Development and Study of the Multi Pixel Photon Counter

Satoru Uozumi (Shinshu University, Japan)
for the KEK Detector Technology Project / Photon Sensor Group
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KEK Detector Technology Project
Photon Sensor Group

(http://rd.kek.jp/)

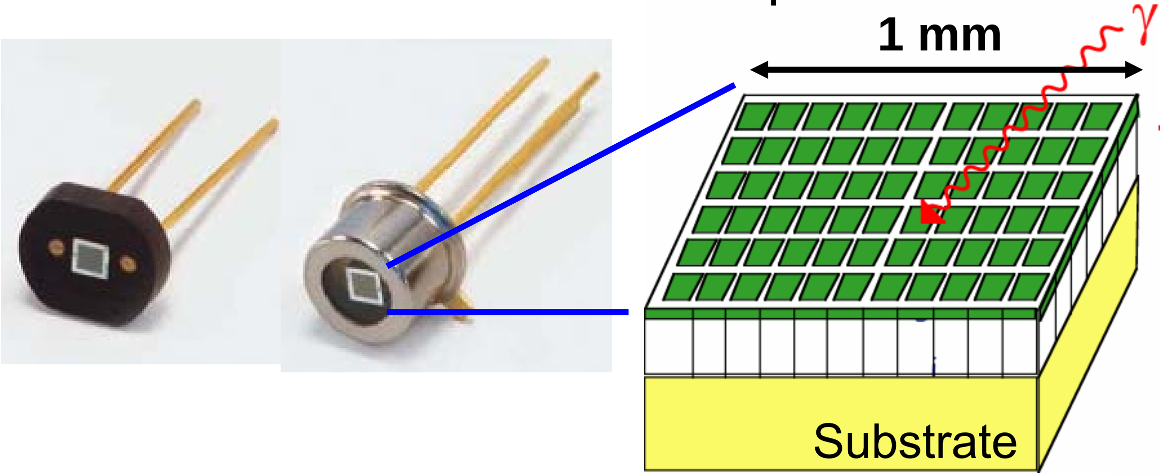
(KEK, Kobe, Kyoto, Nagoya, Nara-WU,
NDA, Niigata, Shinshu, Tokyo/ICEPP, Tsukuba)

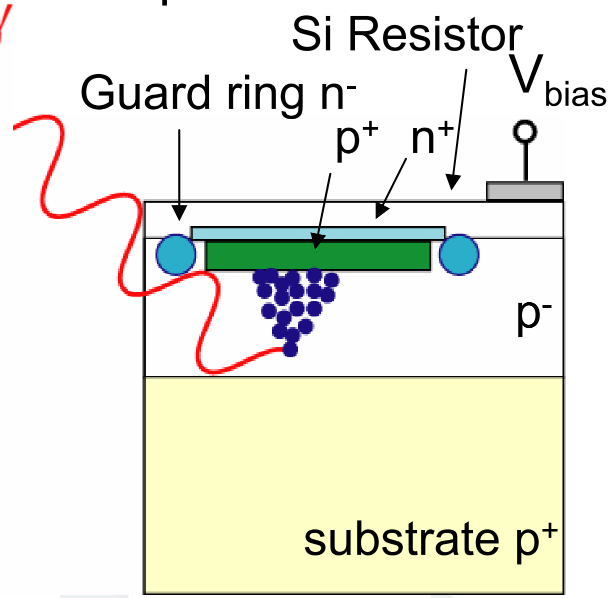
S. Gomi, H. Hano,T. Iijima, S. Itoh, K. Kawagoe, S. H. Kim,
T. Kubota, T. Maeda, T. Matsumura, Y. Mazuka,
K. Miyabayashi, T. Murakami, T. Nakadaira, T. Nakaya,
H. Otono, E. Sano, T. Shinkawa, Y. Sudo, T. Takeshita,
M. Taguchi, T. Tsubokawa, S. Uozumi, M. Yamaoka,
H. Yamazaki, M. Yokoyama, K. Yoshimura, T. Yoshioka

And special thanks to Hamamatsu photonics K.K.

The Multi Pixel Photon Counter (MPPC)

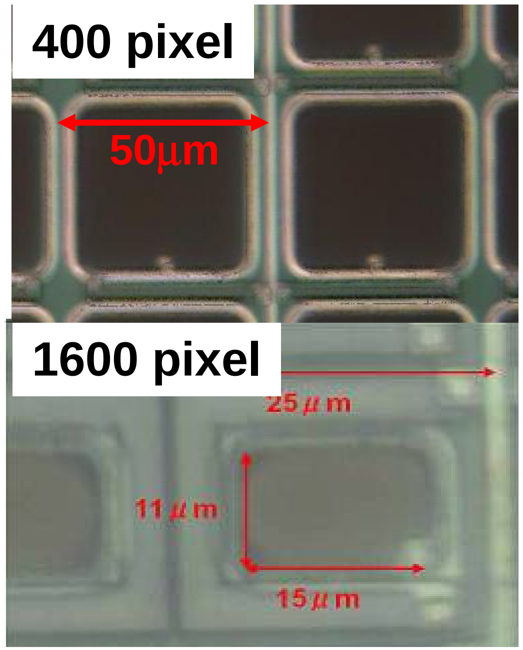
- A silicon avalanche photo-diode with multi-pixel structure -



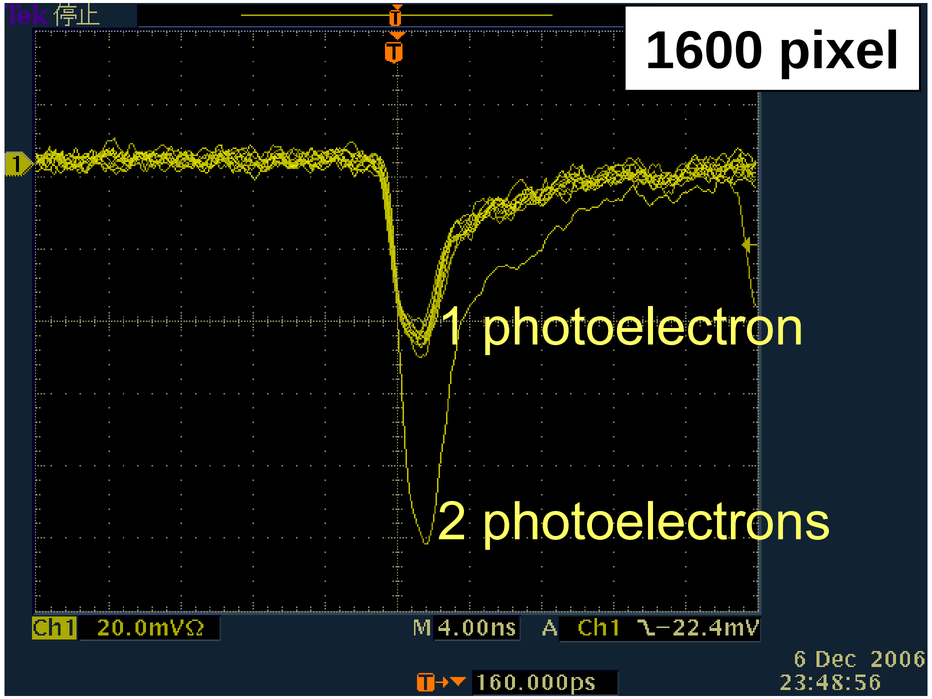


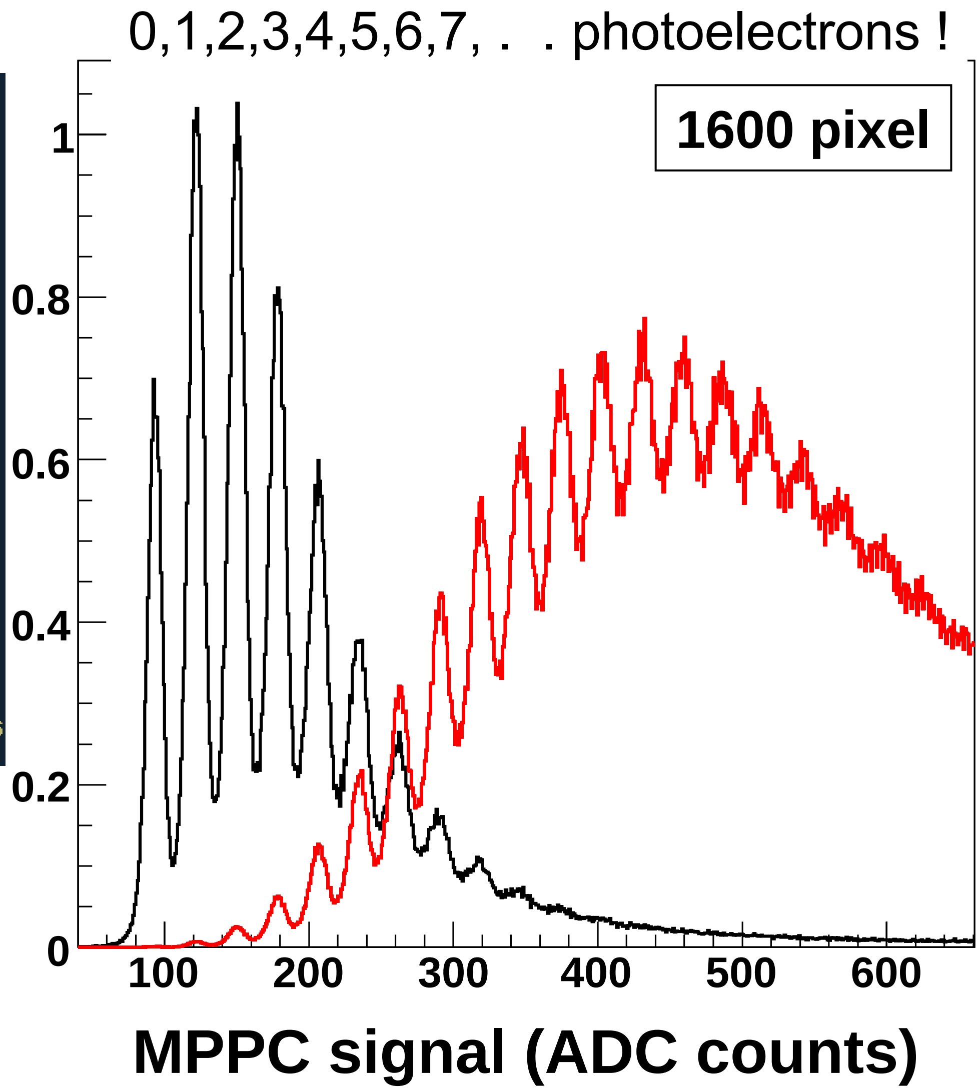
- Each pixel works as a Geiger-mode APD,
- One pixel can count only one photon.
  → need multi - pixel structure for photon counting
- Electric charges from all the fired pixels are summed up and read out as a signal.
- There are 4 different types available:

# of pixels	Sensor size	Pixel size	Geometrical eff.
100		100 μm	~ 0.65
400	1x1 mm^2	50 μm	~ 0.5
1600		25 μm	~ 0.25



Excellent Photon Counting Ability





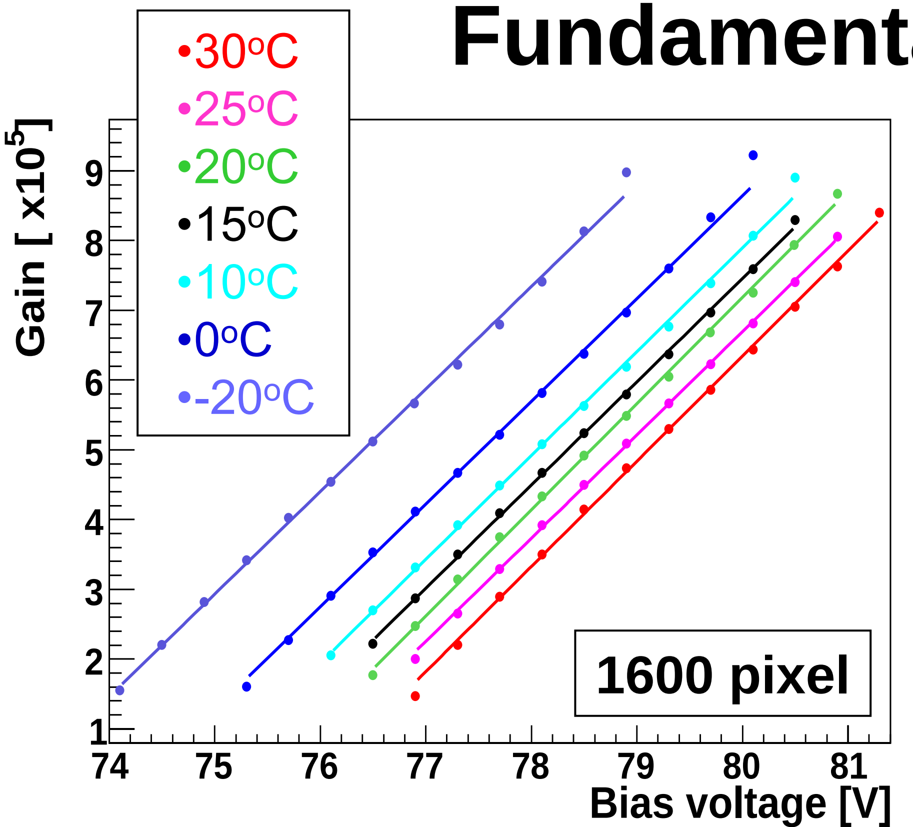
The MPPC has lots of advantages

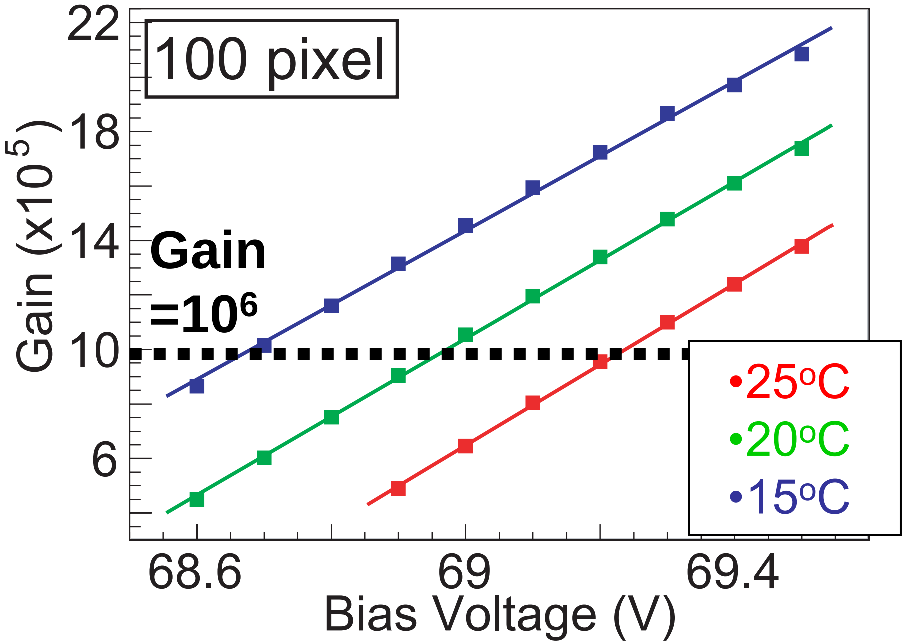
	Photomultiplier	MPPC
Gain	~10^6	10^5~10^6
Photon Detection Eff.	0.1 ~ 0.2	**0.2 (1600pix.) ~ 0.5 (100pix.)**
Response	fast	fast
Photon counting	Yes	Great
Bias voltage	~ 1000 V	~ 80 V
Size	Small	Compact
B field	Sensitive	Insensitive
Cost	Expensive	Not expensive
Dynamic range	Good	Determined by # of pixels
Long-term Stability	Good	Unknown
Robustness	decent	Unknown
Noise (fake signal by thermions)	Quiet	1 pixel noise exist (order of 100 - 500 kHz)

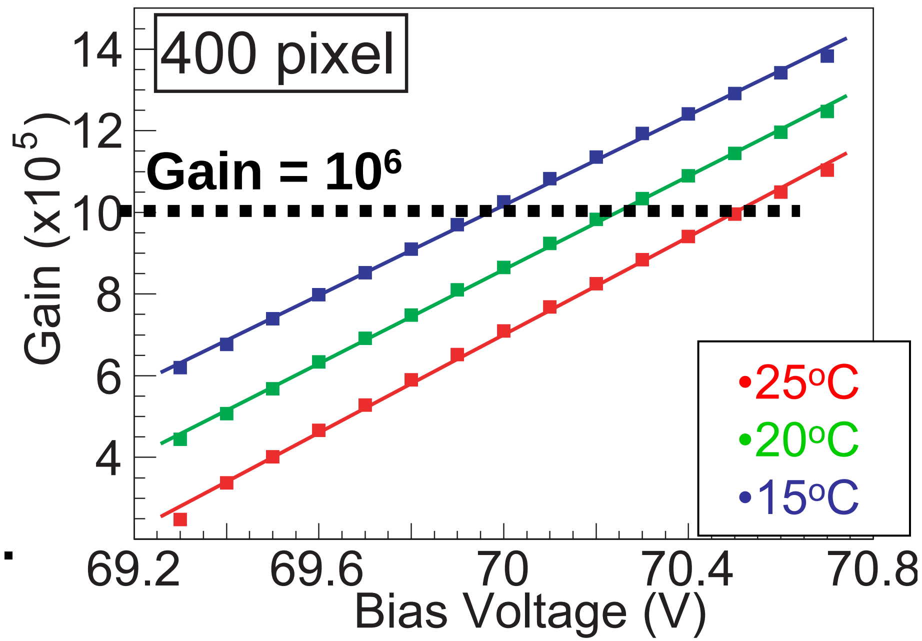
Fundamental performance

- Gain
- Dark Noise Rate
- Inter-pixel Cross-talk
- Photon Detection Efficiency
- Uniformity in a pixel

Fundamental Performance - Gain







$$\text{Gain} = \frac{C}{e}\underline{(V_{\text{bias}} - V_0)}$$

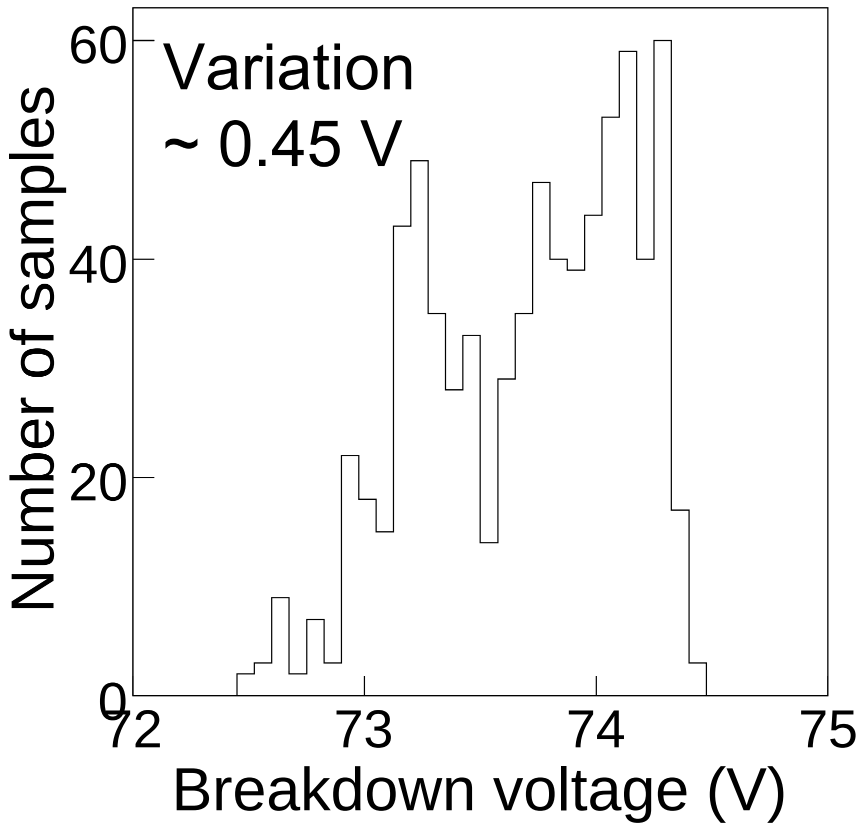
Over-voltage

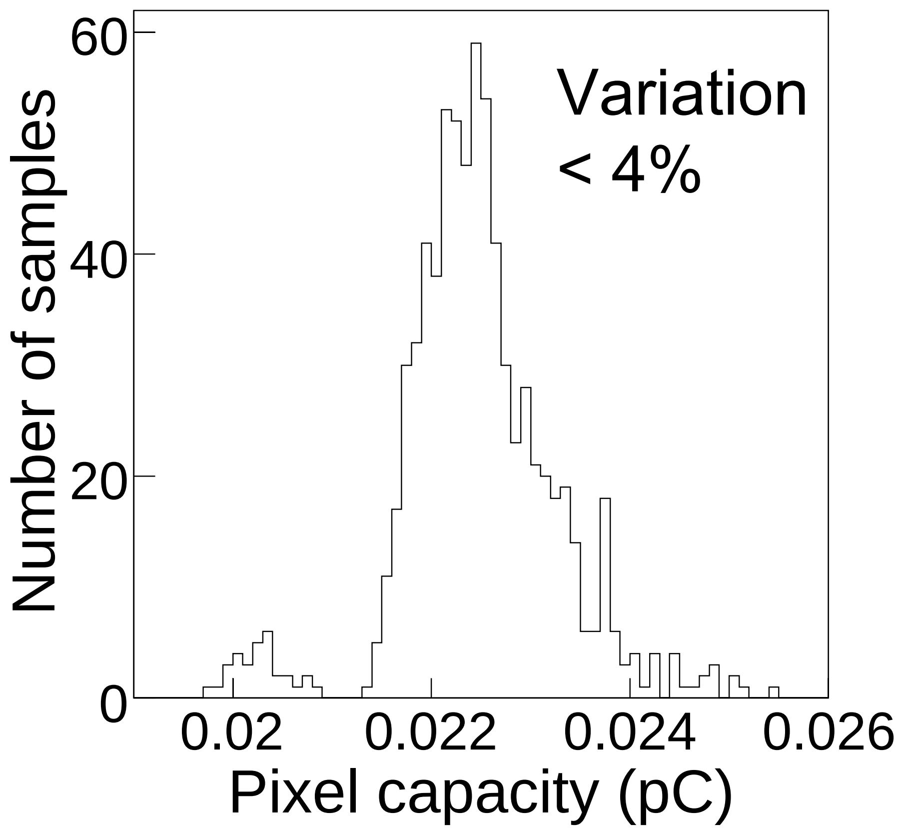
- C … Pixel capacity
- V_0 … Breakdown voltage

- **$V_0 \propto$ temperature ($\Delta V_0/\Delta T$ ~ 50 mV/C°)**
- **Larger pixel size results in larger gain.**

Variation of V_0 and C over 750 MPPCs

(Measured at 15°C)

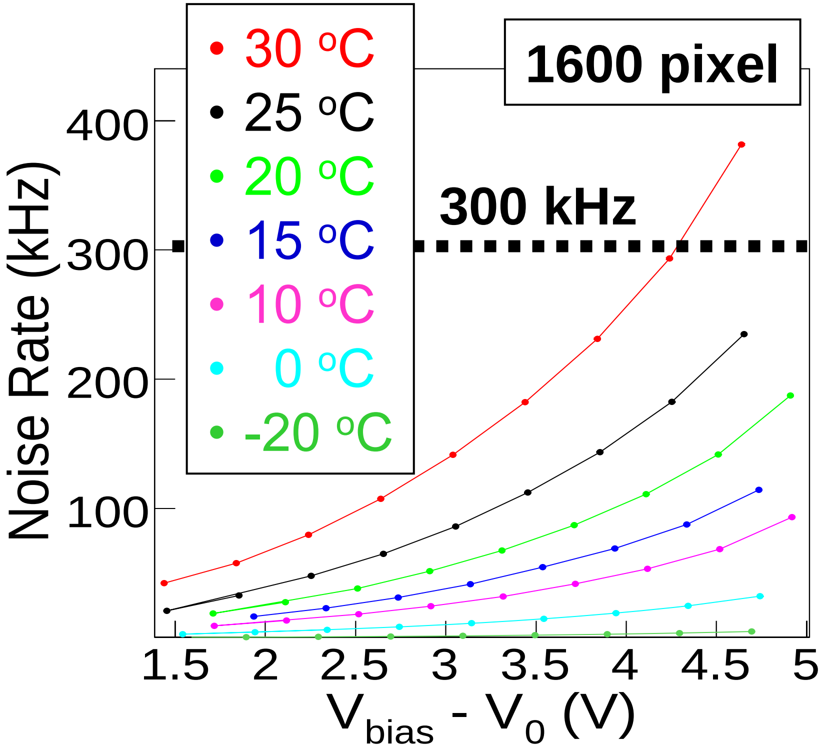


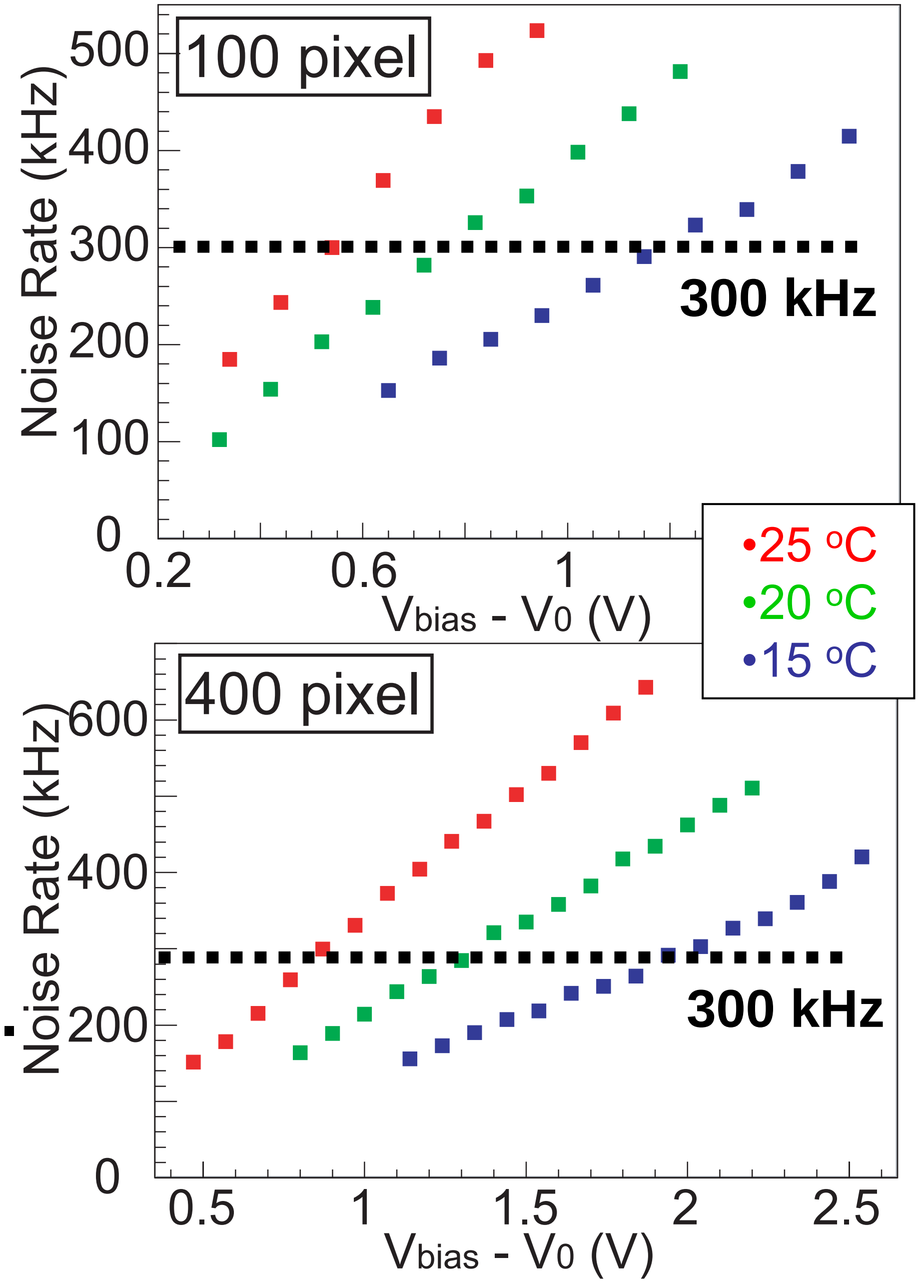


- ~750 pieces of 1600 pixel MPPCs have been tested.
- Device-by-device variation is less than a few %.

→ No need for further selection or categorization on massive use !
Just need a small tuning of operation voltages.

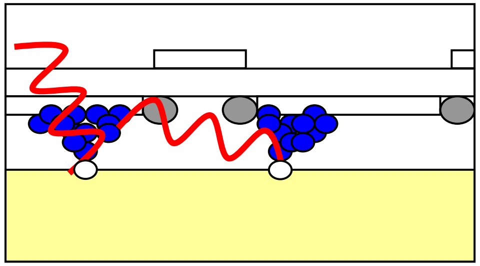
Fundamental Performance – Dark Noise Rate





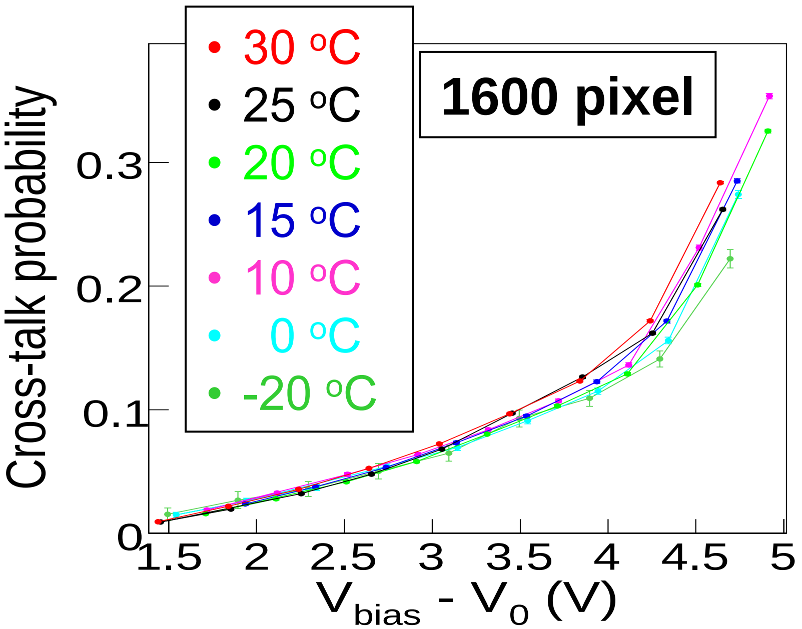
- **The dark noise is caused by thermal electrons.**
- **Its rate depends on both over-voltage and temperature.**
- **More number of pixels**
  → smaller active area
  → fewer noise rate

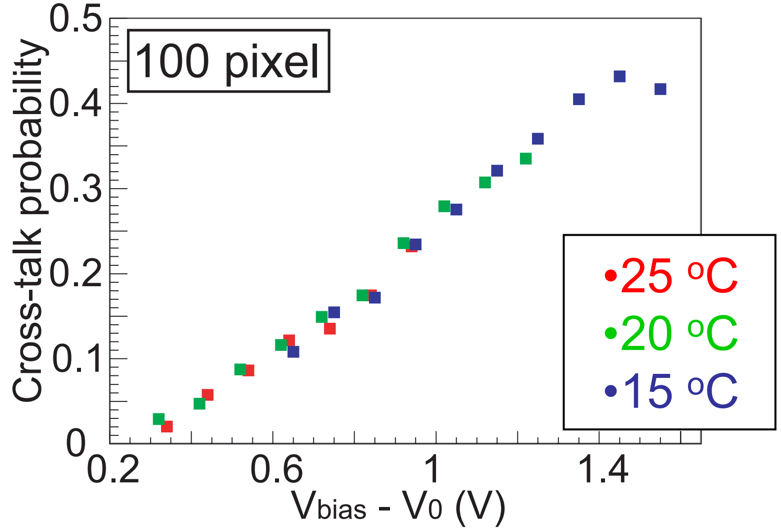
Fundamental Performance
- Inter-pixel Cross-talk -

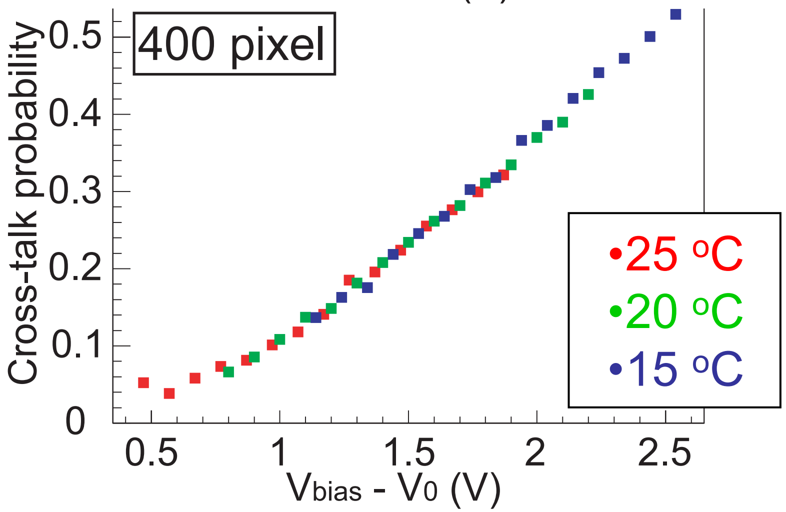


- Inter-pixel cross-talk is caused by a photon created in an avalanche
- Probability of the cross-talk has been measured using dark noise rates:

$$P_{crosstalk} = \frac{\text{Noise Rate}(\geq 2\ \text{pix.})}{\text{Noise Rate}(\geq 1\ \text{pix.})}$$







- Cross-talk probability is affected by over-voltage, but not affected by temperature.

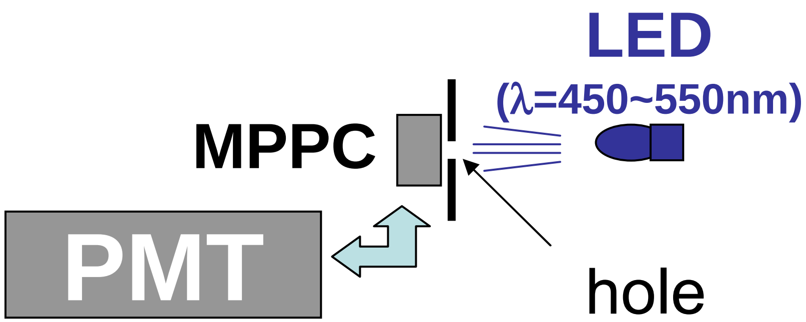
Fundamental Performance
- Photon Detection Efficiency (P.D.E) -

$$PDE(MPPC) = Q.E. \times \epsilon_{Geiger} \times \epsilon_{geom}$$

- Q.E. (~ 0.9) … Quantum Efficiency
- $\varepsilon_{\mathbf{Geiger}}$ (~ up to 0.9 , depends on bias voltage)
  … Probability to cause avalanche
- $\varepsilon_{\mathbf{geom}}$ (0.25 ~ 0.65 , depends on pixel size)
  … Fraction of sensitive region in a sensor

<u>Measurement of relative P.D.E.</u>

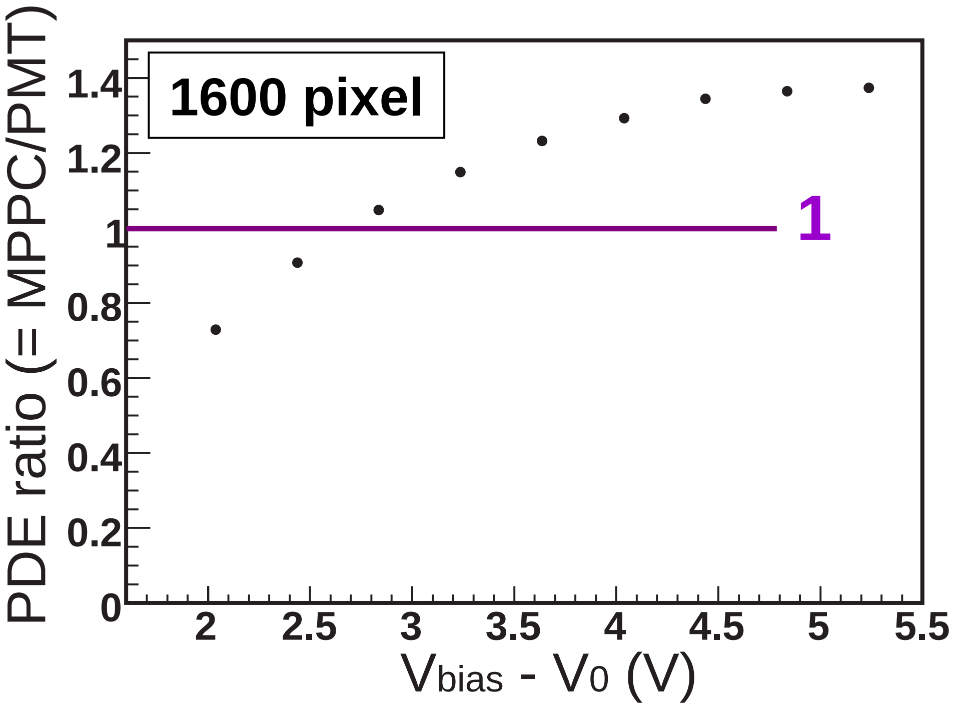
- Inject same light pulse into both the MPPC and the PMT, and compare light yield measured by both:

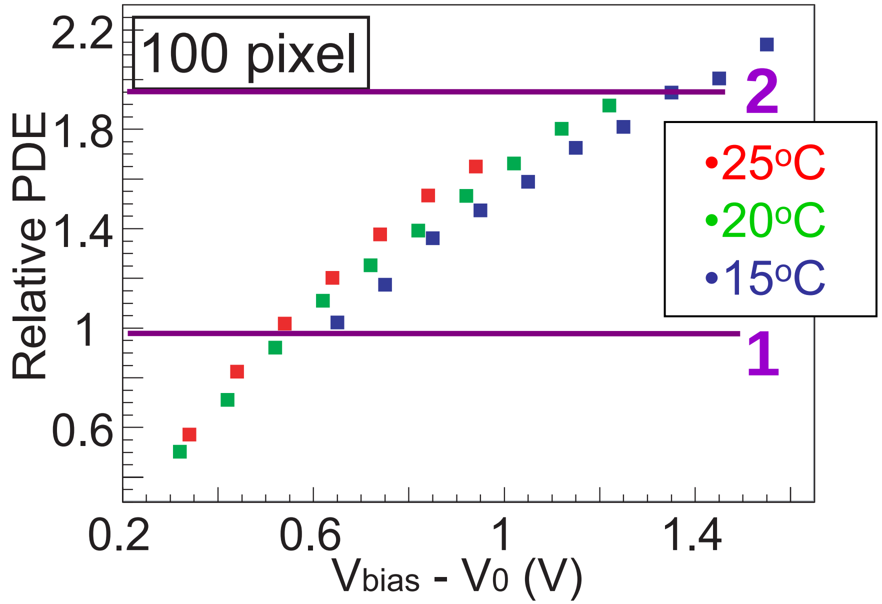


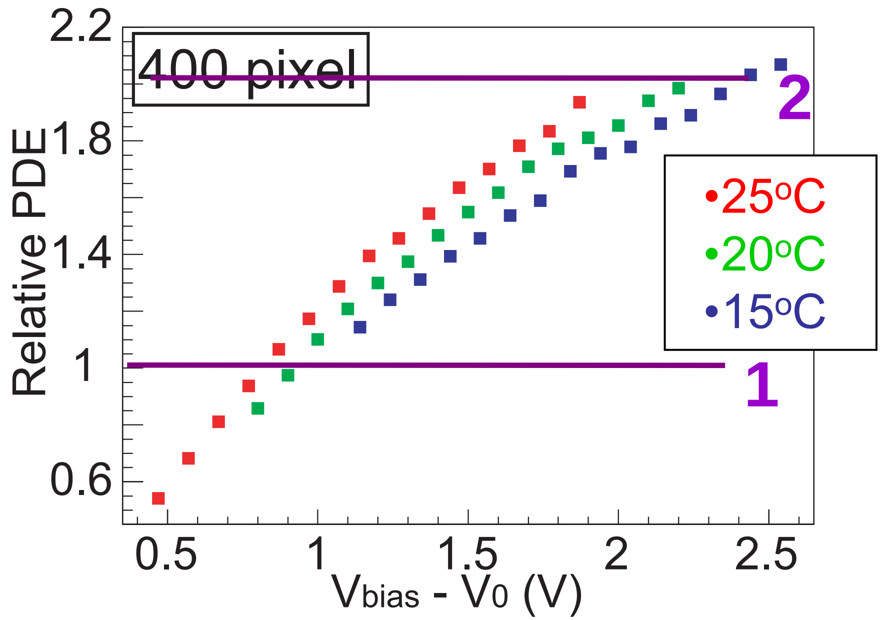
$$\frac{PDE(MPPC)}{\boxed{PDE(PMT)}} = \frac{N_{p.e.}(MPPC)}{N_{p.e.}(PMT)}$$

~15 %

Fundamental Performance
– Photon Detection Efficiency -



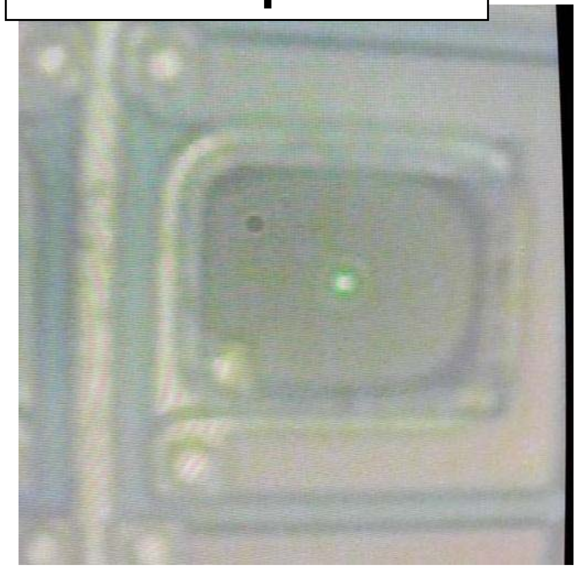




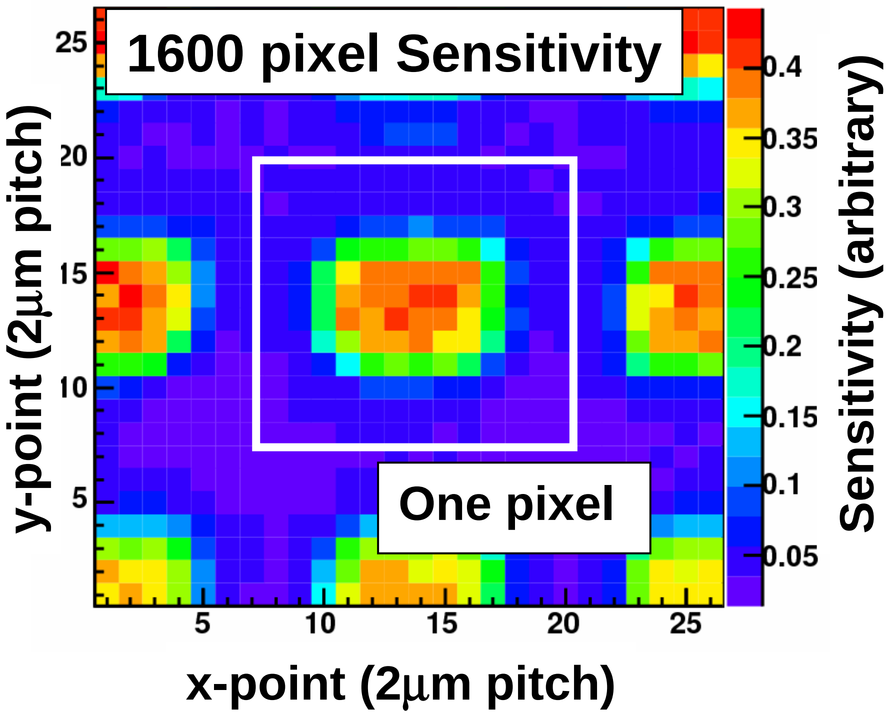
- **PDE of the MPPC is x1~2 of the PMT !**
- Larger pixel size
  → less dead space
  → larger PDE
- The PDE also depends on over-voltage, and slightly affected by temperature change.

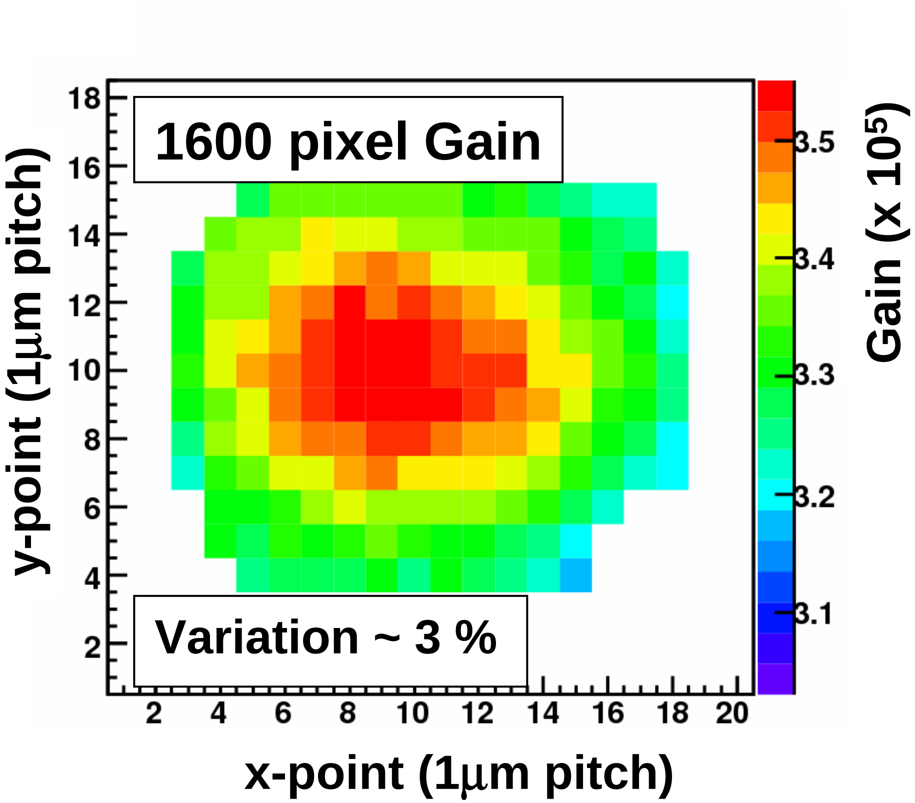
Laser Scan in One Pixel

1600 pixel
Microscopic view



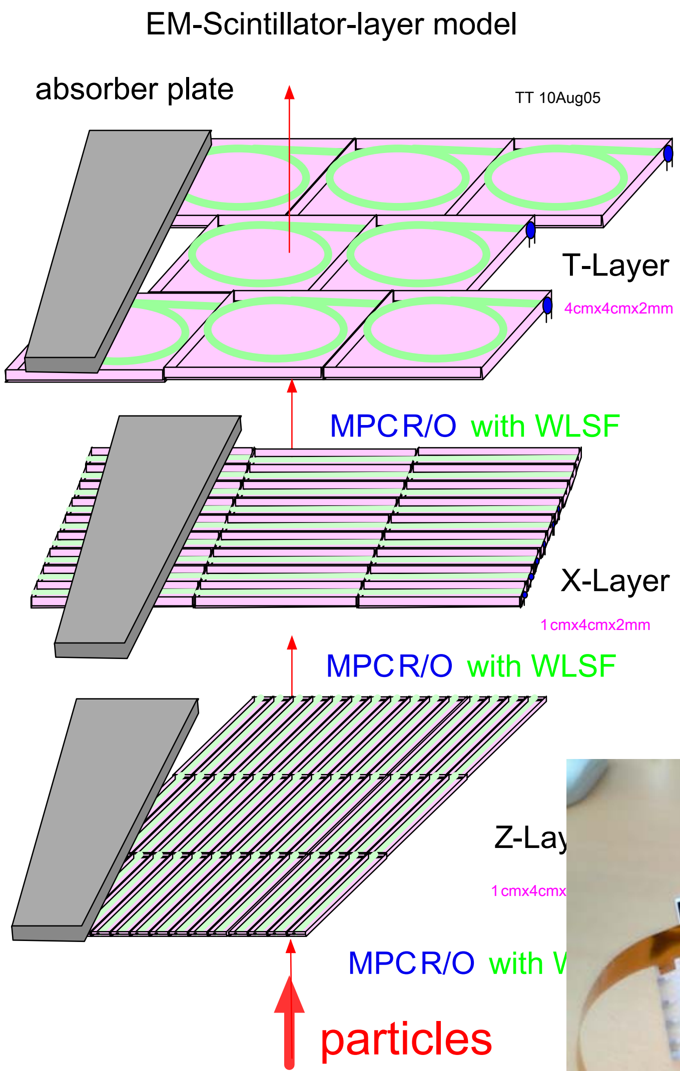
- Pin-point scan has been done using YAG laser (λ = 532 nm) with spot size ~ 1 μm.
- Variation of photon sensitivity and gain in one pixel are evaluated.
- Observed variation is 2 ~ 5 % in a sensitive area for the 100 / 400 / 1600 pixel MPPCs.



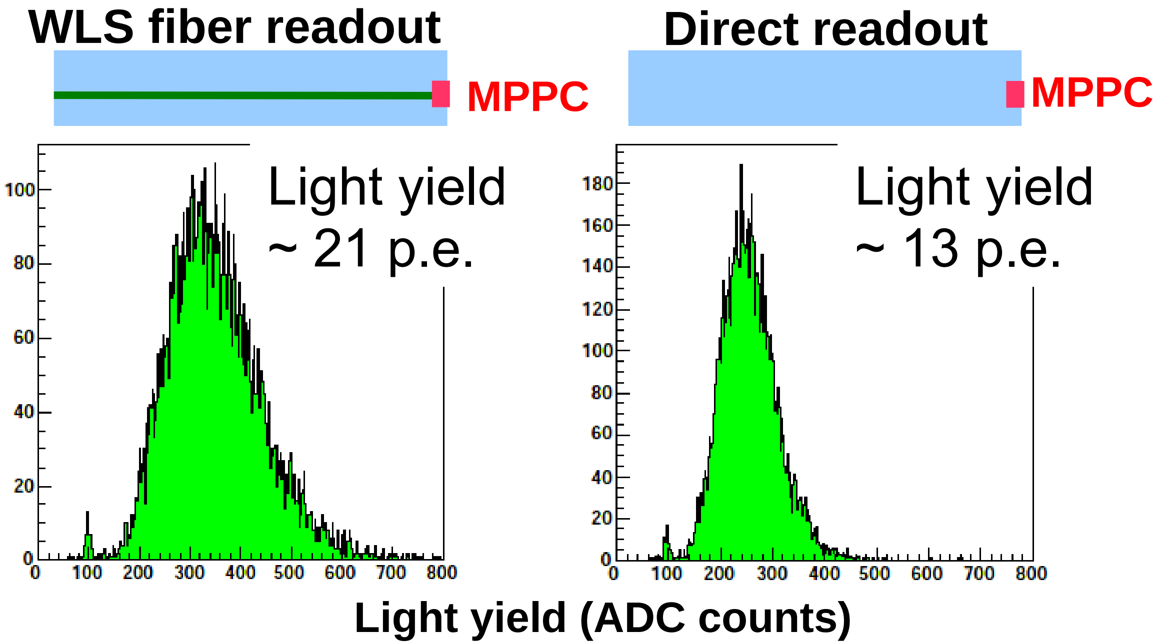


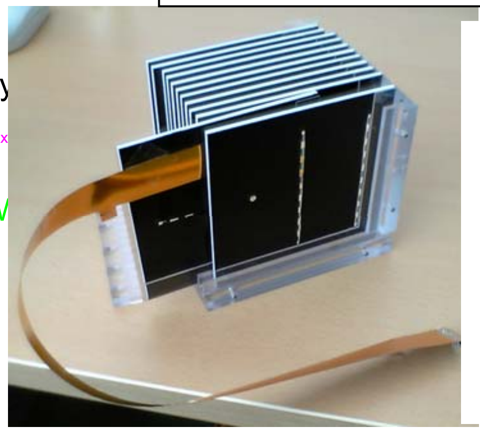
Practical Applications

Application to High Energy Physics
- Calorimeter for linear collider experiment -



Light yield of scintillator strip (1 x 4.5 x 0.2 cm) for beta-ray

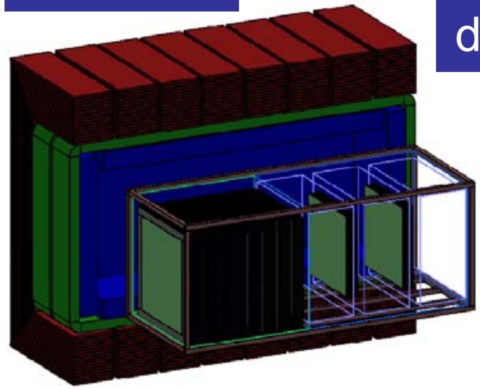




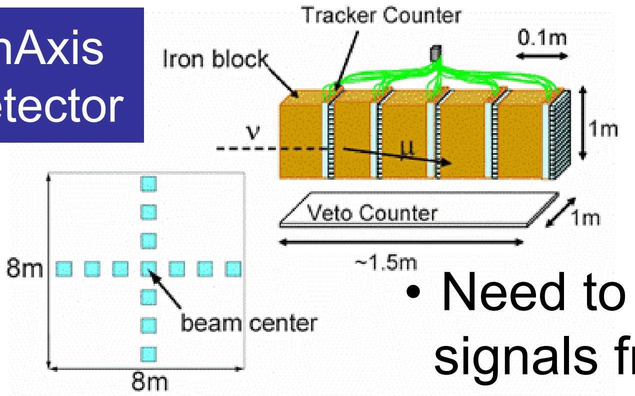
- The MPPC is feasible for strip-type scintillator calorimeter. (size,cost, performance…)
- Dynamic range is the key issue.
- First scintillator-ECAL beam test will start in next week at DESY !

Application to High Energy Physics
- T2K near detectors -

OffAxis detector



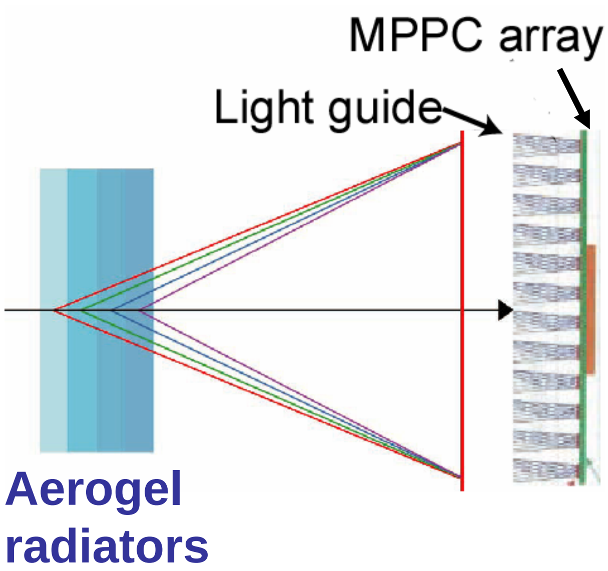
OnAxis detector



Scintillator + WLS fiber
With MPPC readout

- Need to read out large number of signals from WLS fibers in limited space
- Used in 0.2 Tesla magnetic field
- The MPPC is the perfect solution !

- Belle Ring Imaging Cerenkov Detector -



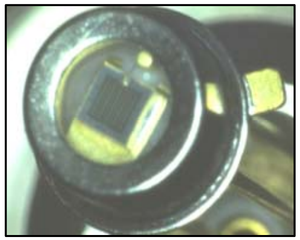
- Capture Cerenkov ring image for particle ID
- For the ring imaging,
  - Sufficient photon detection efficiency
  - Position resolution (~5 mm)

  are required for photon sensor.
- MPPC is a powerful candidate for this purpose,
- Larger sensor area (~3x3 mm^2) is desired in future development.

The MPPC is still evolving …

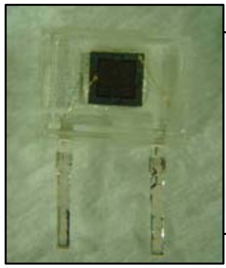
Stay tuned for future development !

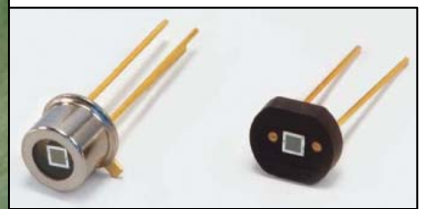
Mar. 2005
- 100/400 pixels
- First sample from Hamamatsu



Jan. 2006
- 100/400/1600 pixels
- Larger PDE
- More pixels

2006-2007
- 100/400/1600 pixels commercialized
- Improved Gain and dark noise
- Tests of massive use





Near future
- **Improved performance**
- **Larger sensor area**
- **More pixels**

?

Summary

- The MPPC is a promising photon sensor which has many remarkable features.
  - High gain, compact size, low-cost, excellent P.D.E., etc ….
- Extensive R&D of the MPPC is ongoing in KEK DTP group collaborating with Hamamatsu photonics.
  - Study and improvement of basic properties … underway
  - Evaluation of variation over many samples … underway
  - Study radiation hardness (for γ-ray, neutron) … just started
  - Evaluate robustness and long-term stability … start soon
  - Test magnetic-field tolerance … near future
- Tests for actual use at several high energy physics experiments are also underway.
- Applications in various other fields are being explored.
  - Positron Emission Tomography, etc…
- The improvement of the performance will be continued toward the “Perfect Photon Sensor” !

Novel Photon Detector Workshop June-2007 Kobe, Japan

The KEK Detector Technology Project group
will host an international workshop
for the future photon sensors.
Check the KEKDTP web site:
http://rd.kek.jp/
Contact : Takeshi.Nakadaira@kek.jp

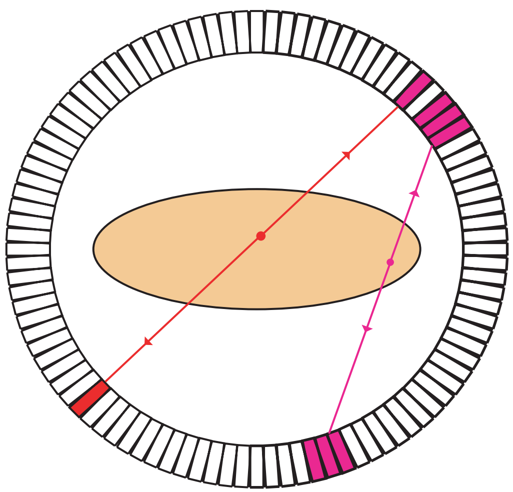
Backups

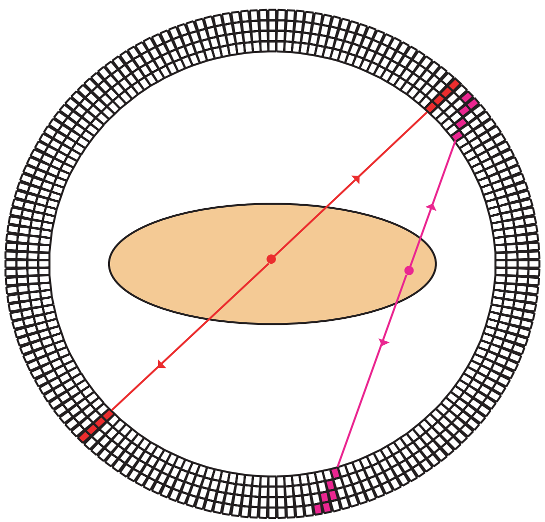
Application to Other Fields

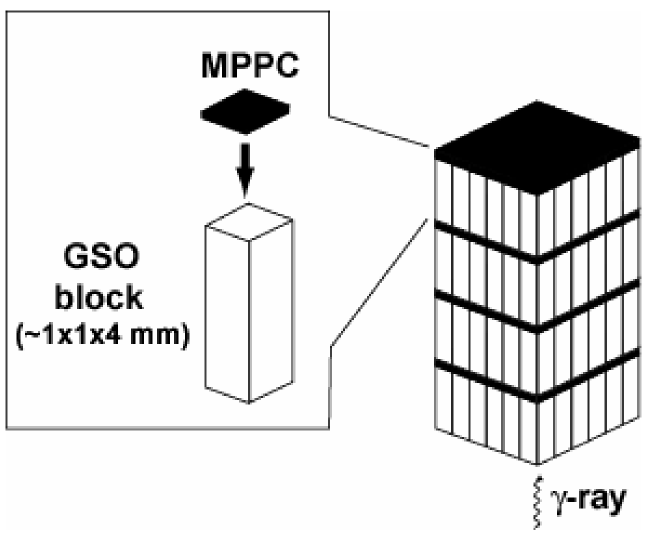
Positron Emission Tomography (PET)

… a powerful method to detect cancer activity.

- Capture gamma pair and identify position of the cancer.
- Spatial resolution is greatly improved by finer granularity (~1 mm of crystal block size).
- MPPC is ideal to read out each individual crystal blocks.



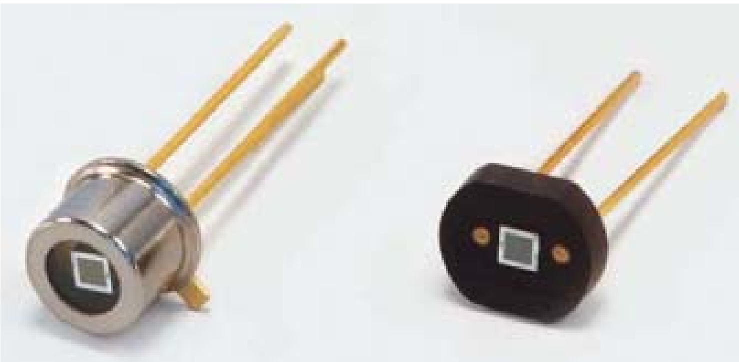




MPPCs on sale

Number of pixels	100	400	1600
Sensor size	1 x 1 mm^2		
Nominal Bias Volt.	70 $\pm$10 V		77$\pm$10 V
Gain (x 10^5)	24.0	7.5	2.75
Noise Rate (kHz)	400	270	100
Photon Detection Efficiency	65 %	50 %	25 %
Temperature dependence ($\Delta V_0/\Delta T$)	50 mV / ^oC		

(Numbers from HPK catalog)



- Hamamatsu photonics is starting to deliver the MPPC.
- See following page for more information:

http://www.hamamatsu.com/news/2006/2006_10_26.html