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SiPM Noise Simulation

HENRY KLEST

U.S. DEPARTMENT OF ENERGY
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EPIC

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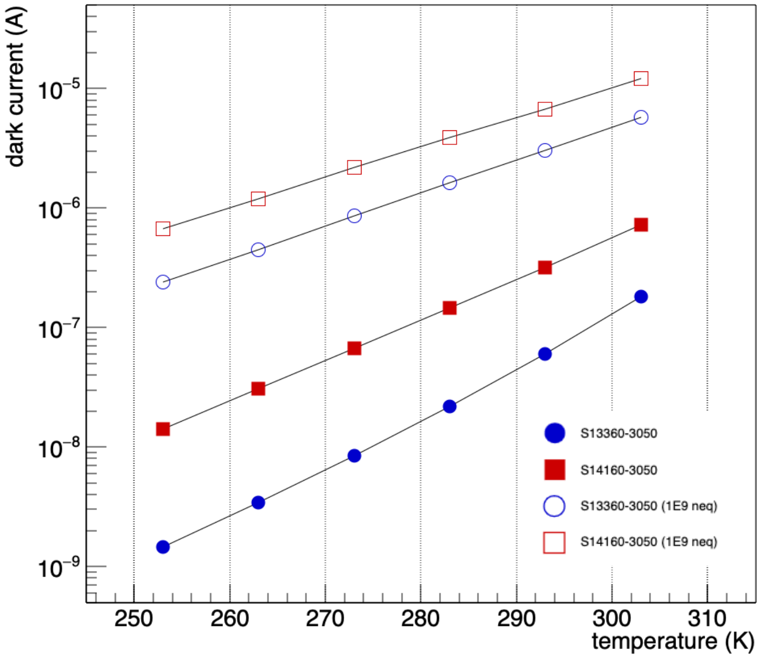
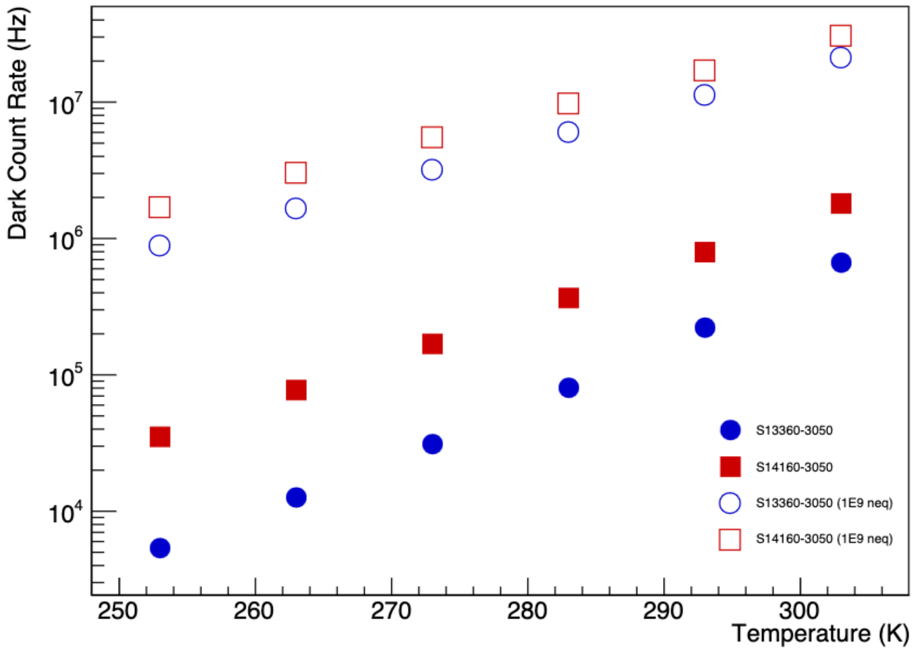
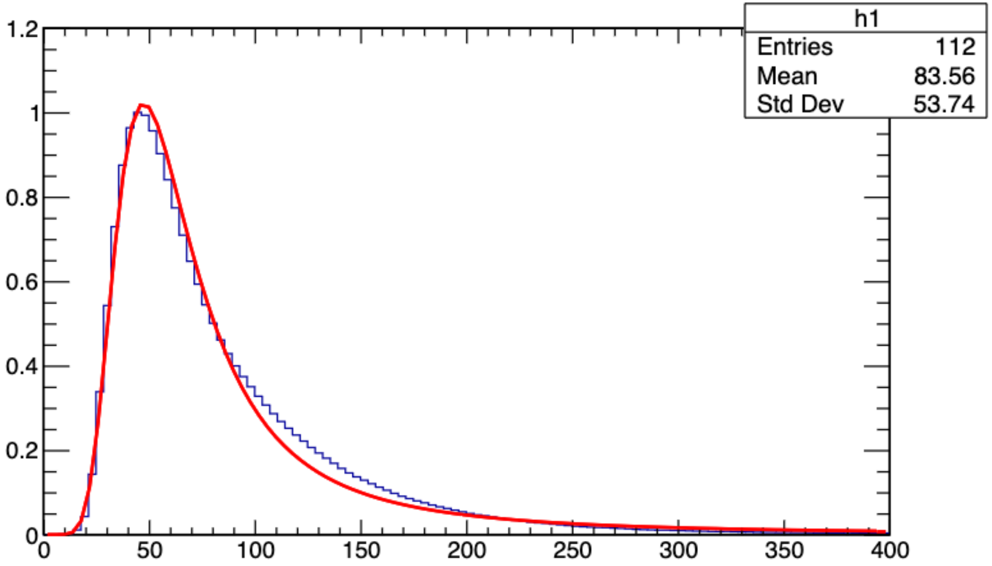
Dark Currents from INFN Measurements

- Scale currents by gain & q_e to get a dark count rate
  - This is a bit naïve, but Roberto indicated it should be alright
- Order of magnitude increase after 1E9 1 MeV neq dose
  - Our conservative estimate of dose for lifetime of experiment was 3E10





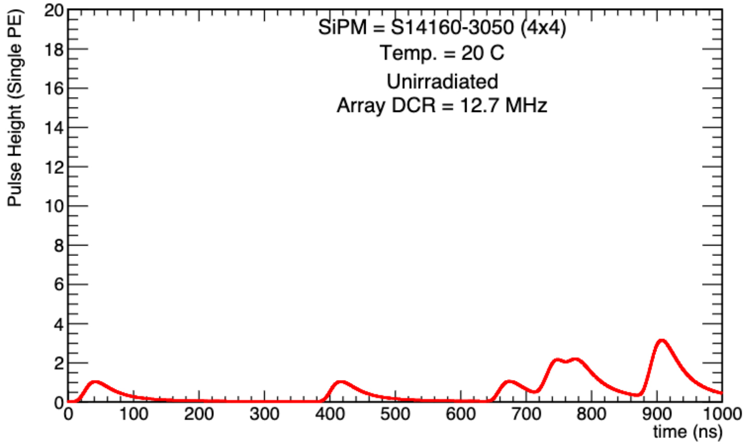
HGCROC Signals



- Pulse from charge injection tests on HGCROC
  - Kindly supplied by Norbert
  - Digitized much faster than HGCROC actually digitizes
  - Landau fit
  - Peak set to 1 photoelectron
- For now, I just do the stupid thing and throw these distributions with the frequency of the DCR
- The reality of how often we will see hits from noise will depend on what ADC value we call a "hit"

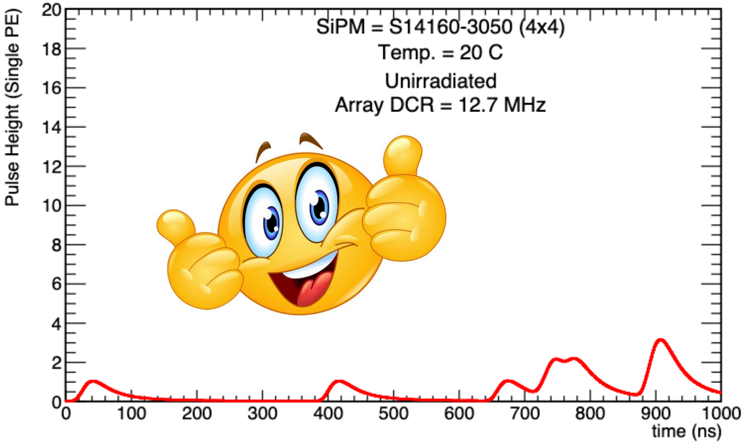
Waveforms

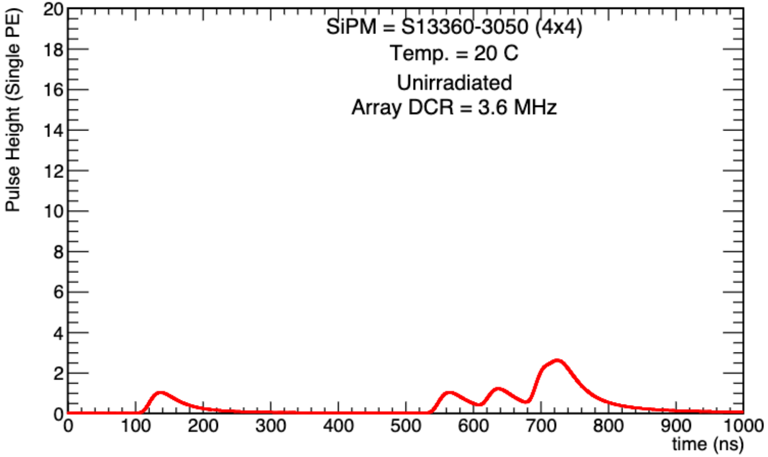
- Created by Monte Carlo which throws Landau distributions with parameters taken from the HGCROC charge injection signal at different time slices with probability defined by the DCR
- Crosstalk produces pulses 2x or 3x as high as the standard single-photon pulse
  - Here a 7% crosstalk probability is assumed for both S14160 and S13360
  - Final crosstalk numbers will depend on the optical coupling to the lightguide

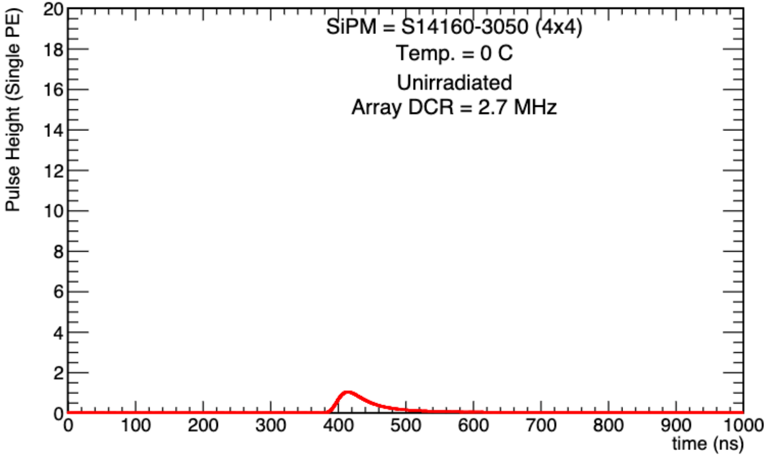


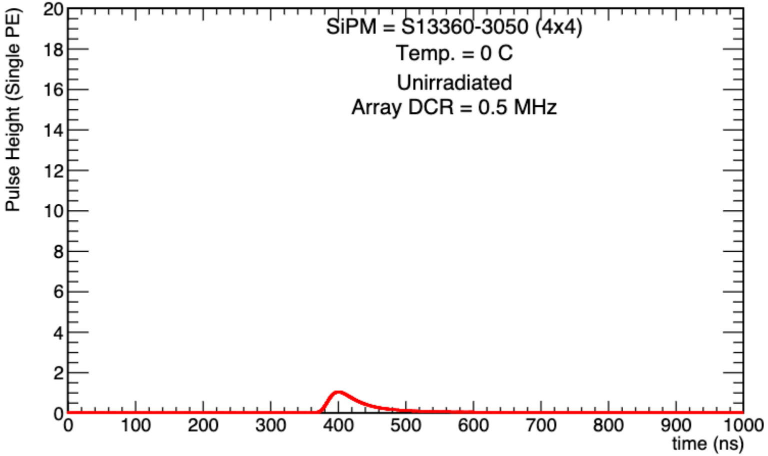
Temperature Dependence

Both sensors look reasonably good before irradiation, could easily set a threshold at 4 or 5 p.e.







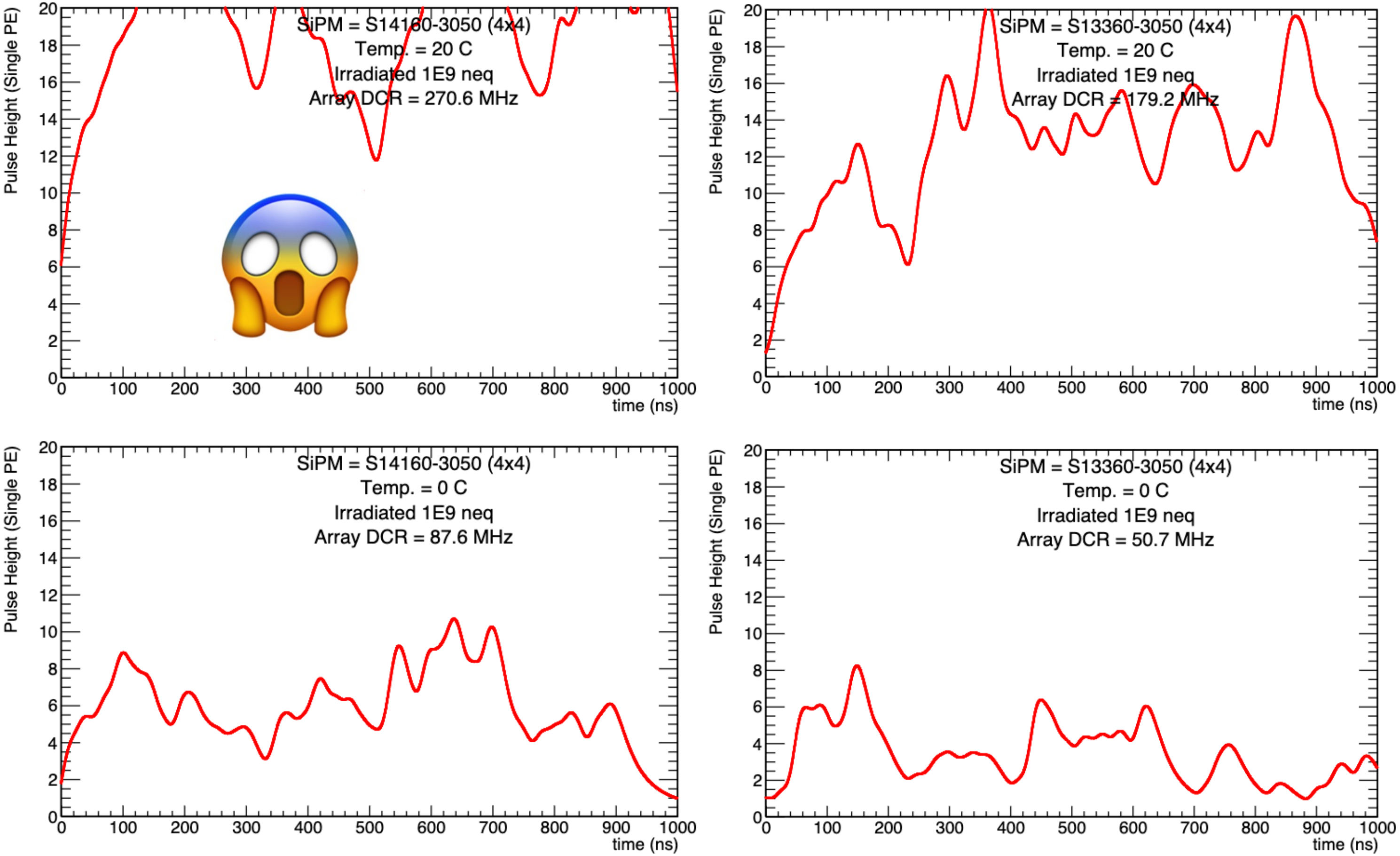


Radiation Damage

0 °C not cool enough to save the MIP for either SiPM after 1E9 1 MeV neq dose

This assumes that the dark *current* produced by irradiation translates directly into dark *counts*, which is the **worst case** scenario

Keep in mind that this represents only ~1/30th of the 10-year expected dose

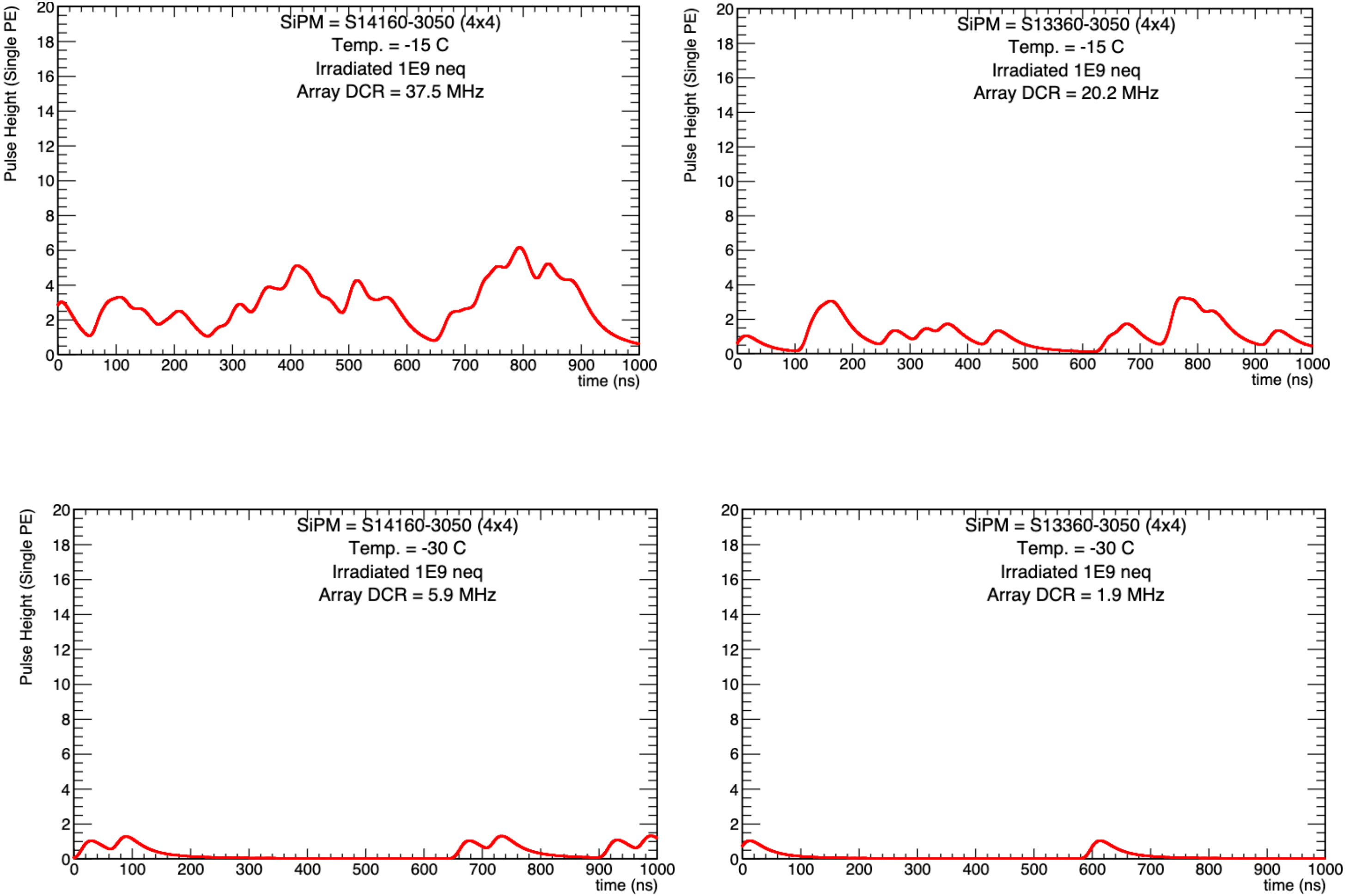


Sub-Zero

Looks acceptable, as expected since -30C is the nominal temperature for the single-photon counting in the dRICH

DCR is an exponential function of temperature

Integration of sub-zero cooling would likely be very challenging, but in principle possible since the dRICH is already doing it

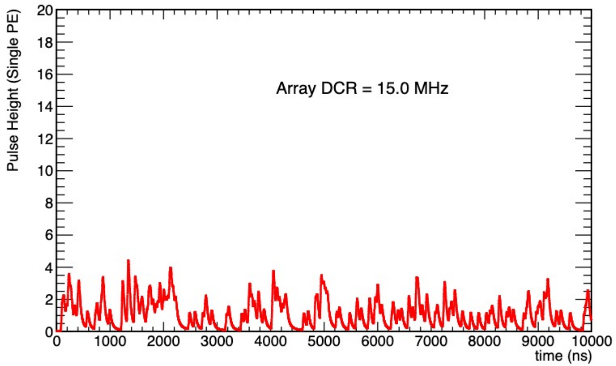


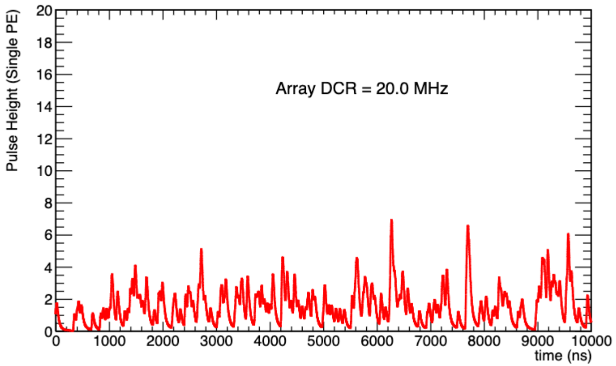
Threshold

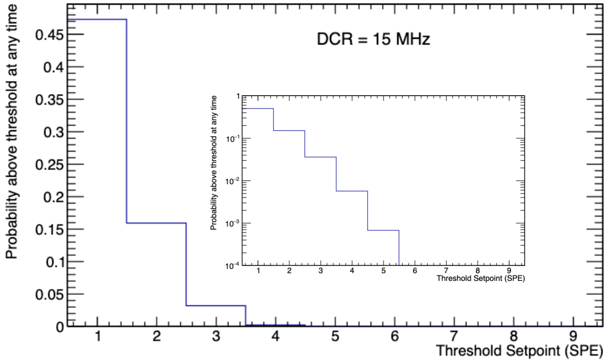
HGCROC will report information whenever the analog input is above a threshold

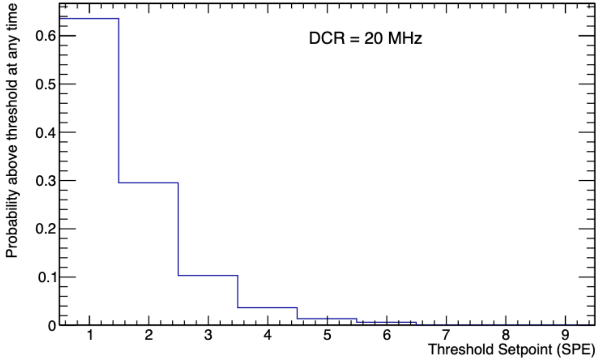
Given HGCROC pulse shapes, seems that something like ~15 MHz could be a reasonable goal for maximum DCR

- In 100 μs, expect analog signal above a 5 N_{pe} threshold ~0.05% of the time



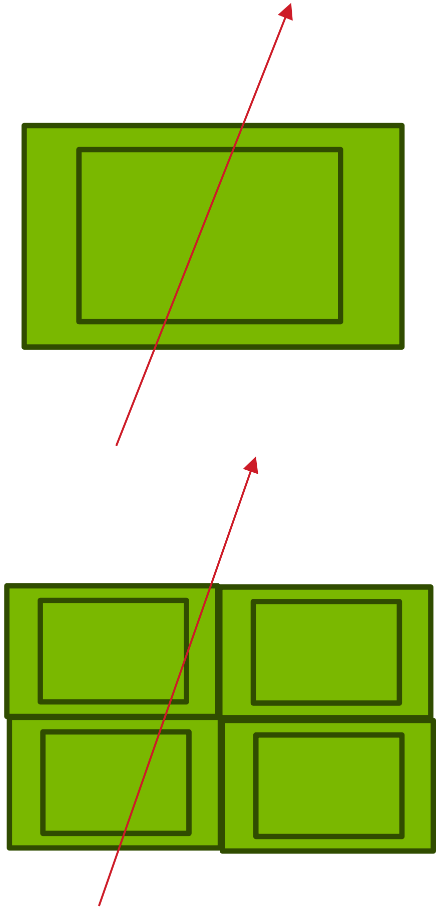






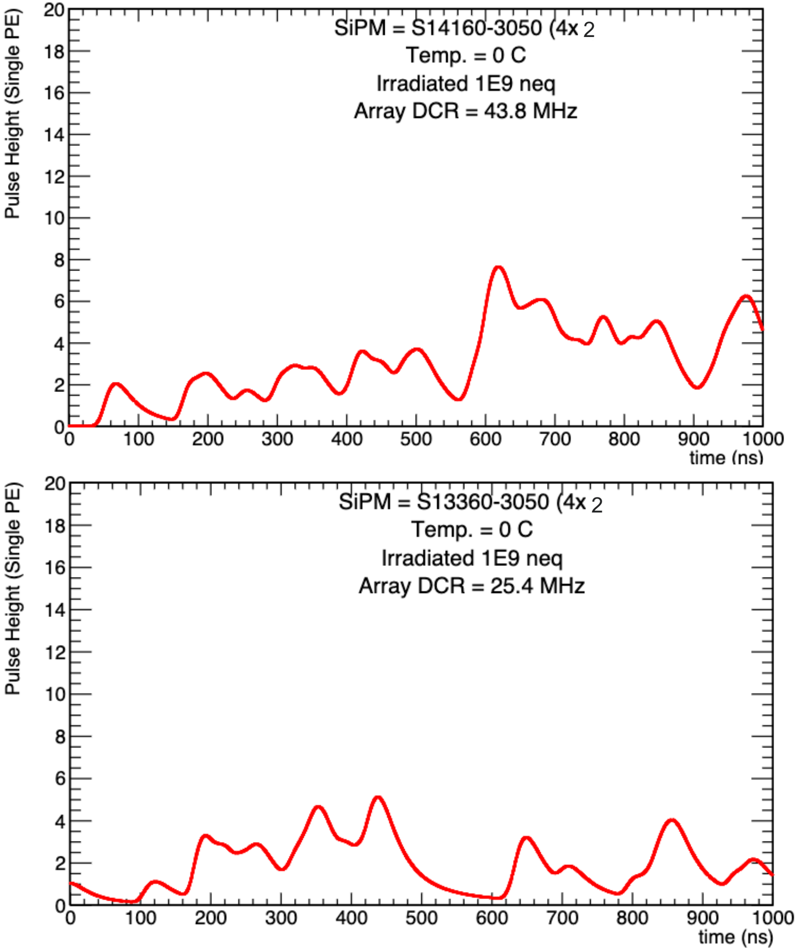
Summing Channels

- How can we reach 15 MHz?
  - What matters for keeping the MIP is that there are less than 15 MHz of noise in the area that the MIP photons are hitting
- Splitting the 4x4 array into four optically isolated 2x2 arrays could ~half the noise on the MIP
  - Set thresholds at ~ ¼ the value of the 4x4 array
  - Four light guides covering smaller areas
  - Unlike a shower, the MIP energy deposit in the SciFi can be approximated as a line
    - Will typically send all its photons to ~two of the four SiPMs!
  - Half the surface area of active SiPM means half the noise



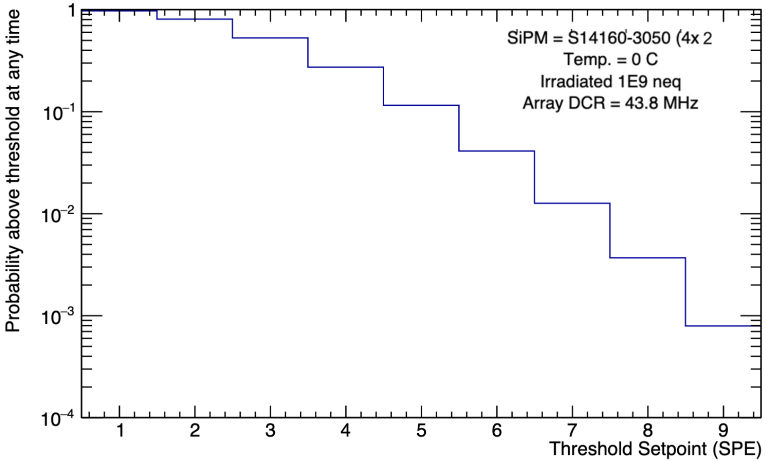
Discussion

- Even with splitting readout channels from 4x4 summed to 2x2 summed, can't reach 15 MHz for irradiated SiPMs even at 0 °C
  - 1x1 channels? 5760*16 = 92k readout channels
- Effects of annealing between runs not considered
  - Time heals all wounds
  - Some studies show 1 month of sitting at room temp. after proton irradiation can decrease dark current by a factor of 2
- Or do as Craig Woody said and use the MIP to cross-calibrate in the early stages of the experiment, then trust that calibration once the MIP is below threshold



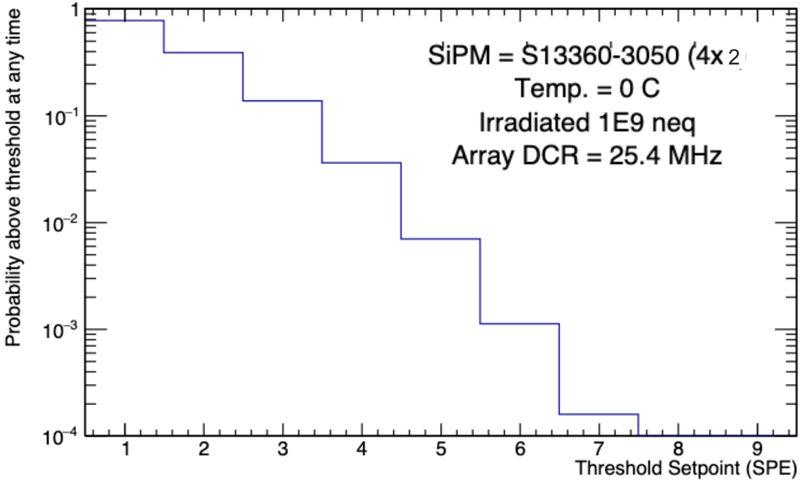
Fraction of time spent above a threshold of N_{SPE} (1 ms simulated)

```
percentage above 2 SPE = 0.805159
percentage above 3 SPE = 0.526815
percentage above 4 SPE = 0.272328
percentage above 5 SPE = 0.115044
percentage above 6 SPE = 0.040986
percentage above 7 SPE = 0.012618
percentage above 8 SPE = 0.003681
percentage above 9 SPE = 0.000791
```



Per channel, expect 11% of samples to be above a 5 p.e. threshold (4.4 MHz)

```
percentage above 2 SPE = 0.38593
percentage above 3 SPE = 0.136293
percentage above 4 SPE = 0.035822
percentage above 5 SPE = 0.006938
percentage above 6 SPE = 0.001113
percentage above 7 SPE = 0.000158
percentage above 8 SPE = 0
percentage above 9 SPE = 0
```



Per channel, expect 0.6% of samples to be above a 5 p.e. threshold (0.24 MHz)

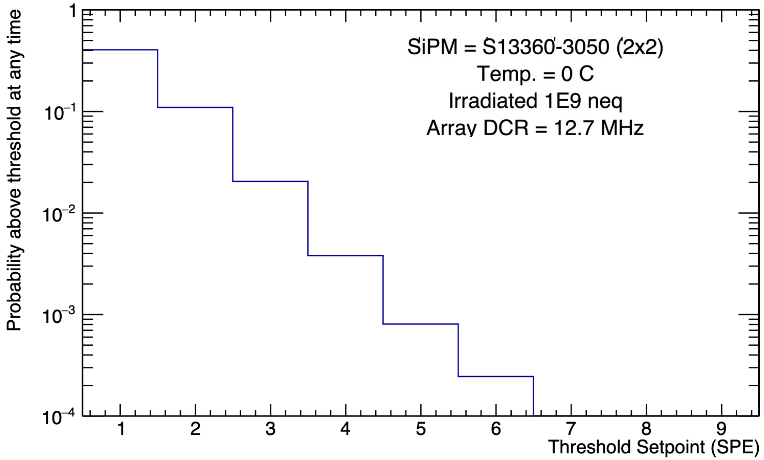
Ignoring time binning effects

HGCROC Bandwidth

2x2 array in 100 μs

- HGCROC sends 32 bits/hit
- Currently each HGCROC has 2 x 1.28 Gbps links
- Max hit rate above threshold: 80 MHz for all channels on that HGCROC
- Anticipate 60 Channels/HGCROC
- Max hit rate of ~1.3 MHz/channel can be passed on by HGCROC
  - For irradiated S13360 with readout split into 2x2, expect total DCR/channel of 12.7 MHz, want a threshold at ~2-3 SPE
    - Above 2 PE 10% of the time ~ 4 MHz
    - above 3 PE 2% of the time ~ 0.8 MHz
    - Cross-talk has much larger effect on operation at lower thresholds
  - Rate/channel situation is slightly worse for split readout due to cross-talk

```
percentage above 1 SPE = 0.403242
percentage above 2 SPE = 0.109232
percentage above 3 SPE = 0.020353
percentage above 4 SPE = 0.00378
percentage above 5 SPE = 0.000802
percentage above 6 SPE = 0.000244
percentage above 7 SPE = 2.4e-05
percentage above 8 SPE = 0
percentage above 9 SPE = 0
```



Conclusion

- With measurements from INFN and HGCROC signals, made some first estimates for what waveforms will look like
- Irradiated sensors very likely to lose the MIP without intervention
  - Additional cooling
  - Annealing
  - Further splitting of channels
- Caveats:
  - Dark Current to DCR conversion
  - Pulse shapes will depend on how many SiPMs are ganged together
  - No room-temperature annealing effect

BACKUP

HGCROC ADC Resolution

- Resolution of 0.4 fC ~ 2500 electrons
- Much smaller than the signal from a single SPAD firing in the SiPM
  - S13360 Gain 1.7E6
  - S14160 Gain 2.5E6

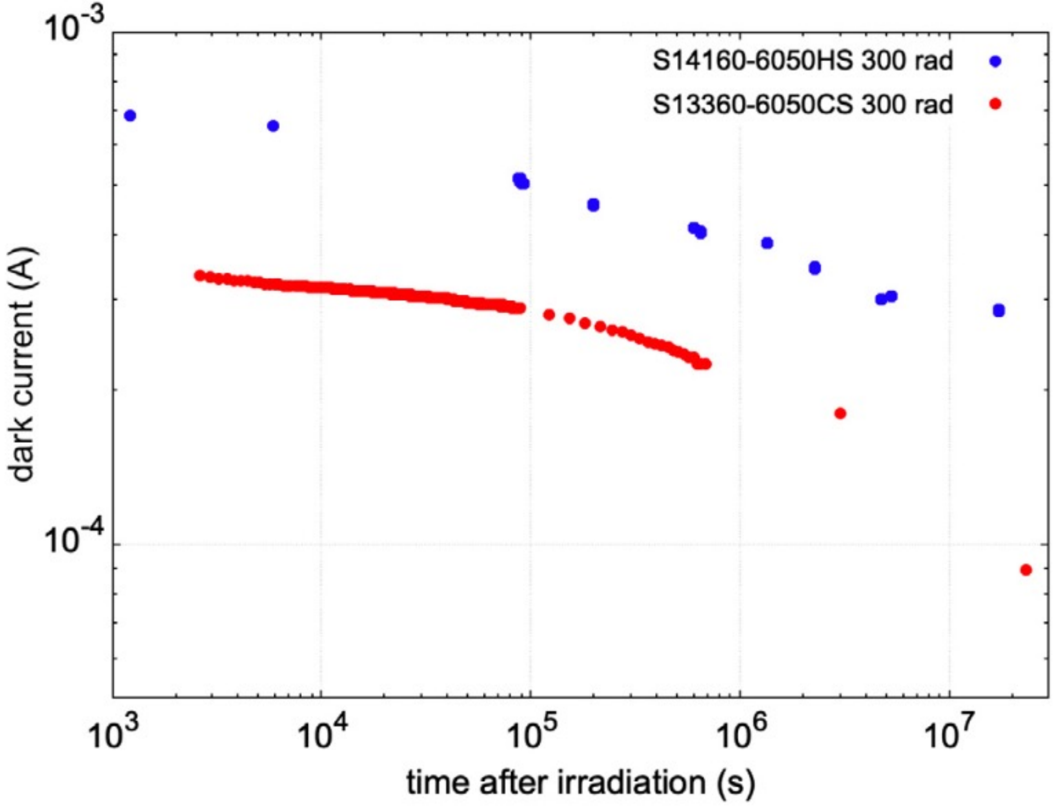
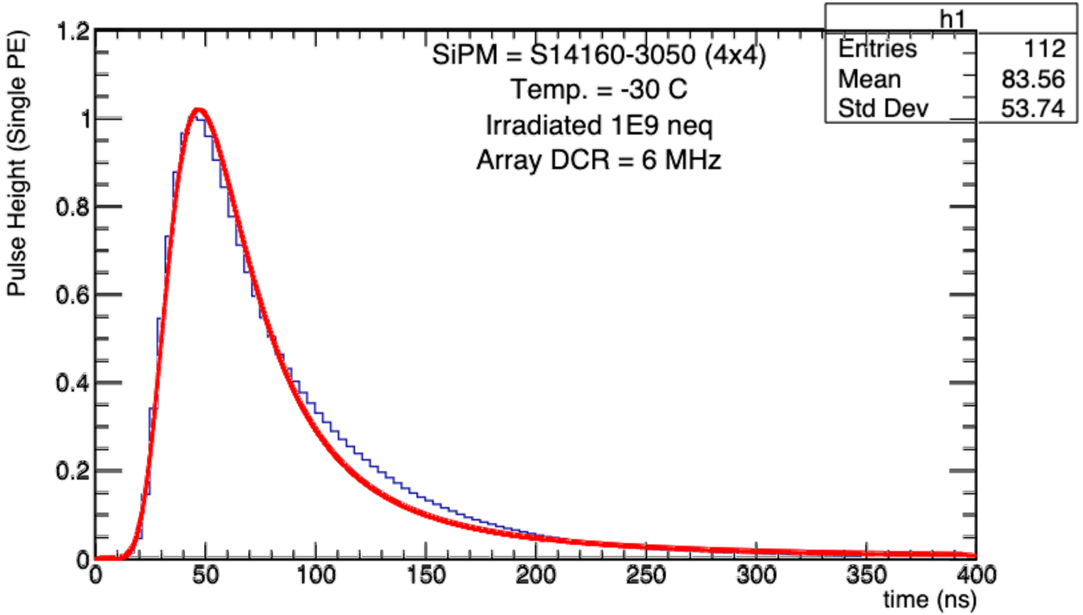
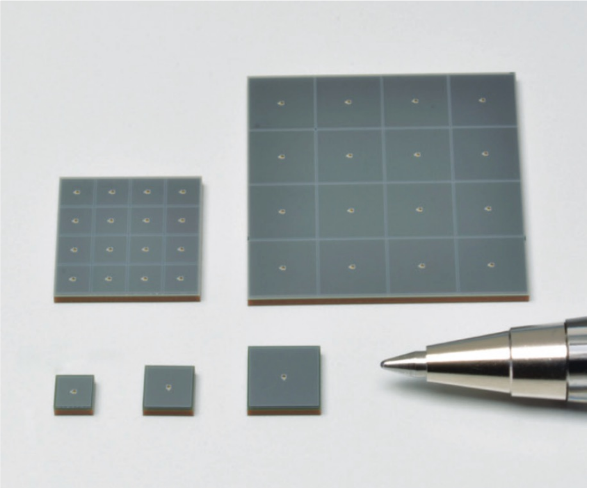


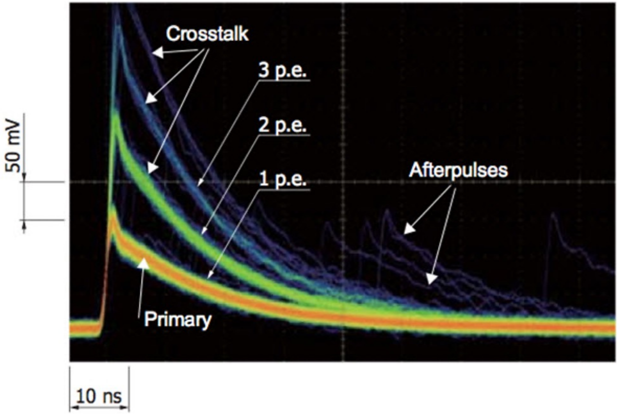
Fig. 2. Dark current in S13 (red) and S14 (blue) as a function of time after 300 rad irradiation at room temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)


SiPM = S14160-3050 (4x4)
Temp. = -30 C
Irradiated 1E9 neq
Array DCR = 6 MHz
h1
Entries 112
Mean 83.56
Std Dev 53.74
Pulse Height (Single PE)
time (ns)
0
0.2
0.4
0.6
0.8
1
1.2
0
50
100
150
200
250
300
350
400

CONSIDERATIONS

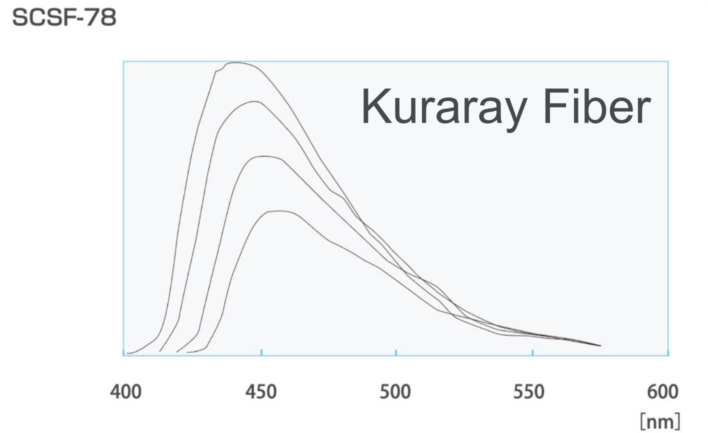
- Photon detection efficiency
- Noise
  - Low dark count rate necessary to see small signals from e.g. MIPs
  - Low crosstalk & afterpulsing preferable
- Pulse shape
  - Fast rise time for z-position resolution
    - Time-projection Calorimeter (TPC)
  - Short tail to reduce signal pileup
  - Consistent over time
  - Proportional to N_{pe}
- Consider the performance in the BIC of Hamamatsu S13660 and S14160 Series
  - Biggest challenge is seeing the MIP at midrapidity, use this as a benchmark

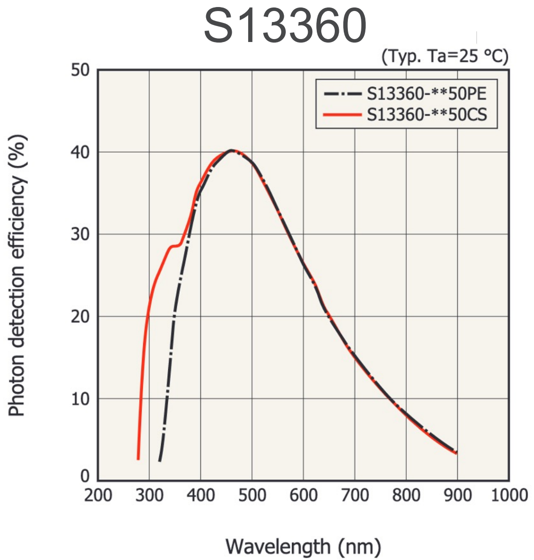


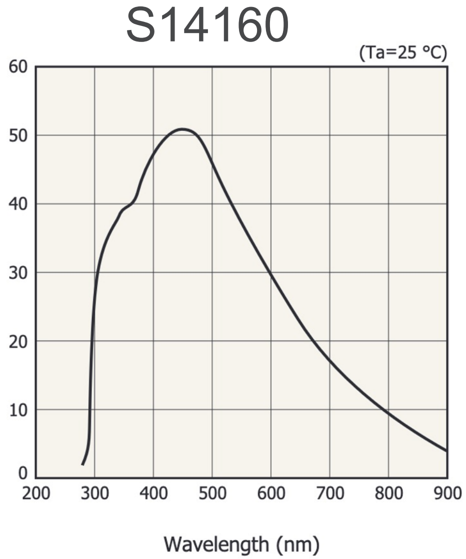


PDE

- PDE important to minimize statistical error on energy measurement & maximize efficiency for small signals
- 50 micron pixel size chosen
  - Trade off between geometric efficiency & saturation point
- Relevant wavelengths determined by emission spectrum of scintillating fibers
  - Both SiPMs peak in PDE near the emission peak around 450 nm
- **S14160 peaks at ~50% PDE**
- **S13360 peaks at ~40% PDE**
- In PDE, S14160 series wins







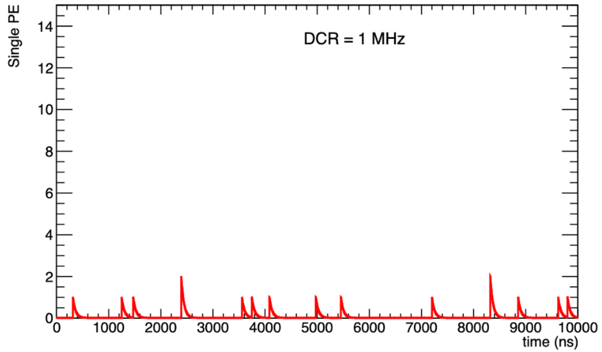
NOISE

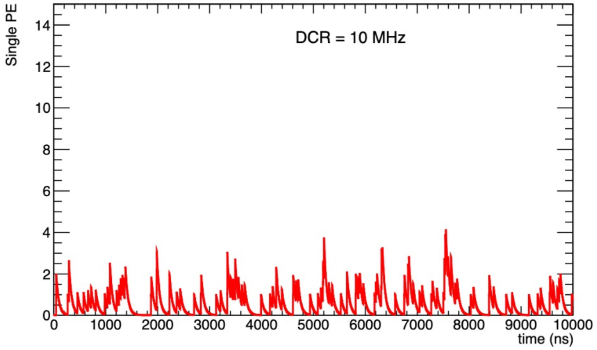
- Dark count rate (DCR) determines threshold
  - MIPs at midrapidity will generate 3-6 N_{pe} on average
    - Would be good to have threshold slightly below MIP
- DCR above a few 10s of MHz will endanger the MIP

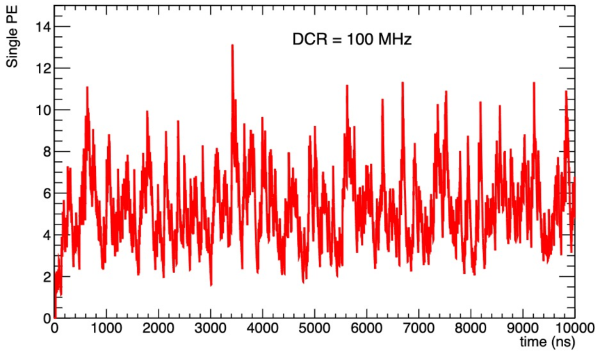
Specification	S13360-3050 (3x3 mm)	S14160-3050 (3x3 mm)
DCR (Typ.)	500 kHz	1 MHz***
Crosstalk (%)	3	7

*** Estimated, differing values in literature

- Signal will gang 1.2 cm x 1.2 cm area (16 3x3 mm or 4 6x6 mm)
  - DCR for one BIC channel will be ~16x value in table
- Plan to test S14160 SiPMs at ANL & Regina



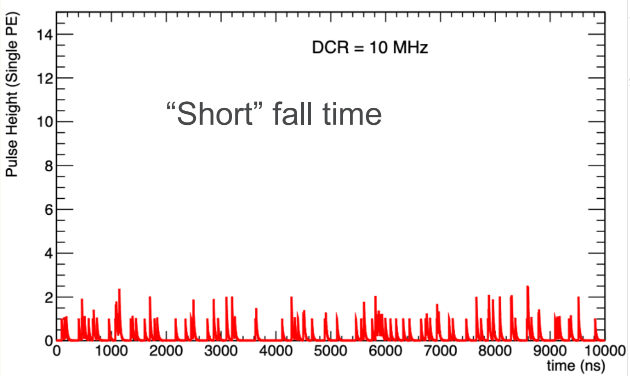


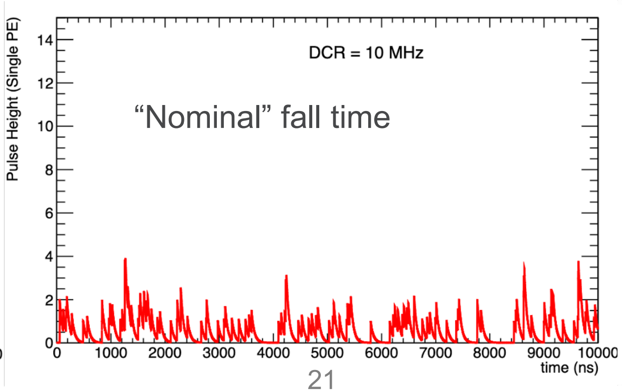


PULSE SHAPE

- Fast rise time improves position resolution in z-direction
  - If not limited by other factors like readout or scintillation decay
- Fast fall time reduces pileup of signals (and dark counts)
  - Shape will depend heavily on the readout circuit

- *Appears* that S14160 has fast rise time, slower fall time than S13360
  - Challenging to compare between papers due to differences in readout
  - Will soon compare the two in an identical setup at ANL
- Should converge on a reasonable target for these parameters based on physics
  - Keeping the MIP, low energy γ





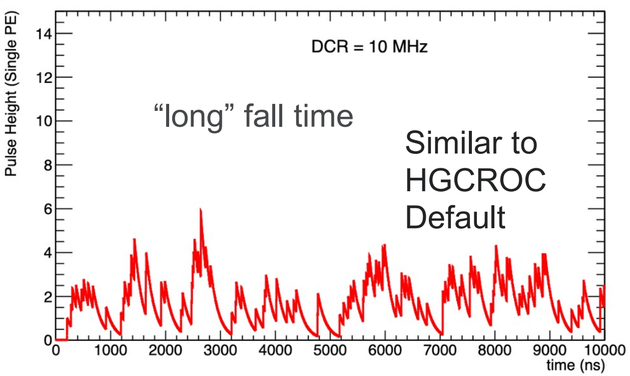


TABLE 1: Barrel Imaging Calorimeter SiPM Specs

Parameter	Specification	Notes	S13360	S14160
Active Area	3 mm x 3 mm (4 x 4 array)	Preassembled array covering 1.2cm x 1.2cm	✅	✅
Pixel Size	50 µm		✅	✅
Package Type	Surface Mount		✅	✅
Peak Sensitivity	450 nm		✅	✅
PDE	~ 50%		❌	✅
Gain	> ~ 2×10^6		~	✅
DCR	Typ.: ~ 500kHz / SiPM Max: < 1.5 MHz / SiPM	DCR applies to each SiPM in the 4 x 4 array	✅	❌ ?
Temperature coefficient of Vop	< 40mV/C		❌	✅
Direct crosstalk probability	< ~ 7%		✅	✅
Terminal capacity	~ 500pF / SiPM	Applies to each SiPM in the 4 x 4 array	✅	✅
Packing granularity				
Vop variation within a tray	< 200 mV		✅	✅
Recharge Time	< 100 ns		✅	✅
Fill Factor	> 70%		✅	✅
Protective Layer	Silicone (n ~ 1.5-1.6)		✅	✅

OPEN/DISCUSSION QUESTIONS

- What DCR can we really tolerate?
  - Depends on signal shape, shorter fall time better
  - With HGCROC-length signals, 10 MHz too large if threshold is 3 N_{pe}

- Do we want to actively temperature control the SiPMs?
  - Maintain a constant DCR by decreasing temp as rad damage accumulates
  - More effective with S13360 series than S14160

- If we go with the S13360 series, how can we compensate the loss in PDE?

- Does the lower operating voltage of the S14160 series benefit us?

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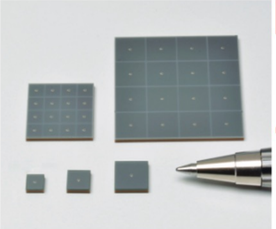
MPPC® (Multi-Pixel Photon Counter)



S14160/S14161 series

Low breakdown voltage type MPPC for scintillation detector

The S14160/S14161 series achieve higher PDE (photon detection efficiency) and lower operation voltage than other MPPC to adapt for PET and radiation monitor application. They achieve small dead space in a photosensitive area with HWB (hole wire bonding) technology (Patent pending). And the gap from the photosensitive area edge to the package edge is only 0.2 mm. This package realizes the four-side buttable arrangement.

Features

- **Higher PDE (50% at λp, $V_{op}=V_{BR}$ + 2.7 V)**
- **Lower voltage (V_{BR}=38 V typ.) operation**
- **Small dead space in photosensitive area**
- **Low afterpulses and crosstalk**
- **High gain: 10^6 order**
- **Excellent time resolution**
- **Immune to effects of magnetic fields**

Applications

- **PET (positron emission tomography)**
- **Radiation monitor**

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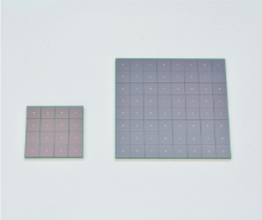
MPPC® (Multi-Pixel Photon Counter) arrays



S13361-3050 series

MPPC arrays in a chip size package miniaturized through the adoption of TSV structure

The S13361-3050 series is a MPPC array for precision measurement miniaturized by the use of TSV (through-silicon via) and CSP (chip size package) technologies. The adoption of a TSV structure made it possible to eliminate wiring on the photosensitive area side, resulting in a compact structure with little dead space compared with previous products. The four-side buttable structure allows multiple devices to be arranged side by side to fabricate large-area devices.
They are suitable for applications, such as medical, non-destructive inspection, environmental analysis, and high energy physics experiment, that require photon counting measurement.

Features

- **Low crosstalk**
- **Low afterpulses**
- **Outstanding photon counting capability (outstanding photon detection efficiency versus numbers of incident photons)**
- **Compact chip size package with little dead space**
- **Low voltage (V_{BR}=53 V typ.) operation**
- **High gain: 10^5 to 10^6**

Applications

- **Astro physical application**
- **High energy physics experiment**
- **Nuclear medicine**
- **PET**
- **Environmental analysis**

PDE: GlueX SiPM Parameters

PDE ~33%

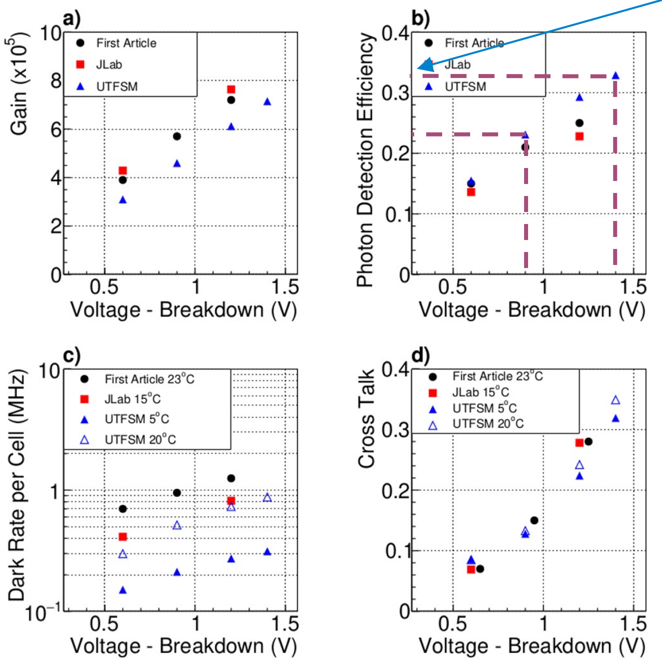


Figure 4: Measurements of the first-article samples (black circles) [20, 25], production samples at JLab (red squares) and production samples at UTFSM (triangles) [21, 22] of four basic SiPM parameters as a function of the voltage over breakdown. a) gain, b) photon detection efficiency, c) dark rate per tile (the dark rate for the array is 16 times higher) and d) cross talk determined from deviations of the single-pixel distributions from a pure Poisson function. As long as the voltage over breakdown is kept constant, the dark rate is the only parameter that has a significant temperature dependence. The nominal operating voltage for the GlueX experiment is 1.4 V above breakdown. (Color online)

The Hamamatsu specification sheets provide the recommended operating voltage for a nominal gain of 7.5 × 10^5 , although our measurements indicate lower gains (Fig. 4a). We determined that this operational voltage on average corresponds to 0.9 V above breakdown; to obtain our setting at an overvoltage of 1.4 V, we added 0.5 V and then adjusted for temperature.

Hamamatsu Multi-Pixel Photon Counter (MPPC) S12045(X):
16 x 3600 pixels (50 um)

arXiv:1801.03088v2 [physics.ins-det] 20 Apr 2018

Construction and Performance
of the Barrel Electromagnetic Calorimeter
for the GlueX Experiment

T.D. Beattie[a], A.M. Foda[a], C.L. Henschel[a], S. Katsaganis[a], S.T. Krueger[a], G.J. Lolos[a], Z. Papandreou[a,*], E.L. Plummer[a], I.A. Semenova[a], A.Yu. Semenov[a], F. Barbosa[b], E. Chudakov[b], M.M. Dalton[b], D. Lawrence[b], Y. Qiang[b,1], N. Sandoval[b], E.S. Smith[b,*], C. Stanislav[b], J.R. Stevens[b,2], S. Taylor[b], T. Whitlatch[b], B. Zihlmann[b], W. Levine[c], W. McGinley[c], C.A. Meyer[c], M.J. Staib[c], E.G. Anassontzis[d], C. Kourkoumelis[d], G. Vasileiadis[d], G. Voulgaris[d], W.K. Brooks[e], H. Hakobyan[e], S. Kuleshov[e], R. Rojas[e], C. Romero[e], O. Soto[e], A. Toro[e], I. Vega[e], M.R. Shepherd[f]

[a]*Department of Physics, University of Regina, Regina, Saskatchewan, Canada S4S 0A2*
[b]*Jefferson Laboratory, Newport News, Virginia 23606, USA*
[c]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[d]*National and Kapodistrian University of Athens, 15771 Athens, Greece*
[e]*Universidad Técnica Federico Santa María, Casilla 110-V Valparaíso, Chile*
[f]*Indiana University, Bloomington, Indiana 47405, USA*

Abstract

The barrel calorimeter is part of the new spectrometer installed in Hall D at Jefferson Lab for the GlueX experiment. The calorimeter was installed in 2013, commissioned in 2014 and has been operating routinely since early 2015. The detector configuration, associated Monte Carlo simulations, calibration and operational performance are described herein. The calorimeter records the time and energy deposited by charged and neutral particles created by a multi-GeV photon beam. It is constructed as a lead and scintillating-fiber calorimeter and read out with 3840 large-area silicon photomultiplier arrays. Particles impinge on the detector over a wide range of angles, from normal incidence at 90 degrees down to 11.5 degrees, which defines a geometry that is fairly unique among calorimeters. The response of the calorimeter has been measured during a running experiment and performs as expected for electromagnetic showers below 2.5 GeV. We characterize the performance of the BCAL using the energy resolution integrated over typical angular distributions for π^0 and η production of $\sigma_E/E = 5.2\%/\sqrt{E(\mathrm{GeV})} \oplus 3.6\%$ and a timing resolution of $\sigma = 150$ ps at 1 GeV.

https://arxiv.org/abs/1801.03088

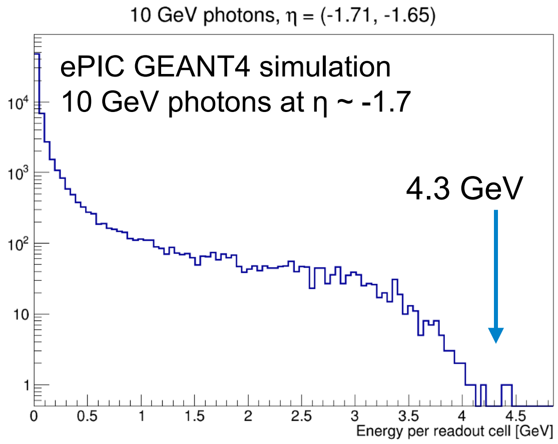
Pixel Size and Number of Pixels

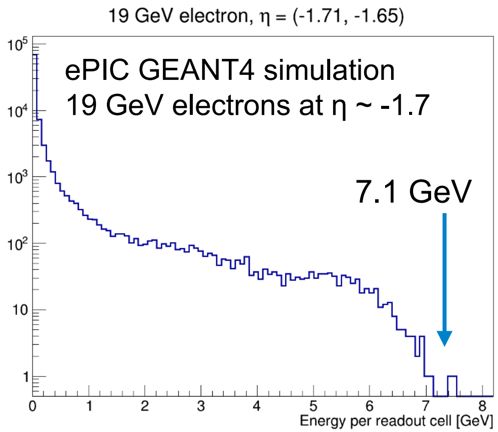
Defined by photoelectron statistics and energy range to be measured

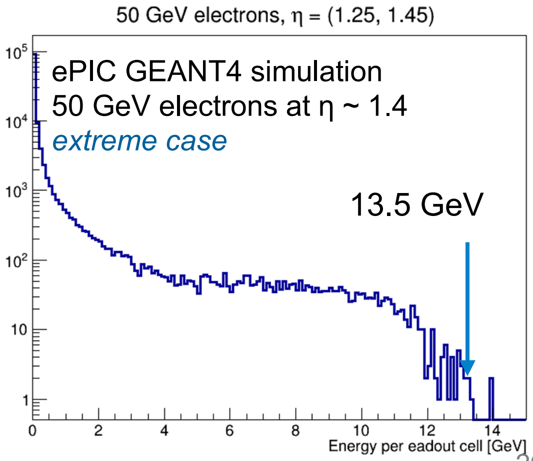
Energy measurement ranges in BECal:

- *Shall provide photon measurements up to 10 GeV* (F-DET-ECAL-BAR.2) *and down to 100 MeV* (F-DET-ECAL.9)
- *Shall provide electron ID up to 50 GeV and down to 1 GeV and below* (F-DET-ECAL-BAR.1)
    - Electron energy measurement needed for e/π separation only (straightforward at high energies)
- Reasonable performance for MIPs needed for calibration and for muon ID

Largest energy deposit occurs for particles at large η (steep angle) where the pathlength in a cell is maximal and the attenuation is minimal.







Photoelectron statistics

From our 2023 Hall D tests using GlueX SiPMs and double-clad Kuraray fibers: **1000 phe/GeV** per side for showers at the center of the Baby BCAL prototype

- Corrected for attenuation: **1077 phe/GeV*** per side

We can scale these results for the **ePIC Barrel ECal*:**

- x 1.5 factor improvement in **SiPM photon detection efficiency**
- x 1.16 factor to account for **better optical coupling**
- x 0.69 reduction accounting for **single-clad** Kuraray fibers

This gives ~ **1239 phe/GeV** per side (fully corrected for attenuation)

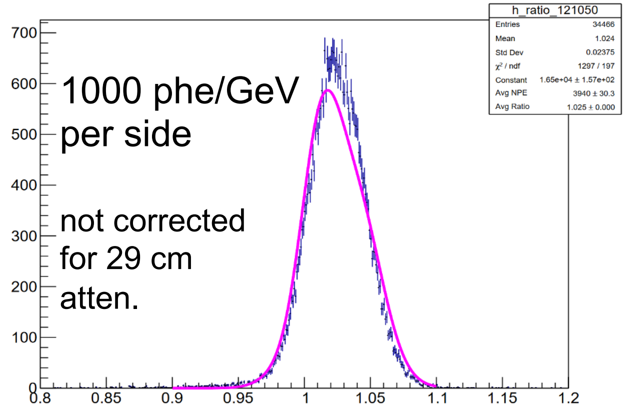
- **10 GeV ɣ at η ~ -1.7:** 5560 phe → **9.8 % max SiPM occupancy**
- **19 GeV e⁻ at η ~ -1.7:** 9181 phe → **16.1 % max SiPM occupancy**
- **50 GeV e⁻ at η ~ 1.4 (most extreme case):** 17456 phe → **30.1% max SiPM occupancy**

Well below the region where large nonlinearities in the SiPM response are expected in almost all cases.

Small non-linear effects possible for some ultra-high energy electrons, which is acceptable (e-π separation straightforward).

* See backup slide for the attenuation length measurement and extraction of those factors

2023 Hall D, Baby BCal, 3.9 GeV e+



2008 Hall B beam test, photons

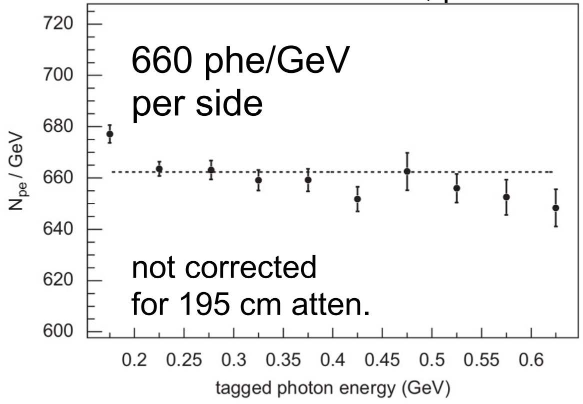
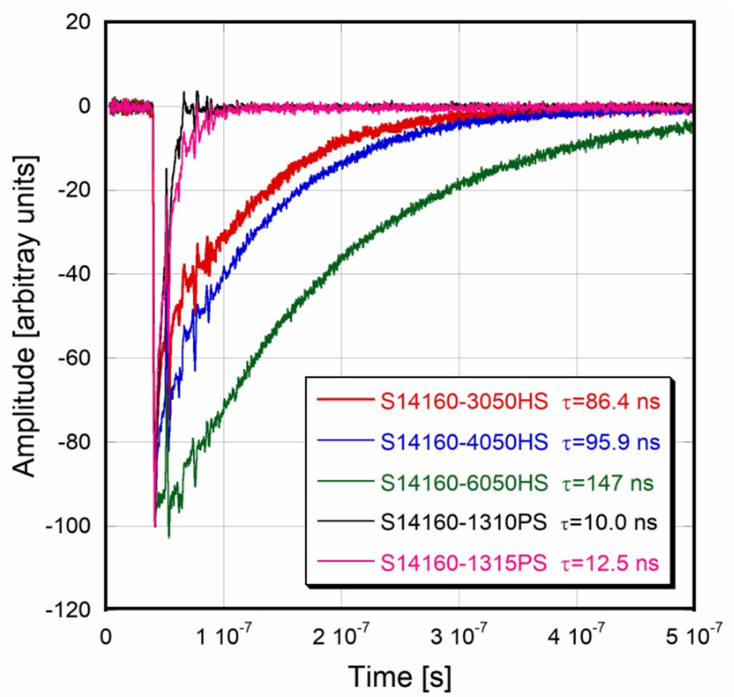


Fig. 16. The number of photoelectrons per GeV per end of the BCAL module is shown as a function of energy. A one parameter fit is plotted (dashed line). For more details see the text.


Amplitude [arbitray units]
Time [s]
20
0
-20
-40
-60
-80
-100
-120
0
1 10-7
2 10-7
3 10-7
4 10-7
5 10-7
S14160-3050HS τ=86.4 ns
S14160-4050HS τ=95.9 ns
S14160-6050HS τ=147 ns
S14160-1310PS τ=10.0 ns
S14160-1315PS τ=12.5 ns

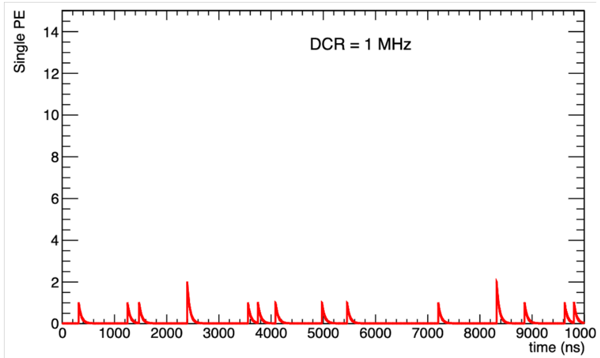
NOISE

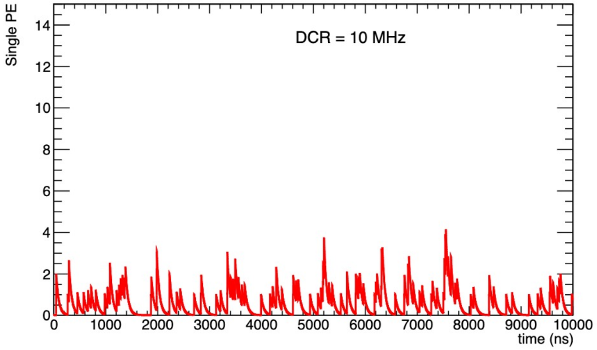
- Dark count rate (DCR) determines threshold
  - MIPs at midrapidity will generate 3-6 N_{pe} on average
    - Would be good to have threshold slightly below MIP
- DCR above a few 10s of MHz will endanger the MIP

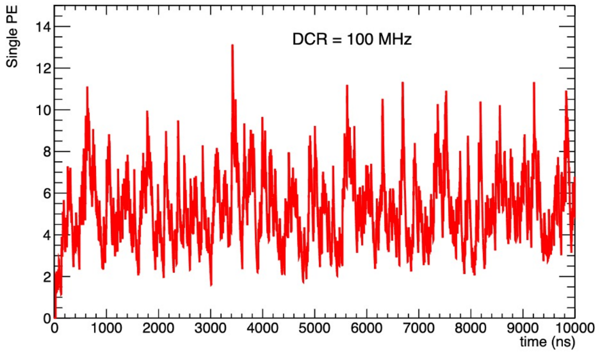
Specification	S13360-3050 (3x3 mm)	S14160-3050 (3x3 mm)
DCR (Typ.)	500 kHz	1 MHz***
Crosstalk (%)	3	7

*** Differing values in literature

- Signal will gang 1.2 cm x 1.2 cm area (16 3x3 mm or 4 6x6 mm)
  - DCR for one BIC channel will be ~16x value in table
- Plan to test S14160 SiPMs at ANL & Regina

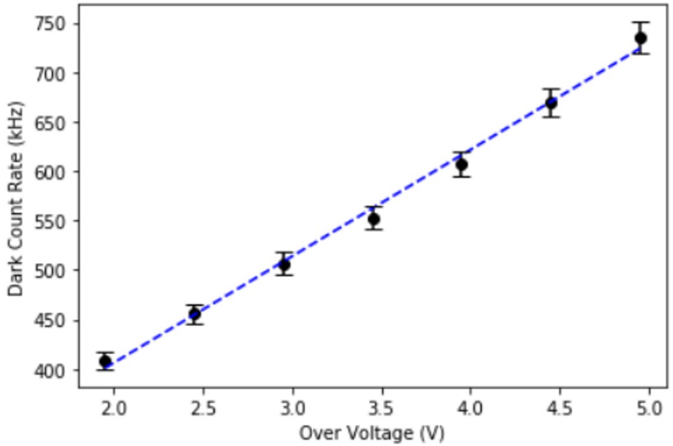


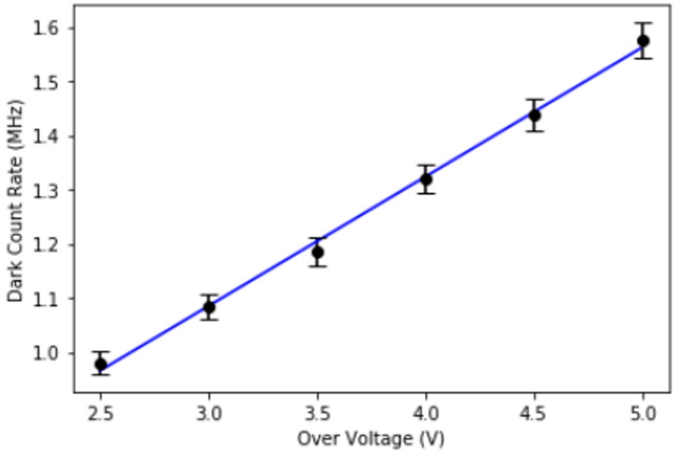


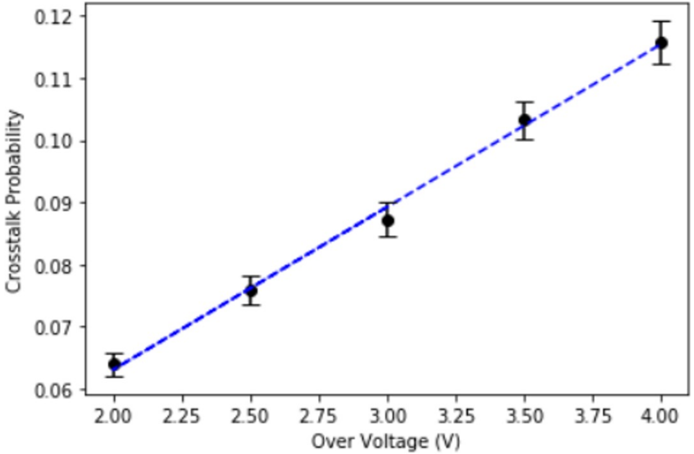


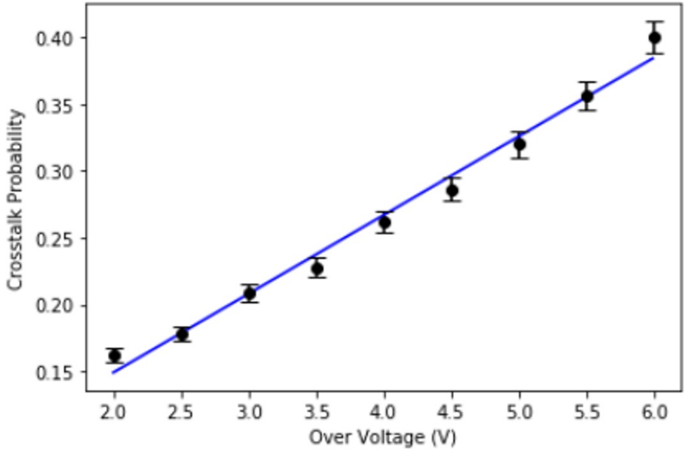
S13360-3050 (3x3 mm)

S14160-3050 (3x3 mm)





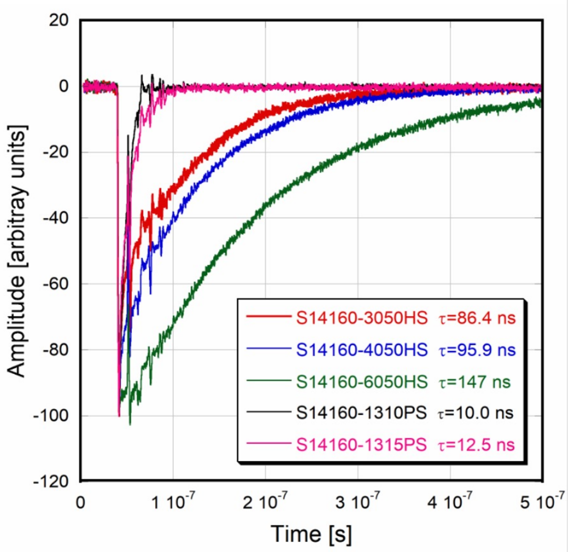


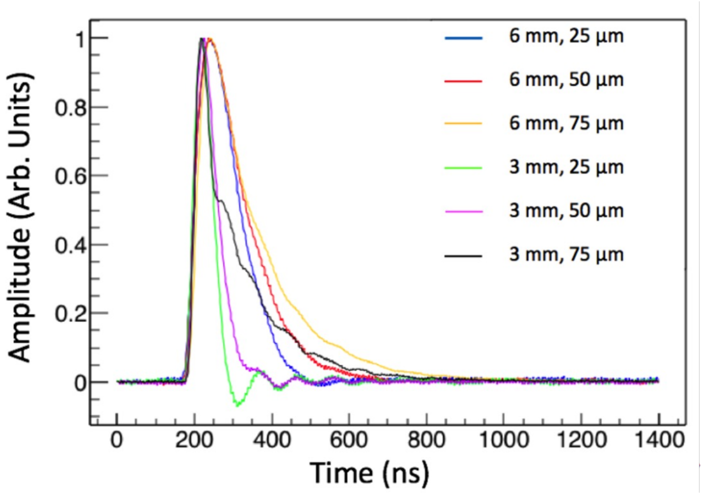


PULSE SHAPE

- Pulse shape strongly defined by how signals are handled
- S14160 has faster rise time, slower fall time

- Larger SiPMs (6x6 mm) have ~2x longer fall times due to capacitance
  – Can we mitigate this in our ganging scheme?

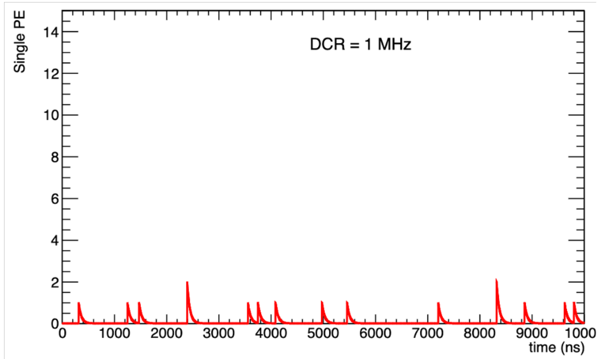


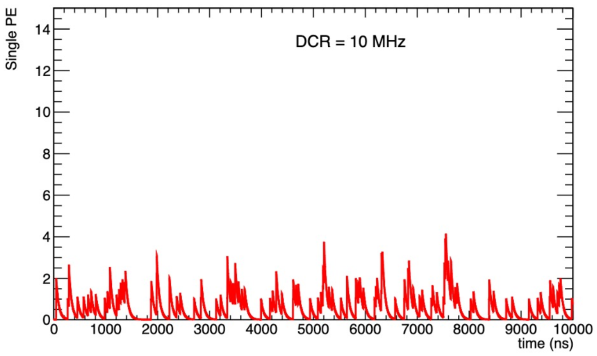


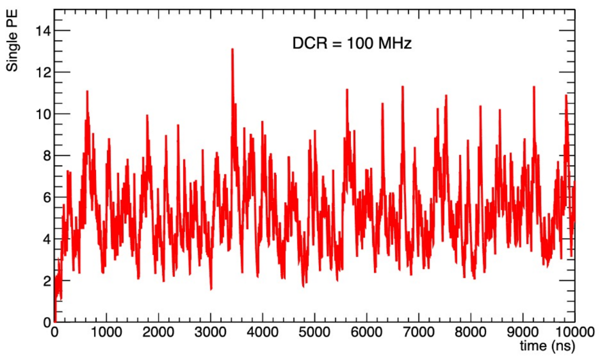
NOISE

- Dark count rate (DCR) determines threshold
  - MIPs at midrapidity will generate 3-6 N_{pe} on average
    - Would be good to have threshold slightly below MIP
- DCR above a few 10s of MHz at the readout will swamp the MIP

- Literature seems divided on noise characteristics of S14160 series
  - Plan to test S14160 SiPMs at ANL & Regina

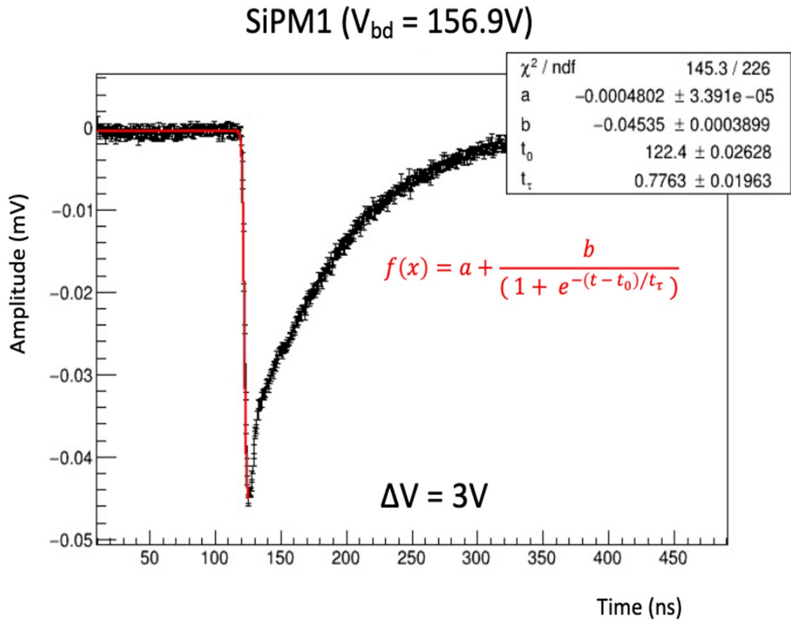


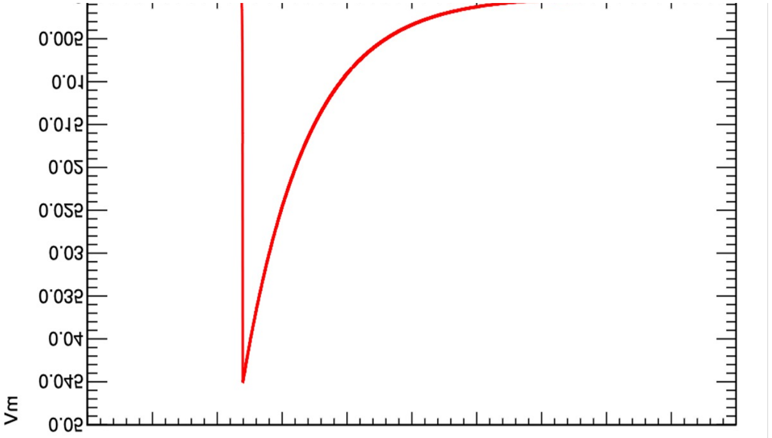




WAVEFORMS

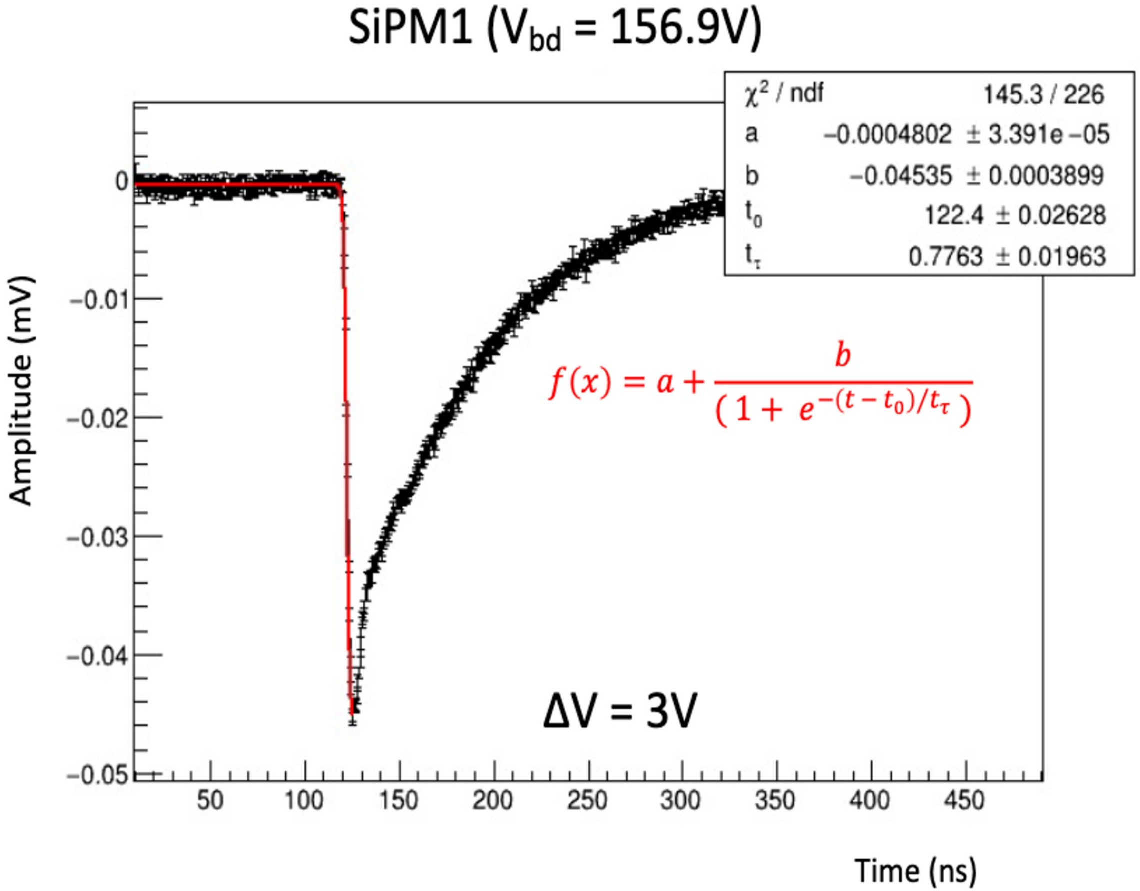
- Parameterize S14161 waveform based on presentation from AMS-100 (here)
- Exponential rise and exponential fall
  - Different time constants
- Pulse height around 0.045 mV
  - Take this as 1 Npe





WAVEFORMS

- Agreement not good but also not so terrible
- Tail a bit wider in the data
- Good enough for now



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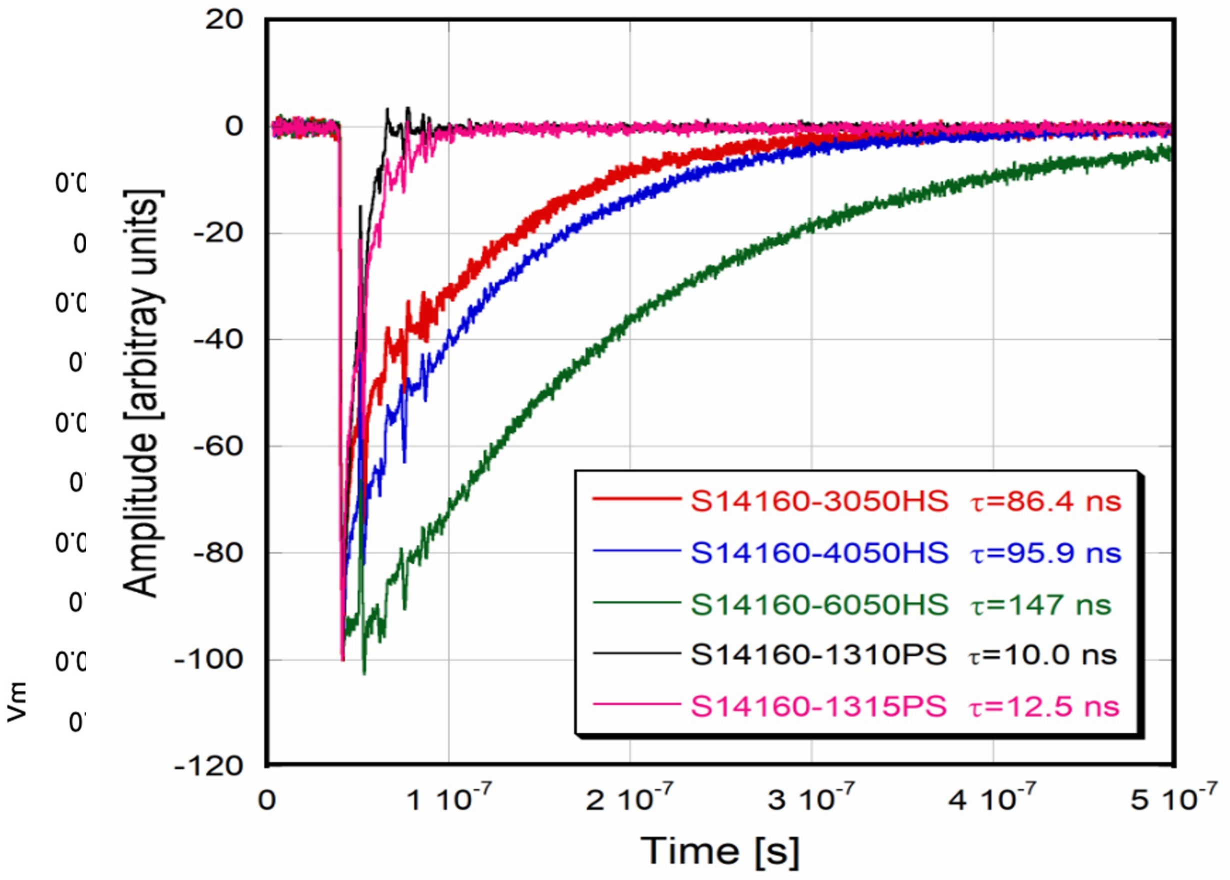
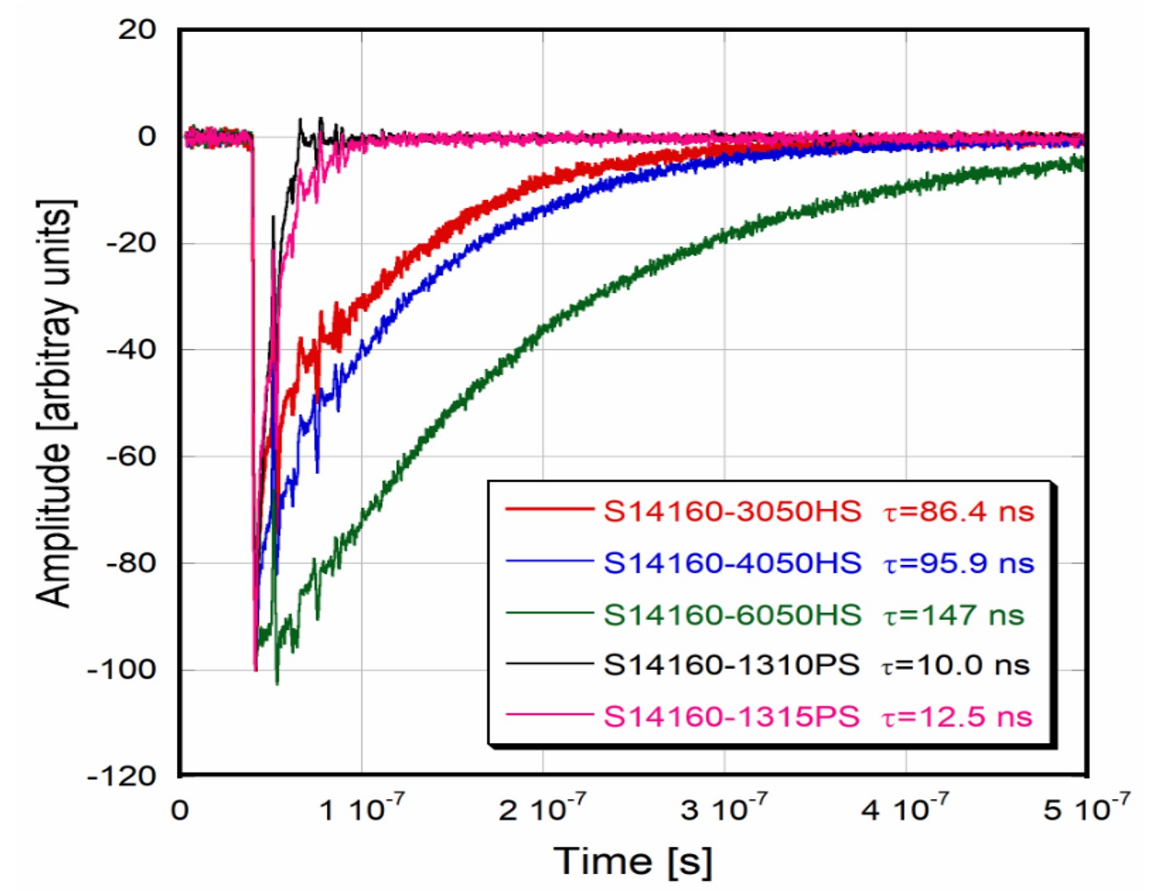


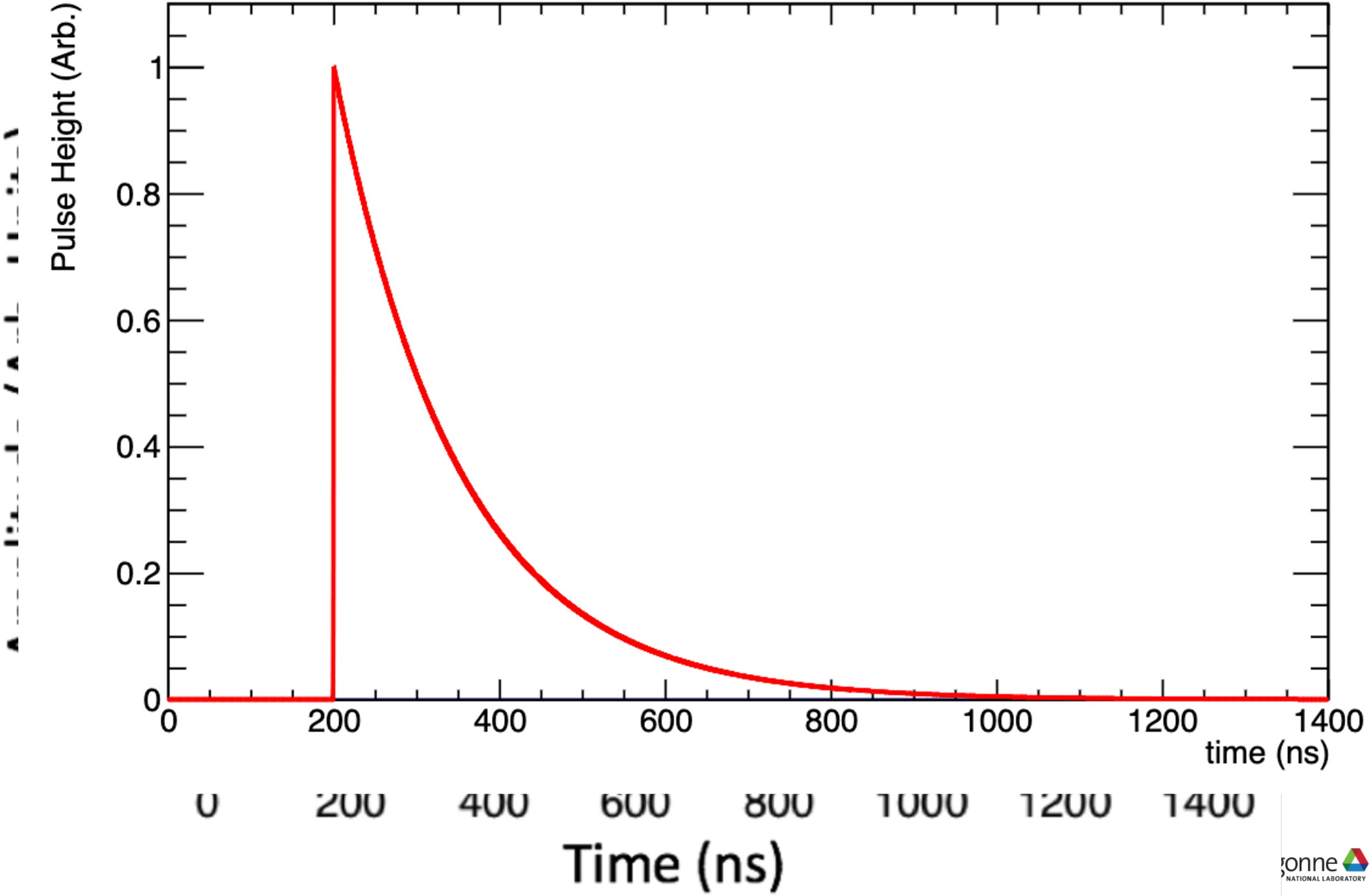
WAVEFORMS

- Ag
  goo
  not

- Tai
  in t

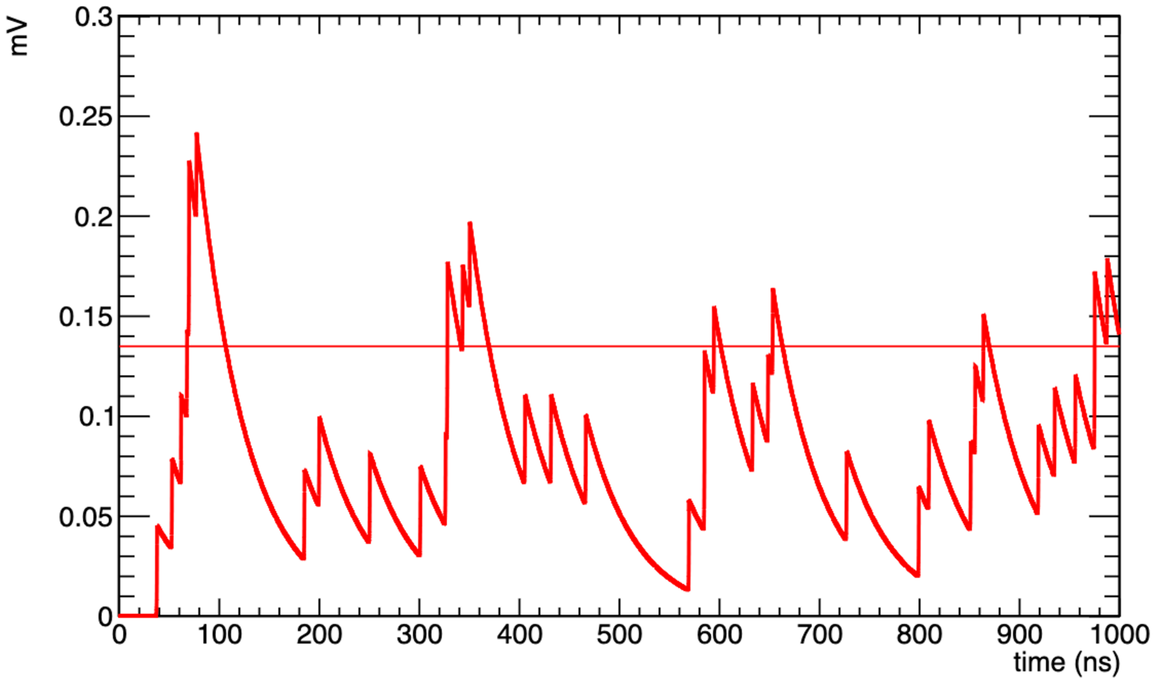
- Go
  for




Pulse Height (Arb.)
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
1200
1400
time (ns)
Time (ns)

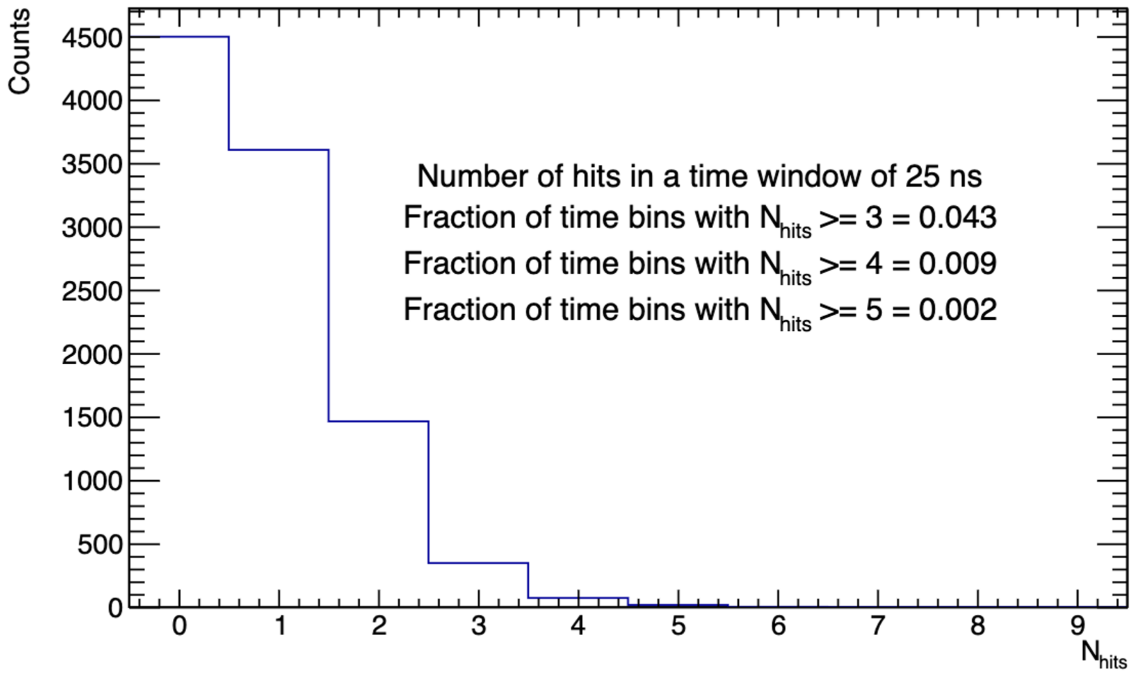
WAVEFORMS

- Monte Carlo throwing signals with expected rate
  - 32 MHz
  - 1 microsecond
- Crosstalk probability of 7% included (should it be, or is it included in the number from Hamamatsu?)
  - Up to two crosstalk hits
    - 3 and greater is a less than 1% effect
- Line drawn at 3 * single photoelectron peak

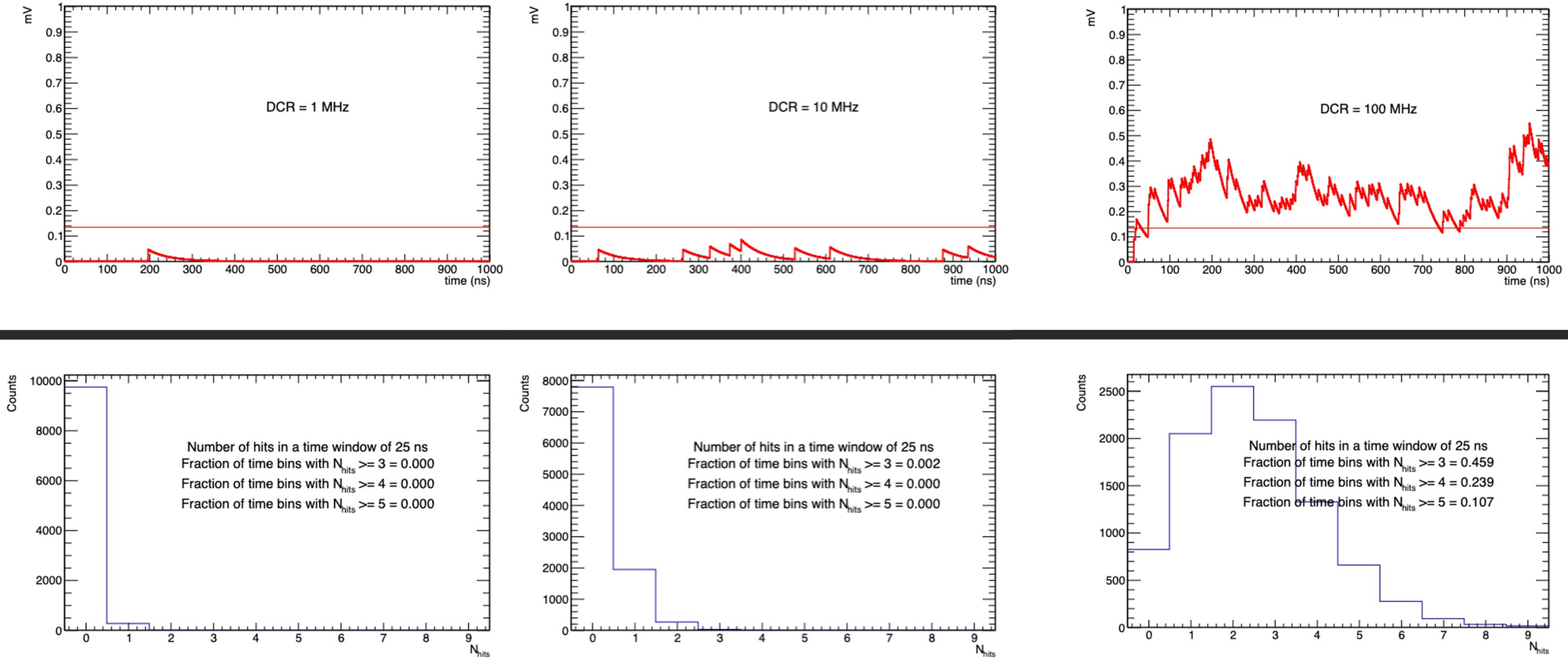


HITS IN HGCROC WINDOW

- Take 25 ns window of HGCROC
- Poissonian distribution with a mean of 0.8
  - 25 ns * 32 MHz
- If threshold is set to 3 * SPE pulse height, 4% of time bins will be triggered
  - 4% of the channels of the detector will be active in ToT mode at any given time

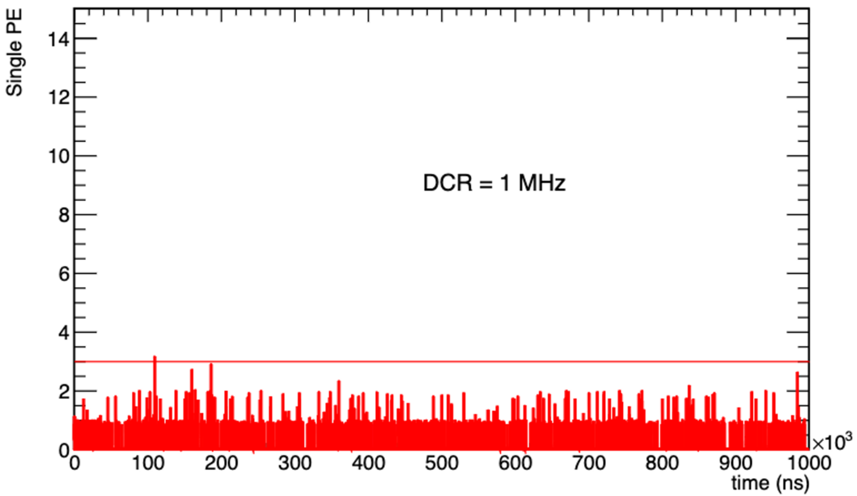


- Threshold of 3 p.e. likely excluded if DCR reaches 100 MHz
  - This also poses an issue because we can't get around it with timing cuts in the same way as the dRICH, the detector could have a signal at any time
    - Bunch crossings every 10 ns, shorter than light propagation time



Threshold (p.e.)	Prob. Above threshold @ 1 MHz	Prob. Above threshold @ 10 MHz	Prob. Above threshold @ 30 MHz	Prob. Above threshold @ 50 MHz	Prob. Above threshold @ 100 MHz
2	0.01%	2%	29%	69%	99%
3	0.0005%	0.3%	8%	36%	94%
4	0%	0.04%	1.7%	14%	79%
5	0%	0.005%	0.2%	4%	57%
6	0%	0%*	0.03%	1.1%	35%
7	0%	0%*	0.005%	0.4%	17%

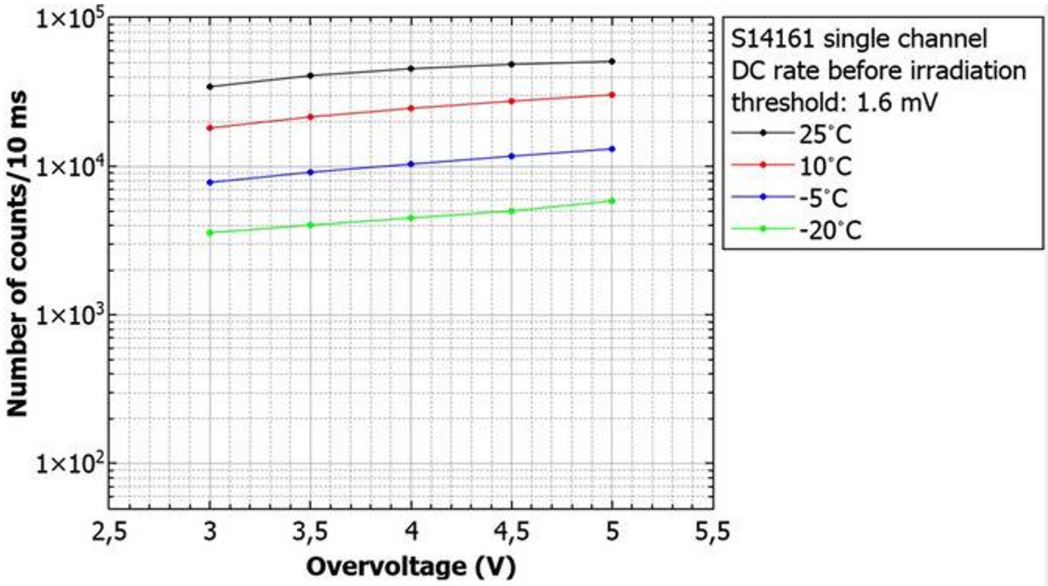
Numerical uncertainty of 0.03%


Single PE
DCR = 1 MHz
time (ns)
×10^3

TEMPERATURE DEPENDENCE

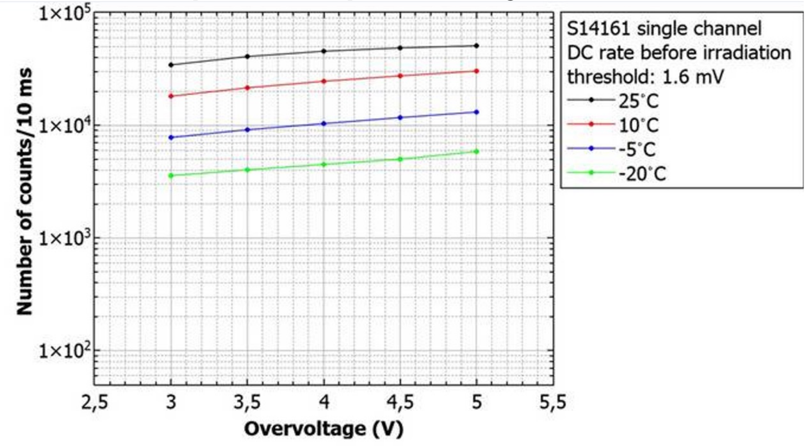
- Conventional wisdom is that DCR is halved for every decrease of 10° C
- "Single-channel" here refers to 1/16 of a 4x4 array (S14161-6050HS-04)
  - DCR numbers for ganged array should be 16x higher
- To reach the ~4 MHz of GlueX with S14161-6050HS-04, need to go to -20° C or lower

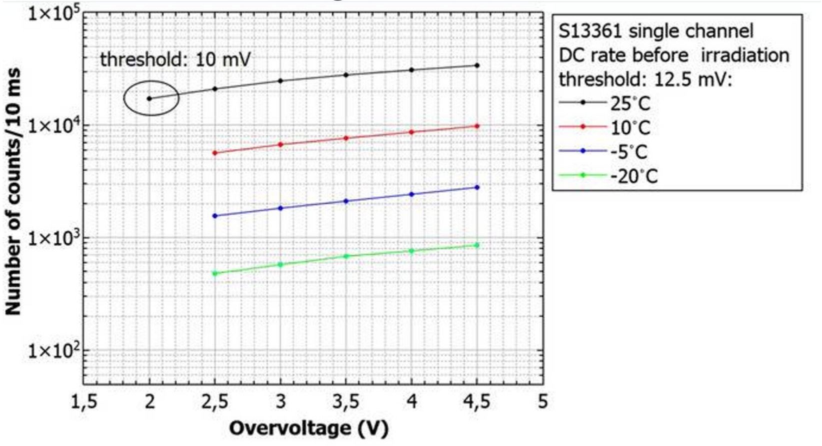
Proton irradiation of SiPM arrays for POLAR-2



TEMPERATURE DEPENDENCE

- The authors of this paper report that DCR of the S14161 is 60% higher than S13361 at 25° C, and a factor of 5 higher at -20° C
  - The DCR of the S14161 is apparently a much slower function of temperature
  - This is bad, because it renders less effective the only handle we have over the DCR
  - On the flip side, probably the DCR increases less if we go above 25° C…



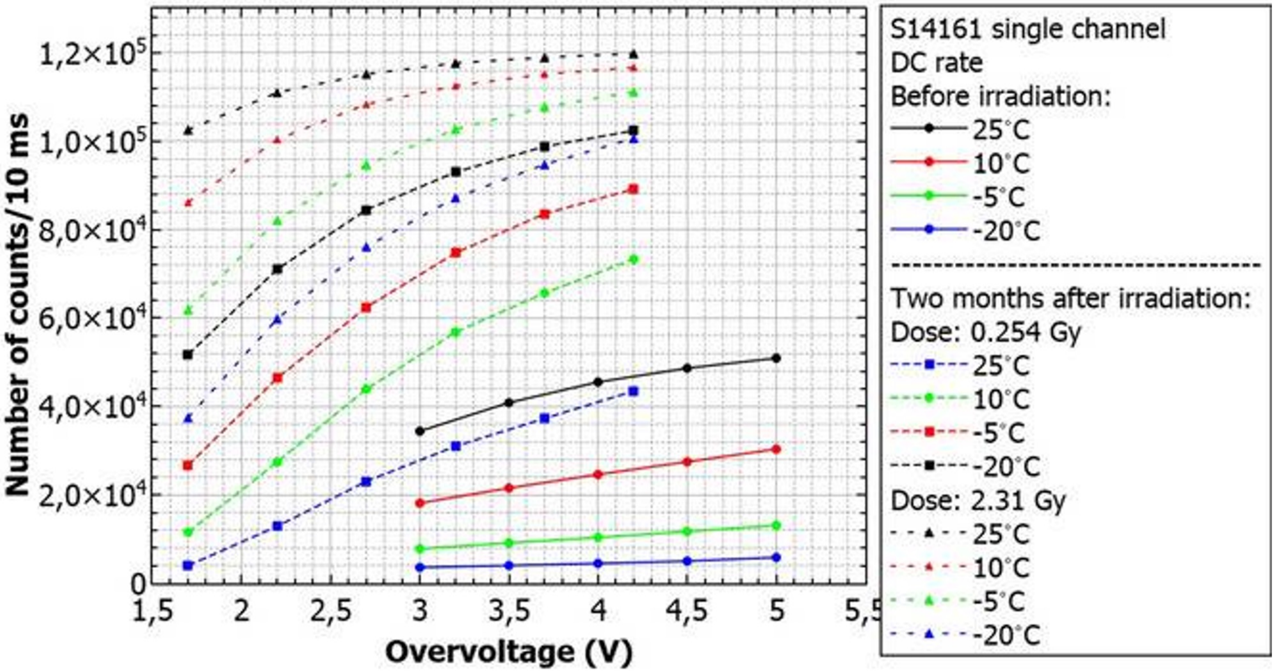


On such a critical point, should consult an expert (Hamamatsu directly?) to see if this behavior is expected or not

RADIATION DAMAGE

Proton irradiation of SiPM arrays for POLAR-2

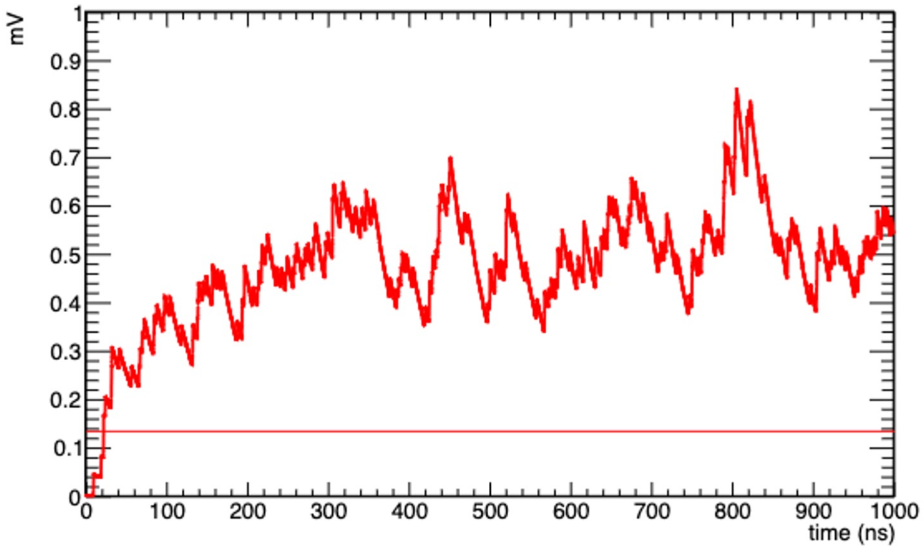
- Pre-radiation DCR around 3 MHz (single channel)
  - At 3V overvoltage
- After ~200 Rad of proton radiation (and two months of waiting), DCR larger by factor of 4
  - Half our expected dose

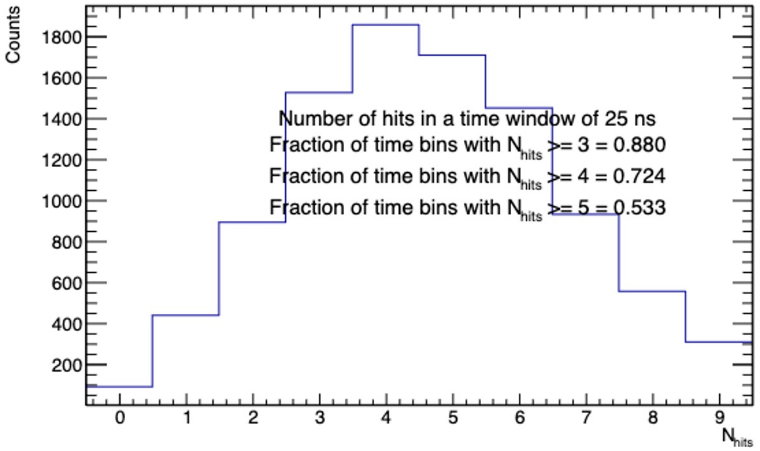


RADIATION DAMAGE

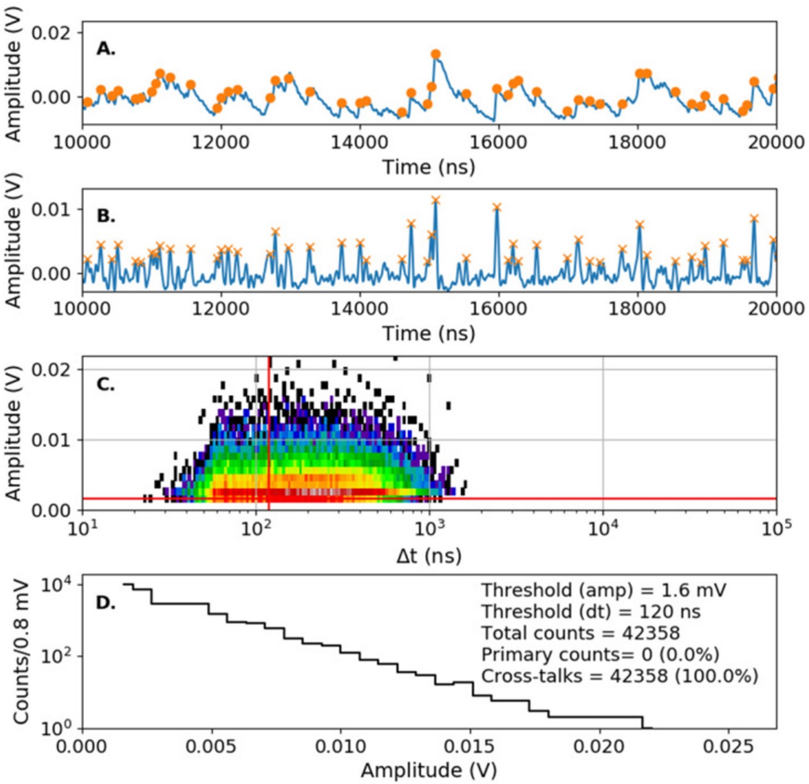
- If we take the numbers provided in this paper seriously, expect 192 MHz of DCR after 200 Rad of radiation damage at room temperature

- This is clearly too large, likely would swamp the MIP
  - Threshold would need to be set at something like 9 Npe or higher





S14161



S13361