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Recent Developments of Photon Counting Devices at Hamamatsu

Solid State Division
Hamamatsu Photonics K.K.

10/23/2020

What Is Photon Counting

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Photon counting

Photon counting technology is very important in detecting weak light.

Applications: Medical, radiation monitoring, biomedical, high energy physics, LiDAR, etc.

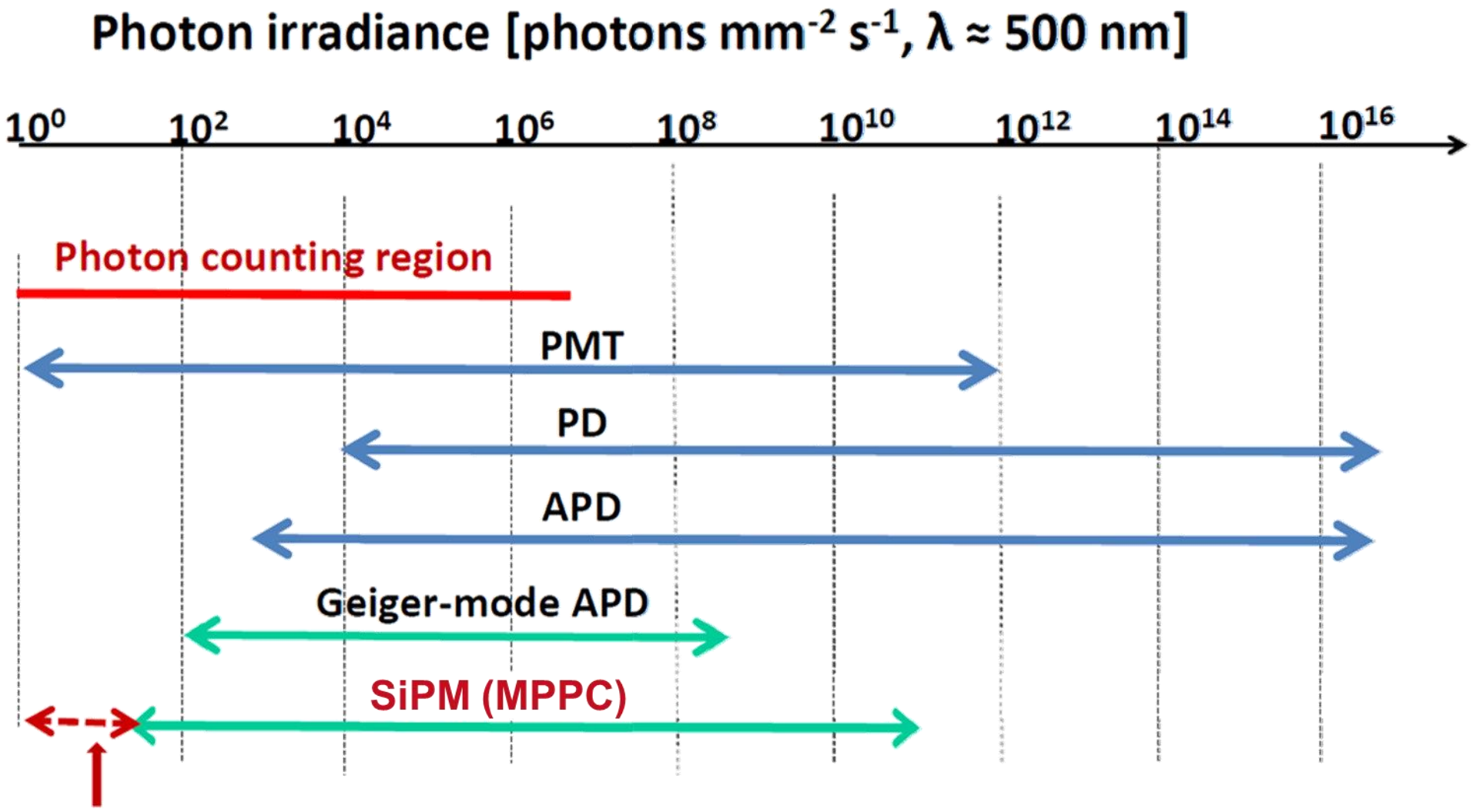
Hamamatsu is well-known as the best supplier of photon counting detectors:

PMTs

Image Intensifiers

EMCCD/sCMOS Cameras

Detectable Photon Levels

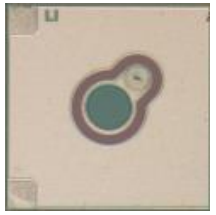


Single photon detection is possible, but with some limitations.

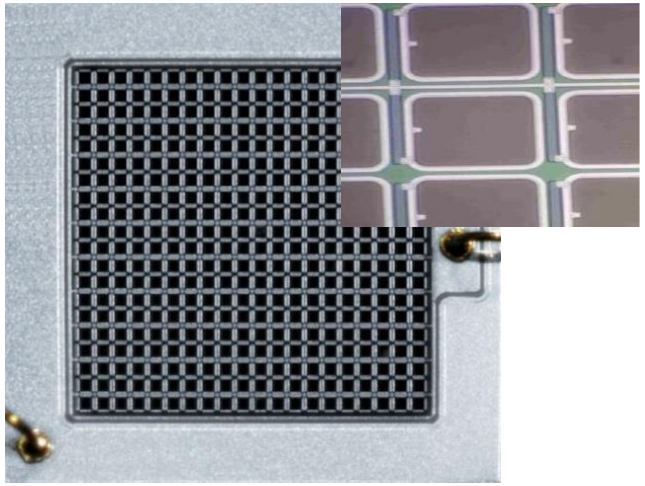
SPPC and MPPC

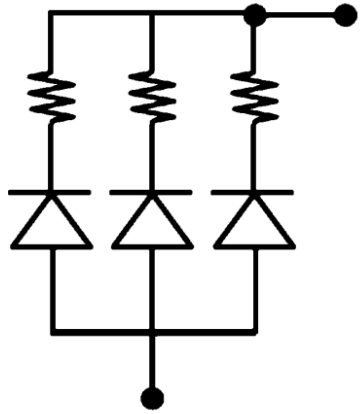
SPPC: Single-Pixel Photon Counter

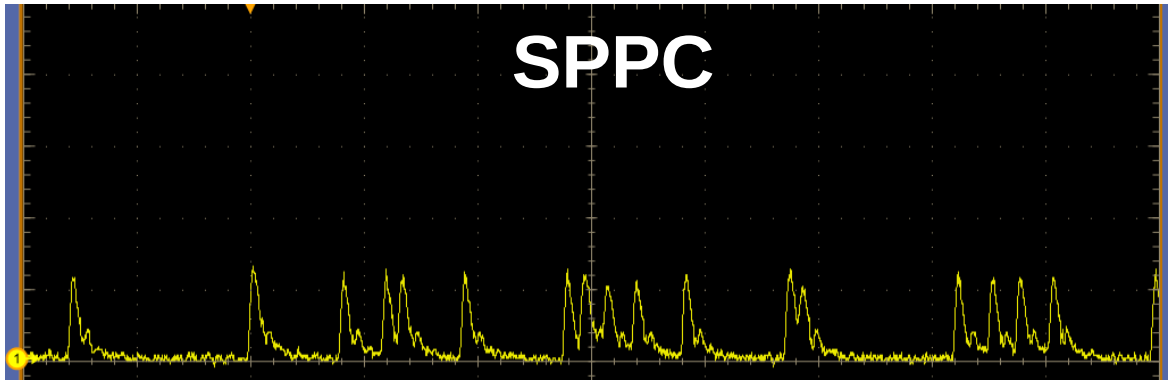
- Only one pixel
- Includes Geiger-mode APD and quenching resistor

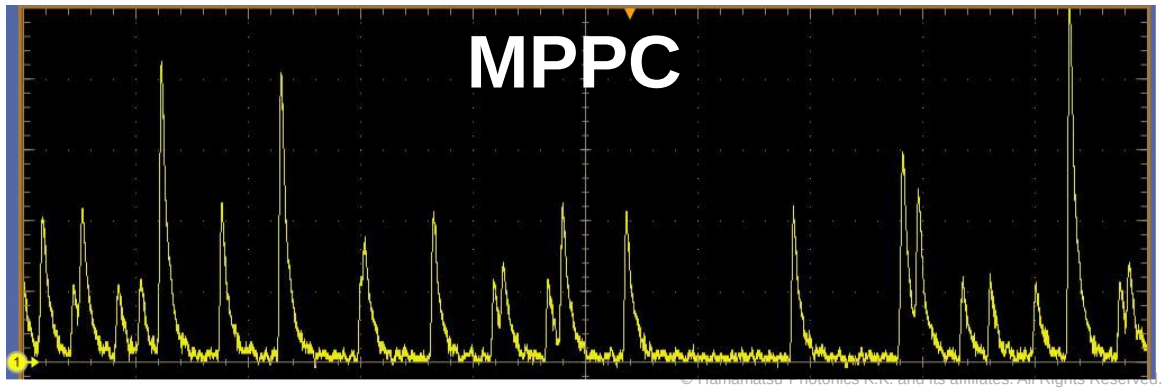


MPPC: Multi-Pixel Photon Counter







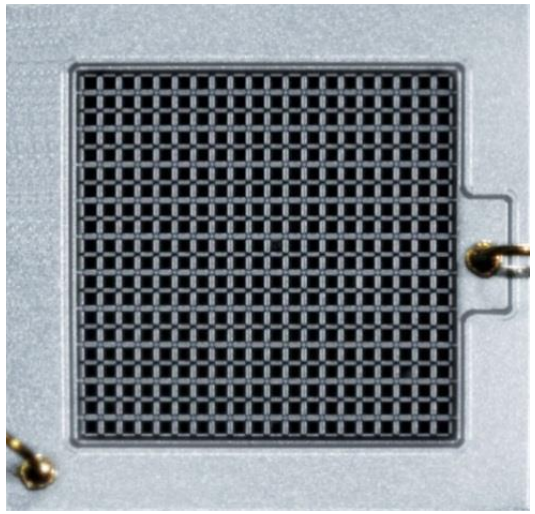


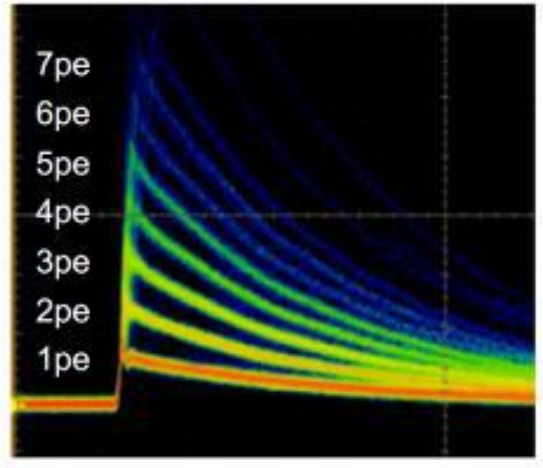
What is an MPPC?

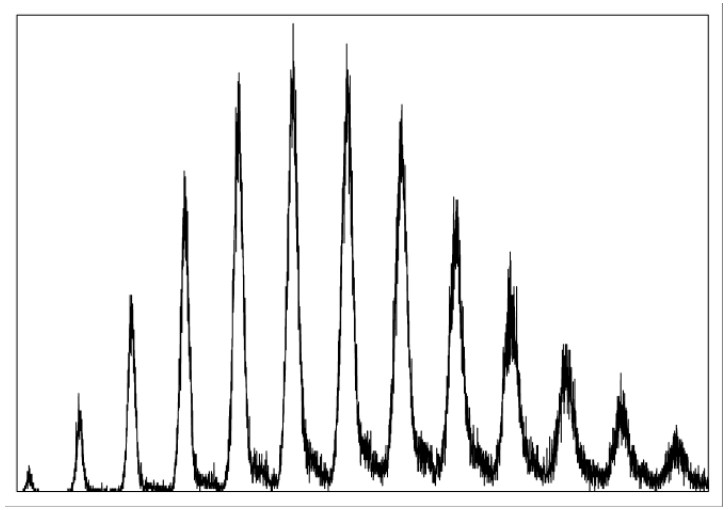
Hamamatsu decided to call SiPM as MPPC.

The MPPC (Multi-Pixel Photon Counter) is one of the devices called SiPM (silicon photomultiplier).

It is a photon-counting device using multiple APD pixels operating in Geiger mode.

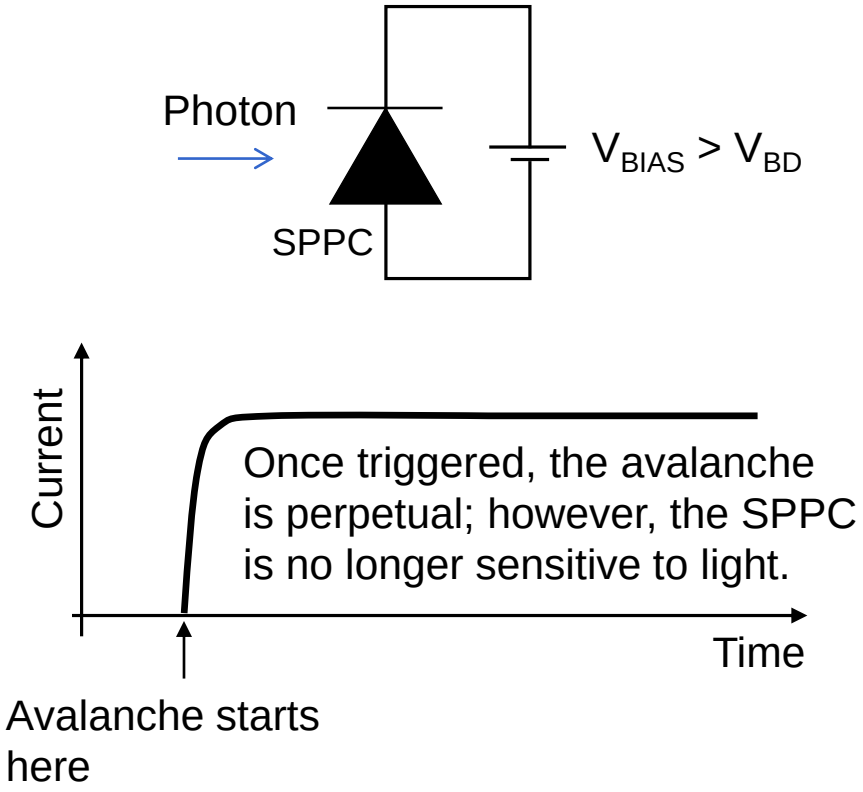


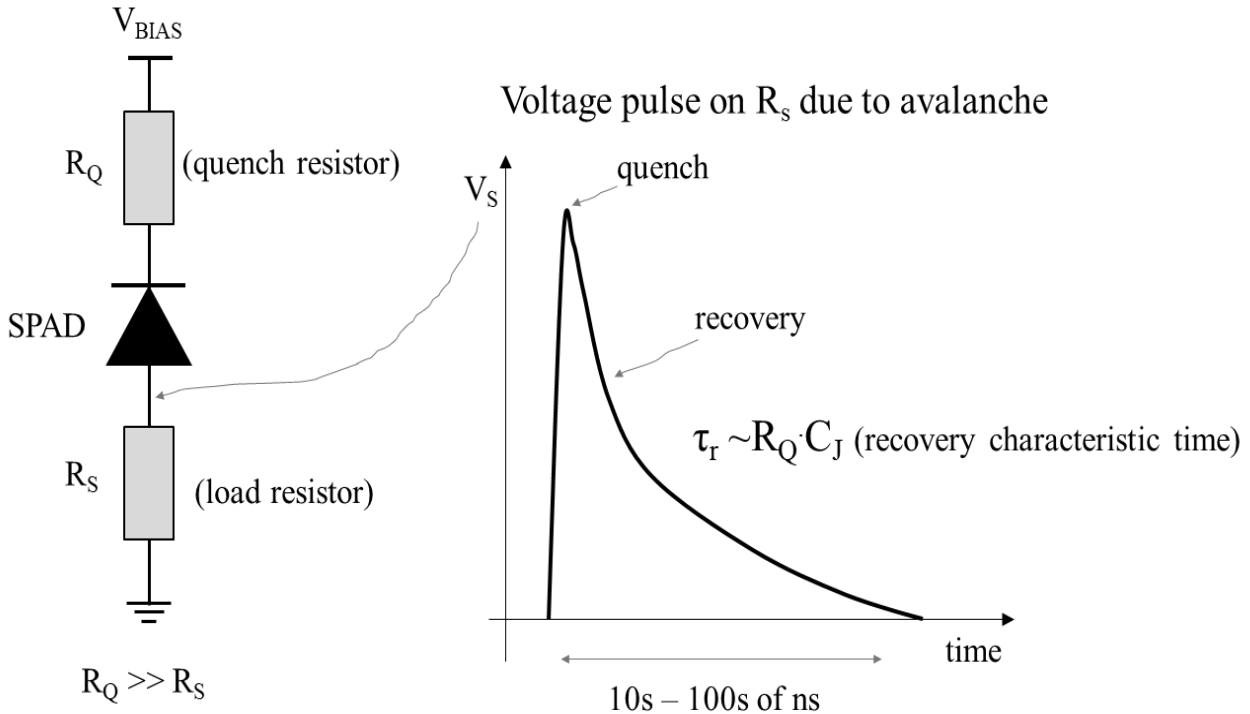




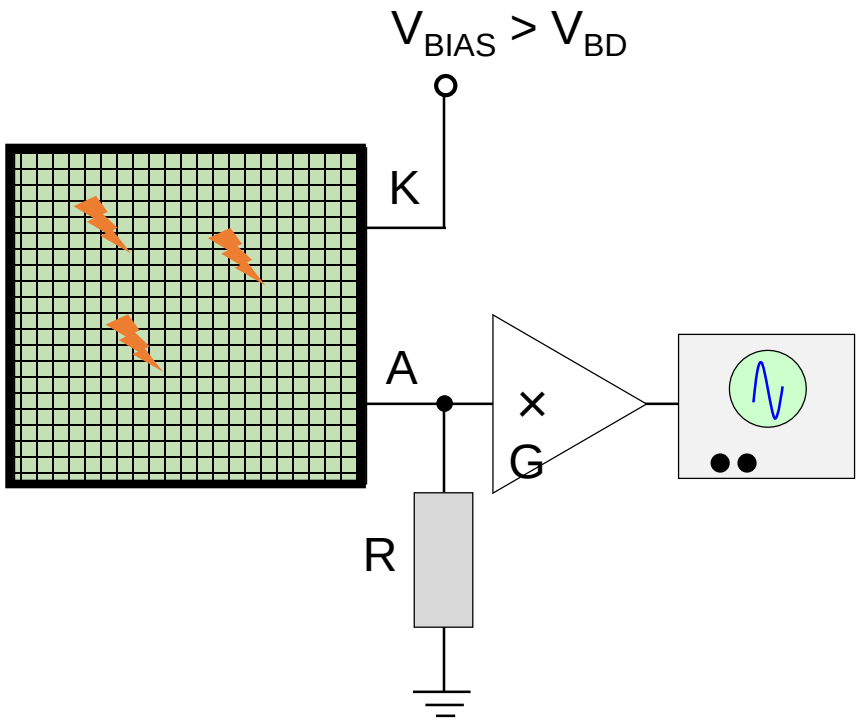
Features of SiPM

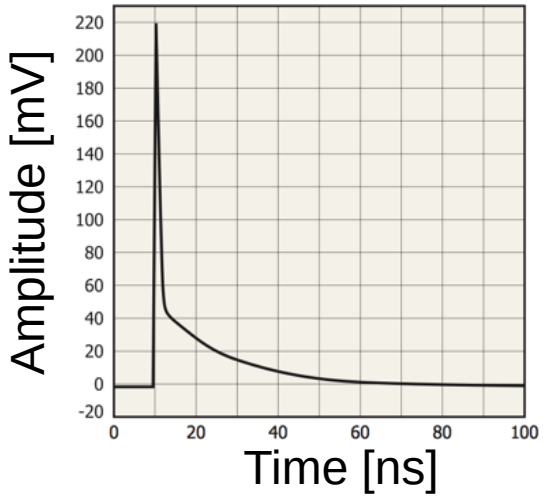
- SPAD only indicates if light is detected or not, basically a digital output, and does not provide any info regarding the intensity of light.





Operation of MPPC (SiPM)





Example of single-photoelectron waveform (1 p.e.)

Gain = area under the curve in electrons

Overvoltage, $\Delta V = V_{BIAS} - V_{BD}$

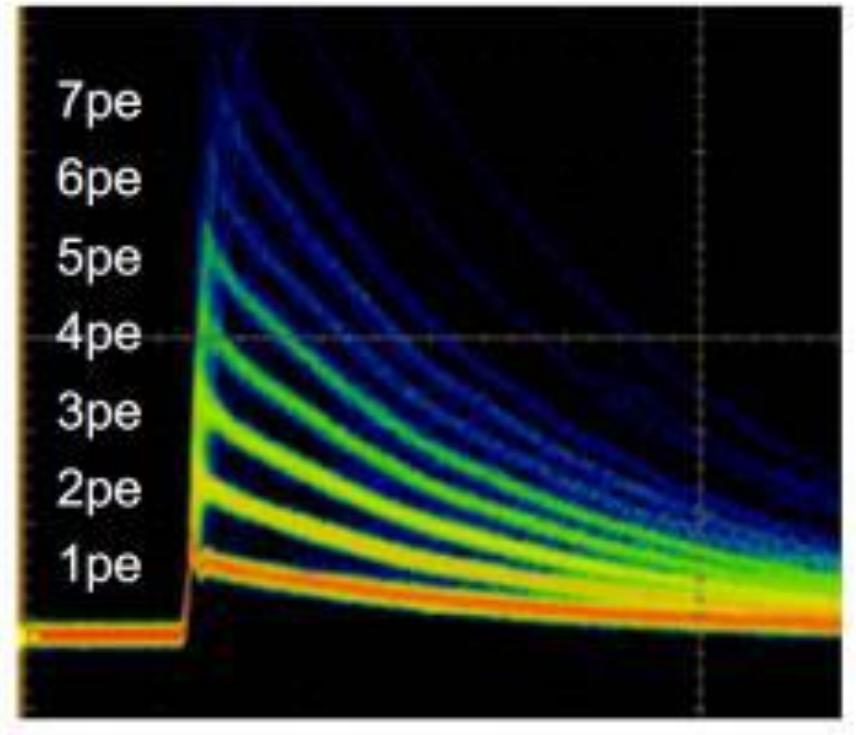
Features of SiPM

Advantages

- Small size and lightweight / thin
- High gain: $10^5 \sim 10^6$
- Low operating voltage: less than 70V
- Larger photosensitive area than APD
- High quantum efficiency
- High-speed response: <200ps
- Room temperature operation
- Insensitive to magnetic fields

Disadvantages

- Large dark count
- Temperature dependence
- Narrow dynamic range
- Large terminal capacitance



MPPC Performance Has Been Remarkably Improved

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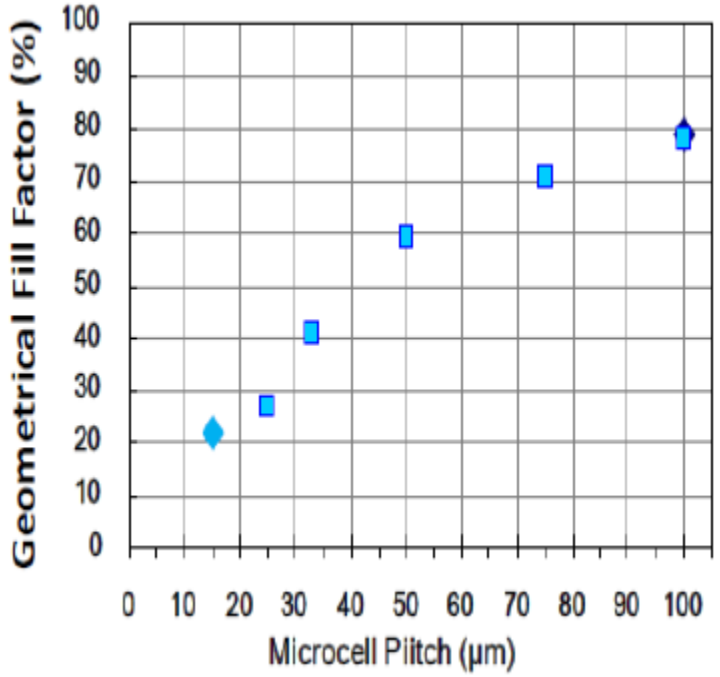
- ✓ Dark Count
- ✓ Afterpulse
- ✓ Crosstalk
- ✓ PDE (Photon Detection Efficiency)
- ✓ Timing Resolution
- ✓ Larger Area (with Assembly Technology)

PDE: Photon Detection Efficiency

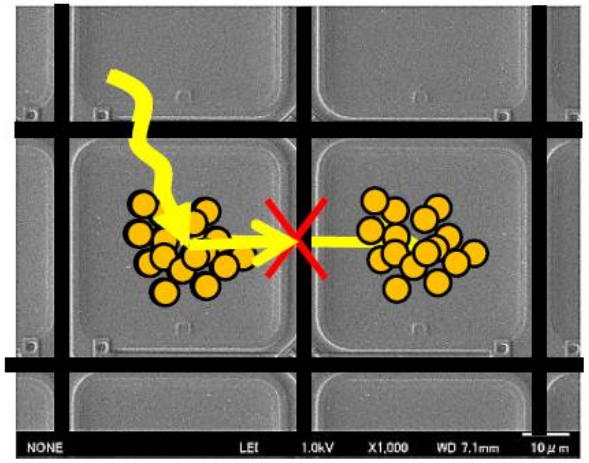
PDE is defined by the equation below.

- PDE = QE x F x AP
- QE: Quantum efficiency
- F: Geometrical fill factor
- AP: Avalanche probability

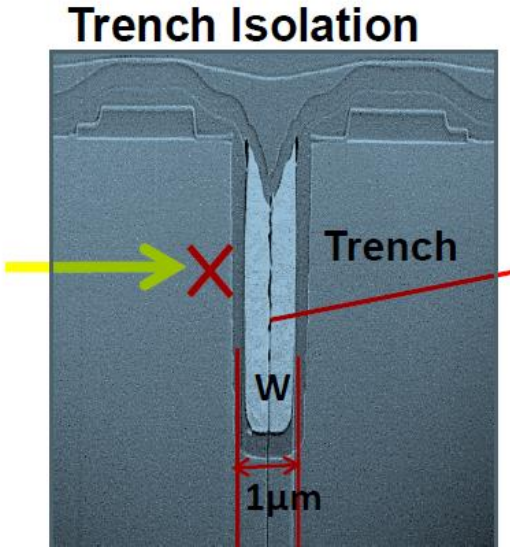


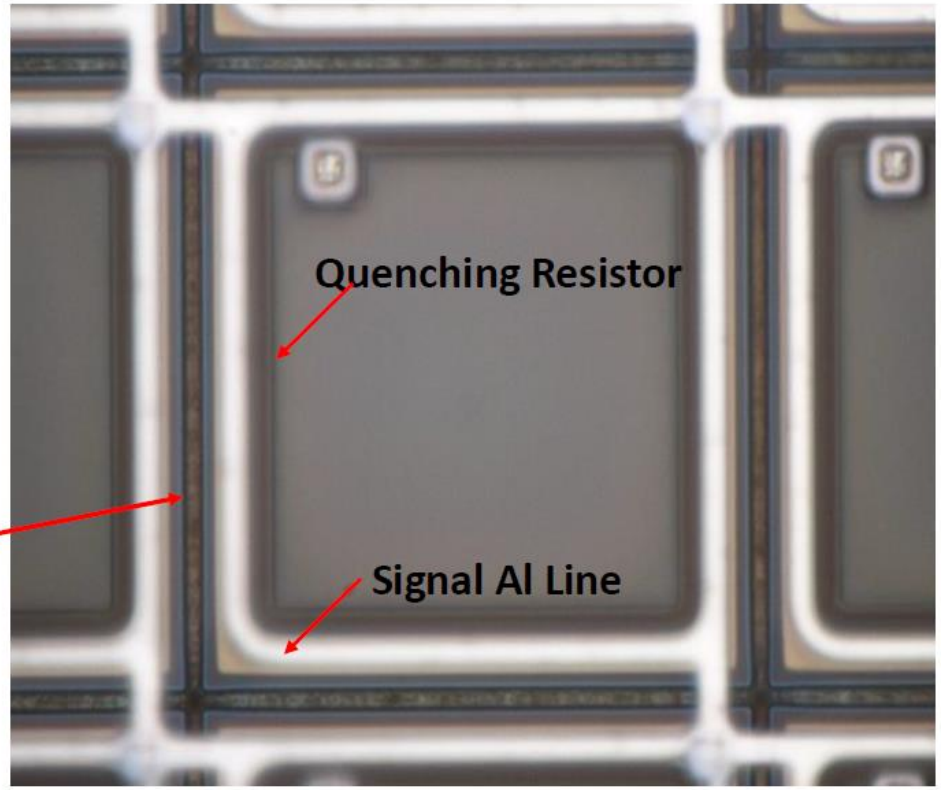
Improving the Fill Factor

- Optimization of the trench and active area

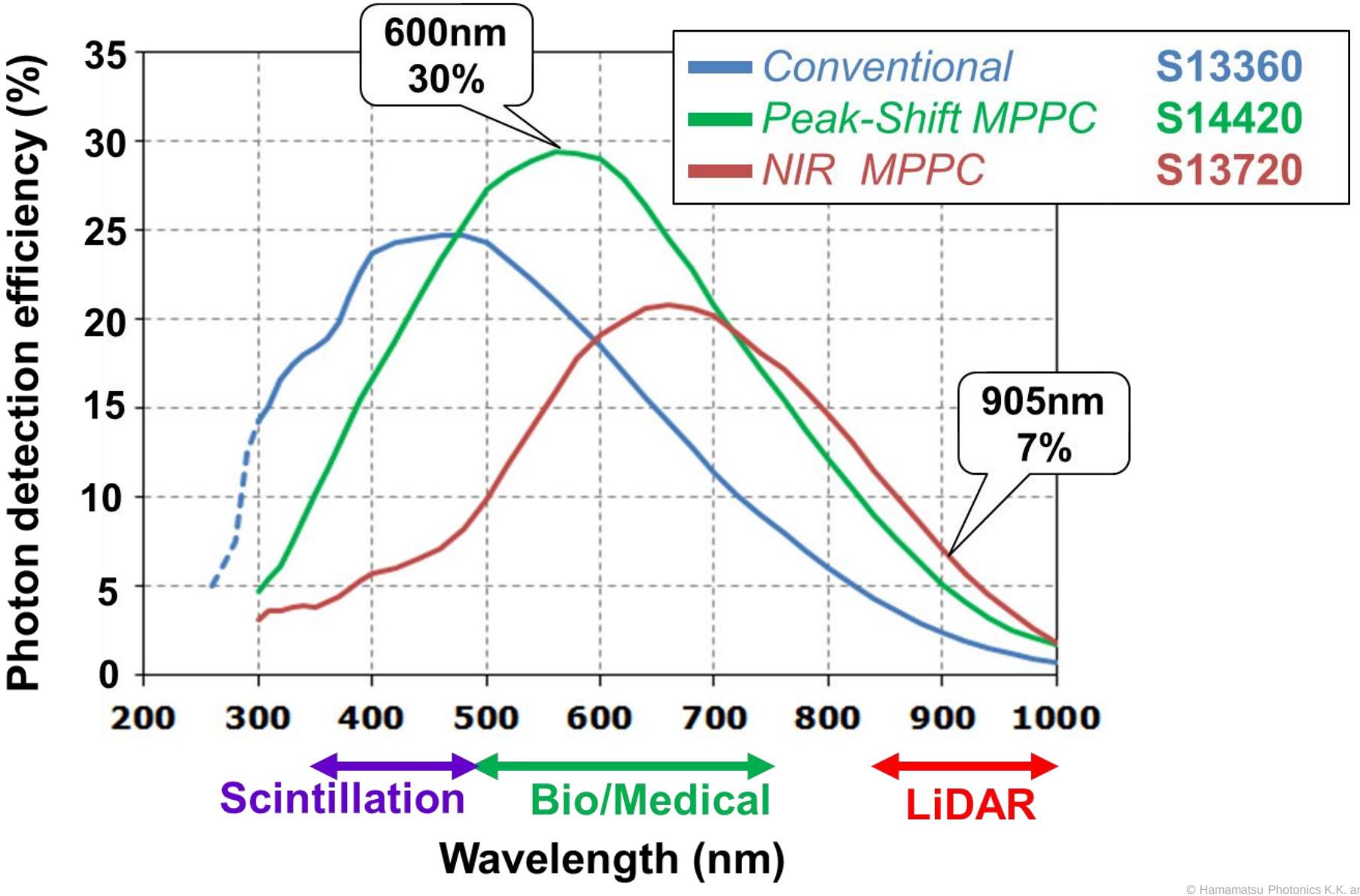


- Trench width ⇒ Minimum
- Active area ⇒ Maximum
  (Higher Fill Factor)





MPPC Series for Industrial Applications



New MPPC Series for Photon Counting Applications

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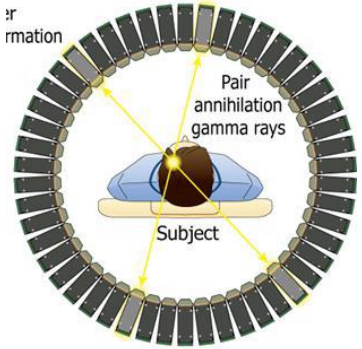
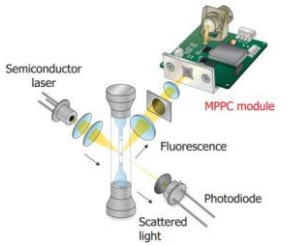
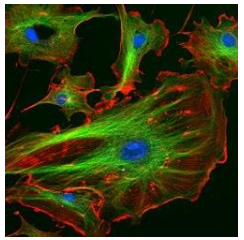
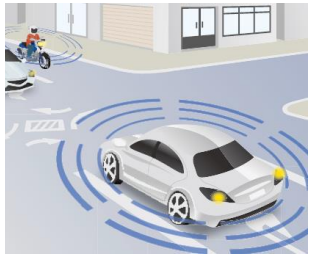
<MPPC Series>	<Application>
S1336x series (UV-VIS: General)	- General use
S1416x series (UV-VIS: Scintillation)	- PET (Positron Emission Tomography) - Radiation monitor
S1442x series (VIS-NIR: Peak shifted)	- Laser microscope - Flow cytometry - Biomedical
S1372x series (NIR: NIR-enhanced)	- LiDAR (Light Detection and Ranging)









HPK's Naming Convention of SPAD Products

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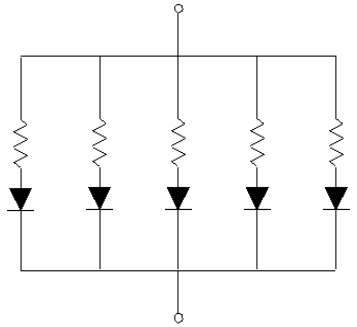
SPAD
(Single-Photon Avalanche Diode)

Geiger-mode APD that detects single photons

SPPC
(Single-Pixel Photon Counter)

MPPC®
(Multi-Pixel Photon Counter)



***This naming is unique to Hamamatsu products.**

Comparison of MPPC & SPPC

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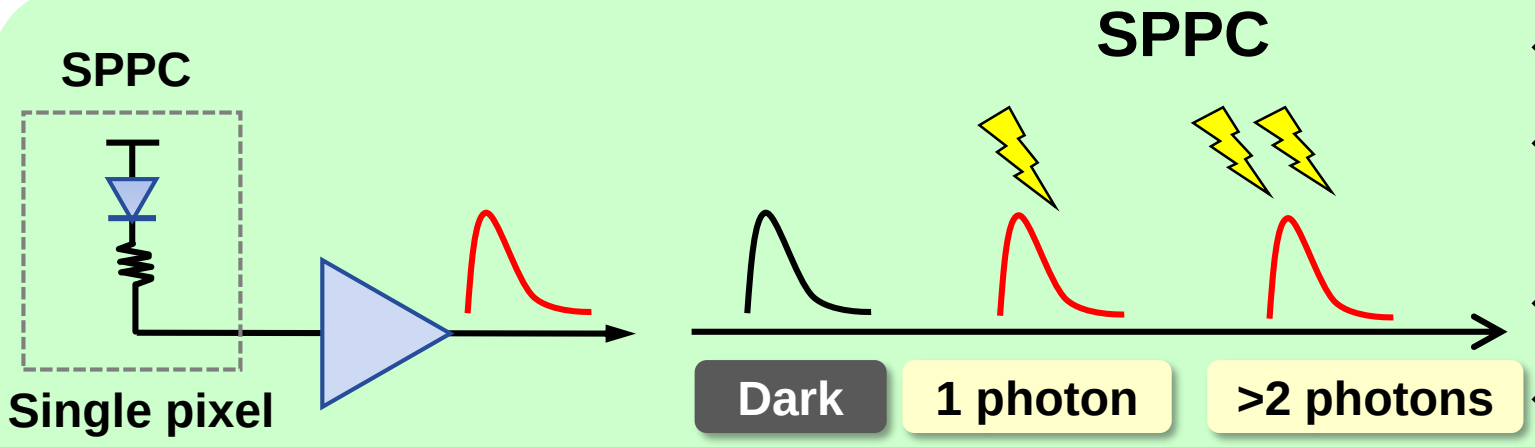
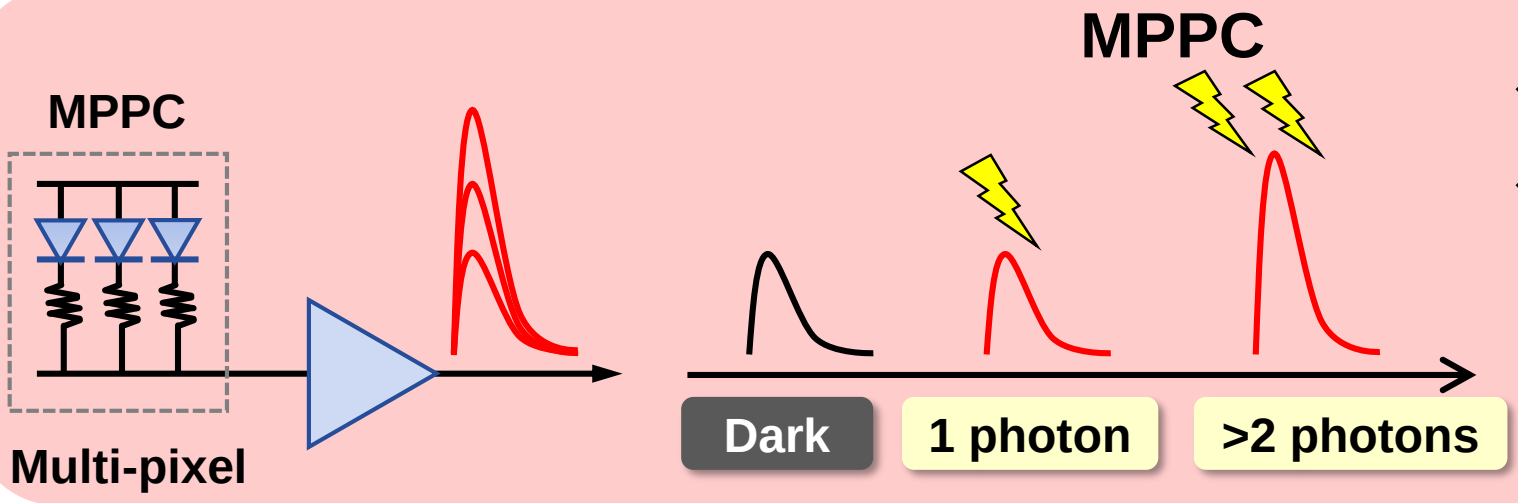
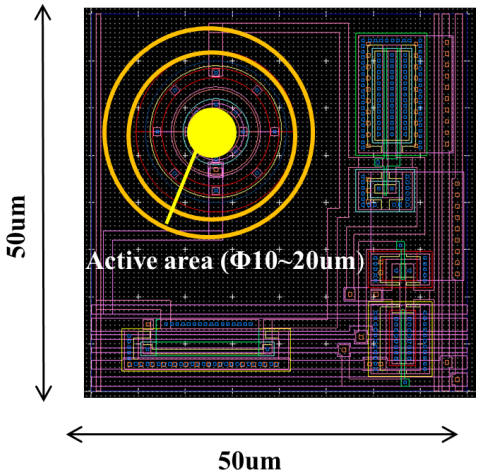


- Single pixel
- High opening ratio
  Can detect long distances
- Counts only one photon
- Histogram or time correlated (not direct TOF)

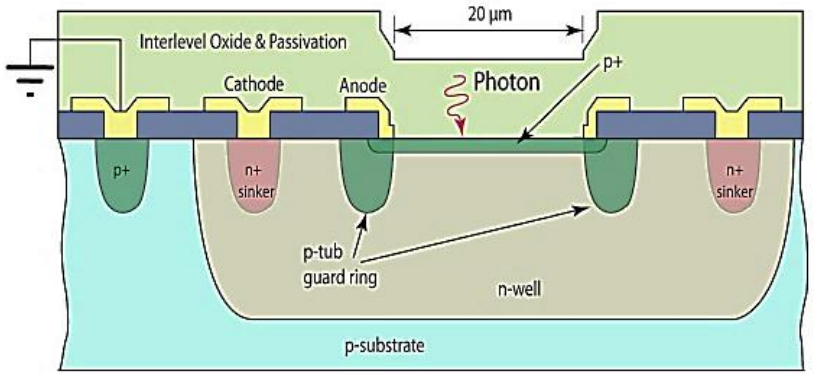


- Multi-pixel
- Counts multiple photons
  Possible to detect distance in ambient light conditions

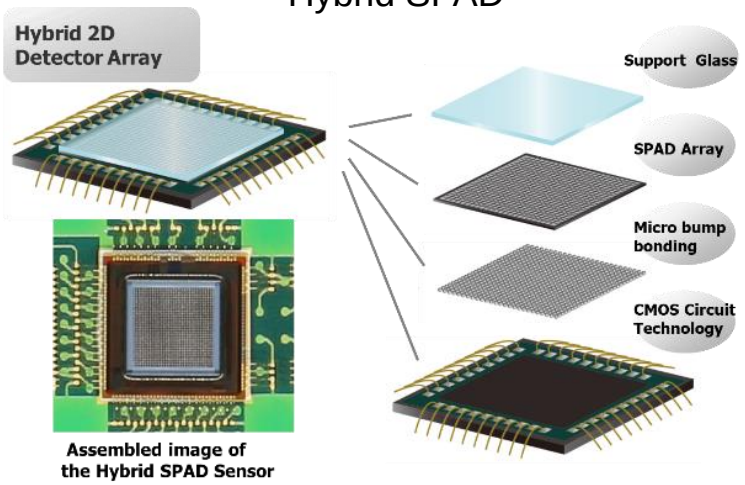
Monolithic SPAD vs. Hybrid SPAD



Monolithic SPAD



Hybrid SPAD



	Monolithic	Hybrid
Detector	Low NIR sensitivity since fill factor is limited	Higher NIR sensitivity since electronics/ASIC are separate
Aperture ratio	Low	High
Speed	High	Good
Components cost	Low	Medium
Challenges	Finer design rule	Bump bonding, Back illuminated

ASIC Function for Different Applications

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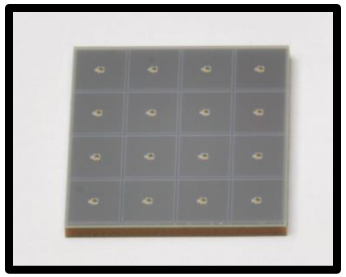
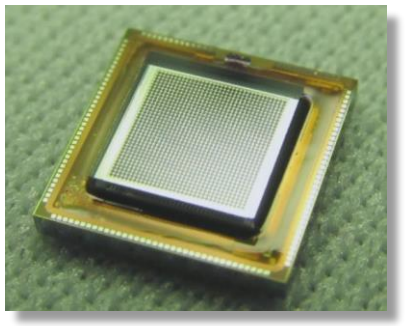
<Detector>



SiPM



SPAD

<ASIC Function>

=

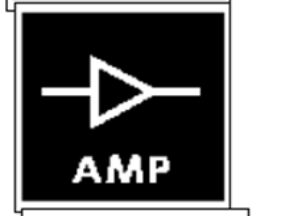
PET

LiDAR

=

X-ray photon counting

+



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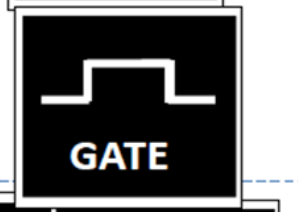
Flow cytometer



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Spectrometer

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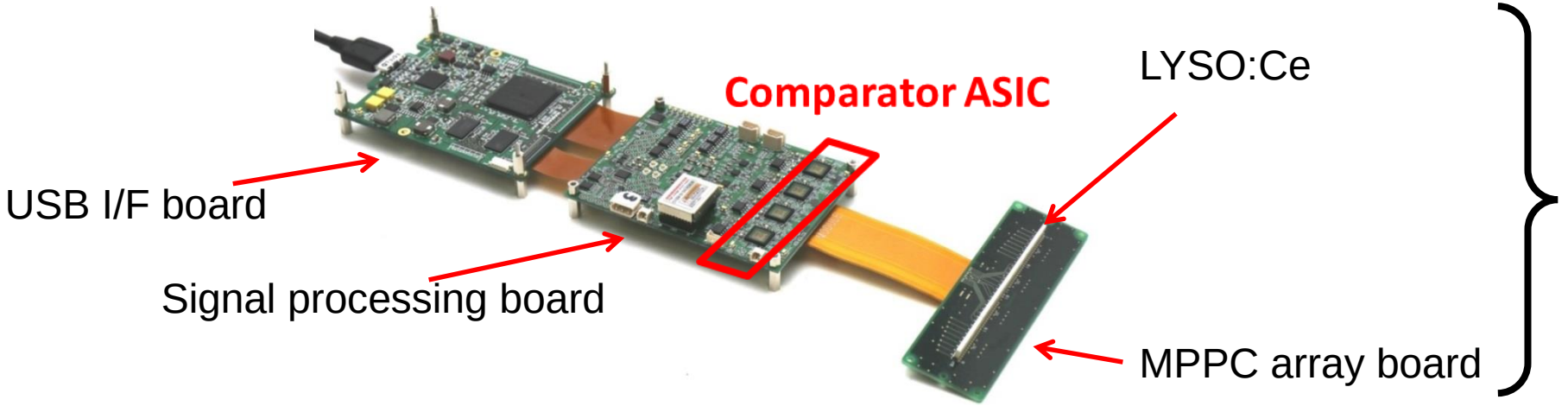
Microscopy

<Application>

X-ray Photon Counting Module

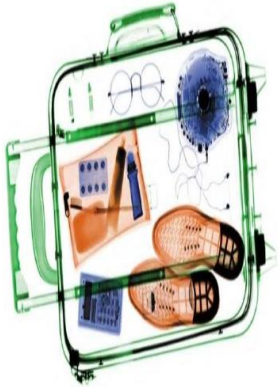
1st Gen X-ray photon counting module



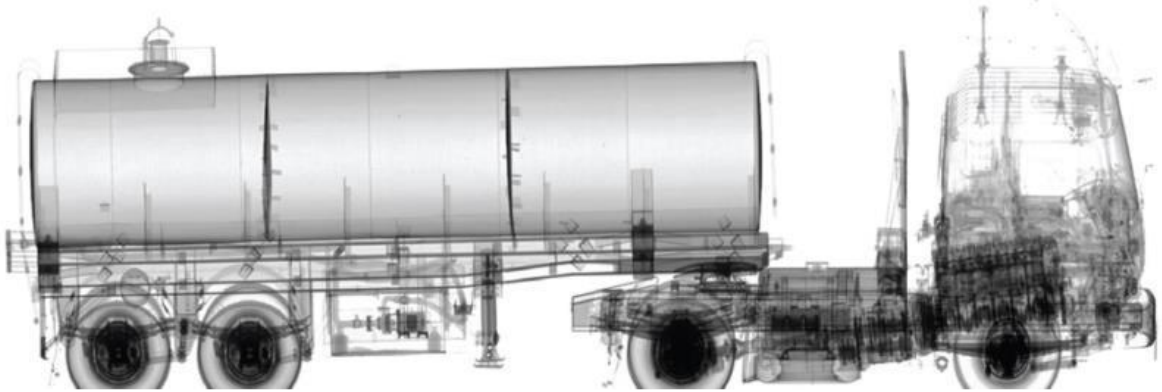
Module box

Applications of X-ray photon counting

Bone densitometry



Baggage inspection



Cargo inspection

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MPPC for PET Applications

PET: Positron Emission Tomography

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Hamamatsu Photonics K.K.

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TOF (Time of Flight)-PET

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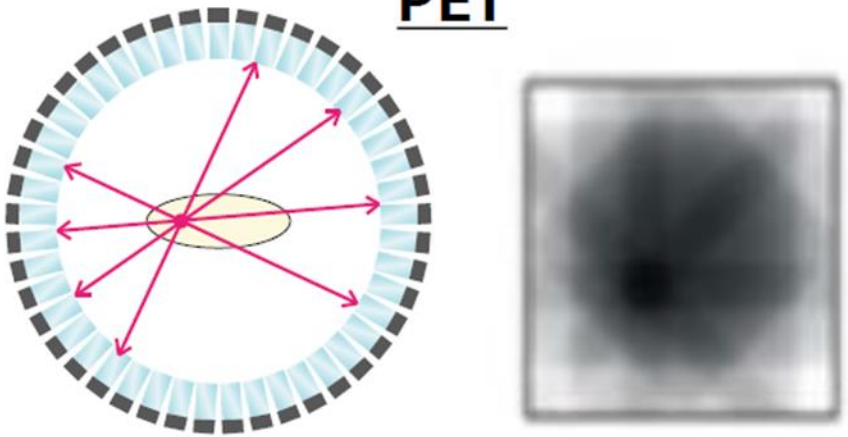
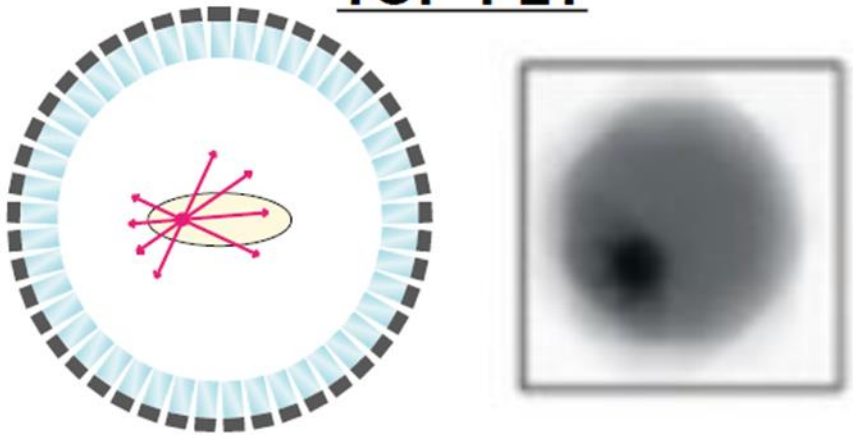
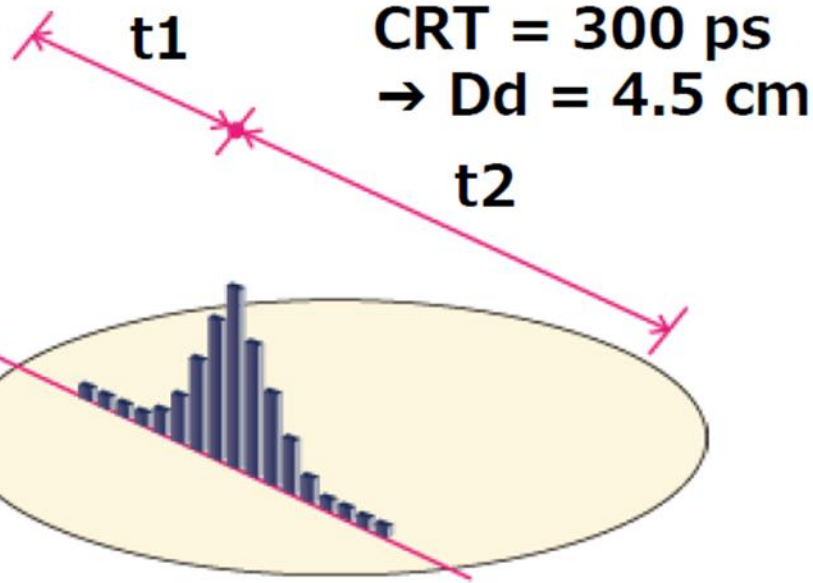
PET



TOF-PET

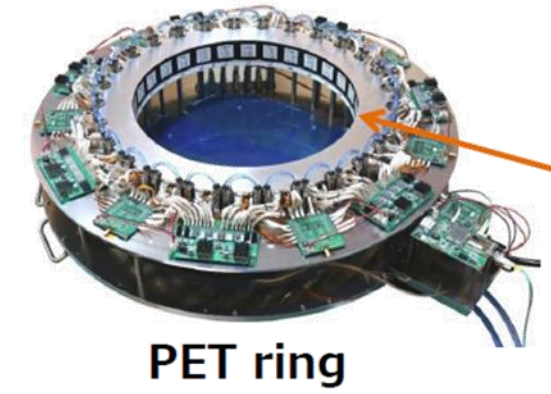




Market demand spec was
CRT=280ps
But recently less than 200ps

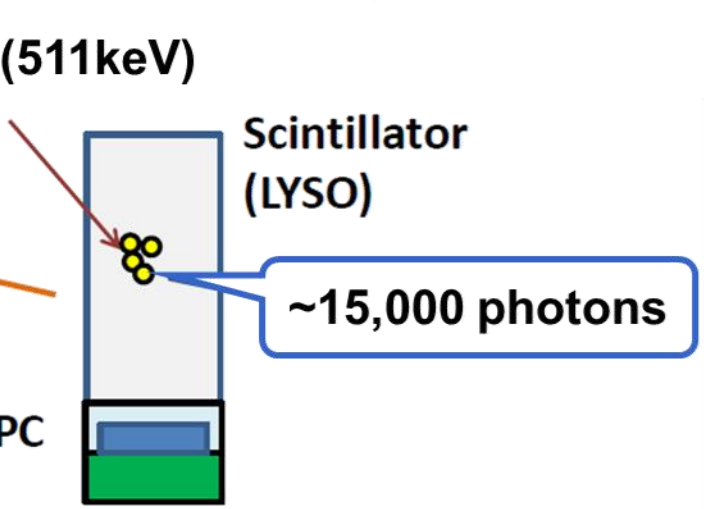
CRT (Coincidence Resolving Time) FWHM

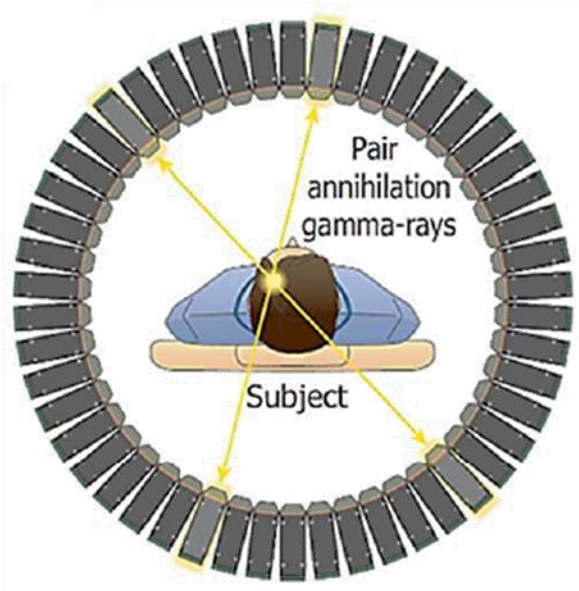
Why Is PET a Photon Counting Application?

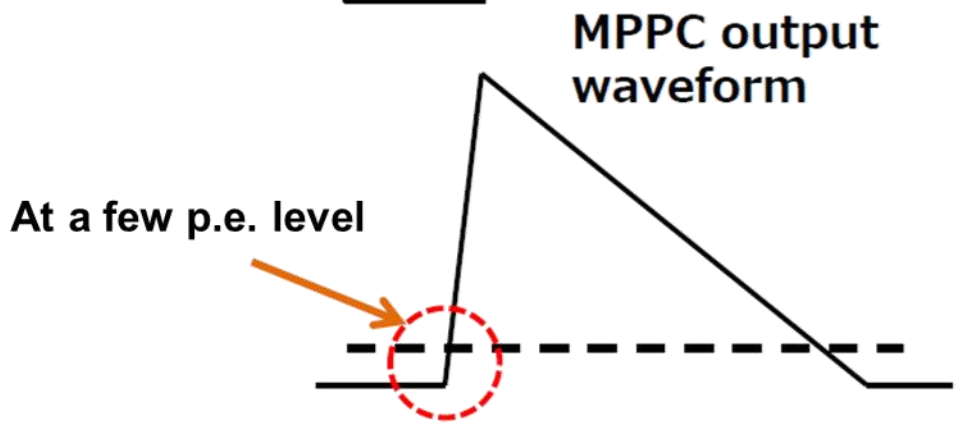


PET ring

Module







The timing threshold is to be set as low as possible in order to reduce the fluctuation.

MPPC S1416x Series

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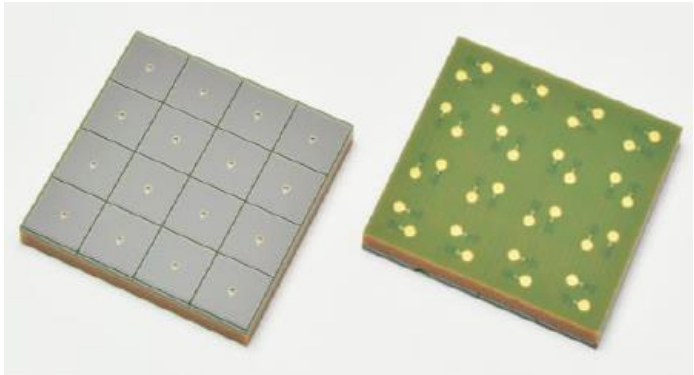
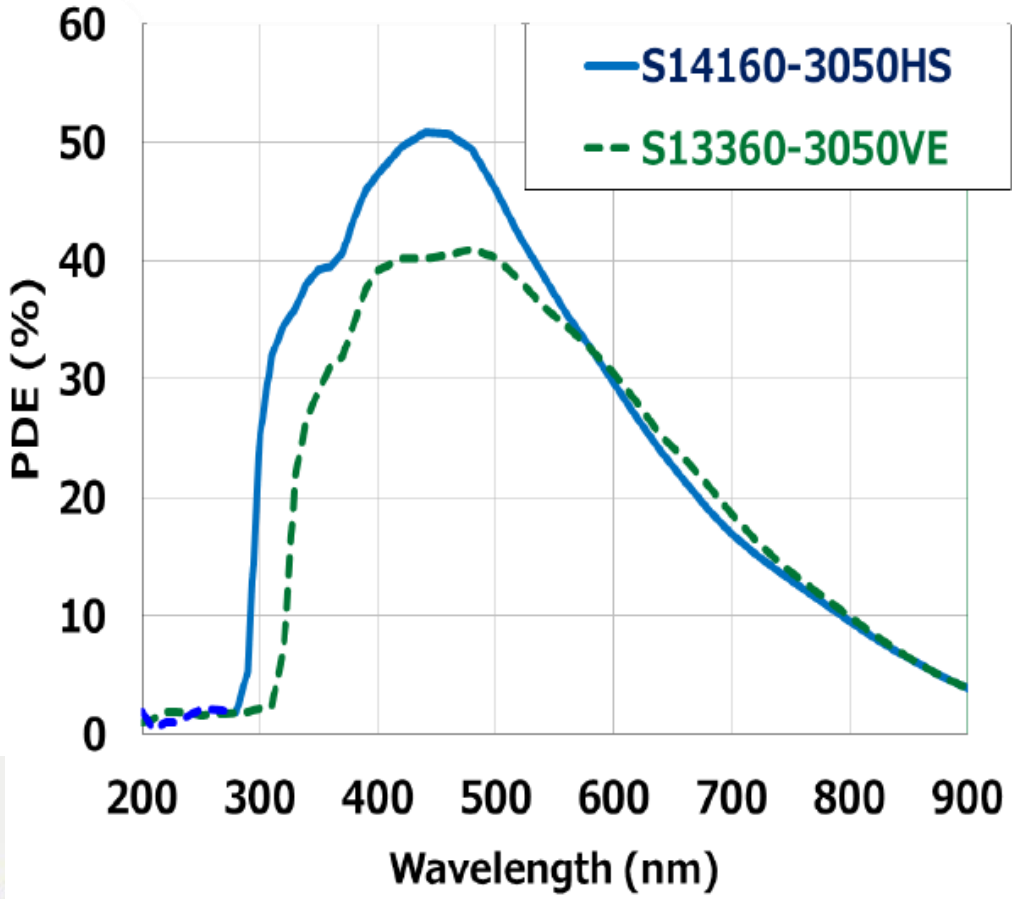
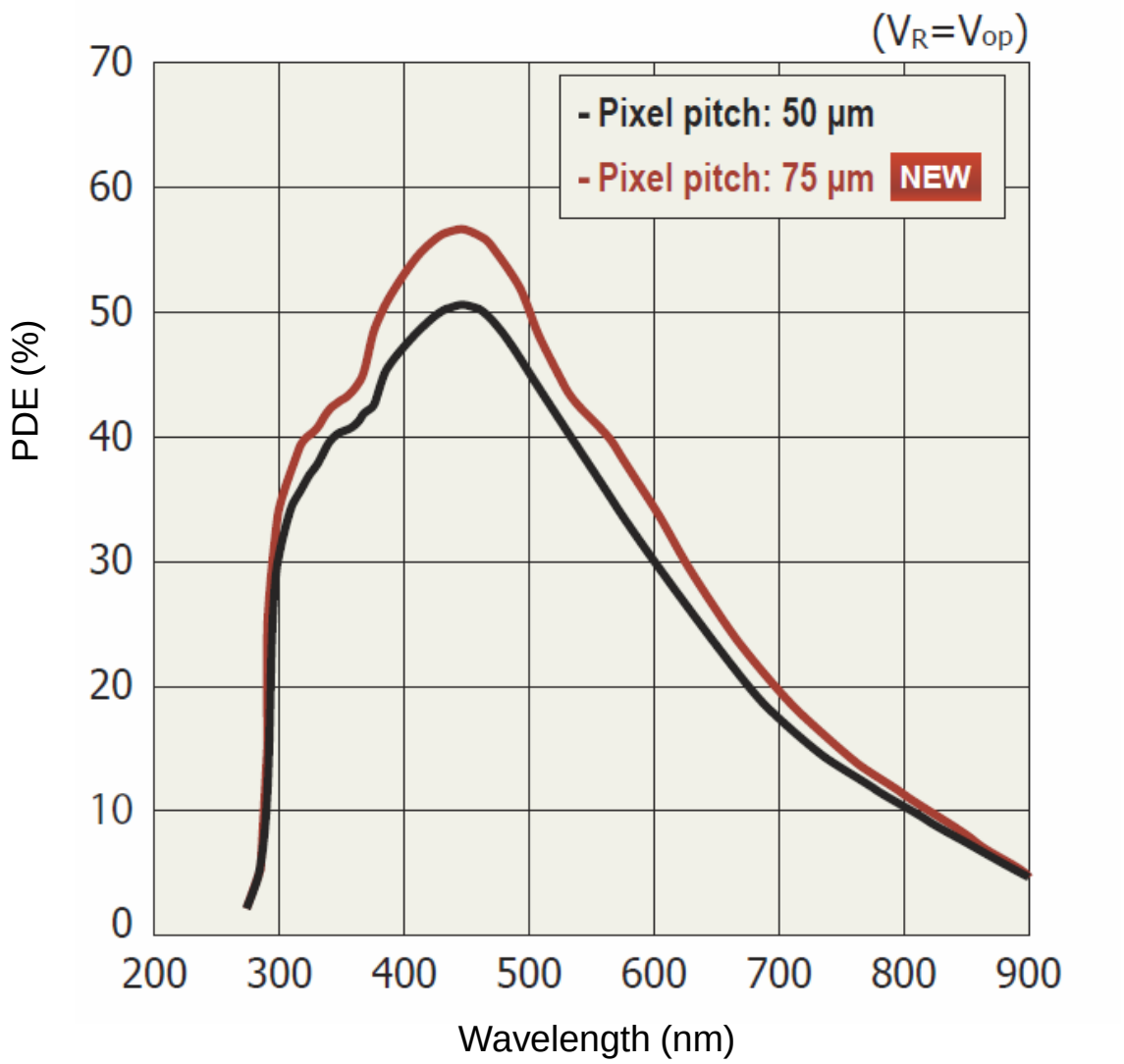
Features

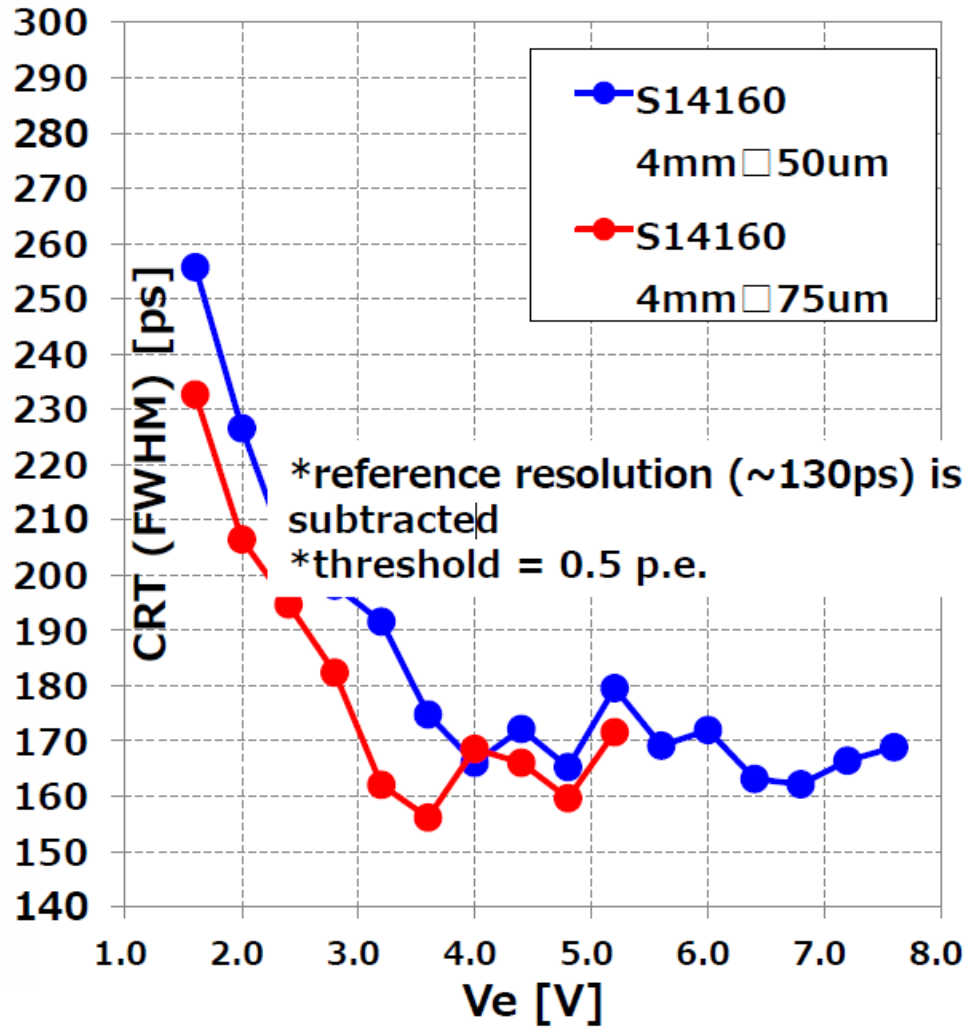
- Lower cost
- High PDE around 450nm
- Lower voltage operation: Vbr = 37V
- Lower temp coef. of Vop: 34mV/℃
- Tile-able on 4 sides
- Active area lineup：3x3, 4x4, 6x6 mm single and 2D array





PDE and CRT





HPK ASIC for PET (Latest Version)

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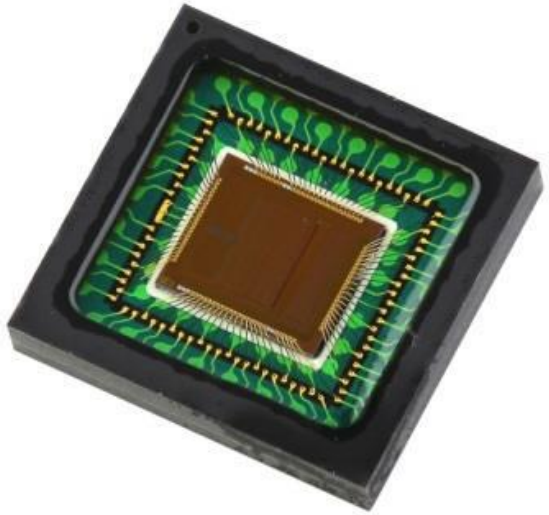
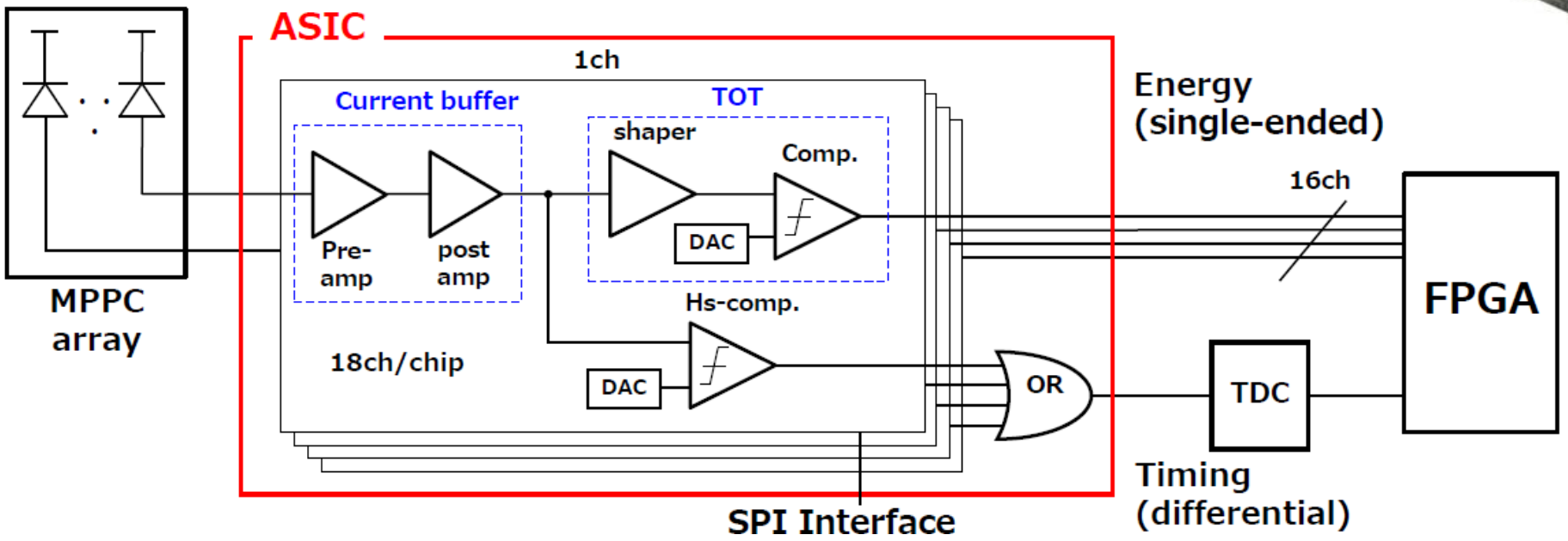
Features

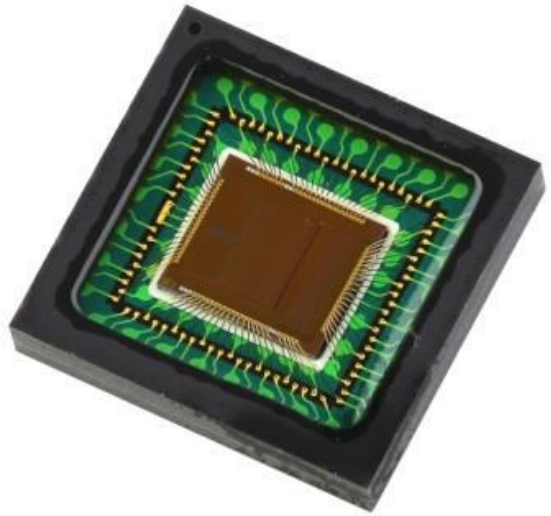
- Low power consumption: 4.5mW/ch, 81mW/chip
- Number of channels: 18ch/chip
- **<200ps** CRT at FWHM (3.14mm□, 20mm LFS)
- <15% energy resolution at FWHM (3.14mm□, 20mm LFS)
- High dynamic range: ~20mA max.
- High count rate: >1Mcps/chip max.

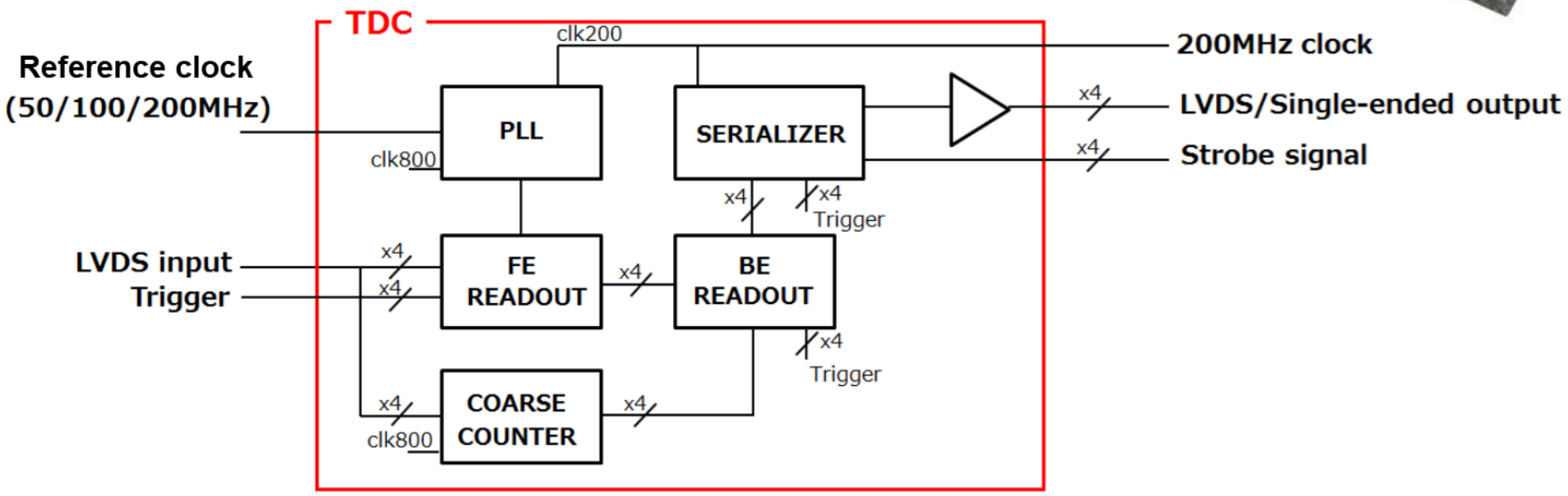




HPK TDC Specifications

	HPK TDC
Resolution	~15ps
Dynamic range	1.28us
Power consumption	~12mW/ch
Maximum count rate	10Mhz/ch
# of channels	4ch/chip



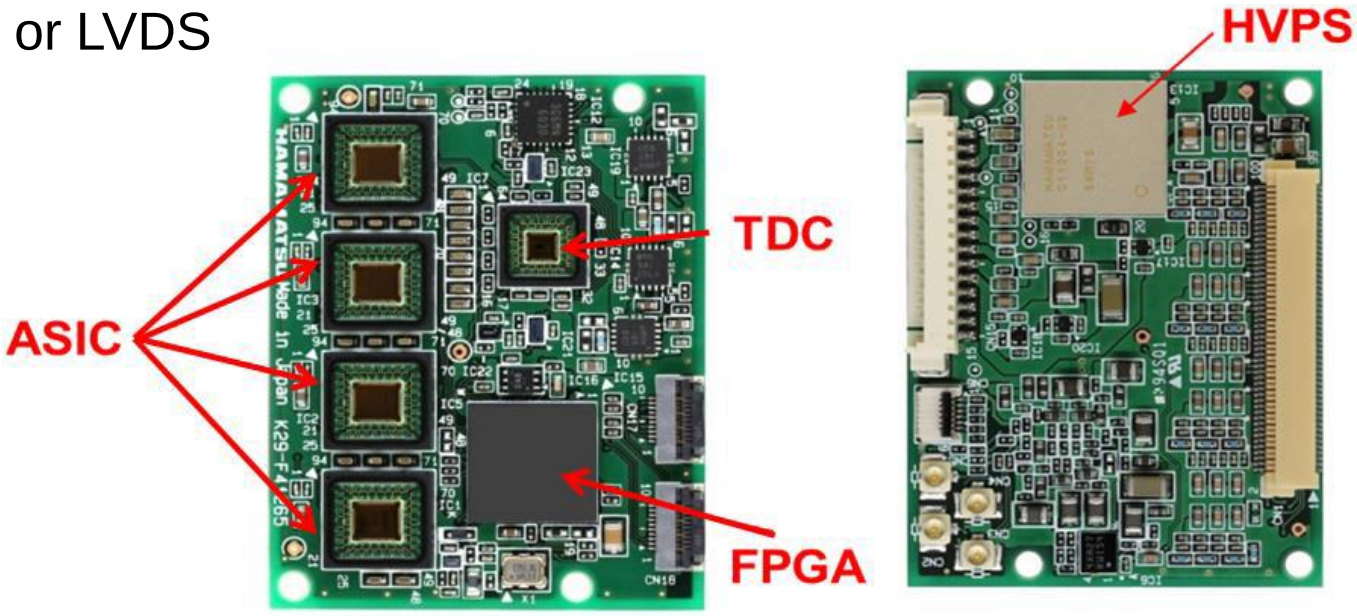


Signal Processing Board CRT

- ASIC board is optimized for SUPER TOF-PET measurement.
- Signal processing board includes ASIC, TDC, HVPS, and FPGA.

Features

- Low power consumption: ～1.3W
- Excellent coincidence resolving time: <200ps
- High energy resolution: ～12% (511keV, LYSO)
- Automatic temperature compensation
- Digital I/F: High-speed serial or LVDS



Timeline of MPPC PET Module Development

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non-TOF → TOF

Introduction

Development

NSS 2010

8x8 PET module C11206-0808

NSS 2012

DOI type, Brain PET
Four-layer DOI PET Module
Central Research Lab.

NSS 2013

PET module Prototype

CRT~500ps

NSS 2014

TOF-PET module for Evaluation

CRT~280ps

NSS 2015

TOF-PET module for Prototype

Reliability
Productivity

NSS 2016~

Low cost
Low power

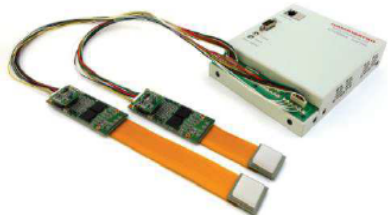
Mass production
OEM

CRT~260ps

CRT improvement

CRT~210ps

Development of ASIC for TOF Improvement of MPPC
Reduction of optical crosstalk



MPPC PET Module's Key Components

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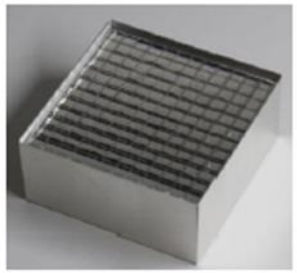
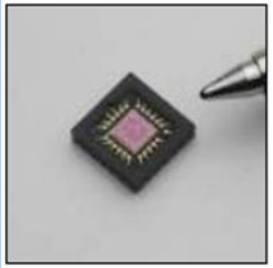
■ Lutetium scintillator

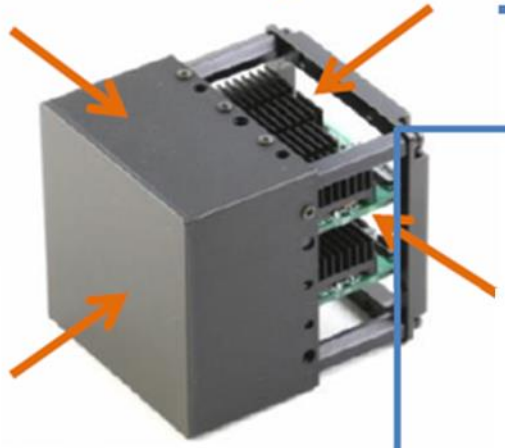


High quality crystal
- **High light output**
- **No deliquescence**
- **Superior time resolution**

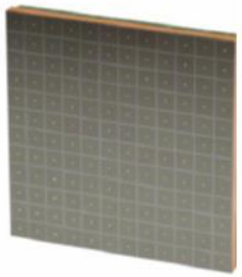
■ ASIC: FE & TDC



High performance CRT
- **Low power consumption**
- **High maximum count rate**
- **Customizable**



■ MPPC: S1416x series



- **Low crosstalk**
- **Low afterpulse**
- **Low voltage:**
  Vop=37V typ.
- **High PDE: 50%**
- **High gain: 10^5 to 10^6**

■ High voltage power supply

- **Low power consumption**
- **Low cost**
- **Customizable**

Lineup of Power Supply for PET

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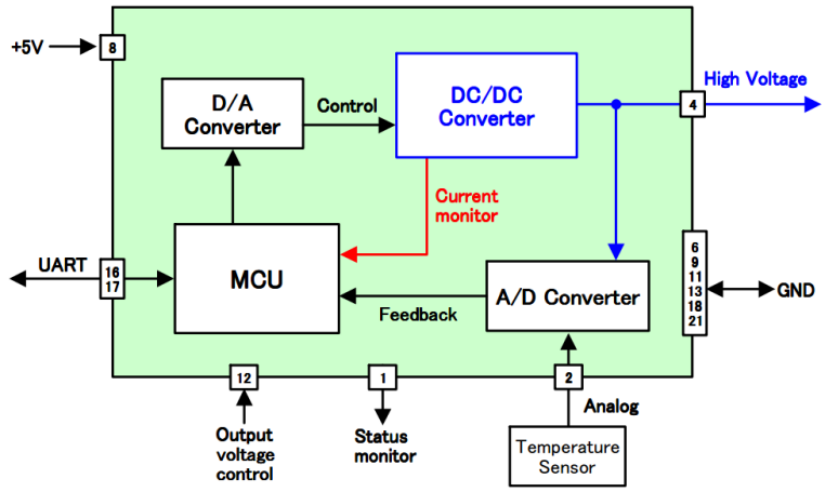
Features

- ✓ MR compatible: C11204-03/-04
- ✓ Includes temperature compensation function
- ✓ Small size: 11.5x11.5mm (SMD type)

Selection:

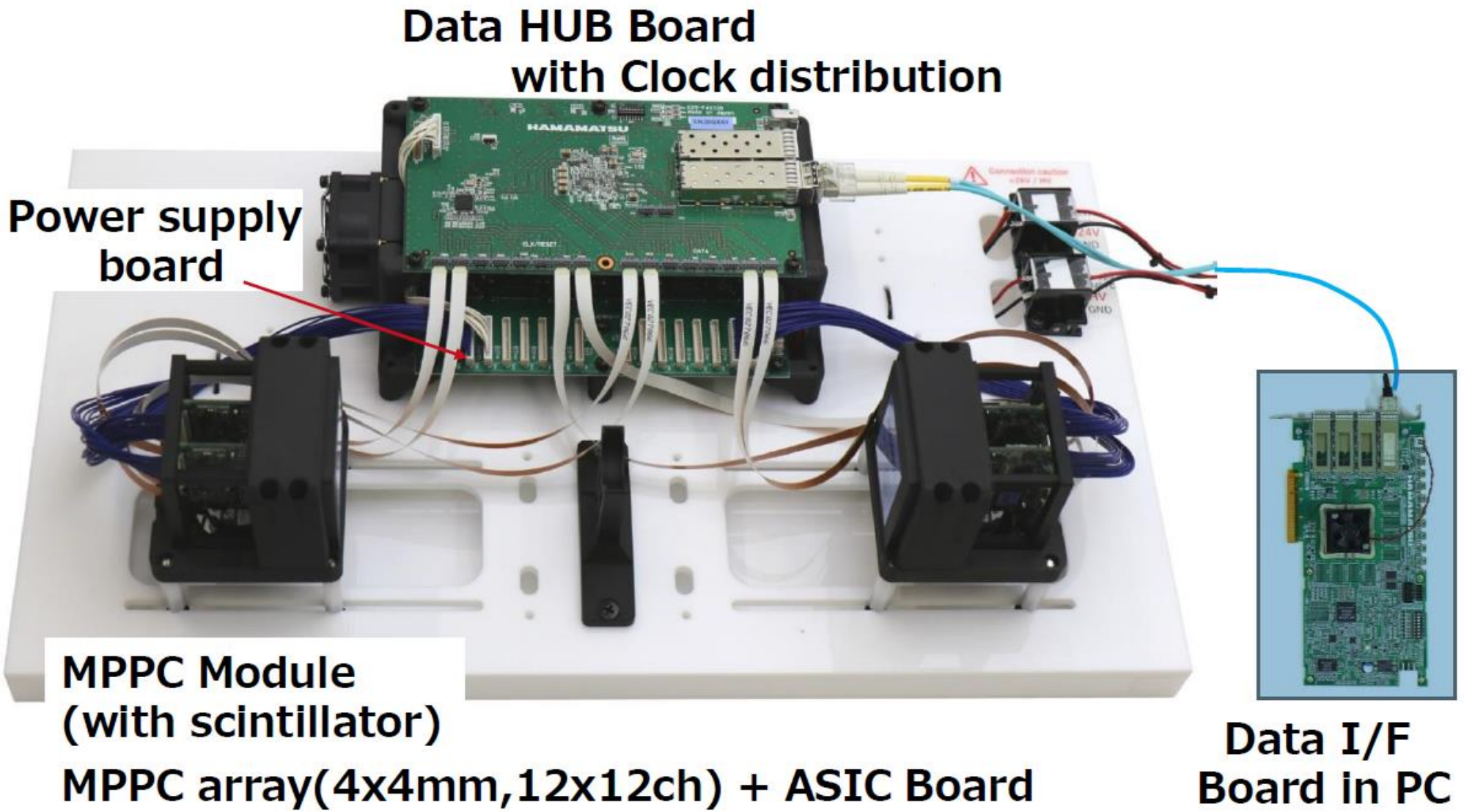
- C11204-01, -02 : High precision type
- C11204-03, -04 : MR compatible type

C11204-02

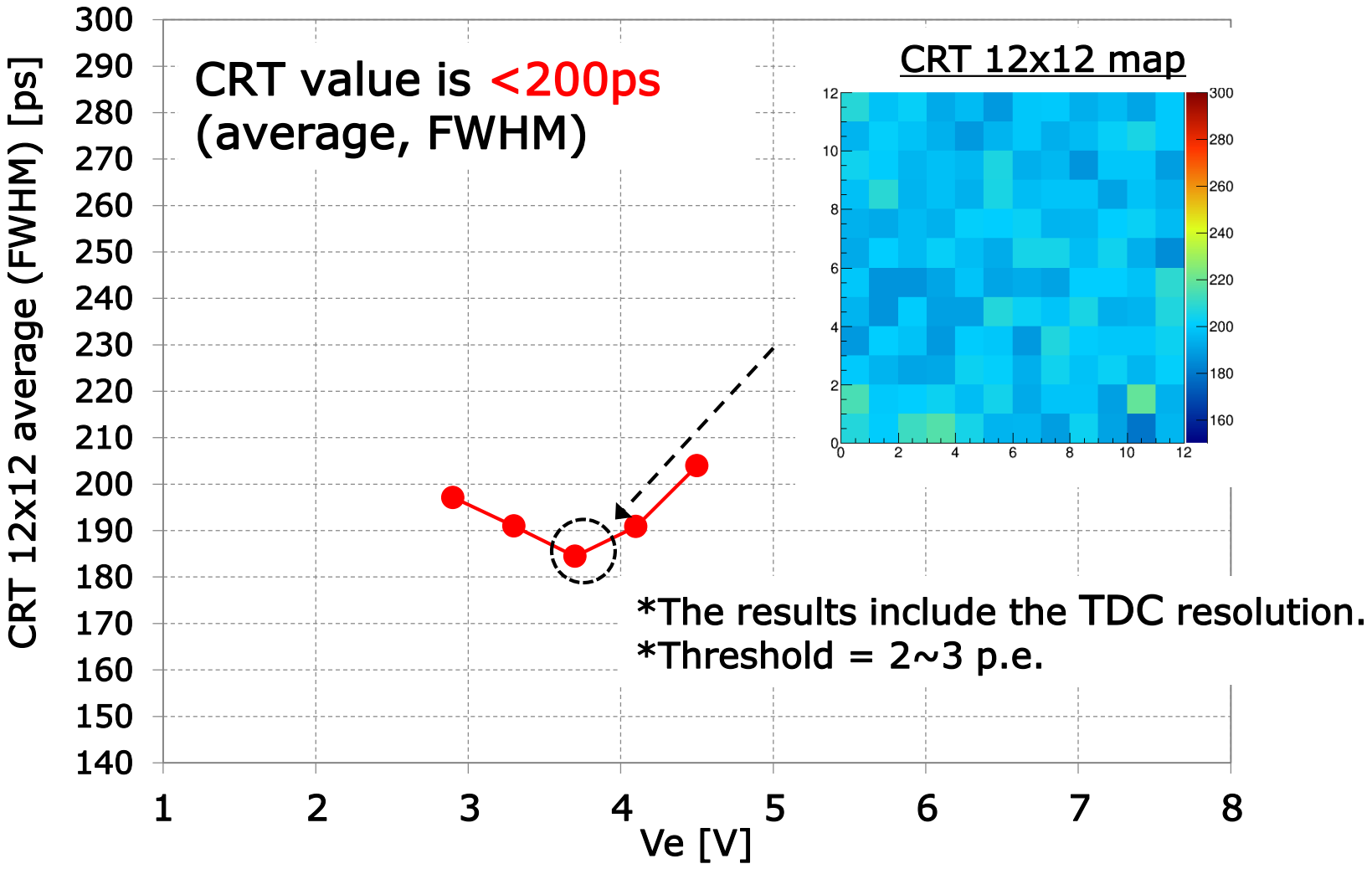


Item		Package Type	MR Compatibility	Features
	C11204-01	With Leads	-	- High precision - Low ripple noise
	C11204-02	Surface Mount	-	- High precision - Low ripple noise - Compact 11.5x11.5mm
	C11204-03	With Leads	Yes	- MR compatible - Low price
	C11204-04	Surface Mount	Yes	- MR compatible - Low price - Compact 11.5x11.5mm

PET Module Test Kit



New Standard Module CRT (12x12 Array Module)



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CRT: Further Improvements

Reduce to less than 150ps

Solid State Division
Hamamatsu Photonics K.K.

10/15/2020

How to Improve CRT (Timing Resolution)

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There seems to be 3 ways to improve CRT.

1. Improve the rise time of the scintillator photon

Much research has focused on Cherenkov UV light. But practical implementation is not easy.

2. Improve PDE

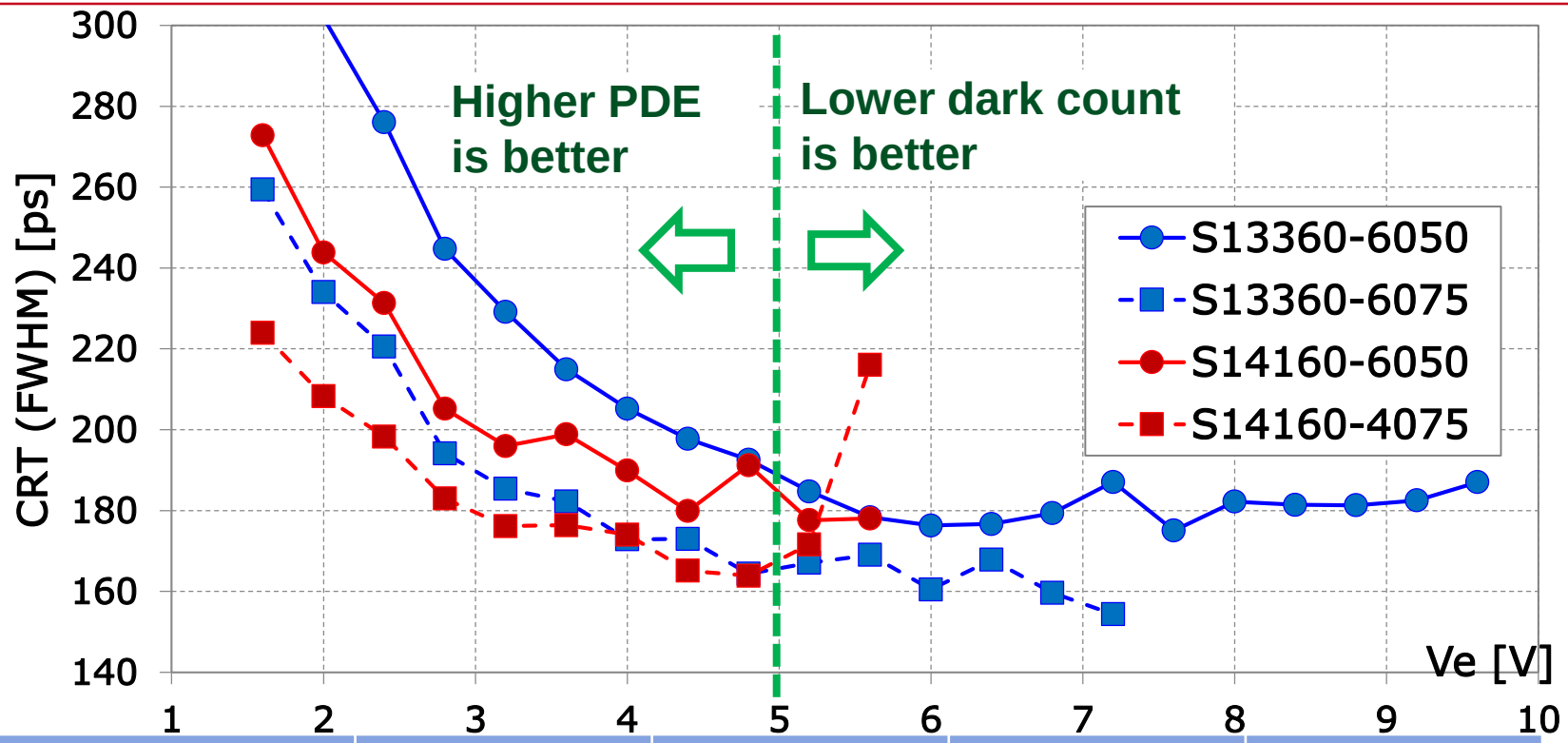
PDE of SiPM has been improved in recent years. However, further big improvements are not realistic, and the current PDE should be sufficient.

3. Optimize size and performance of SiPM

This approach looks most promising to decrease CRT down to 100ps.

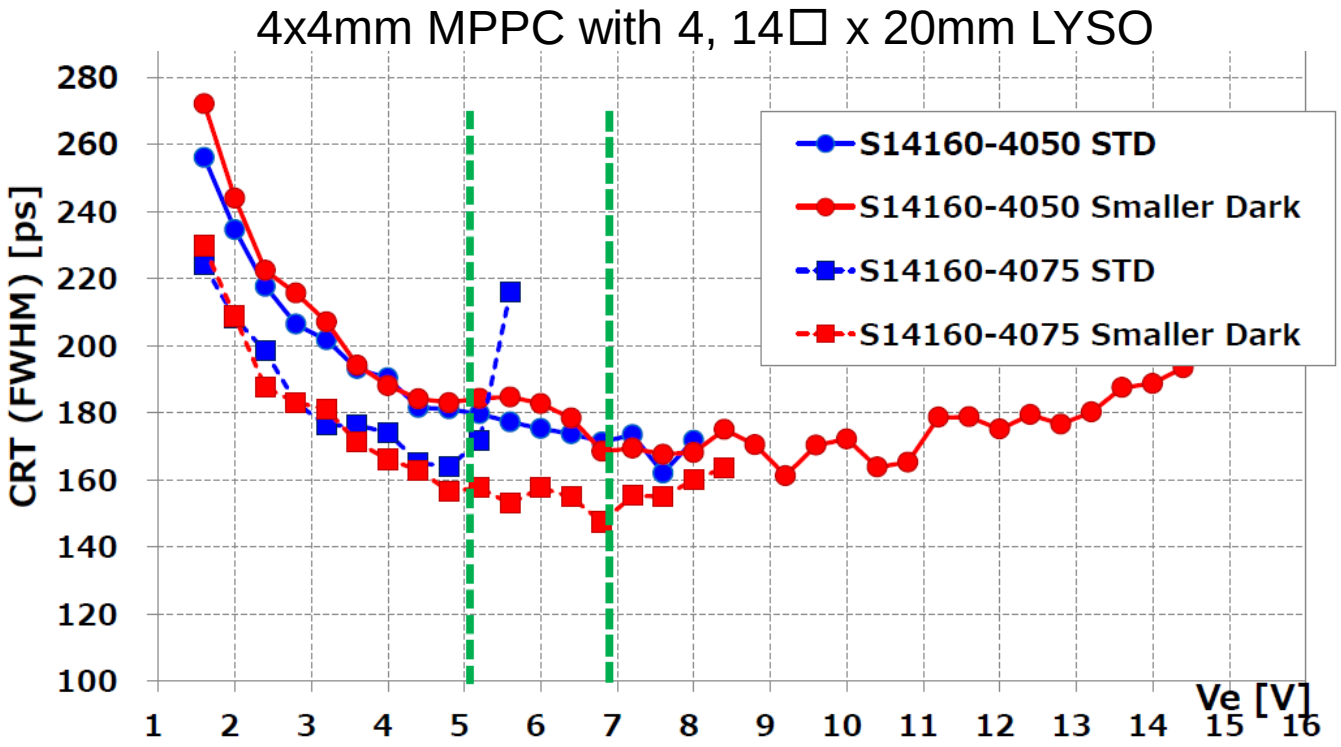
- Keep the higher PDE
- Lower the background (Id, AP, CT, etc.)

Single MPPC CRT Evaluation
Individual Readout 6mm□ with 20mm LYSO



	S13360 50um	S13360 75um	S14160 50um	S14160 75um
PDE [%]	40	50	50	60
Dark count [kcps]	0.5	0.5	2.2	1.0
Crosstalk ＋ Delay [%]	3	7	7	16
CRT [ps] at 5V & 7V	190, 180	165, 160	180, improved	165, improved

CRT Improvement by Decreasing Dark Count



	S14160-4050 STD	S14160-4050 Smaller Dark	S14160-4075 STD	S14160-4075 Smaller Dark
PDE [%]	50	50	60	60
Dark count [kcps]	0.5	0.4	2.2	1.0
CT+Delay [%]	14	6	21	17
CRT [ps] at 5V & 7V	180, 170	180, 170	170, ----	160, 150

SPTR of MPPC
In-Pixel SPTR Measured with Spot Laser

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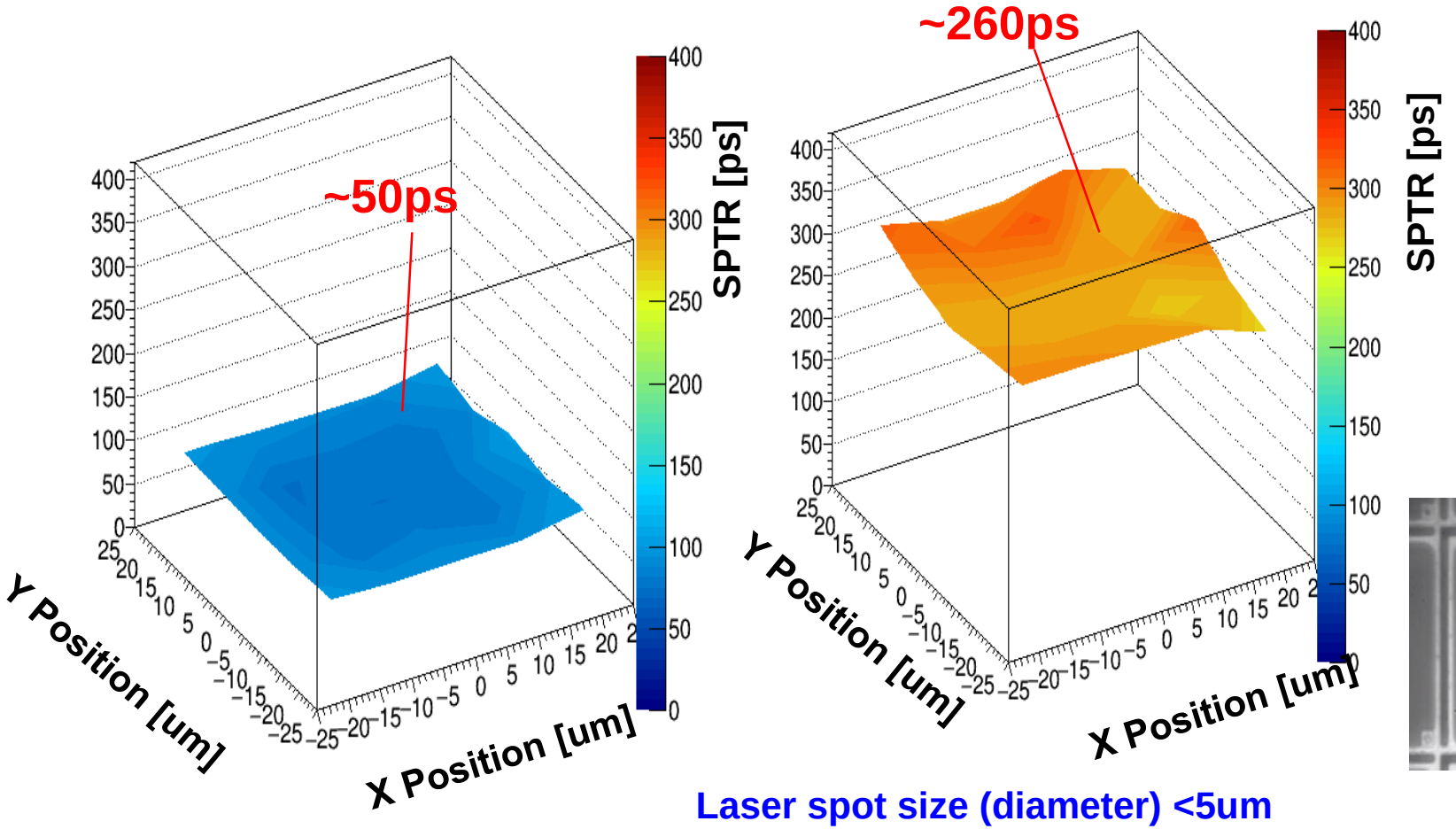
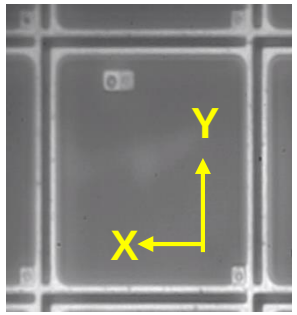
S13360-1350 (50μm, 1.3mm□)

S13360-3050 (50μm, 3mm□)





Laser spot size (diameter) <5um

CRT Experiment for Proof-of-Concept

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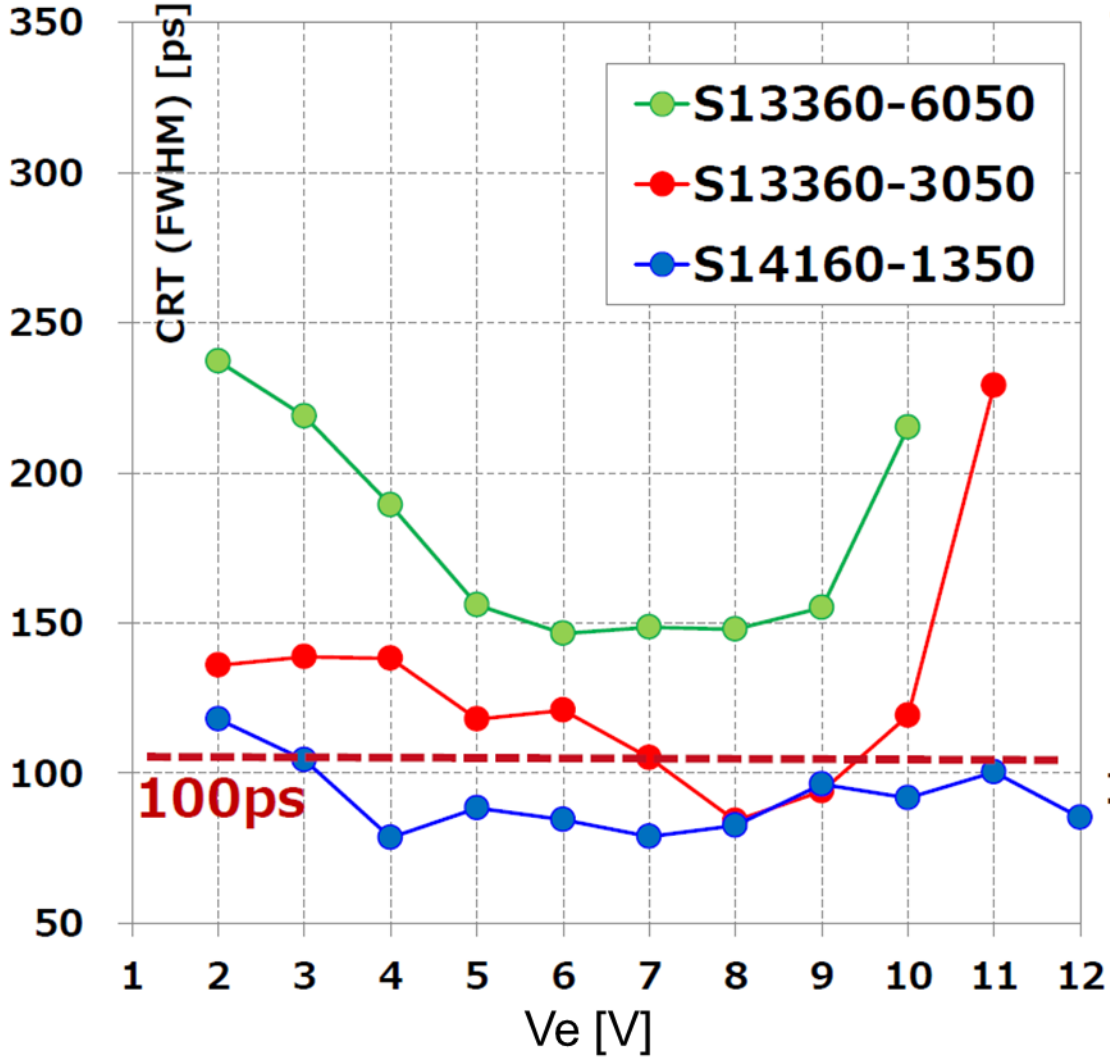
CRT depends on the MPPC's size

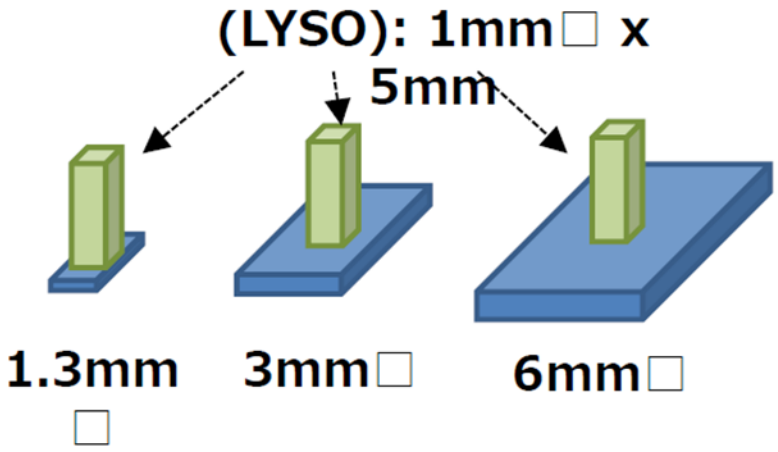


Small MPPC has better timing resolution.

6mm□ ~150ps

3mm□ 90~100ps

1.3mm□ ~80ps



HPK's PET Module Development

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2018~2019
NSS/MIC
Conventional

2020 NSS/MIC
New Standard

2021 NSS/MIC
Next Target

ASIC modification

Readout method
New ASIC design

CRT ~260ps
Commercial

CRT ~200ps
Commercial

CRT ~150ps
Sample shipment by
2021 NSS/MIC

Next Target: CRT ~150ps

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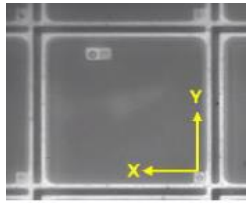
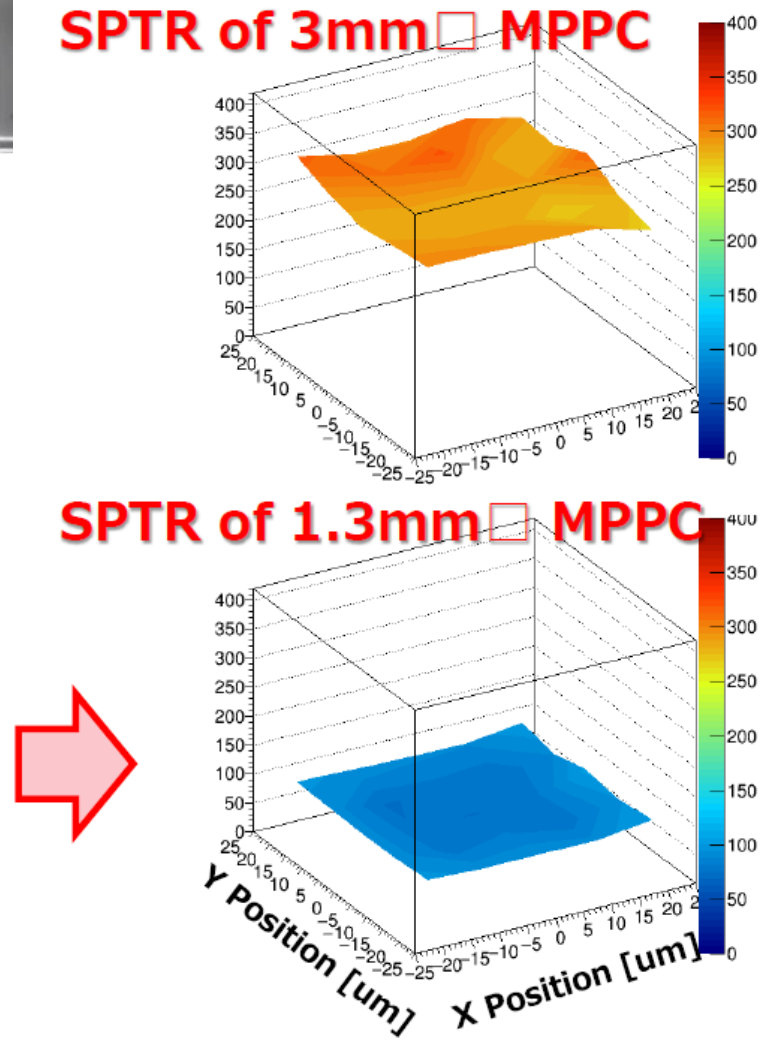


3 methods for improving CRT.

1. Improve the rise time of the scintillator photon
Many researchers are investigating how to achieve this by using Cherenkov light.

2. Improve PDE
PDE of SiPM has been improved in recent years.
The increase in PDE is limited by MPPC's fill factor.

3. Improve SPTR of MPPC
Improving SPTR is quite easy because SPTR is strongly related to capacitance, and a small MPPC has very good SPTR.



How to Achieve ~150ps

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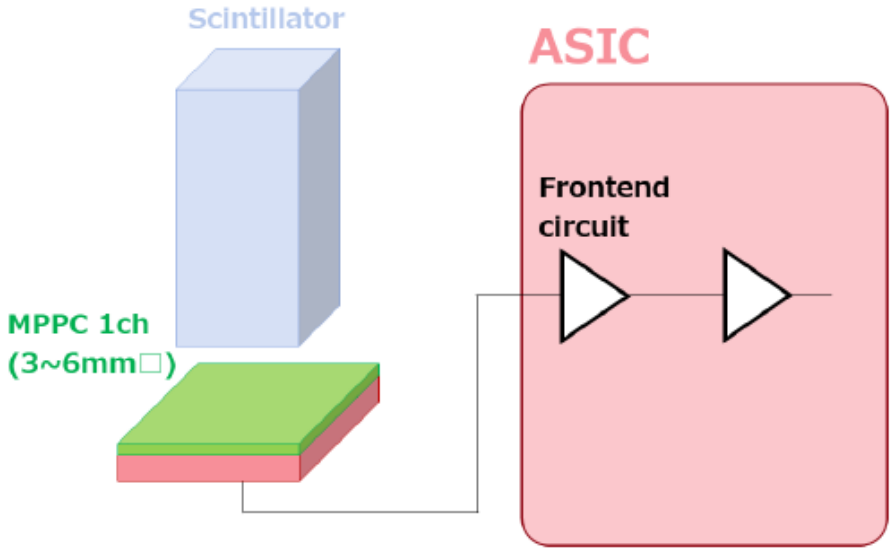
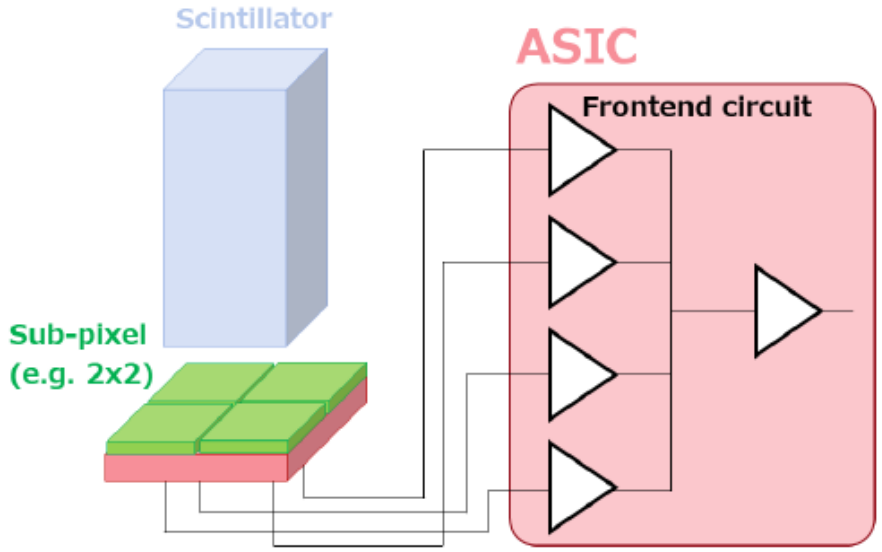
Divide MPPC into sub-pixels

- **Conventional Readout**



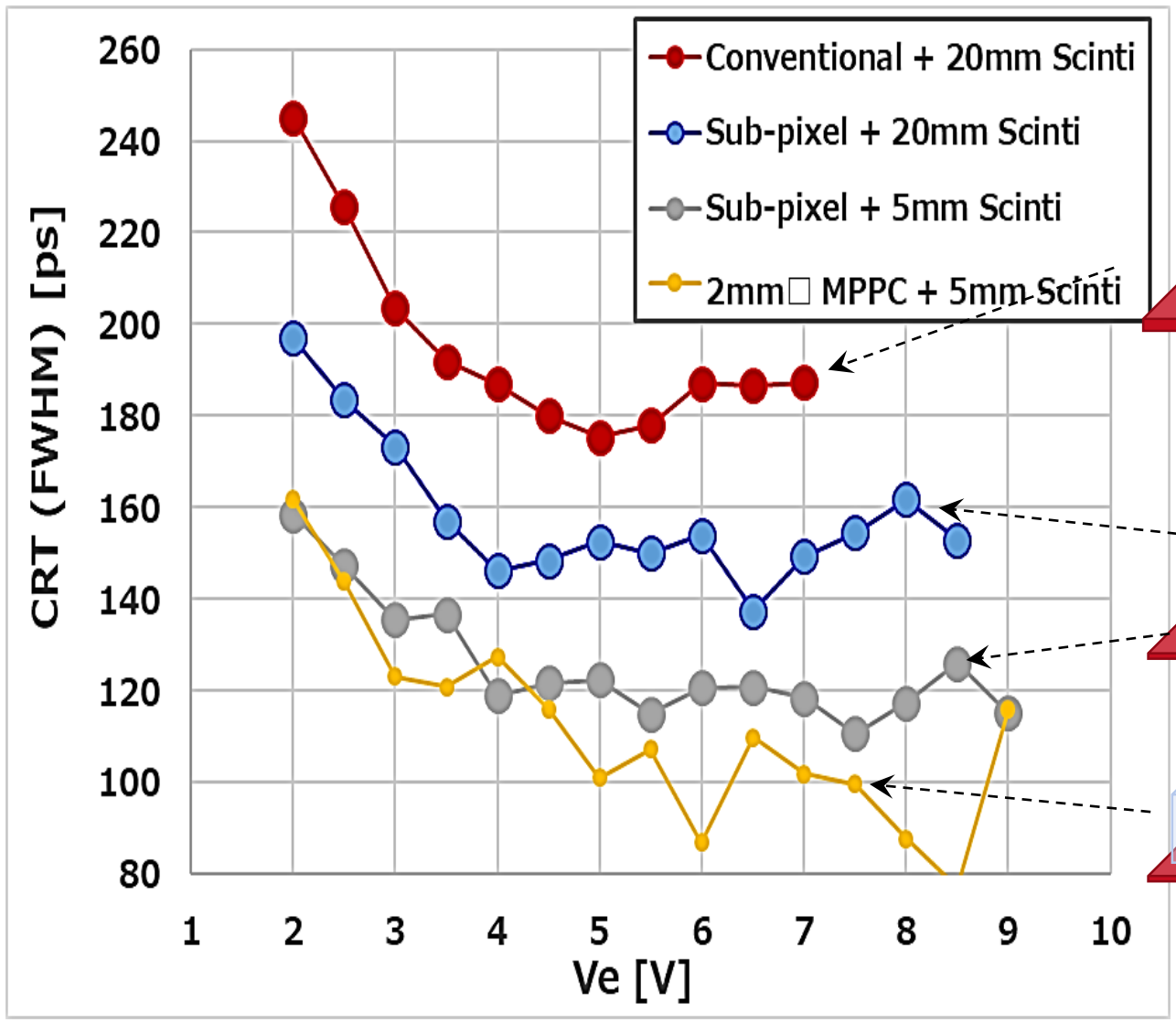
- MPPC and ASIC channels are connected 1 by 1.
- SPTR is not very good because of the MPPC's large capacitance.

- **Sub-pixel Readout**



- MPPC is divided into sub-pixels.
- MPPC's capacitance is small, which results in better SPTR and CRT.

Experimental CRT Results of Sub-Pixel MPPC



Preliminary

4mm□ S14160-50
3.14mm□ x 20mm
LYSO

Sub-pixel S14160-50
3.14mm□ x 20/5mm
LYSO

1.75x2.0mm/ch

Sub-pixel
S14160-50
1mm□ x 5mm
LYSO

Experimental Results

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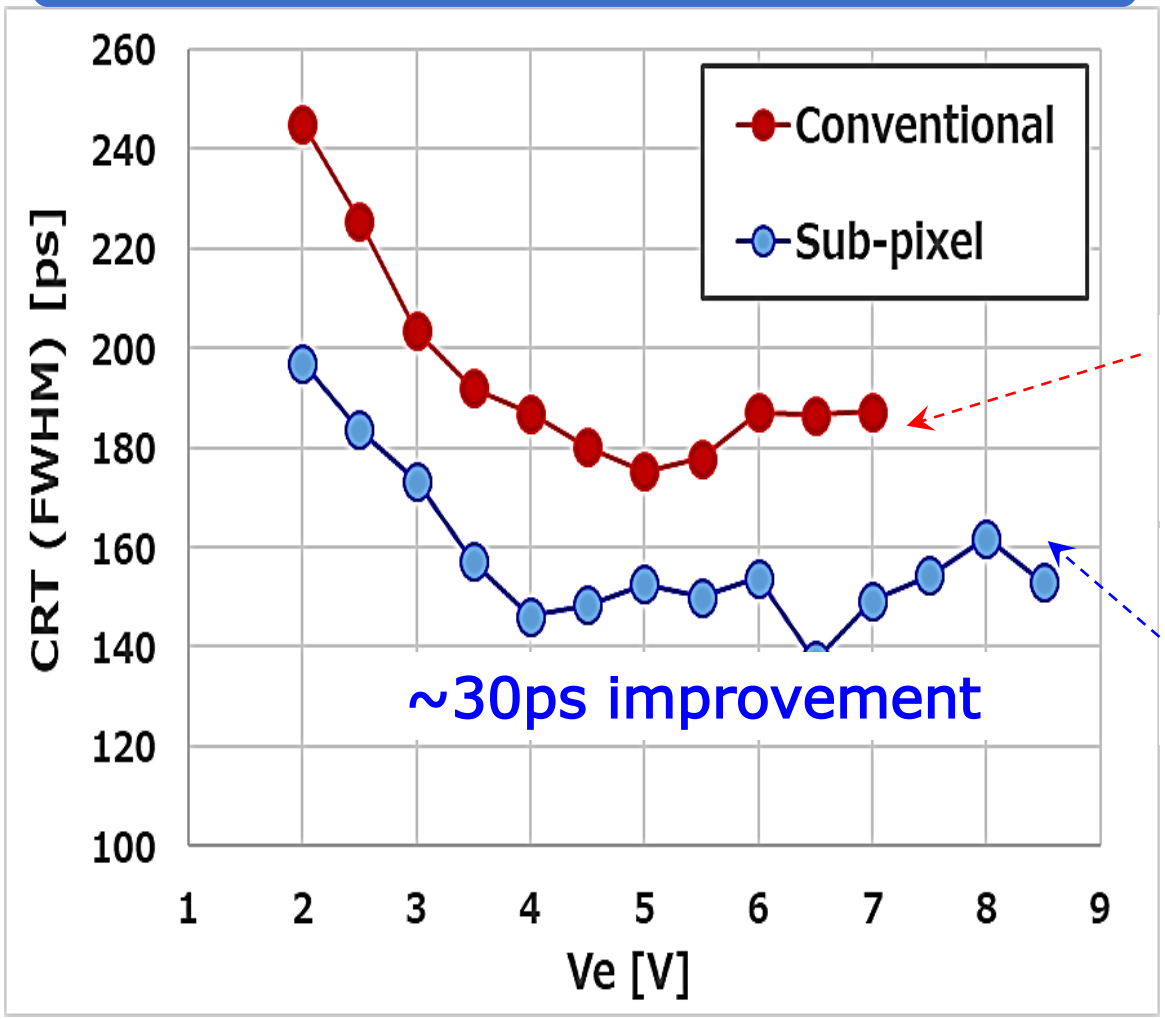
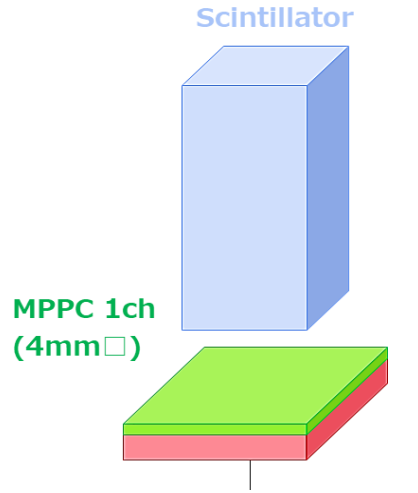
Experimental results with 20mm LYSO

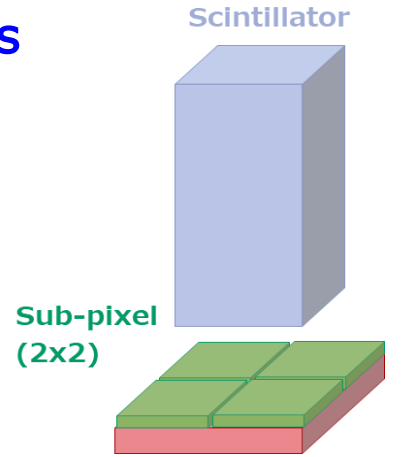
Preliminary



S14160 series
4mm□

S14160 series
3.5x4.0mm,
2x2 sub-pixel





Summary

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HPK standard PET module

- 200ps standard PET module is available for sale.
- All components required for PET are included in the module.
- HPK's PET module makes it easy to build a TOF-PET ring.

Next target: 150ps PET Module

- 150ps PET module with sub-pixel readout is under development.
- Preliminary experiments show positive results.
- Optimization of the number of sub-pixels and the ASIC will be performed.
- We plan to ship samples by 2021 NSS/MIC.

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