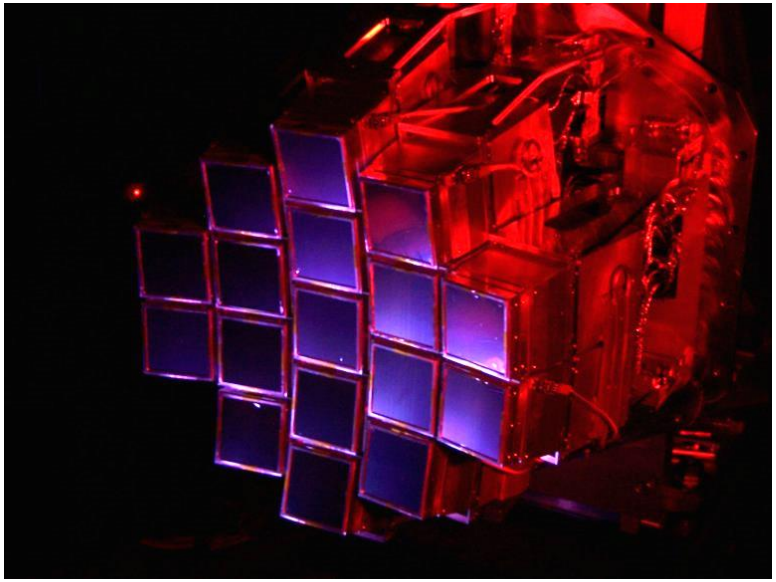
- 20 Telescopes
- 62.3 x 62.3 mm^2 Active Area
- Pitch 1.8 mm
- 1024 Pixels per telescope



Chip and Sensor Array

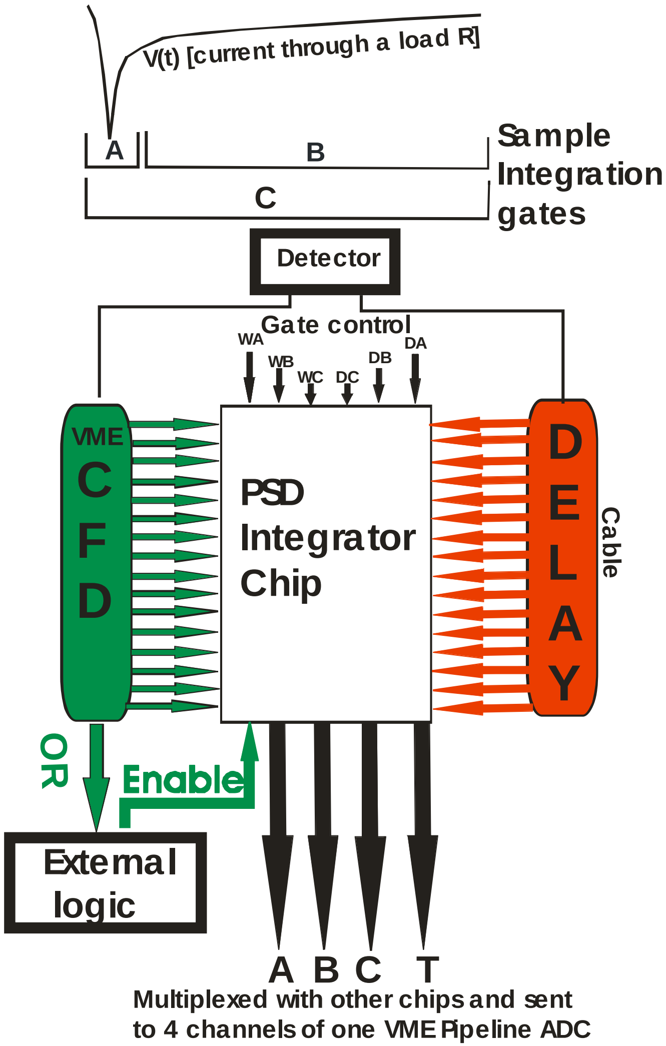


Earlier IC developed in our lab currently being used in Physics experiments around the country



HiRA Detector Array at MSU

Overview of Pulse Shape Discrimination (PSD) System



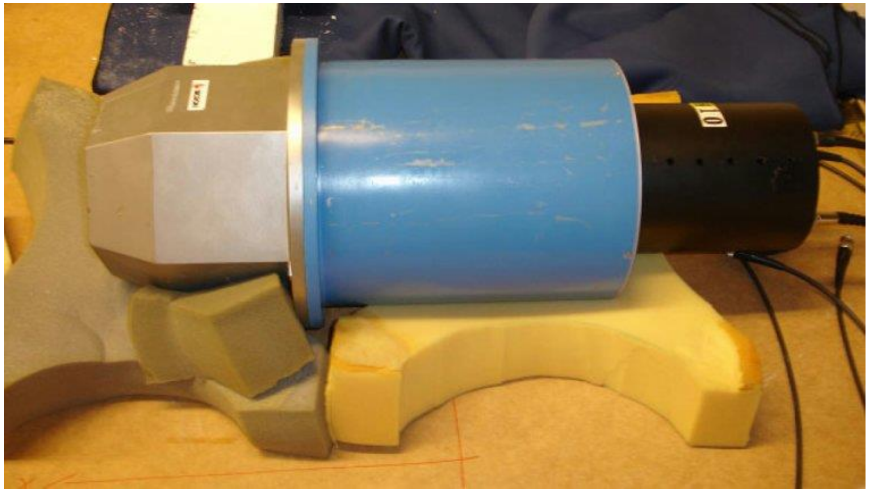
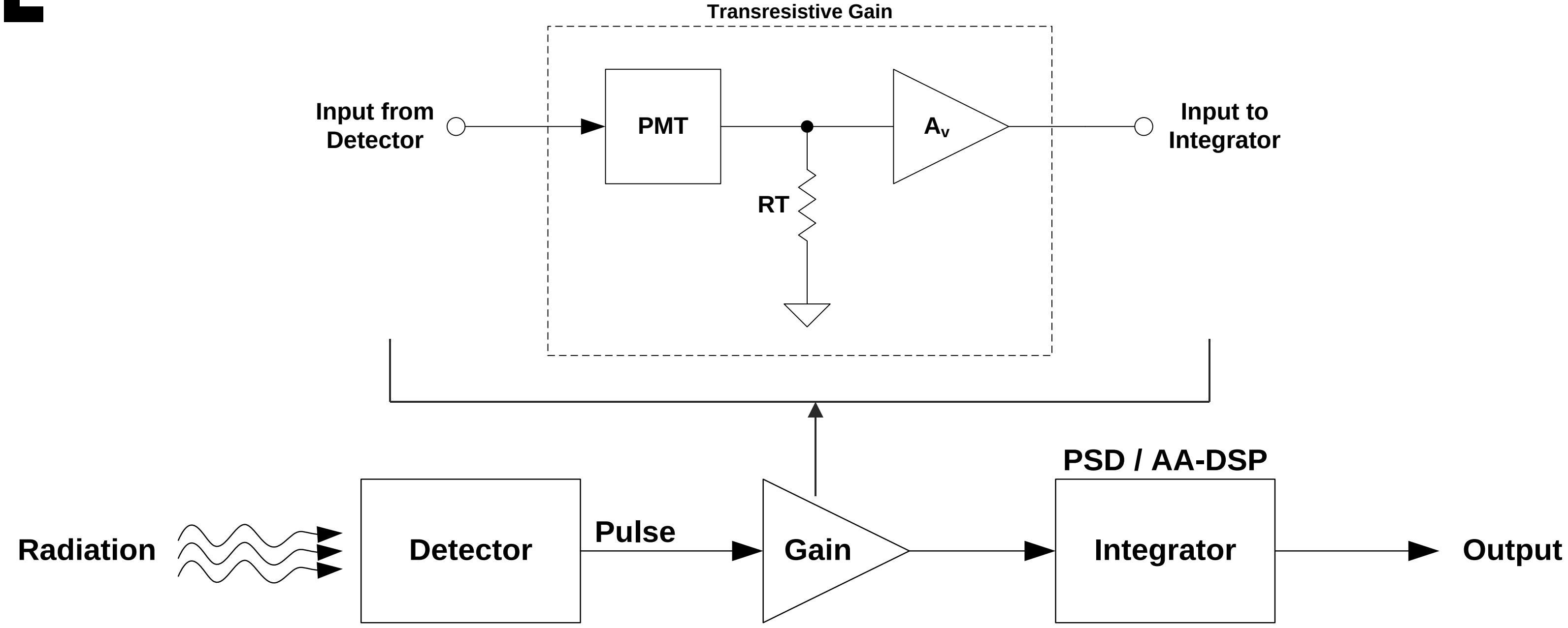


Image taken from a diploma thesis by Mikael Höök titled "Study of the pulse shape as a means to identify neutrons and gammas in a NE213 detector".

- Detector (PMT or photodiode)
- External discriminators (CFDs)
- External delay lines so we can start integrations before arrival of pulse
- External control voltages determine Delay and Width of integration periods
- Outputs A, B, C integrator voltages and relative time, T

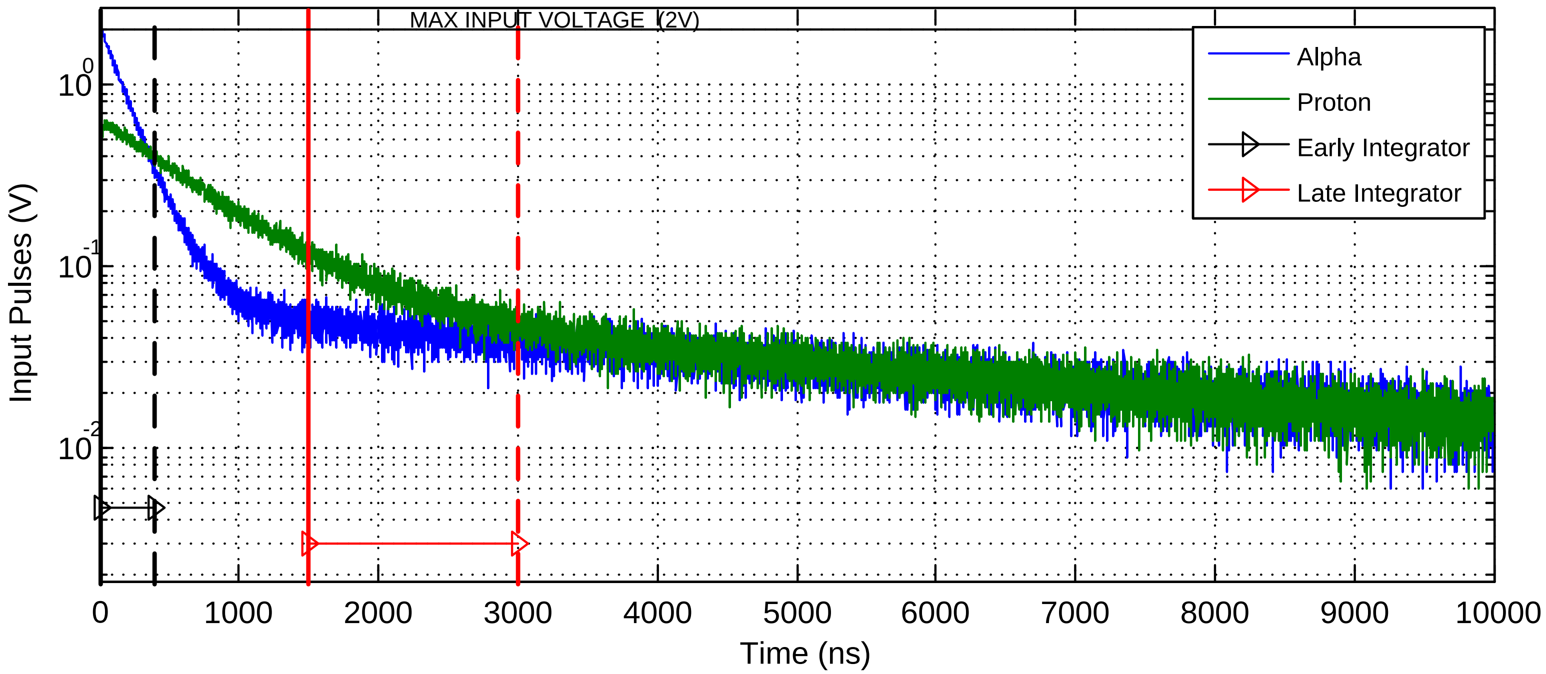
System Model



- Many different detectors can be used.
- The pulse is amplified through a transresistive gain stage.
- It is then integrated over a particular region.

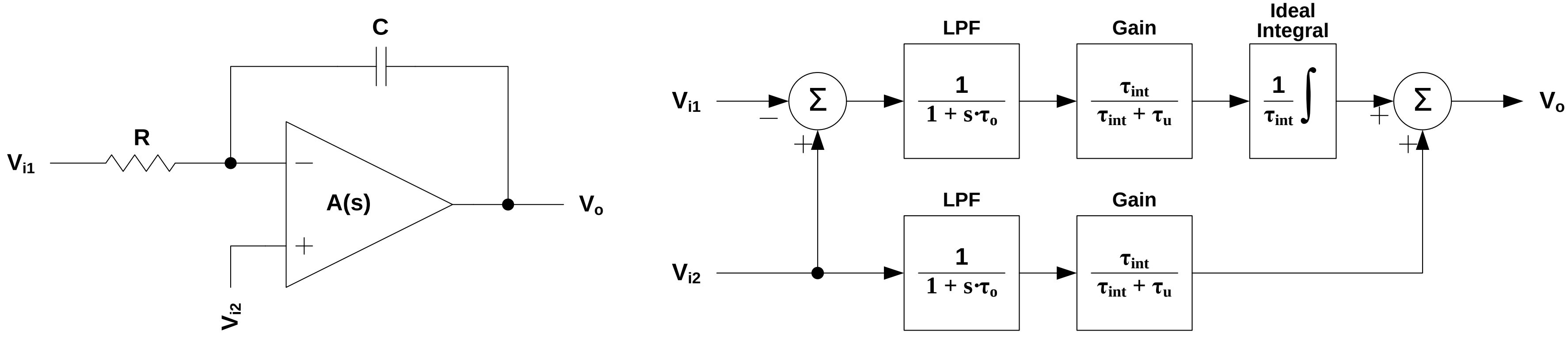
Simulated input pulses for CsI(Tl)

Plot of alpha and proton input pulses using a CsI(Tl) detector for 100 MeV incident radiation



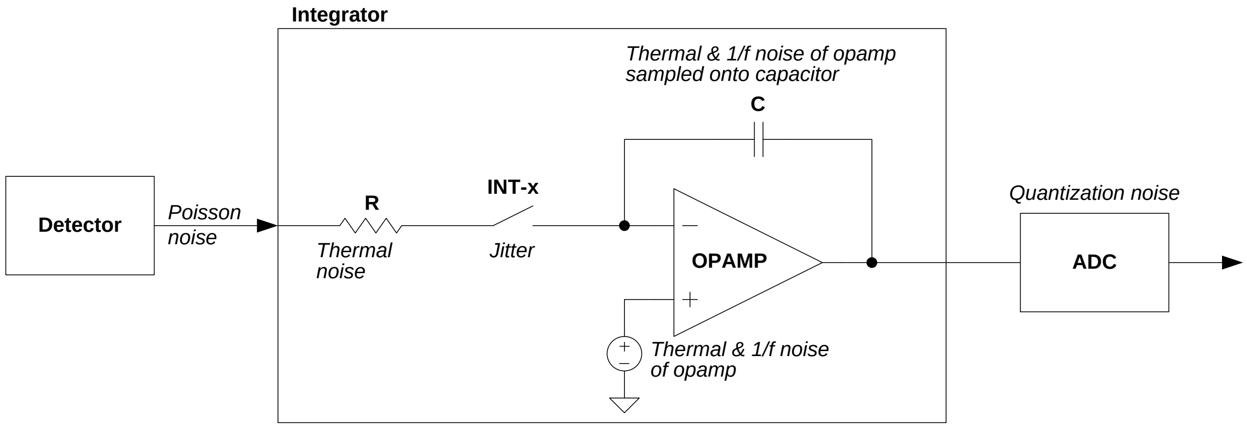
- Integrators
  - Early 0 to 400 ns
  - Late 1500 to 3000 ns
- Integration periods at the beginning of the signal are assumed to start before the pulse (at -5 ns).

Integrator Model



- Simple integrator model with a dominant pole
- Derived response characterizes the integrator and is used for analytical derivations of the system noise

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 the integration period
  - **RI** – thermal noise from the integrating resistor sampled onto the integrating capacitor
  - **OTA_{t+}** – continuous additive input-referred thermal noise of the op amp
  - **$OTA_{t,smpl}$** – thermal noise of the op amp sampled onto the integrating capacitor
  - **OTA_{f+}** – continuous additive input-referred 1/f noise of the op amp
  - **$OTA_{f,smpl}$** – 1/f noise of the op amp sampled onto the integrating capacitor
- **ADC** – quantization noise of an analog-to-digital converter with n-bit resolution

Derived Noise Equations

Poisson: $$\sigma_p{}^2 = \frac{q \cdot Ar_{GAIN}}{\tau_{INT} + \tau_u} \cdot |V_{OUT}|$$

Jitter:

$$VOF_i = E_{rad} \cdot \frac{k_{\det} \cdot q \cdot Ar_{GAIN}}{\tau_{\text{int}} + \tau_u} \cdot \frac{A}{\tau_{Fi} - \tau_{Ri}} \cdot \tau_{Fi} \cdot e^{-\frac{Ti}{\tau_{Fi}}} \cdot \left(1 - e^{-\frac{T}{\tau_F}}\right)$$

$$VOR_i = -E_{rad} \cdot \frac{k_{\det} \cdot q \cdot Ar_{GAIN}}{\tau_{\text{int}} + \tau_u} \cdot \frac{A}{\tau_{Fi} - \tau_{Ri}} \cdot \tau_{Ri} \cdot e^{-\frac{Ti}{\tau_{Ri}}} \cdot \left(1 - e^{-\frac{T}{\tau_{Ri}}}\right)$$

$$\sigma_j{}^2 = \left(\sum_{i=1}^{n} c_{i,Ti}\right)^2 \sigma_{Ti}{}^2 + \left(\sum_{i=1}^{n} c_{i,T}\right)^2 \sigma_T{}^2$$

$$c_{i,Ti} = -\left(\frac{VOF_i}{\tau_{Fi}} + \frac{VOR_i}{\tau_{Ri}}\right)$$

$$c_{i,T} = \frac{VOF_i}{\tau_{Fi}} \frac{e^{-T/\tau_{Fi}}}{1 - e^{-T/\tau_{Fi}}} + \frac{VOR_i}{\tau_{Ri}} \frac{e^{-T/\tau_{Ri}}}{1 - e^{-T/\tau_{Ri}}}$$

where i = 1, 2, …, n for n exponentials

Integrating resistor: $$\sigma_{RI,t}{}^2 = 4 \frac{kT}{C_{INT}} \frac{T}{\tau_{INT}} \left(\frac{\tau_{INT}}{\tau_{INT} + \tau_u}\right)^2$$

OTA:

$$\sigma_{OTA,t}{}^2 = \sigma_{RI,t}{}^2 \frac{RN}{R_{INT}}$$

$$\sigma_{OTA+,t}{}^2 = kT \cdot RN \cdot \frac{1}{\tau_o} \cdot \left(\frac{\tau_{\text{int}}}{\tau_{\text{int}} + \tau_u}\right)^2$$

$$\sigma_{OTA,f}{}^2 = \sigma_{OTA+,f}{}^2 \cdot \left(\frac{T}{\tau_{INT}}\right)^2$$

$$\sigma_{OTA+,f}{}^2 = Kf \cdot \ln\left(\frac{t_{cal}}{\tau_o}\right) \cdot \left(\frac{\tau_{\text{int}}}{\tau_{\text{int}} + \tau_u}\right)^2$$

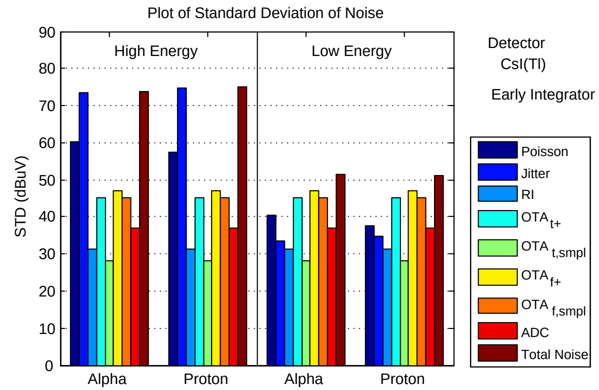
ADC: $$\sigma_{ADC}{}^2 = \frac{1}{12} \left(\frac{VO_{\max}}{2^{ADC_{bits}}}\right)^2$$

Total: $$\sigma_{TOTAL}{}^2 = \sigma_p{}^2 + \sigma_j{}^2 + \sigma_{RI,t}{}^2 + \sigma_{OTA,t}{}^2 + \sigma_{OTA+,t}{}^2 + \sigma_{OTA,f}{}^2 + \sigma_{OTA+,f}{}^2 + \sigma_{ADC}{}^2$$

Noise breakdown for CsI(Tl)

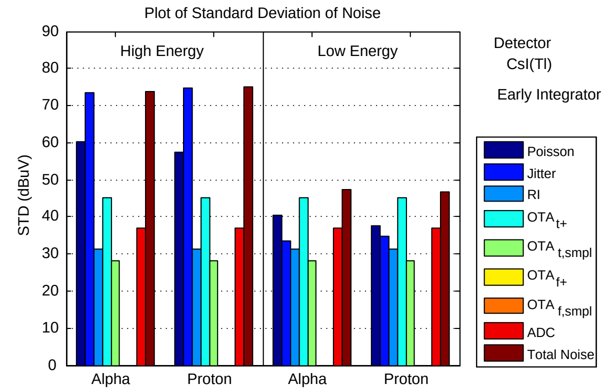
Early Integrator

0 to 400 ns



SNR	=	43.72	36.89	26.21	20.69	dB
Energy	=	100.00	100.00	1.00	1.00	MeV

1/f noise included

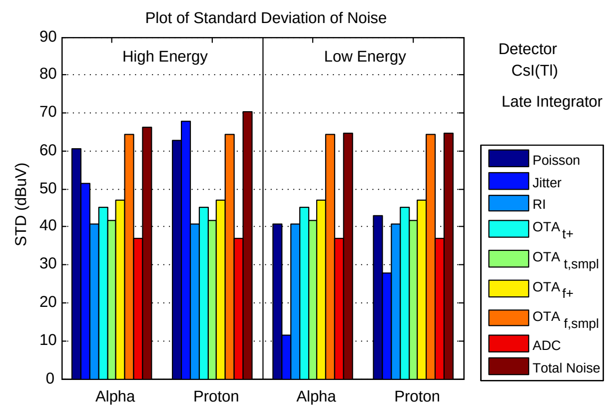


SNR	=	43.74	36.90	30.32	25.04	dB
Energy	=	100.00	100.00	1.00	1.00	MeV

No 1/f noise

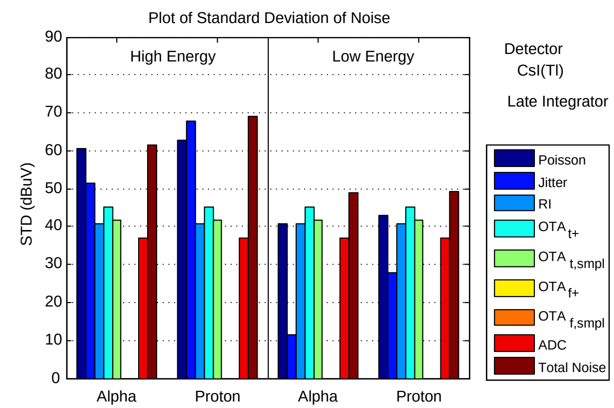
Late Integrator

1500 to 3000 ns



SNR	=	43.96	44.20	5.56	9.96	dB
Energy	=	100.00	100.00	1.00	1.00	MeV

1/f noise included

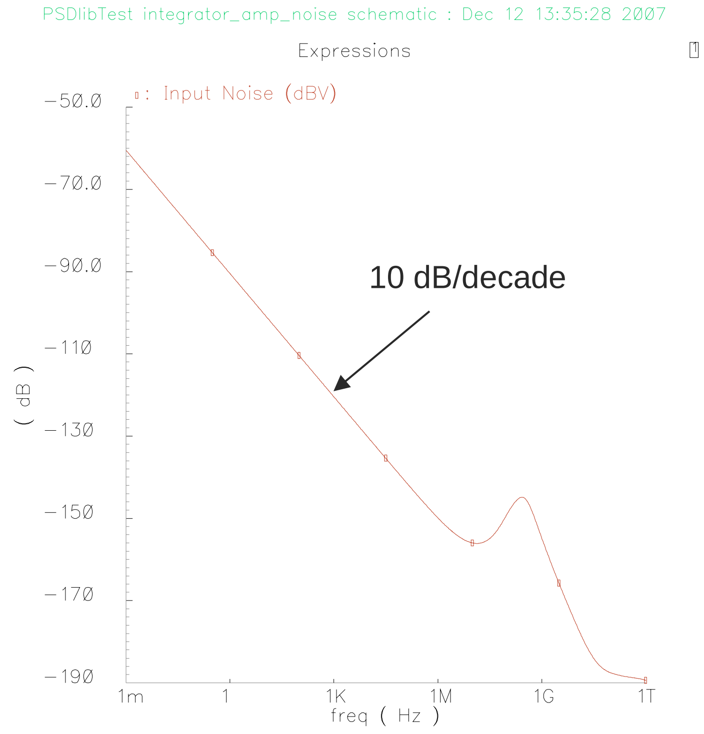


SNR	=	48.81	45.50	21.41	25.36	dB
Energy	=	100.00	100.00	1.00	1.00	MeV

No 1/f noise

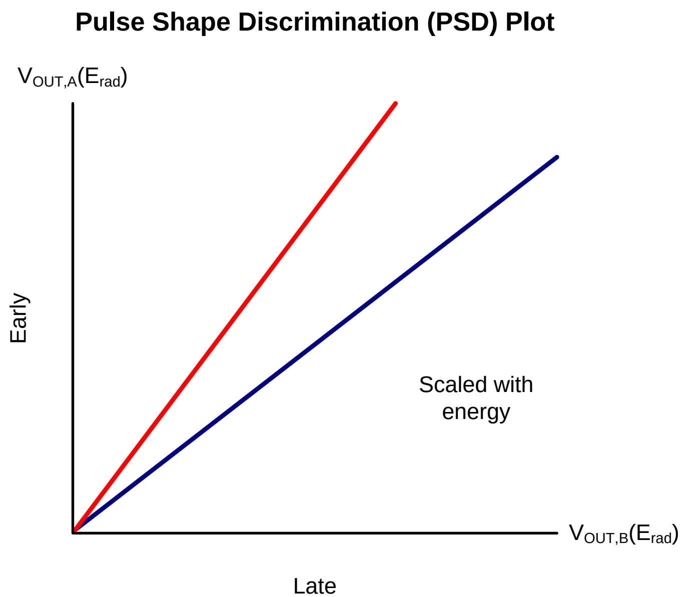
1/f noise

- Currently it represents an unrealistic worst case
- Can be improved by correlated double sampling if mostly constant
- Plan to numerically simulate 1/f noise in order to get an empirical equation



1/f noise spectrum

Analytical Predictions of Variance of Angular PSD Plots

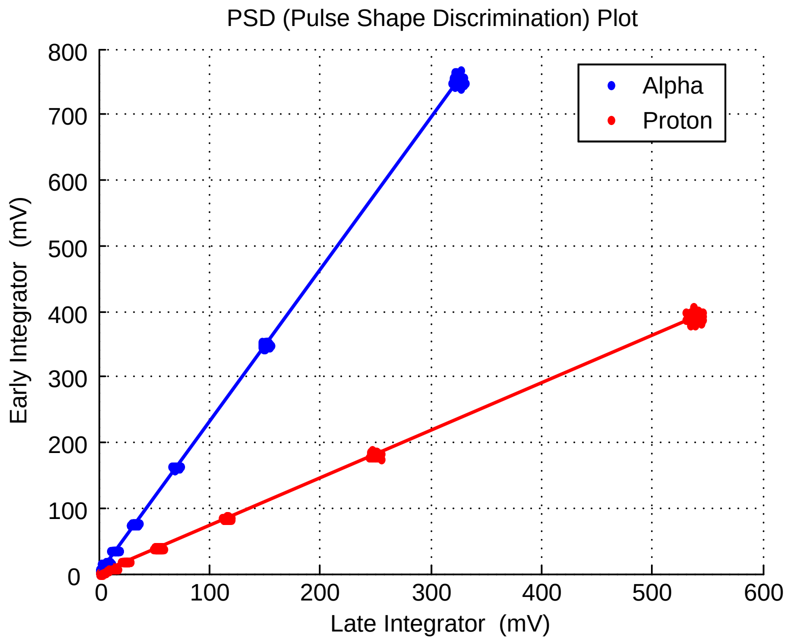


$$\theta = \tan^{-1}\left(\frac{A}{B}\right)$$

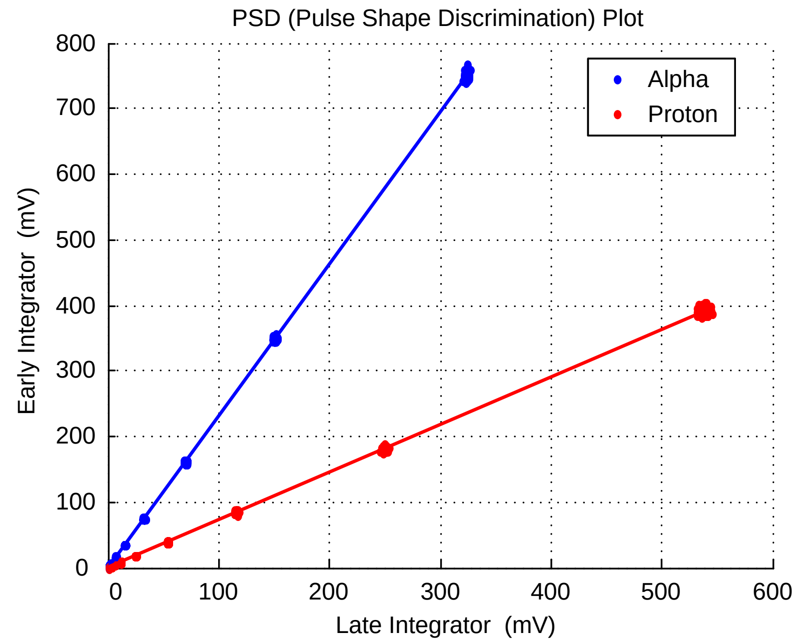
$$\operatorname{var}(\theta) = \frac{\sin^2 2\theta}{4} \cdot \left[\frac{1}{SNR_A^{\;2}} + \frac{1}{SNR_B^{\;2}}\right]$$

- Variance of angular PSD plot depends on the signal-to-noise ratio of the early (A) and late (B) integrators.
- Small signal-to-noise ratios, which correspond to low-energy particles, results in a larger variance in angle which is consistent with simulation.

Pulse shape discrimination plot for CsI(Tl)



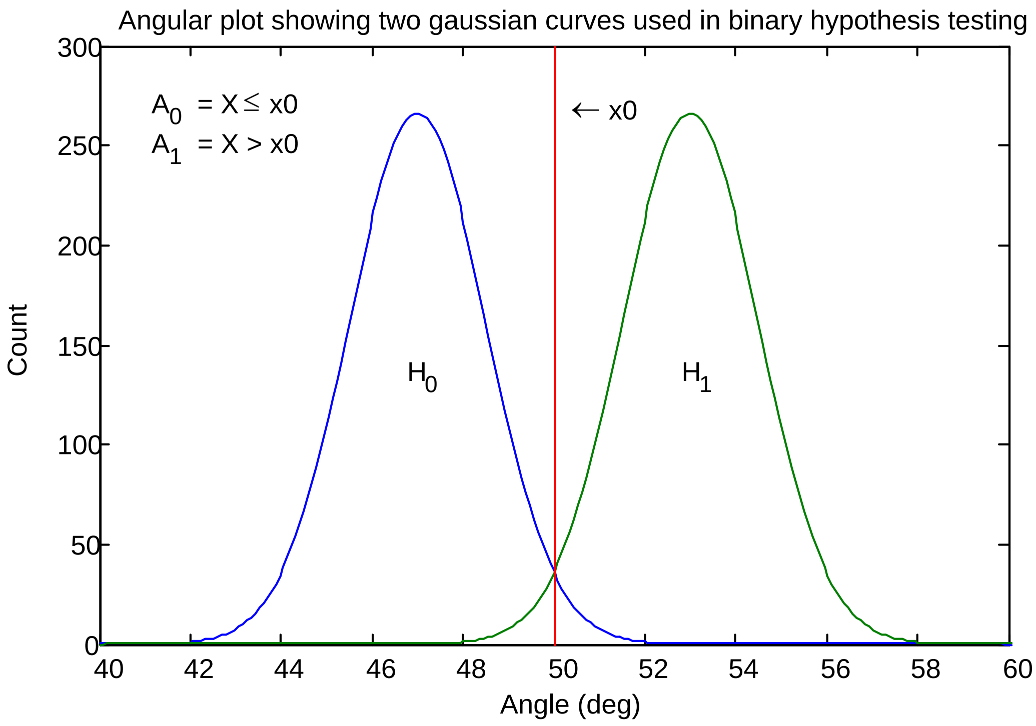
1/f noise included



No 1/f noise

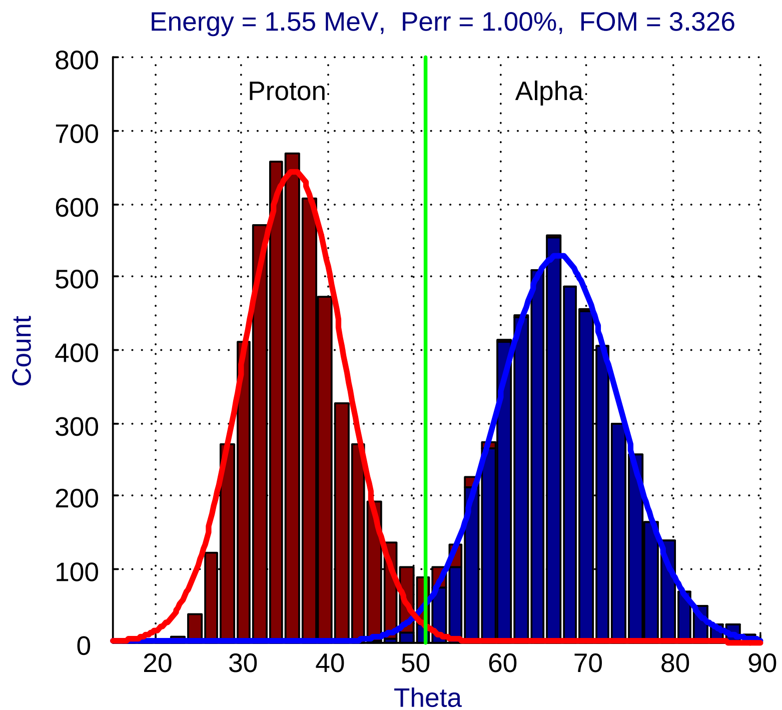
Energy Max: 100 MeV
Includes all noise sources

Hypothesis Testing

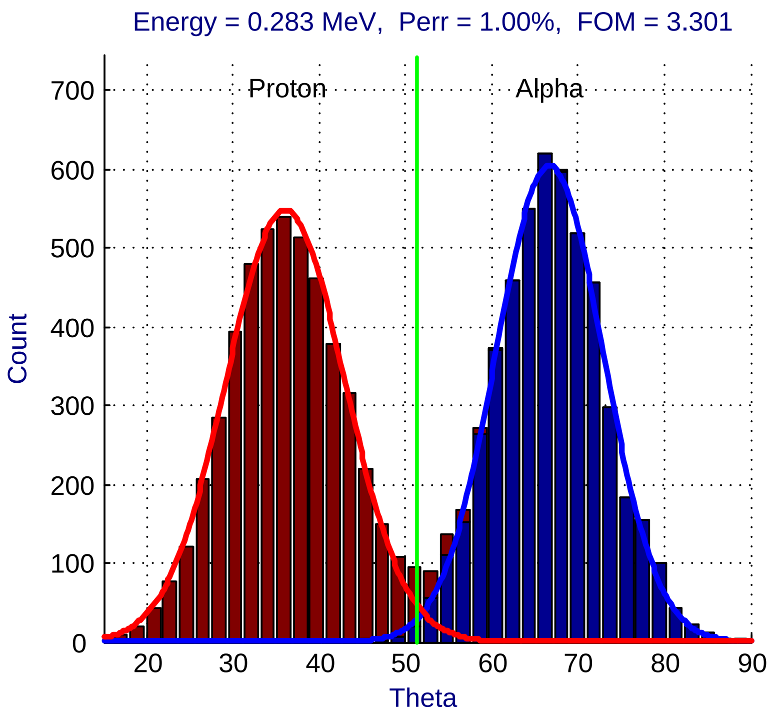


- Use hypothesis testing to calculate the probability of a misclassification of a particle
- Can be used to estimate the dynamic range of the system

Angular histogram plot for CsI(Tl)



1/f noise included



No 1/f noise

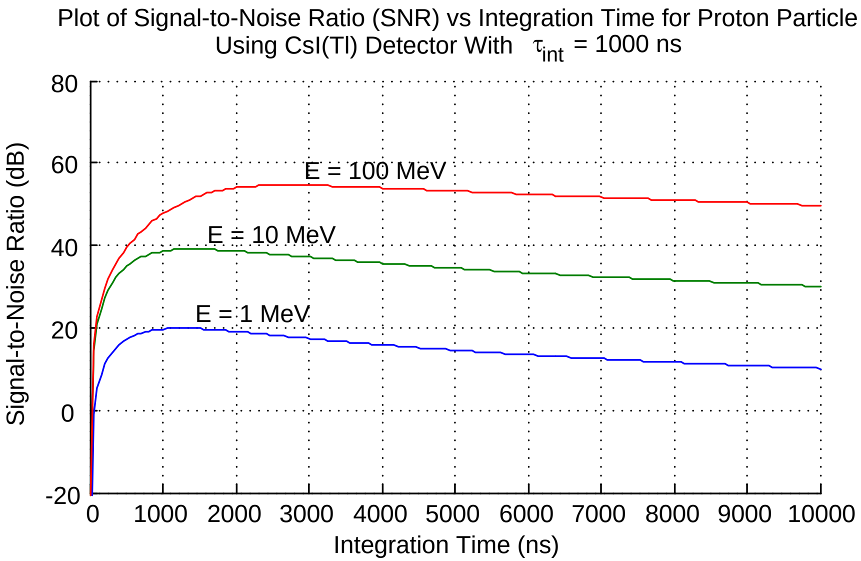
Energy Max: 100 MeV
5000 realizations
Includes all noise sources

Optimization

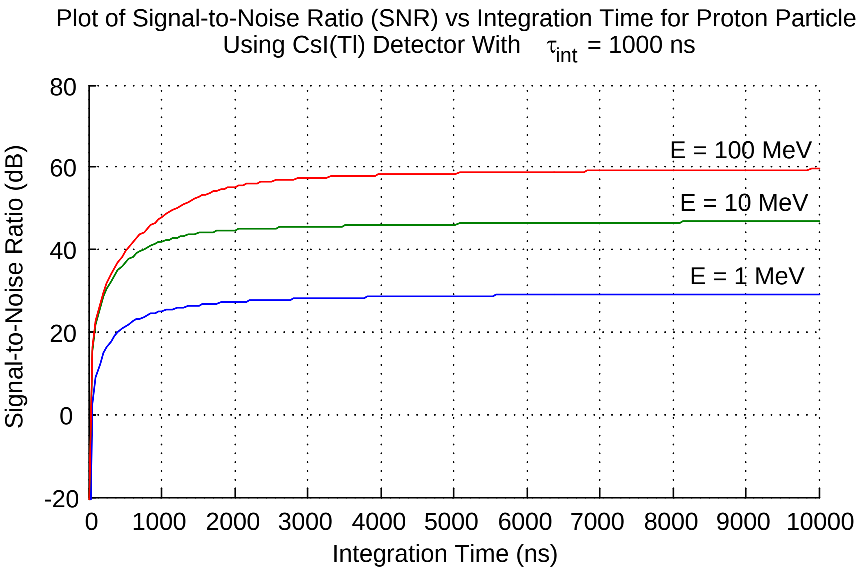
$$FOM = \frac{\left|\theta_1 - \theta_0\right|}{\sqrt{\mathrm{var}\left(\theta_1\right) + \mathrm{var}\left(\theta_0\right)}}$$

- Pulse shape discrimination can be improved by optimizing the integration regions under a pulse.
- Figure of merit (FOM) is computed as the difference between the means divided by the square root of the sum of the variances.
- Maximizing the FOM will improve discrimination by spreading the angles of the particles and reducing noise.

Integrating for energy for CsI(Tl)



1/f noise included



No 1/f noise

* τ_{int} was chosen for the largest energy and integration time

Summary of CsI(Tl)

- CsI(Tl) is a slow detector which produces pulses with long time constants.
- 1/f noise greatly affects system performance in the longer integration regions which is why we need to come up with a better equation.
- For CsI(Tl), we can discriminate between an alpha and a proton particle down to between 283 keV and 1.55 MeV for a 1% probability of a misclassification.

Summary of liquid scintillator

- Liquid scintillator is a fast detector which produces pulses with short time constants and requires more gain.
- 1/f noise also affects the system performance of this detector.
- For liquid scintillator, we can discriminate between a neutron and a gamma particle down to between 535 keVee and 1.44 MeVee for a 1% probability of a misclassification.

Conclusion

- Proposed IC can be used with many different detectors and for many different applications.
- Although the main purpose of this IC is pulse shape discrimination, it can also be used as a general purpose integrator to get energy information.
- Equations were derived that predict the noise at the output of an integrator. The performance of pulse shape discrimination depends on the signal-to-noise ratio of the individual integrators.
- Optimizing the integration regions under a pulse can improve pulse shape discrimination. A figure of merit was defined in order quantify the performance of the PSD system.
- We need a better understanding of 1/f noise to more accurately predict system performance. Correlated double sampling may be necessary to deal with 1/f noise.