SiPM Test Facilities at BNL

Thomas Tsang
Instrumentation Division

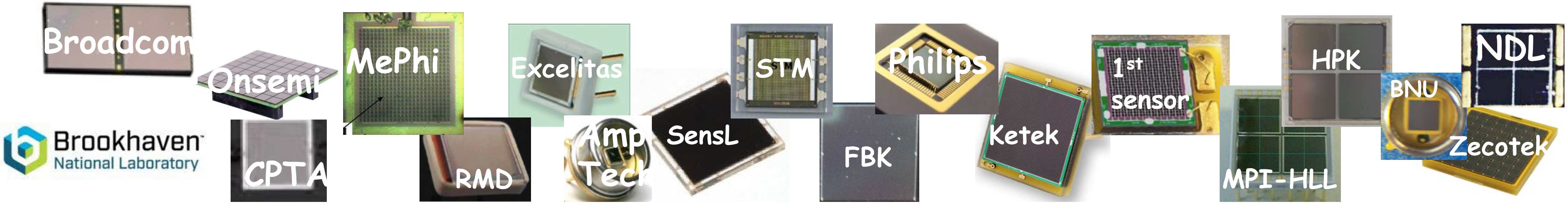
DUNE FD3 Mini-Workshop Toward a Combined Photon Detection and Field Cage System
June 26-28, 2023
Stony Brook University Physics Building

Brookhaven National Laboratory

Outline:

- Types of SiPM tested, SiPM measurement setup
- Recap of DUNE SiPMs
- Challenge and solution on large SiPM capacitance
- nEXO SiPMs selection status: HPK & FBK
- Light readout concept using LArASIC Cold Electronics – IEEE 2021
  - Photoelectron spectroscopy: response to single and multiple photoelectron
  - Charge calibration, SiPM avalanche gain, S/N ratio
  - Timing and coincidence resolution
  - Time coincidence detection of Dark Pulses
- SiPM terminal capacitance measurements

SiPM R&D and production around the globe



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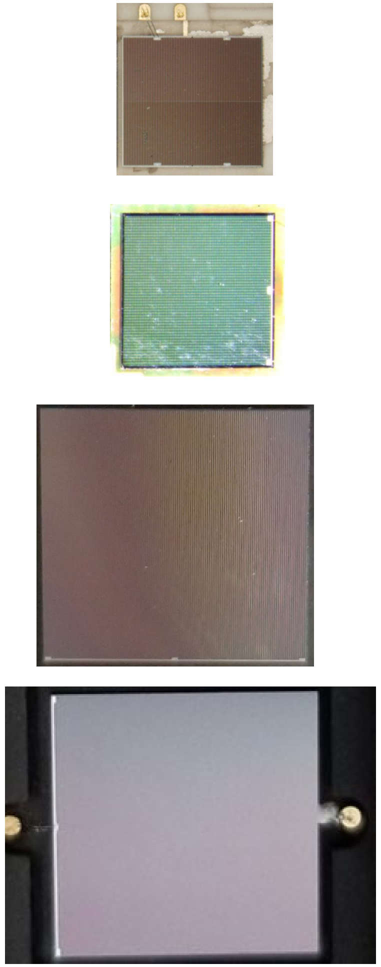
SiPM tested from various vendors

FBK

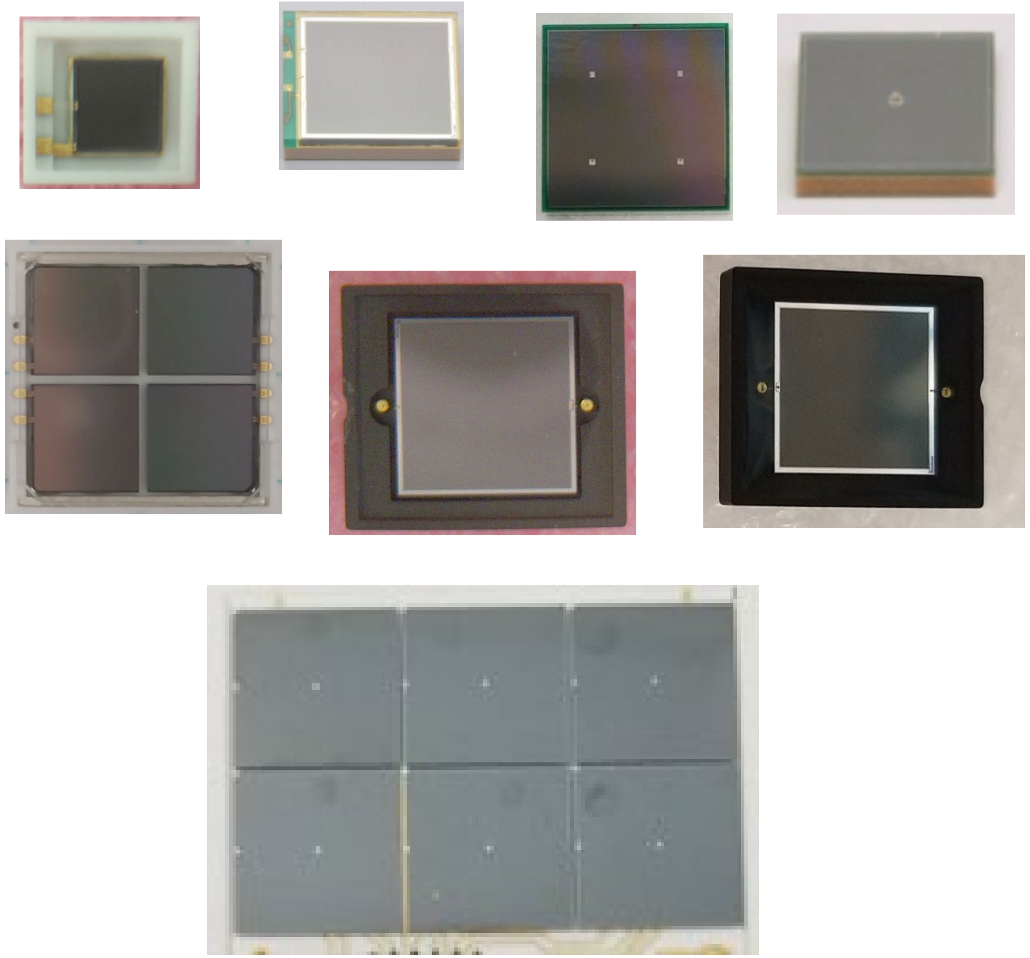
3x3 mm^2

6x6 mm^2

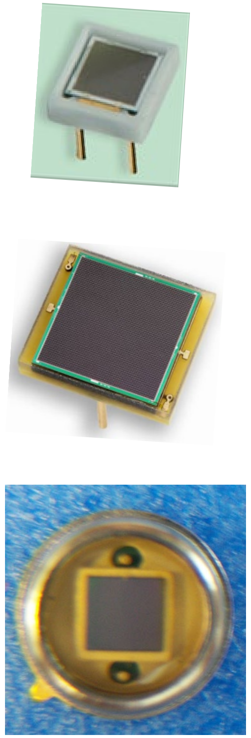
10x10 mm^2



HPK



others

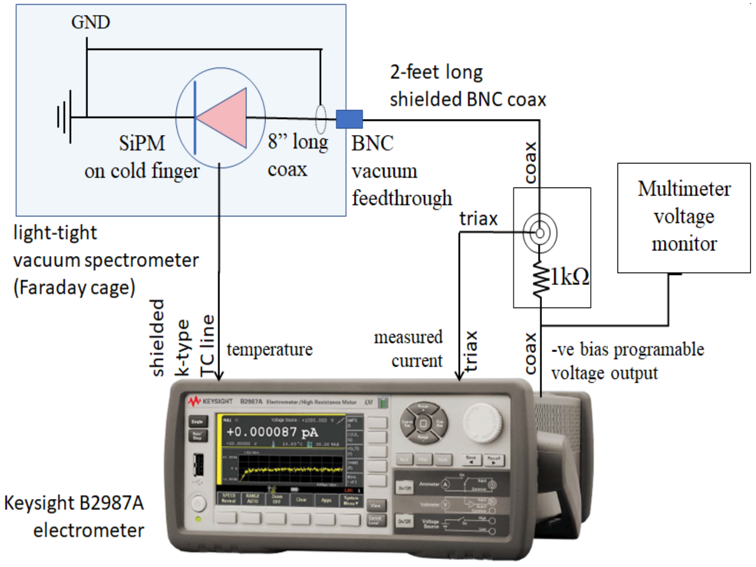


pixel size 15 µm to 75 µm

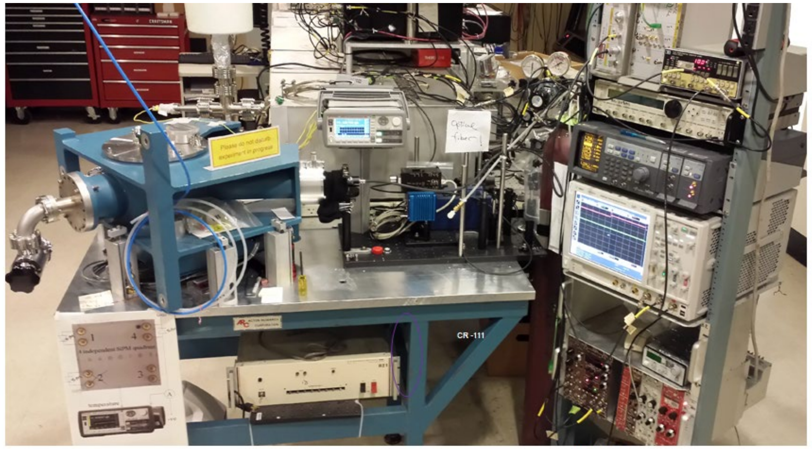
The Instrumentation Division at BNL has been testing SiPMs from various vendors for difference science programs in the past 8 years; primary targeted to operate SiPMs in cryogenic temperature and in noble liquids.

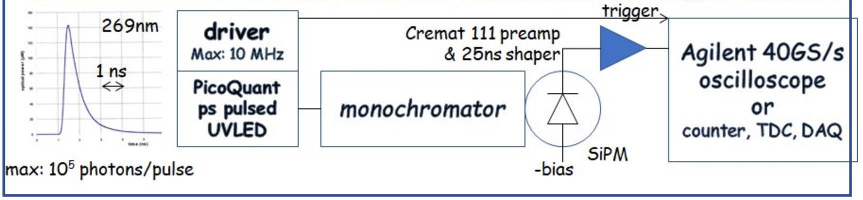
- Packaging and bond bare SiPM chips to various carriers
- Current-voltage (IV) characterization: at room temperature, 165K, 85K in vacuum, LN_2, and in purified LAr, LXe, and LKr
- Charge gain, µcell and terminal capacitance, quench resistance, $V_{breakdown}$, I_{dark}
- time correlated and time uncorrelated avalanche noise measurements: optical cross-talk (CT), after-pulse (AP), and thermally activated dark count (DCR), respectively.
- photodetection efficiency (PDE) from VUV to NIR wavelength range and photon number resolving (PNR) capability.

IV measurement



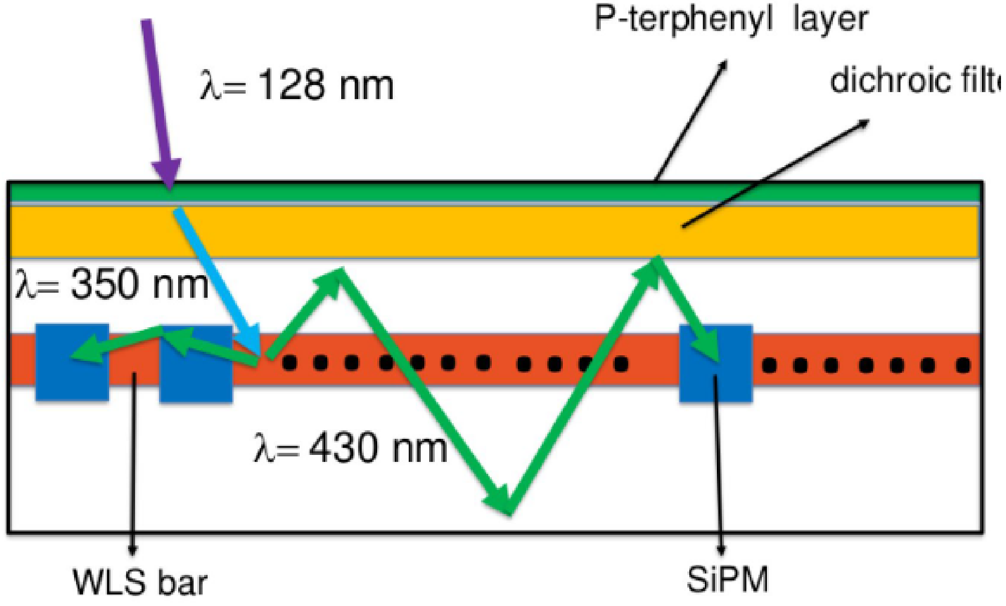
charge gain, noise, and PDE measurement





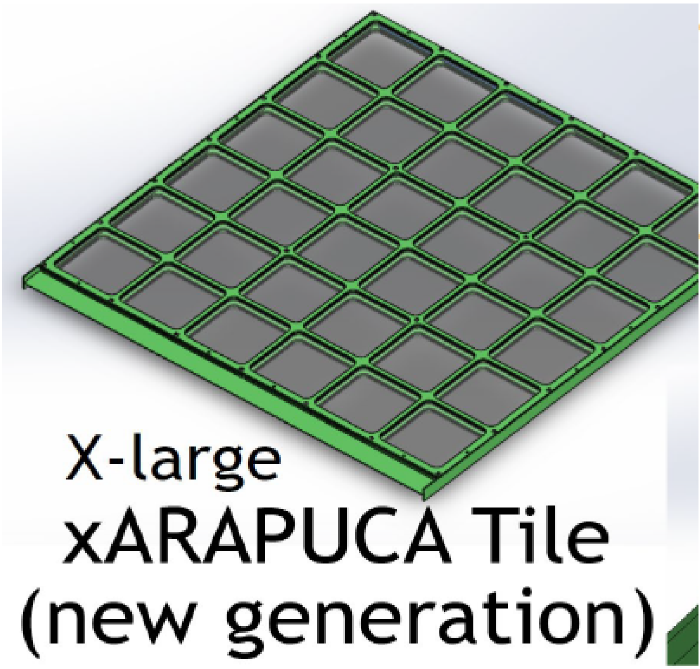
SiPM test in purified noble Liquid

DUNE FD-2: ARAPUCA (Argon R&D Advanced Program at UniCAmp).



Credits: F. Terranova

- ➢ 160 SiPMs (40 per side)
  - ➢ Glued to WLS Bar for improved optical contact
- ➢ SiPMs mounted on Kapton flexi-PCB



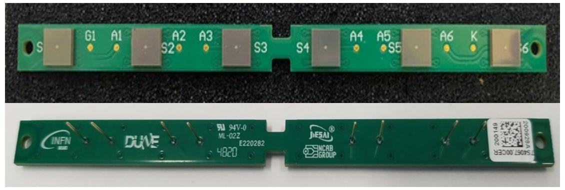
X-large
xARAPUCA Tile
(new generation)

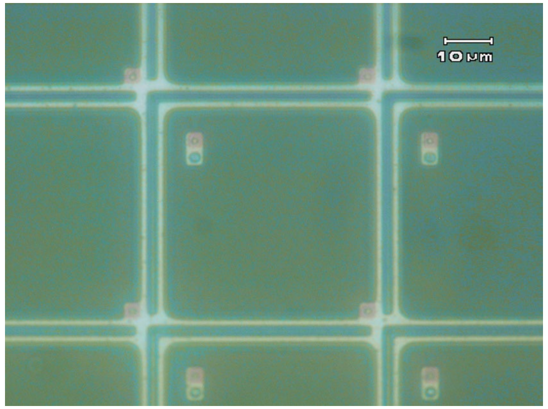
- Optical area
  - 600 mm x 600 mm=3600 cm^2
- SiPM area
  - 160 x 0.36 cm^2 ≈60 cm^2
  - ≈1.7 % of opt. area
  - SiPM array capacitance ≈200 nF for V_{bd}~45 V;
  - ≈260 nF for V_{bd}~37 V

Readout a challenge for DUNE and SBND!

M.C. Queiroga Bazetto, V.L. Pimentel, A.A. Machado and E. Segreto, in Campinas, Brazil

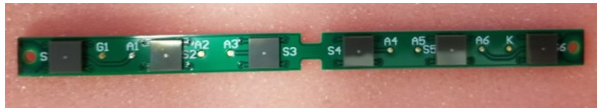
DUNE S13360-6050-HS-HRQ high R_q, normal V_{bd}

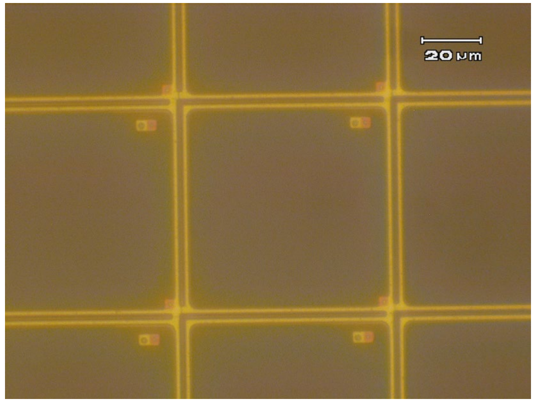




S13360-6050-HS-HRQ spec.	
area	6x6 mm^2
pixel size	50 μm
# of pixels	14331
V_bd (RT, LN2)	53 V, 42 V
Capacitance	1.28 nF

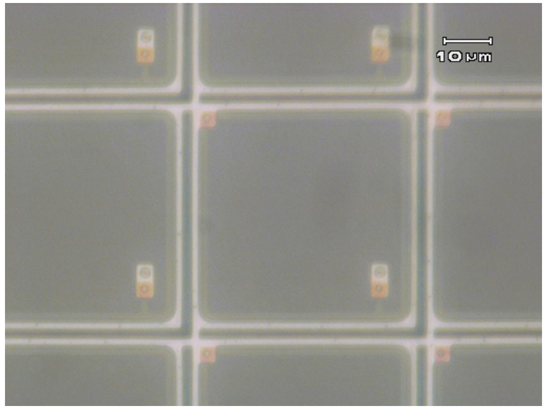
DUNE S13360-6075-HS-HRQ high R_q, normal V_{bd}





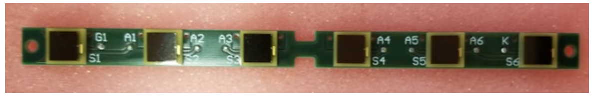
S13360-6075-HS-HRQ	
area	6x6 mm^2
pixel size	75 μm
# of pixels	6364
V_bd (RT, LN2)	51 V, 41 V
Capacitance	1.9 nF

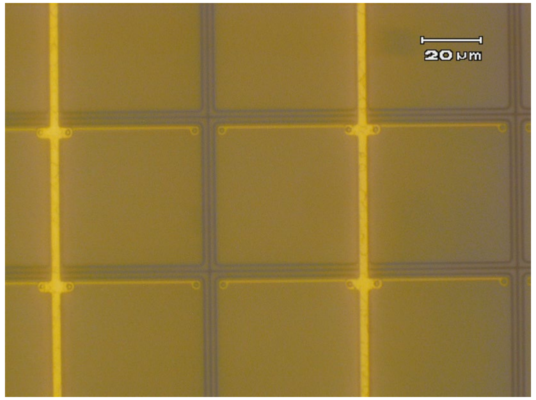
ProtoDUNE FNAL S14160-6050-HS low V_{bd}



S14160-6050-HS	
area	6x6 mm^2
pixel size	50 μm
# of pixels	14331
V_bd (RT, LN2)	38 V, 32 V
Capacitance	~2.3 nF

DUNE FBK triple-trench 50μm low V_{bd}

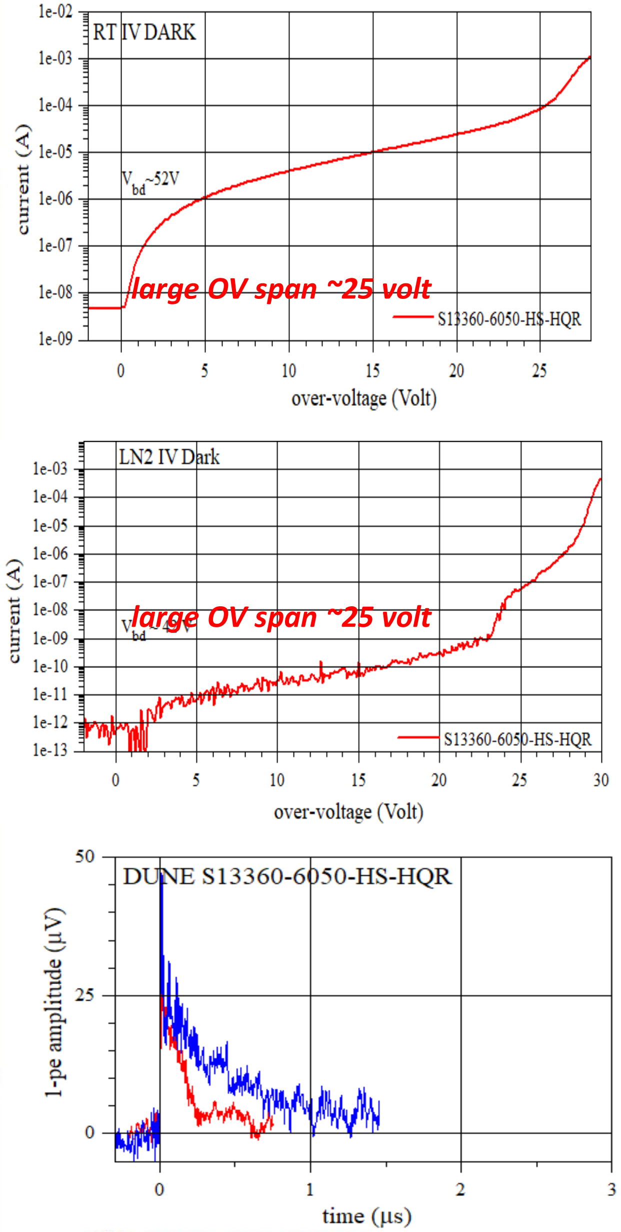




FBK tiple-trench	
area	6x6 mm^2
pixel size	50 μm
# of pixels	11188
V_bd (RT, LN2)	31 V, 27 V
Capacitance	2.6 nF

Drawback of a lower V-breakdown → higher capacitance → higher power to drive readout electronics

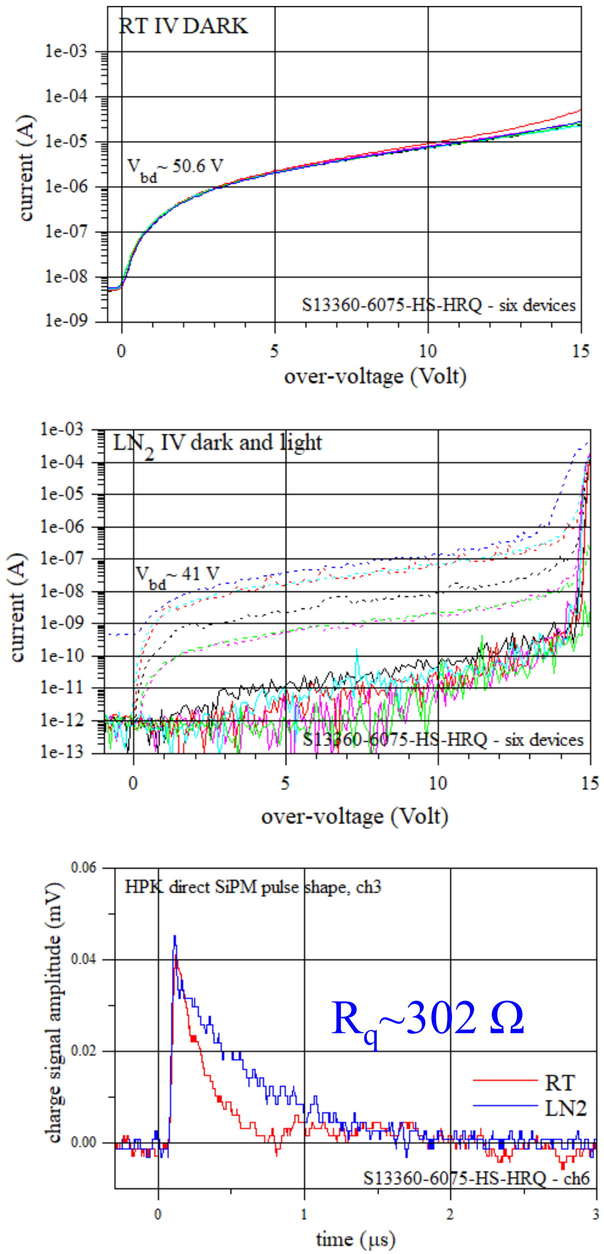
DUNE S13360-6050-HS-HRQ high R_q, normal V_{bd}



large OV span ~25 volt

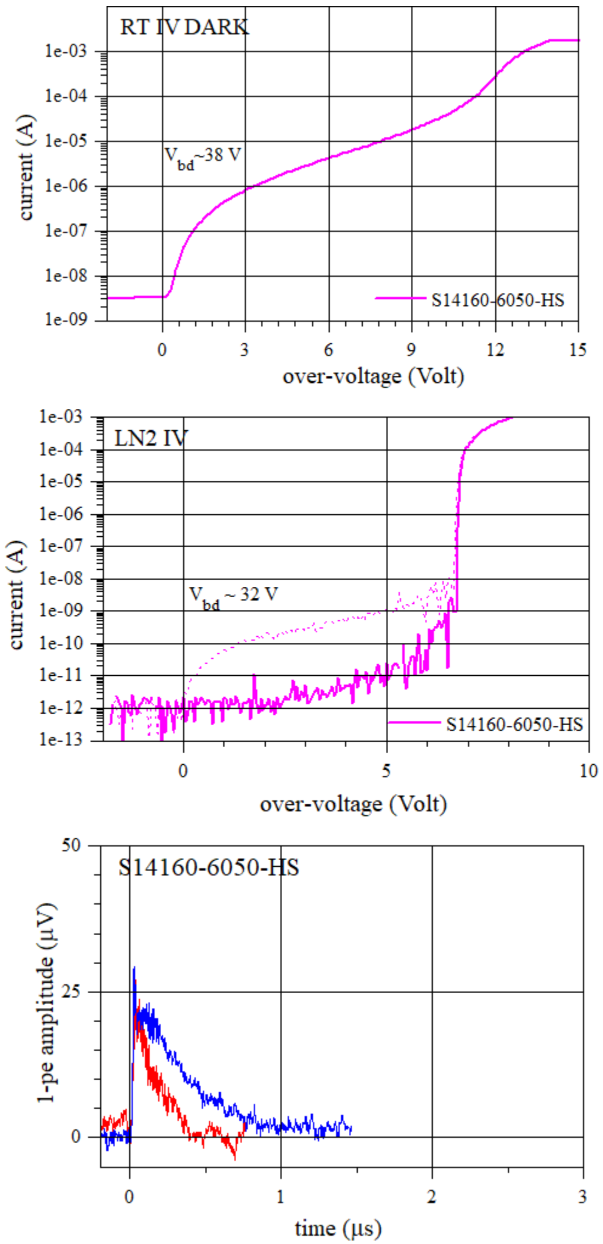
large OV span ~25 volt

DUNE S13360-6075-HS-HRQ high R_q, normal V_{bd}

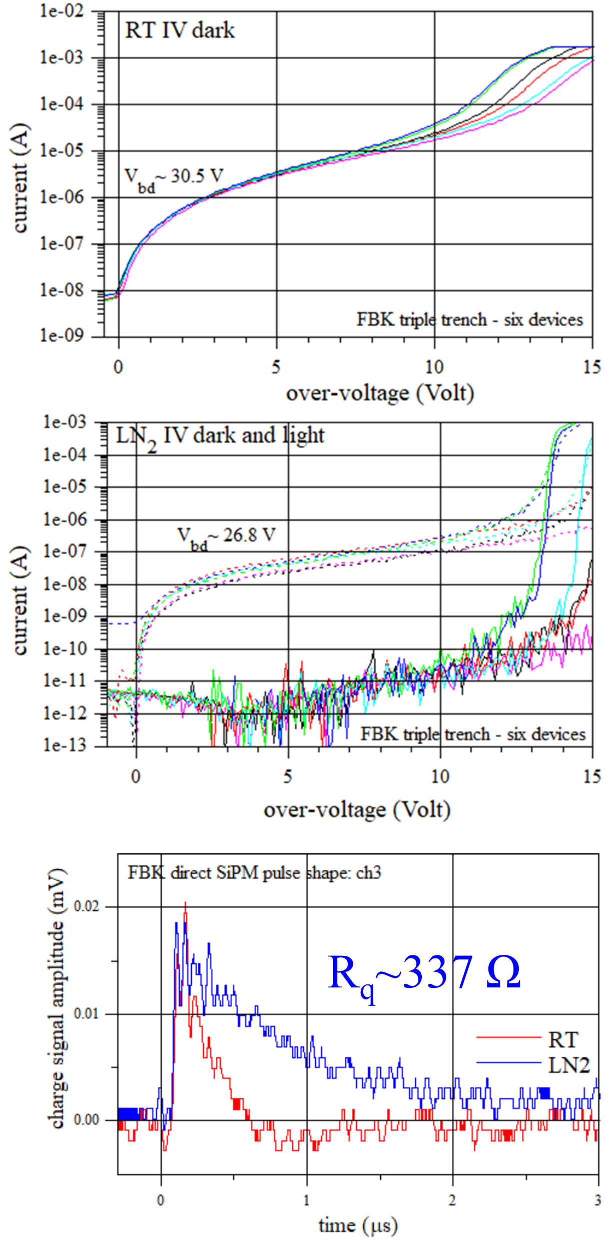


R_q~302 Ω

ProtoDUNE FNAL S14160-6050-HS low V_{bd}



DUNE FBK triple-trench 50μm low V_{bd}



R_q~337 Ω

nEXO SiPM light readout: requirements

- The energy, timing, and event resolution must be met in order to achieve the 10^{28} year half-life sensitivity to 0νββ.
- For a 6% light collection efficiency, ~6240 photoelectrons will distribute over ~4.6 m^2 surface of the photon detectors.
- A SiPM sub-array of 6 cm^2 will detect approximately ***one photon on average***.
- The photon readout electronics must be able to efficiently detect and ***identify single photoelectron events***.

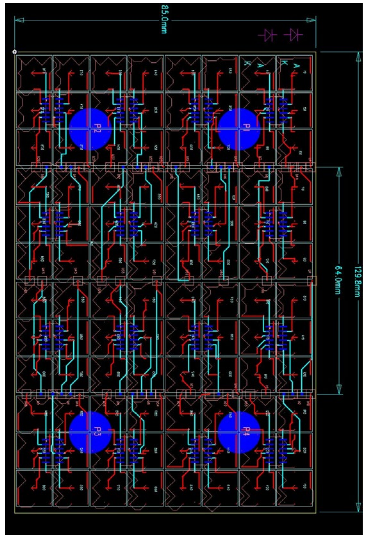
Parameter	Value	Comment
Signal range [pe^-]	100 pe	Need a large dynamic range, simulation shown ~100 pe can be captured in a single channel.
SNR for 1-pe^-	> 15	ensure a negligible accidental rate due to electronics noise compared to the SiPM dark noise rate
1-pe energy resolution	< 0.1 pe	To satisfy the nEXO energy resolution requirements.
Timing resolution	< 100 ns	With a dynamic range of 100 pe, a $\pm 3\sigma_t$ coincidence window, would satisfy the nEXO energy resolution requirements.
Readout non-linearity	< 1%	strict integral linearity requirement from the magnitude of the electronic readout response to the SiPM charge signal response
Max. event rate [events/s]	4×10^3	calibration by radioactive sources, DCR, photon flash

nEXO SiPM
Light Detector Readout

6 cm^2 SiPMs
3P2S

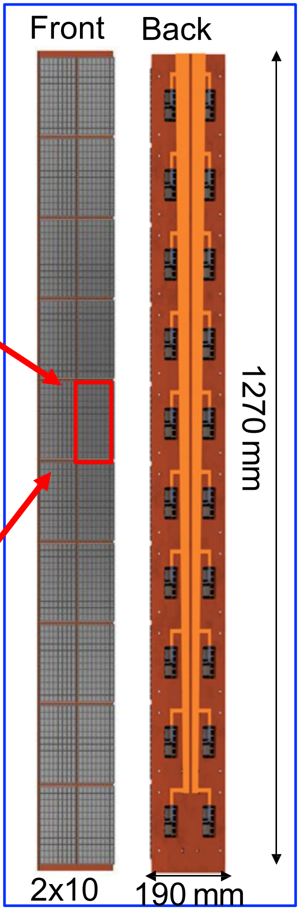
TSV
75 µm/pixel
SiO_2 carrier

96 cm^2 SiPMs tile



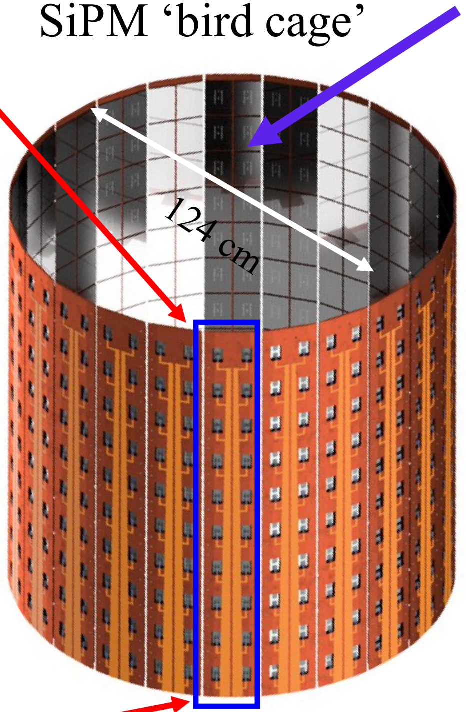
16 channels
3P2S connection

Stave



SiPM 'bird cage'

λ=175 nm

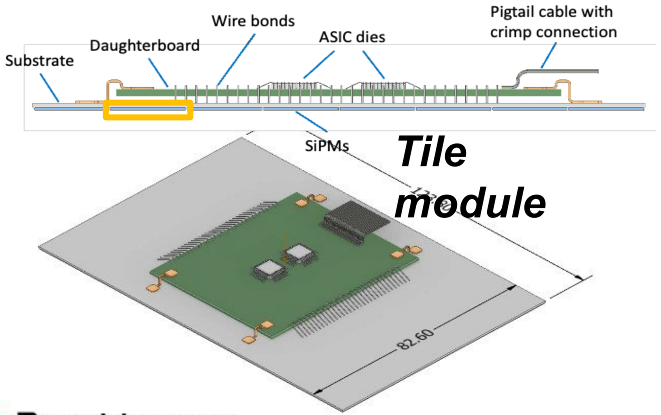


x 24

Total tiles: 480
24x(2x10)

Total 6 cm^2 subarrays: 7680
480x16

Total SiPM area: 4.6 m^2
7680x6 cm^2



Tile module

Technology	HPK	FBK
$V_{operating}$ (RT) [V]	50	30
C /area [nF/cm^2]	**3.5**	**8.5**
C (6 cm^2) / channel [nF]	**21**	**51**
C (8P2S) [nF]	**5**	**12.5**
V (2S) [V]	100	60

Very large subarray capacitance/channel

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SNR>10 for single photo electrons & radio-pure components are essential for nEXO.

nEXO SiPM selection

Vendor selection criteria:

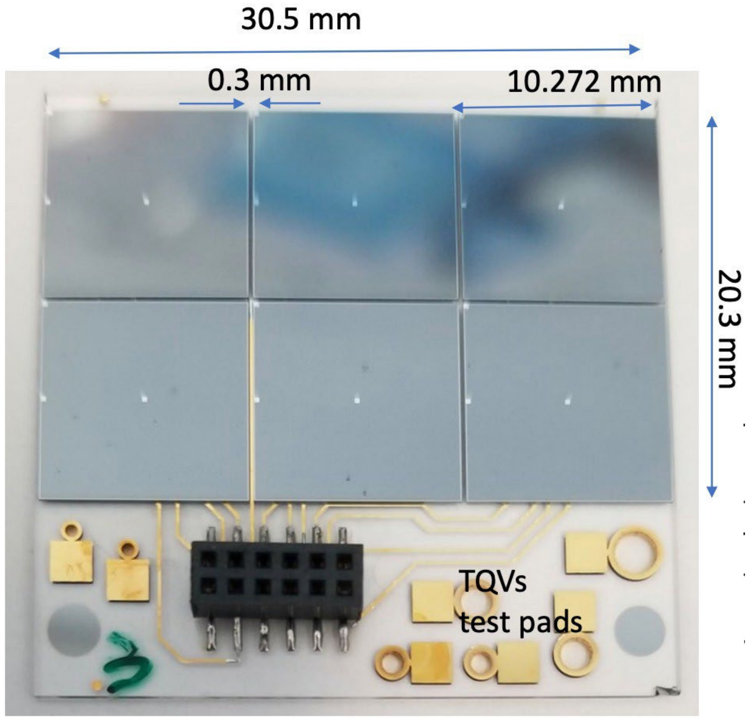
1. Meets nEXO radioactive background and PDE, CA, DCR requirements
2. TSVs are available to avoid need for wirebonds on tile module front side
3. Time scale for production and testing requirements does not delay the overall nEXO development path
4. High uniformity of devices in realistic final production, to minimize testing and device selection requirements during assembly
5. Cost (including risk) minimized while meeting criteria 1-4 above.

D. Moore, Jan. 2022 nEXO Collaboration Meeting

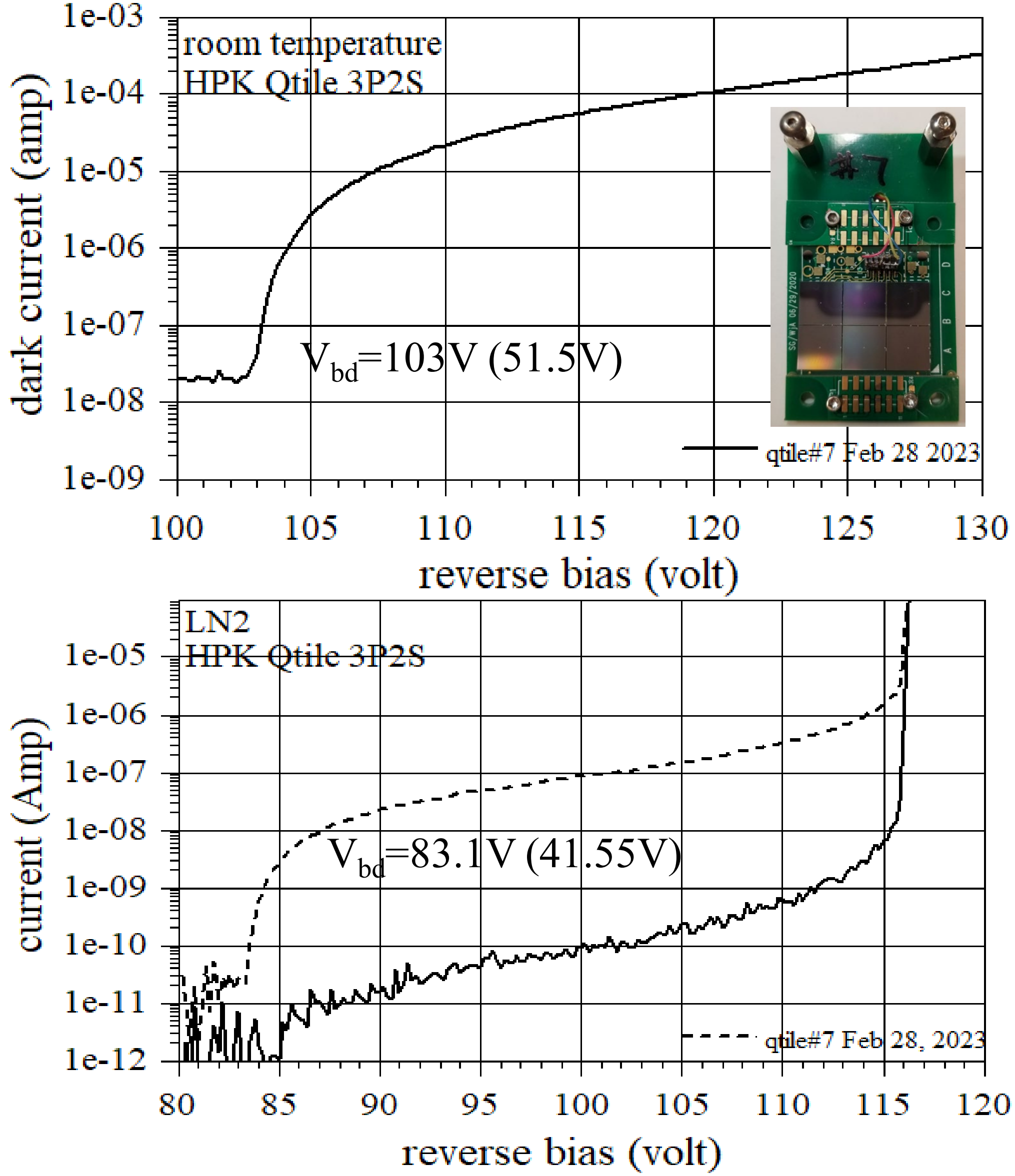
175 nm, 165K	HPK	FBK
SiPM radioactive background <0.5%	yes	yes
PDE >15%	yes	yes
DCR < 10 Hz/mm^2	yes	yes
Correlated noise <0.4 pe	yes	yes
1 cm^2 array size	yes	Yes, but have issues
TSV	yes	not yet
V_bd uniformity	in progress	unknown
prototype issue	packaging	IV

HPK 6 cm^2 SiPM silica tile: IV

HPK 6x1 cm^2 SiPMs with TSVs

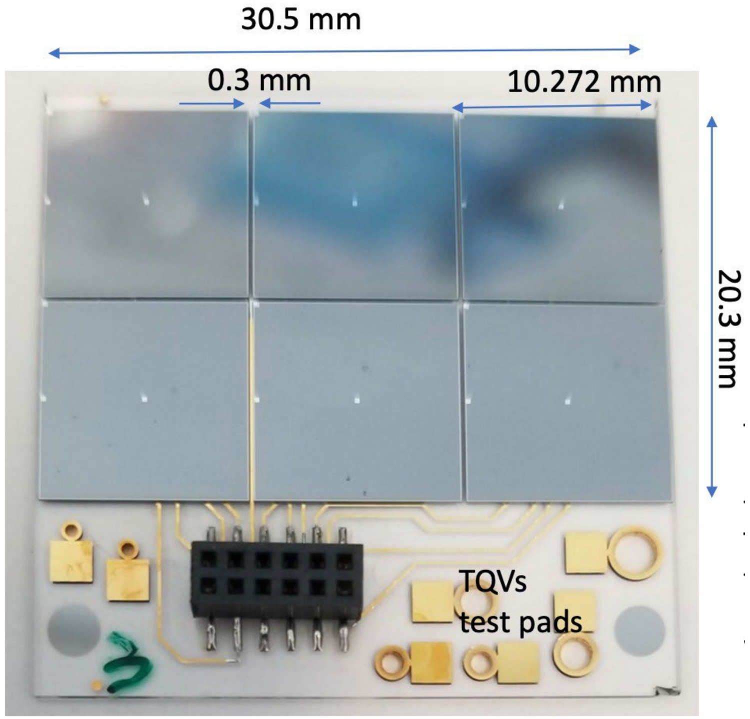


3P2S IV: room & LN$_2$



HPK 6 cm^2 SiPM silica tile: PDE

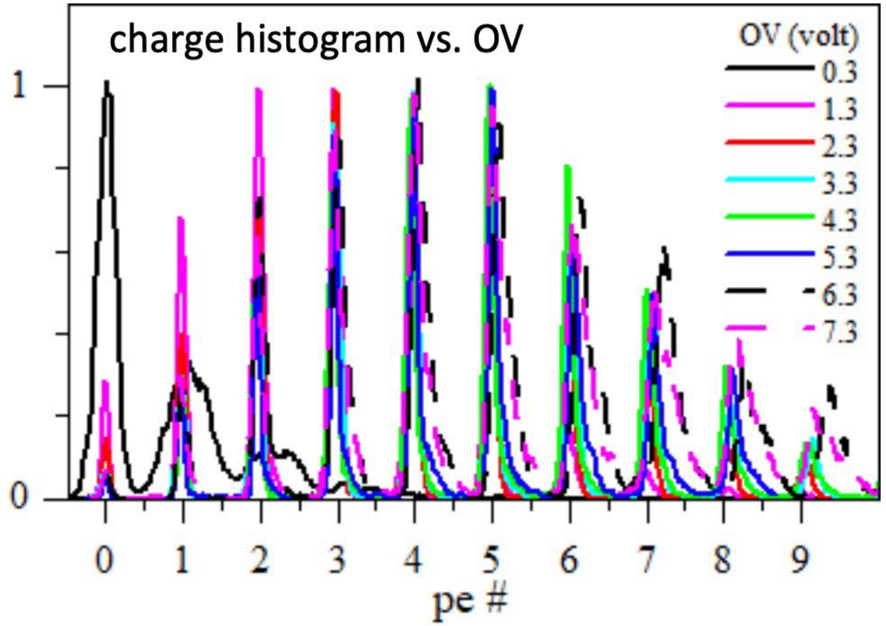
HPK 6x1 cm^2 SiPMs with TSVs



HPK SiPMs with TSVs perform well.

Need to verify PDE at 175 nm and test in LXe

PDE data (1ns pulse, 268 nm)

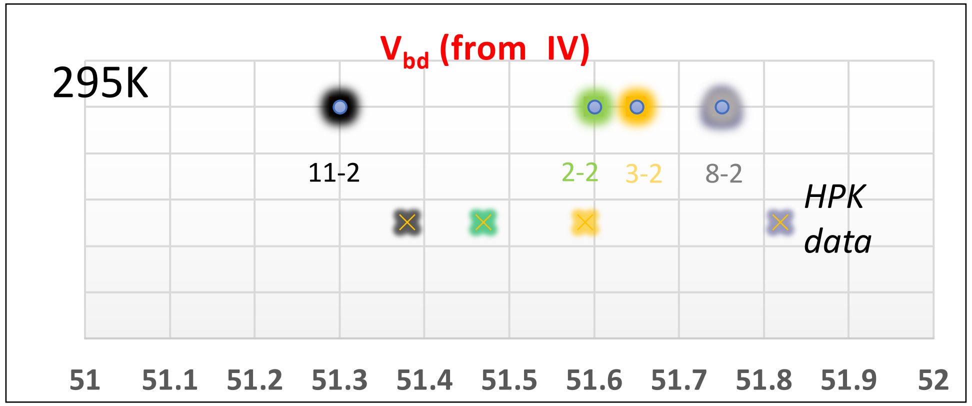


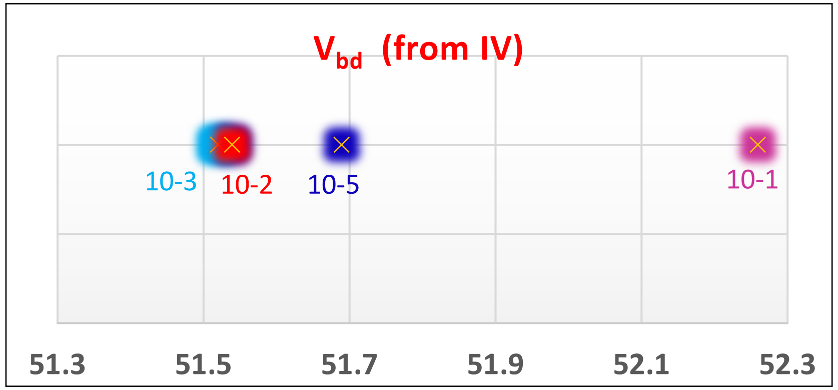
Summary of data

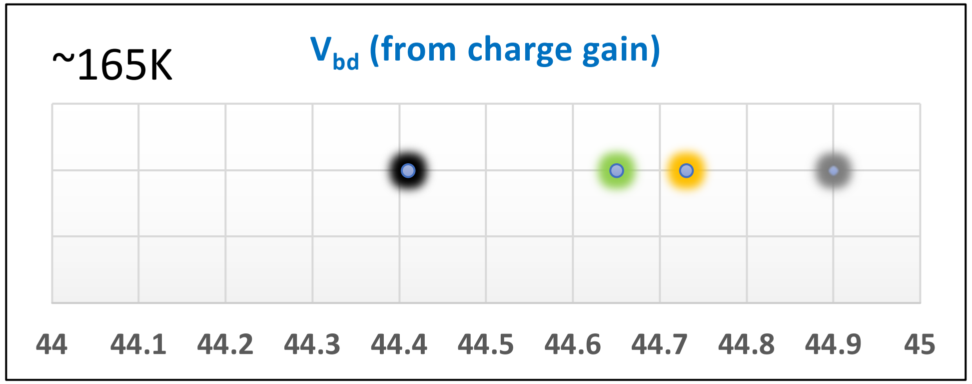
~4V OV	unit	room	cold ~155K
V-breakdown	Volt	51.5	44.5
overvoltage span	Volt	>15	>15
R_quench	Ω	23	31
Charge gain	x10^6		1.48
DCR	Hz/cm^2		~20
1-pe resolution	%		3.7
CA	pe		0.05
µCell capacitance	fF	243	233
µCell capacitance	nF/cm^2	4.3	4.11
PDE (268 nm)	n/c		0.165

previous PDE measurements
~0.18 (268 nm)
~0.22 (175 nm)

HPK 6 cm^2 SiPM silica tile: *correlation of V_{bd} from RT to LN_2*

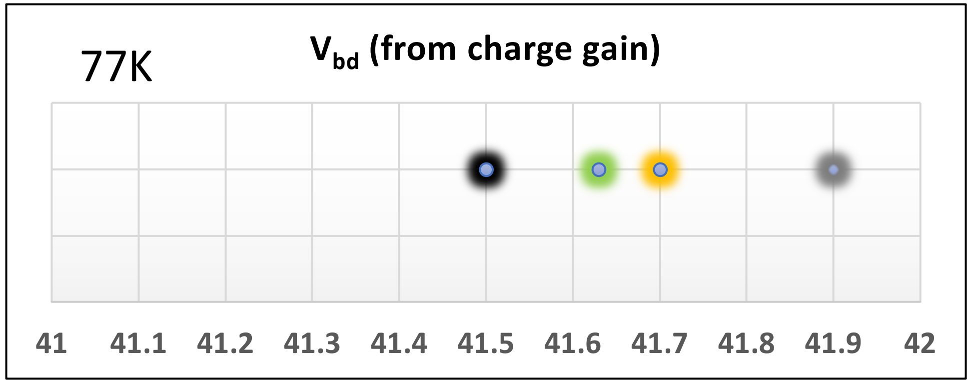


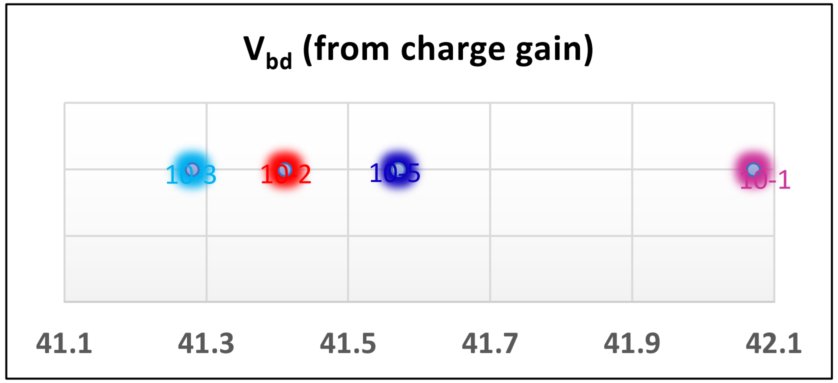




device # - channel #

V_{bd} determined from extrapolated zero-charge gain measurement





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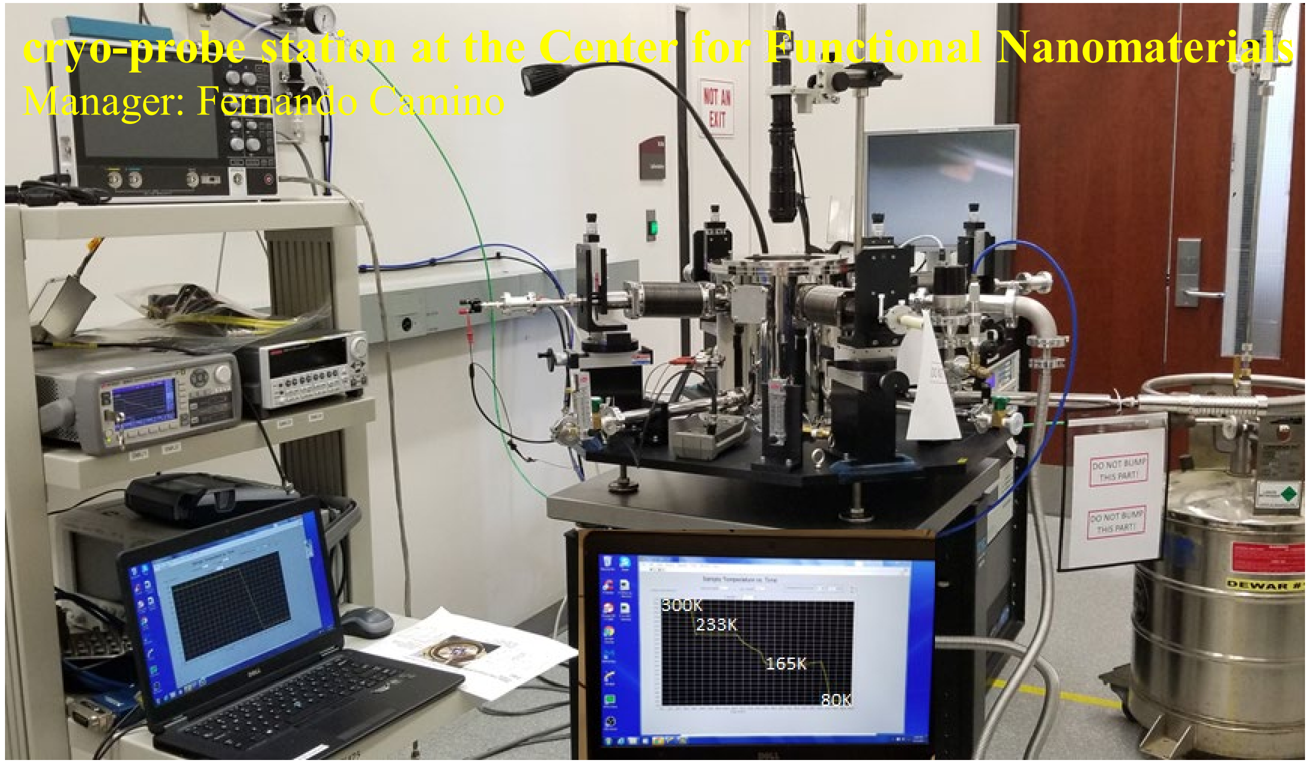
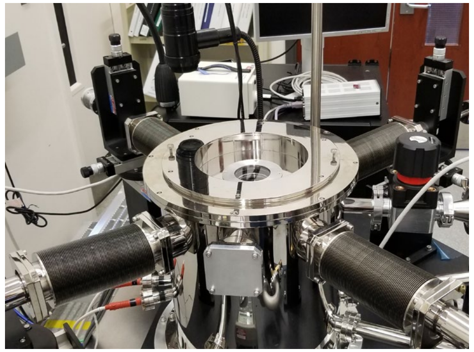
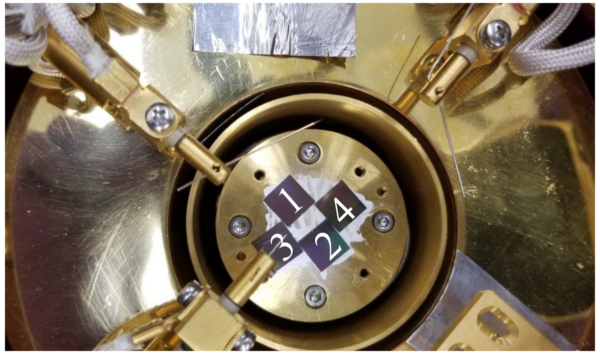
- larger sample size continue to show evidence of V_{bd} correlation
- ***Charge gain match of SiPM tiles may be projected from RT to cold***

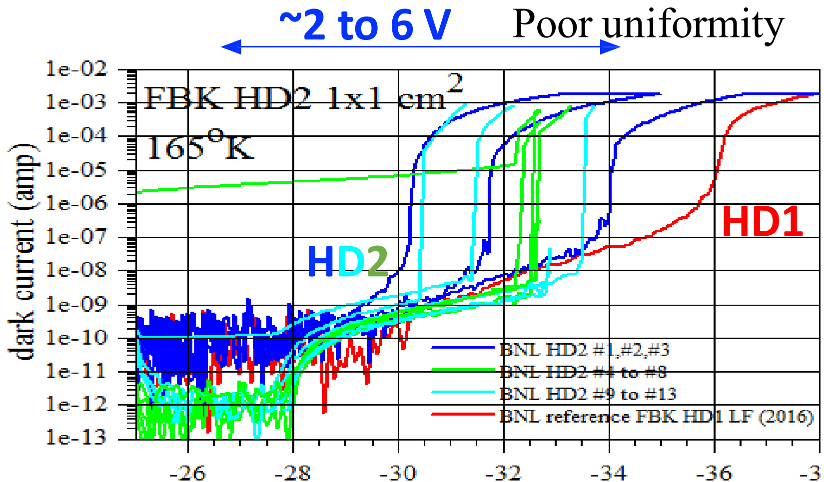
FBK prototypes: IV at RT, 233K 165K & 80K


cryo-probe station at the Center for Functional Nanomaterials

Manager: Fernando Camino

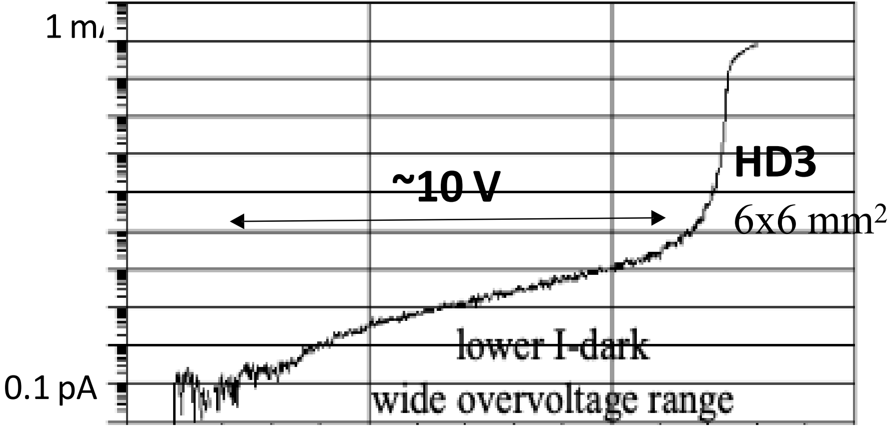





~2 to 6 V Poor uniformity

HD2

HD1

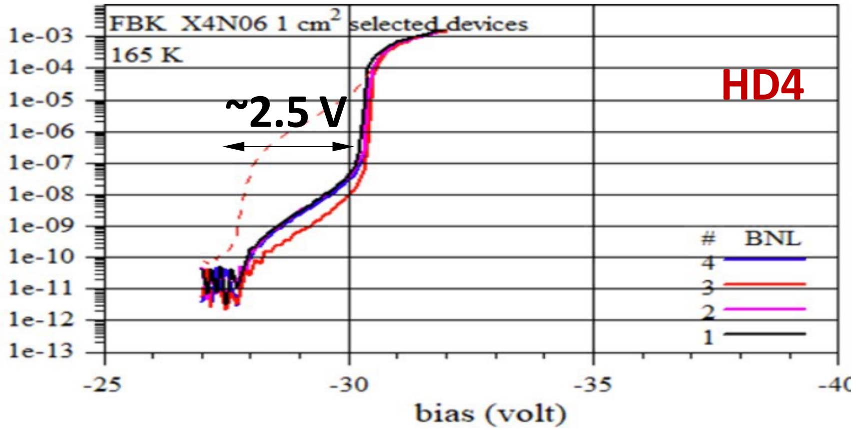

~10 V

HD3

6x6 mm^2

lower I-dark

wide overvoltage range


~2.5 V

HD4

fails the nEXO requirement for >3 V OV

Charge Readout concept: weak coupling to amplifier using HPK SiPM Minitiles

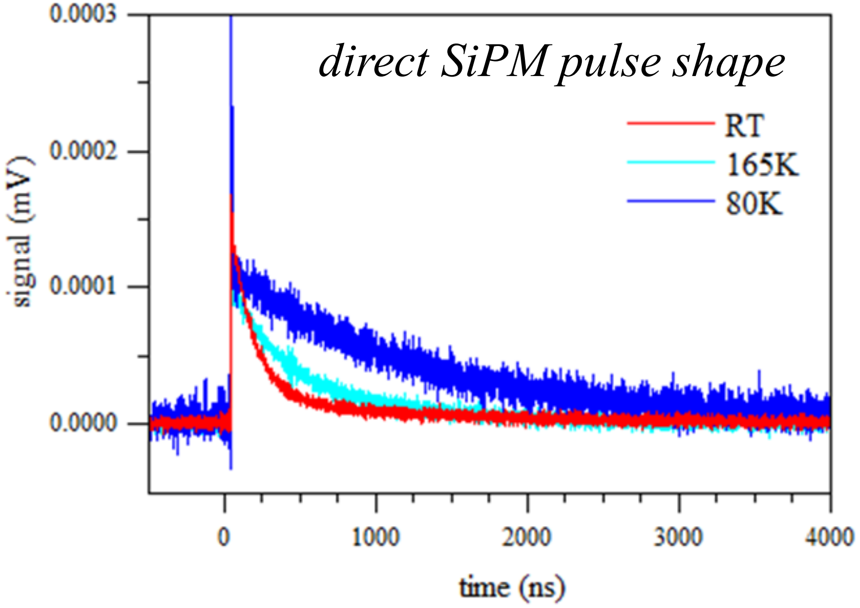
Thomas Tsang, Shanshan Gao, Sergio Rescia, Hucheng Chen, and Veljko Radeka

2021 IEEE/MIC

To know the number of detected photons, the charge of the signal must be measured. two most common approaches:

- ***Charge integration***

- Amplitude measurement

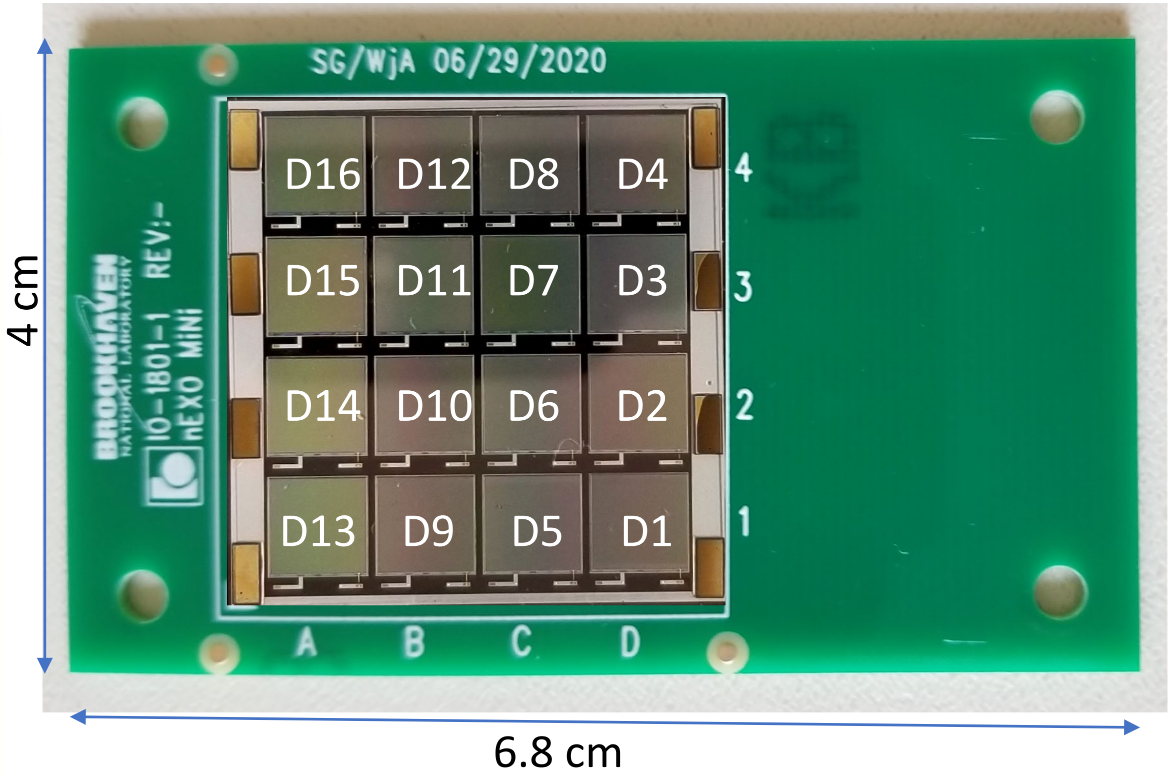


Both methods have their advantages and disadvantages.

HPK SiPM Minitile arrays

S13775-9121 [4x4x(0.6 cm)^2]

HPK minitile board



active area=5.76 cm^2

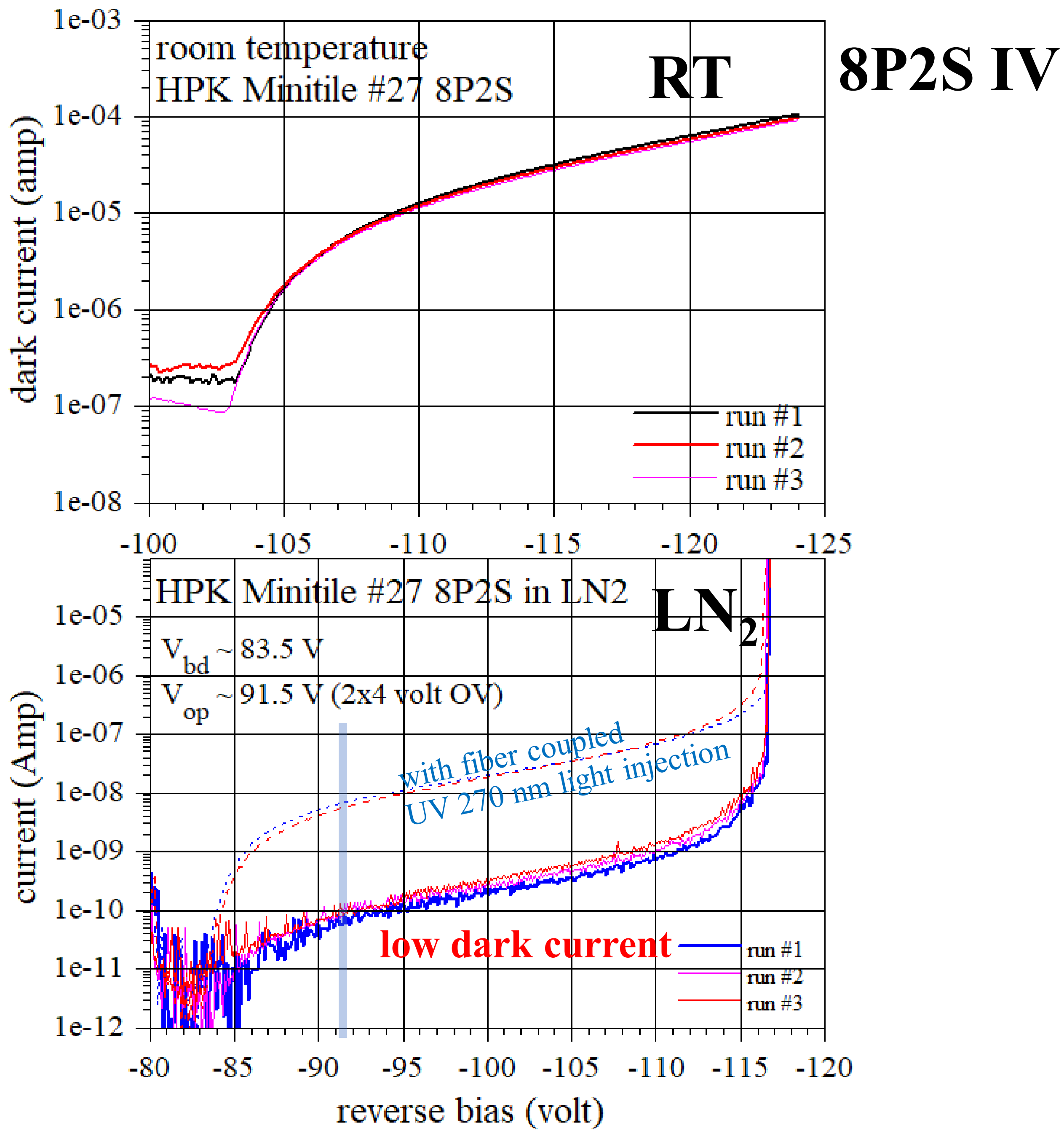
N_{cell} =16x13923=222768 pixels (50 μm pixel)

$C_{\mu cell}$ (RT) =86 fF

$C_{Terminal}$ (RT)=1.2 nF (3.3 nF/cm^2)

C_{total}(16P) SiPM tile ~ 20 nF

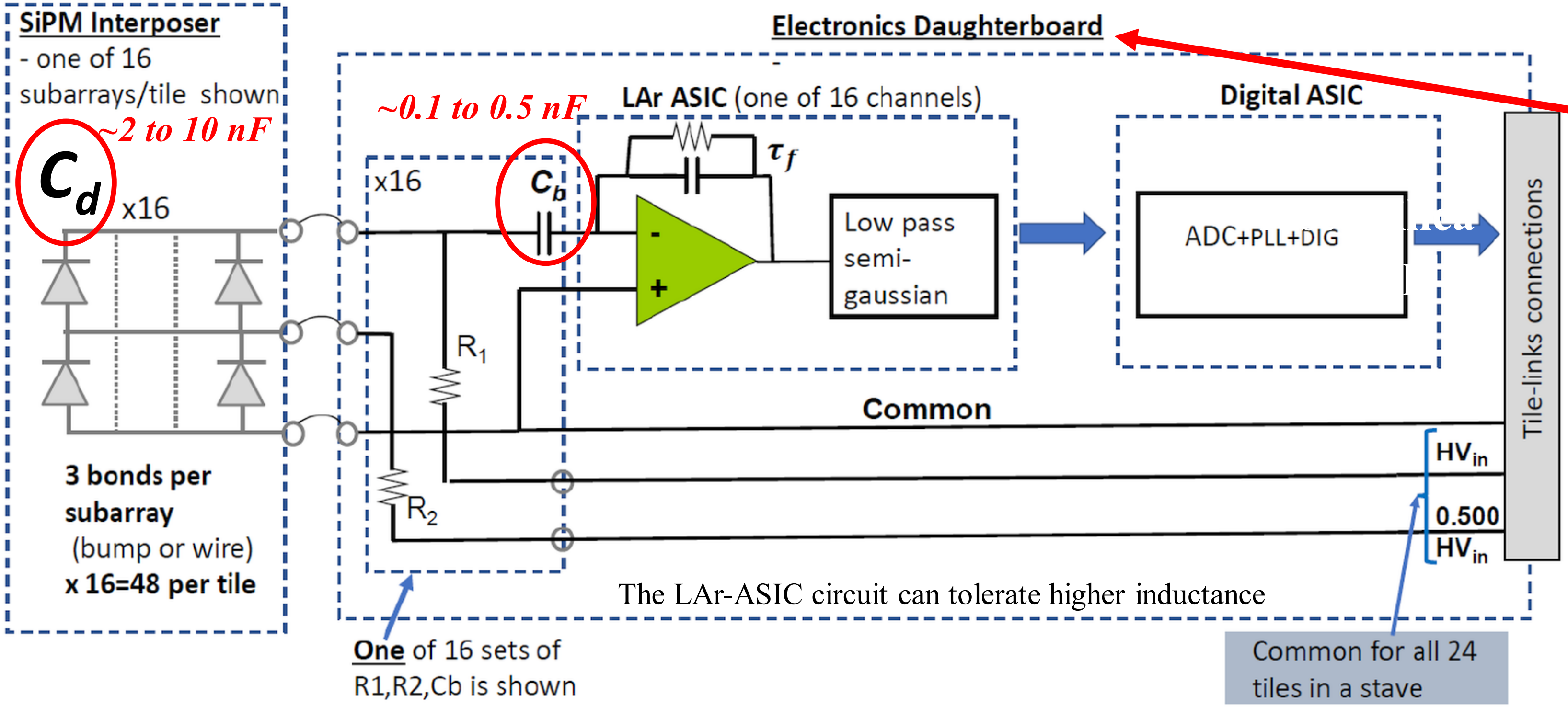
C_{total}(8P2S) SiPM tile = 4.8 nF



At ~4V OV I_{dark} (DCR) RT→LN$_2$ drops ~10^{-5}

Photoelectron spectroscopy, charge calibration, SiPM avalanche gain, electronics gain response to single and multiple photoelectrons both #27 and #28

Demonstration of readout concept: weak coupling to amplifier, $C_b << C_d$


SiPM Interposer
- one of 16 subarrays/tile shown

~2 to 10 nF

3 bonds per subarray (bump or wire) **x 16=48 per tile**

Electronics Daughterboard

~0.1 to 0.5 nF

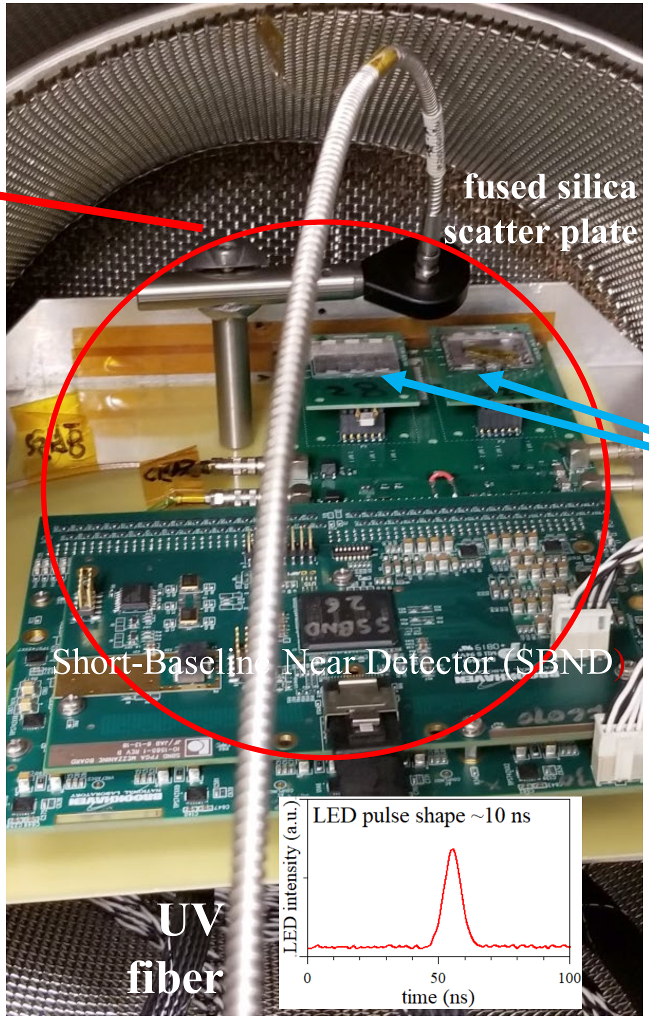
LAr ASIC (one of 16 channels)

Digital ASIC

The LAr-ASIC circuit can tolerate higher inductance

One of 16 sets of R1,R2,Cb is shown

Common for all 24 tiles in a stave



16 SiPMs ganged in 8P2S

LArASIC P2:

16 **independent** ASIC input channels

peaking time: **1 μs** (programmable 0.5, 1, 2, 3 μs)

ASIC gain: **4.7 mV/fC** (programmable 7.8, 14, 25 mV/fC)

C_{cal}=185 fF

ADC *sampling rate:* 2 MS/s (0.5 μs/time tick)

10 MHz ref. clock locked to the LED trigger & ADC sampling clock

Reference: channel 0

Minitile 8P2S: channel 1, #28

Minitile 8P2S: channel 13, #27

only 2 ASIC channels are used.

LArASIC readout by ADC and FPGA shown in the photo

Data streaming mode, 45sec/data

Data collection: LabView

Data analysis: Python

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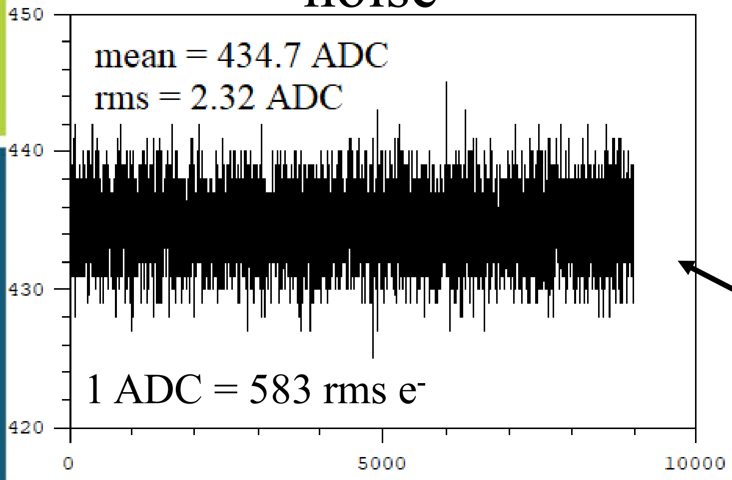
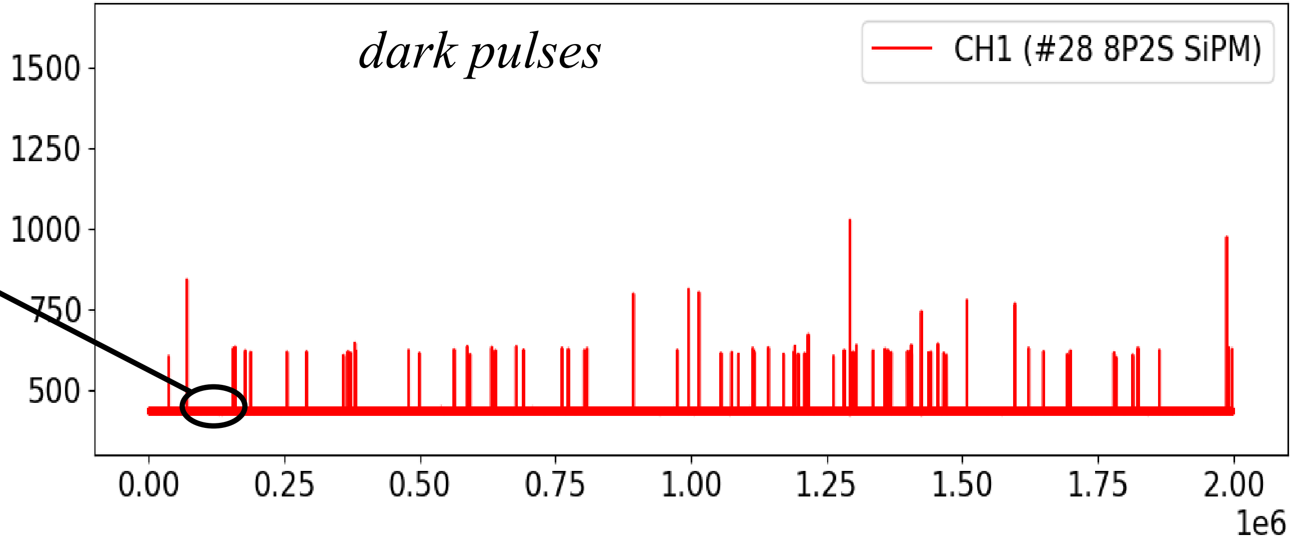
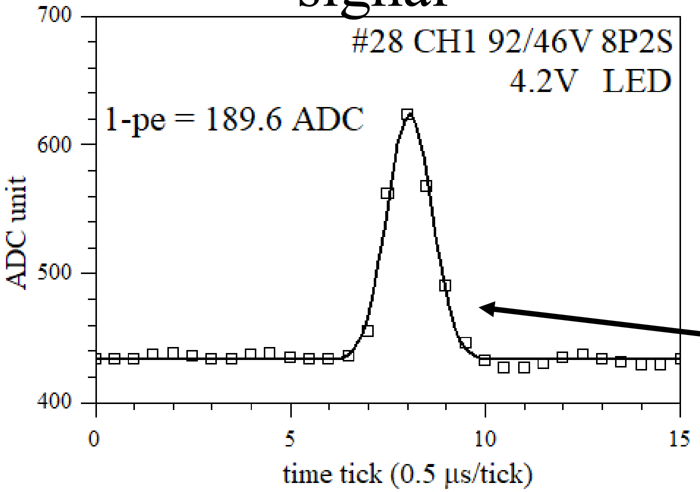
in LN_2 @ 4.2 V OV 8P2S 4.8 nF: subset of raw signal trace (1 second)

noise

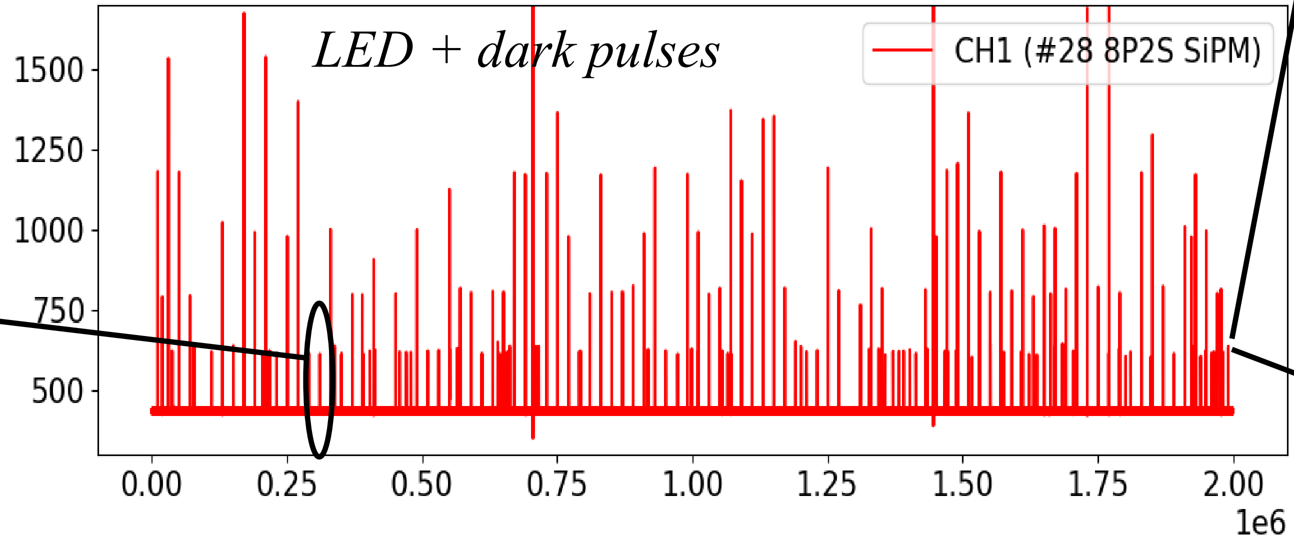




signal

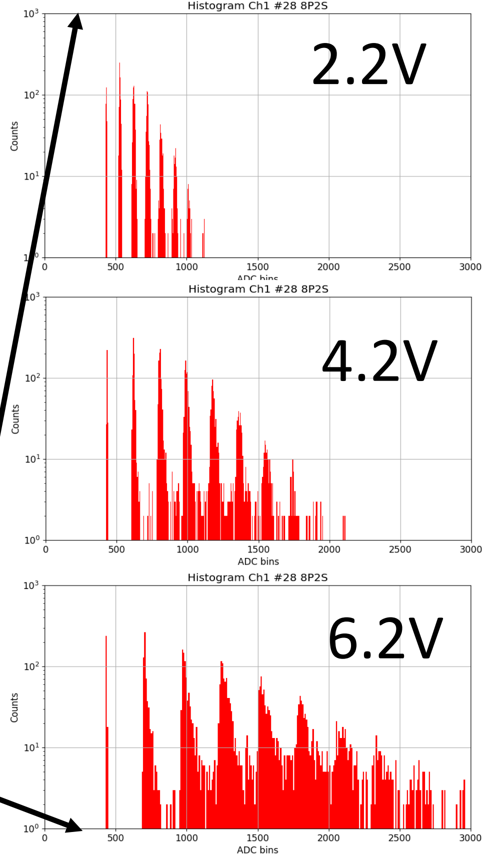


S/N = 189.6/2.32 ≈ 82



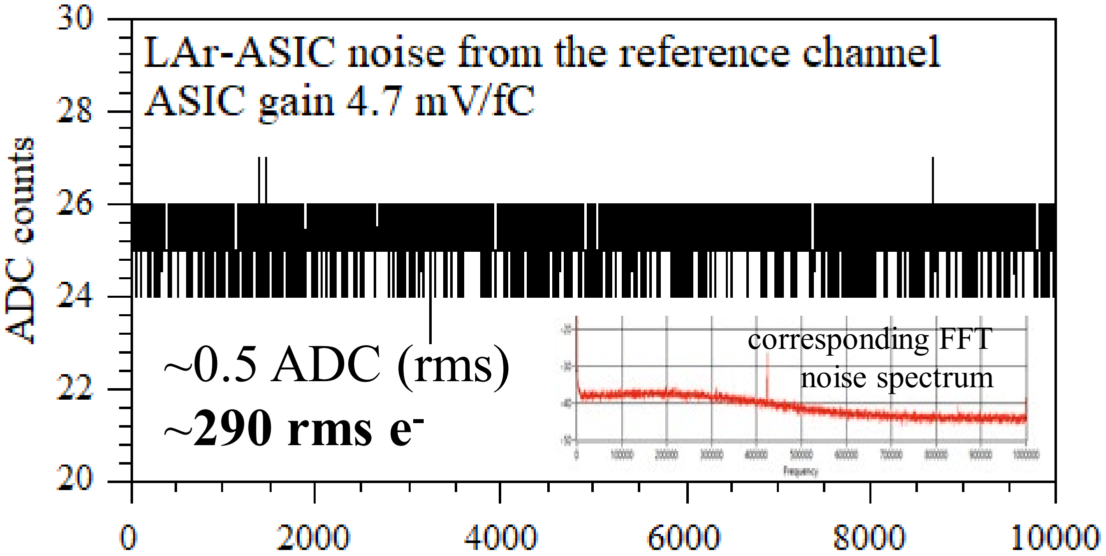
Time tick [0.5μs/tick] total of 1 second

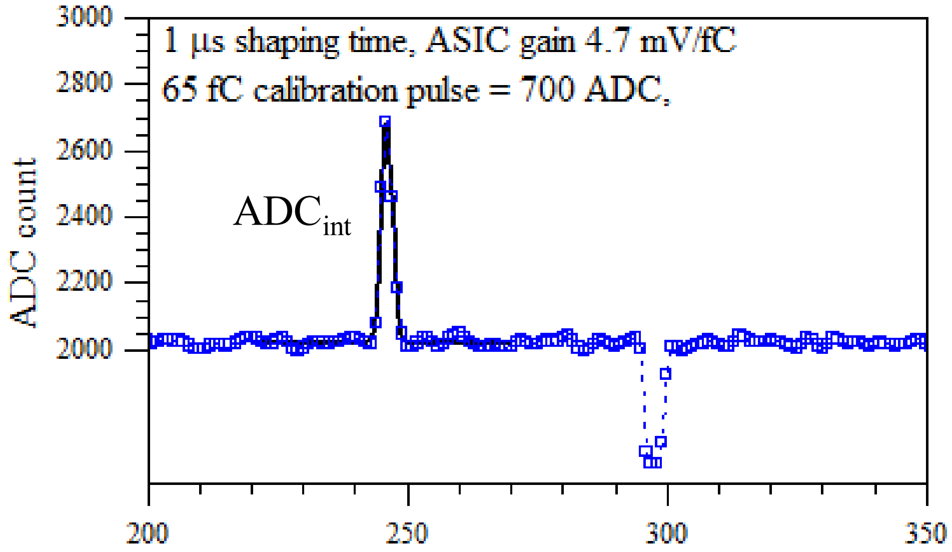
signal charge histogram



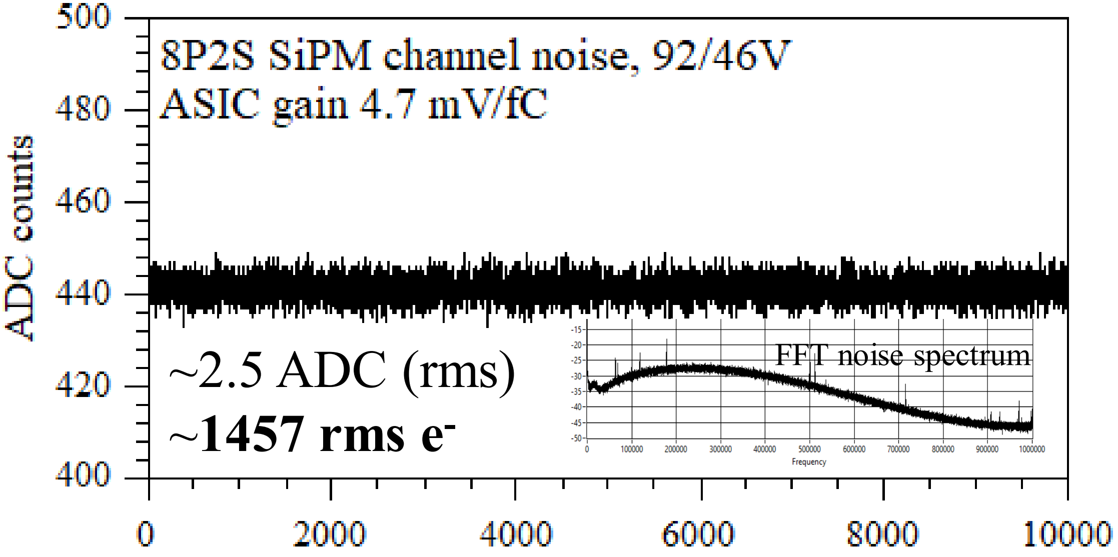
Electronic noise and Gain Calibration

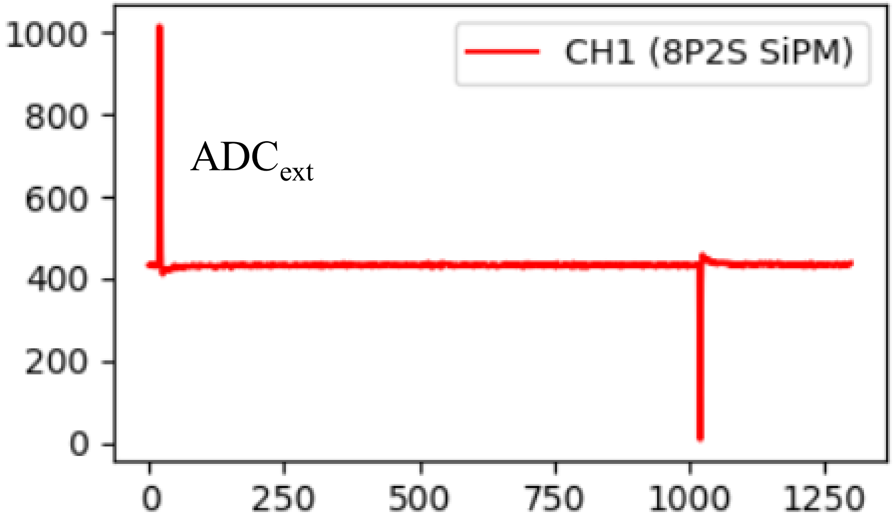
Reference channel





Signal channel





Time tick [0.5µs/tick]

Time tick [0.5µs/tick]

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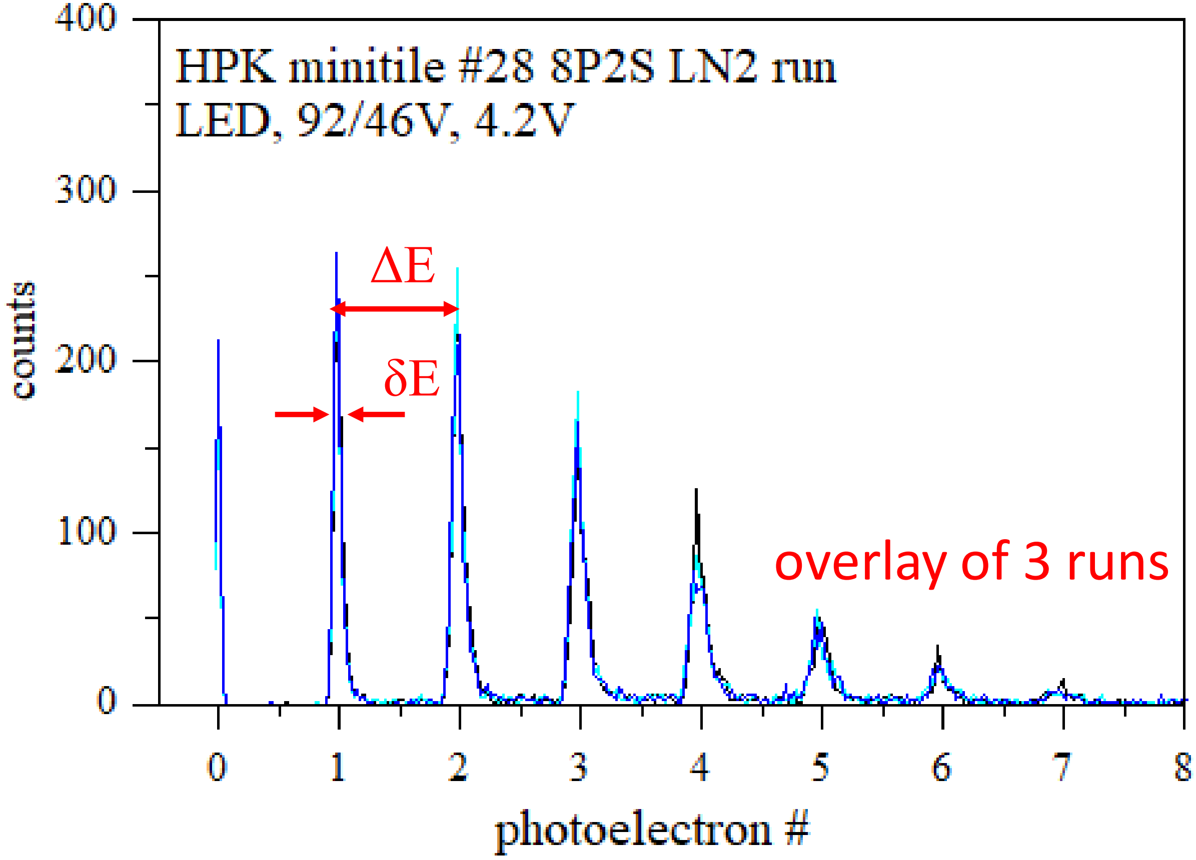
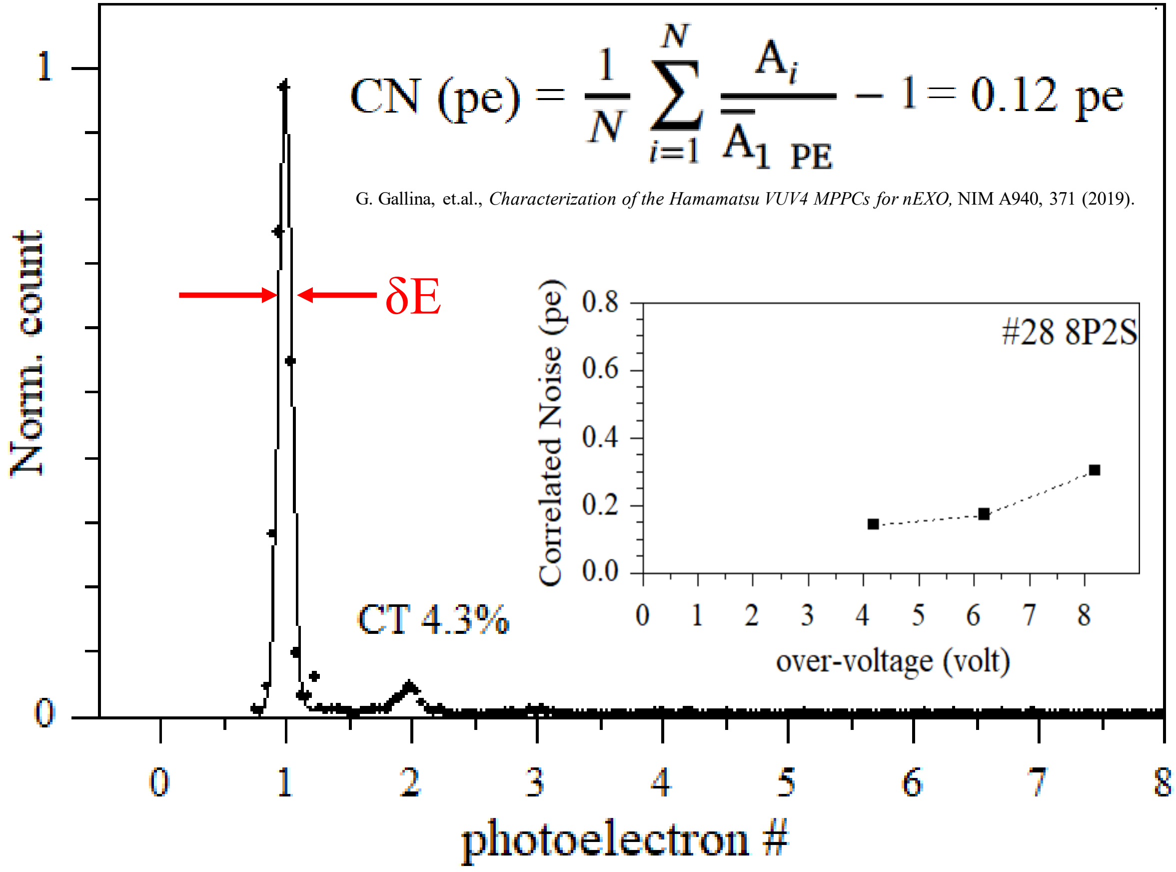
in LN$_2$: single-photoelectron charge histogram

LED photon flash (triggered)



dark pulse



$$\mathrm{CN\ (pe)} = \frac{1}{N}\sum_{i=1}^{N}\frac{A_i}{\overline{\overline{A}}_{1\ \mathrm{PE}}} - 1 = 0.12\ \mathrm{pe}$$

G. Gallina, et.al., *Characterization of the Hamamatsu VUV4 MPPCs for nEXO,* NIM A940, 371 (2019).

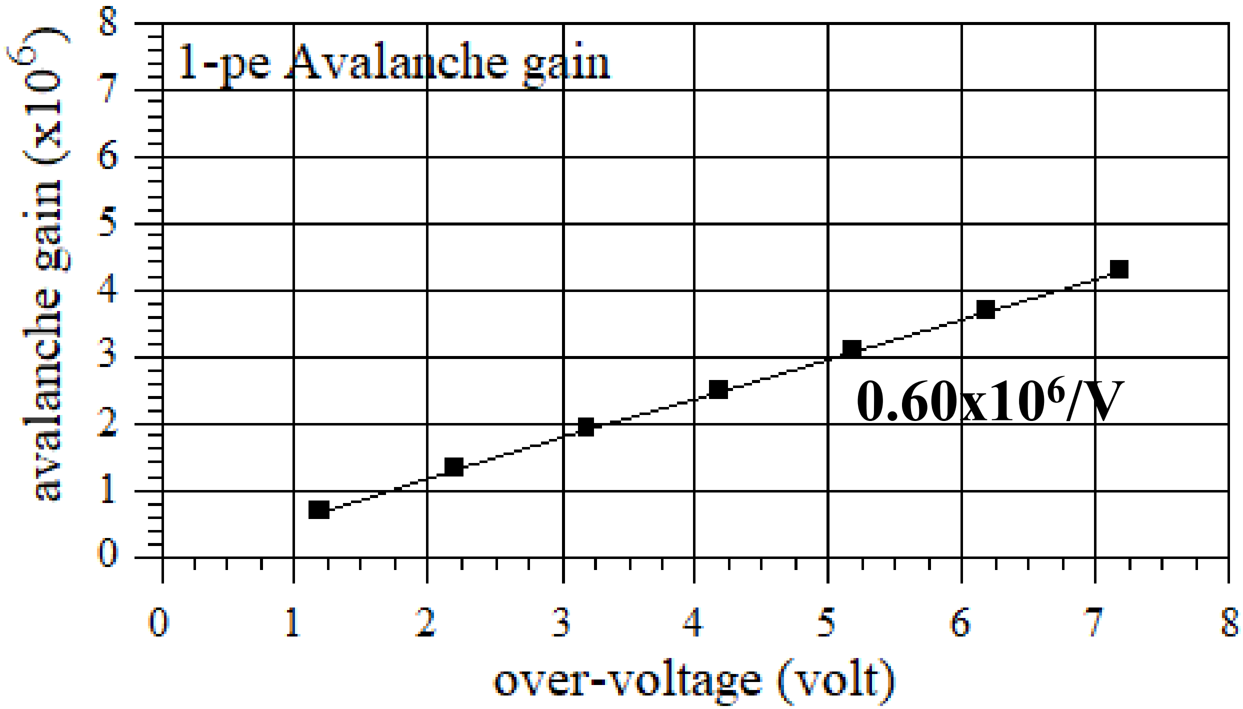
Photon rate: ~80 Hz (trigger rate 100 Hz)

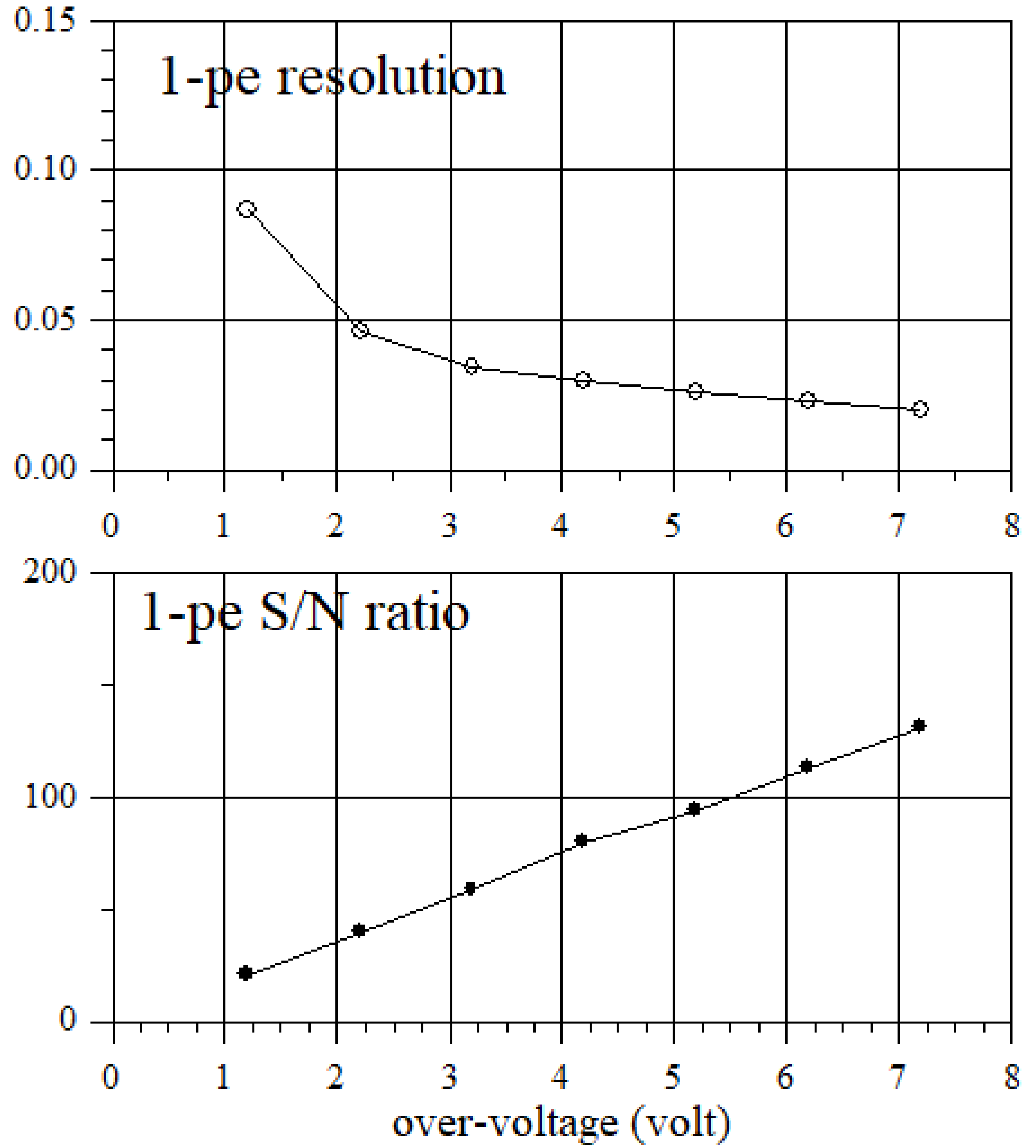
1-pe resolution ($\frac{\delta E}{\Delta E}$): <3.5% rms

DCR: ~96 Hz (0.17 Hz/mm^2)

1-pe resolution: ~5% rms

Avalanche gain, S/N, resolution (8P2S, 4.8 nF), in LN_2





Avalanche gain of both channels are similar

$$Avalanche\ gain = \frac{C_{\mu cell}}{e}(OV)$$

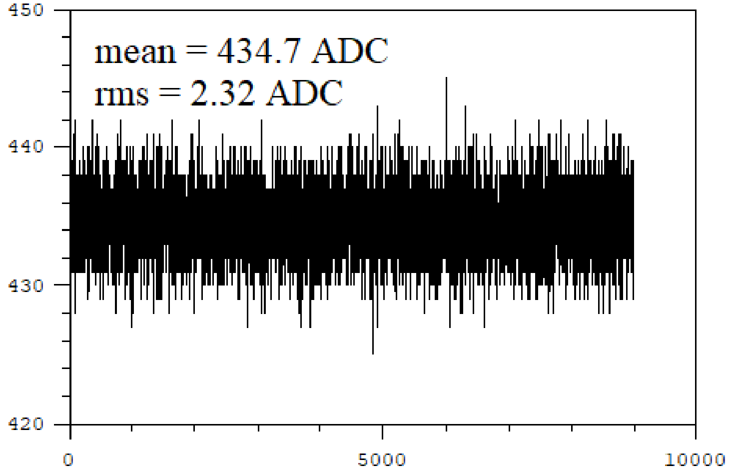
$C_{\mu cell}$ ~ 90 fF

$C_{\mu cell} = \varepsilon_o \varepsilon_{Si} \frac{A}{d}$, d=depletion thickness

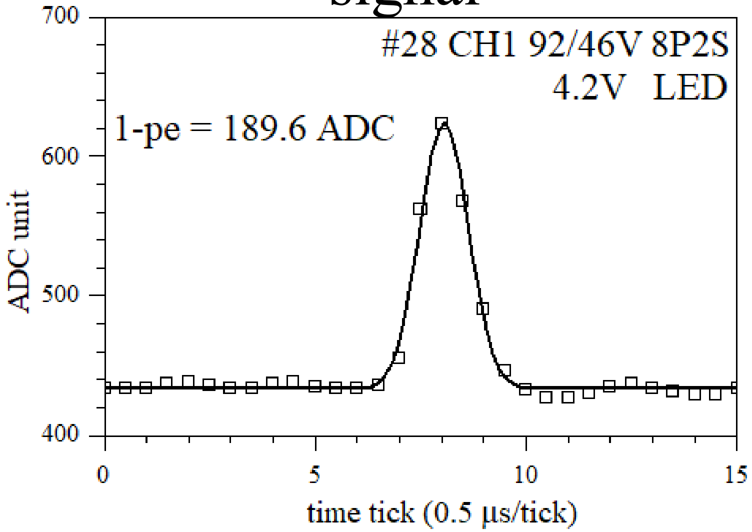
timing resolution, and coincidence resolution

Minitile #28 8P2S in LN_2 @ 4.2 V : subset of raw signal trace (0.1 second)

noise

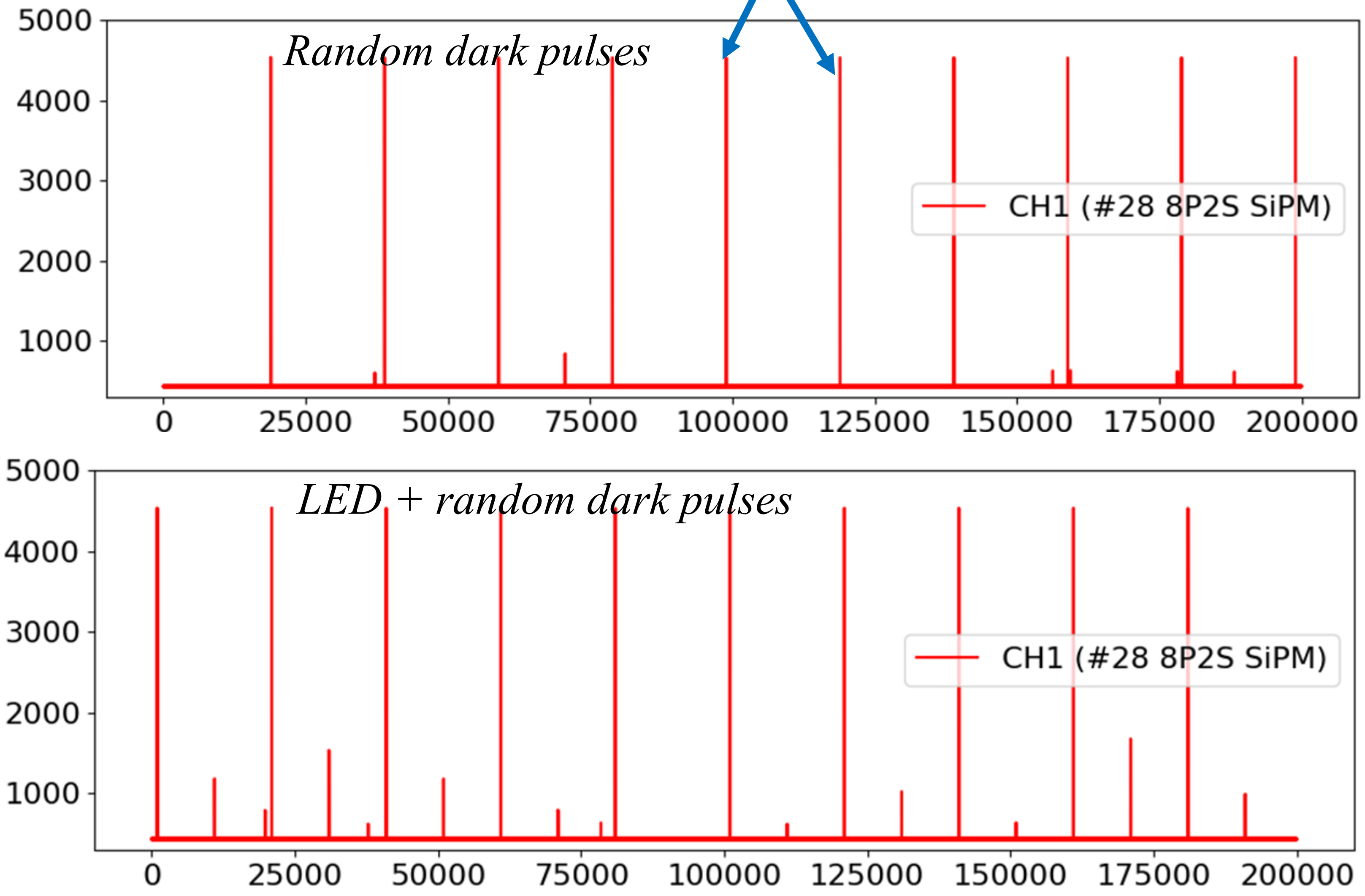


signal



time marker added on bit #12 (trigger) 10 ms apart

2 MHz sampling clock and 100 Hz LED trigger are locked



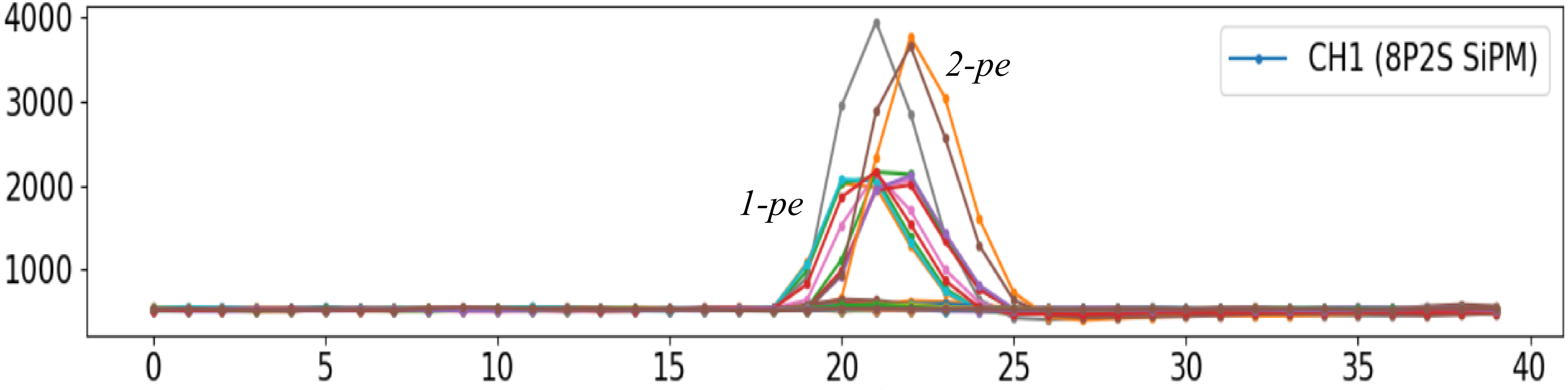
Time tick [0.5µs/tick] total of 0.1 second

S/N = 189.6/2.32 = 81.7

time coincidence detection: 10 MHz reference clock lock OFF

Photon flash trigger (100 Hz) and the 2 MHz ADC can dither by 0.5 µs (1 time-tick)

single photoelectrons

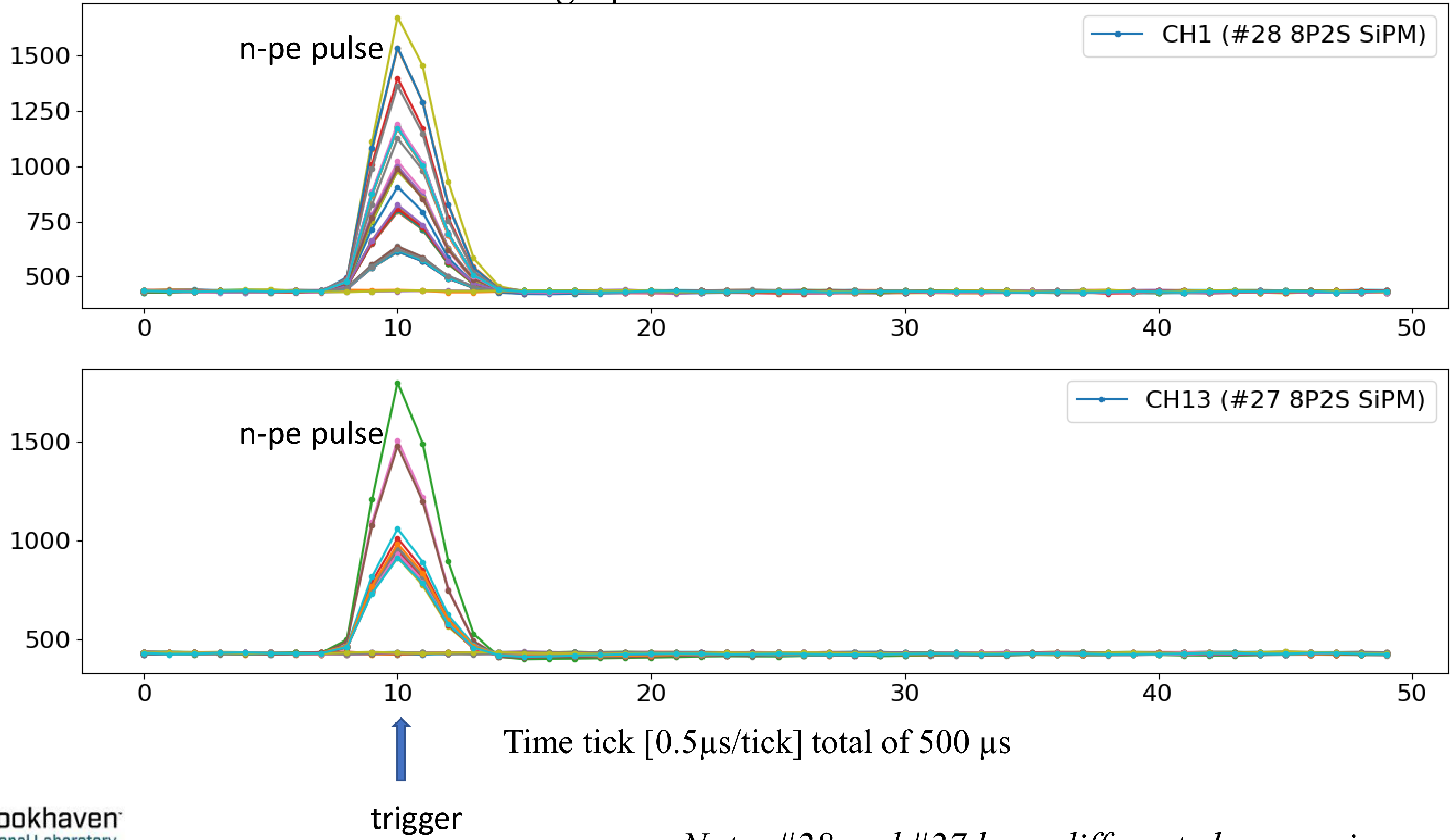


Time tick [0.5µs] total of 20 µs

trigger

time coincidence detection: 10 MHz reference clock lock ON

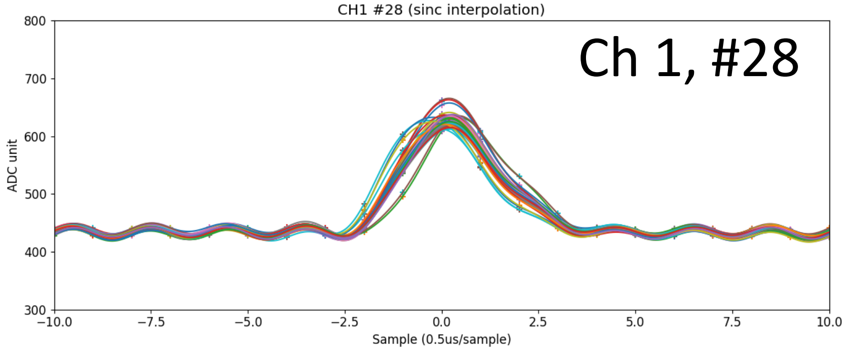
single photoelectrons

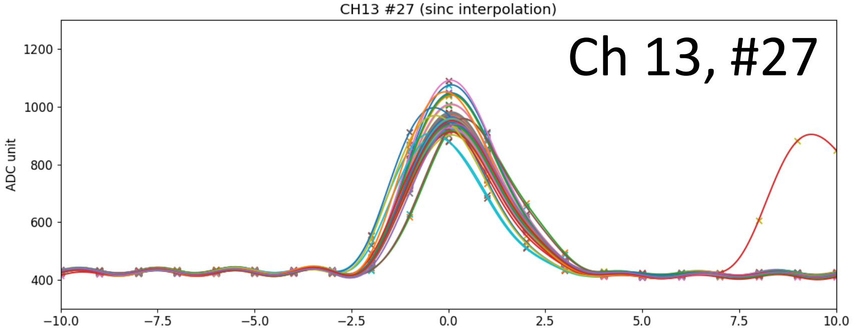


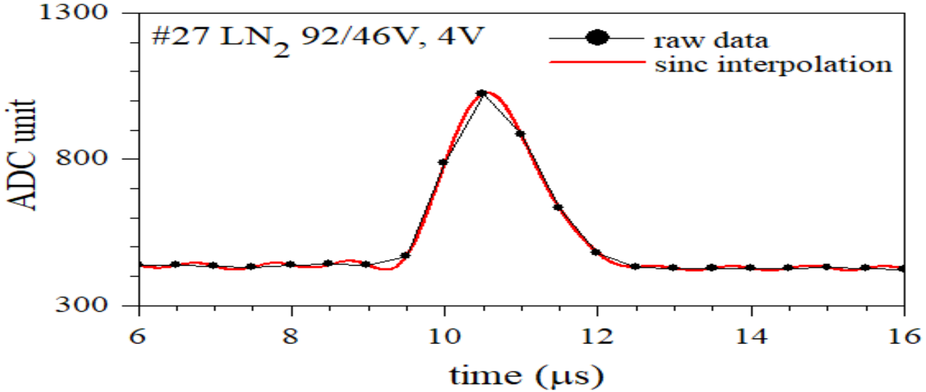
Note: #28 and #27 have different charge gain

Single-Photoelectron Timing and Coincidence Resolution

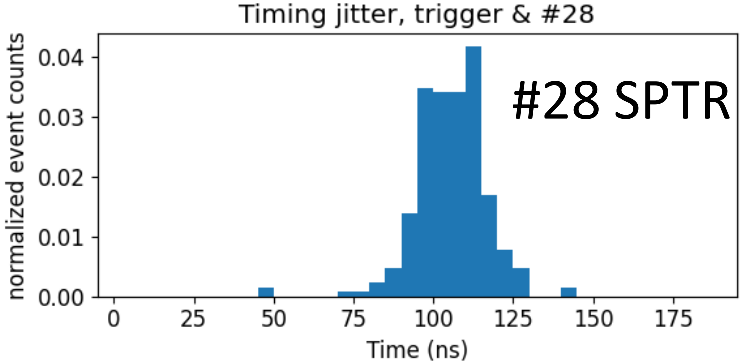
Select ONLY 1-pe pulses

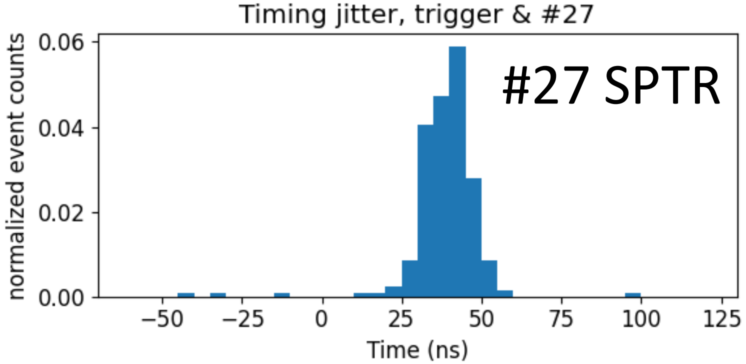


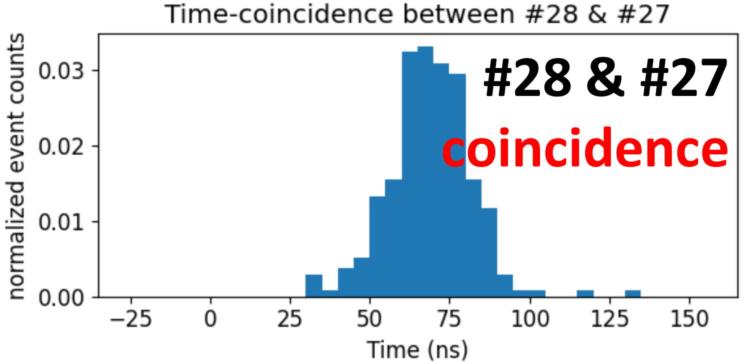




1-pe time jitter histogram, 45 sec data







Photon flash 100 Hz
ADC sampling rate 2 MHz

LN_2 4V	Average rate (Hz)	SPTR (ns)
#28	96	9.94
#27	250.6	6.57
Coinc.	67.3	**~11 ns**

coincidence window = 0.5 µs

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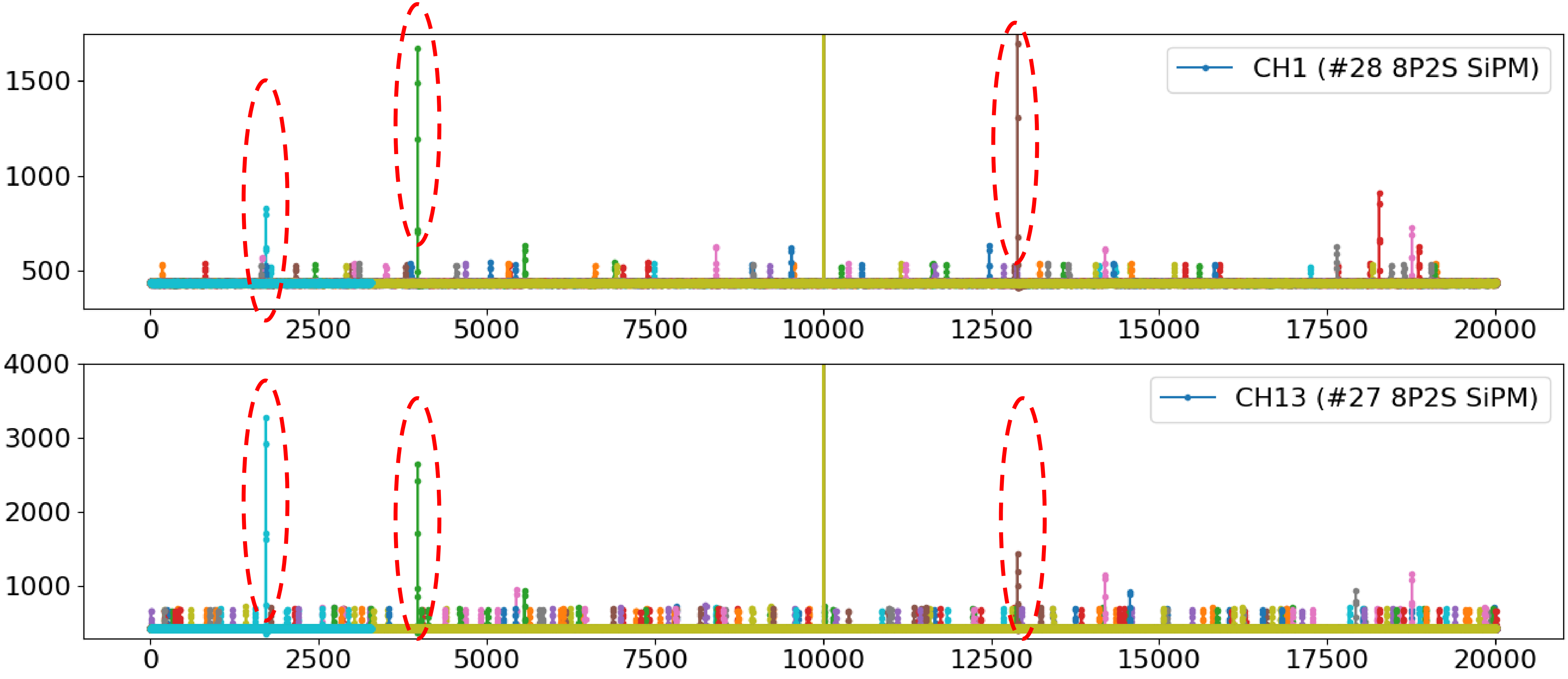
sinc-interpolation + peak finding led to ~10 ns timing resolution

Time coincidence detection of Dark Pulses …

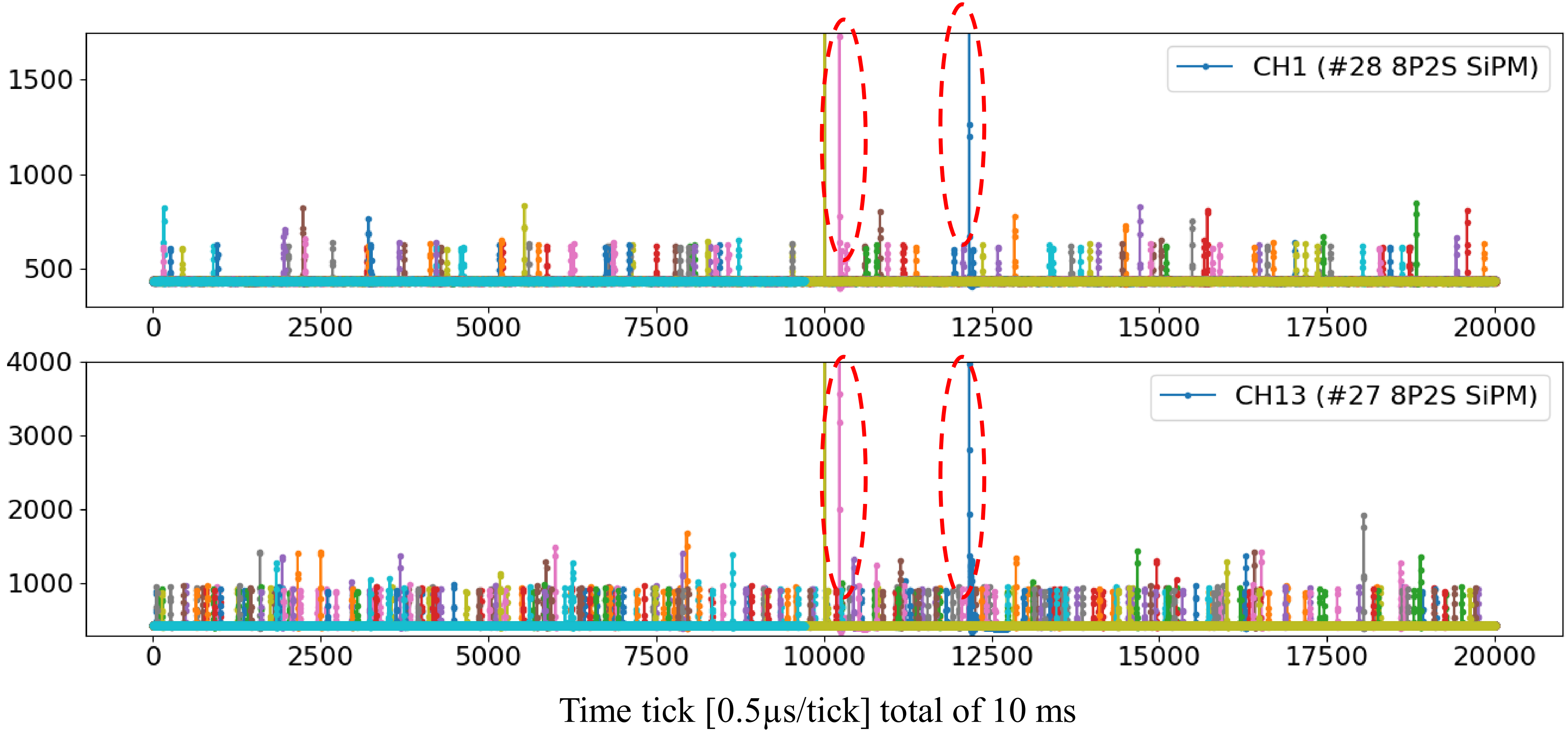
unexpected time-correlated DARK events (2.2V, 10 ms cumulative)



Time tick [0.5µs/tick] total of 10 ms

time-coincident events ~1% of total DCR

unexpected time-correlated DARK events (4.2V, 10 ms cumulative)



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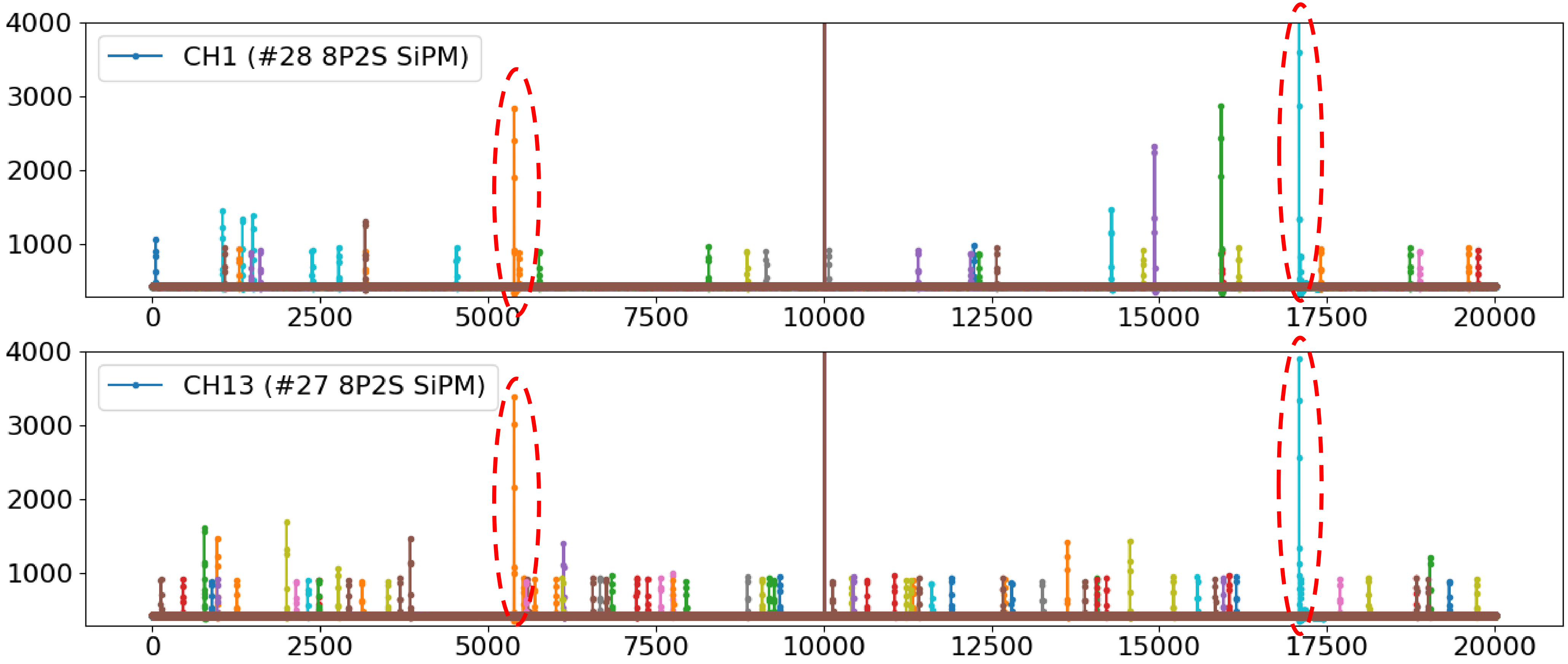
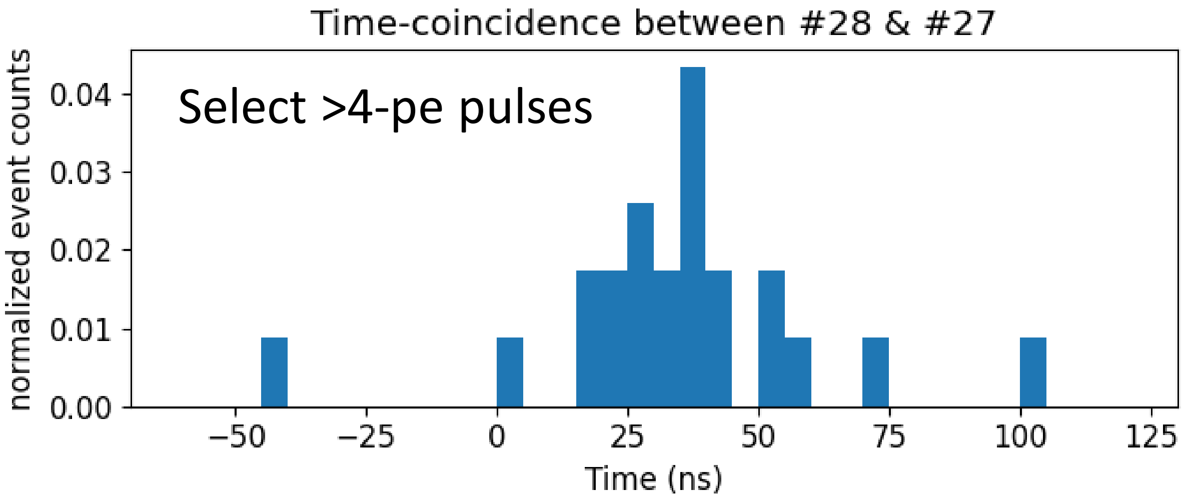
unexpected time-correlated DARK events (4.2V, 10 ms cumulative)



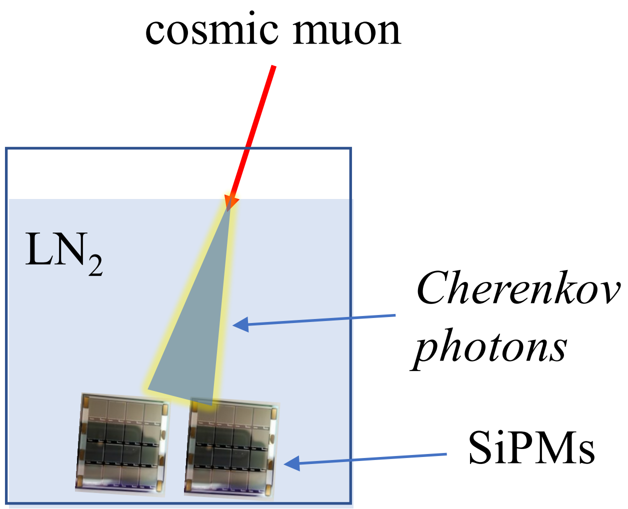
Time tick [0.5µs/tick] total of 10 ms

Hypothesis of time-correlated DARK events: cosmic muon triggered



LN_2 4V	Muon trigger Rate (Hz)	Coinc time (ns) rms
#28	1.3	
#27	1.8	
Coinc.	0.3	**9.2 ns**

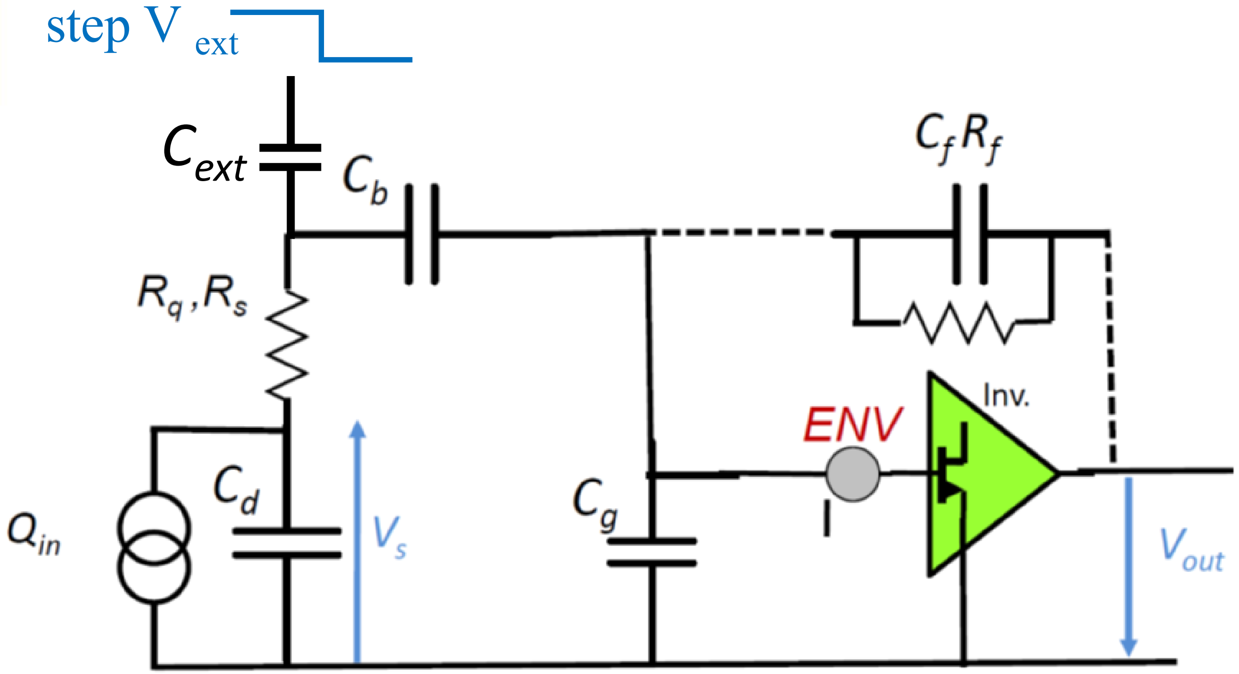
Accidental coincidence = 2 R_{28} R_{27} (0.5 us) = 2.25x10^{-6} << coincidence rate 0.28



1. event rate in Dark ~1 Hz, ~1% of total DCR (~100Hz)
2. We believe intense >n-photoelectron light pulses are triggered by cosmic muon
3. At sea-level, cosmic-muon event rate ~1 muon/cm^2/minute
4. SiPMs tile quartz window, quartz scatter plate, and ~200 cm^3 LN_2 could see ~Hz of Cherenkov light.

SiPM terminal capacitance measurements

Terminal capacitance (C_d) measurement & charge calibration in LArASIC



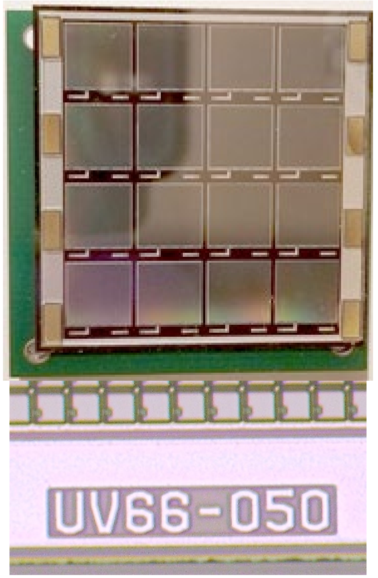
minitile in LArASIC Cd calculation	
gain (mV/fC)	4.7
C b (pF)	500
C int (pF)	0.183
C ext (pF)	1
V int (volt)	0.35
V ext (volt)	0.5
ADC int (ADC)	700
ADC ext (ADC)	to be measured

$$\frac{C_d}{C_b} = \left[\frac{V_{ext}}{V_{int}}\right]\left[\frac{C_{ext}}{C_{int}}\right]\left[\frac{ADC_{int}}{ADC_{ext}}\right] - 1$$

HPK 5.76 cm^2 SiPM tile 8P2S

$C_{terminal}$ (room) ~5.8 nF

$C_{terminal}$ (LN_2) 1.9 nF

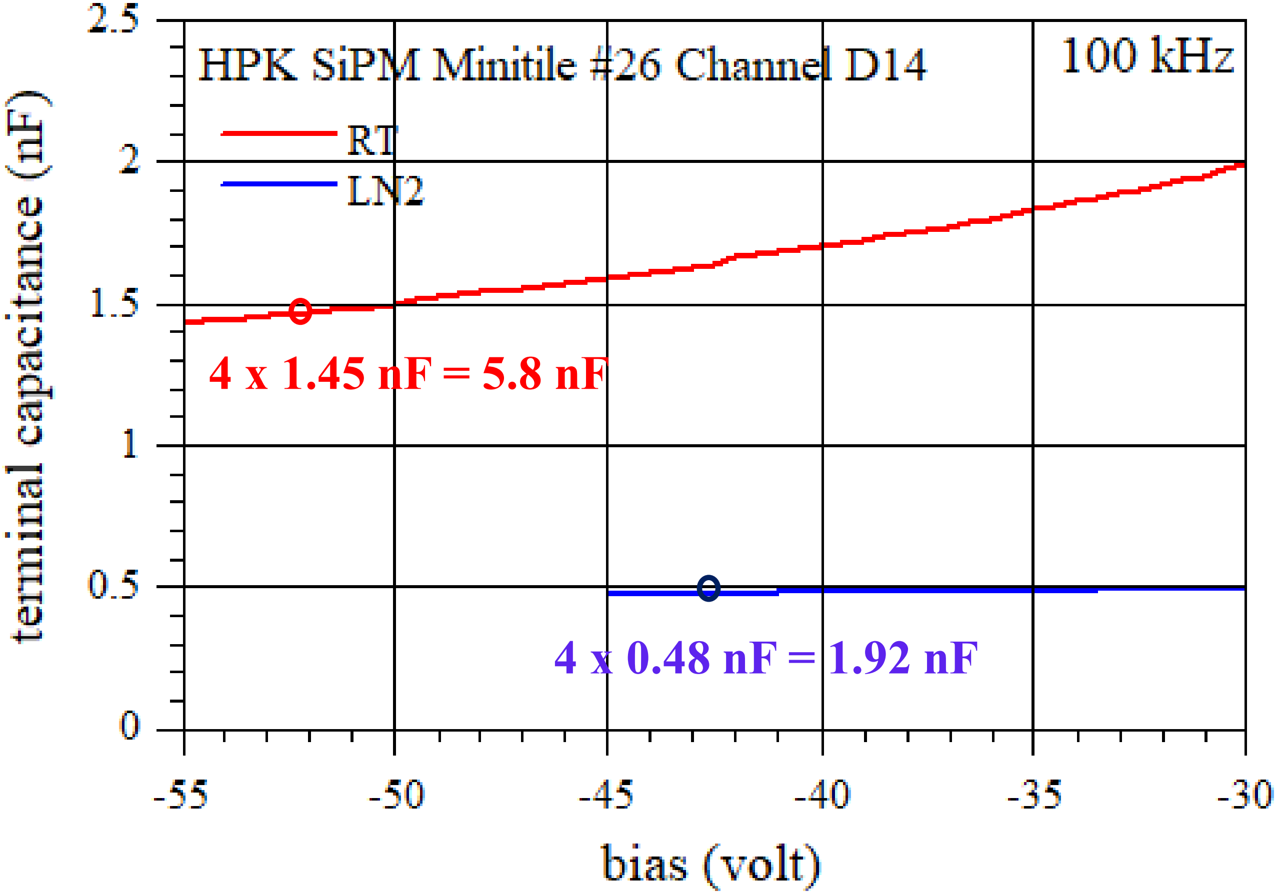


Terminal capacitance (C_d) measurement using LCR bridge

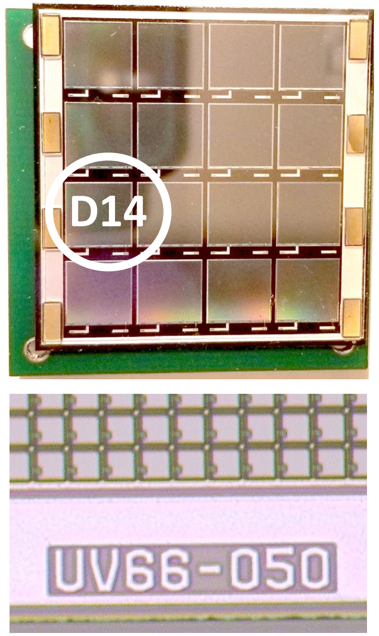
HPK Minitile #26, ***single*** 6x6 mm^2 SiPM ***#D14***

KeySight B1500A
semiconductor device analyzer

Feb 5, 2021, measured on KeySight B1500A



Minitile

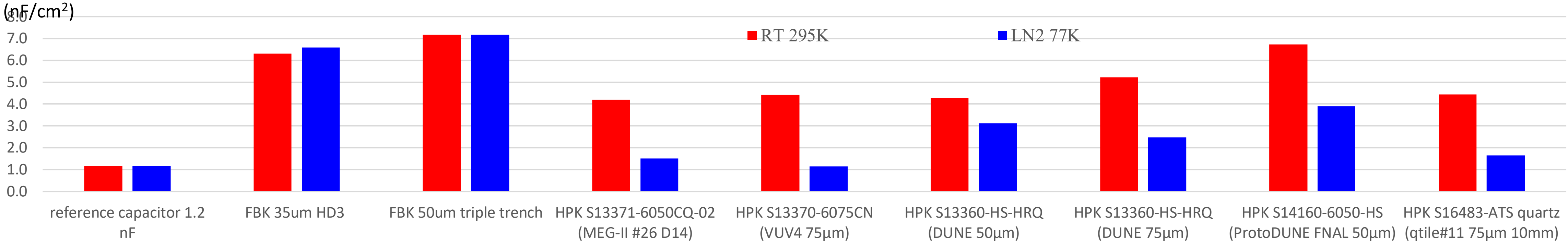


HPK Minitile SiPM terminal capacitance drop by a factor of ~3 from RT to LN$_2$
(but µCell capacitance remain approx. the same)

Terminal capacitance of various SiPMs: RT and LN_2

Terminal capacitance measured by a Cremat bridge	RT			LN2				
	nF	(nF/cm2)		nF	(nF/cm2)		gain/OV	cap.
							x 10^6	(nF/cm2)
reference capacitor 1.2 nF	1.17	1.170		1.17	1.170			
FBK 35um HD3	2.269	6.302		2.370	6.583		0.57	6.47
FBK 50um triple trench	2.578	7.161		2.58	7.167		1.43	7.11
HPK S13371-6050CQ-02 (MEG-II #26 D14)	1.510	4.194		0.540	1.500		0.68	4.22
HPK S13370-6075CN (VUV4 75µm)	1.590	4.417		0.410	1.139			
HPK S13360-HS-HRQ (DUNE 50µm)	1.540	4.278		1.120	3.111		0.666	4.28
HPK S13360-HS-HRQ (DUNE 75µm)	1.880	5.222		0.890	2.472		1.484	4.19
HPK S14160-6050-HS (ProtoDUNE FNAL 50µm)	2.420	6.722		1.400	3.889		1.104	5.50
HPK S16483-ATS quartz (qtile#11 75µm 10mm)	4.430	4.430		1.660	1.660		1.48	4.18

Terminal Capacitance of SiPM at ~0V over-voltage
measurement: Cremat CR111 + 1 µs shaper 0.47 nF decoupling cap.



- HPK SiPM terminal capacitance drops significantly from RT to LN_2 → higher S/N ratio
- µCell capacitance remain approx. the same → same charge gain
- Lowering of HPK's SiPM terminal capacitance in LN_2 have much benefit in photon readout: s/n improvement, lower total readout channels, lower overall detector cost …

But we have yet to understand this phenomenon