NeuPix: A Highly Programmable ASIC for SiPM Readout

CPAD Workshop 2022

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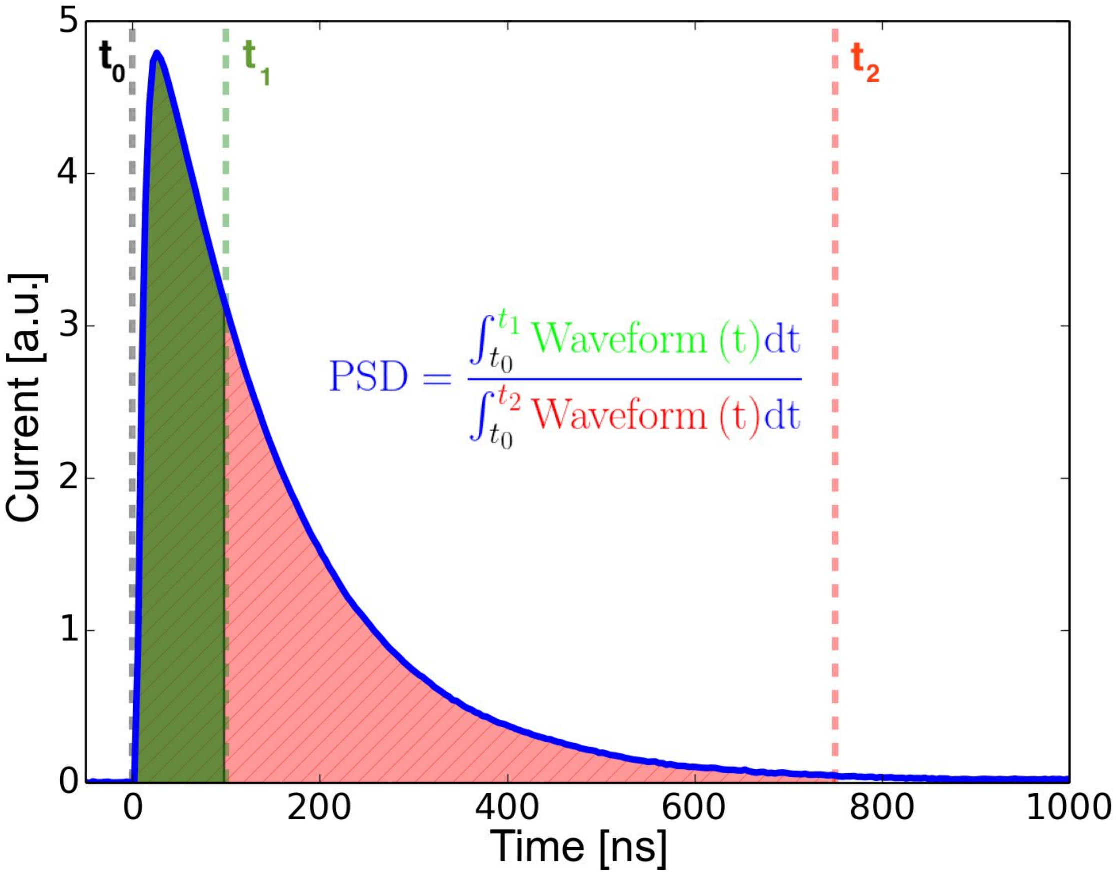
December 1, 2022

Overview: Pulse Shape Discrimination

- Emission spectra can depend on the type of interacting particle, especially due to differences in the various excited states which decay with different decay constants

- These characteristics are recorded in the temporal profile of the resultant signal pulse



We are defining and implementing an electronic version of this concept on a custom chip (NeuPix) that discriminates between neutrons and gammas based on the PSD quantity, as defined above.

Why Analog PSD?

- Current schemes of discriminating particles by their induced pulse shape (PSD) involve digitizing the pulse and performing PSD on the data. This consumes considerable power and the per channel cost is expensive.
- Development of an ASIC that can perform analog PSD will consume much less power, have a much lower cost per channel when mass produced, and will, eventually, be cryogenic compatible.
- Applications include
  - **Nuclear non proliferation monitoring:** Such an ASIC could serve as the front-end of a sensor array or be a component of a larger readout system in novel neutron detection systems of generic topologies.
  - **Liquid noble-based dark matter searches**: Liquid nobles (e.g. argon) have a pronounced PSD signature, which has been used in dark matter searches. Our ASIC could find use in LAr-based detectors, once it has been made cryogenic compatible. Our collaborator, the ASIC design group at LBNL, has this expertise.
  - **Neutron radiography:** Current approaches are not fully digital. Our ASIC provides the capability for fast turnaround and real-time analysis.

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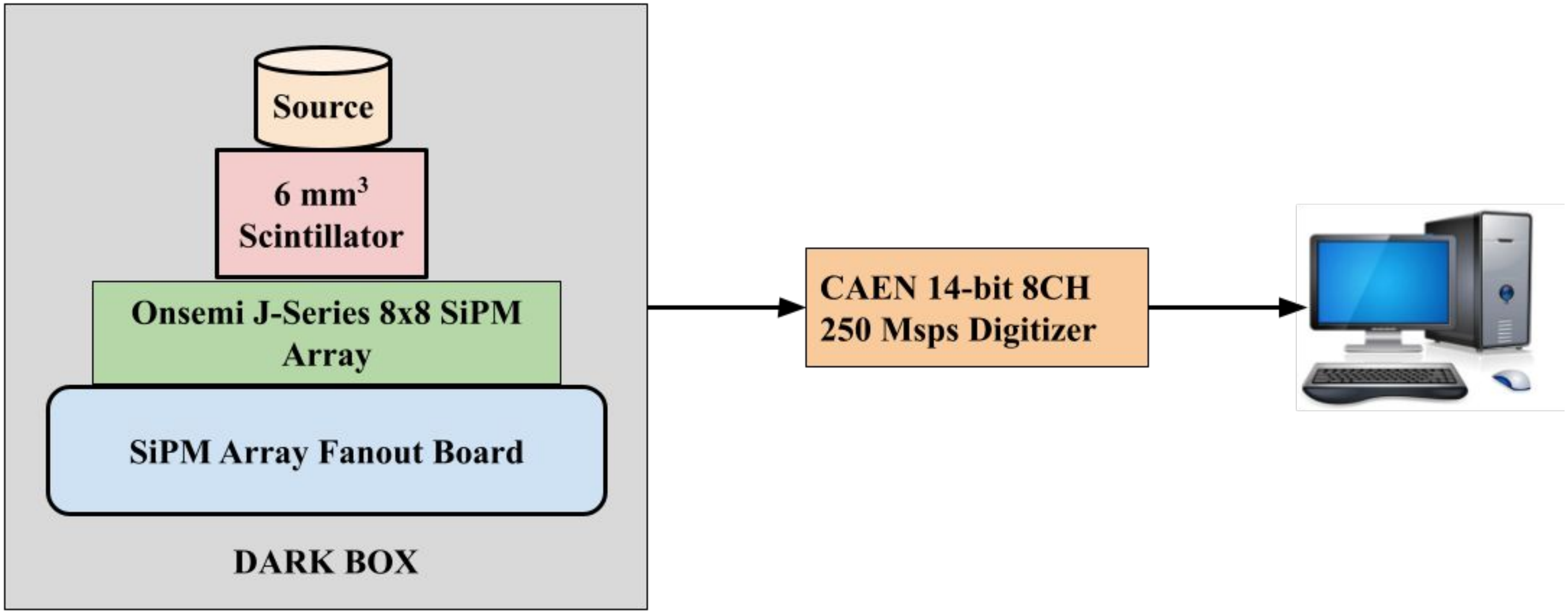
Project Goals

- Develop a demonstration ASIC for use in conjunction with SiPMs coupled to plastic/organic scintillator materials. Proceeded on two parallel fronts
  a. Implement the ASIC's core logic in analysis software for a design validation study
  b. Fabricate the ASICs in a shared wafer run (180nm process)

- Software version of the ASIC scheme was applied to digitized data collected from a scintillator + SiPM characterization test bed, which was exposed to sealed neutron and gamma sources

SiPM + Scintillator Characterization Test Bed



- Set-up couples a 6x6x6 mm^3 block of scintillator to a 6x6 mm^2 Onsemi J-Series SiPM
- SOUT and FOUT outputs are recorded by a 14-bit, 250 Msps CAEN digitizer
- Two different scintillators: Stilbene and EJ-276

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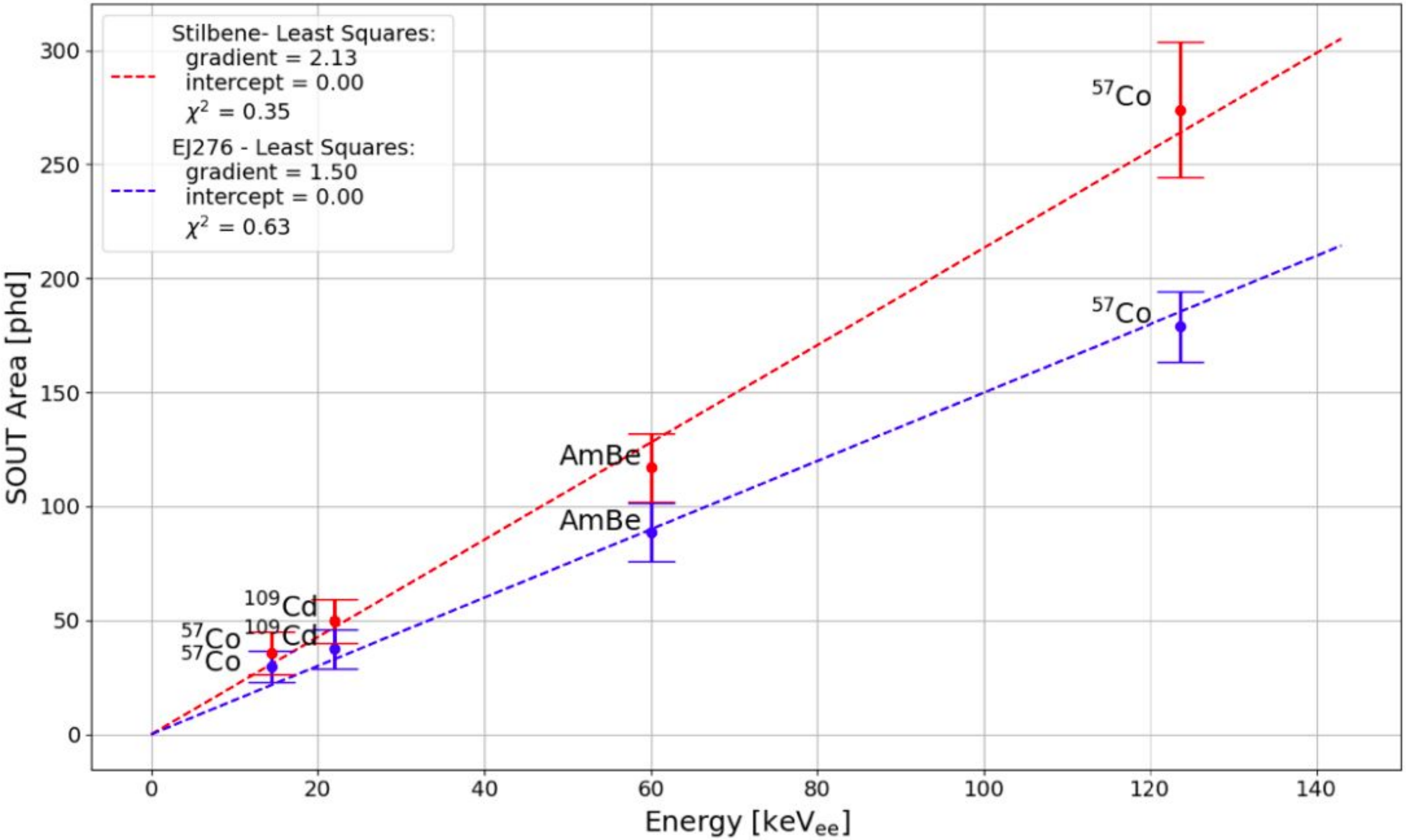
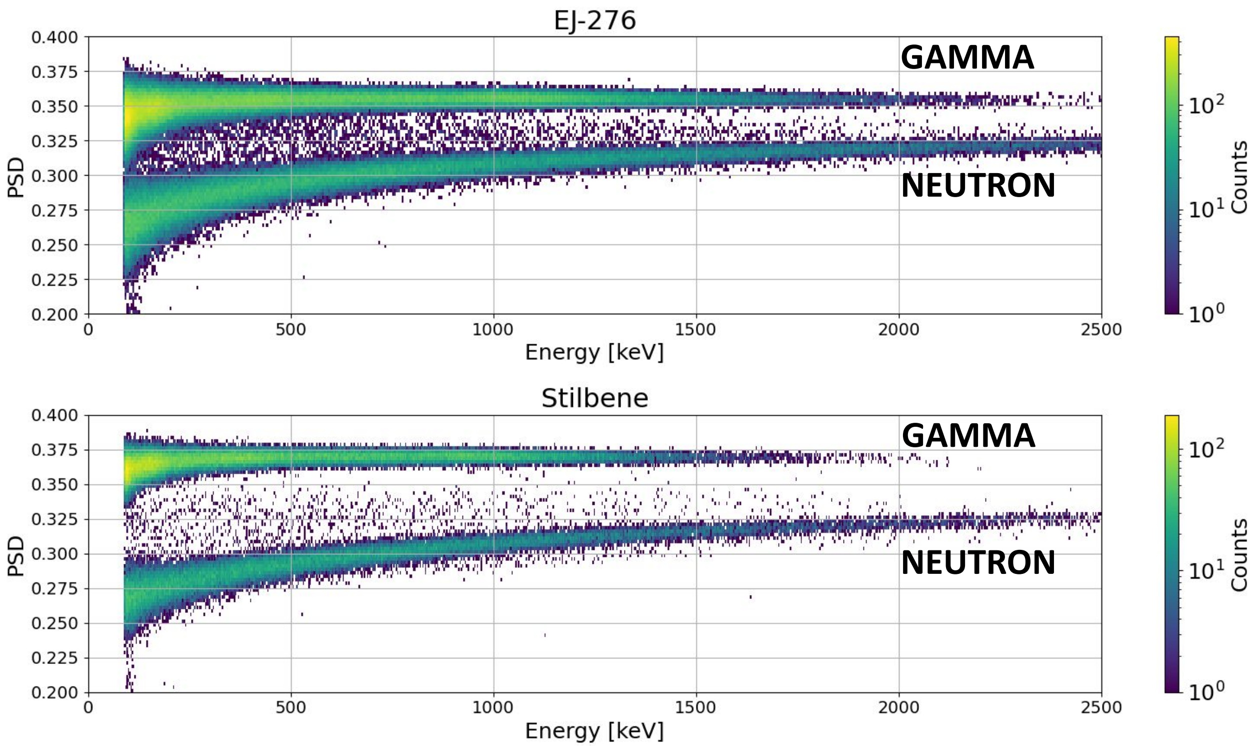
SiPM Response is Linear



- **Stilbene:** 2.13 photons detected per keV
- **EJ-276:** 1.50 photons detected per keV

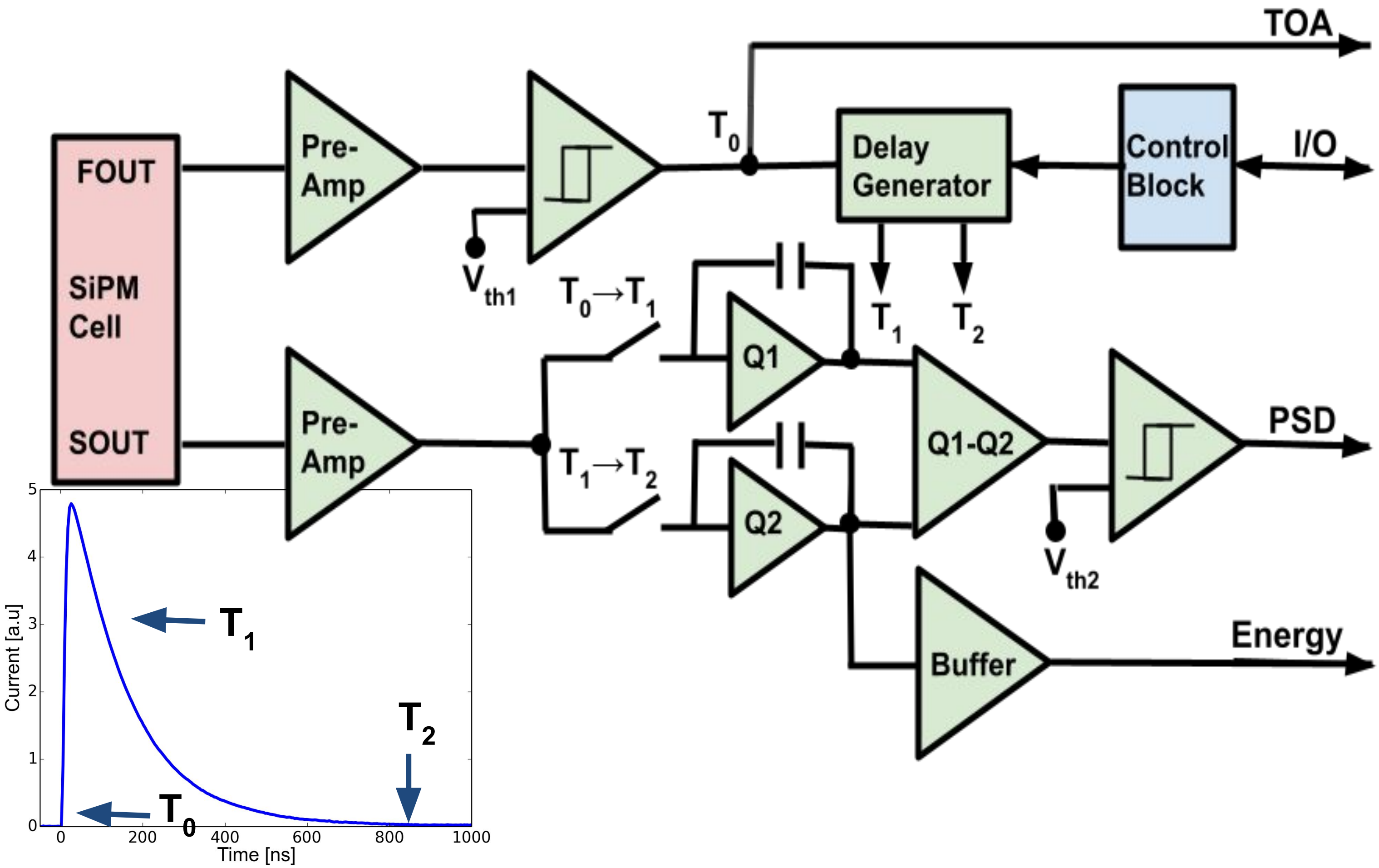
Example of PSD Capability



- PSD definition as given in Slide 3
- Dataset consists of 130k (stilbene) and 280k (EJ-276) AmBe events
- Good separation down to 100 keV is visible. EJ-276 does not do well below ~100 keV
- Also depends on the light collection efficiency of a particular design
- See arXiv:2209.13979 by Boxer et al. for more information

Conceptual One Channel Diagram

Onsemi SiPMs provide both capacitively coupled (**FOUT**) and resistively coupled (**SOUT**) channels



ASIC outputs:

a) **Fast time of arrival pulse (trigger)**

b) **PSD classification bit**

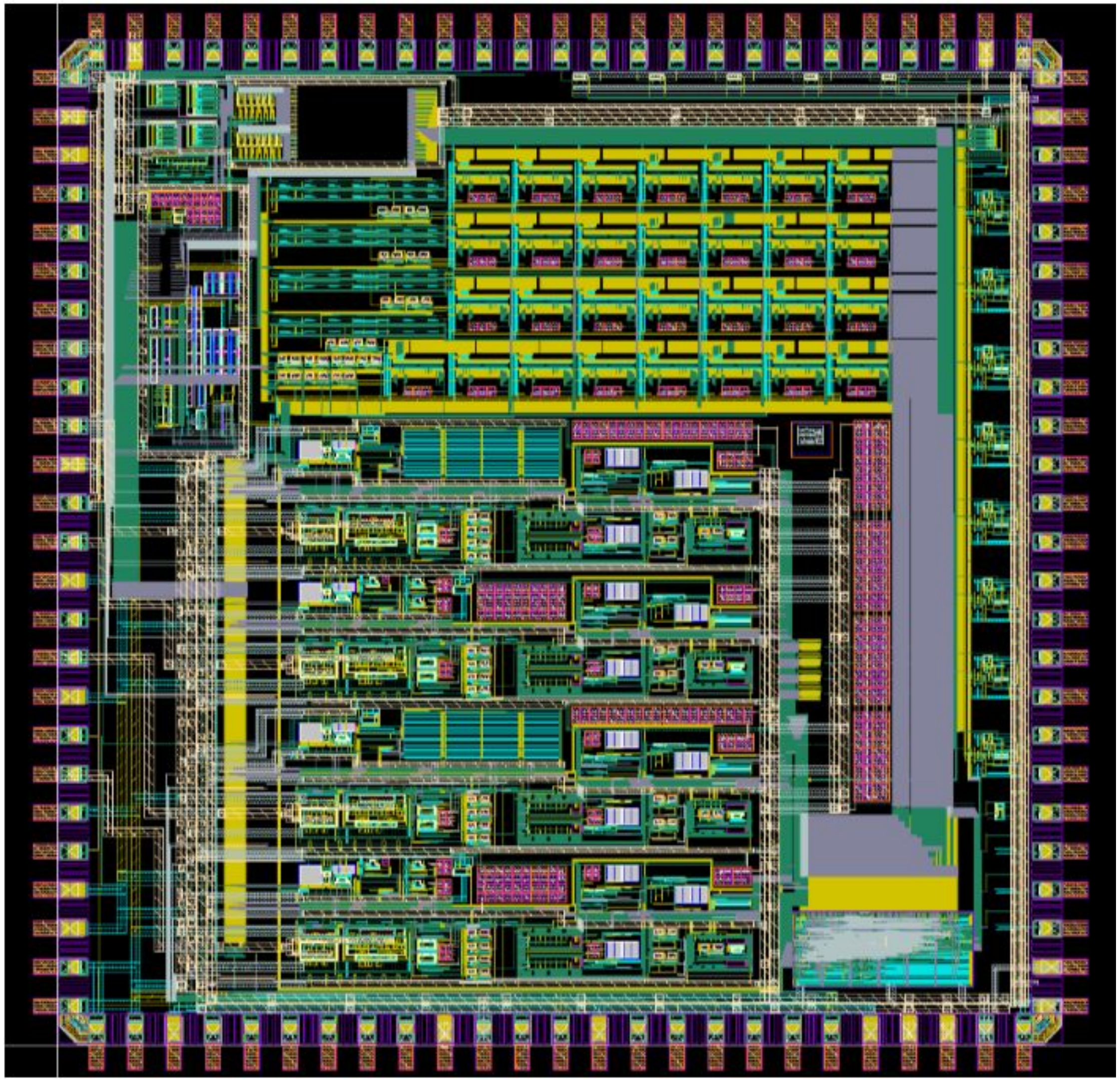
c) **Total energy**

NeuPix Design Features

- Real-time tagging of neutrons against gamma background → analog PSD circuit implemented on chip
- Dual input polarity capable SOUT frontend (with a programmable TIA gain of 30-180x)
- Adaptabile PSD for different target materials → Programmability provided on-chip for a selection of short and long integration windows depending on material properties. Fine tuning of total integration up to ~2.5µs and ~200ns for partial integration windows
- Two methods of generating partial, total, and hold delay lines are implemented on chip → Current starved inverters (proven) and ramp generator (less power hungry) are to be compared for performance
- FOUT frontend is expected to provide rise times < 1ns on chip
- Designed for maximum diagnostics → All important nodes are available as external outputs for inspection
- Front-end system is designed primarily for Onsemi SiPMs. However, off-chip adaption is possible for use with other sensors (e.g. PMTs, MCPs, LAPPDs, etc.)

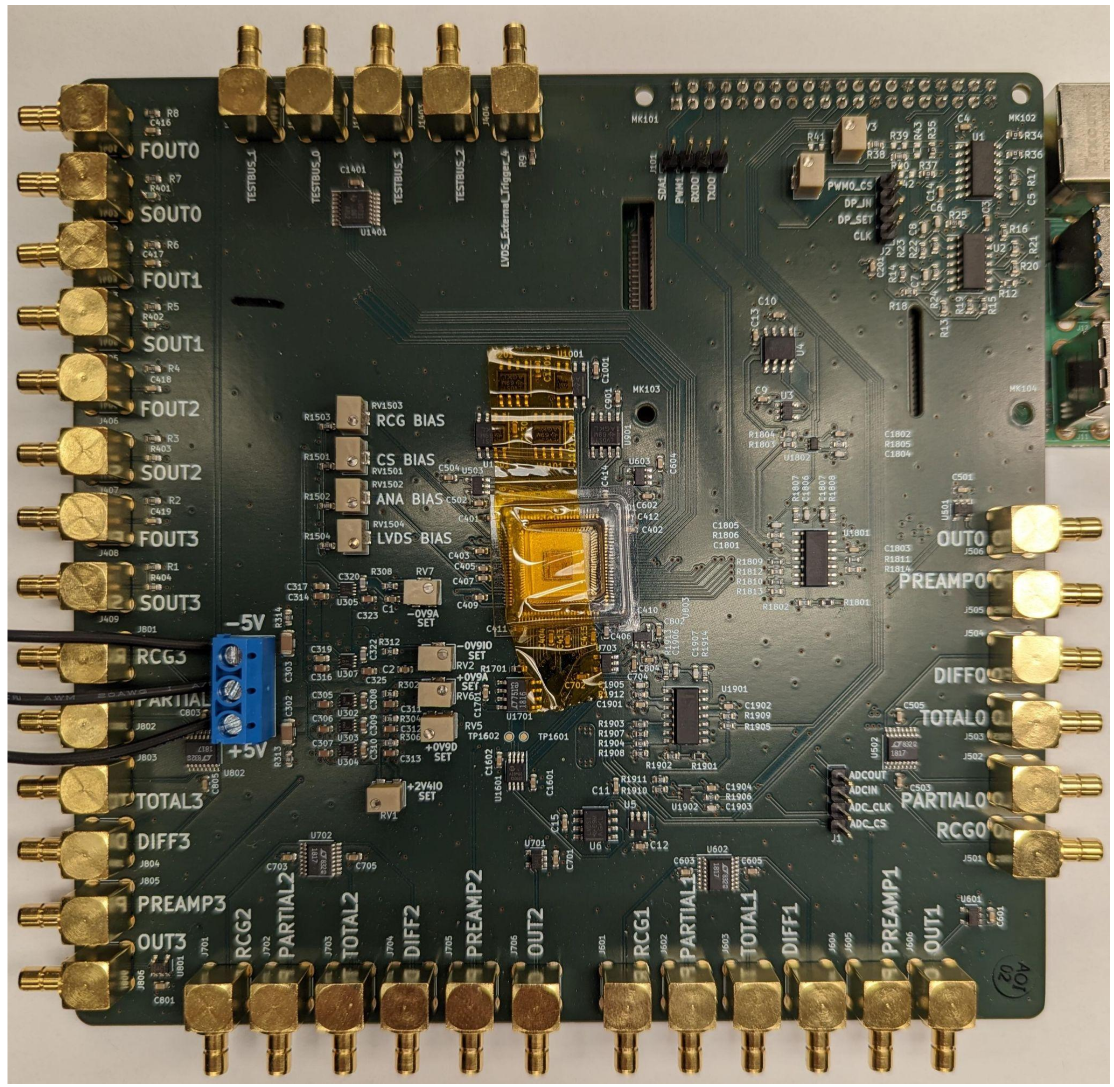
NeuPix Layout

- A prototype 4-channel ASIC has been designed and fabricated using the 180 nm process
- NeuPix has been designed and fabricated
- Bench testing is proceeding currently
- Preliminary bench results follow



NeuPix Readout Board

- A 4-channel readout board has been designed and laid out for characterization and calibration of NeuPix
- Outputs from NeuPix are fed to various connectors on the board
- Four digital test busses allow monitoring of FOUT signal chain
- Can set bias currents/thresholds via onboard potentiometers



Preliminary Testing

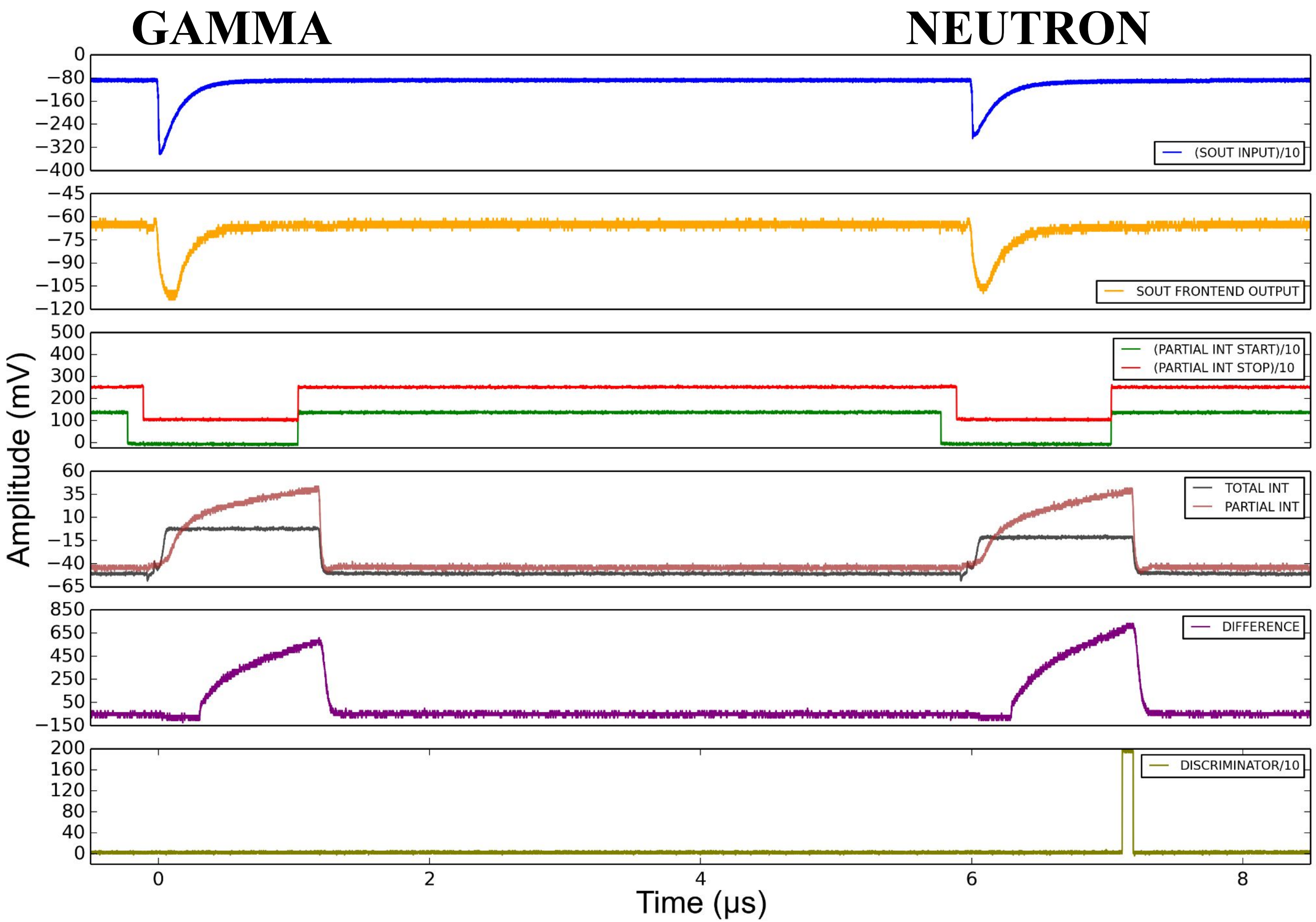
- **Initial calibration tests in progress**

- Preliminary waveforms are from averaged, digitized AmBe data collected using the SiPM-characterization testbed and stilbene scintillator (shown previously here) passed into NeuPix from an arbitrary waveform generator

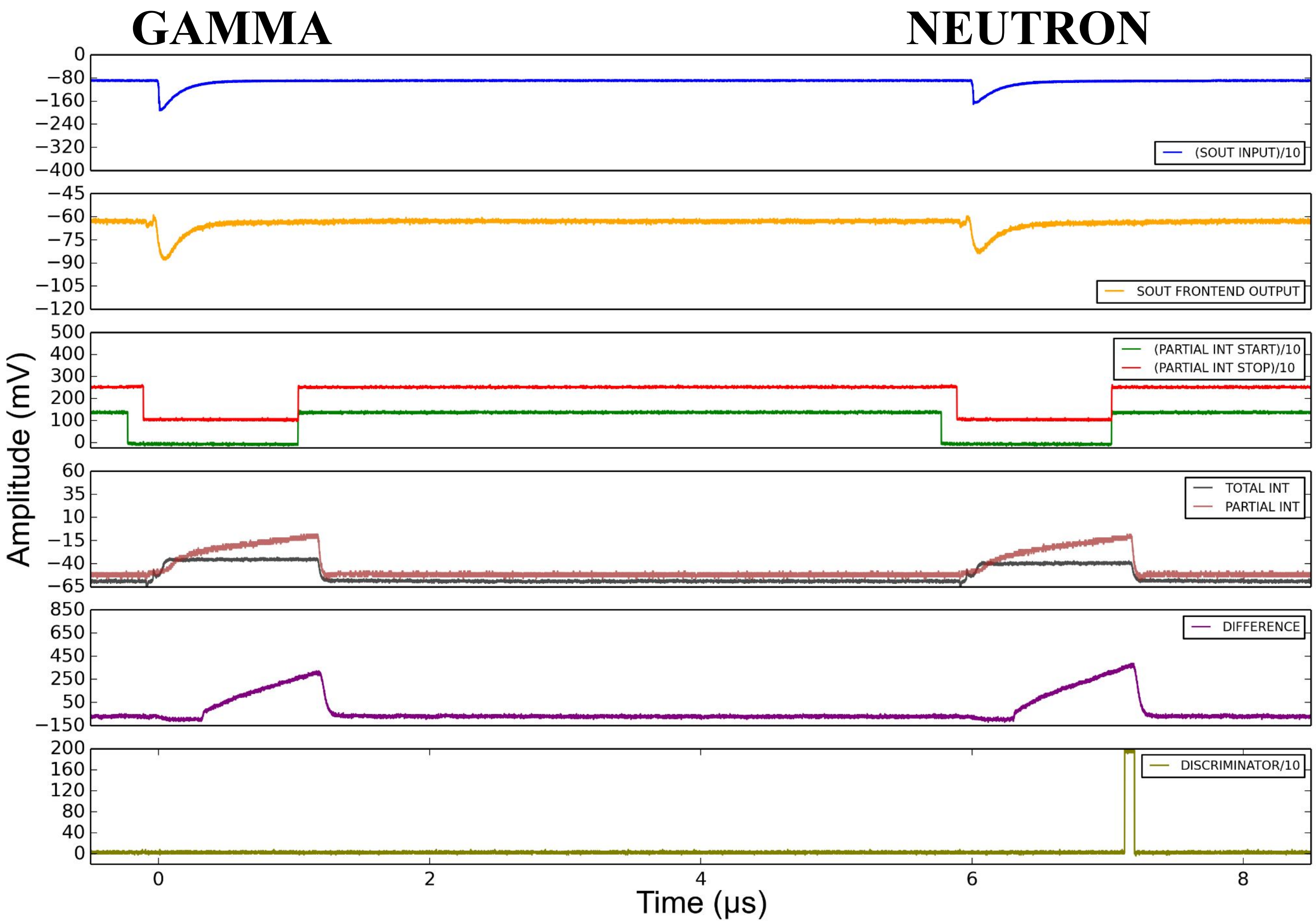
- PSD capability at different energies have proven that the chip can be configured and operated successfully down to 100 keV equivalent energy

- Coupling to a SiPM and confirming real-time PSD is forthcoming

250 keV Equivalent - AWG pulses

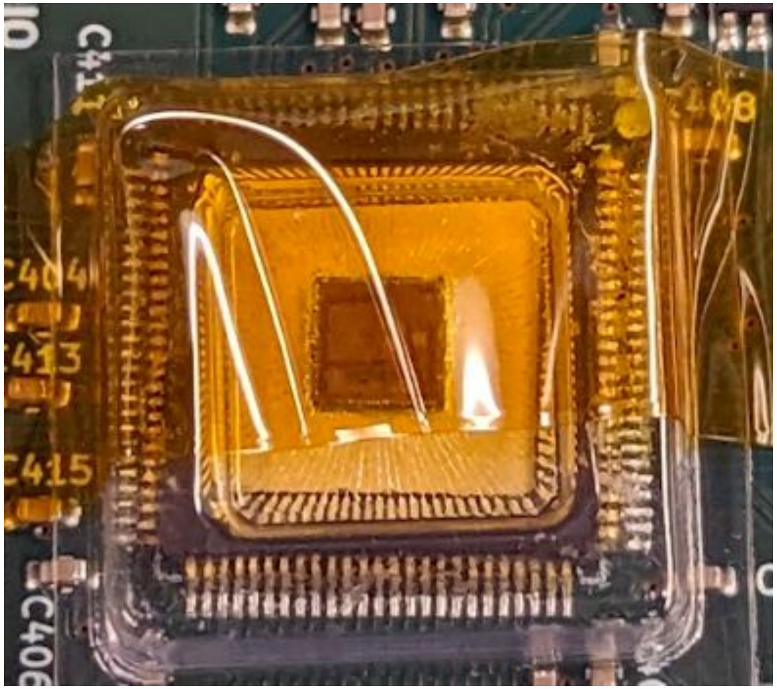


100 keV Equivalent - AWG pulses



Conclusions

- A 4-channel ASIC has been developed for performing real-time analog PSD. Preliminary testing has proven PSD capability and real-time analog PSD testing is ongoing



- The ASIC can be used with single output sensors such as PMTs although the current design is focused on SiPM readout

- The next step will be to proceed to a 32 or 64 channel version. This will involve transporting the design from 180 nm to a 65 nm process

- Some modifications will be needed to make it functional at LAr temperatures

- Continued calibration and testing results from **NeuPix** are coming soon

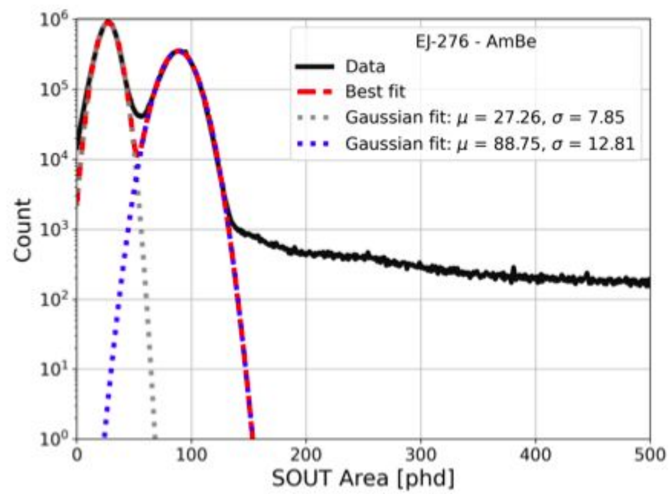
- Development of a full-fledged neutron double scatter camera underway and always looking for new applications of **NeuPix**

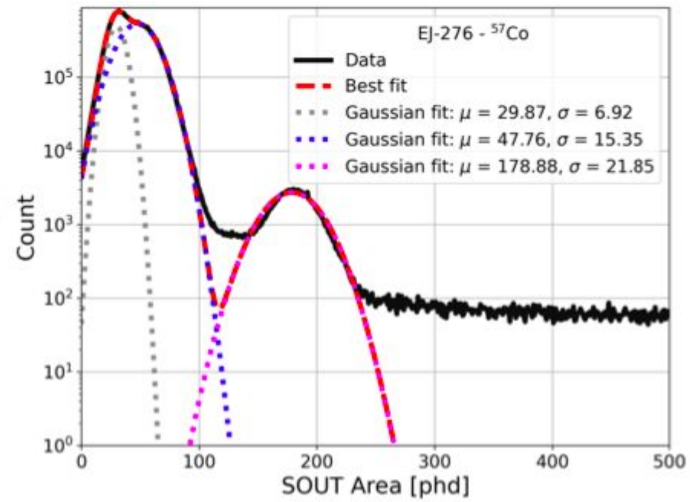
This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number **DE-NA0003996**

Backup Slides

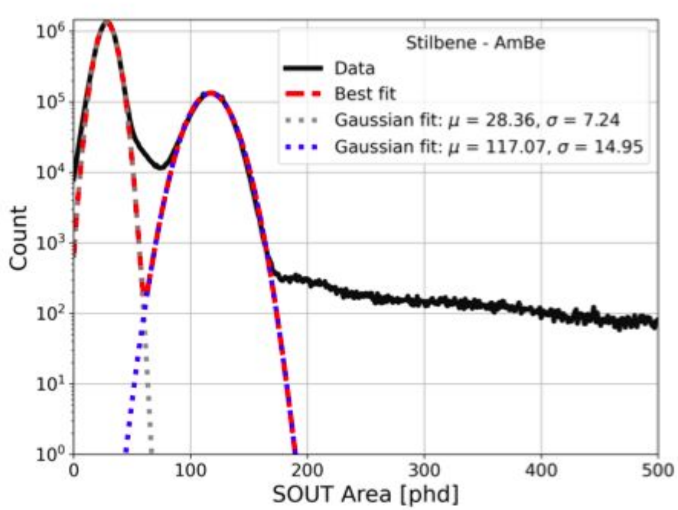
Energy Calibration with Neutron/Gamma Sources

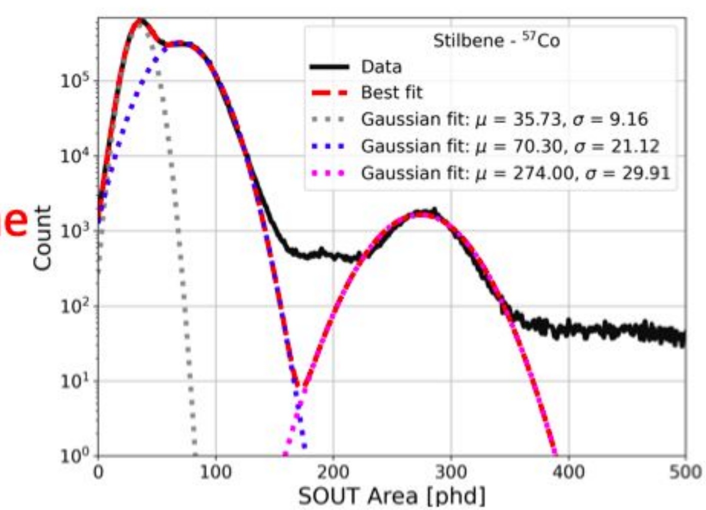
EJ-276



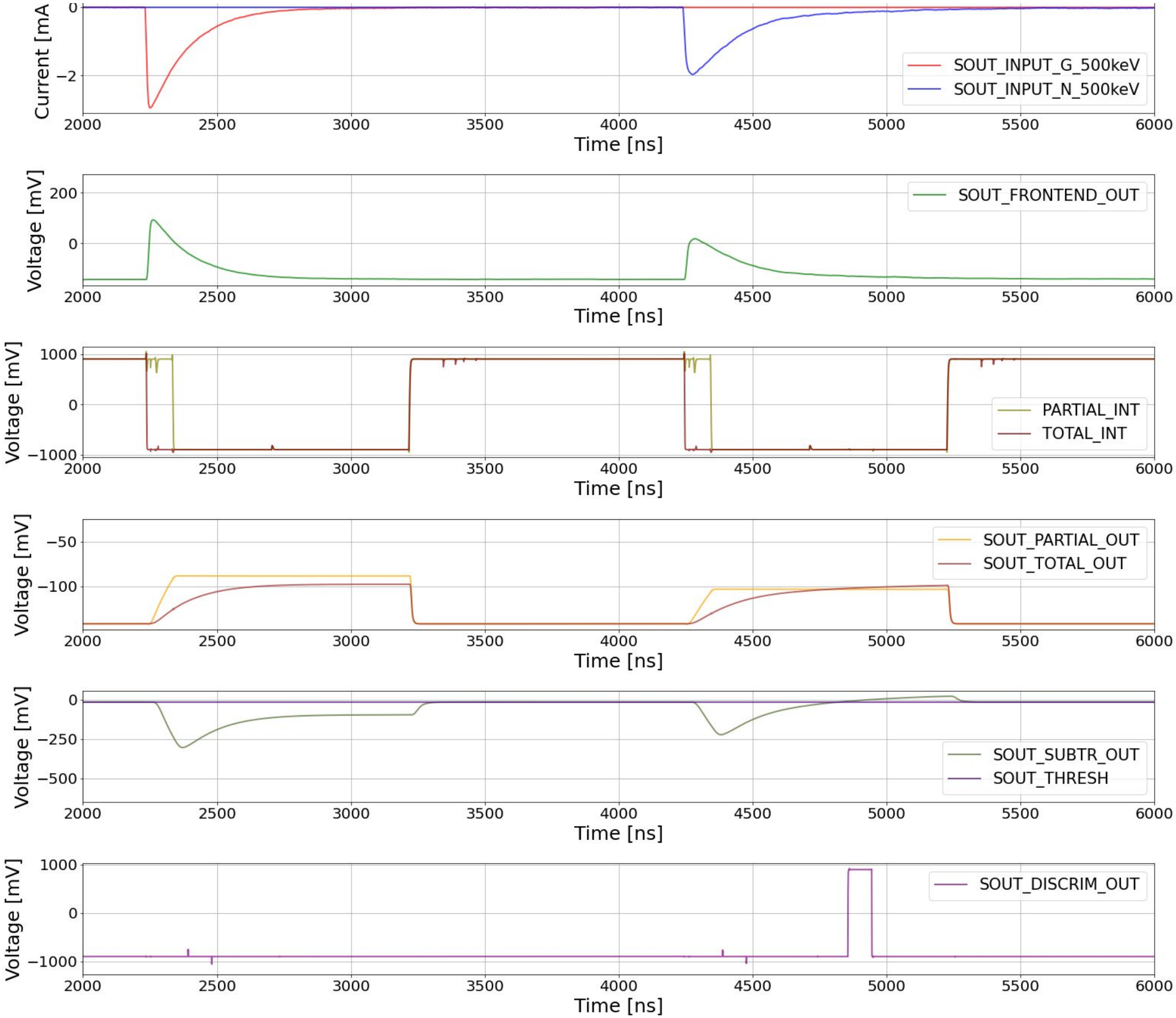


Stilbene





Full SOUT Signal Chain - Simulation

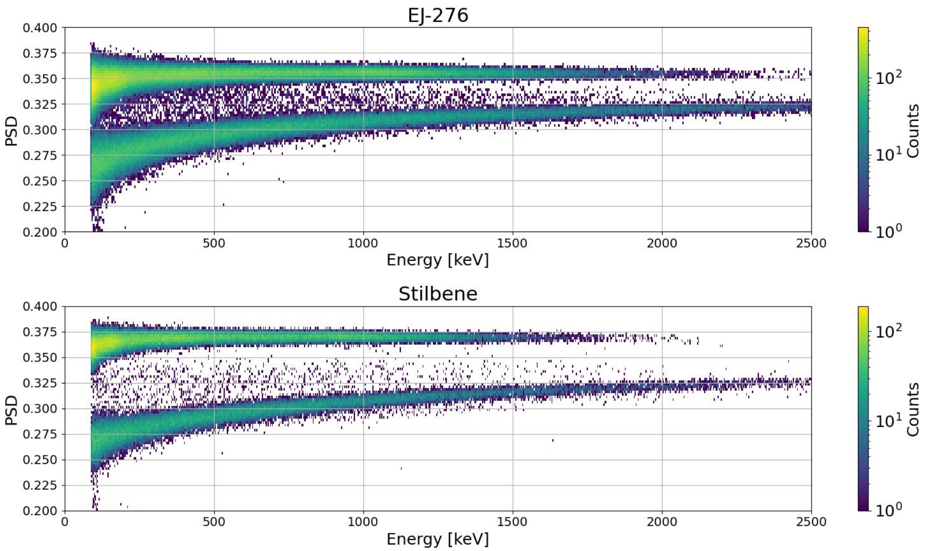


Backup Slides

Real-Time PSD Subtraction Space I

$$\mathrm{PSD} = \frac{\int_{t_0}^{t_1} \mathrm{Waveform}(t)\,dt}{\int_{t_0}^{t_2} \mathrm{Waveform}(t)\,dt} = \frac{I_{partial}}{I_{total}}$$

$$\mathrm{PSD}\,(I_{total}) - I_{partial} = 0$$



Scaling the total integration and subtracting the partial integration is the same as performing a ratio

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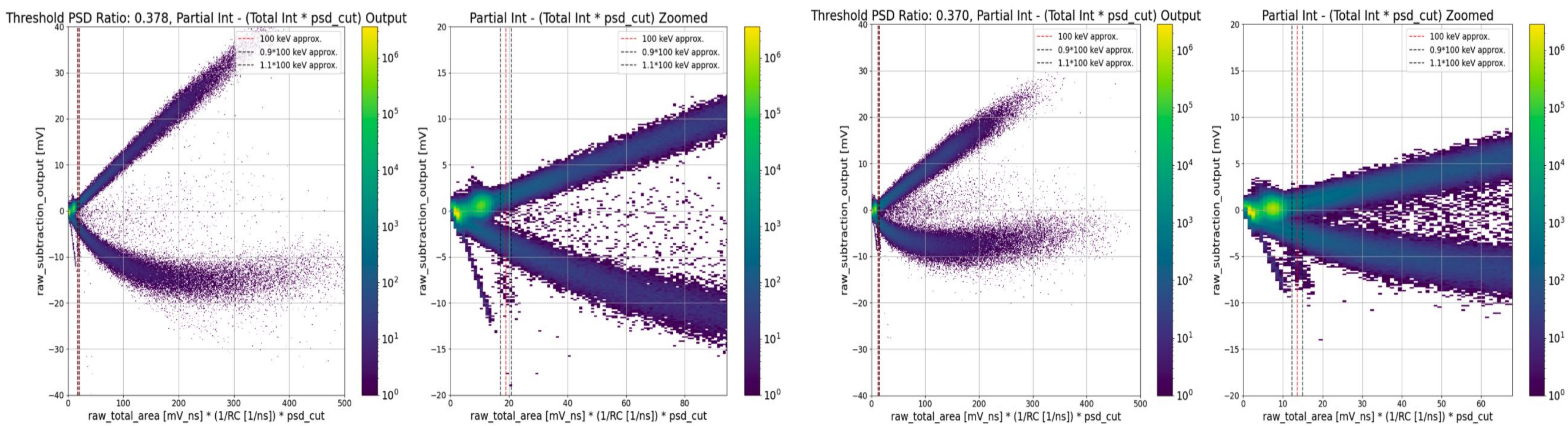
Real-Time PSD Subtraction Space II



- PSD defined by looking at difference between partial and total integrals
- Band widths get narrower at lower energies
- PSD capabilities shown down to 100 keV
- Setting final SOUT discriminator sets subtraction threshold
- Setting FOUT front-end discriminator sets energy threshold

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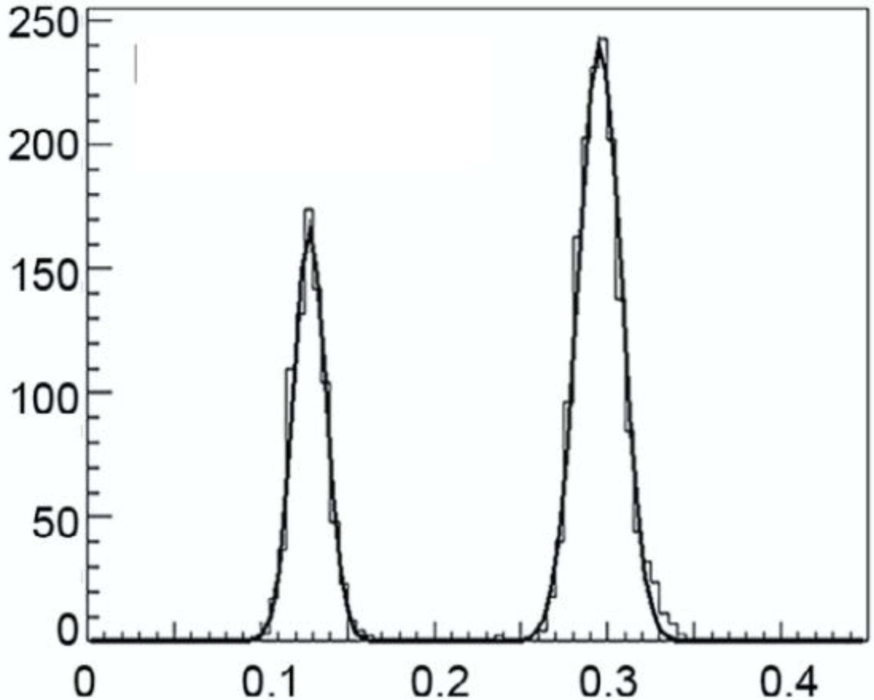
Figure of Merit

$$\mathrm{FOM} = \frac{\mu_\gamma - \mu_n}{2.355\,(\sigma_\gamma + \sigma_n)}$$



Taken from doi.org/10.1016/j.nima.2018.01.093 by Zaitseva et al.

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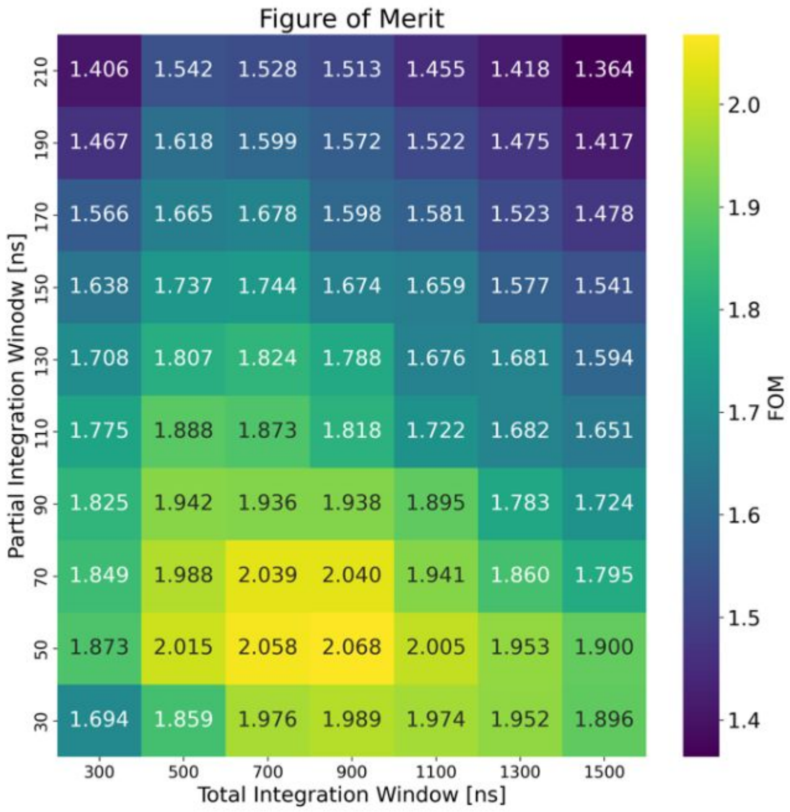
Figure of Merit Stilbene



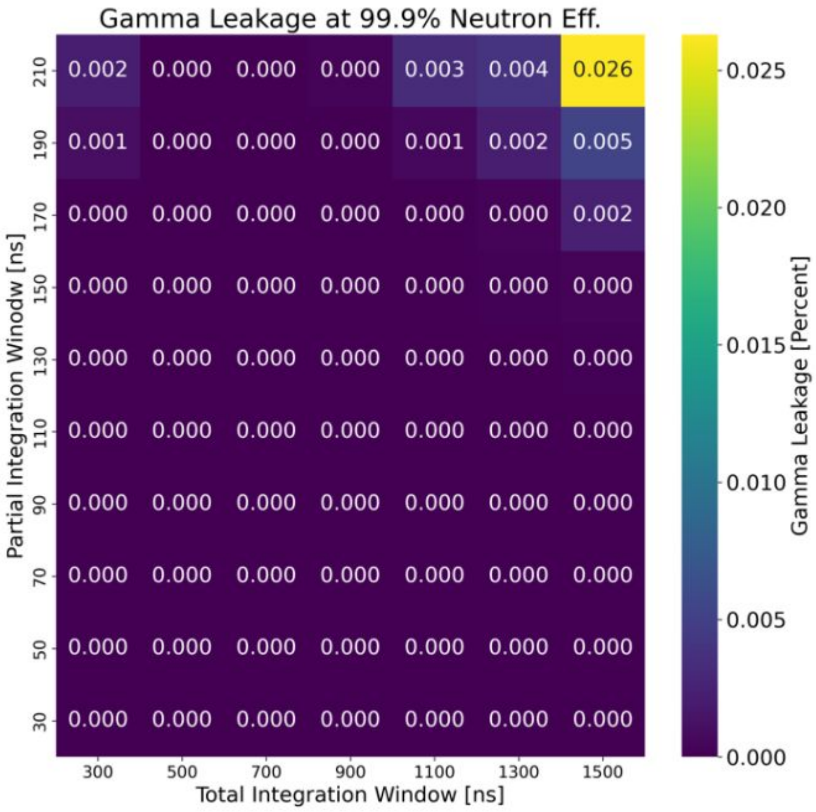


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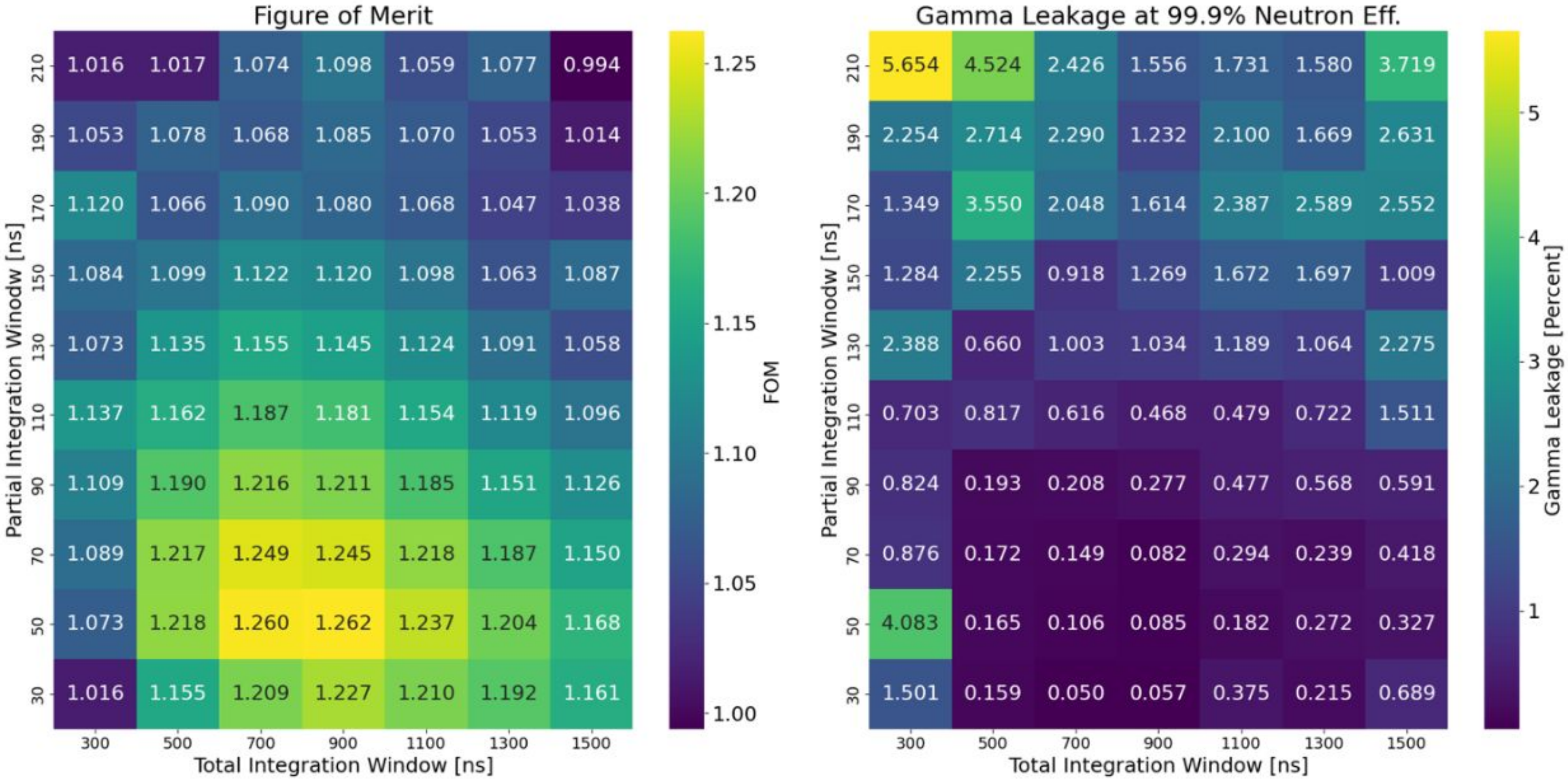
Figure of Merit EJ-276



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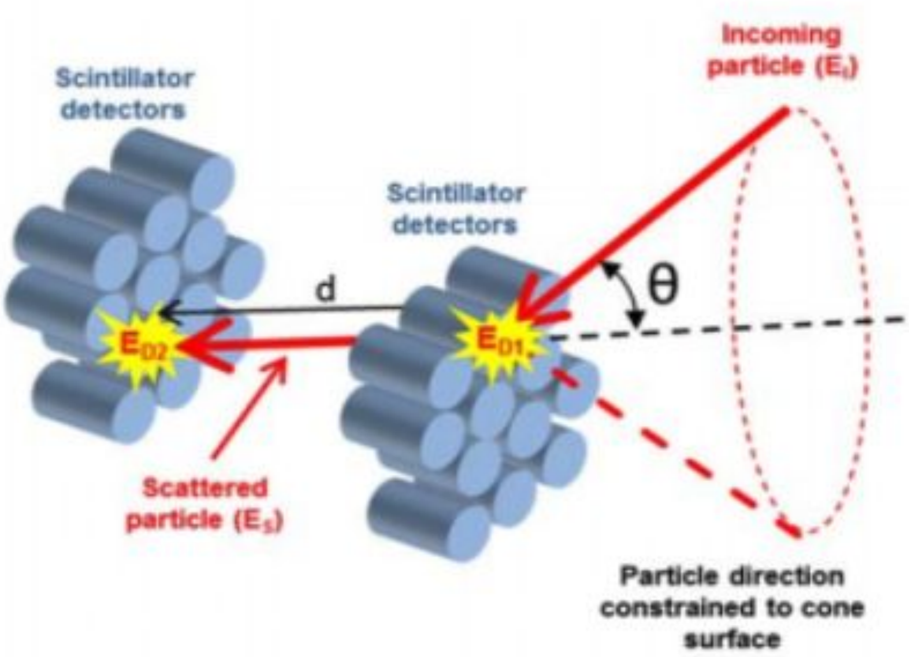
Neutron Double Scatter Camera



$$E_{I,N} = E_{S,N} + E_{D1,P}$$

$$E_{S,N} = \frac{1}{2} m \left(\frac{d}{\tau}\right)^2$$

$$\theta = \sin^{-1}\left(\sqrt{\frac{E_{D1,P}}{E_{S,N}}}\right)$$

Rev. Sci. Instrum. 87, 083307 (2016); https://doi.org/10.1063/1.4961111