Silicon Photomultiplier Characterization for the GlueX Barrel Calorimeter

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On behalf of the GlueX collaboration*

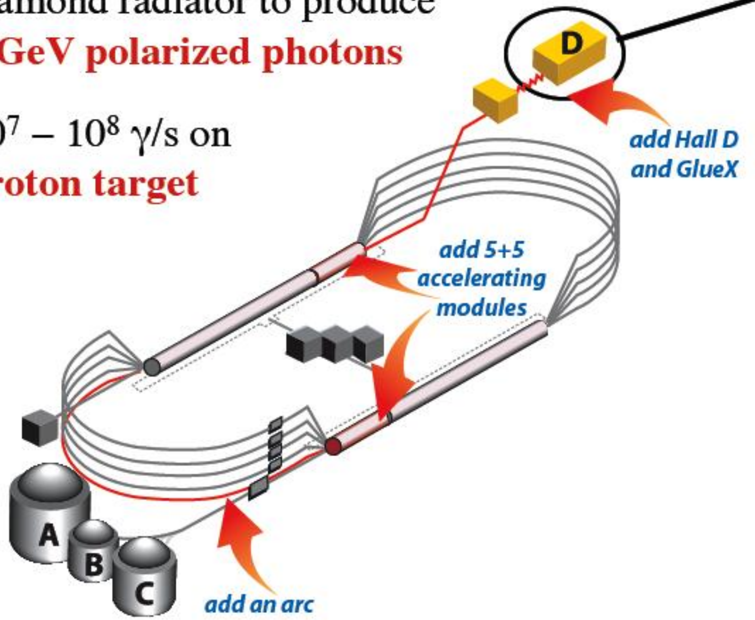
**www.gluex.org*

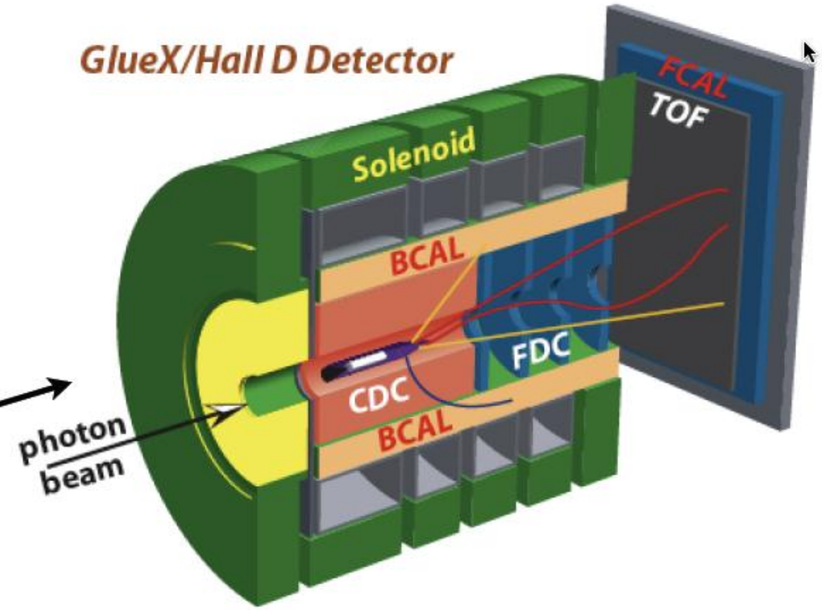
**www.jlab.org/12GeV*

GlueX overview

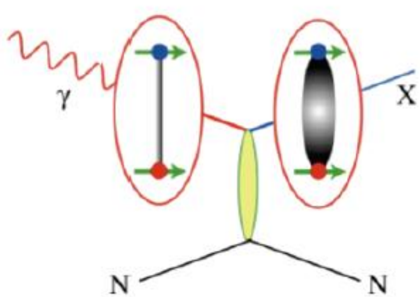
Use **9 GeV polarized photons** on a **proton target** to produce **hybrid mesons** with exotic J^{PC}:

- 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}

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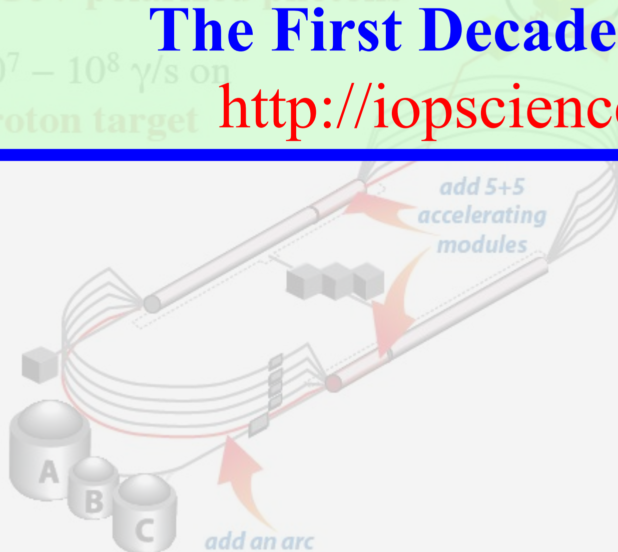
New Insights into the Structure of Matter: The First Decade of Science at Jefferson Lab

http://iopscience.iop.org/1742-6596/299/1



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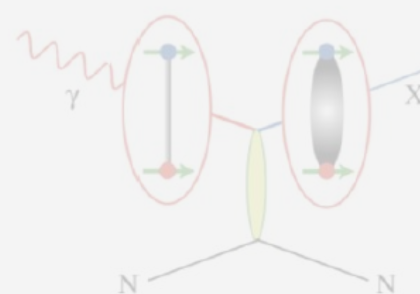
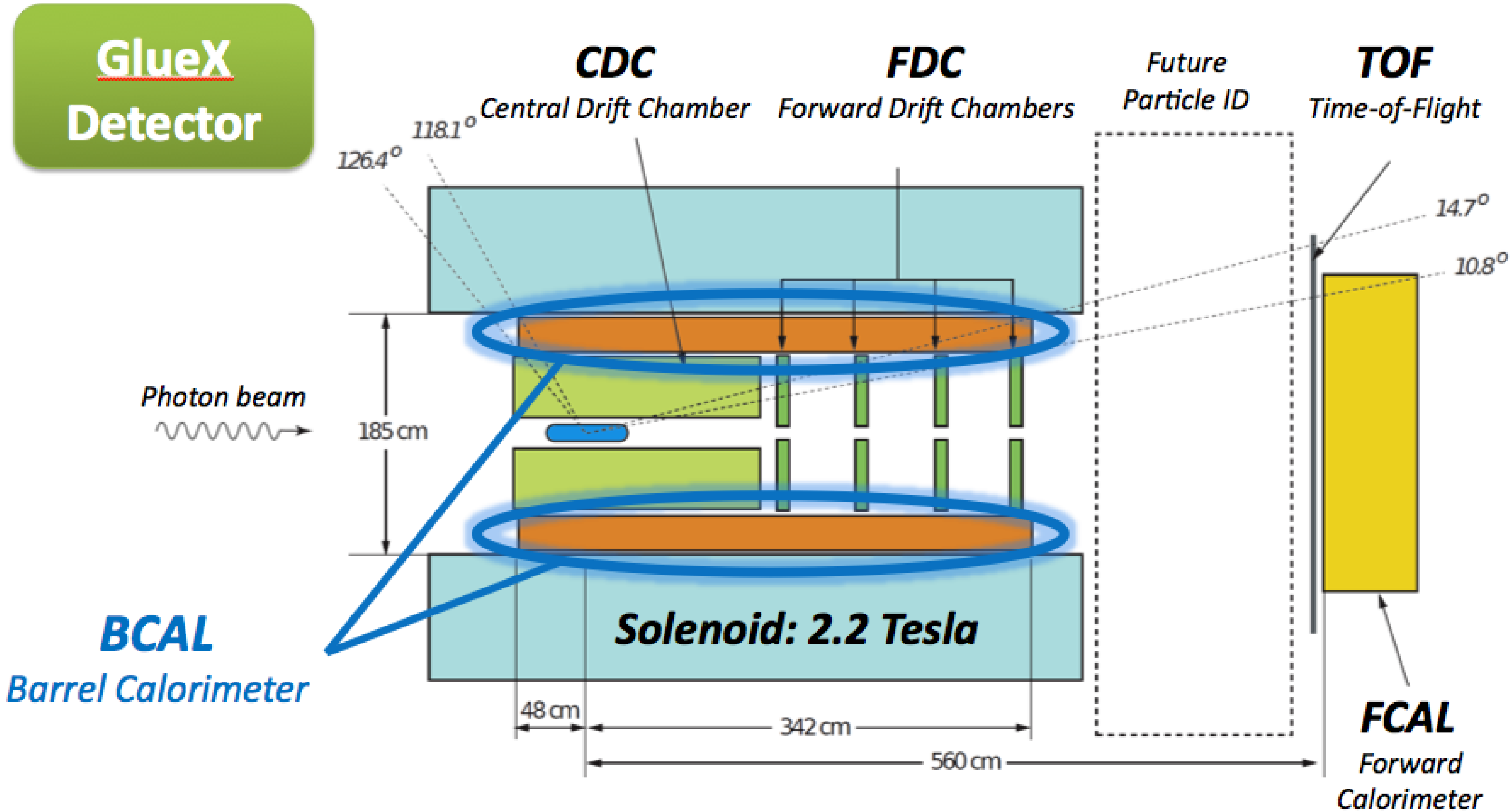


- use "amplitude analyses" to distinguish J^{PC}

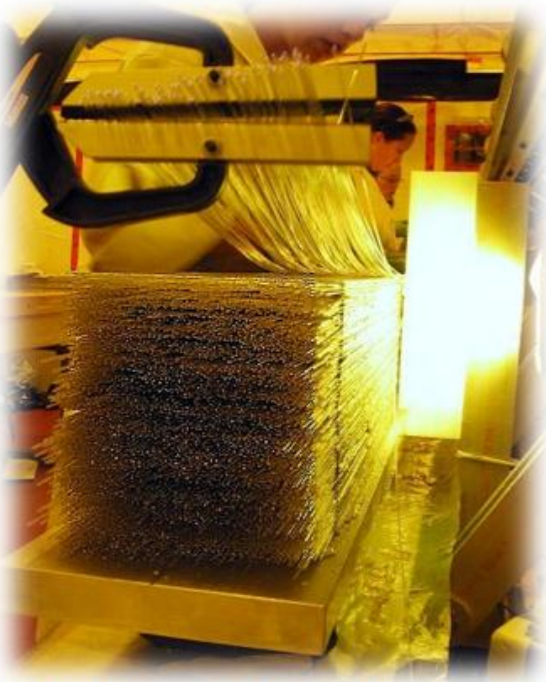
Barrel Calorimeter - BCAL



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

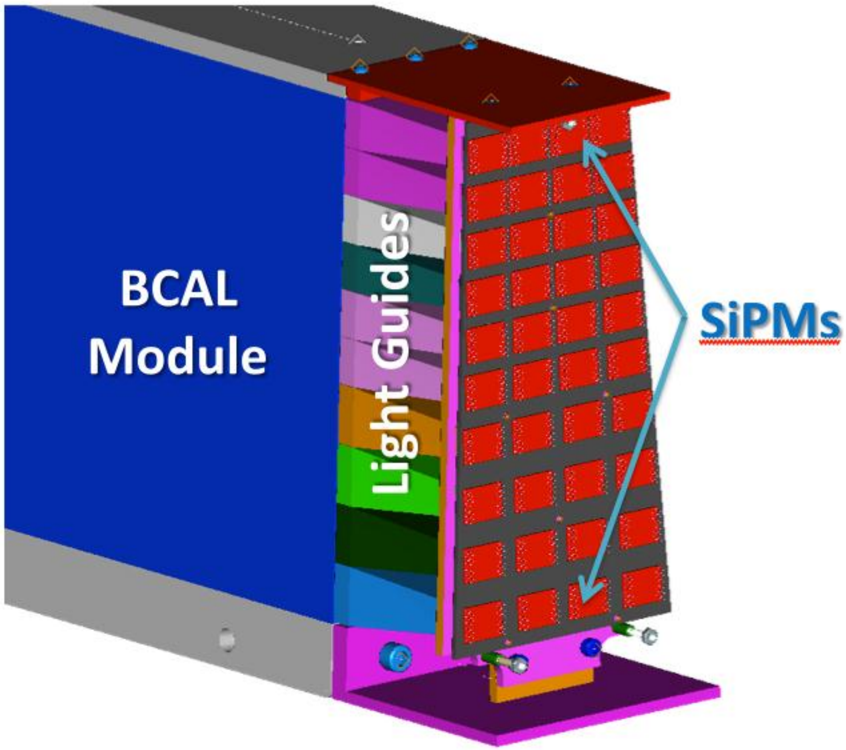


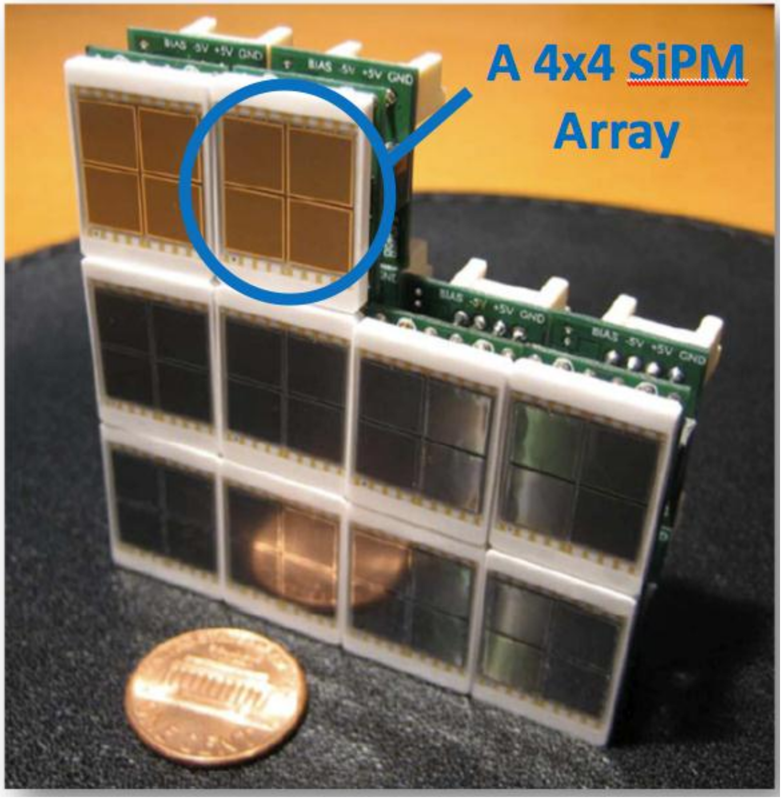
BCAL module being assembled from layers of fibers and Pb

- 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

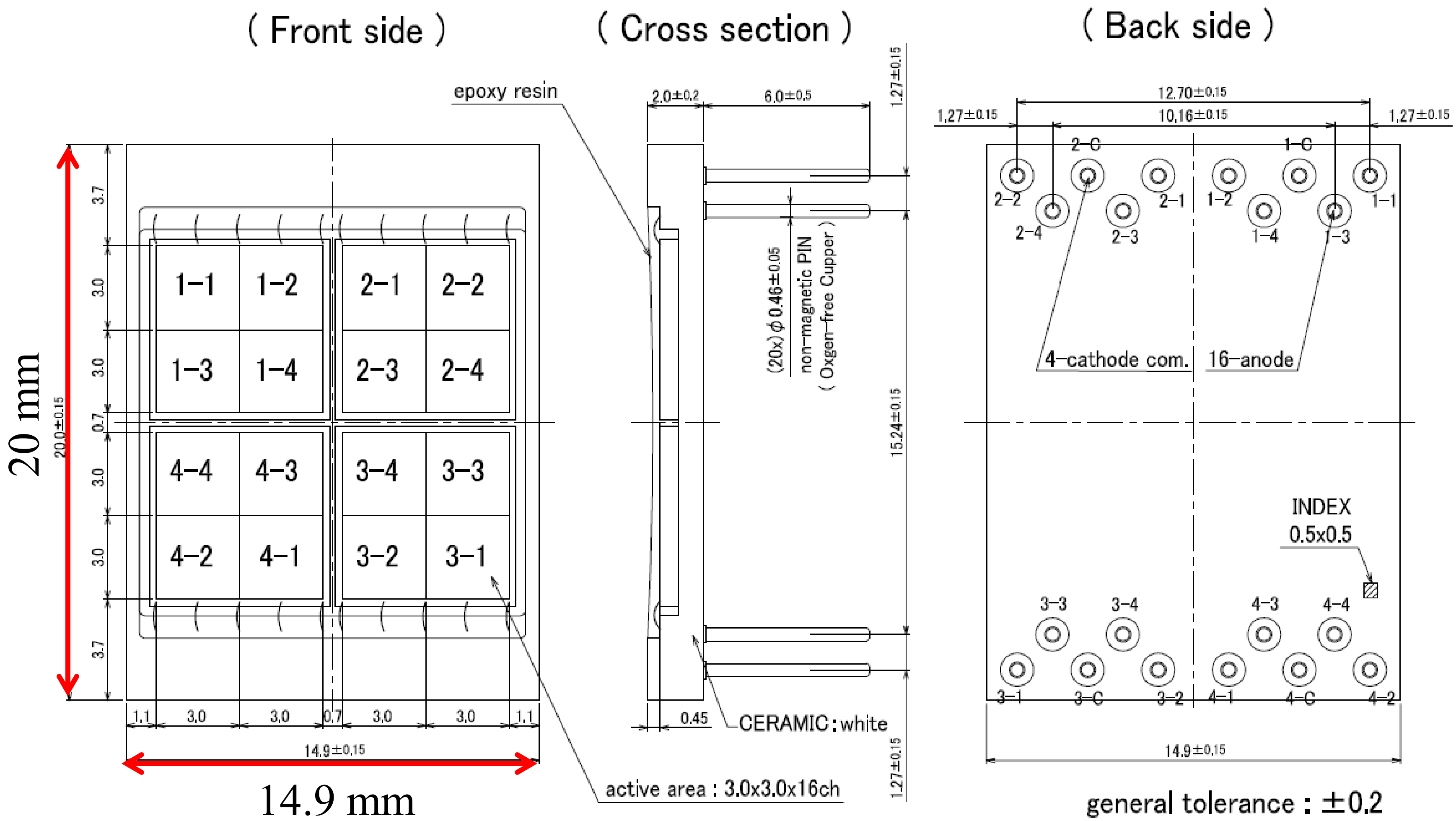




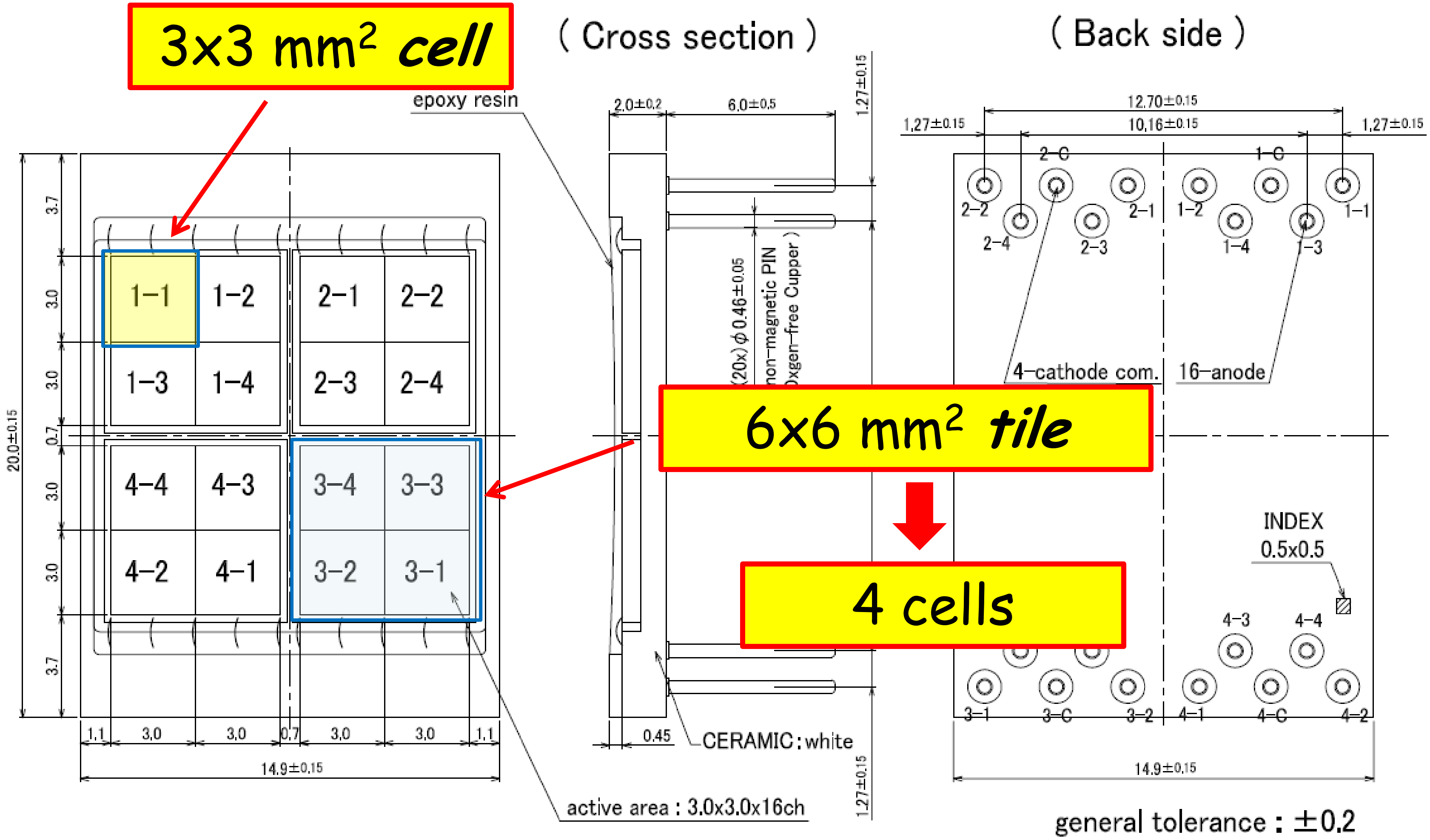
- 4x4 array of 3x3 mm^2 SiPM cells
- 50 μm microcells
- 57,600 microcells per array
- Photon Detection Efficiency (PDE) > 20%

- 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

Hamamatsu SiPM array (S12045(X))



Hamamatsu SiPM array



Requirement of SiPM for BCAL

- Major requirements:
  - Gain: $(0.5 \sim 2.0)\times10^6$
  - Photon detection efficiency: > 19 %
  - Dark rate: < 100 MHz
  - Gain and PDE variation in array: < 7.5%
  - Average gain variation among samples: < 7.5%
- Other requirements:
  - Geometry, size of active area
  - Pulse width: < 100 ns
  - Sensitivity to magnetic field (exception 1)
  - Sensitivity to radiation (exception 2)

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✧ Literature supports immunity to high magnetic fields

✧ Test of whole readout system needed as final check

  - Pulse width: < 100 ns
  - Sensitivity to magnetic field (exception 1)
  - Sensitivity to radiation (exception 2)

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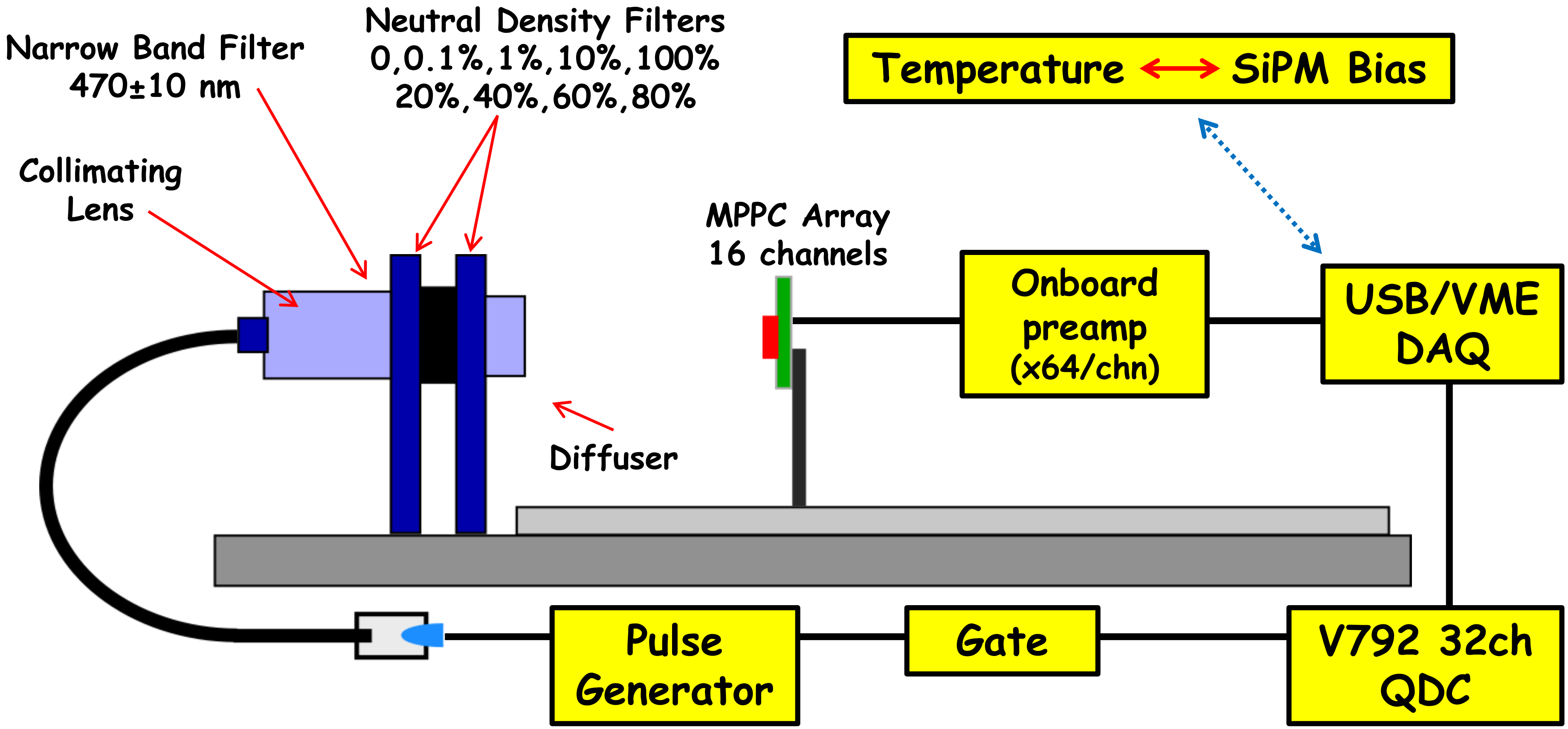
  - Geom
  - Pulse
  - Sensitivity to magnetic field (exception 1)
  - Sensitivity to radiation (exception 2)

✧ Return to this issue later in talk

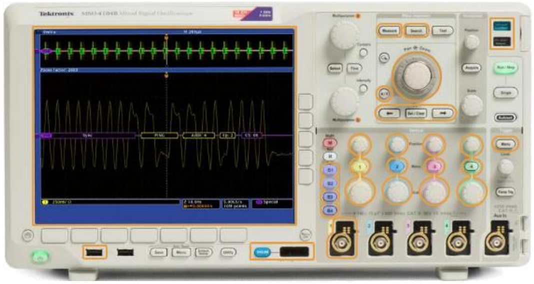
SiPM First Article Test

- March 2011
  - Received 80 samples from Hamamatsu
  - Test key characteristics of all samples before acceptance of full order (4000 units)
  - Gain, PDE, Dark Rate (Current), Response Uniformity, Crosstalk (+ afterpulses)
  - Radiation sensitivity (neutrons)
  - Magnetic field sensitivity – *in progress*
- September 2011
  - Arrival of first production batch (500) of SiPMs
  - Need to characterize 16 at a time (256 elements)

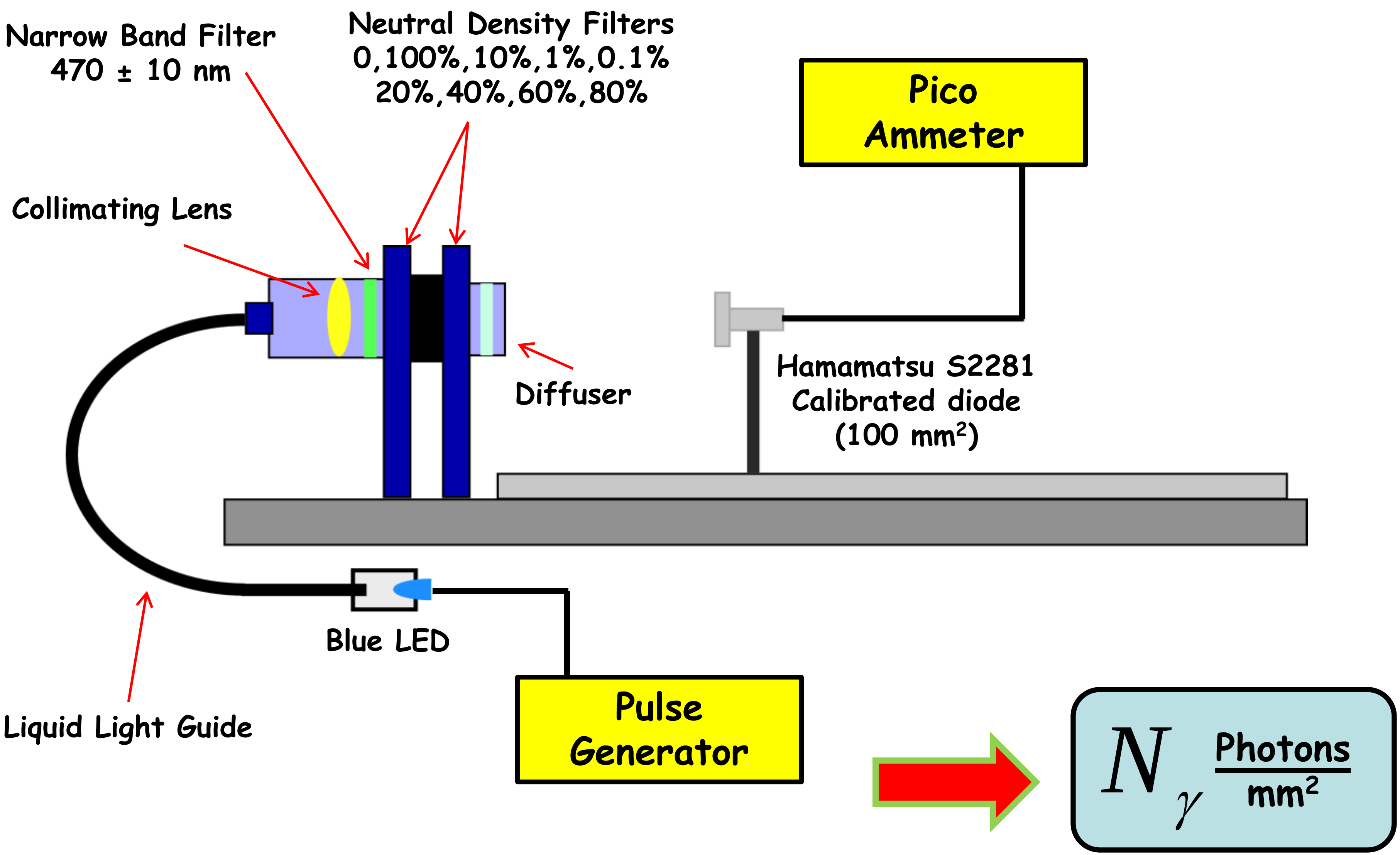
JLAB Workstation – Gain, PDE, Dark Rate, Crosstalk



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

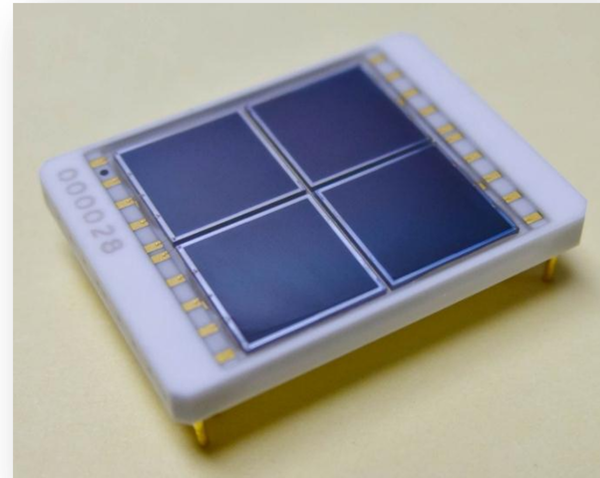


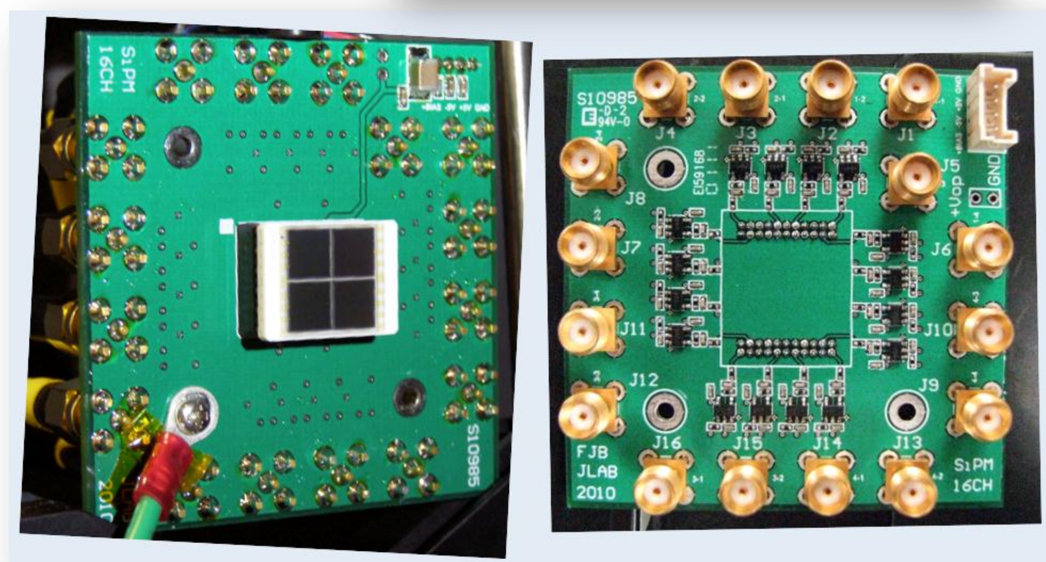
JLAB Workstation – Light Source Calibration



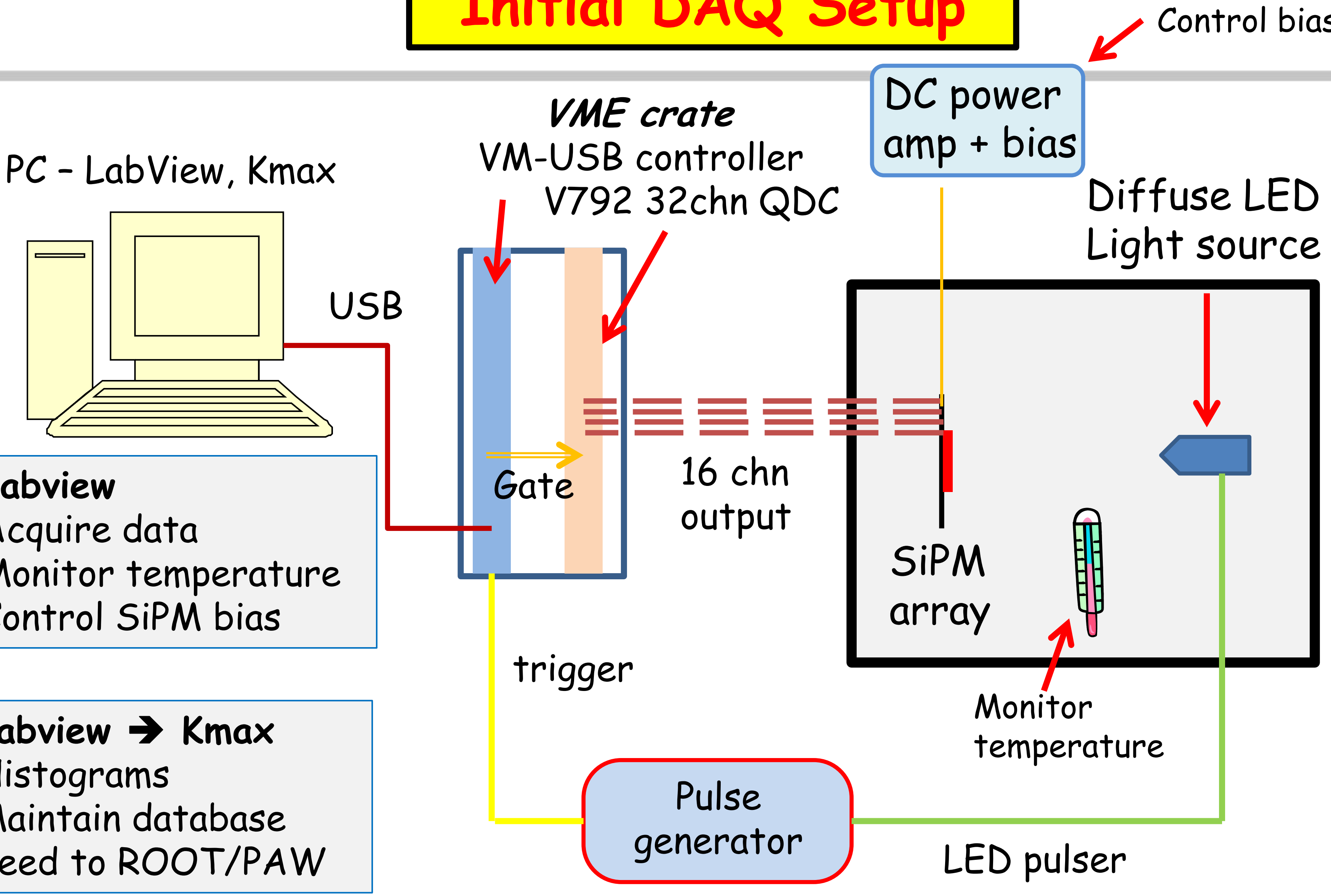
SiPM and Preamplifer

- 4x4 array of 3x3 mm SiPM
  - 50 ∝m pixel: 57600
  - 16 outputs
  - 4 power inputs
- Preamplifier for the test
  - 16 individual amplification and outputs
  - High gain mode (×67)





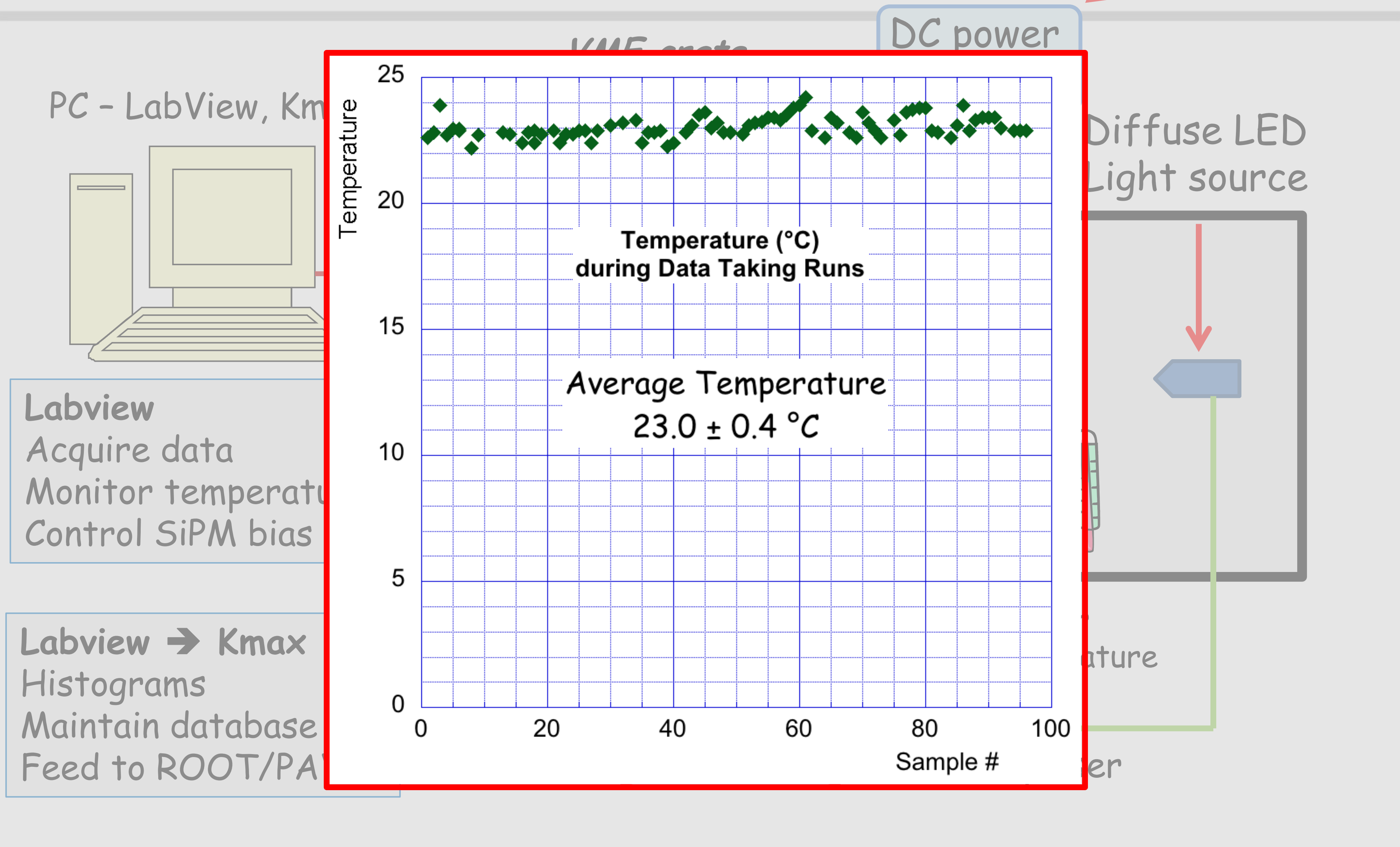
Initial DAQ Setup



Labview
Acquire data
Monitor temperature
Control SiPM bias

Labview → Kmax
Histograms
Maintain database
Feed to ROOT/PAW

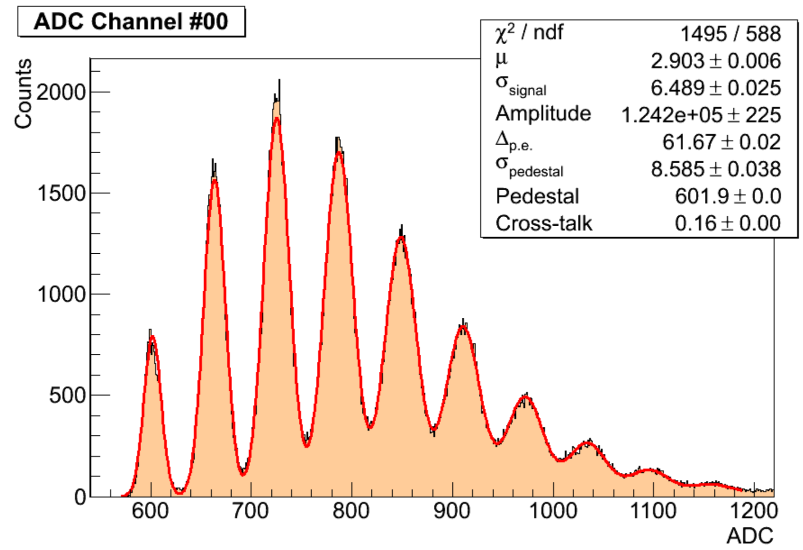
Initial DAQ Setup



Data Analysis

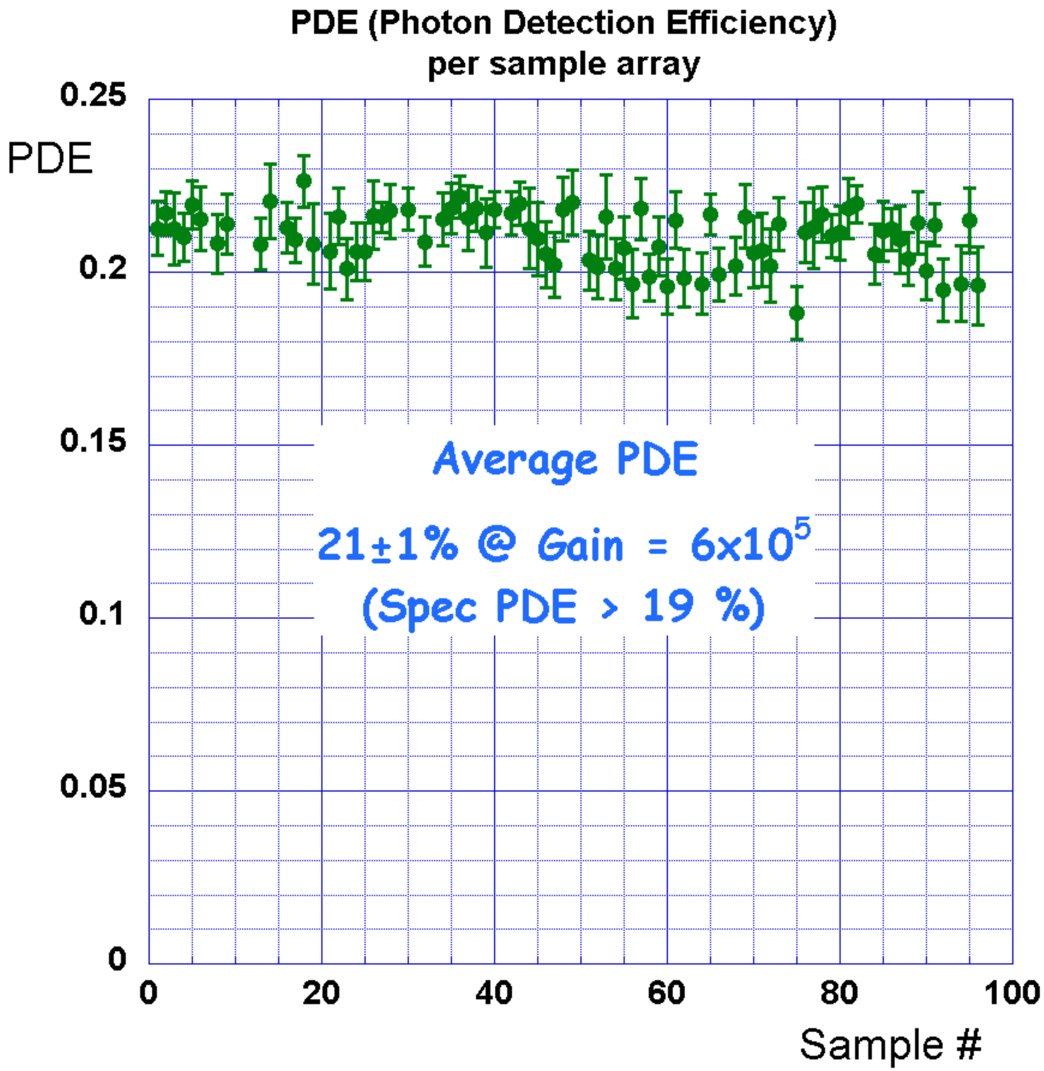
- Fit individual QDC spectra

$$\sum_{N=1}^{\infty} G\left(a \cdot \sum_{n+m=N} \left(P(n,\mu)\cdot P(m, n\Delta\mu)\right), \sigma(N)\right)$$



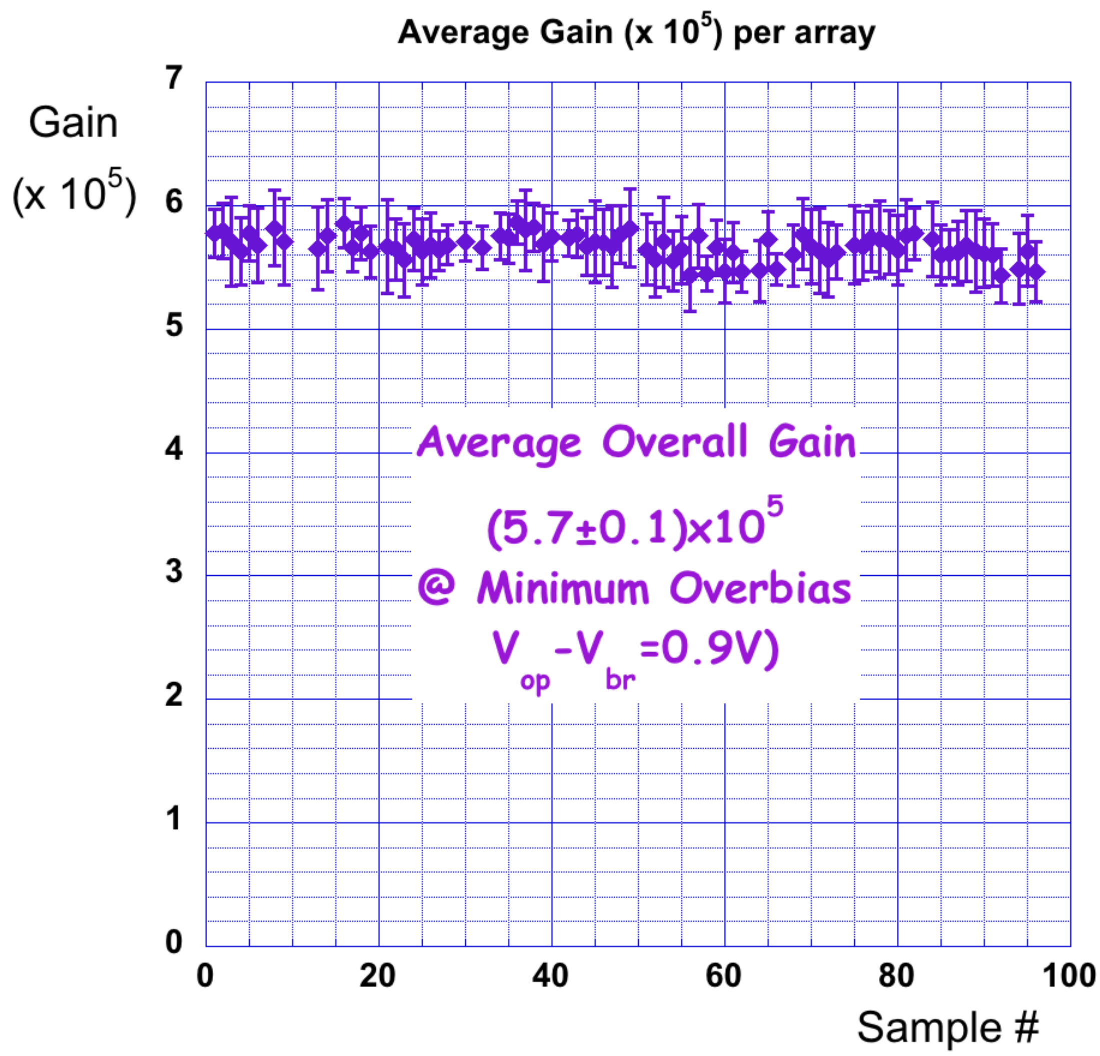
- ***G***: Gauss distribution
- ***P***: Poisson distribution
- ***a***: gain
- ***μ***: number of primary fired pixels
- ***Δμ***: probability of cross talk + afterpulse in gate (1 μs)
- ***σ***: width of individual pixel peaks
  - $\sigma(N) = (\sigma_{ped}{}^2 + N\,\sigma_{sig}{}^2)^{-1/2}$

Photon Detection Efficiency



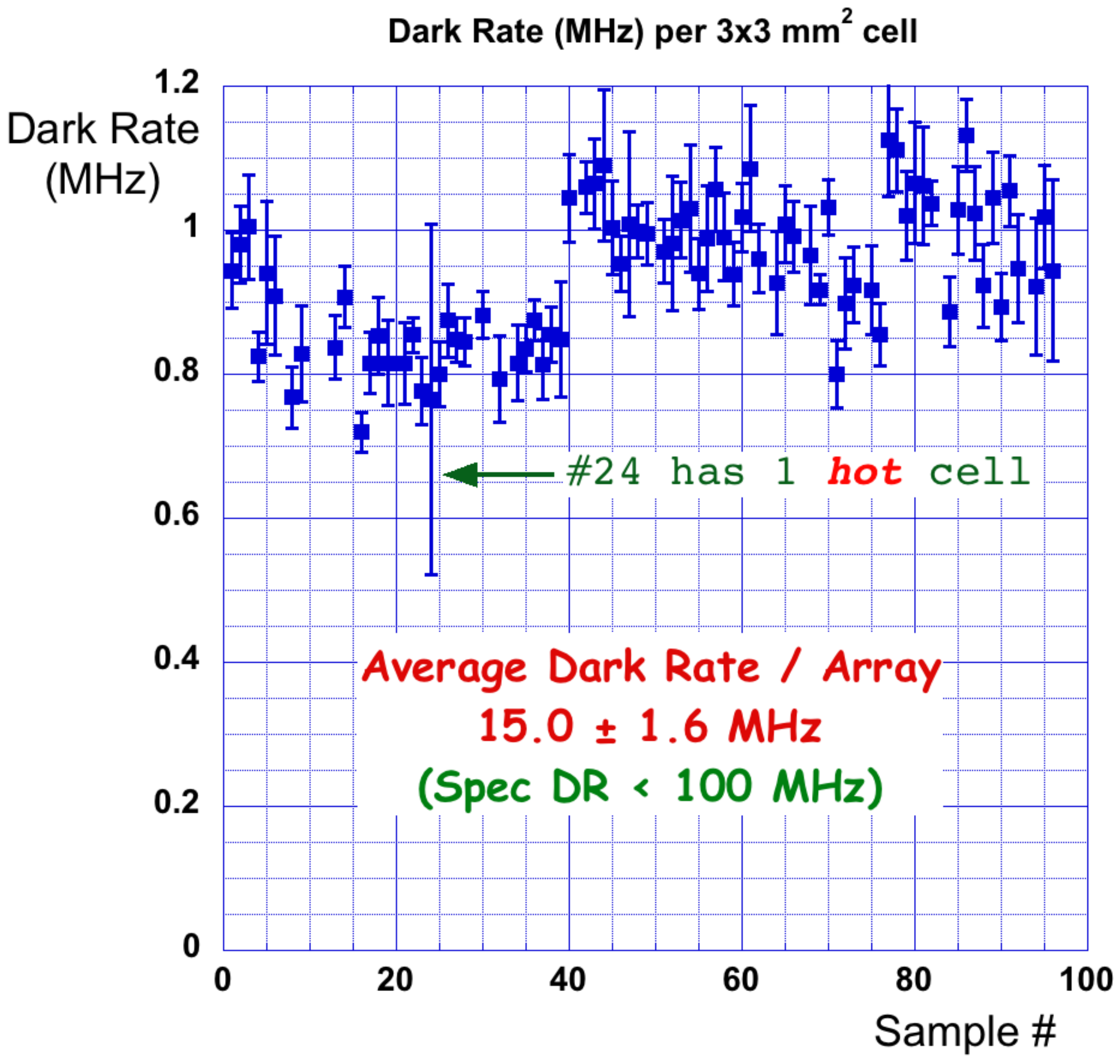
At Nominal Gain
7.5×10^5
PDE = 26%

Gain



Average Gain (x 10^5) per array
Gain
(x 10^5)
7
6
5
4
3
2
1
0
0
20
40
60
80
100
Sample #
Average Overall Gain
$(5.7\pm0.1)\times10^5$
@ Minimum Overbias
$V_{op}-V_{br}$=0.9V)

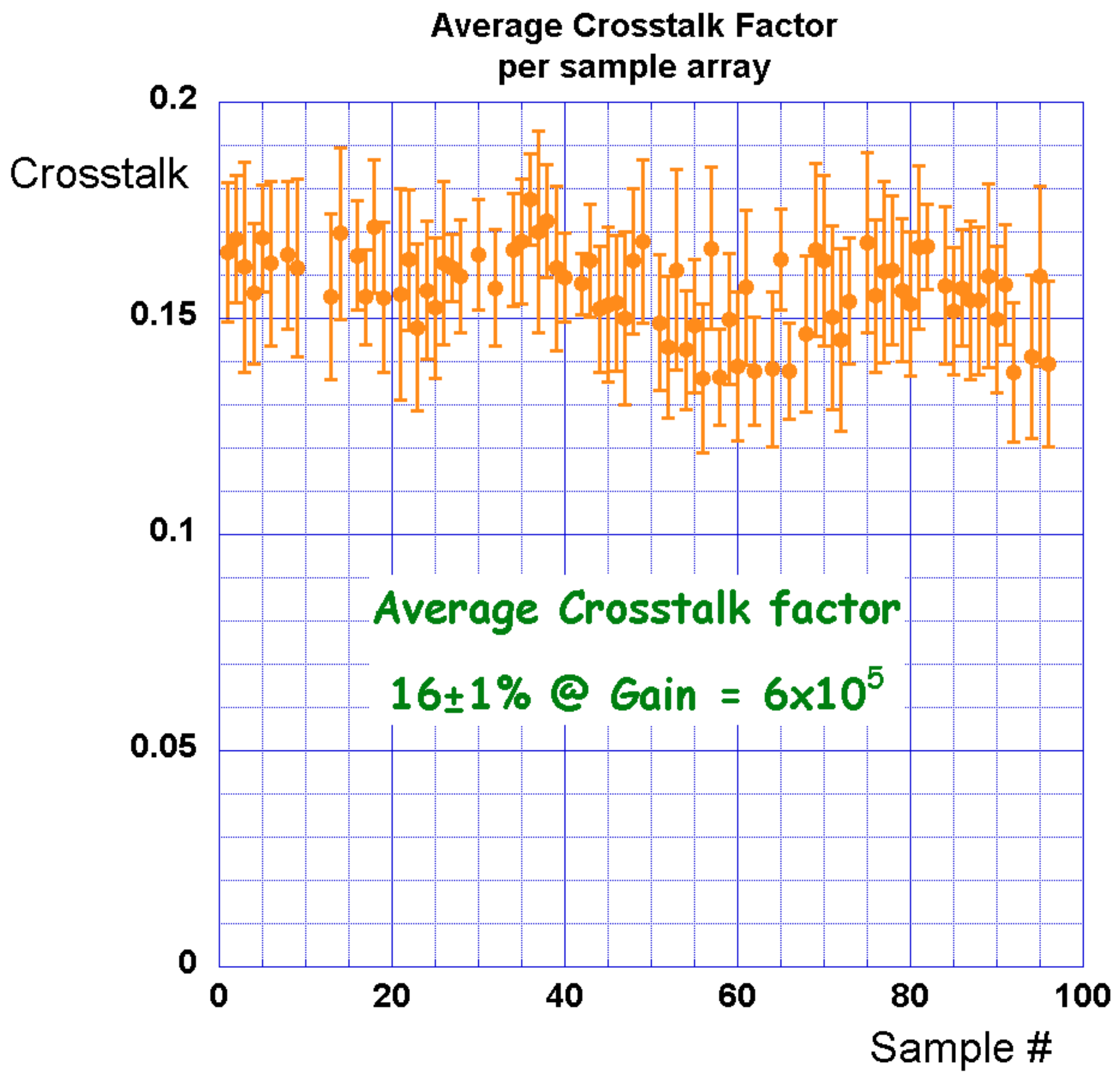
Dark Rate



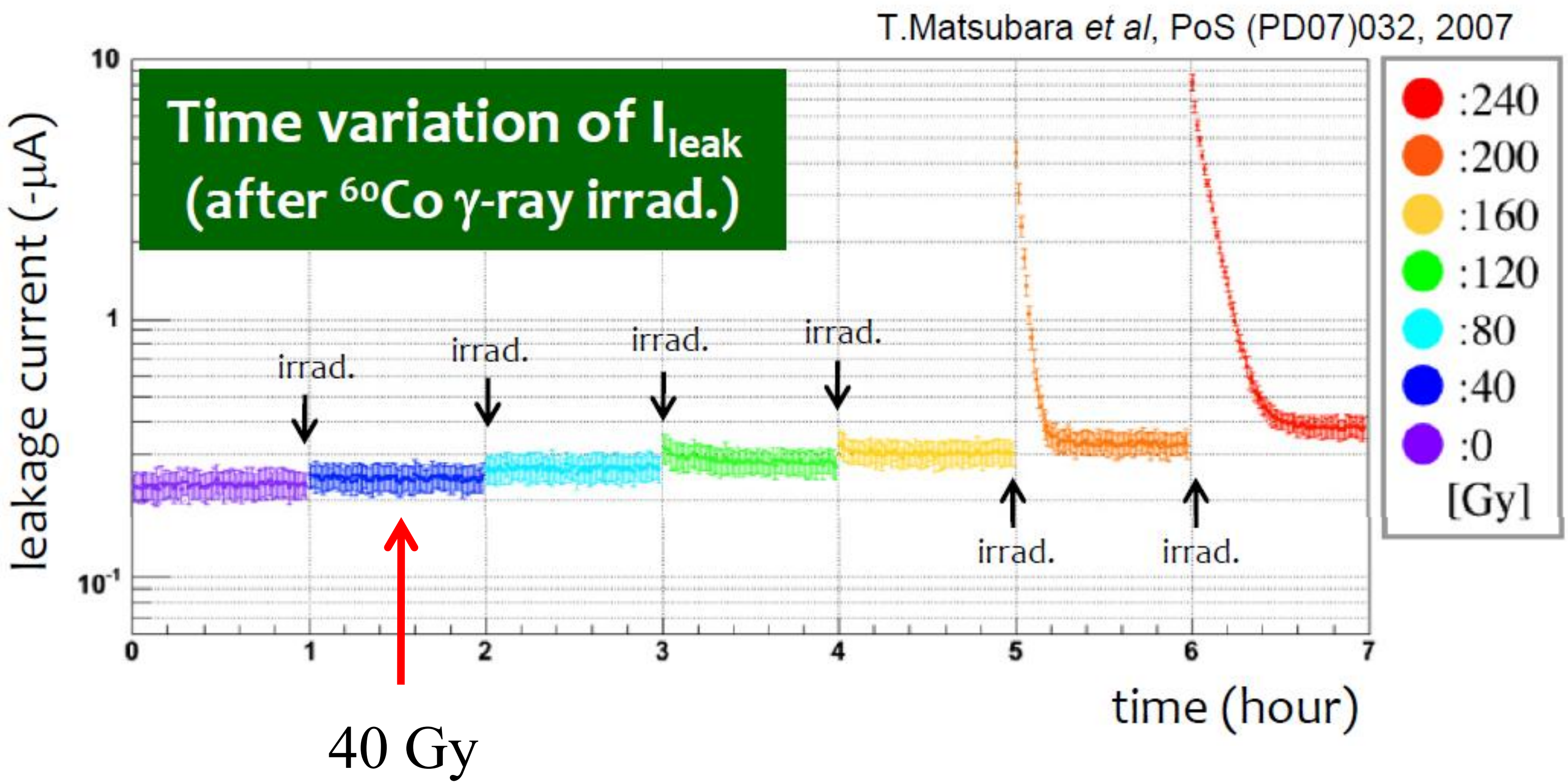
At Nominal Gain
7.5×10^5
DR = 24 MHz

Factor x4 LESS than original prototypes

Cross Talk + After Pulse in 1 μs



Radiation Tolerance - Gamma

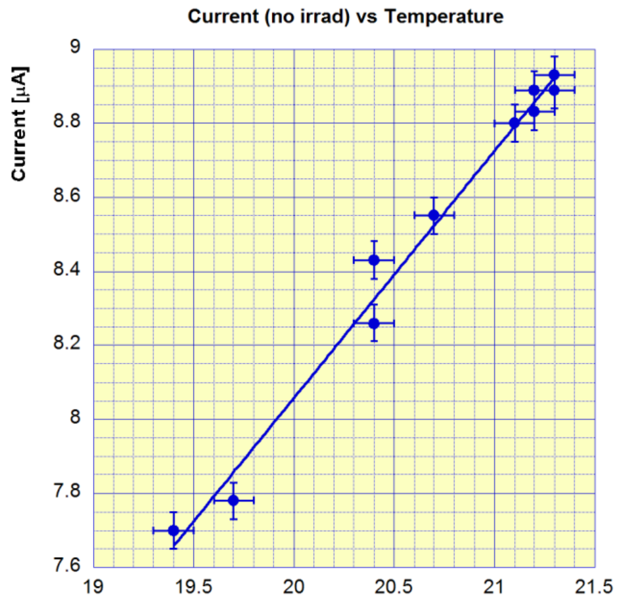


For GlueX => < 2 Gy/10 yrs

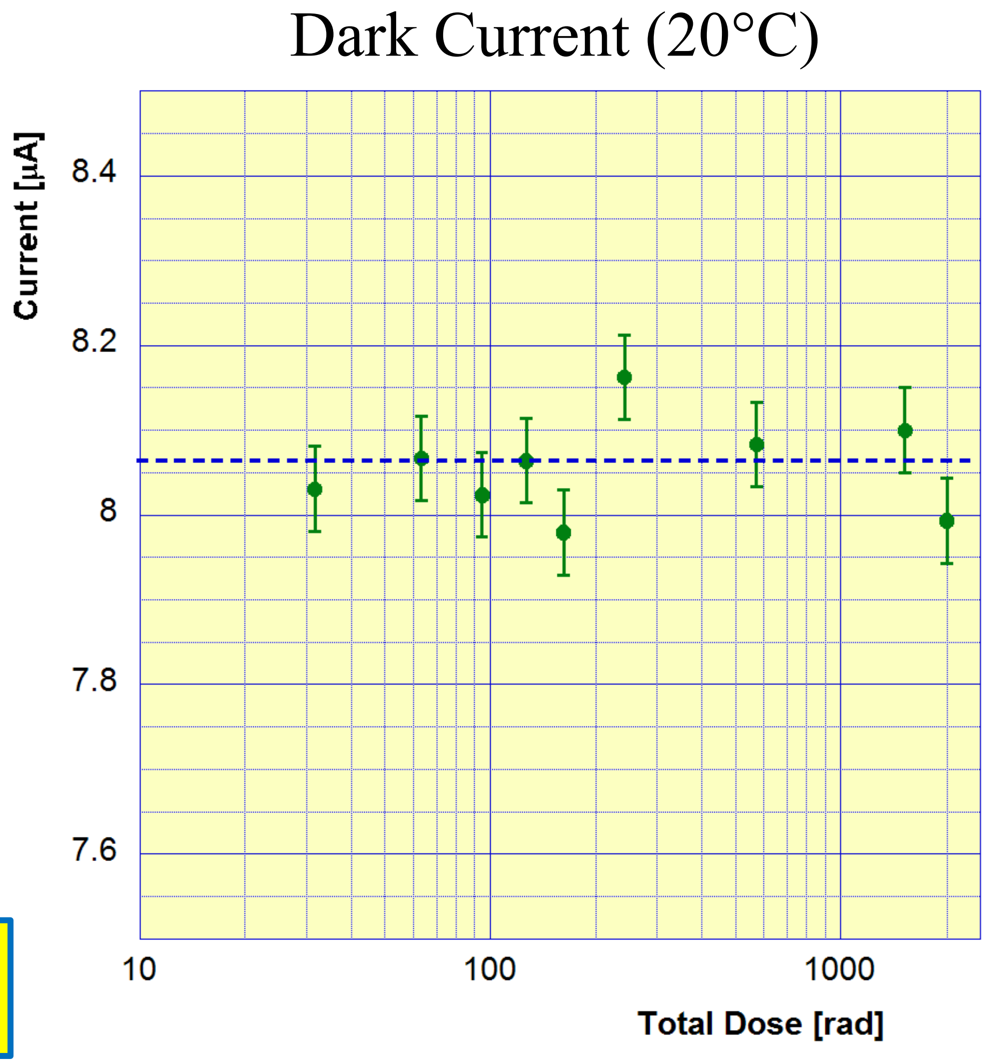
Toru Matsumura

KEK Detector Technology Project

Irradiation with Cs-137 source to 20 Gy



Renorm dark current vs T
and apply to Irrad Data

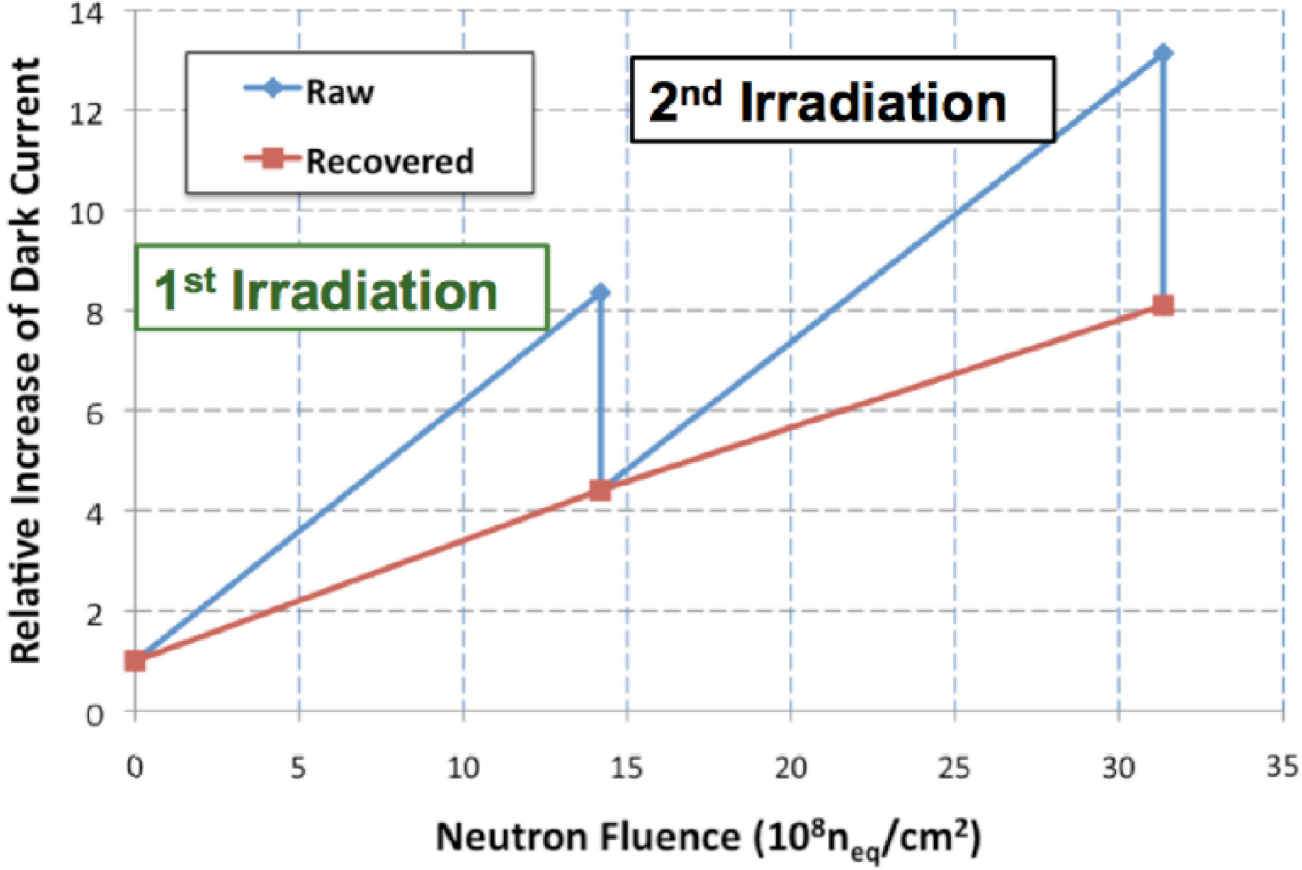


No discernible
effect

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

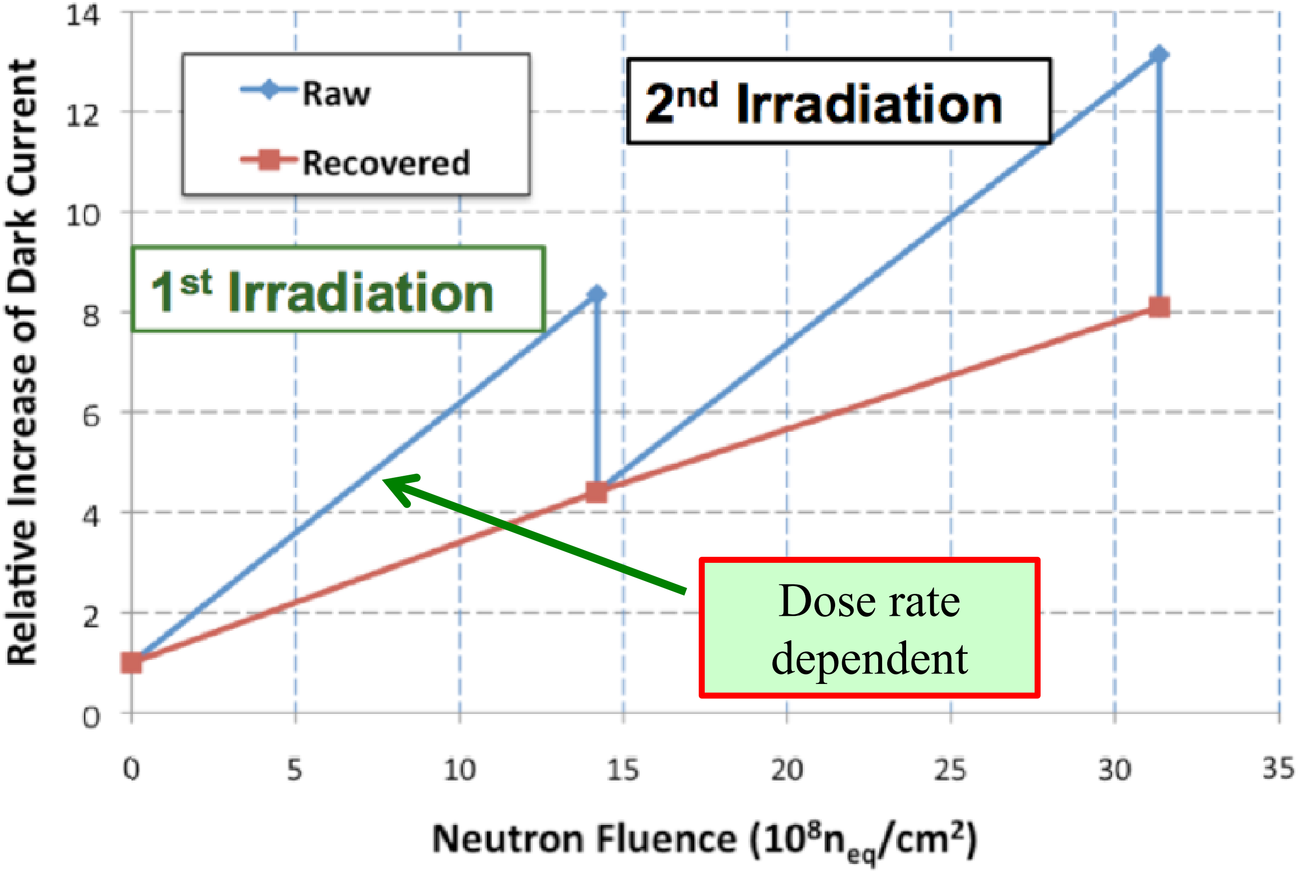
SiPM Neutron Radiation Test



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

-> 3×10^8 $n_{eq}/cm^2/year$

SiPM Neutron Radiation Test



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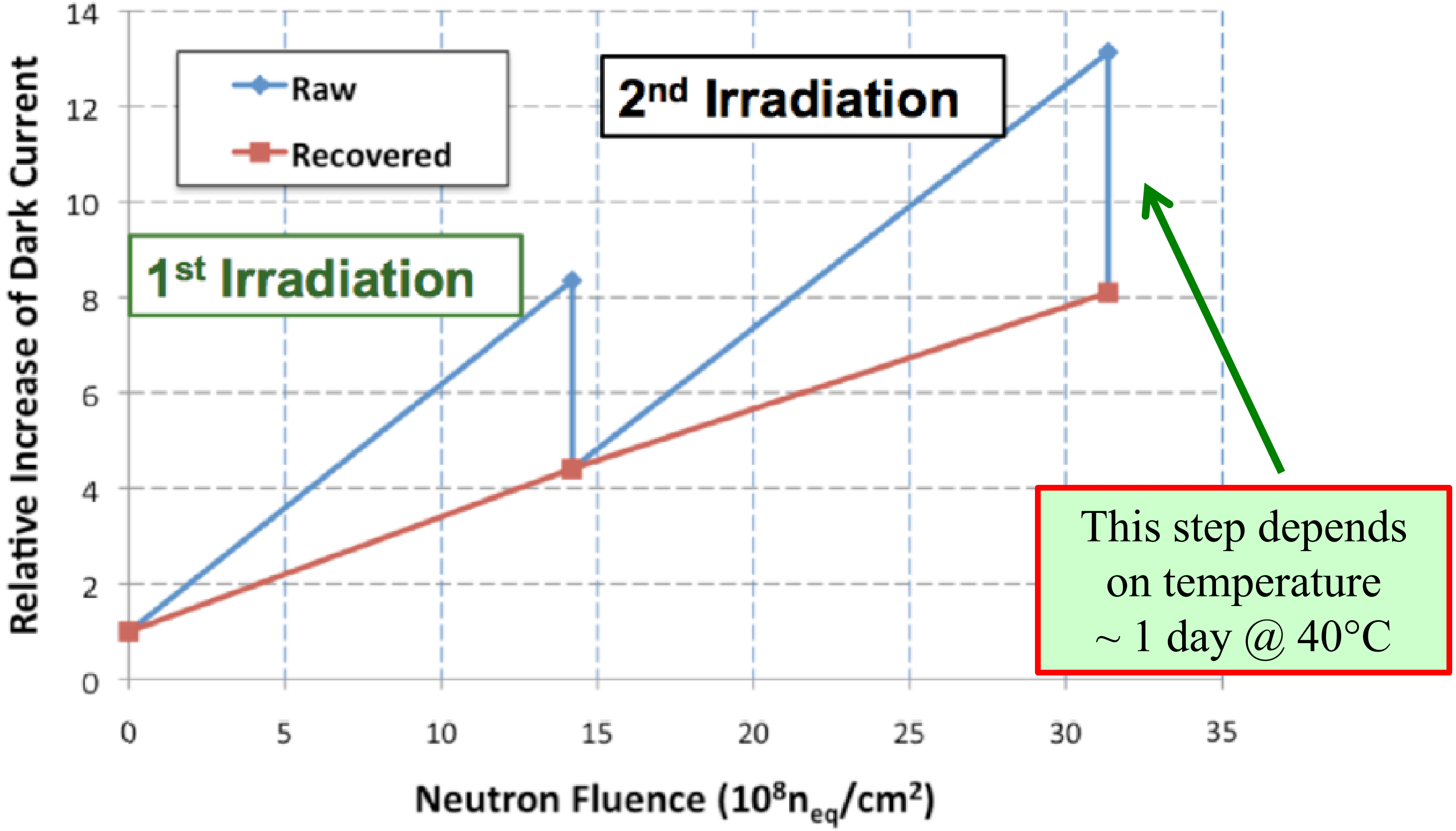
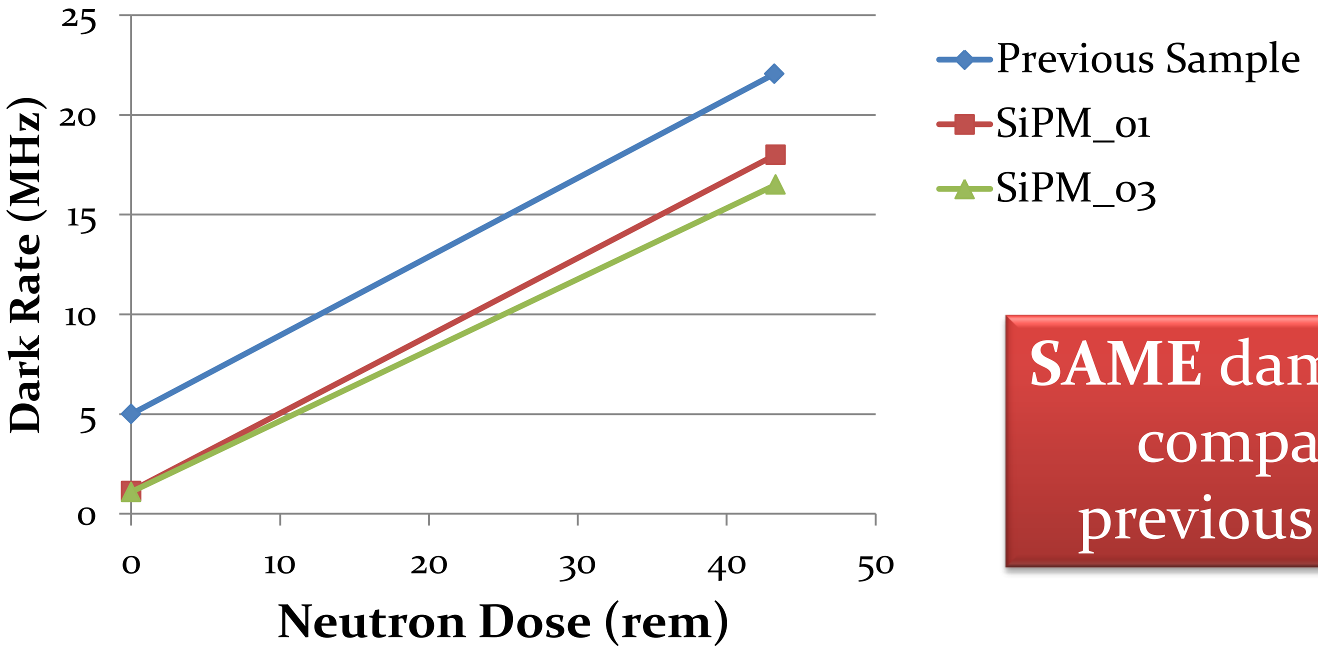


Neutron Fluence with 10^8 g/s on LH_2 Target with 1/3 efficiency

-> $3\times10^8\ n_{eq}/cm^2/year$

Radiation Damage

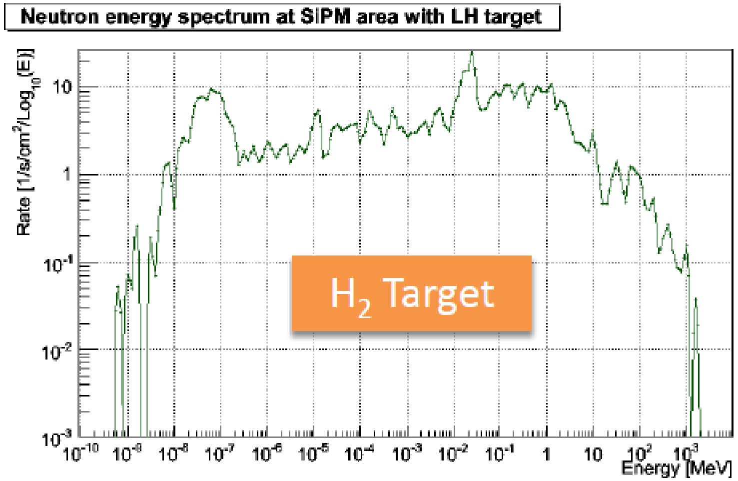
- Two first article samples were irradiated by AmBe neutron source (provided by JLAB RadCon group)
  - Total dose: 43.3 rem (~ 5 years high luminosity running on LH_2 target in Hall D).
  - Both samples were then annealed at 40°C

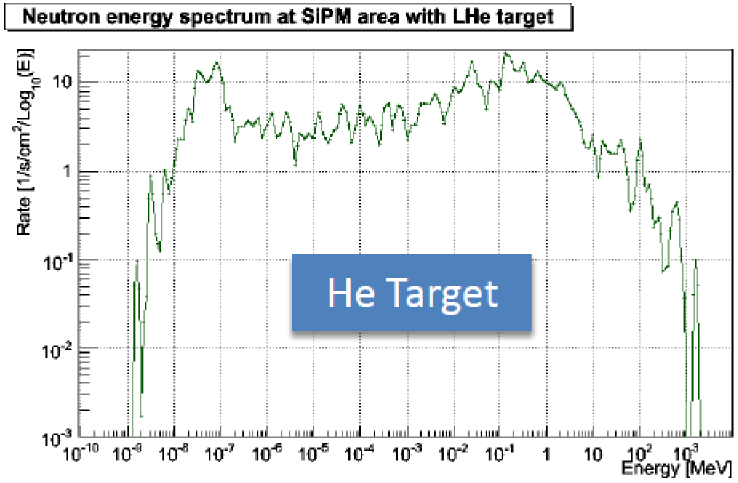


SAME damage slope compared to previous sample!

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
- Upstream rates are 4 times lower.





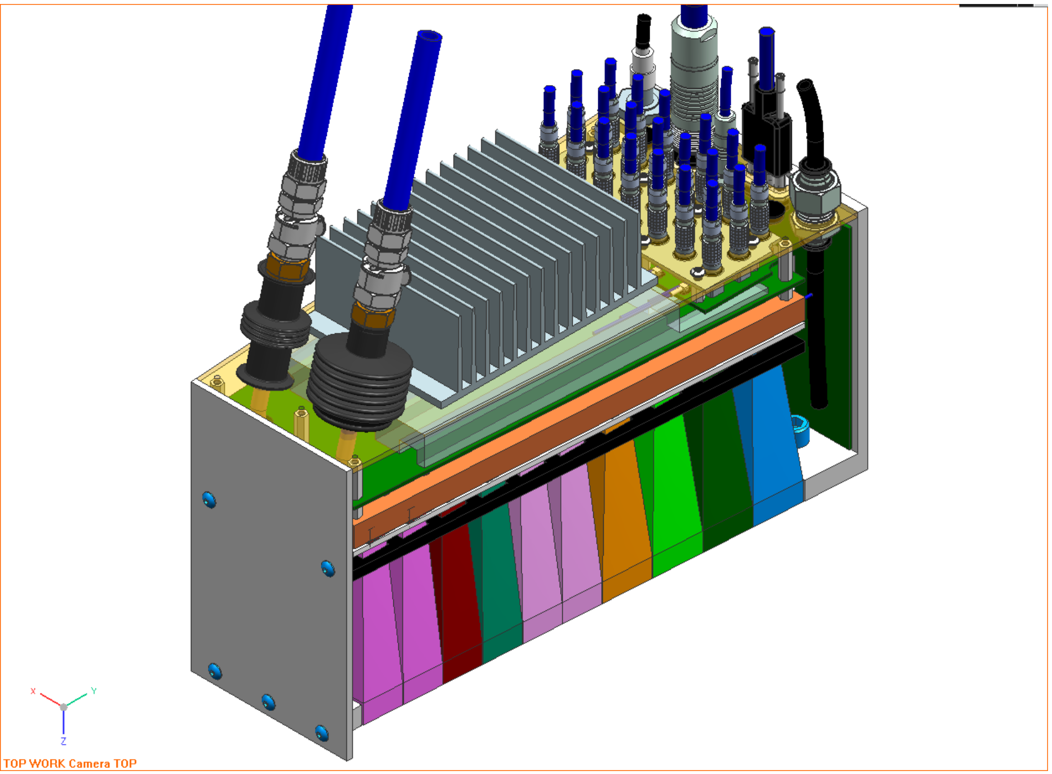
1 rem → $2.6 \times 10^7\ n_{eq}/cm^2$

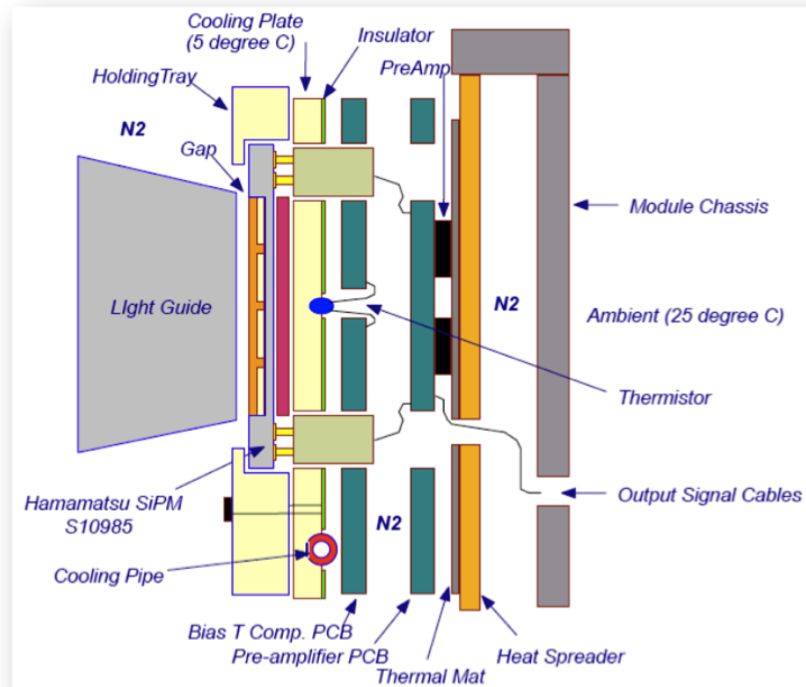
How to Extend the Lifetime?

- 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
- *OK- but need further R&D work on rad-hardening of SiPMs – DOE/EIC grant to pursue this now*

SiPM Readout includes Temperature Control

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





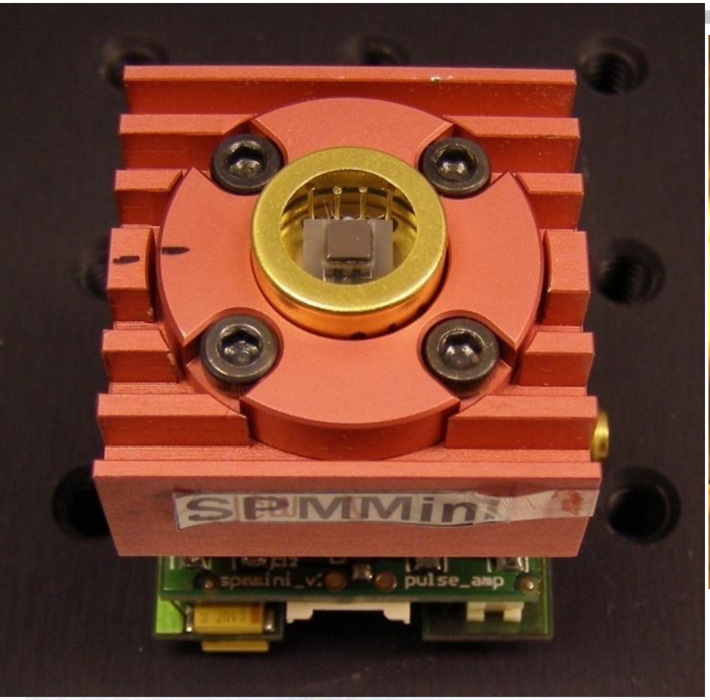
- Downtime ➔ SiPMs will be heated to ~40°C
- Achieve post-irradiation anneal to residual level

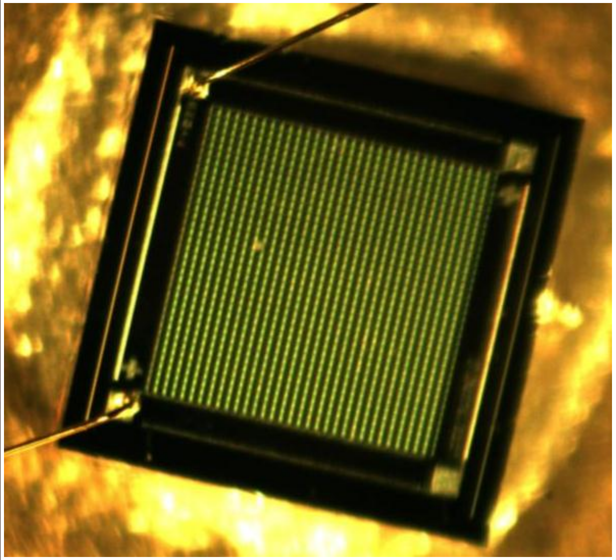
Summary and To-do List

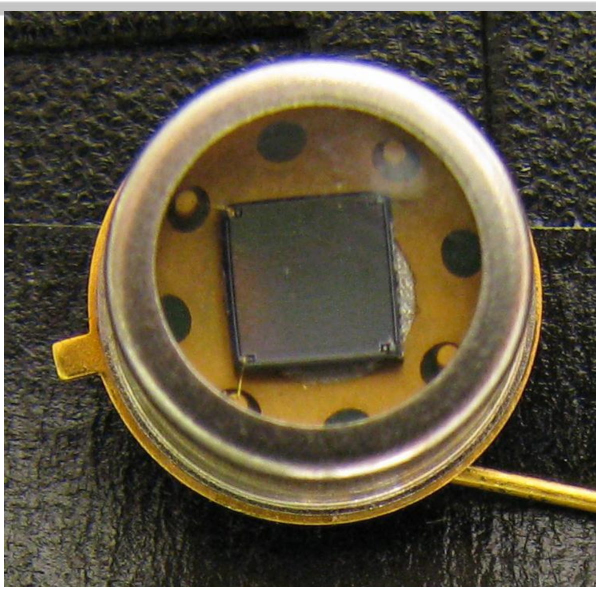
- First article of SiPM from Hamamatsu showed very good performance and has been approved
- Much lower dark rate with new samples
- Increase of dark rate due to radiation damage unchanged
- To-do list
  - Preparation for the production test
    - 4000 units – 1/3 @ JLAB, 2/3 USM (Chile)
    - *Test 16 or 32 SiPM arrays at a time – all channels*
  - Development of full readout/cooling setup
    - Temperature dependence test
    - Test of readout module sensitivity to magnetic field

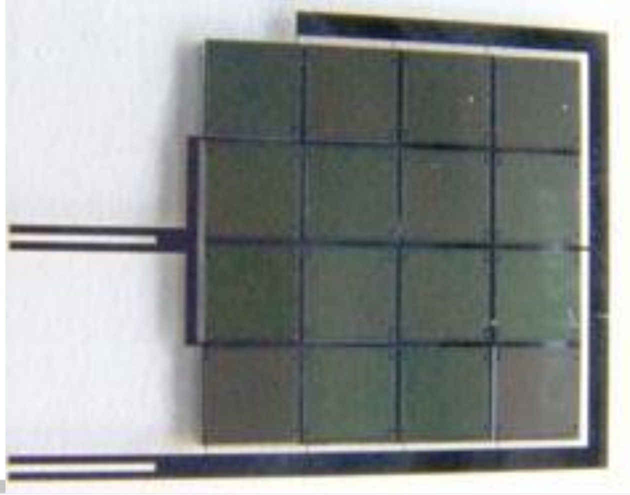
Backup Slides

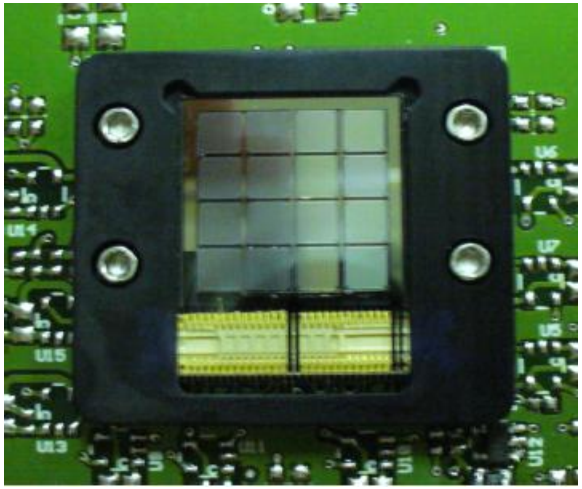
Example Devices for Initial Studies

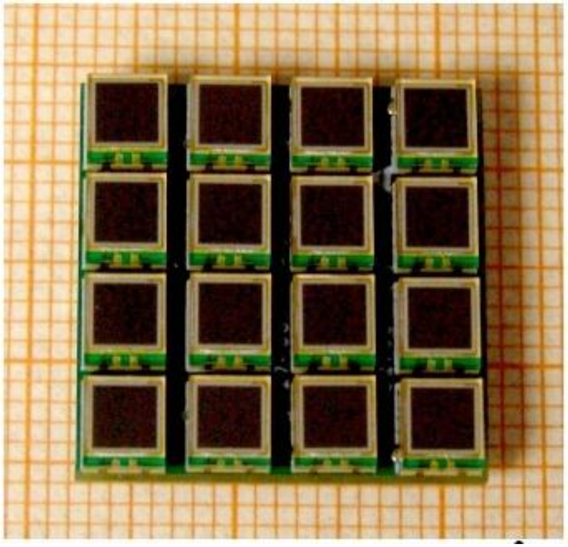






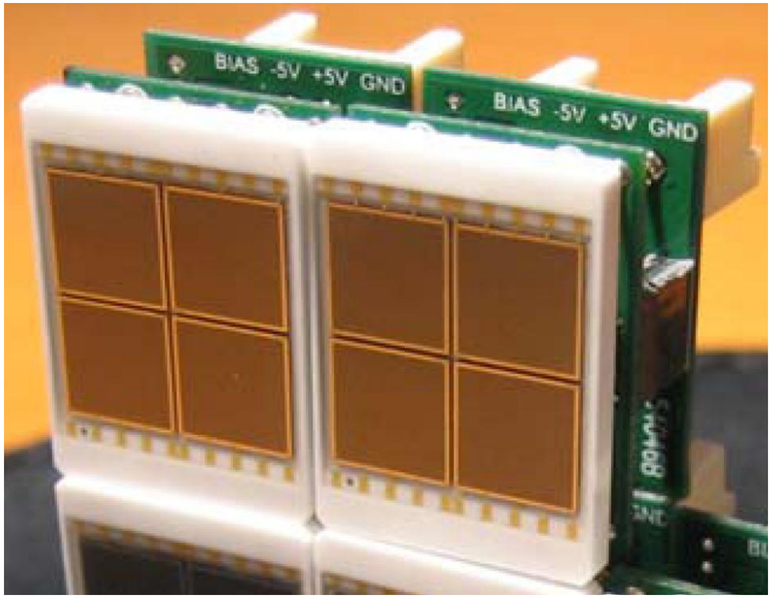






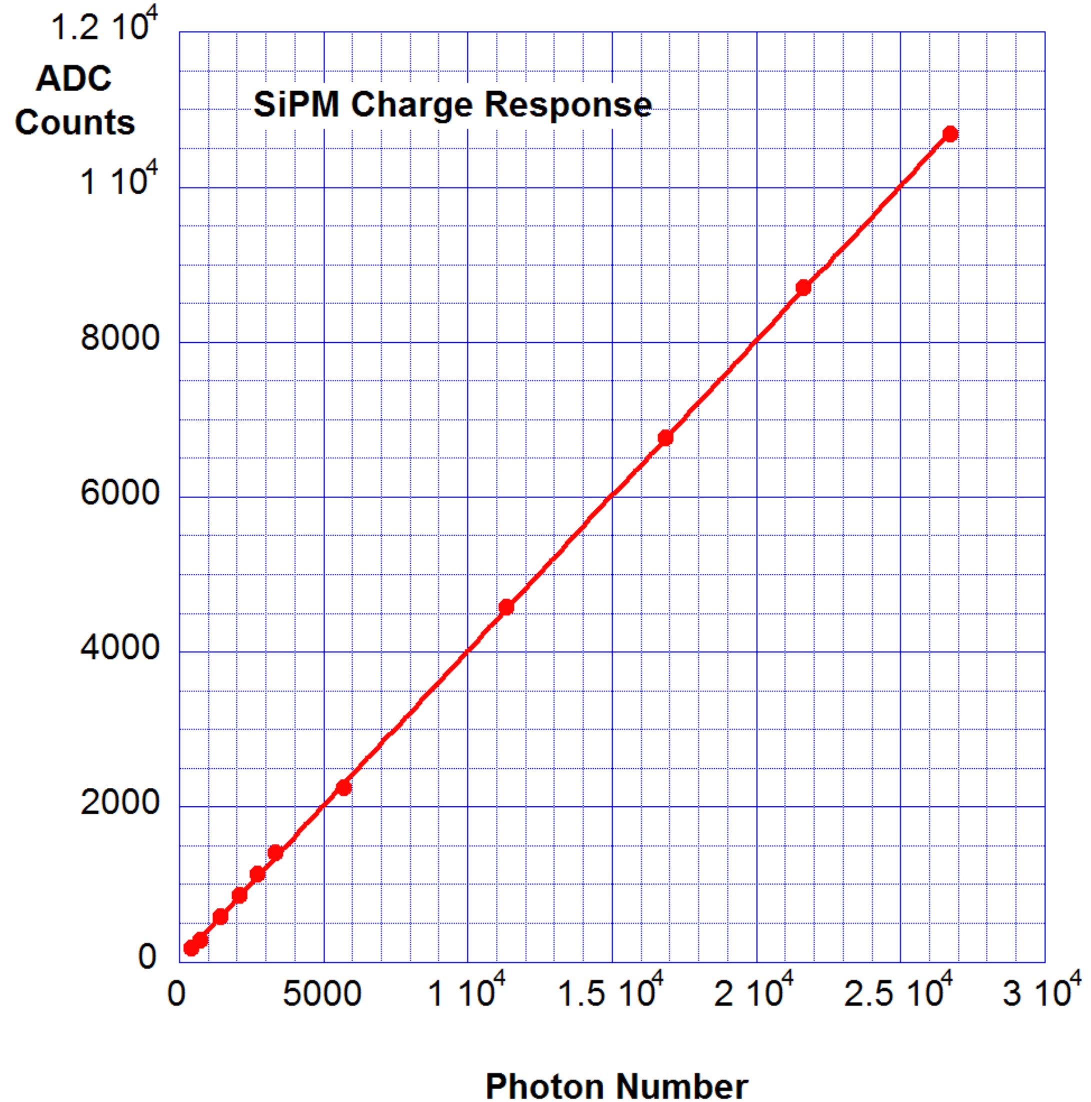
Original SiPM Array Prototypes

Hamamatsu MPPC

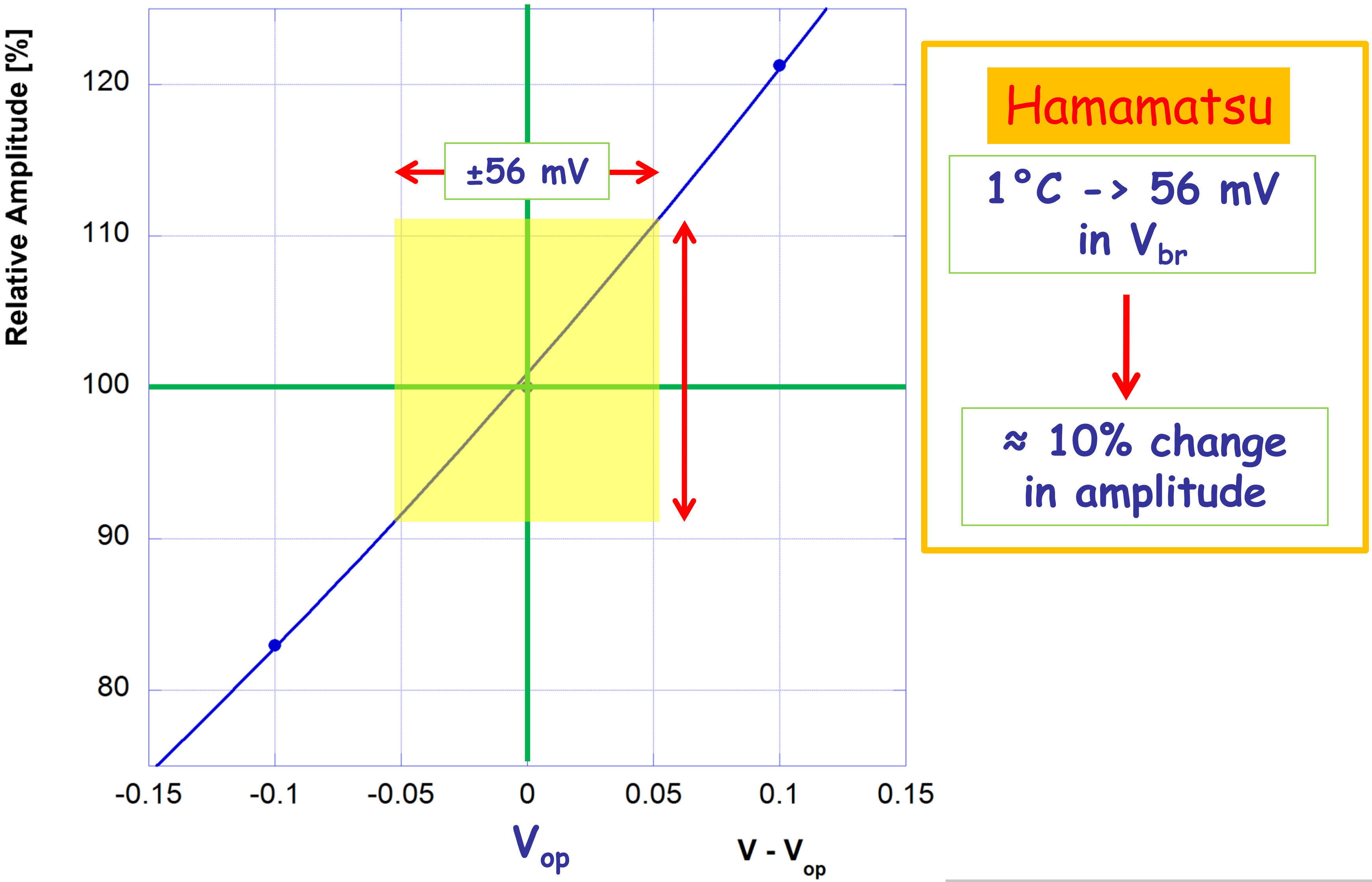


SensL SiPM4

Linear Response of Array



Implication for Temperature Stability

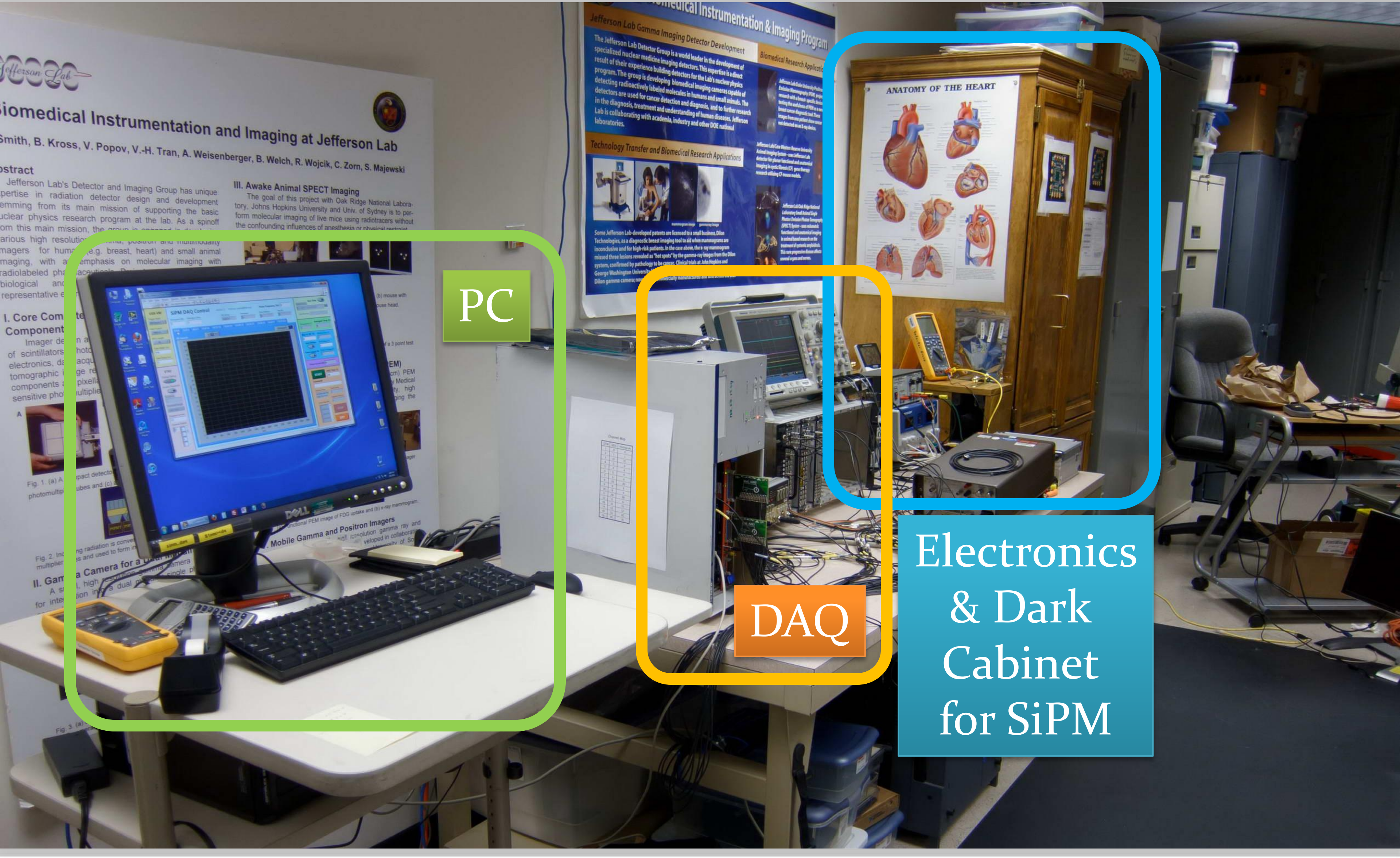


Temperature & Stability

- 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

Test Setup

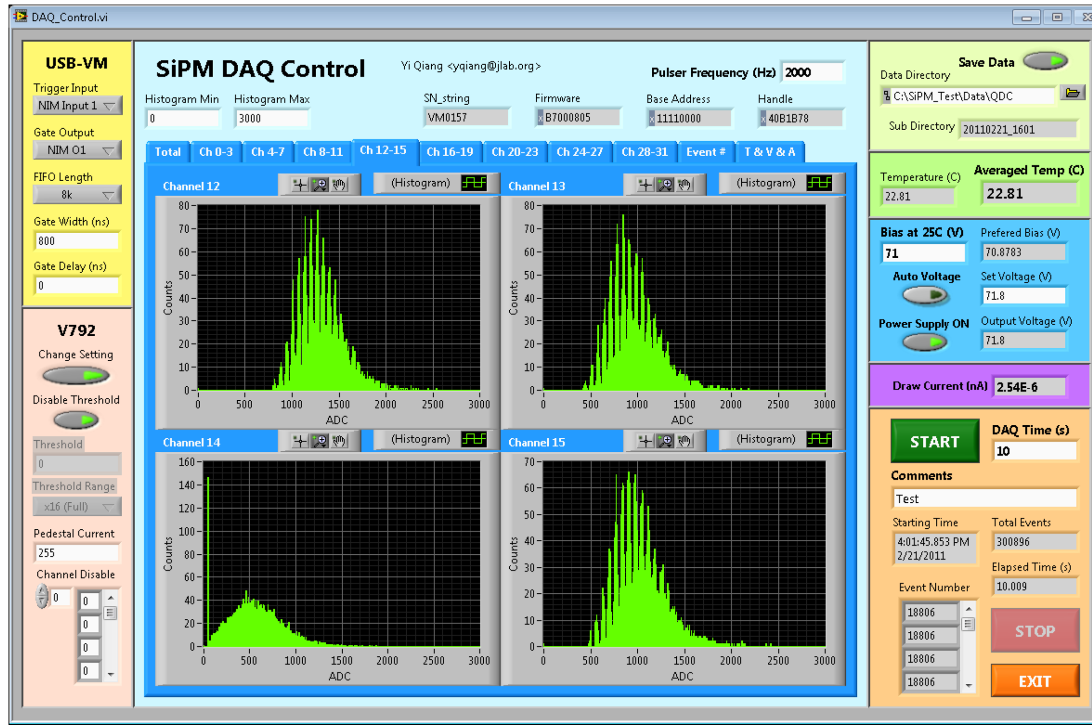

PC
DAQ
Electronics & Dark Cabinet for SiPM
ANATOMY OF THE HEART

DAQ

- HP8116A pulse generator
  - Drive LED with 5ns wide pulse
  - Send trigger signal to DAQ
- Wiener VM-USB VME controller
  - USB interface
  - LabVIEW driver
  - Produce 1 μs gate to QDC
- CAEN V792 QDC
  - 12 bit
  - 32 channels
  - Low noise

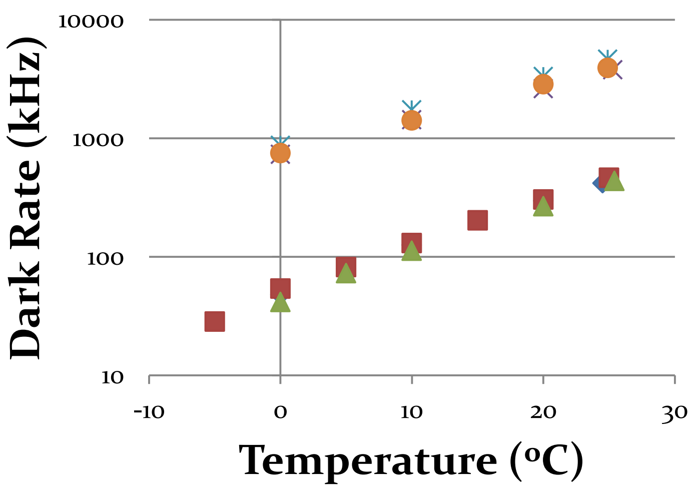
LabVIEW Control and Logging

- Controls
  - Bias Voltage
  - Pulse frequency
  - DAQ parameters:
    - Gate
    - Delay …
- Records
  - QDC readings
  - Temperature
  - Bias Voltage
  - Draw current



Temperature and Voltage Correction

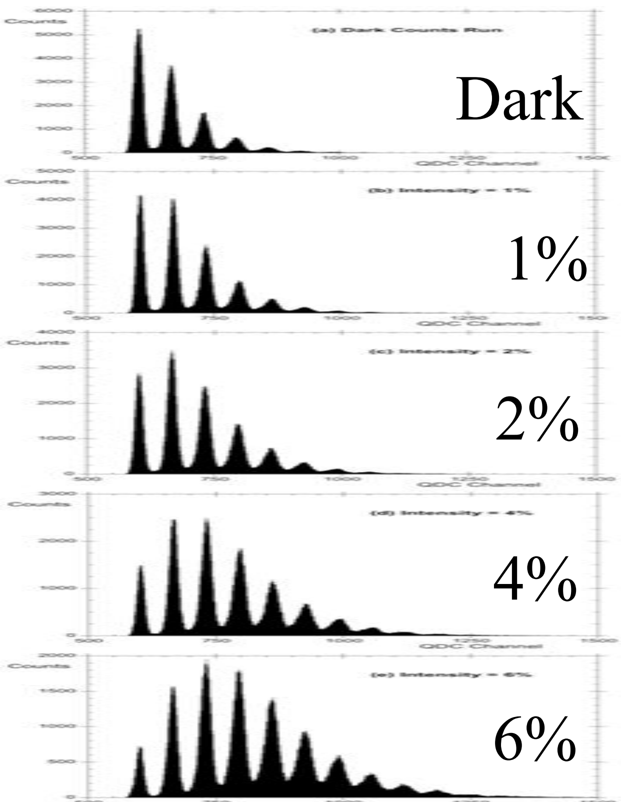
- The operational bias voltage of SiPM array specified by Hamamatsu is for 25^{o}C
- Corrections are applied to the extracted quantities to get values at 25^{o}C and specified bias voltage
- Correction coefficients are obtained from previous measurement or Hamamatsu spec sheet

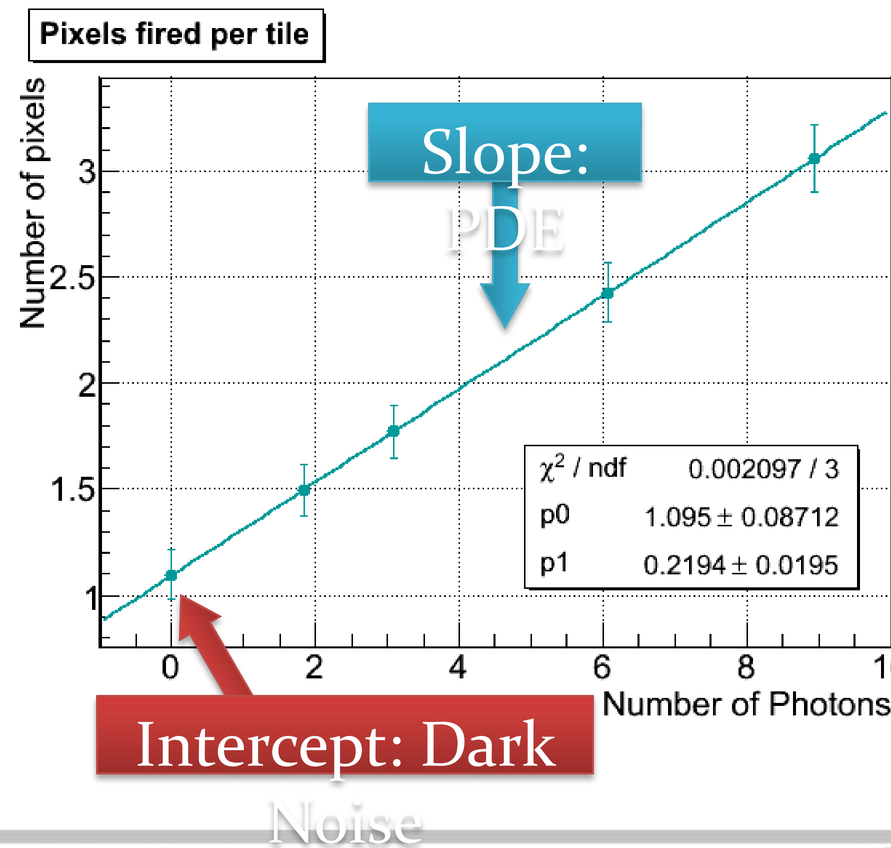


Previously measured temperature dependence of dark noise

Dark Noise and PDE

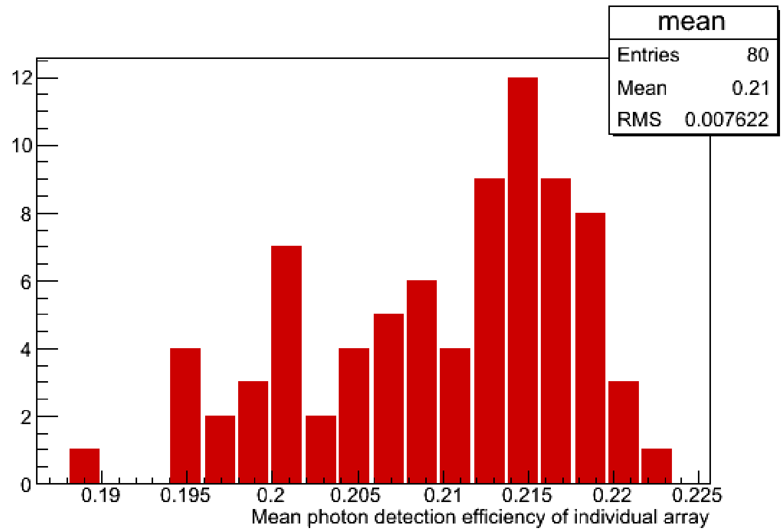
- Five filter settings: dark, 1%, 2%, 4% and 6%
- The LED light intensity was calibrated using a Hamamatsu calibrated photodiode

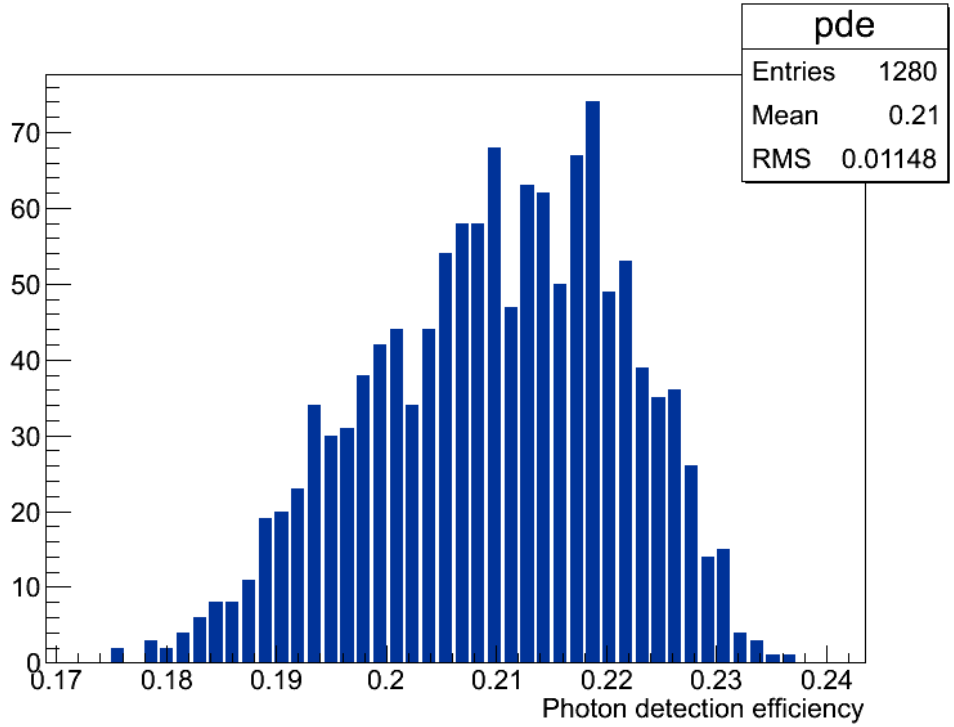


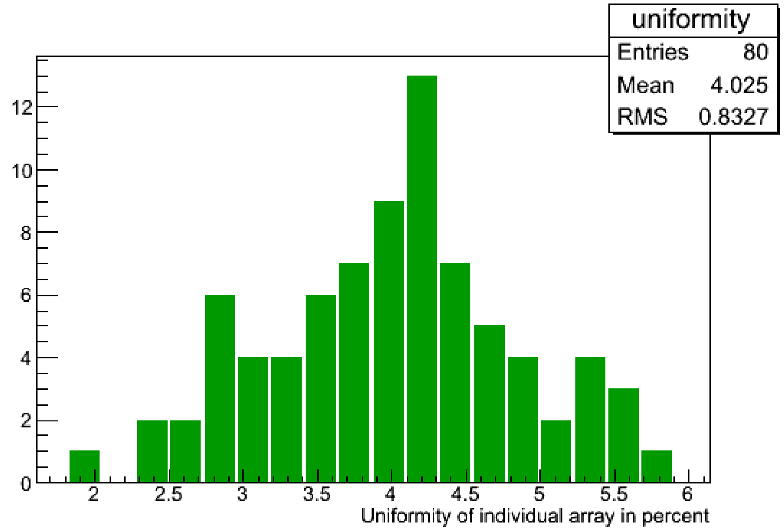


Photon Detection Efficiency

- Variation among samples: 3.6 %
- Uniformity in an array: 4.0%
- Overall uniformity: 5.5%

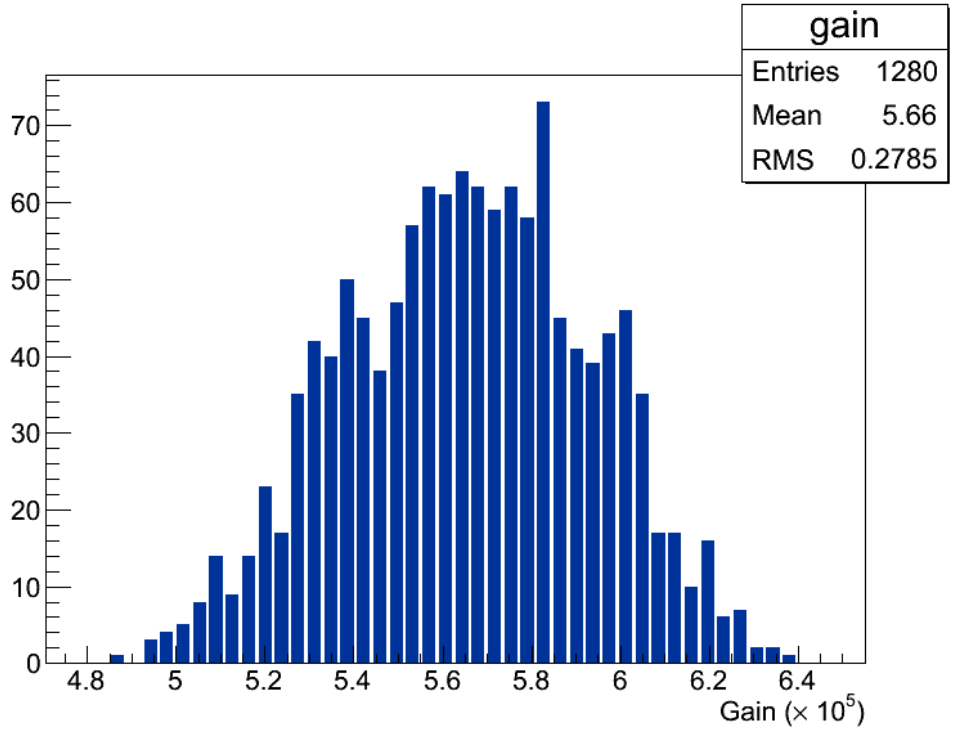


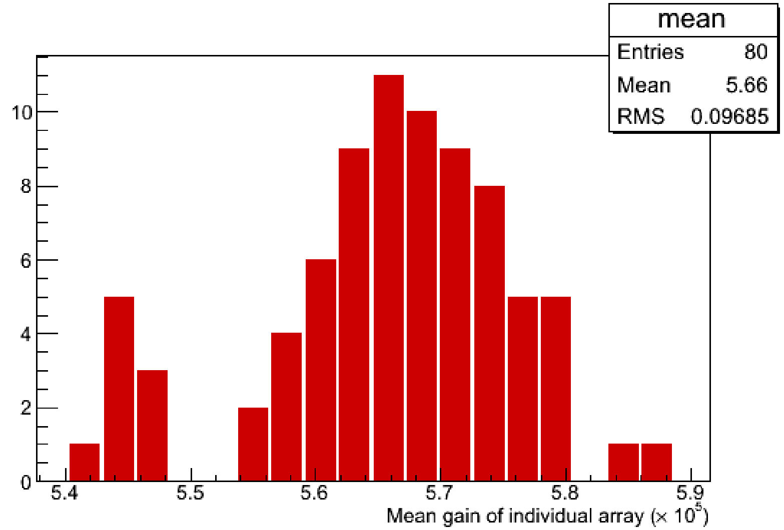


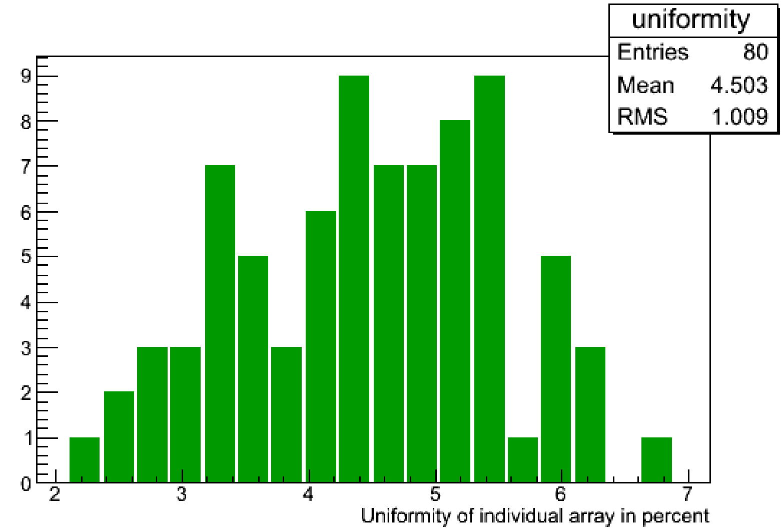


Gain and Its Uniformity

- Variation among samples: 1.7 %
- Uniformity in an array: 4.5%
- Overall uniformity: 4.9%

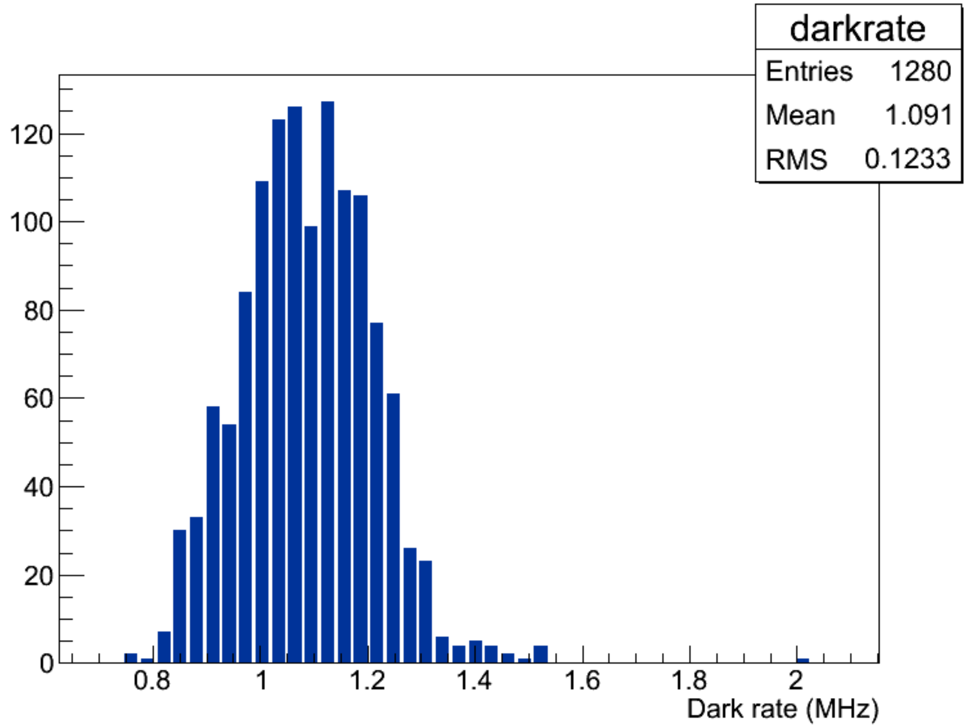


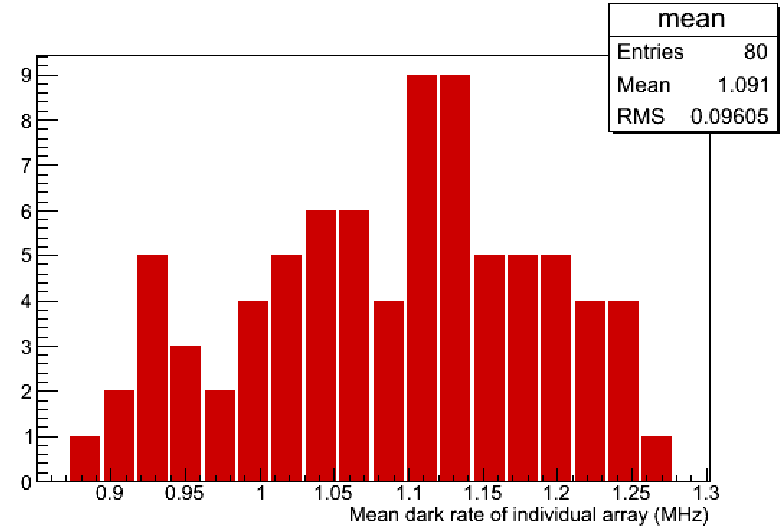


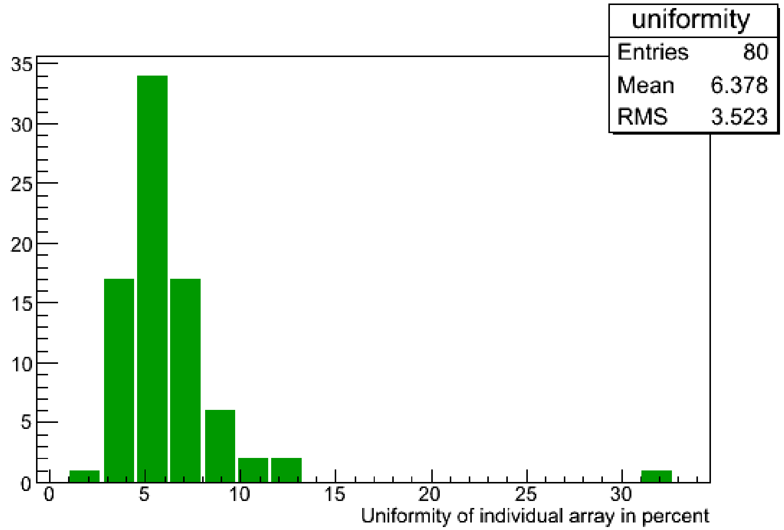


Dark Rate

- Variation among samples: 8.8 %
- Uniformity in an array: 6.4%
- Overall uniformity: 11.3%
- 4 times lower than previous samples!

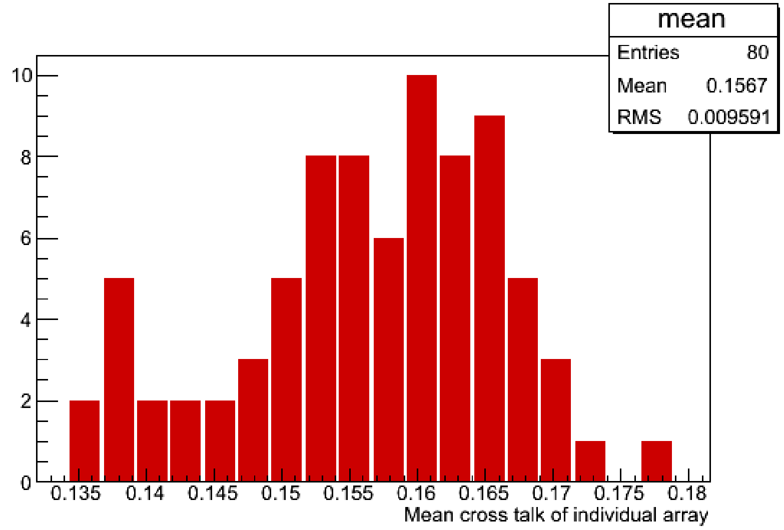


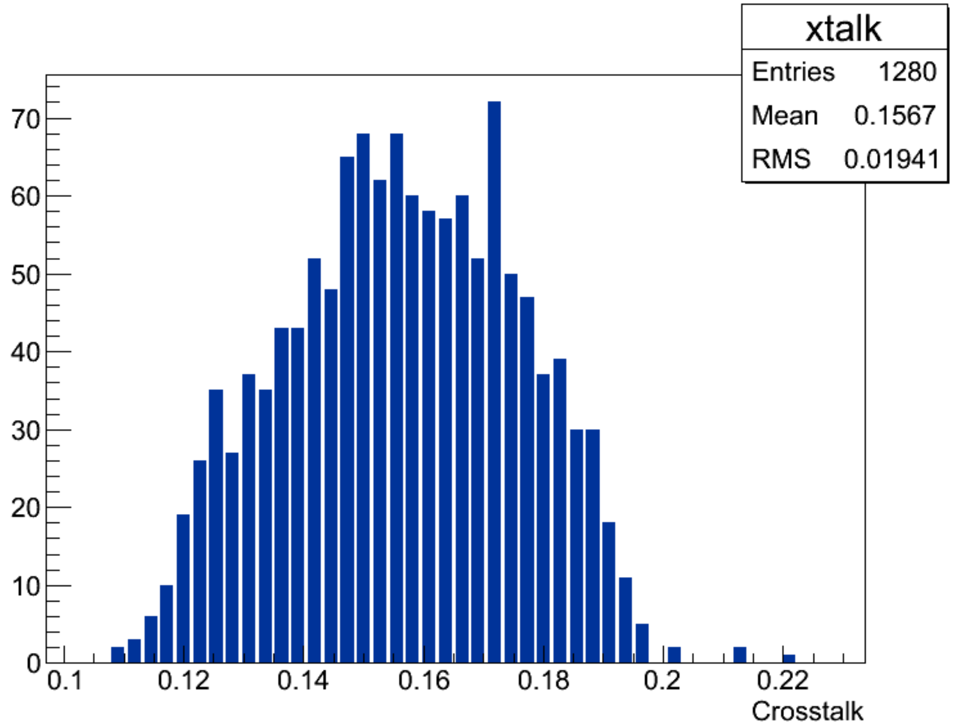


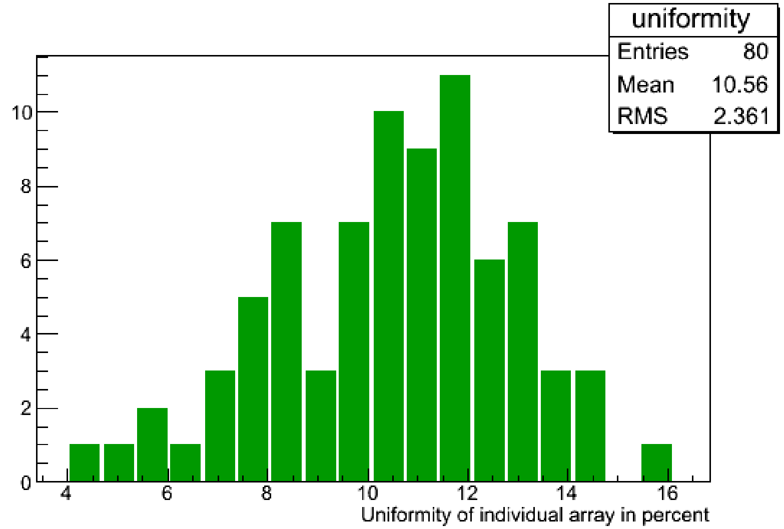


Cross Talk + After Pulse in 1 μs

- Variation among samples: 6.1 %
- Uniformity in an array: 10.6%
- Overall uniformity: 12.4%

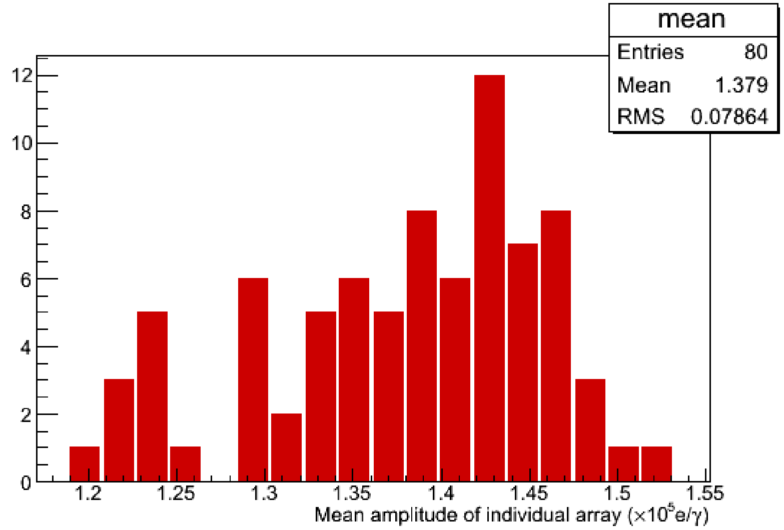


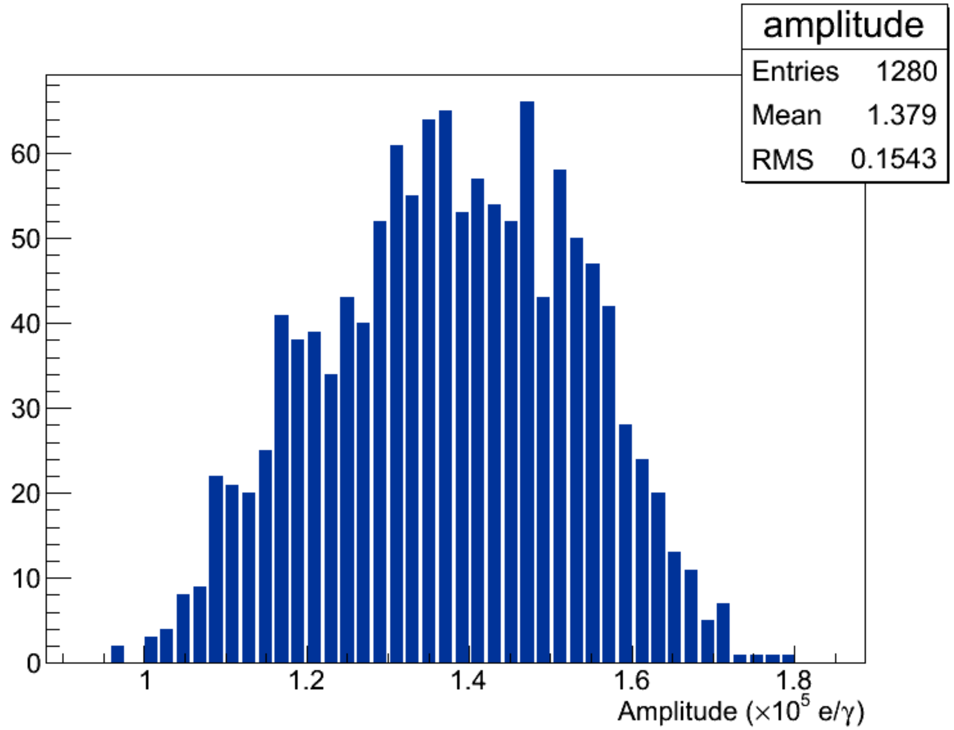


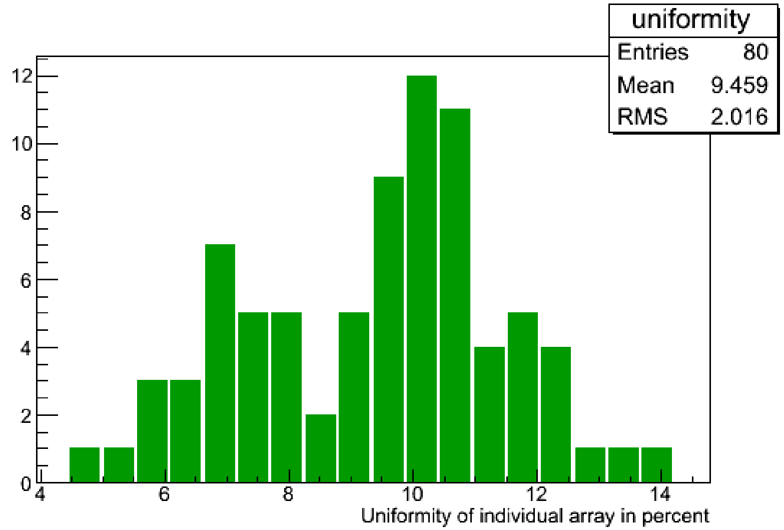


Total Amplitude: gain × PDE × (1+X-talk)

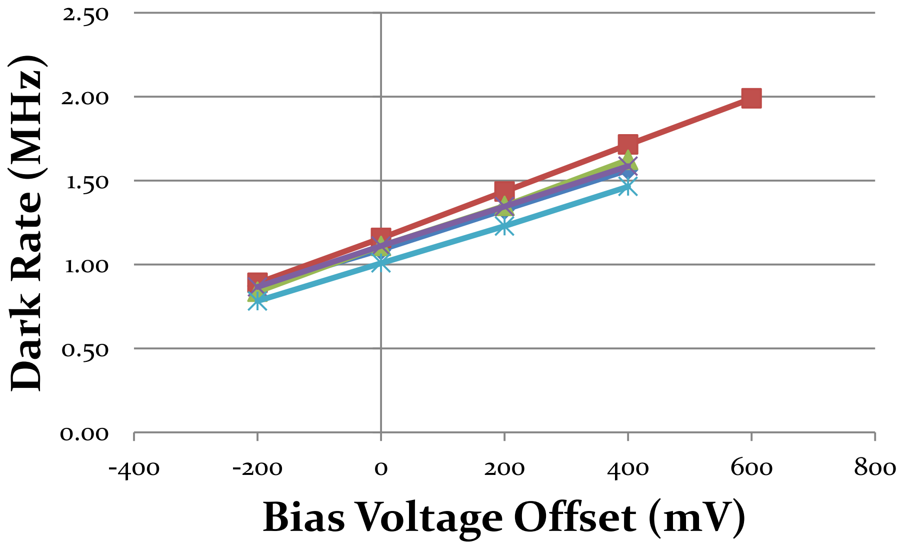
- Nominal amplitude: 1.38×10^5 e/γ
- Variation among samples: 5.7 %
- Uniformity in an array: 9.5%
- Overall uniformity: 11.2%

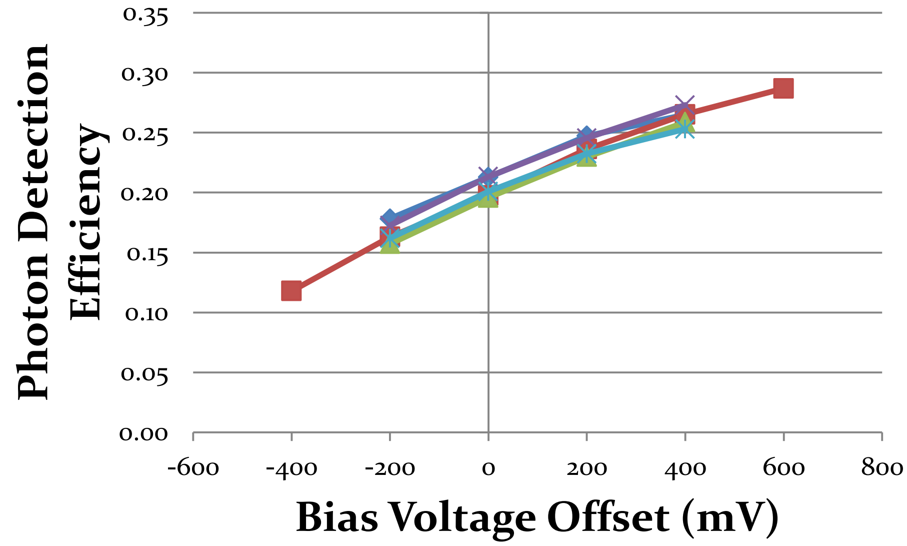


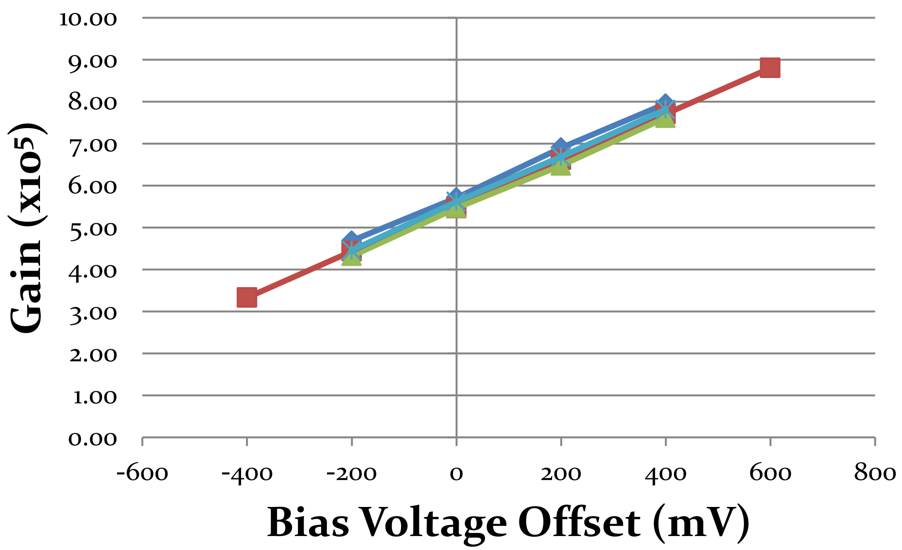


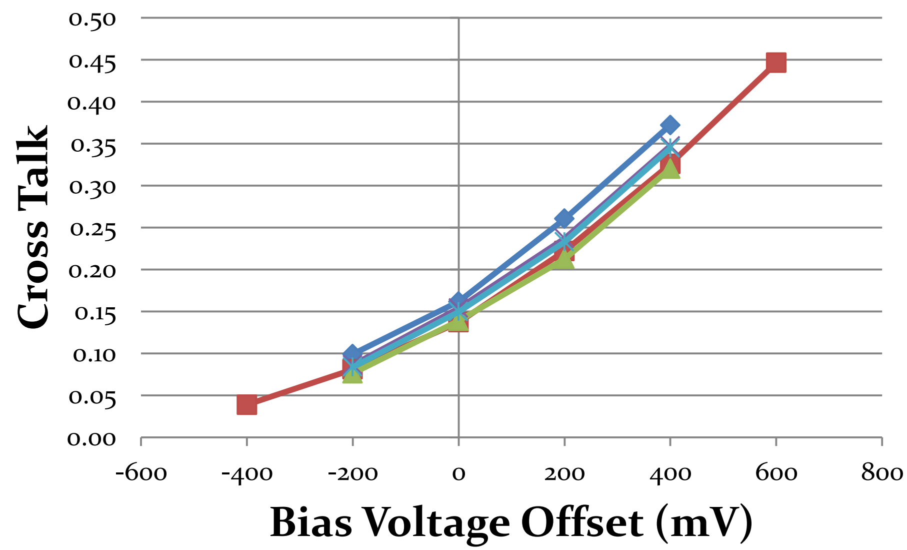


Bias Voltage Dependence

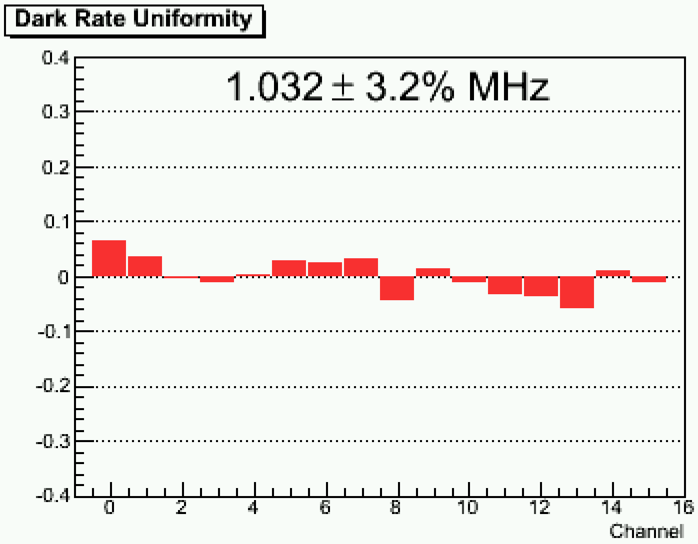


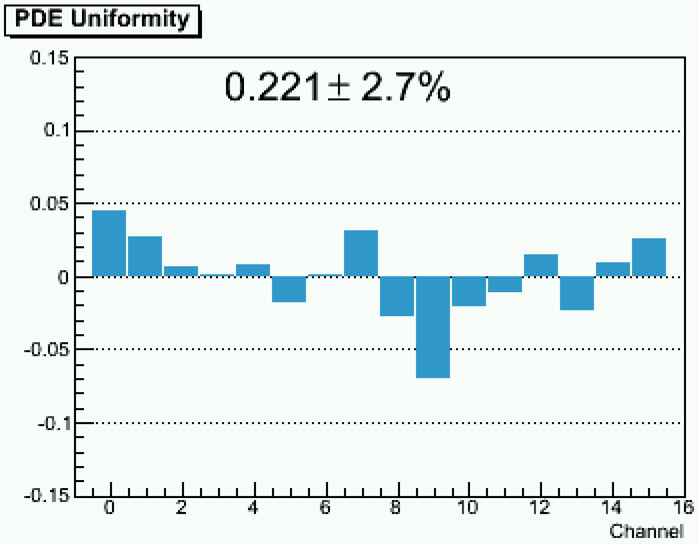


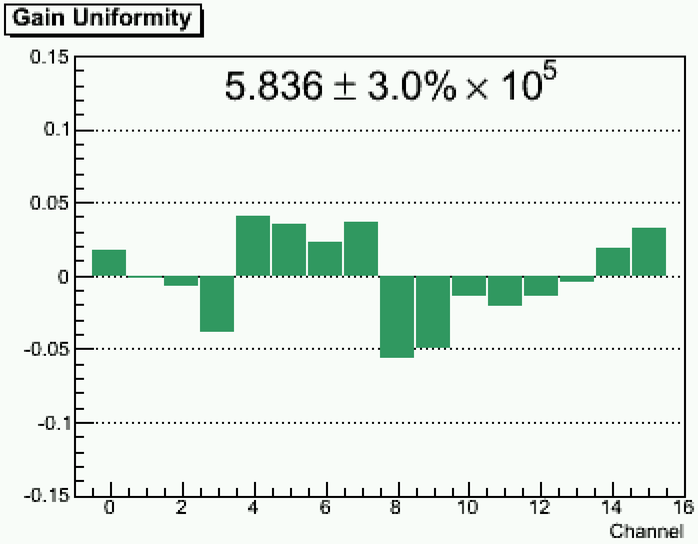


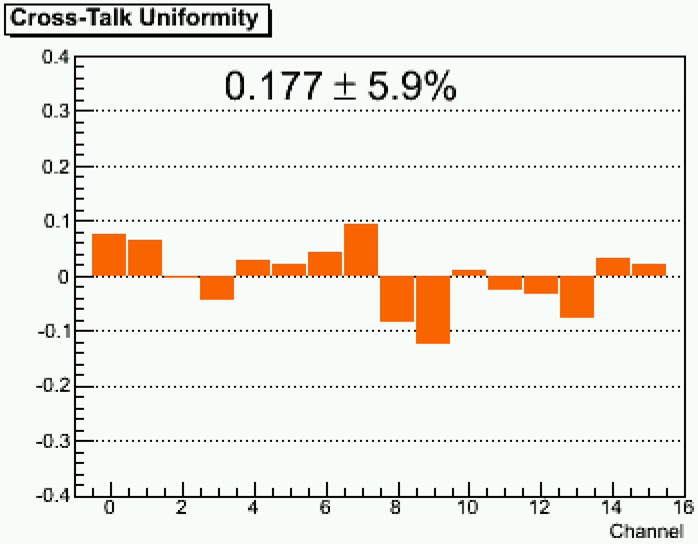


Typical Uniformites of an Array

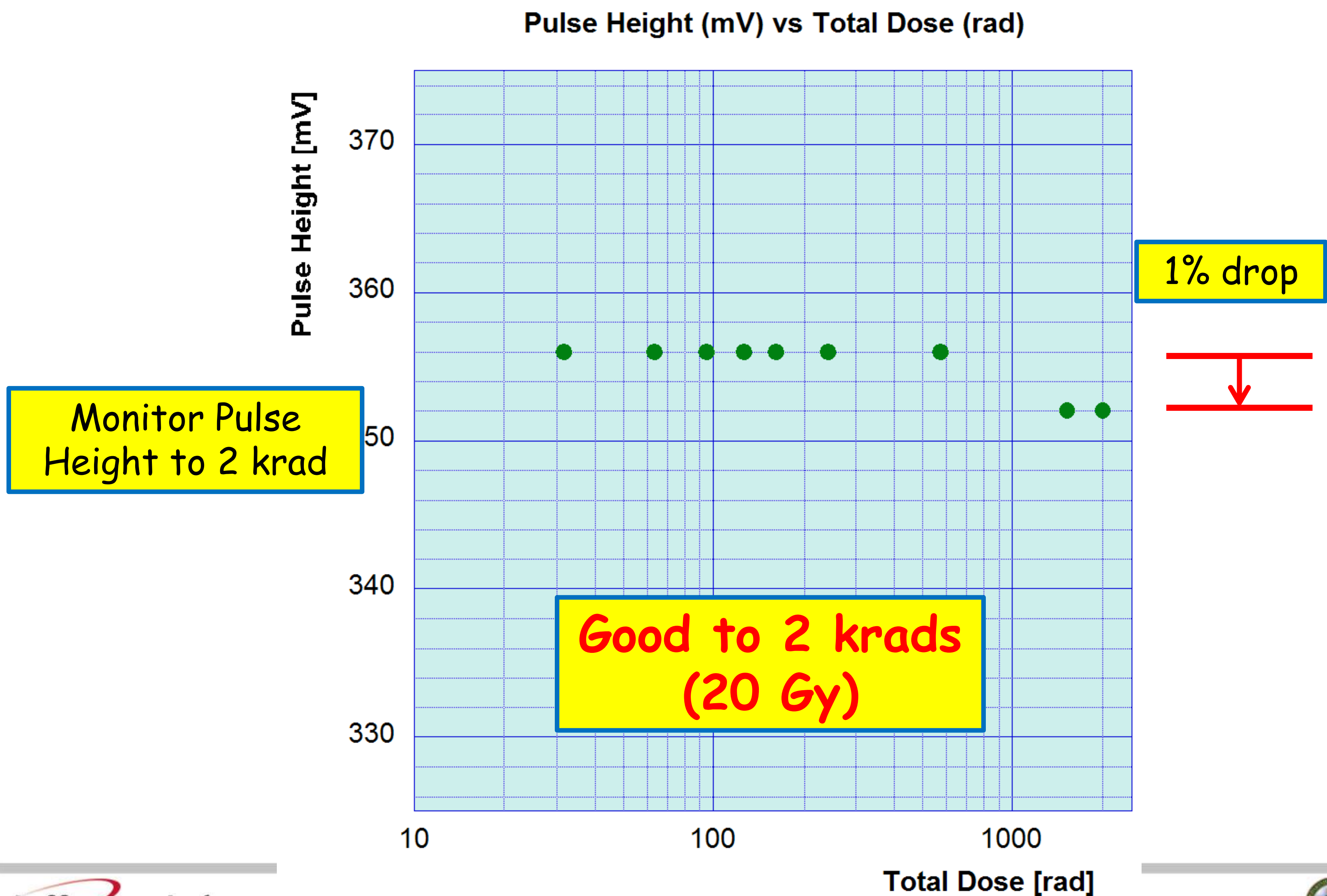








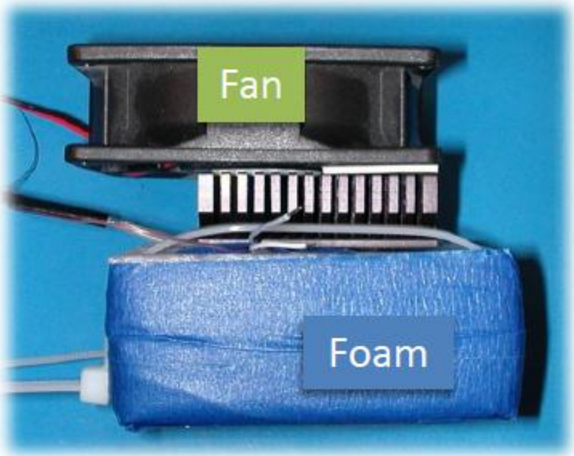
Minimal Effect from γ Irradiation



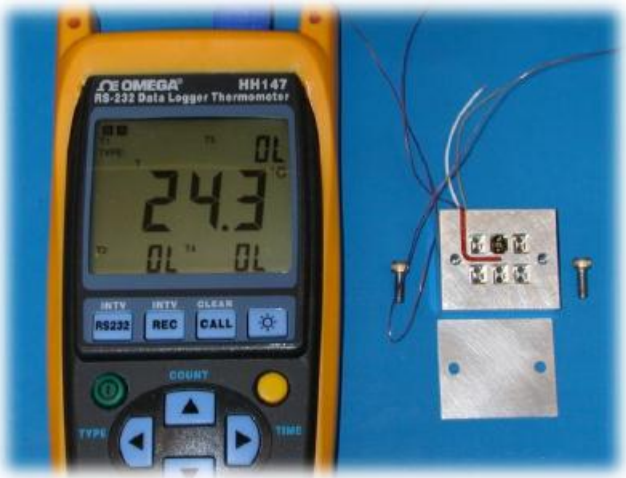
SiPM Neutron Radiation Test

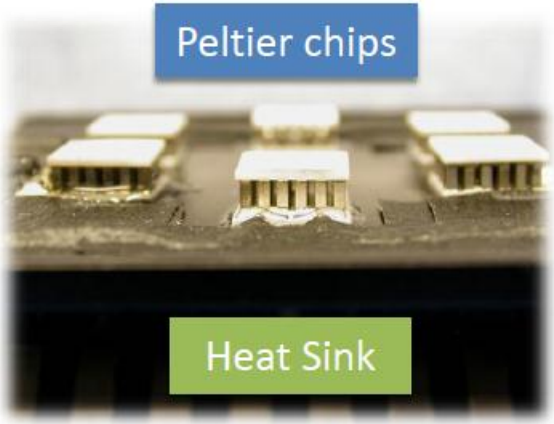
- Test condition
  - Two irradiations with AmBe: 4.3 and 5.2 rem.
  - Recovered at 0, 25, 40 and 60°C.
- Conclusion
  - Higher temperature brings faster recovery:
    - $\tau \sim 5$ days for 25°C
    - $\tau < 1$ day for 40 and 60°C
  - Damage independent on previous radiation dose or recovery condition.
  - Recovered dark current goes linearly with the radiation dose.

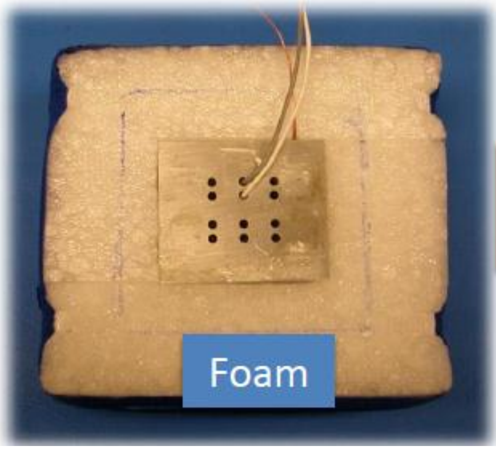
Irradiation Setup

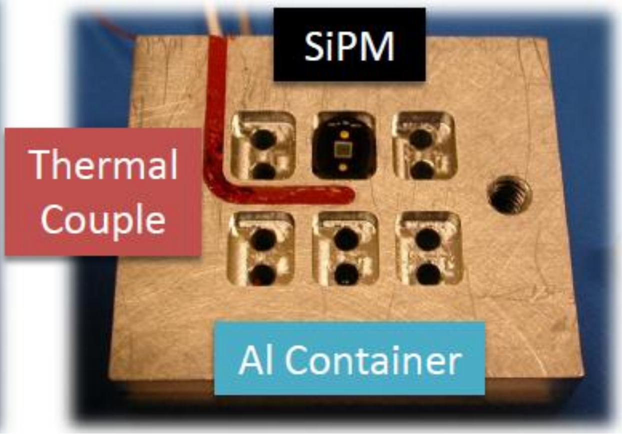


With six Peltier effect chips, the device can cool six SiPMs to -10°C at 25°C room temperature.

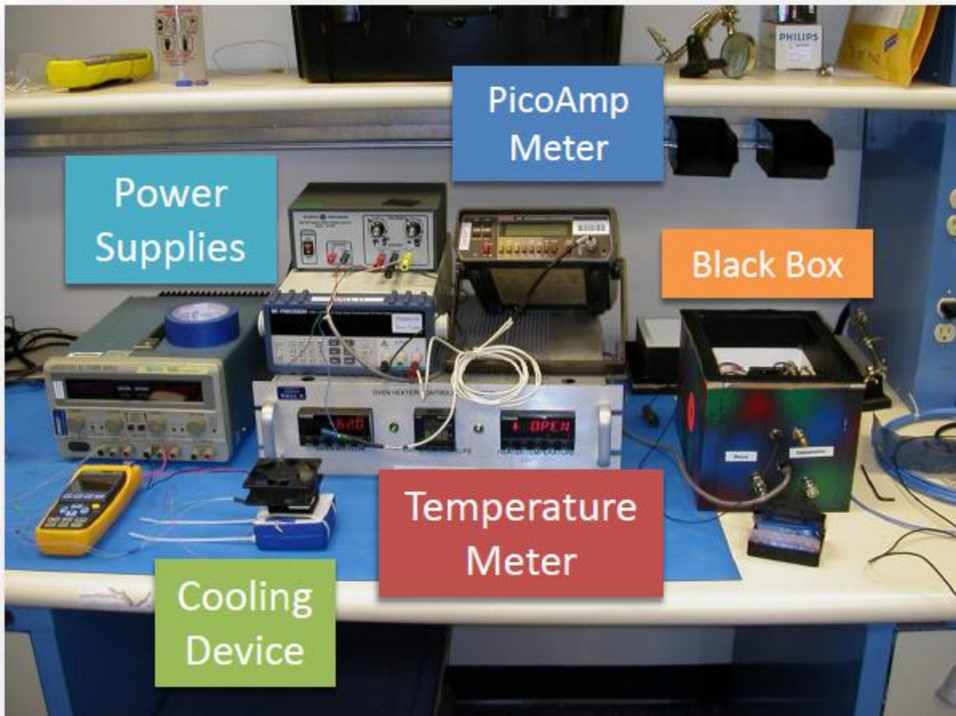






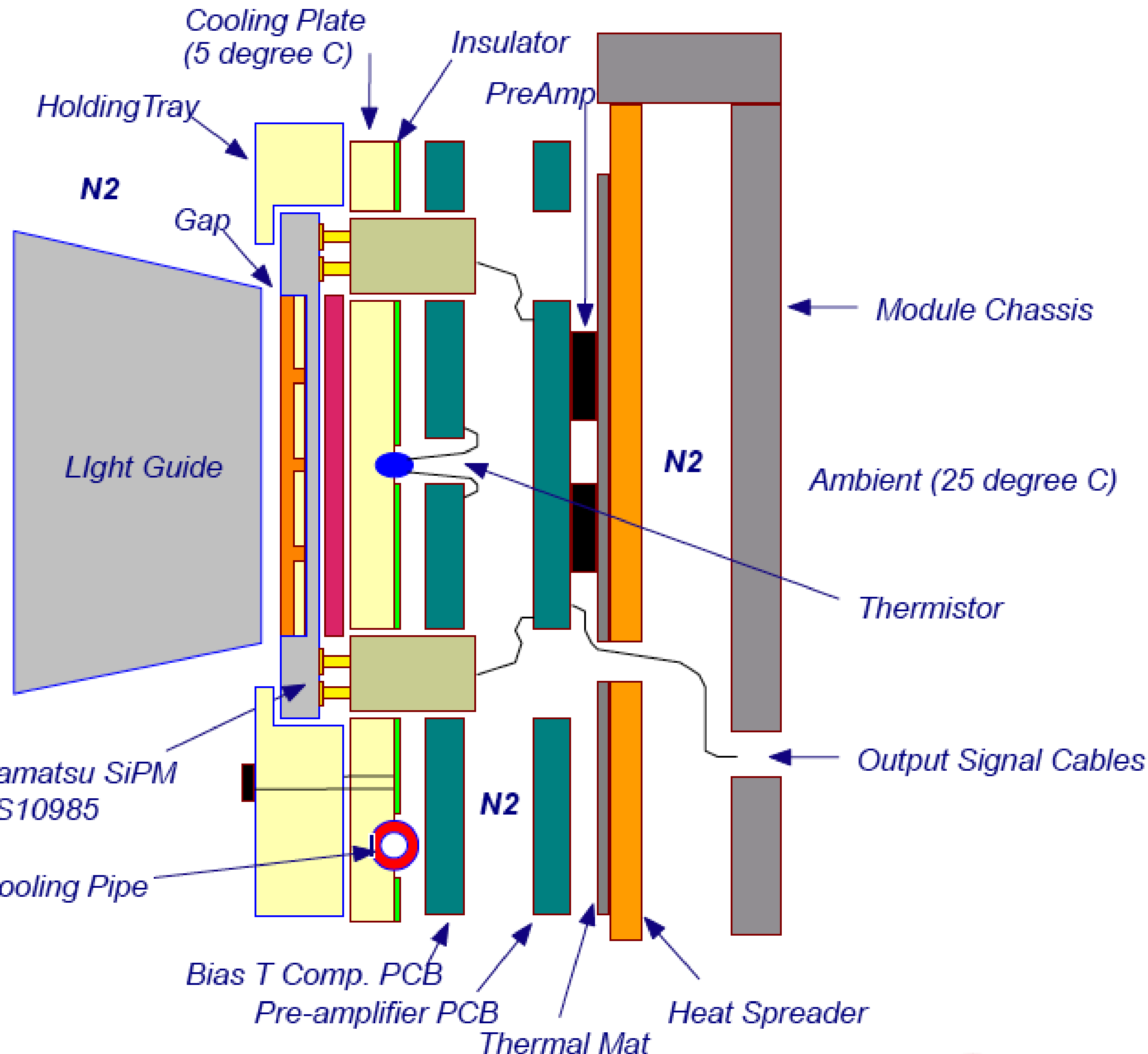


Irradiation Setup

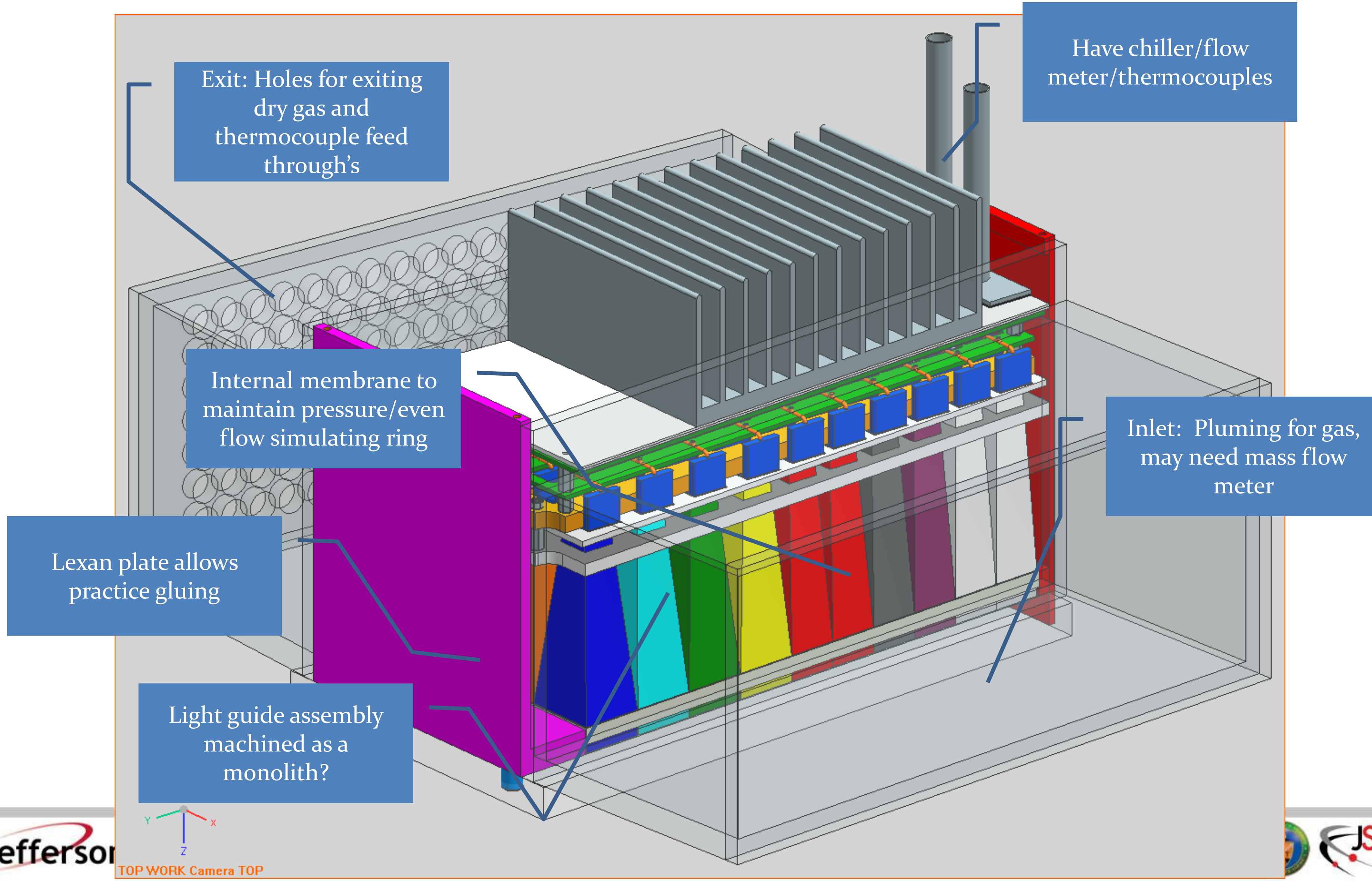


BCAL Readout Cooling Concept

Cutaway View
Single SiPM Shown

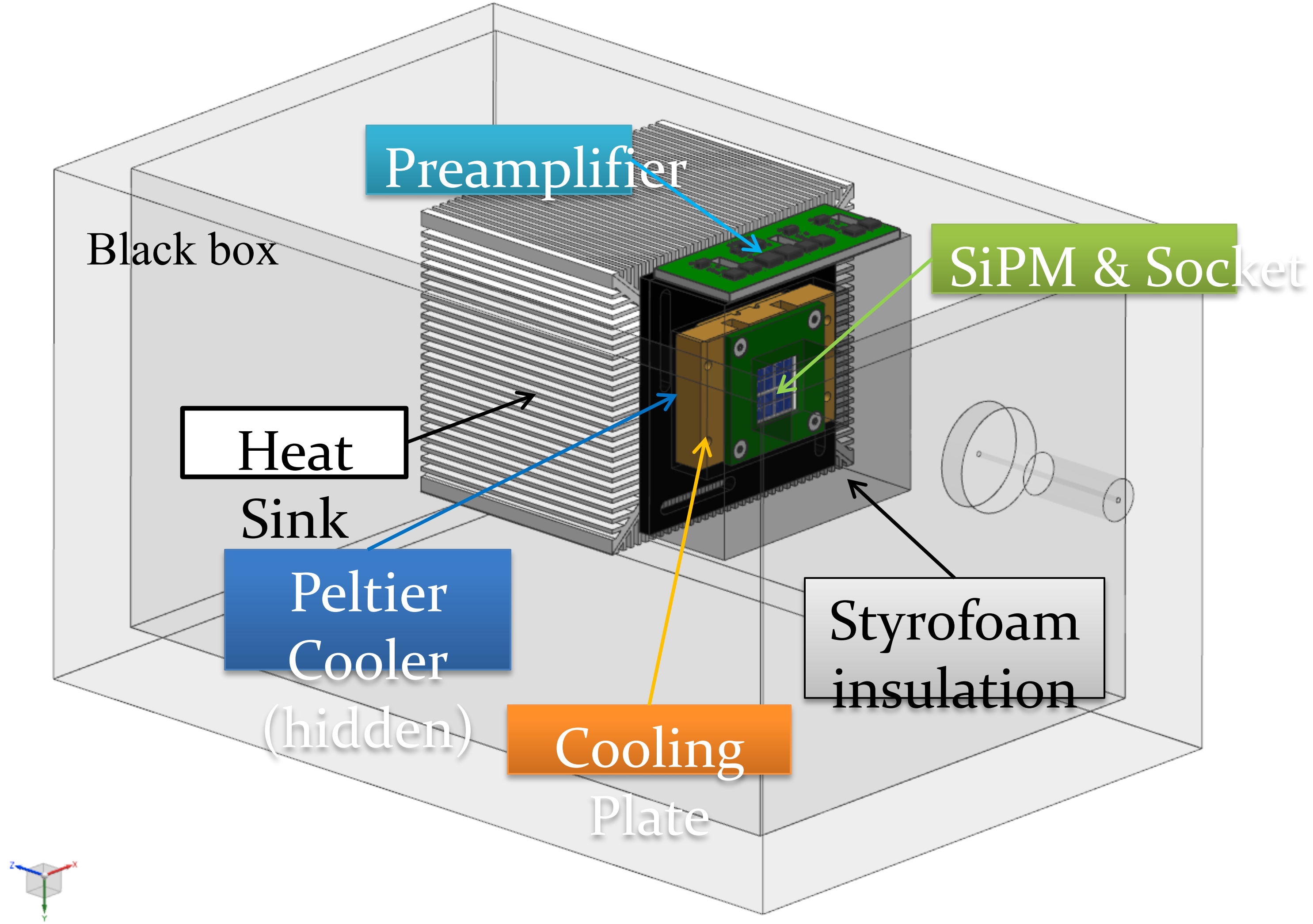


Prototype to test cooling concept



Temperature Test

➢ A coolling box is being built for such a test



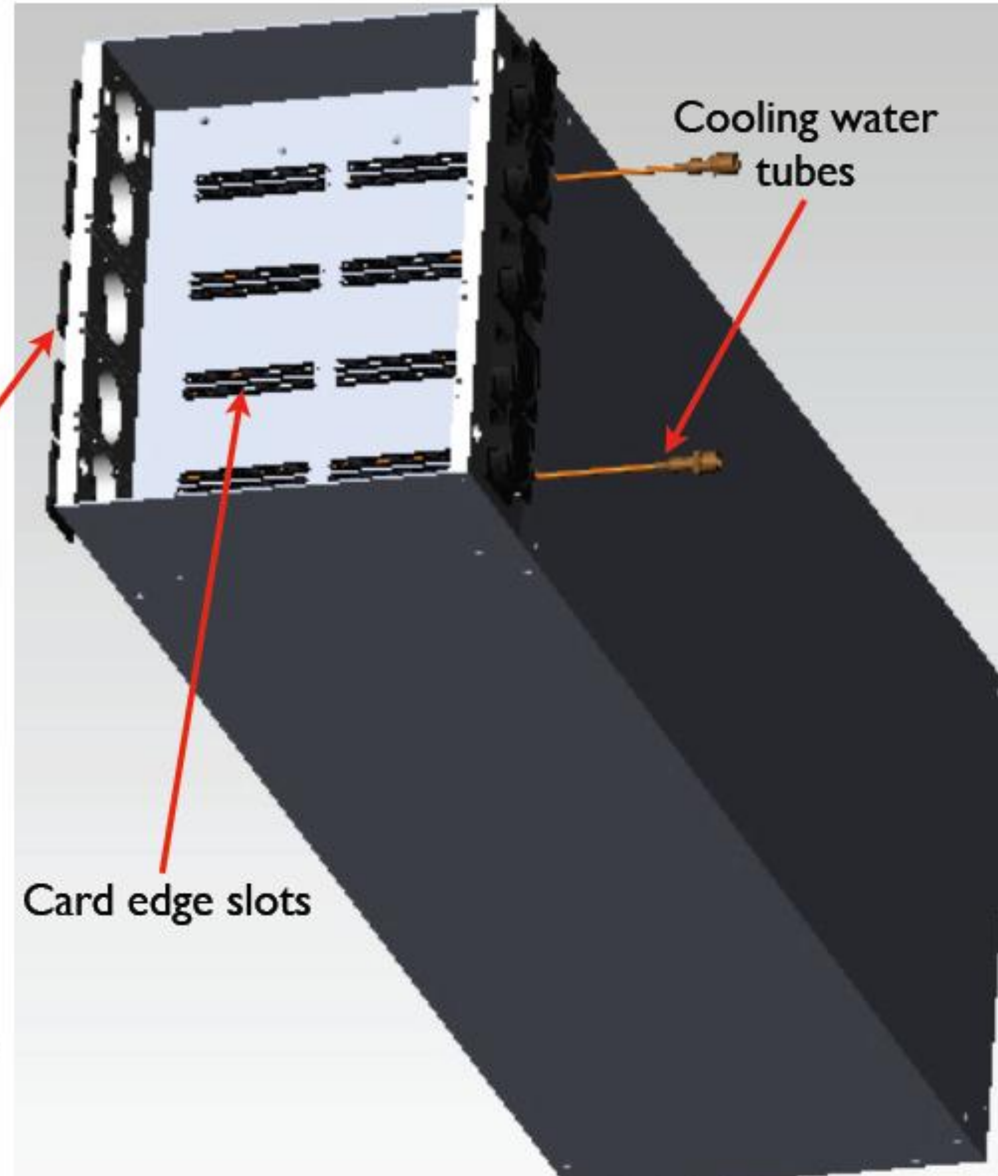
Large-scale testing of SiPMs at USM

- Chilean import issues now seem to be under control
  Small percentage charged monthly
- Finishing design of second prototype board for mounting SiPMs
  More modular design; quickly-replaceable amplifiers, daughterboard for current measurement function
- Providing for test of up to 32 modules at a time
- Optical box under construction, will be completed in ~1-2 weeks
- Chiller for temperature control in house, tested

Reminder: testing facility concept

Dark box, 0.5 m long
32 MPPCs mounted inside

Fans for air cooling of electronics



Pavlo Bazalyeyev, new technician, with student holding copper plate

Materials seen are for dark box construction (aluminum plate).