# Proposal to Test Improved Radiation Tolerant Silicon Photomultipliers

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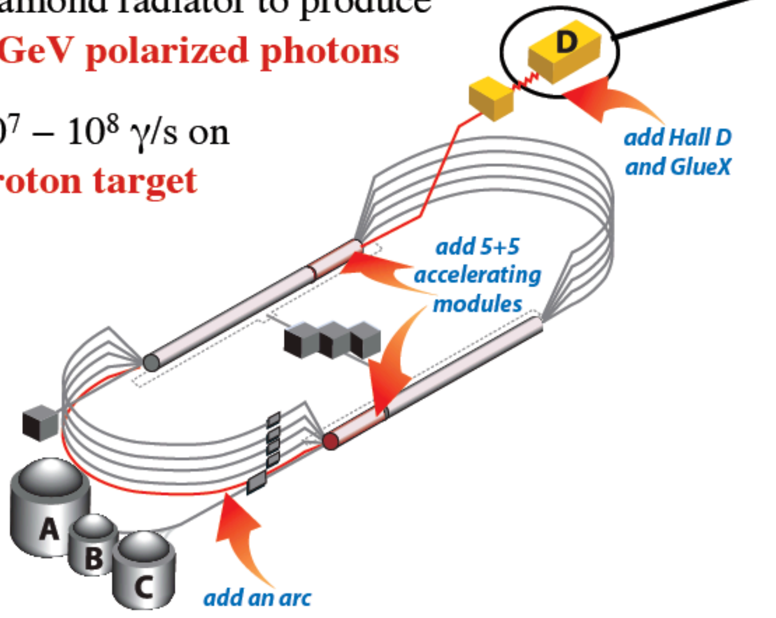
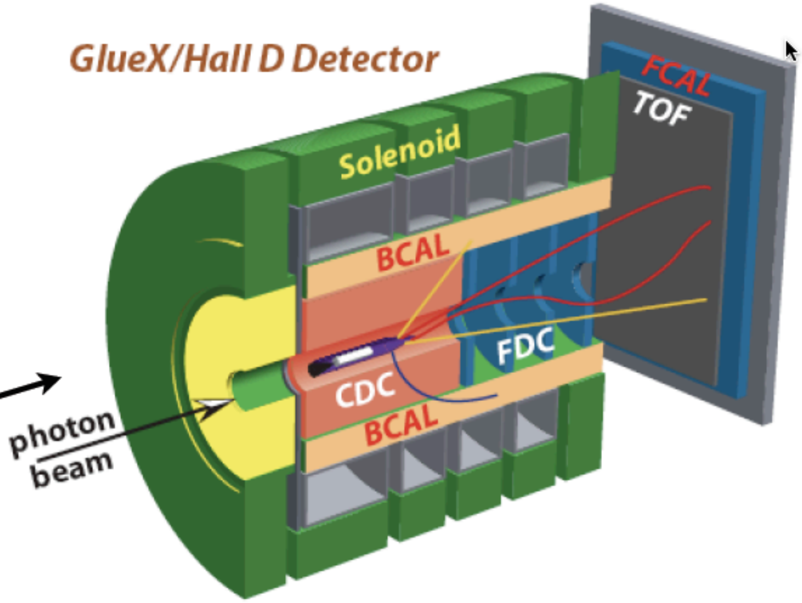
# GlueX overview

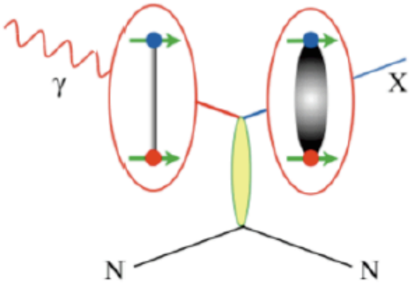
Use **9 GeV polarized photons** on a **proton target** to produce **hybrid mesons** with exotic $J^{PC}$:

- part of the JLab 12 GeV upgrade
  *(in Newport News, Virginia)*
- data expected in 2014
- use 12 GeV electrons and a diamond radiator to produce **9 GeV polarized photons**
- $10^7 - 10^8$ γ/s on **proton target**





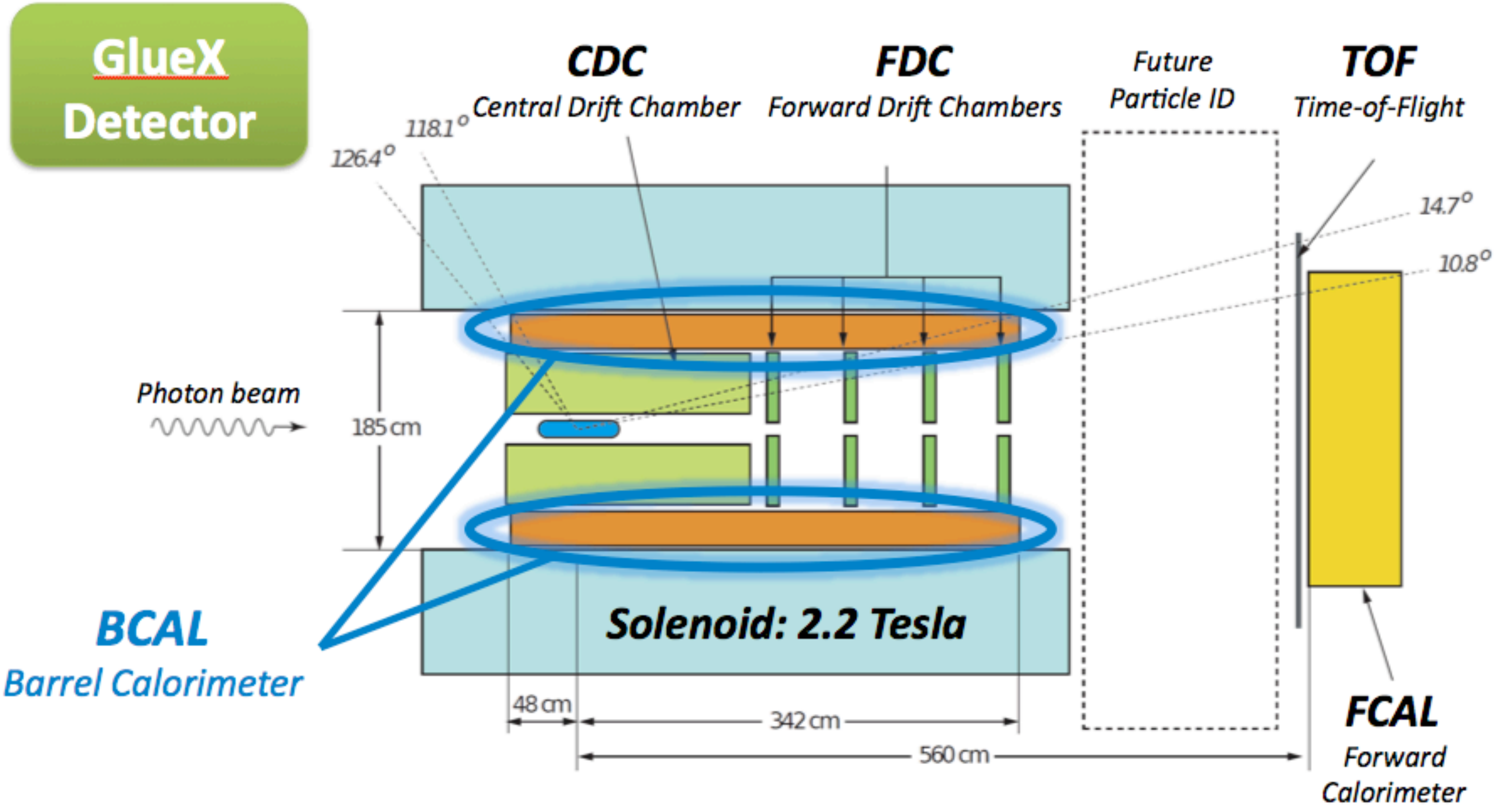
- produce **hybrid mesons** with exotic $J^{PC}$:



- use "amplitude analyses" to distinguish $J^{PC}$

# Barrel Calorimeter - BCAL

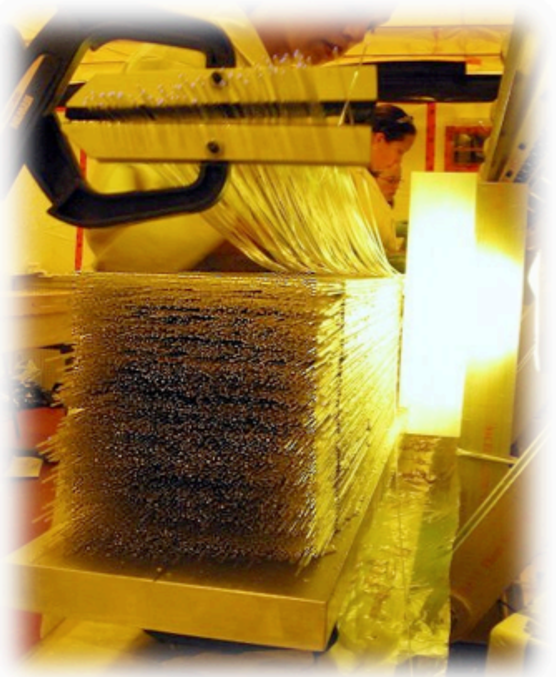
**GlueX Detector**



A **390 cm** long **Electromagnetic** **Barrel Calorimeter** (**BCAL**) is inserted into the solenoid which generates a **2.2 Tesla** magnetic field to detect particles in large angles. It measures *energy deposition* between 50 MeV to 5 GeV and provides *timing* and *position* information.

# BCAL – University of Regina

## Barrel Calorimeter

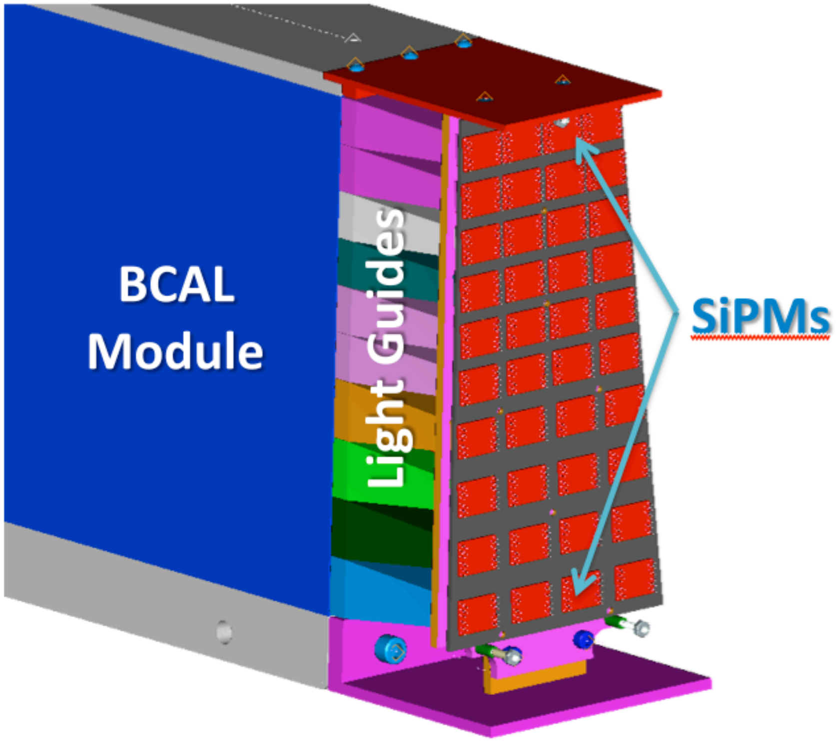


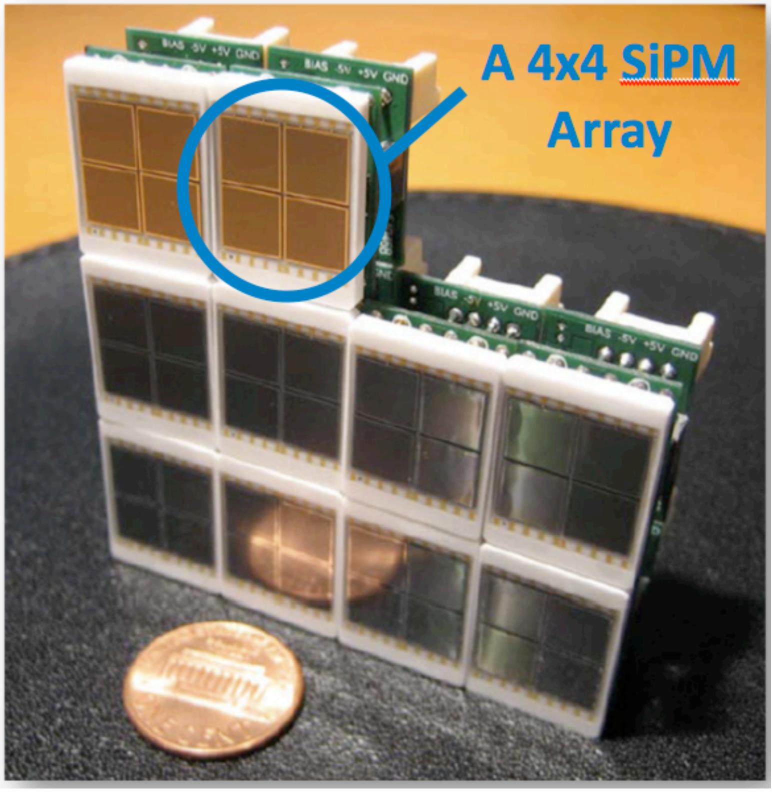
BCAL module being assembled from layers of fibers and Pb

- 48 modules arranged into cylinder
- Scintillating fiber + Pb
- 12.5% sampling fraction
- $\sigma_E/E = \frac{5.5\%}{\sqrt{E}} \oplus 1.6\%$
- $\sigma_z = \frac{5mm}{\sqrt{E}}$
- $\sigma_t = \frac{75ps}{\sqrt{E}} \oplus 33ps$
- $11^o < \alpha < 120^o$
- Double-ended readout
- 300 km of fiber

Polished BCAL module demonstrating optical clarity with cell phone held to opposite end

# BCAL Photodetector



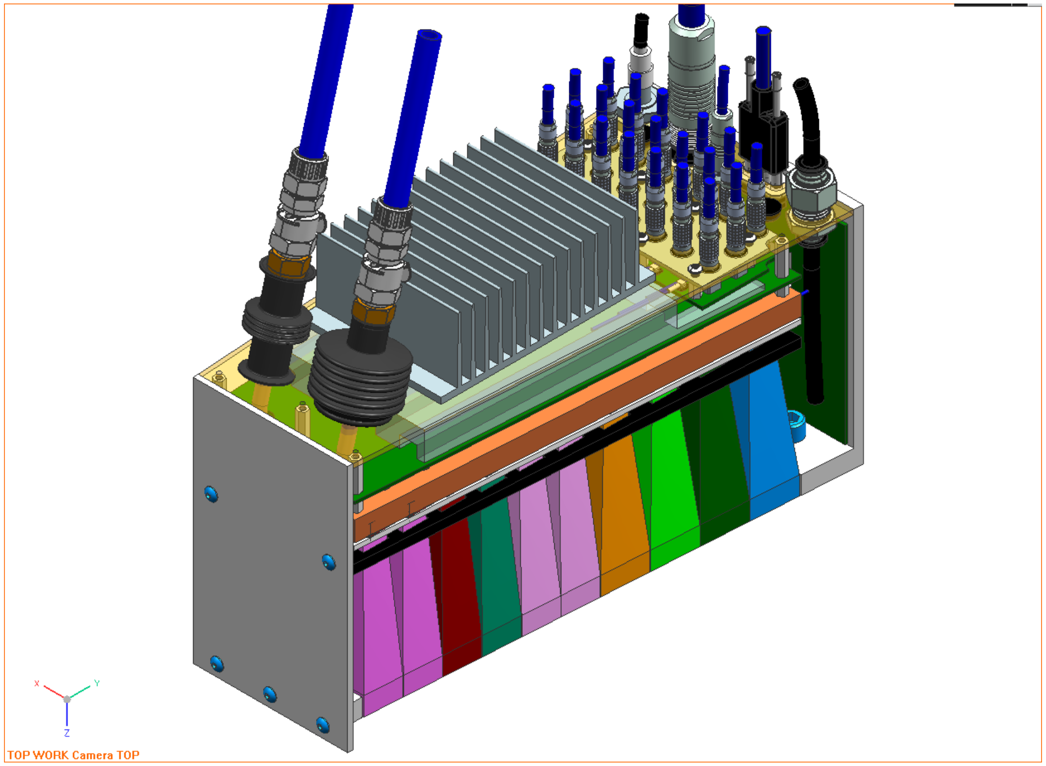


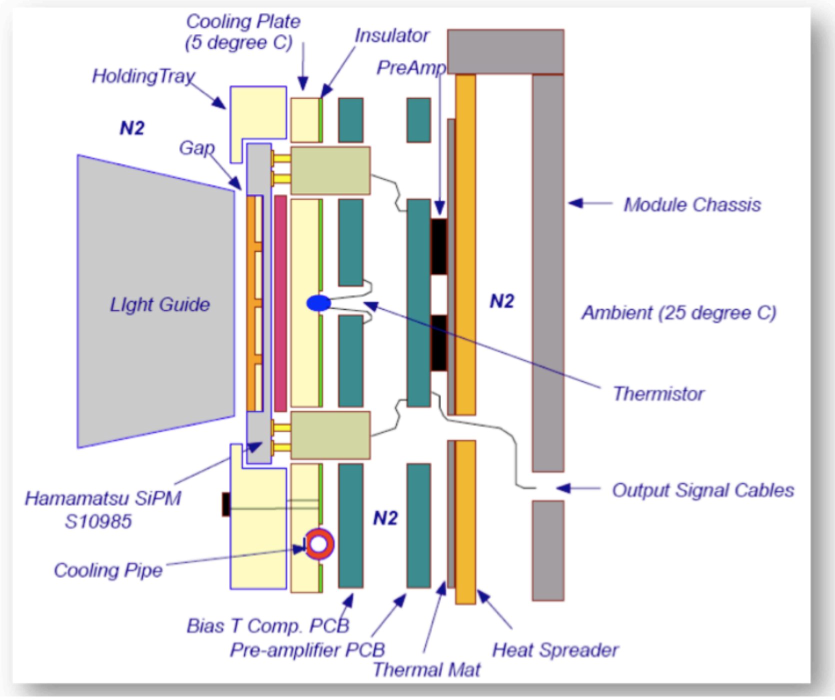
- 4x4 array of 3x3 mm$^2$ SiPM cells
- 50 $\mu$m microcells
- 57,600 microcells per array
- Photon Detection Efficiency (PDE) > 20%

- Gain ~ $10^6$
- Immune to strong magnetic fields
- Noise = 24 MHz per array
- Total SiPMs needed = 3,840
- 48 modules x 40 SiPMs x 2 sides

# SiPM Readout – Temperature Control

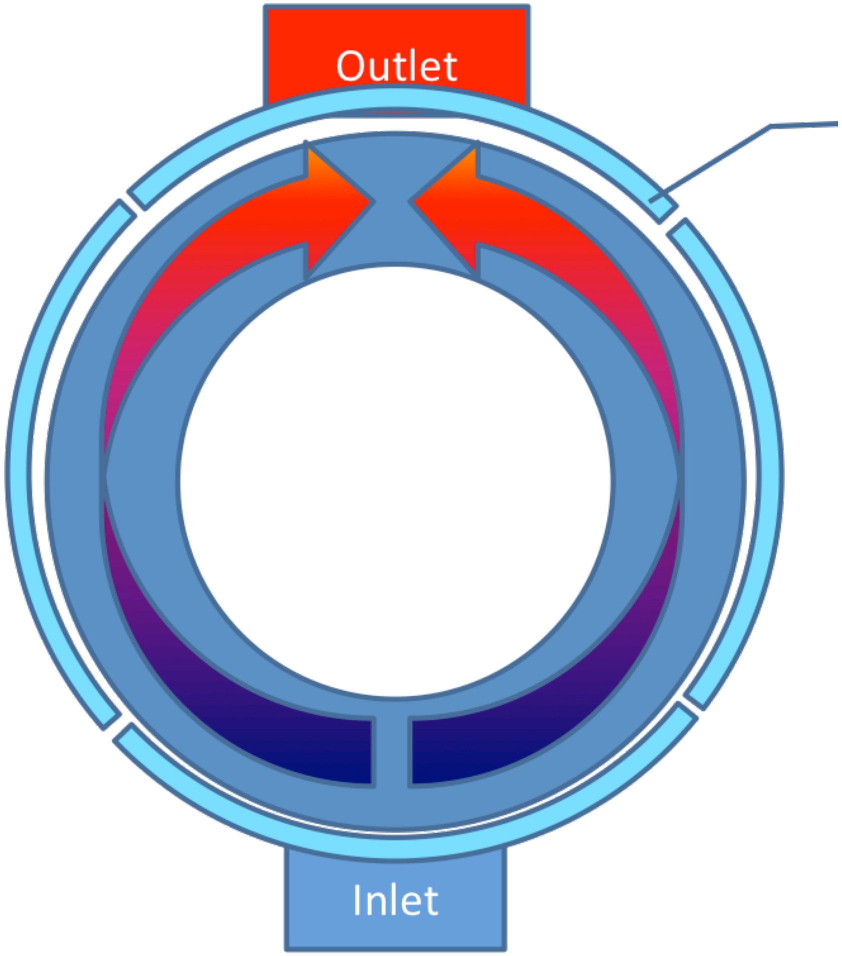
- SiPMs will be cooled to 5°C
- This will reduce dark noise and minimize effects of neutron irradiation





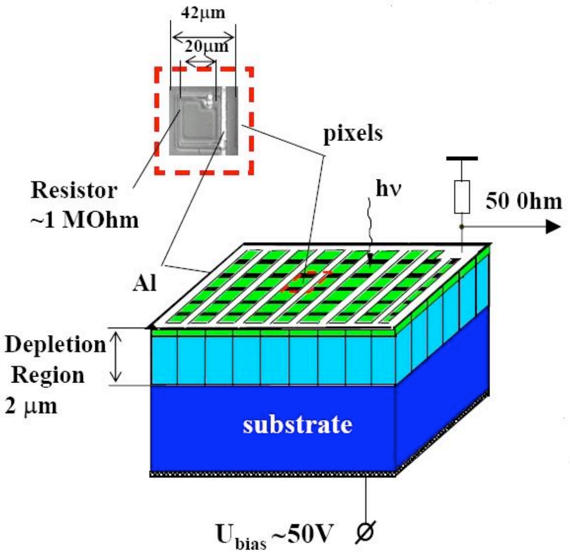
- Downtime ➔ SiPMs will be heated to ~40°C
- Achieve post-irradiation anneal to residual level

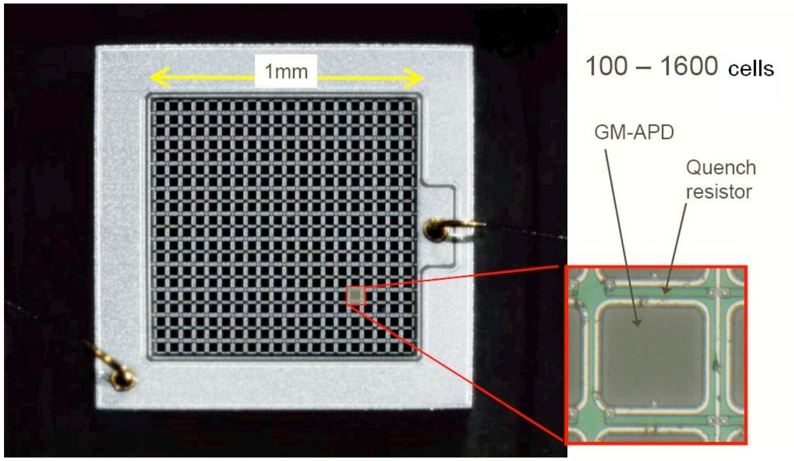
# Circulation of dry nitrogen (or air)

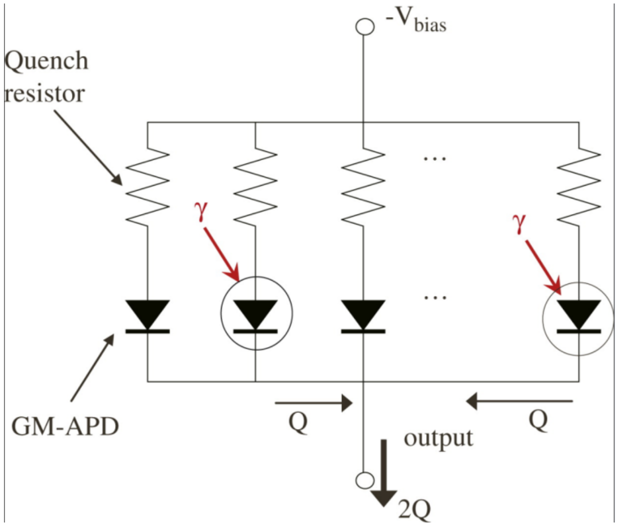


All wedges are connected and dry nitrogen flows throughout the readout volume to keep moisture out.

# A Bit of History



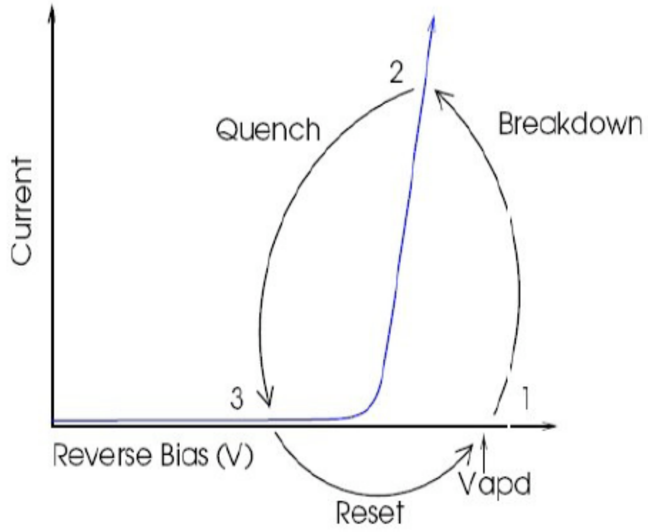




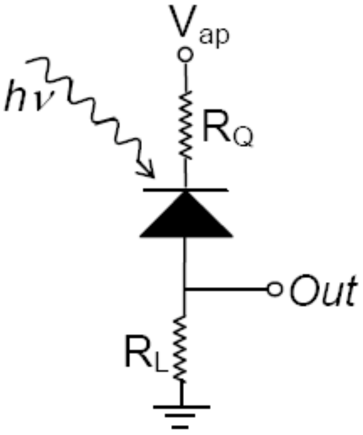
Example SiPM – V. Golovin, Z. Sadygov
NIM A504 (2003) 48

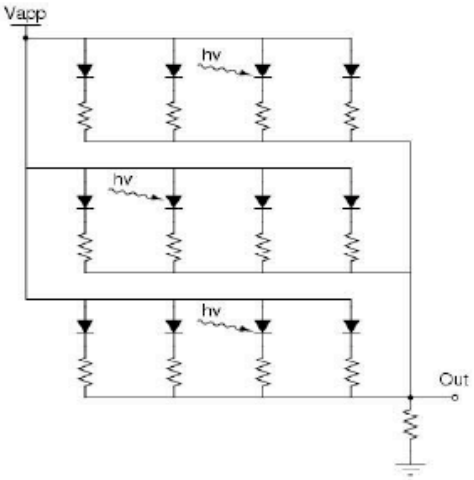
Array of microcell G-APDs readout in parallel – sum binary signal into analog sum

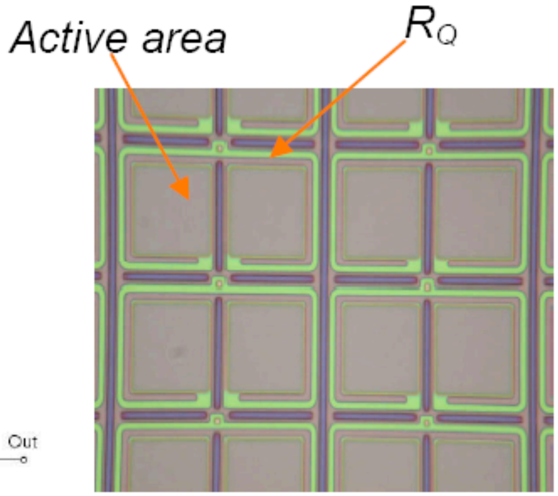
# Multipixel Geiger mode APD



→ Silicon PMT

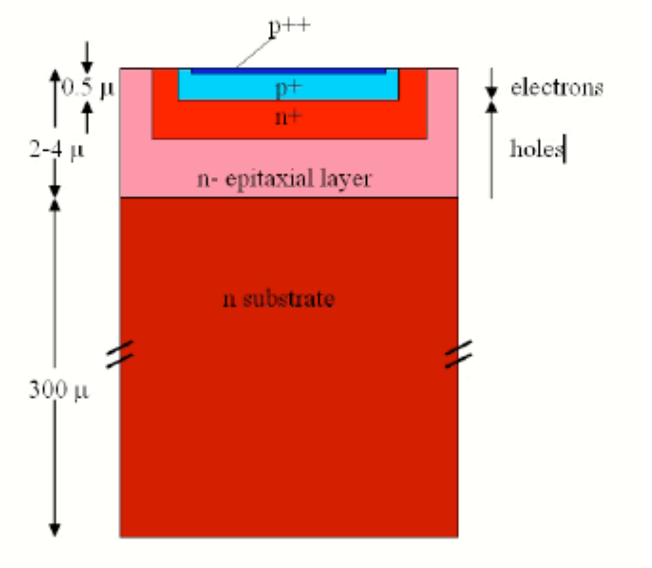






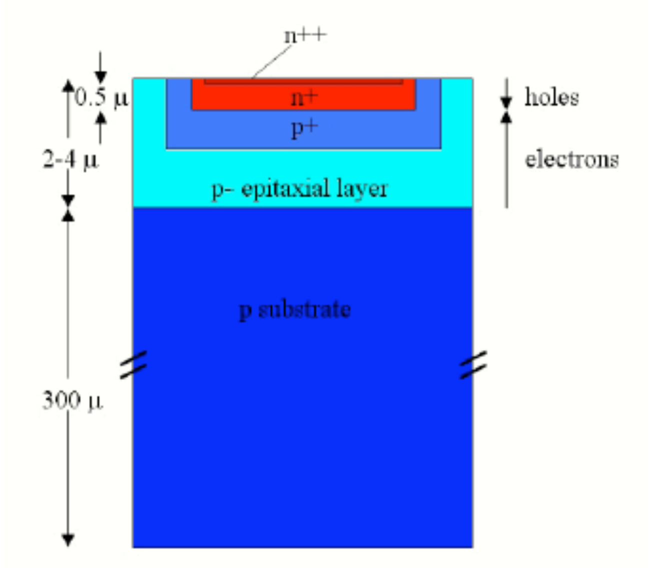
# G-APD Structures

Hamamatsu



“p on n”
Higher breakdown voltage (70V)
Blue-peaked sensitivity
Less dark noise

SensL

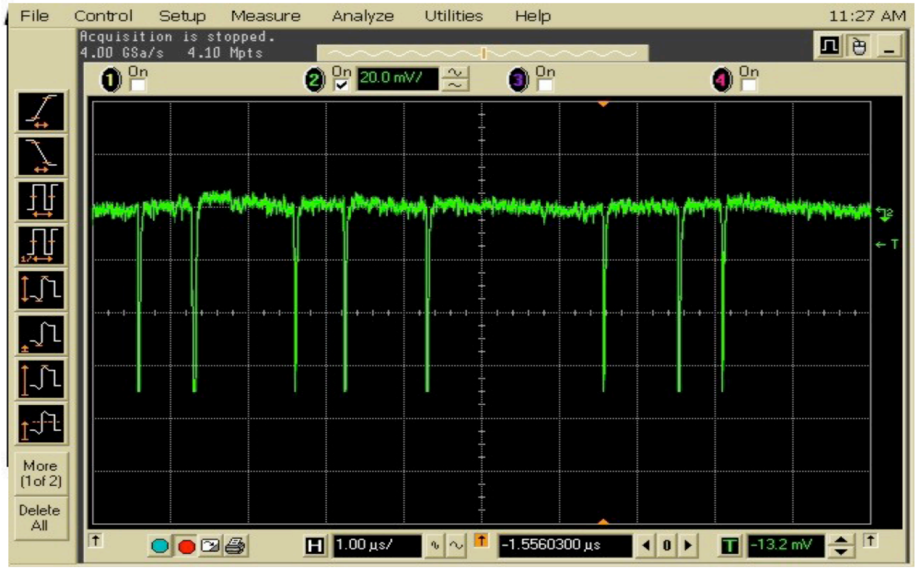


“n on p”
Lower breakdown voltage (30V)
Green-red sensitivity
More dark noise

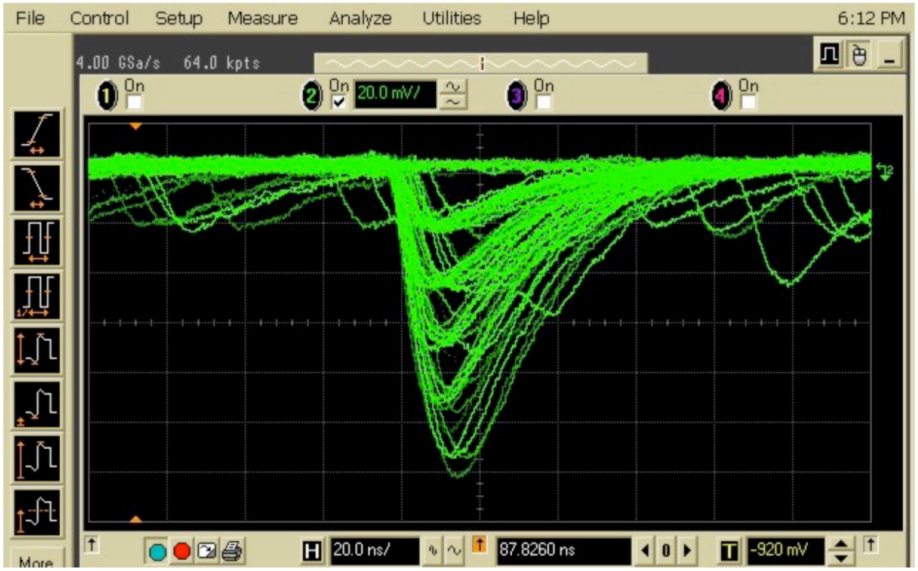
# Silicon Photomultiplier

Uniform gain – $10^5$ – $10^6$

Resolve single photons



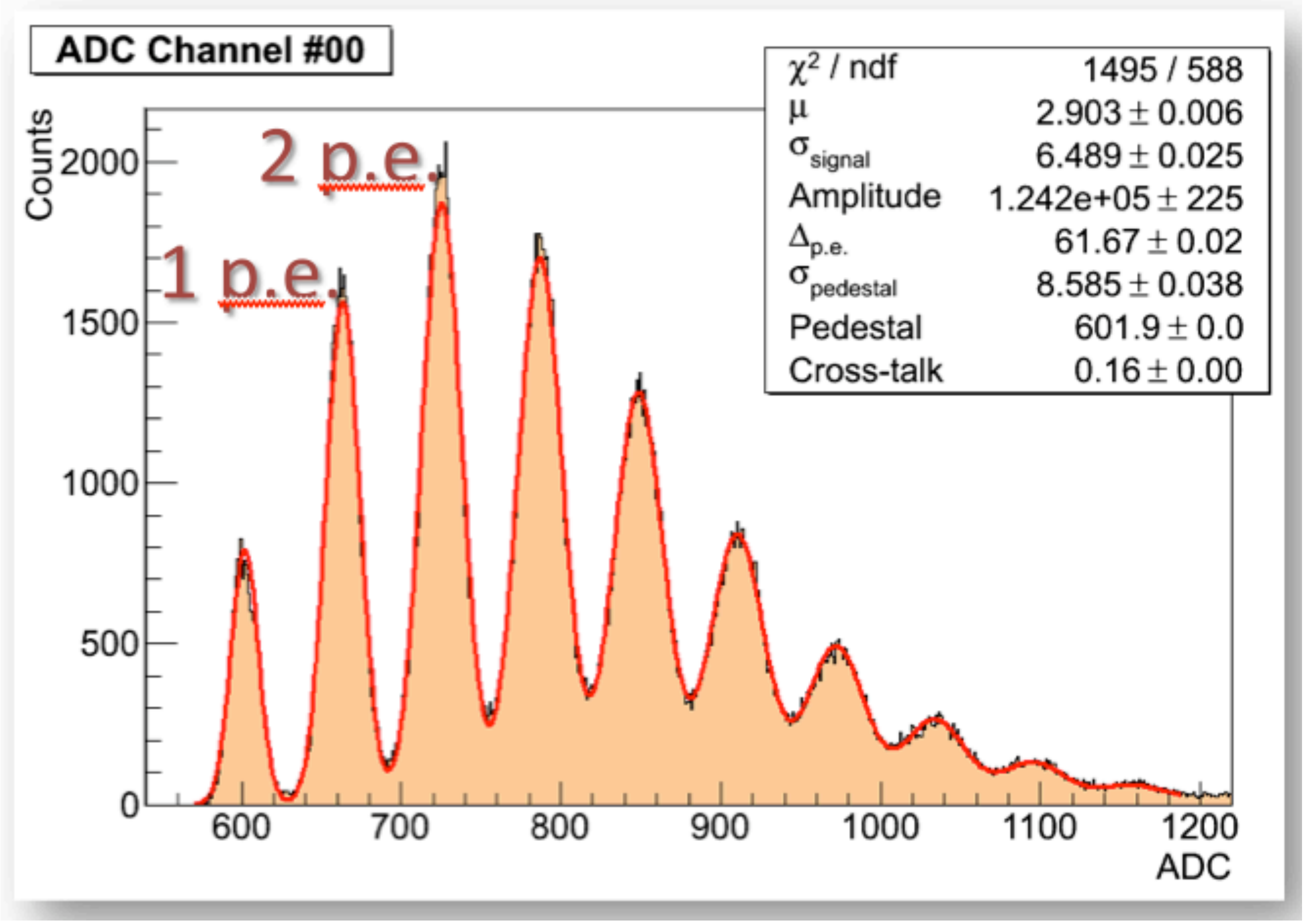
Acquisition is stopped.
4.00 GSa/s 4.10 Mpts
① On ☐ ② On ☑ 20.0 mV/ ③ On ☐ ④ On ☐
H 1.00 µs/ -1.5560300 µs T -13.2 mV



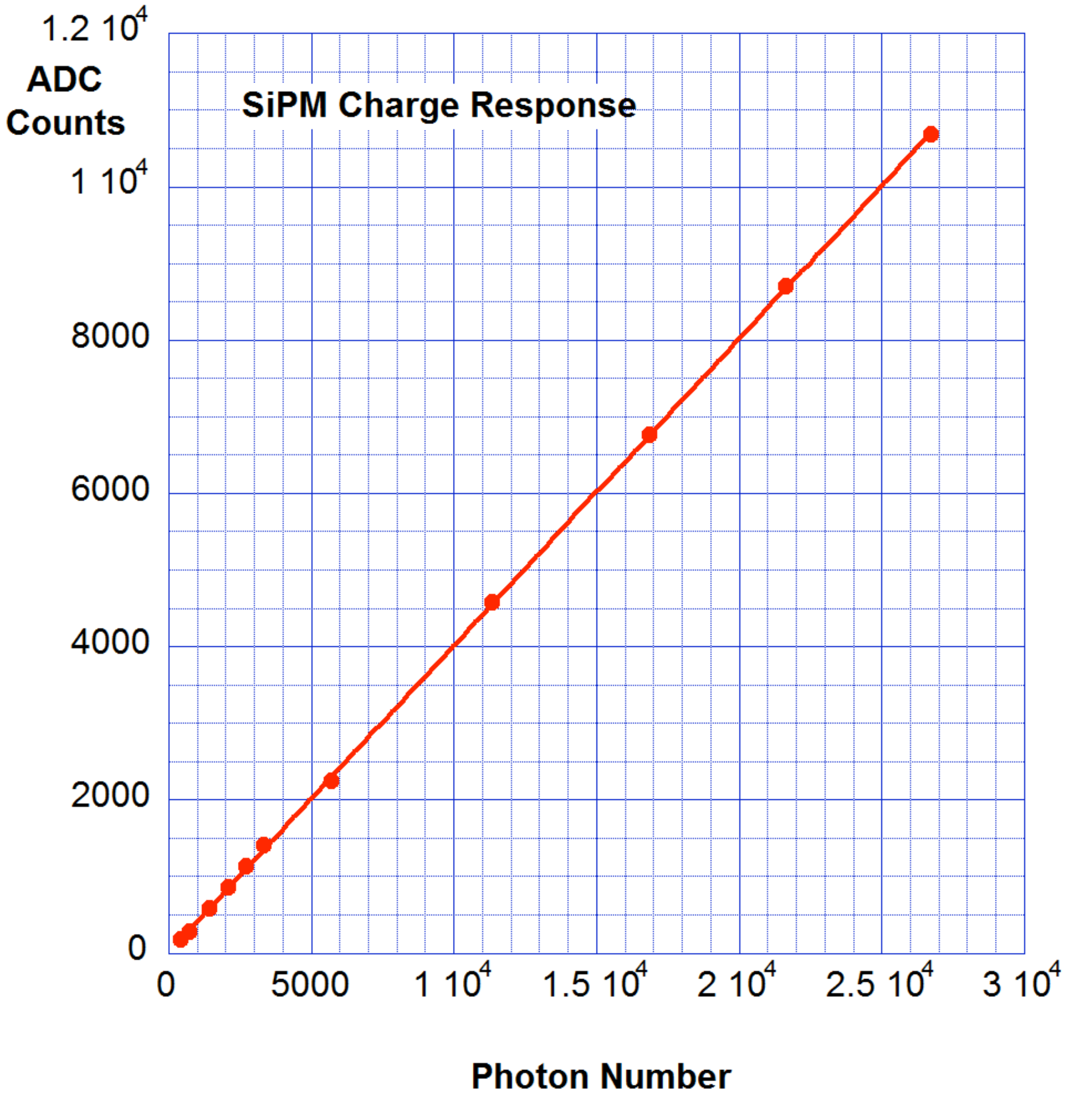
4.00 GSa/s 64.0 kpts
① On ☐ ② On ☑ 20.0 mV/ ③ On ☐ ④ On ☐
H 20.0 ns/ 87.8260 ns T -920 mV

Sum the pixels – $N_{signal} \sim N_\gamma$ for $N_\gamma \ll N_{pixels}$

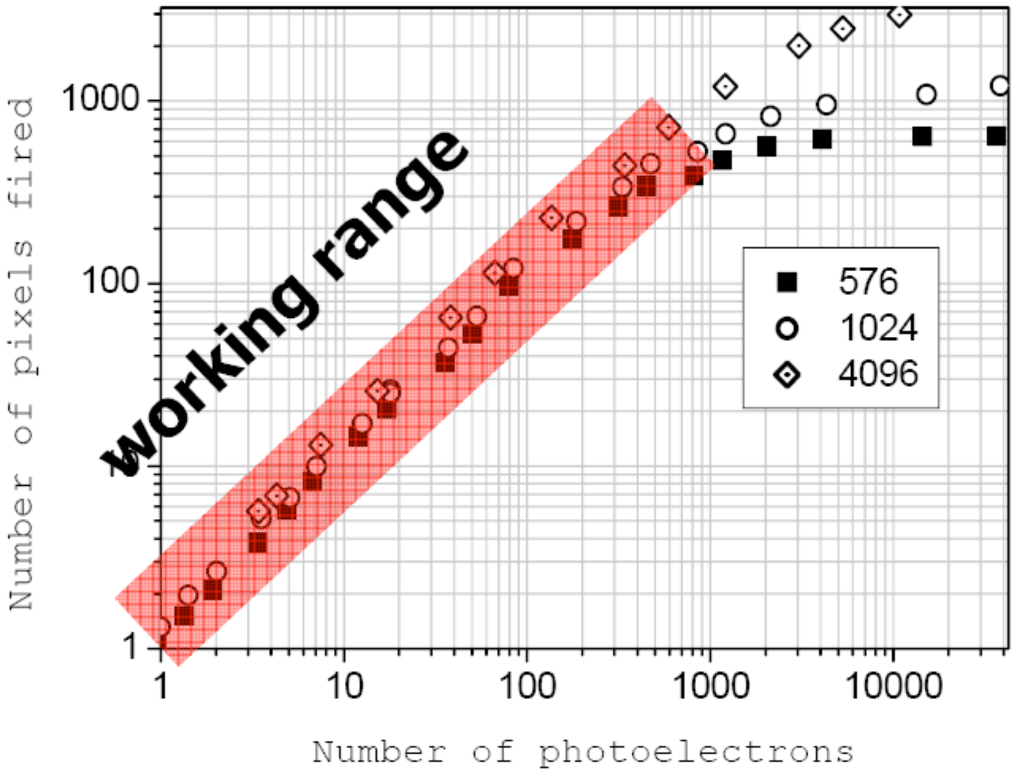
# Counting Photons at Room Temperature



# Linear Response

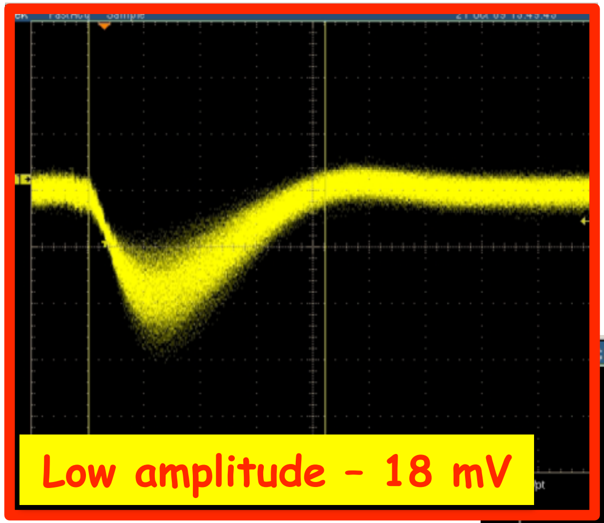


# Dynamic Range



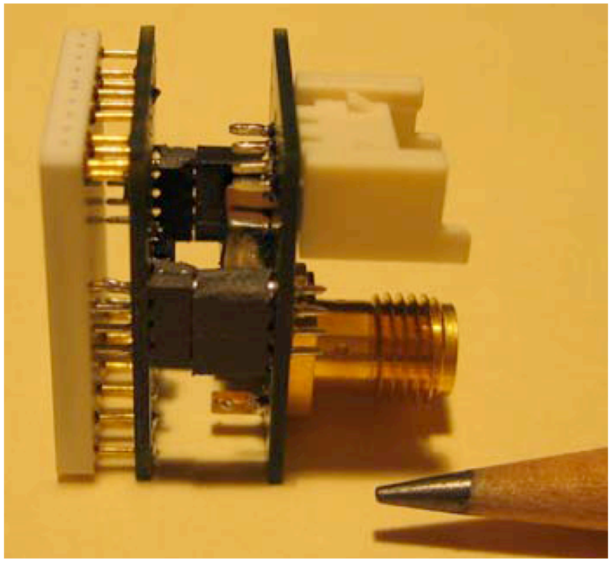
$$N_{firedcells} = N_{available} \cdot \left[ 1 - e^{-\frac{N_{photon} \cdot PDE}{N_{available}}} \right]$$

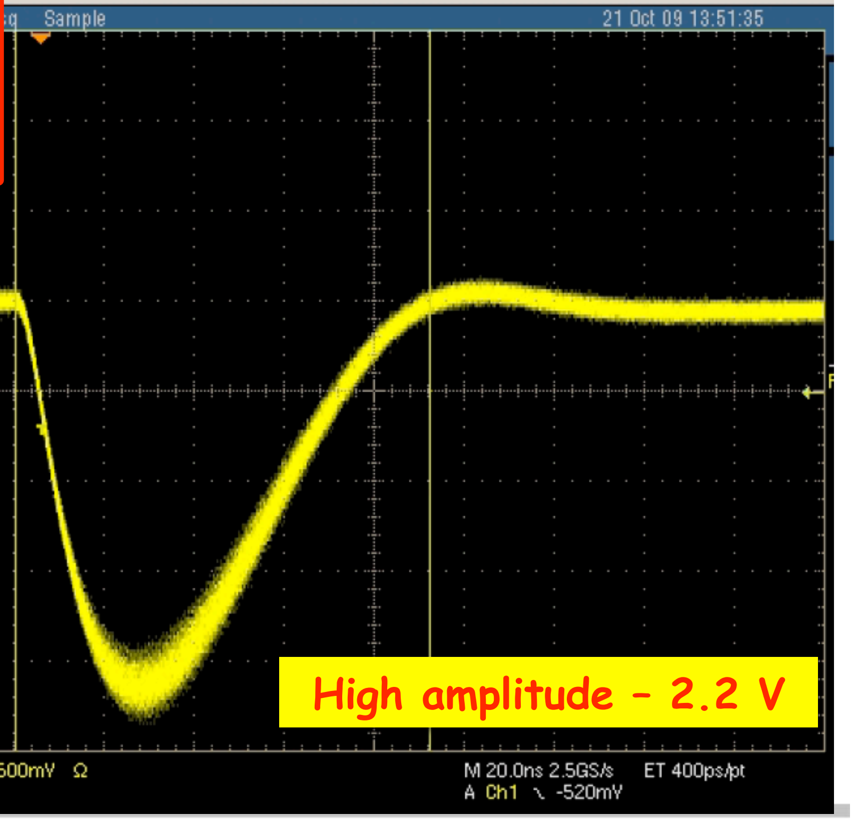
# First Signals from Hamamatsu Unit



Low amplitude – 18 mV

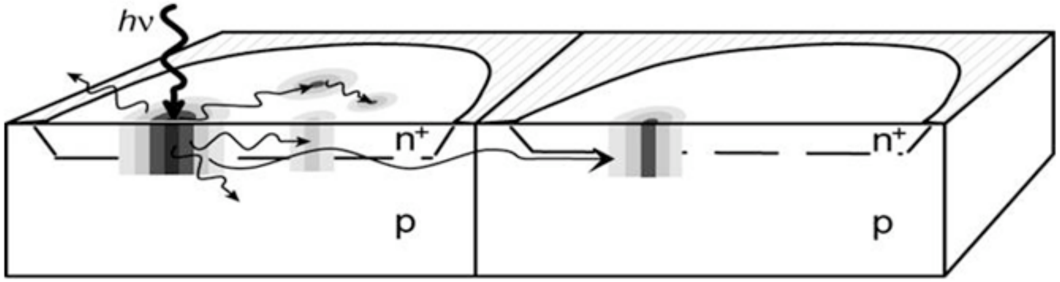
Source – fast blue LED
Ouput Risetime – 13-14 ns
Output Width – 75 ns

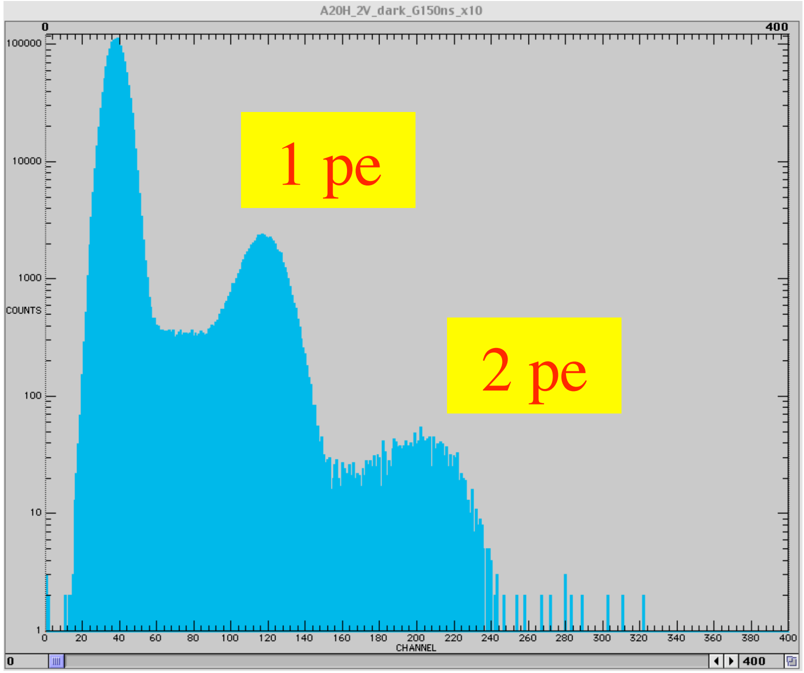




High amplitude – 2.2 V

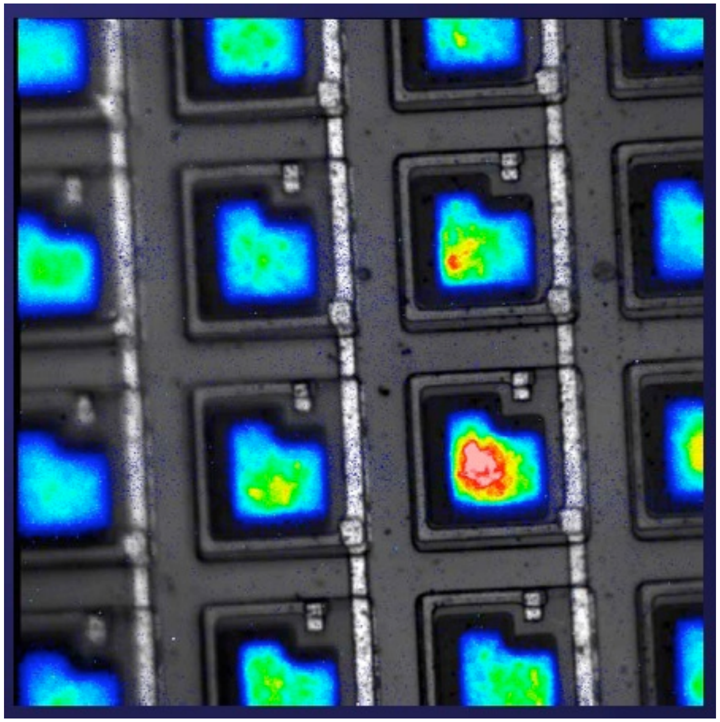
# CrossTalk – 1 pe gives 2 pe



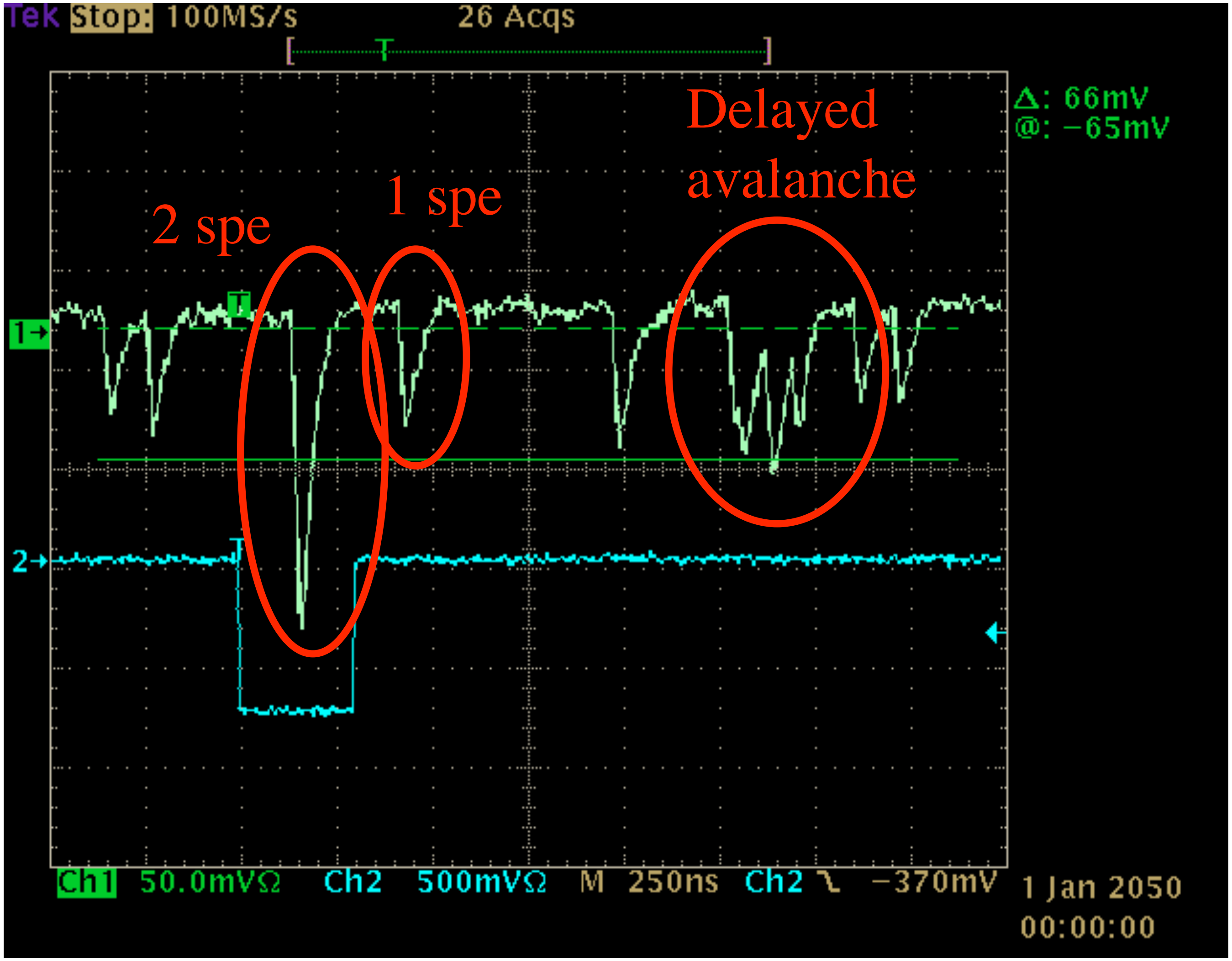


1 pe

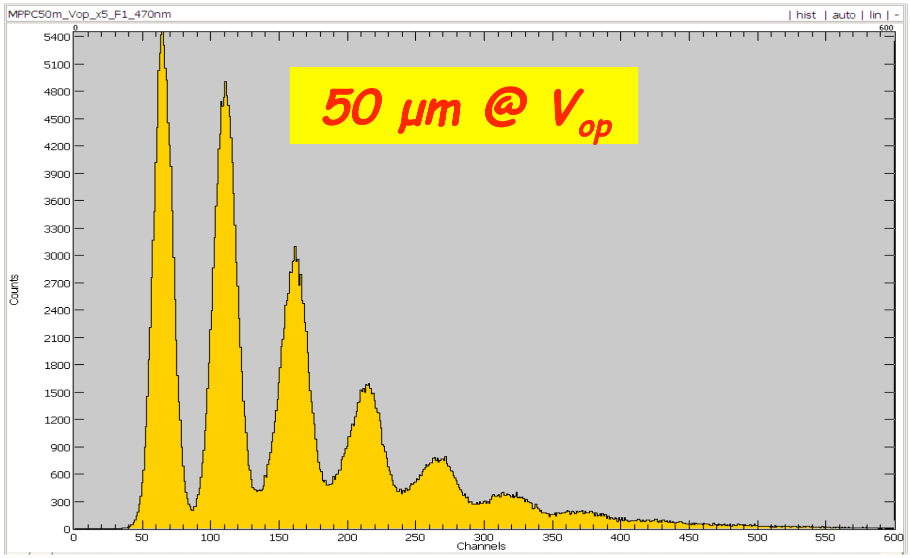
2 pe

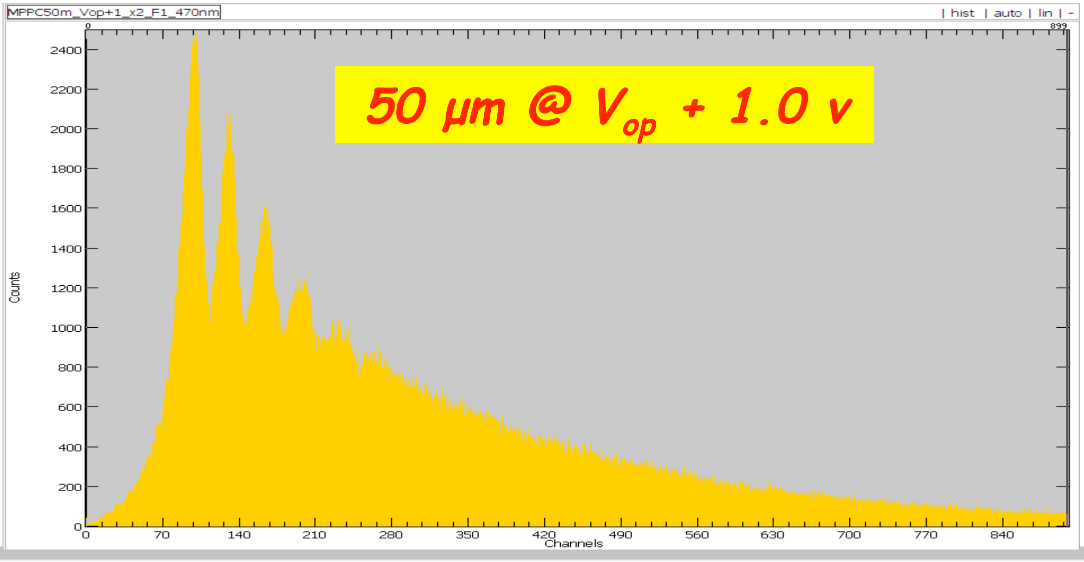


# Dark Noises

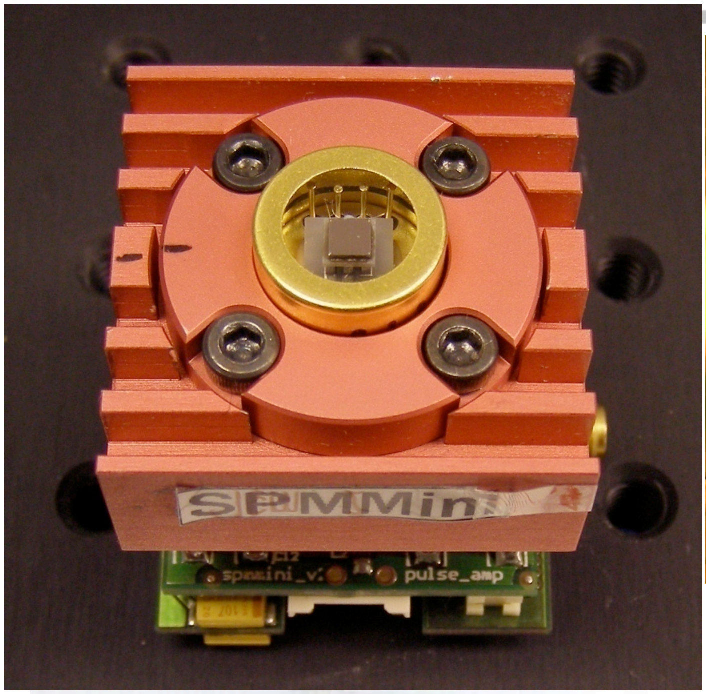

Tek Stop: 100MS/s
26 Acqs
Δ: 66mV
@: −65mV
2 spe
1 spe
Delayed avalanche
1→
2→
Ch1 50.0mVΩ
Ch2 500mVΩ
M 250ns
Ch2 ⮧ −370mV
1 Jan 2050
00:00:00

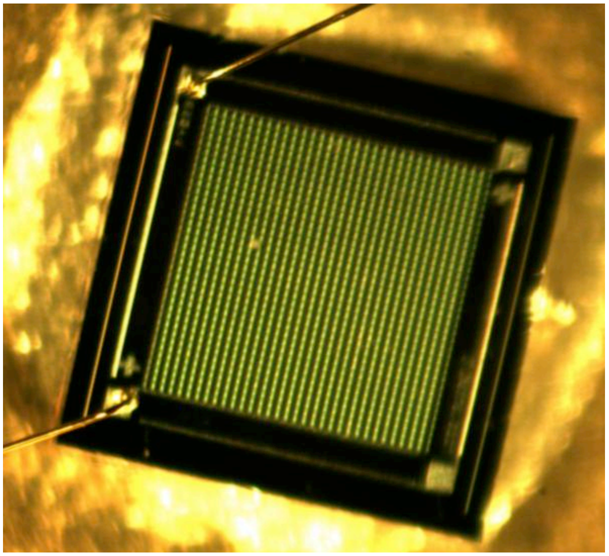
# Effect of excessive bias in Hamamatsu MPPC

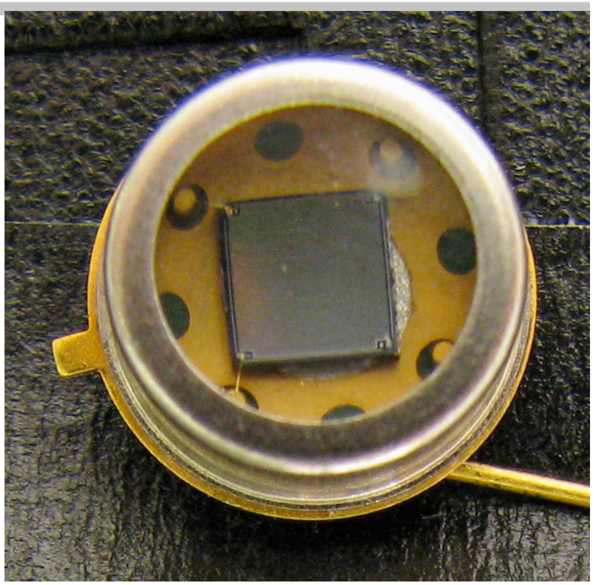

50 μm @ $V_{op}$

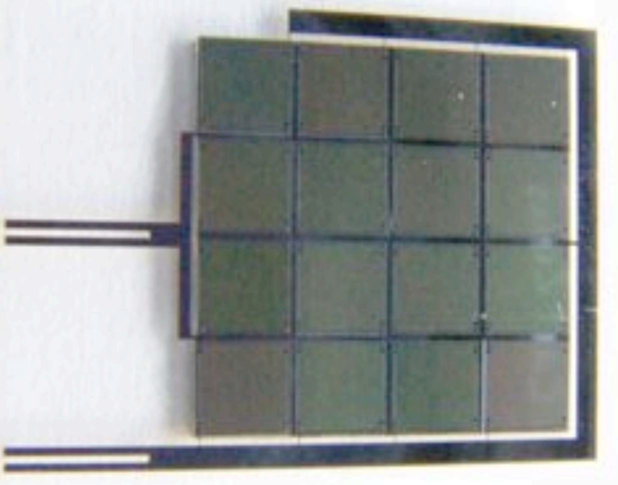

50 μm @ $V_{op}$ + 1.0 v

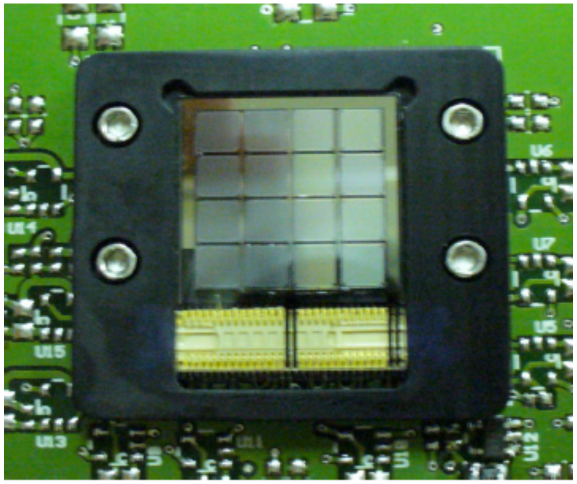
# Example Devices

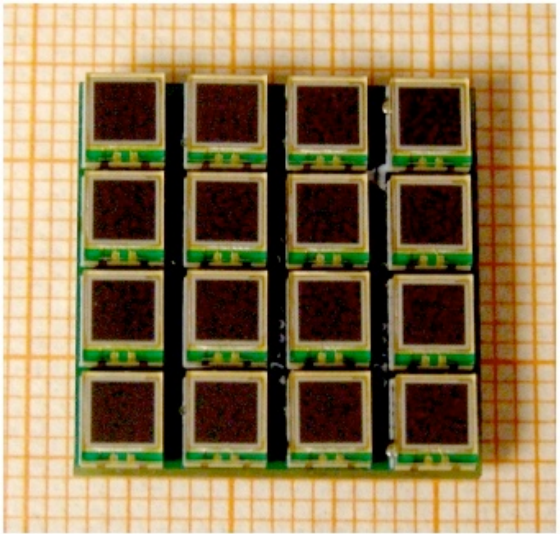












# Hamamatsu (Japan)

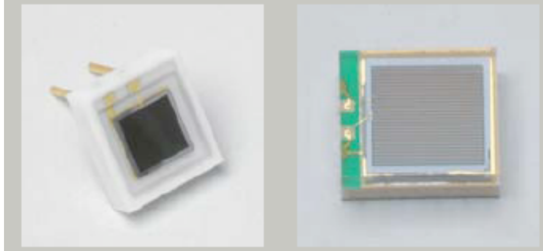
Active area: 1 × 1 mm type

Metal type

Ceramic type

SMD type

Active area: 3 × 3 mm type

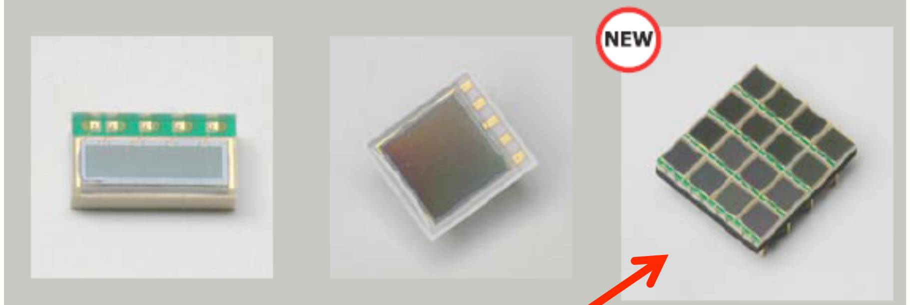


Ceramic type

SMD type

TE-cooled type

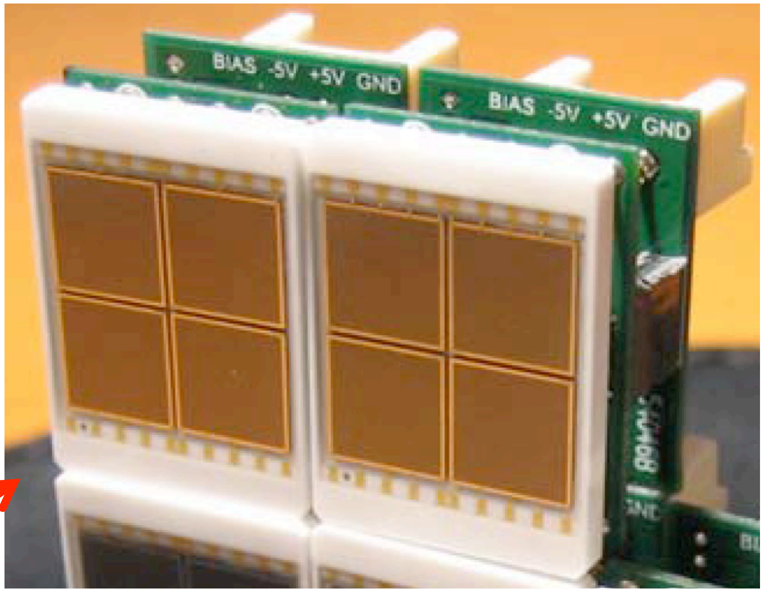
MPPC array



1 × 4 ch type

2 × 2 ch type

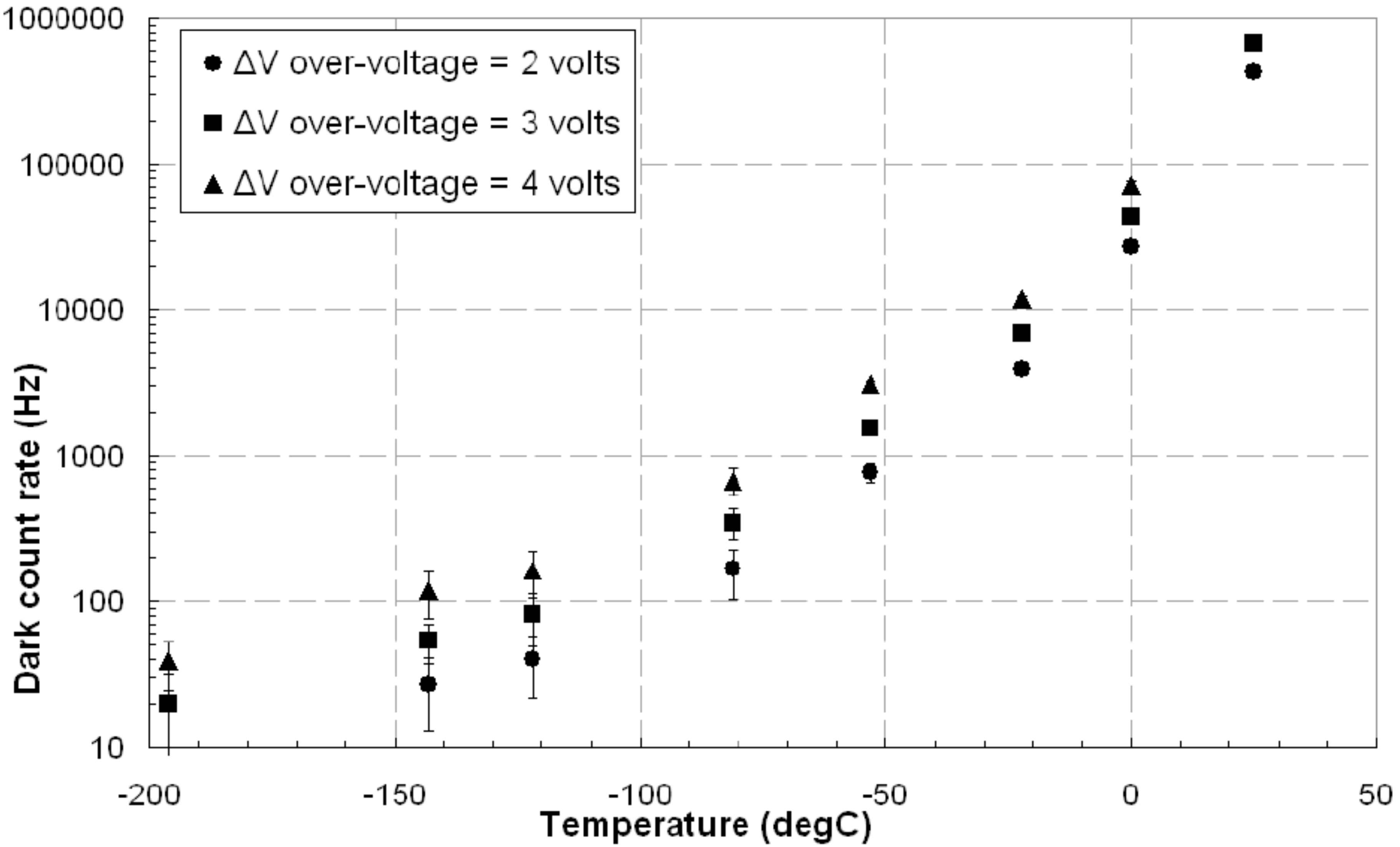
4 × 4 ch type



For bioimaging

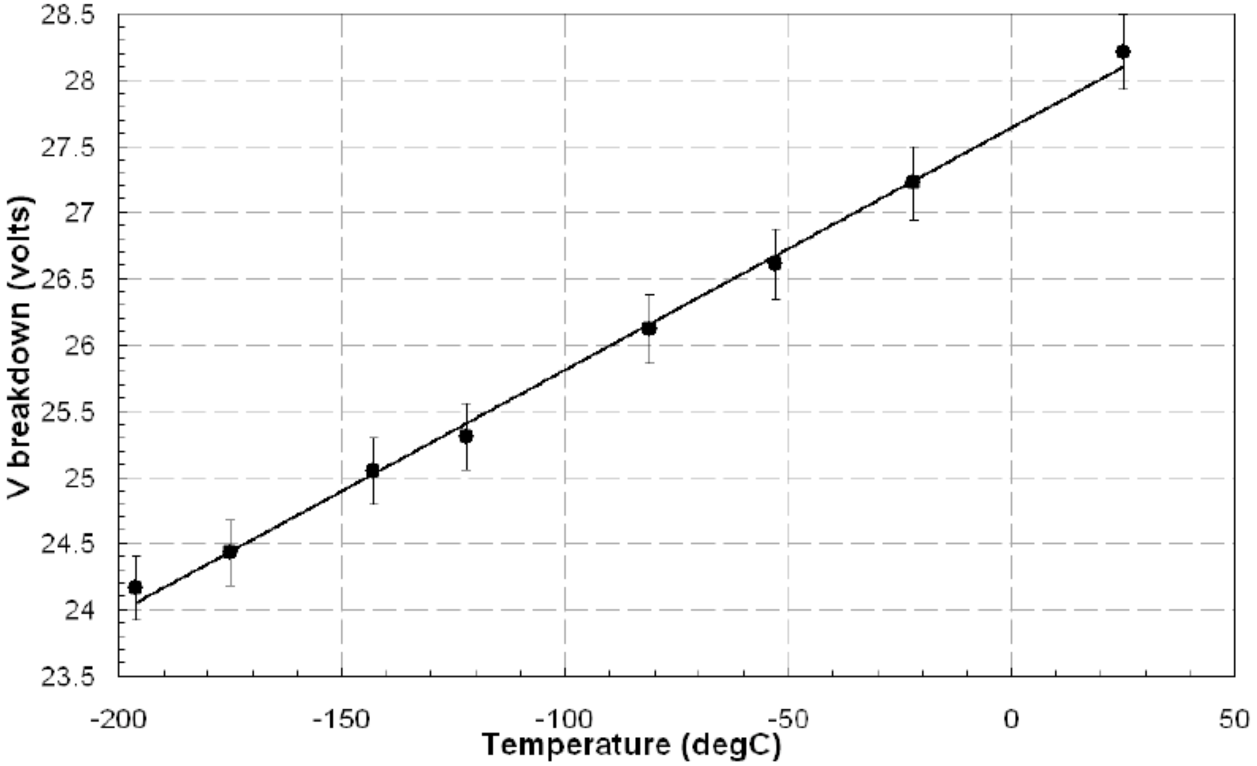
For GlueX

# Dark Rate vs Temperature



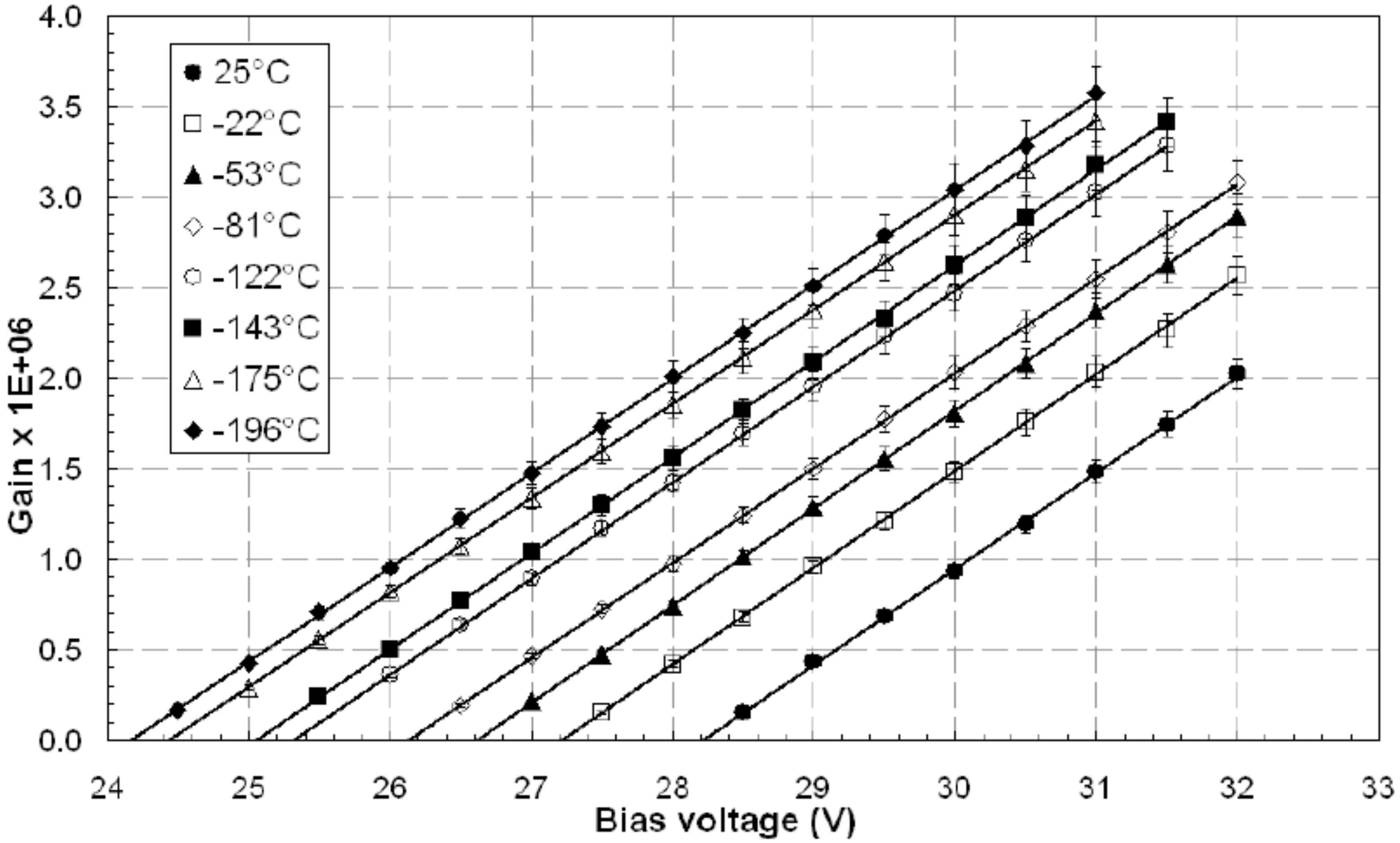
Ref: Lightfoot *et al*., **J. Inst.,** Oct. 2008

# Breakdown Voltage vs Temperature



Ref: Lightfoot *et al*., **J. Inst.,** Oct. 2008

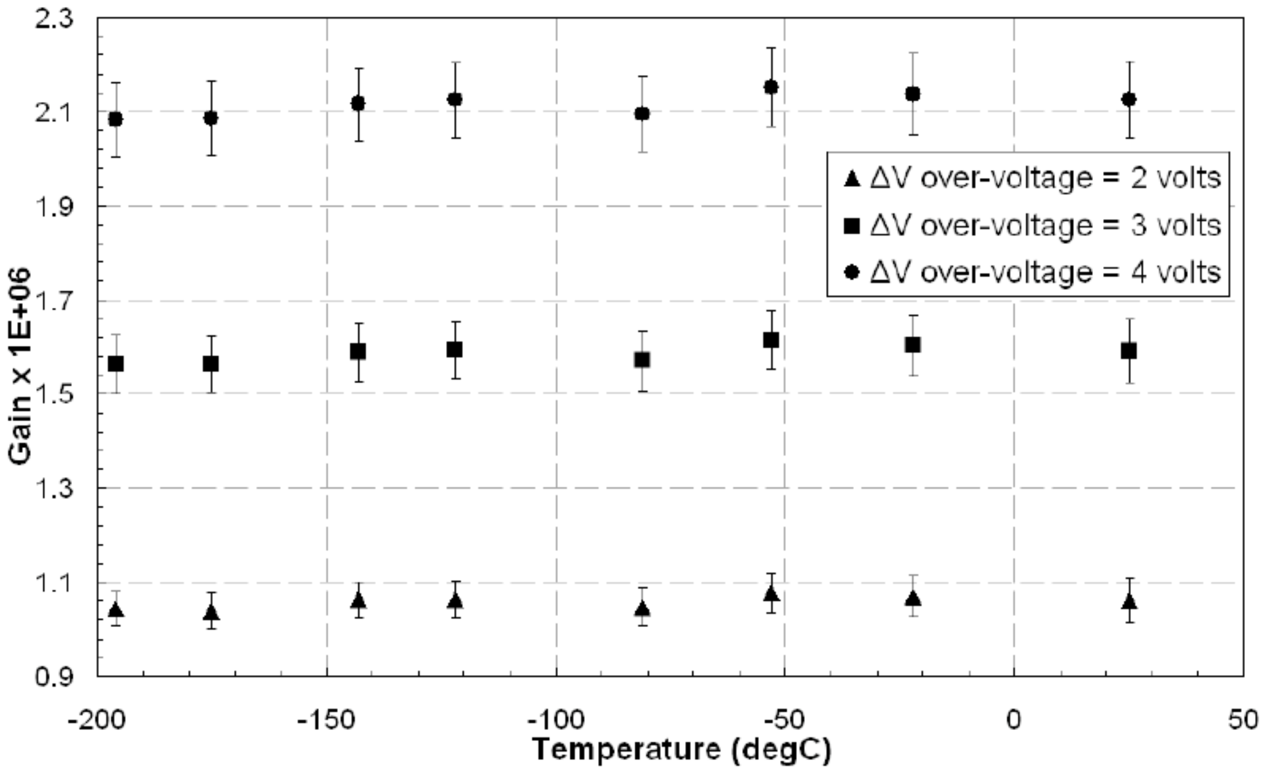
# Gain vs Temperature



$V_{br}$ as temp. decreases

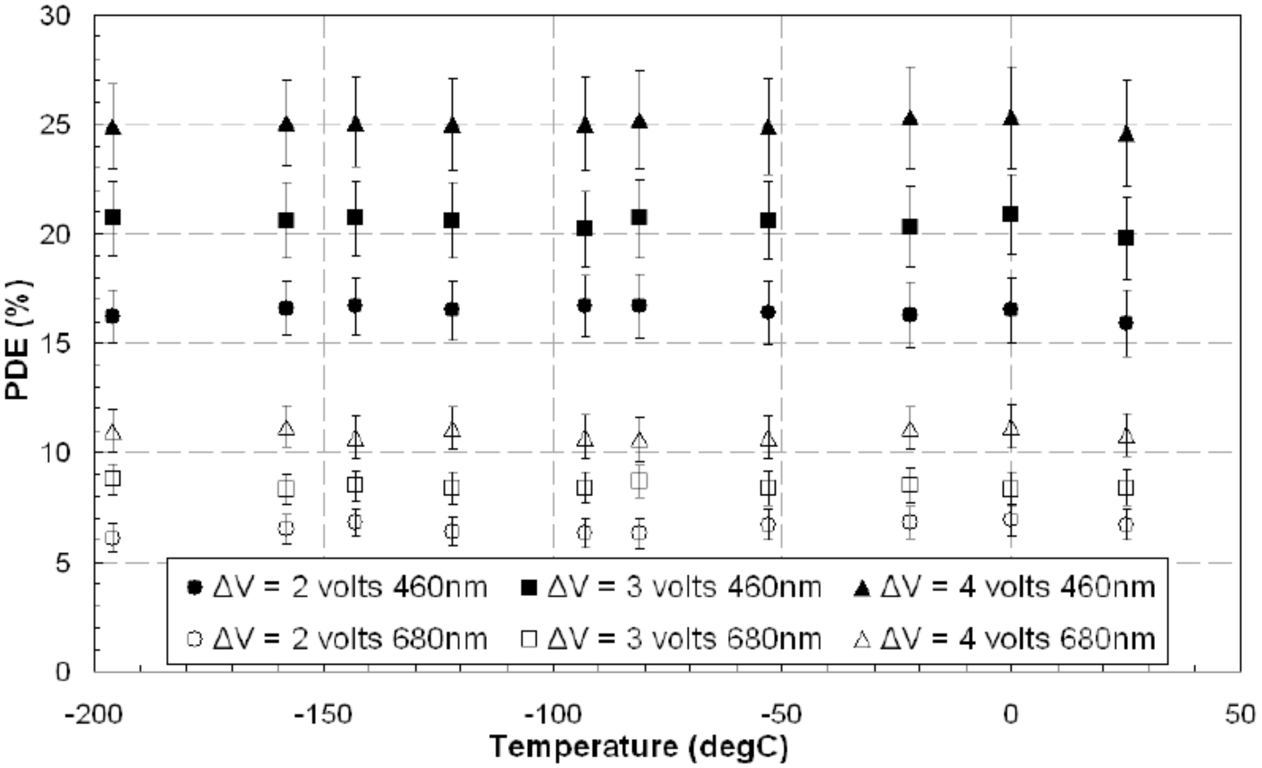
Ref: Lightfoot *et al*., **J. Inst.,** Oct. 2008

# Gain vs Temperature @ Constant Overbias



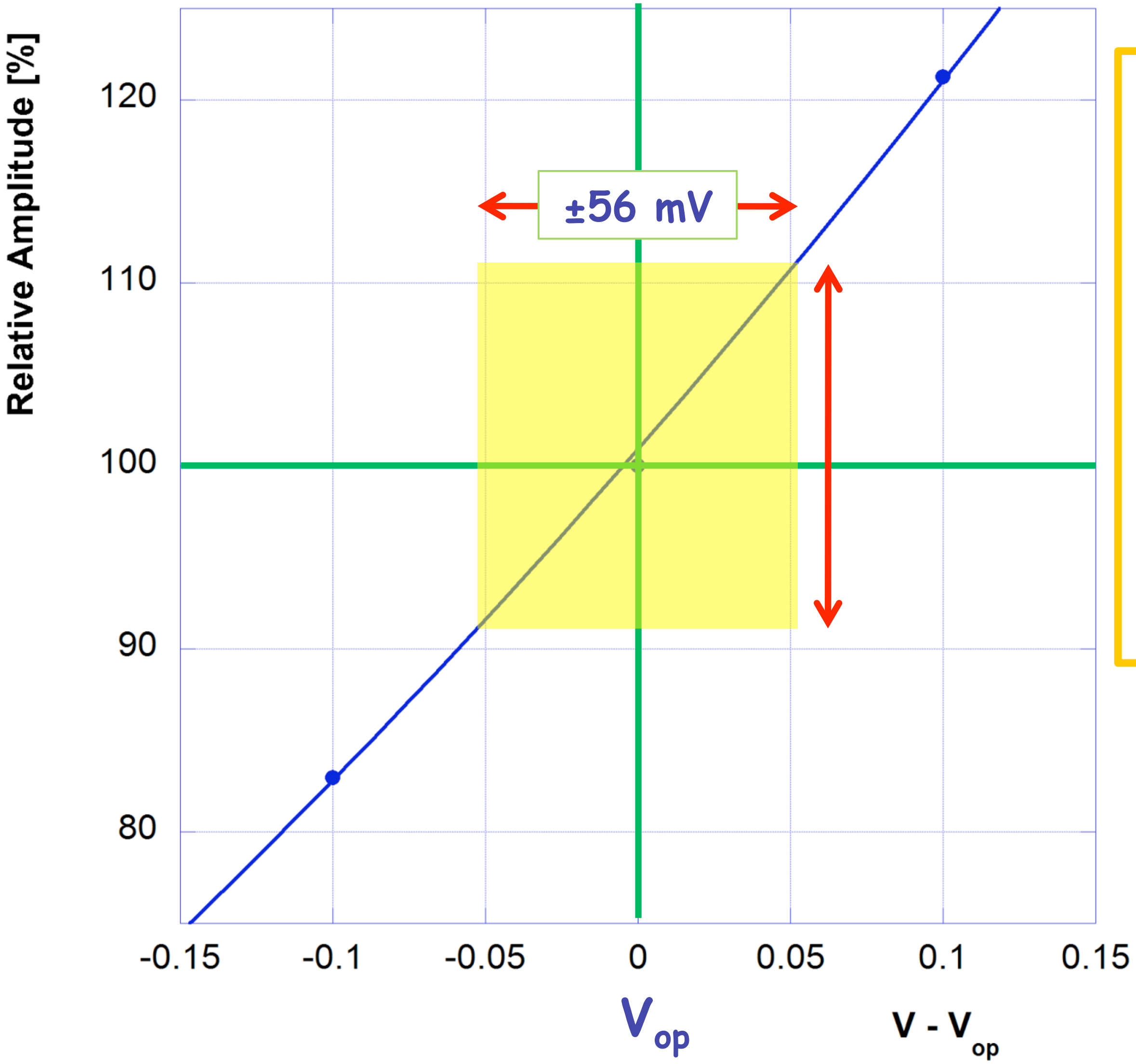
Ref: Lightfoot *et al*., **J. Inst.,** Oct. 2008

# PDE vs Temperature @ Constant Overbias



Ref: Lightfoot *et al*., **J. Inst.,** Oct. 2008

# Implication for Temperature Stability



**Hamamatsu**

1°C -> 56 mV in $V_{br}$

↓

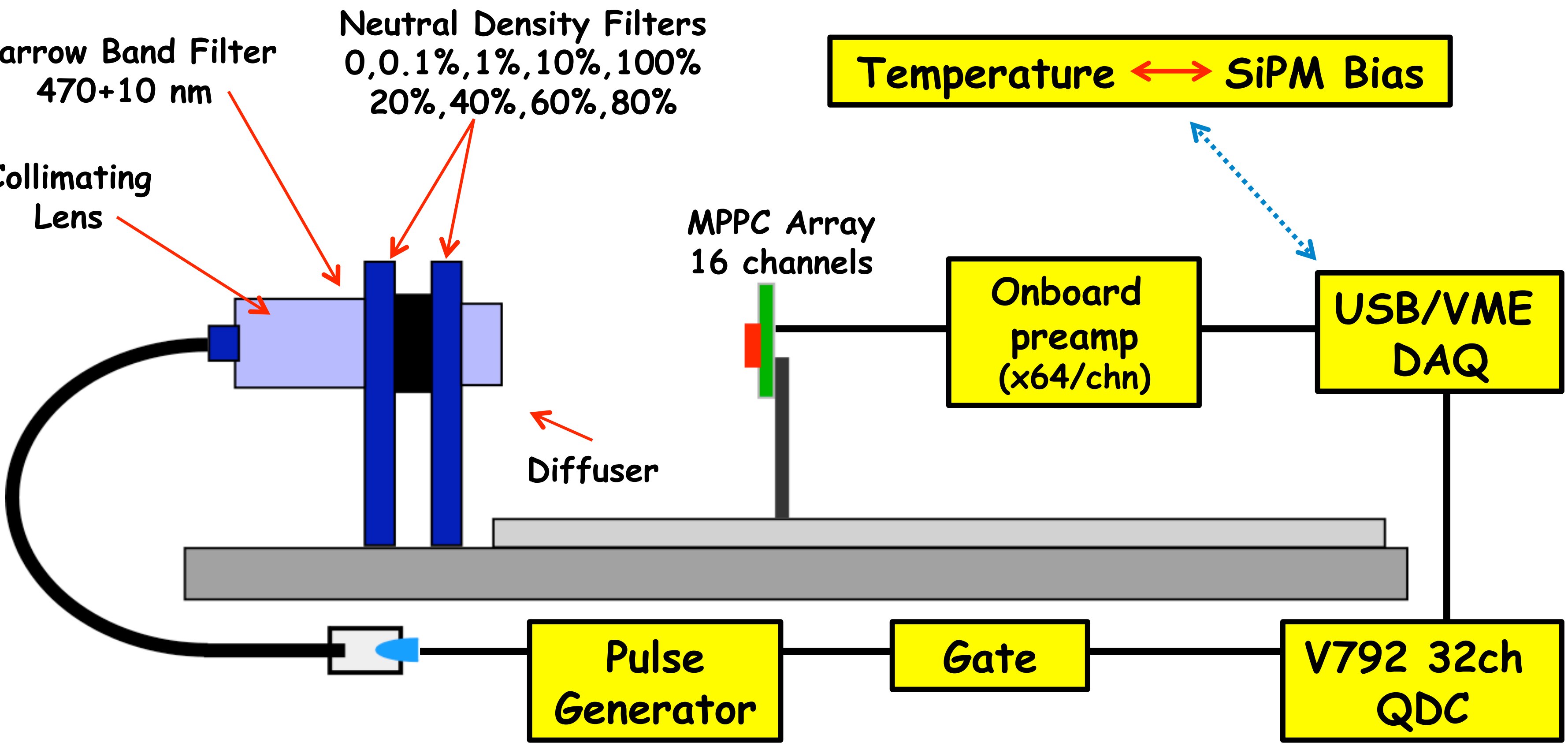
≈ 10% change in amplitude

# Temperature & Stability

- At Constant Overbias ➔ Gain independent of Temperature
  - ➡ *Same goes for PDE*
- Gain varies rapidly with Overbias (1-4 volts)
  - ➢ Output Response strongly dependent upon Temperature
  - ➢ Temperature should be stable for Stable Output

- Dark Rate dependent upon Overbias
- Dark Rate decreases rapidly with decreasing Temperature
  - ➢ Dark Rate can be improved with Temperature Control

# JLAB Workstation – Gain, PDE, Dark Rate, Crosstalk



Narrow Band Filter
470+10 nm

Neutral Density Filters
0,0.1%,1%,10%,100%
20%,40%,60%,80%

**Temperature ↔ SiPM Bias**

Collimating
Lens

MPPC Array
16 channels

**Onboard preamp (x64/chn)**

**USB/VME DAQ**

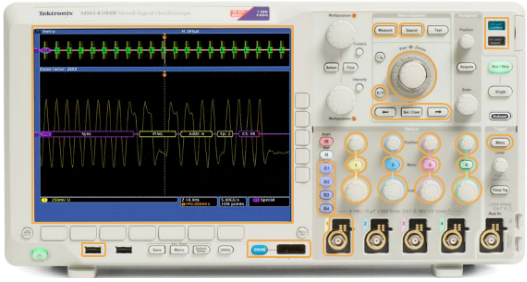
Diffuser

**Pulse Generator**

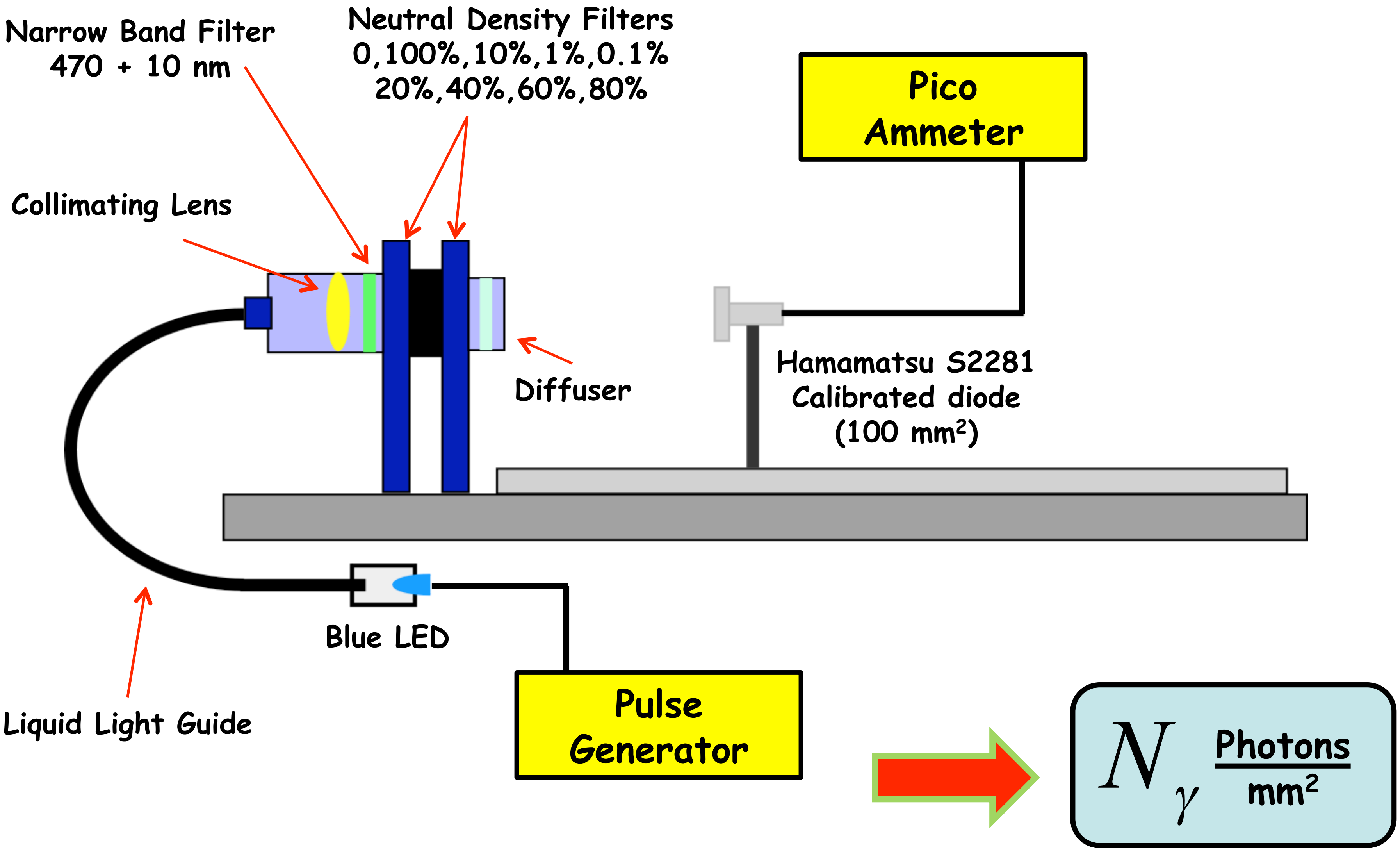
**Gate**

**V792 32ch QDC**

Can also acquire waveforms for further analysis
*dark rate, crosstalk, delayed pulses*



# JLAB Workstation – Light Source Calibration



Narrow Band Filter
470 + 10 nm

Neutral Density Filters
0,100%,10%,1%,0.1%
20%,40%,60%,80%

Pico Ammeter

Collimating Lens

Diffuser

Hamamatsu S2281
Calibrated diode
(100 $mm^2$)

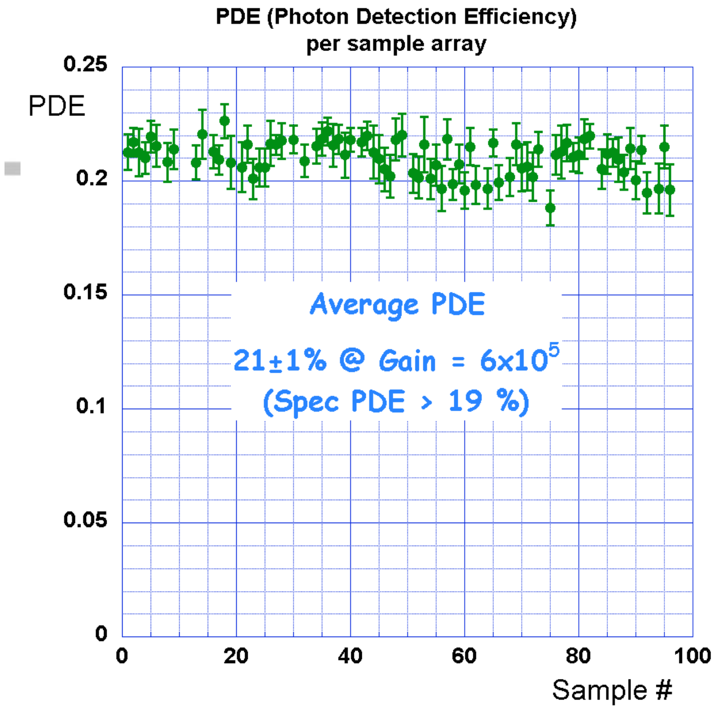
Blue LED

Liquid Light Guide

Pulse Generator

$$N_\gamma \; \frac{\text{Photons}}{\text{mm}^2}$$

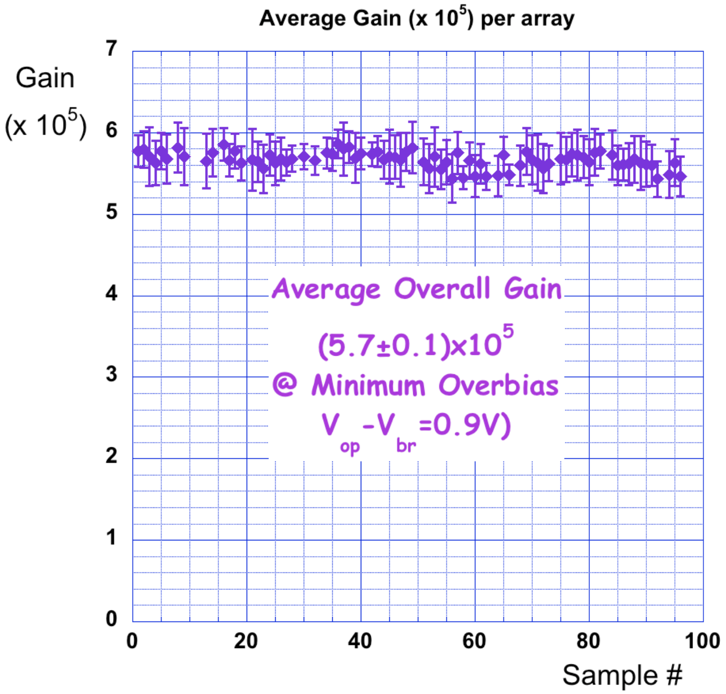
# Some 1st Article Results



Average PDE

21±1% @ Gain = $6 \times 10^5$

(Spec PDE > 19 %)



Average Overall Gain

$(5.7 \pm 0.1) \times 10^5$

@ Minimum Overbias

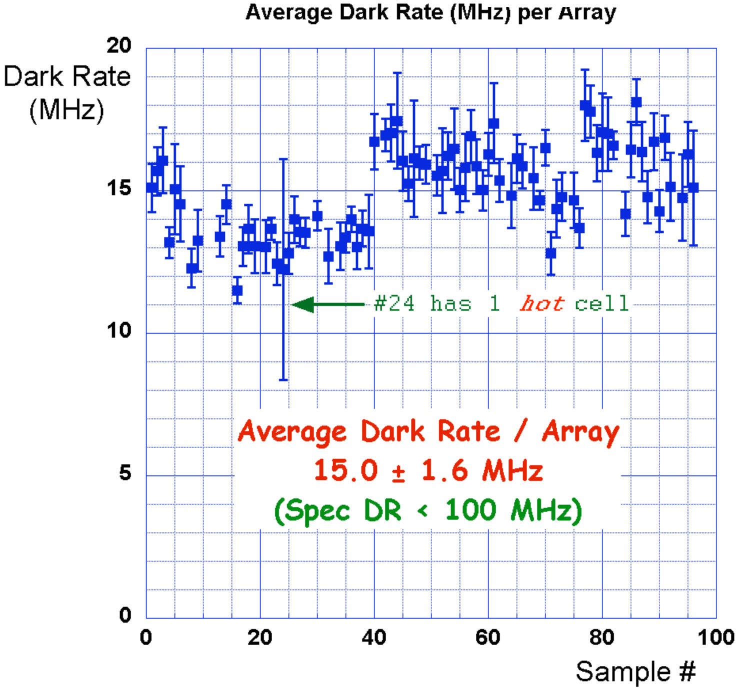
$V_{op} - V_{br} = 0.9V$)

At Nominal Gain

$7.5 \times 10^5$

PDE = 26%

DR = 24 MHz

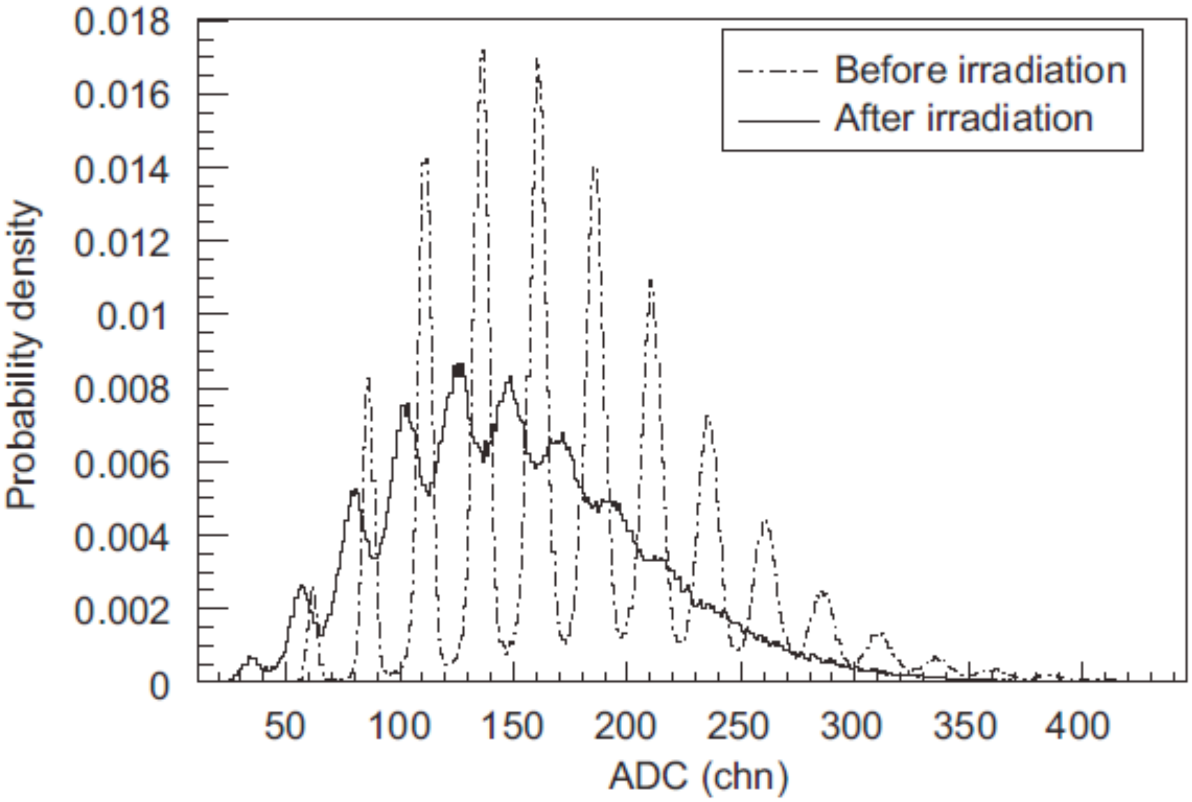


Average Dark Rate / Array

15.0 ± 1.6 MHz

(Spec DR < 100 MHz)

# Effect of Irradiation



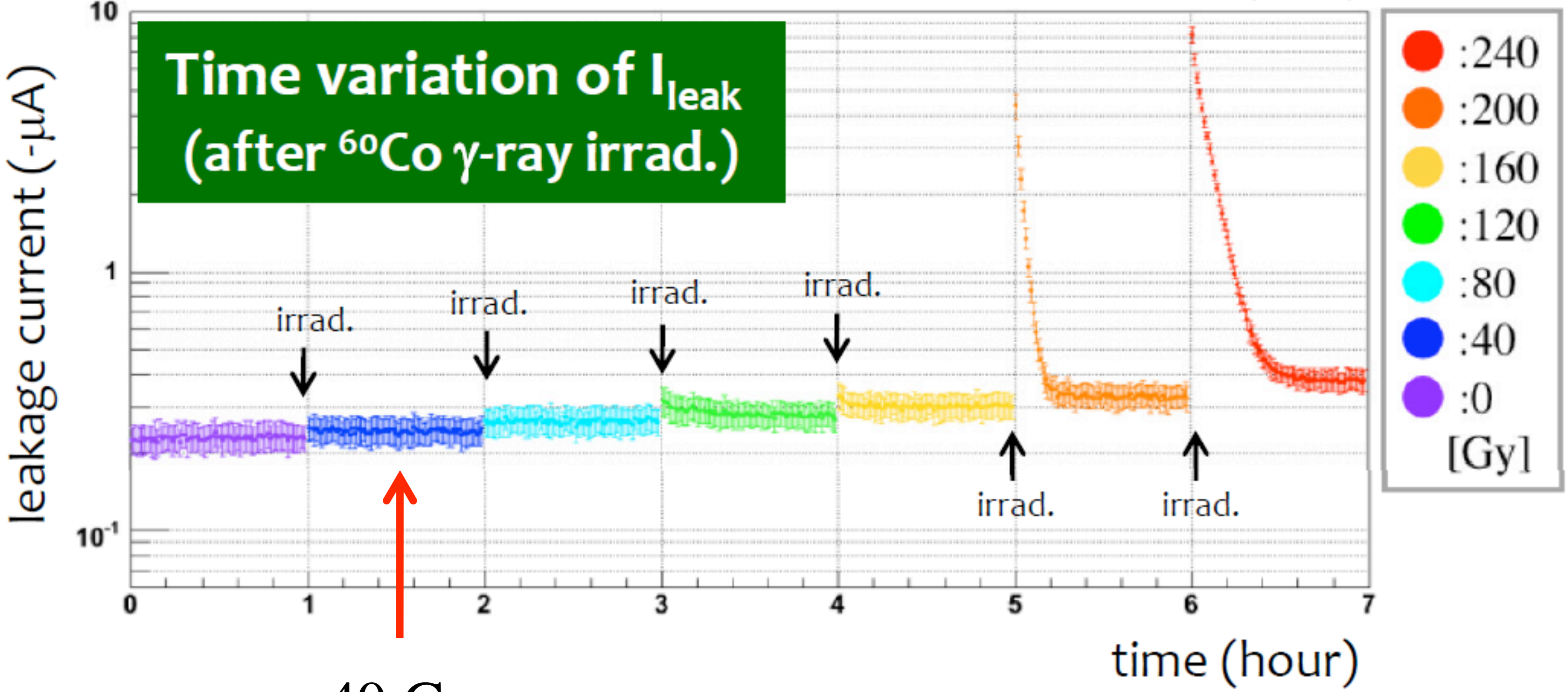
Noise and radiation damage in silicon photomultipliers exposed to electromagnetic and hadronic radiation

S. Sánchez Majos, P. Achenbach*, C. Ayerbe Gayoso, J.C. Bernauer, R. Böhm, M.O. Distler, M. Gómez Rodríguez de la Paz, H. Merkel, U. Müller, L. Nungesser, J. Pochodzalla, B.S. Schlimme, Th. Walcher, M. Weinriefer, C.J. Yoon

Nuclear Instruments and Methods in Physics Research A 602 (2009) 506–510

# Gamma Irradiation

T.Matsubara *et al*, PoS (PD07)032, 2007



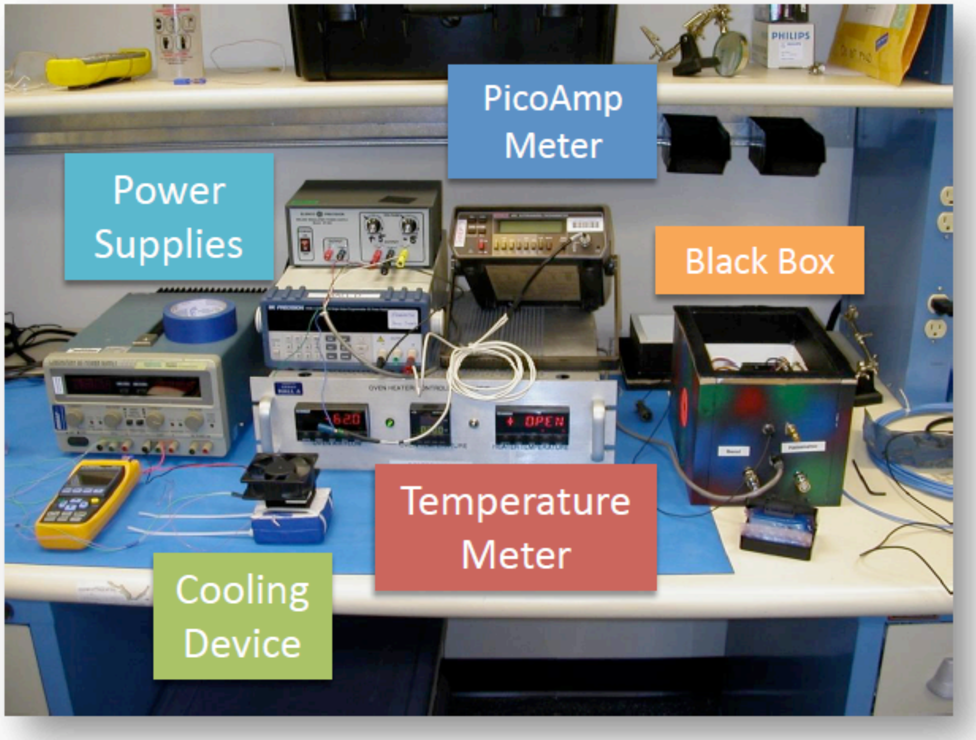
40 Gy

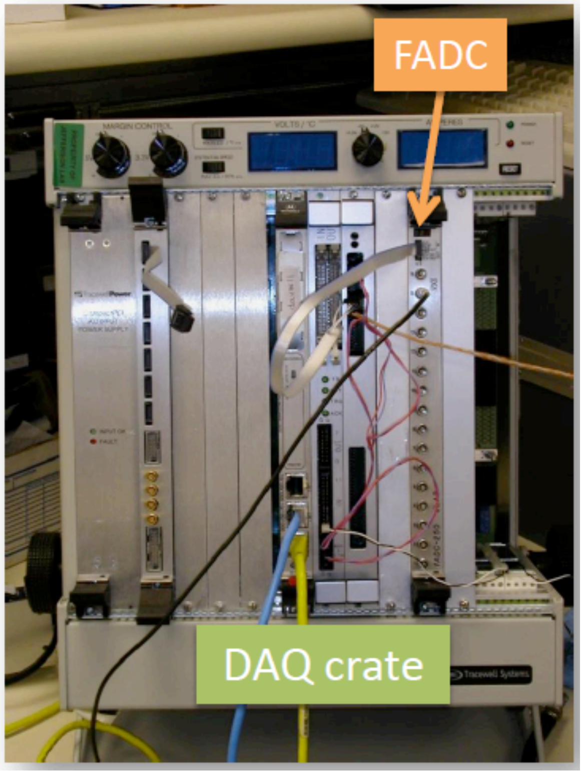
**For GlueX => < 2 Gy/10 yrs**

**Toru Matsumura**

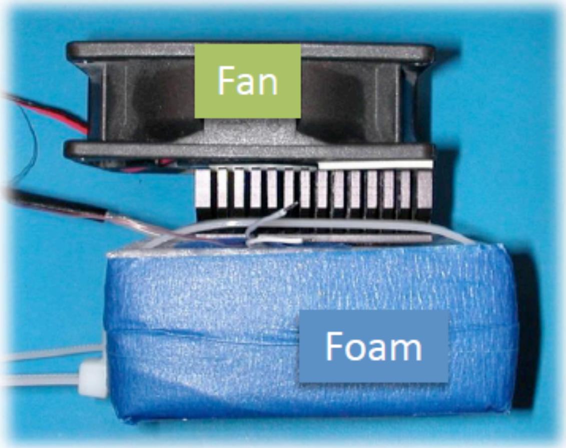
**KEK Detector Technology Project**

# Irradiation Setup

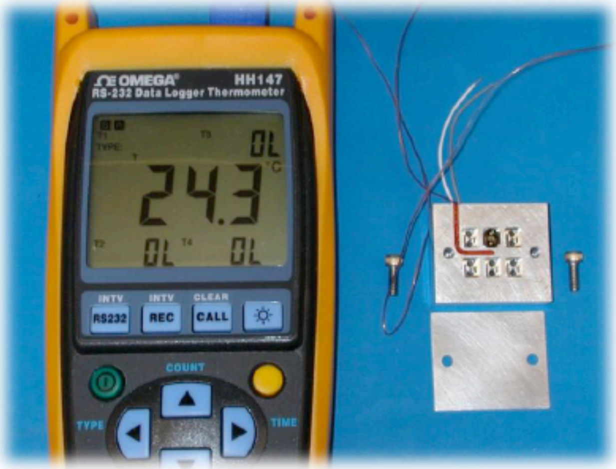


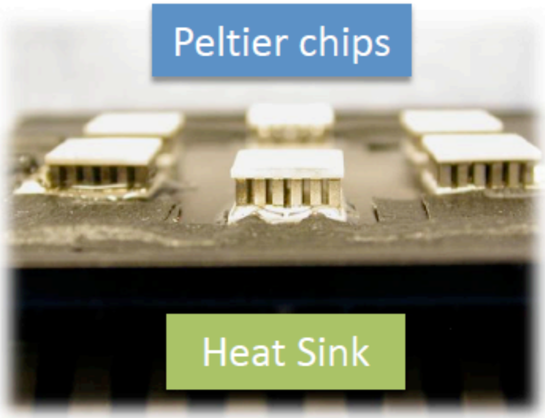


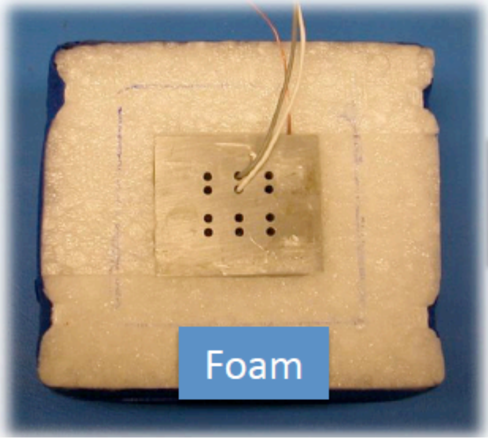
# Irradiation Setup

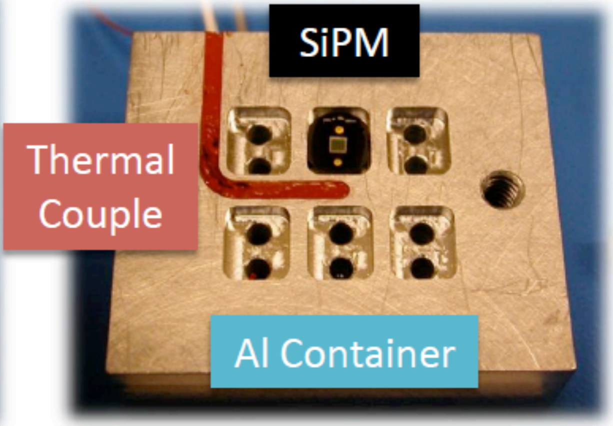


With six Peltier effect chips, the device can cool six SiPMs to -10°C at 25°C room temperature.

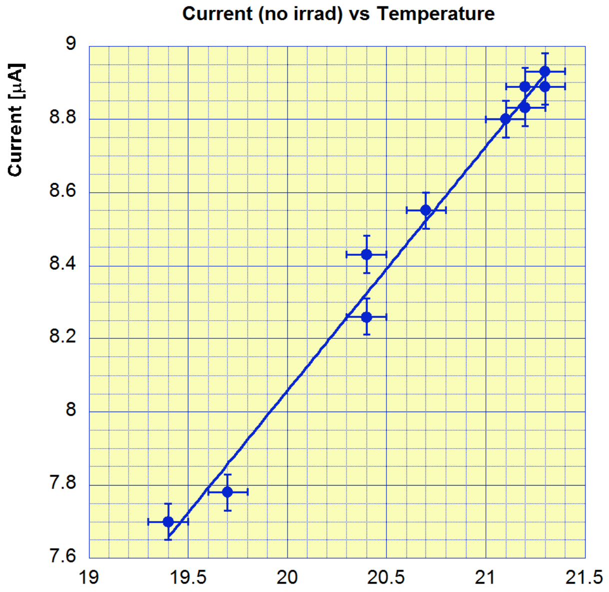




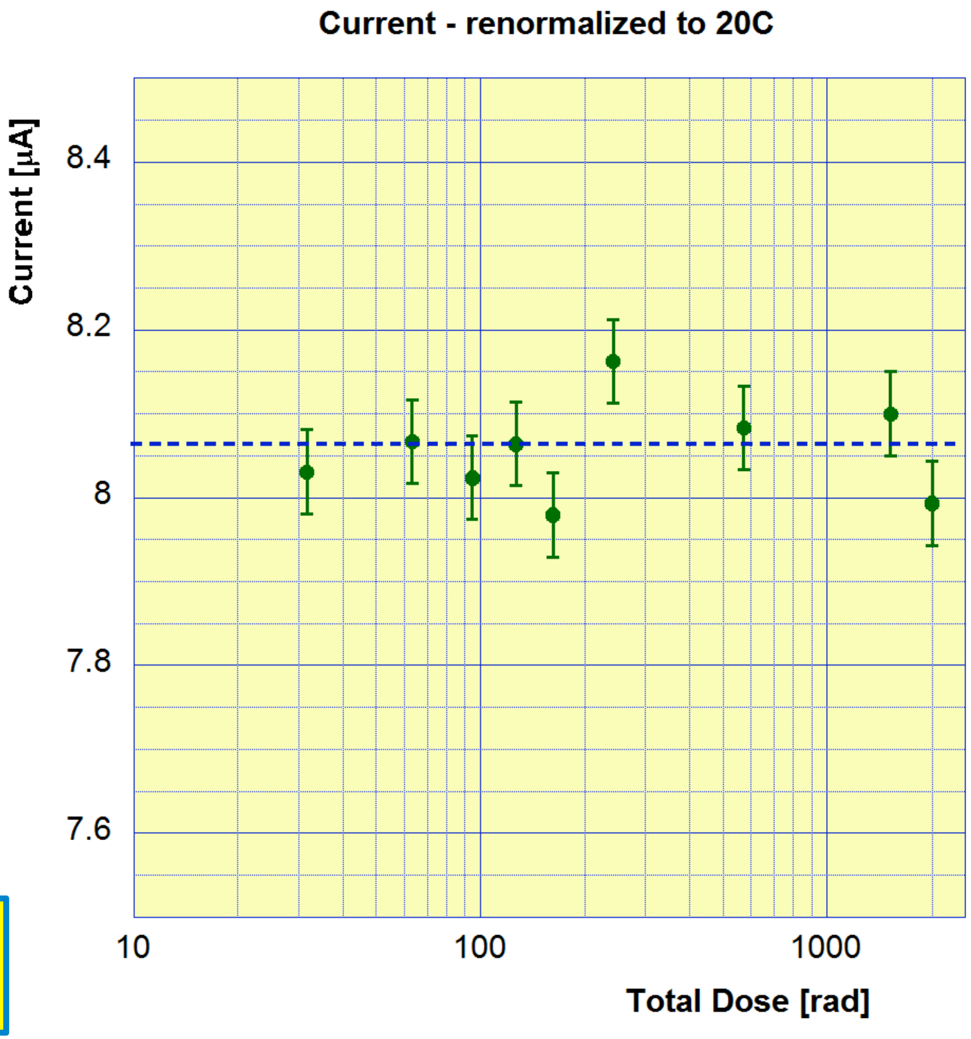




# Irrad with Cs-137 source to 20 Gy

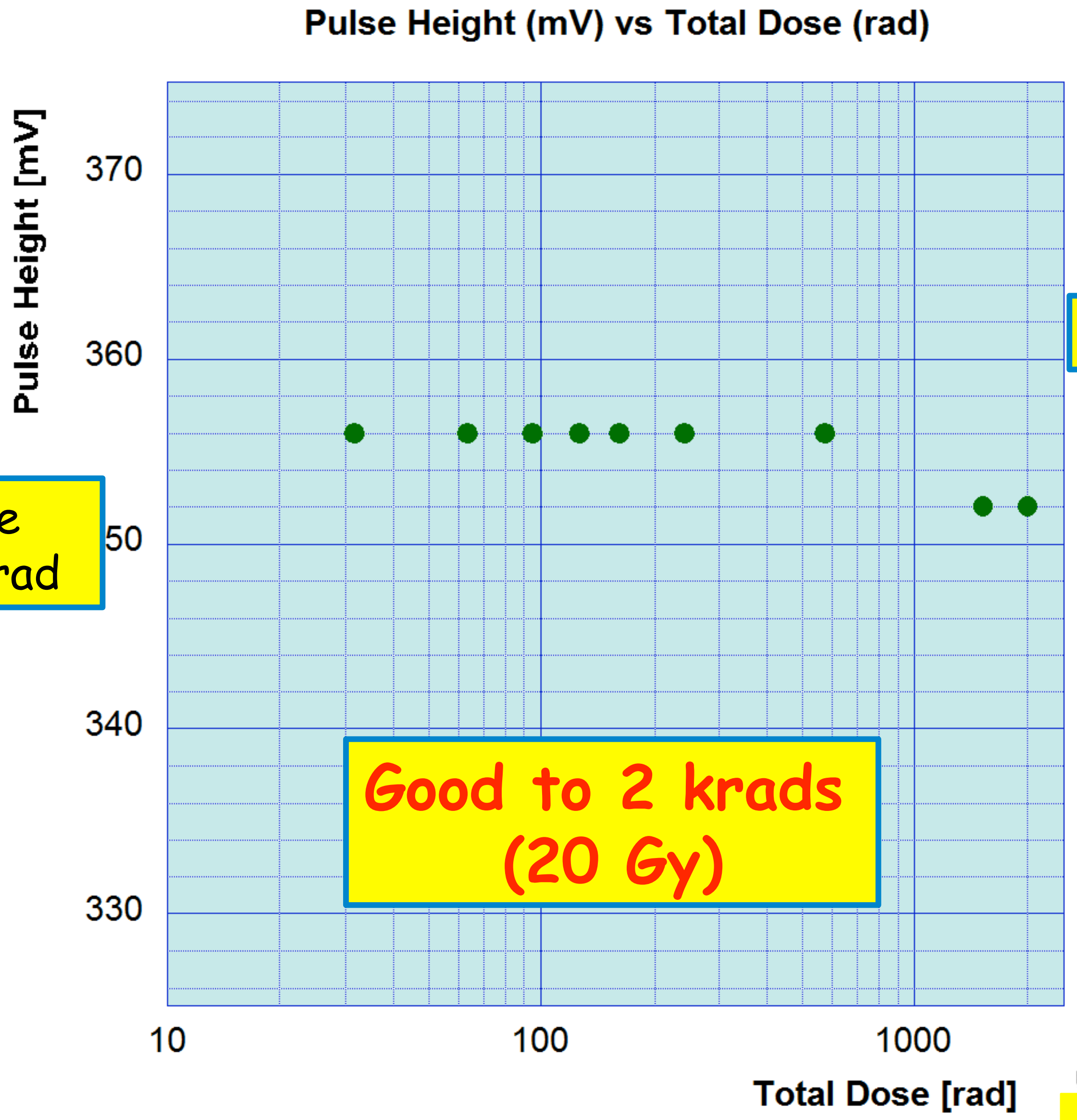


Renorm dark current vs T and apply to Irrad Data



No discernible effect

# Minimal Effect from γ Irradiation



Monitor Pulse Height to 2 krad

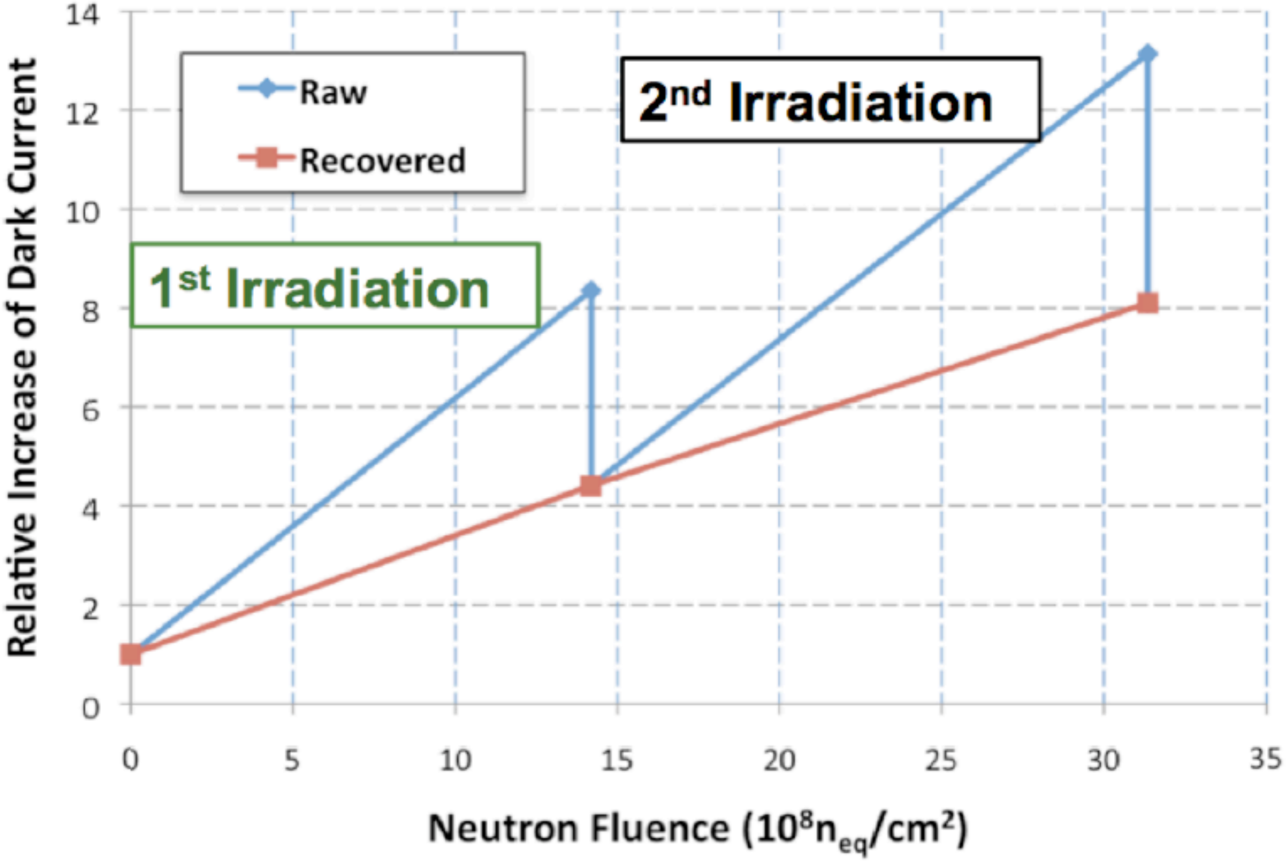
Good to 2 krads (20 Gy)

1% drop

# Neutron Irradiations

- Literature shows high energy neutrons can be ~ x10 worse in their damage on silicon device vs photons
- Inhouse JLAB simulations shows ~ > $10^8$ $cm^{-2}$ (1 Mev eqv) neutrons per year
- Variety of initial neutron irradiations at JLAB – both uncontrolled (Hall A background) and with controlled AmBe source
  - PDE and Gain don't seem affected
  - Dark noise rises linearly with dose
  - Dose rate – can anneal out some damage to residual level
  - Anneal rate strongly temperature sensitive

# SiPM Neutron Radiation Test



Neutron Fluence with **$10^8$ g/s** on **$LH_2$** Target with **1/3** efficiency

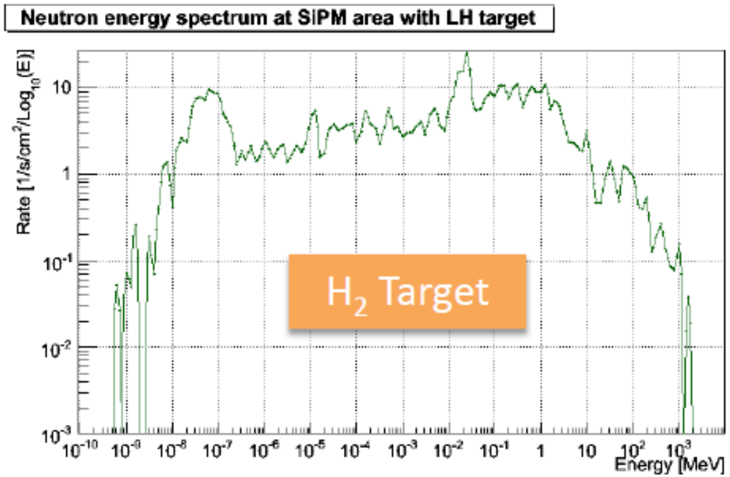
-> **$3 \times 10^8$ $n_{eq}/cm^2/year$**

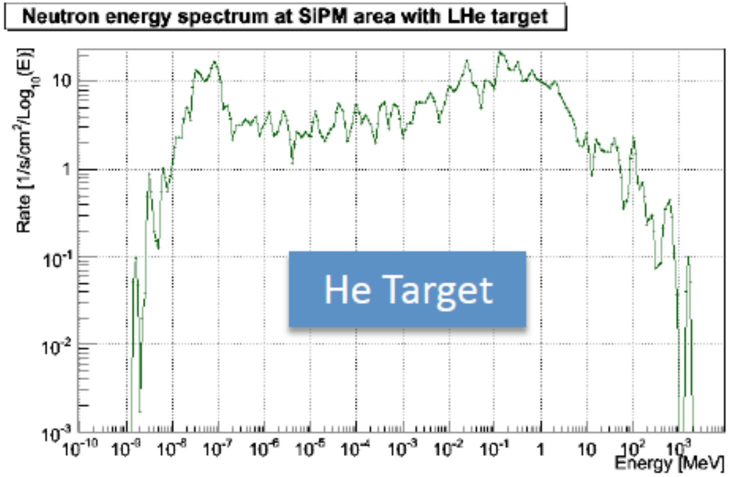
# Life Time of SiPM in Hall D

- Current margin for the increase of dark rate: factor of **5**.
- Dose simulated in Hall A:
  - 34 rem → $8.2 \times 10^8\ n_{eq}/cm^2$
- Rates through downstream BCal SiPMs in Hall D with $10^8\ \gamma/s$:
  - $H_2$: 4.3 – 3.3 mrem/H
  - He: 6.5 – 4.9 mrem/H
- Life time for 100% efficiency:
  - $H_2$: 0.9 – 1.1 years
  - He: 0.6 – 0.8 years

D'oh!

- Upstream rates are 4 times lower.





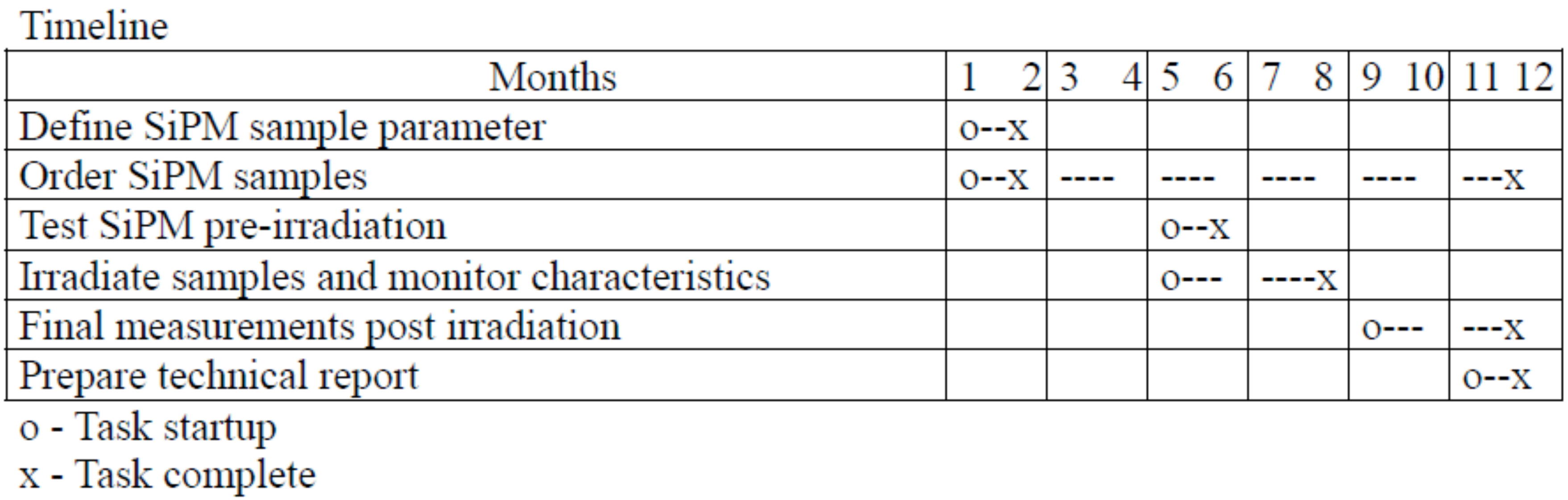
1 rem → $2.6 \times 10^7\ n_{eq}/cm^2$

# How to Extend the Lifetime?

- Expected Running efficiency ➔ 1/3
- Run SiPMs at lower temperature
  - 5°C with 1/3 Dark Noise
- During Beam downtimes – run at elevated temperature (~40°C) to rapidly anneal to residual level
- Cool down to 5°C for Beam On and continue
- With this prescription, expect:
  - for $H_2$ target ➔ 8-10 years
  - for He target ➔ 5-7 years
- Conclusion – ***dodged that bullet.....for now***

# A Need for some Extra R&D

- Hamamatsu has already approached JLAB in collaborative venture to try out – perhaps – more rad-hard samples
- GlueX (Hall D) already committed to 4,000 of present version – no more tweaks
- JLAB Detector Group in good position to continue rad tolerance R&D with low impact on other activities
- This can benefit the physics community as a whole
- As minimum – provide some funding to Hamamatsu to spur on R&D at their end
- Also need some funding to tweak the setup – GlueX SiPM work will overflow into this to help



Timeline

| Months | 1 2 | 3 4 | 5 6 | 7 8 | 9 10 | 11 12 |
|---|---|---|---|---|---|---|
| Define SiPM sample parameter | o--x | | | | | |
| Order SiPM samples | o--x | ---- | ---- | ---- | ---- | ---x |
| Test SiPM pre-irradiation | | | o--x | | | |
| Irradiate samples and monitor characteristics | | | o--- | ----x | | |
| Final measurements post irradiation | | | | | o--- | ---x |
| Prepare technical report | | | | | | o--x |

o - Task startup

x - Task complete

# Funding request

- Sample cost (Hamamatsu)….$35,000
- Setup improvements………...$  5,000
- *JLAB overhead…..…..…..…..$17,000 (42%)*

- **TOTAL…………$57,000**