Development of Multi-Pixel Photon Counter and Application to T2K experiment

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Seminar at University of Rome “La Sapienza”

Outline

- Introduction
  - T2K and near detectors
  - Motivation for new sensor development
- Multi-Pixel Photon Counter (MPPC)
  - Operation principle
  - Performance
- Summary

Introduction

T2K and near detectors

Motivation for new photosensor development

T2K Experiment

- Long baseline neutrino experiment in Japan
  - Search for ν_e appearance from ν_μ beam
  - Precision measurements of ν_μ disappearance
- Start from April 2009

Recent milestone #1:
Proton beam circulated in the MR!

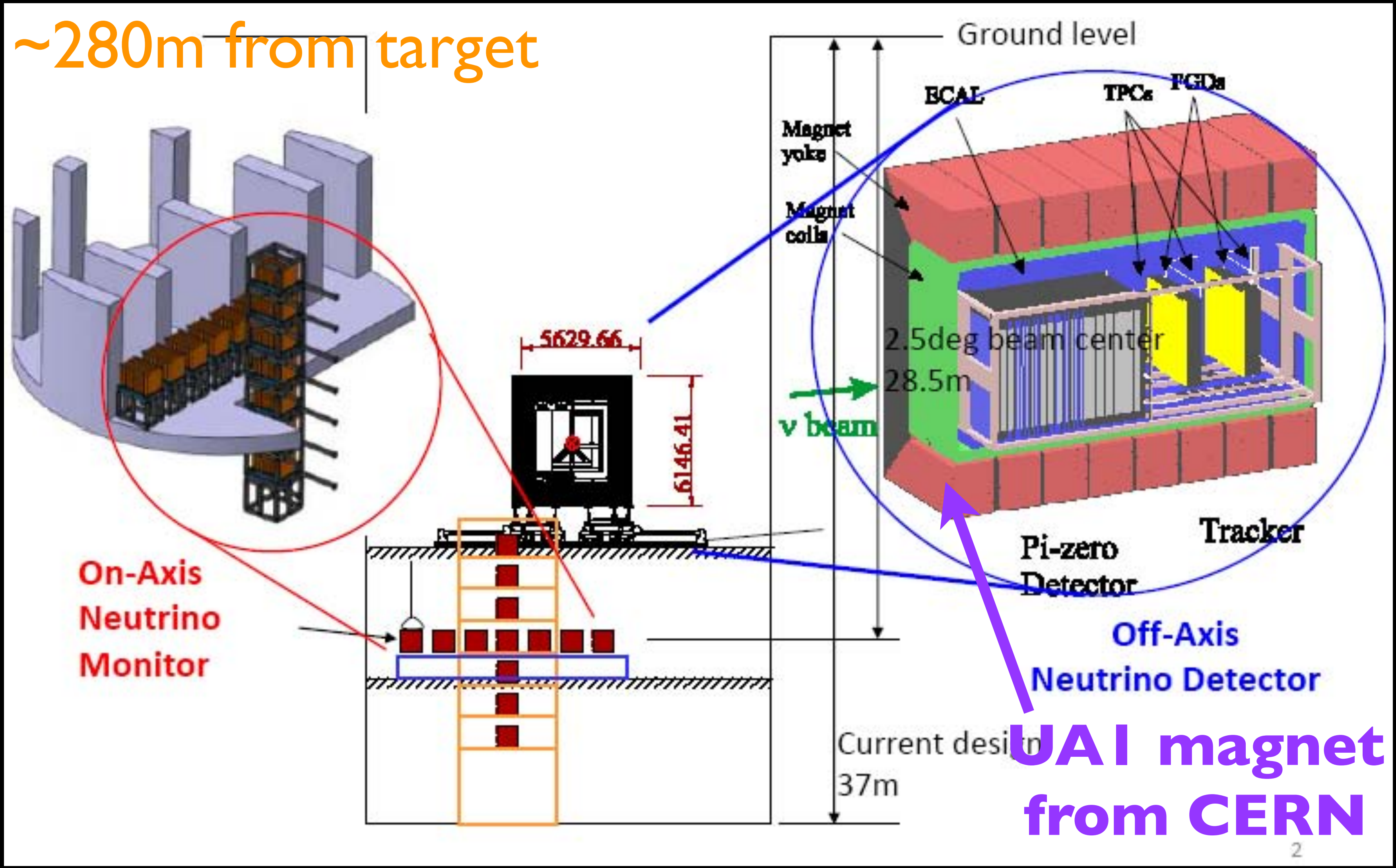
■Beam injection, rf capture and beam extraction to beam dump were successfully demonstrated on May 22, 2008.

The next step is to accelerate beams to 30 GeV. It will start in December of this year.

On May 22, 2008

T.Koseki, 4th J-PARC PAC

T2K Near Detectors

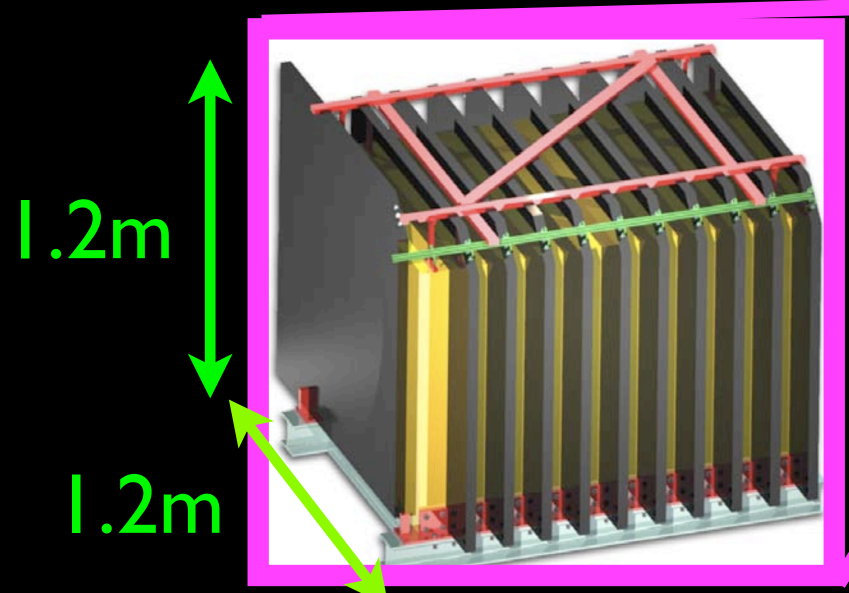


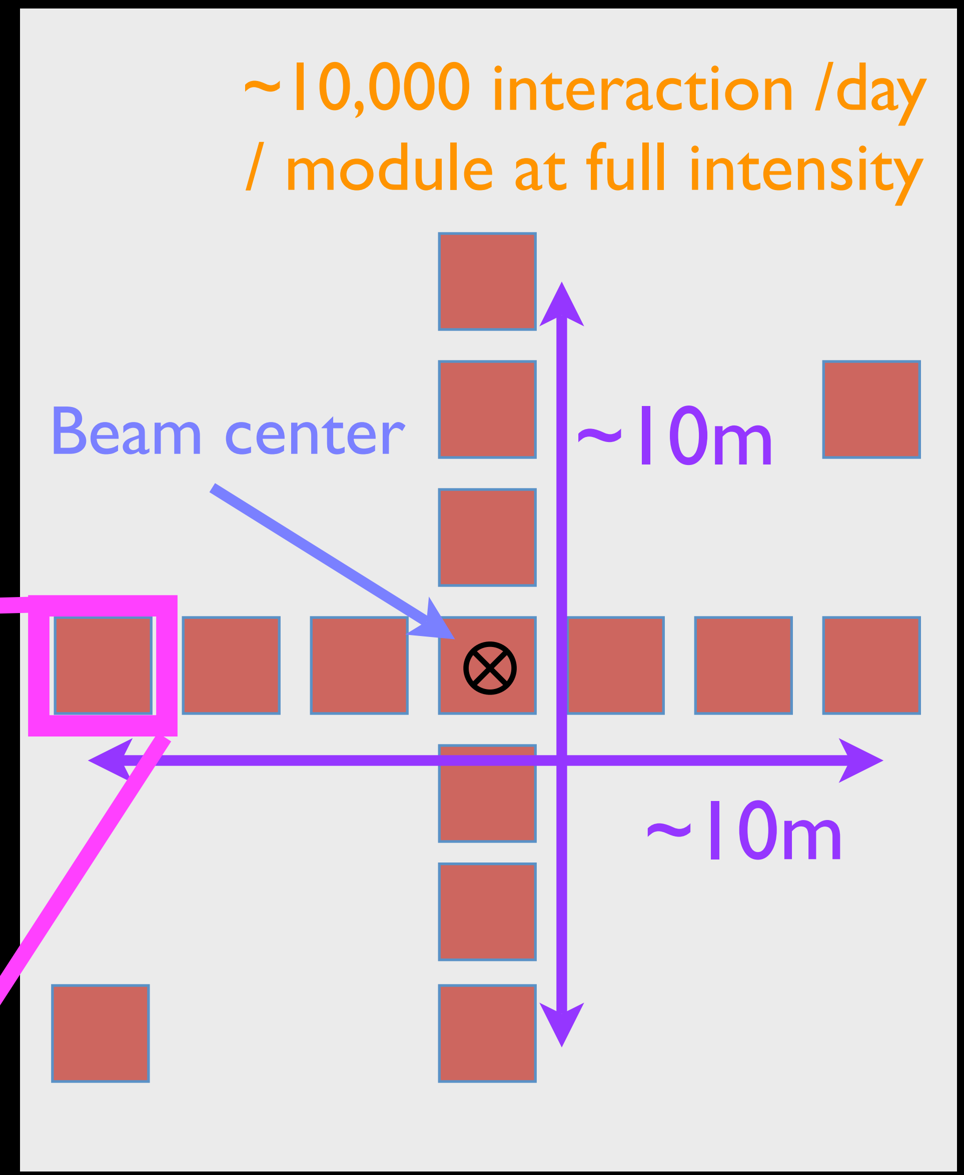
Characterize neutrino beam at production.

On-axis detector

Named 'INGRID'

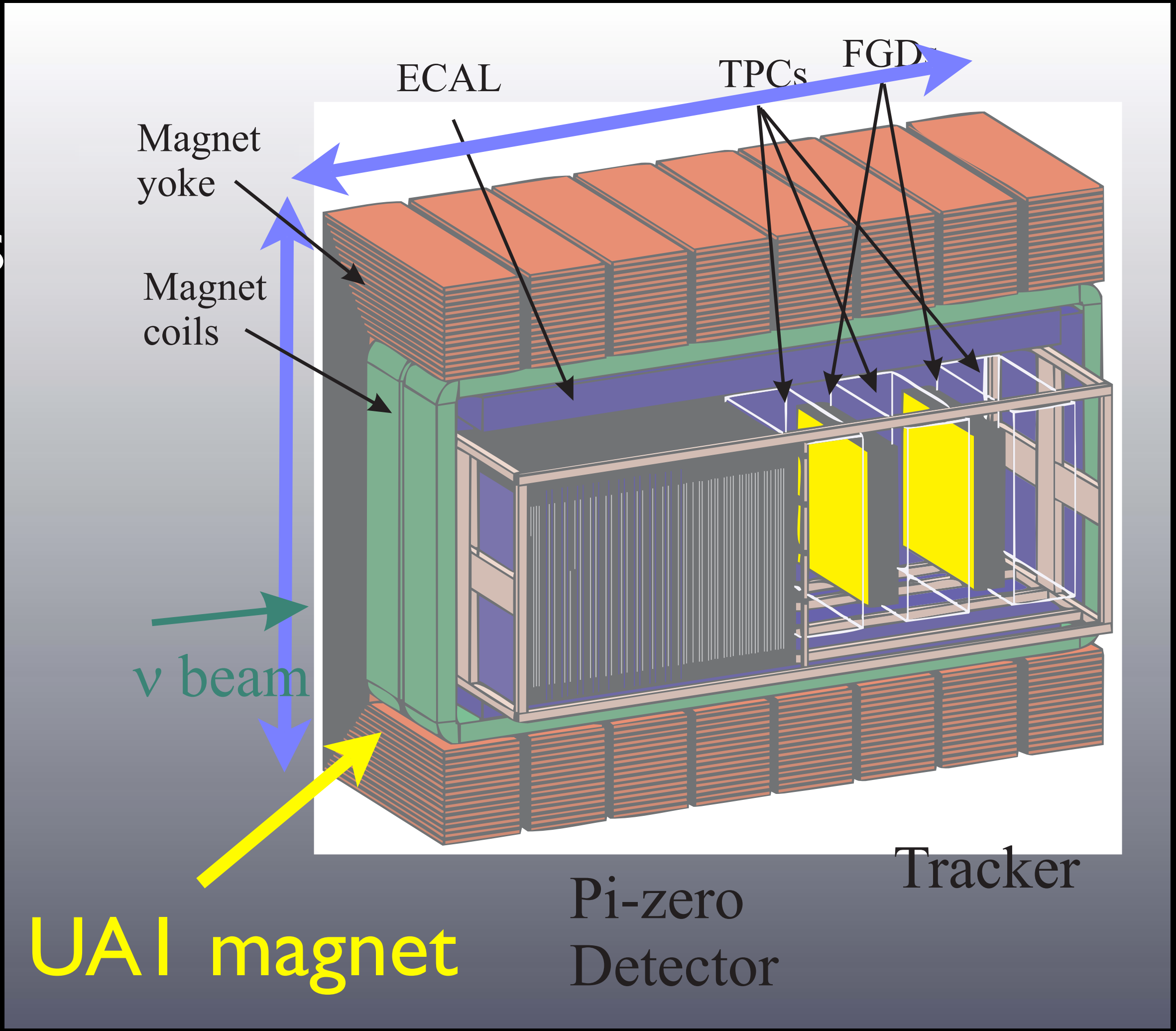
- Array of Fe(target)-scintillator(tracker) stack
- Measure ν beam profile, monitor beam stability





Off-axis detectors

- Measure ν flux/spectrum/composition/interaction at production
- Several sub-detectors with specific functions
  - FGD/TPC/P0D/ECAL/SMRD
- Inside 0.2T B-field by UA1 magnet

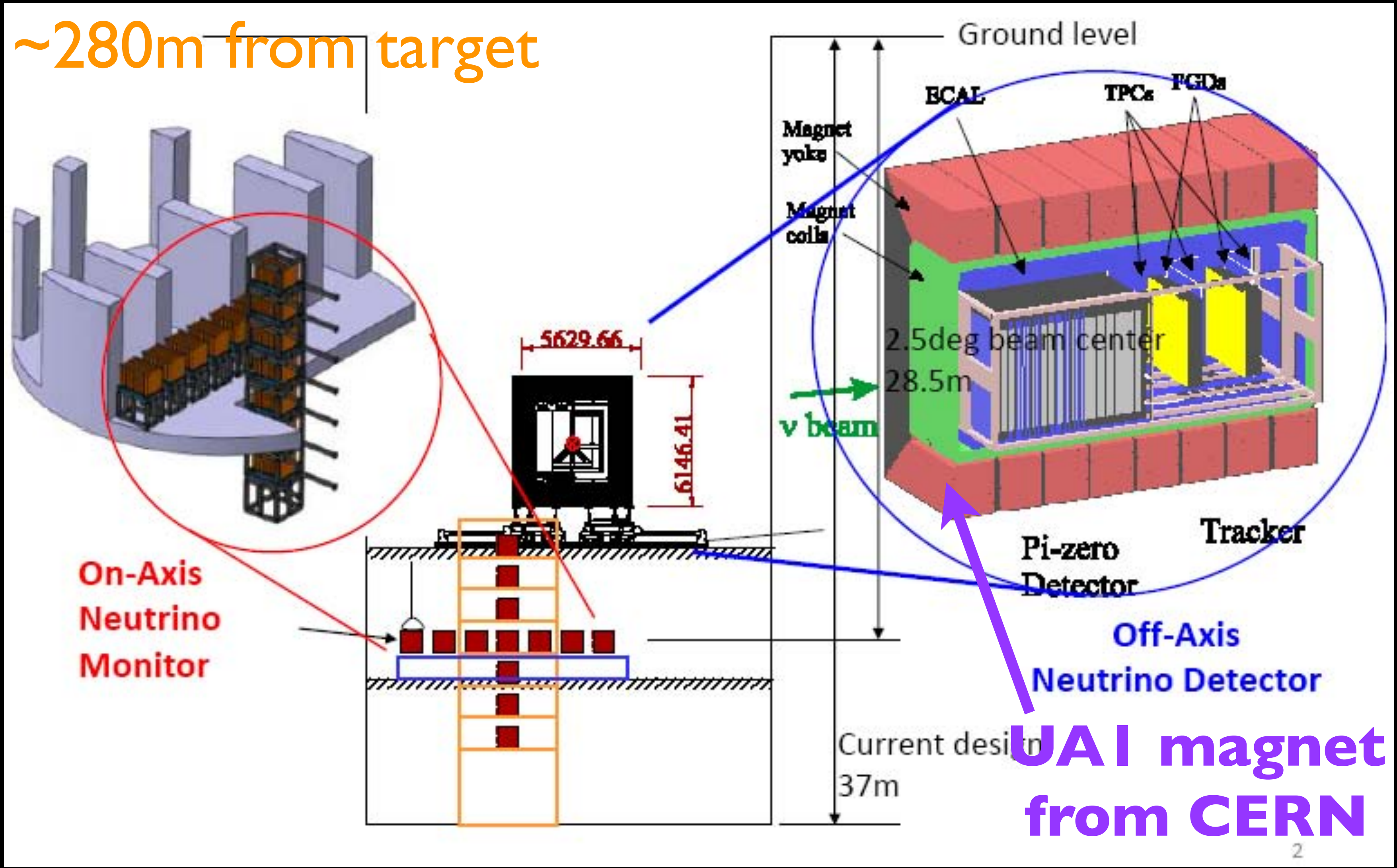


Recent milestone #2: UA1 magnet installed in ND280 pit!

Great contribution from Rome group in initial stage of project

Completed on June 21, 2008

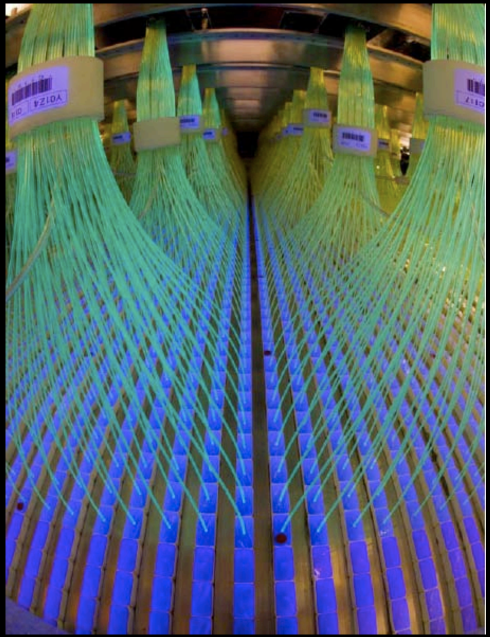
T2K Near Detectors



Characterize neutrino beam at production.

Common technique: WLS fiber readout

- All but TPC will use plastic scintillator + wavelength shifting fiber readout
  - Successful in recent neutrino detectors (K2K-SciBar, MINOS, MINERvA, SciBooNE, ...)
- Kuraray Y11 (1mm diameter) chosen as the fiber
- Photosensor matched with fiber readout needed!



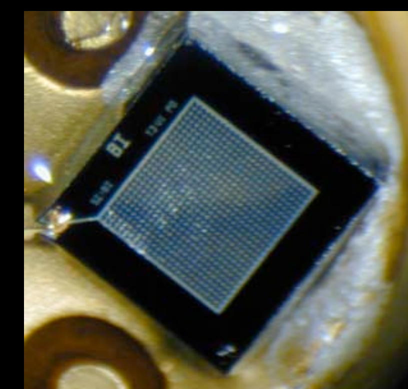
Photosensor requirements for T2K-ND

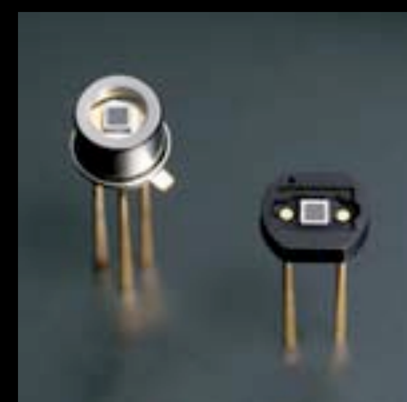
Constraints/situation	Requirements
Enough light yield	PDE >PMT for green light
0.2T B-field	Immunity to magnetic field
Limited space	Compact, stable
Low interaction rate	Radiation hardness not an issue
Timing from accelerator available	Dark noise less harmful, ~1MHz OK
Large number of channels (~60,000 in total)	Easy operation, price ¥$€

Multi-Pixel Photon Counter (MPPC)

“Silicon Photo-multiplier”??

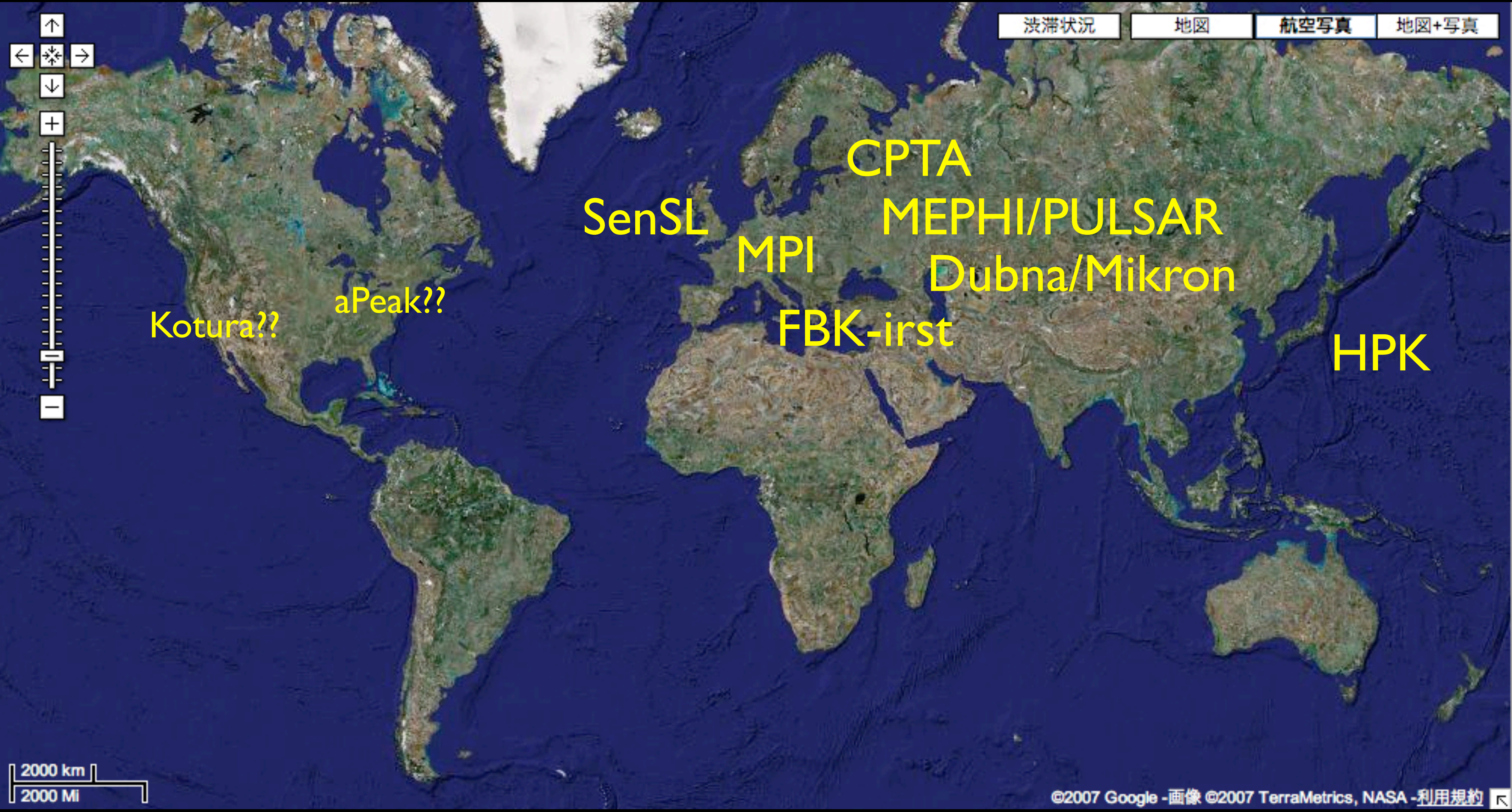
- Known in many many names...
  - SiPM
  - MRS-APD
  - SPM
  - MPGM APD
  - AMPD
  - SSPM
  - GM-APD
  - MPPC
  - .....





- Reflecting progress in many places in short time.

R&D over the world



Old map: now more exist..

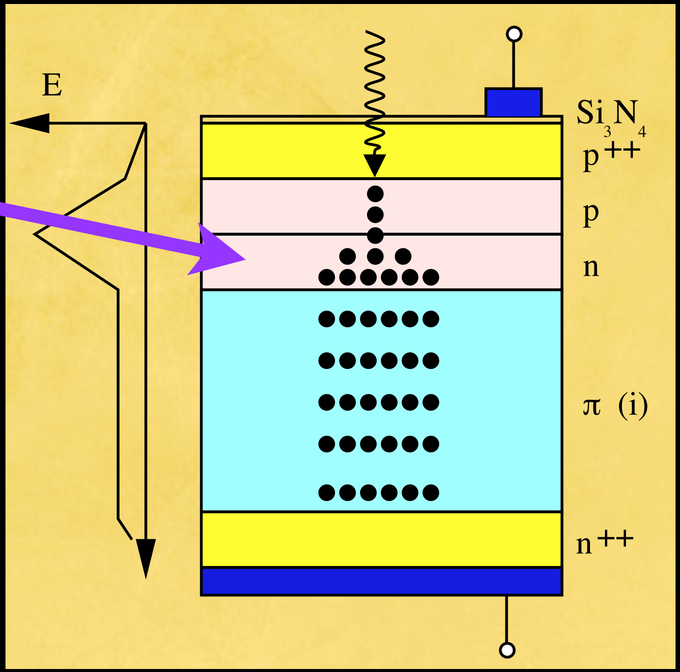
Why interesting?

- Many advantages:
  - High (10^5-10^6) gain with low voltage (<100V)
  - High photon detection efficiency
  - Compact and robust
  - Insensitive to magnetic fields
- Although as many possible drawbacks *at this moment*:
  - Only small size (typically ~mm^2) available
  - High dark count rate (100kHz-1MHz/mm^2)
  - Optical cross-talk and after-pulse

Operation principles

Avalanche Photodiodes (APDs)

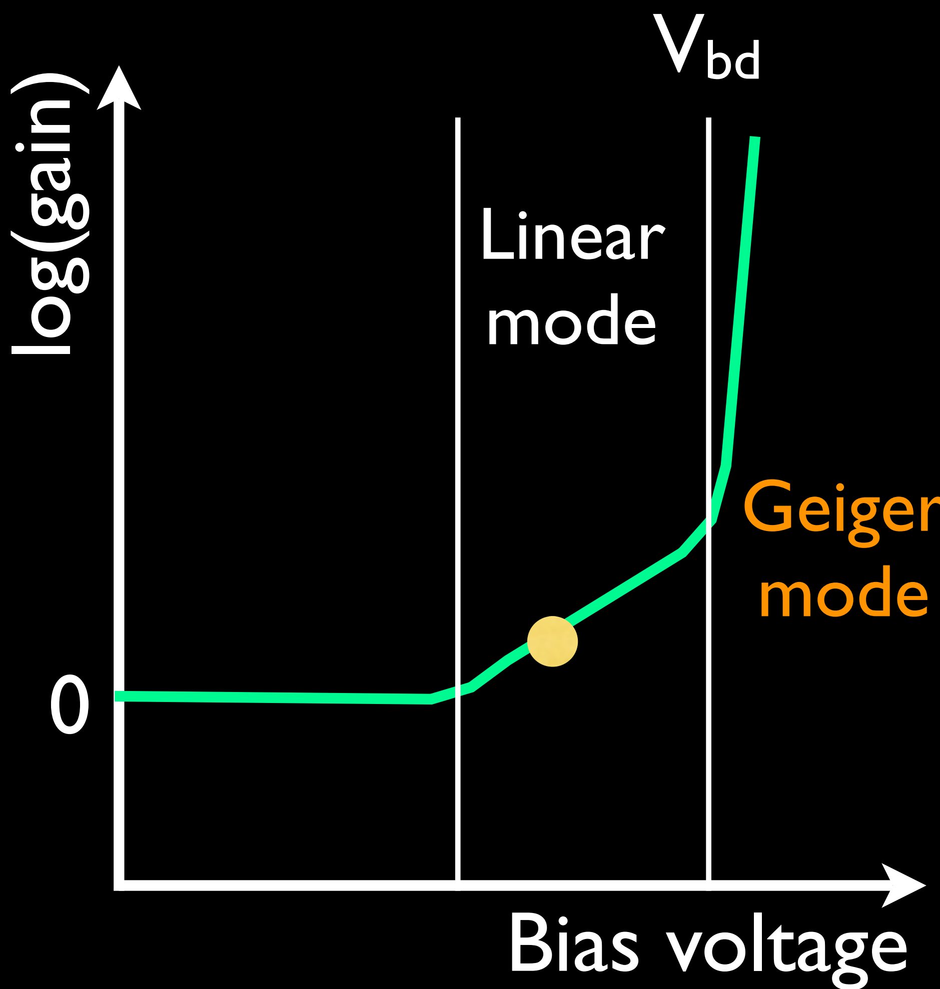
- Photon creates e-h pair near surface
- Avalanche amplification in reverse-biased region
- Linear operation below breakdown voltage (V_{bd}): output charge ∝ number of e-h pairs ∝ number of incident photons
  - Typical internal gain: 10-100 (~1000 some case)



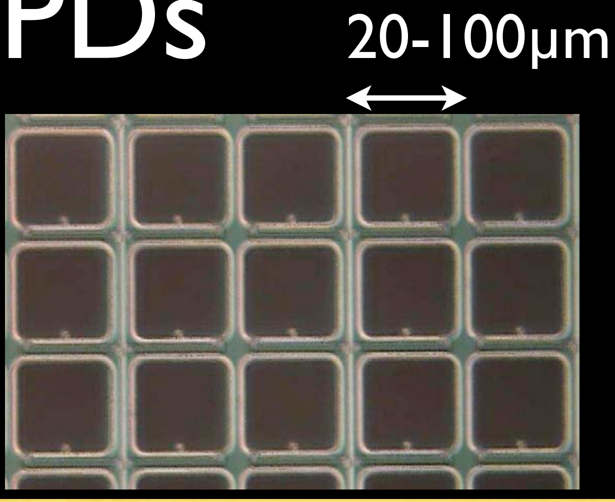
Schematics of APD for CMS-ECAL

Geiger-mode operation of APDs

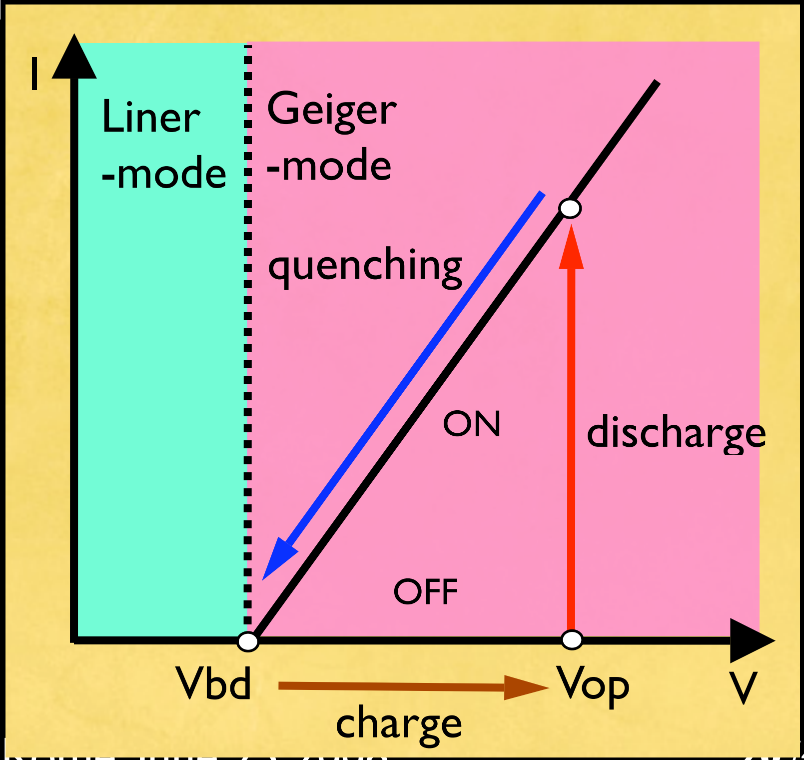
- Operation above the breakdown voltage
- High internal gain
- Binary device
  - Same amount of charge regardless of number of incident photons
- Discharge may be 'quenched' by external register



Counting Photons with Geiger-mode APDs

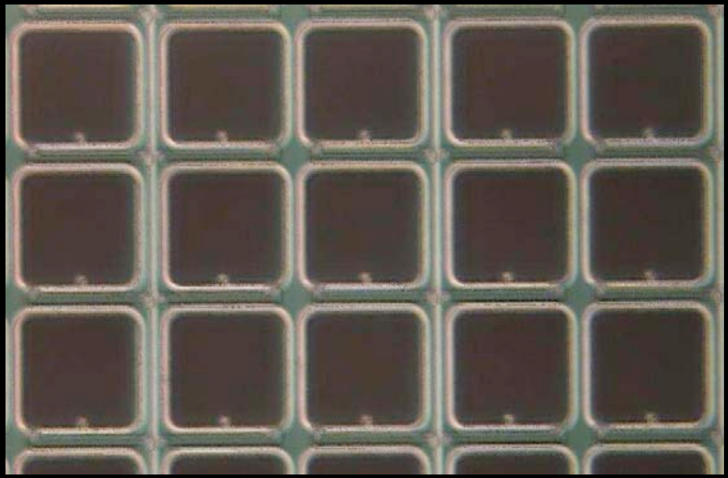


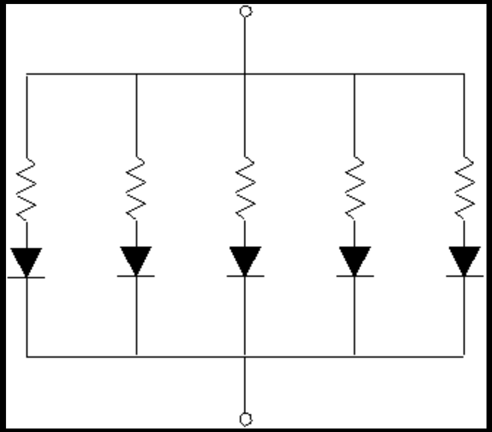
- Divide APD into many small pixels.
    - Each pixel works independently in Geiger mode
- Incident photon 'fires' an APD pixel *but not others*
    - Output charge from one pixel: $Q=C_{pixel} \cdot (V_{op}-V_{bd})$
    - C_{pixel}~10-100fF and $\Delta V \equiv V_{op}-V_{bd}$~1-2V gives Q~10^5-10^6e



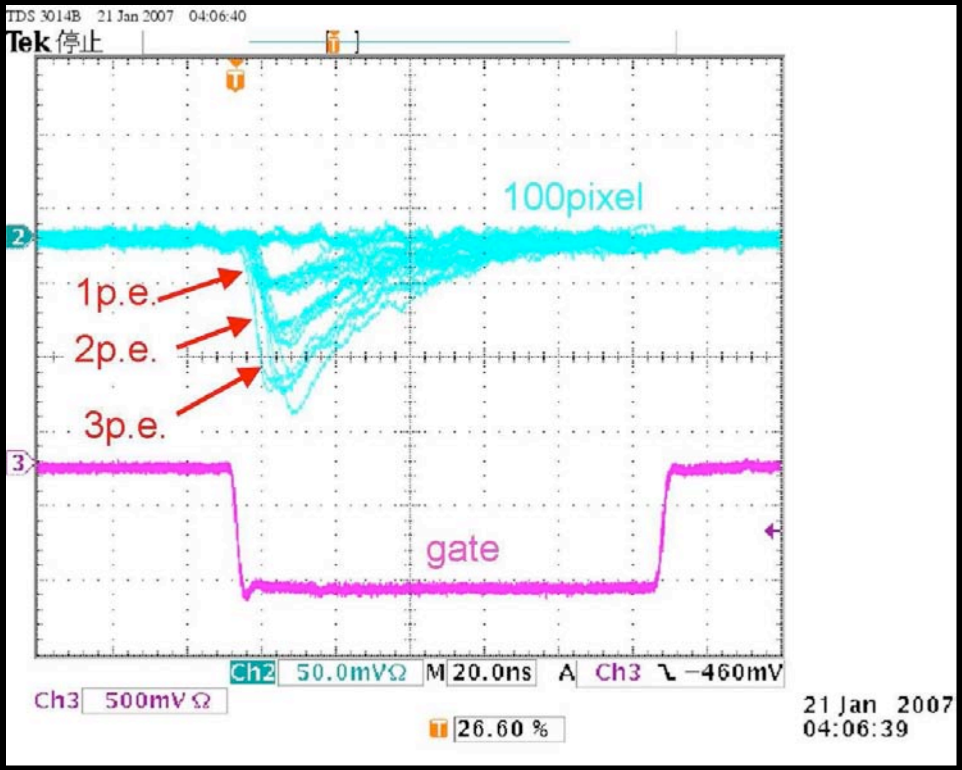
Operation of Multi-pixel Geiger-mode APDs

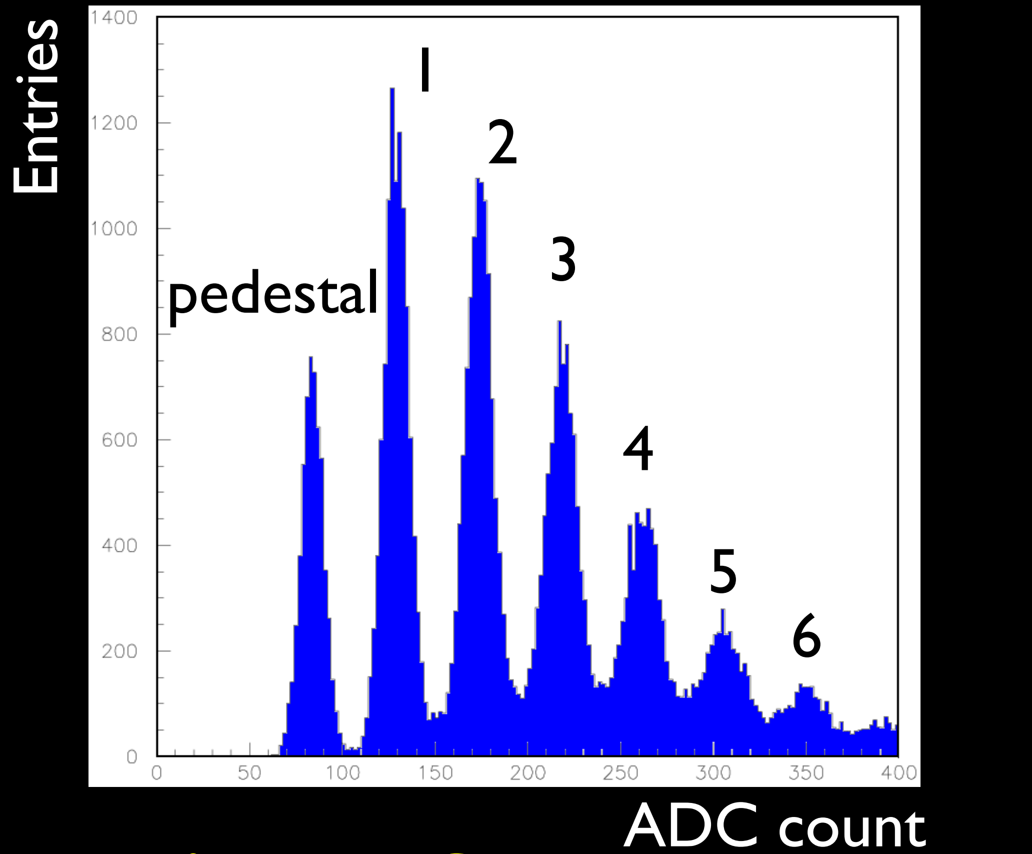
- All the pixels are connected in parallel
  - Taking sum of all pixels, one can know how many pixels are fired ∝ how many photons are incident !





Output from Multi-pixel Geiger-mode APD





Clear separation of 1,2,3... photoelectron (p.e.) peaks!

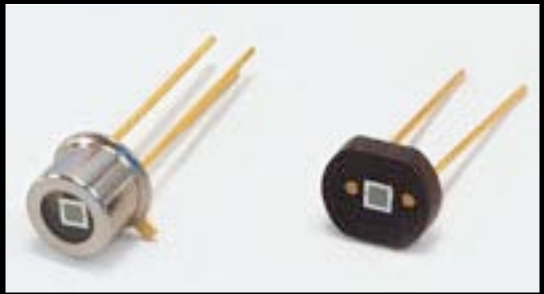
[@ room temperature]

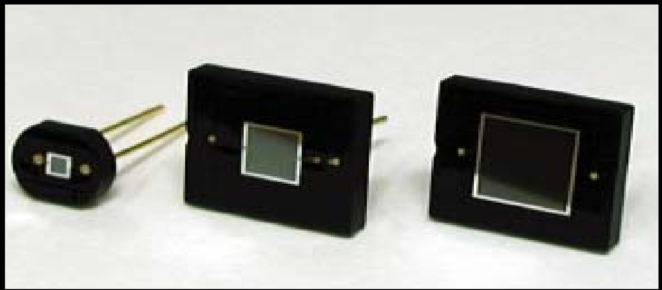
Comparison of photo-sensors

	PMT	APD	`SiPM'
Gain	10^6-10^7	~100	10^5-10^6
Operation voltage(V)	1-2k	300-500	<100
Active area	~>100cm^2	~10mm^2	~1mm^2
Dark count (Hz)	<1k		0.1-1M
Photon detection efficiency (blue-green)	~15%	75-80%	20-40%
Magnetic field	x	o	o

MPPC by Hamamatsu

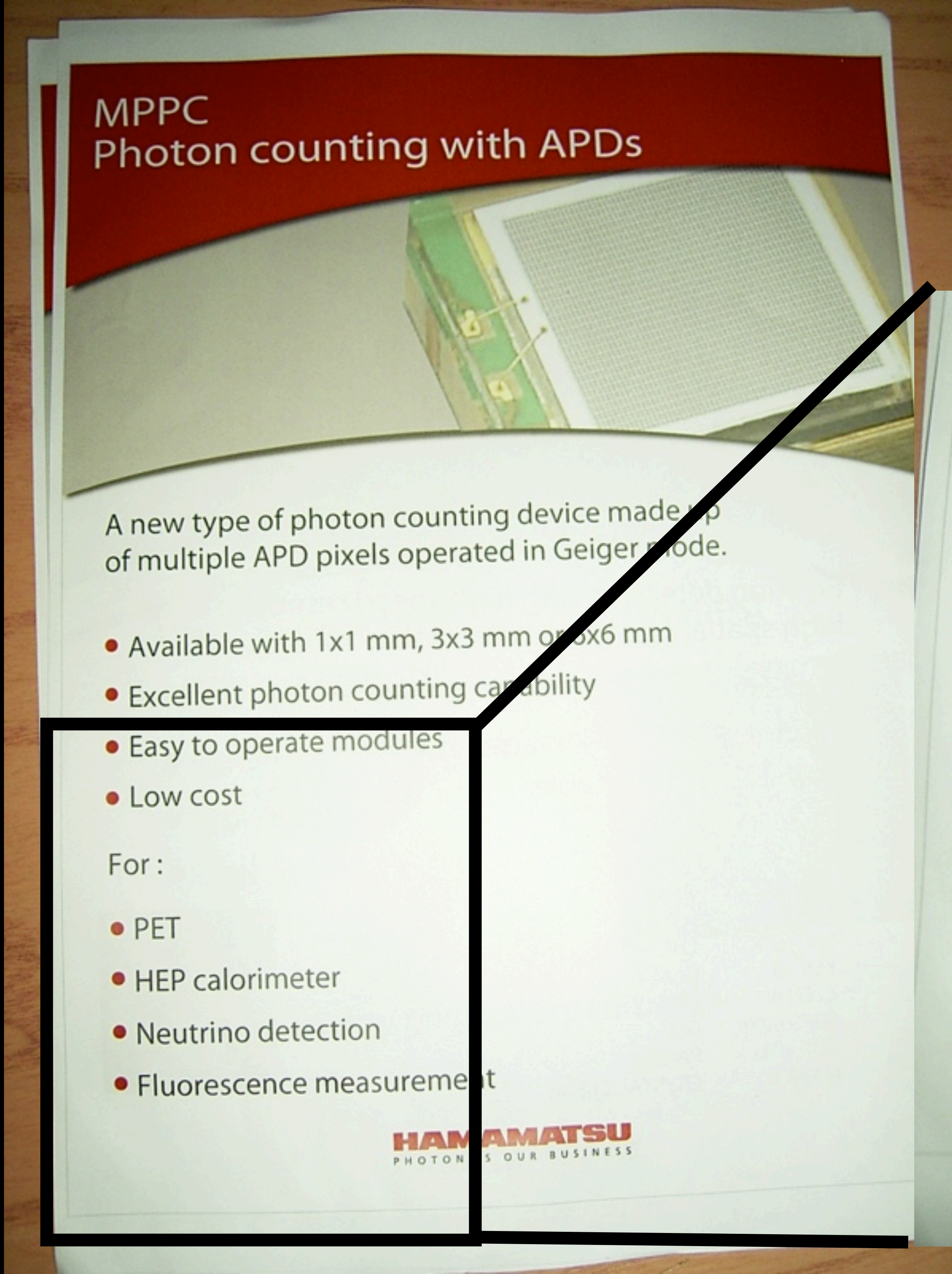
- Structure based on CMS-APD
- Currently availabel:
  - 1x1mm^2 or 3x3mm^2 active area
  - 100/50/25 μm pixel pitch
  - Metal or ceramic package
- In future..
  - Larger area (array)
  - More variations of package

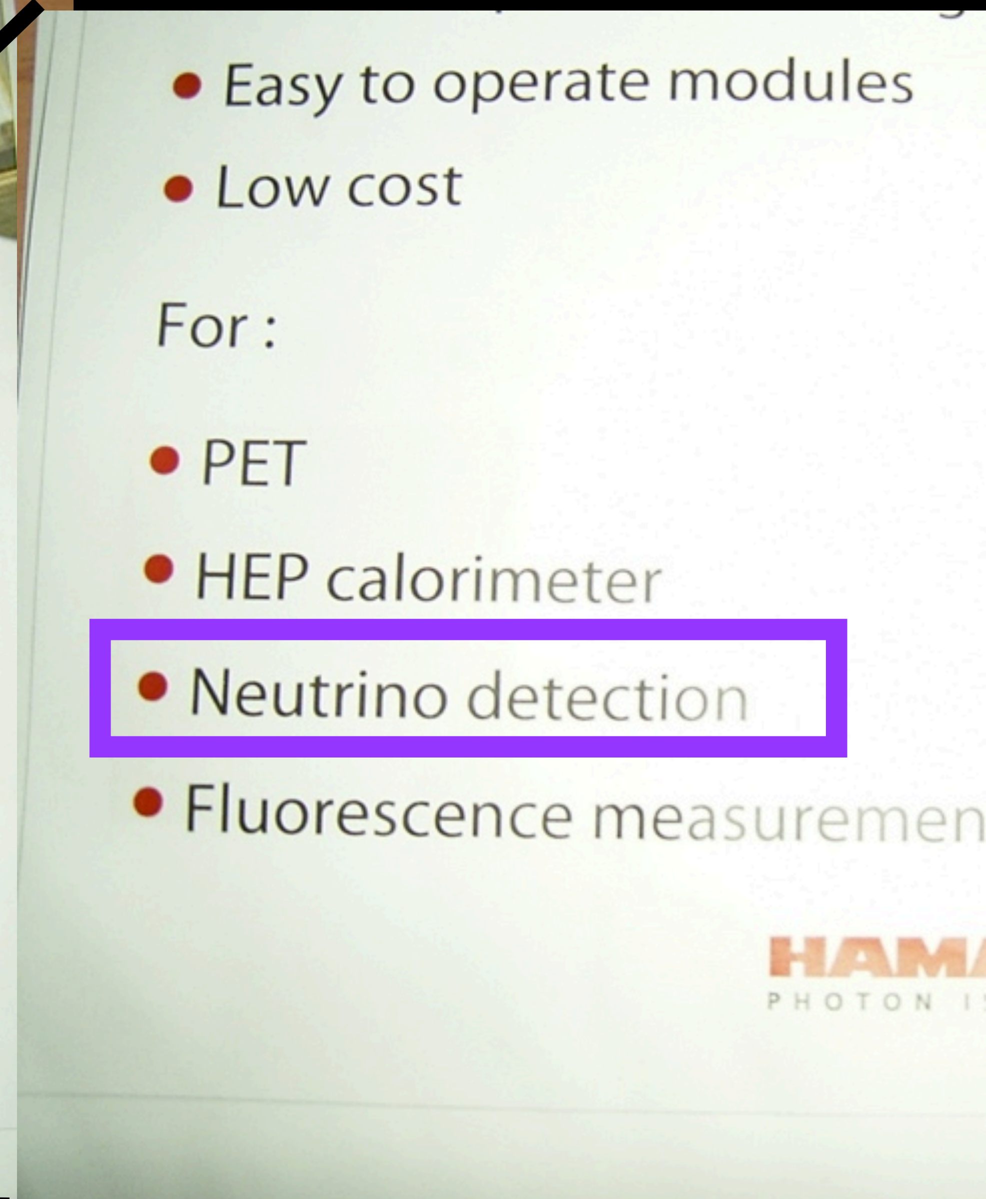




Selected by T2K in Aug. 2005

MPPC is for neutrino detection!



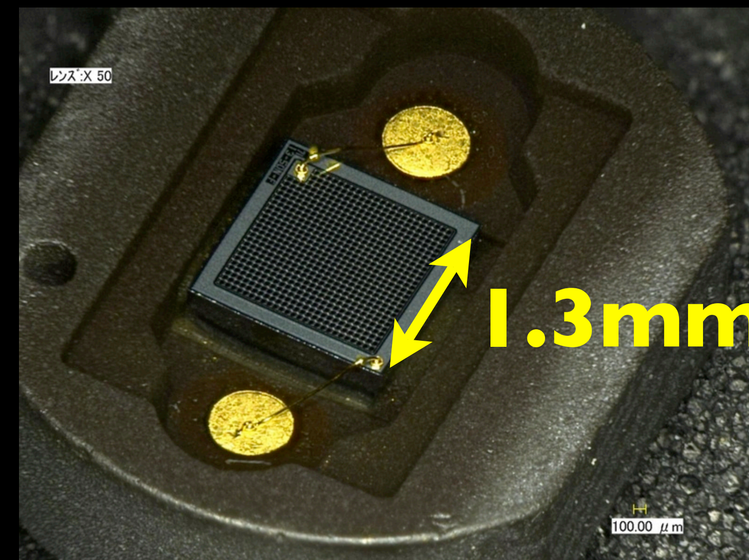


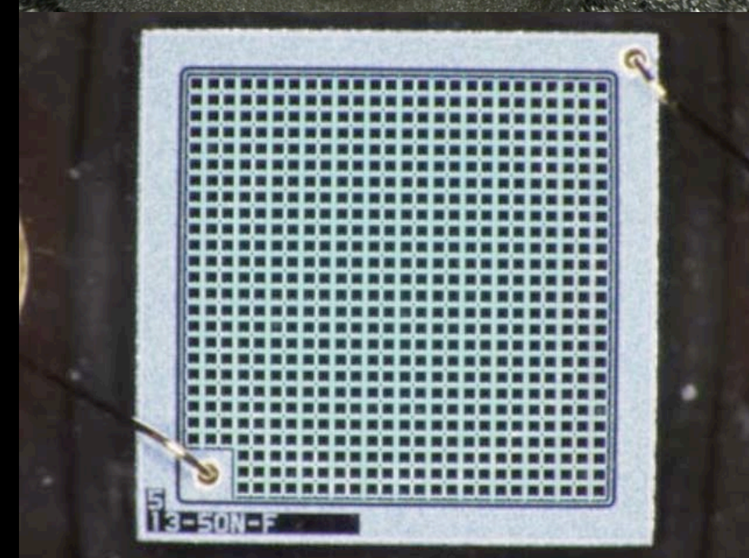
MPPC Spec for T2K

Item	Spec
Active area	$1.3\times1.3mm^2$
Pixel size	$50\times50\mu m^2$
Number of pixels	667
Operation voltage	70V (typ.)
Photon detection eff. @ 550nm	>15%
Dark count (gain=7.5×10^5)	<1.35Mcps(0.5pe) <0.135Mcps(1.5pe)
Number of device	~60,000
Price (if order 60,000)	¥1900/pcs.

S10362-13-050C

Specially developed for T2K



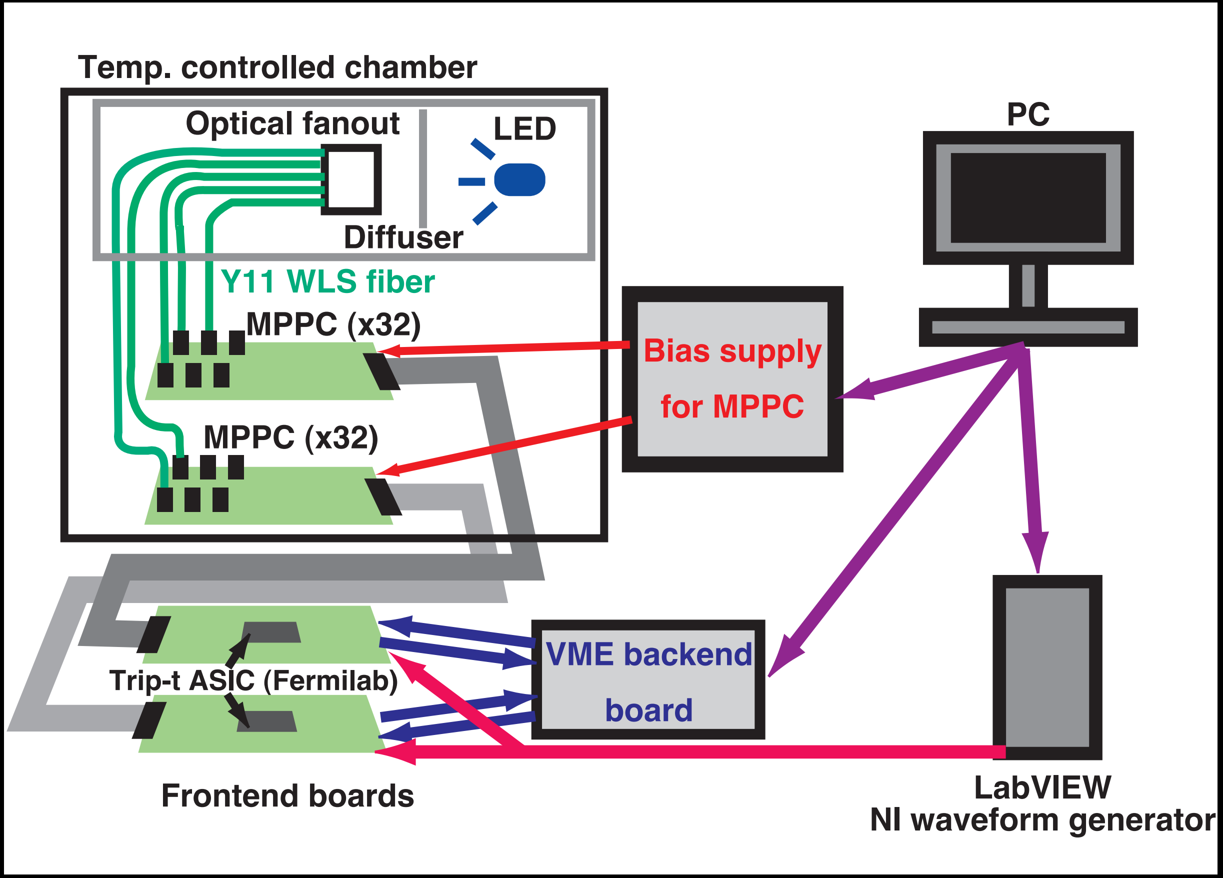


MPPC performance

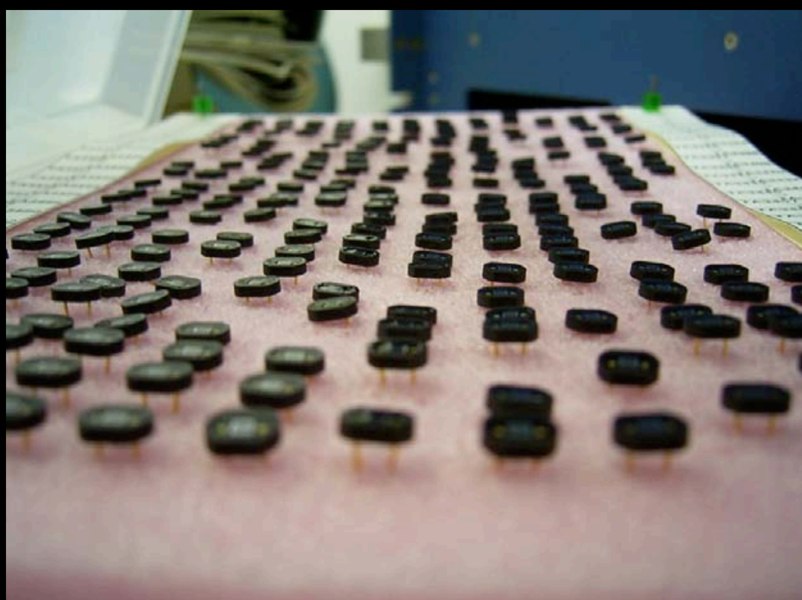
Gain
Noise
Photon detection efficiency
Cross-talk/afterpulse
Light yield with scintillator

Measurement setup

- Measurement of charge with
  - Three temperatures (15,20,25°C)
  - 0.1V step scan
  - With and without light source (pulse LED +WLS fiber)
- 64 MPPCs simultaneously
- Fully automated



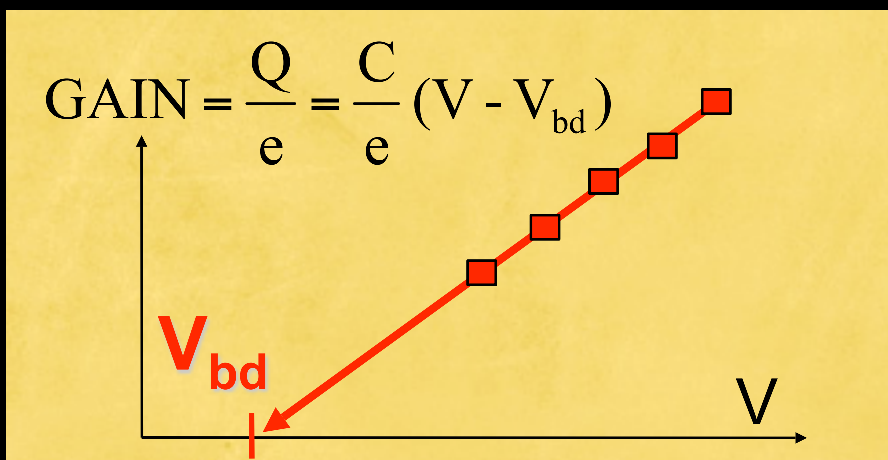
- One measurement = 1.5 hours
- 6 measurements (384 MPPCs) / day possible (with our hard-working students)
- ~10,000 MPPCs tested at Kyoto. (15,000 by the end of July)

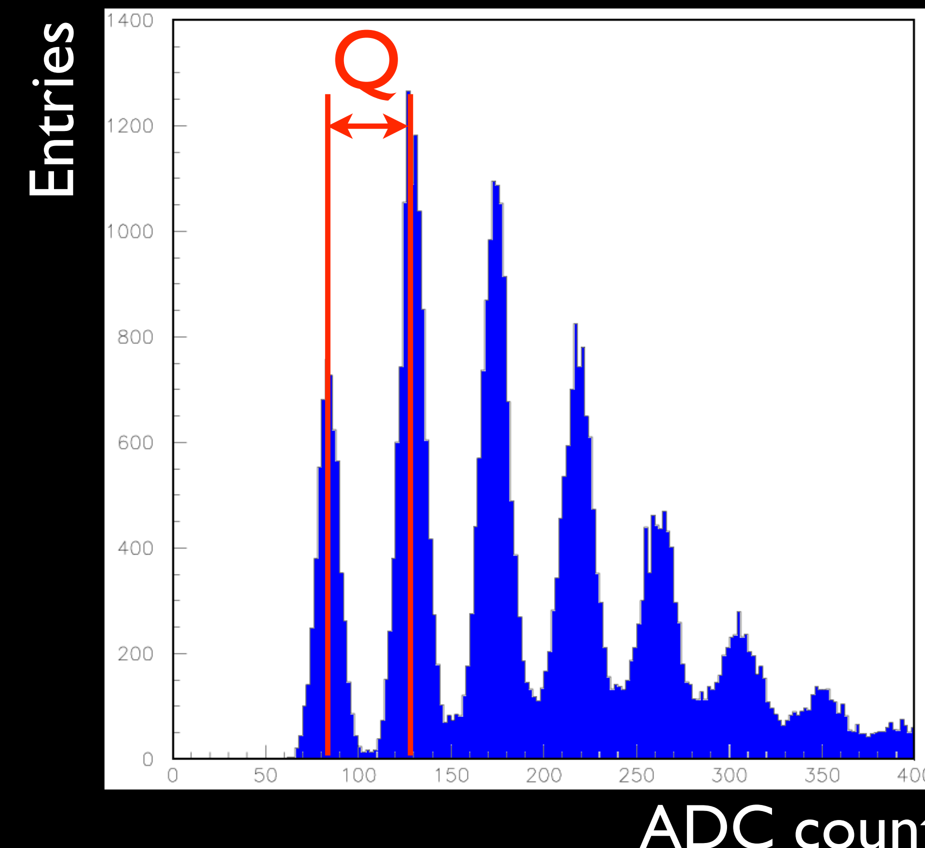


~30,000 MPPCs shipped (incl. other countries)

Gain&V_{bd}

- Gain of MPPC can be measured with well-separated p.e. peaks: Gain=Q/e



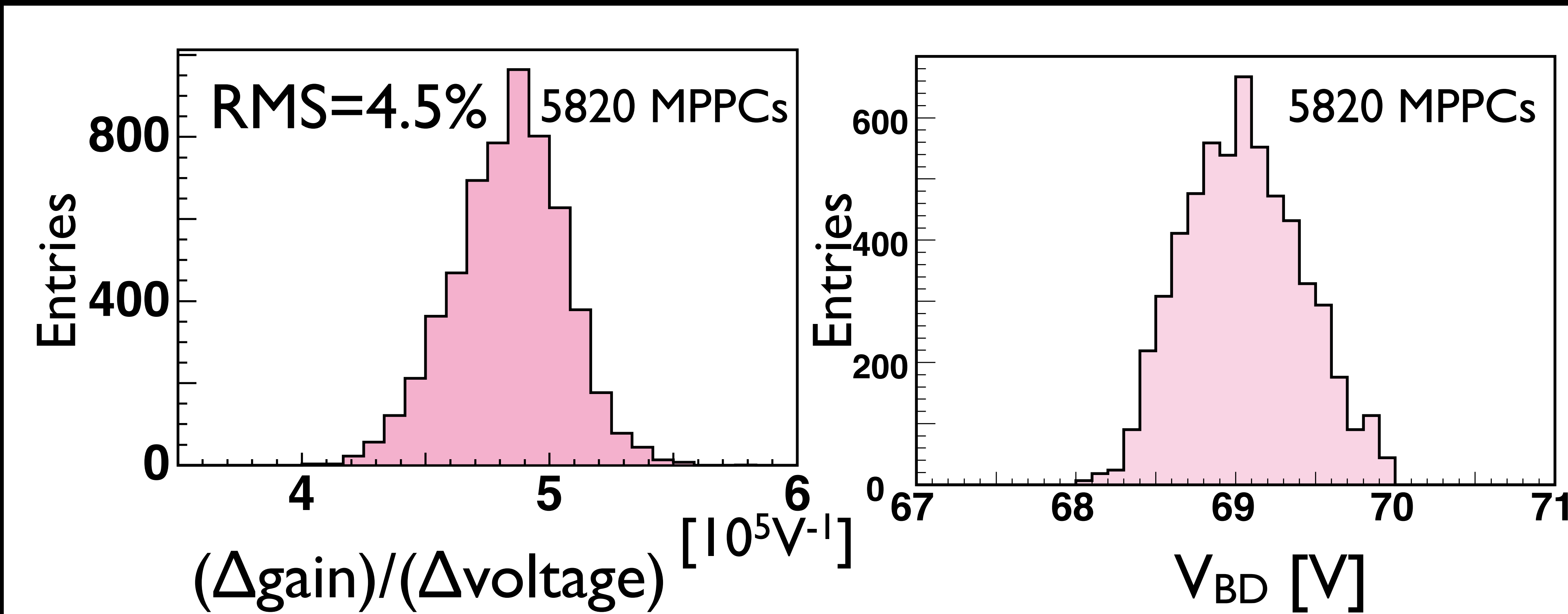


- Using linear relation, breakdown voltage (V_{bd}) also derived

Gain/V_{BD} for T2K-MPPC

For 5820 MPPCs

25°C

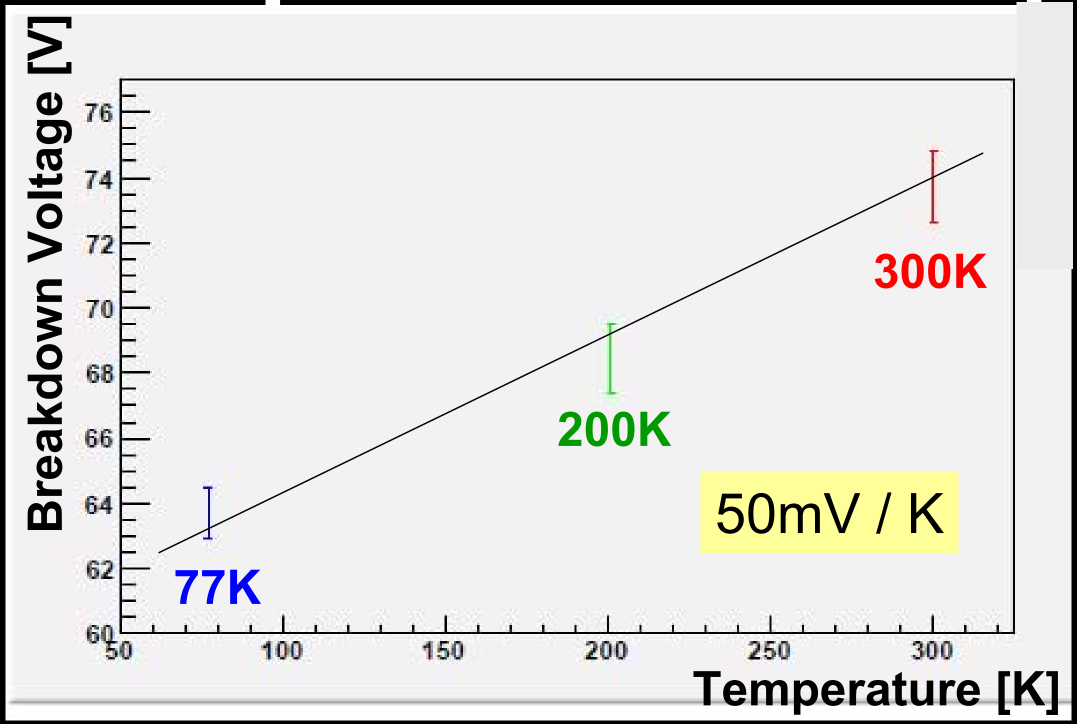


5×10^5 with $\Delta V = 1V$

*calibration of scale under re-evaluation

High gain,
Excellent device uniformity.

Temperature dependence



H. Otono @PD07

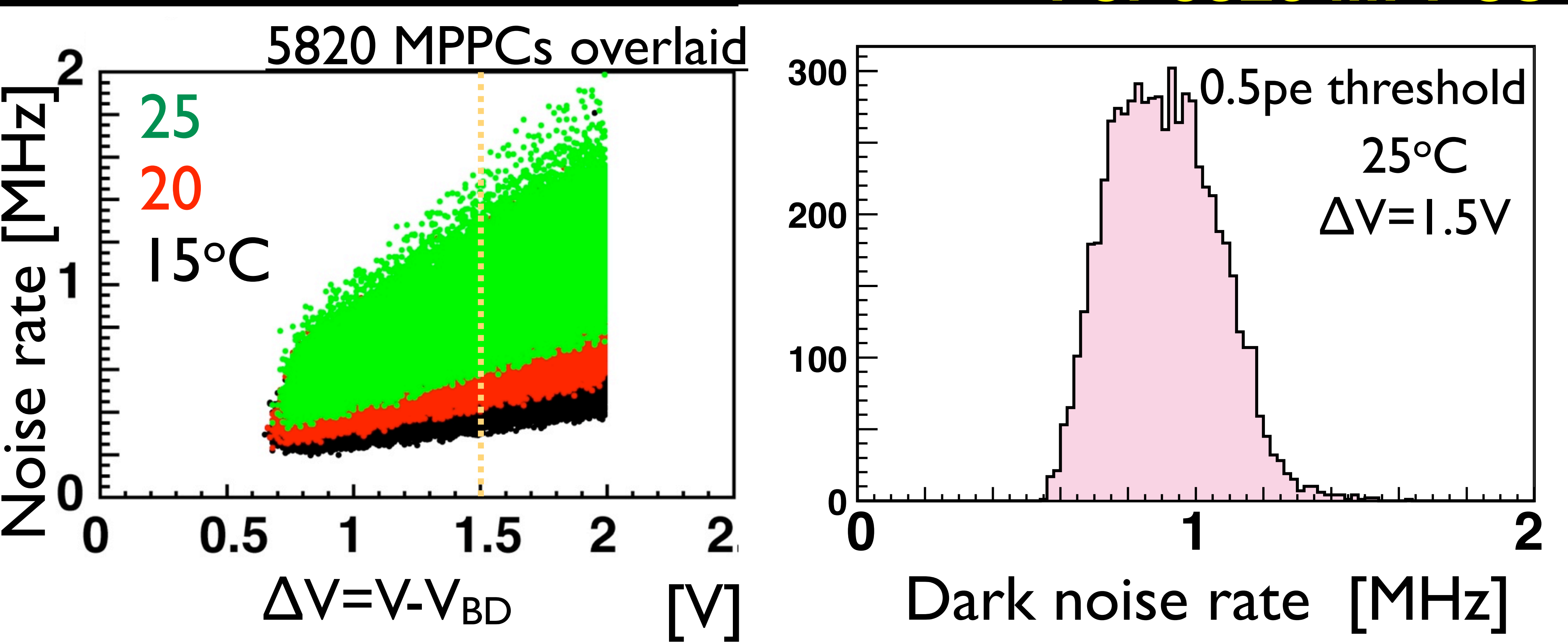
1600 pixel

(Also many measurements around room temperature)

- Many parameters of MPPC are known to depend on 'over-voltage' $\Delta V \equiv V - V_{bd}$
- V_{bd} linearly depends on temperature dVbd/dT~-50mV/K

Dark noise

For 5820 MPPCs



Device/temperature dependence seen

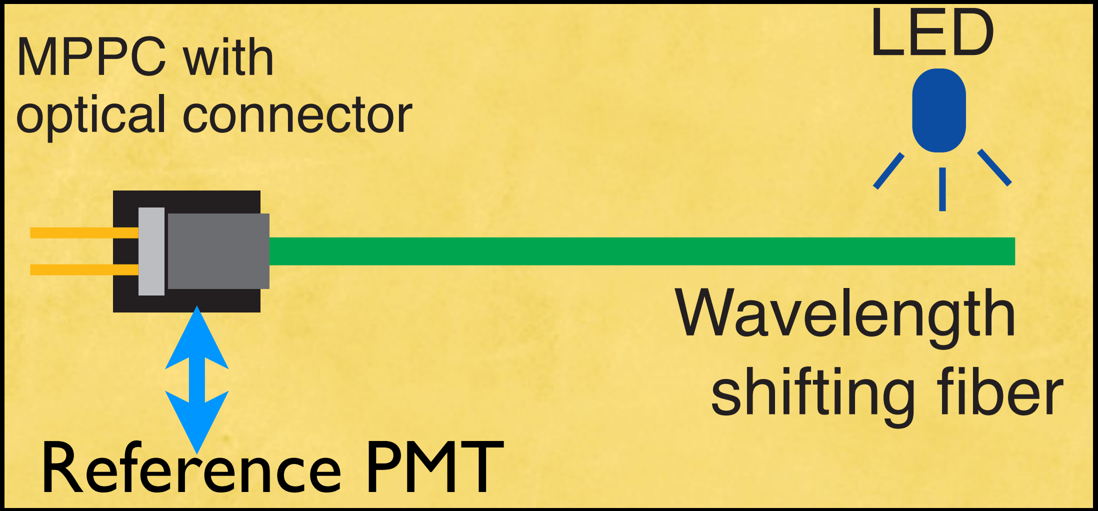
Satisfy our requirements

Photon Detection Efficiency (PDE)

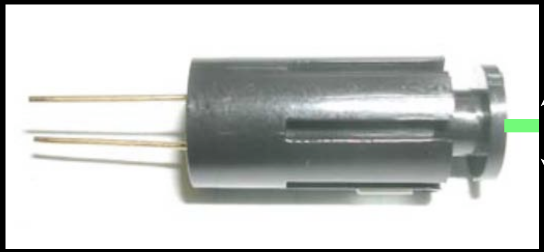
- Probability of detecting single photon entering the surface of device
- Three major components:
  - Geometrical efficiency (~60% for 50μm pixel MPPC)
  - Quantum efficiency
  - Probability to trigger Geiger avalanche
    - Depends on over-voltage.

Photodetection efficiency (PDE)

- Relative to a reference PMT (QE~15% for green light by catalogue).
- Number of p.e. derived from fraction of pedestal events and Poisson stat.



Optical connector developed to ensure good contact.



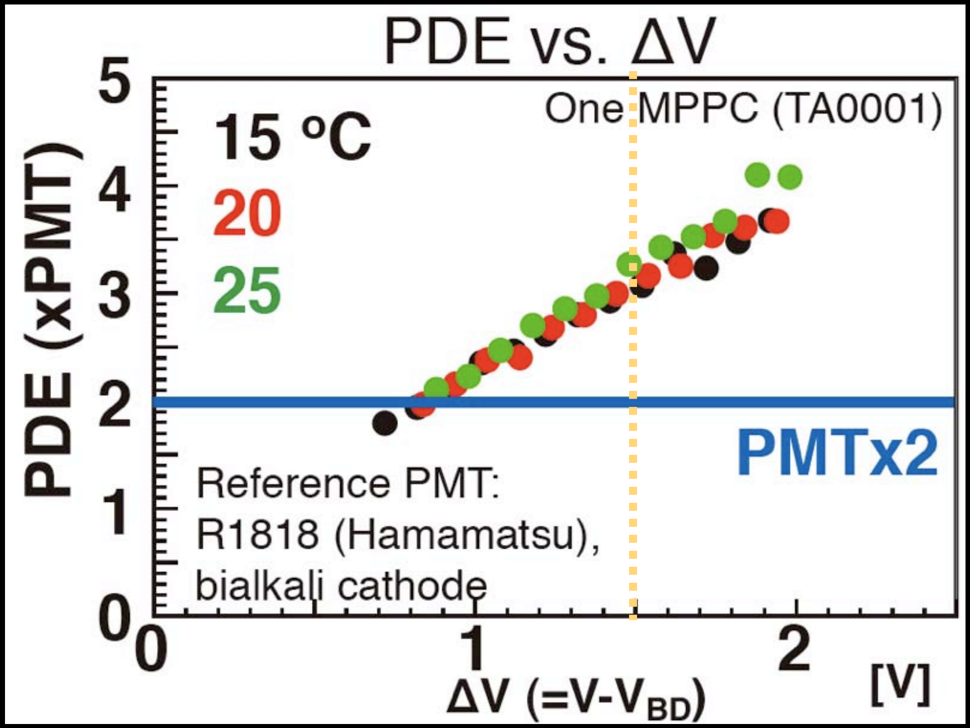
8mm

18mm

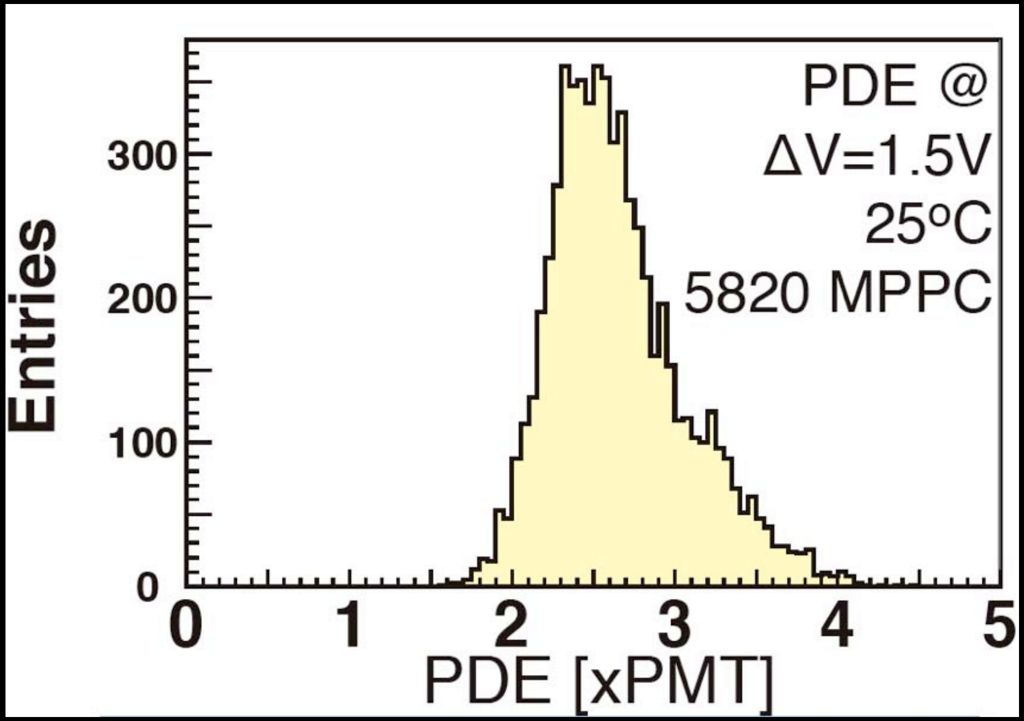
MPPC holder

Fiber glued to this piece

PDE



Temp. dependence is small (except effect from V_{BD})



Excellent PDE.
(loss at coupling included)

Systematics in calibration being checked

Optical cross-talk

- Photons created during avalanche can enter neighboring pixels
  - They can trigger additional avalanche → optical cross-talk
- Increase excess noise factor

After-pulse

- Carrier trapped in impurity state may be released after certain time and cause delayed avalanche in the same pixel, or after-pulse
- Also increase excess-noise factor

Measurement of cross-talk and after-pulse

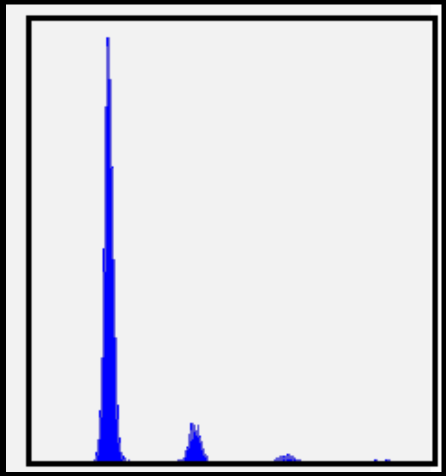
Charge (ADC) distribution

Fraction of pedestal events

Poisson statistics

Estimate `true' 1p.e. events

Comparison

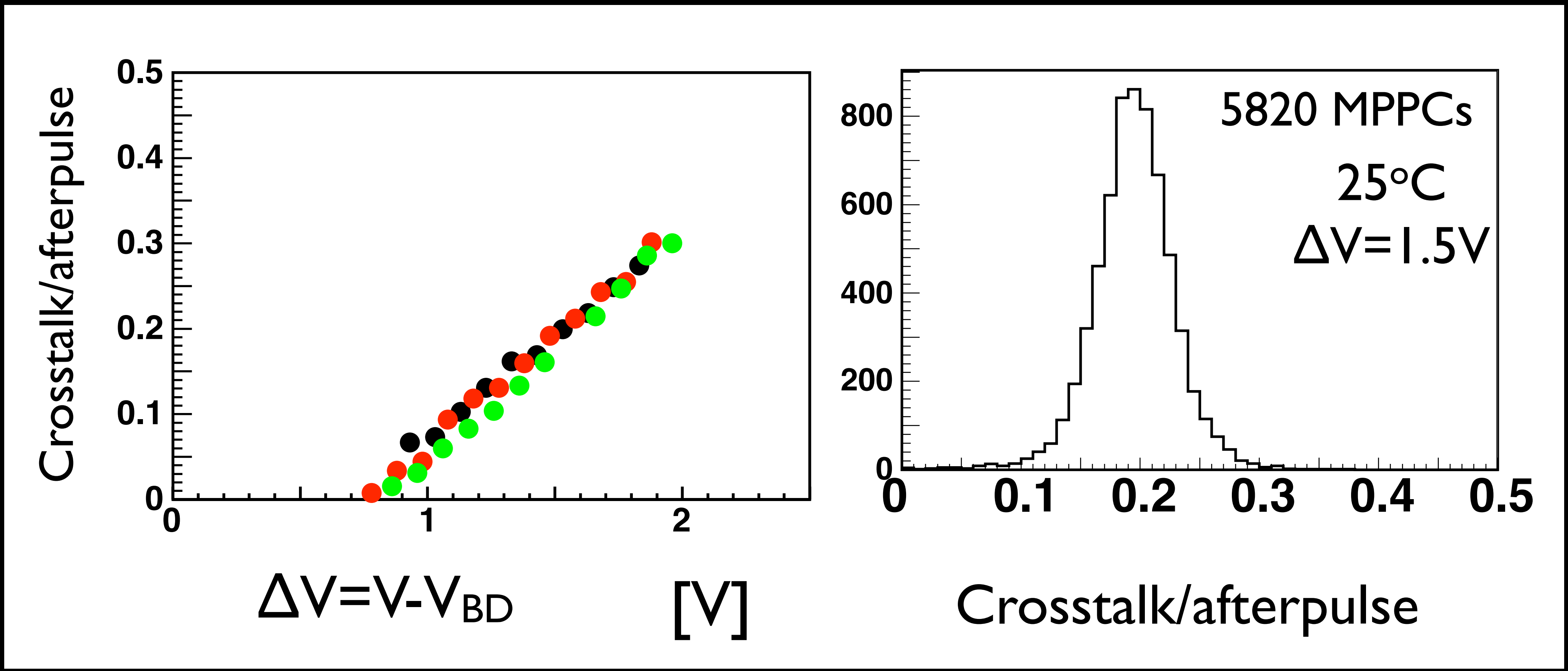


Observed 1p.e. events

Probability of cross-talk&after-pulse

*Only combined probability can be measured with this technique.

Crosstalk+afterpulse

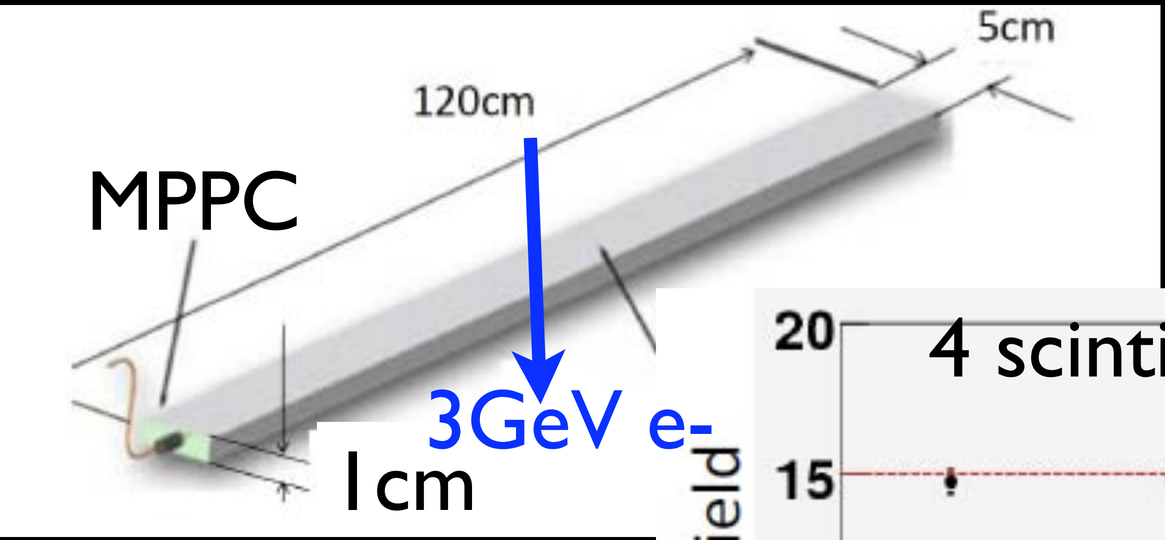


200ns gate

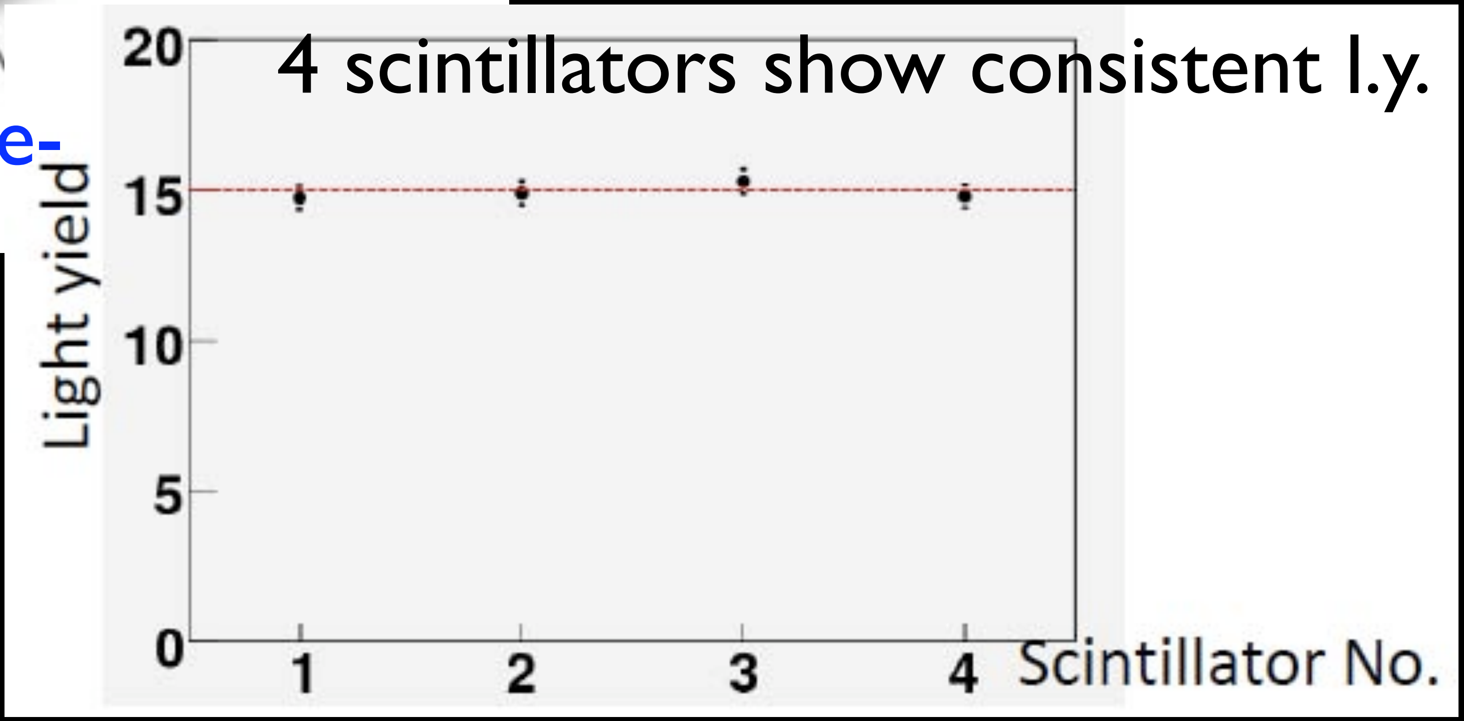
Tolerable level for our use.
Suppression under study for other uses.

Light yield with scintillator

~25°C
ΔV=1.5V



Scintillator for on-axis detector



- ~15p.e. with WLS fiber (Y11, 1mm dia.) and real scintillator (produced at Fermilab).

Summary of performance

	ΔV=1.0V	ΔV=1.5V
Gain	5×10^5	8×10^5
Noise	0.4-0.8	0.6-1.2
PDE	~1.5xPMT	~2.5xPMT
Cross-talk/ afterpulse	~0.05	~0.2

Operation voltage: ΔV=1~1.5V,
depending on detector functionality

Summary

- We have developed a new photodetector, MPPC, for T2K experiment.
  - Excellent performance
  - Established WLS readout
  - Mass production/testing in progress
- T2K will start from the next year. Stay tuned!

Grazie mille!

References

- M. Taguchi, Master's thesis (written in English) http://www-he.scphys.kyoto-u.ac.jp/thesis/master/taguchi_mt.pdf
- M. Yokoyama et al., "Development of MPPC," SNIC06
- S. Gomi et al., "Development of MPPC," IEEE NSS 2006
- S. Gomi et al., NIM A581, 427 (2007)
- Presentations/proceedings at PD07 workshop at Kobe http://www-conf.kek.jp/PD07/

Backup

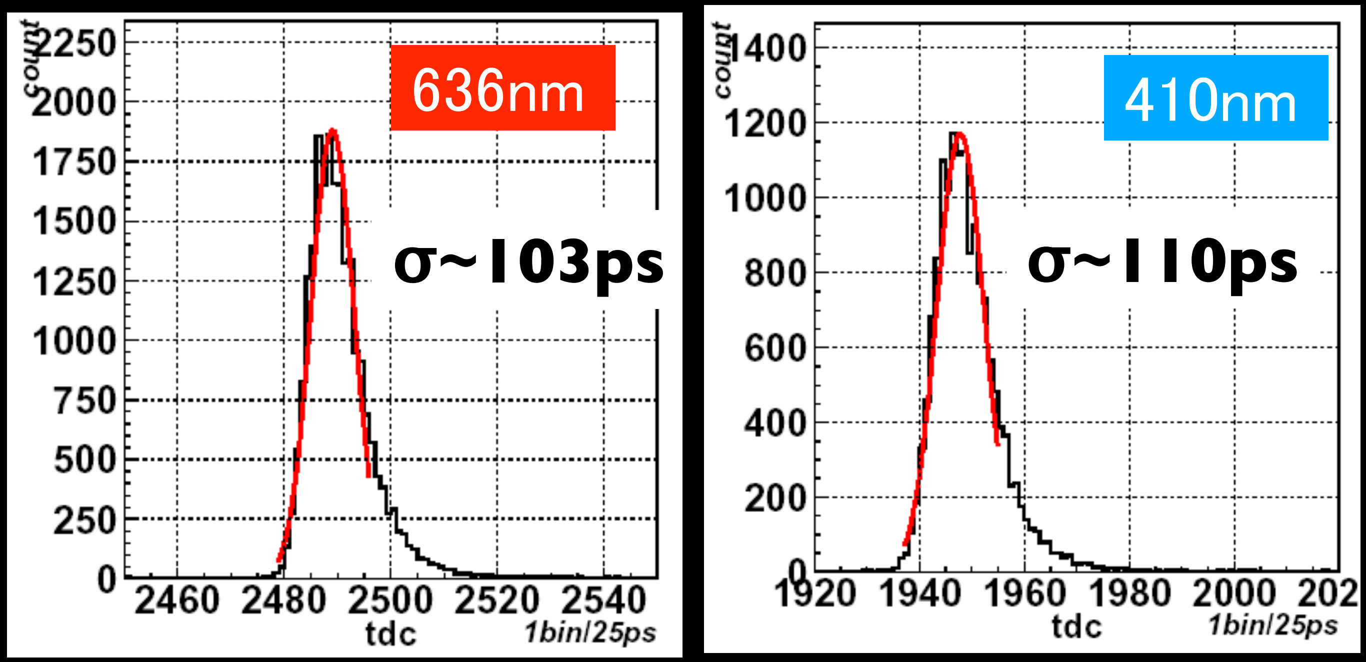
Device stability

- Long term / High temp tests at INR (Oct. 07~)
  - High temperature test (20 MPPCs)
    - Kept at ~80°C for 31-days with biased
    - One ‘died’ 1 month after heating (reason not known yet…)
  - Other 19 (+ 10 non-heated) stable till now
- High temperature test at LSU
  - 3 MPPCs heated to 80°C for ~14 hours/day
  - Stable for ~200 days

Timing resolution

Measured w/ pulse laser
636 / 410nm

Sample MPPC
Bias -71.5V
Threshold 0.5pe
Only Single photon data

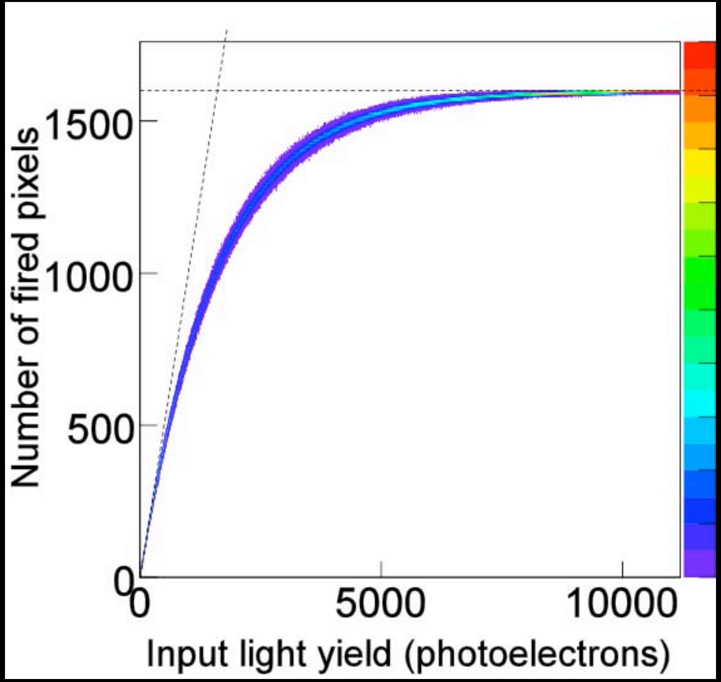


Time walk corrected.

T. Iijima @PD07

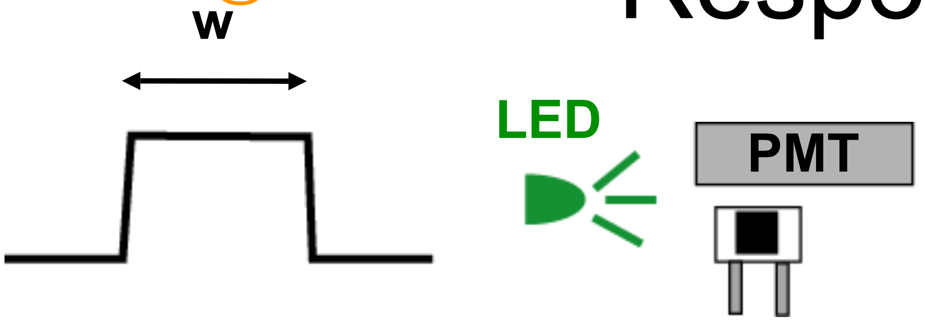
Dynamic range

- Intrinsically limited by finite number of pixels
  - Affected by cross-talk probability
  - Also depends on time structure of input photons

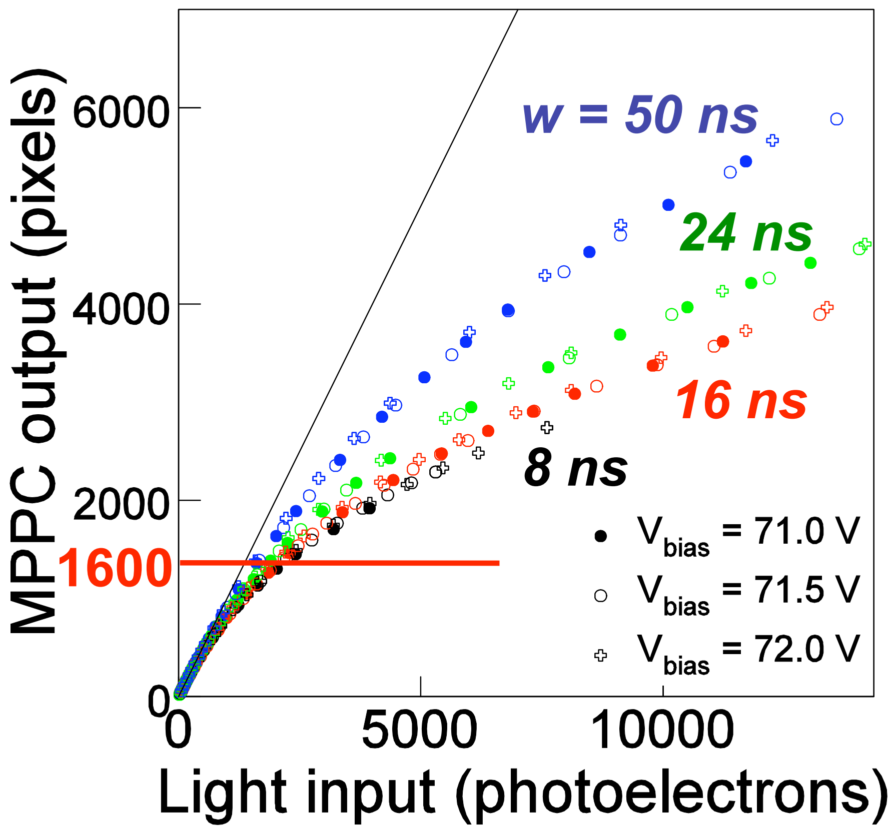


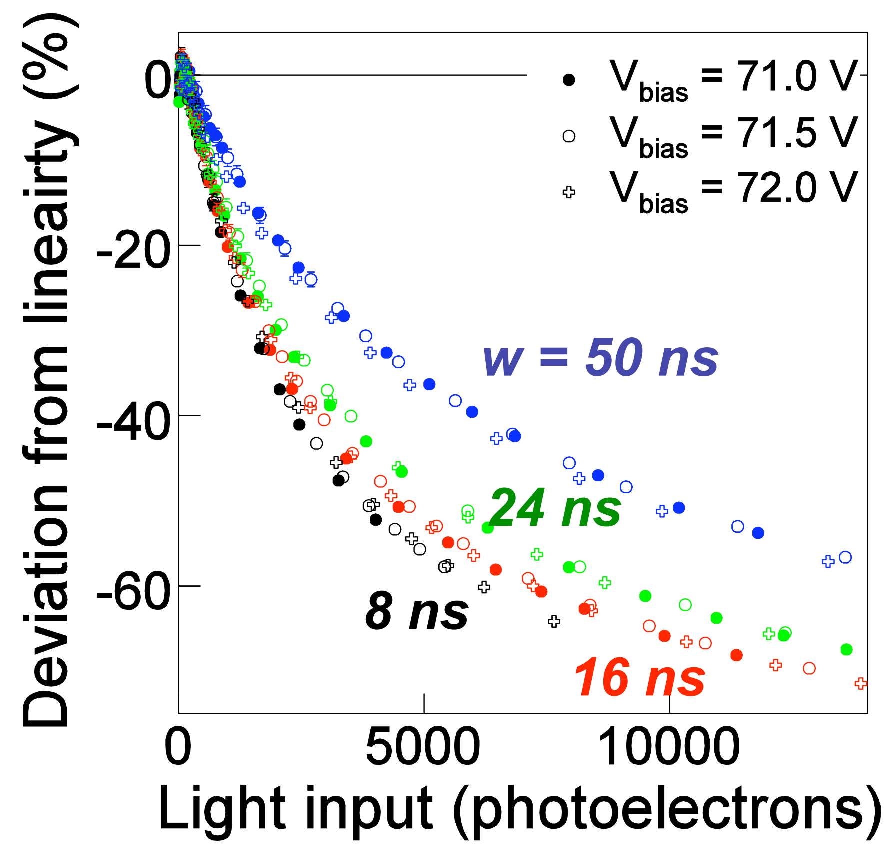
S.Uozumi @ PD07

Response Curve



Response curves taken with various width of LED light pulses.
(gate width = 100 ns)

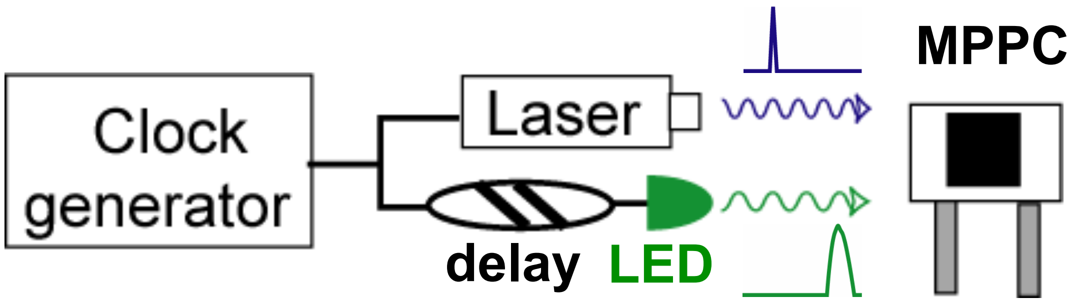




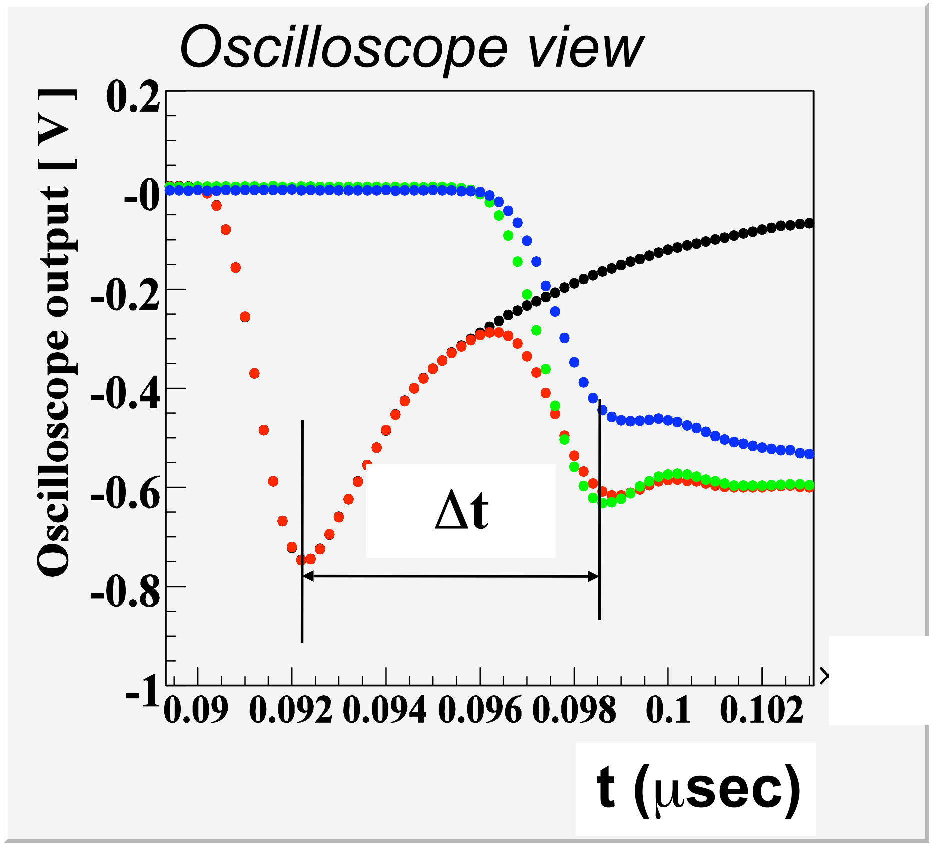
- **Dynamic range is enhanced with longer light pulse,**
- **Time structure of the light pulse gives large effects in non-linear region.**
- **No significant influence with changing bias voltage.**
- **Knowing time structure of scintillator light signal is crucial**
  -> study is ongoing.

Recovery Time Measurement

S.Uozumi @ PD07



- Inject blight laser pulse (width=52 ps) into the MPPC
- After delay of Δt, inject blight LED light pulse, and measure MPPC outpu for the LED pulse.
- Compare the MPPC output for the LED pulse with and without the first laser pulse.

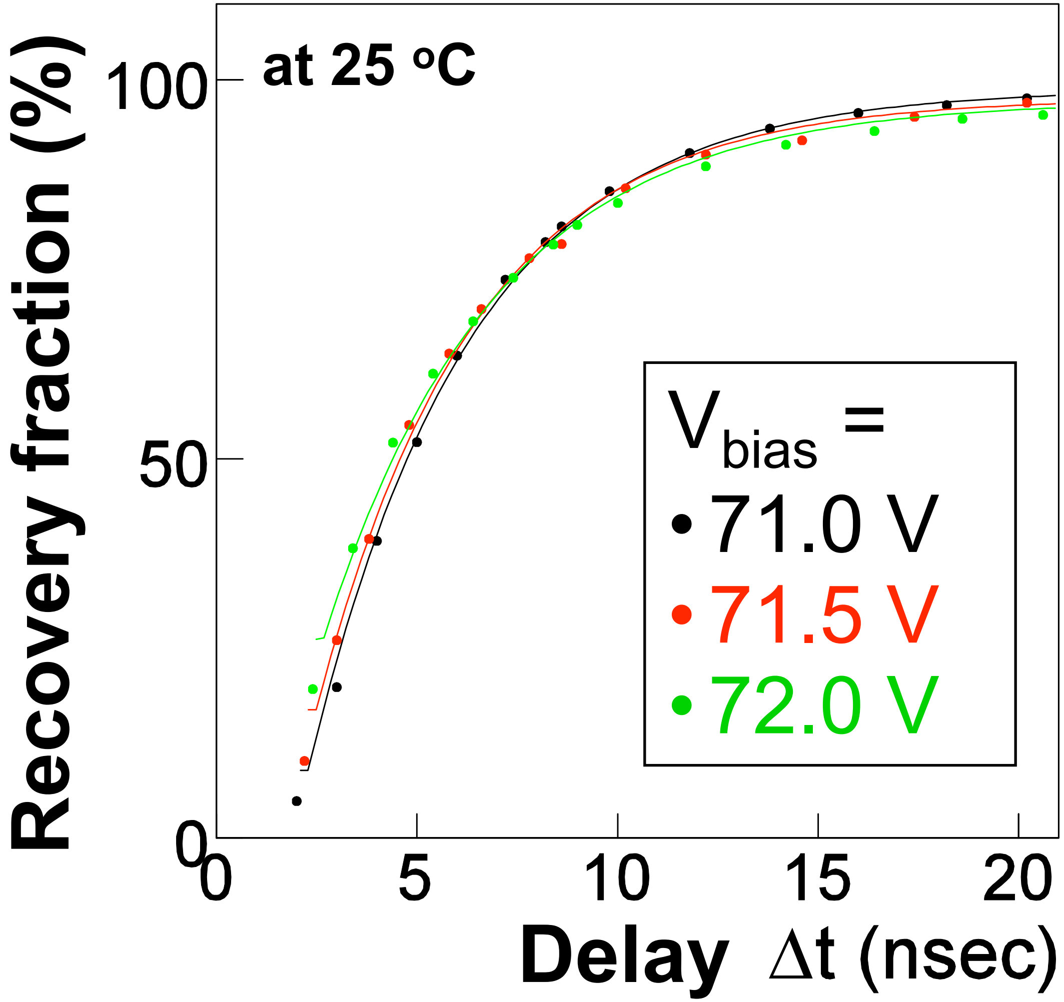


Black … MPPC output for Laser pulse
Green … MPPC output for LED pulse
Red … Laser + LED
Blue … (Laser+LED) - Laser

Ratio of Blue / Green shows recovery fraction.

S.Uozumi @ PD07

Recovery Time Result



The curve is fitted by a function

$$f(\Delta t) = A(1 - e^{-(\Delta t - t_D)/\tau})$$

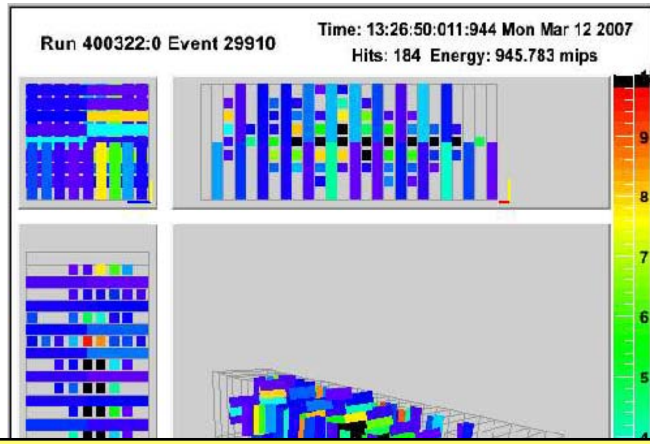
t_D : dead time

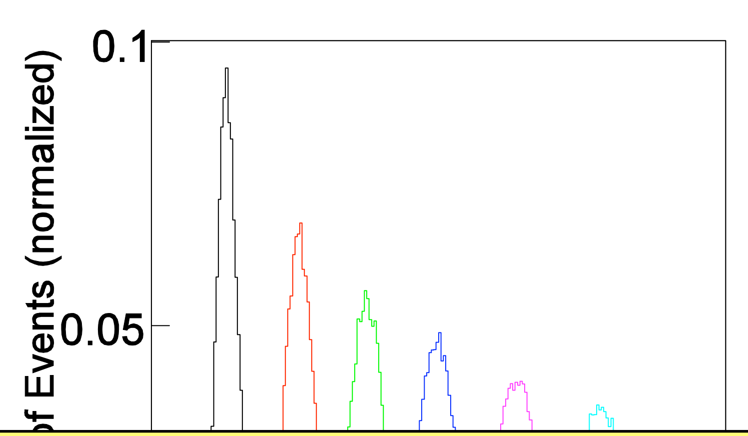
τ : recovery time

V_{bias} (V)	τ (nsec)	t_D (nsec)
71.0	4.1 $\pm$ 0.1	1.9 $\pm$ 0.1
71.5	4.0 $\pm$ 0.1	1.7 $\pm$ 0.1
72.0	4.2 $\pm$ 0.1	1.3 $\pm$ 0.1

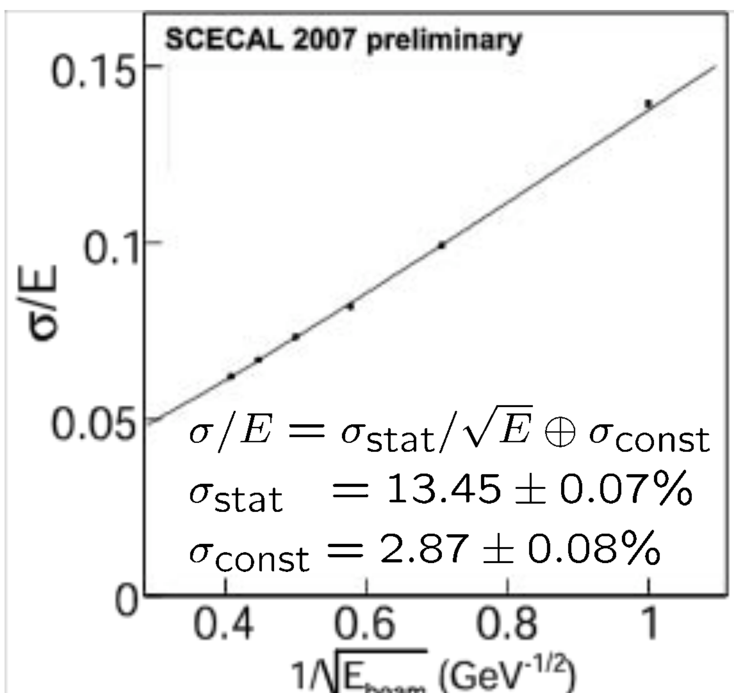
- Recovery time of the 1600-pixel MPPC ~ 4 ns.
- The shape does not depend on bias voltage.

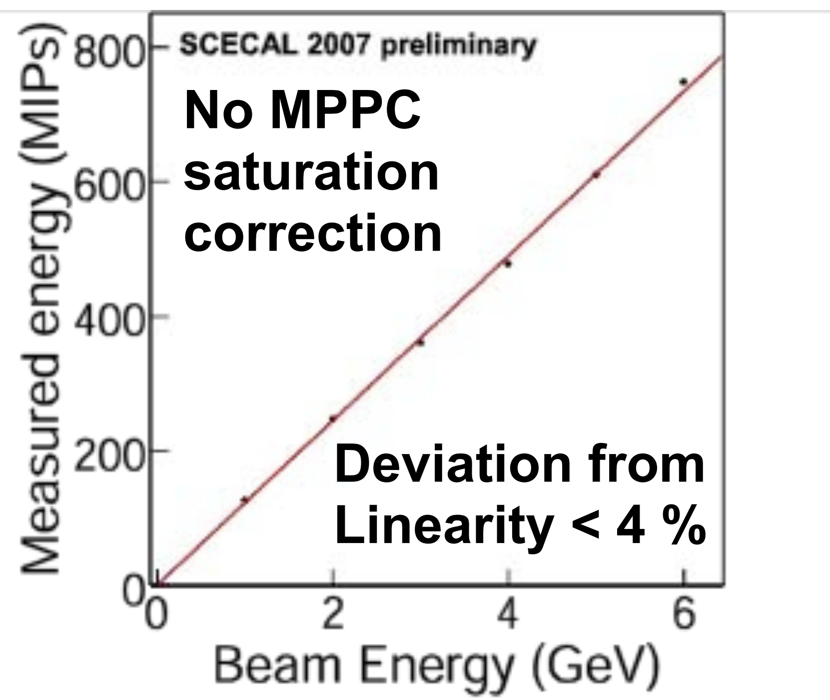
Results with tungsten absorber



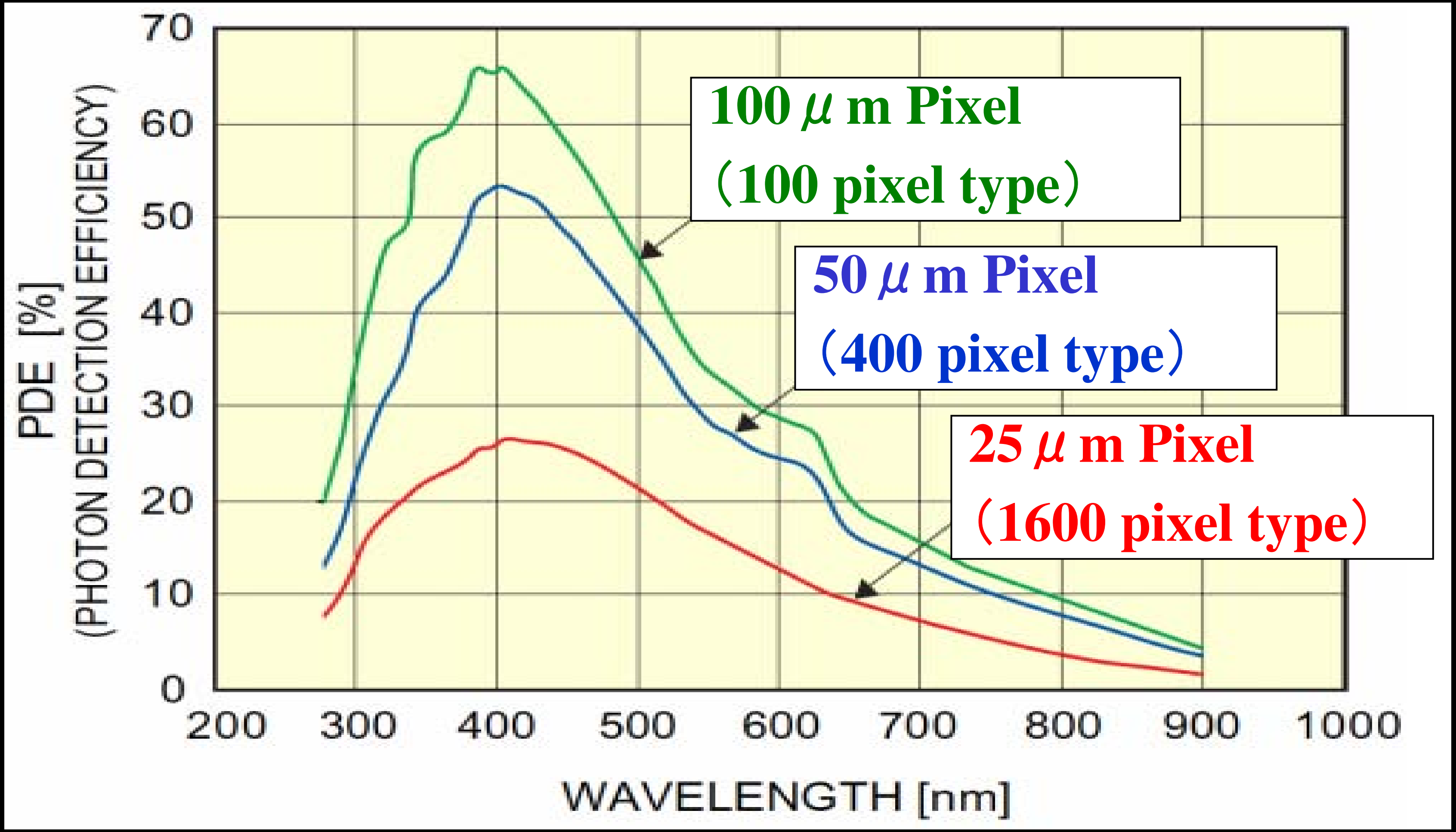


The calorimeter with the MPPC is working!
Dynamic range seems to be enhanced
(expect more study with higher beam energy in 2008).





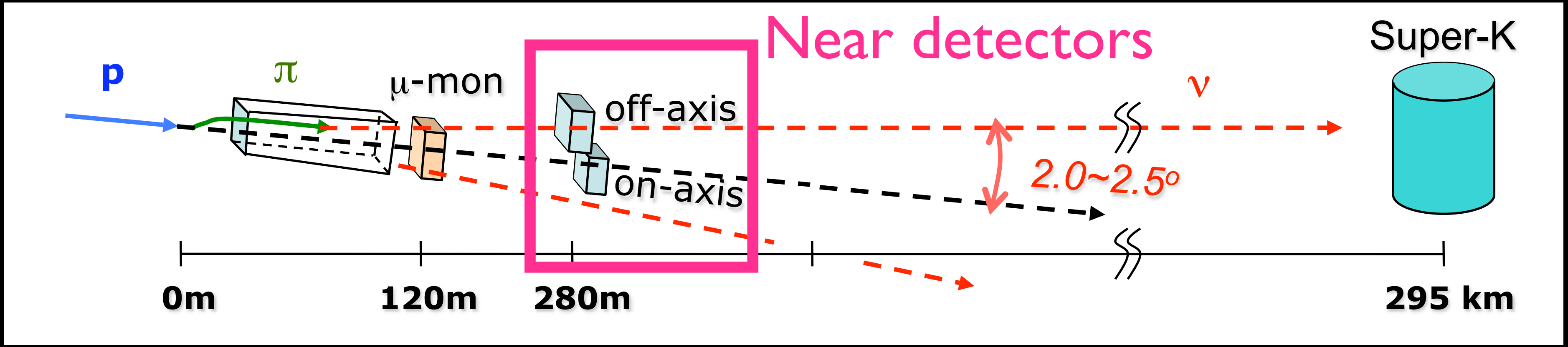
PDE from catalogue



* Measured with current:
includes effects from *cross-talk and after-pulse*.

Magnet transportation

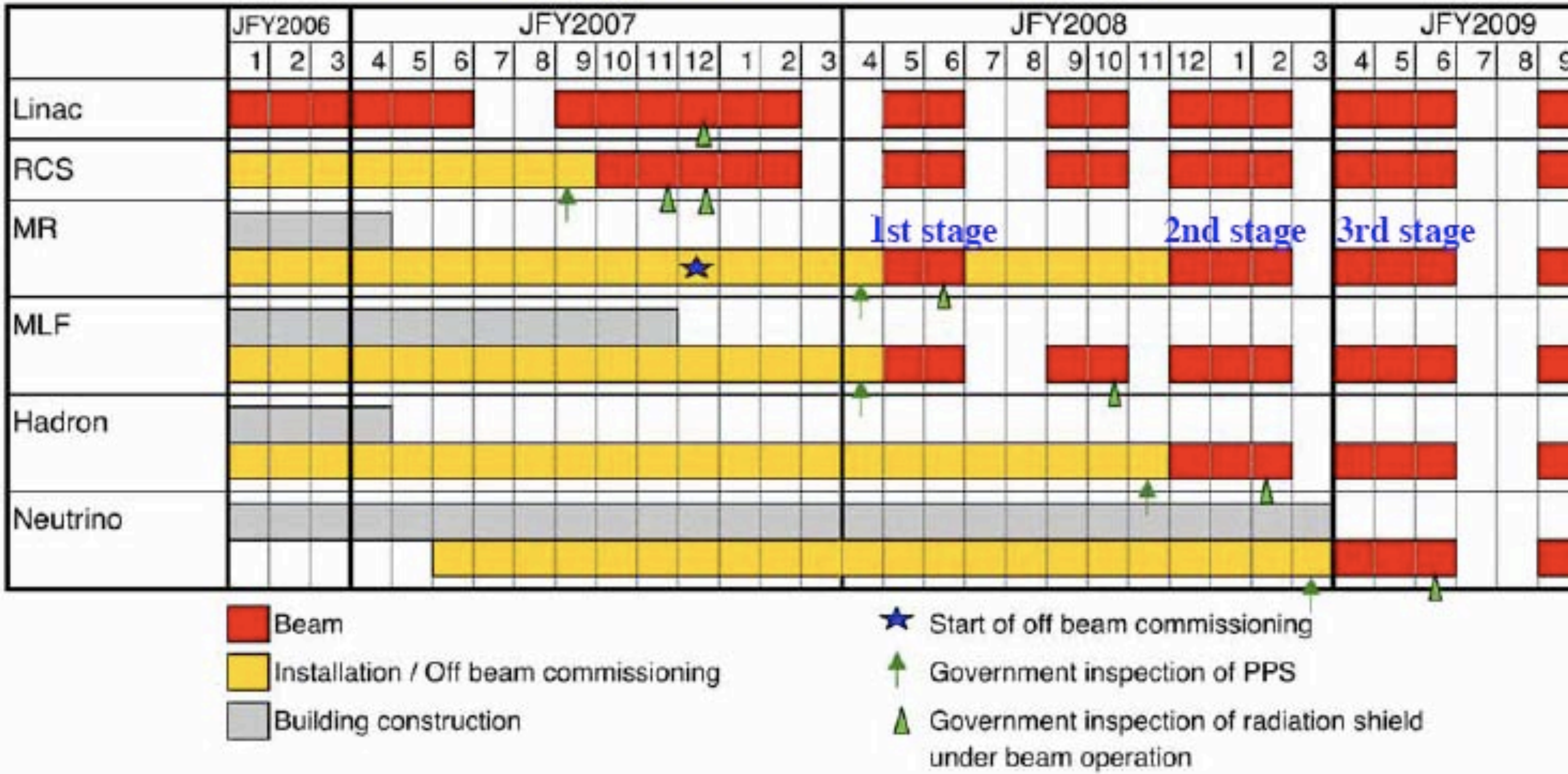
T2K exp. layout



- Intense ν beam via π decay ('superbeam')
  - ~5μsec 'spill', 0.2-0.3 Hz cycle
- Two-detector configuration:
  - Near detector at J-PARC site
  - Super-Kamiokande detector

} Comparison → ν oscillation study w/ small syst. error

Schedule of beam commissioning

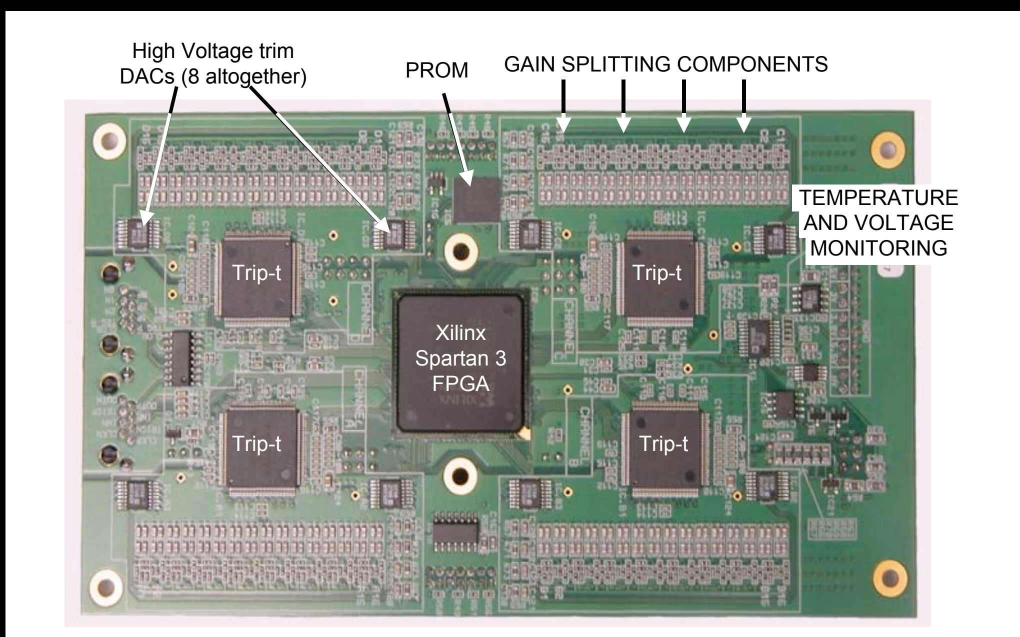


MR schedule

May 2008: MR (and MLF) beam commissioning starts.
July -Nov. 2008 : Installation of slow extraction devices, some fast extraction devices and neutrino beamline components.

Readout electronics

- Two options of readout ASIC
  - Trip-t (Fermilab) for INGRID/P0D/ECAL/SMRD
  - AFTER (Saclay) for FGD

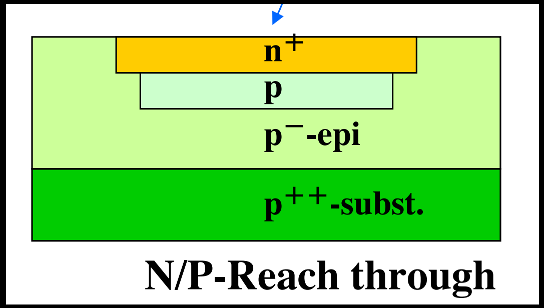


Trip-t frontend board developed in UK

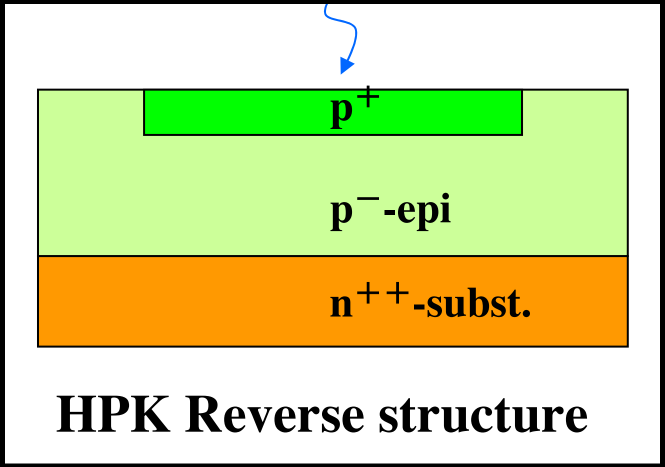
AFTER electronics by Saclay

MPPC structure

Usual device:
n+ on p/p-



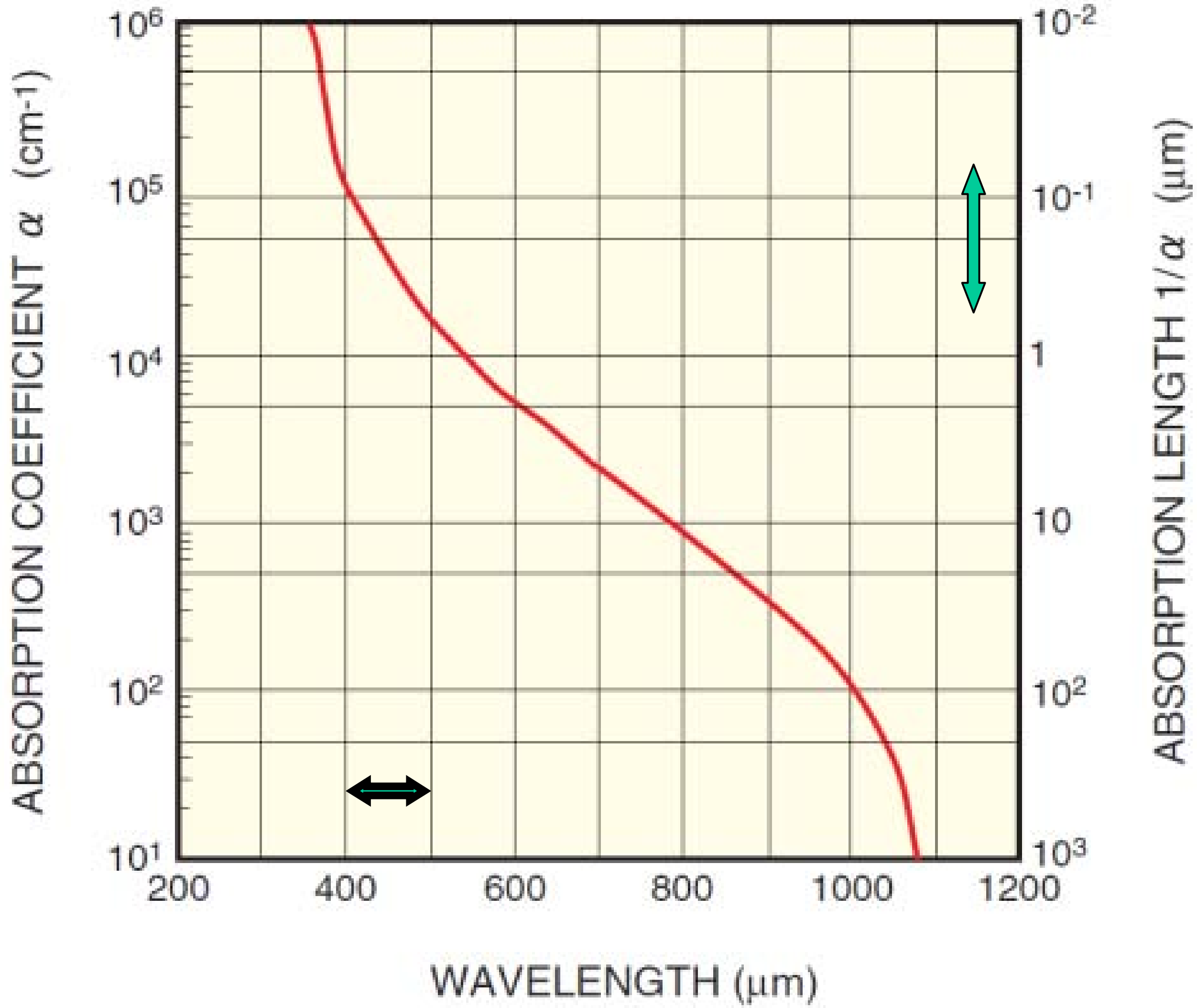
'Reverse structure': p+ on p- epi



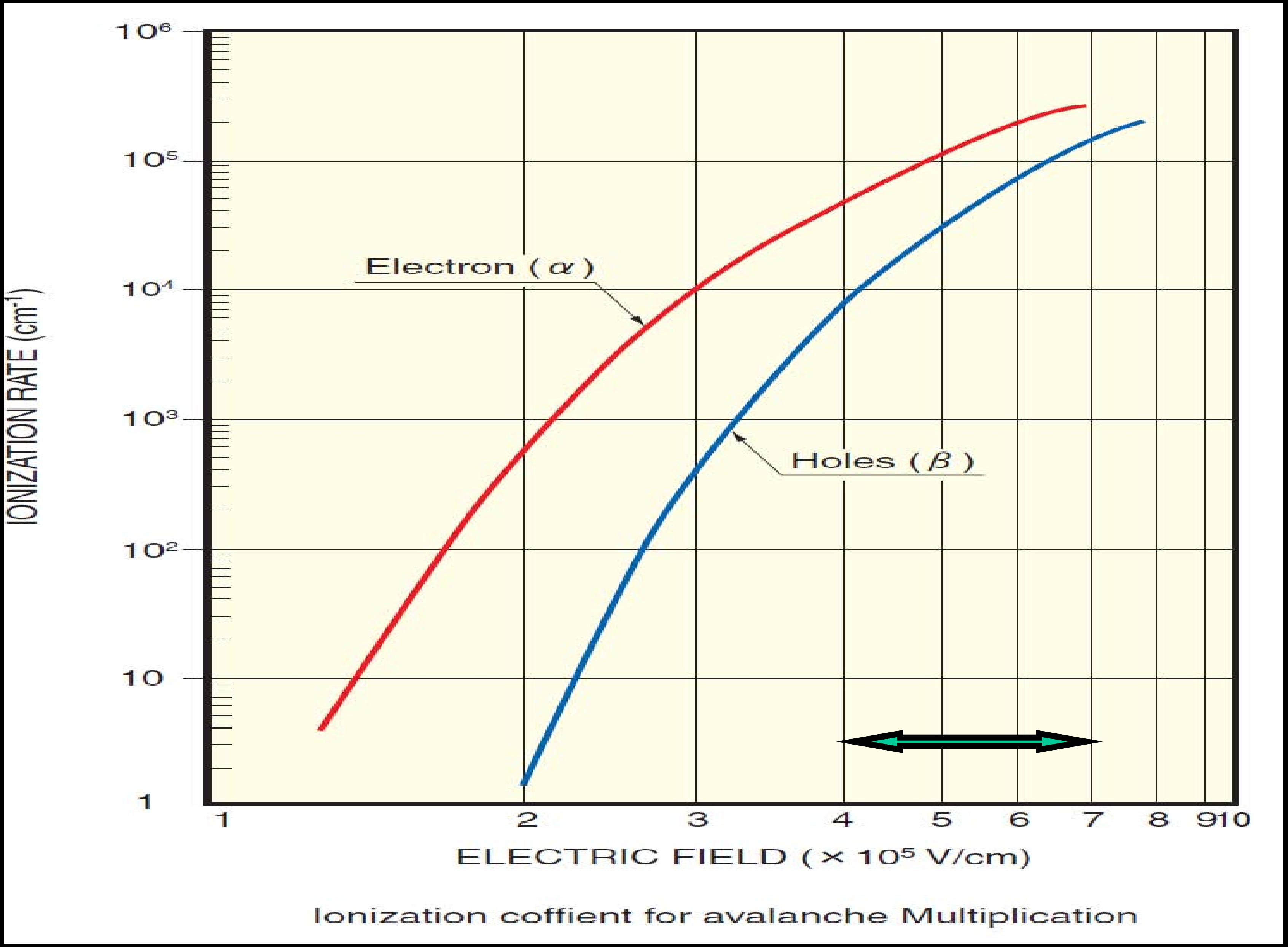
K. Yamamoto @ PD07

- Used for CMS-ECAL APD
- Better quantum efficiency to shorter wavelength

Photo Absorption coefficient of Silicon



K. Yamamoto @ PD07



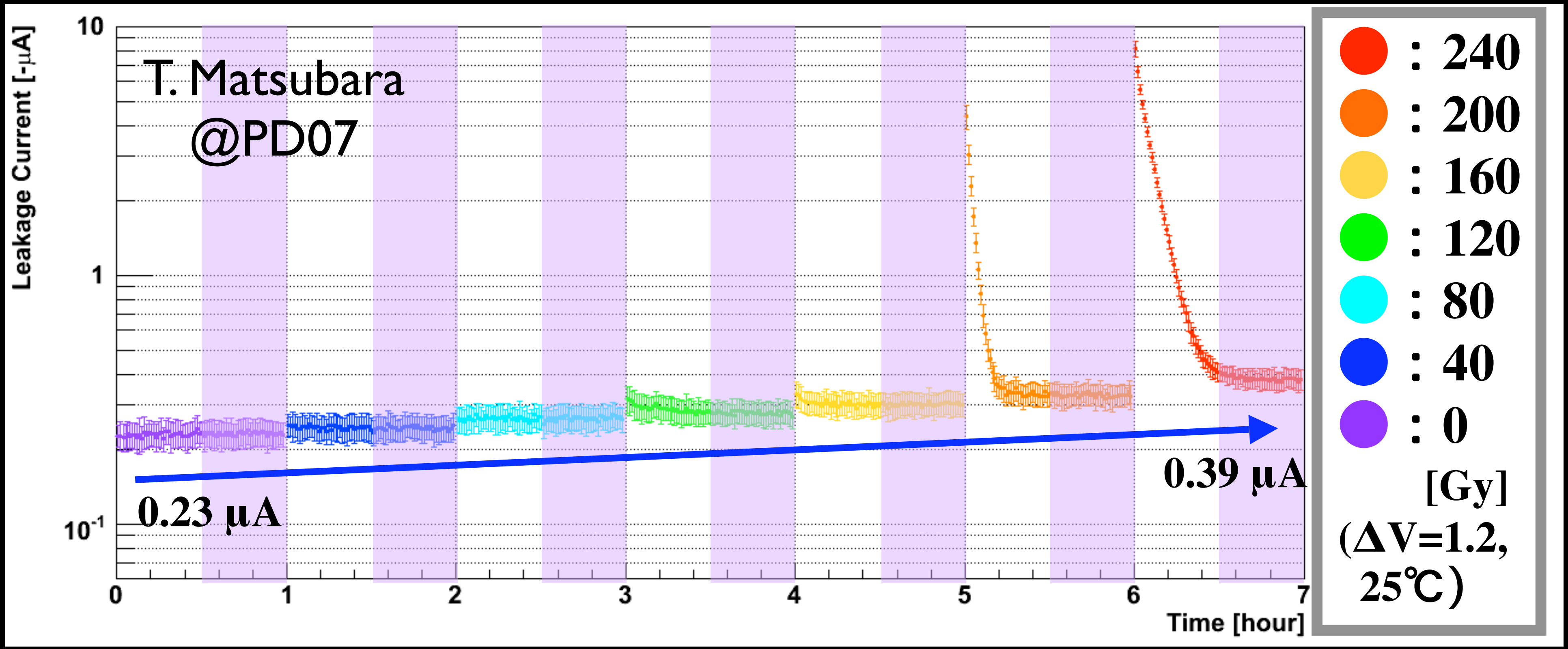
K. Yamamoto @ PD07

Radiation effects

- Several studies in Japan:
  - γ-ray irradiation with ^{60}Co
  - Proton irradiation at RCNP 53.3MeV cyclotron
  - Neutron irradiation at reactor (ongoing, not reported here)

γ-ray irradiation

^{60}Co

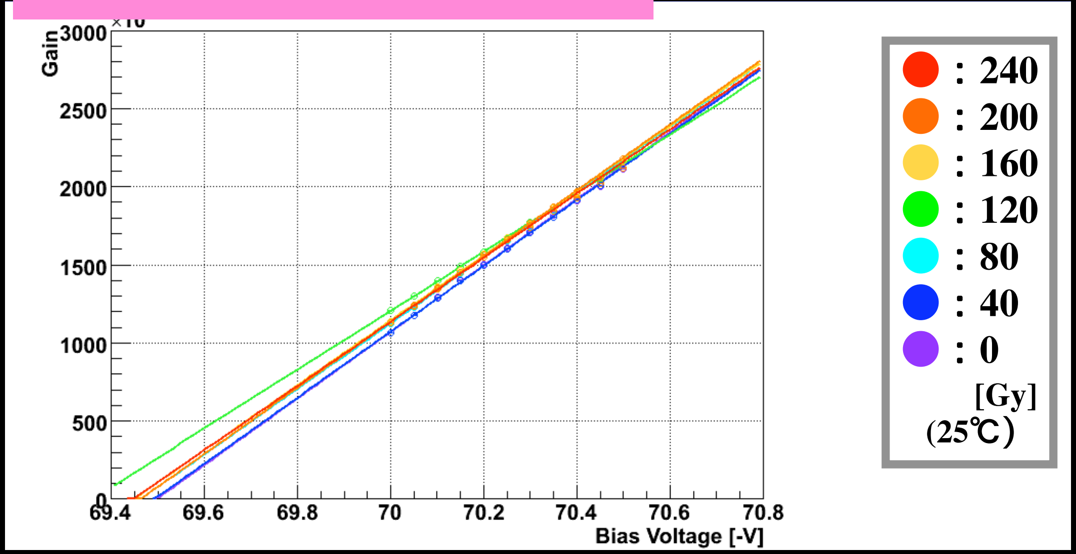


- Leakage current after every 40Gy irradiation
- Annealing observed

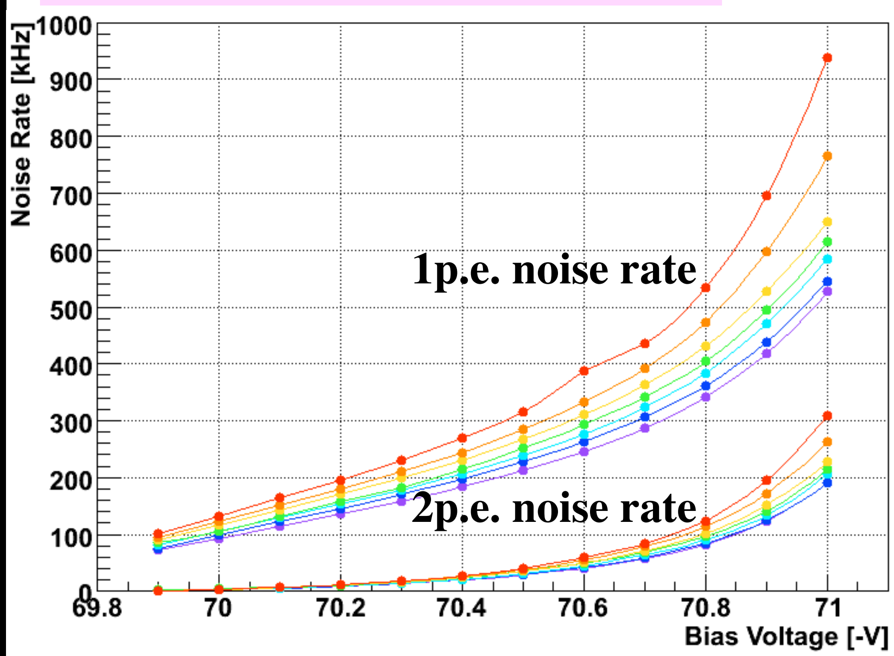
γ-ray irradiation

T. Matsubara
@PD07

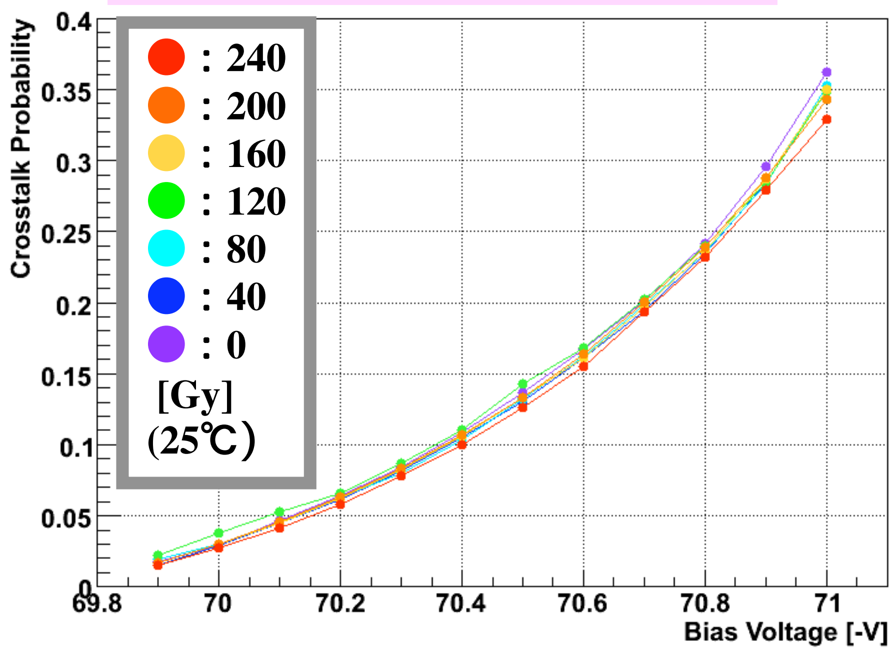
Gain vs Bias voltage



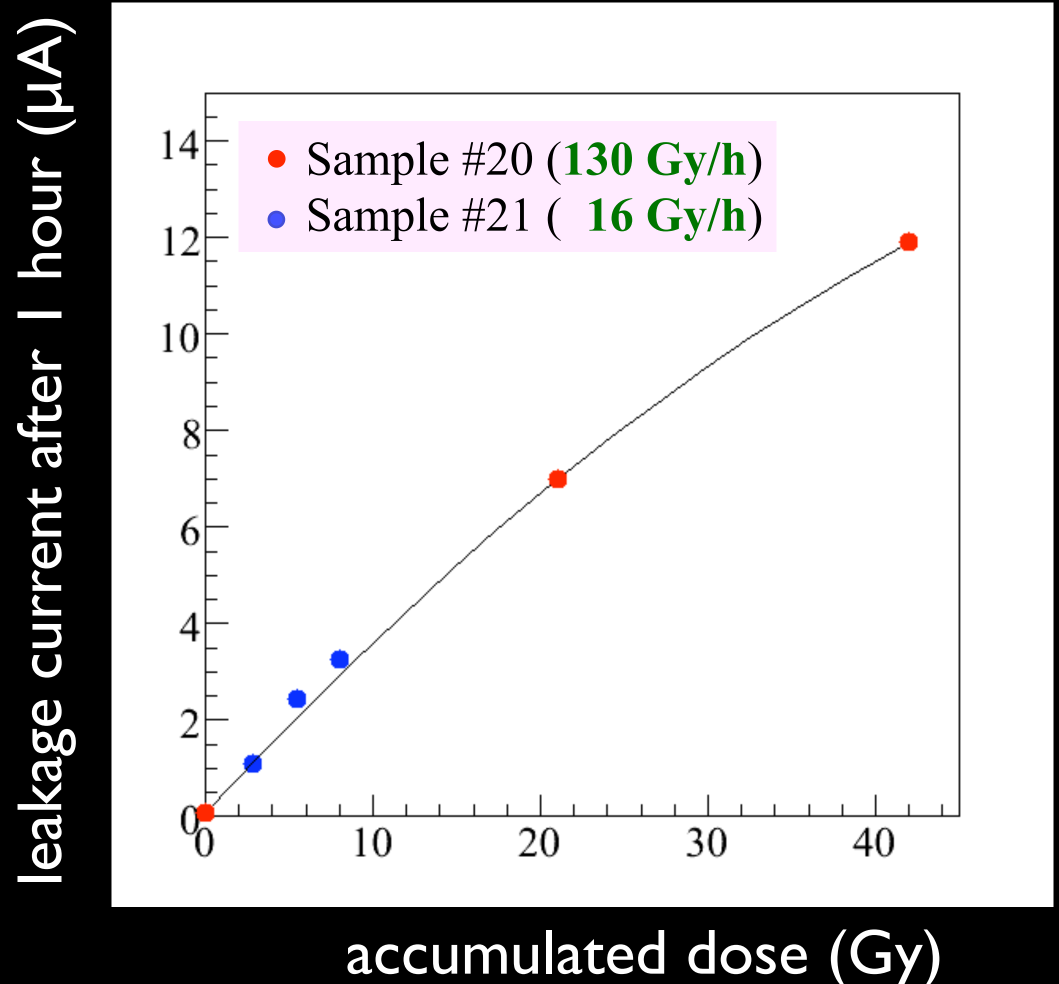
Noise rate vs Bias voltage



Crosstalk vs Bias voltage



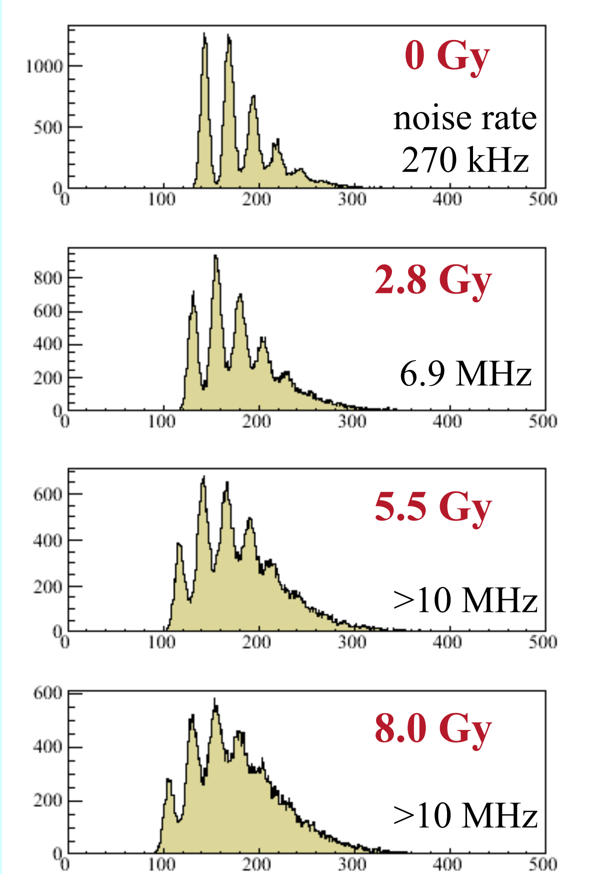
Proton irradiation



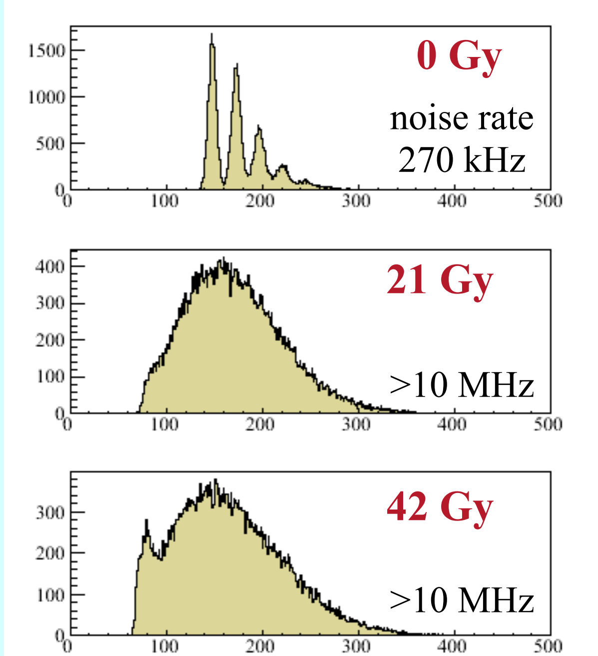
T. Matsumura
@PD07

Proton irradiation

Sample #21 (16 Gy/h)



Sample #20 (130 Gy/h)



gate width : 55 ns

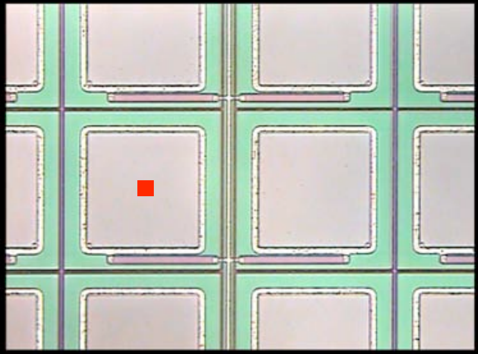
Noise-rate measurements were limited due to scaler performance

T. Matsumura @PD07

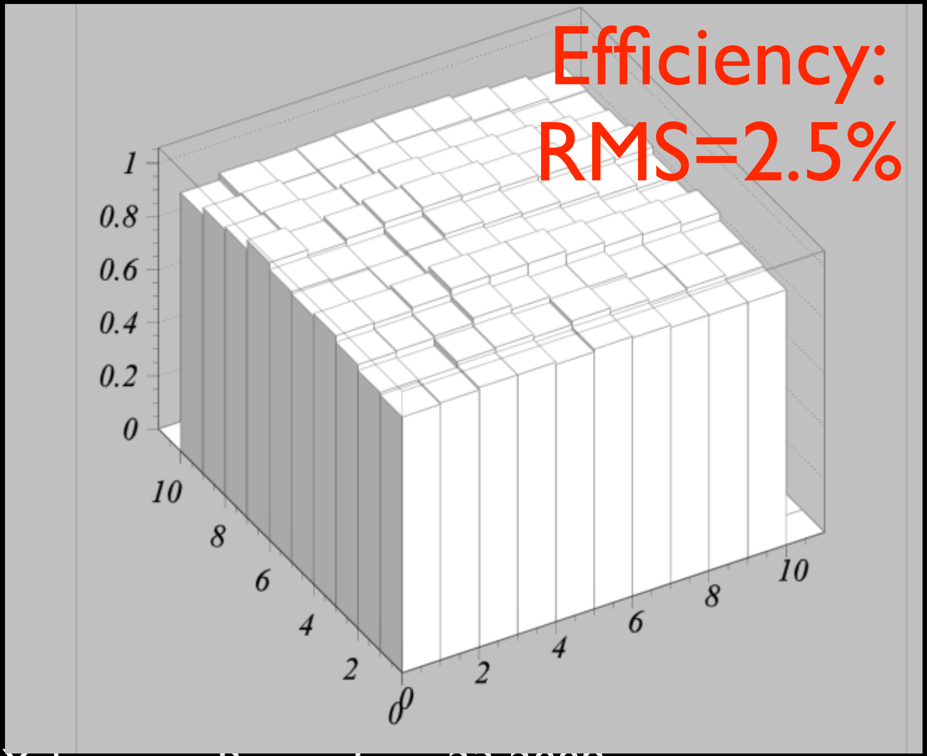
- Photon-counting capability is lost due to baseline shifts and noise pile-up after 21 Gy irradiation.

*Results with early prototype

Response with spot laser



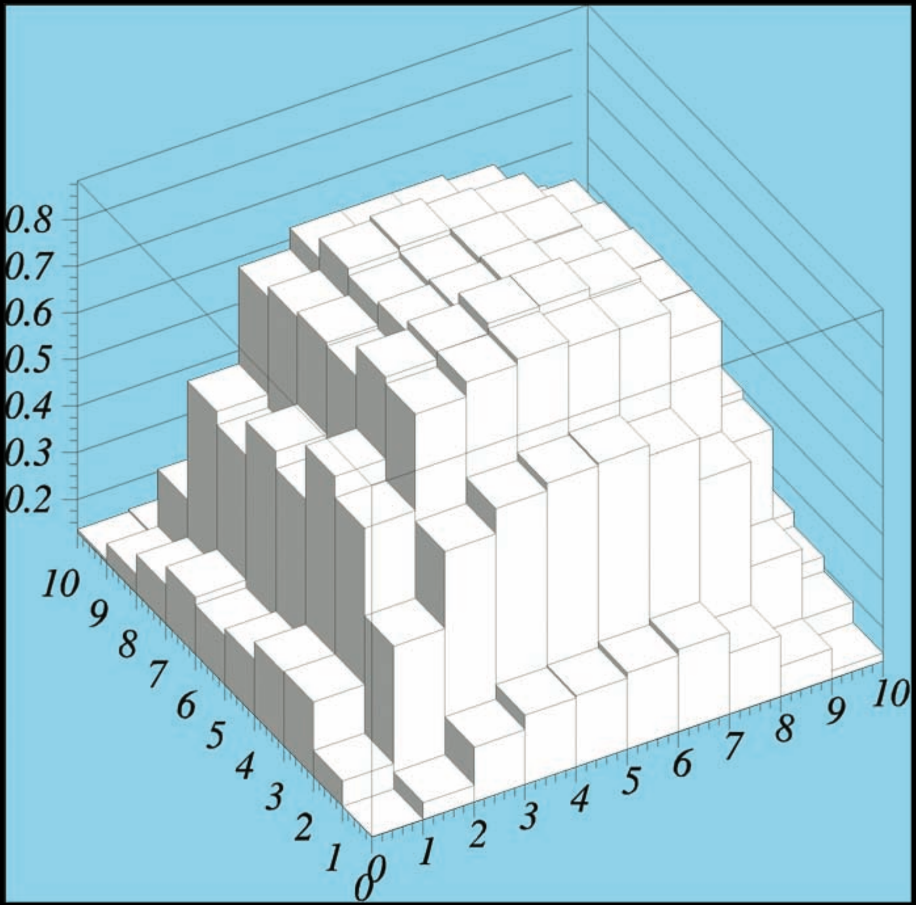
- Inject laser light to center of each pixel
  - spot size ~10um
  - 100 pixel sample (pixel size 100um)
- Uniform response of all 100 pixels
  - Gain: RMS=3.6%



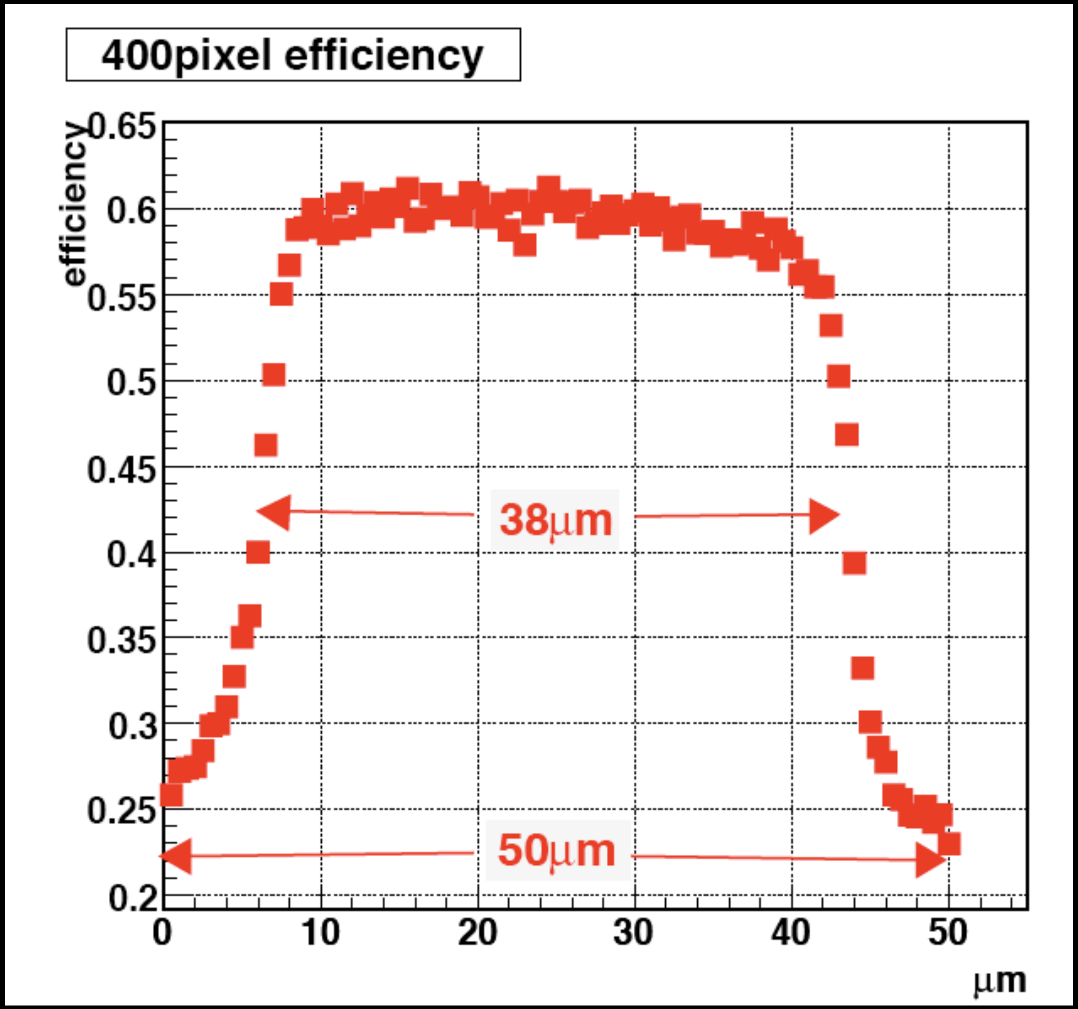
Promising device!

*Results with early prototype

- Laser scan inside a single pixel (100μm pitch)
- Flat response in active region



Effective area



50μm pitch pixel