HAMAMATSU
PHOTON IS OUR BUSINESS

Current status of Hamamatsu Si detectors mainly for High Energy Physics Experiments

HAMAMATSU PHOTONICS K.K.

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HAMAMATSU PHOTONICS K.K.
Solid State Division

Outline

1. SSD (Silicon Strip Detector) for tracker of many HEP experiments
2. Development of large area PAD detector
3. APD(Avalanche Photo Diode) for LHC-CMS
4. MPPC® (Multi Pixel Photon Counter) for HEP application
5. MPPC® for medical application

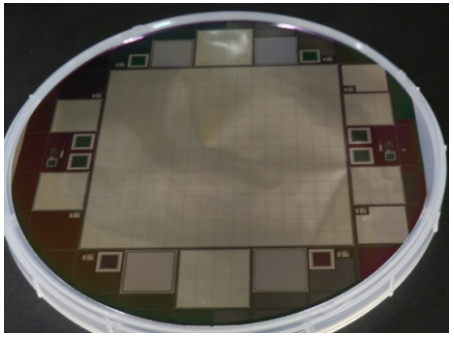
Hamamatsu Si detectors for HEP

Particle detection

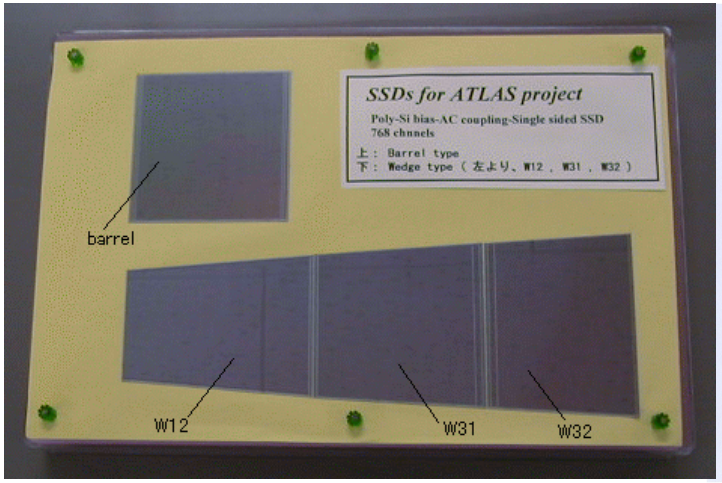
Silicon Strip Detector(SSD)

Silicon Pixel Detector

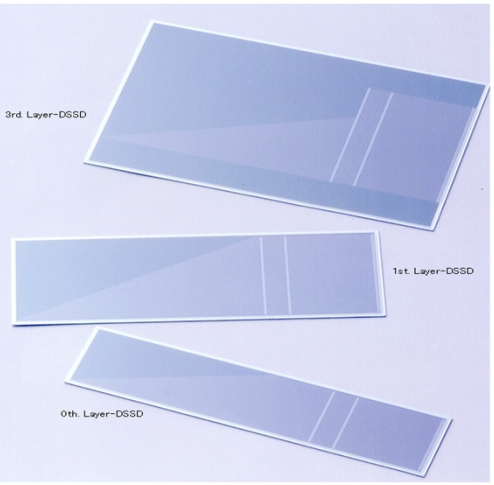
Silicon PAD Detector



PAD



SSSD



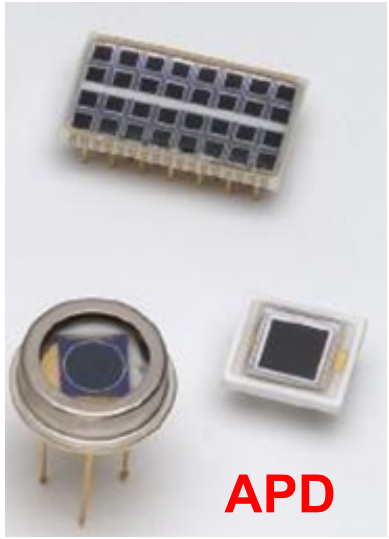
DSSD

Photo detection

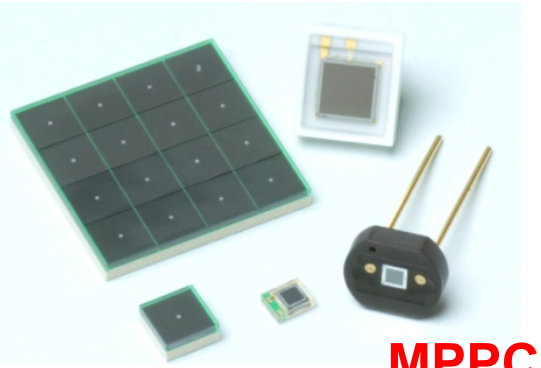
Silicon Photo Diode(PD)

Silicon Avalanche Diode(APD)

Multi Pixel Photon Counter(MPPC®)



APD



MPPC

1. SSD (Silicon Strip Detector) for tracker of many HEP experiments

2. Development of large area PAD detector

3. APD(Avalanche Photo Diode) for LHC-CMS

4. MPPC® (Multi Pixel Photon Counter) for HEP application

5. MPPC® for medical application

Review of main SSDs made by Hamamatsu（～1999）

PROJECT	DETECTOR TYPE	size	QTY.	period
MARKⅡ	DC-SSSD 3type	3chip/4inch	44	1987
CLEOⅡ	AC-DSSD 3type Pside: punch-through , Nside: poly-Si & DML	1chip/4inch 2chip/4inch	122	1993～1994
DELPHI	AC-DSSD 2type both-side: poly-Si , Nside: DML	2chip/4inch	130	1993～1994
DELPHI up grade	AC-SSSD , FOXFET	2chip/4inch	330	1994
NOMAD	AC-SSSD , FOXFET	2chip/4inch	650	1996～1997
CLEOⅢ	DC-DSSD , Pside: DML	2chip/4inch	550	1997～1999
CDF-SVX	AC-DSSD 3type both-side: poly-Si , Nside: DML	1chip/4inch 2chip/4inch	360	1997～1999
CDF-ISL	AC-DSSD both-side: poly-Si , Pside: stereo	1chip/4inch	550	1998～1999
PAMELA	AC-DSSD Pside: punch-through , Nside: poly-Si & DML	2chip/4inch	60	1997
KEK-B(BELLE)	AC-DSSD both-side: poly-Si , Nside: DML	2chip/4inch	180	1998
ZEUS	AC-SSSD 3type , poly-Si	1chip/4inch	950	1999

Review of main SSDs made by Hamamatsu（2000～）

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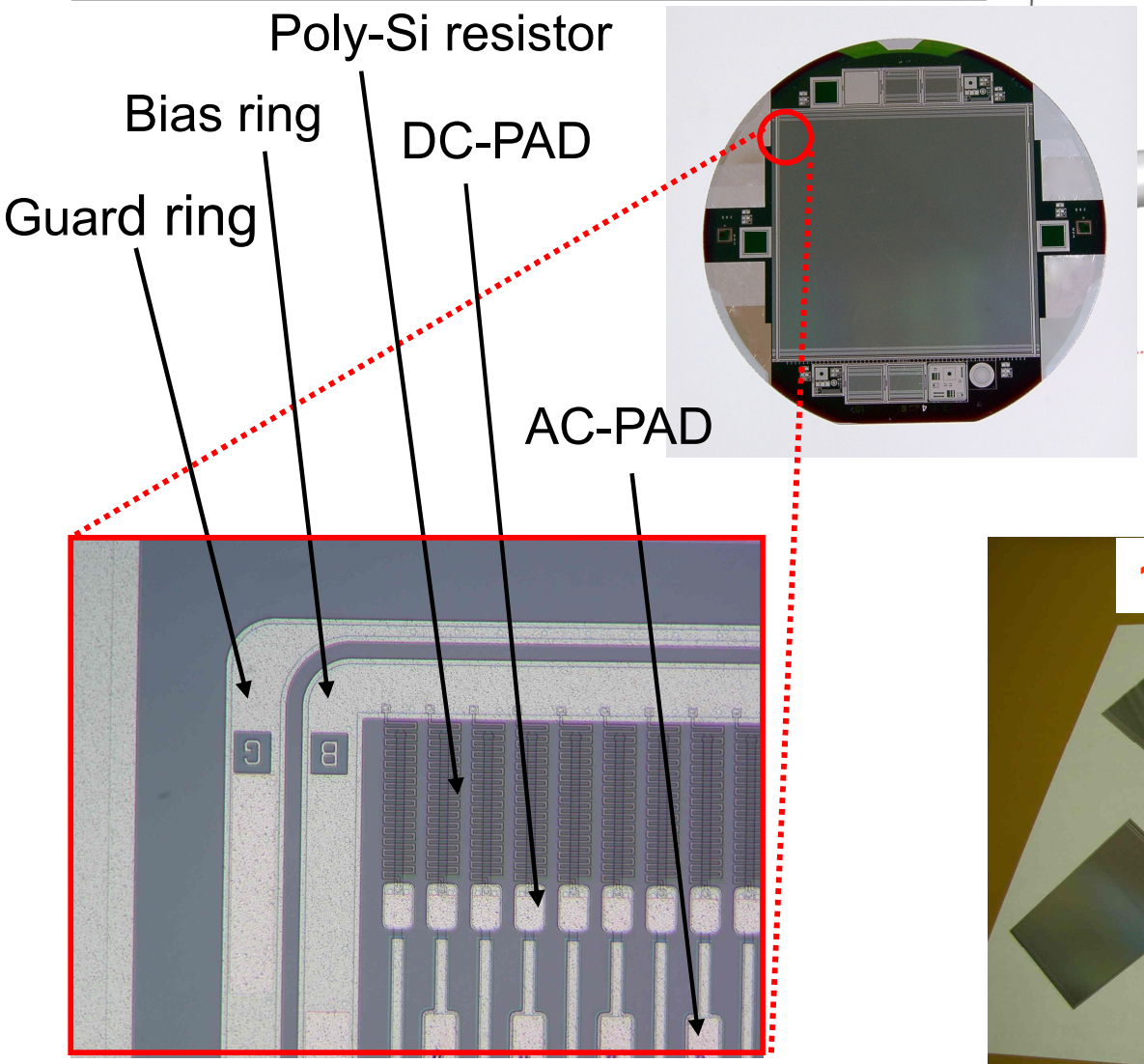
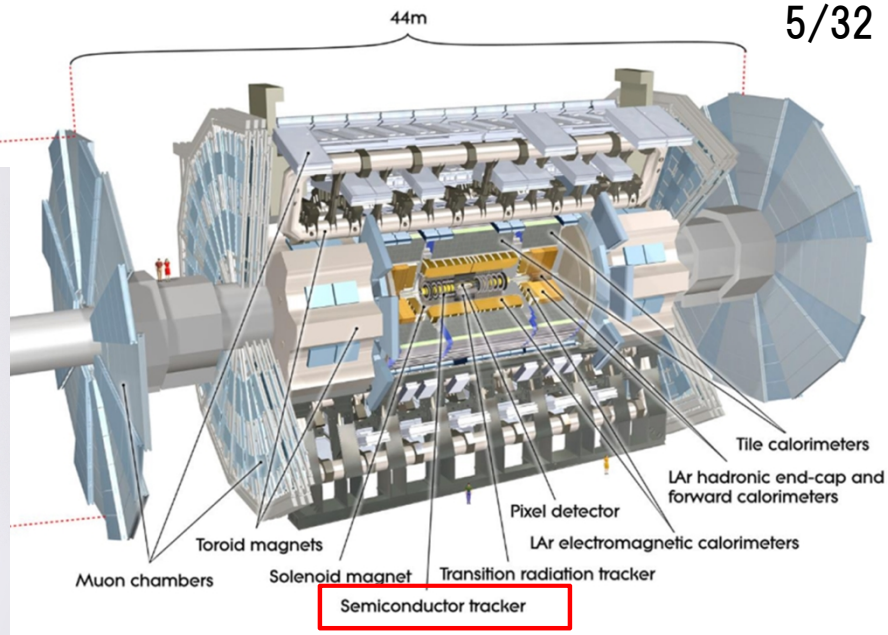
PROJECT	DETECTOR TYPE	size	QTY.	period
AGILE	AC-SSSD , poly-Si	1chip/6inch	500	2000
PAMELA	DC-SSSD	1chip/6inch	300	2000
BELLE up grade	AC-DSSD , both-side: poly-Si	2chip/4inch	250	2000～2002
ATLAS	AC-SSSD 6type , poly-Si	1chip/4inch	15500	2001～2003
GLAST	AC-SSSD , poly-Si	1chip/6inch	11500	2001～2003
CMS	AC-SSSD 14type , poly-Si	1chip/6inch	24000	2003～2006
LHC-b	AC-SSSD , poly-Si	1chip/6inch	560	2005～2006
ALICE	AC-SSSD 2type , poly-Si	1chip/6inch	106	2005～2006
Phenix	Strippixel , DML	3chip/6inch	600	2007
PP2PP	AC-SSSD 2type , poly-Si	1chip/6inch	120	2003～2007
FVTX	AC-SSSD 2type , poly-Si	3chip/6inch	450	2009～2010
ASTRO-H	DC-DSSD , DC-PAD , Pside: DML	3chip/6inch	260	2007～2011
STAR-HFT	AC-SSSD , poly-Si	2chip/6inch	216	2012
HALL-B	AC-SSSD(stereo) 3type , poly-Si	1chip/6inch	434	2012
BELLE-II	AC-DSSD , 2type , Poly-Si	1chip/6inch	265	2011～2014
DAMPE	AC-SSSD , poly-Si	1chip/6inch	768	2014

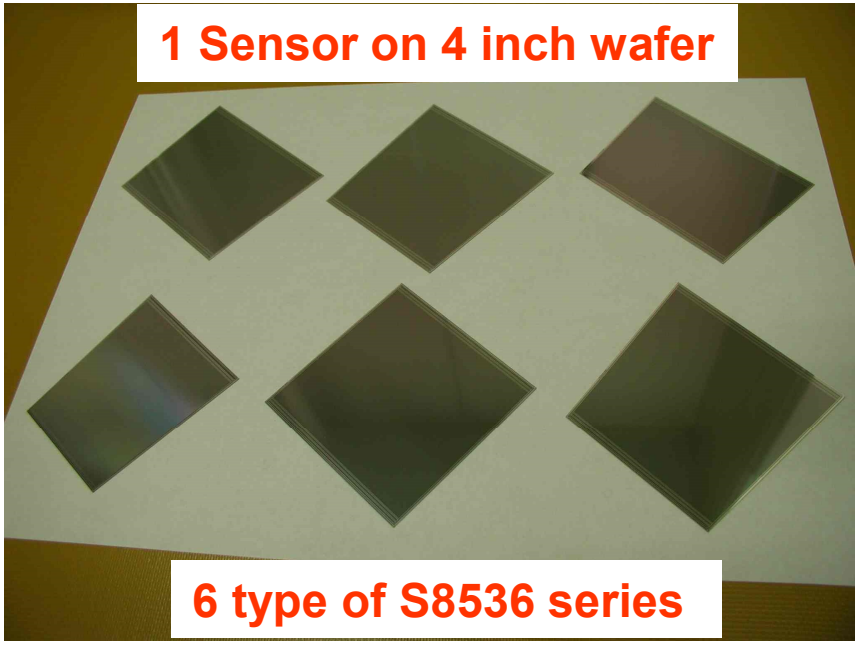
ATLAS-SSSDs



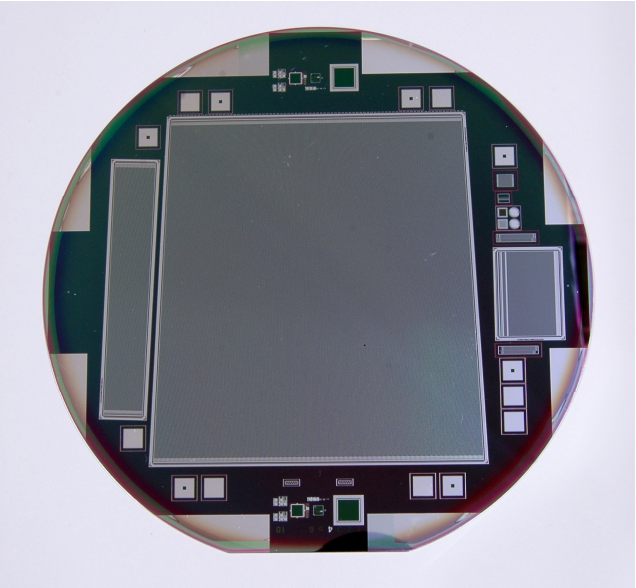
AC coupling-SSSD



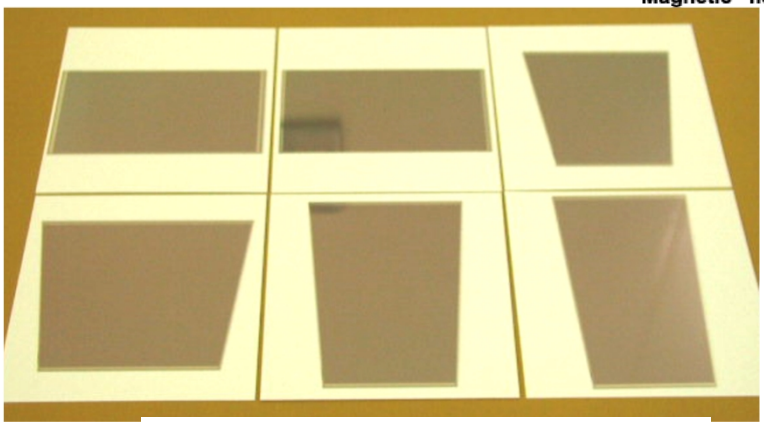
provided from ATLAS experiment groups



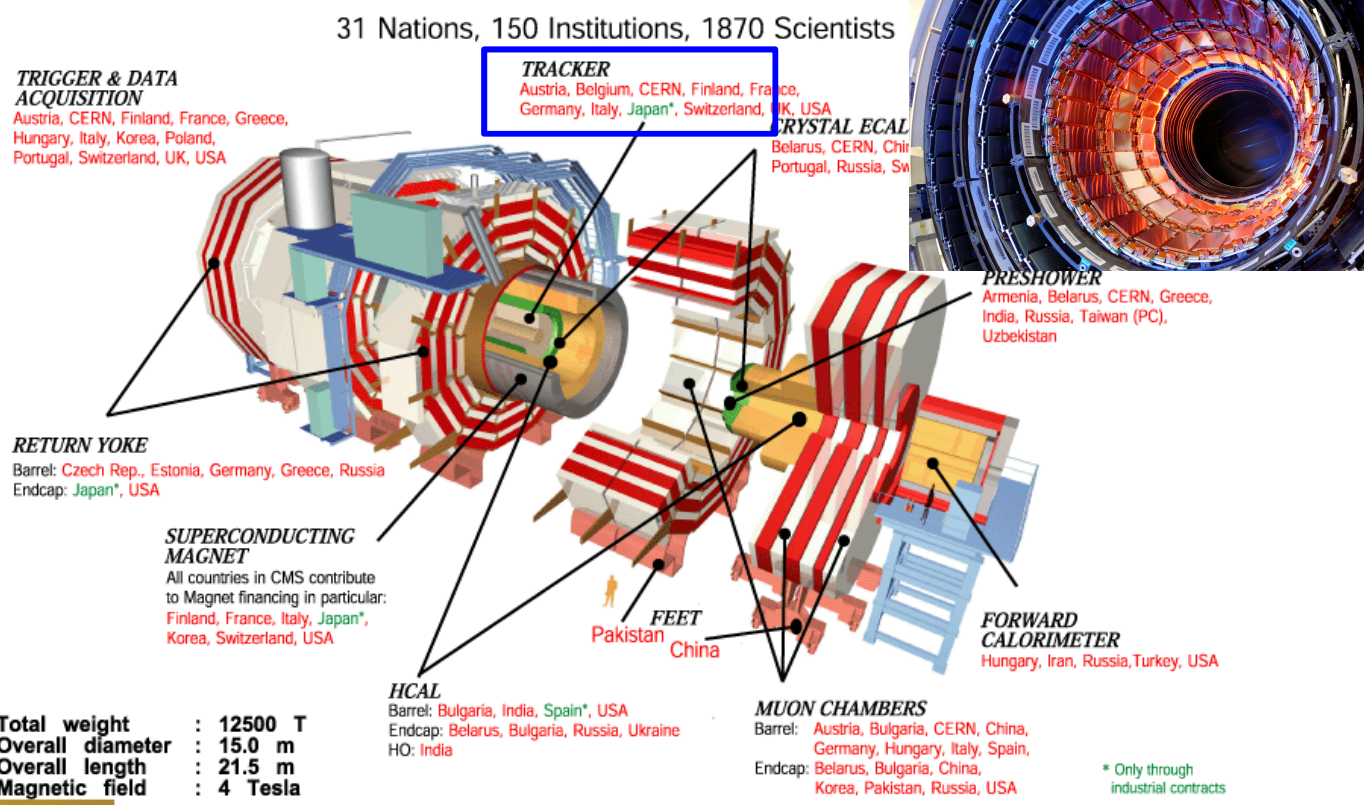
CMS-SSDs



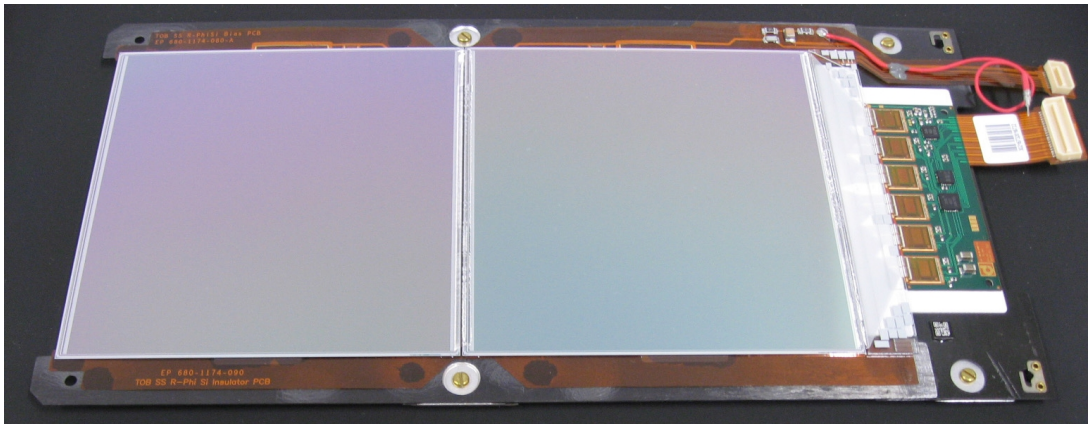
1 Sensor on 6 inch wafer



S9153, S9154 series

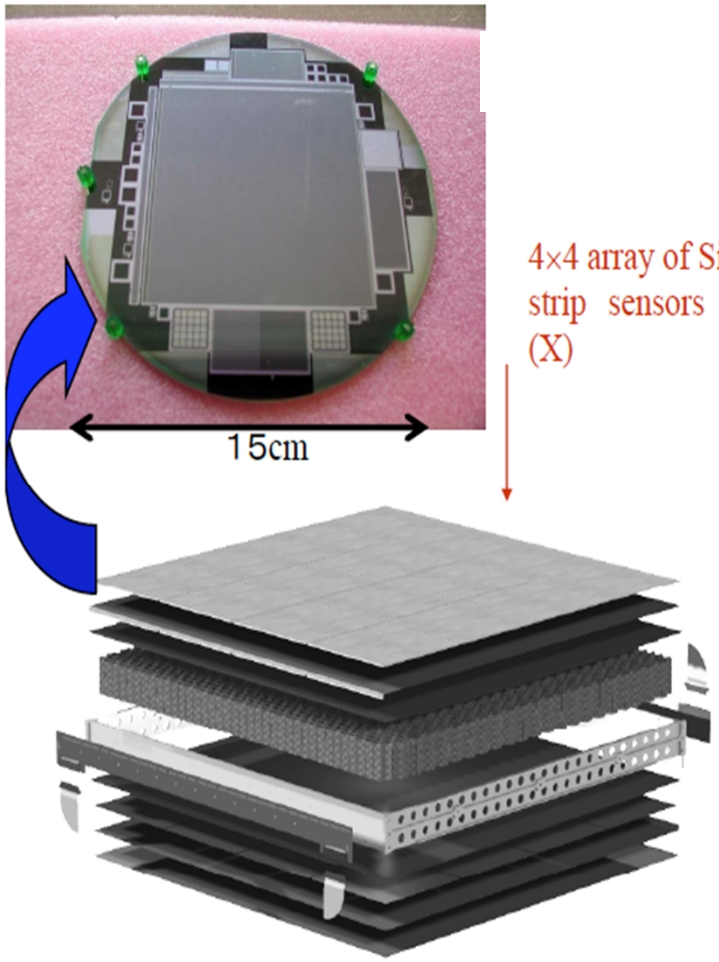


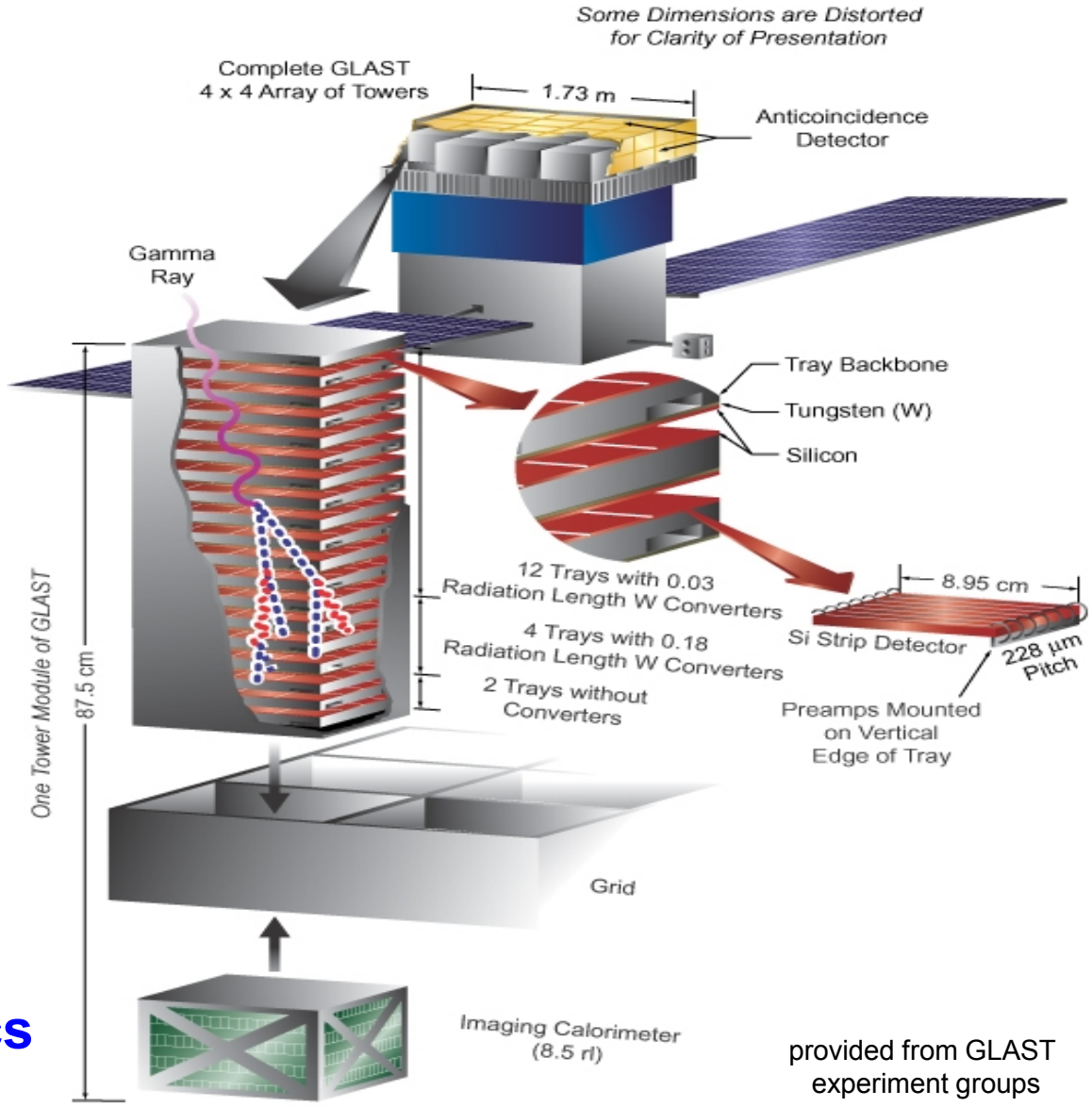
Total weight	:	12500 T
Overall diameter	:	15.0 m
Overall length	:	21.5 m
Magnetic field	:	4 Tesla



provided from CERN experiment groups

Fermi(GLAST)-SSSD



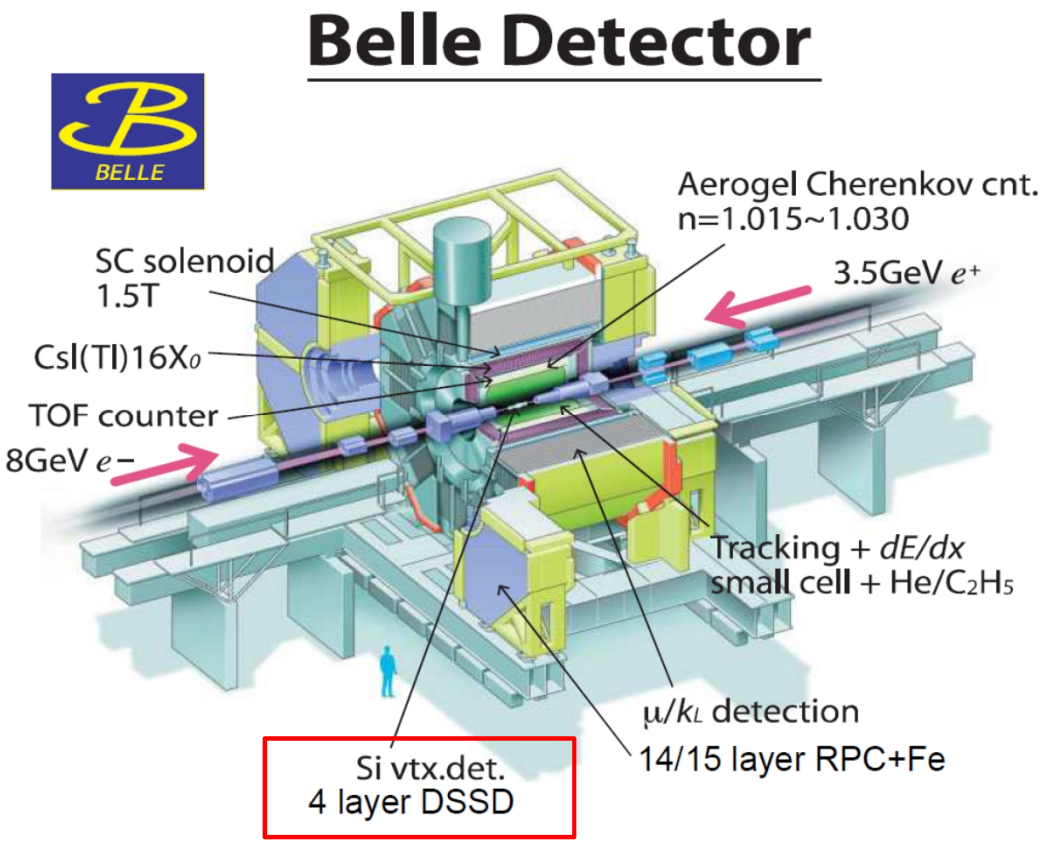


Total strip detectors:11,000pcs
8.95x8.95 mm 228µm pitch

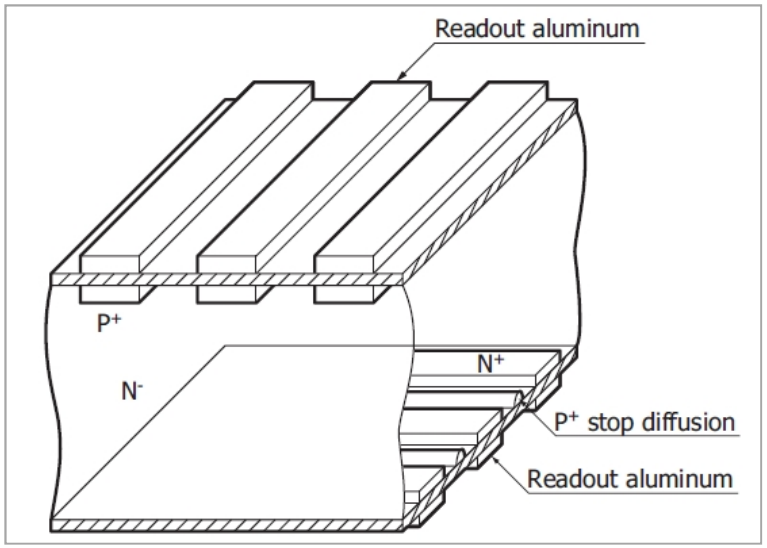
provided from GLAST experiment groups

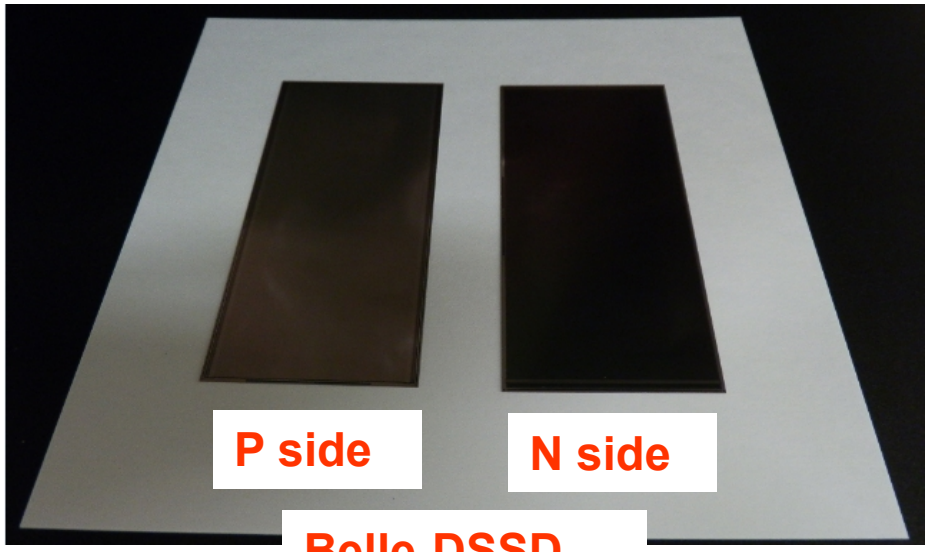
Belle - DSSD

Double Side SSD (DSSD) from 6inch wafer



provided from Belle experiment groups



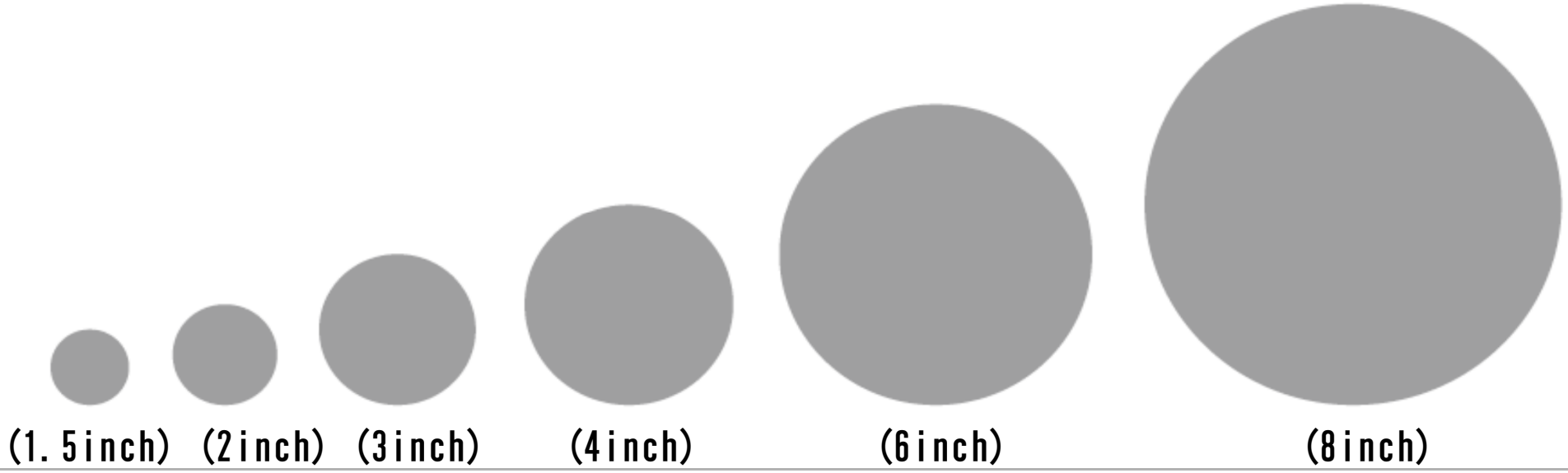


Belle-DSSD

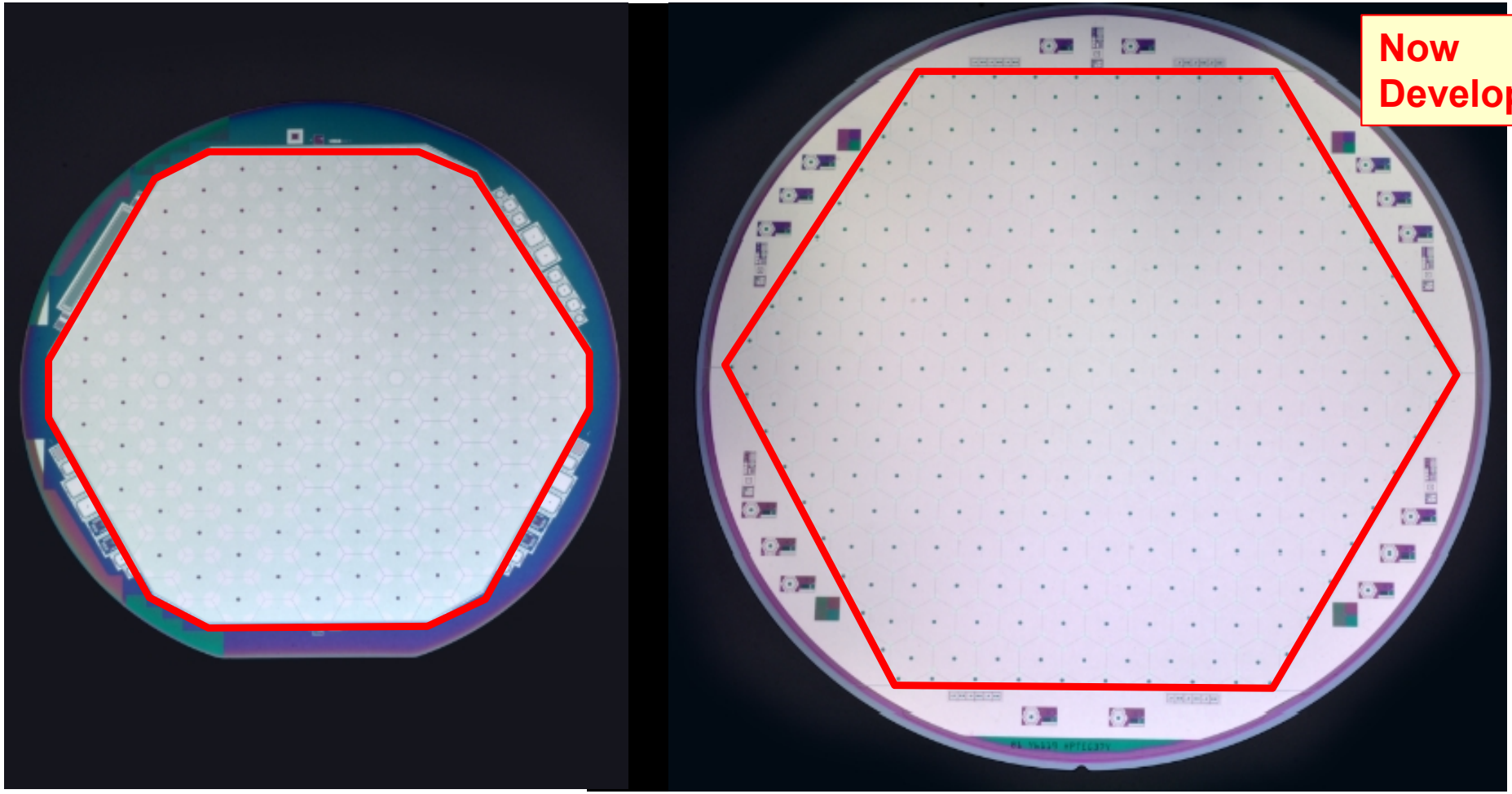
1. SSD (Silicon Strip Detector) for tracker of many HEP experiments
2. **Development of large area PAD detector**
3. APD(Avalanche Photo Diode) for LHC-CMS
4. MPPC® (Multi Pixel Photon Counter) for HEP application
5. MPPC® for medical application

History of Hamamatsu Si wafer size

Wafer size	Production term
φ1.5inch	1972～1985
Φ2inch	1975～1986
Φ3inch	1983～1996
Φ4inch	1987～2008
Φ6inch	1998～
Φ8inch	developing



Development of 8inch-PAD detector



6inch-PAD detector

- 12 Polygon shape chip
- 109 x Hexagonal PADs + α

8inch-PAD detector

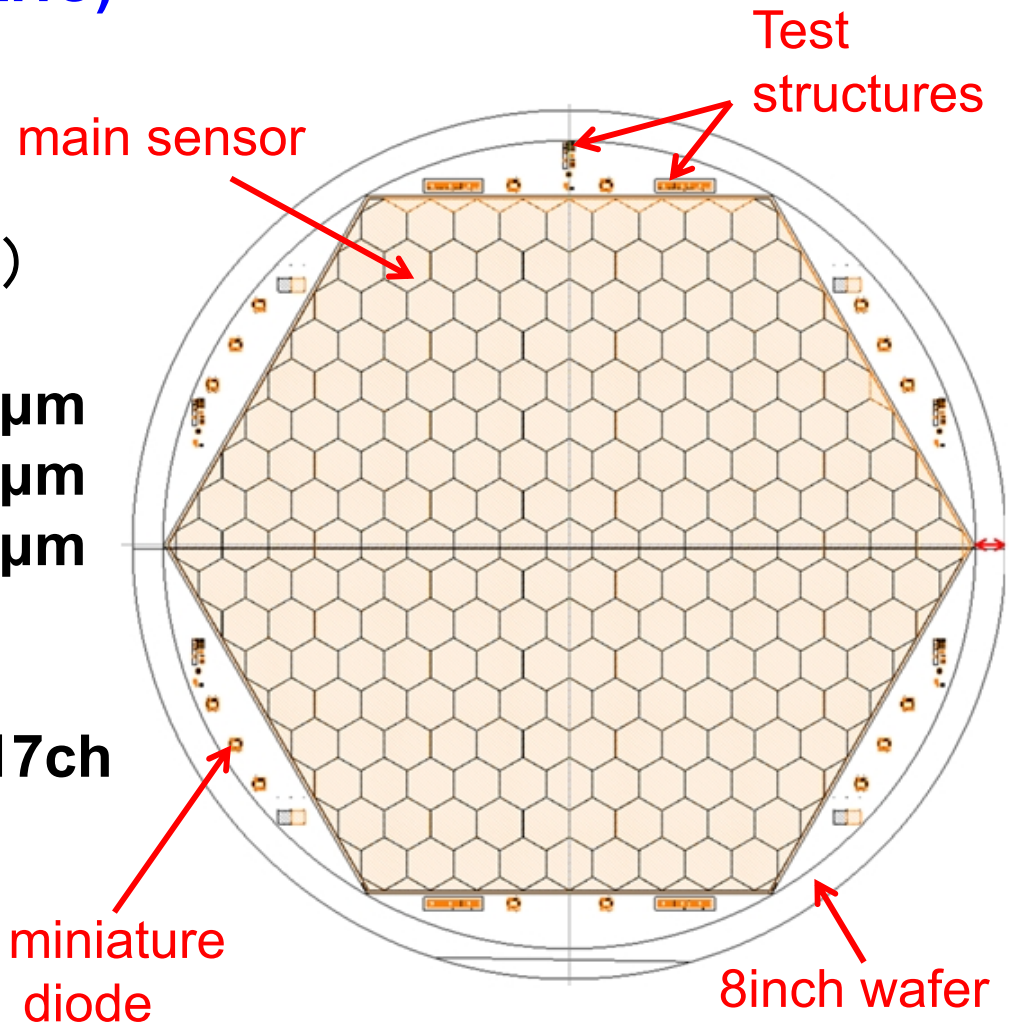
- Hexagonal shape chip
- 217 x Hexagonal PADs + α

Development of 8inch-PAD detector

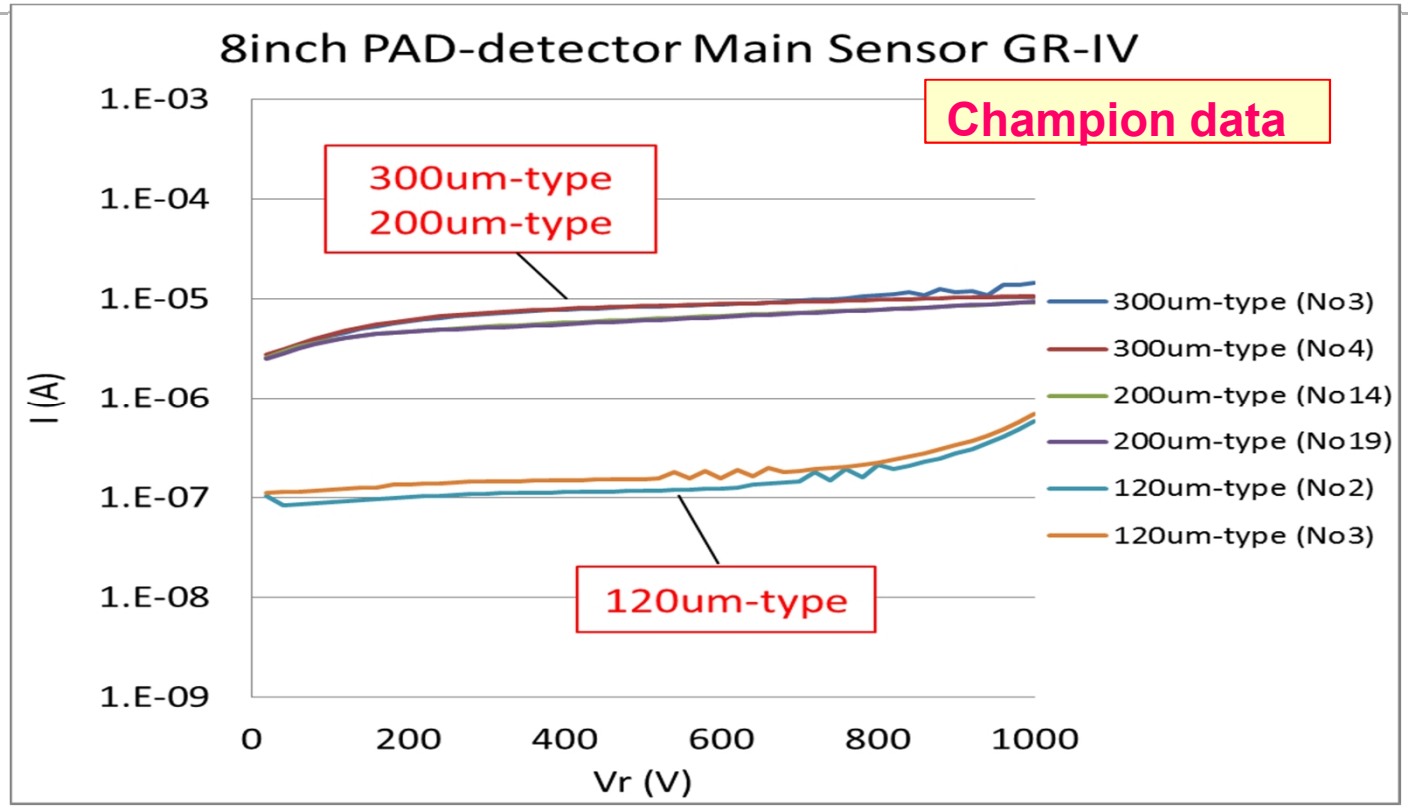
■ Our 1st Proto-type
（target for CMS-HGCAL HL-LHC)

- Size : 8 inch
- Type : N+ in p
  （P-substrate and N-PAD）
- Thickness : 3types
  - ・Active 300μm、Physical 300μm
  - ・Active 200μm、Physical 200μm
  - ・Active 120μm、Physical 300μm

- Size of PAD :~ 1cm2
- Number of Hexagonal PAD : 217ch



Result-1
Guard-Ring I-V of Main Sensor



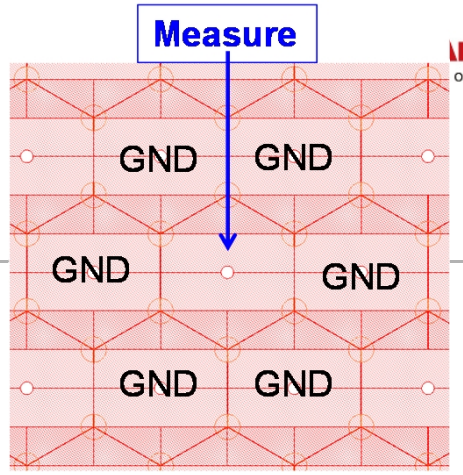
—300μm and 200μm type

1000V voltage tolerance, but higher dark current compared to 120μm-type or conventional 6inch.

—120μm type

1000V voltage tolerance and low dark current.

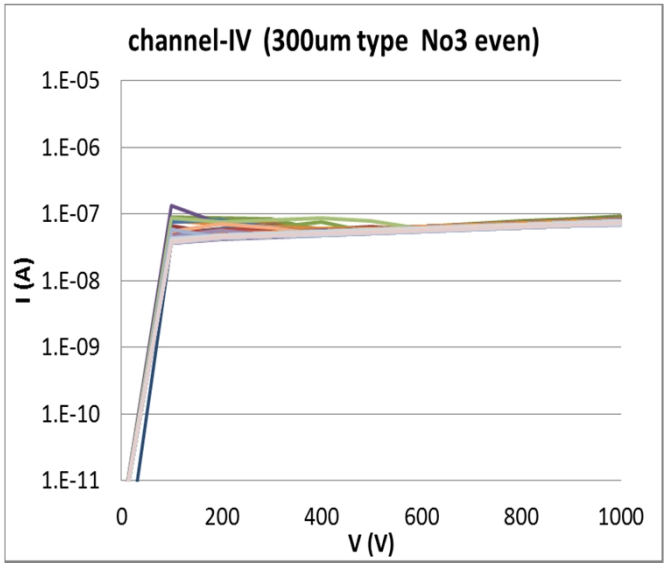
Result-2
Channel I-V of Main Sensor



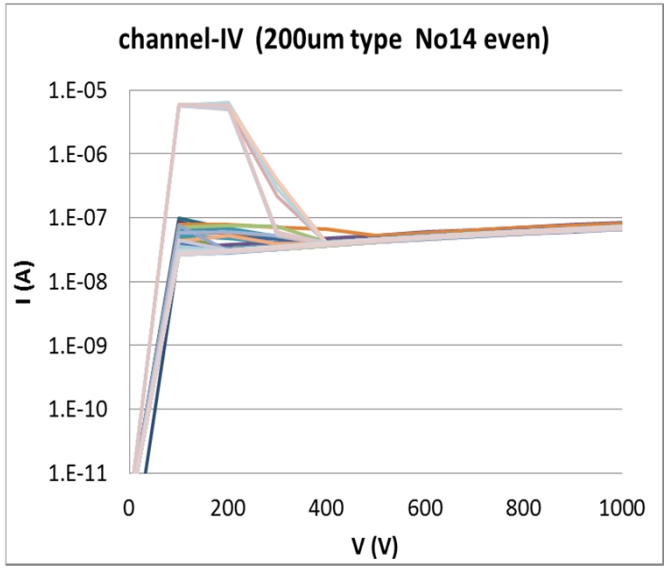
■ We measured IV curve of every channels with surrounded channels GND.

Champion data

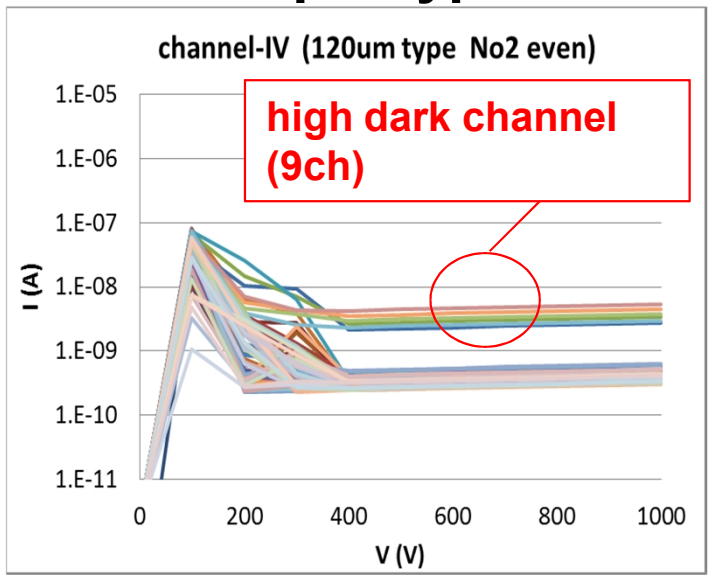
300μm type



200μm type



120μm type



—300μm and 200μm type

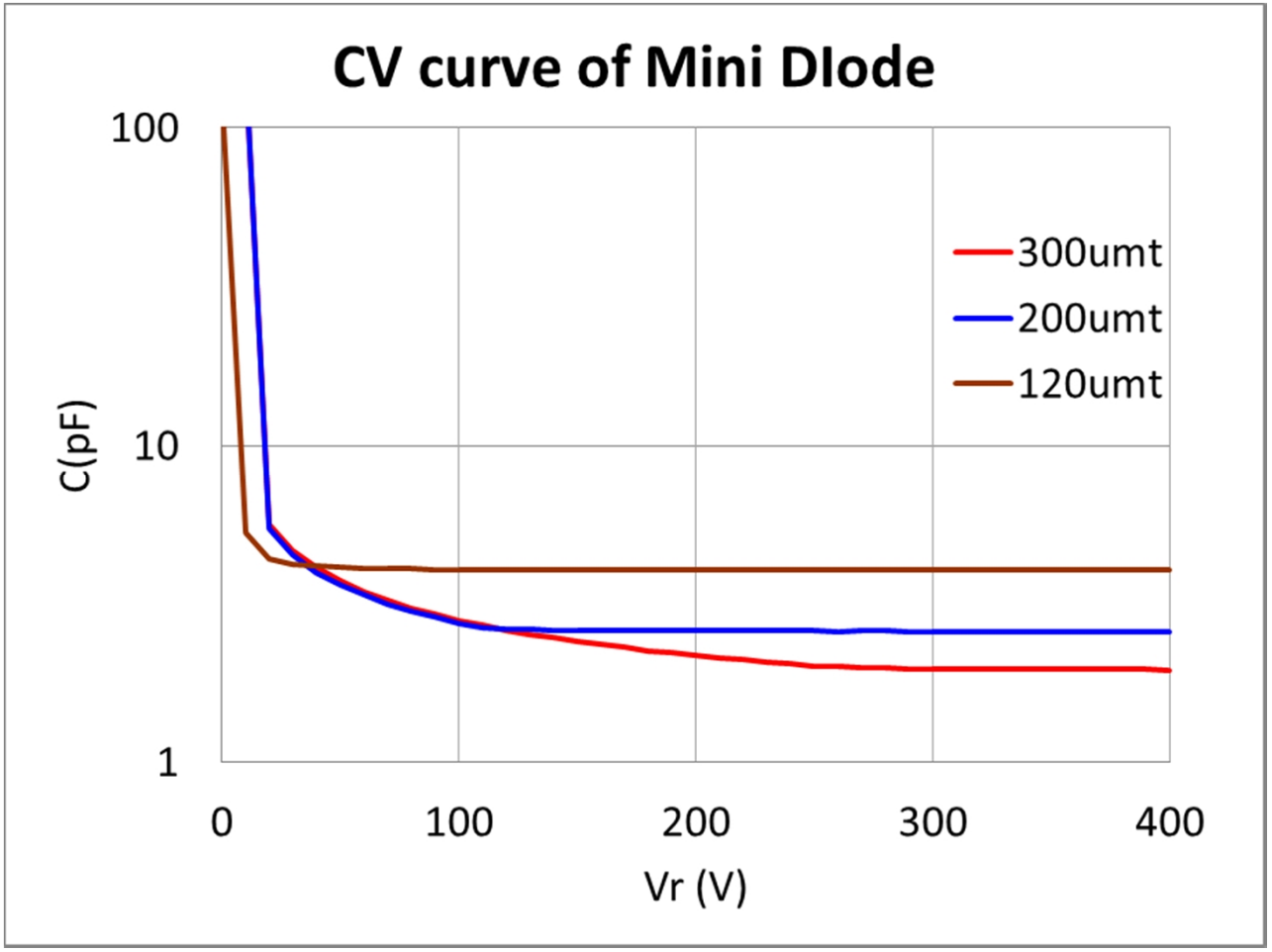
1000V voltage tolerance, but higher dark current.

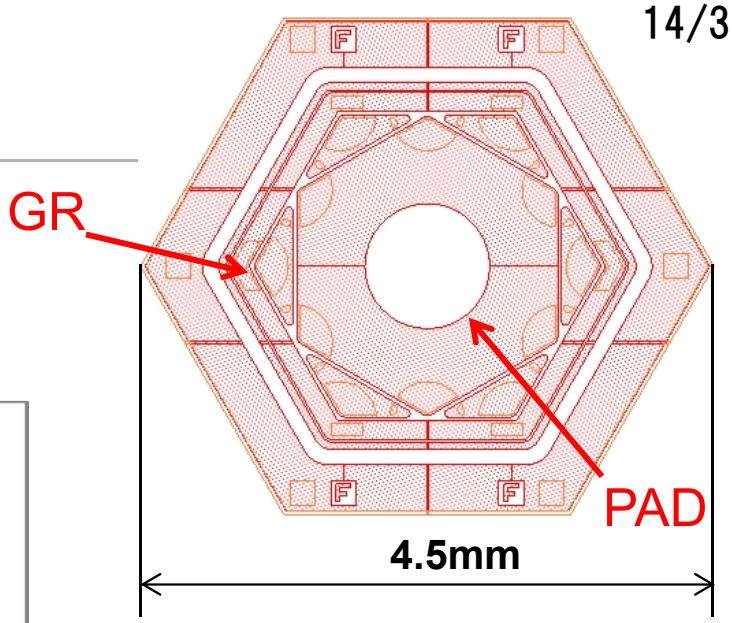
—120μm type

Some specific chs have higher dark. (→We almost know the cause)

Result-3
C-V curve of Mini Diode

■ **We measured CV curve of Mini Diode and estimated the full depletion voltage.**





Full depletion voltage

300µm type : ~280V
200µm type : ~130V
120µm type : ~ 30V

Future prospect of 8inch wafer production

○DC-type : PAD-detector, PIXEL

- Development stage ～2019
- will be available 2020～

○AC-type : AC coupled SSD

- Development stage 2020～2022
- will be available 2023～

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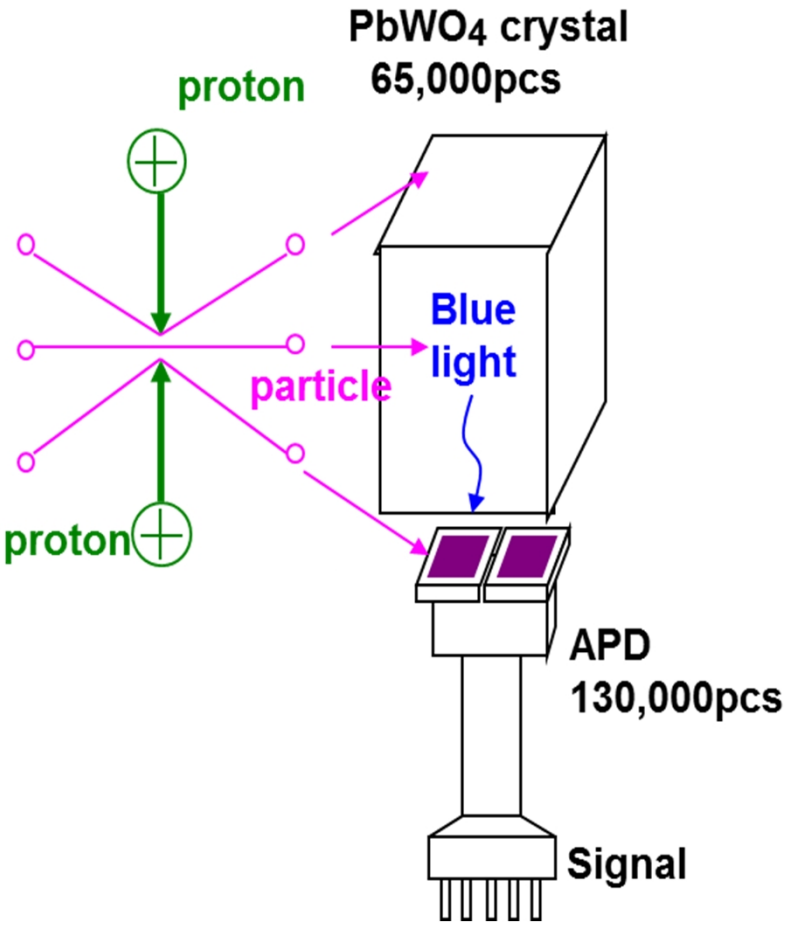
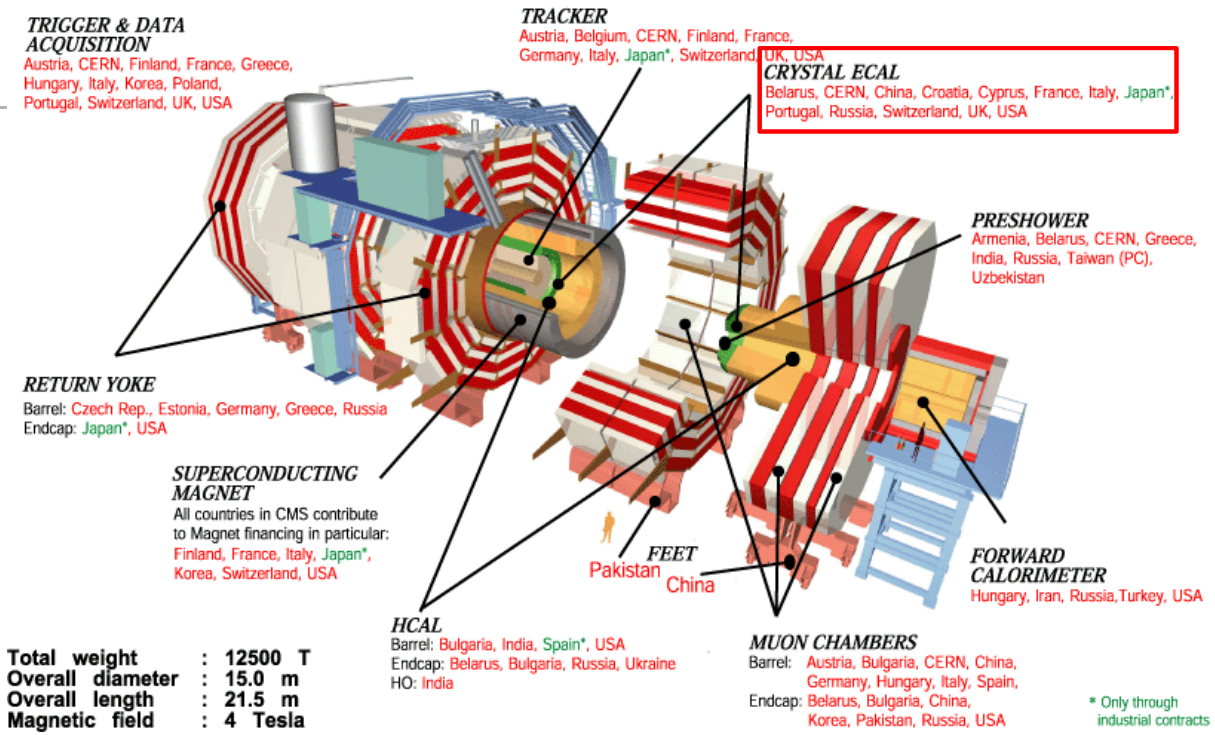
CMS-APD

About 130,000 pieces of APD are used for CMS-ECAL





provided from CERN experiment groups

Spec.(Ta = 25℃)

STD No	S8148
active area	5 x 5 mm2
breakdown voltage (VB)	> 325 V
Operating Voltage (VR)	300 - 450 V
Difference VB-VR	> 25 V
Dark current at VR	< 50 nA
Capacitance at VR	65 - 85 pF
Quantum efficiency at VR, 430nm	75 ± 5%
Passivation layer	SiN
Protective coating	Epoxy Resin

Characteristic required for the CMS-APD

APD is used in a high magnetic field
⇒ require to operate at high magnetic field

$PbWO_4$ crystal
65,000pcs

proton

Blue light from crystal is weak.
⇒ require high blue sensitivity and low noise

Blue light

particle

proton

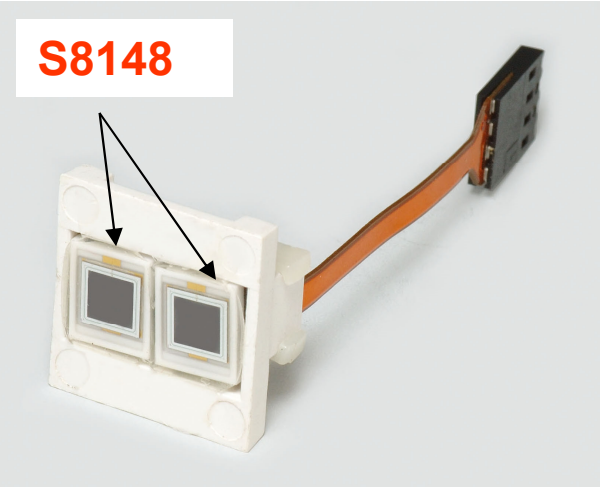
Radiation hit directly to APD.
⇒ require high radiation tolerance (2E13 n-eq/cm^2) and less sensitive to incident radiation background

APD needs large area to cover a crystal

APD
130,000pcs

Signal

APD are controlled from outside the accelerator
⇒ require low bias dependence and easy to control



1. SSD (Silicon Strip Detector) for tracker of many HEP experiments
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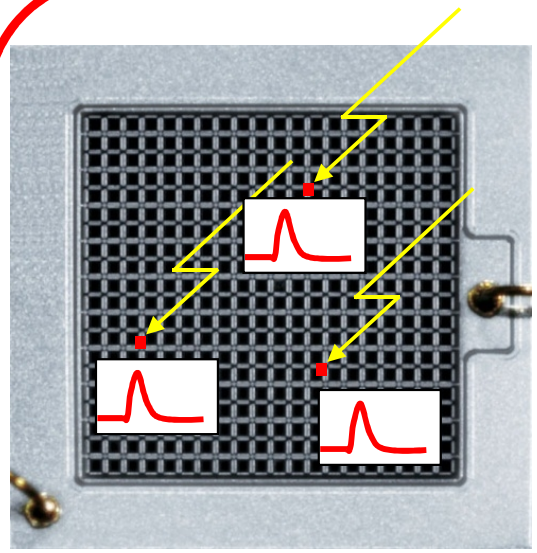
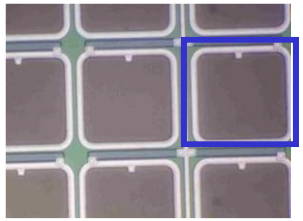
MPPC® Technology Overview

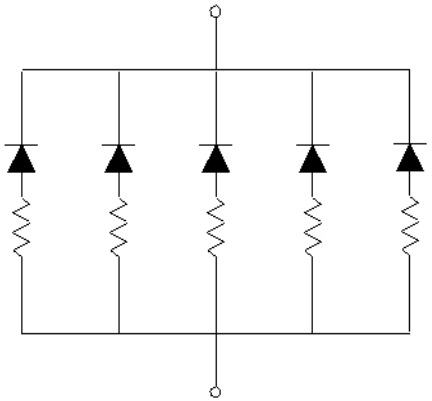
➢What is an MPPC®?

- **M**ulti-**P**ixel **P**hoton **C**ounter
  a new type of photon-counting device
  made up of multiple APD pixels
  operated in Geiger mode





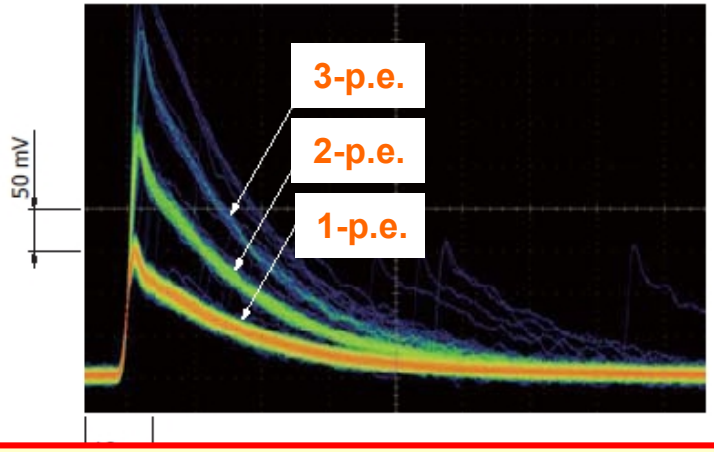
pixel



Output is summation of all pixel output

➢Features

- Small size / light weight
- Room temperature operation
- Low bias operation : ～40V
- High gain: 10^5 to 10^6
- Excellent timing resolution
- Insensitive to magnetic fields
- Simple readout circuit operation



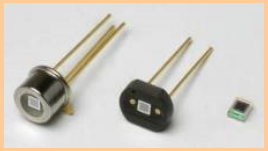
$$Q_{out} = N_{fired} \times C_{pixel} \times (V_{op}-V_{BR})$$

$$N_{fired} = PDE \times N_{photon}$$

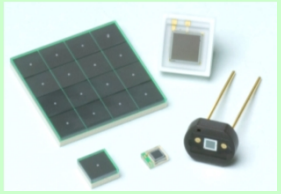
History of MPPC®s

Noise

2007
1st generation
(S10362 series)

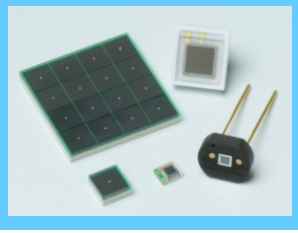


2013
2nd generation
(S1257x series)



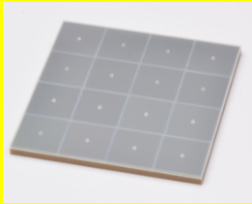
w/ Low afterpulse

2015
3rd generation
(S1336x series)



w/ High Fill factor

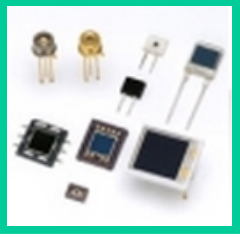
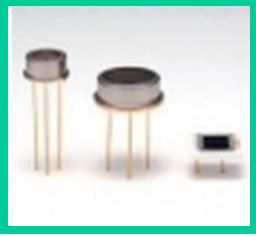
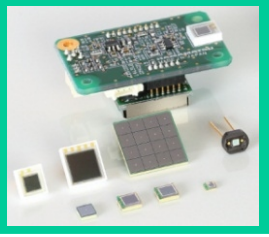
2017 ***New***
4th generation
(S1416x series)



Low Operation voltage

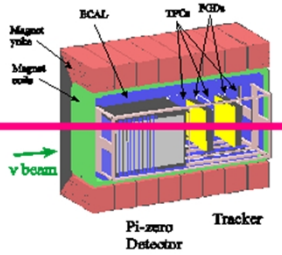
Sensitivity (PDE)

Characteristics comparison of PD,APD,MPPC and PMT

	PD	APD	MPPC	PMT
				
Gain	1	10^2	10^5 - 10^6	10^5 – 10^7
Operation voltage	5 V	100 – 500 V	~40 V	800 – 1000 V
Large area	No	No	Scalable	Yes
Readout circuit	Complex	Complex	Simple	Simple
Detection efficiency	High	High	High	Middle
Noise	Low	Middle	Middle	Low
Timing reso.	-	-	High	Middle
Energy reso.	High	Middle	High	High
Ambient light resist.	Yes	Yes	Yes	No
Magnetic resist	Yes	Yes	Yes	No
Compact	Yes	Yes	Yes	No

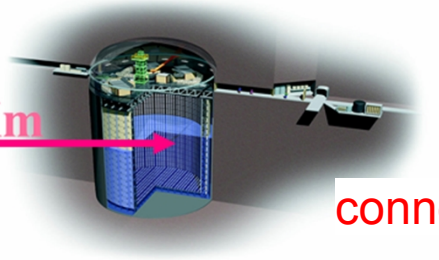
MPPC® for T2K Experiment (2008)

J-PARC
in Tokai-mura

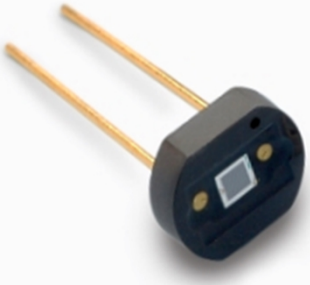


Fronting Detector
in J-PARC

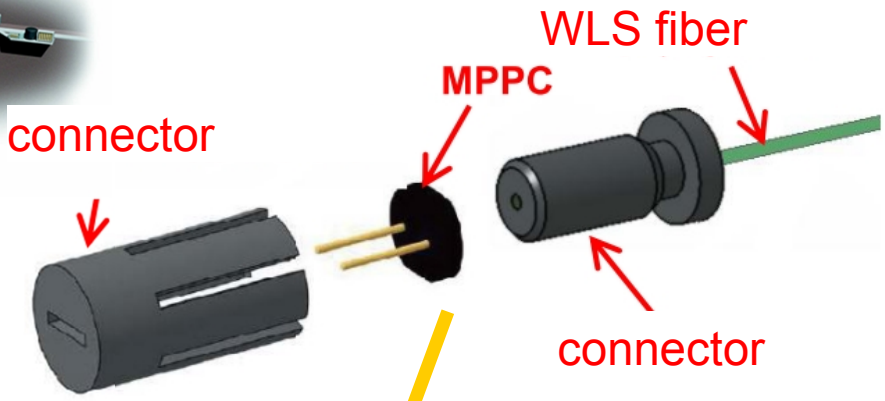
295Km

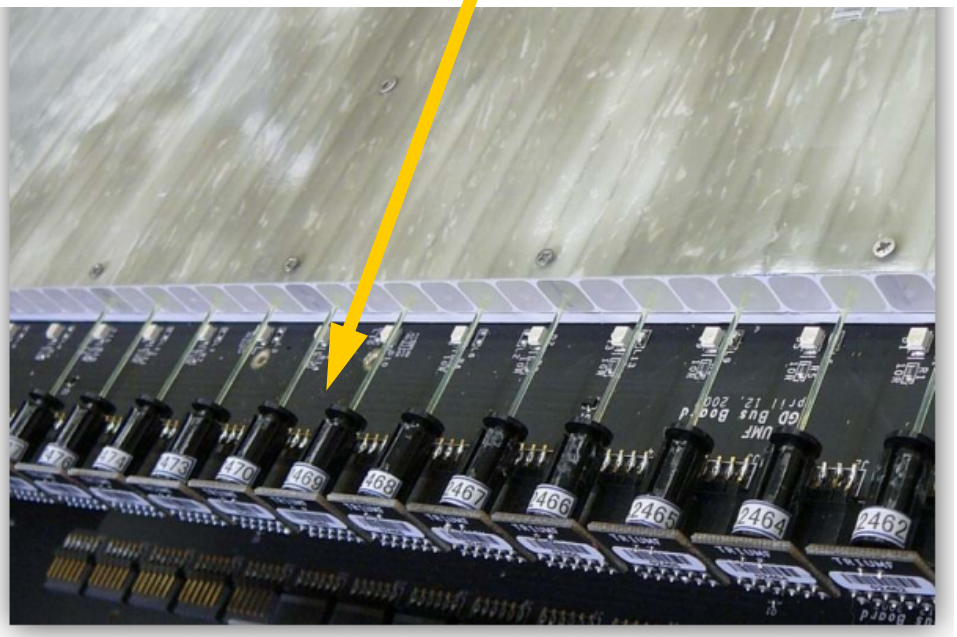


Super
KAMIOKANDE



S10362-13-050C
Installed 56kpcs.



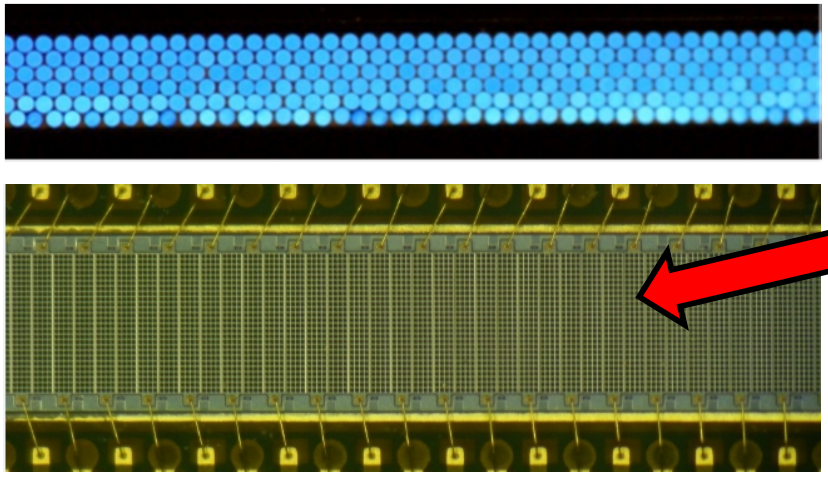


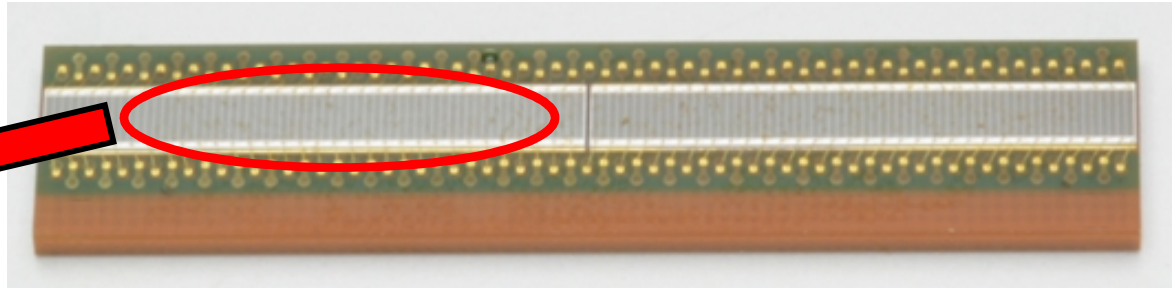
(Provided from Kyoto University)

Required properties

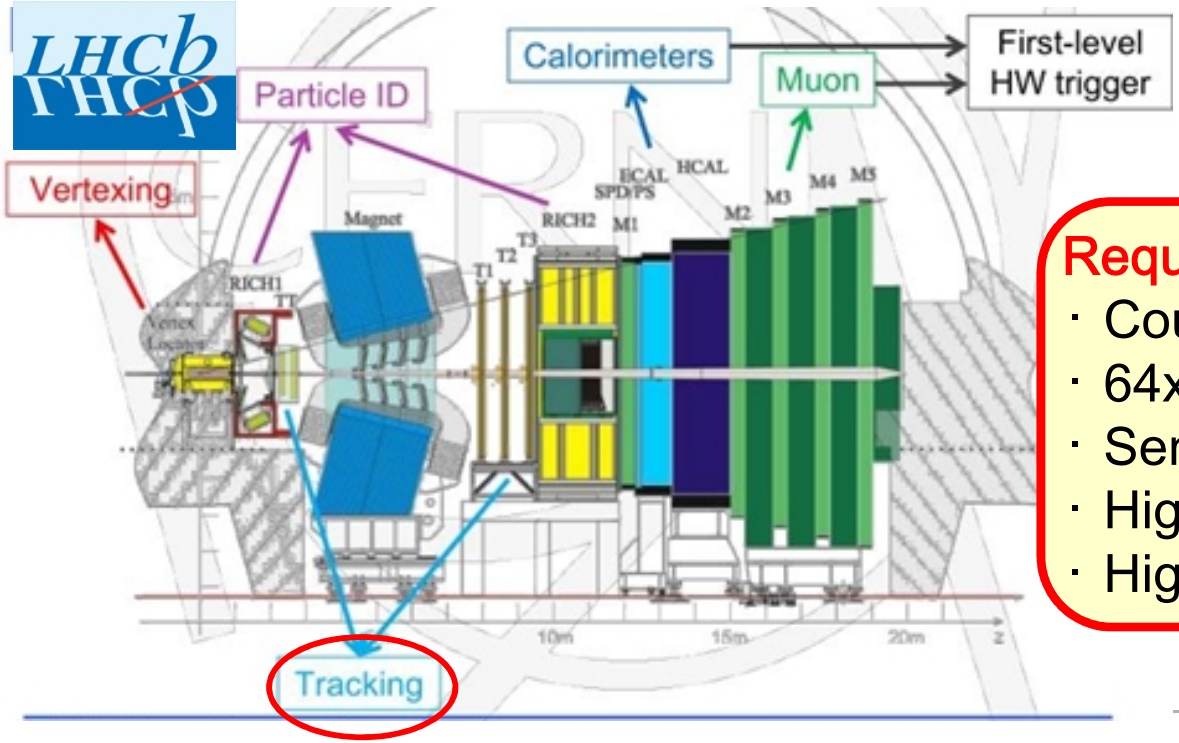
- Good coupling to φ1mm fiber
- High PDE for 525nm
- Withstand high magnetic field

MPPC® for LHCb SciFi Tracker





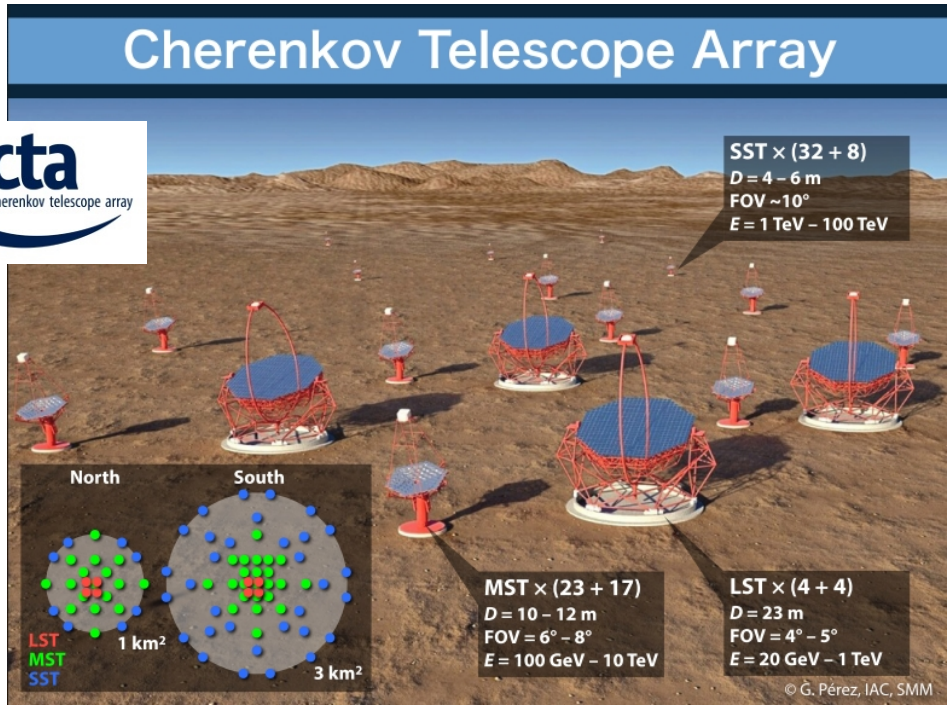
S13552



Required properties

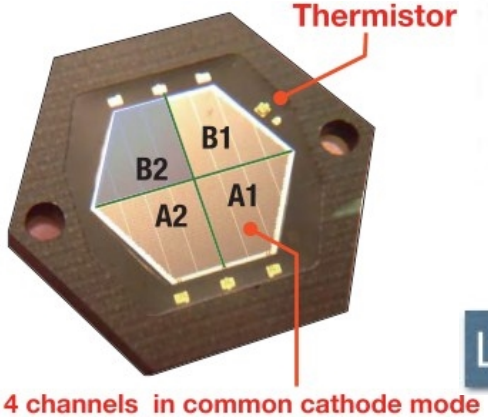
- Coupled with SciFi matrix
- 64x2ch fine pitch MPPC® array
- Sensitive area: 0.23x1.5mm p0.25mm
- High position accuracy
- High PDE @400nm

MPPC® for Cherenkov Telescope Array

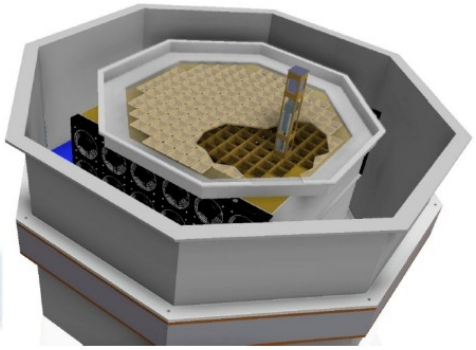


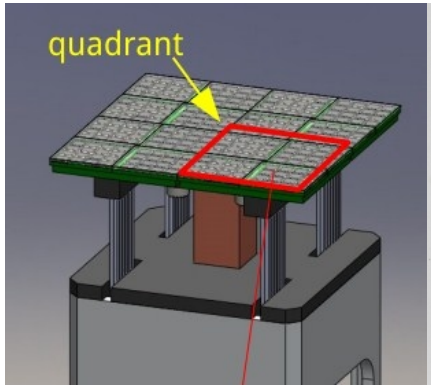
Required properties

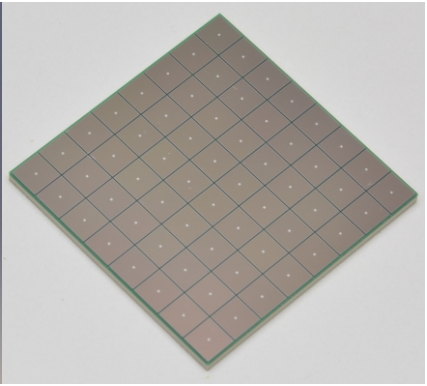
- High PDE @300nm
- High Gain
- Low cross talk
- Low dark count
- Large sensitive area



Light guides

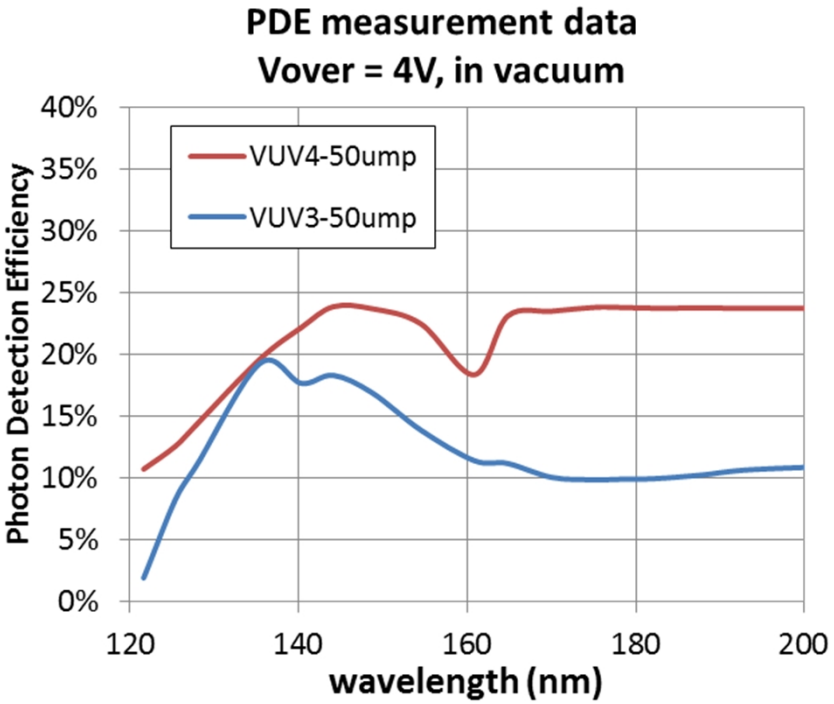


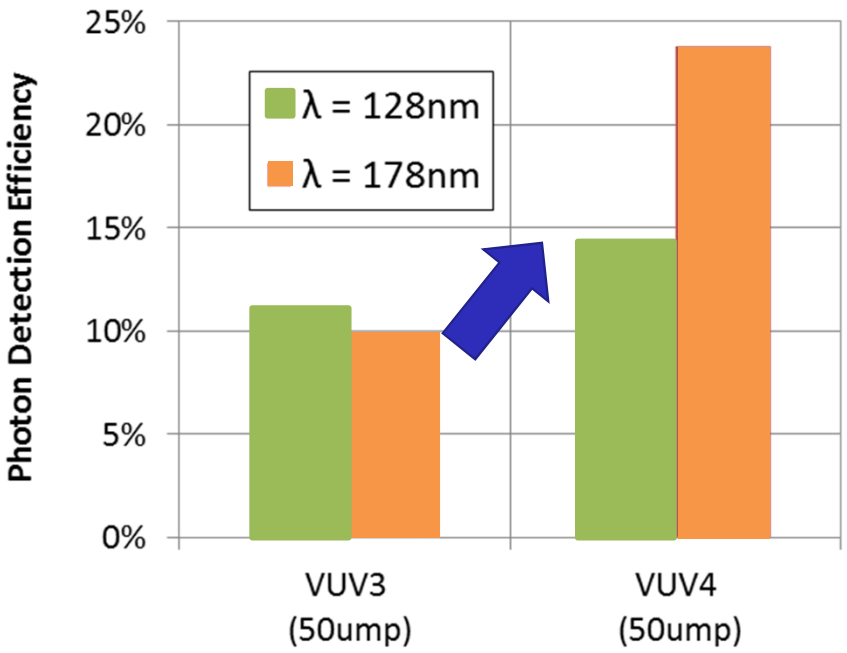




Improvement for VUV sensitivity

(VUV4:S13370 series) ref) K.Yamamoto, et al., ICHEP 2016, ID:450



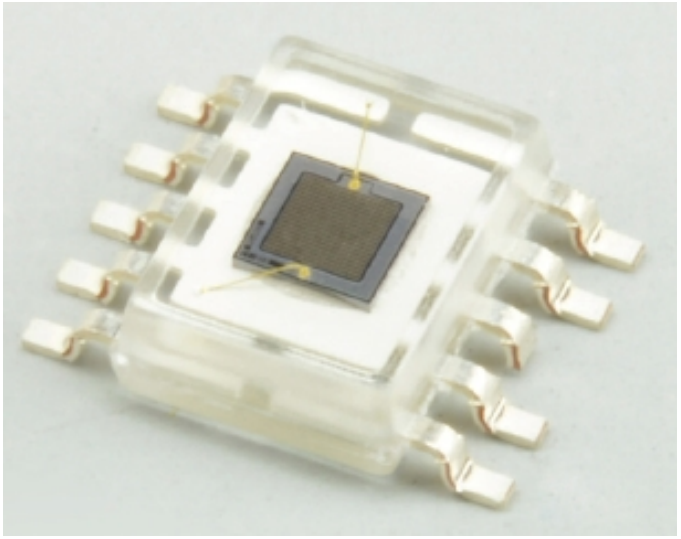


- VUV-MPPC has VUV-sensitivity down to 120nm.
- New developed VUV-MPPC (4th generation: VUV4) is improve photo detection efficiency, which is much higher in comparison with previous VUV-MPPC (VUV3).
- Optical cross-talk is still suppressed by the inter-pixel trench structure.
- VUV4-MPPC achieved improvement of Signal-Noise ratio.

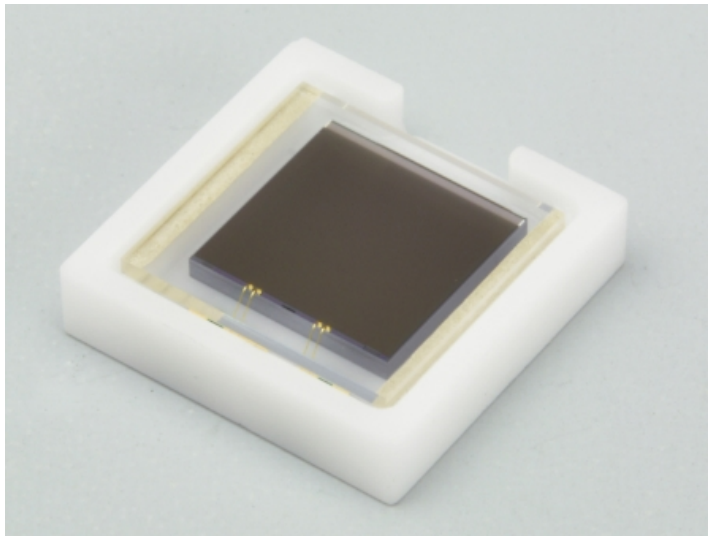
Ultralow-RI Package for physics

ref) K.Yamamoto, et al., ICHEP 2016, ID:450

For indirect detection (1mm SQ.)



For direct detection (6mm SQ.)



Package type:

Plastic mold (for indirect detection)

Pure ceramic (for direct detection)

RI level:

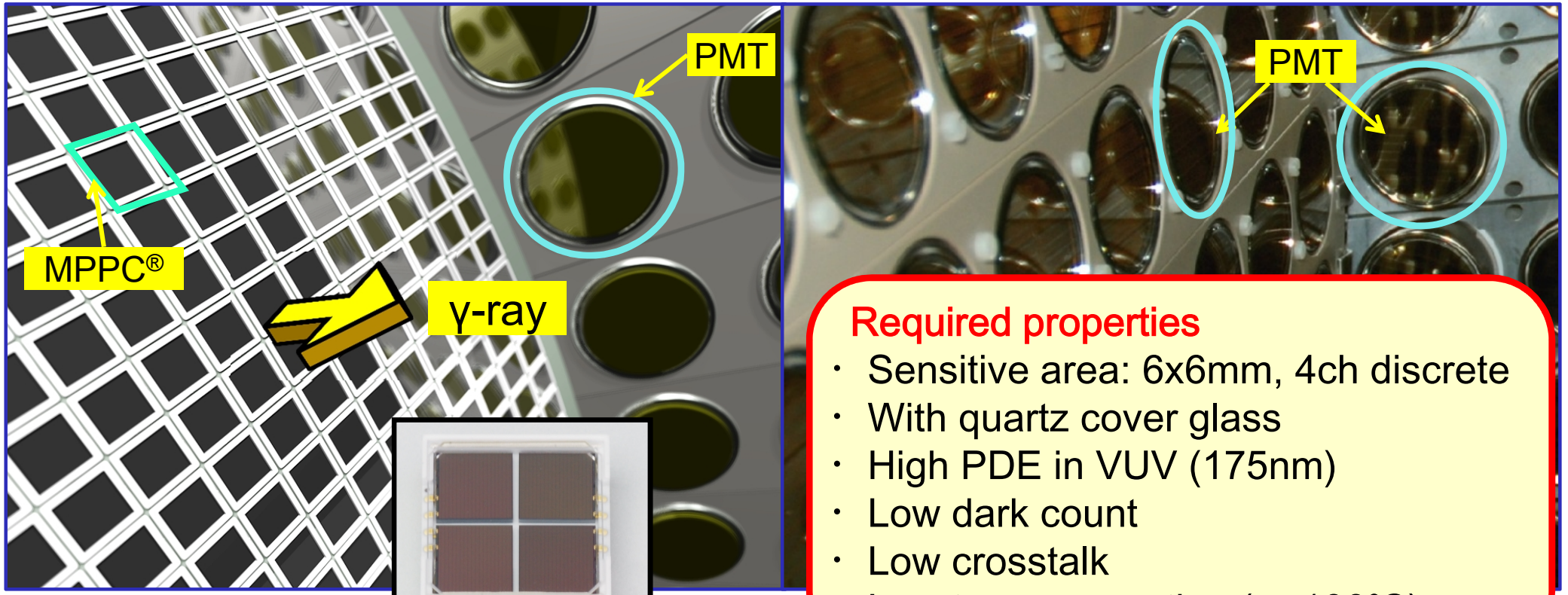
All radioactive nuclides has not been quantified in on-ground measurement at HPK.

High precision RI measurements are ongoing with some customers.

MPPC® for MEG Ⅱ

MEG experiment : searching for μ+ → e+ + γ decay
Liquid xenon *γ*-ray detector will be upgraded
2” PMT → MPPC® for VUV (175nm) total 4,000pcs.

MEG Ⅱ (CG image) ← **MEG**



S13371-6050CQ-02

Required properties

- Sensitive area: 6x6mm, 4ch discrete
- With quartz cover glass
- High PDE in VUV (175nm)
- Low dark count
- Low crosstalk
- Low temp. operation (< -100℃)

1. SSD (Silicon Strip Detector) for tracker of many HEP experiments
2. Development of large area PAD detector
3. APD(Avalanche Photo Diode) for LHC-CMS
4. MPPC® (Multi Pixel Photon Counter) for HEP application

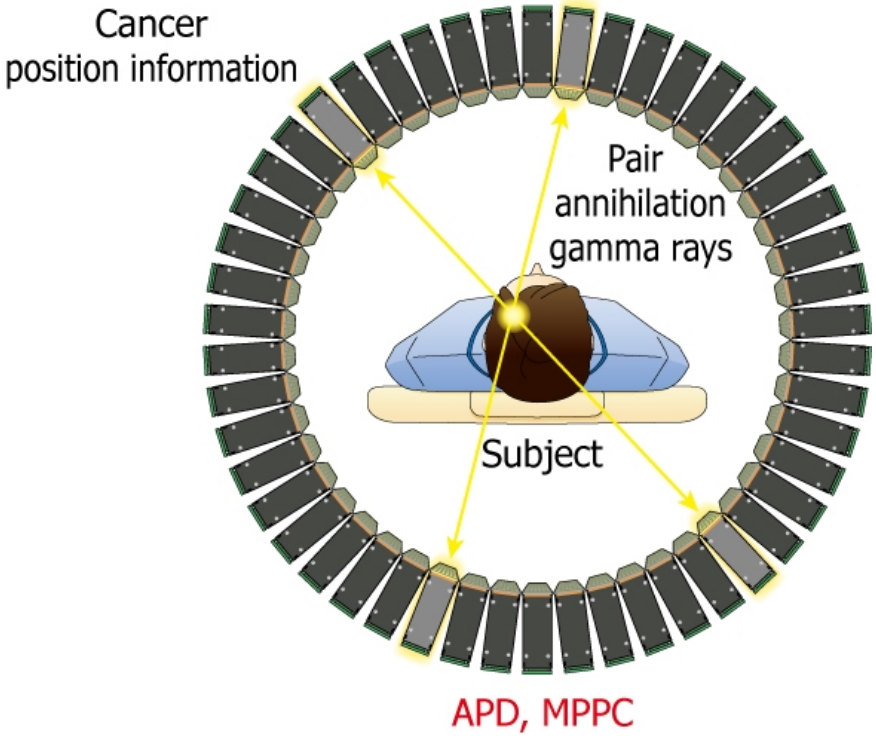
5. MPPC® for medical application

MPPC® for PET

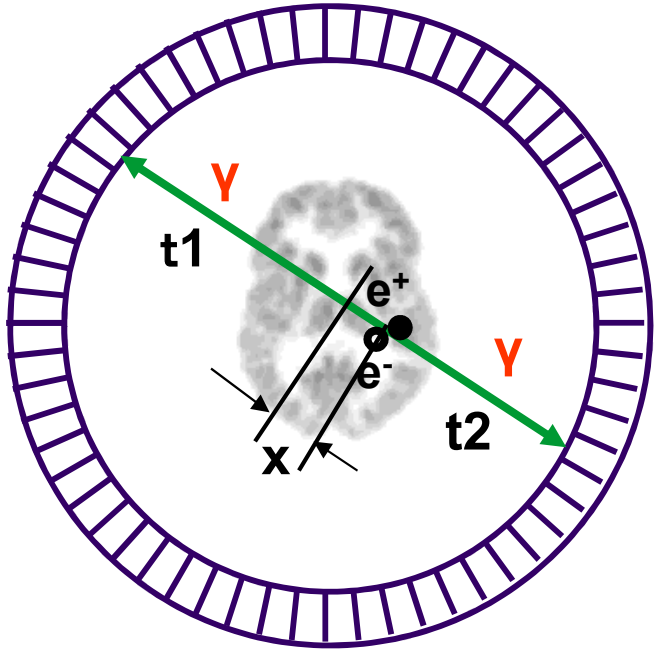
APDs or MPPCs arranged around 360° detect pair annihilation gamma-rays to capture the target position such as cancer tissue.

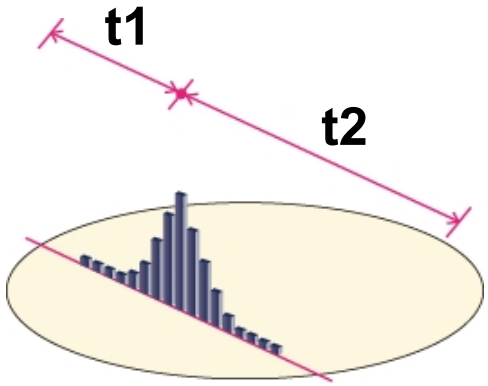
APDs and MPPCs can be used with MRI because they are not affected by magnetic fields.

In addition, MPPCs are useful for TOF-PET because they have good timing resolution.



Notion of TOF-PET





$$X = \frac{(t2 - t1) \cdot c}{2}$$

MPPC® for scintillation

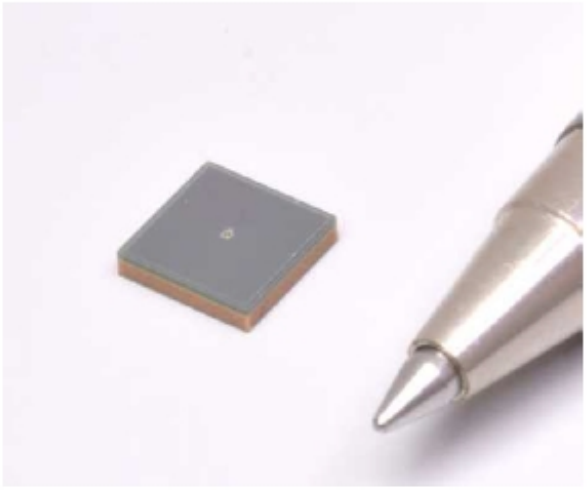
S14160 series : 3x3, 4x4, 6x6mm^2

Low Break down voltage type. S14161 series (1x1 icnch array)

■ Overview

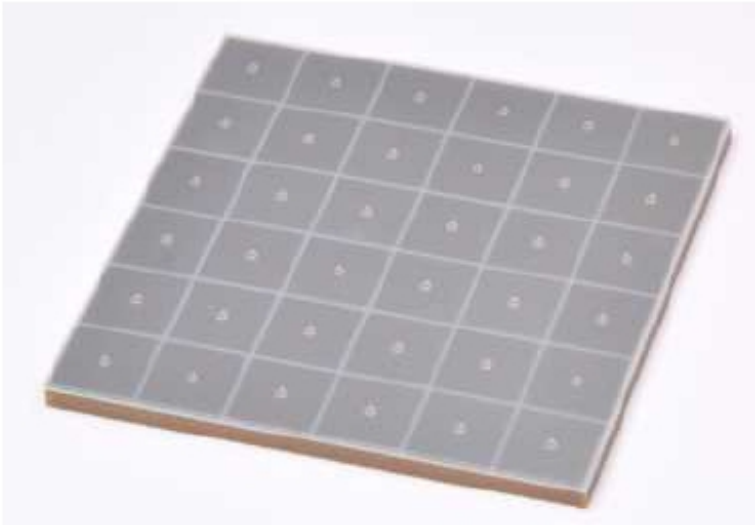
S14160/S14161 series achieve higher PDE and lower operation voltage than other MPPC to adapt for PET and radiation monitor application.

HWB type achieve small dead space in active area with HWB(Hole Wire Bonding) technology**(Patent pending)**. And the gap from active area edge to package edge is only 0.1mm.This package realizes the 4-side tileable arrangement.



■ Features

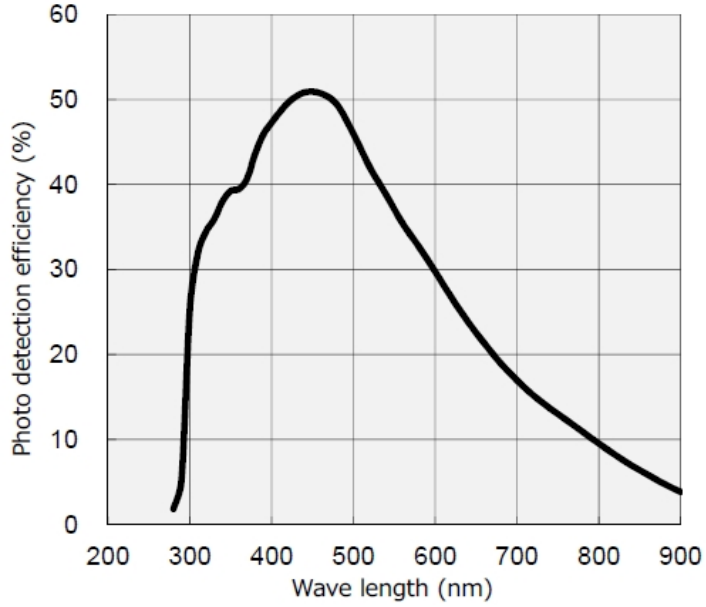
- Higher PDE (50% at λp, V_{BR}+2.7V)
- Lower voltage (V_{BR}=37V Typ.) operation
- Small active area dead space
- Low after pulse and cross-talk
- High gain: 10^5 ~10^6

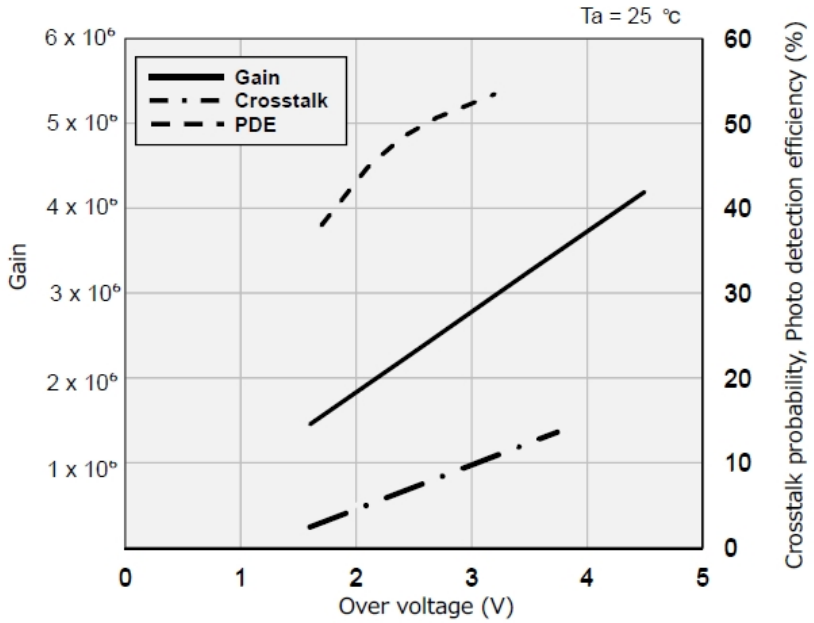


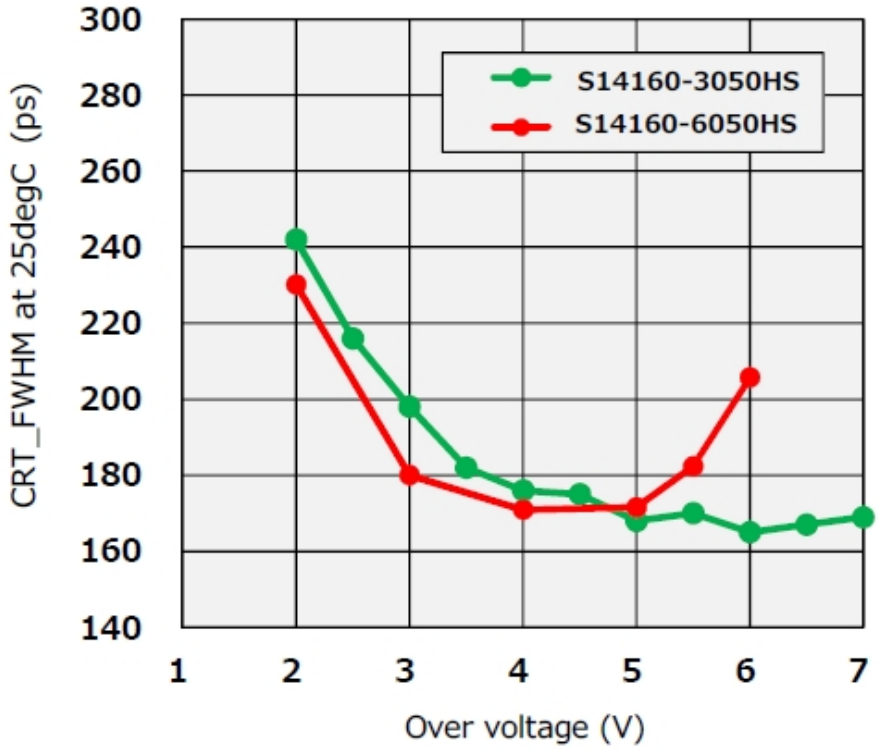
■ Application

- PET
- Radiation monitor

Characteristics of S14160 series

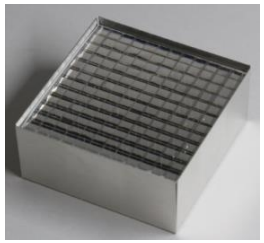






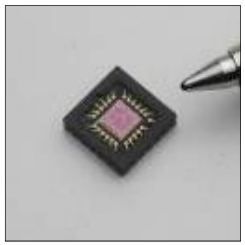
HPK MPPC® PET module

■ Lutetium scintillator

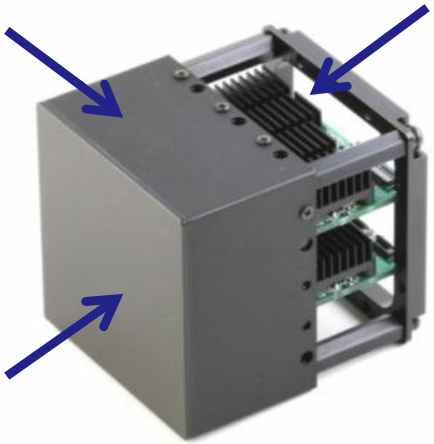


- Low cost
  (mass production zone)

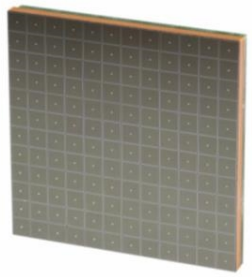
■ ASIC



- Low cost
  (manufacturing under mass production stage)



■ MPPC:
best type for PET-OEM



- Best selected MPPC for PET
- cost down

→ **S14161 Series**

- ➢ All components are suitable for PET application
- ➢ Big advantage for performance and cost

Summary

1. The history of Hamamatsu SSD is more than 30 years, and SSDs have been used for many HEP experiments.

2. As a new development, we started developing 8-inch PAD detector, and we have obtained several trial results. First we proceed with DC-type, and after that also plan to AC-type.

3. We have developed and delivered APDs and MPPC®s for HEP experiments as well as SSDs.

4. MPPC®'s various characteristics for example sensitivity, noise, after pulse have been improved.

5. MPPC® is widely used in medial fields like PET, in addition to HEP experiments.

Closing

- At this Hiroshima Symposium,
  I will participate fully 12/11～15.
- We also exhibit Hamamatsu booth
  during the symposium.
- If you have any interests or、、
  please feel free to speak to me !

Thank you for your attention.

jp.hamamatsu.com