Novel Multi-pixel Silicon Photon Detectors and Applications in T2K

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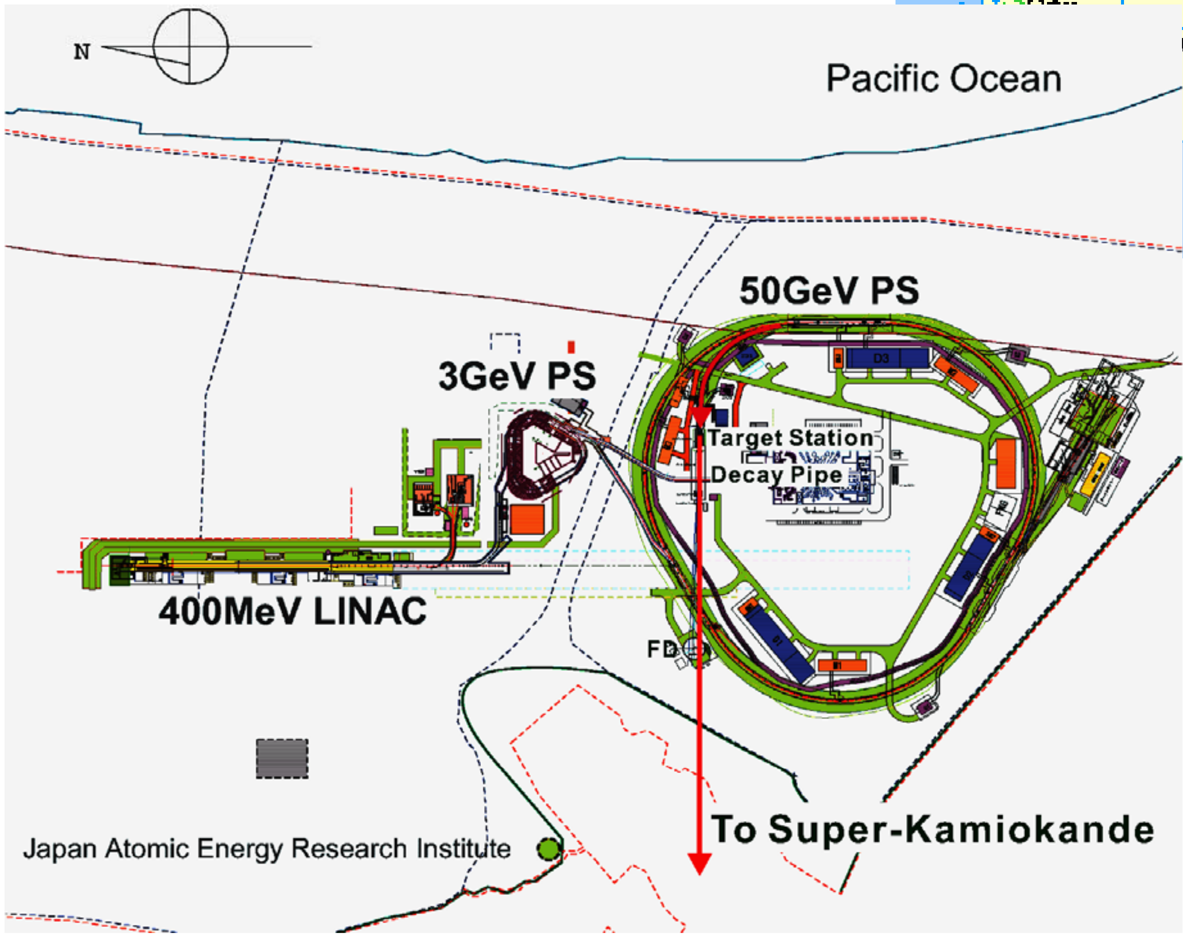
T2K Overview

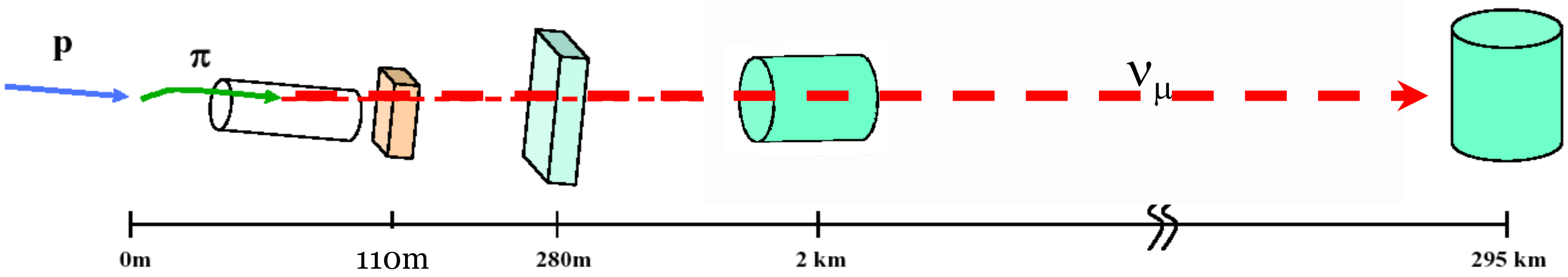
- T2K is Tokai to Kamioka long baseline neutrino oscillation experiment (Japan)
- It consists of beamline from J-PARC, near (ND280) and far (SuperK) detectors
- One of the goals is to measure θ_{13} neutrino oscillation parameter by ν_e appearance from ν_μ beam
- ND280 on-axis detector is to measure beam parameters
- ND280 off-axis detector consists of several sub-detectors, all in ~0.2T magnetic field
    - Accurate momentum measurements
    - Charge discrimination

T2K Overview

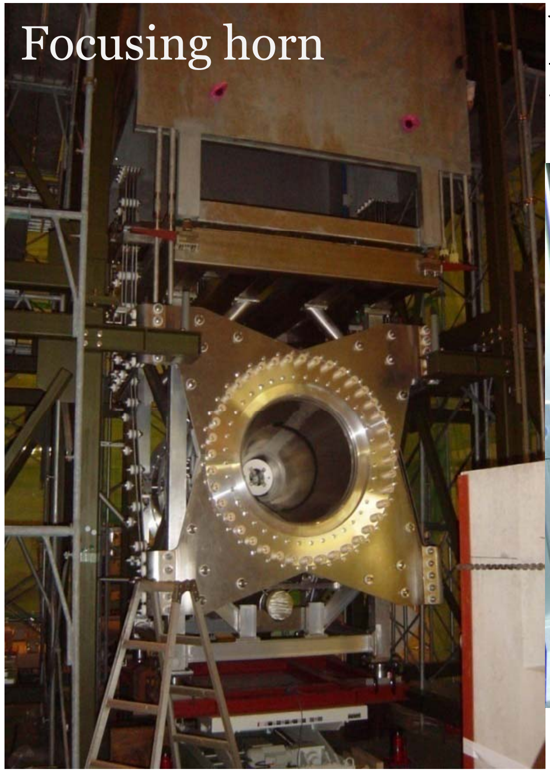


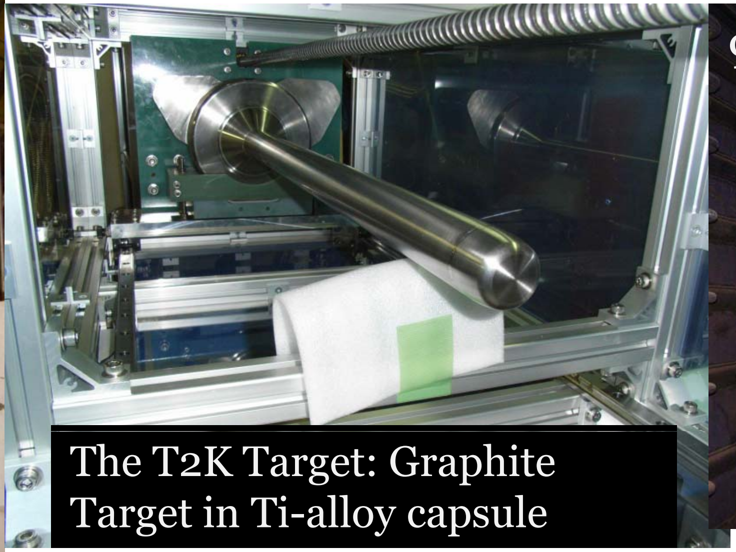
- Up to 0.75 MW, 30 GeV proton beam
- ~0.6GeV energy neutrino beam energy
- Data taking to start by end of 2009

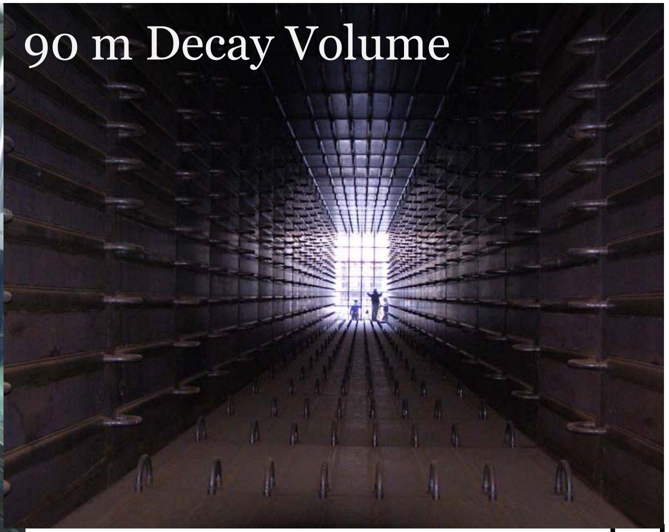
T2K – Neutrino beamline



From left to right: extracted proton beam, beam target and focusing horn system (toroidal B field), decay volume (filled with Helium), beam dump (not shown), muon monitor, ND280, 2km detector (proposed only), SuperK.


Focusing horn

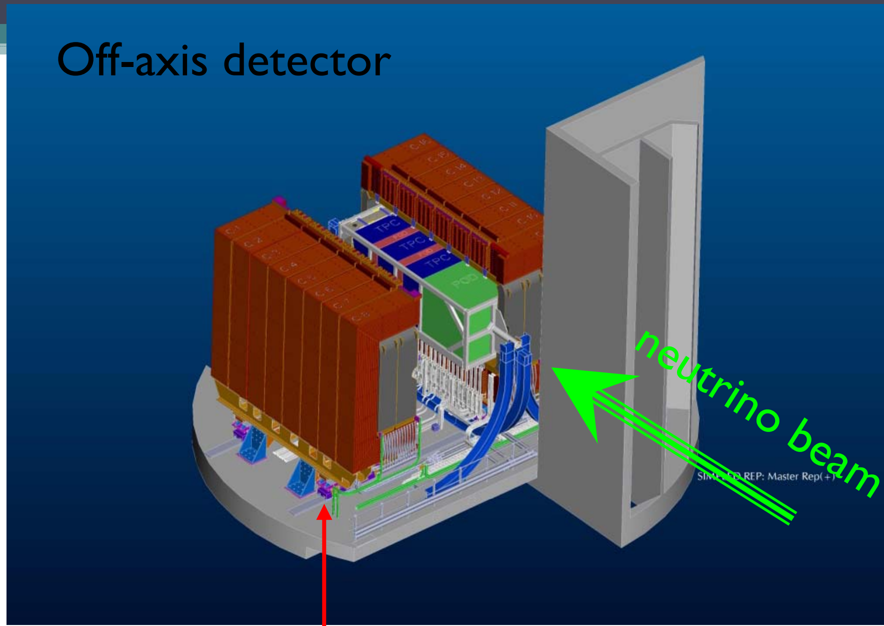

The T2K Target: Graphite Target in Ti-alloy capsule

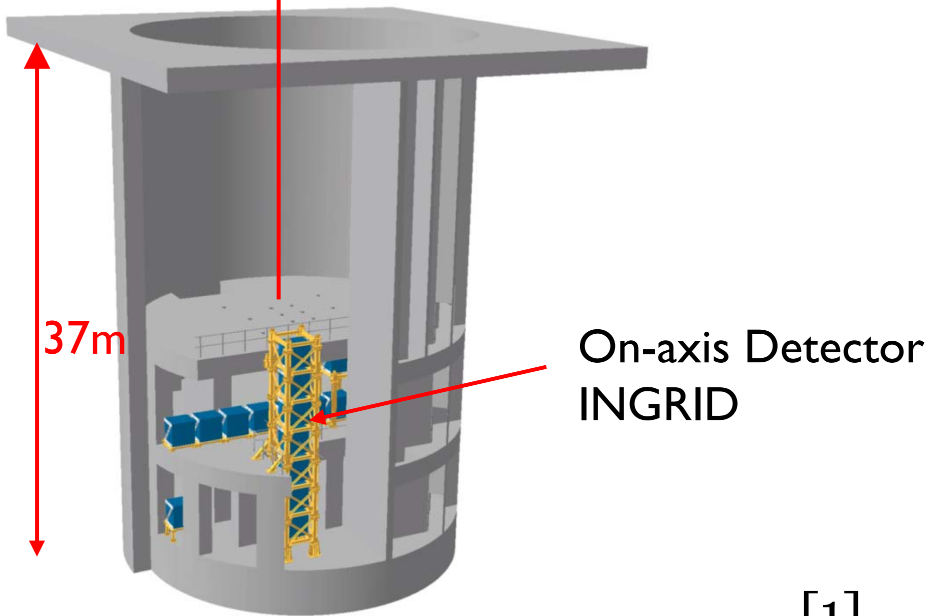

90 m Decay Volume

[1]

T2K-ND280

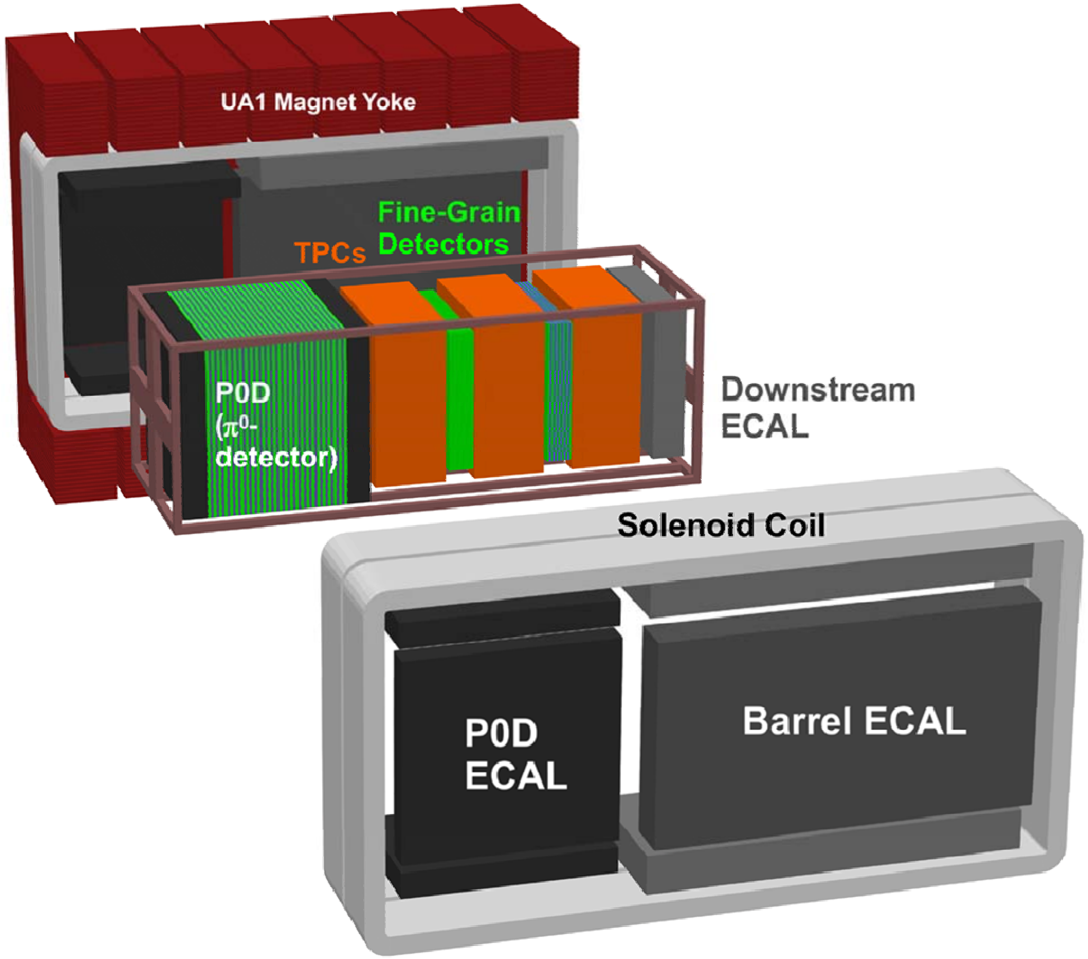
- On – Axis Detector
  - ✓ Beam monitoring
  - ✓ Beam direction
  - ✓ Beam Intensity and profile
- Off – Axis Detector
  - ✓ Neutrino Beam Energy Spectrum
  - ✓ Beam Flux
  - ✓ Beam ν_e Contamination
  - ✓ Background Processes
  - ✓ Cross Sections





[1]

T2K ND280



- Off-axis sub-detectors
  - P0D - Pi-Zero Detector
  - FGD-fine grained detector
  - TPC – time projection chamber
  - Downstream ECAL – electromagnetic calorimeter
  - UA1 magnet – ~0.2T
  - SMRD – Side Muon Range Detector (inside yoke)

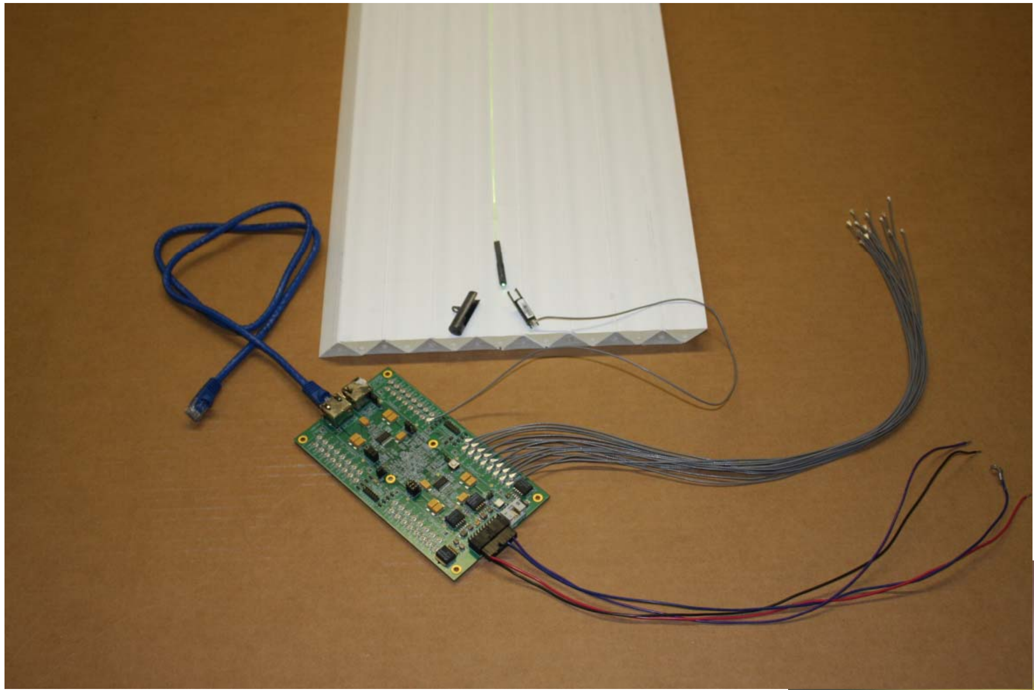
T2K and Multi-pixel Silicon Photon Detectors

- All ND280 detectors (except TPC) will have in common the following:
  - Scintillator
  - WLS fiber
  - Photon readout scheme
  - ~0.2T Magnetic Field (except INGRID)
    - Important to find efficient, high performance photon detector that operates in magnetic field.

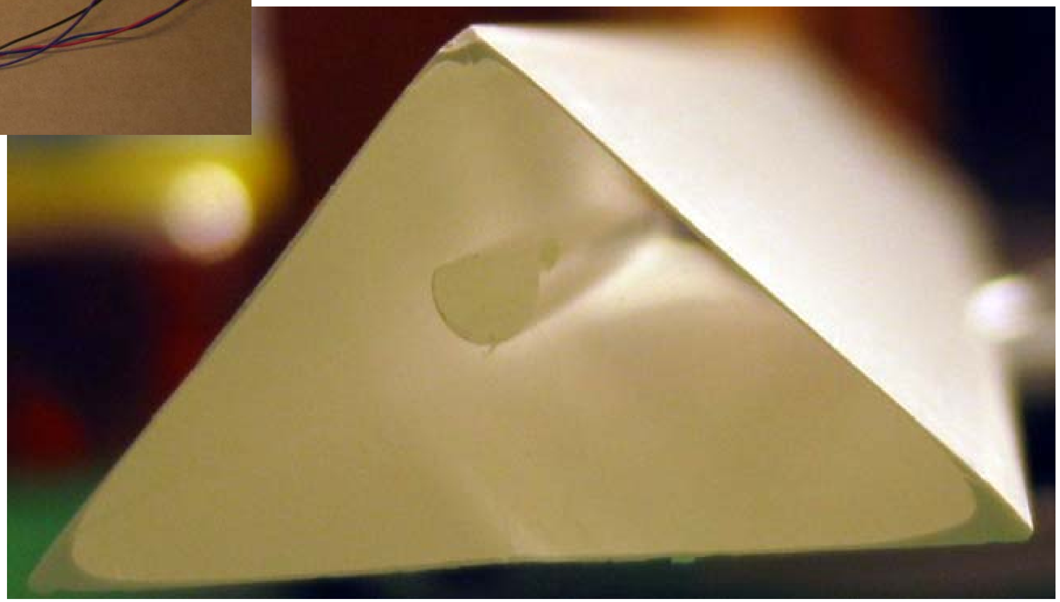
T2K-P0D

- Super Kamiokande is a water Cherenkov far detector for T2K
- Will look for ν_e appearance from ν_μ beam
- Background is dominated by two sources:
  1. ν_e events from the primary beam
  2. The NC π^0 production by muon neutrinos where the π^0 is mis-ID
- P0D is designed to measure NC π^0 production cross section on water
- P0D is a series of x-y triangular extruded TiO_2 coated scintillator bars with co-extruded hole [2]
  - Wavelength shifting fibers with single side readout
    - A set of x-y planes is called a p0dule

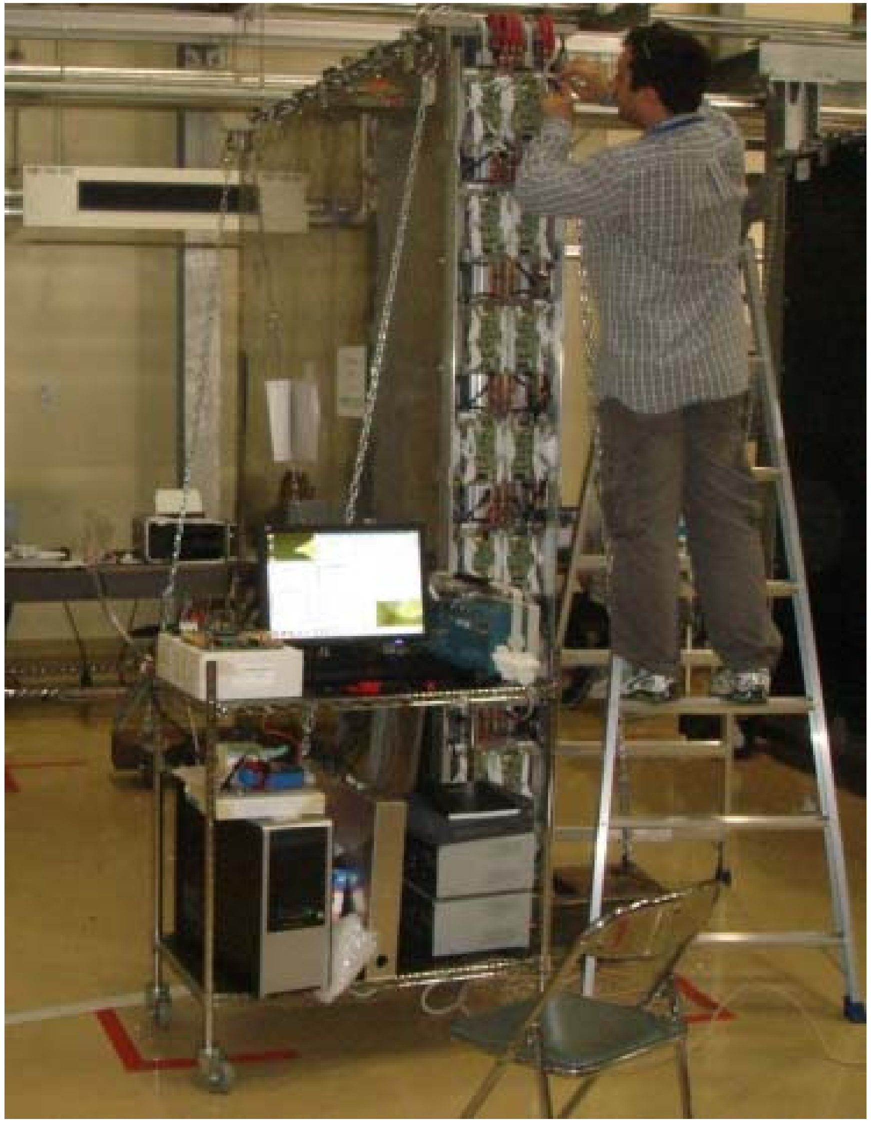
T2K-P0D/MINERvA Scintillator bar

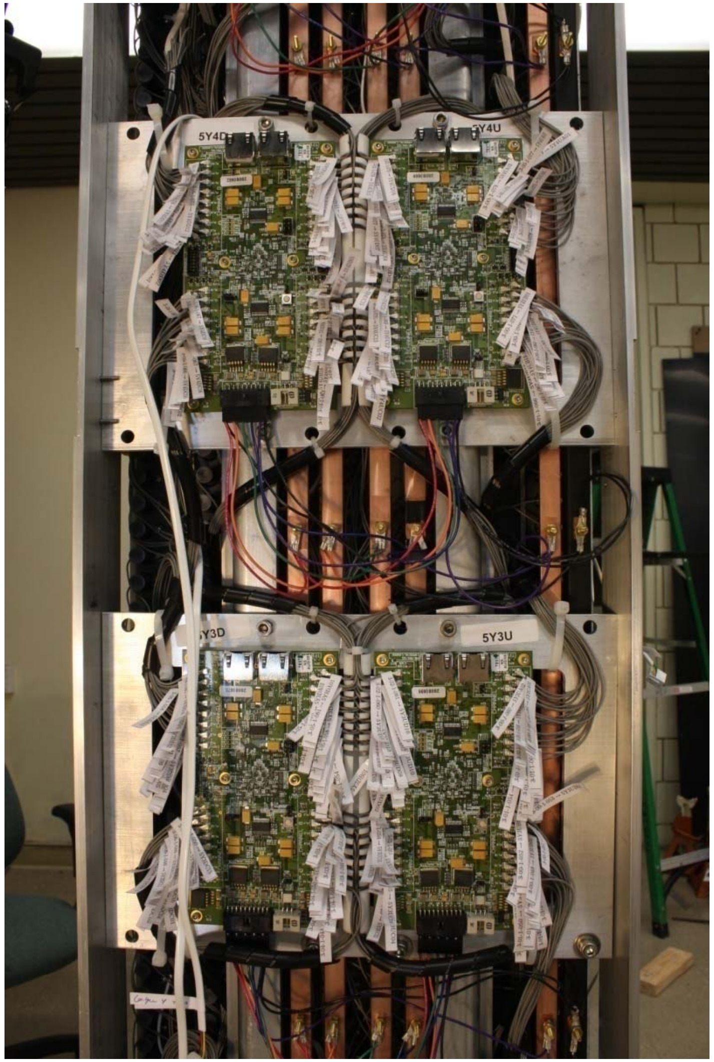


- Base - 33.0±0.5 mm
- Height - 17.0 ±0.5
- Co-extruded hole center position from base - 8.5 ±0.25mm.
- TiO_2 reflective coating layer thickness - 0.25mm.



JPARC: P0D Ecal being readied for cosmic run





T2K P0D and Multi-pixel Silicon Photon Detectors

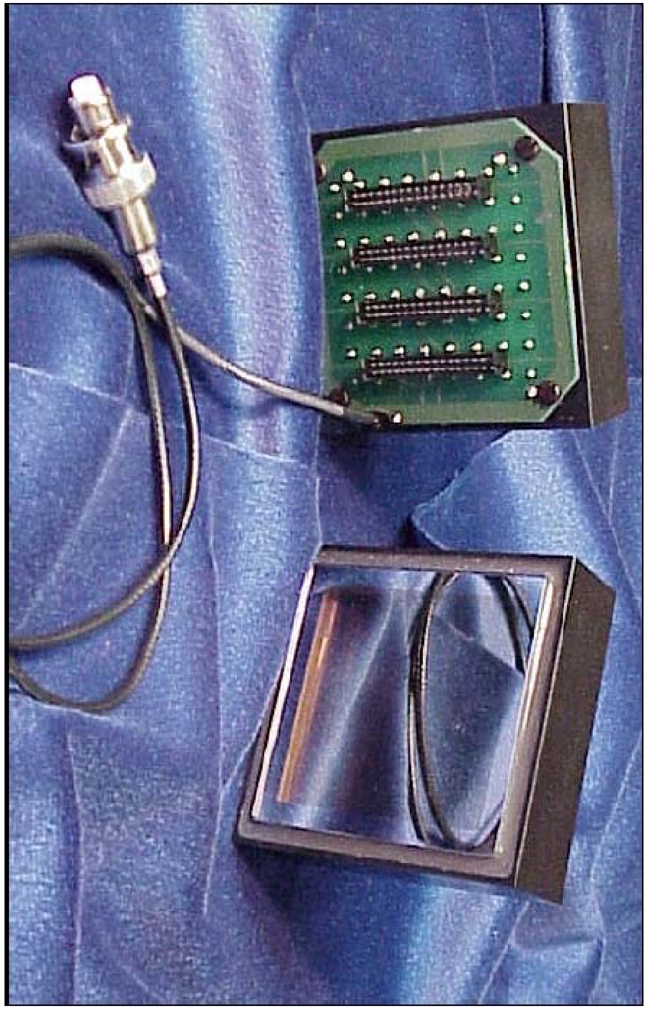
- Photo detector requirements:
  - In 0.2T magnetic field – limits choice
  - Within magnet, space is limited
    - Small size
  - Reliable
    - At lest 10 years
  - Inexpensive
    - Limited budget

1000 pixel MRS diode

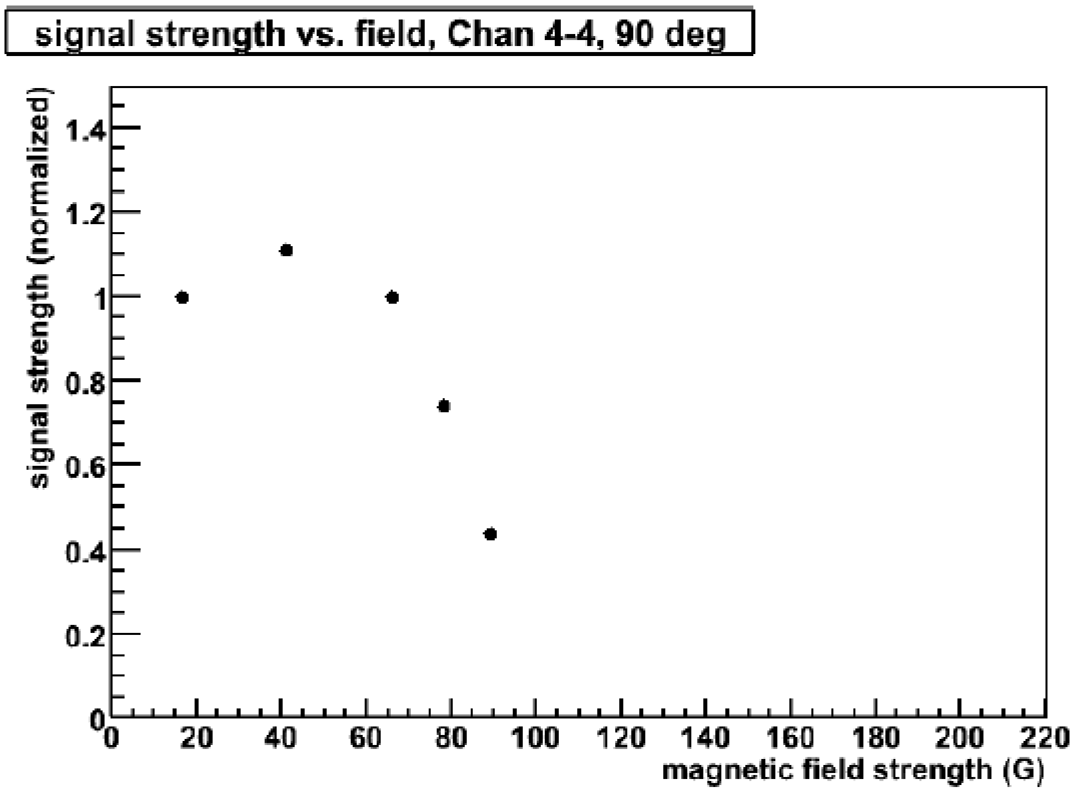
- Options explored at SB:
  - MCP–MAPMT - Micro-channel plate Multi-anode PMT [3]
  - Multi-pixel Silicon Photon Detectors
    - SiPM (Silicon PMT) [4]
    - MRS (Metal - Resistive layer – Semiconductor diode) [5]
    - MPPC – Multi-Pixel Photon Counter [6]

Other Photo Detectors - MCP – MAPMT

- Burle 85011-501 device [3]
  - Based on multichannel plate technology
  - Gain typ. $7*10^7$
  - Anode uniformity: 1:1.5
  - HV of -2600V
  - Max PDE at 400nm
  - Expensive
- Tested at SB with Magnetic Field (by Lisa Whitehead)
  - Sensitive to B-field
  - Channel crosstalk



Other Photo Detectors - MCP – MAPMT

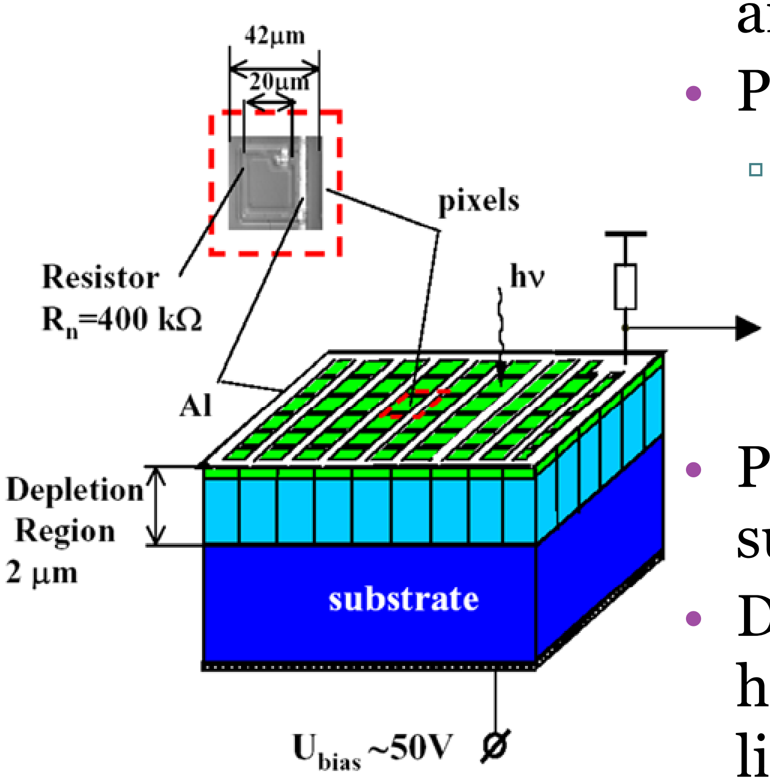


P0D will be in 2000 G

- Test results of Burle 85011-501 device at Stony Brook/BNL by Lisa Whitehead
- Shows clear magnetic field dependence

[7]

Multi-pixel family – Operational Principle

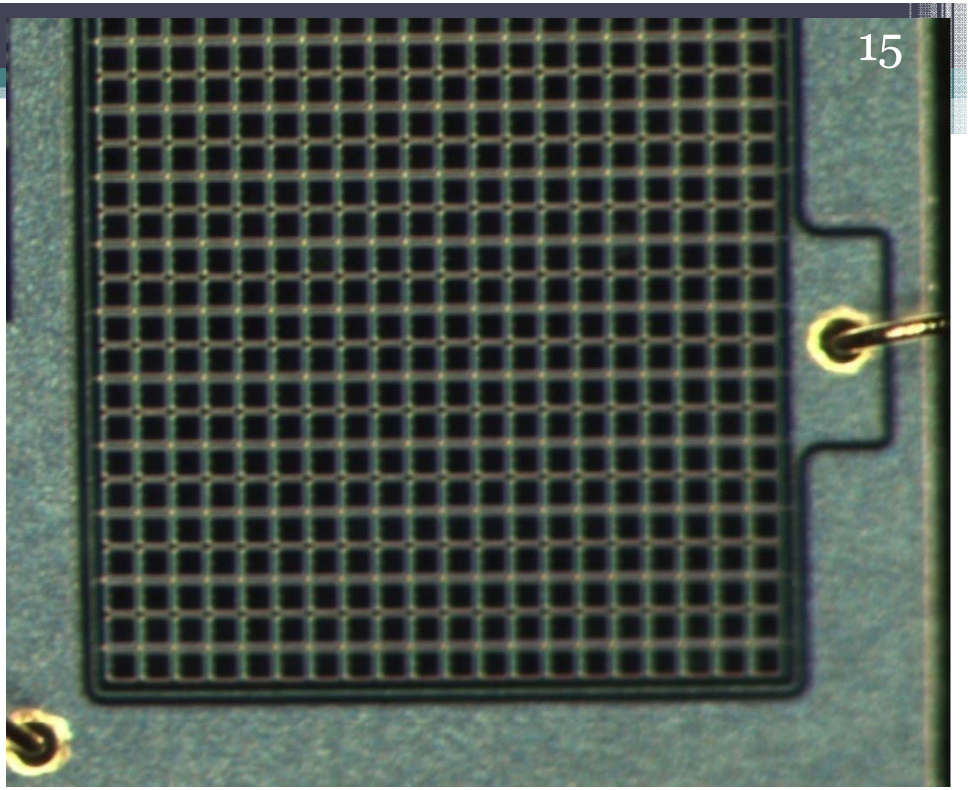


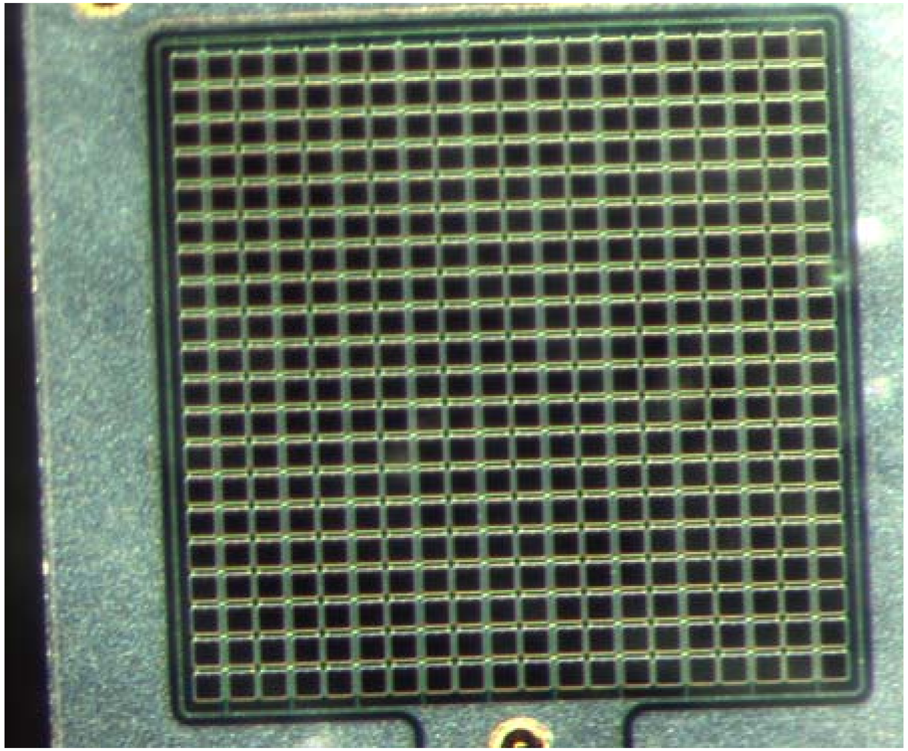
~600 pixel 1mm² MRS diode

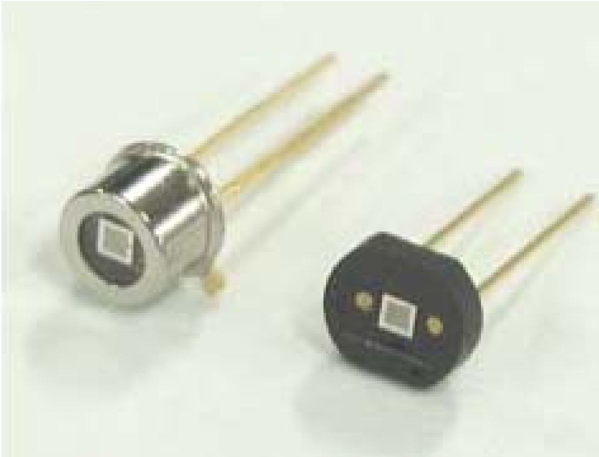
- Each pixel (typ. up to 100µm x 100µm) is an APD in limited Geiger mode
- Passive quenching by film resistor
  - As avalanche develops, current rises, voltage drop over resistor and reduces bias below avalanche limit
    - Protects from high light levels
- Pixels output is collected to a common substrate
- Due to surface structure, these devices have overall PDE of 15-30% for green light (~500nm)
  - Each pixel PDE (~60%-70%) is comparable to APD
- Total PDE is comparable or higher to that of the green-extended PMT.

Under a Microscope

- Hamamatsu MPPC
  - 400 pixel, 1mm x 1mm



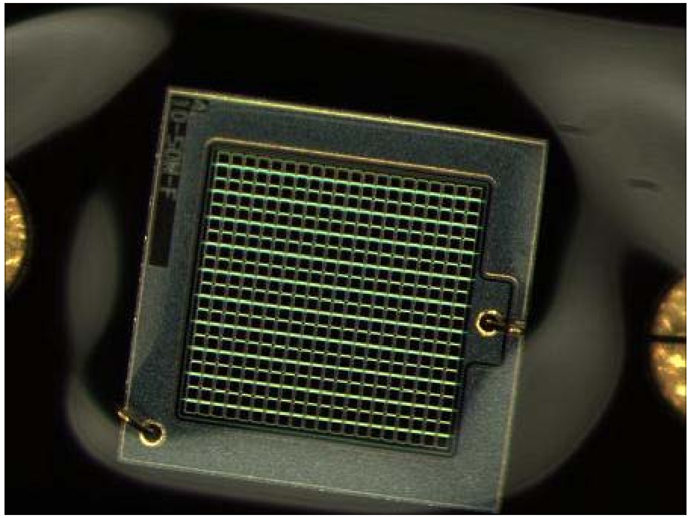




Multi-pixel Photon Detectors MPPC - at a quick glance

- Pros:
  - Low bias (~70V)
  - Not susceptible to magnetic field
  - Small size
  - Survives exposure to high light levels
  - Inexpensive (relatively)
  - PDE typ. ~40%-50% (400nm)
  - Gain typ. $7 \cdot 10^5$
- Cons:
  - High dark noise with complex structure
  - New product – untested on a large scale

S10361-050U MPPC

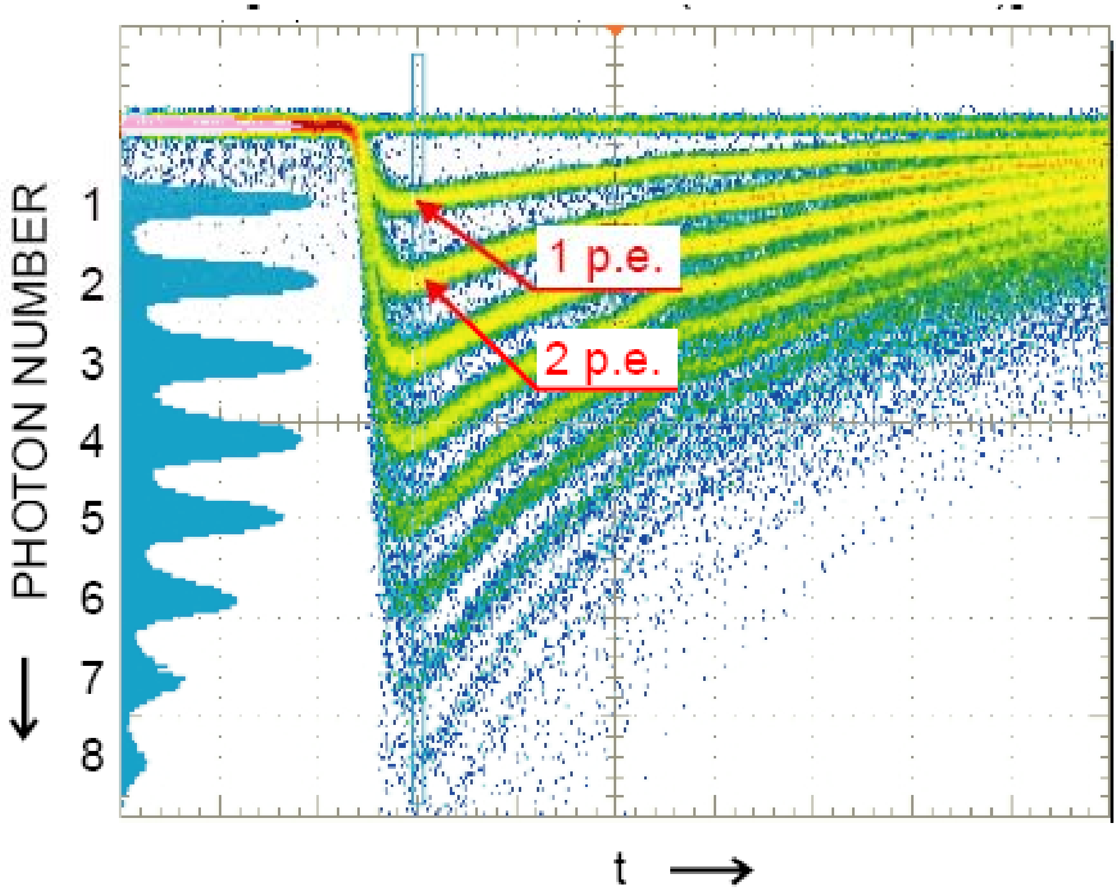


MPPC – Additional Characteristics

- For model S10361-050U
  - Chip size - 1.5 x 1.5 mm^2
  - Active area - 1 x 1 mm^2
  - Pixel size - 50 x 50 μm^2
  - Number of pixels – 400
    - (a sub-model S10363-050U for T2K ~667, non square)
  - Pixel effective size - $38.1 \times 38.8\ \mu m^2$
  - Geometric efficiency - 61.5%
  - Time resolution – 220 ps
  - Temp. coeff. of bias voltage – 50 mV/^{o}C
  - Dark count rate ~$270 \cdot 10^3$/sec

[8]

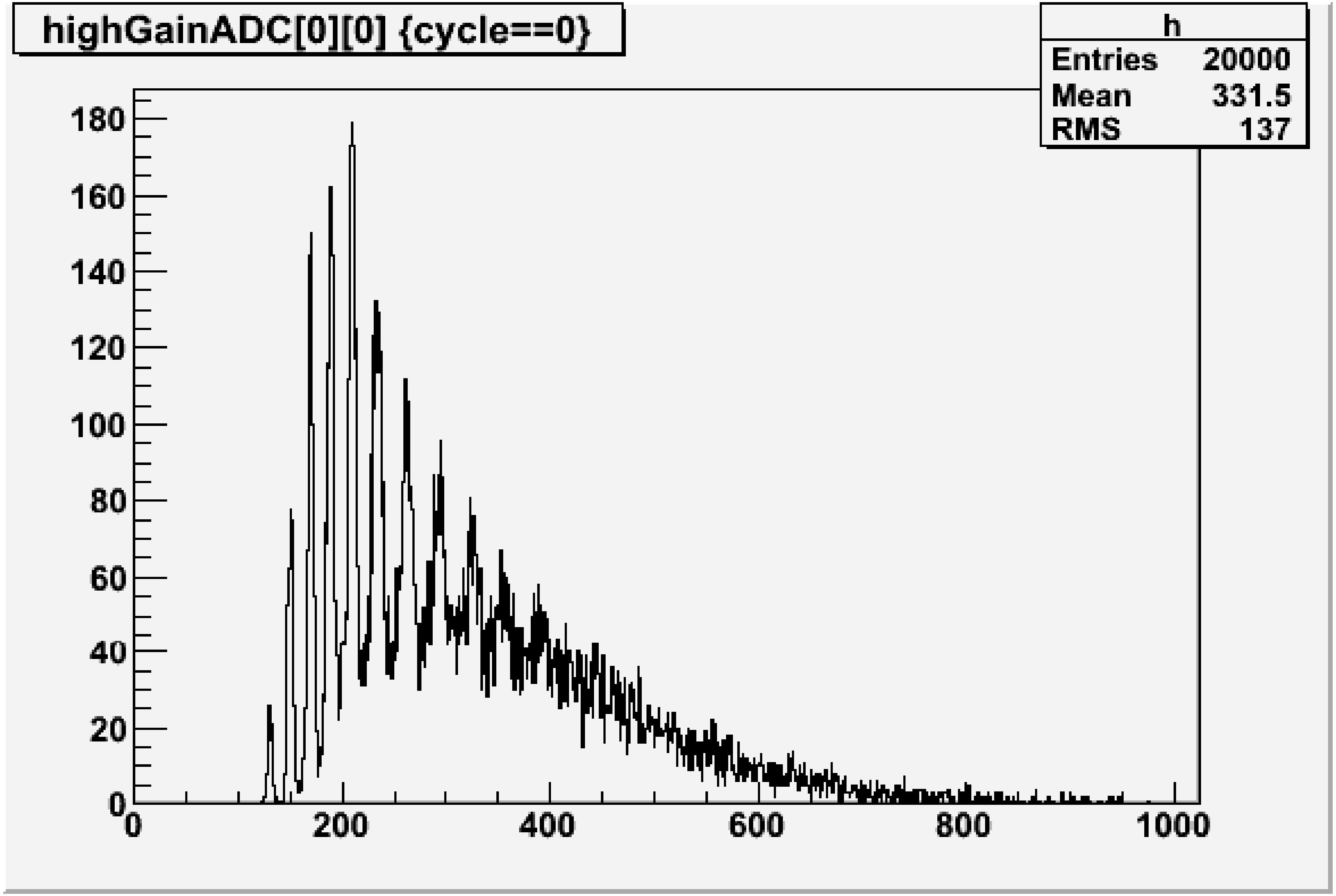
MPPC – PE calibration



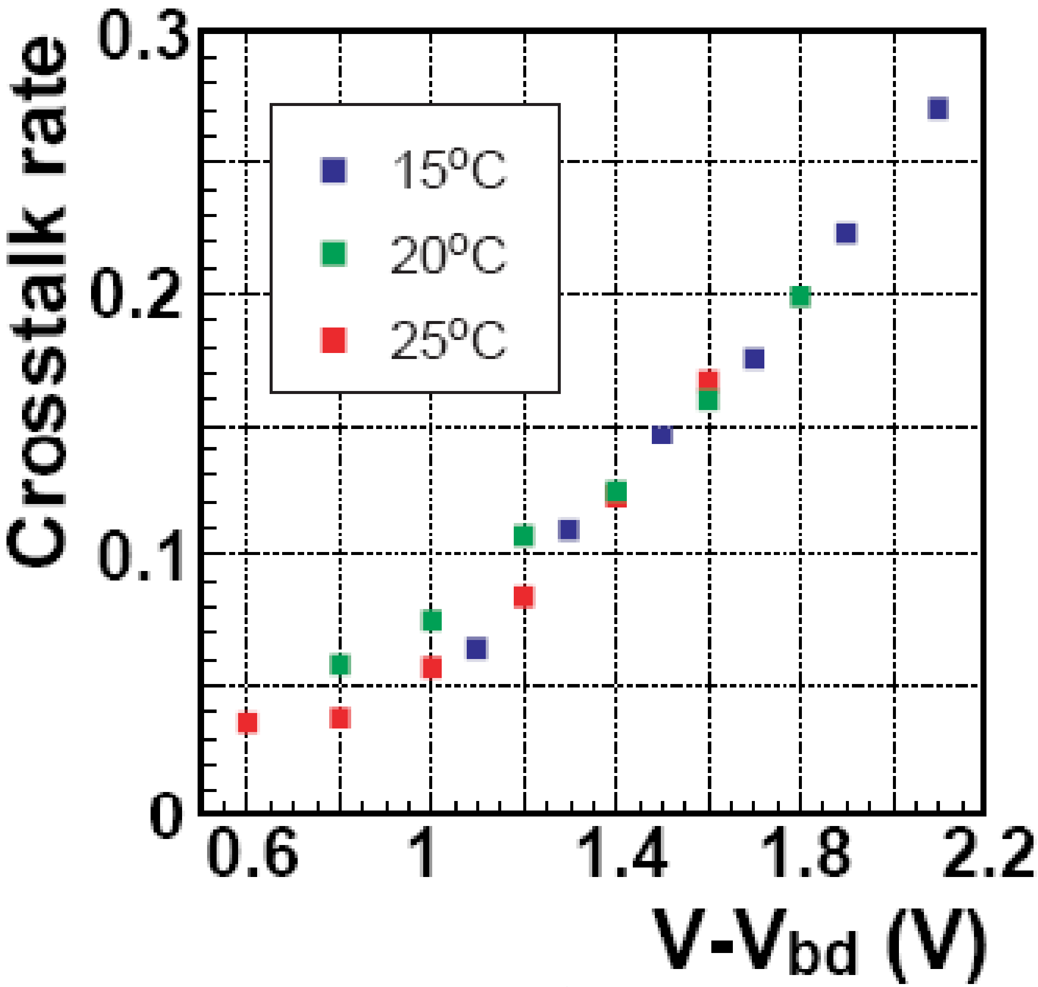
[8]

- Each pixel fires upon photon detection - 1 PE
- Output is a sum of pixels fired
  - Get PE separation

MPPC – PE calibration



MPPC – Pixel Cross Talk

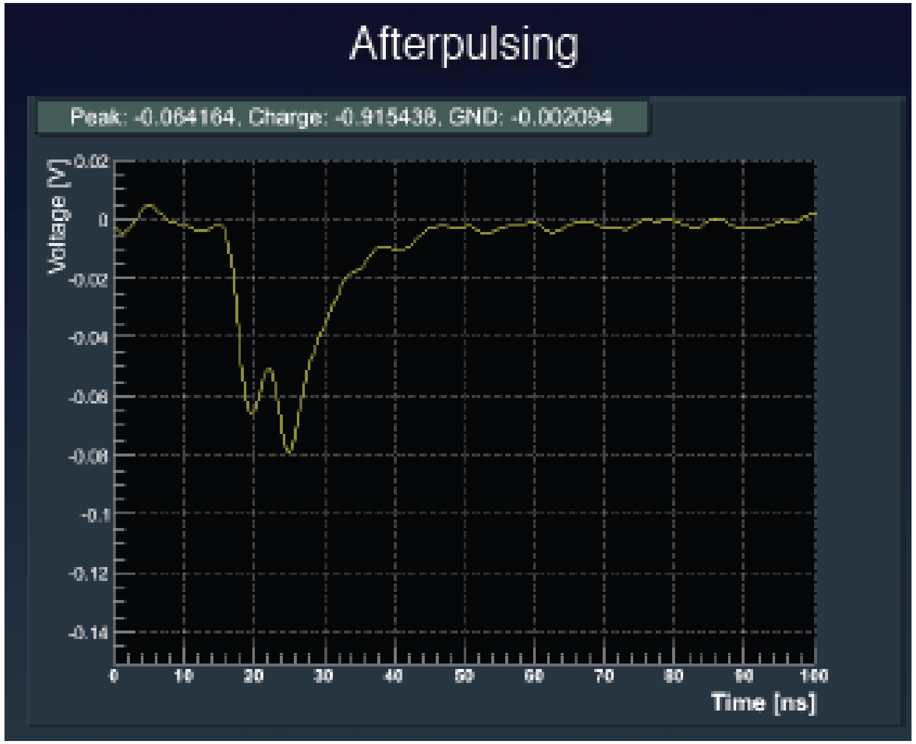


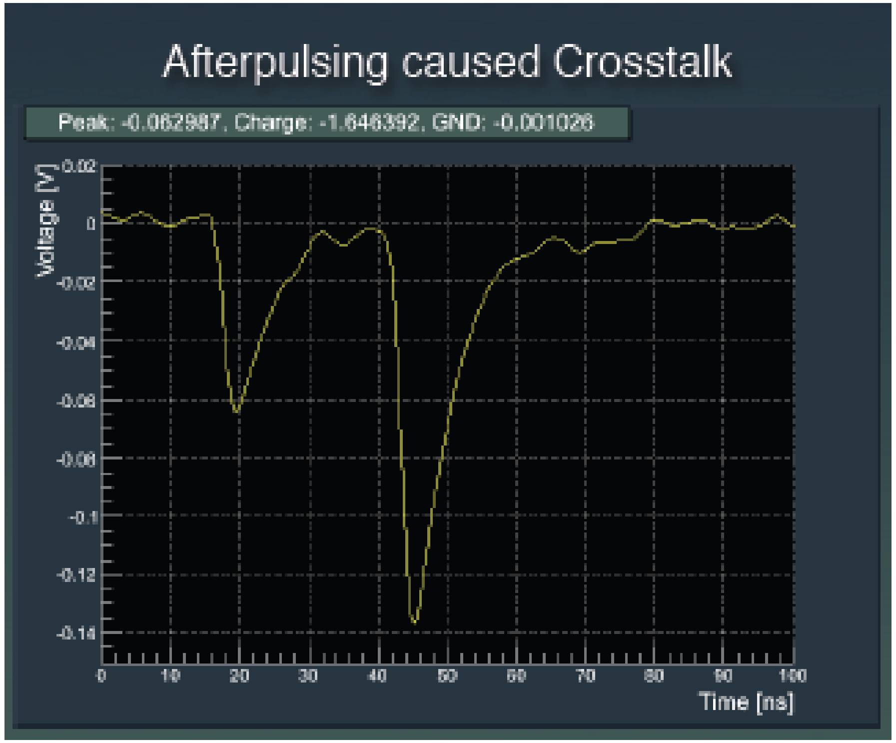
Cross-talk rate as a function of V – $V_{breakdown}$. [9]

- If recombination photon from the avalanche, or e^-, leaks from firing pixel to neighbor one, can cause avalanche there – Pixel Cross Talk
- These new pixel signals will come at ~same time as ones cause by photons, same amplitude and shape
  - Under nominal operation bias, cross-talk on order of 5-6%

MPPC – Pixel After-pulsing

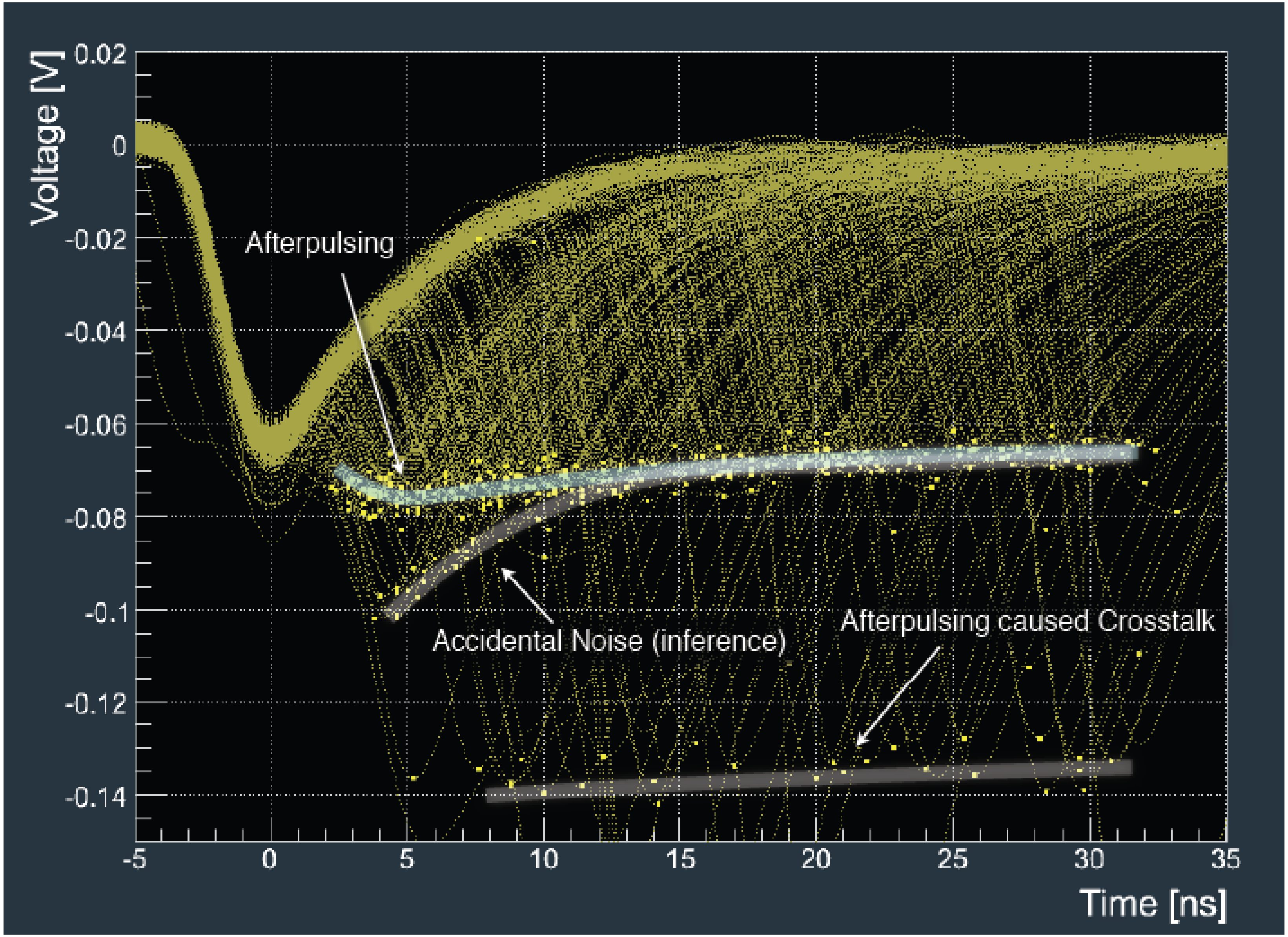
- After pixel fires, some e⁻ are caught in traps (impurities and lattice defects)
- Can trigger another avalanche
- New amplitude depends on pixel recovery state
- After-pulse can cause cross-talk or another after-pulse





[10]

MPPC – Pixel After-pulsing



[10]

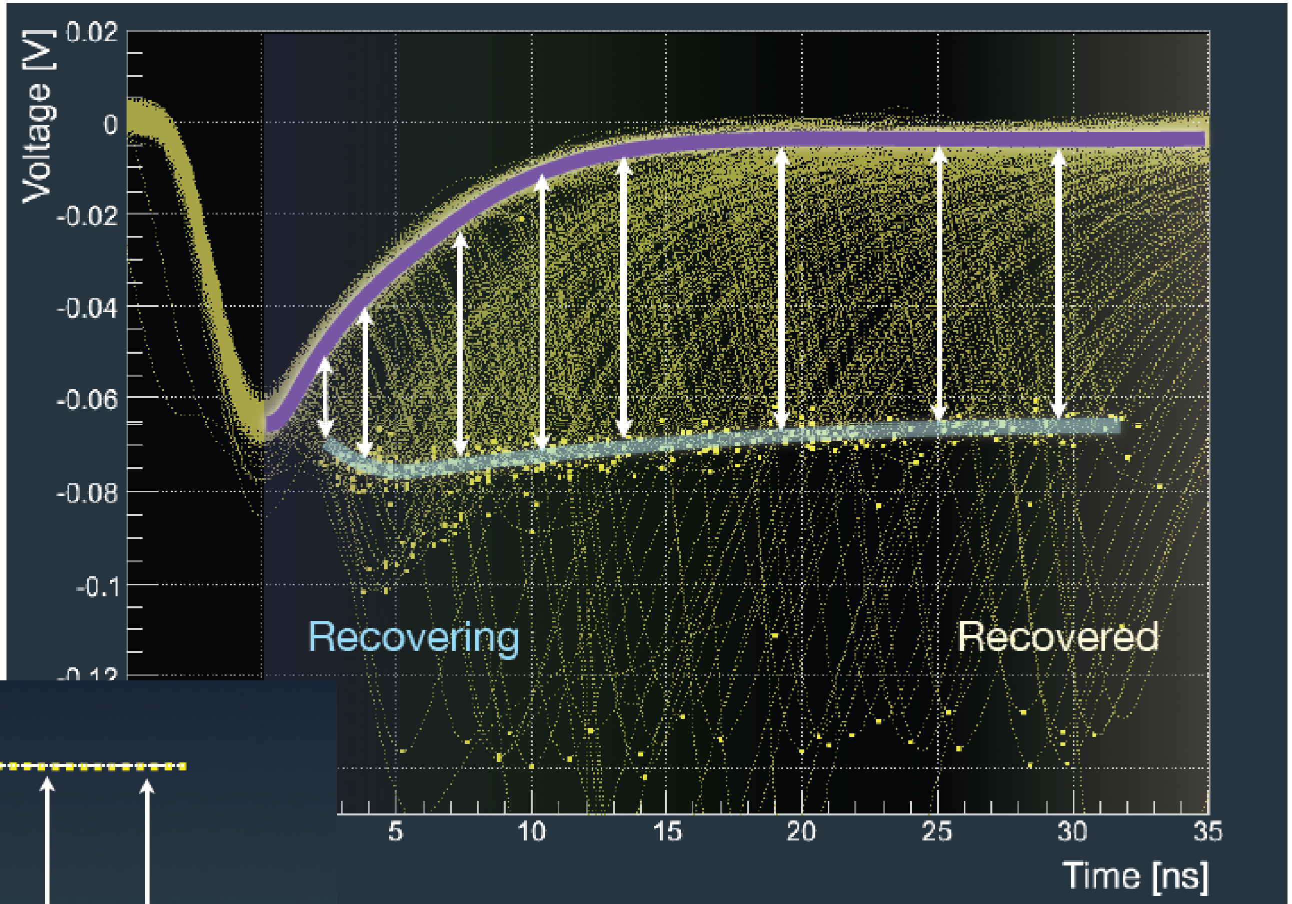
MPPC – Pixel After-pulsing - Recovery

Fit with double exponent:
•Short time const - ~19ns
•Long time const - ~85ns

After-pulsing probability
• (short) - ~6.1%
• (long) - ~5.9%

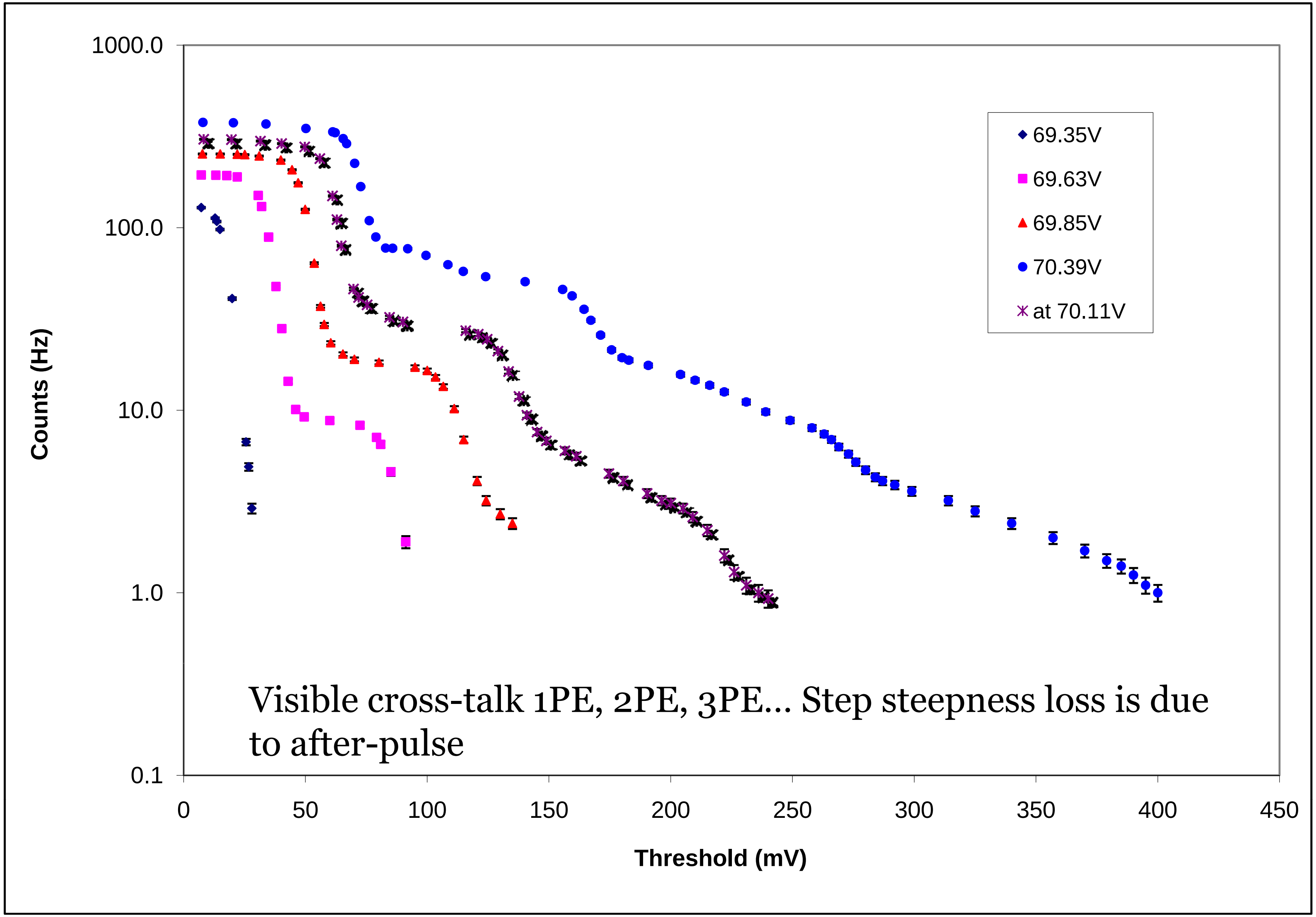
Cross-talk - ~5.7%

[11]

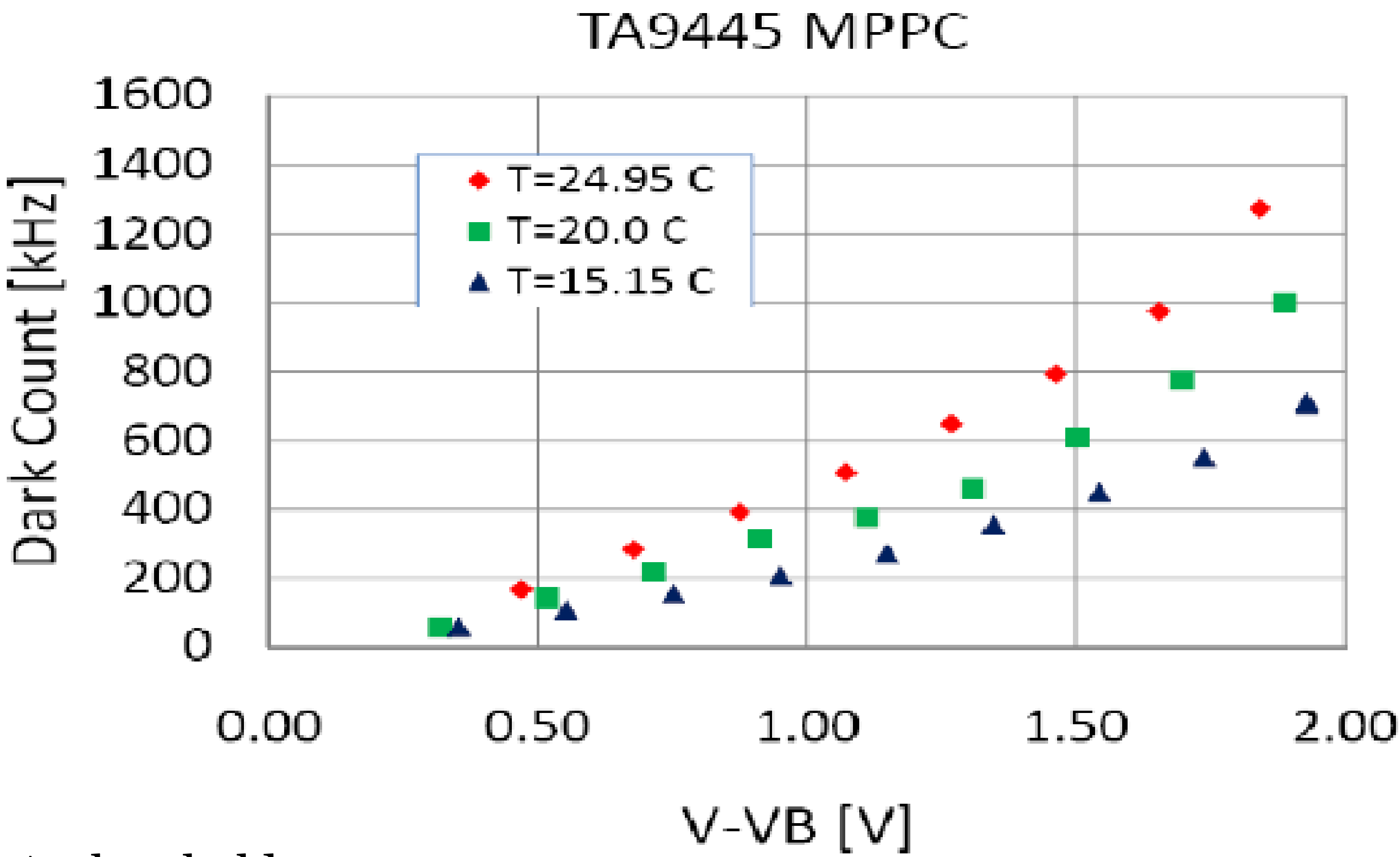


[10]

MPPC – Dark Noise Counts vs. Threshold for several bias values



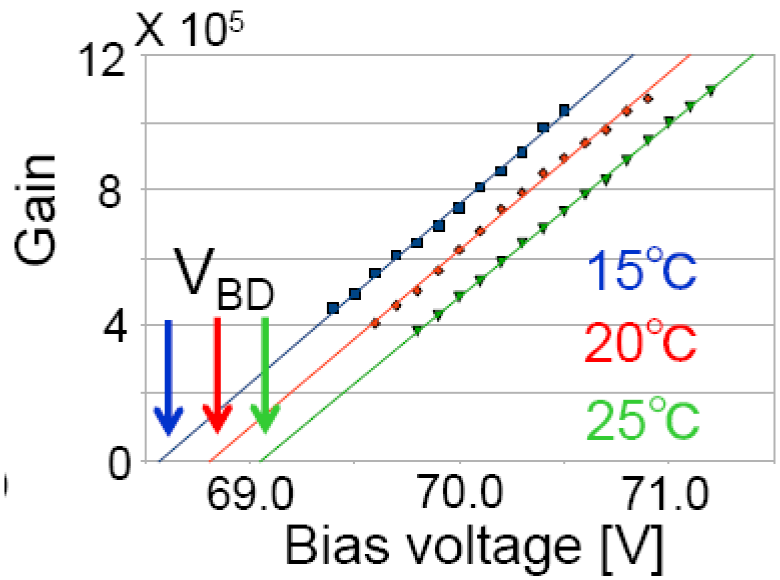
MPPC – Dark Noise Counts vs. Bias at different T values



At threshold = 0.5 p.e.

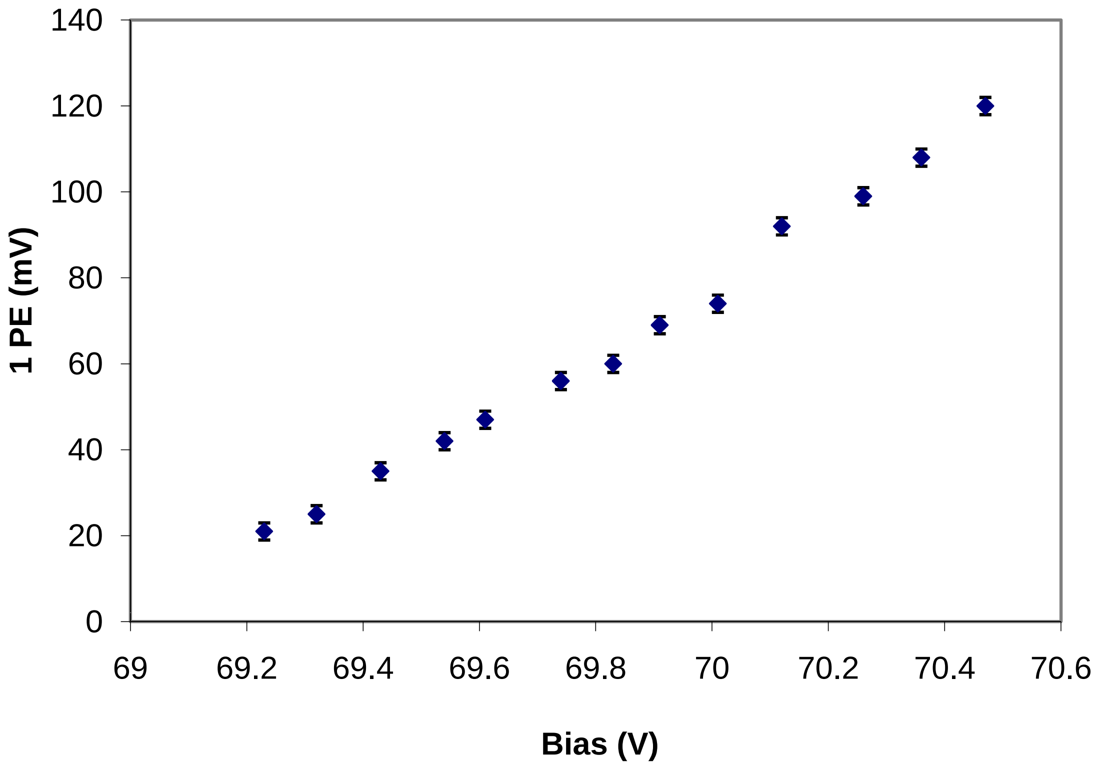
[9]

MPPC Gain



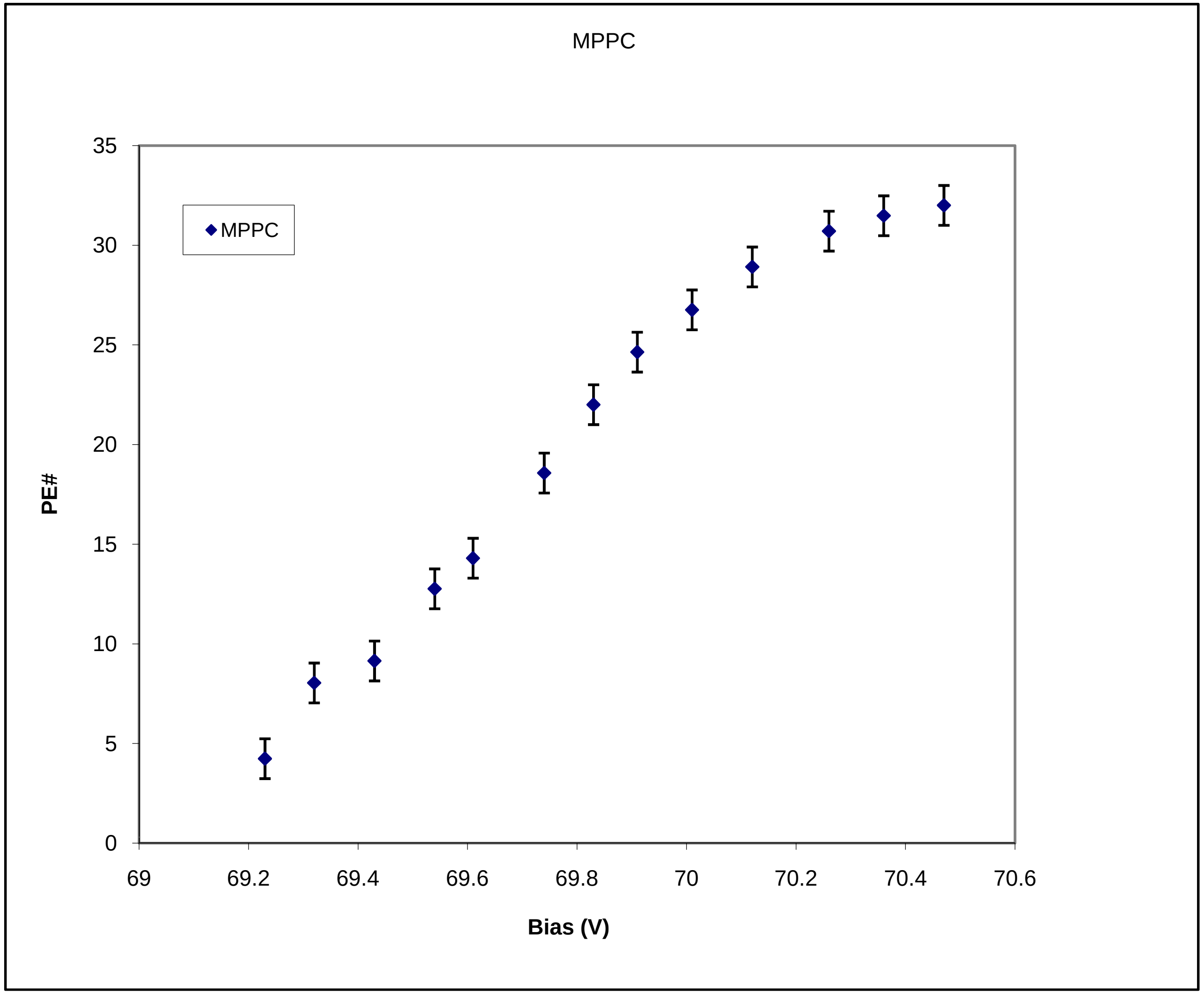
Using temp. coeff. of bias voltage – 50 mV/°C
At Kioto Univ. [13]

Single PE Amplitude vs. Bias



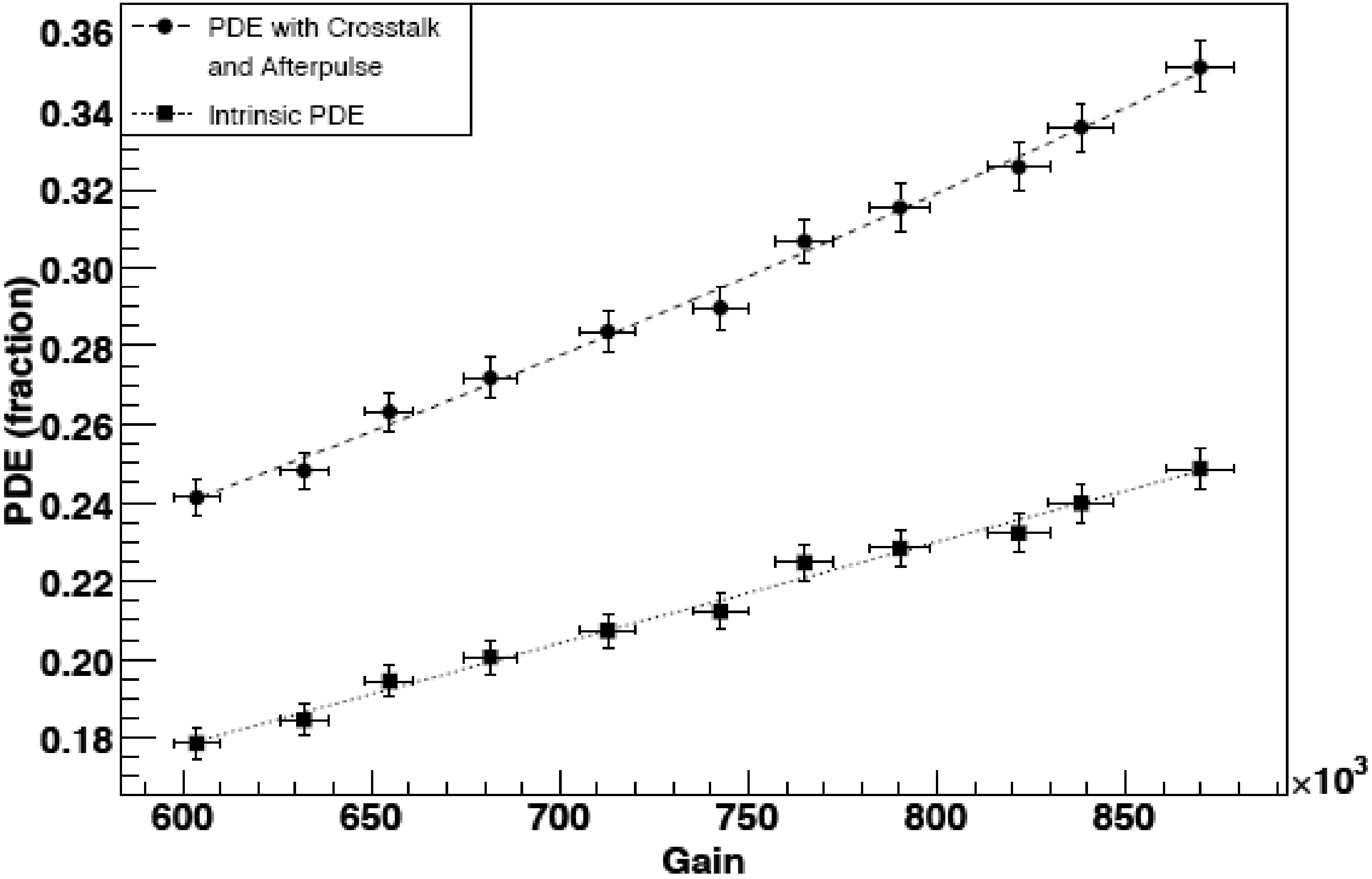
For this sensor, bias range is ~69.1V to ~70.9V
~100x amplifier is used

Signal in #PE vs Bias



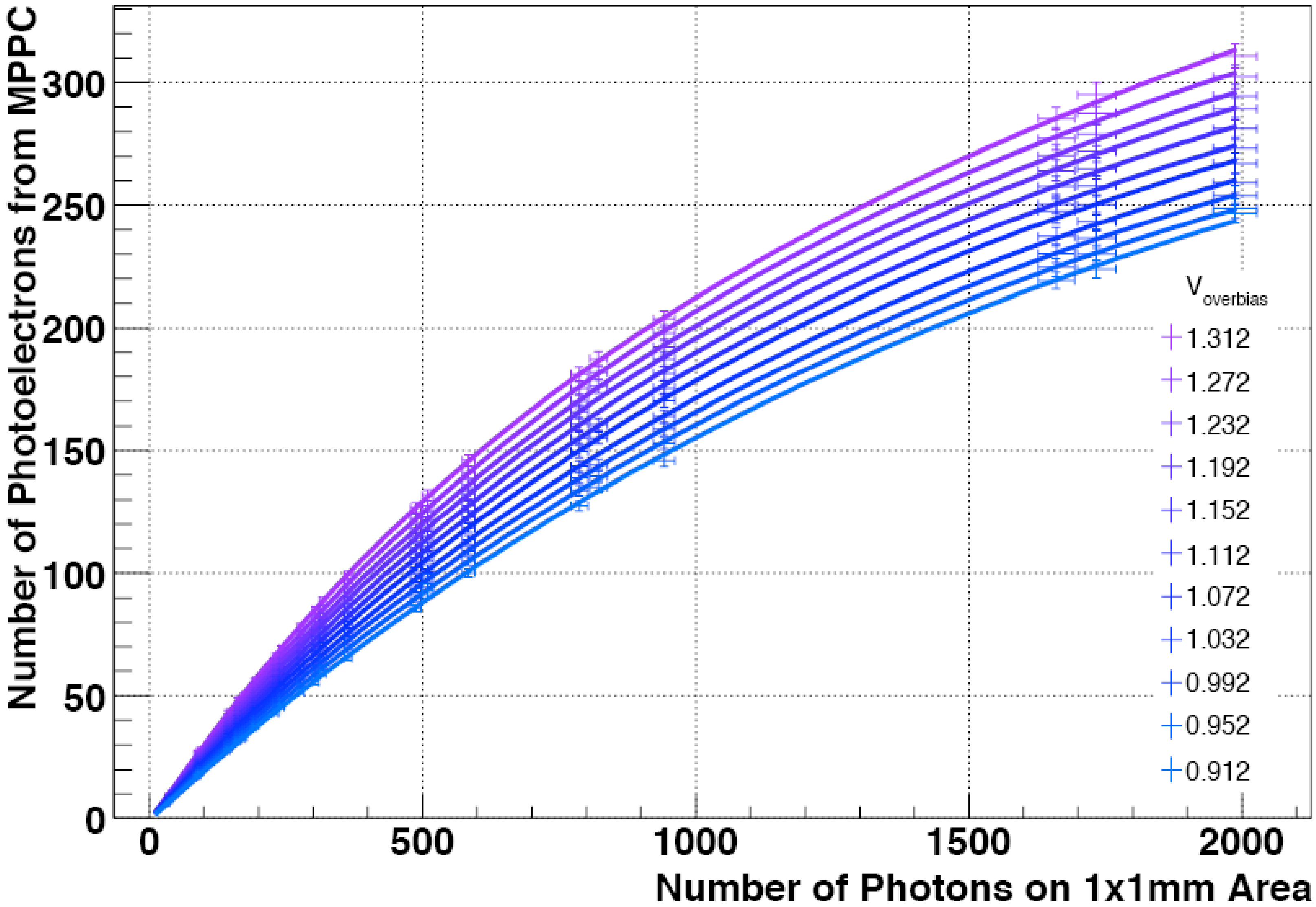
Part of increase is due to cross-talk, dark noise and short after-pulse increase rate. Further increase is limited by narrow gate (~30ns).

MPPC - PDE



- At 470nm
- Thus cross-talk and after-pulsing increase apparent PDE [9]

400 pixel MPPC Linearity

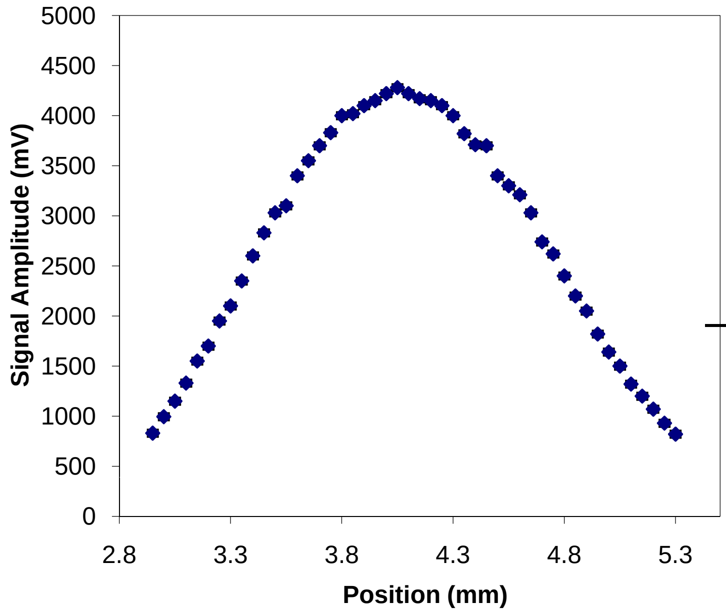


[9]

Multi-pixel family
B-field, Irradiation, Alignment effect

- Multipixel photo sensors were tested in 9T at FNAL
- A number of orientations w.r.t.
- No effect detected (<1%), no quench damage

- Effects of 1MRad on Multipixel photo sensors studied (protons)
- No output change (<1%)

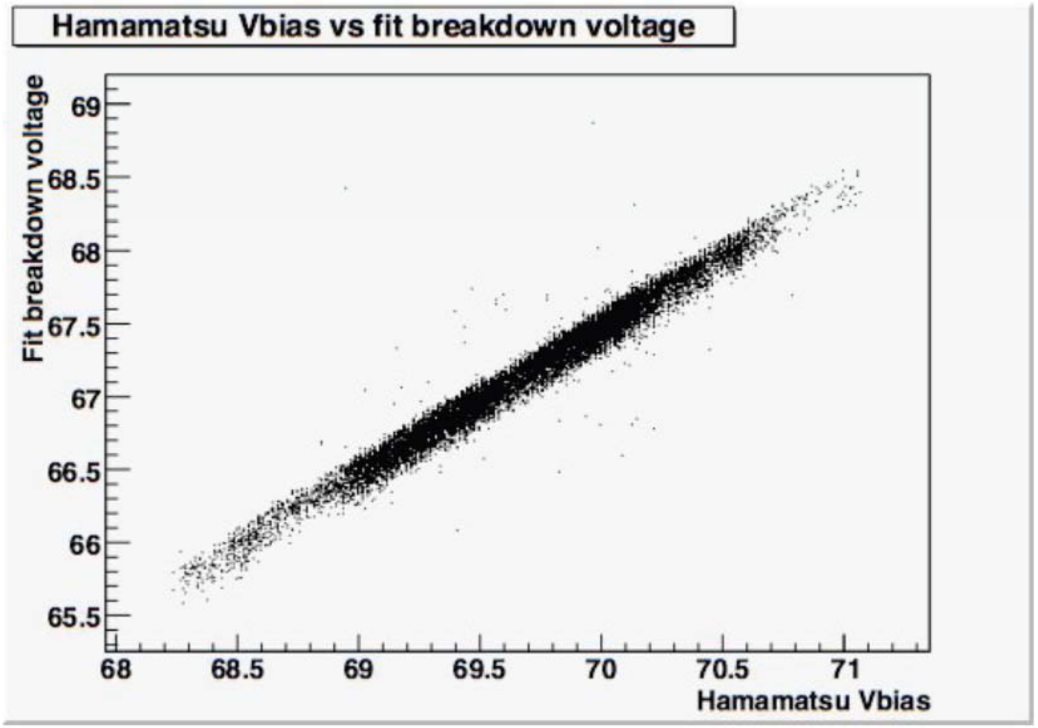


- Alignment studies. Shown - signal amplitude versus the position of the 0.94mm clear fiber for multipixel photo sensors sensor.

MPPC Large Scale Deployment

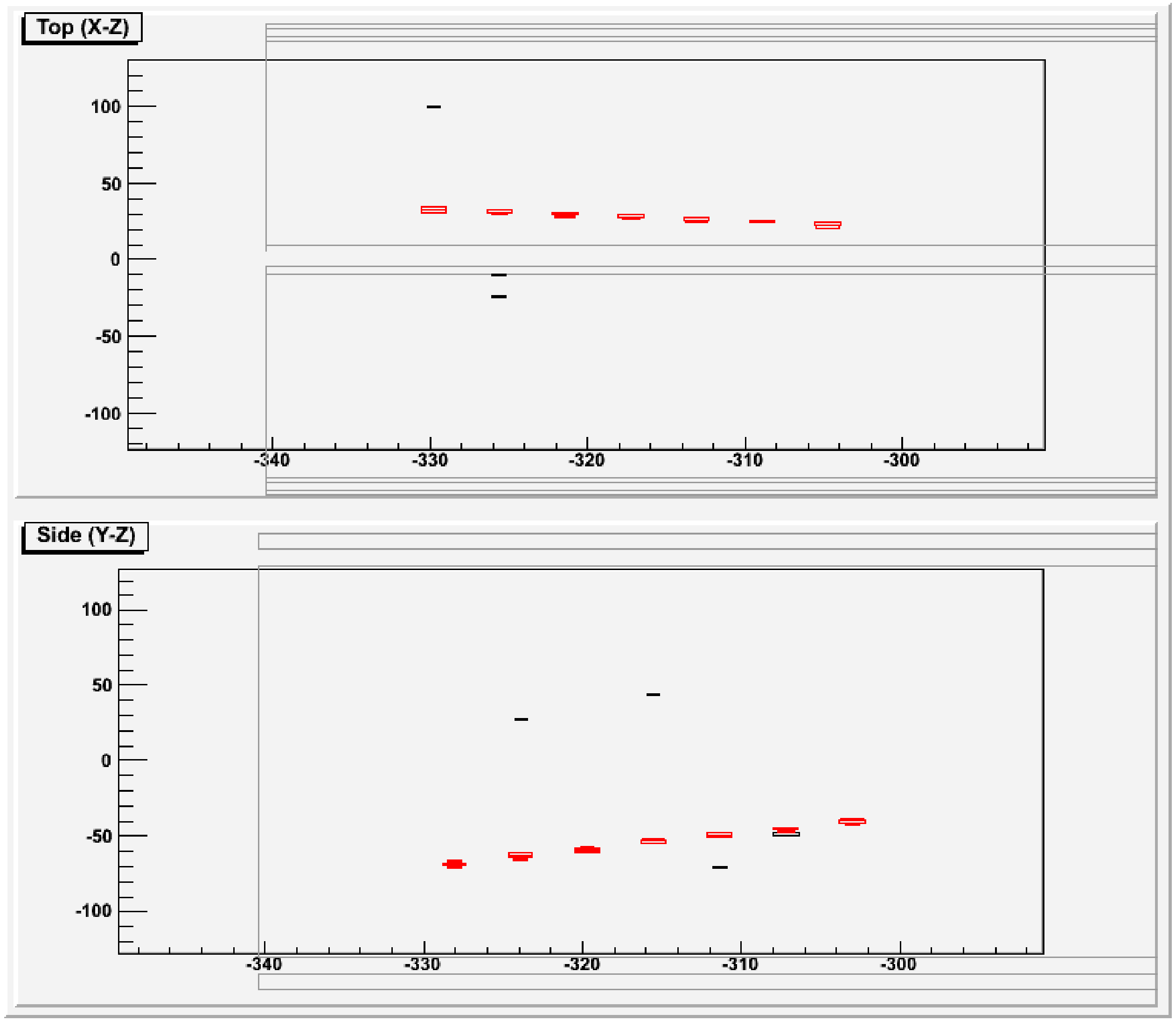
- Each sensor tested before installation
  - At CSU
    - Found 83 bad (mostly ones strongly deviated from expected characteristics) from ~11k shipment
- Additional testing after installation
  - Found 14 more bad
    - 2 had surface damage
- After transit to Japan
  - 2 more sensors found bad

- Bias Spread between sensors
  - (plot by CSU)
  - Mostly between 69 and 71V



Cosmic Data

- Using PoD UPSTREAM ECAL only
- At JPARC facility (June 09)
  - Averaged over full ~2m length- see ~20PE/MeV



Conclusion

- Overall, MPPC sensors are found to be reliable and an attractive choice for HEP applications
  - Especially in B field environments
- Sensors characteristics appear stable
  - Gain
  - Dark Noise
  - Dependability
- Sensors with larger area are being developed
- Other possible applications include medical imaging devices, portable detectors, security systems, etc…

References

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