NIST Center for Neutron Research

Measuring Detector Deadtime using Arrival Time Statistics

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NIST
National Institute of Standards and Technology
U.S. Department of Commerce

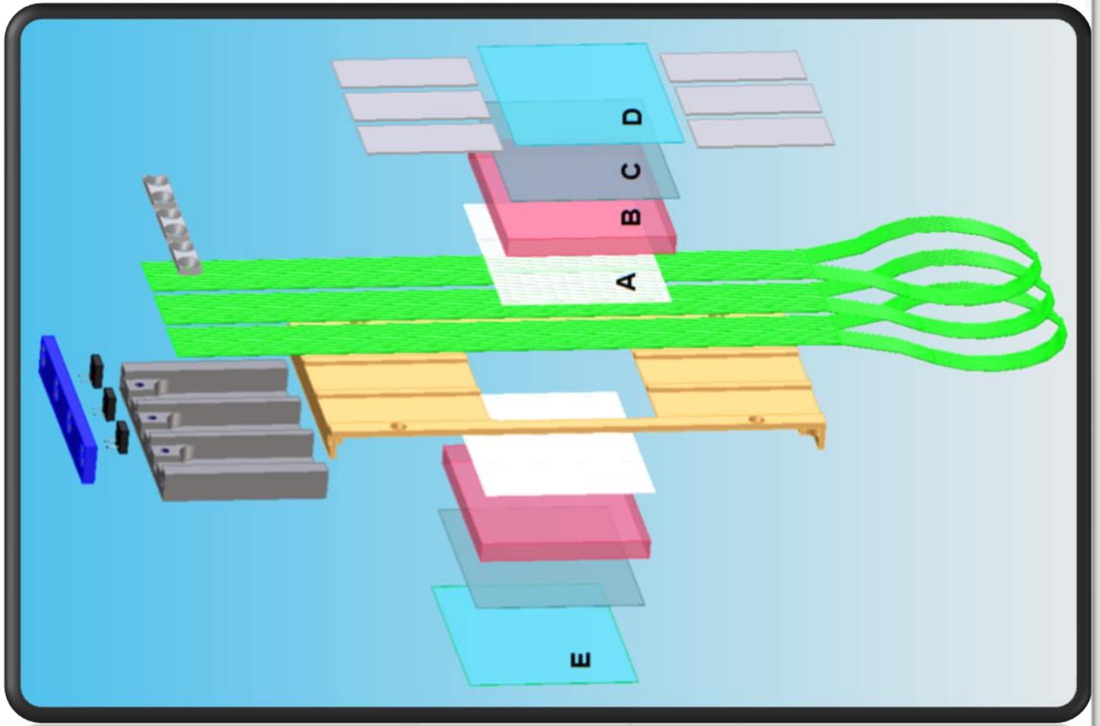
The CANDOR Detector

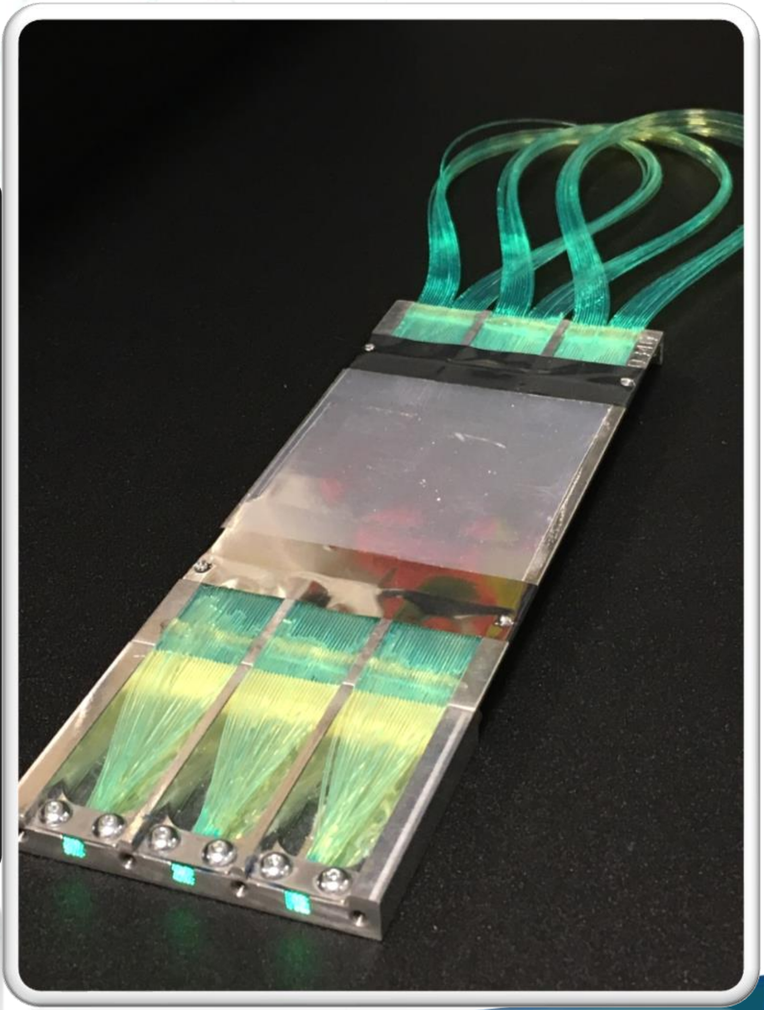
- The NIST Center for Neutron Research (NCNR) has developed an ultrathin (2mm) ^{6}LiF:ZnS(Ag) scintillating neutron detector

- The detector generates a light pulse after it absorbs a neutron

- We use these detectors in the Chromatic Analysis Neutron Diffractometer or Reflectometer (CANDOR)

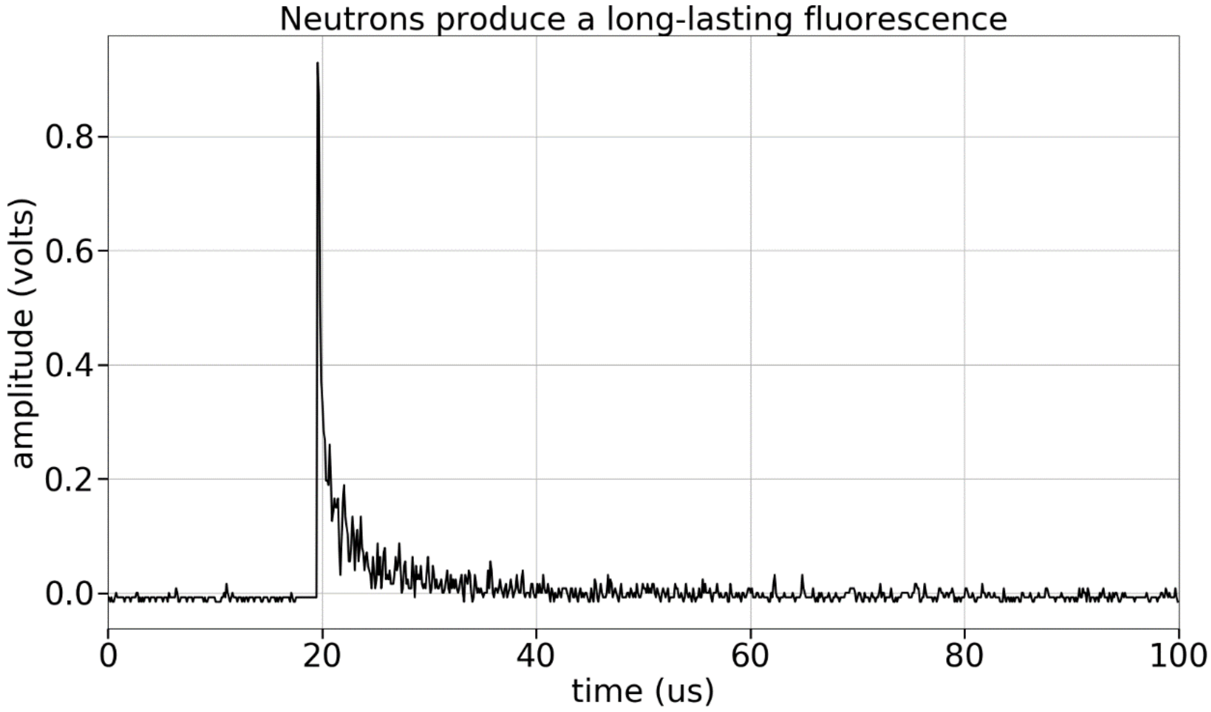
The CANDOR Detector





Long Neutron Fluorescence

- Significant fluorescence out to 60µs
- 60µs is too long a hold-off time before processing the next pulse. Too much deadtime.



Definitions

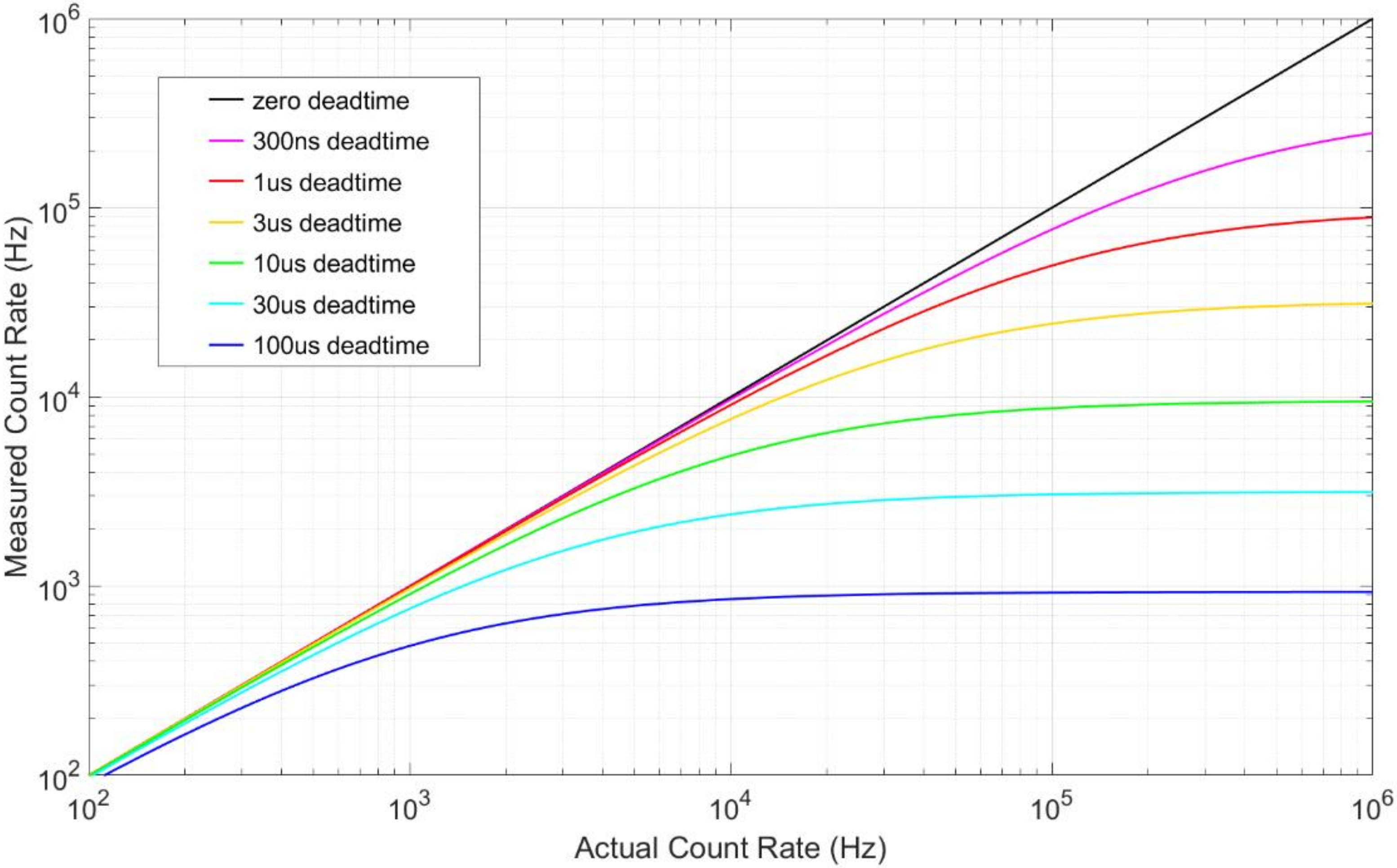
- Deadtime – Period of insensitivity following a neutron detection. < 1μs is desired
- Double-count – Mistakenly counting the same neutron event twice. < 0.1% is OK
- Adaptive Cooloff – Compensating for fluorescent decay in a proportional manner

Importance of Deadtime

- For accurate measurements, scientists calculate their actual count rate from measured count rate and the deadtime of the detector.
- The uncertainty of deadtime corrections grows rapidly at high count rates, as the detector becomes saturated with counts.
- Scientists need to know what their detector deadtime is, and detector deadtime should be kept as small as possible.

Deadtime (τ)

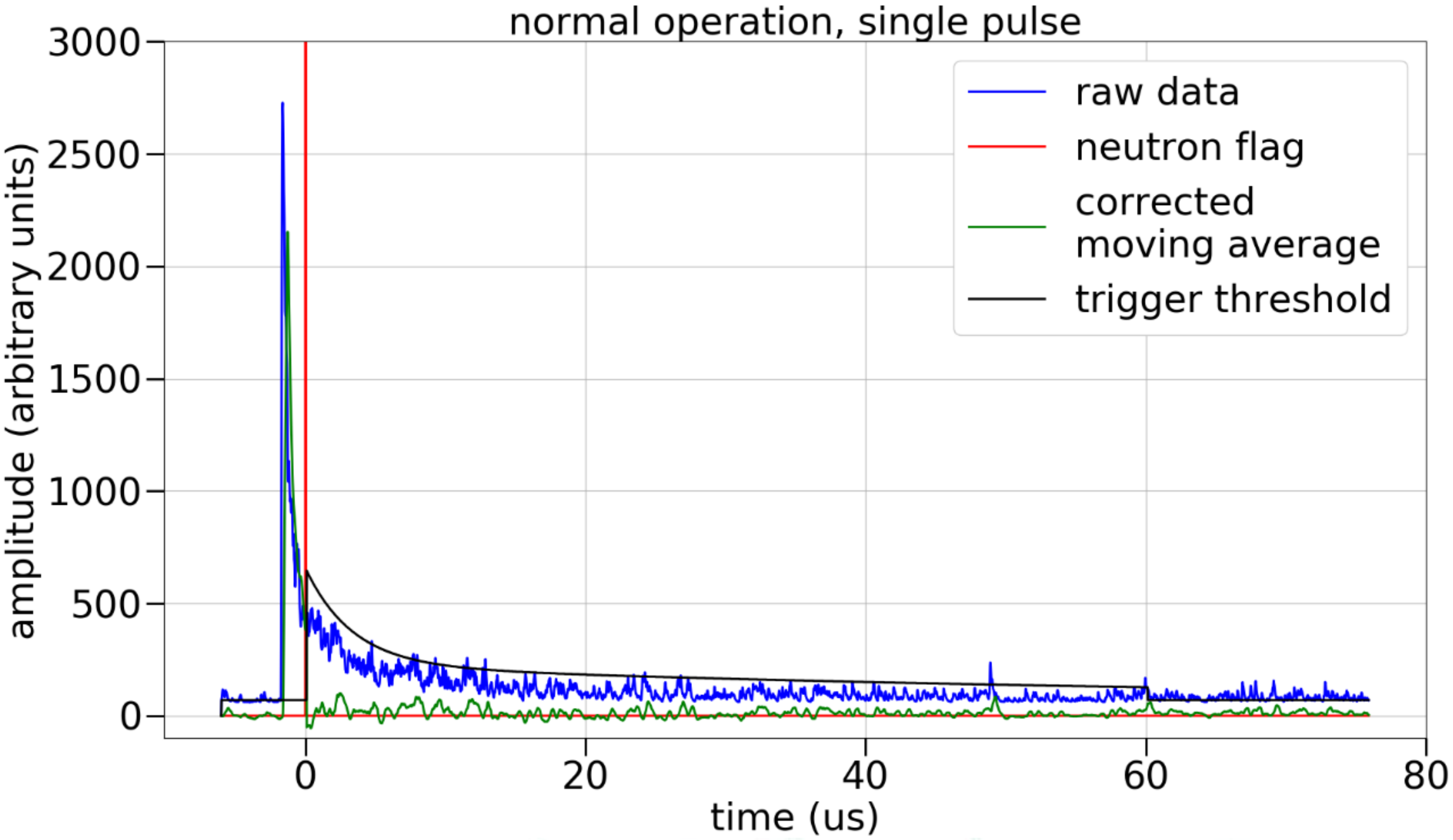
$$N_{actual} = \frac{N_{measured}}{1 - N_{measured}\left(\frac{\tau}{T}\right)}$$



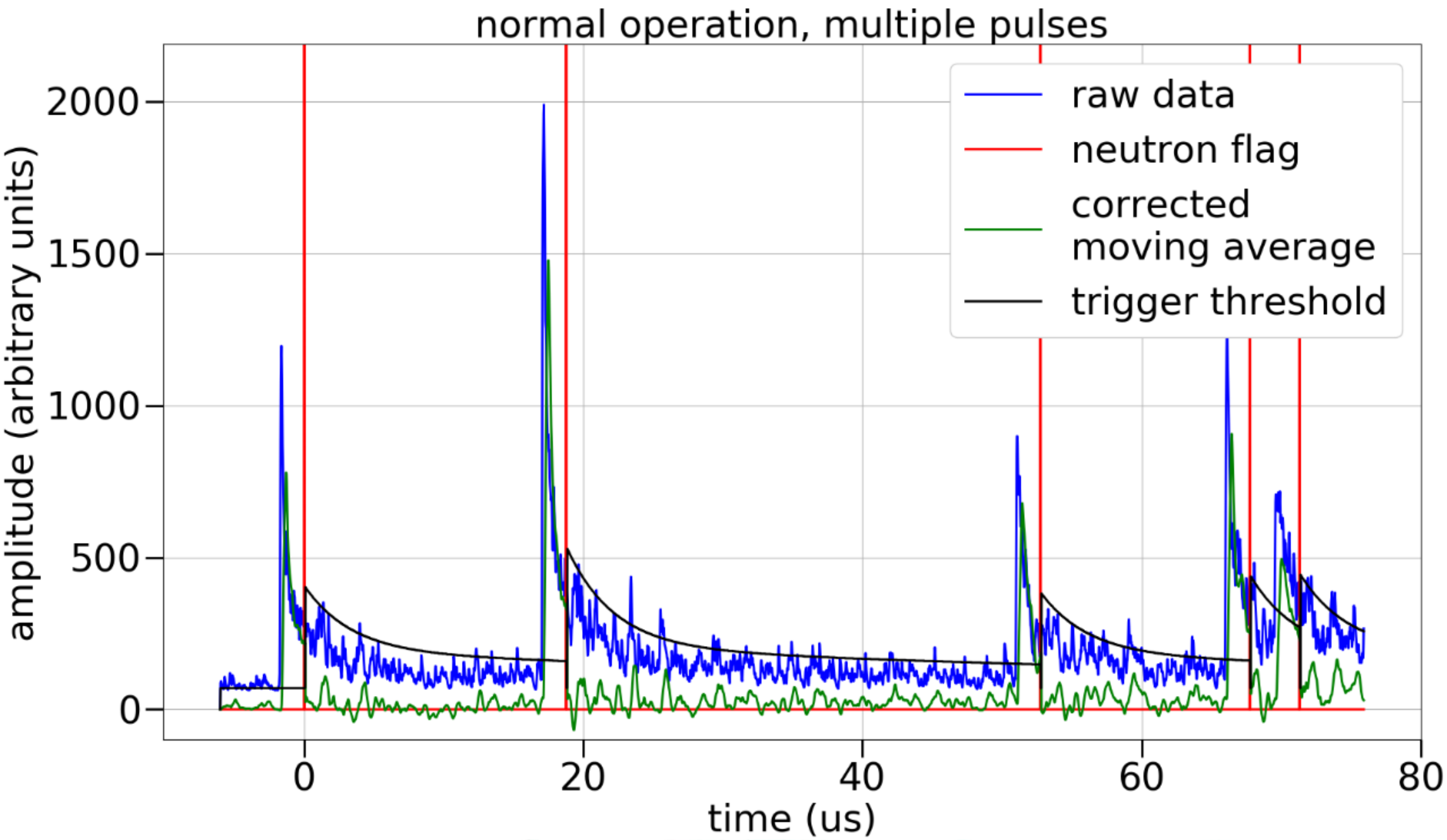
Adaptive Cooloff algorithm

- The scintillation pulse follows of 2-term exponential decay.
- The signal variance also follows a 2-term exponential decay.
- While looking for the next pulse, we subtract the mean of the previous pulse, and we raise our detection threshold by 5.5 standard deviations.

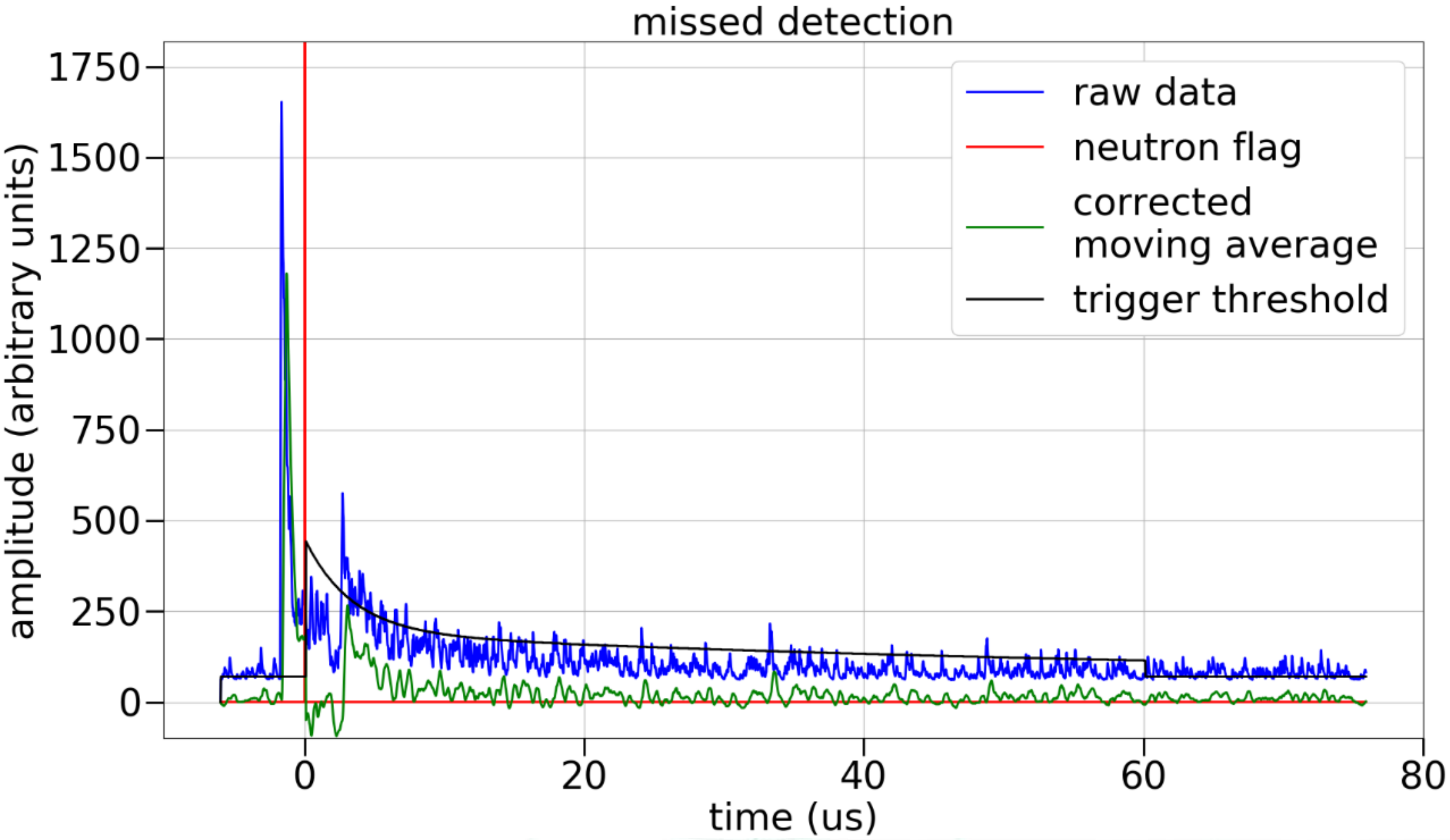
Adaptive Cooloff algorithm



ILA traces (real numbers from FPGA)

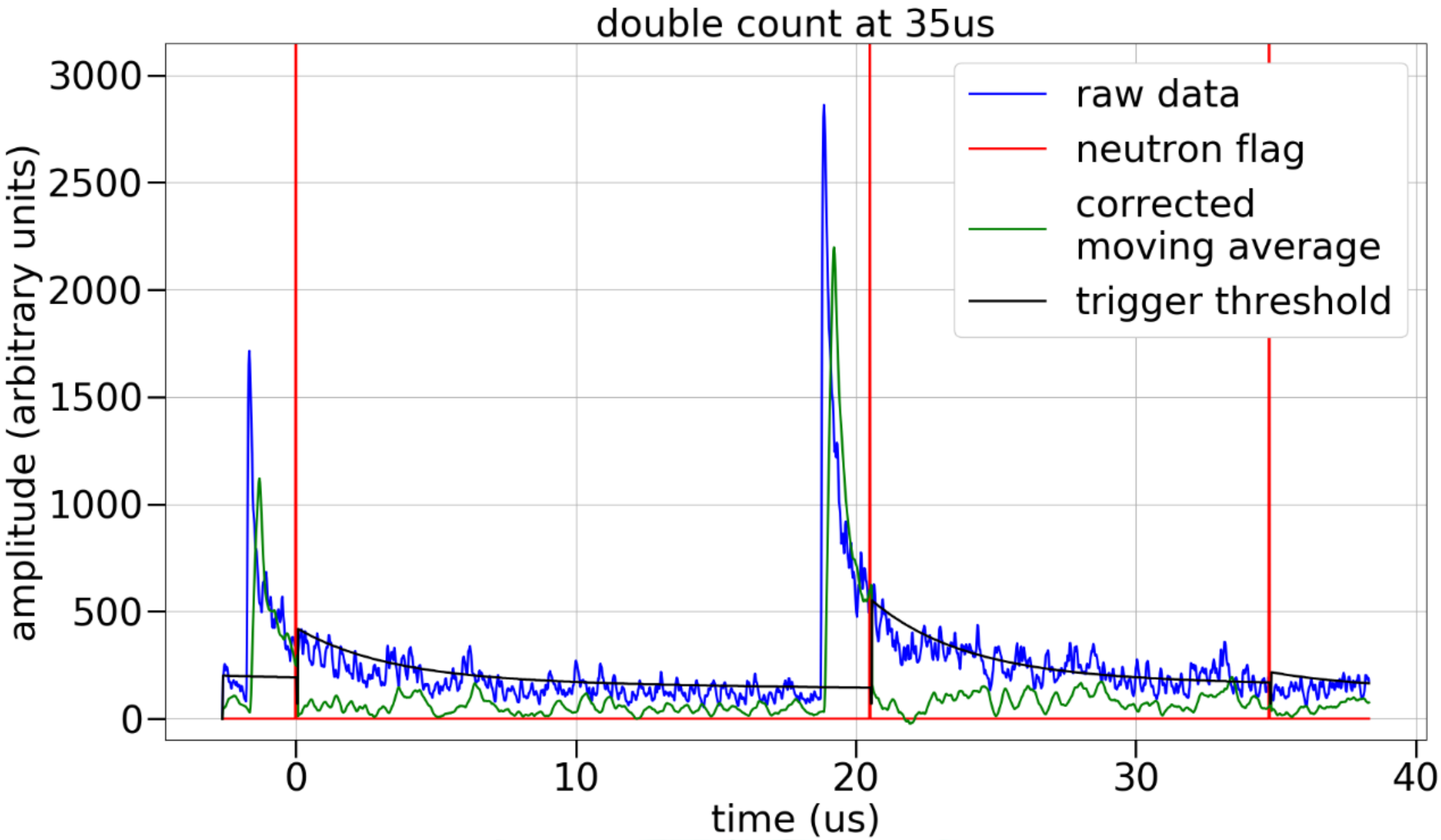


Missed Detection contributes to deadtime



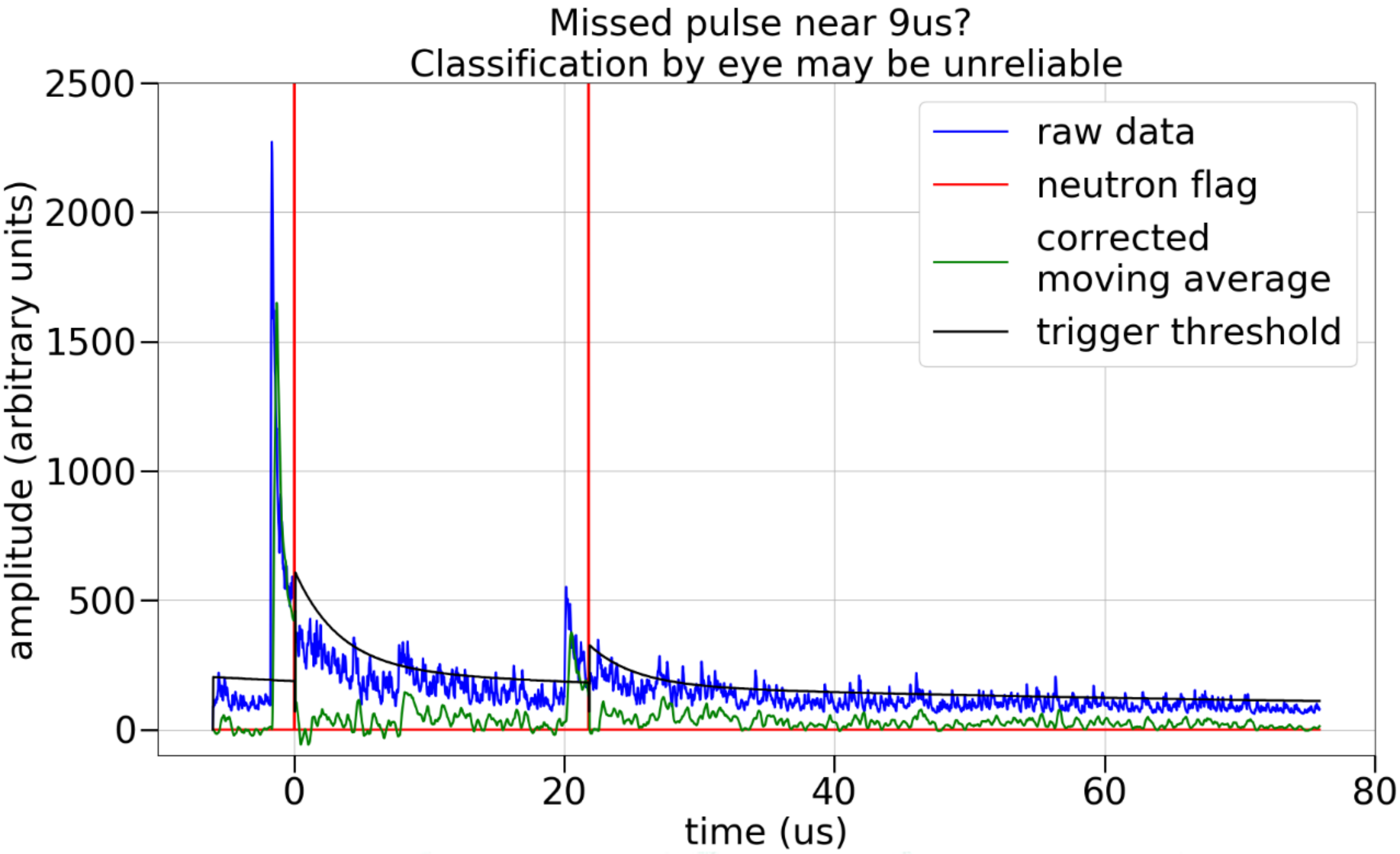
Threshold reduced to 3.25 SD from 5.5 SD

- No observed double counts at 5.5 SD



Is it a neutron? Or variance?

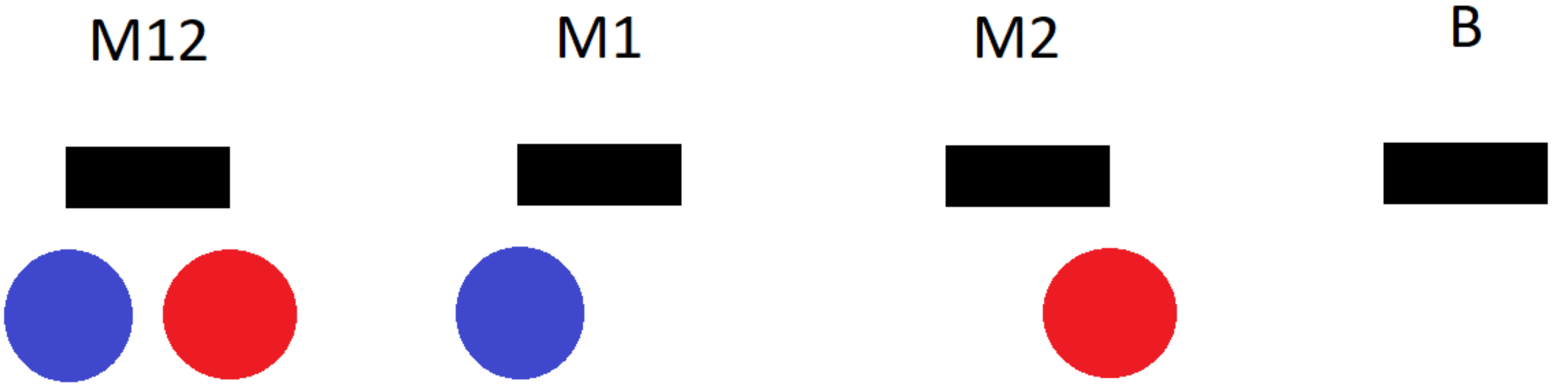
- A statistical measurement method would be better than subjective observations



Measuring Deadtime (τ)

- 2-source method is the established method

$$\tau = \frac{M_1 + M_2 - M_{12} - B}{M_{12}^2 - M_1^2 - M_2^2}$$



M12 M1 M2 B

The 2-source method isn't feasible when…

- You need two intense isotopic sources, which are hazardous to handle.
- Maybe you don't have access to these sources.
- Maybe you don't want to handle these sources.

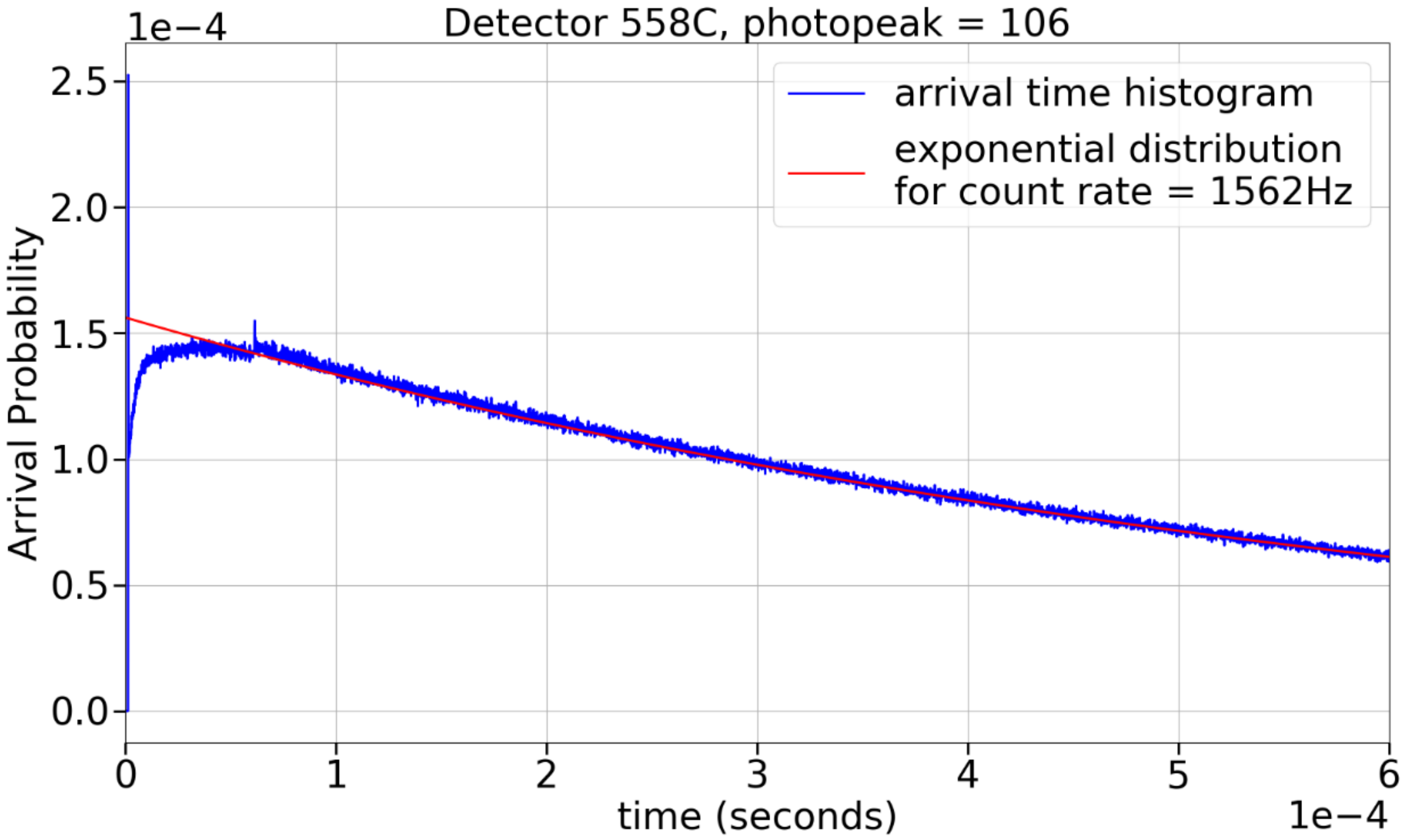
Deadtime from Arrival Time statistics

- Our reactor source is a **constant flux** source
- Neutrons at PHADES follow Poisson process.
- Arrival time probability follows an exponential distribution. λ = count rate

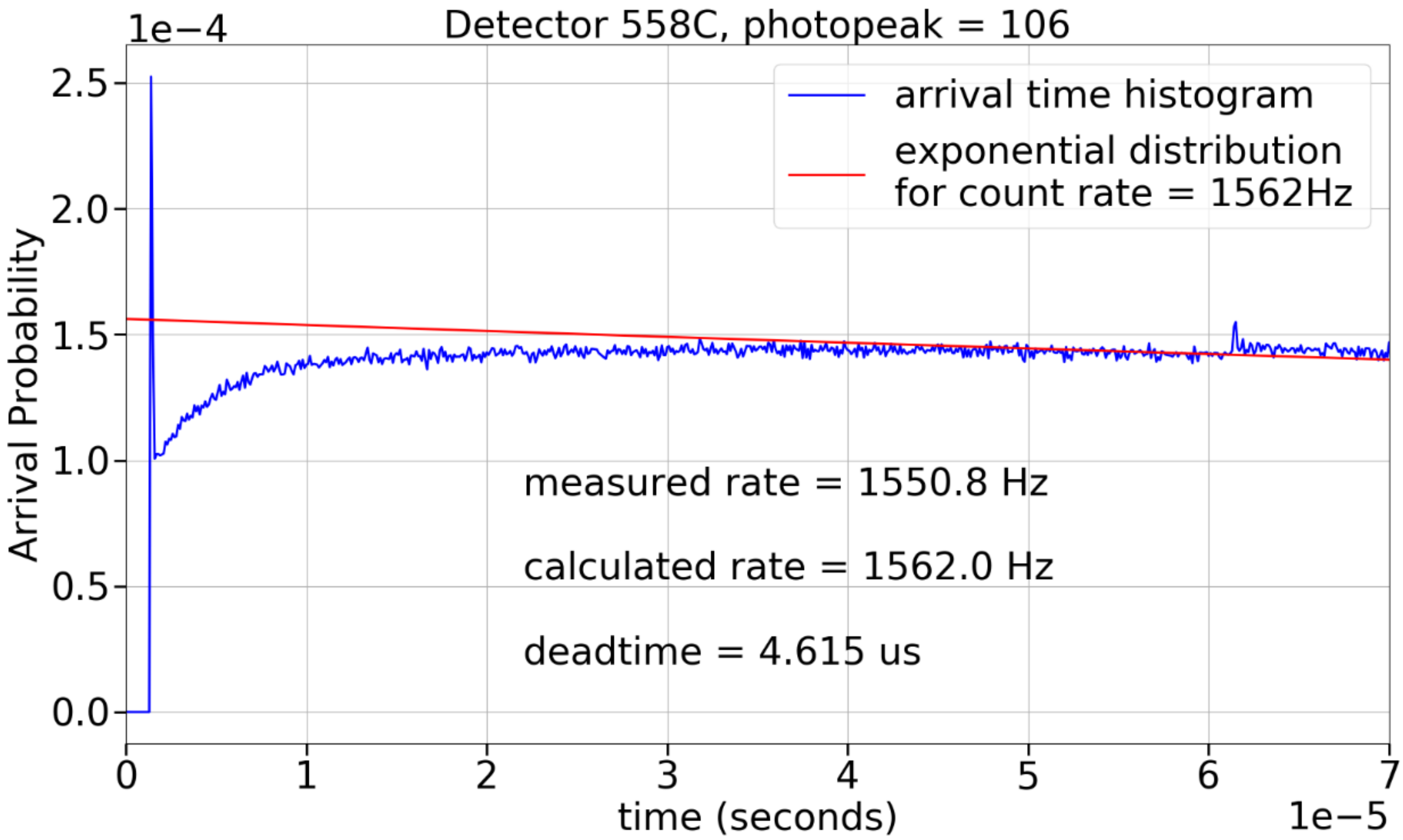
$$P(t_1 < X < t_2) = e^{-\lambda t_1} - e^{-\lambda t_2}$$

- CANDOR_DAQ has timestamping capability. Each event's arrival time is recorded with 100ns precision.

PDF of time elapsed between 2 consecutive events



Algorithm Behaviors are Visible



Calculating Deadtime

(1) $\tau = \sum_{n=0}^{end\ of\ adaptive\ cooloff} \left(1 - \frac{M[n]}{T[n]}\right) \times timestamp\ resolution$

M[n] = measured PDF, T[n] = theoretical PDF

(2) $r_{actual} = \frac{C_{total}}{T_{total} - C_{total}\tau}$

r = rate, C = counts, T = time

(3) $\lambda = r_{actual} \times timestamp\ resolution$

(4) $P(t_1 < X < t_2) = e^{-\lambda t_1} - e^{-\lambda t_2}$

Iterate Calculations

- Once deadtime is calculated, the actual count rate changes, which changes lambda, which changes the exponential distribution, which changes the deadtime calculation

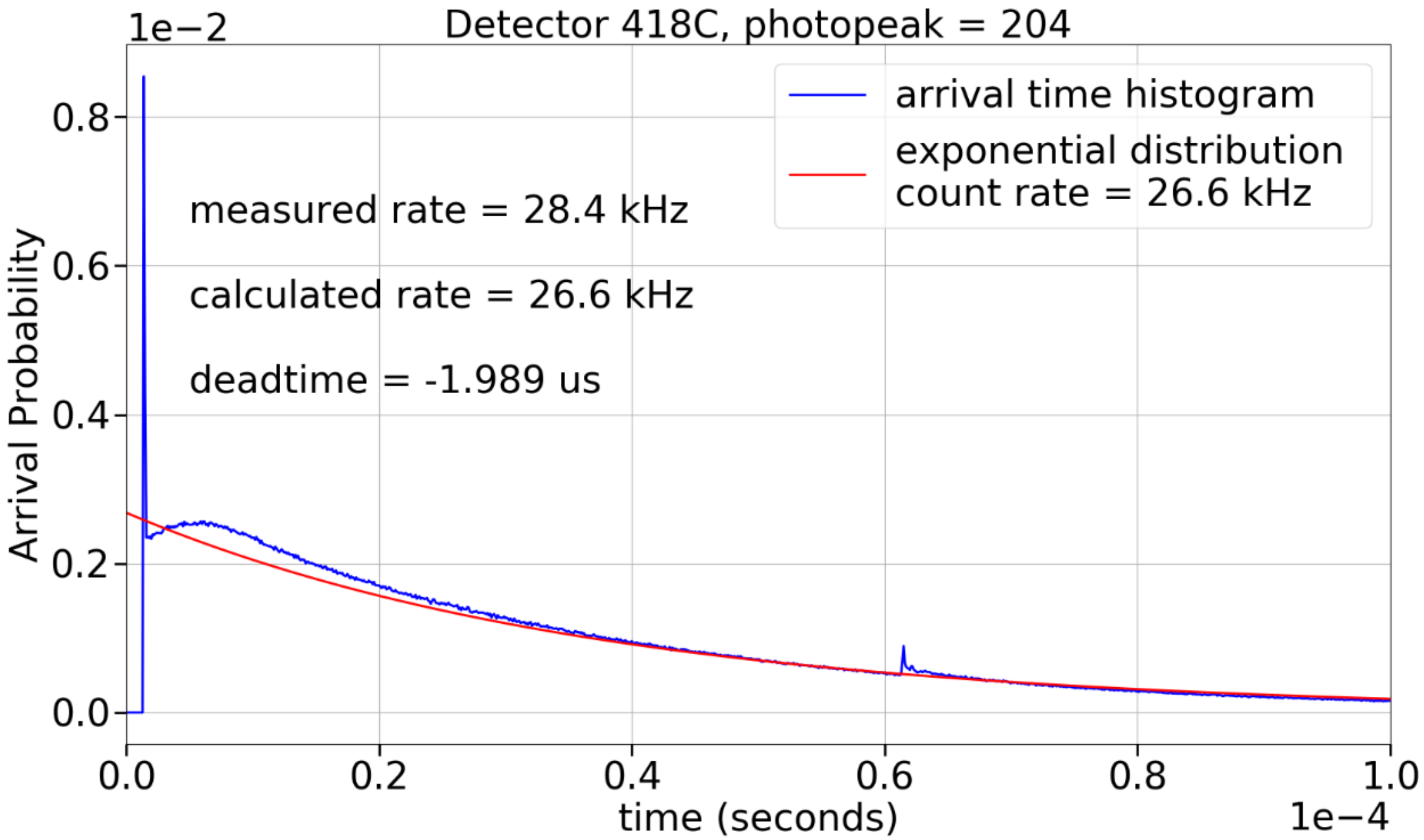
- Convergence after ~20 iterations

Caveats?

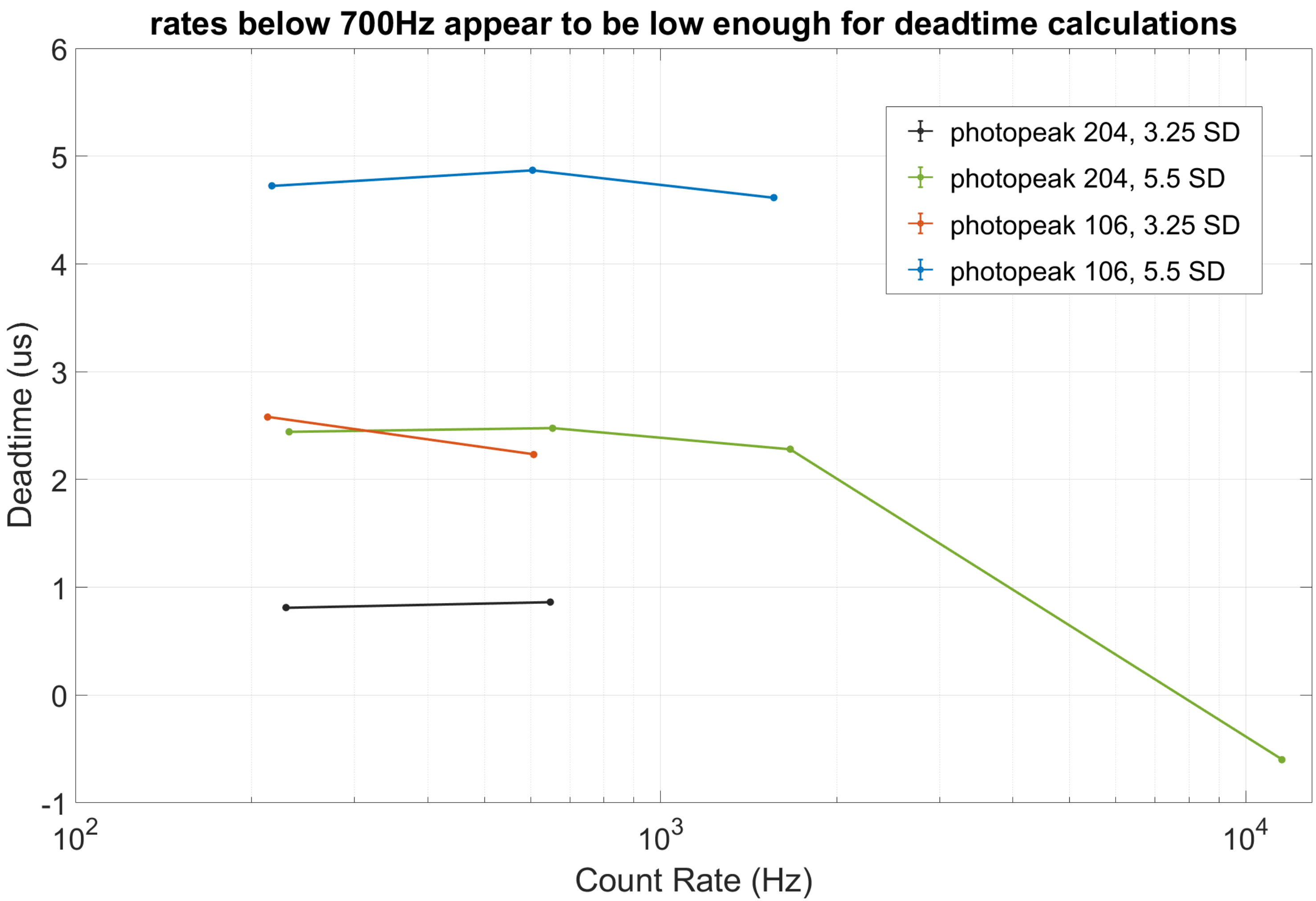
- Must count for an appropriate amount of time
  - In our case, 1E+7 events were recorded for a good histogram

- Must use an appropriate count rate
  - A PDF must integrate to 1. Like a water balloon, if you squeeze one end, it will bubble up on the other end. Cannot have significant distortion within the calculation period. After is OK.

Count rate too high

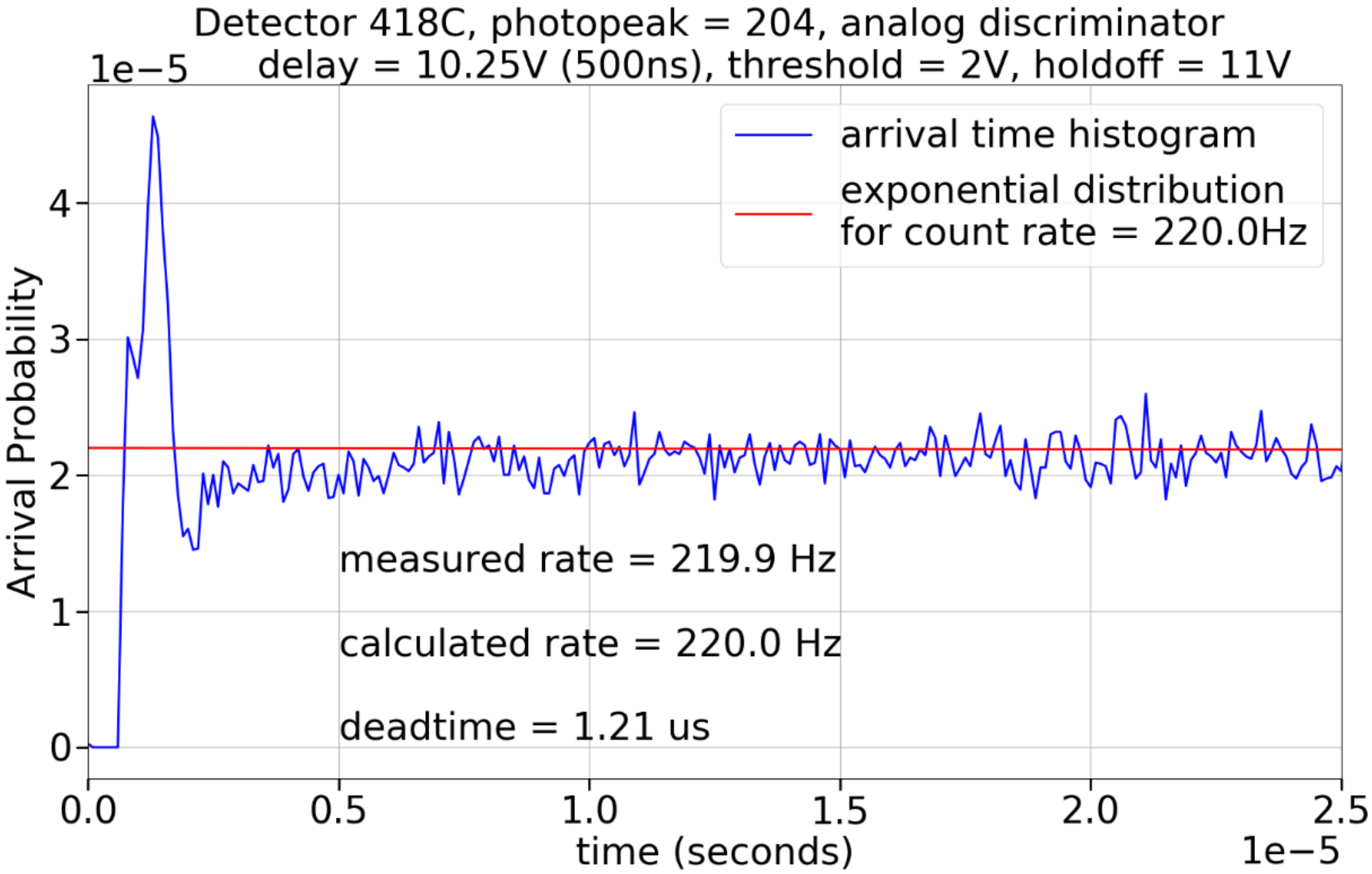


Results


rates below 700Hz appear to be low enough for deadtime calculations
6
5
4
3
2
1
0
-1
Deadtime (us)
10^2
10^3
10^4
Count Rate (Hz)
photopeak 204, 3.25 SD
photopeak 204, 5.5 SD
photopeak 106, 3.25 SD
photopeak 106, 5.5 SD

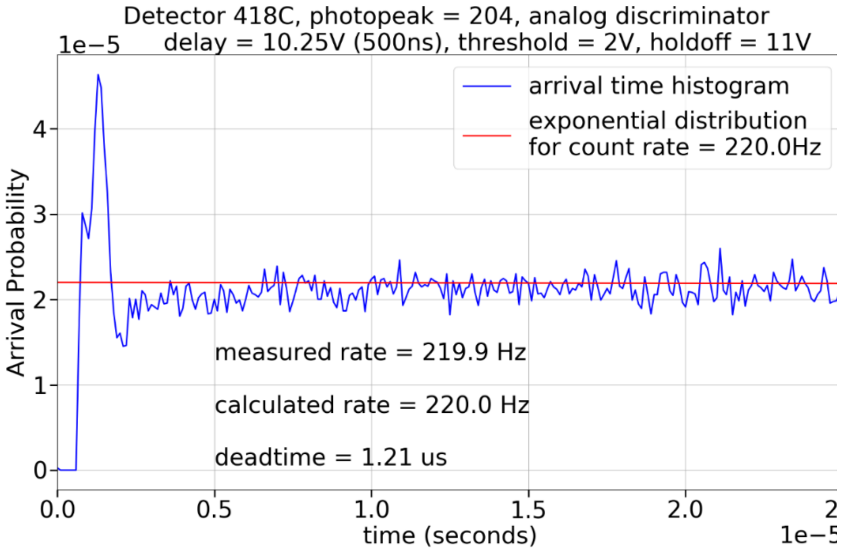
Analog Discriminator

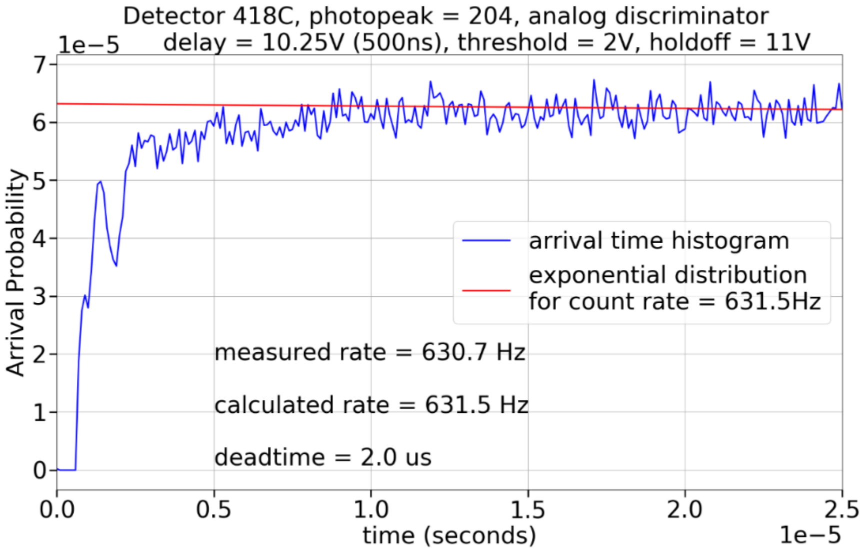
- Also has an adaptive cooloff function, but has not been tuned/finessed well… shows doublecounts in the PDF



PDF change at 2 count rates

- The doublecount feature is still present at 631Hz, but is smaller than at 220Hz





Interesting!

- At a low count rate, there are more double counts compared to missed counts.
- Missed counts increase with count rate. They are related to the deadtime fraction.
- Doublecounts are independent of the count rate. They are a function of the adaptive cooloff profile.

Calculate Deadtime AND Doublecounts

- We have two PDFs and two unknowns. Let’s come up with some equations.

$$measured\ counts = theoretical\ counts - missed\ counts + doublecounts$$

$$missed\ counts = theoretical\ counts \times\ \tau\ \times r_{actual}$$

$$double\ counts = theoretical\ counts\ \times\ d$$

τ = deadtime
r_{actual} = actual count rate
$\tau \times r_{actual}$ = deadtime fraction
d = double count fraction

Equations

- $M_1 = T_1(1 - \tau r_1 + d)$
- $M_2 = T_2(1 - \tau r_2 + d)$
- $\tau = \frac{\frac{M_2}{T_2} - \frac{M_1}{T_1}}{r_1 - r_2}$
- $d = \frac{M_1}{T_1} + \tau r_1 - 1$
- $M = 1 - \left(\sum_{n=0}^{end\ adaptive\ cooloff} T[n] - M[n]\right)$
- T = 1

Results

Detector	photopeak	Adaptive cooloff theshold	PSD	deadtime	deadtime uncertainty	doublecount fraction	doublecount uncertainty
418C	204	11V	analog	2.465 µs	0.105 µs	2.59E-03	7.51E-05
558C	106	11V	analog	6.474 µs	0.146 µs	1.07E-03	4.31E-05
418C	204	5.5 SD	digital	2.487 µs	0.142 µs	1.11E-05	1.06E-04
558C	106	5.5 SD	digital	4.910 µs	0.130 µs	3.88E-05	8.80E-05
418C	204	3.25 SD	digital	0.902 µs	0.146 µs	1.84E-05	1.08E-04
558C	106	3.25 SD	digital	2.050 µs	0.144 µs	-1.11E-04	1.00E-04

Take-aways

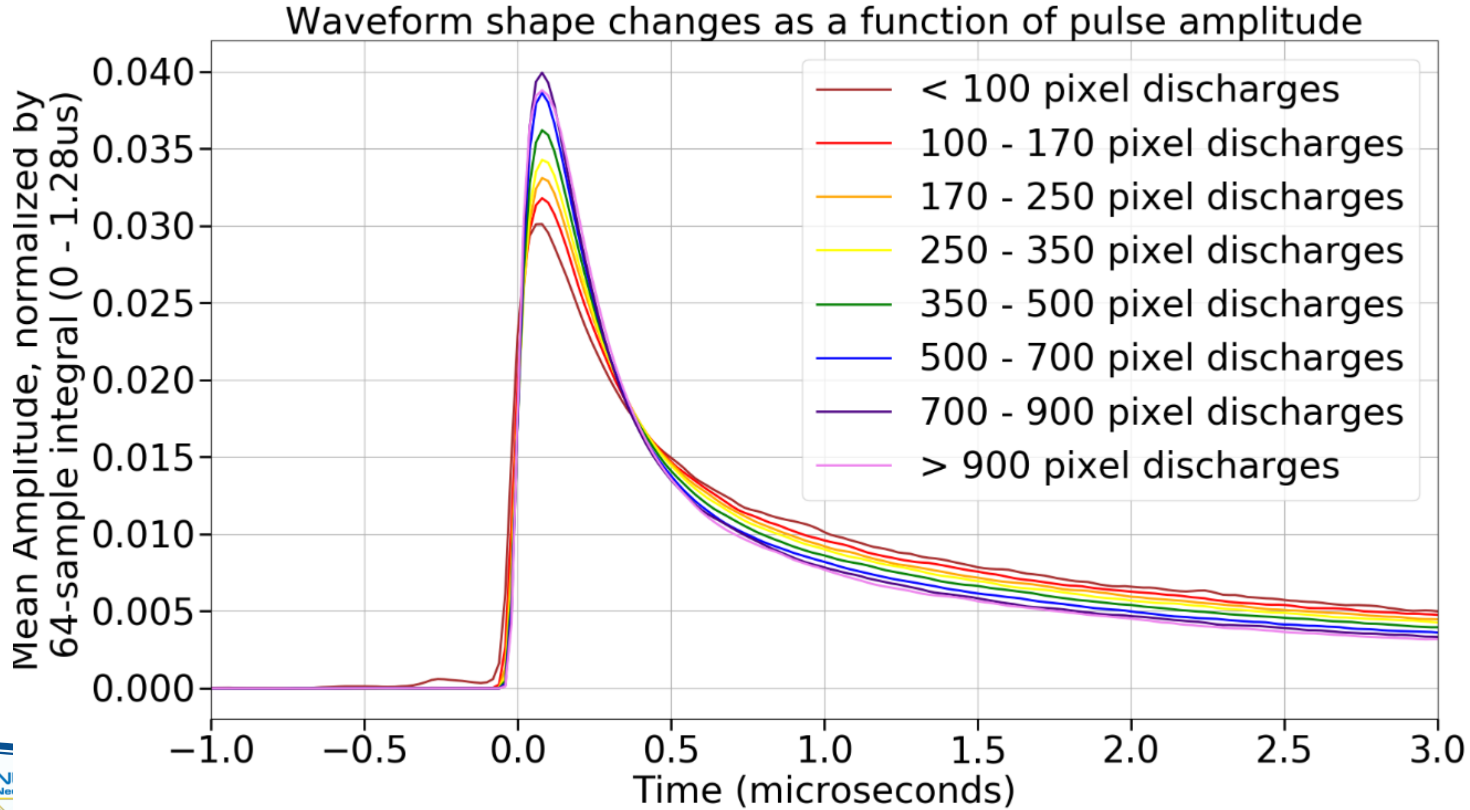
- Scientists need to know what their detector deadtime is for accurate measurements at high count rates.
- For a detector developer, deadtime can be measured with the two-source method.
- If the two-source method isn't feasible (radiological hazard, sources unavailable)…
- … AND if you have a timestamper, then you can calculate the deadtime from arrival time statistics.
- You can even calculate the doublecount fraction too!

Thank You!

- Questions?

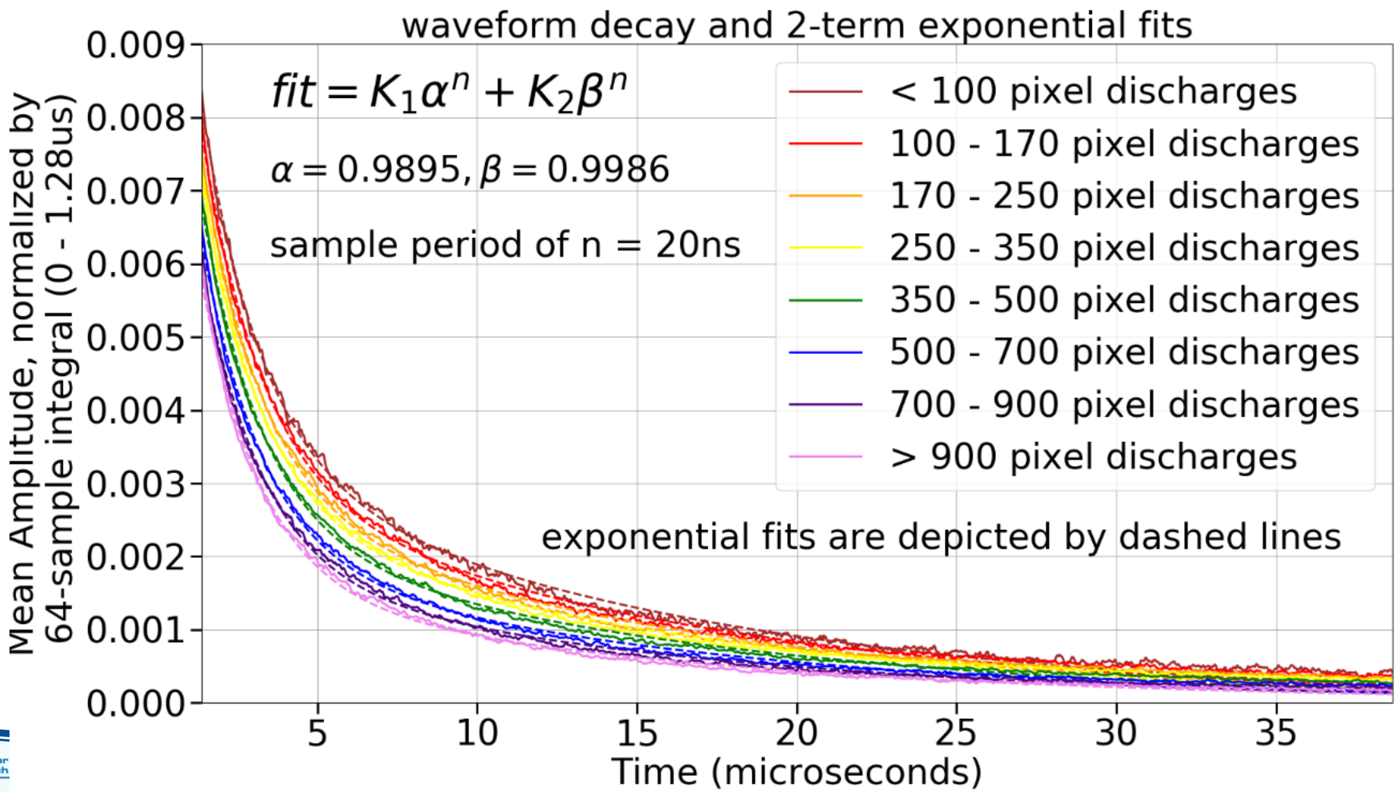
Average Neutron Decay

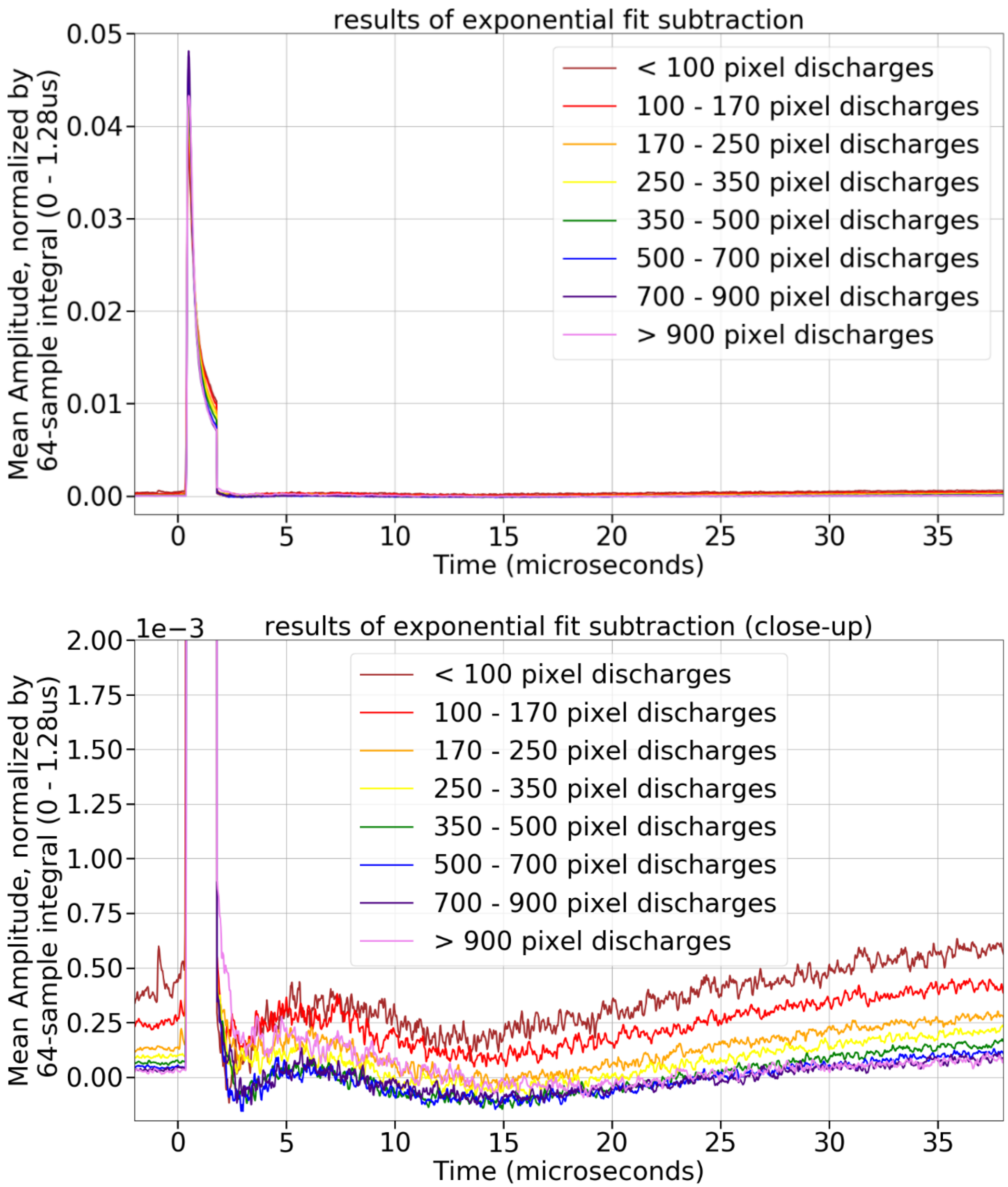
- Decay changes slightly with amplitude. Why??



2–term exponential decay

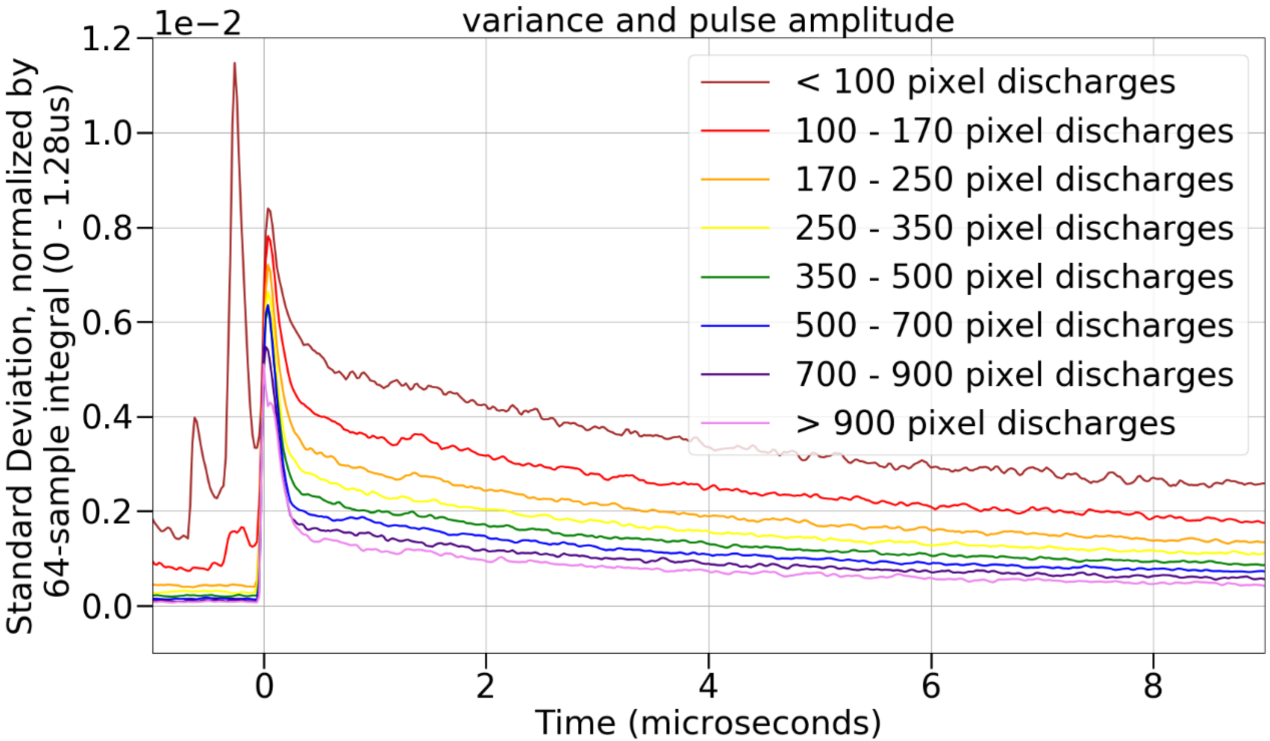
$$f[n] = k_1 \alpha f[n-1] + k_2 \beta f[n-1]$$




results of exponential fit subtraction
0.05
0.04
0.03
0.02
0.01
0.00
Mean Amplitude, normalized by 64-sample integral (0 - 1.28us)
0
5
10
15
20
25
30
35
Time (microseconds)
< 100 pixel discharges
100 - 170 pixel discharges
170 - 250 pixel discharges
250 - 350 pixel discharges
350 - 500 pixel discharges
500 - 700 pixel discharges
700 - 900 pixel discharges
> 900 pixel discharges
results of exponential fit subtraction (close-up)
1e−3
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Mean Amplitude, normalized by 64-sample integral (0 - 1.28us)
0
5
10
15
20
25
30
35
Time (microseconds)
< 100 pixel discharges
100 - 170 pixel discharges
170 - 250 pixel discharges
250 - 350 pixel discharges
350 - 500 pixel discharges
500 - 700 pixel discharges
700 - 900 pixel discharges
> 900 pixel discharges

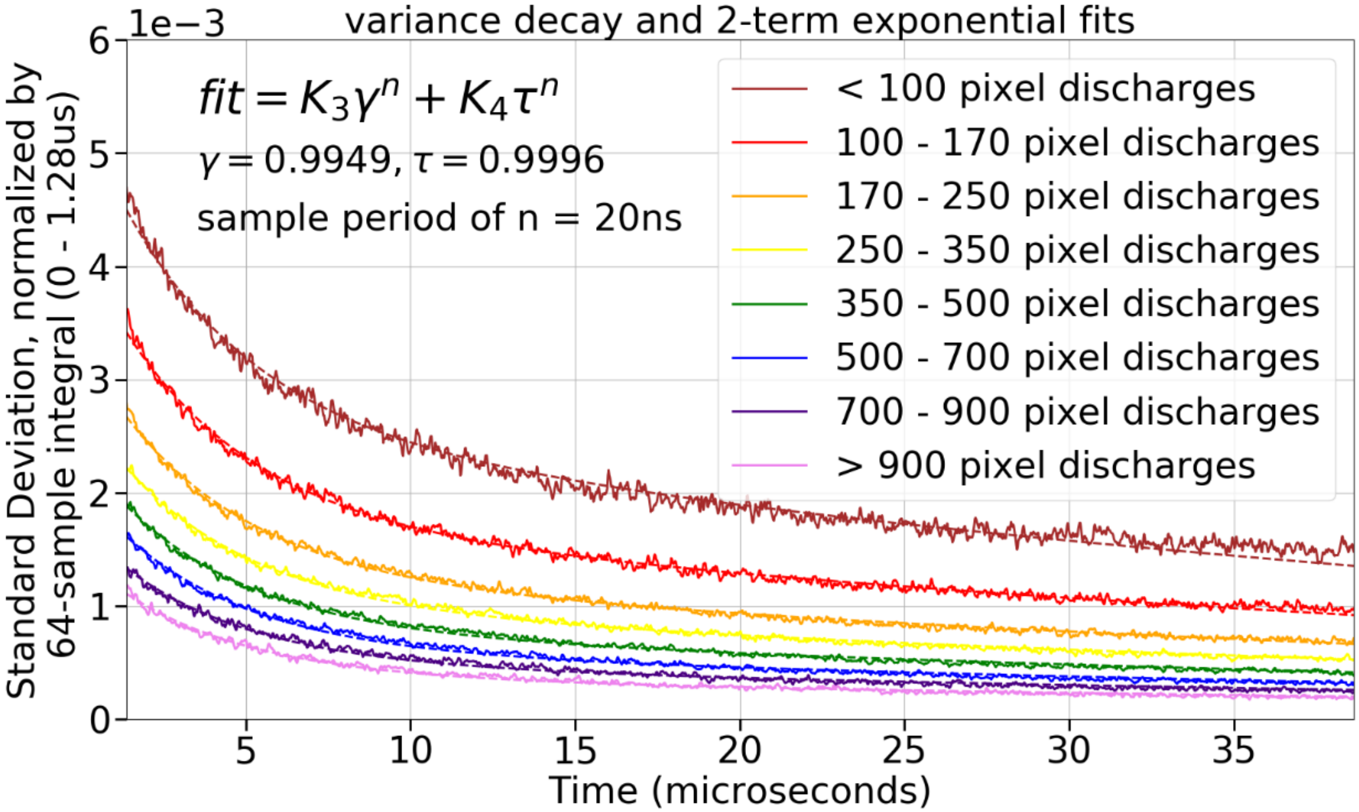
Subtract the mean, but variance is still a problem

- Larger pulses have more photons, less variance, smoother shape, better statistics

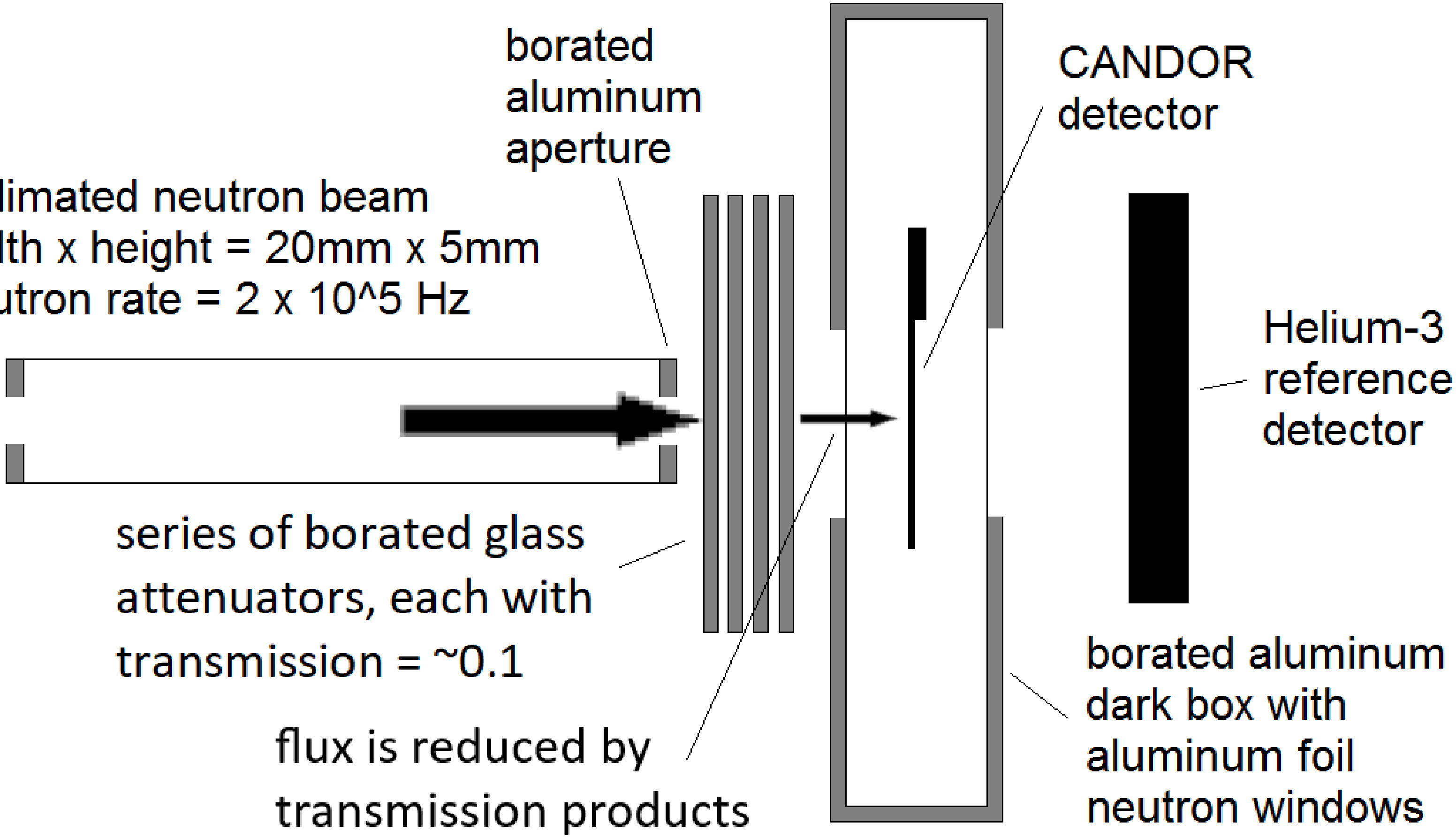


Variance is also a 2-term exponential

$$f[n] = k_3 \gamma f[n-1] + k_4 \tau f[n-1]$$



Attenuator Superposition Method at PHADES



borated aluminum aperture

collimated neutron beam
width x height = 20mm x 5mm
neutron rate = 2 x 10^5 Hz

CANDOR detector

Helium-3 reference detector

series of borated glass attenuators, each with transmission = ~0.1

flux is reduced by transmission products

borated aluminum dark box with aluminum foil neutron windows

Hypothetical Example…

- Original Beam Rate = 1E+5 Hz (neutrons per second)

- Attenuator A Transmission = 0.1
- Attenuator B Transmission = 0.1
- Attenuator C Transmission = 0.1
- Attenuator D Transmission = 0.1

- Beam Rate ABCD = 10 Hz (neutrons per second)
- Beam Rate ABC = 100 Hz (neutrons per second)
- Beam Rate AB = 1000 Hz (neutrons per second)
- Beam Rate A = 10000 Hz (neutrons per second)

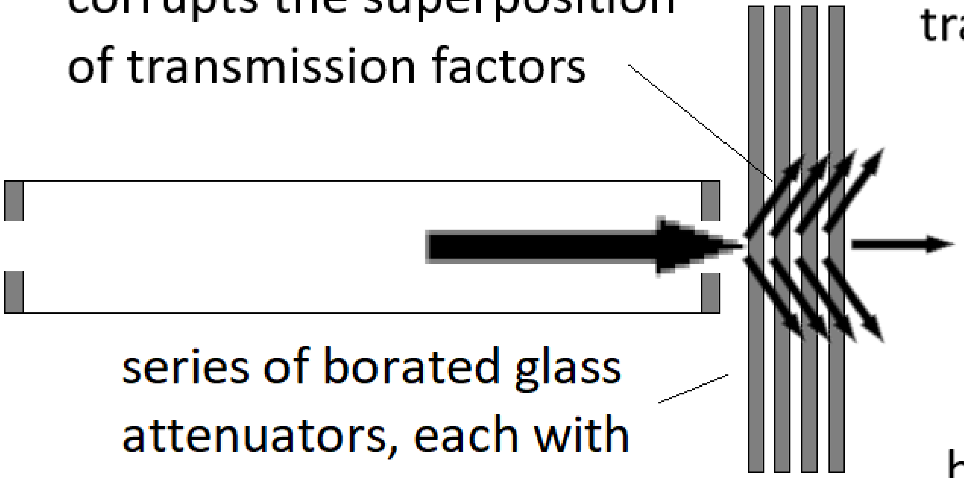
- If measured Beam Rate A = 9500 Hz, then there is 5% deadtime fraction

Attenuators	Measured Rate (Hz)	Measured Uncertainty (Hz)	Calculated Rate (Hz)	Calculated Uncertainty (Hz)	Deadtime (µs)	Deadtime Uncertainty (µs)
none	106220	141	166580	1334	3.41	0.05
A	23997.4	34.2	24753.9	222.8	1.27	0.37
H	10701.9	14.5	10548.5	96.0	−1.36	0.87
AC	3915.63	6.21	3655.33	36.18	−18.17	2.74
AH	1632.51	2.84	1567.51	15.65	−25.34	6.46
FG	670.01	1.15	672.03	6.77	4.82	15.2
FH	668.37	1.15	670.38	6.75	4.83	15.2
GH	667.61	1.15	669.61	6.74	4.83	15.3
AGH	99.50	0.31	99.51	1.08	15.38	113.6
CGH	98.88	0.31	99.10	1.09	37.54	115.6
FGH	42.65	0.15	42.56	0.47	31.83	267.9

Results

- The test should show consistent deadtime calculations over the entire range of count rates. It did not. There were even negative deadtimes! Impossible!
- The experiment failed to take scattered neutrons into account.
- The collimator should have been placed after the attenuators to remove scattered neutrons… requires significant re-design & machined parts

Illustration of failed test



scattering of attenuators corrupts the superposition of transmission factors

combined transmission is lower than the product of individual attenuator transmissions

series of borated glass attenuators, each with transmission = ~0.1

... because low angle scattered neutrons are absorbed by subsequent attenuators, or scattered again