“Silicon-based Photomulipliers” a new generation of photon detector

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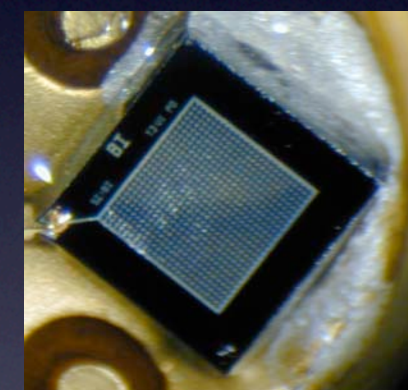
Outline

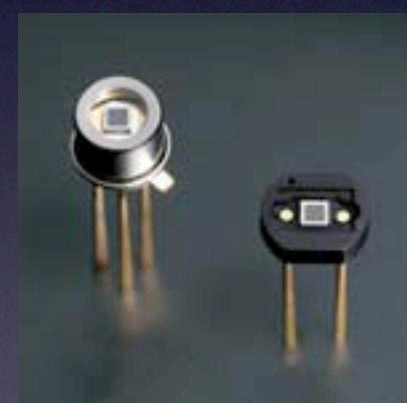
- Introduction
- Operation principle
- Multi-Pixel Photon Counter (MPPC)
  - Performance
  - Future developments
- Summary

Introduction

“Silicon Photo-multiplier”??

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





- Reflecting progress in many places in short time.

R&D over the world

Some maybe missing..

Why so 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

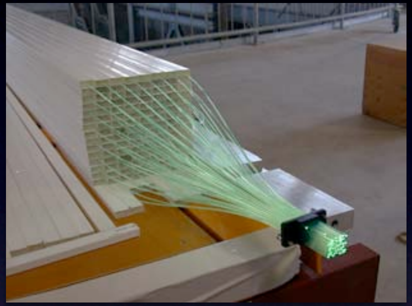
Example of considered applications

- HEP
  - Neutrino detectors
  - ILC calorimeter/muon detectors
  - Aerogel-RICH for super-B, ...
- Astrophysics
  - Air Cherenkov telescopes, ...
- Medical
  - PET, ...

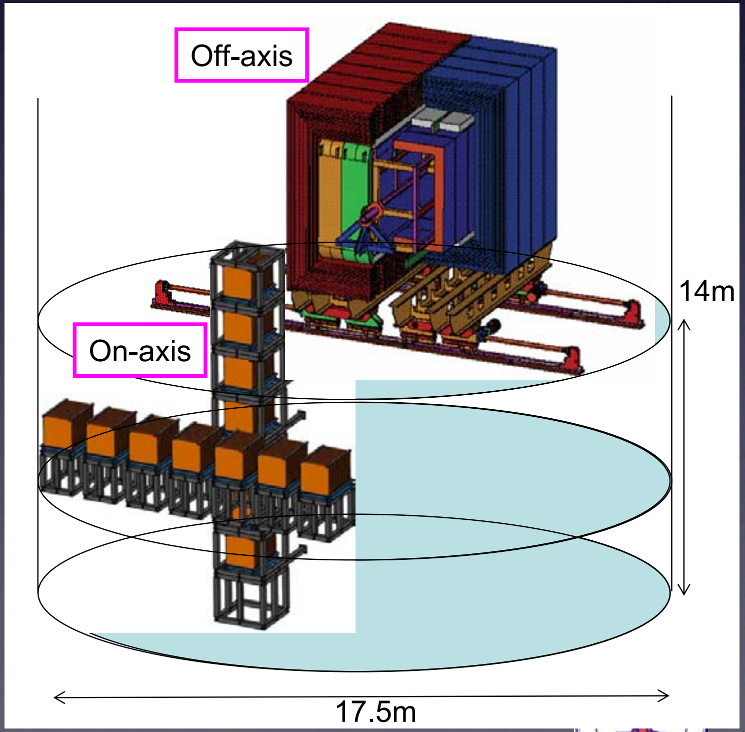
Example of application:

T2K near detectors

(Long baseline ν oscillation experiment from 2009)



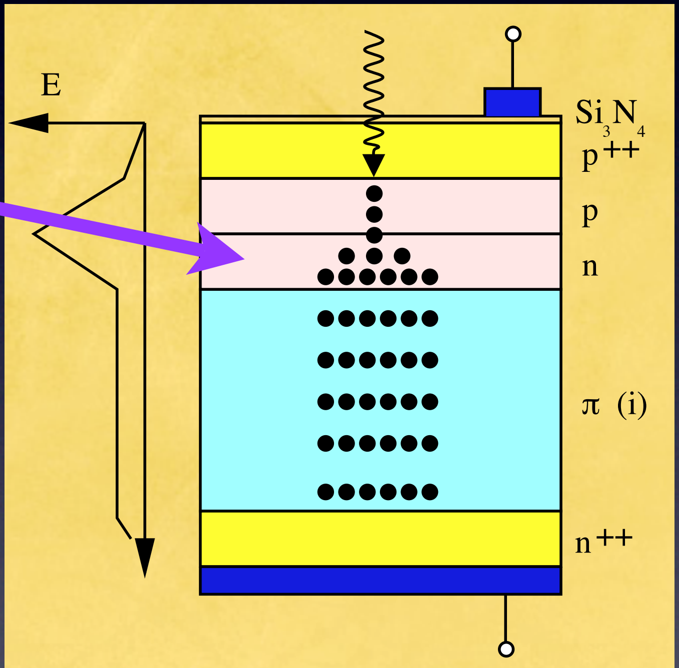
- Measure ν properties just after production
- Most of sub-detectors will use plastic scintillators + wavelength-shifting fibers
  - Some placed inside magnetic field
  - Severe constraint on available space
- Chosen MPPC (Hamamatsu device) as the photo-sensor
  - ~60,000 channels in total
  - First use in large-scale real exp.



Operation principles

Avalanche Photodiodes (APDs)

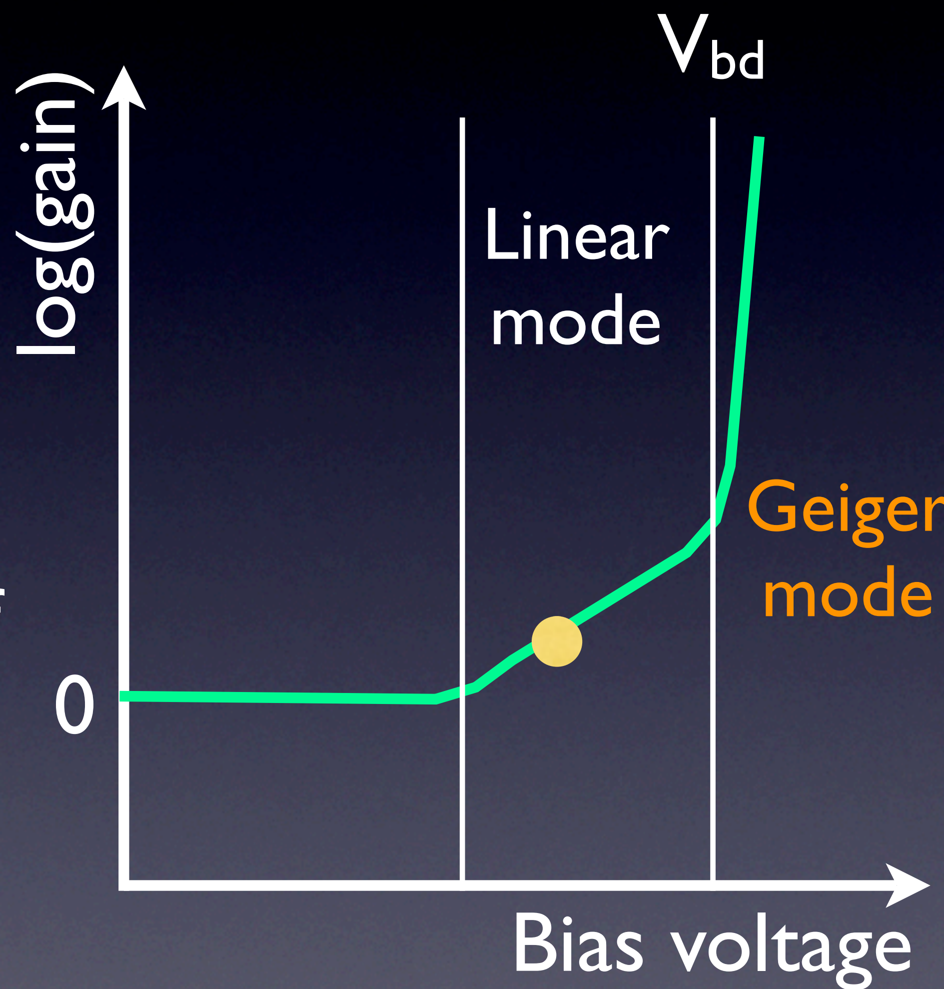
- Photon creates e-h pair near surface
- Avalanche amplification in reverse-biased region
- Linear operation below breakdown voltage (V_{bd}): output charge $\propto$ number of e-h pairs $\propto$ number of incident photons
  - Typical internal gain: 10-100 (~1000 some case)



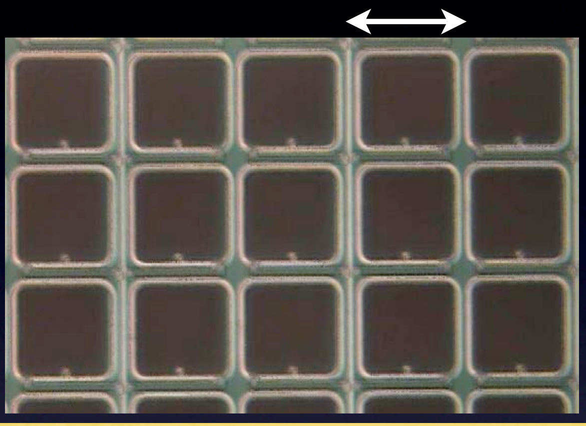
Schematics of APD for CMS-ECAL

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

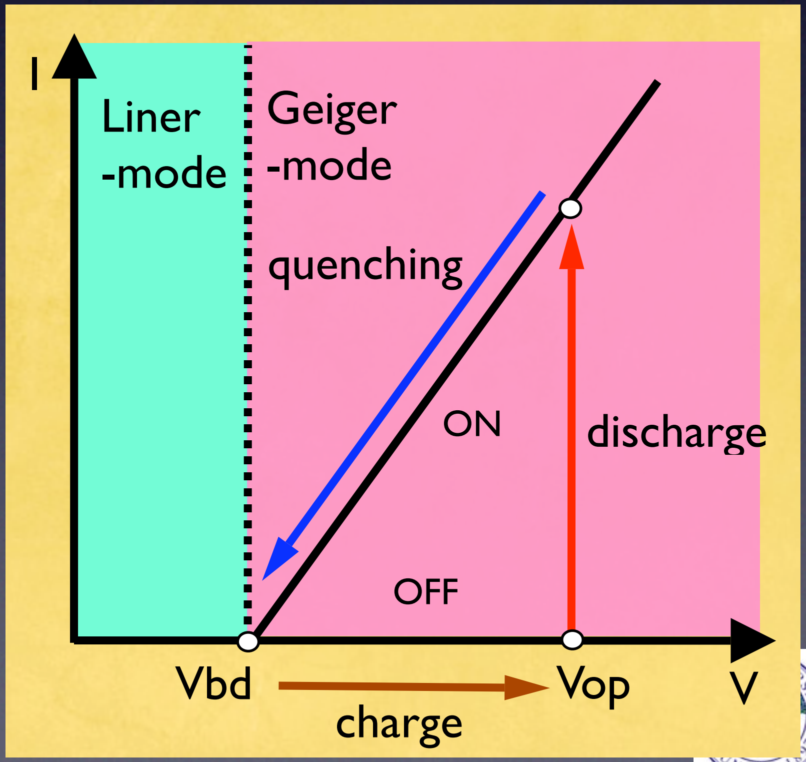


Counting Photons with Geiger-mode APDs



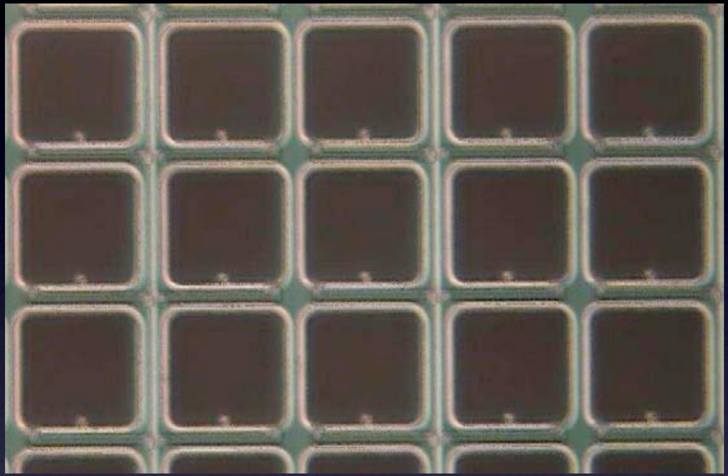
- Divide APD into many small pixels.
  - Each pixel works independently in Geiger mode
- Incident photon 'fires' an APD pixel *but not others*
  - Output charge from one pixel: $Q_{pixel}=C_{pixel} \cdot (V_{op}-V_{bd})$
  - C_{pixel}~10-100fF and $\Delta V \equiv V_{op}-V_{bd}$~1-2V gives

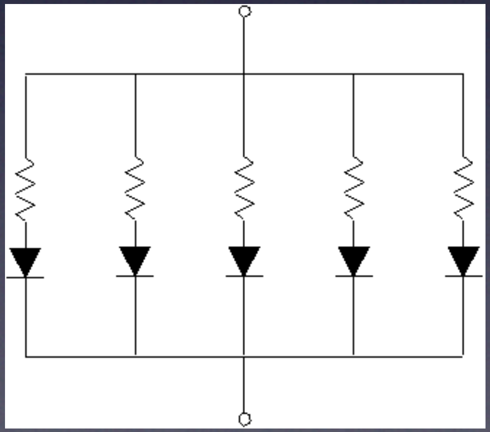
    Q_{pixel}~10^5-10^6e



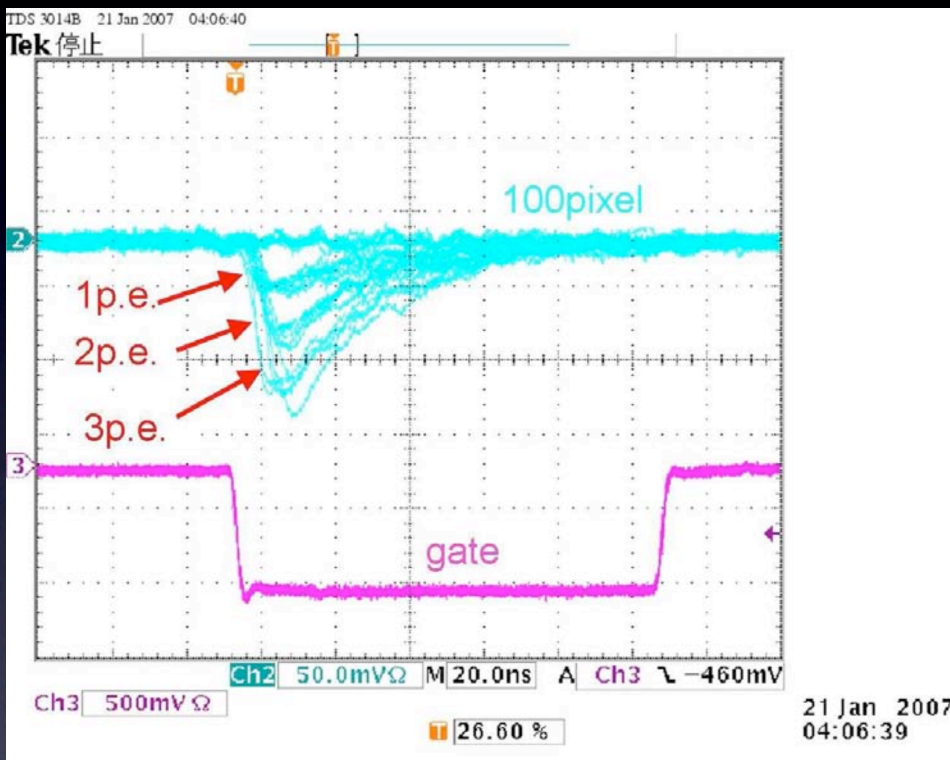
Operation of Multi-pixel Geiger-mode APDs

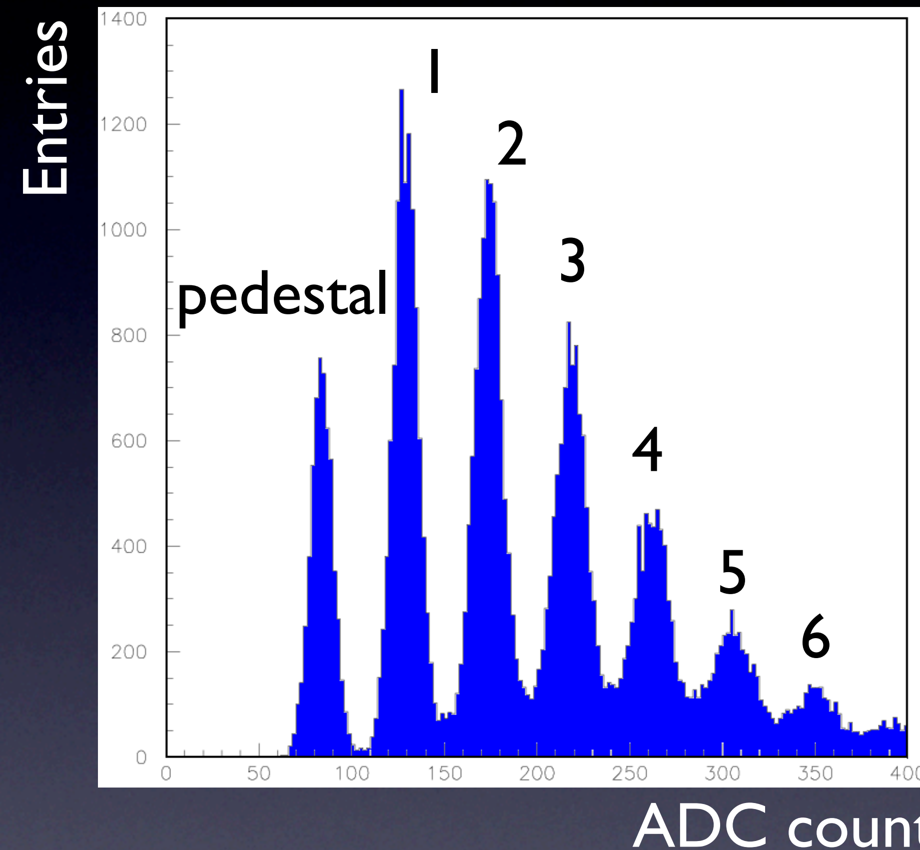
- All the pixels are connected *in parallel*
  - Taking sum of all pixels, one can know how many pixels are fired ∝ how many photons are incident !
  - $Q=\sum Q_{pixel}=N \cdot Q_{pixel}$





Output from Multi-pixel Geiger-mode APD





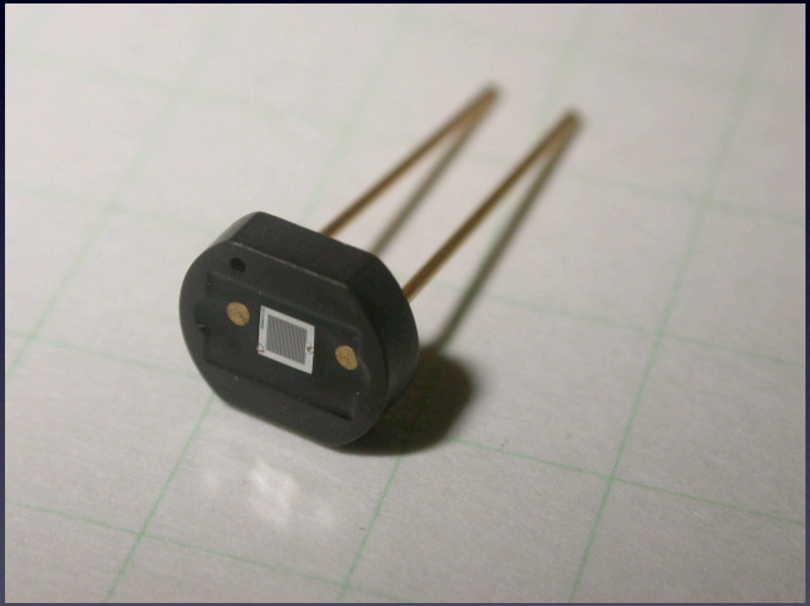
Clear separation of 1,2,3... photoelectron (p.e.) peaks!

[@ room temperature]

Comparison of photo-sensors

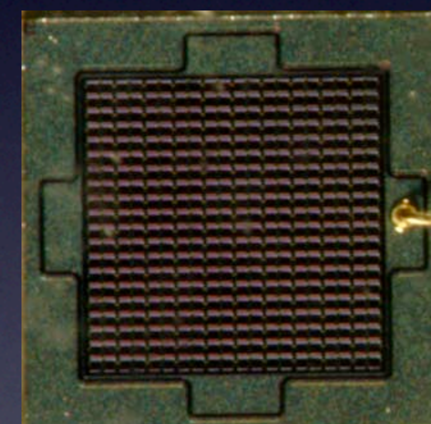
	PMT	APD	`SiPM'
Gain	10^6-10^7	~100	10^5-10^6
Operation voltage(V)	1-2k	300-500	<100
Active area	~>100cm^2	~10mm^2	~1mm^2
Dark count (Hz)	<1k		0.1-1M
Photon detection efficiency (blue-green)	~15%	75-80%	20-50%
Magnetic field	x	o	o

Multi-Pixel Photon Counters (MPPC)

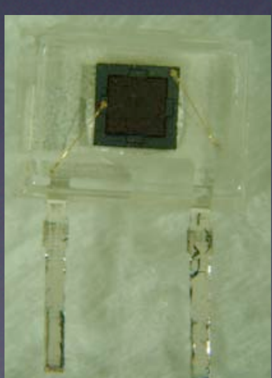


Menlo Park Presbyterian Church →
www.mppc.org

MPPC by Hamamatsu



- Structure based on <u>CMS-APD</u>
- Currently on catalogue:
  - 1x1mm^2 active area
  - 100/50/25 μm pixel pitch
  - Metal or ceramic package
- In future..
  - Larger area: 3x3mm^2 (5x5mm^2)
  - Larger pixel pitch
  - More variations of package



Spec by Hamamatsu

■Electrical and optical characteristice (Ta = 25℃)

Parameter		1600	400	100	Unit
Chip size		1.5 x 1.5			mm
Effective active area		1 x 1			mm
Number of pixels		1600	400	100	–
Pixel size		25 x 25	50 x 50	100 x 100	um
Geometric efficiency		30.8	61.5	78.5	%
Sensitivity	$\lambda = \lambda p$	400			nm
	Quantum efficiency	70 min.			%
	PDE	25	50	65	%
Operating voltage		77±10	70±10	70±10	V
Gain		2.75E+05	7.50E+05	2.40E+06	–
Dark count		100	270	400	Kcps
Terminal capacitance		35			pF
Time resolution (FWHM)		250	220	250	ps
Temp coefficient of bias voltage		50			mV/℃

*The last letter of each product number indicates which type of package is used. (U : Can , C : Ceramic)

*1: The figures in PDE (Photon Detection Efficiency) include cross-talk and after pulse.

Performance of MPPC

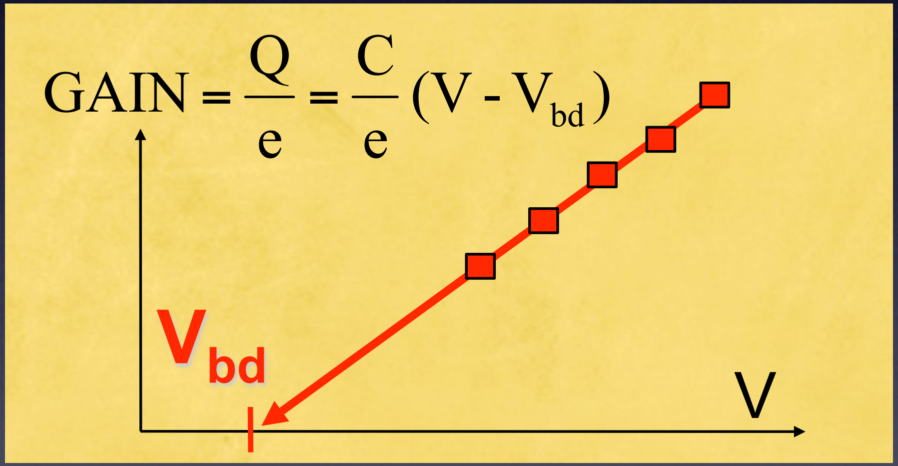
for 50μm pitch device, unless noted

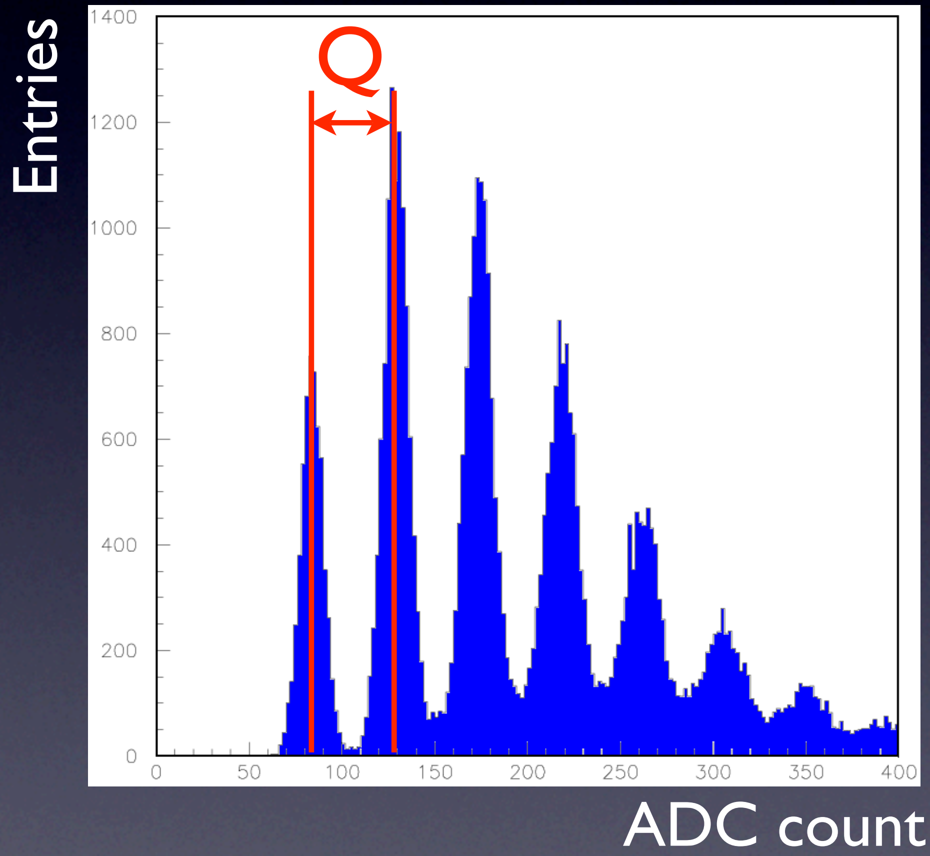
Key performance (1)

- Basic parameters
  - Gain
  - Noise
  - Photon detection efficiency
  - Timing resolution

Gain&V_{bd}

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

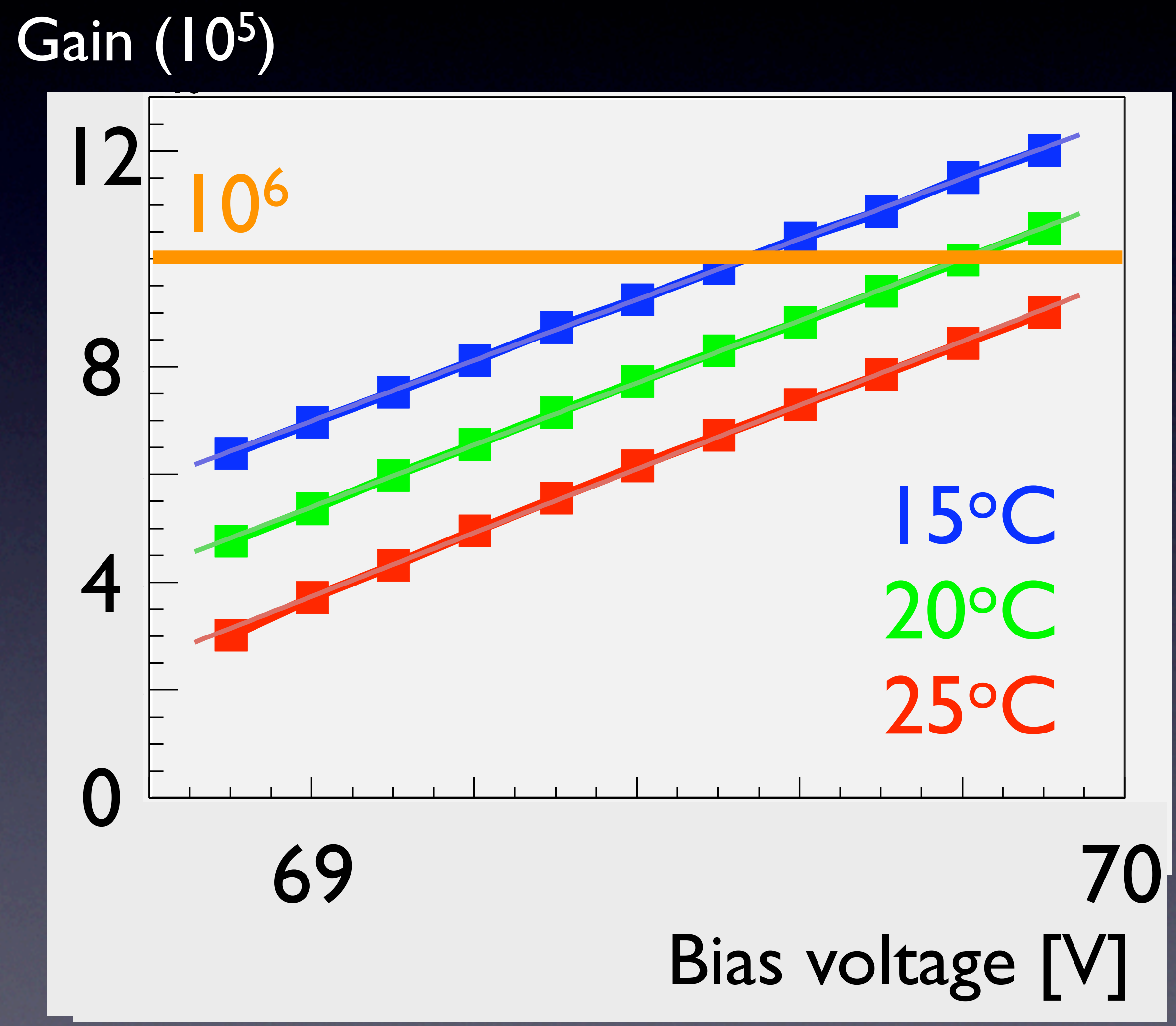




- Using linear relation, breakdown voltage (V_{bd}) also derived

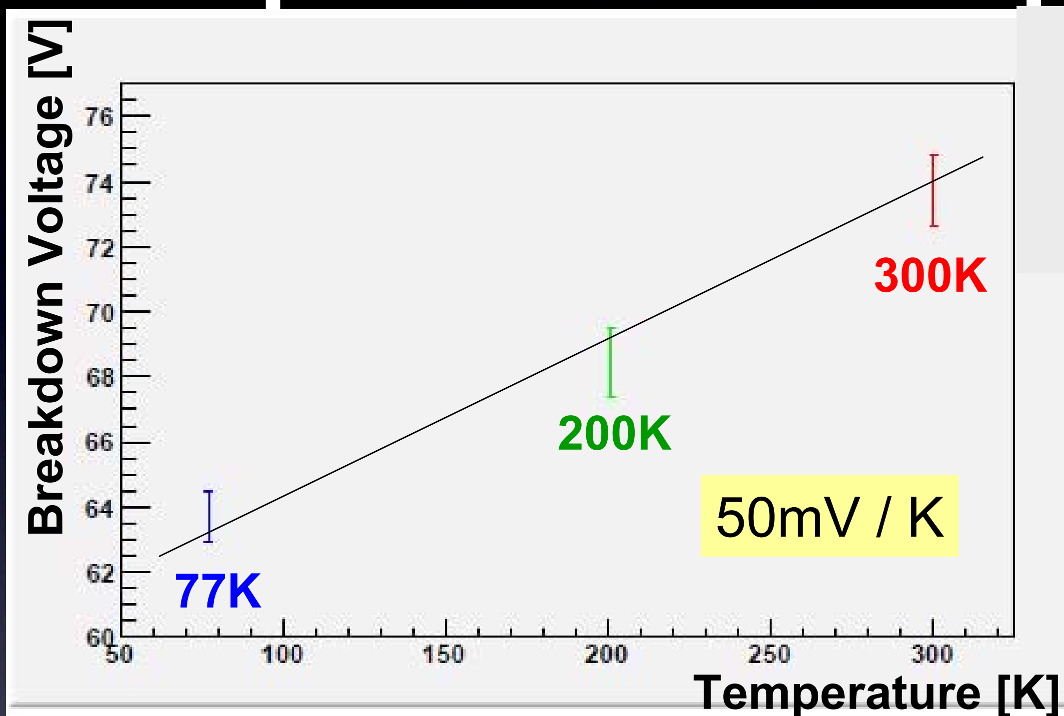
Measured gain

- MPPC has ~10^6 internal gain.



HPK spec is 7.5x10^5
(ΔV~1.3V)

Temperature dependence



H. Otono @PD07

1600 pixel

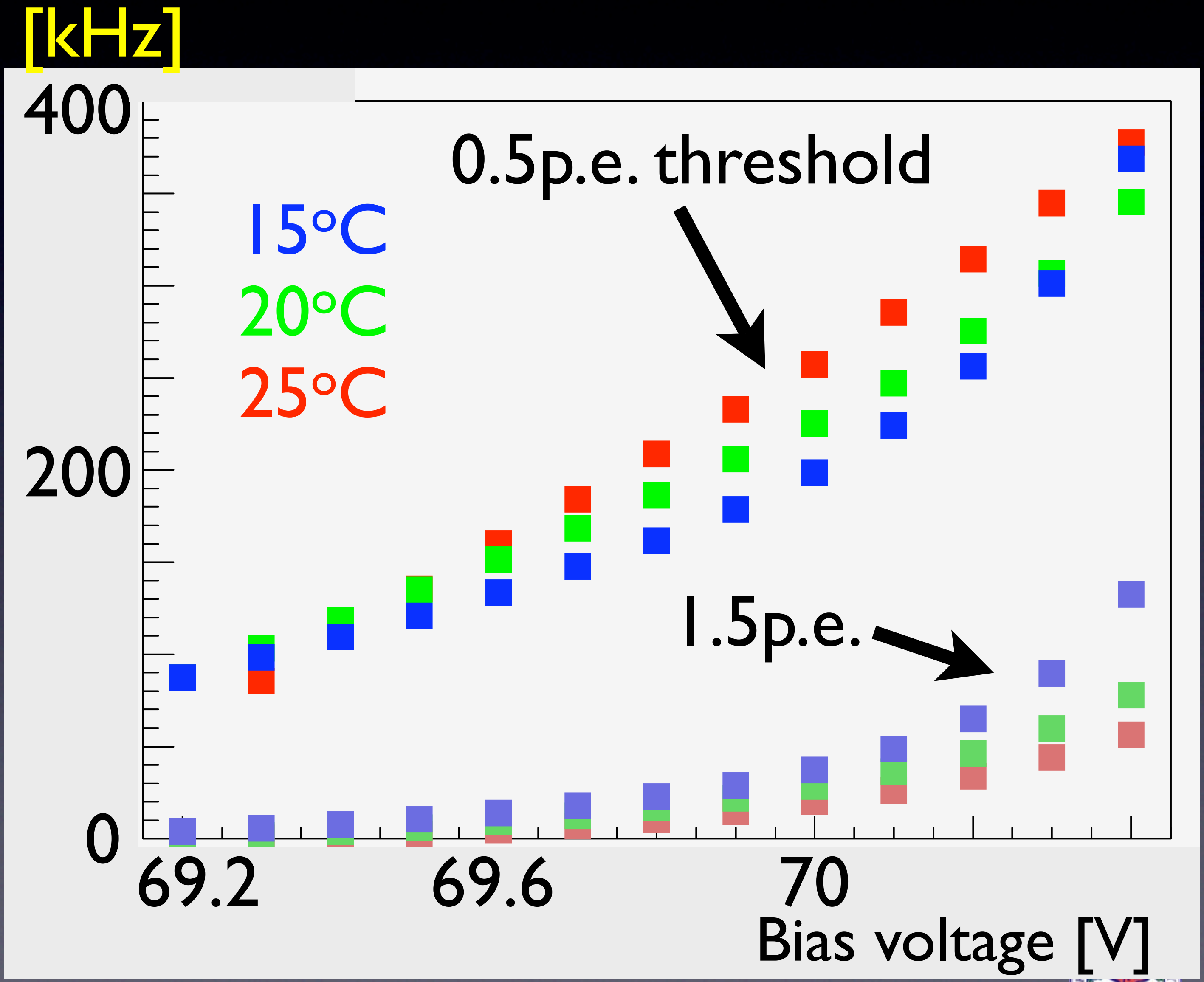
(Also many measurements around room temperature)

- 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 rate

- Measured with scaler
- 1p.e. noise dominates

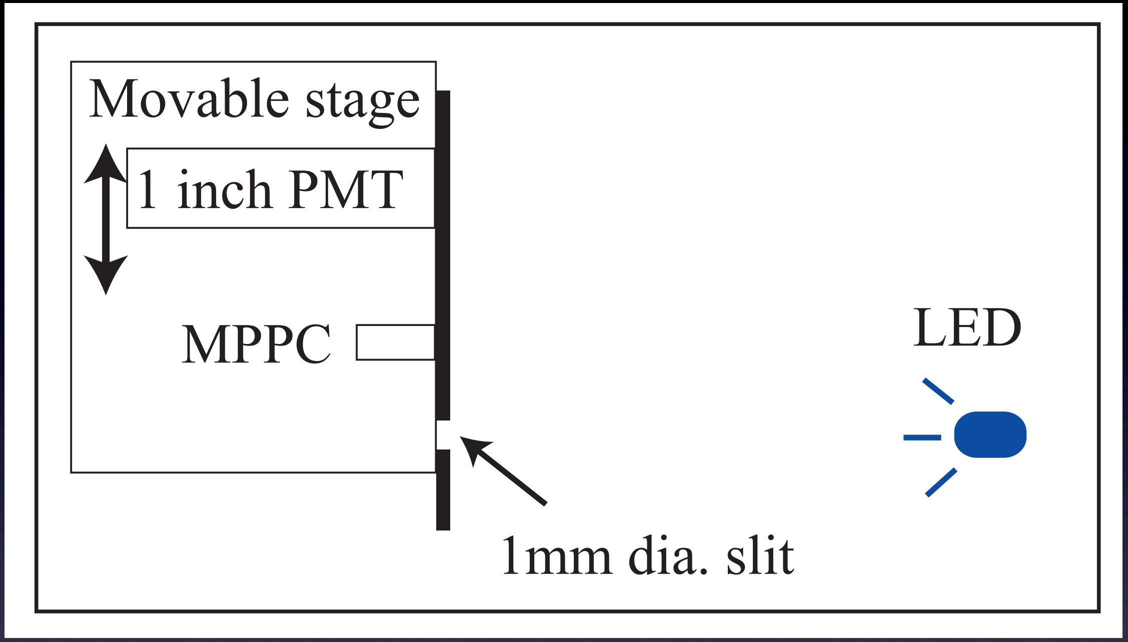
~ order lower than other ‘SiPM’ type devices



Photon Detection Efficiency (PDE)

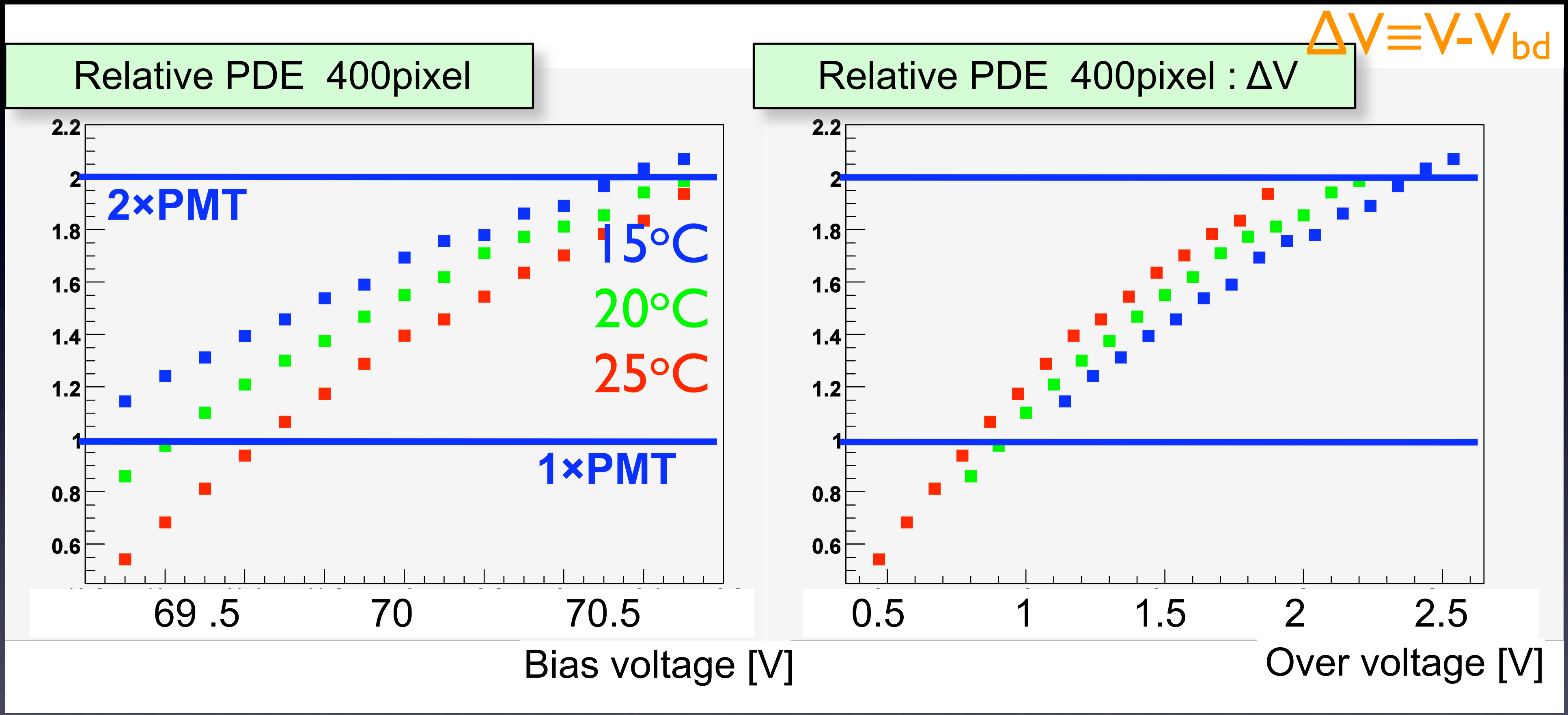
- Probability of detecting single photon entering the surface of device
- Three major components:
  - Geometrical efficiency (30/60/78% for 25/50/100μm pixles)
  - Quantum efficiency
  - Probability to trigger Geiger avalanche
    - Depends on over-voltage.

Photon Detection Efficiency



- Measured using PMT (bialkali, QE~15% by catalogue) as reference
  - Compare detected number of p.e.
- Light source: Blue LED (Nichia NSPB500S, peak λ~470nm)

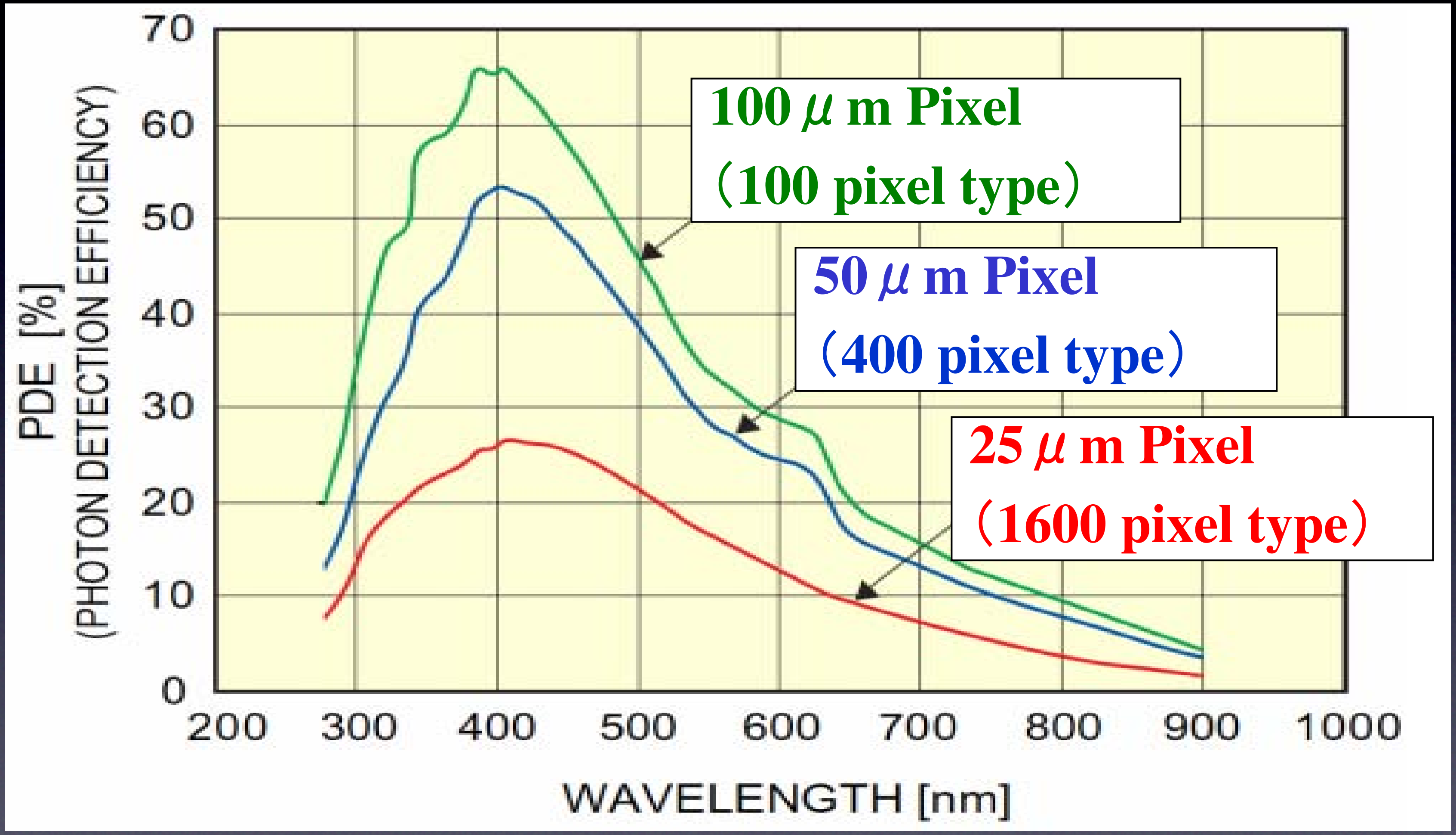
Photon Detection Efficiency



- PDE for MPPC is higher than PMT.

*p.e. for MPPC derived from pedestal fraction to avoid cross-talk and after-pulse effects.

PDE from catalogue



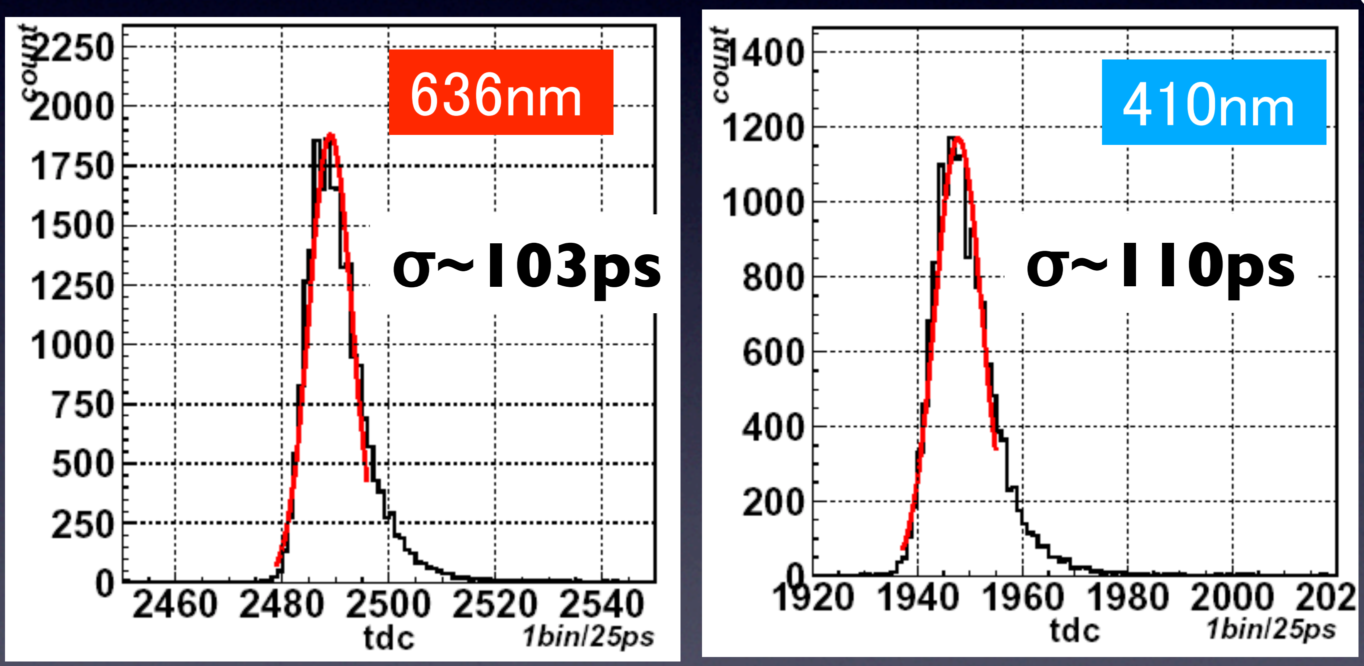
* Measured with current:

includes effects from *cross-talk and after-pulse*.

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

Key performance (2)

- Parameters under intensive study..
  - Optical cross-talk
  - After-pulse
  - Radiation effects

Optical cross-talk

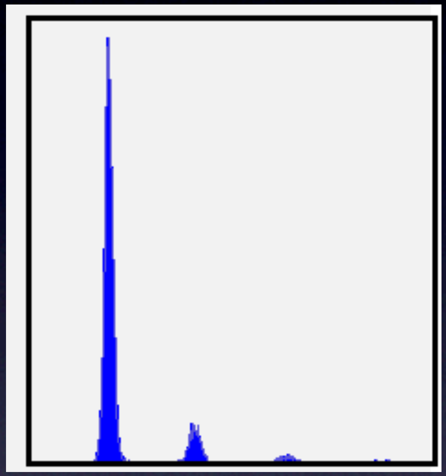
- Photons created during avalanche can enter neighboring pixels
  - They can trigger additional avalanche → optical cross-talk
- Increase excess noise factor

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

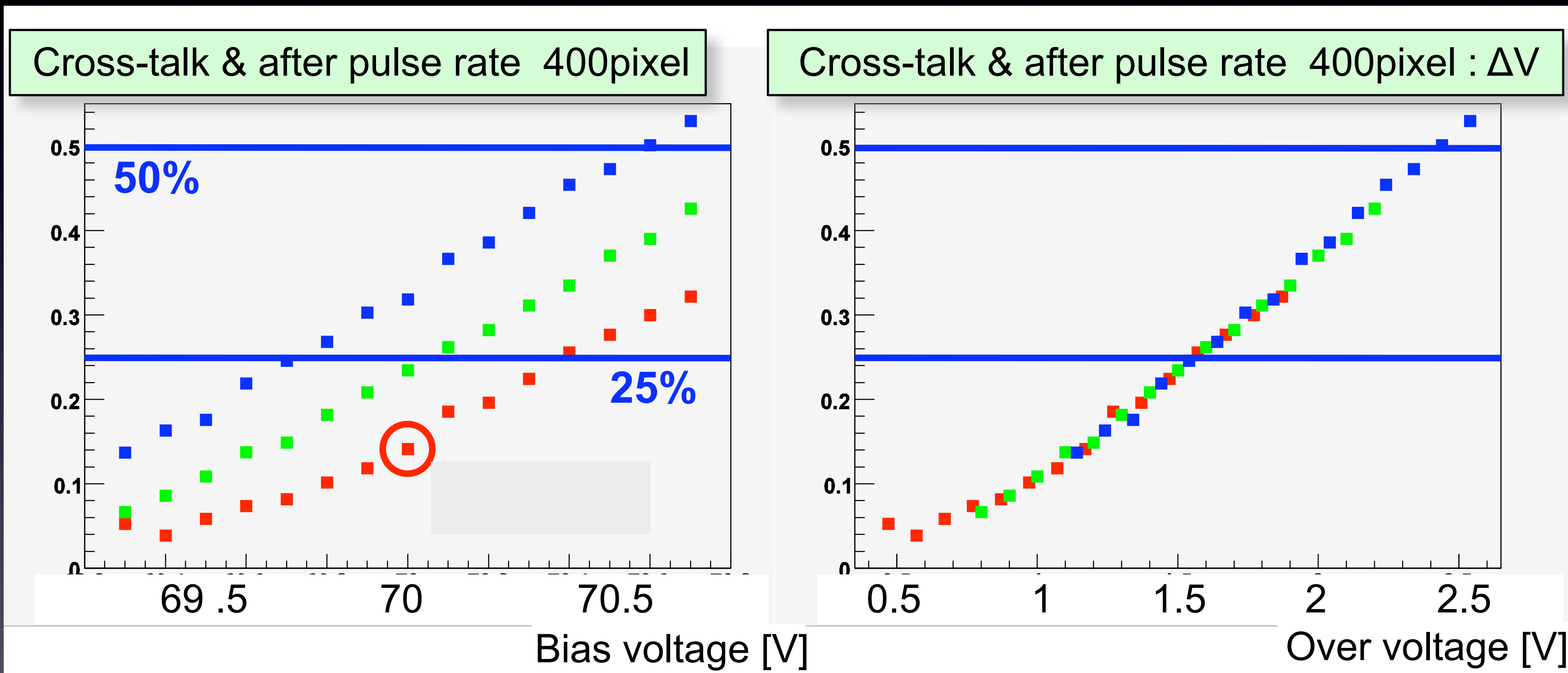
Observed 1p.e. events

Probability of cross-talk&after-pulse

*Only combined probability can be measured with this technique.

Cross-talk & after-pulse

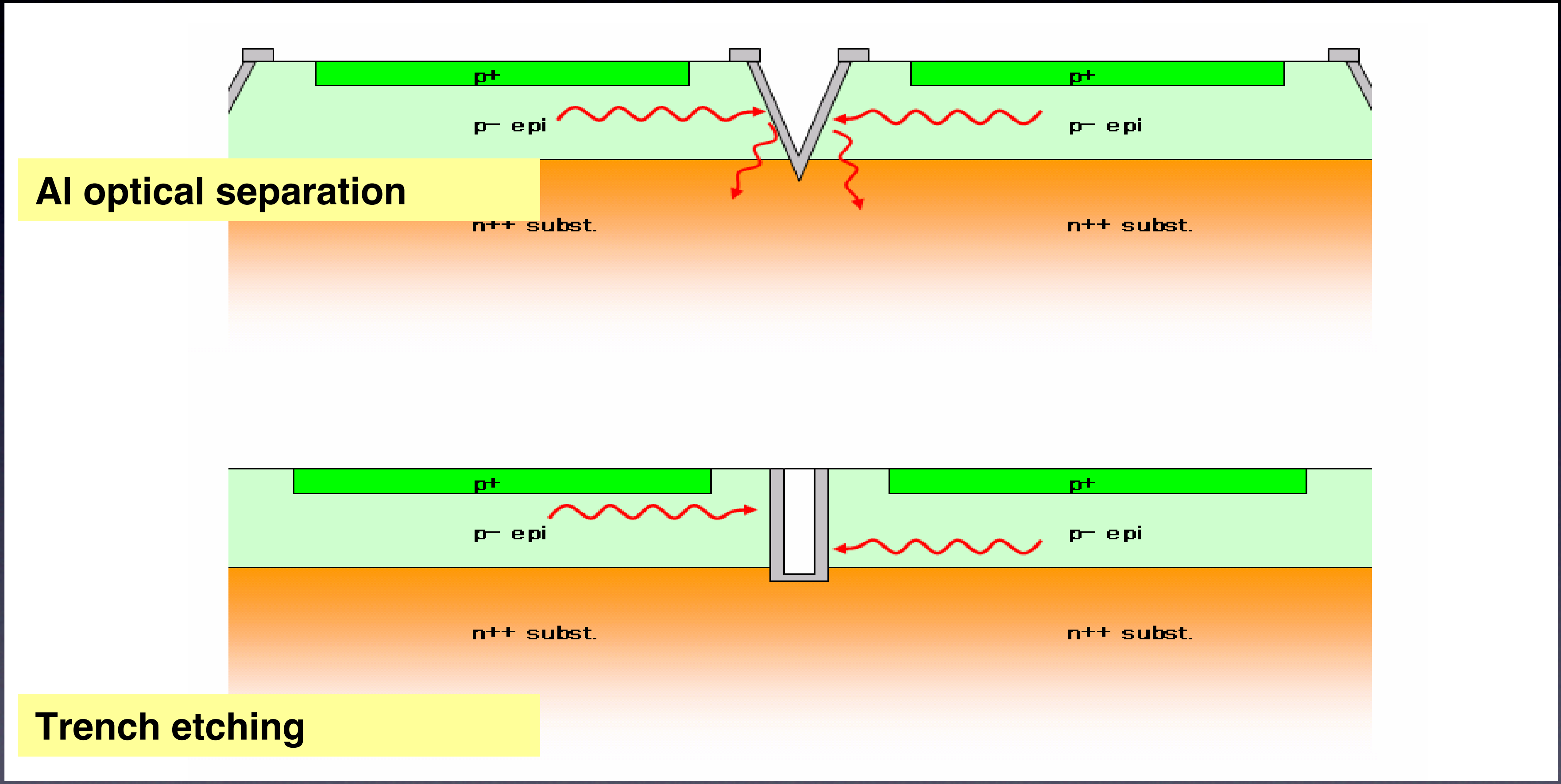
Gate width: 800ns



S. Gomi
(Kyoto)

Significant effect observed.
Depends on over-voltage.

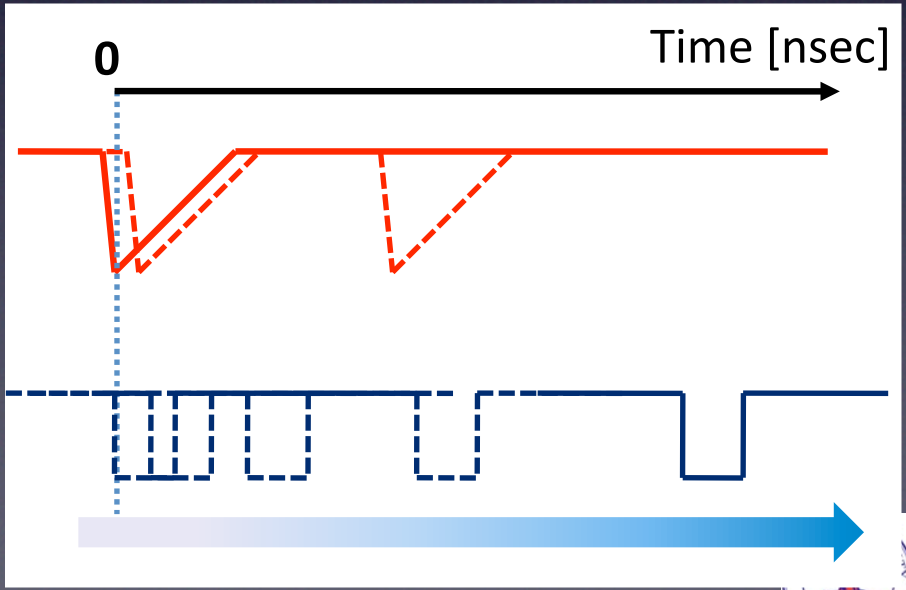
Possibility of cross-talk suppression



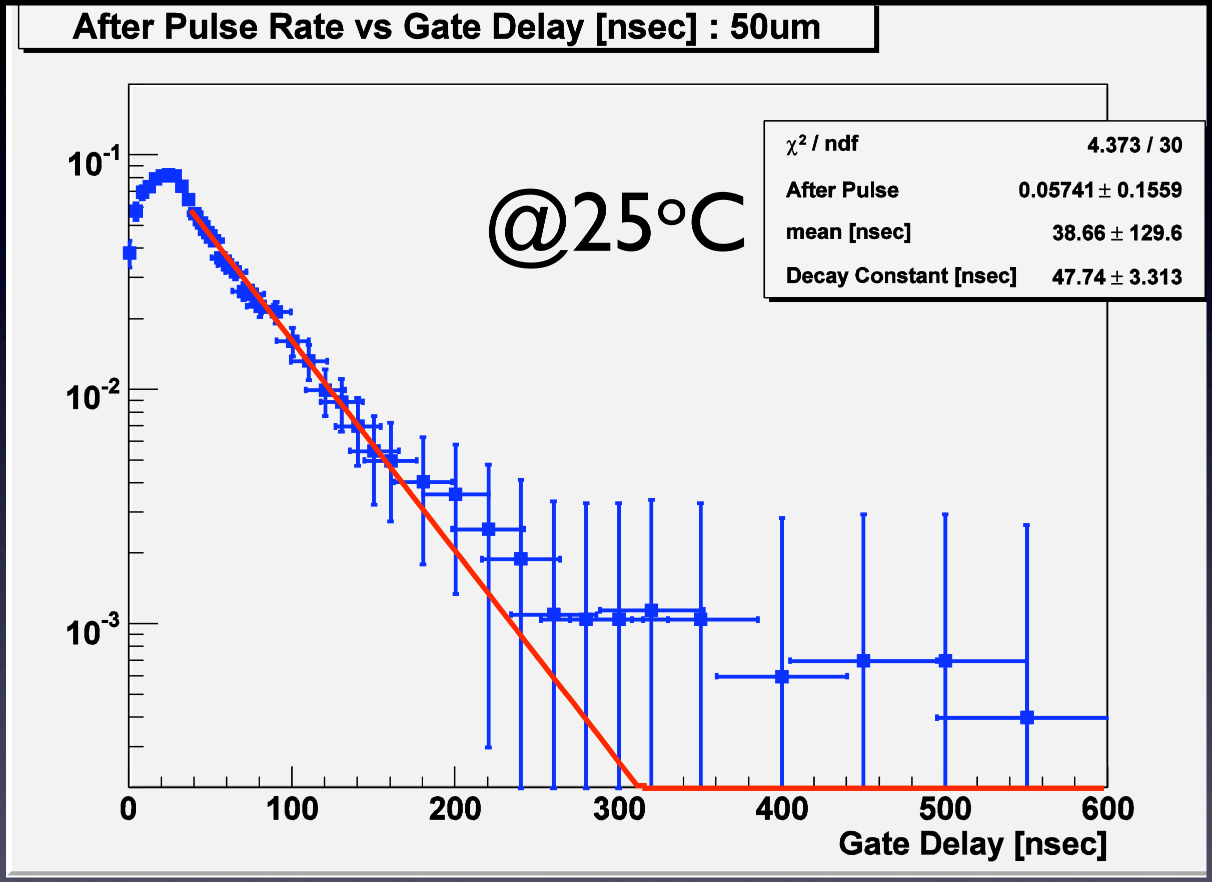
K.Yamamoto @ PD07

Study of after-pulse

- Special structure with only one pixel
  - No cross-talk effect
  - Pixel structure identical to usual ones
- Using delayed gate with self-trigger, measure time constant of after-pulse



Measured time constant



S. Gomi
(Kyoto)

- ~50ns for 50μm pixel (~150ns for 100μm)

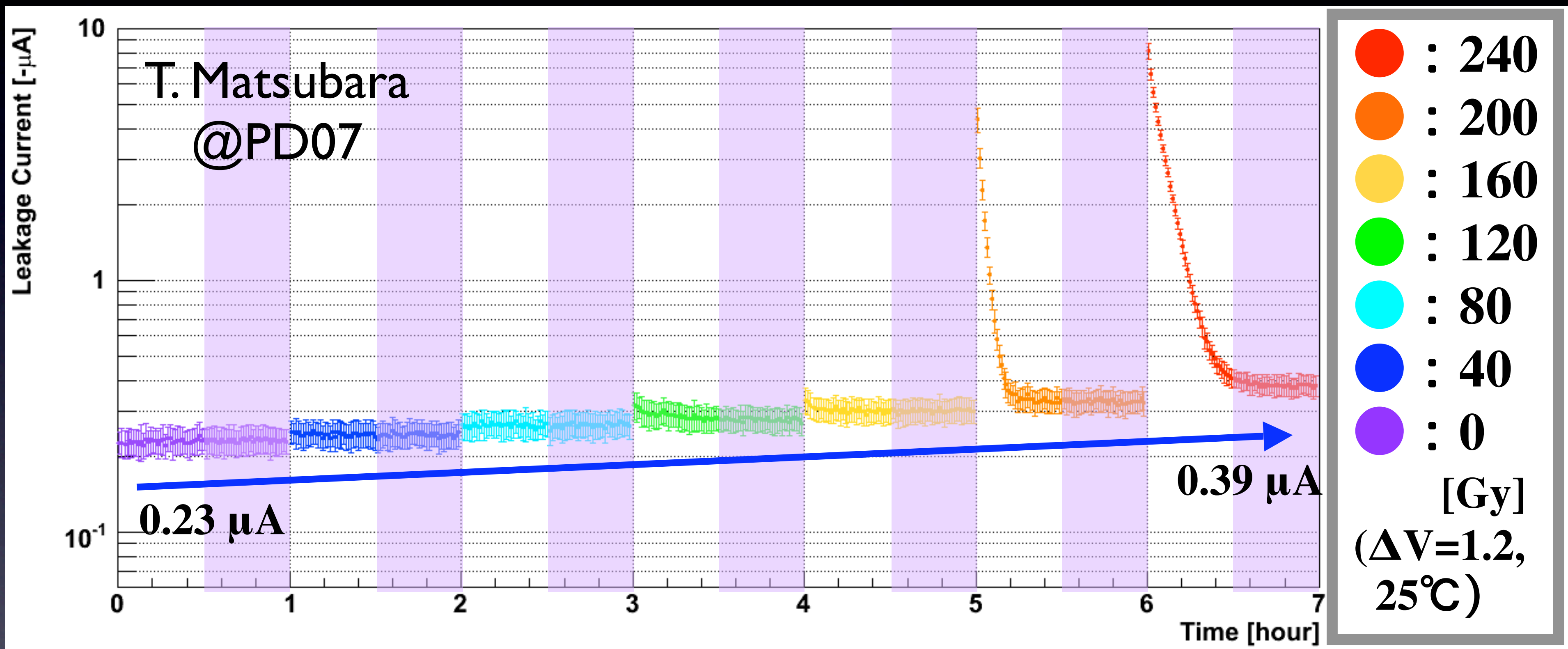
More study in near future.

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

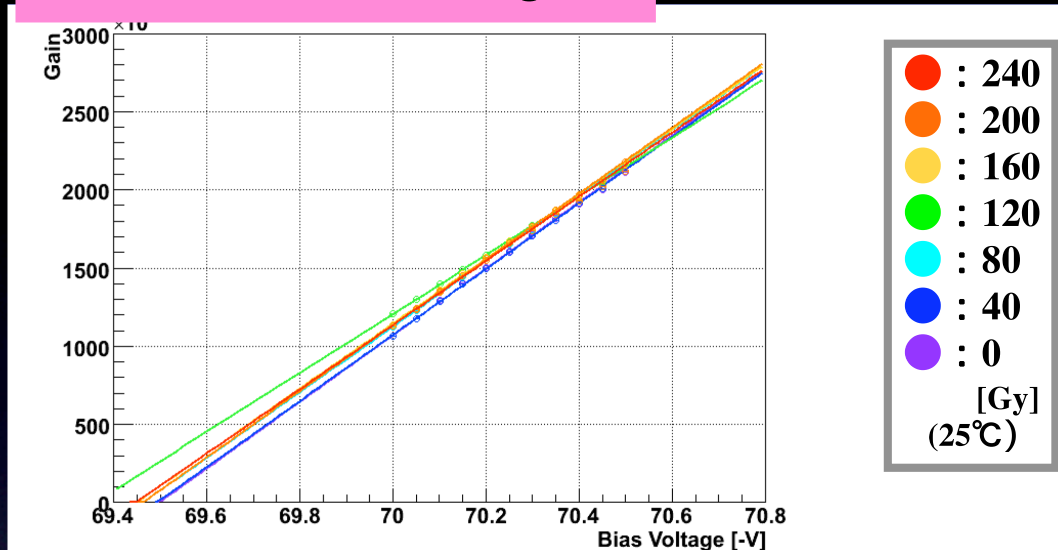


- Leakage current after every 40Gy irradiation
- Annealing observed

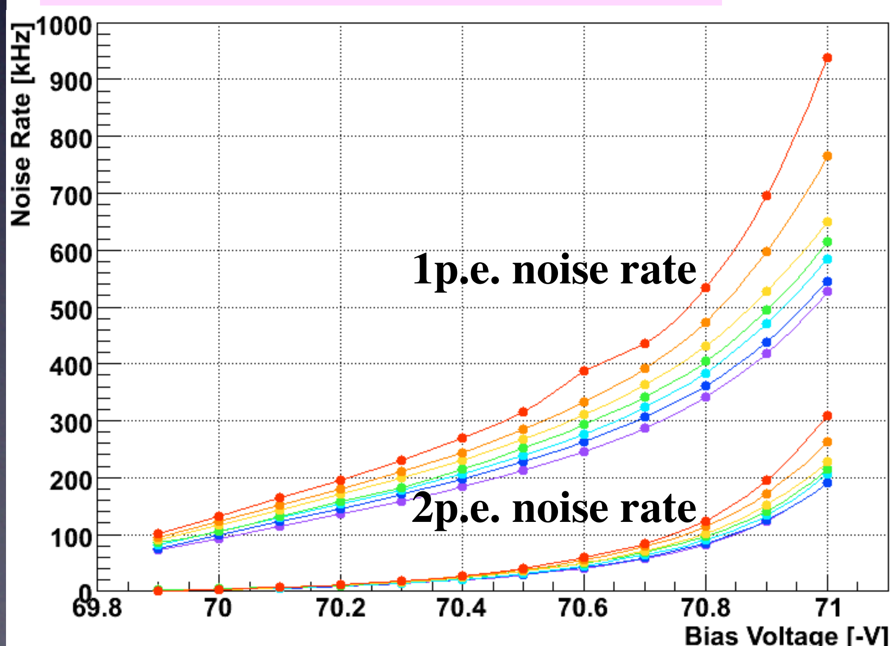
γ-ray irradiation

T. Matsubara
@PD07

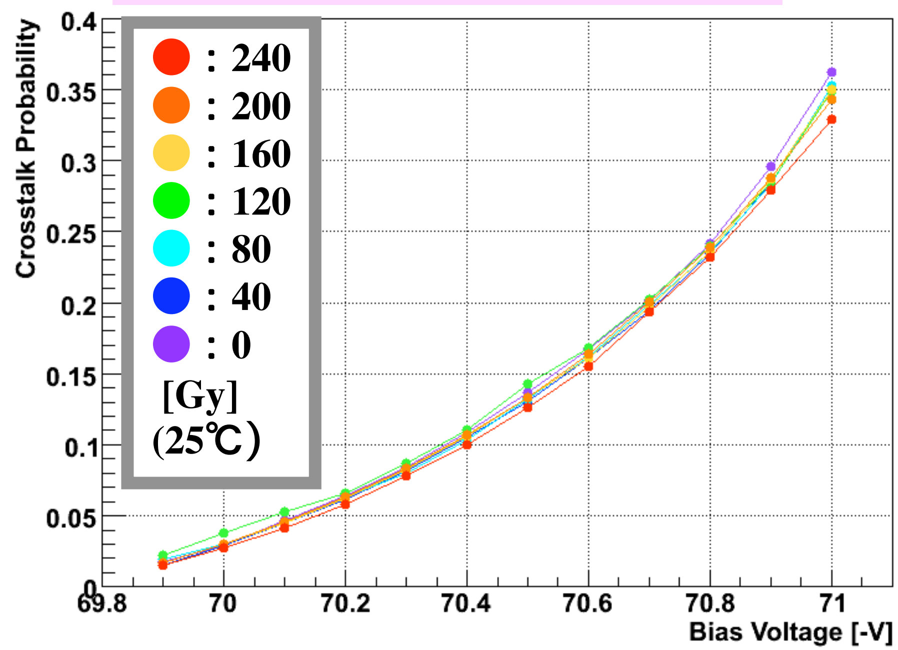
Gain vs Bias voltage



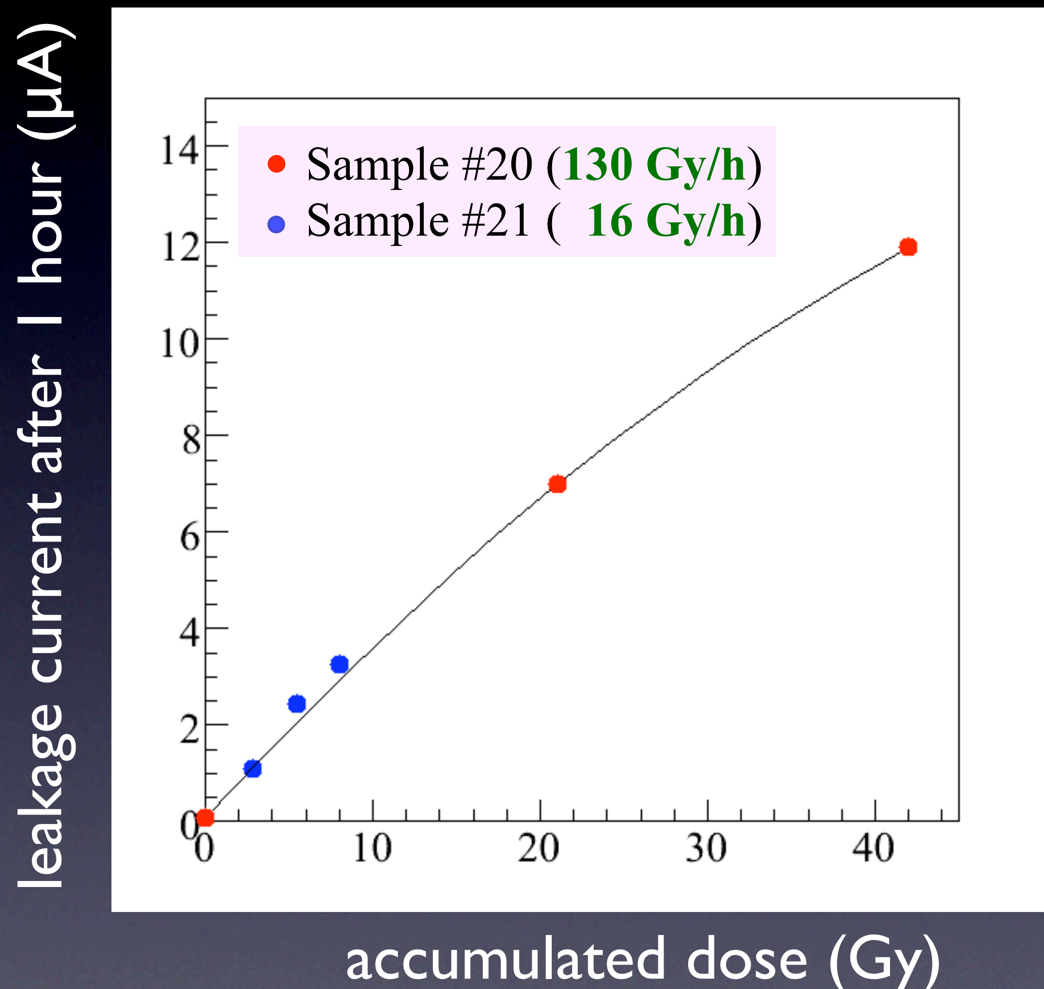
Noise rate vs Bias voltage



Crosstalk vs Bias voltage



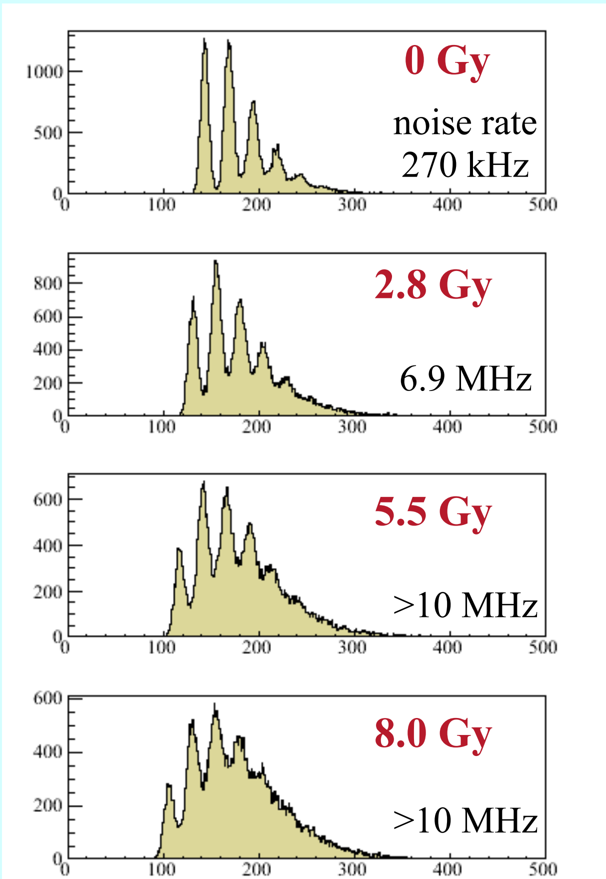
Proton irradiation



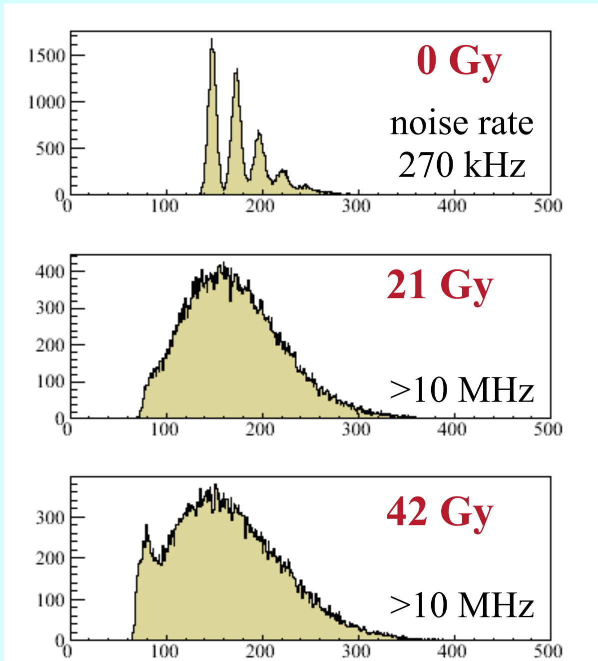
T. Matsumura
@PD07

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.

Are you interested?

- 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

For more information,

- Workshop for photo-detectors, especially focusing on Geiger-mode APDs, was held in June at Kobe.
- Presentations are available on the web.

http://www-conf.kek.jp/PD07/

- 'PD08' will be held in fall 2008 in Matsumoto (central Japan).

Final remarks

- MPPC (and other pixelized Geiger-mode APD) has many attractive features.
- Still new device:
  - There is much room for improvement/optimization
  - Many intense R&D ongoing over the world
- Direction of development depends on usage
  - Important parameters different for each application

- Hope this talk helps to understand current situation and to design your experiment!

	Gain	Noise	Dynamic range	PDE	Cross-talk	Cost	......
Number of pixels	–		+	–			
ΔV	+	+		+	+		
Temp	–	+		–	+	?	
Special structure					–?	+?	
Active area		+		+		+?	
....							

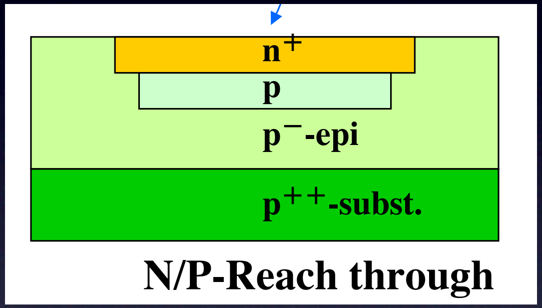
* Not a complete table but biased by personal view
** There may also be correlation...

Thanks!

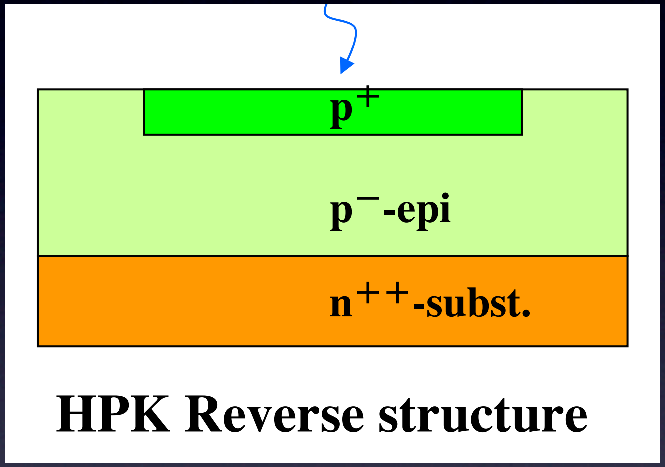
Backup

MPPC structure

Usual device:
n+ on p/p-



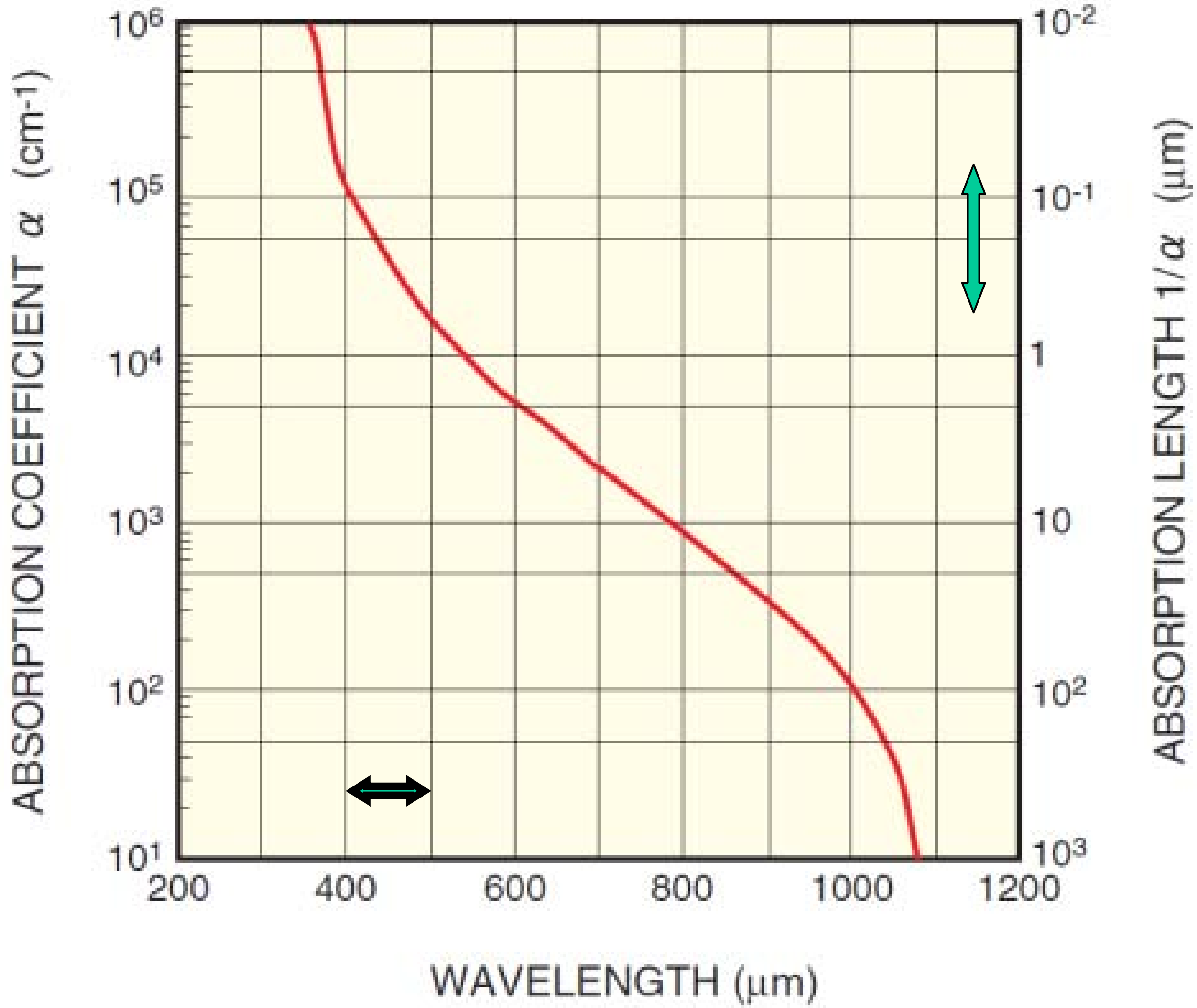
'Reverse structure': p+ on p- epi



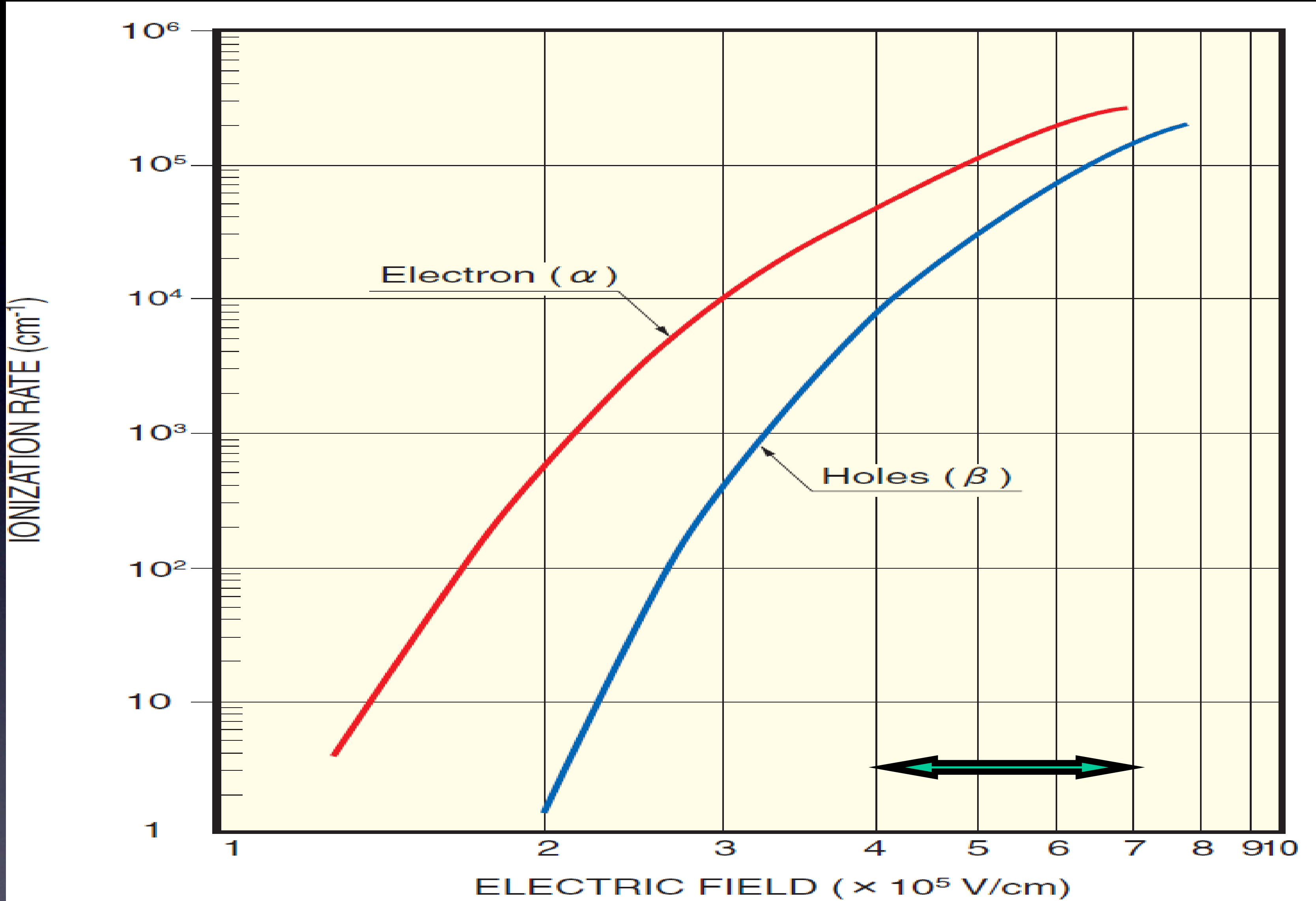
K. Yamamoto @ PD07

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

Photo Absorption coefficient of Silicon



K. Yamamoto @ PD07

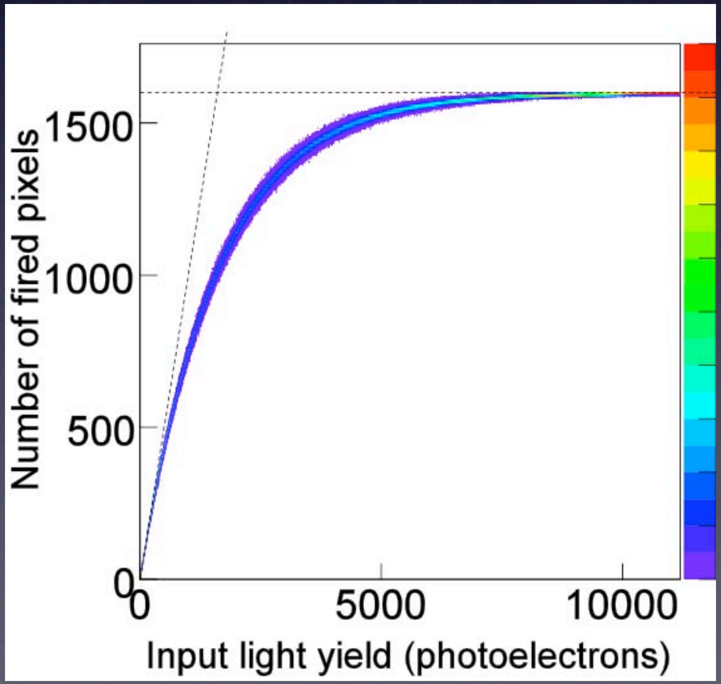


Ionization coffient for avalanche Multiplication

K. Yamamoto @ PD07

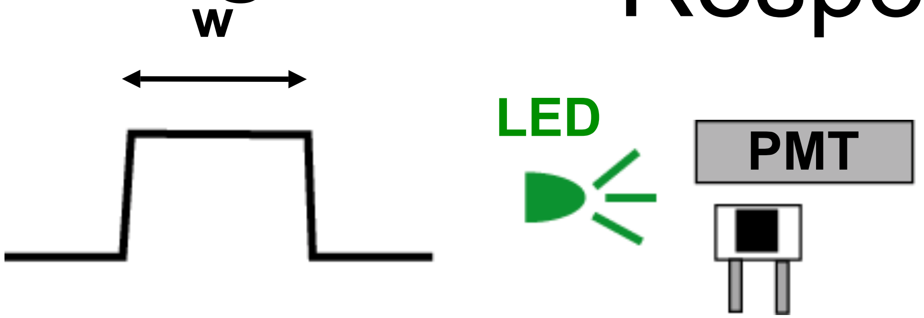
Dynamic range

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

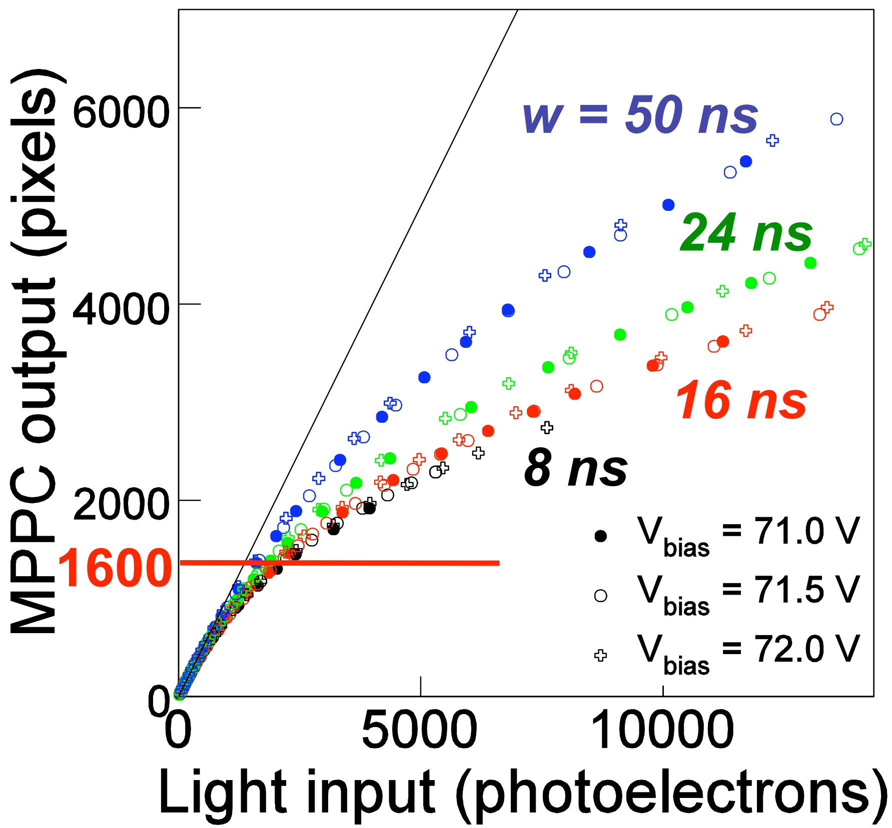


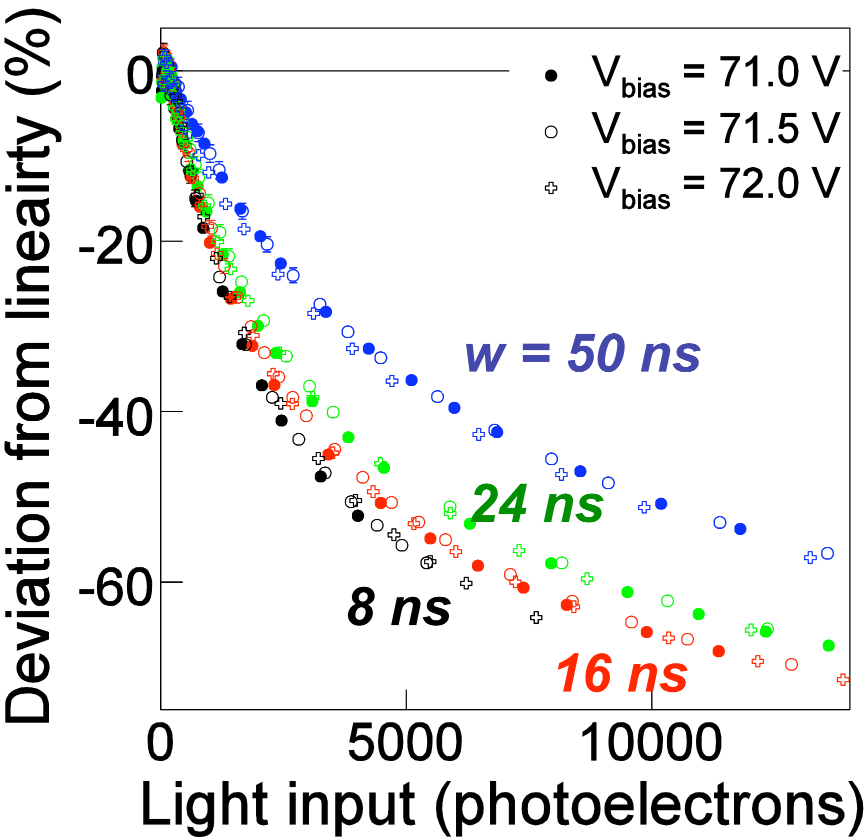
Response Curve

S.Uozumi @ PD07



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

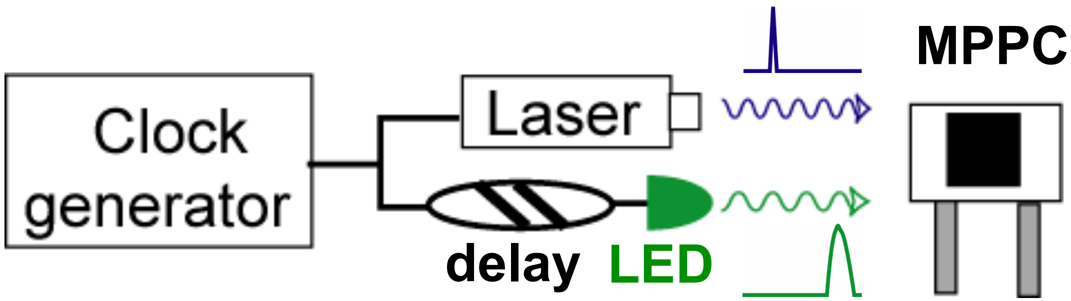




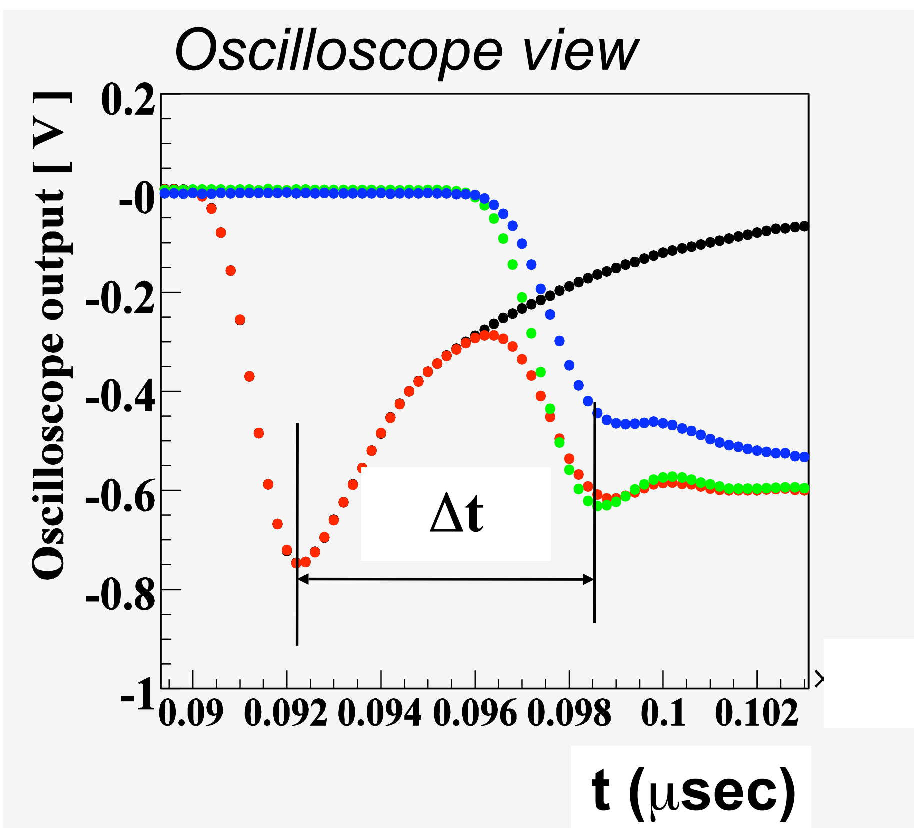
- **Dynamic range is enhanced with longer light pulse,**
- **Time structure of the light pulse gives large effects in non-linear region.**
- **No significant influence with changing bias voltage.**
- **Knowing time structure of scintillator light signal is crucial**
  -> study is ongoing.

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

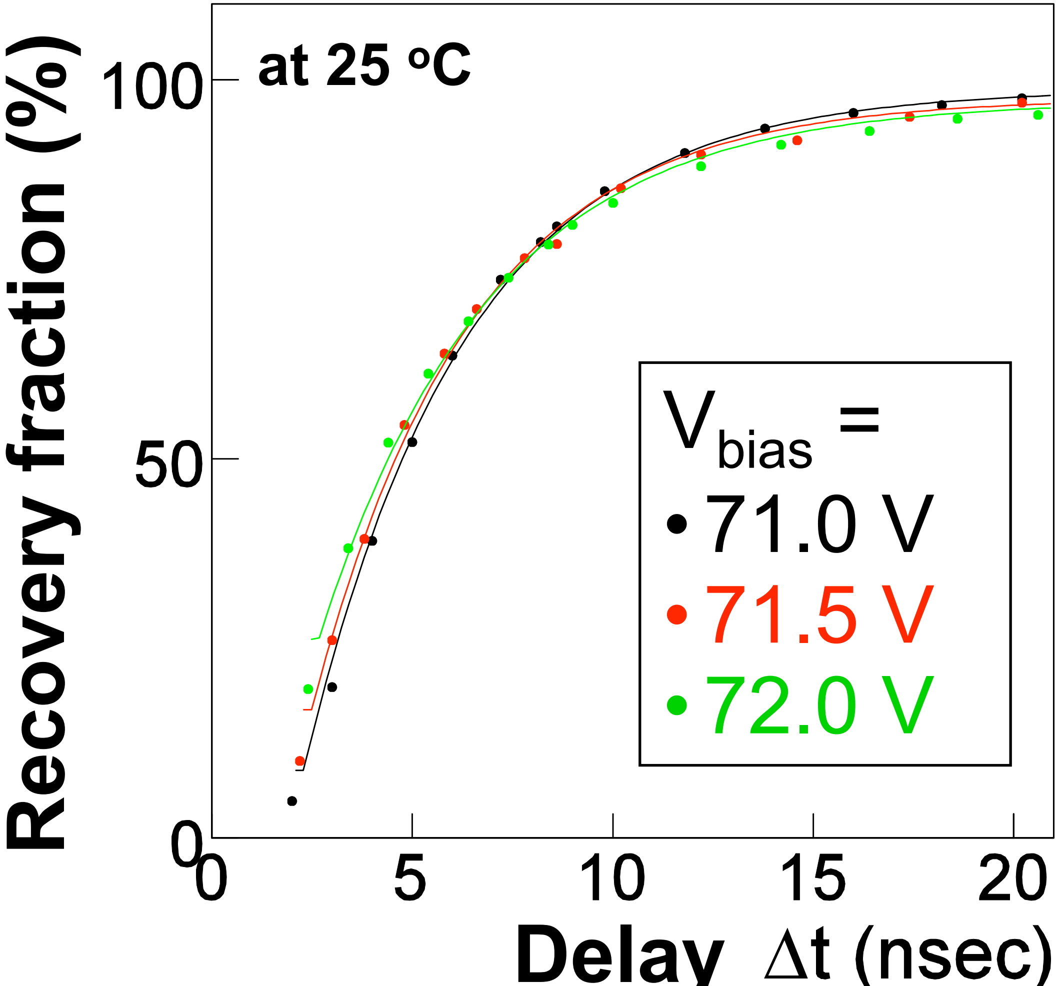
Red … Laser + LED

Blue … (Laser+LED) - Laser

Ratio of Blue / Green shows recovery fraction.

S.Uozumi @ PD07

Recovery Time Result



The curve is fitted by a function

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

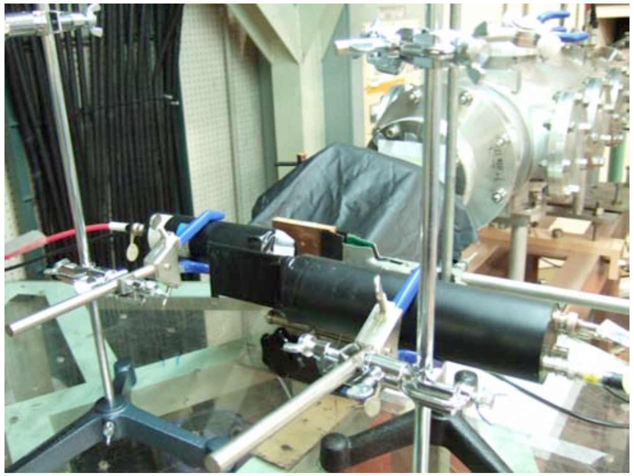
t_D : dead time

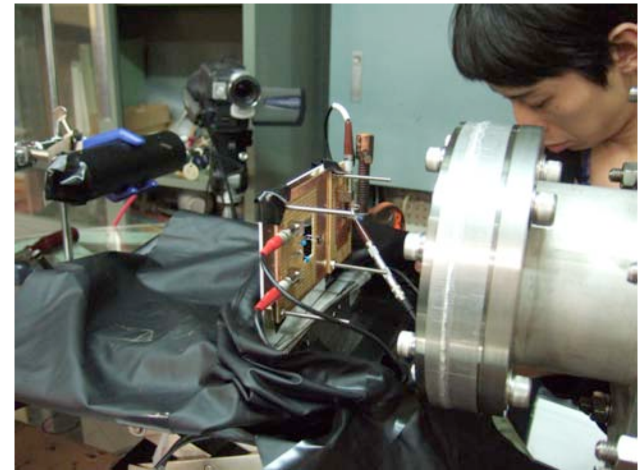
τ : recovery time

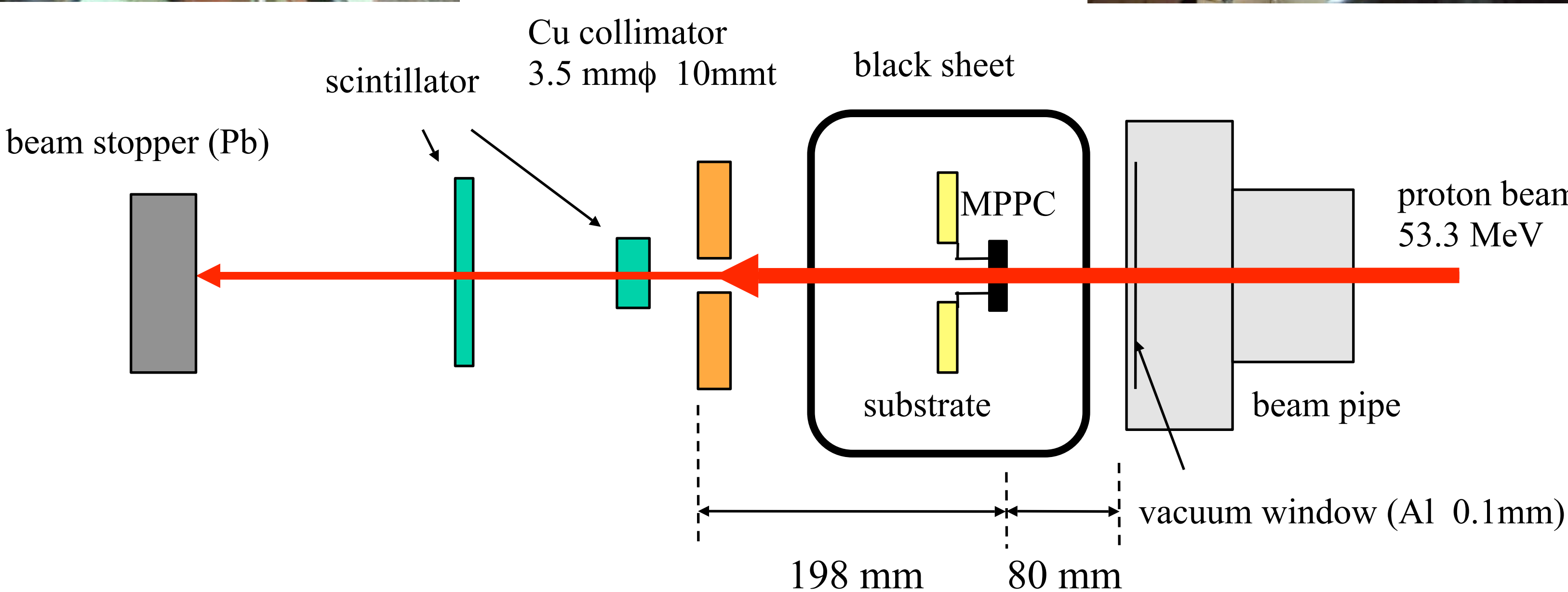
V_{bias} (V)	τ (nsec)	t_D (nsec)
71.0	4.1 ± 0.1	1.9 ± 0.1
71.5	4.0 ± 0.1	1.7 ± 0.1
72.0	4.2 ± 0.1	1.3 ± 0.1

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

Experimental setup





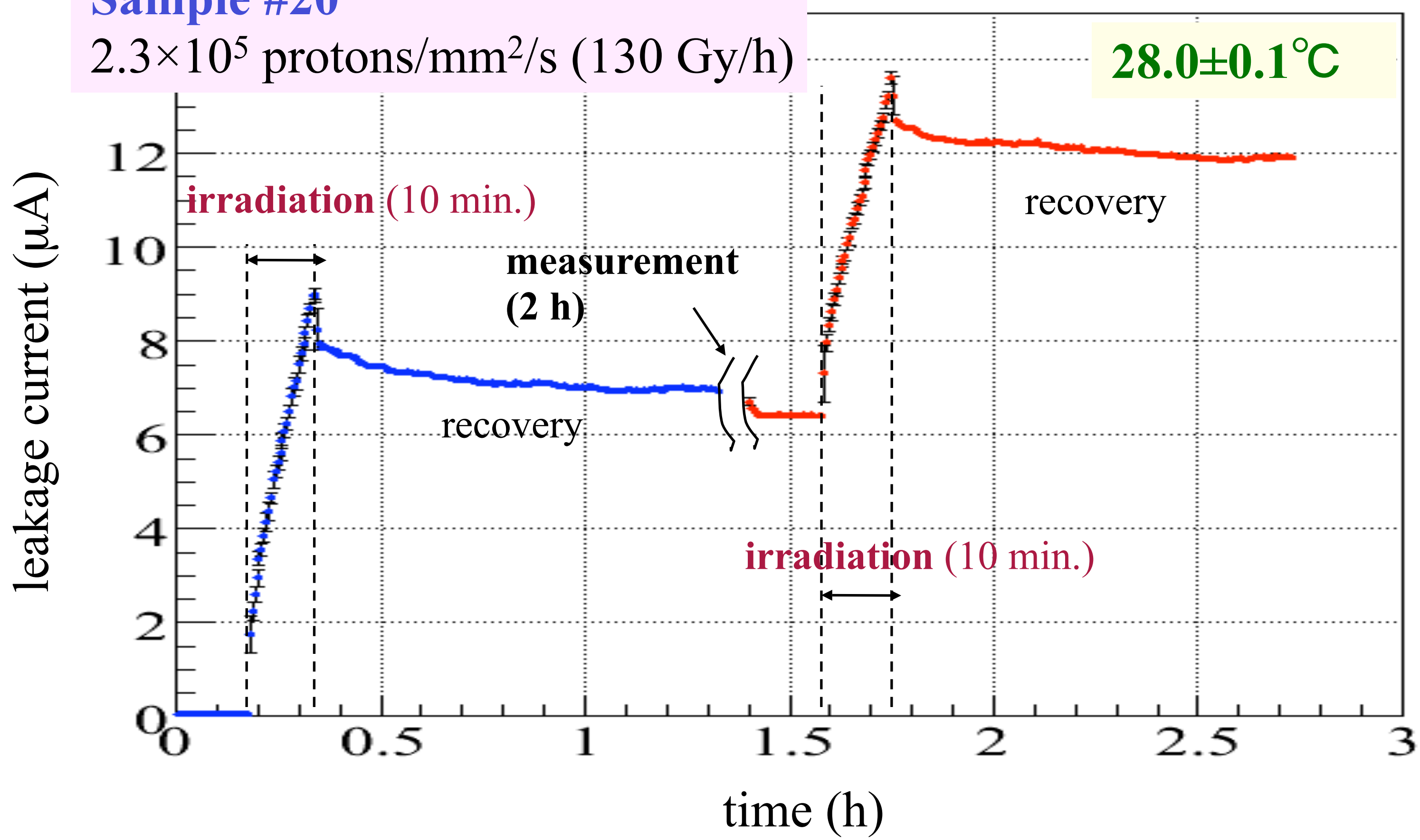


- **Beam intensity** ... monitored with two plastic scintillates

Variation of the leakage current
(higher flux irradiation)

T.Matsumura @ PD07

Sample #20
2.3×10^5 protons/mm^2/s (130 Gy/h)

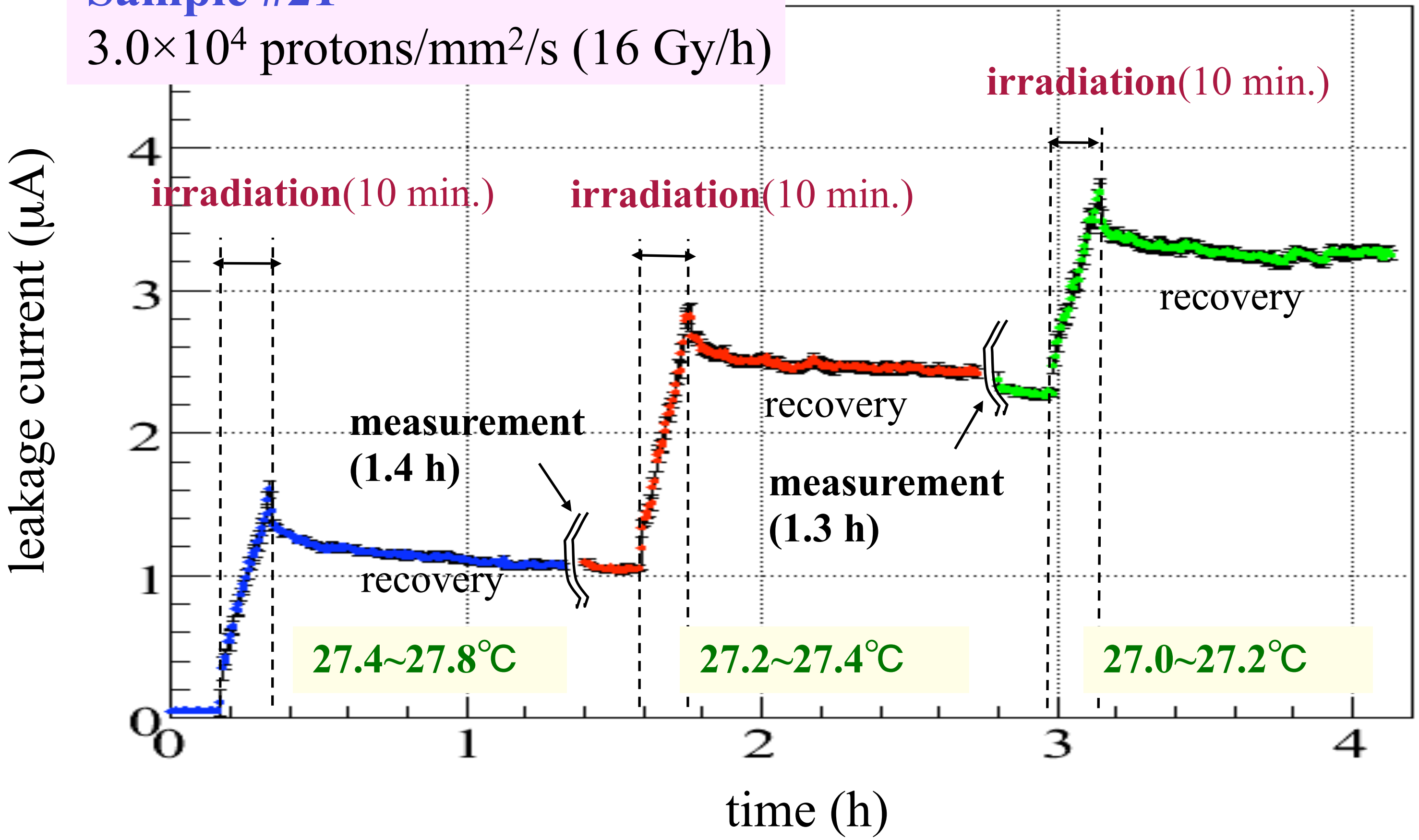


- The leakage current lineally increases with irradiated doses.
- Annealing effects are seen. But the radiation damage is not completely recovered within a few hour.

Variation of the leakage current
(lower flux irradiation)

T.Matsumura @ PD07

Sample #21
3.0×10^4 protons/mm^2/s (16 Gy/h)



- Similar tendency was observed as the higher-flux irradiation except for increasing rates of the leakage current.