Broadcom SiPM AFBR-S4N66P024M (2x10)

<u>one single element</u>

6x6 mm^2/each

Total: 0.36 cm^2

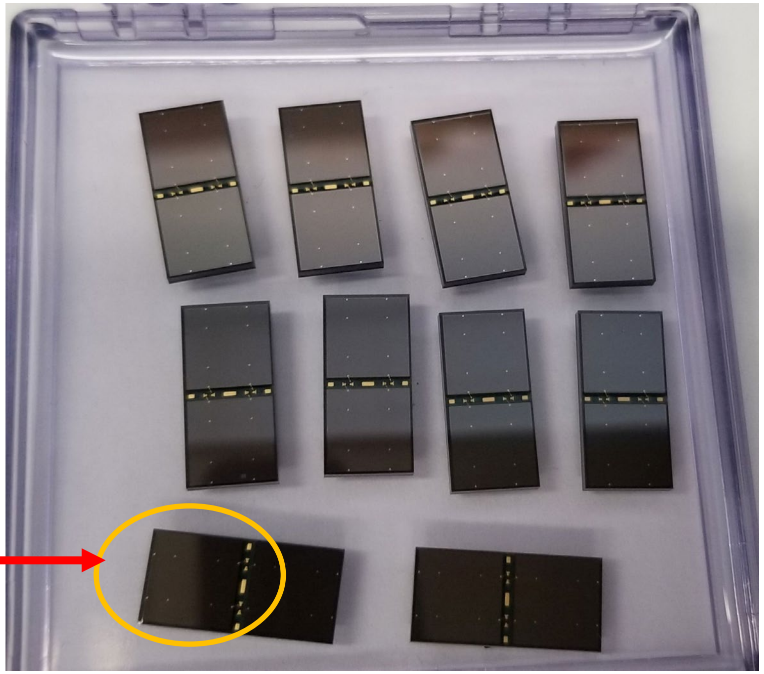
N_{cell}=22428

$C_{terminal}$	RT	LN_2
per element	~2.91 nF	~2.98 nF
per cm^2	~8.1 nF/cm^2	~8.3 nF/cm^2

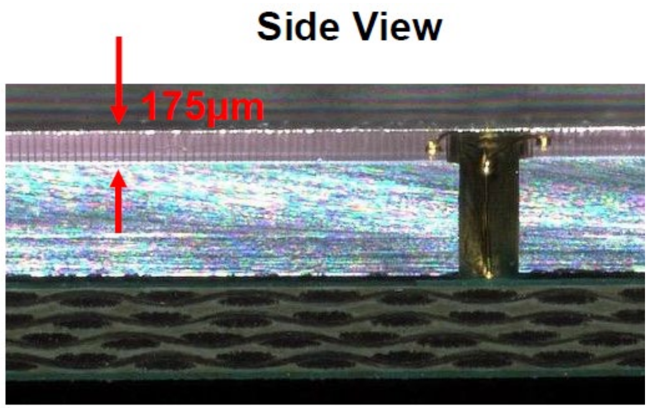
$C_{terminal}$ slightly larger in cold !

when connected in 8P2S

$C_{terminal}$ ~ 12 nF (5.76 cm^2)

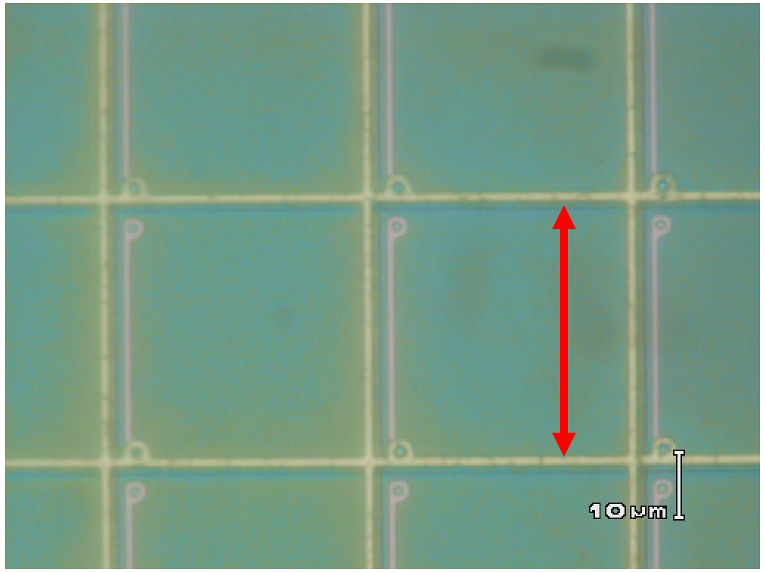


epoxy resin window: 175 µm thick



BROADCOM

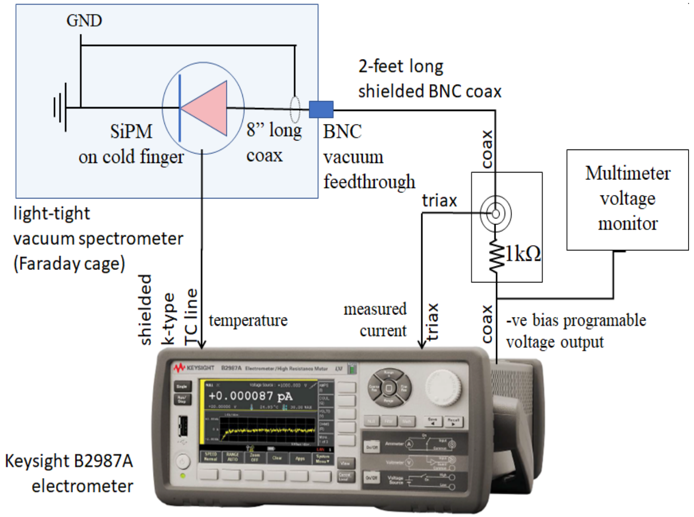
Claudio Piemonte 2023 IEEE

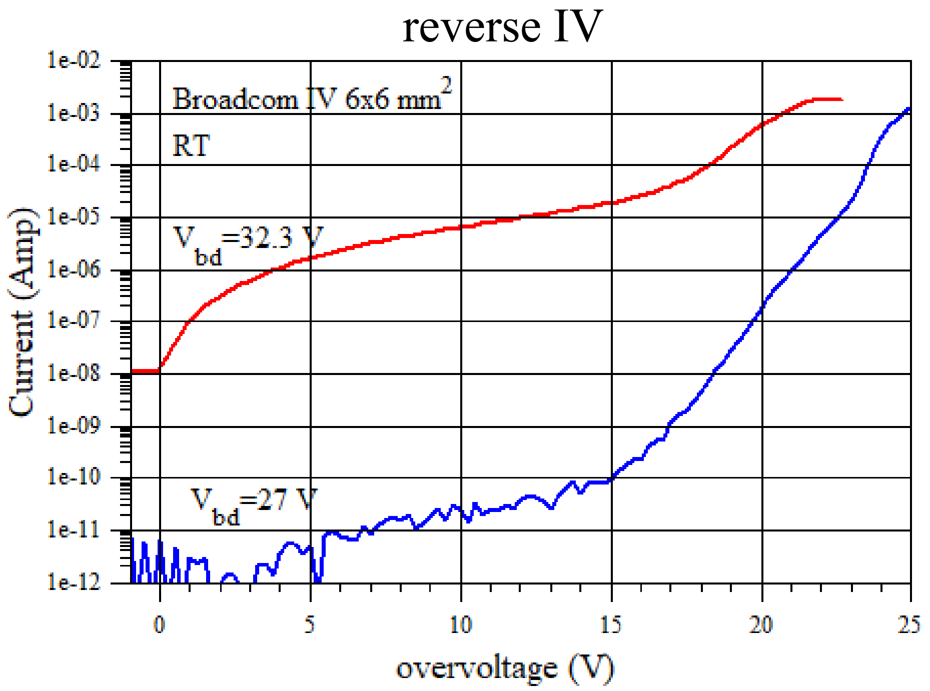


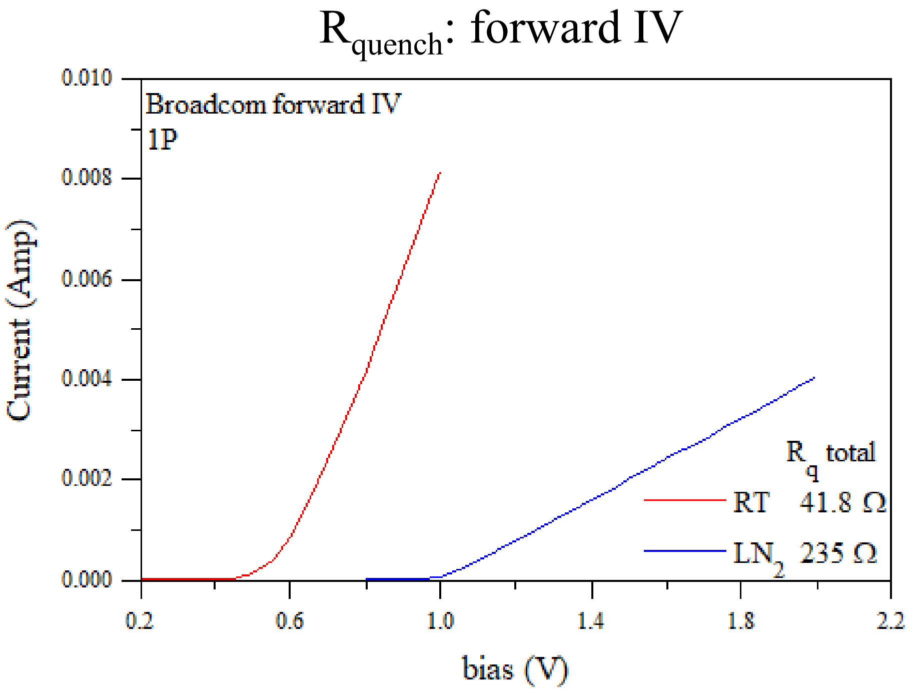
pixel size: 40 µm

IV measurement

Broadcom 6x6 mm^2





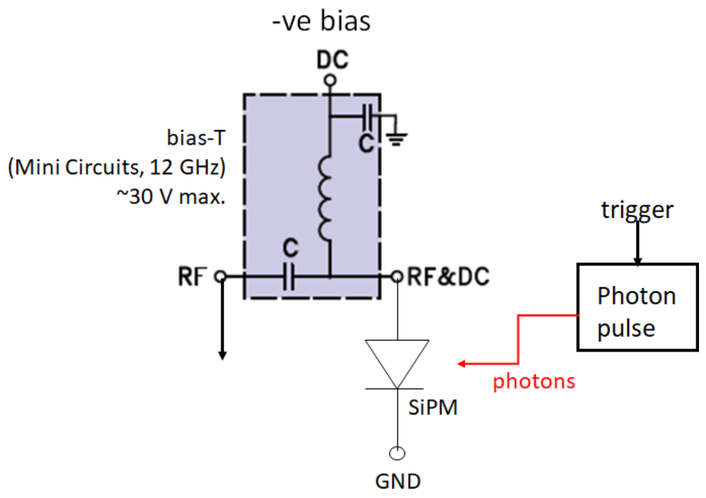


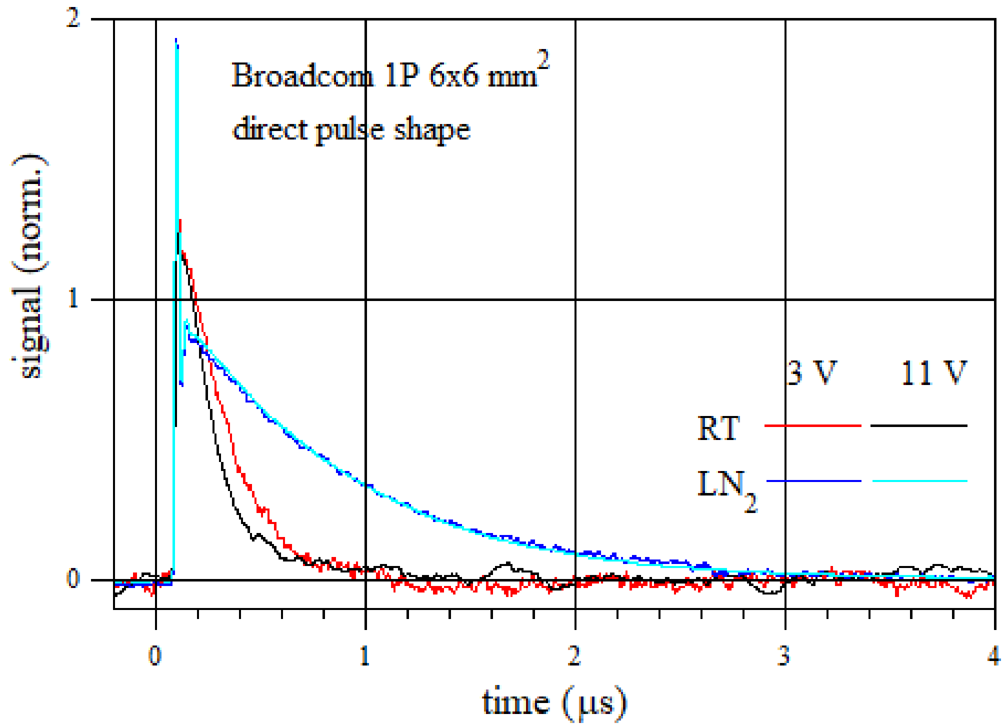
Broadcom 6x6 mm^2	RT	LN_2
$V_{breakdown}$	32.3 V	27 V
R_{quench}	41.8 Ω	235 Ω

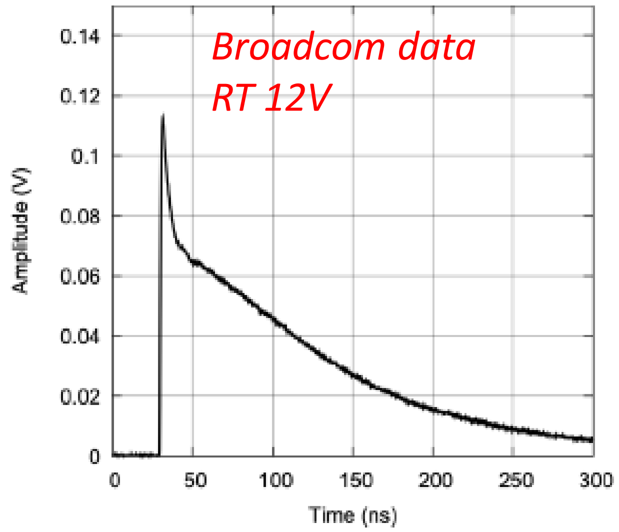
R_{quench} is larger in LN_2 (3 µs shaper is used)

Direct pulse shape: 1-pe

Broadcom 6x6 mm^2





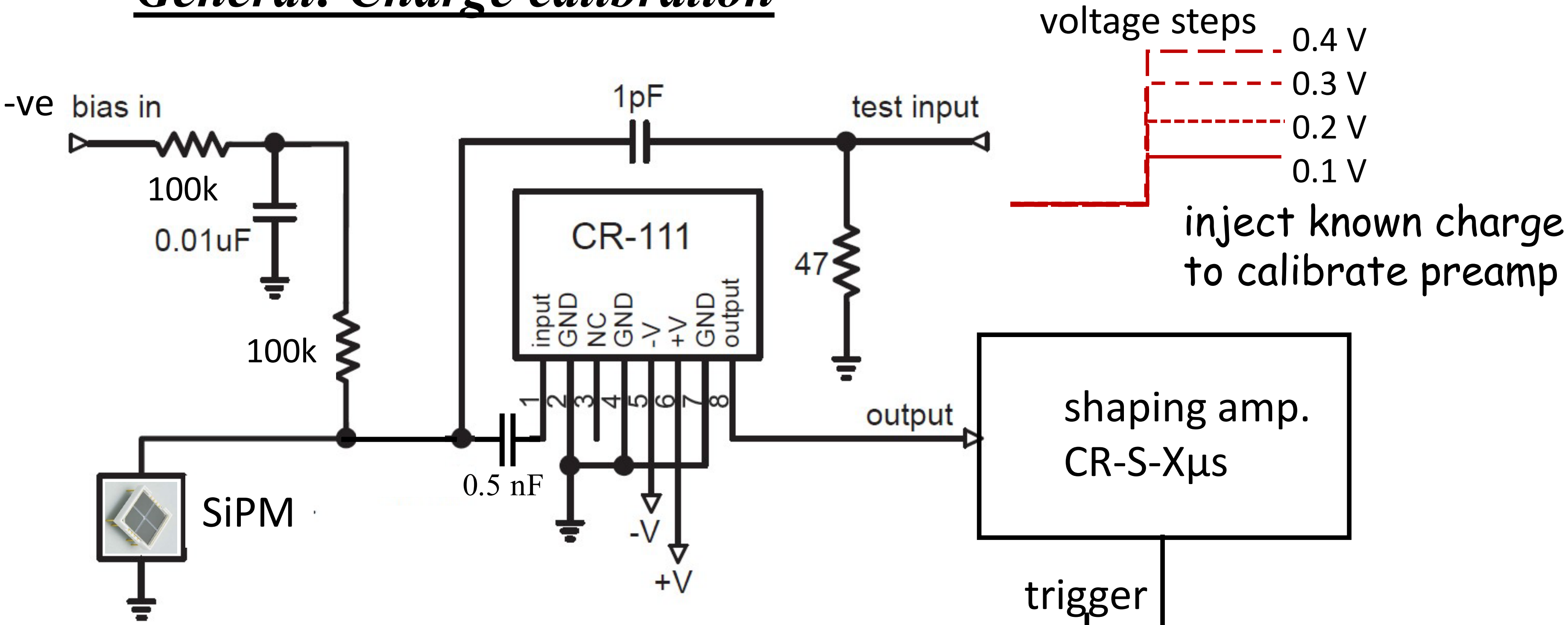


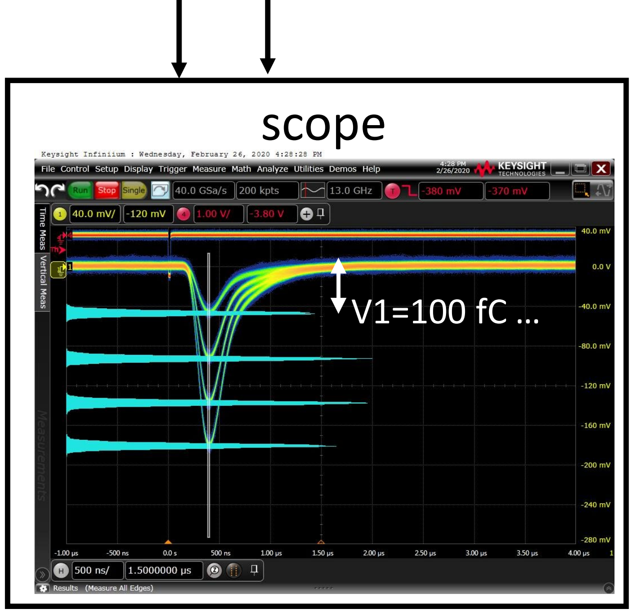
photoelectron charge = $\int V dt$, incomplete charge collection if not fully integrated

RT: fall time shorter at higher OV

LN_2 : fall time independent of OV

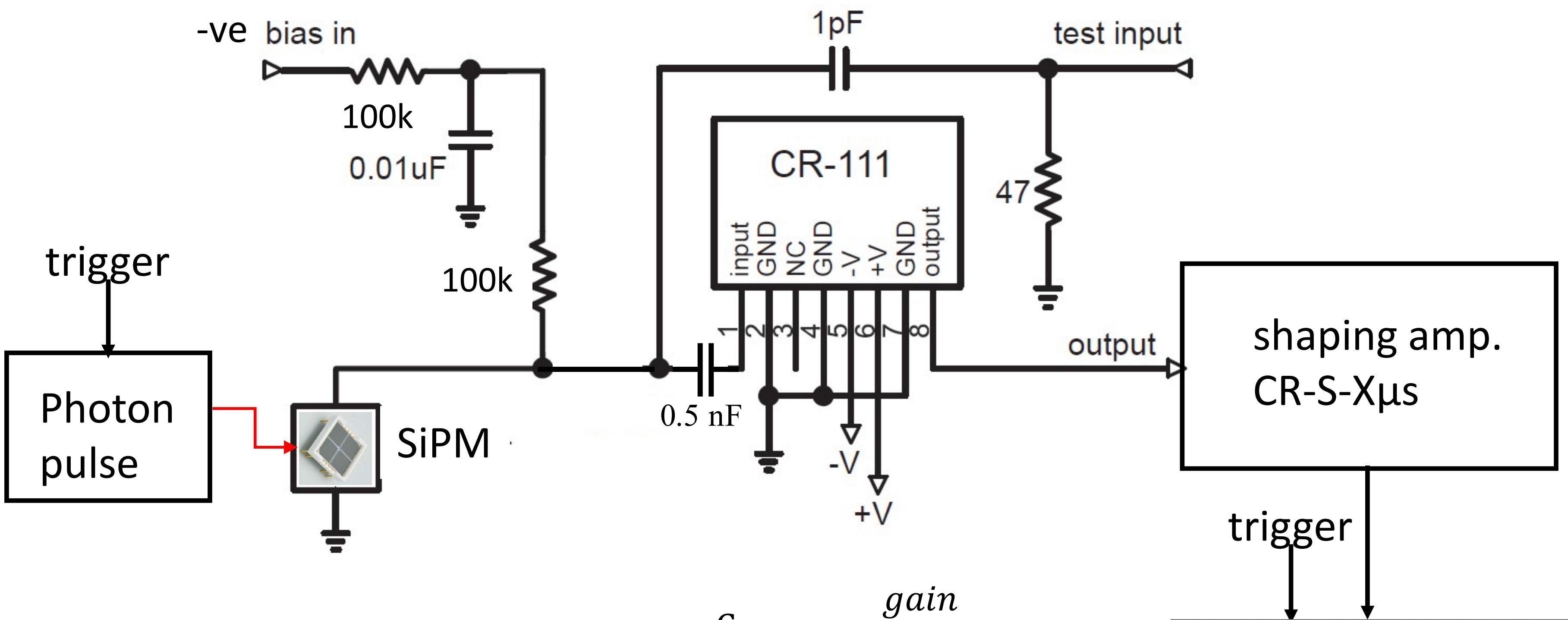
General: Charge calibration





SiPM connected and biased

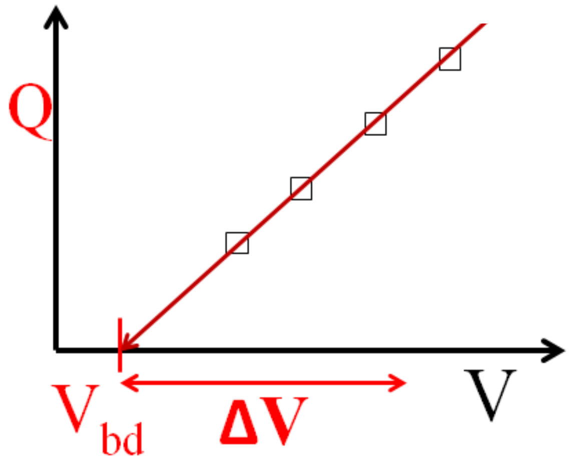
General: SiPM charge gain measurement – (zero charge gain method)

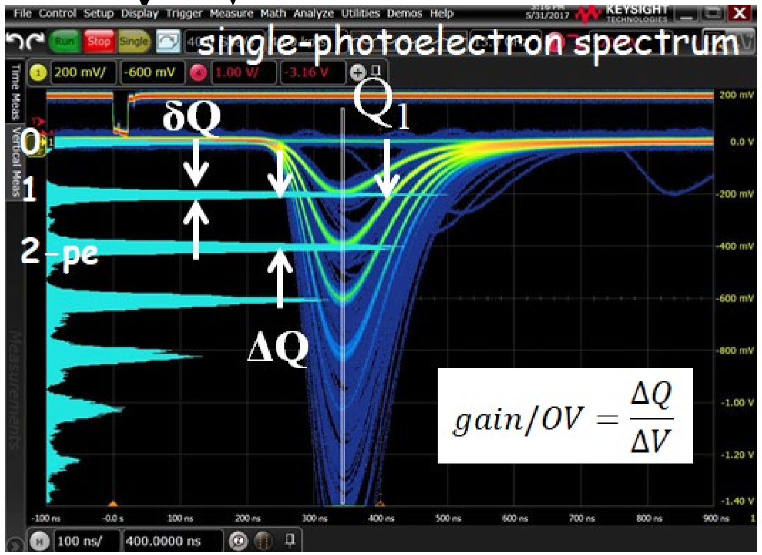


- gain measured from well resolved photoelectron peaks

- breakdown voltage linearly extrapolated

$$C_{\mu cell} = \frac{gain}{(V - V_{bd})}e$$

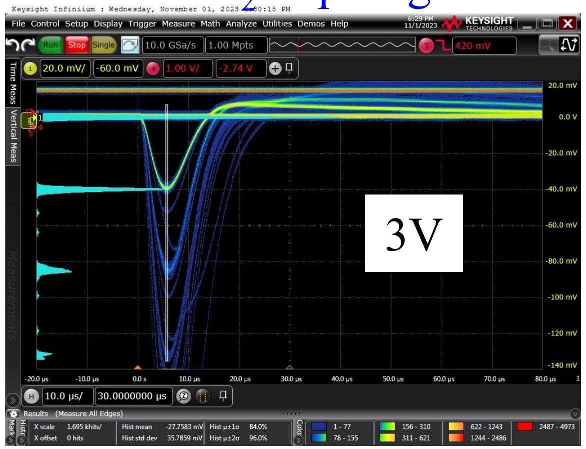


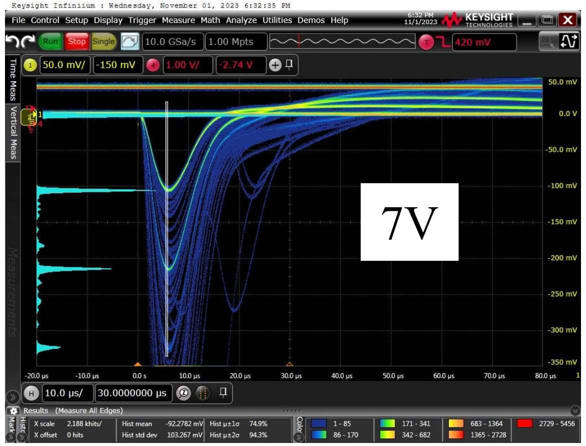


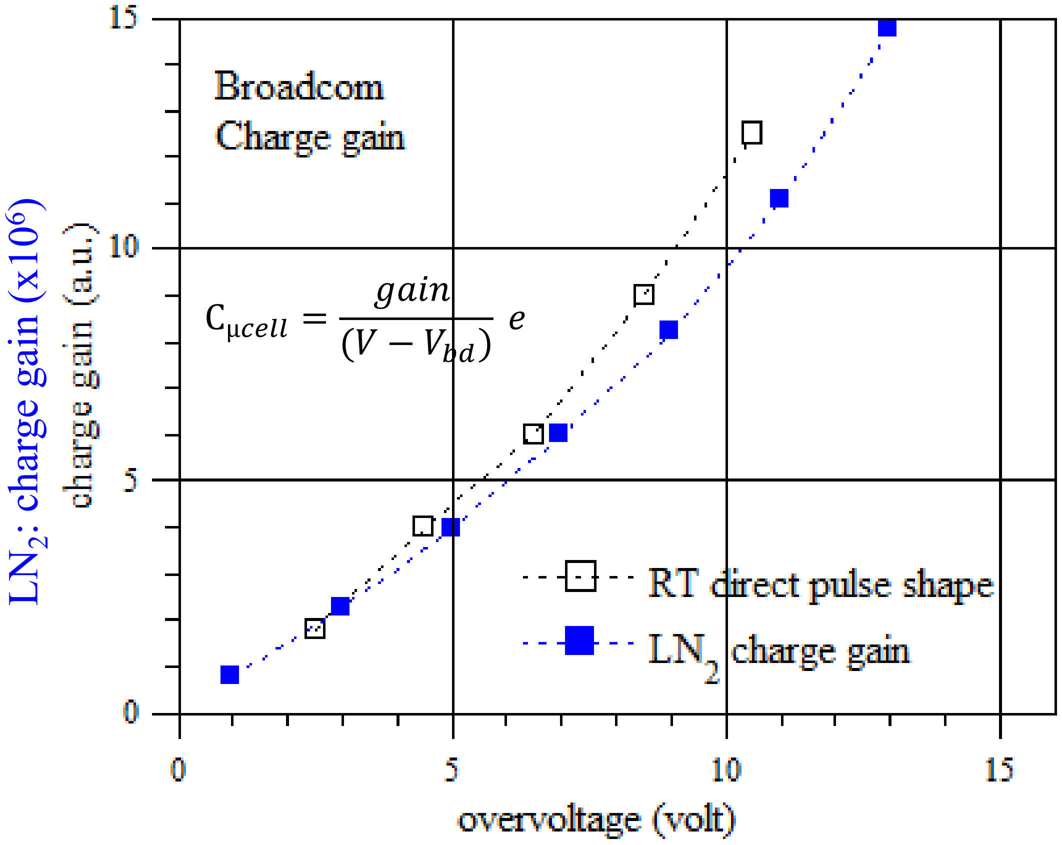
1-pe charge gain

Broadcom 6x6 mm^2

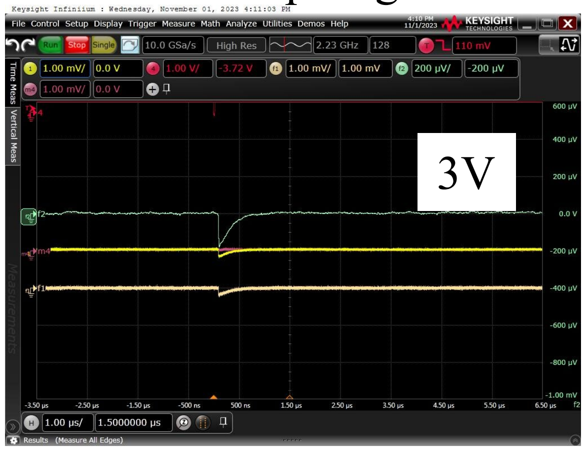
LN_2 :1-pe signal

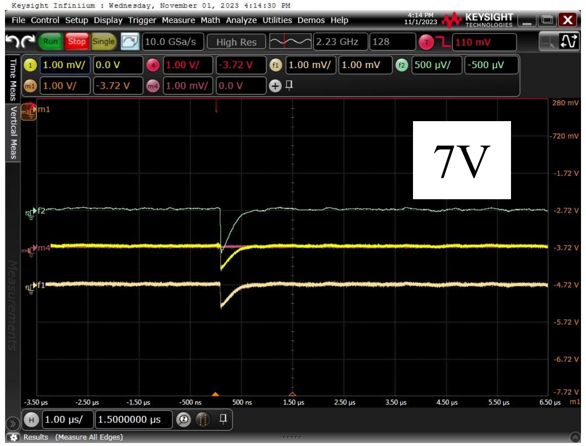






RT: n-pe signal





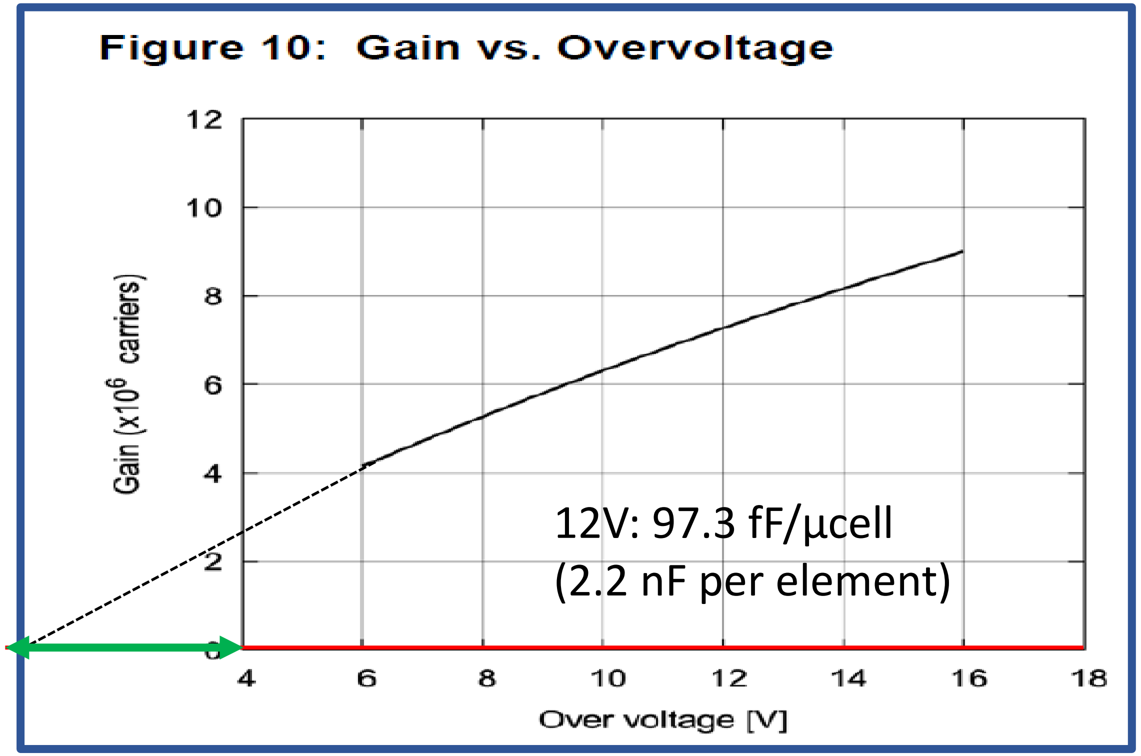
~0.77 x10^6/OV at 5V

~128 fF/µcell @ 5V (~2.8 nF per element)

charge gain appears slightly nonlinear

Broadcom 1-pe gain data (room temperature)

doesn't appear to cross at 0V



doesn't appear to cross at 0V

CT, correlated noise, DCR, PDE …

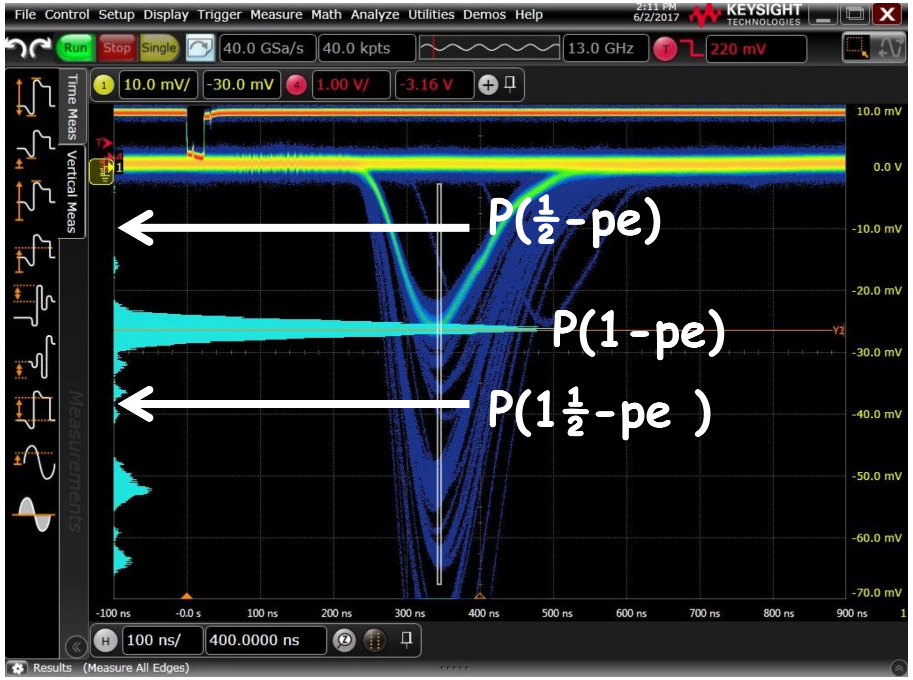
1. Charge gain and correlated noise are determined from single-photon pulse measurements by attenuating a 50kHz repetition rate 405 nm photon source to <0.04 photons/pulse.
2. Correlated noise factor CT & AP, are determined from count rate P(1½-pe)/P(½-pe) and P(½-pe, delayed with 1 to 10 μs gate window)/P(½-pe), respectively.
3. PDE is obtained by fitting a Poisson distribution to the photoelectron spectrum, against the incidence # of photons.

General: time-correlated crosstalk (CT)

SR400 time-gated photon counter (gate width 50 ns)

Attenuate to « 1-photon/pulse
Determine 1-pe signal level
Measure count rate at ½-pe & 1½-pe levels

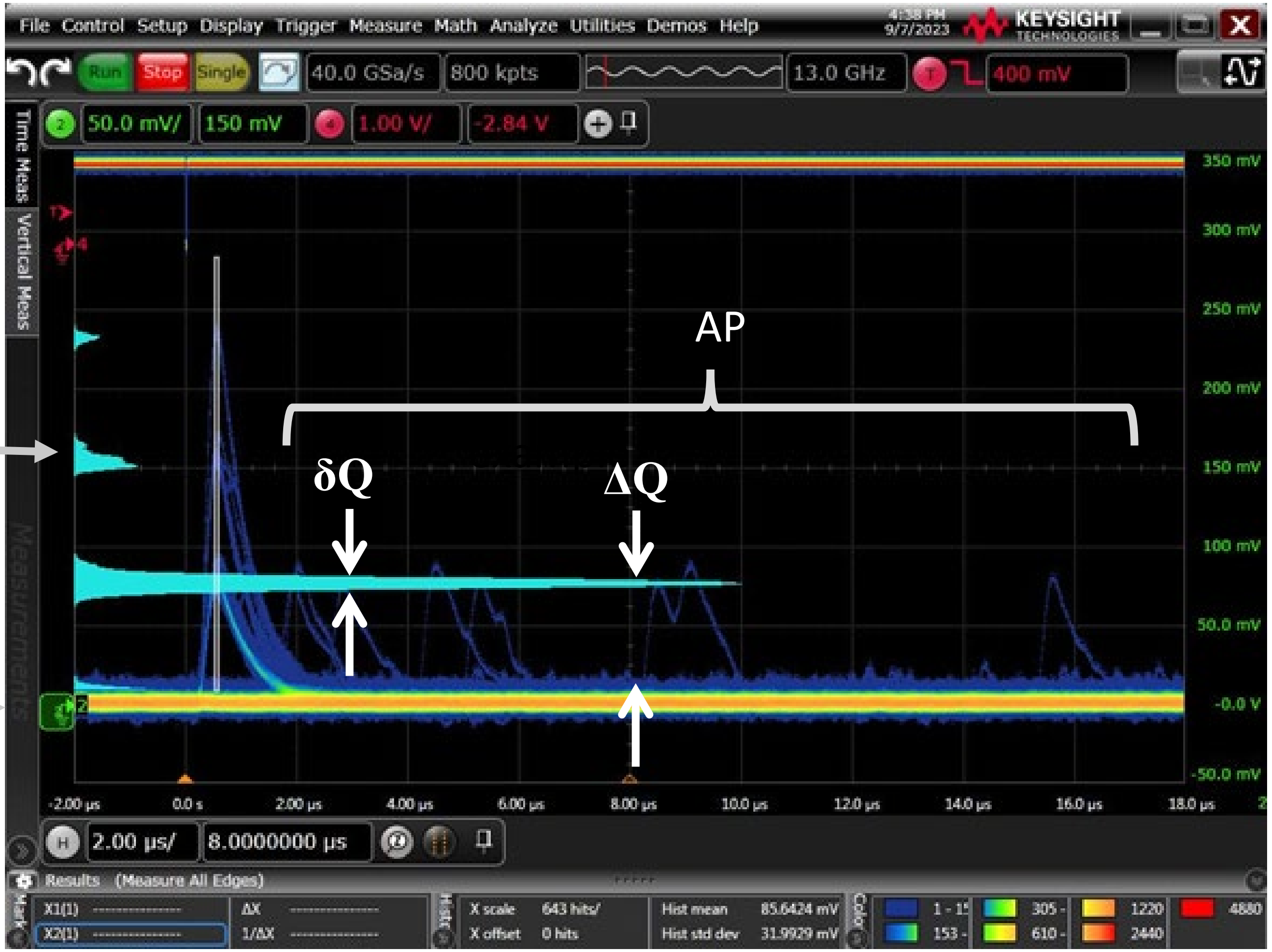
$$\text{crosstalk} = \frac{\text{count rate } {}^{3}\!/_{2}\text{-pe}}{\text{count rate } {}^{1}\!/_{2}\text{-pe}}$$



General: time-correlated afterpulse (AP) etc ...

SR400 time-gated photon counter (gate width 1 to 18 μs)

$$CT = \frac{P(1½\text{–pe})}{P((½\text{–pe})}$$



$$1pe\ resolution = \frac{\delta Q}{\Delta Q}$$

P(0): electronic noise

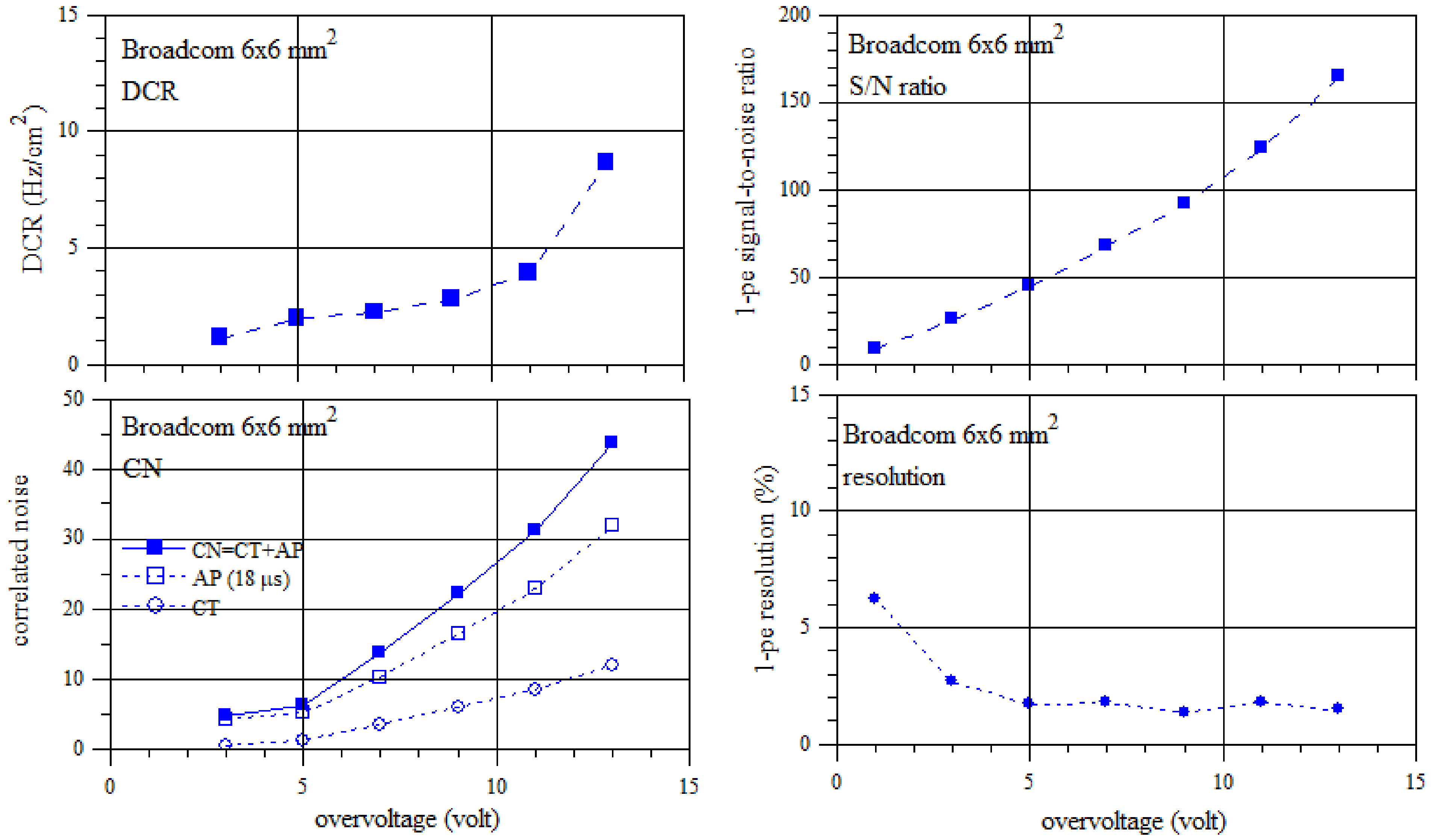
$\delta P(0\ )$~14 fC

$$S/N = \frac{\Delta Q}{\delta P(0)}$$

$$AP = \frac{count\ rate\ [P(½\text{–pe}, delayed\ gate\ \Delta T\ [\sim 1\ to\ 18\ \mu s])}{1pe\ count\ rate\ [P((½\text{–pe})]}$$

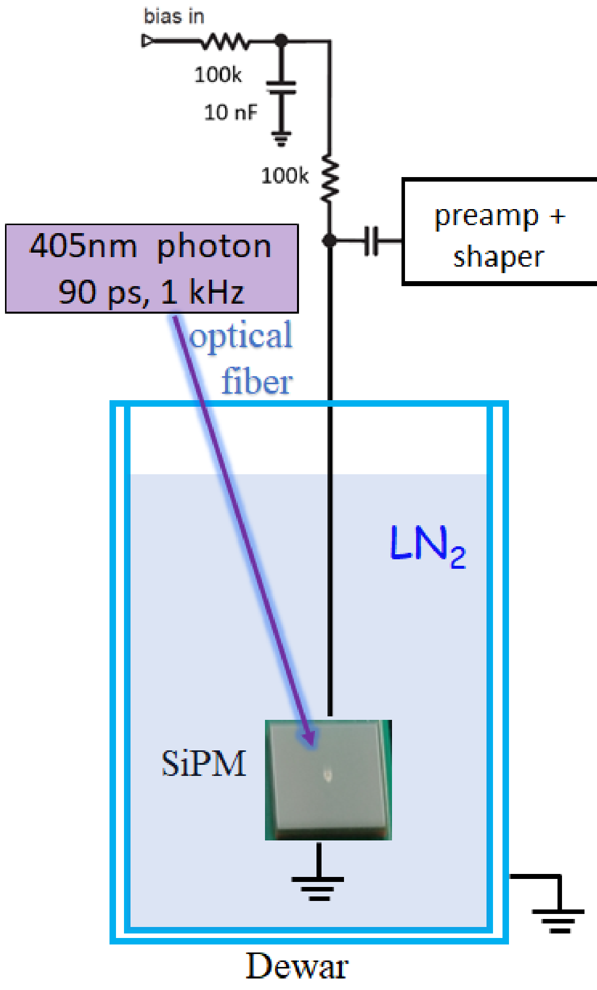
Broadcom 6x6 mm^2

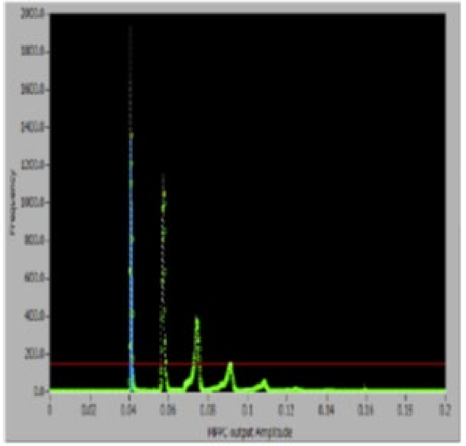
LN_2 :1-pe signal



- DCR & 1-pe resolution are sufficiently low
- CN < 15%, S/N ~70 below 7V,

PDE is calculated by fitting a Poisson distribution to the photoelectron spectrum





- $P(n, x) = \frac{n^x e^{-n}}{x!}$

- $P(n, 0) = \frac{\left(\frac{N_{ped}}{N_{tot}}\right)}{\left(\frac{N_{ped}^{dark}}{N_{tot}^{dark}}\right)}$ (<- dark pulse correction)

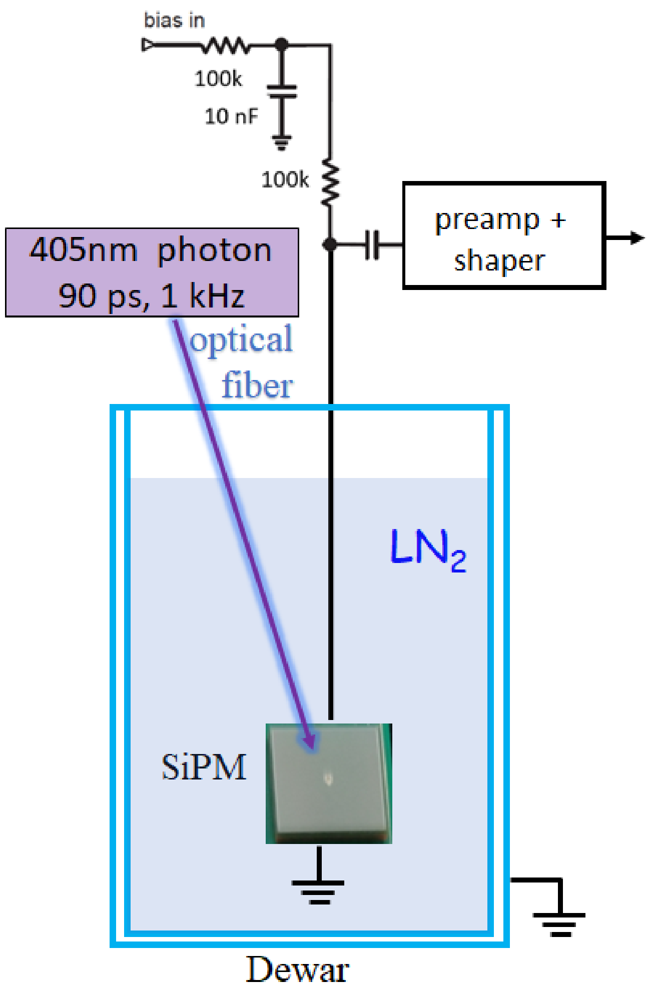
$$n = -\ln\left(\frac{\frac{N_{ped}}{N_{tot}}}{\frac{N_{ped}^{dark}}{N_{tot}^{dark}}}\right) = -\ln\left(\frac{N_{ped}}{N_{tot}}\right) + \ln\left(\frac{N_{ped}^{dark}}{N_{tot}^{dark}}\right)$$

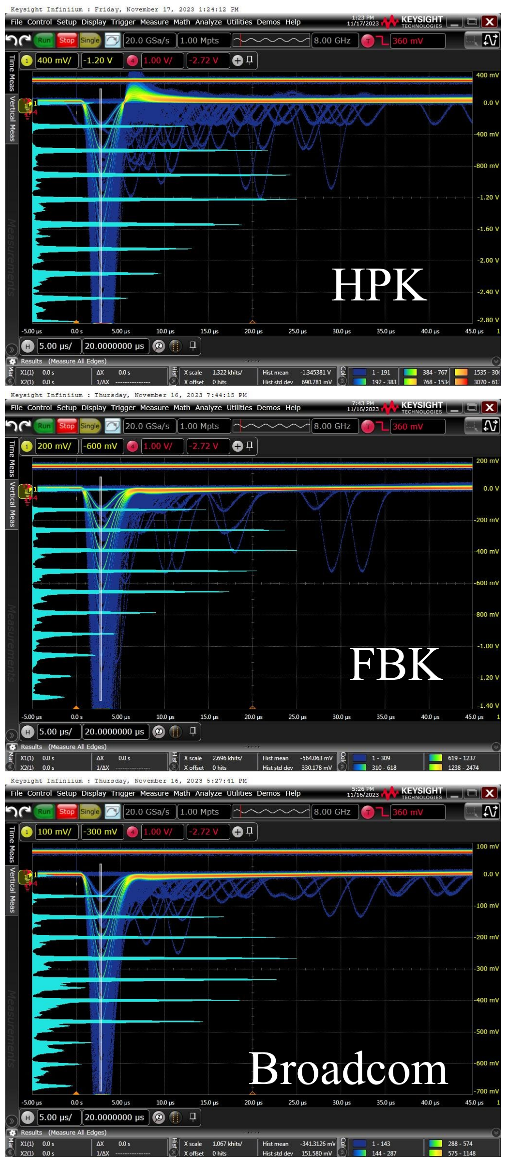
n: average number of photons detected by MPPC
x: number of photons detected by MPPC

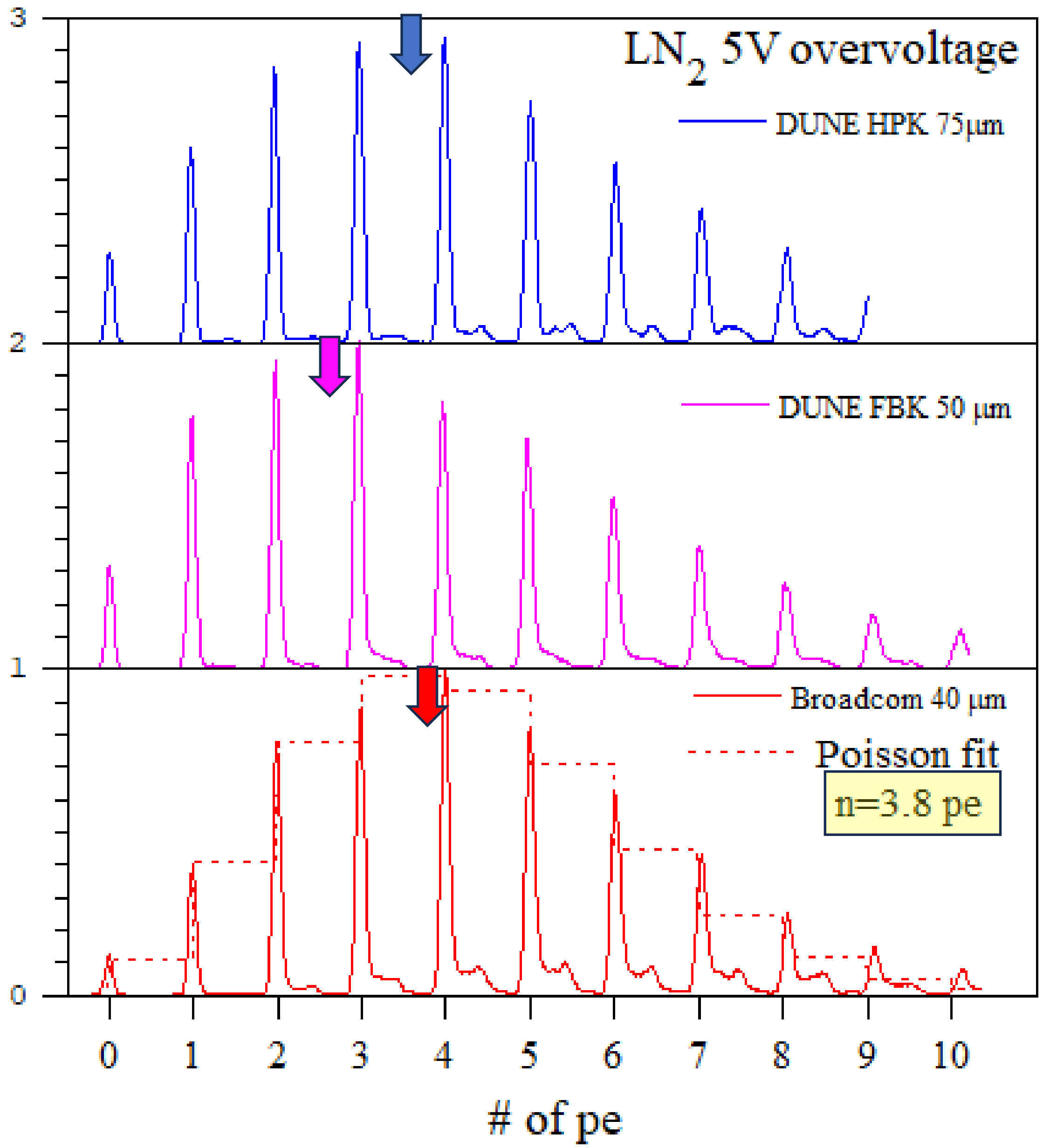
N_{ped} : number of events at 0 p.e. during pulsed light measurement
N_{tot} : number of all events during pulsed light measurement
N_{ped}^{dark} : number of events at 0 p.e. in dark state
N_{tot}^{dark} : number of all events in dark state

n = Poisson fitted mean number of photoelectrons

relative PDE in LN_2 (Broadcom, DUNE FBK, DUNE HPK)







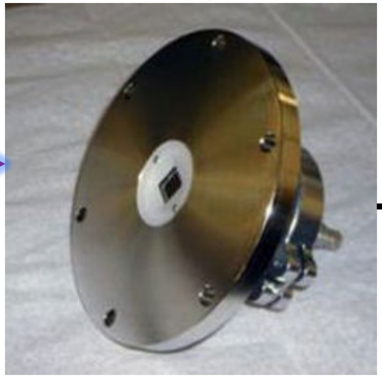
Number of incidence photons is determined from the measured photocurrent at the selected wavelength from a NIST calibrated photodiode

attenuate the intensity to a few photons/pulse

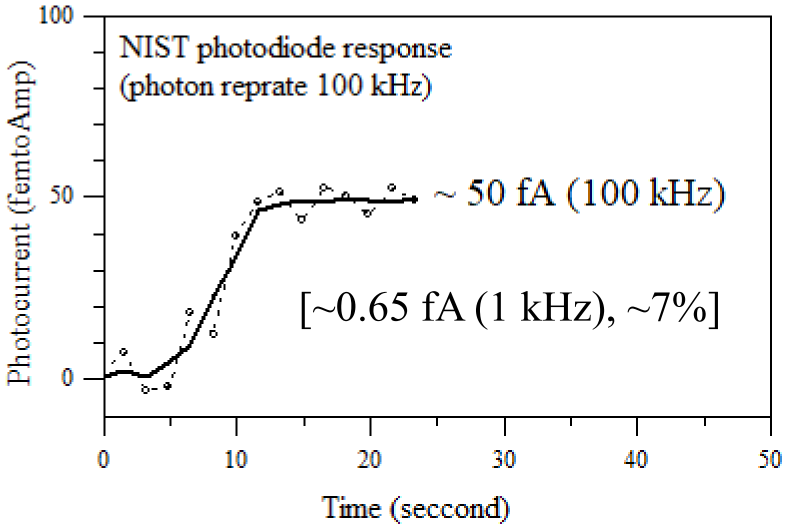
405nm photon
90 ps, 100 kHz

optical fibers

NIST calibrated pd
(0.19 A/W @ 405nm)



Electrometer
(average photocurrent)



$$\# \; of \; 405 \; nm \; photons = \frac{0.65 \; fA}{(1 \; kHz)\left(0.19\frac{A}{W}\right)(1.6x10^{-19} J/eV) \; (3.06 \; eV)} (0.86) =$$ 6.01 photons/pulse

PDE in LN_2 (Broadcom, DUNE FBK, DUNE HPK)

$$PDE = \frac{\#\,pe}{\#\,h\nu} = F_{geometry} \times QE_{e-p}(\lambda, T) \times \varepsilon_{avalanche}(\Delta V, \lambda, T)$$

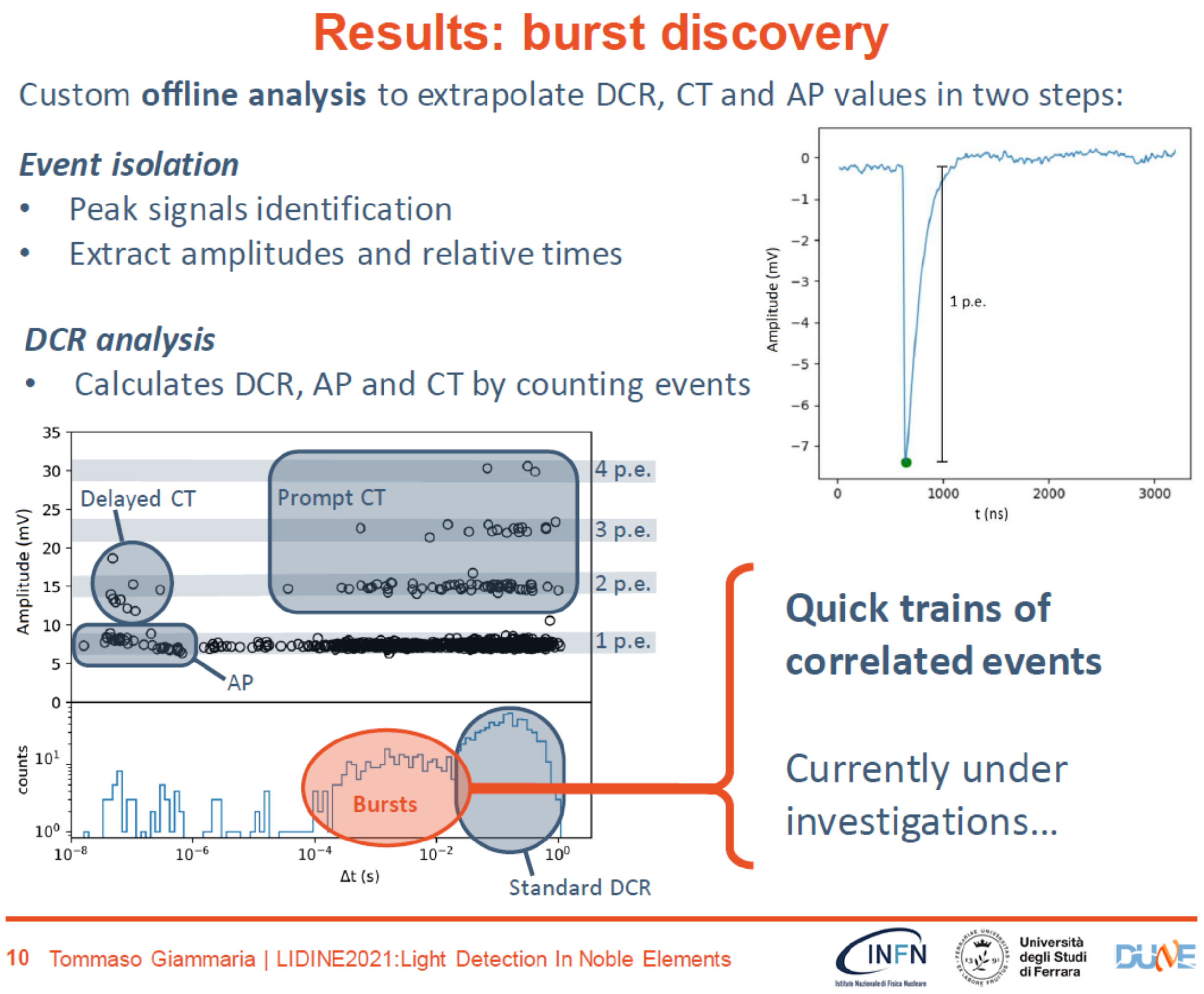
geometric — photon — photoelectron

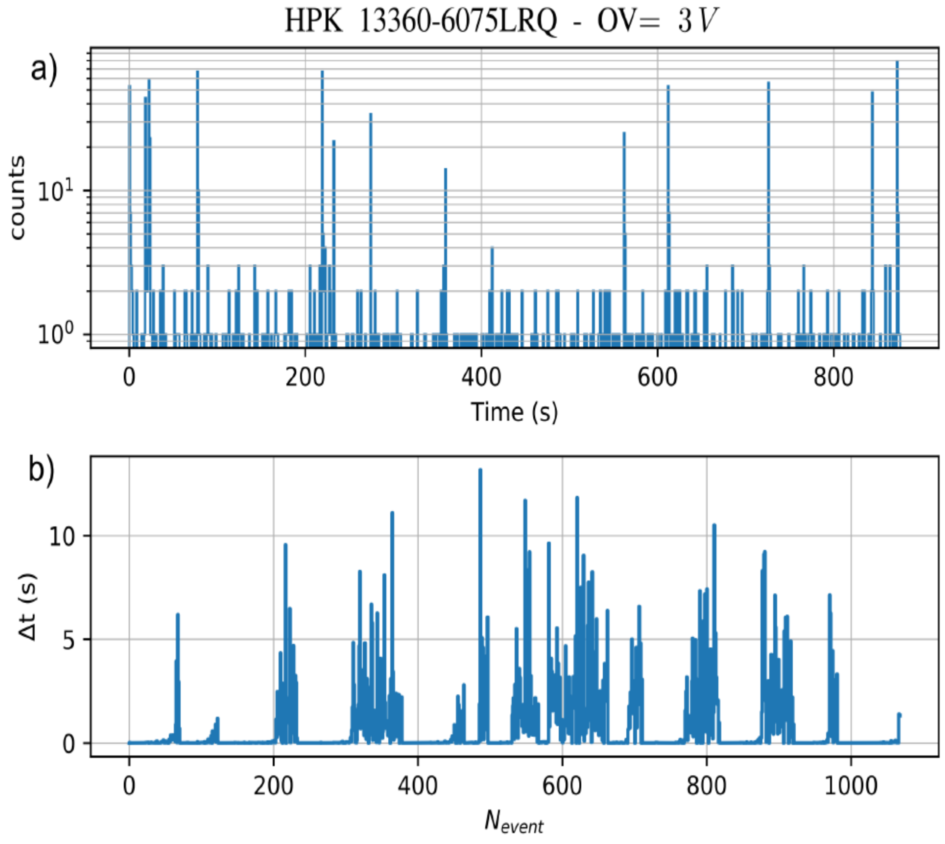
$$PDE\,(Broadcom, 405\,nm, 5V, LN_2) = \frac{\#\,photoelectrons\ out}{\#\,photons\ in} = \frac{3.8}{6.01} = 0.63$$

PDE @ 405 nm 5V OV in LN2	Poisson fitted n-pe	absolute PDE (±7%)	Spec. RT
DUNE HPK 75 µm	3.15	0.52	~0.47
DUNE FBK 50 µm	2.93	0.48	n/c
Broadcom 40 µm	3.8	0.63	~0.62

event burst phenomenon

recent observation of event burst phenomenon: *DUNE & DarkSide*

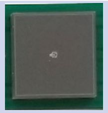
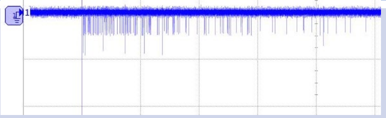
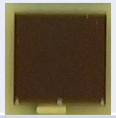
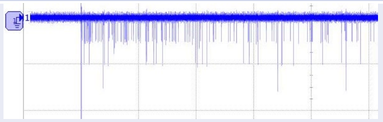
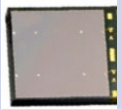
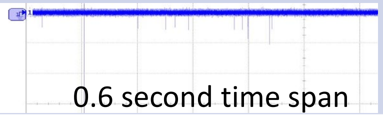




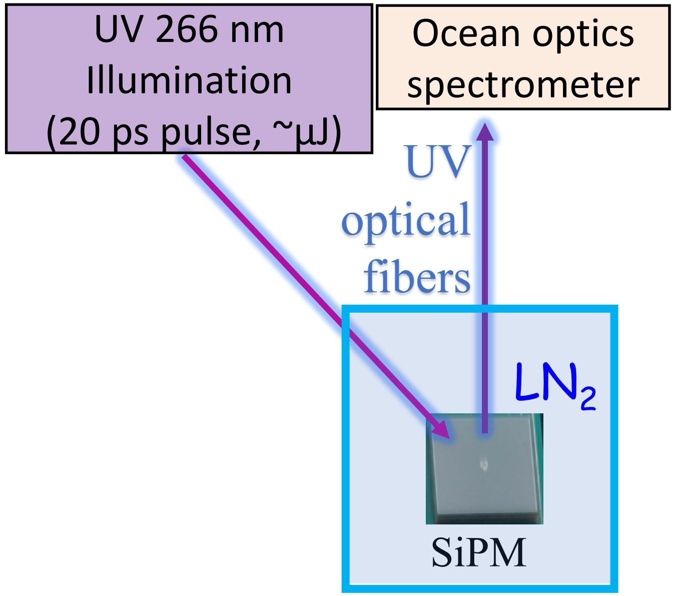
M. Spanu, '*Summary of SiPM tests and comparison*,' DUNE Collaboration Meeting, Jan 26, 2021.
M. Guarise et al, '*A newly observed phenomenon in the characterisation of SiPM at cryogenic temperature*,' JINST 16 T10006, 2021.

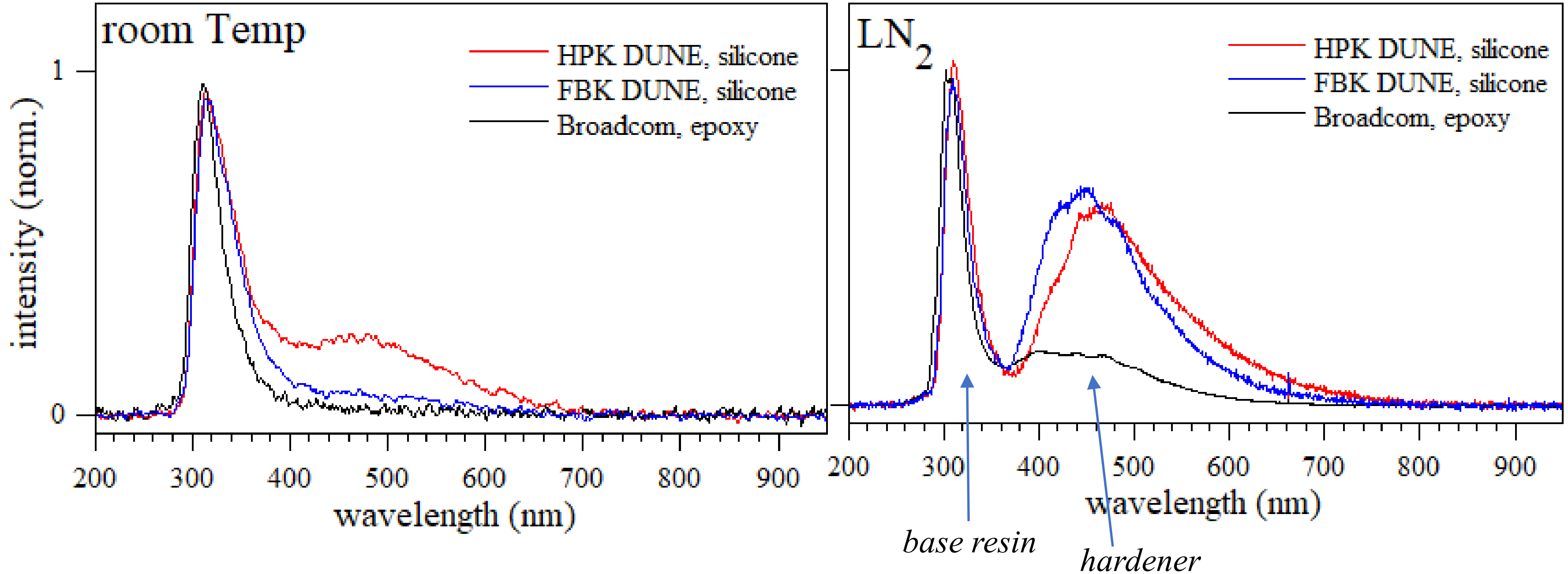
Francesco Terranova: additional studies with new prototypes SiPMs are in progress within the DUNE PDS Consortium.

event burst phenomenon observed at BNL (SiPMs in LN_2 in completed darkness) *LIDINE2022*

#	Vendor & Model	device	pixel	substrate	connect.	window	spectral resp.	Burst, events/30 minutes	
1	HPK S13360-HS-HRQ (DUNE)		75 µm	PCB	hole wire bond	silicone resin, 150 µm	280 - 900 nm	Yes, 5	
2	FBK triple trench (DUNE)		50 µm	PCB	wire bond	silicone resin, xx µm	~300 to 900 nm	Yes, 10	
3	Broadcom		40 µm	PCB	wire bond	epoxy resin 175 µm	~300 to 900 nm	No or low	

photoluminescence of SiPMs at room temperature and in liquid nitrogen.





Broadcom SiPM

PROs:

- PDE is slightly higher than DUNE FBK or DUNE HPK
- No event burst is observed – no afterglow

CONs:

- DCR in LN_2 is slightly higher but well manageable
- Correlated noise (CT & AP) is slightly higher
- Charge gain appears nonlinear with overvoltage
- Terminal capacitance is high at room or in LN_2

Readout of Broadcom 4x4 SiPM connected in 8P2S (5.76 cm^2)

Broadcom 4x4 SiPM connected in 8P2S (5.76 cm^2)

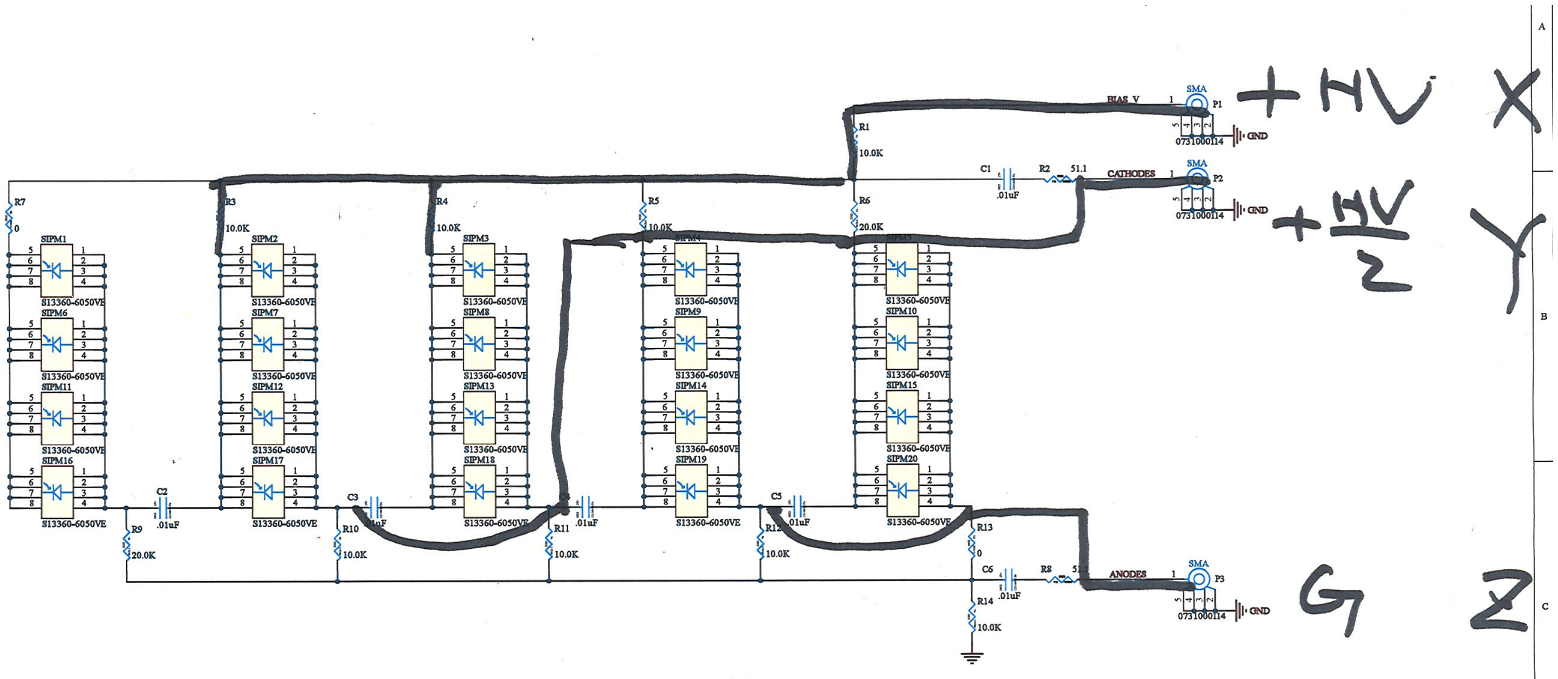
<u>8P2S: 16 SiPMs</u>

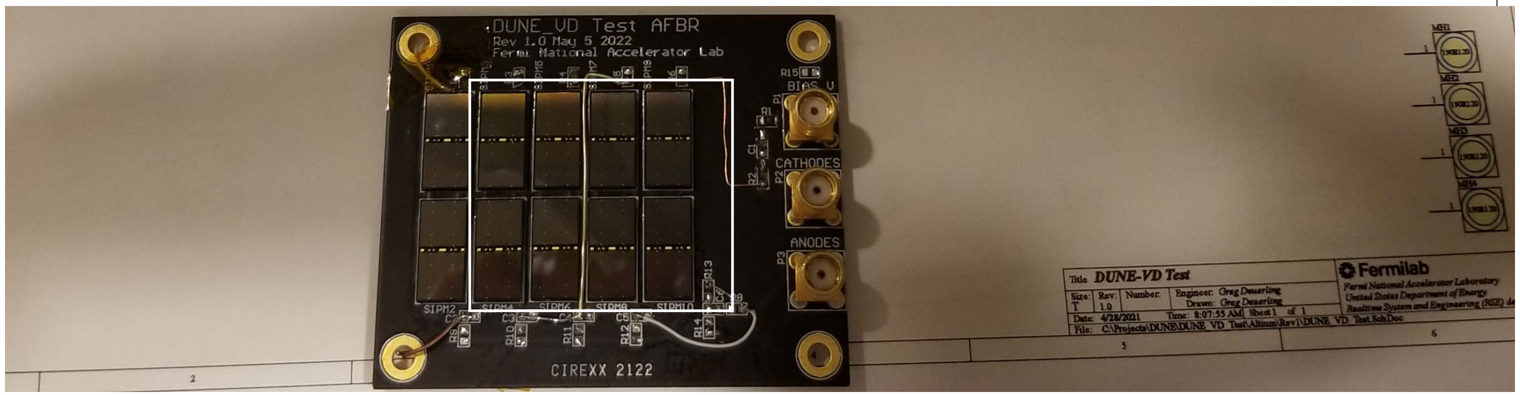
6x6 mm^2/each

Total: 5.**76 cm^2**

$C_{terminal}$	RT	LN_2
total	~11.4 nF	~12.8 nF

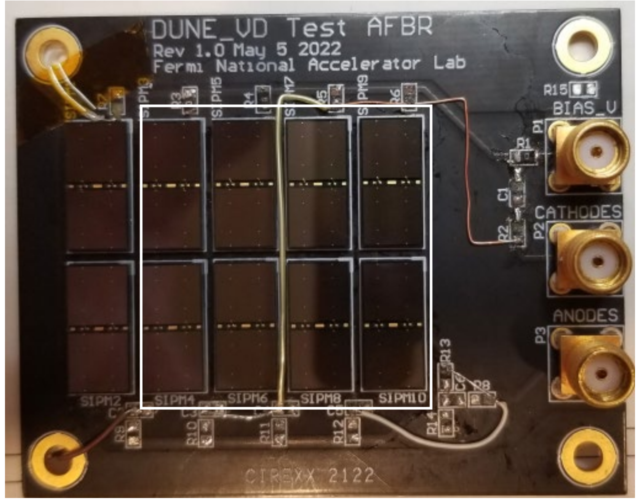
$C_{terminal}$ larger in cold

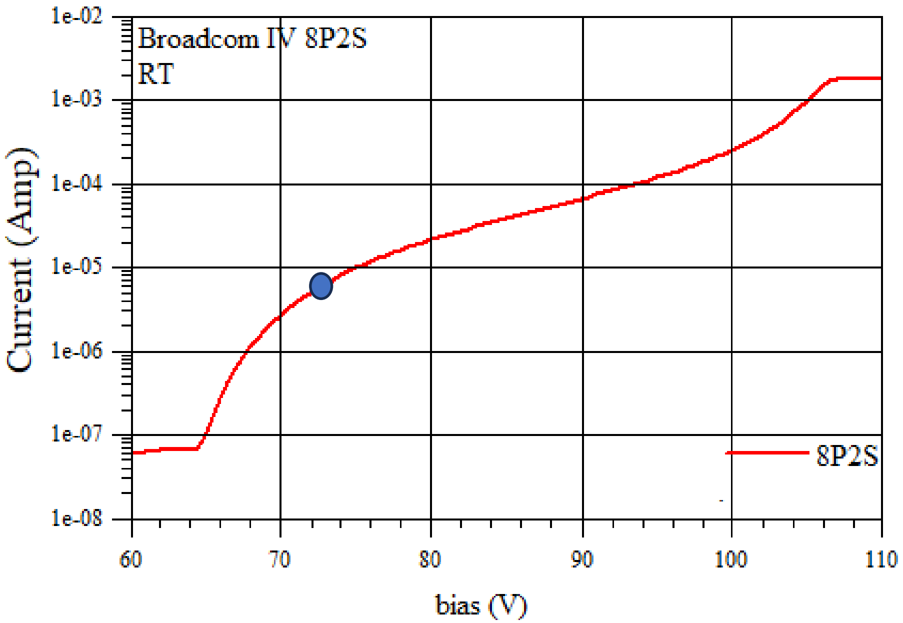


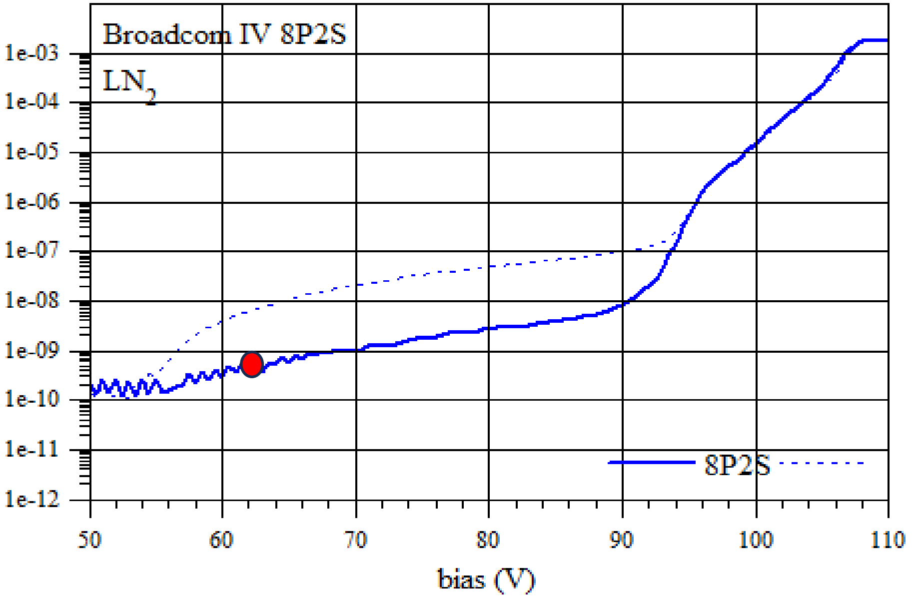


16 SiPMs connected in 8P2S (5.76 cm^2)

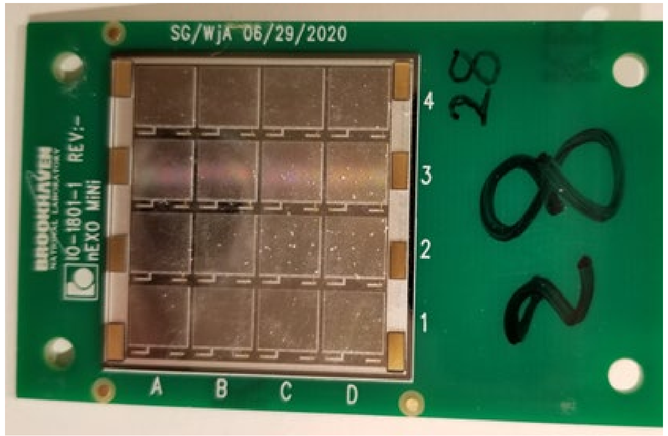
Broadcom AFBR-S4N66P024M
~11.4 nF (RT), ~12.8 nF (LN_2)

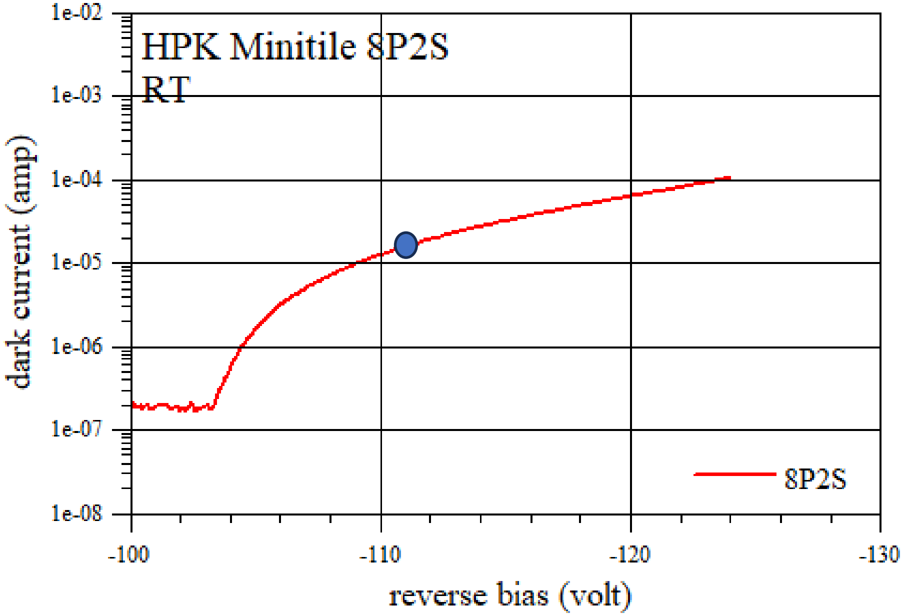


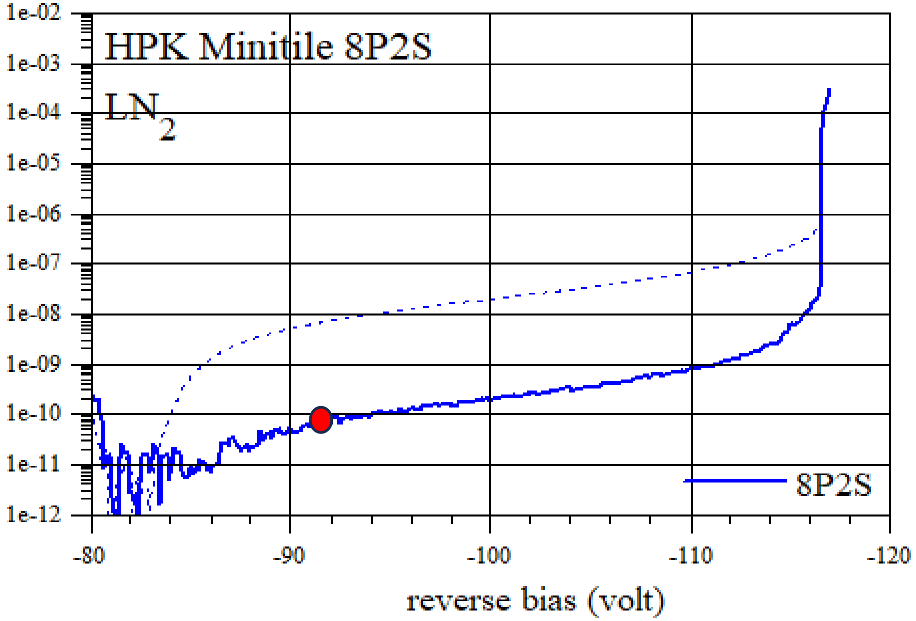




HPK minitile VUV
~5.8 nF (RT), ~1.9 nF (LN_2)





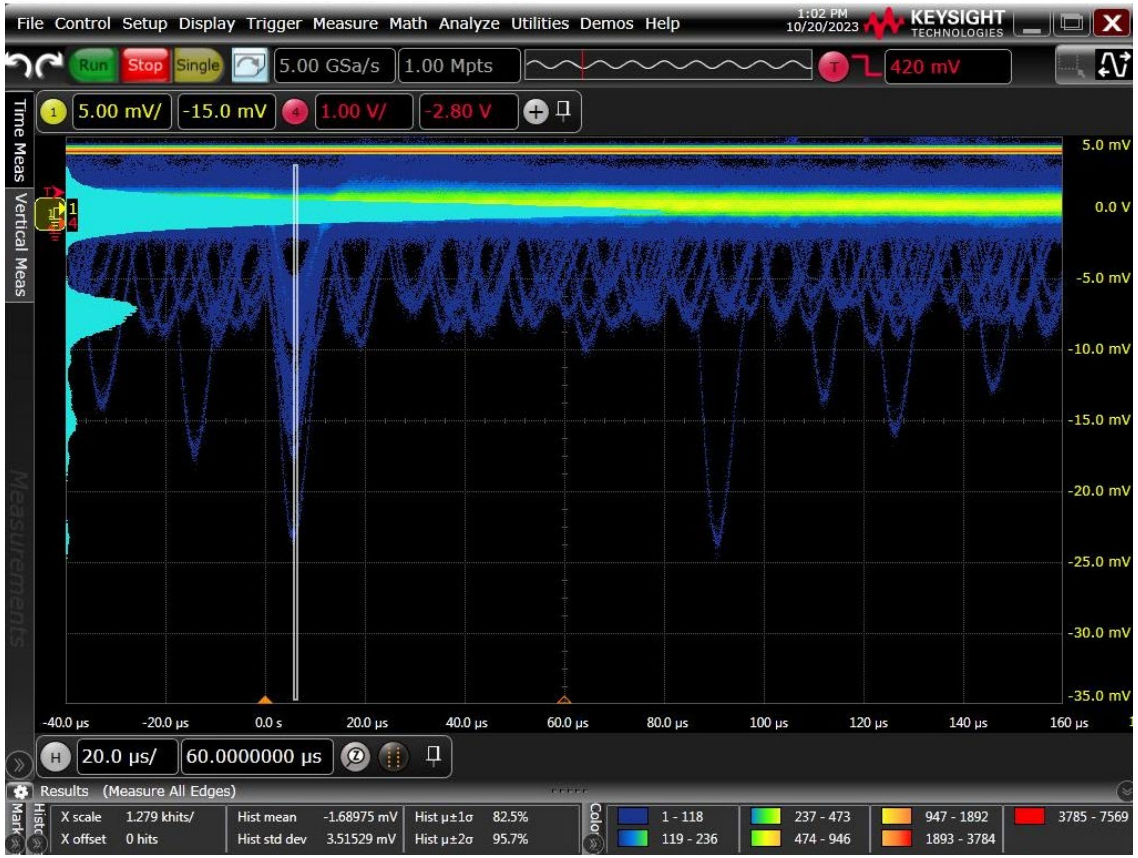


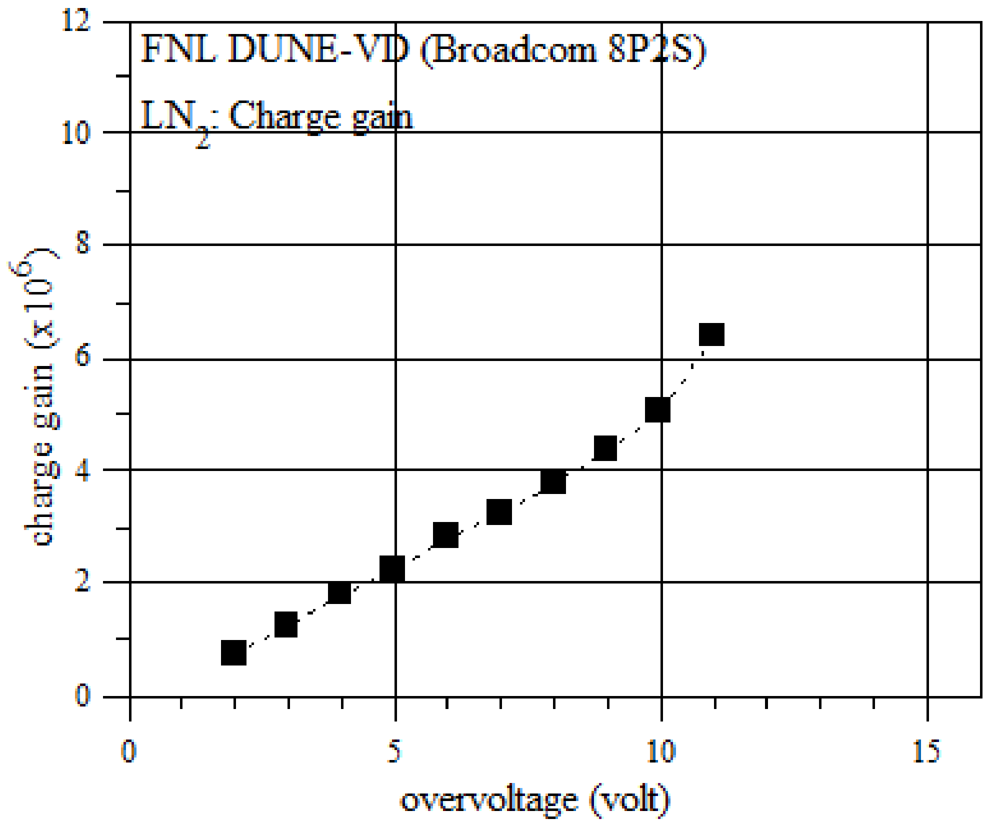
Broadcom SiPM connected in 8P2S (5.76 cm²)
in LN_2 *(illumination 90ps 405nm)*

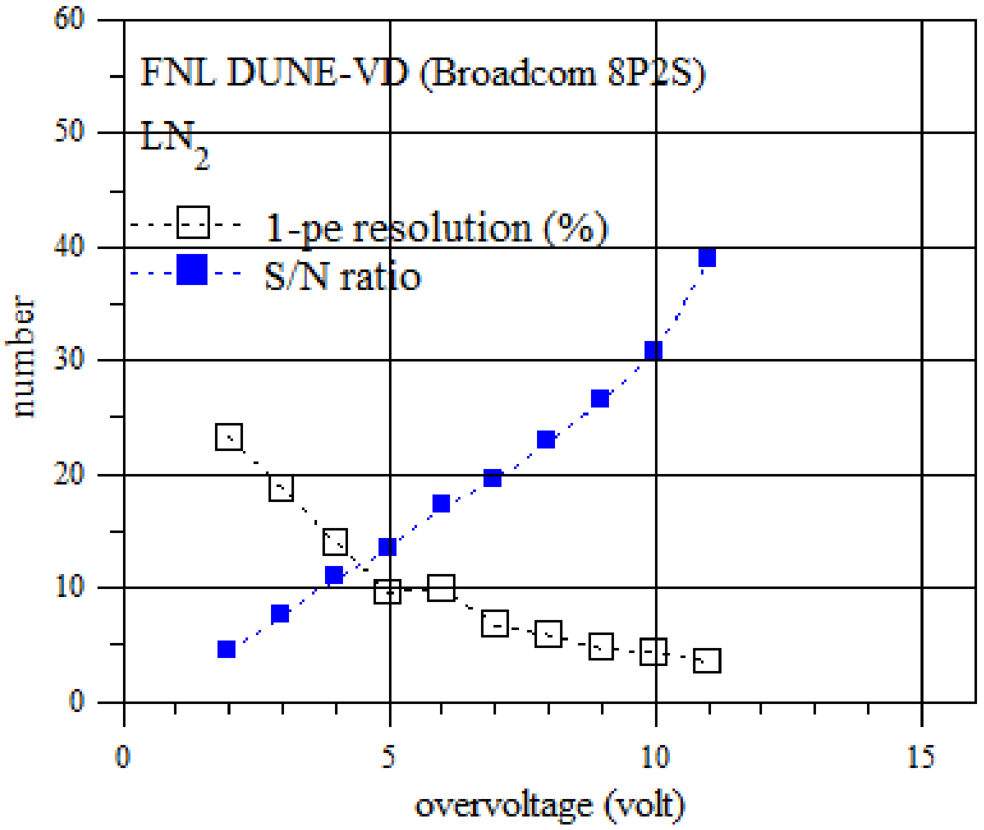
readout of photoelectron pulse: warm preamp+shaper (3 μs)

n-pe detection

1-pe detection







Charge gain ~ 0.5×10^6/OV
C_{cell} ~ 81 fF
$C_{terminal}$ ~ 12.8 nF (5.76 cm^2, 8P2S)

@ 5V overvoltage
S/N ~14
1-pe resolution ~7%

LN$_2$ LArASIC run: Minitiles #27, #28 (8P2S)

LArASIC

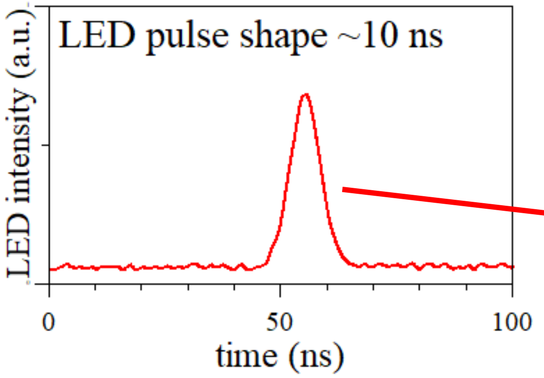
1 μs peak

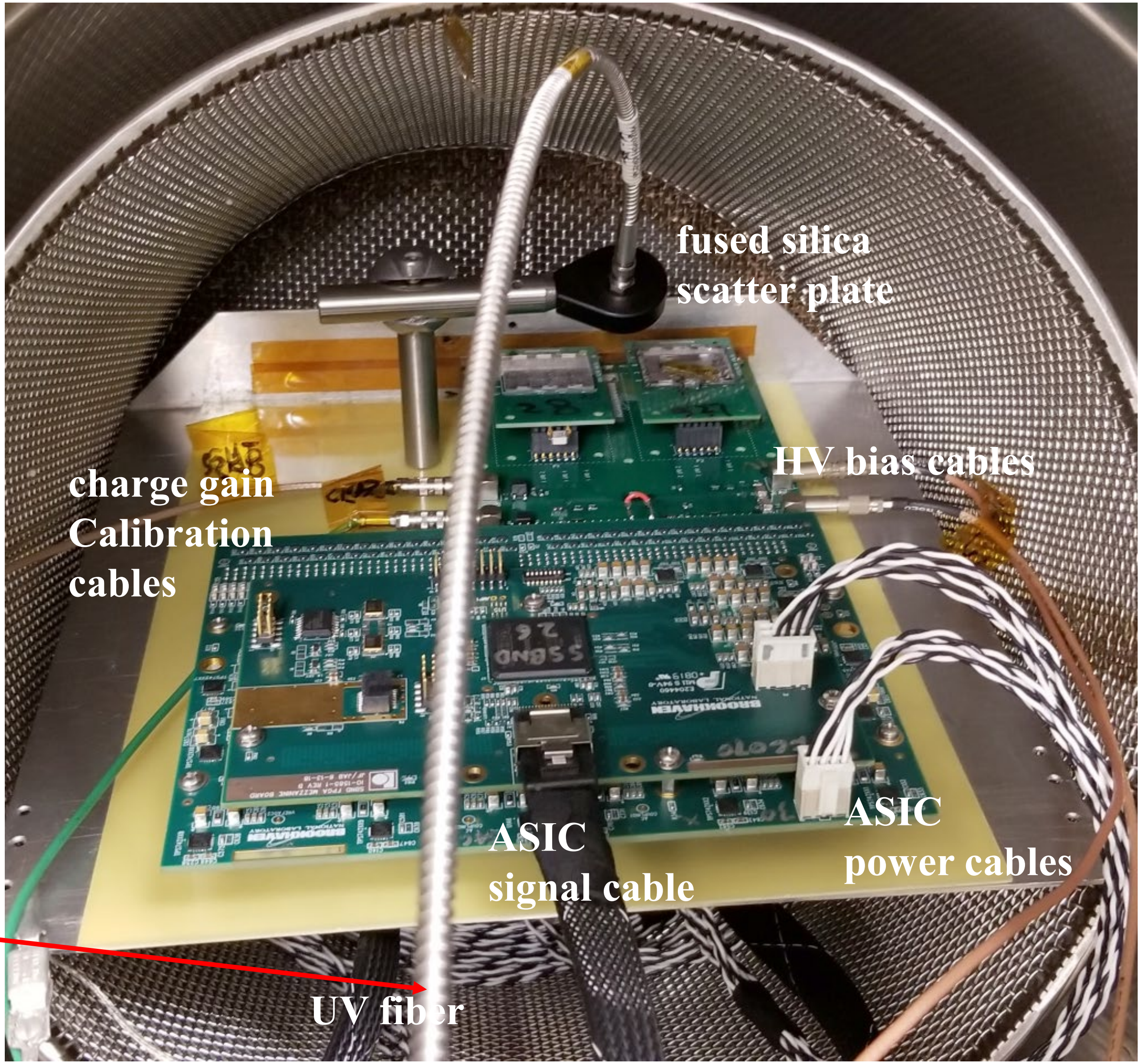
4.7 mV/fC

2 MHz ADC (0.5 us/bin)

10 MHz ref. clock lock

Photon flash rate 100 Hz

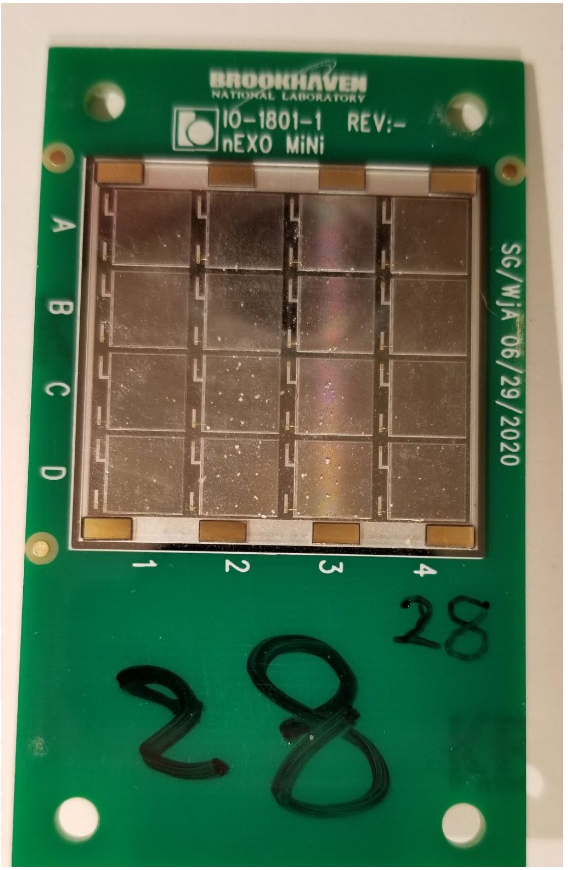




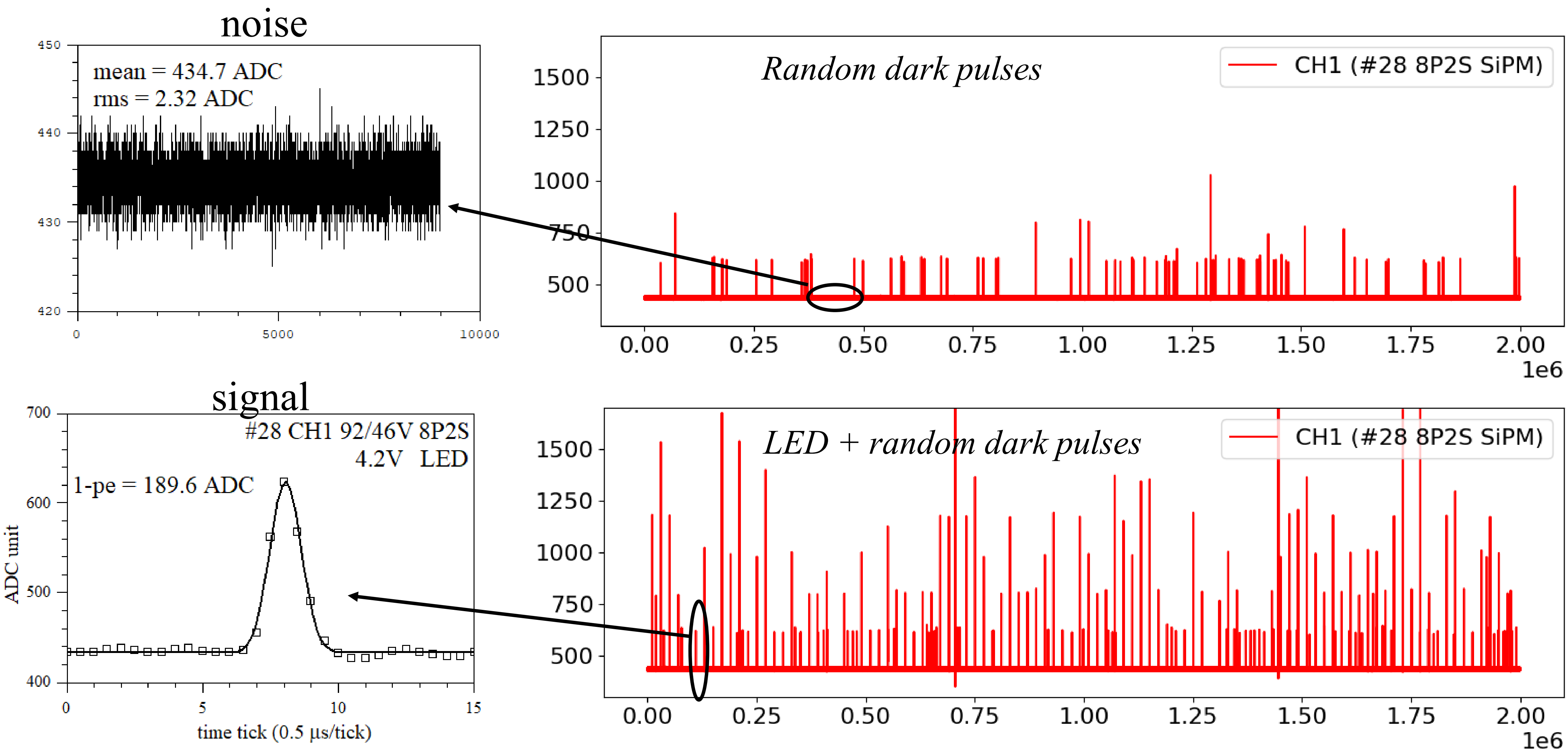
Data streaming mode

Data collection: LabView

Data analysis: Python



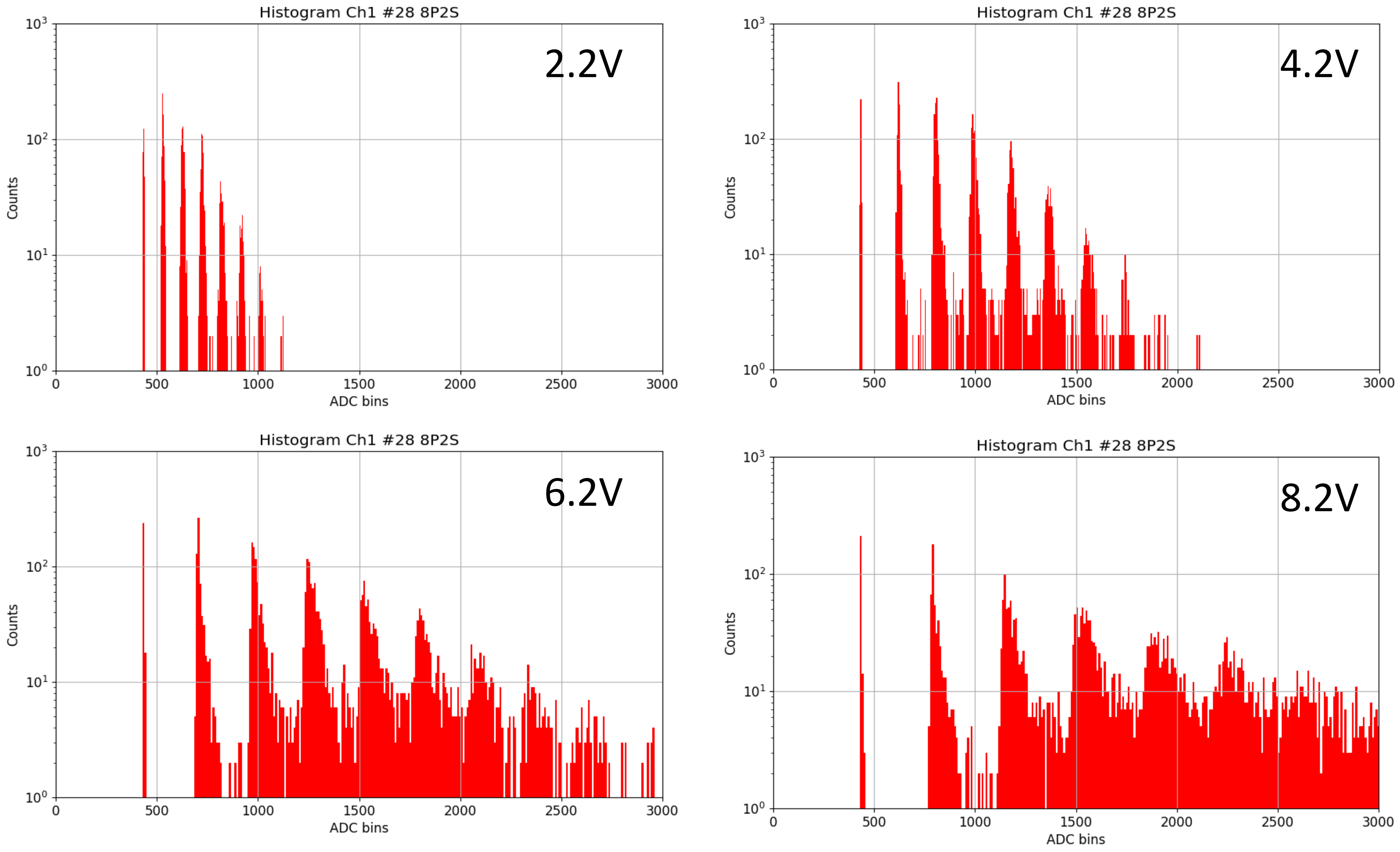
Minitile #28 8P2S in LN_2 @ 4.2 V : subset of raw signal trace (1 second)



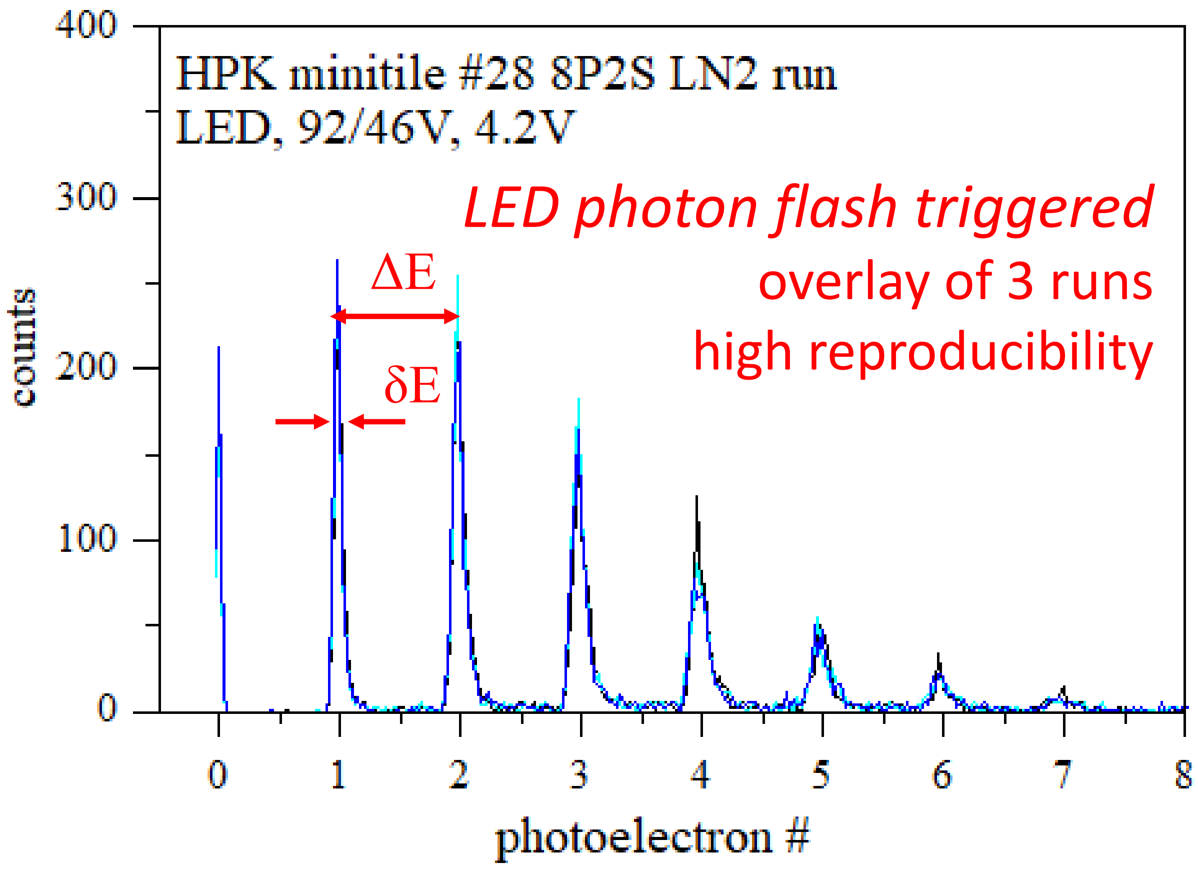
Time tick [0.5µs/tick] total of 1 second

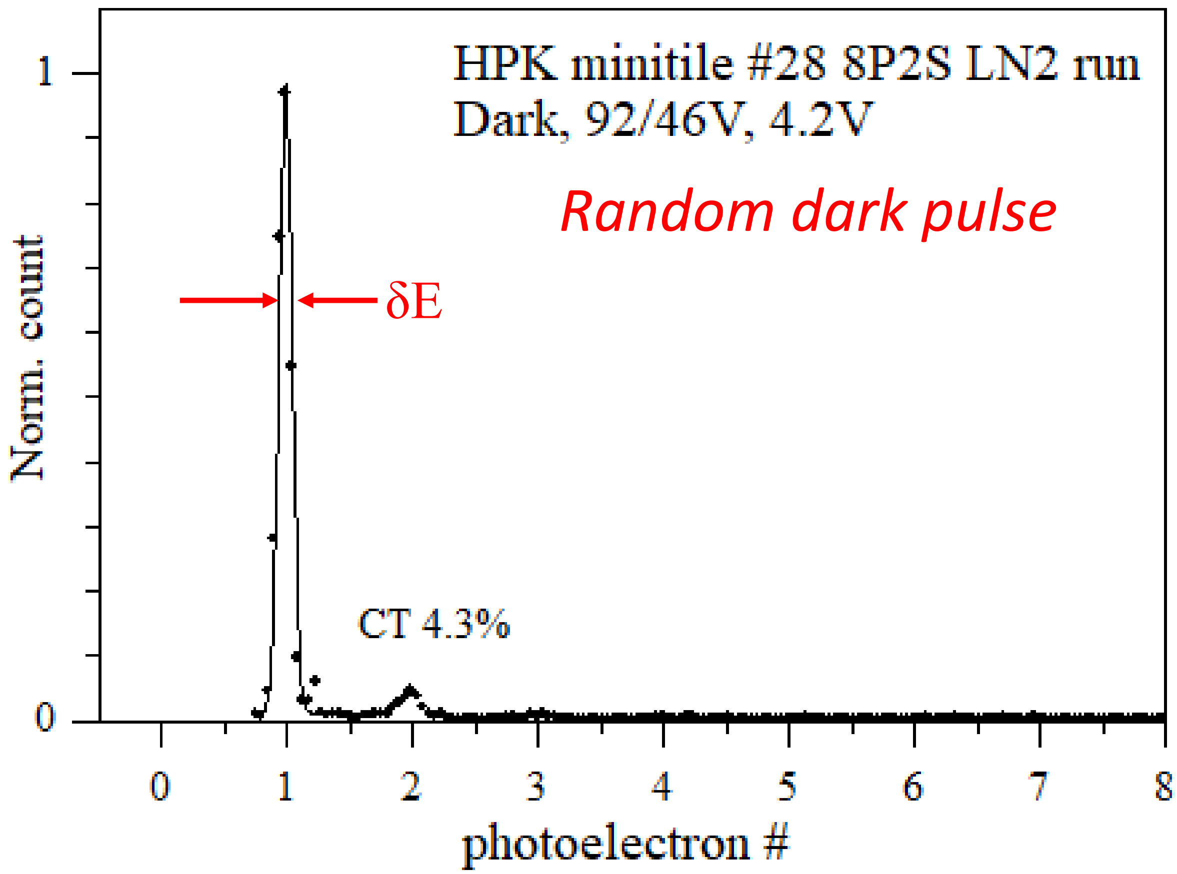
S/N = 189.6/2.32 = 81.7

Minitile #28 8P2S: Charge Histogram, LN_2



Minitile #28 8P2S: Charge Histogram, LN_2





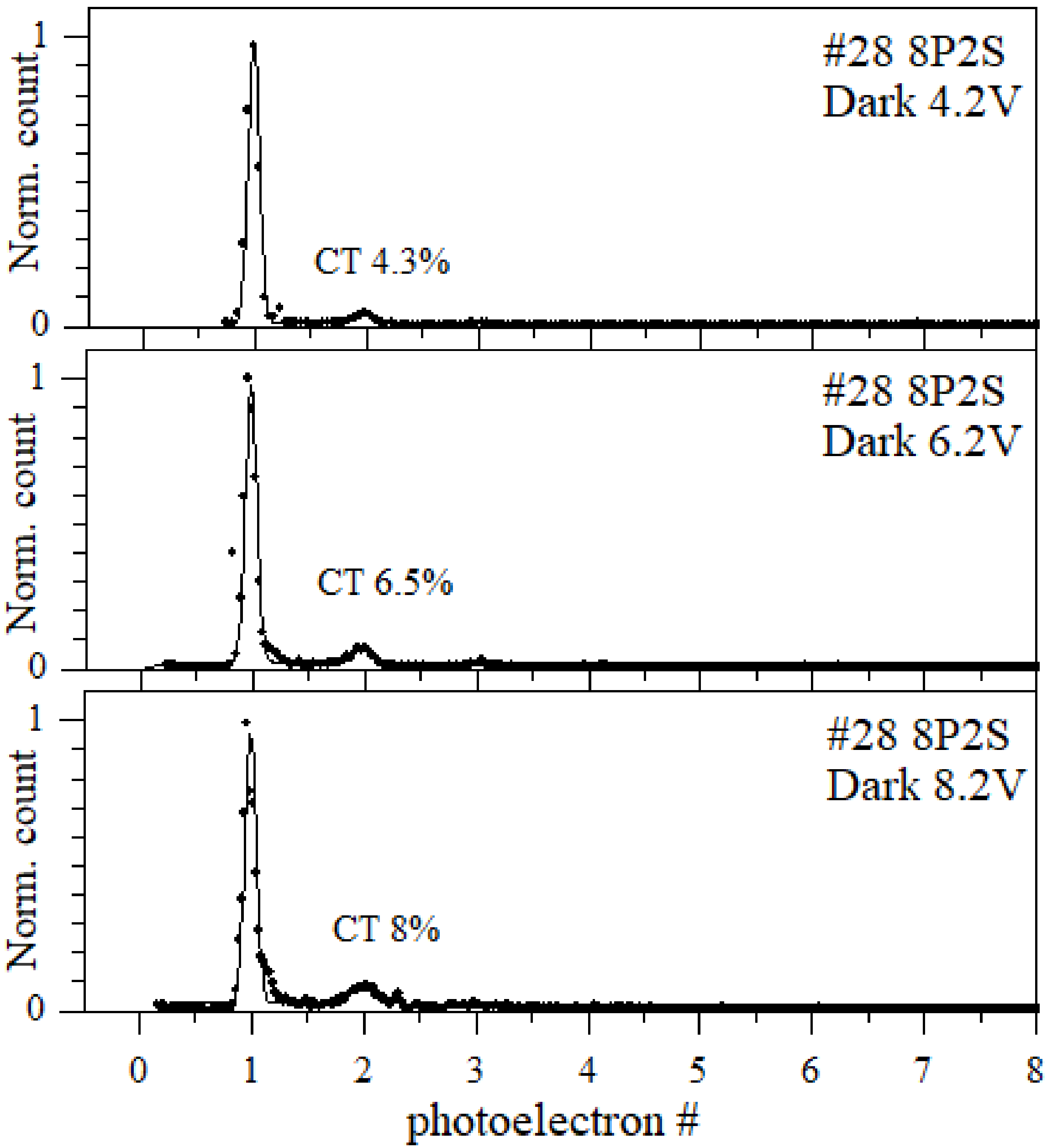
Photon rate: ~80 Hz (trigger rate 100 Hz)

1-pe resolution ($\frac{\delta E}{\Delta E}$): 3 to 3.5% rms

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

1-pe resolution (δE): ~5% rms

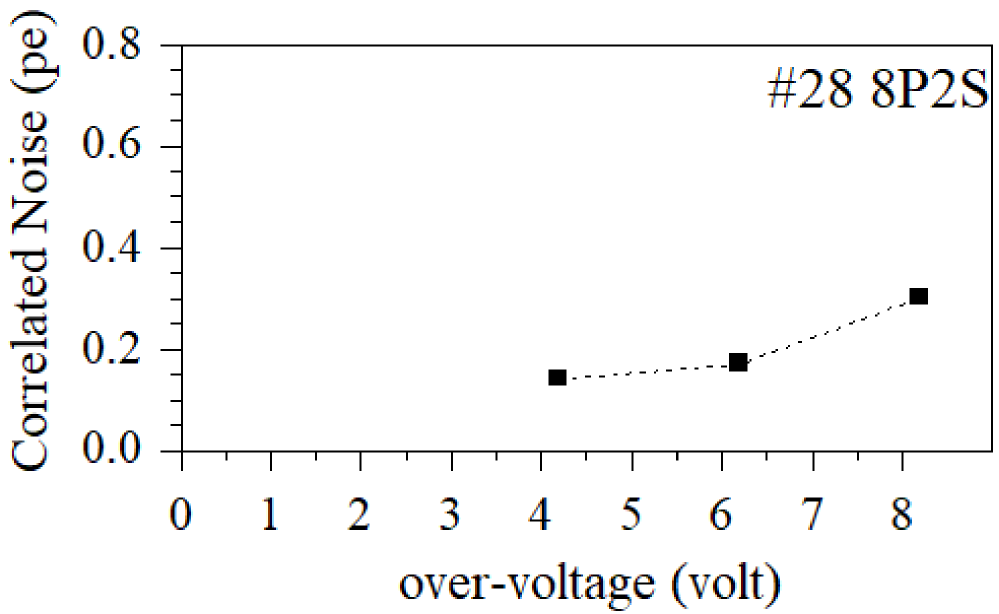
Minitile #28 8P2S in LN2 random dark pulse Charge Histogram



$$\text{Correlated Noise (pe)} = N_{APA} = \frac{1}{N}\sum_{i=1}^{N}\frac{A_i}{\bar{A}_{1\ PE}} - 1$$

A_i = charge of prompt pulse i
$\bar{A}_{1\text{-PE}}$ = average charge of 1-pe pulse
N = number of prompt avalanches analyzed

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



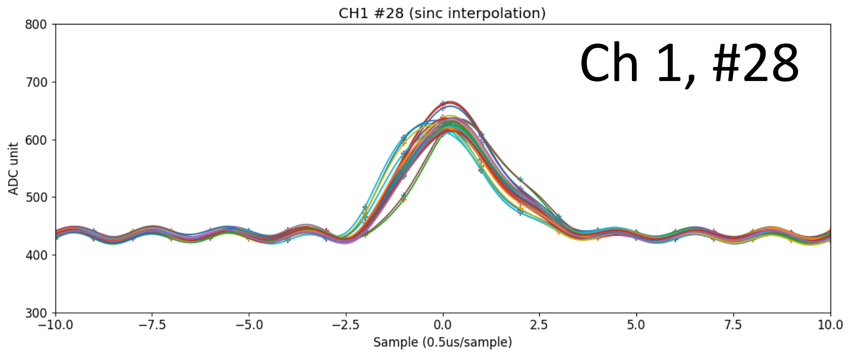
Correlated Noise (@ 4V) ~ 0.12 pe

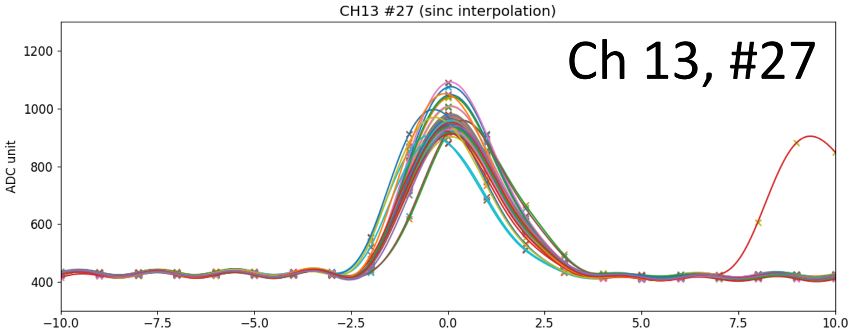
waveform reconstruction and 1-pe timing resolution, 10 MHz lock ON

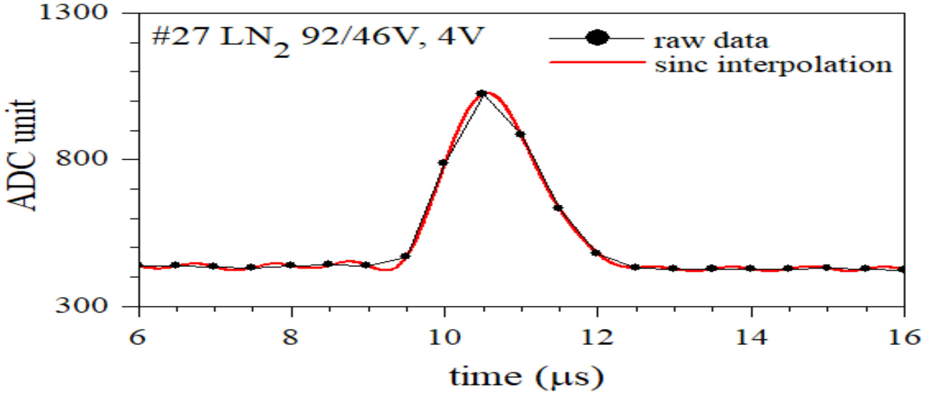
Select ONLY 1-pe pulses

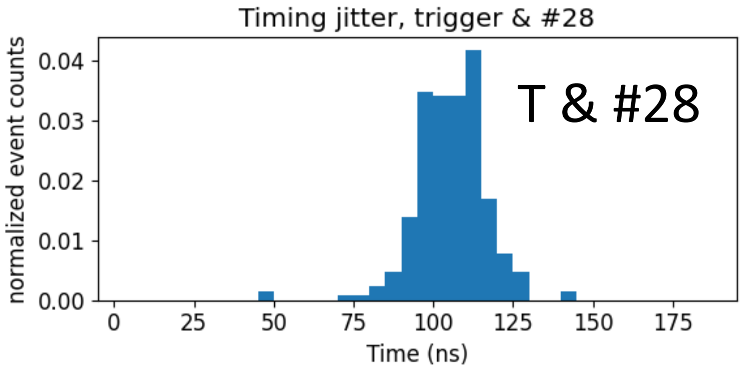
1-pe time jitter histogram, 45 sec data

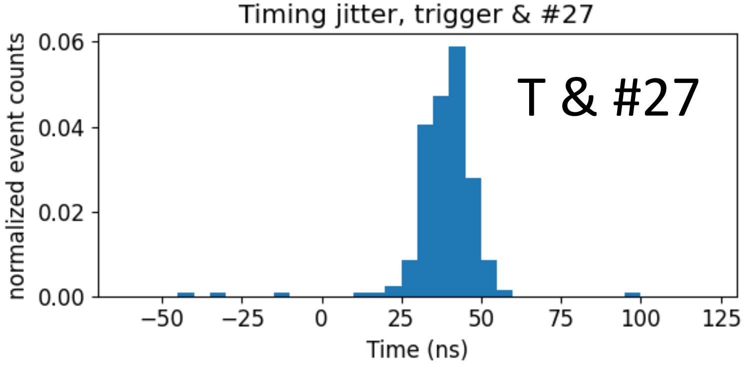
Gaussian fit of histogram

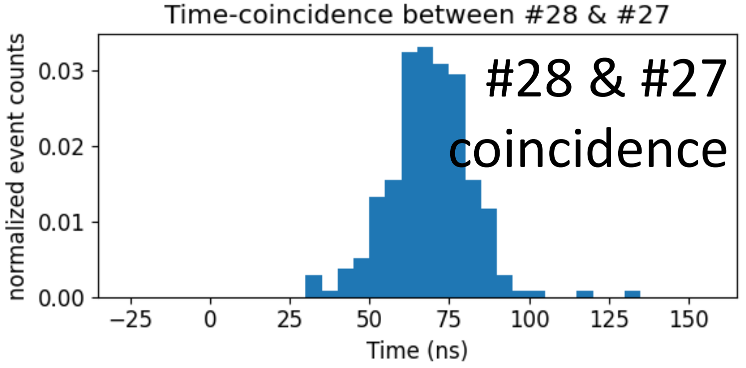


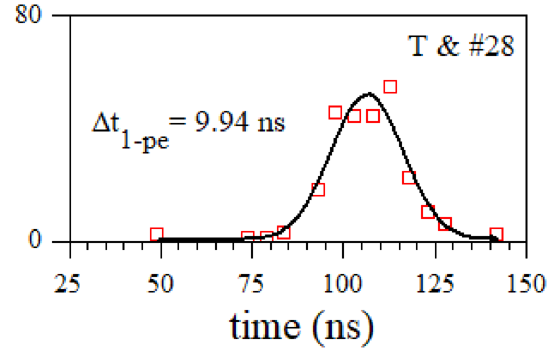


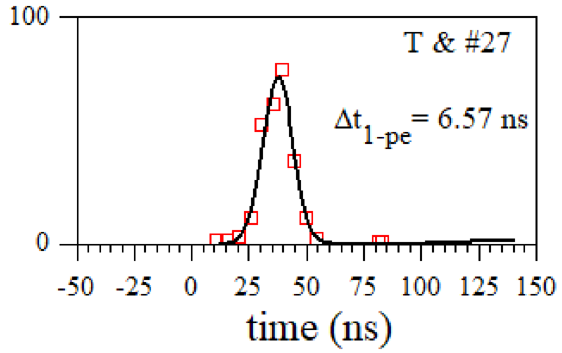


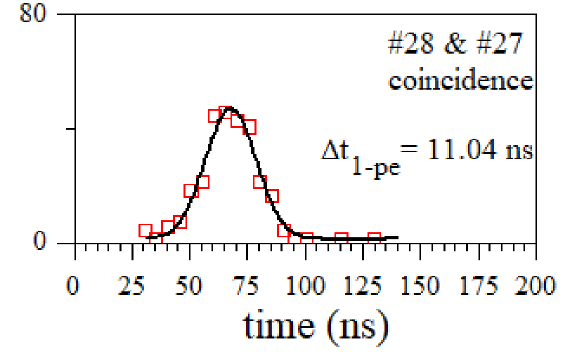












sinc-interpolation + peak finding led to good timing analysis