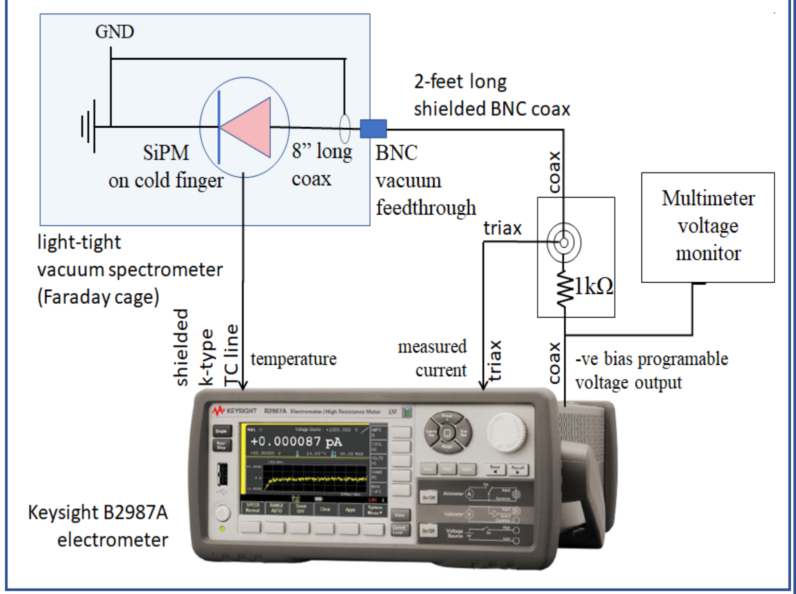
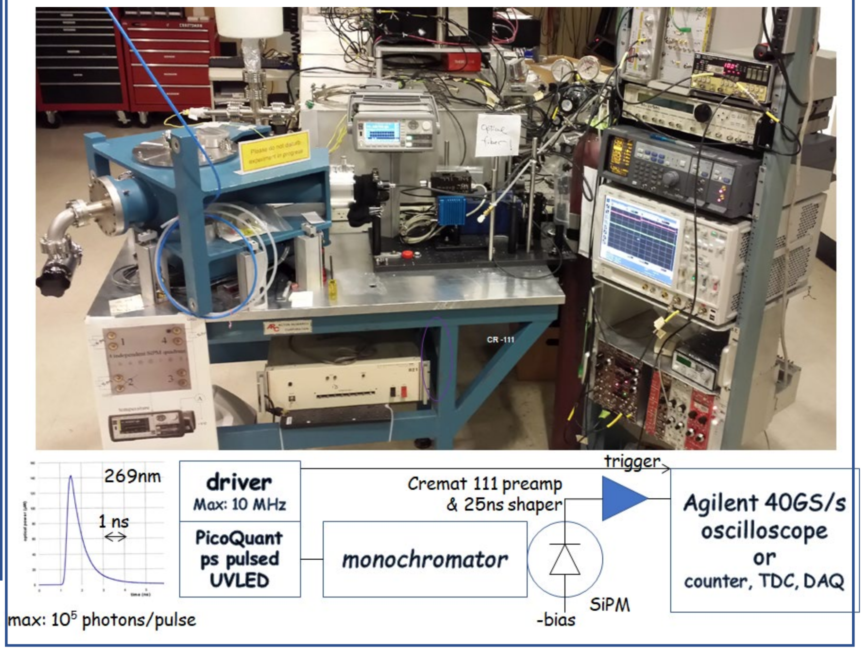
The Instrumentation Division at BNL has been testing SiPMs from various vendors in the past years; primary targeted to operate SiPMs in cryogenic temperature and in noble liquids.

- 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.

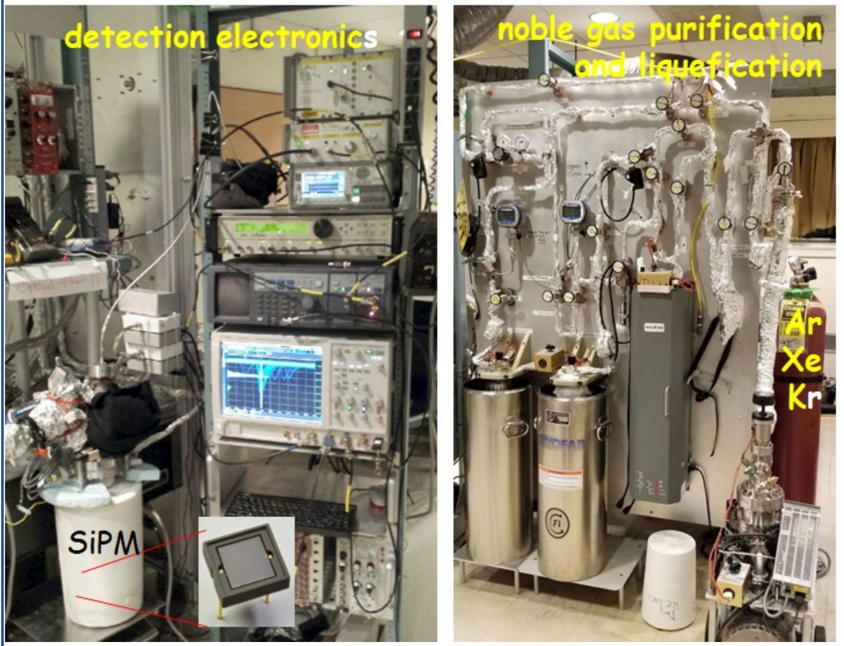
IV measurement



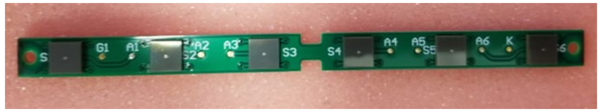
charge gain, noise, and PDE measurement

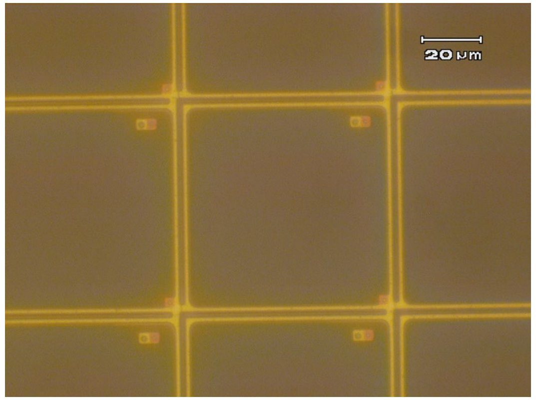


SiPM test in purified noble Liquid



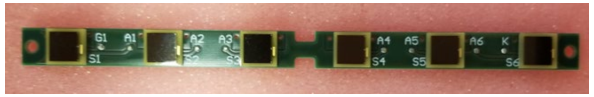
DUNE S13360-6075-HS-HRQ
high R_q, normal V_{bd}

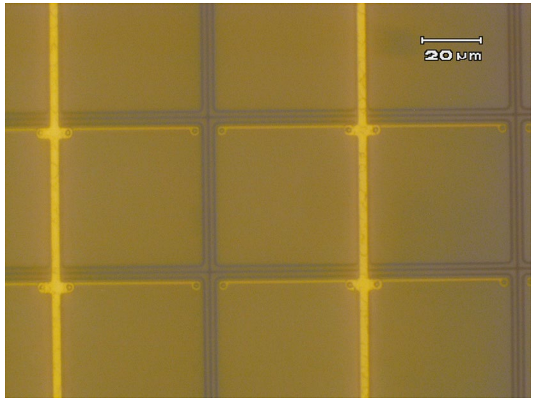




S13360-6075-HS-HRQ	
area	6x6 mm^2
pixel size	75 µm
# of pixels	6364
V_bd (RT, LN2)	51 V, 41 V
Capacitance	1.9 nF

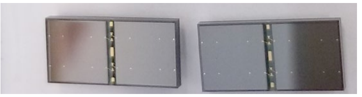
DUNE FBK triple-trench 50µm
low V_{bd}

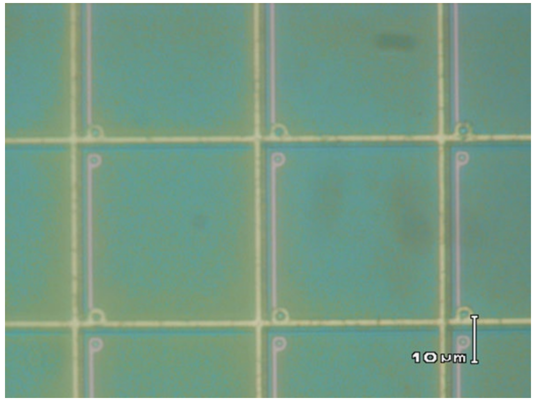




FBK tiple-trench	
area	6x6 mm^2
pixel size	50 µm
# of pixels	11188
V_bd (RT, LN2)	31 V, 27 V
Capacitance	2.6 nF

Broadcom AFBR-S4N66P024M
40µm low V_{bd}



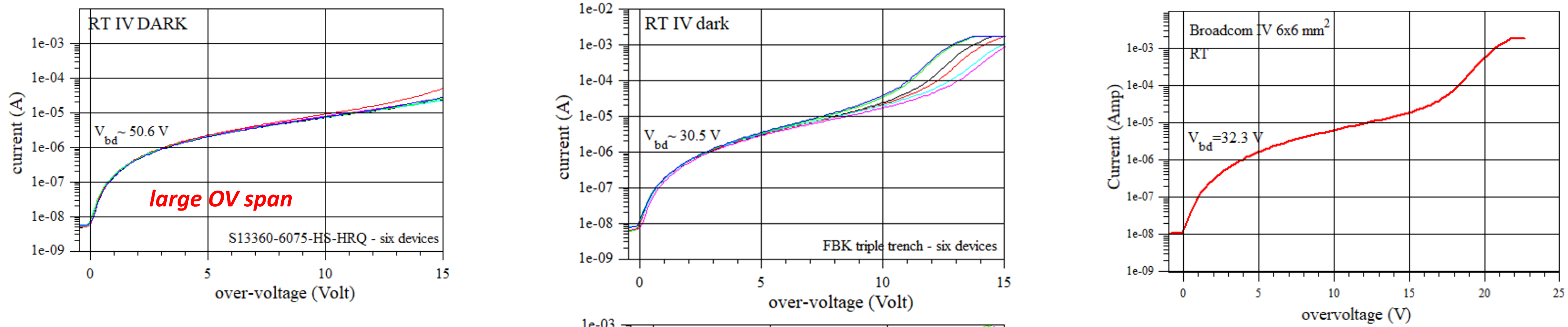


Broadcom	
area	6x6 mm^2
pixel size	40 µm
# of pixels	22428
V_bd (RT, LN2)	32.3 V, 27 V
Capacitance	2.9 nF

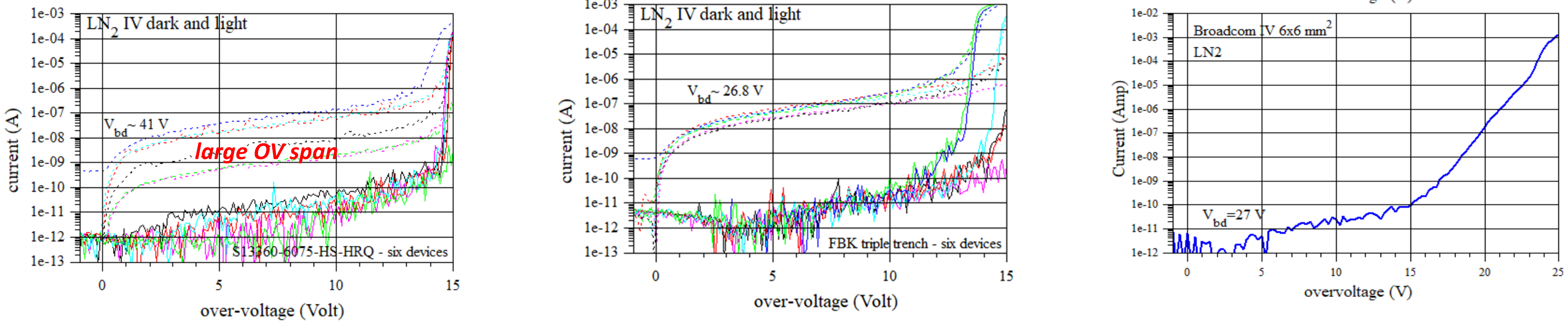
lower V-breakdown → higher capacitance → higher power to drive readout electronics

DUNE S13360-6075-HS-HRQ high R_q, normal V_{bd} | **DUNE FBK triple-trench 50µm low V_{bd}** | **Broadcom**

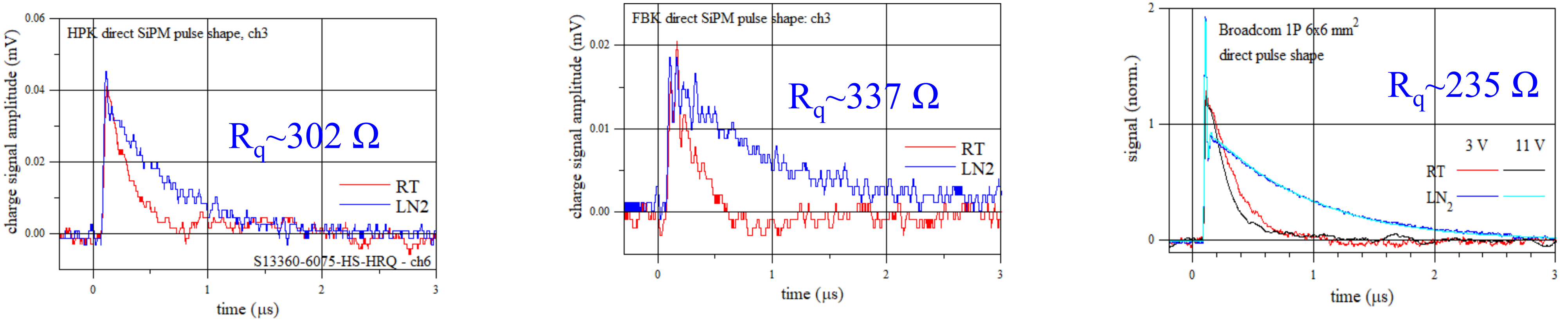
IV Room Temp.



IV LN_2

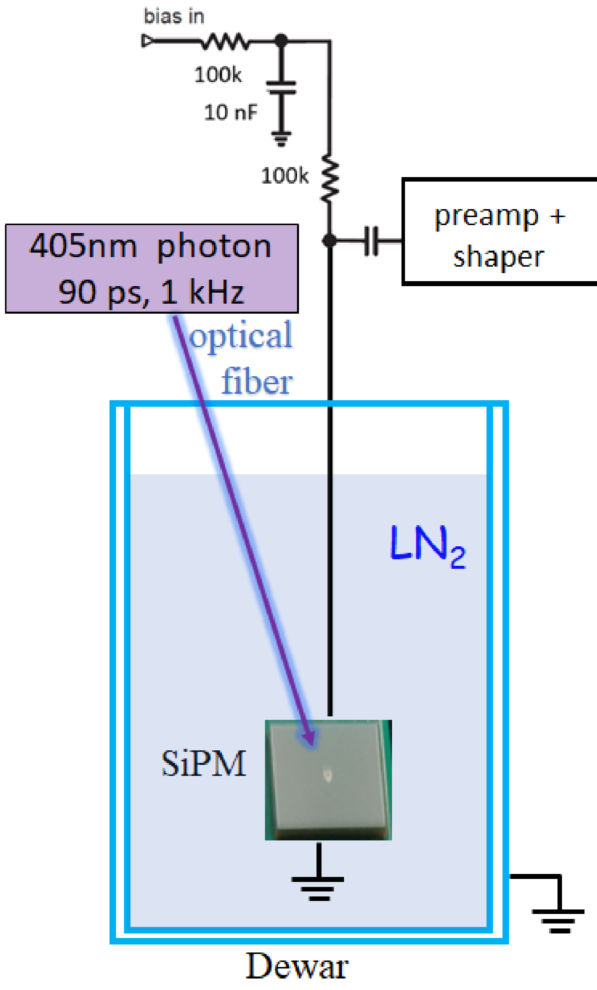


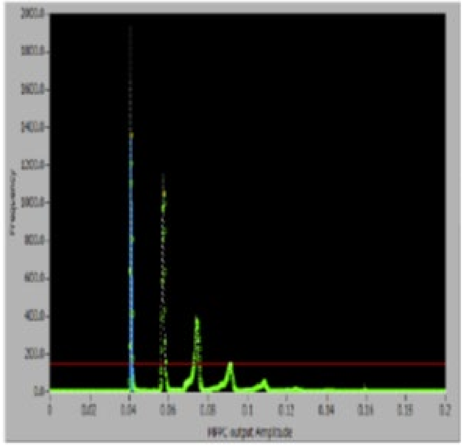
direct pulse shape



PDE, correlated noise, etc…

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





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

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

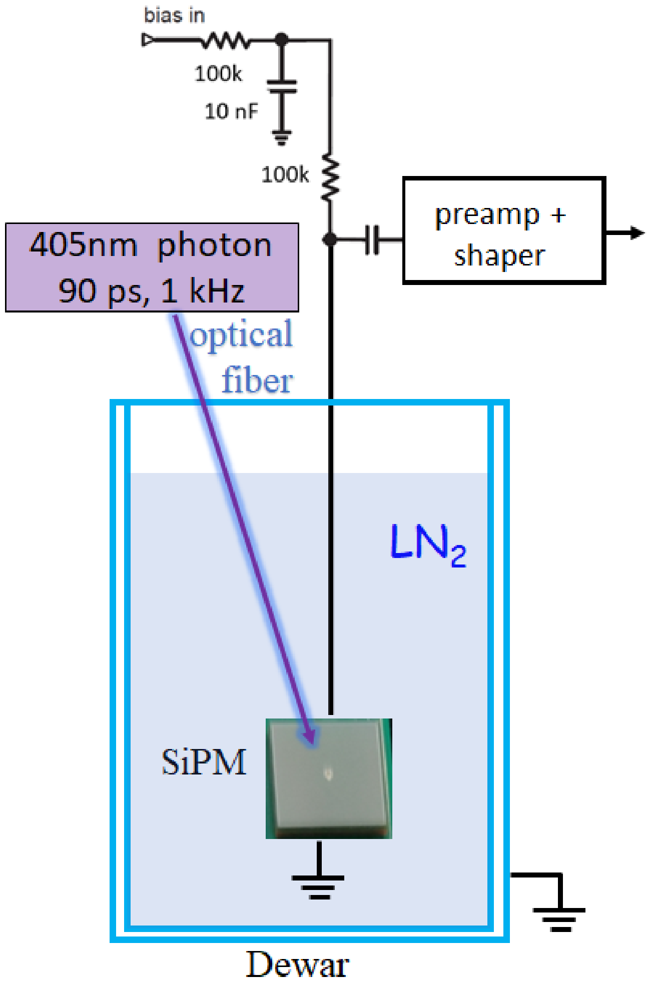
- $P(n, 0) = \frac{\left(\frac{N_{ped}}{N_{tot}}\right)}{\left(\frac{N_{ped}^{dark}}{N_{tot}^{dark}}\right)}$ (<- dark pulse correction)

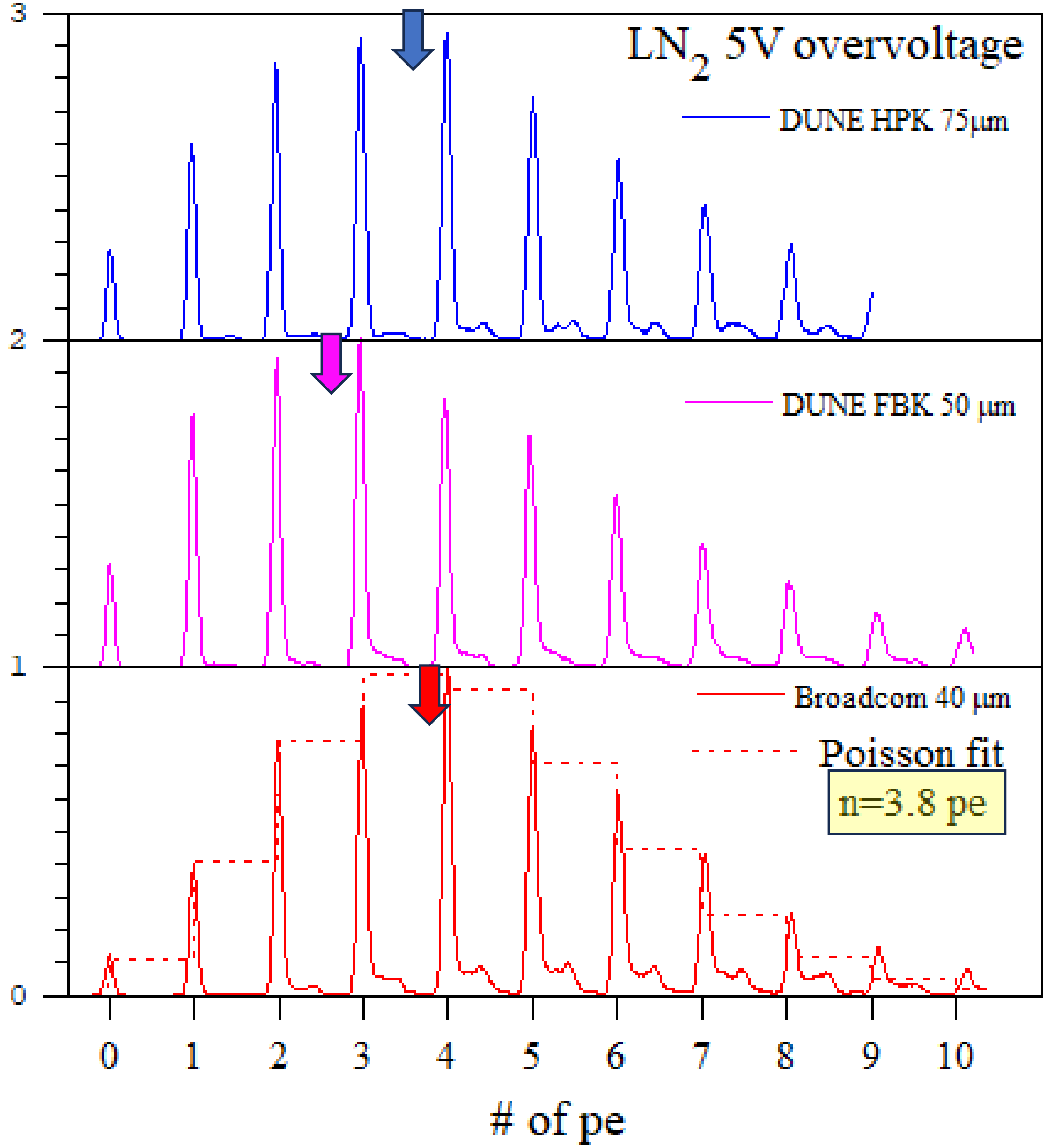
N_{ped} : number of events at 0 p.e. during pulsed light measurement
N_{tot} : number of all events during pulsed light measurement
N_{ped}^{dark} : number of events at 0 p.e. in dark state
N_{tot}^{dark} : number of all events in dark state

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

n = Poisson fitted mean number of photoelectrons

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





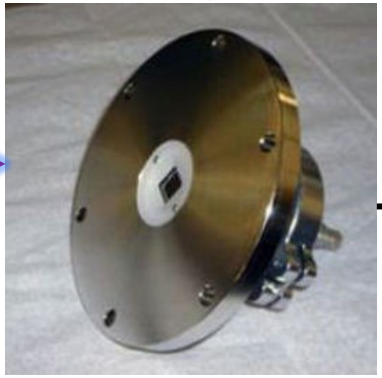
Number of incidence photons is determined from the measured photocurrent at the selected wavelength from a NIST calibrated photodiode

attenuate the intensity to a few photons/pulse

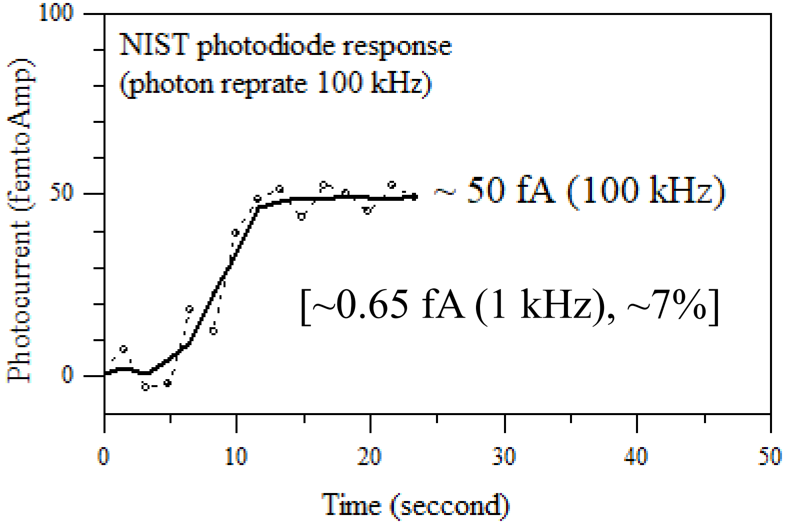
405nm photon
90 ps, 100 kHz

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)

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

geometric — photon — photoelectron

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

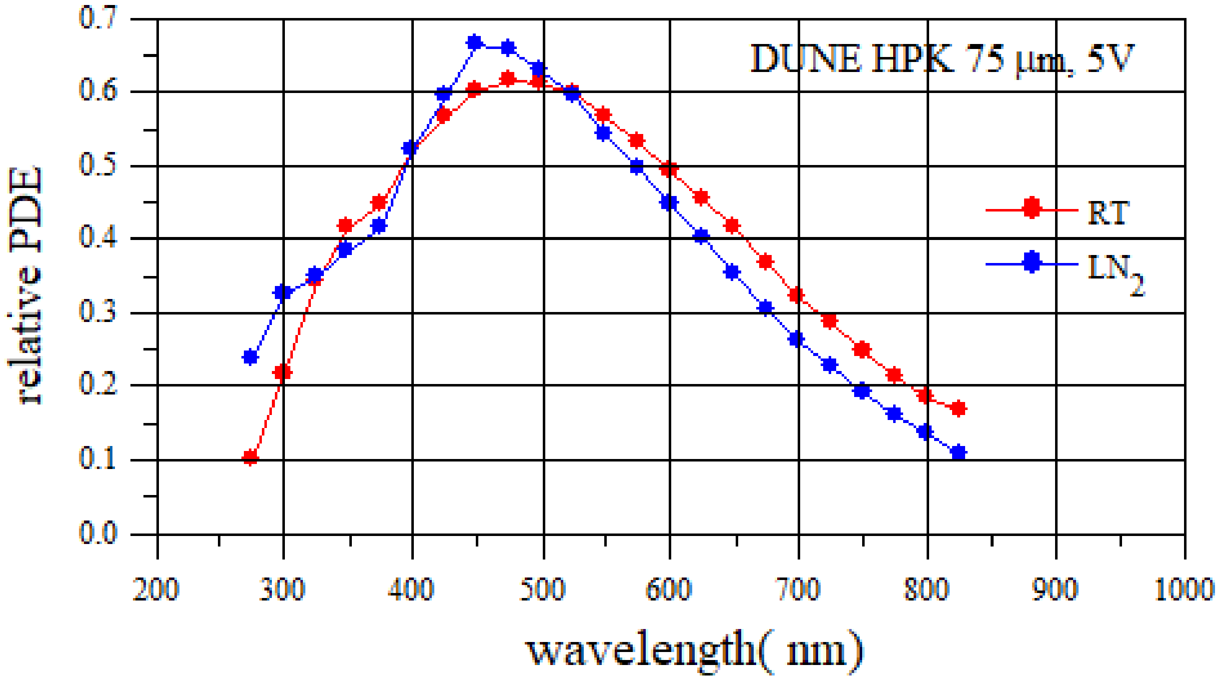
PDE @ 405 nm 5V OV in LN2	Poisson fitted n-pe	absolute PDE (±7%)	Spec. RT
DUNE HPK 75 µm	3.15	0.52	~0.47
DUNE FBK 50 µm	2.93	0.48	n/c
Broadcom 40 µm	3.8	0.63	~0.62

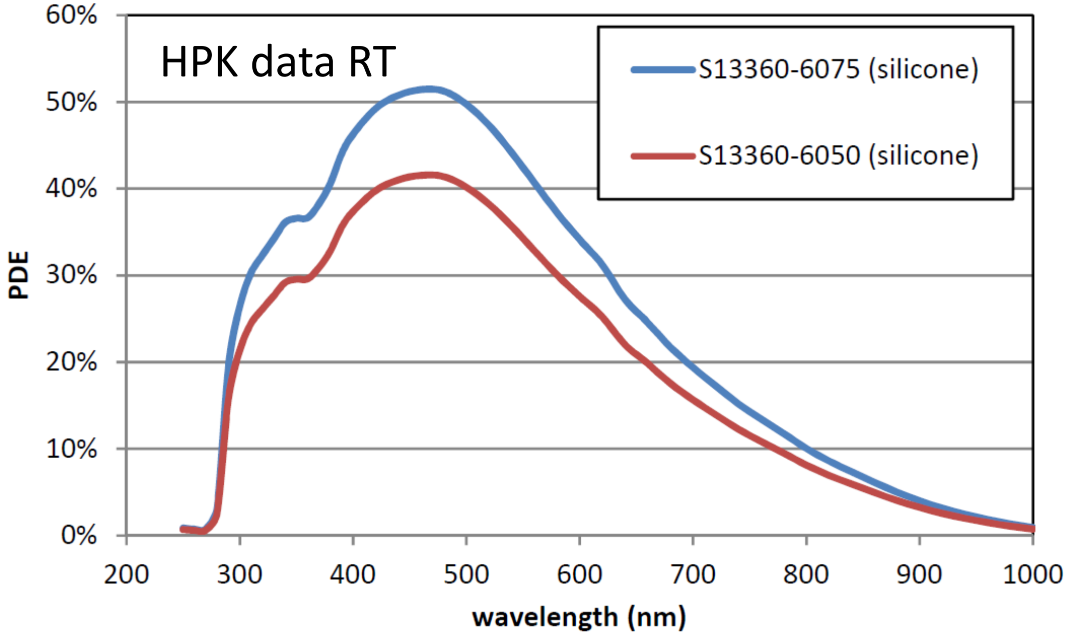
DUNE HPK: PDE spectral response – use white light source and calibrate against NIST photodiode

$$PDE_\lambda = [spectral\ reponse]_\lambda \times \frac{[PDE_{pulse}]_{405nm}}{[spectral\ reponse]_{405nm}}$$

noted: CT & AP – photoelectron effect, wavelength independent

PDE (QE) = photon effect, depends on wavelength





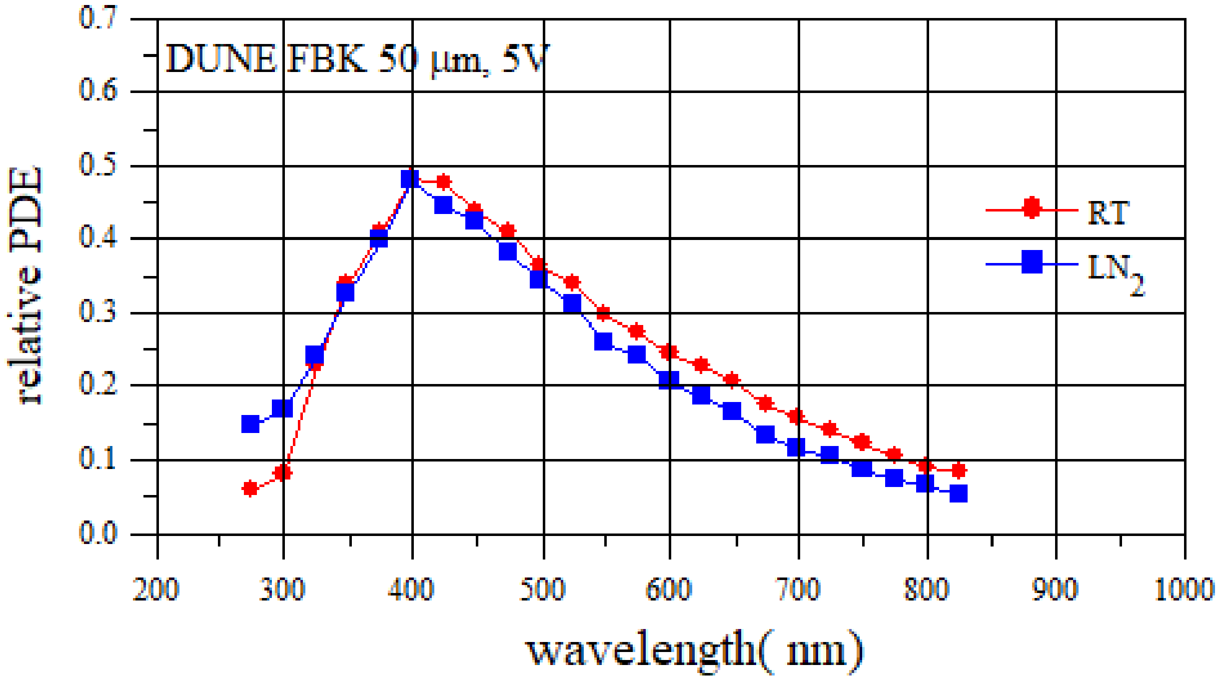
Spectral PDE response generally agrees with HPK (peak at ~460 nm) – also has a slight blue shift behavior in LN_2

DUNE FBK: PDE spectral response – use white light source and calibrate against NIST photodiode

$$PDE_\lambda = [spectral\ reponse]_\lambda \times \frac{[PDE_{pulse}]_{405nm}}{[spectral\ reponse]_{405nm}}$$

noted: CT & AP – photoelectron effect, wavelength independent

PDE (QE) = photon effect, depends on wavelength



FPK data RT

N/C

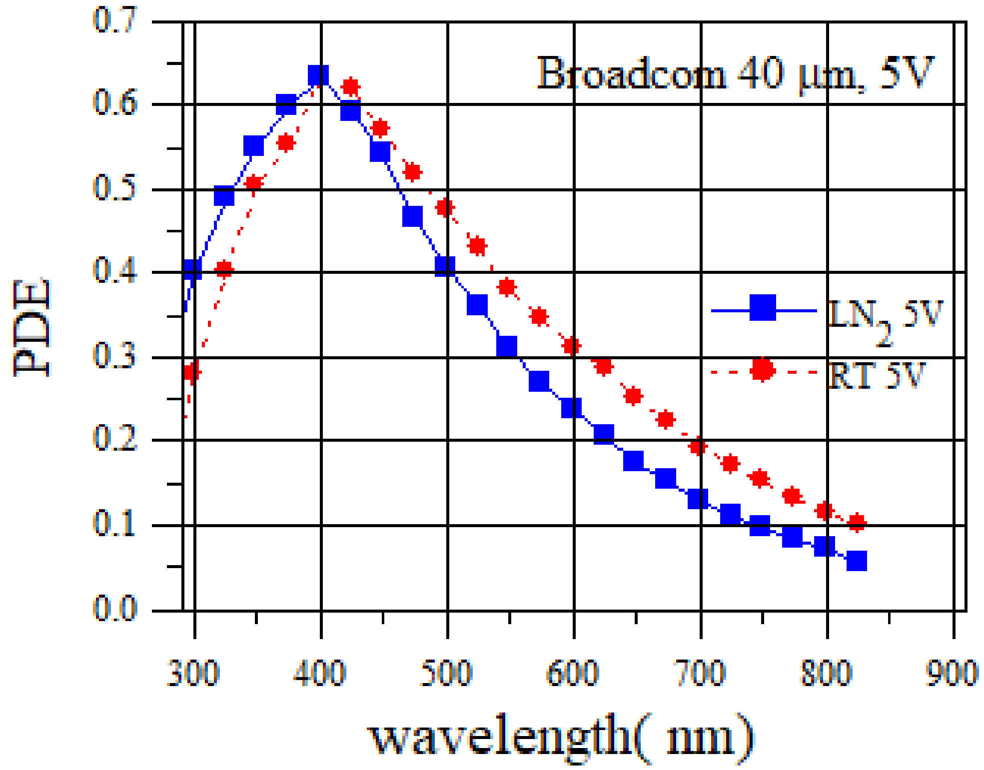
Can't compare to FBK data (peak at ~400 nm) – may have a very slight blue shift behavior in LN_2

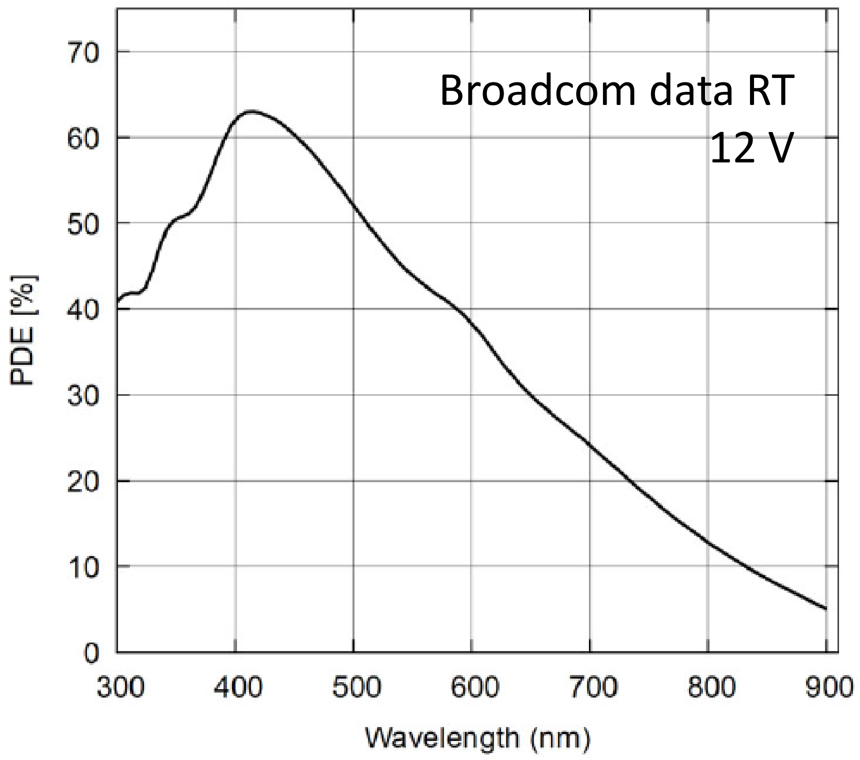
Broadcom: PDE spectral response – use white light source and calibrate against NIST photodiode

$$PDE_\lambda = [spectral\ reponse]_\lambda \times \frac{[PDE_{pulse}]_{405nm}}{[spectral\ reponse]_{405nm}}$$

noted: CT & AP – photoelectron effect, wavelength independent

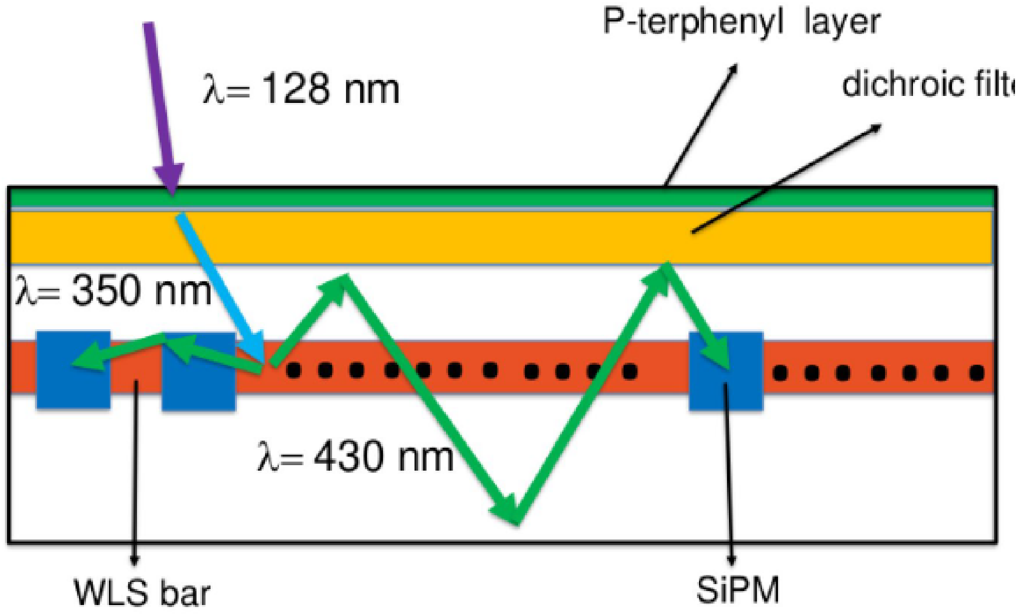
PDE (QE) = photon effect, depends on wavelength





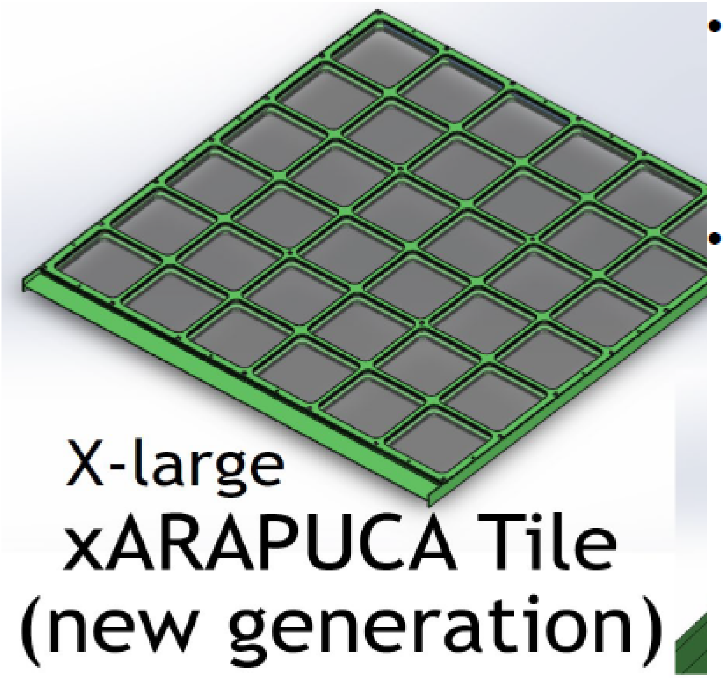
SiPM array readout concept

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



- **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!

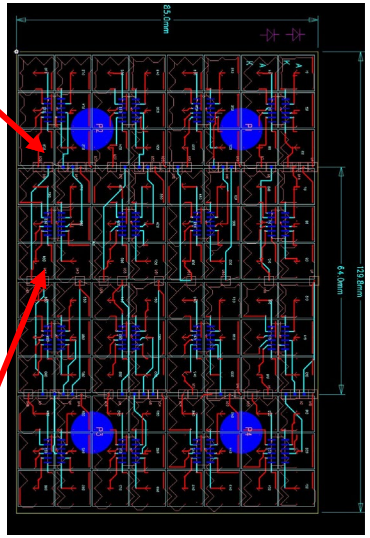
M.C. Queiroga Bazetto, V.L. Pimentel, A.A. Machado and E. Segreto, in Campinas, Brazil

nEXO SiPM Light Detector Readout

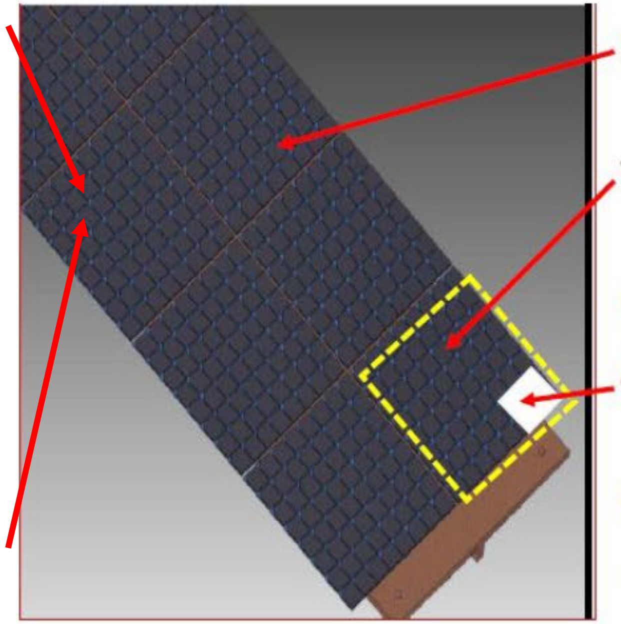
6 cm^2 SiPMs
3P2S

TSV
75 µm/pixel
SiO_2 carrier

96 cm^2 SiPMs tile



16 channels
3P2S connection



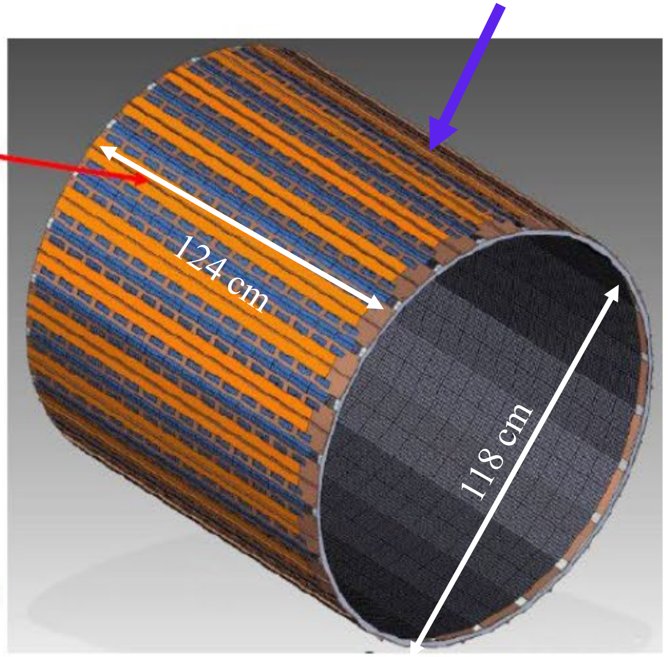
Staves: 24

Tiles : **24** x 2 x 10 = **480**

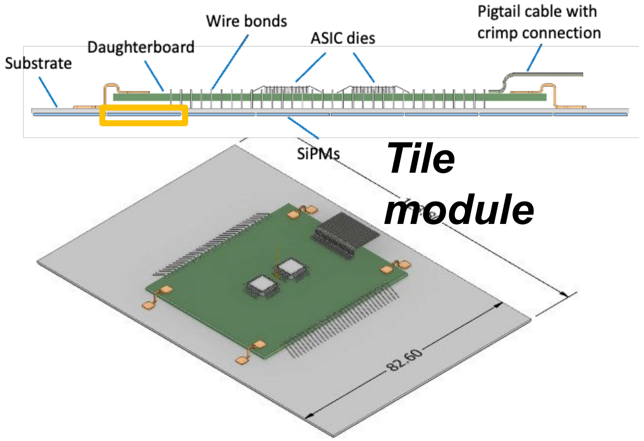
Sub-arrays 6 cm^2:
480 x 16 = **7680**

SiPM Area: **7680** x 6 cm^2=
= = **4.6 m^2**

λ=175 nm



SiPM ‘bird cage’



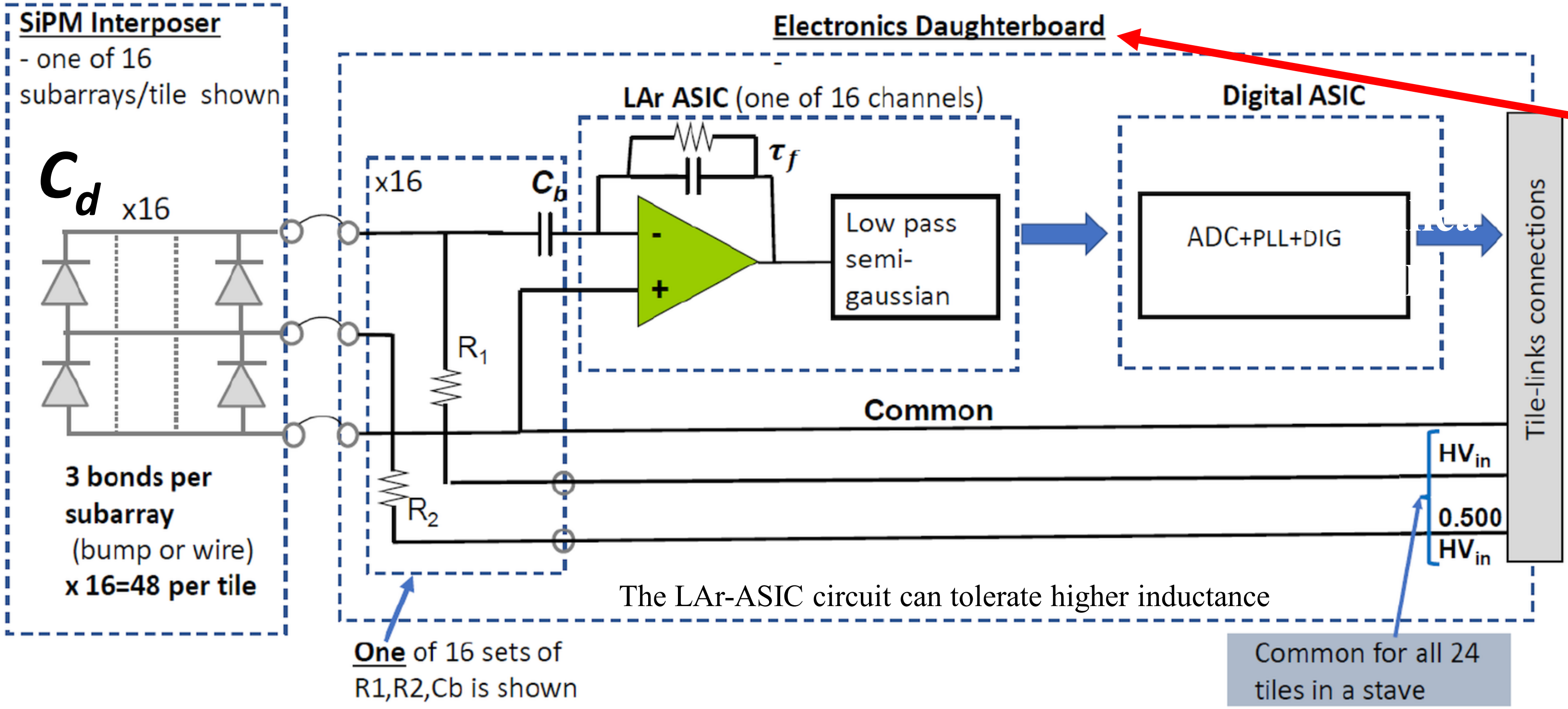
Tile module

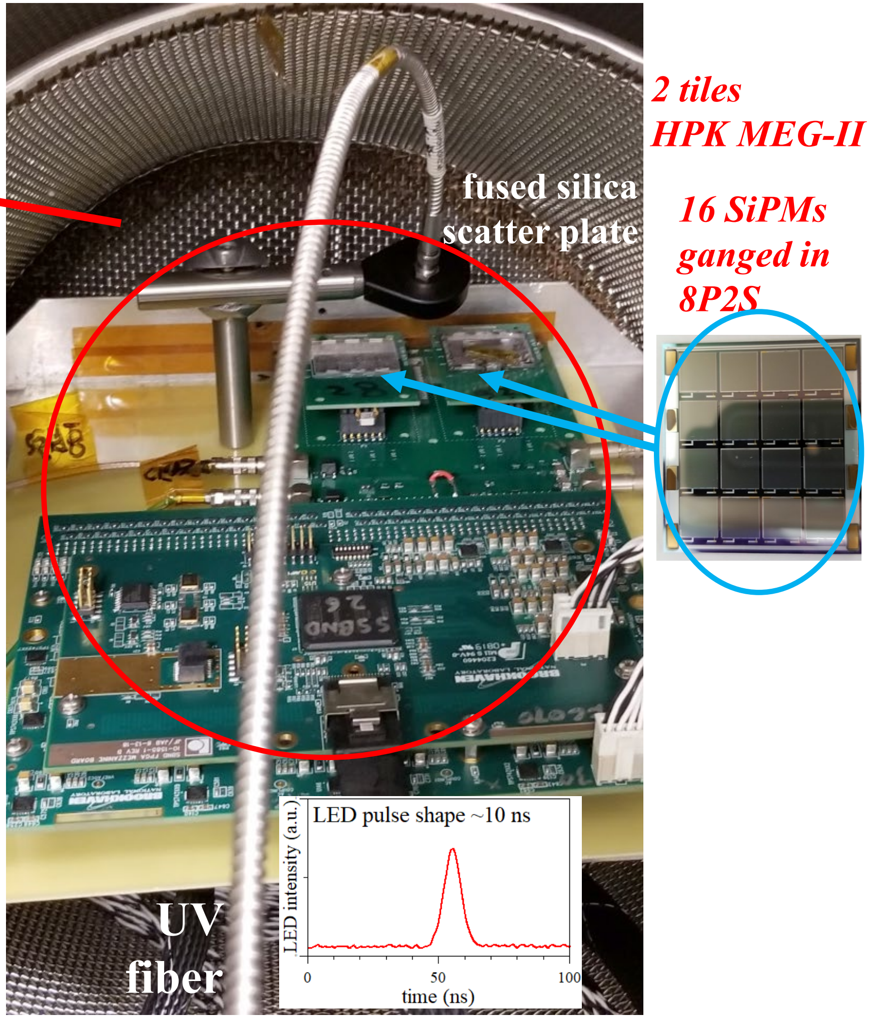
Technology	HPK	FBK
$V_{operating}$ (RT) [V]	50	30
C /area [nF/cm^2]	**3.5**	**8.5**
C (6 cm^2) / channel [nF]	**21**	**51**
C (8P2S) [nF]	**5**	**12.5**
V (2S) [V]	100	60

Very large subarray capacitance/channel

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

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





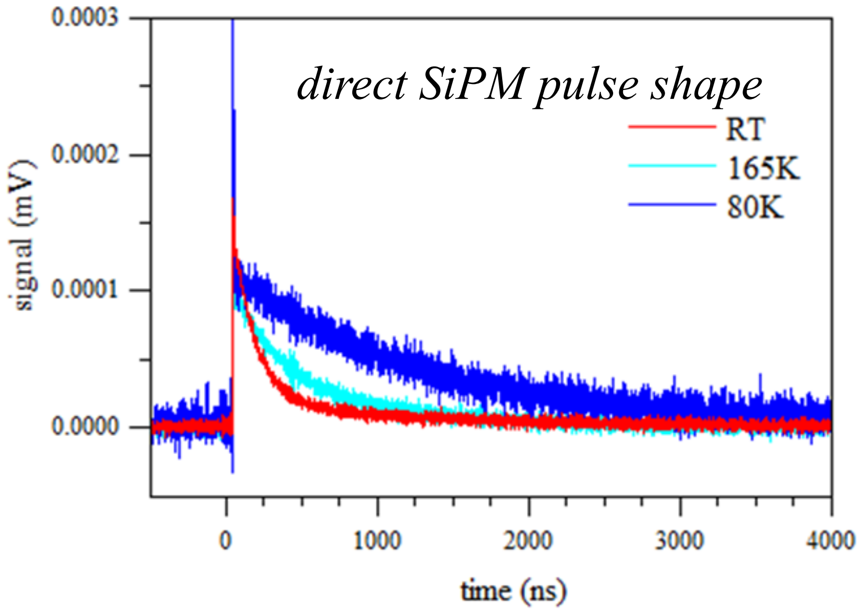
LArASIC P2:
16 **independent** ASIC input channels
peaking time: **1 µs** (programmable 0.5, 1, 2, 3 µs)
ASIC gain: **4.7 mV/fC** (programmable 7.8, 14, 25 mV/fC)
C_{cal}=185 fF
ADC *sampling rate:* 2 MS/s (0.5 µs/time tick)
10 MHz ref. clock lock

Reference: channel 0
Minitile 8P2S: channel 1
Minitile 8P2S: channel 13
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

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

- Charge integration



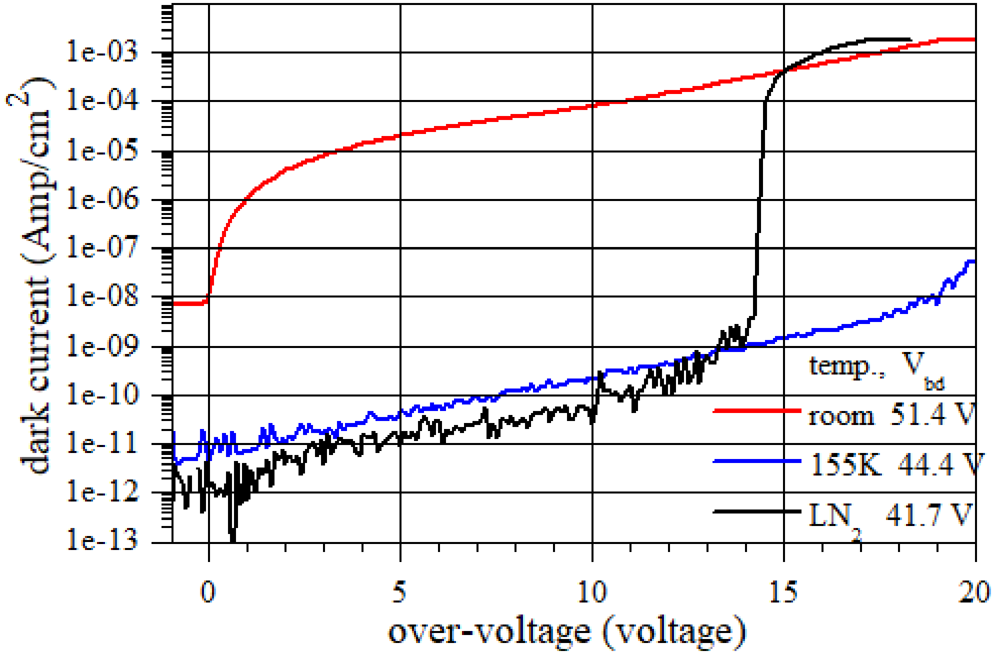
- Amplitude measurement

Both methods have their advantages and disadvantages.
or a combination of both

Charge Readout concept: weak coupling to amplifier

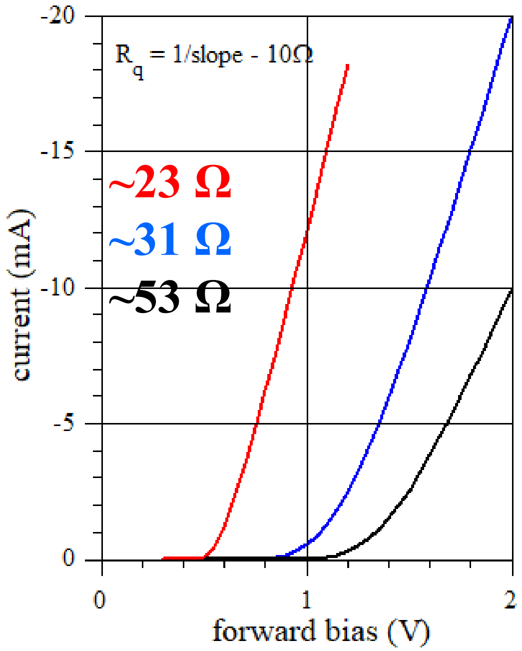
SiPM parameters

IV plots



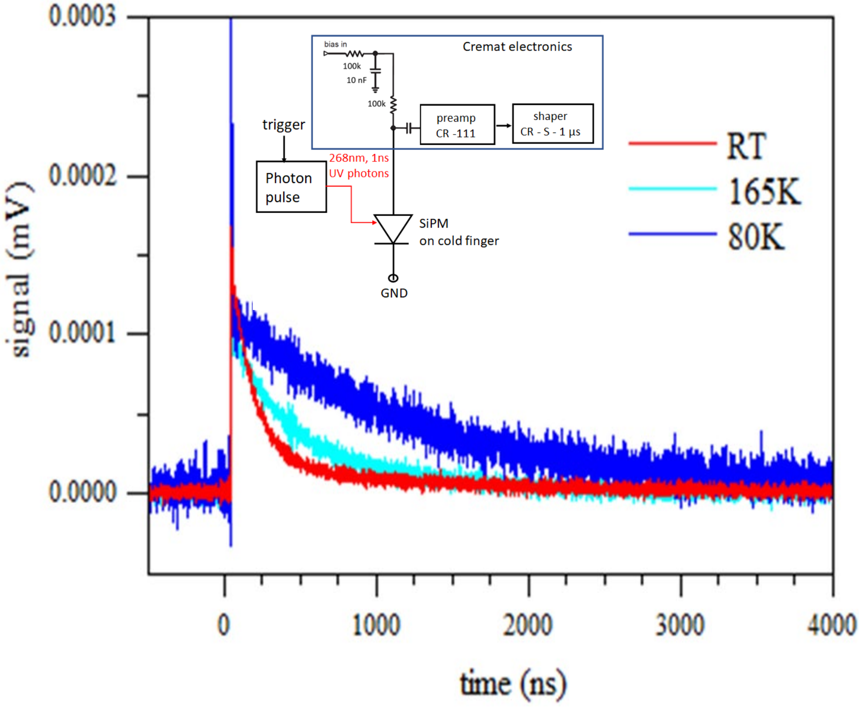
>10 volt operating voltage

quench resistance



R_{quench} increase in cold

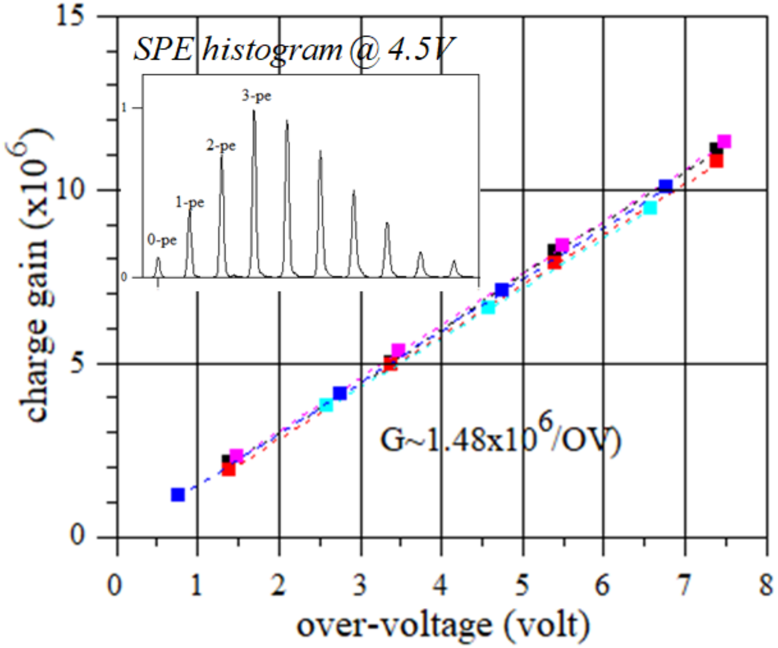
direct SiPM pulse shape



recovery time increase in cold

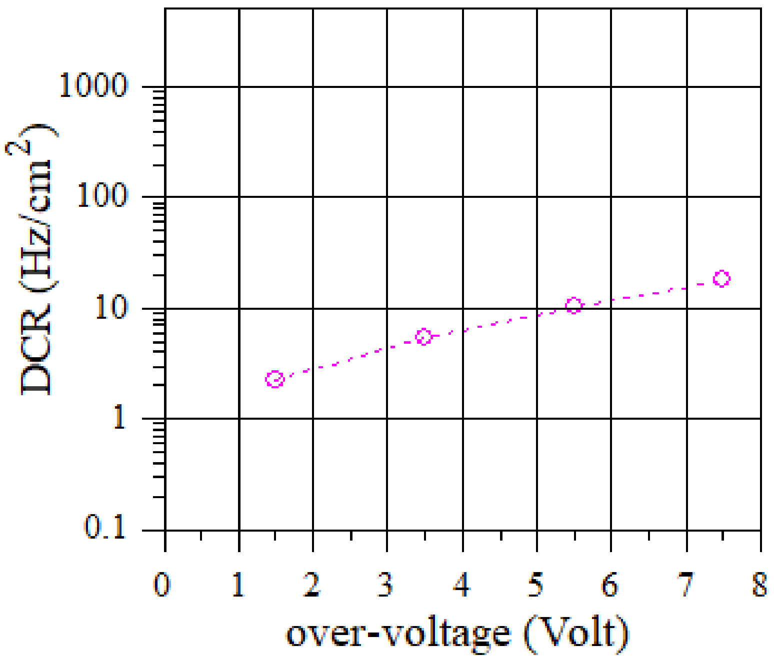
SiPM parameters

charge gain (in LN_2)



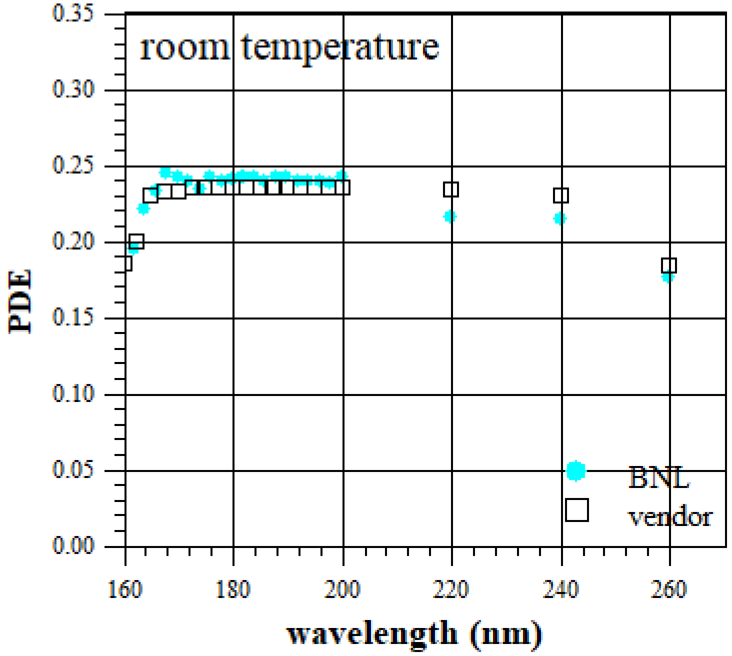
excellent photon number resolving capability

DCR (in LN_2)



extremely low dark rate

PDE (room)

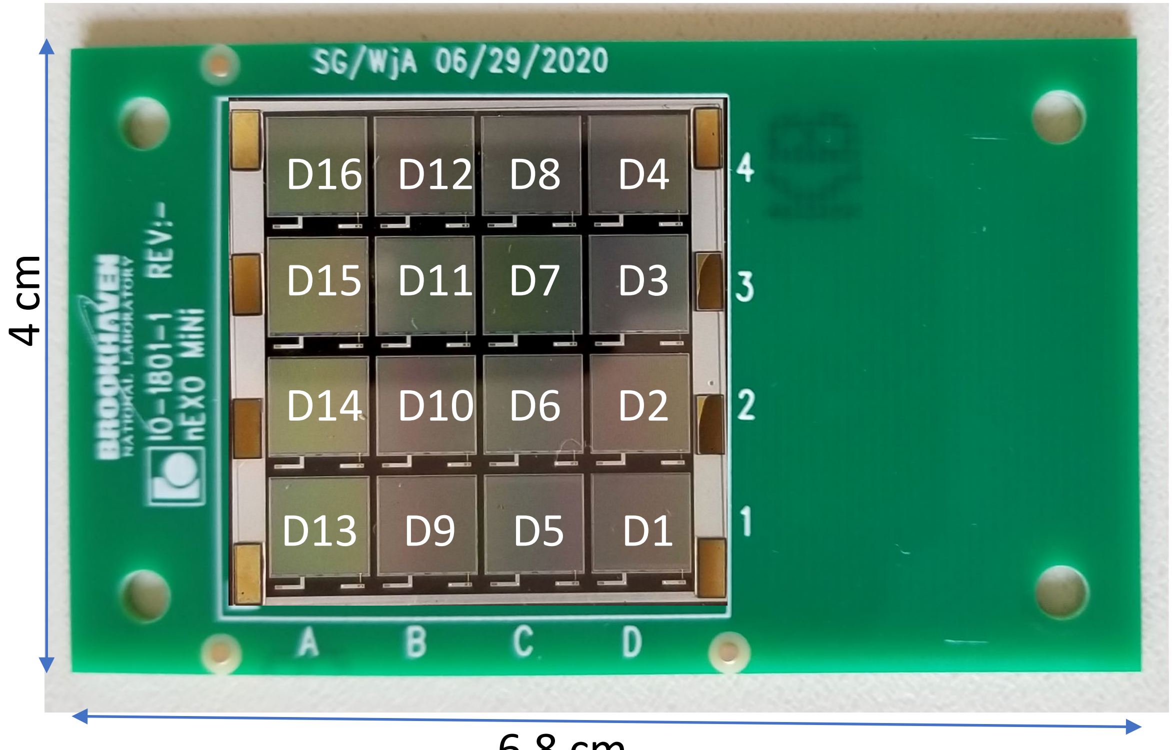


PDE agrees well with vendor

HPK SiPM Minitile arrays

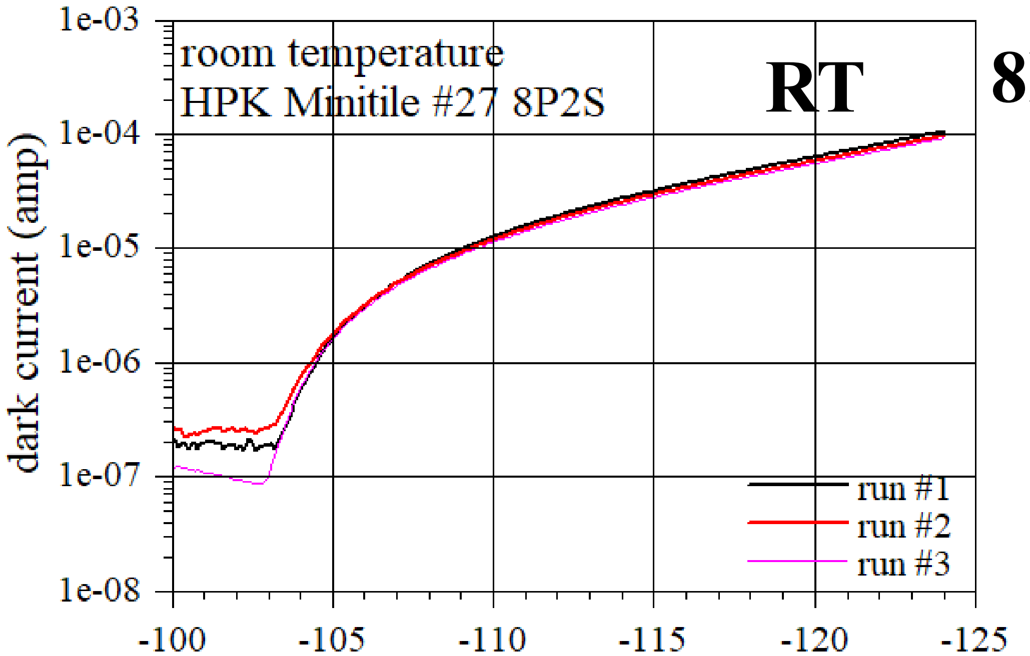
S13775-9121 [4x4x(0.6 cm)^2]

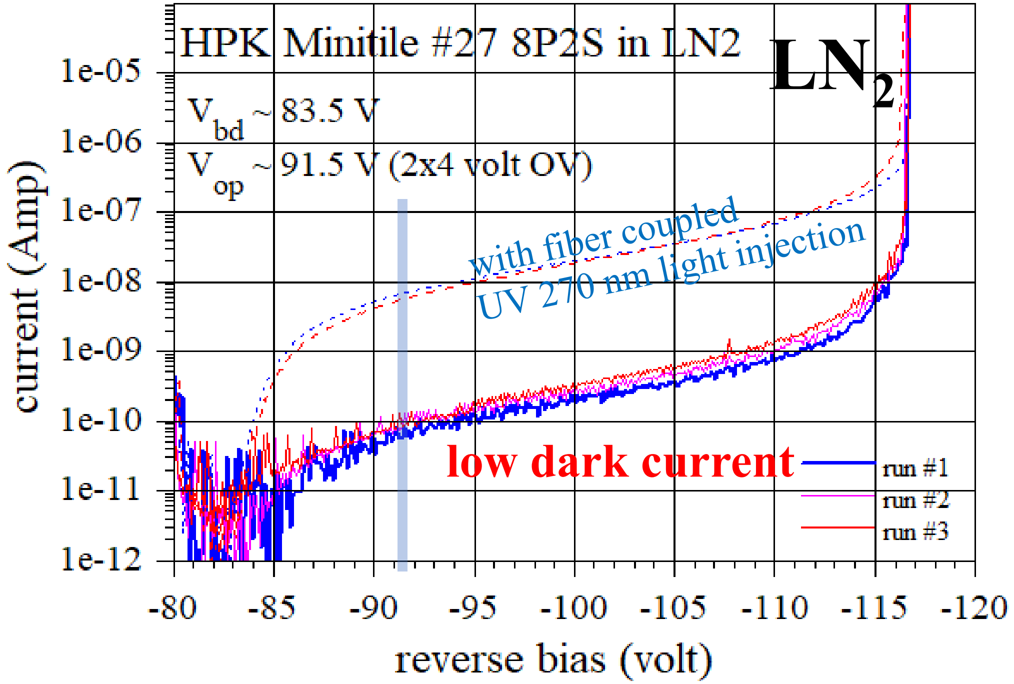
HPK minitile board



- active area=5.76 cm^2
- N_{cell} =16x13923=222768 pixels
- $C_{\mu cell}$ (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***

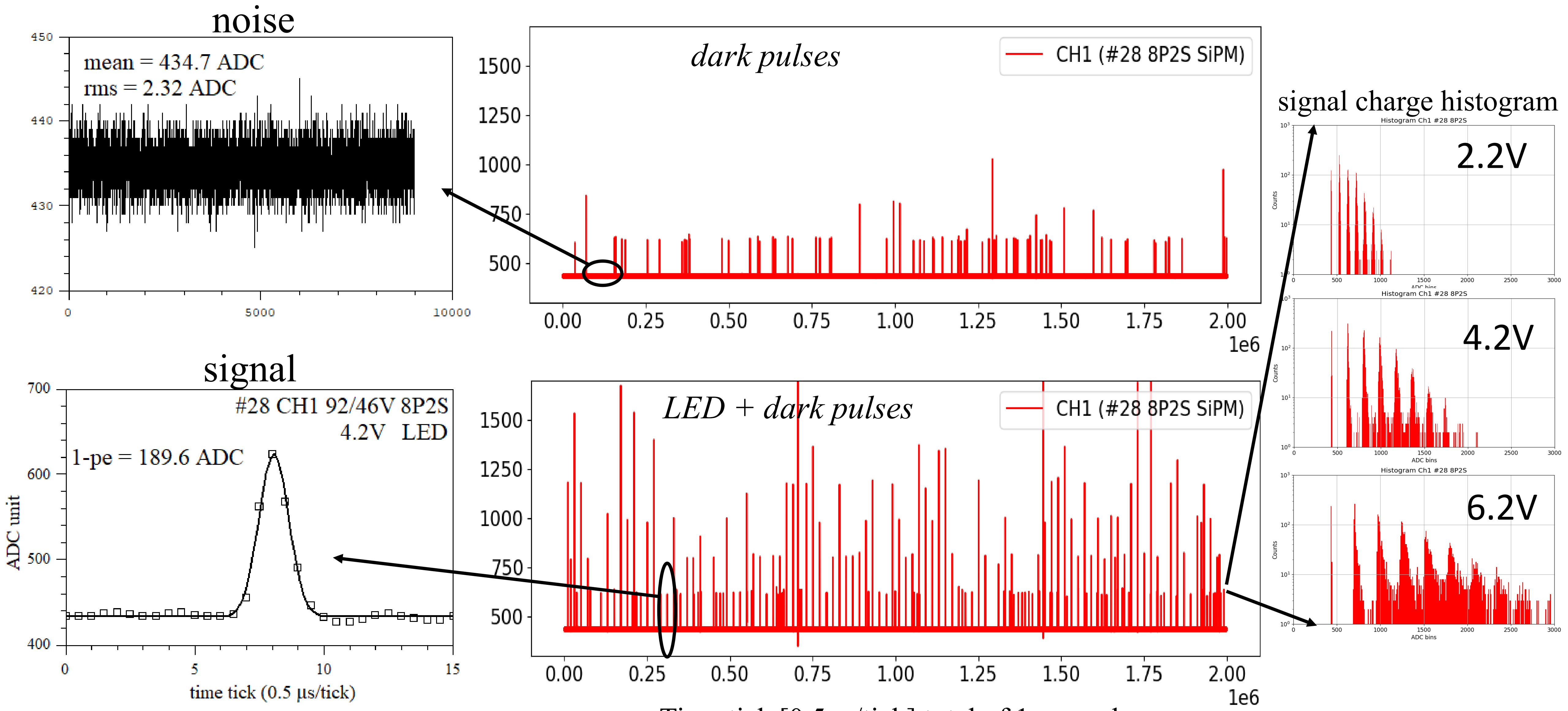
8P2S IV





At ~4V OV I_{dark} (DCR) RT→LN_2 drops ~10^{-5}

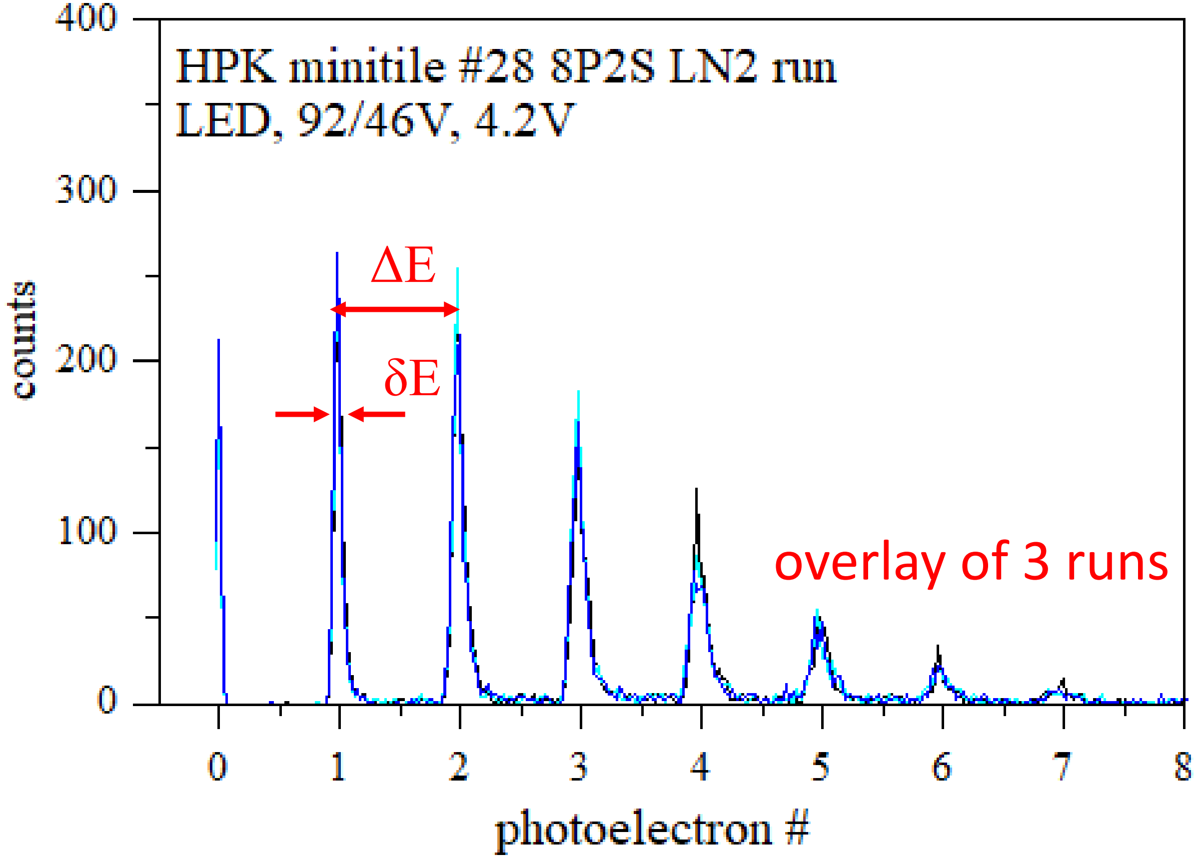
in LN_2 @ 4.2 V OV 8P2S 4.8 nF: subset of raw signal trace (1 second)



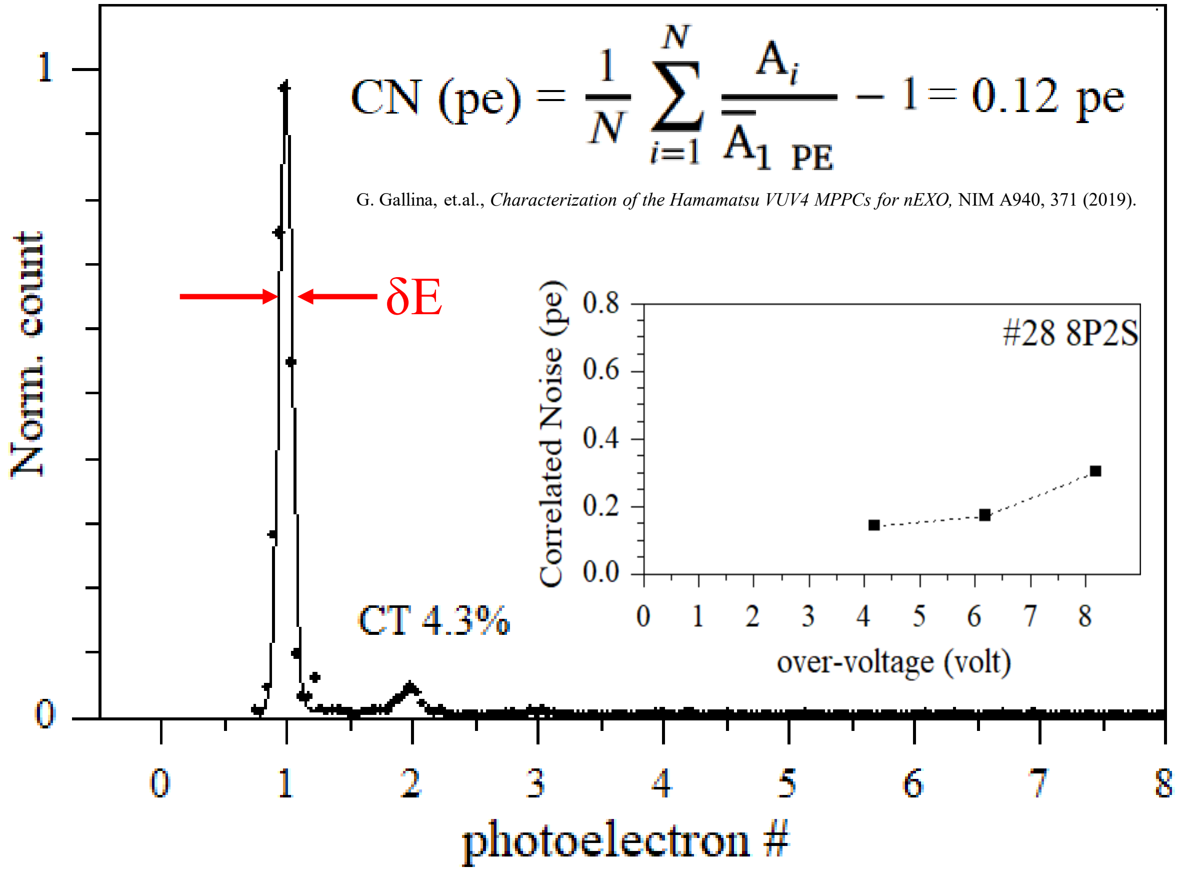
S/N = 189.6/2.32 ≈ 82

in LN_2: single-photoelectron charge histogram

LED photon flash (triggered)



dark pulse



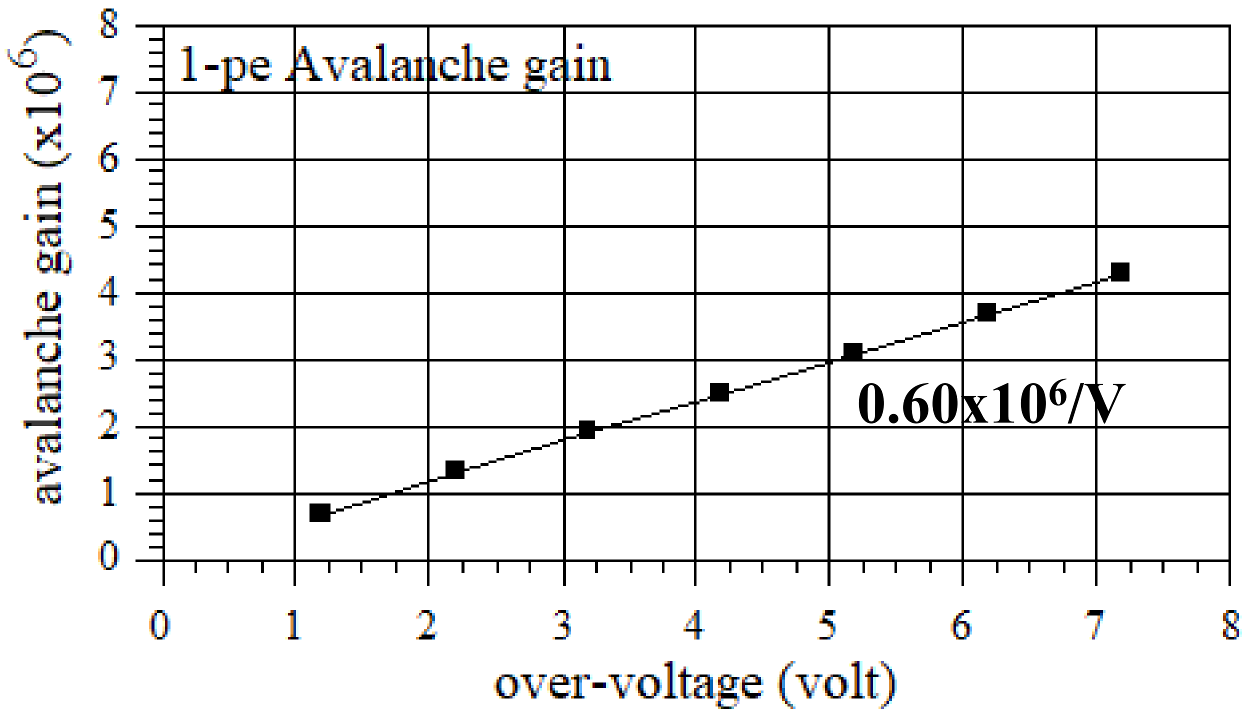
Photon rate: ~80 Hz (trigger rate 100 Hz)

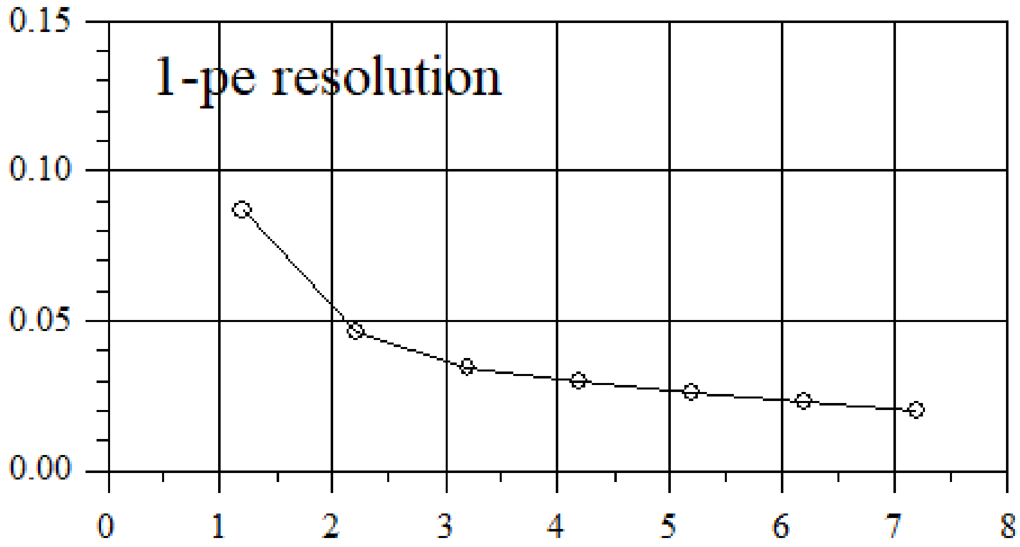
1-pe resolution ($\frac{\delta E}{\Delta E}$): <3.5% rms

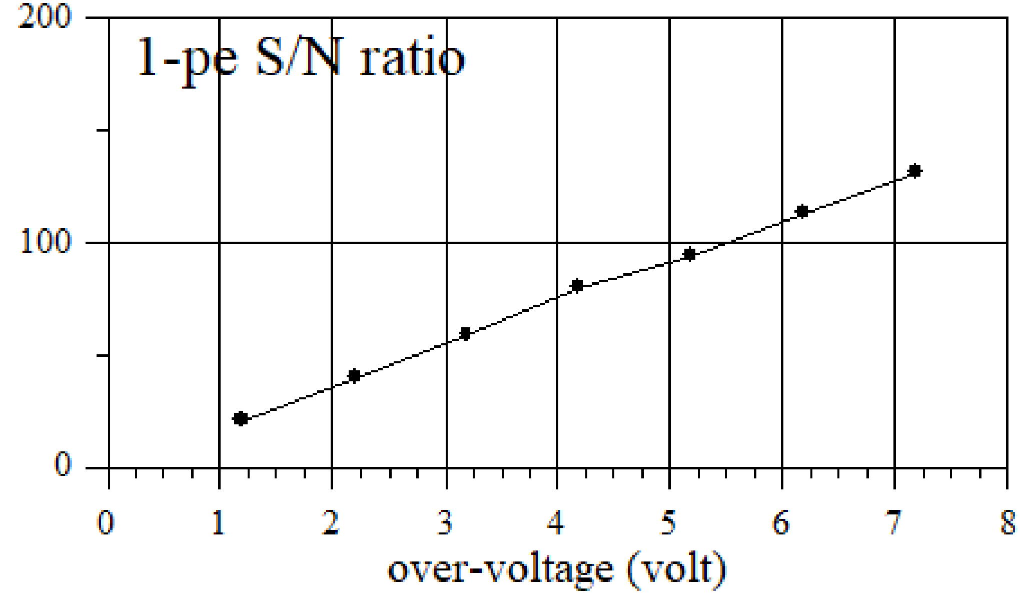
DCR: ~96 Hz (0.17 Hz/mm^2)

1-pe resolution: ~5% rms

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







Avalanche gain of both channels are similar

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

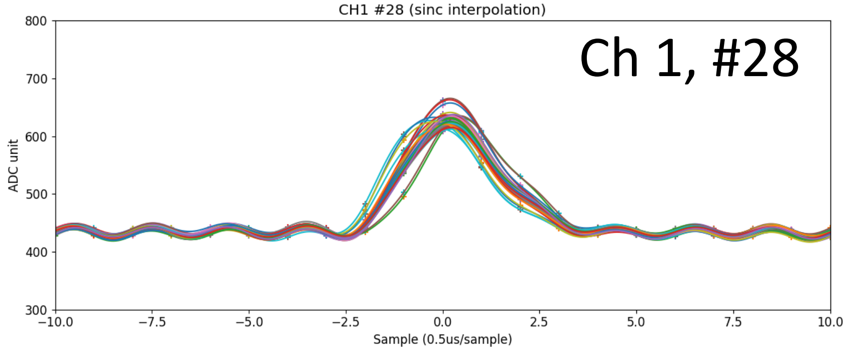
$C_{\mu cell}$ ~ 90 fF

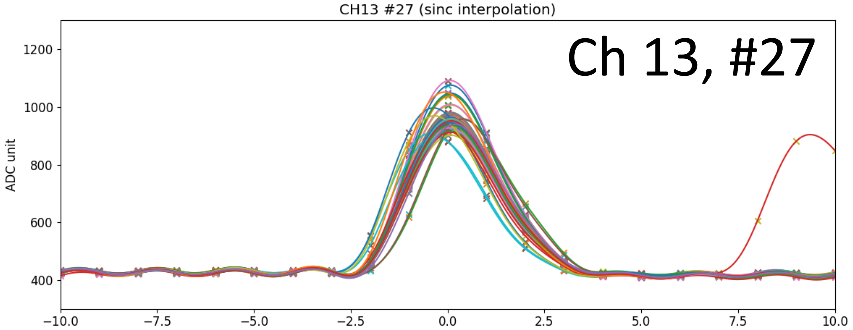
$C_{\mu cell} = \varepsilon_o\ \varepsilon_{Si}\ \frac{A}{d}$, d=depletion thickness

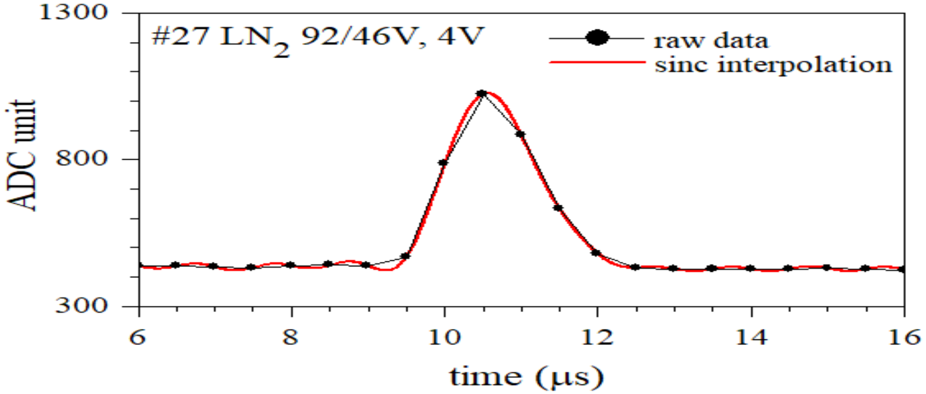
Single-Photoelectron Timing and Coincidence Resolution

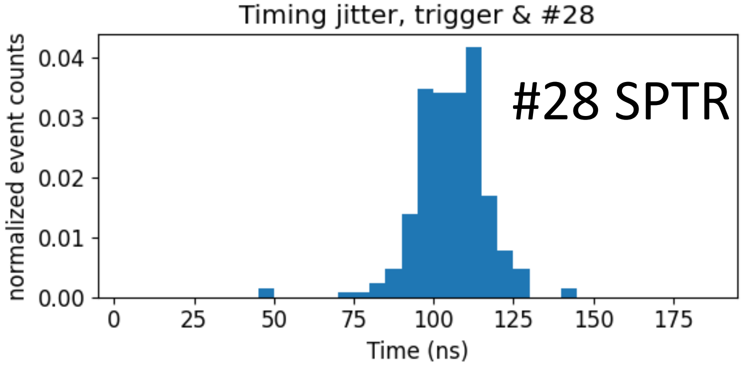
Select ONLY 1-pe pulses

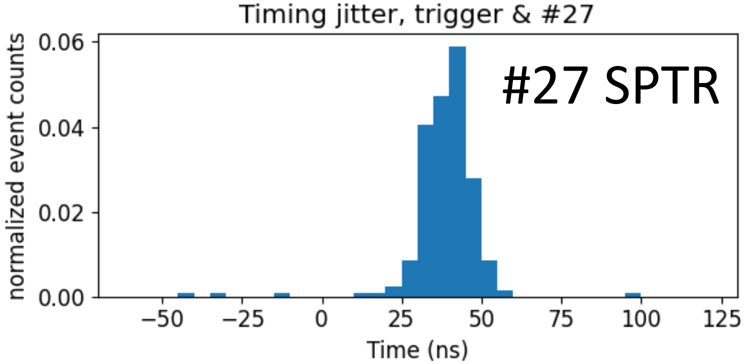
1-pe time jitter histogram, 45 sec data

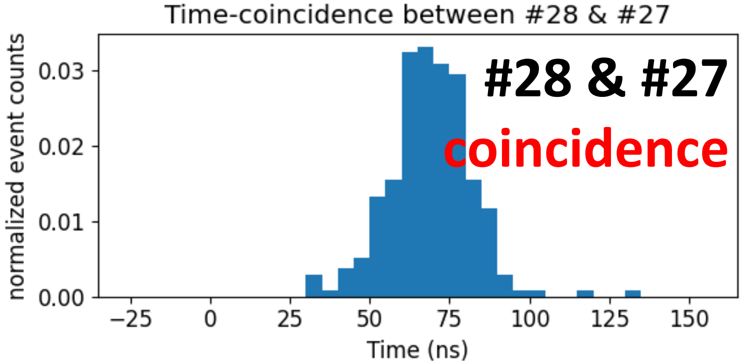












Photon flash 100 Hz
ADC sampling rate 2 MHz

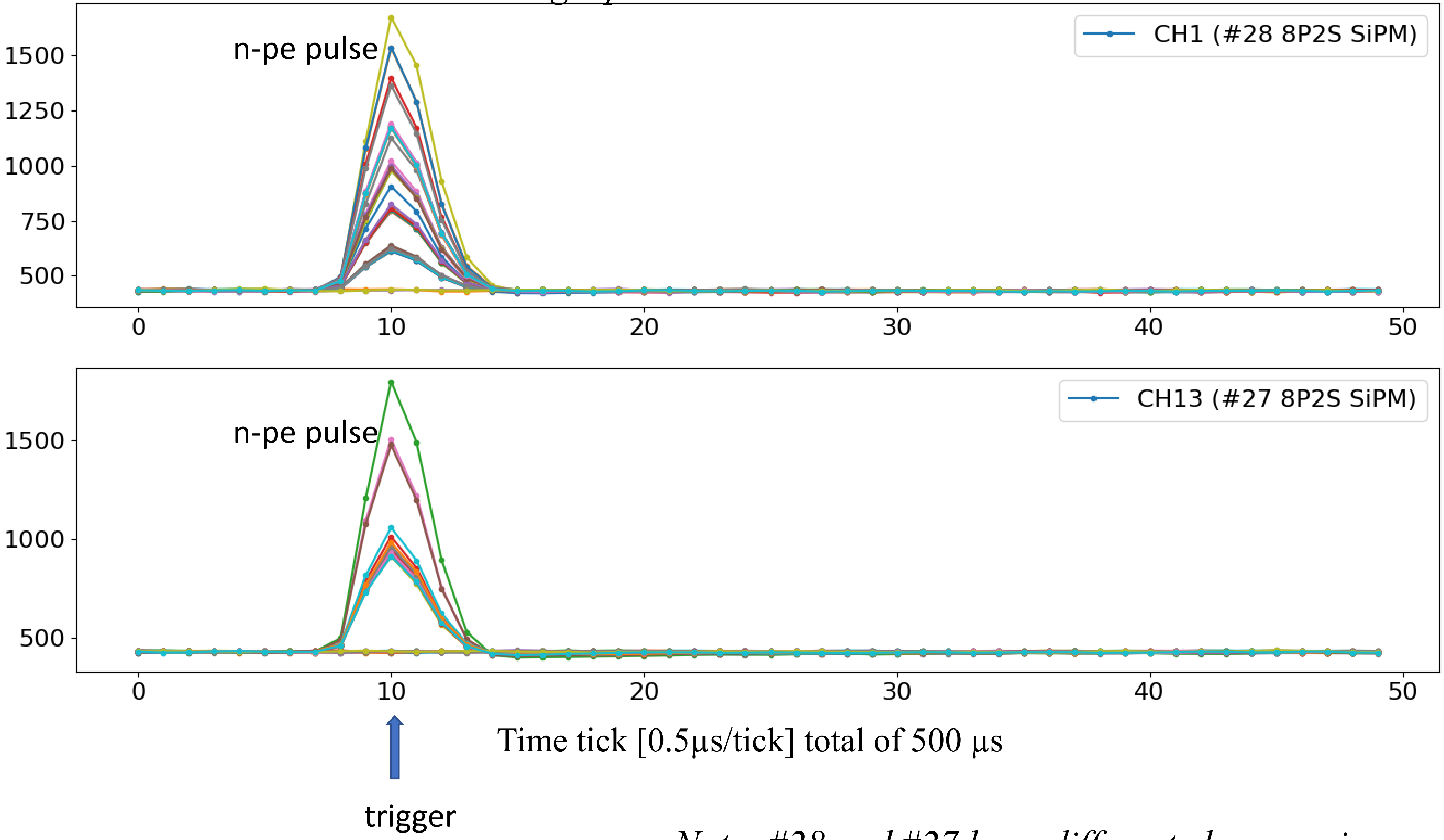
LN_2 4V	Average rate (Hz)	SPTR (ns)
#28	96	9.94
#27	250.6	6.57
Coinc.	67.3	**~11 ns**

coincidence window = 0.5 μs

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

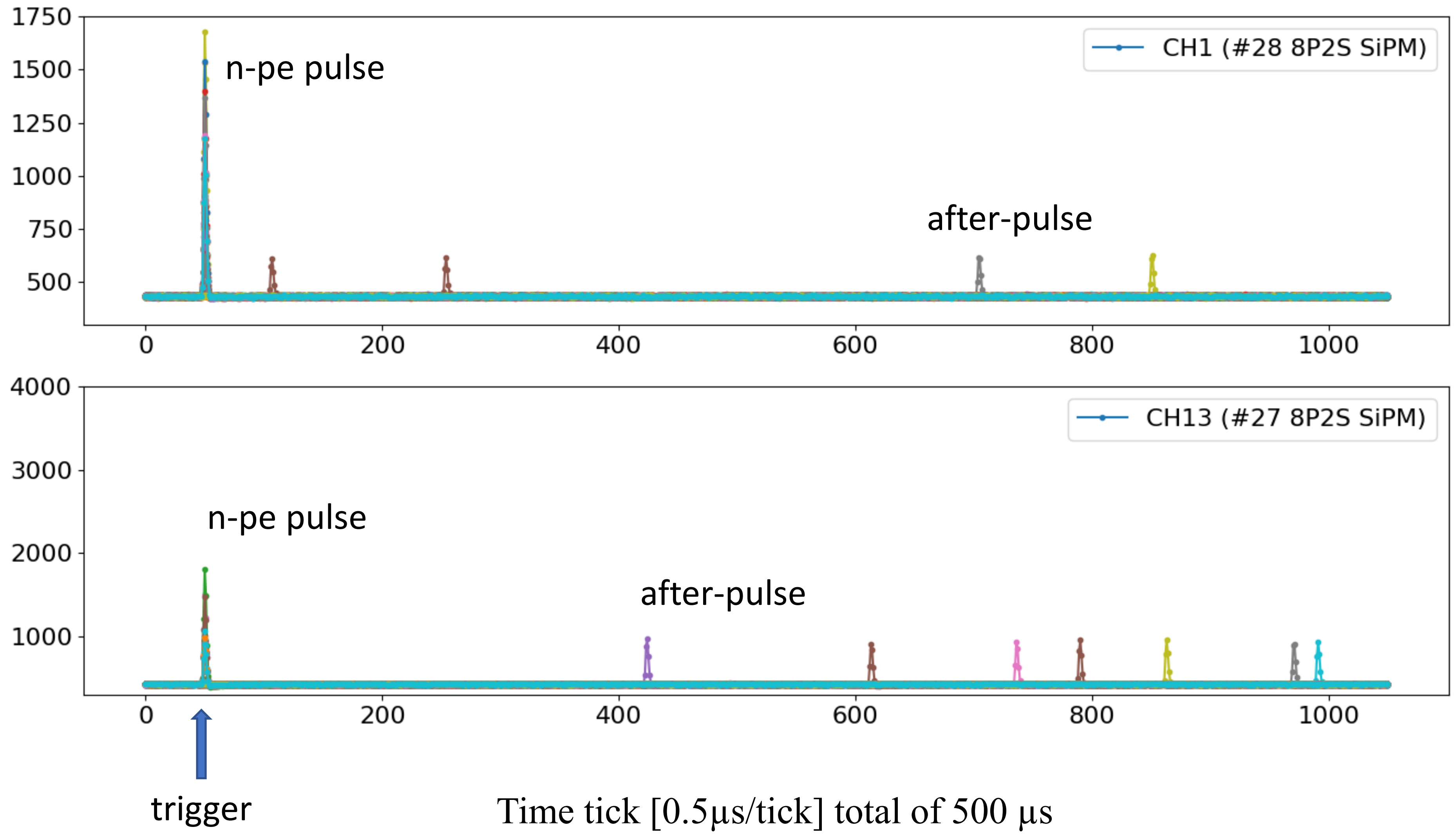
time coincidence detection: minitiles #27 & #28 – 10 MHz lock ON

single photoelectrons



Note: #28 and #27 have different charge gain

time coincidence detection: minitiles #27 & #28 – 10 MHz lock ON



Time tick [0.5µs/tick] total of 500 µs

after-pulse longer than µs: release of trapped charges after a characteristic time that depends on the type of the trapping centers and its occurrence probability increase in cryogenic temperature.

Mass testing of SiPMs

NIM A610 (2009)

T2K - Japan

Mass production test of Hamamatsu MPPC for T2K neutrino oscillation experiment

M. Yokoyama [a,*], T. Nakaya [a], S. Gomi [a], A. Minamino [a], N. Nagai [a], K. Nitta [a], D. Orme [a], M. Otani [a], T. Murakami [b], T. Nakadaira [b], M. Tanaka [b]

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[b] IPNS, High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

For quality assurance of the T2K neutrino detectors
~60,000 SiPMs (HPK) were tested:
gain (G), breakdown voltage (V_{bd}), noise rate (DCR), photo detection efficiency (PDE), and cross-talk (CT) and after-pulse(AP) rate are measured as functions of the bias voltage (V_b) and temp. (T)

NIM A985 (2021)

INFN - Milano

Cryogenic SiPM arrays for the DUNE photon detection system

A. Falcone [a,*], A. Andreani [c], S. Bertolucci [b], C. Brizzolari [a], N. Buckanam [d], M. Capasso [f], C. Cattadori [a], P. Carniti [a], M. Citterio [c], K. Francis [e], N. Gallice [c], A. Gola [f], C. Gotti [a], I. Lax [b], P. Litrico [g], A. Mazzi [f], M. Mellinato [a], A. Montanari [b], L. Patrizii [b], L. Pasqualini [b], G. Pessina [a], M. Pozzato [b], S. Riboldi [c], P. Sala [c], G. Sirri [b], M. Tenti [a,b], F. Terranova [a], M. Torti [a], R. Travaglini [b], D. Warner [d], R. Wilson [d], V. Zutshi [e]

[a] INFN Milano Bicocca and University of Milano Bicocca, Department of Physics, Milano, Italy
[b] INFN Bologna and University of Bologna, Department of Physics, Bologna, Italy
[c] INFN Milano and University of Milano, Department of Physics, Milano, Italy
[d] Colorado State University, Fort Collins, CO, USA
[e] Northern Illinois University, Department of Physics, DeKalb, IL, USA
[f] Fondazione Bruno Kessler, Trento, Italy
[g] INFN, Laboratori Nazionali del Sud (LNS), Catania, Italy

For quality assurance of the DUNE photon detection system
100-1000 SiPMs (FBK & HPK) were tested:
cryo-reliability: electric and mechanical stability vs. thermal cycle,
I–V curve, Dark Count Rate (DCR) and correlated noise CN(OV).
Single photoelectron sensitivity as a function of the total number of sensors connected.

BNL ?

For quality assurance of the FD3-4 photon detection system
test of x # SiPMs (FBK & HPK) are being discussed:
I-V, G, V_{bd}, DCR, CN: CT, AP (OV), relative PDE ...