History and Current Status of Hamamatsu Si detectors for High Energy Physics Experiment

K.Yamamura*, S.Kamada , K.Yamamoto

HAMAMATSU PHOTONICS K.K.

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HAMAMATSU PHOTONICS K.K.
Solid State Division

Outline

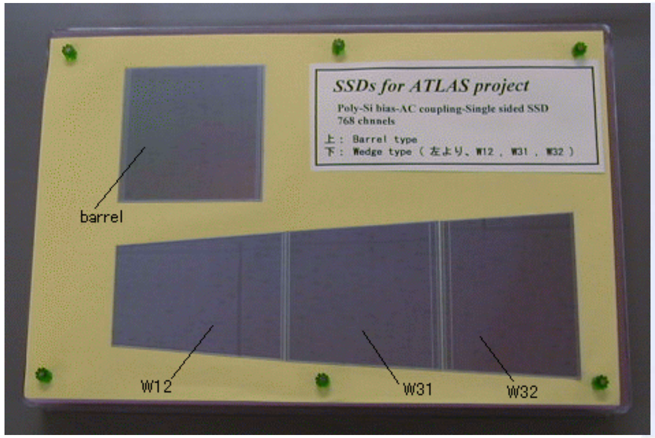
1. Development and production history of
   Hamamatsu SSD (Silicon Strip Detector)
2. Our technology for SSD
3. SSD and APD(Avalanche Photo Diode) for LHC
4. Development and characteristic of
   MPPC® (Multi Pixel Photon Counter)
5. MPPC® for HEP application

Hamamatsu Si detectors for HEP

Direct detector

Silicon Strip Detector(SSD)

Silicon Pixel Detector



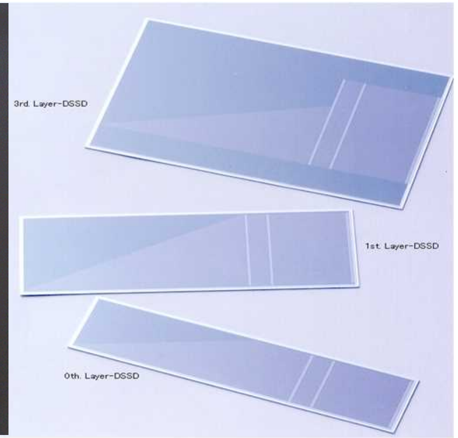
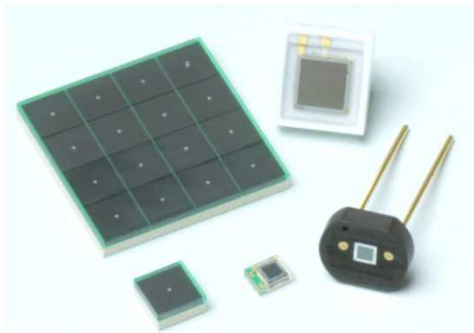


Photo detector

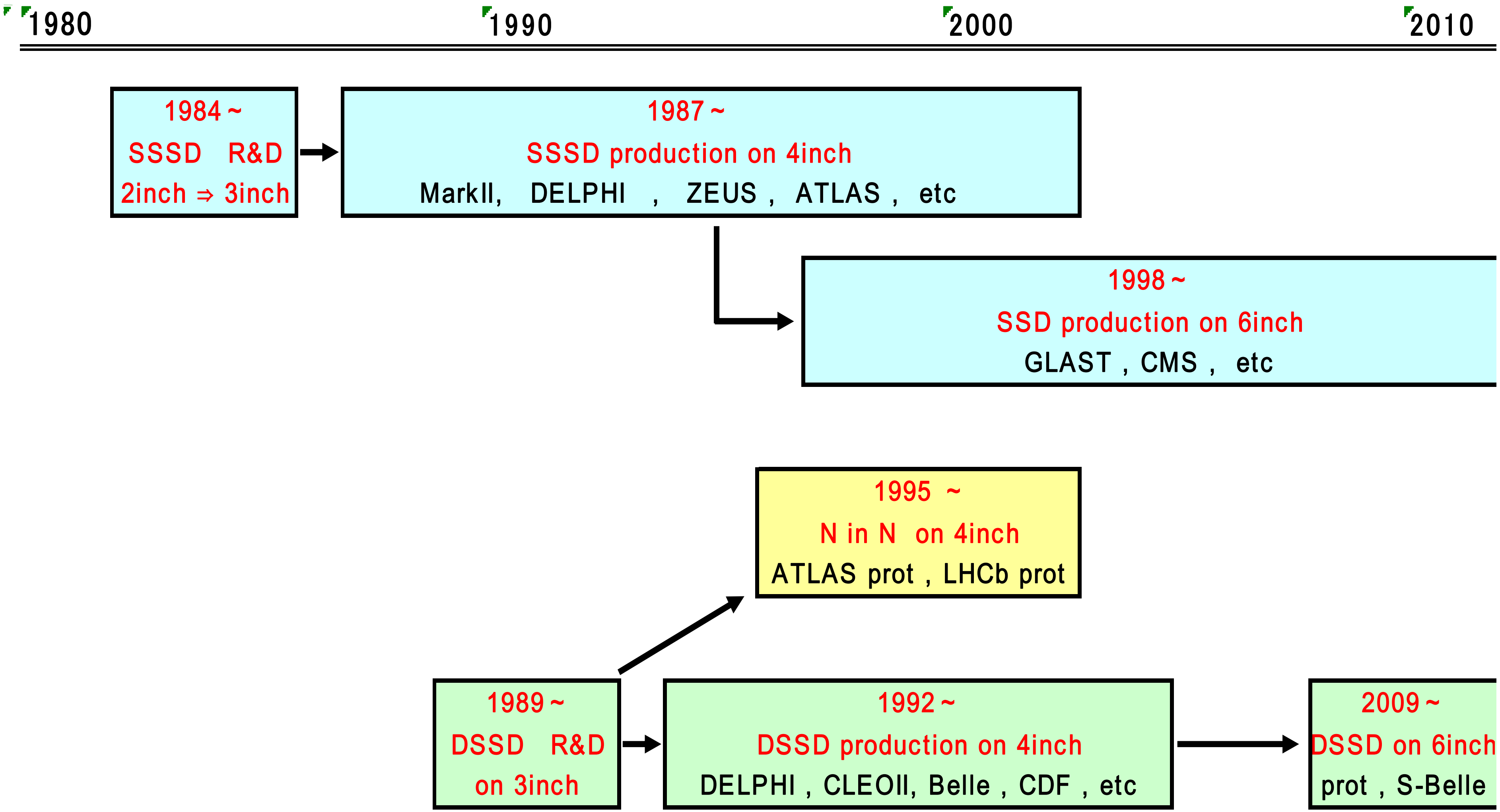
Silicon Photo Diode(PD)

Silicon Avalanche Diode(APD)

Multi Pixel Photon Counter(MPPC®)



Development and Production History of SSDs at Hamamatsu



Review of main SSDs made by Hamamatsu （～1999）

PROJECT	DETECTOR TYPE	size	QTY.	period
MARK Ⅱ	DC-SSSD 3type	3chip/4inch	44	1987
CLEO Ⅱ	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～）

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

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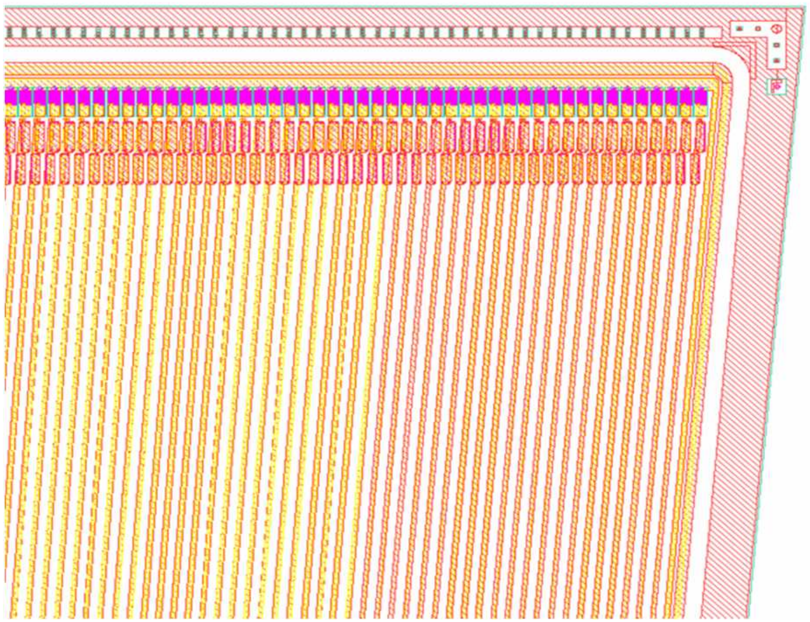
2. **Our technology for SSDs**
3. SSD and APD(Avalanche Photo Diode) for LHC
4. Development and characteristic of MPPC® (Multi Pixel Photon Counter)
5. MPPC® for HEP application

Design of Photo masks

CAD soft on PC is mainly used for Si detectors.
Each coordinates of figures can be inputted
by macro program made by EXCEL etc.



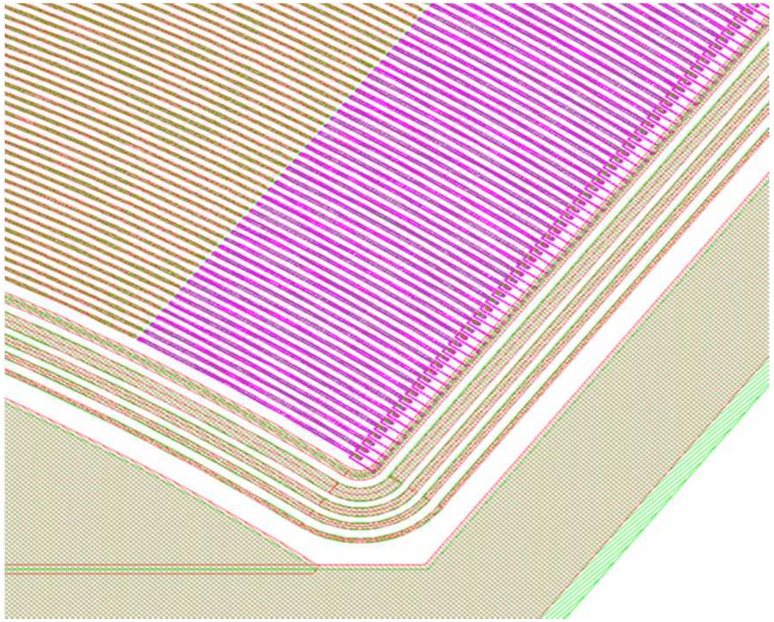


Photo-mask design of complicated shape like any angle or rounded strips pattern are acceptable.

Wafer process

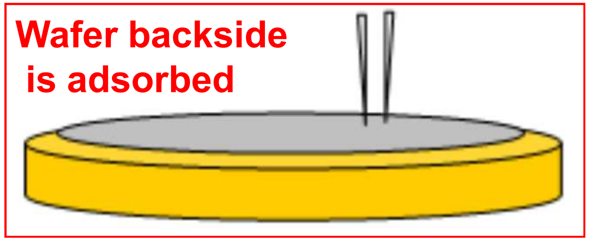
Nearly 10,000 of 6 inch wafers are processed per month.
We have process lines for PD, Bipolar photo IC , CCD, C-MOS and MEMS Devices

For SSDs

2,000 wafers per month were processed for LHC mass production.
Available type : SSSD or DSSD, AC or DC-coupling , Double-metal
Available thickness : 150 to 650um for SSSD ,
320 and 500um for DSSD

- **Oxidation**
- **Photolithography**
- **Ion Implantation**
- **Poly-Si process**
- **Metal Evaporation**
- **Passivation**

Wafer probing



Example of Probing for SSDs

1) Lot check using TEG
   - implant resistance
   - poly-Si resistance
   - Flat-band voltage
   - capacitance of Cc
   - IV & CV of Monitor PD

2) IV curve of main chips
   Chose good wafers

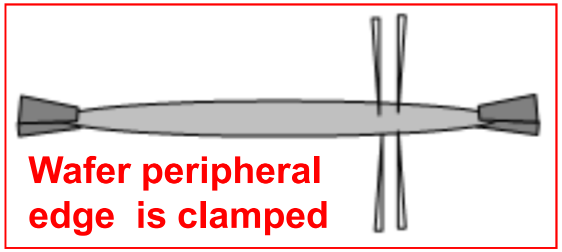
3) Put chip serial number
   Binary notation at Scratch PADs on chip

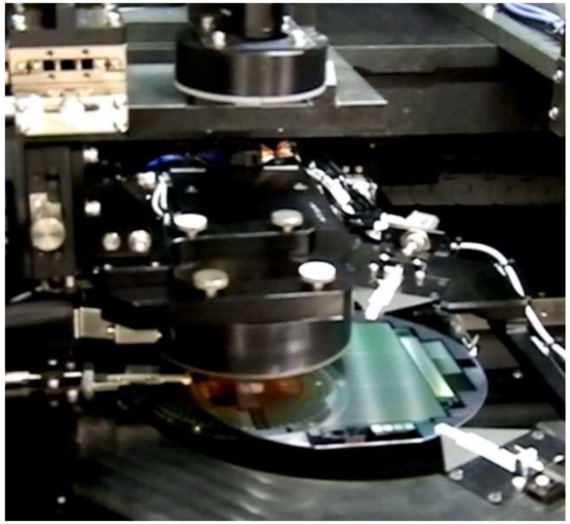
(Dicing)

4) AC & DC check of strips

5) IV & CV curve of main chips

Double sided Wafer probing





Restriction

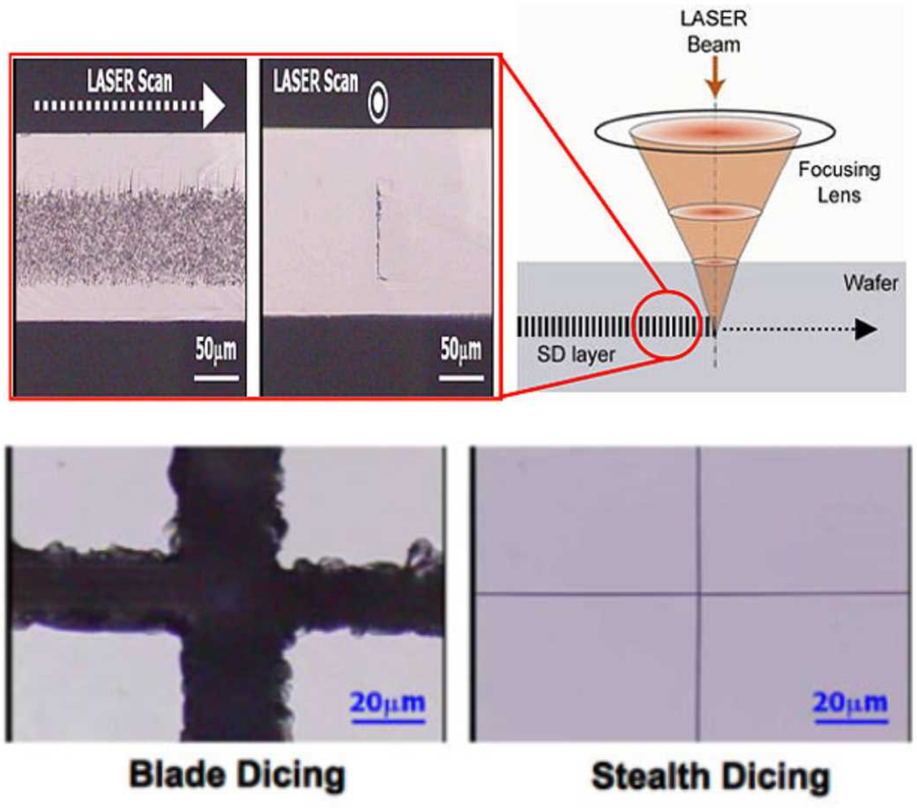
1) Wafer shape
2) Larger than 80um☐ pad size

Example of Probing

1) DC check of N strips for DSSD
   - require P side biasing
2) TSV-MPPC with back side PADs
   - require front side illumination

Stealth Dicing Technology

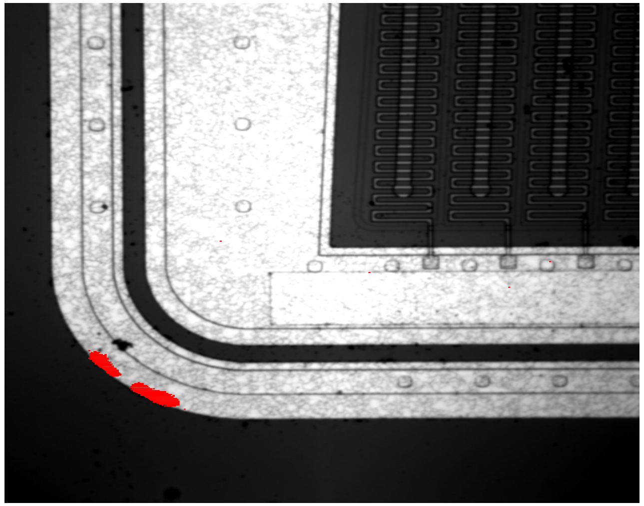
We also have Stealth dicer in addition to the traditional blade dicer.
Polygon shape, chips of different size can be cut without chipping

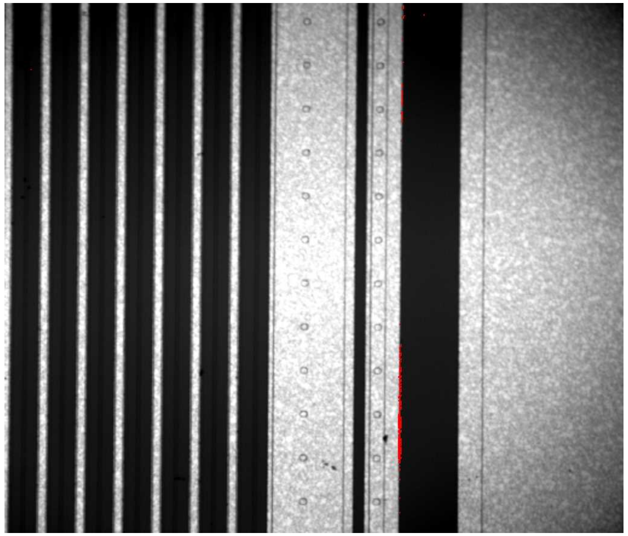


[from Hamamatsu homepage]

Baby detectors, Test structures, Mos diodes , Monitor diodes can be cut by stealth dicer in one set and one program.

Failure Analysis





< Phemos system >

Easy to know where is weak points
and lower break down voltage

- Design of photomask mainly for guard rings and edge of stripes
- Analysis of popcorn noise by micro plasma
- Contamination and defects analysis made by process and handling

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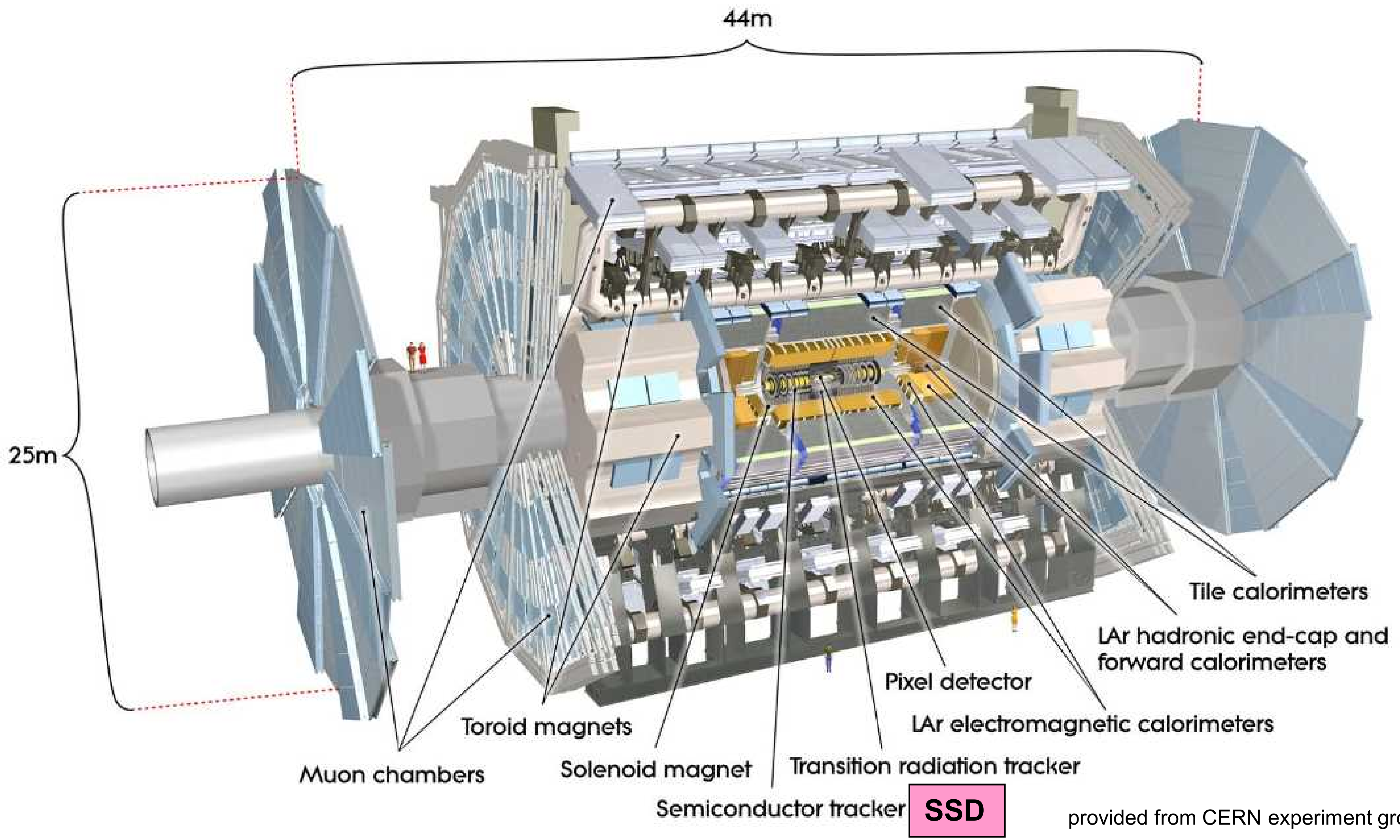
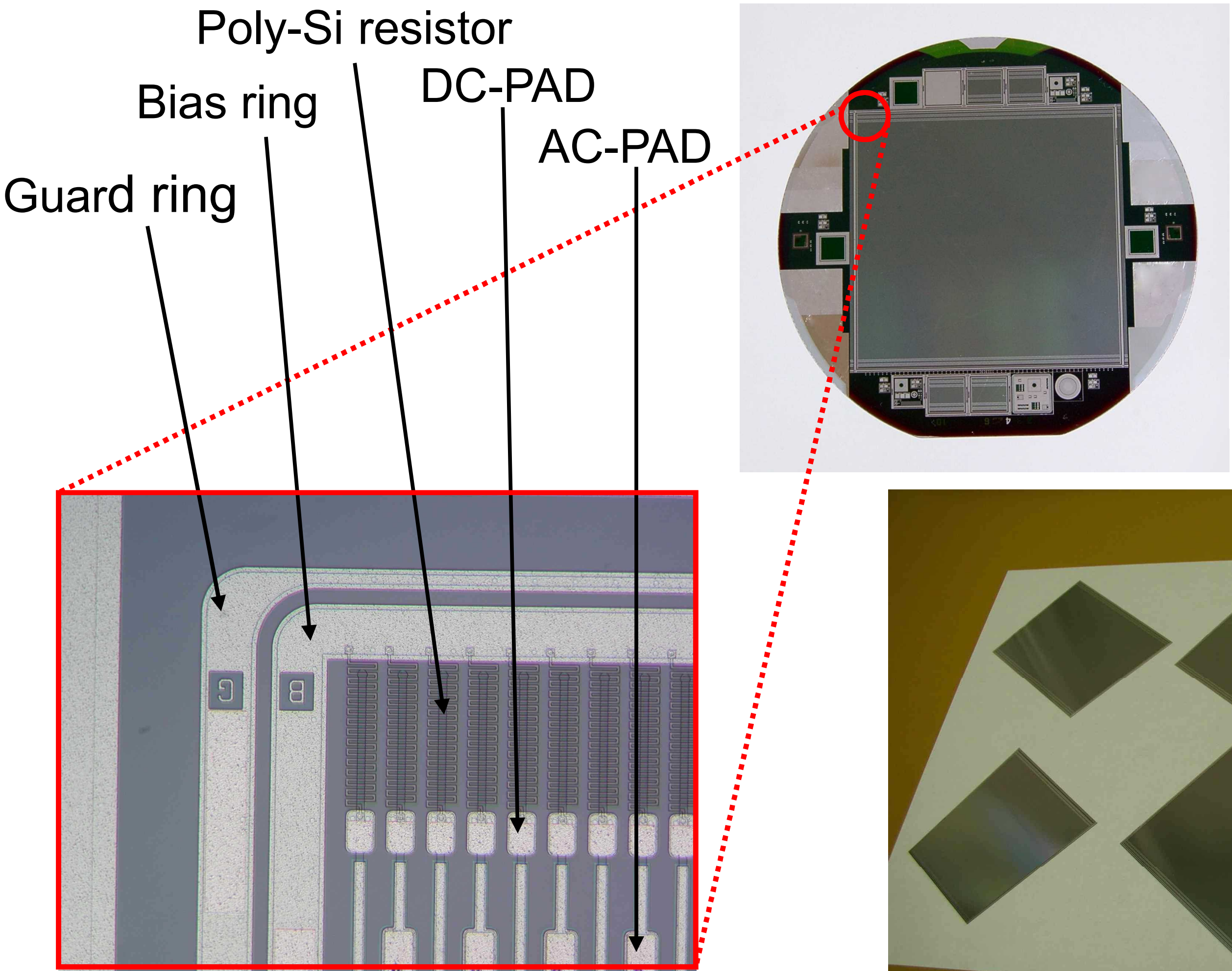
ATLAS - SSD



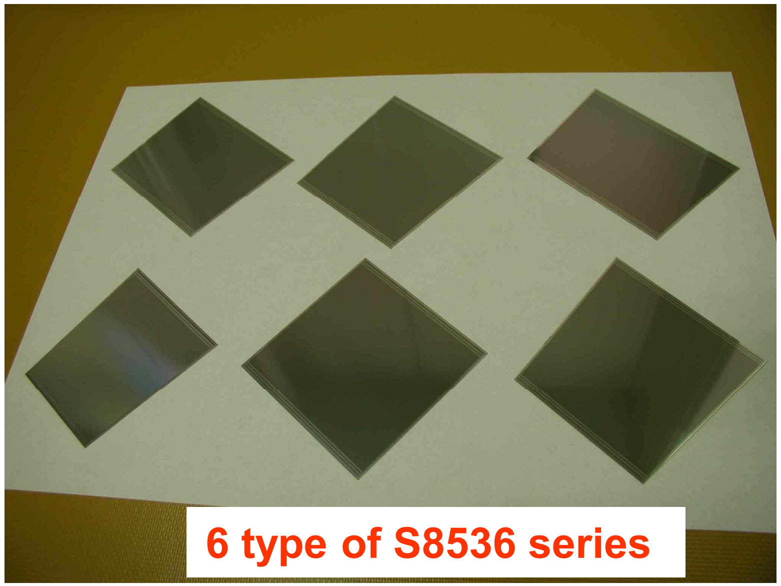
provided from CERN experiment groups

ATLAS-SSD (S8536 series)



1 Sensor on 4 inch wafer

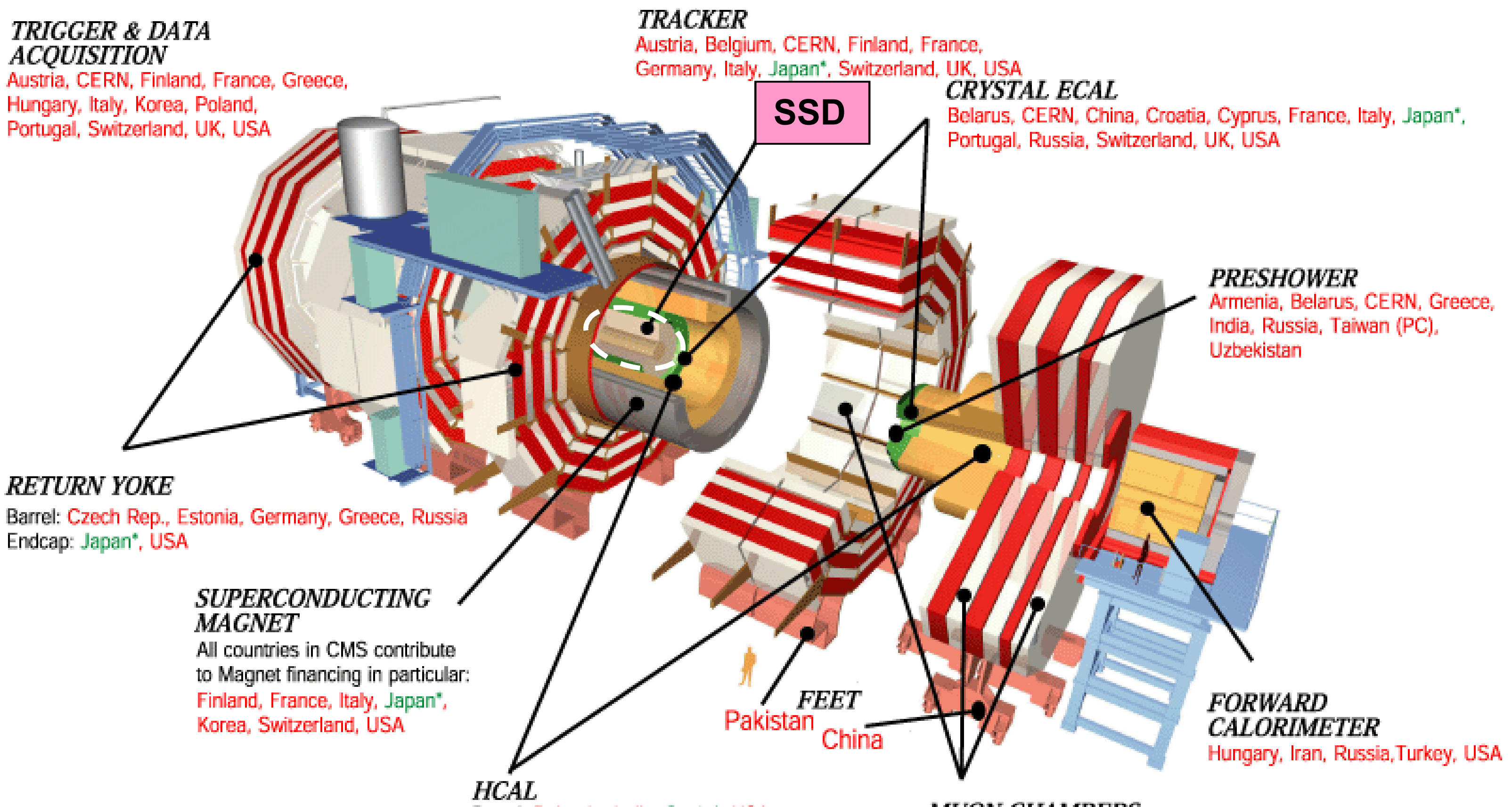
AC coupling-SSSD



6 type of S8536 series

CMS - SSD

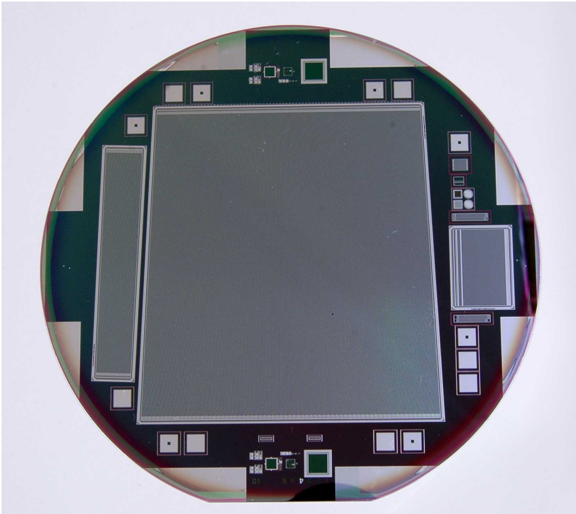
31 Nations, 150 Institutions, 1870 Scientists



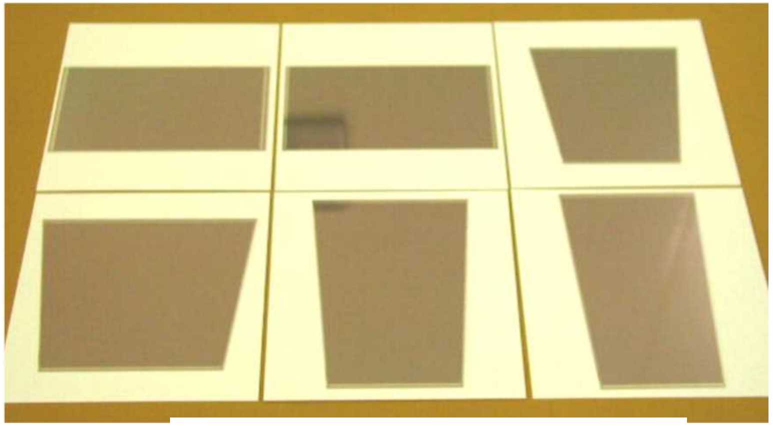
Total weight	:	**12500 T**
Overall diameter	:	**15.0 m**
Overall length	:	**21.5 m**
Magnetic field	:	**4 Tesla**

provided from CERN experiment groups

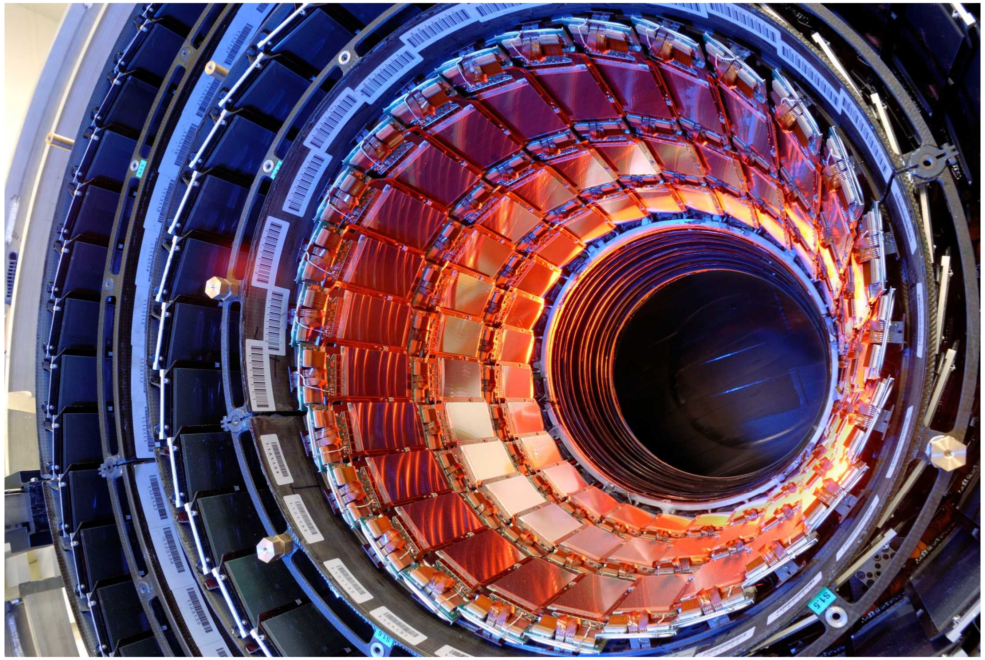
CMS-Si tracker and SSD



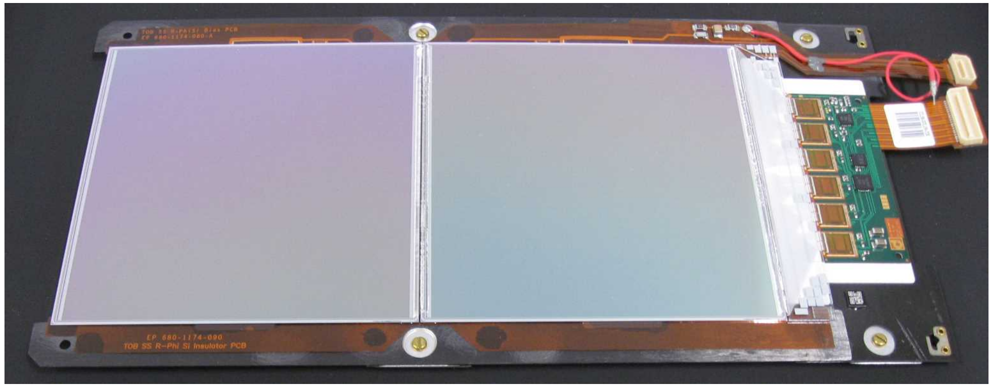
1 Sensor on 6 inch wafer



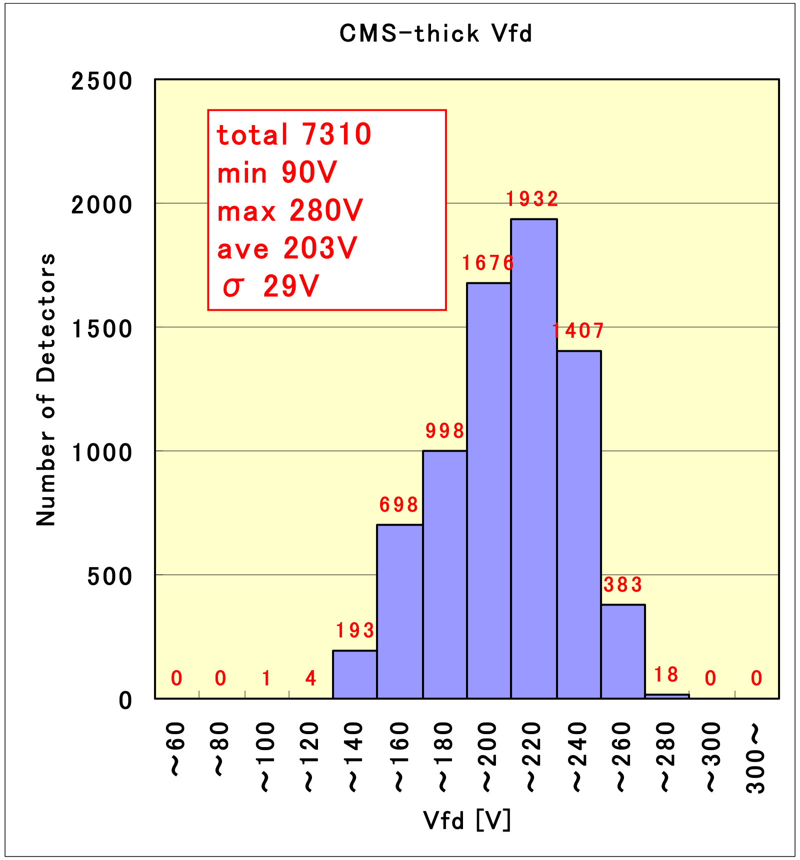
S9153, S9154 series

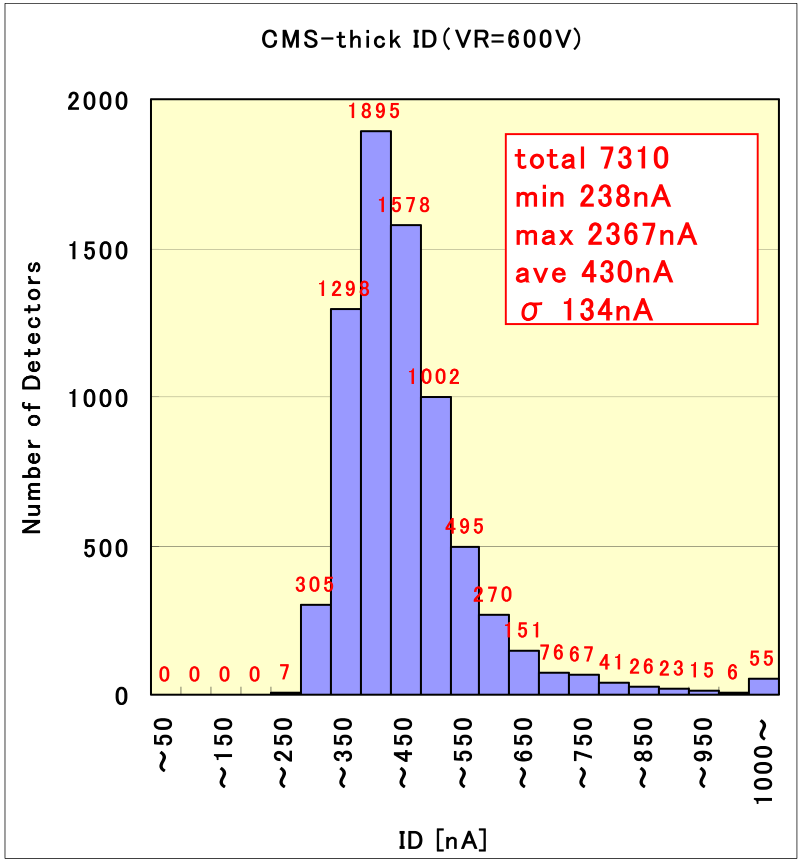


provided from CERN experiment groups



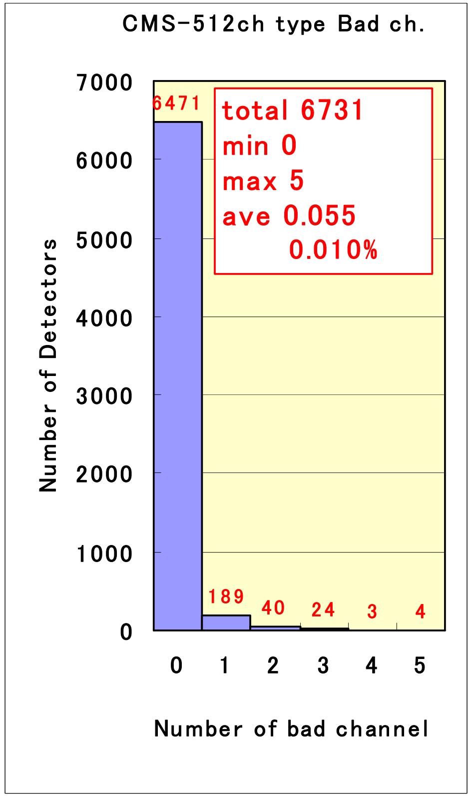
Vfd and Leakage current for CMS-thick type SSDs

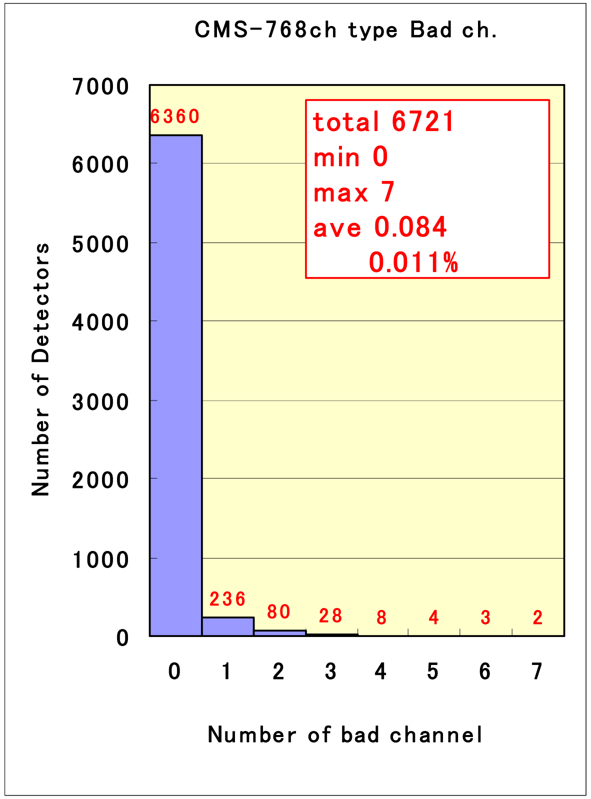


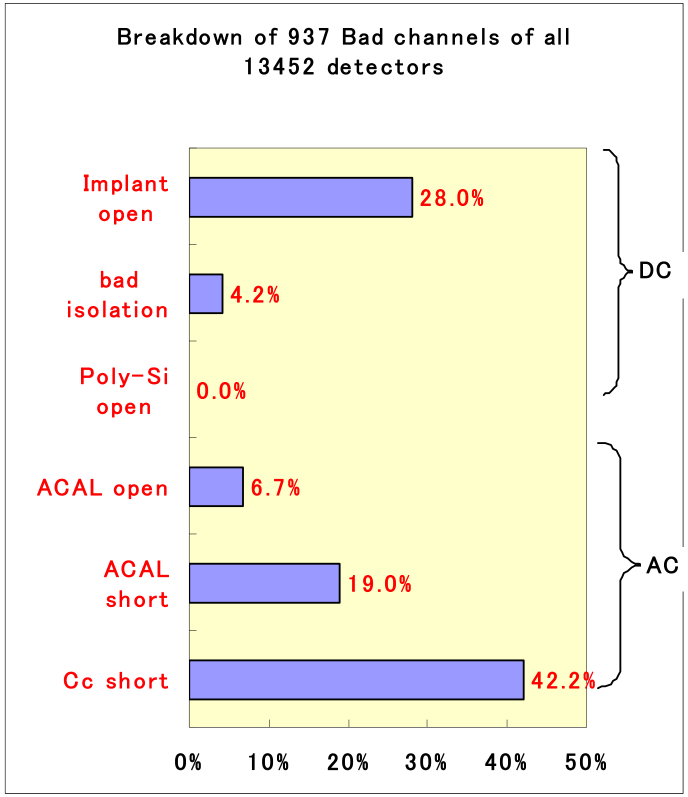


Vfd distribution is due to the resistance variation of the wafer material.
Dark current distribution is good and much less than specification.

Bad channel rate for CMS-SSDs



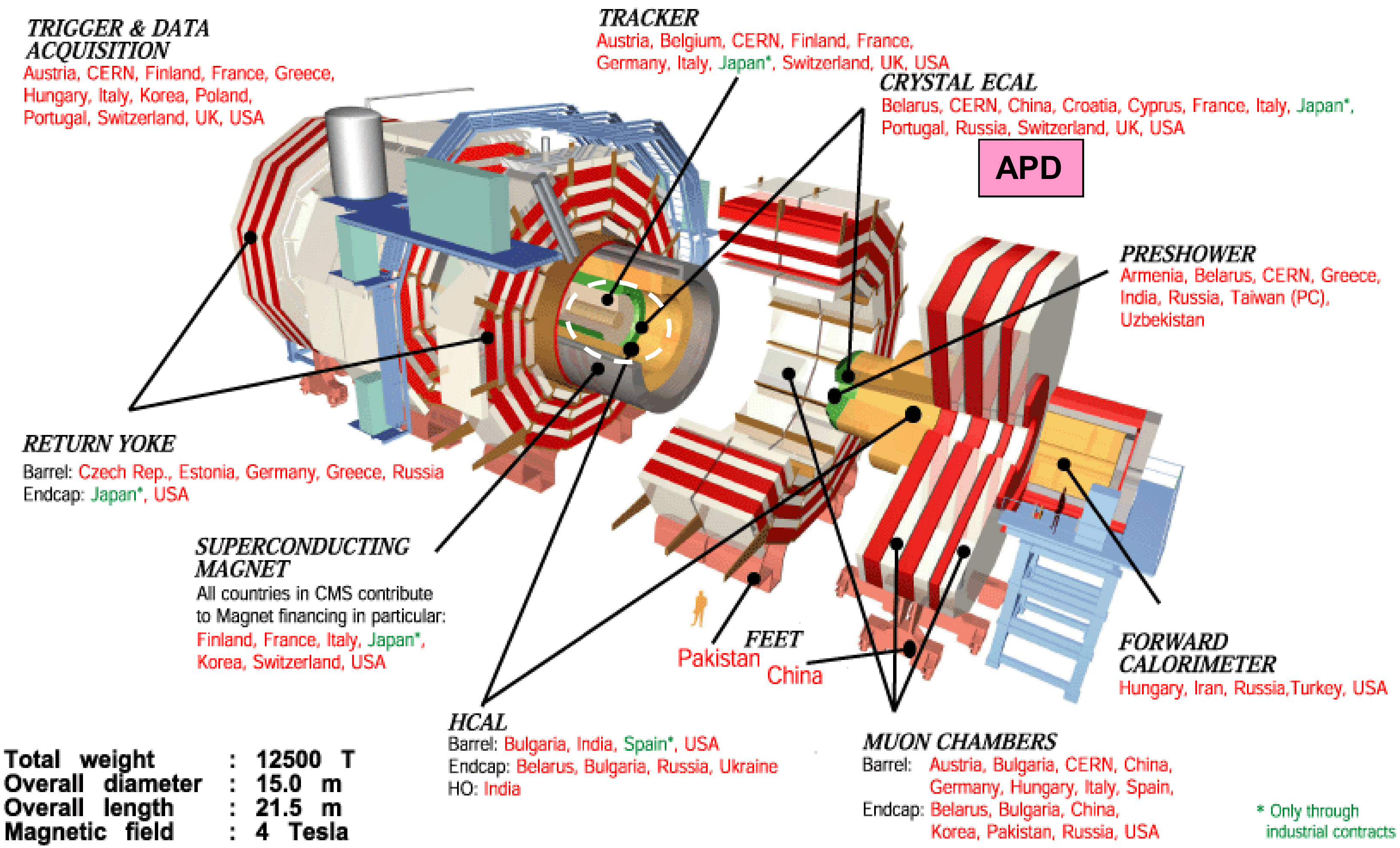




More than 95% of detector are perfect with no bad channels.
The average of bad channel rate is around 0.01%.
Short of Cc, Open of strip implant, short of AC AL are main factor of bad channel.

CMS - APD

31 Nations, 150 Institutions, 1870 Scientists



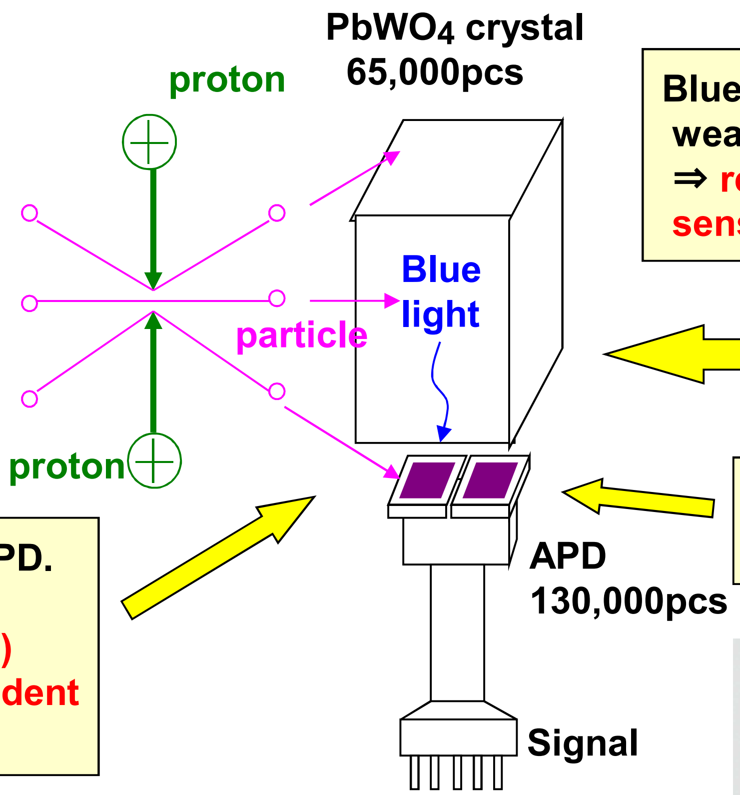
Total weight	:	**12500 T**
Overall diameter	:	**15.0 m**
Overall length	:	**21.5 m**
Magnetic field	:	**4 Tesla**

provided from CERN experiment groups

Characteristics required for the CMS-APD

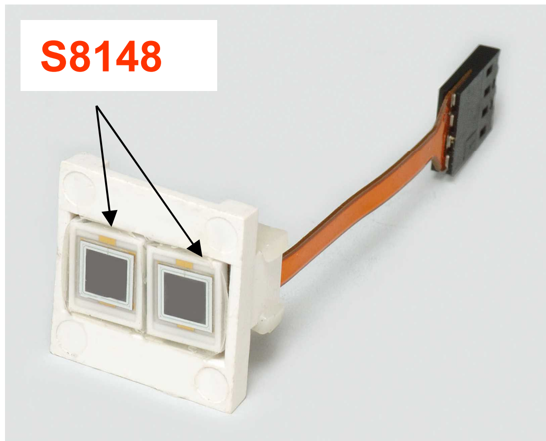
APD is used in a high magnetic field
⇒ require to operate at high magnetic field

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



APD needs large area to cover a crystal

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



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

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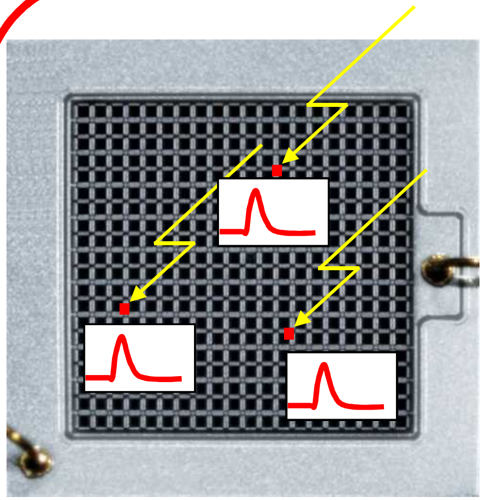
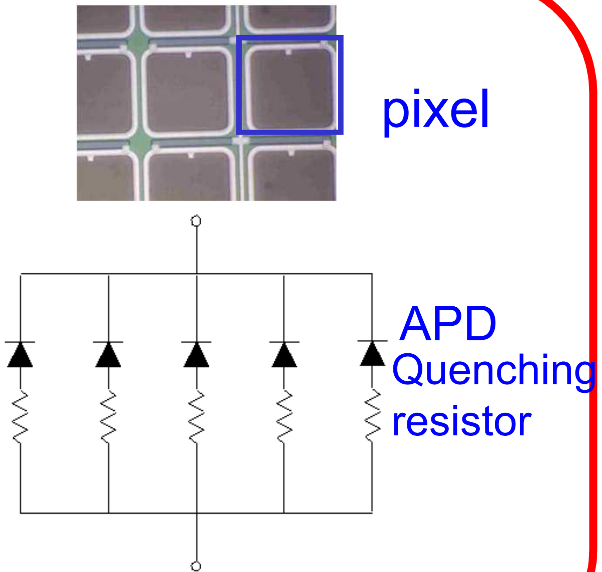
MPPC® Technology Overview

➢What is an MPPC®?

- Multi-Pixel Photon Counter
  a new type of photon-counting device made up of multiple APD pixels operated in Geiger mode

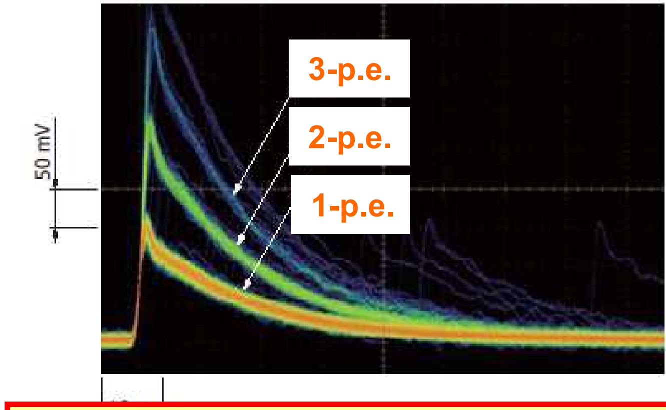




Output is summation of all pixel output

➢Features

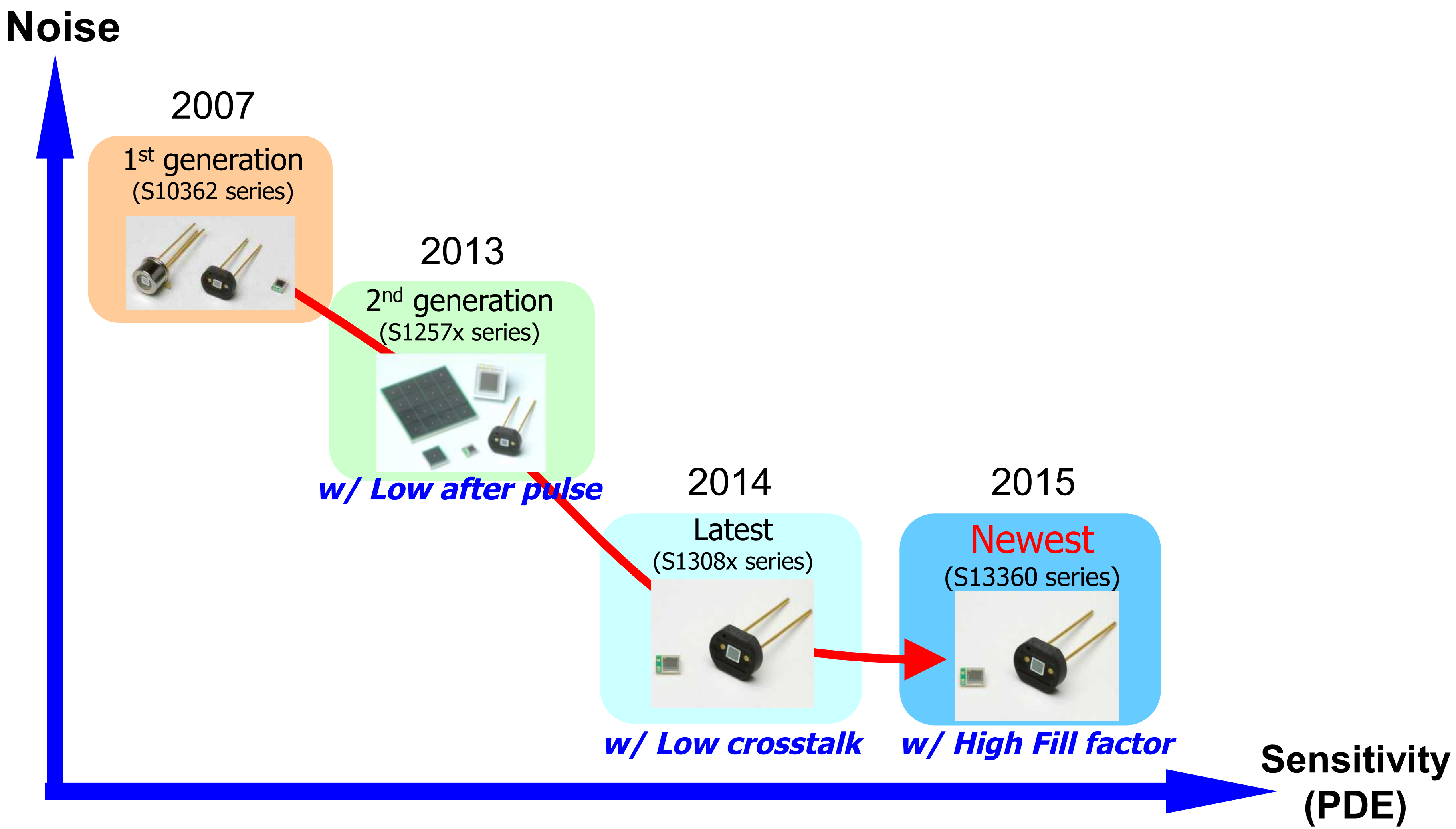
- Small size / light weight
- Room temperature operation
- Low bias operation : ～70V
- High gain: 10^5 to 10^6
- Excellent timing resolution
- Insensitive to magnetic fields
- Simple readout circuit operation



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

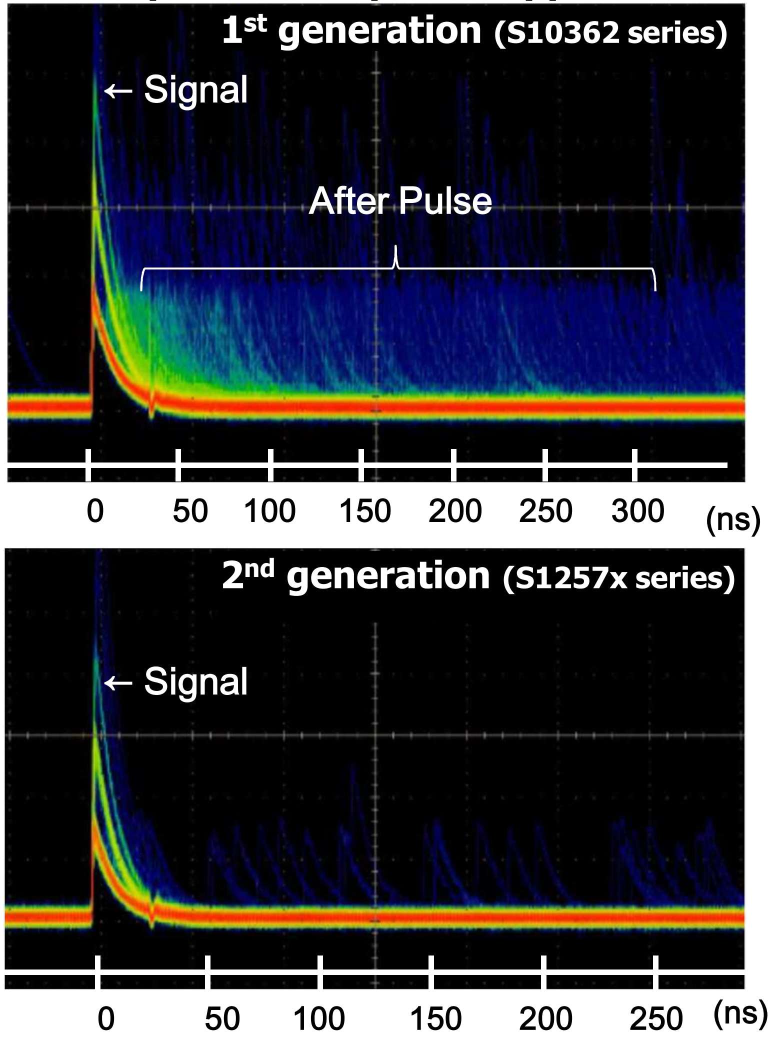
$$N_{fired} = PDE \times N_{photon}$$

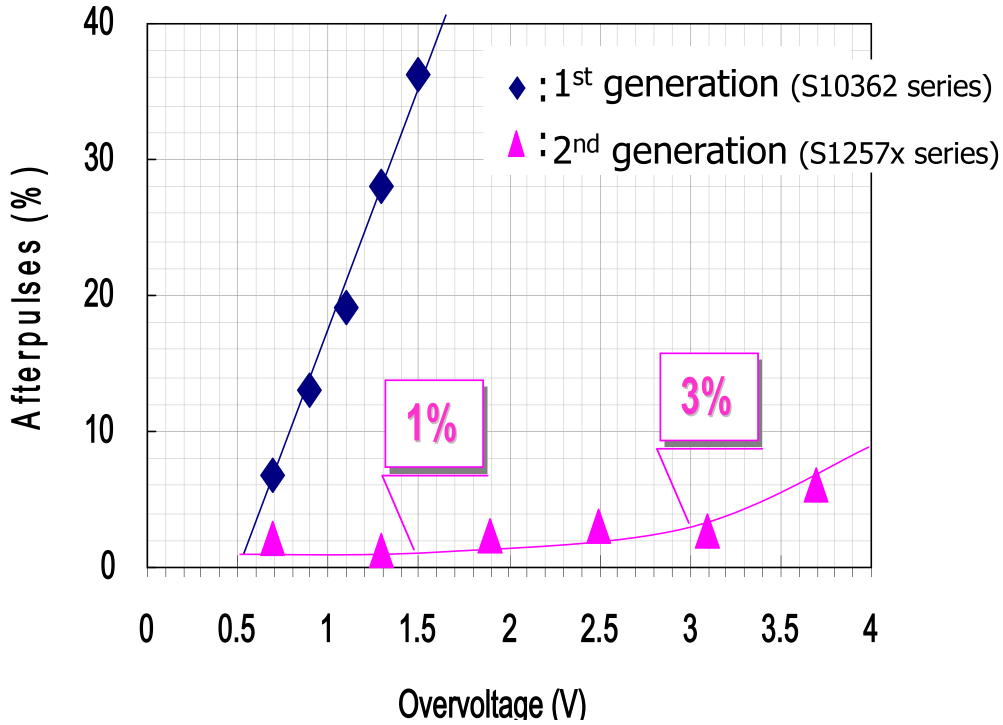
Latest Development of MPPC®s



Low After Pulses

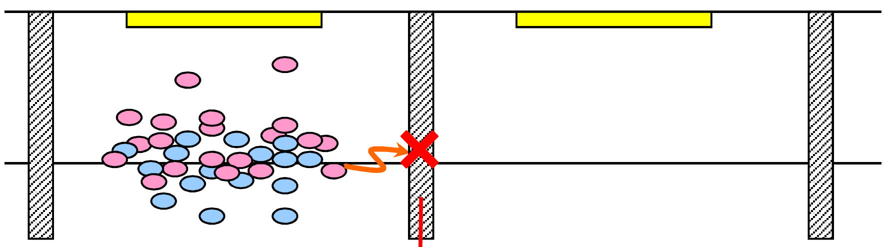
Example of After pulse suppression

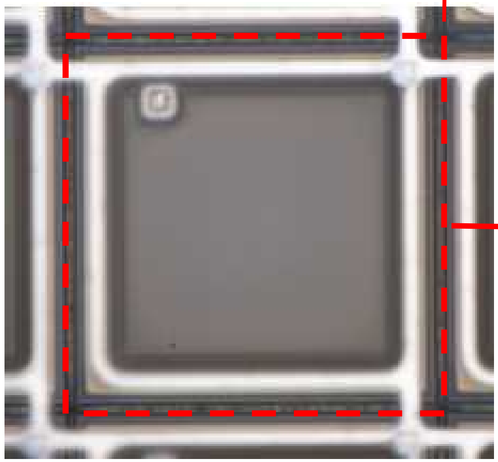




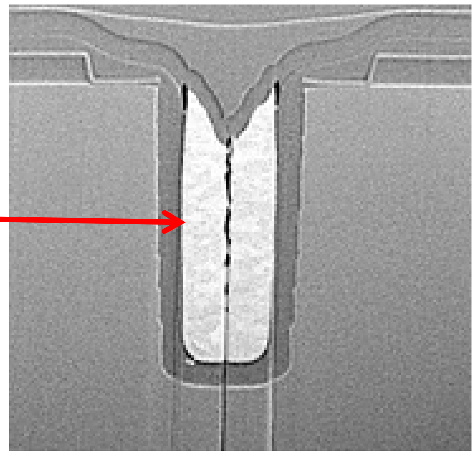
After pulse probability has been suppressed by optimization of structure and material.
All new MPPC® series have very lower after pulses compared with conventional type.

Crosstalk Suppression by Trench isolation

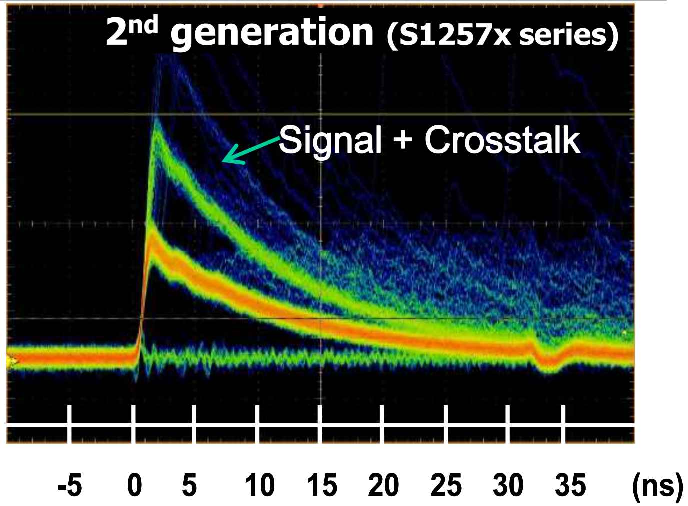


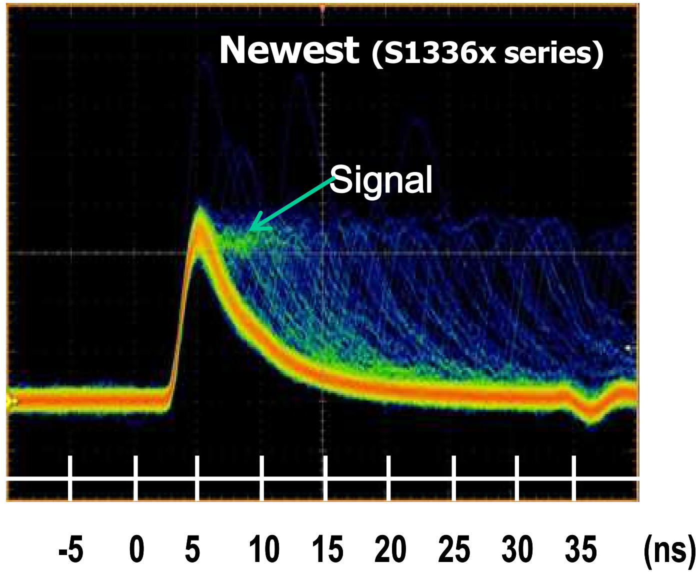


Top view of pixel



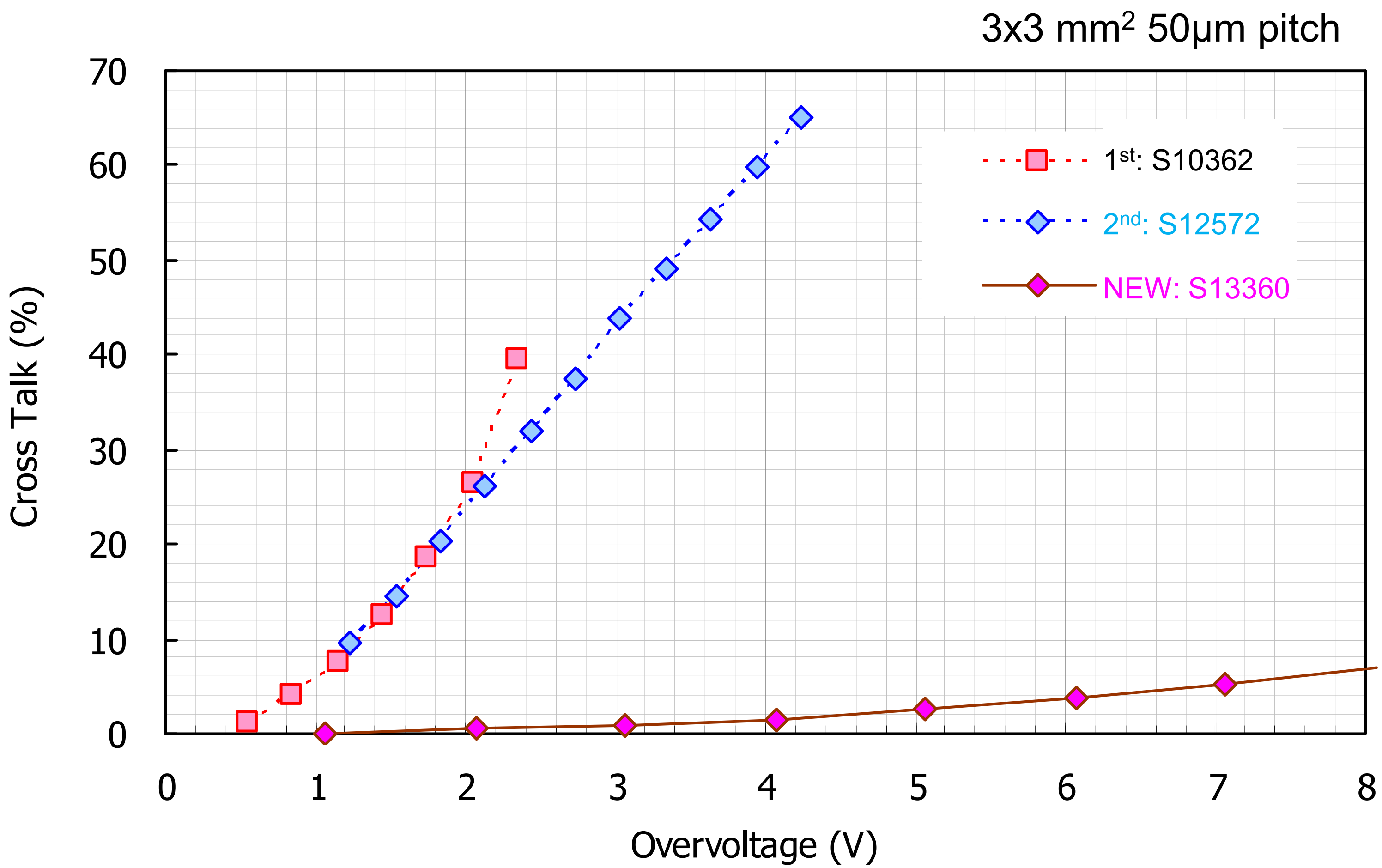
Cross section of trench





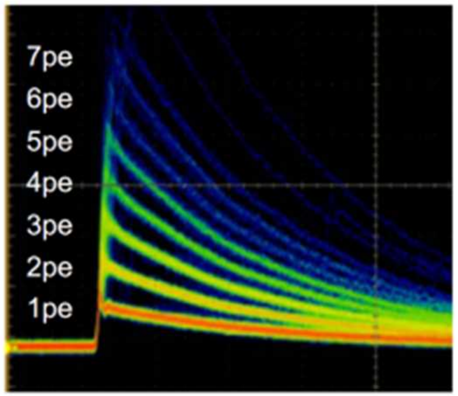
Low cross talk series each MPPC® micro cell is surrounded by an optical trench isolation.
It prevents penetration of generated secondary photons to neighboring micro cells.

Crosstalk comparison

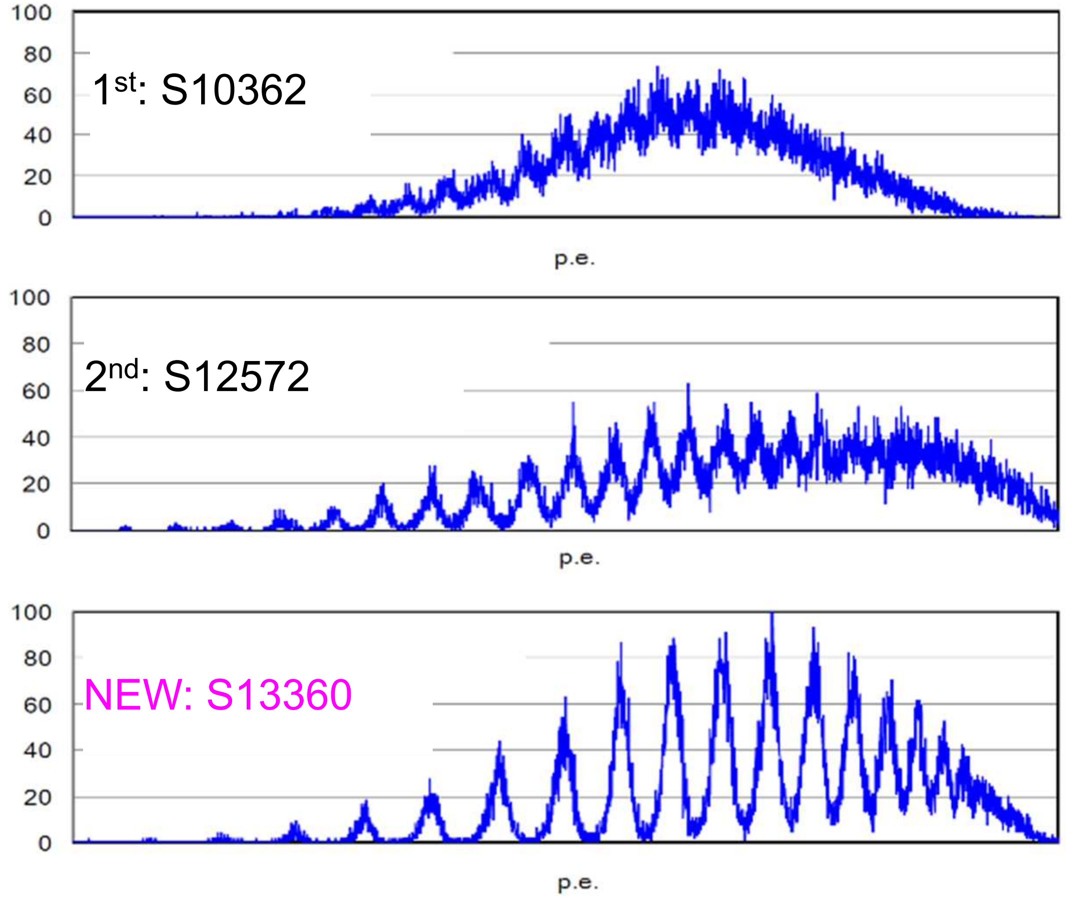


3rd generation MPPC have drastically improve crosstalk and it can be used at higher overvoltage

Pulse height distribution comparison

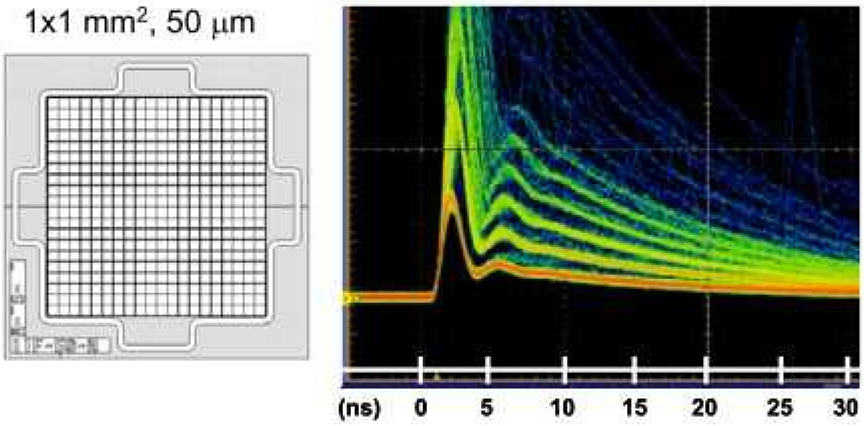


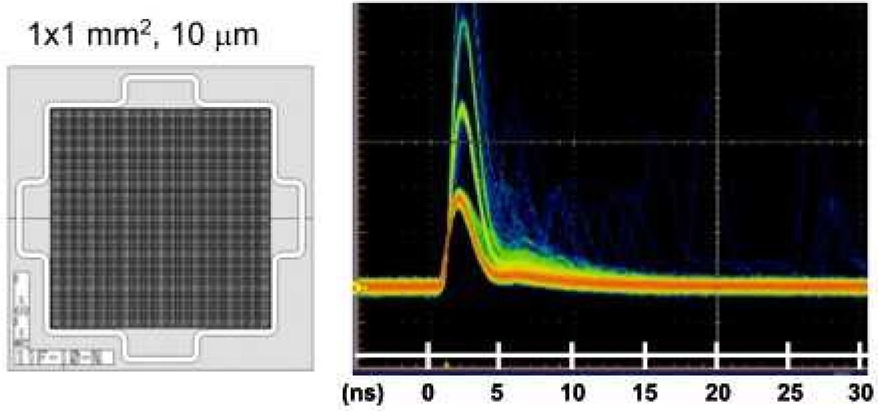
3x3 mm^2 50µm pitch



As generation increases, pulse height distribution is improved.
Third generation is excellent photon-counting capability

Dynamic range of MPPC®



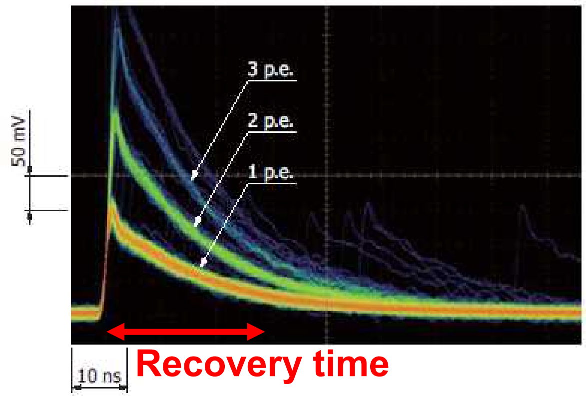


MPPC® maximum output is determined by;

- **Large number of MPPC® pixels**
- **Short recovery time**

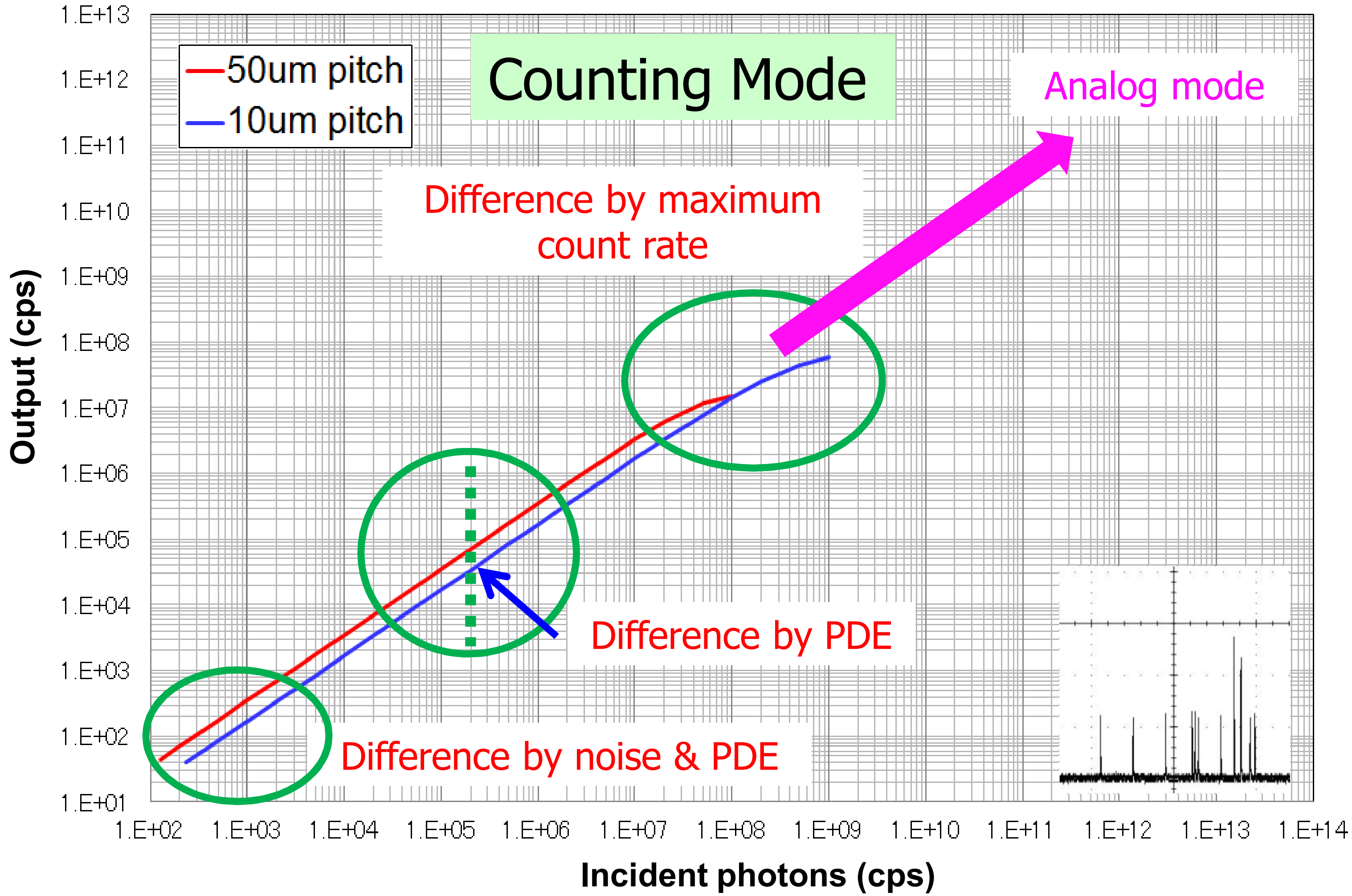
Merit and Demerit of small pixel

Merit⇒ Large number of pixels ,
Short recovery time
Demerit⇒ Small fill factor, Low PDE



Dynamic range by readout method of MPPC®

Photosensitive area : 3x3mm



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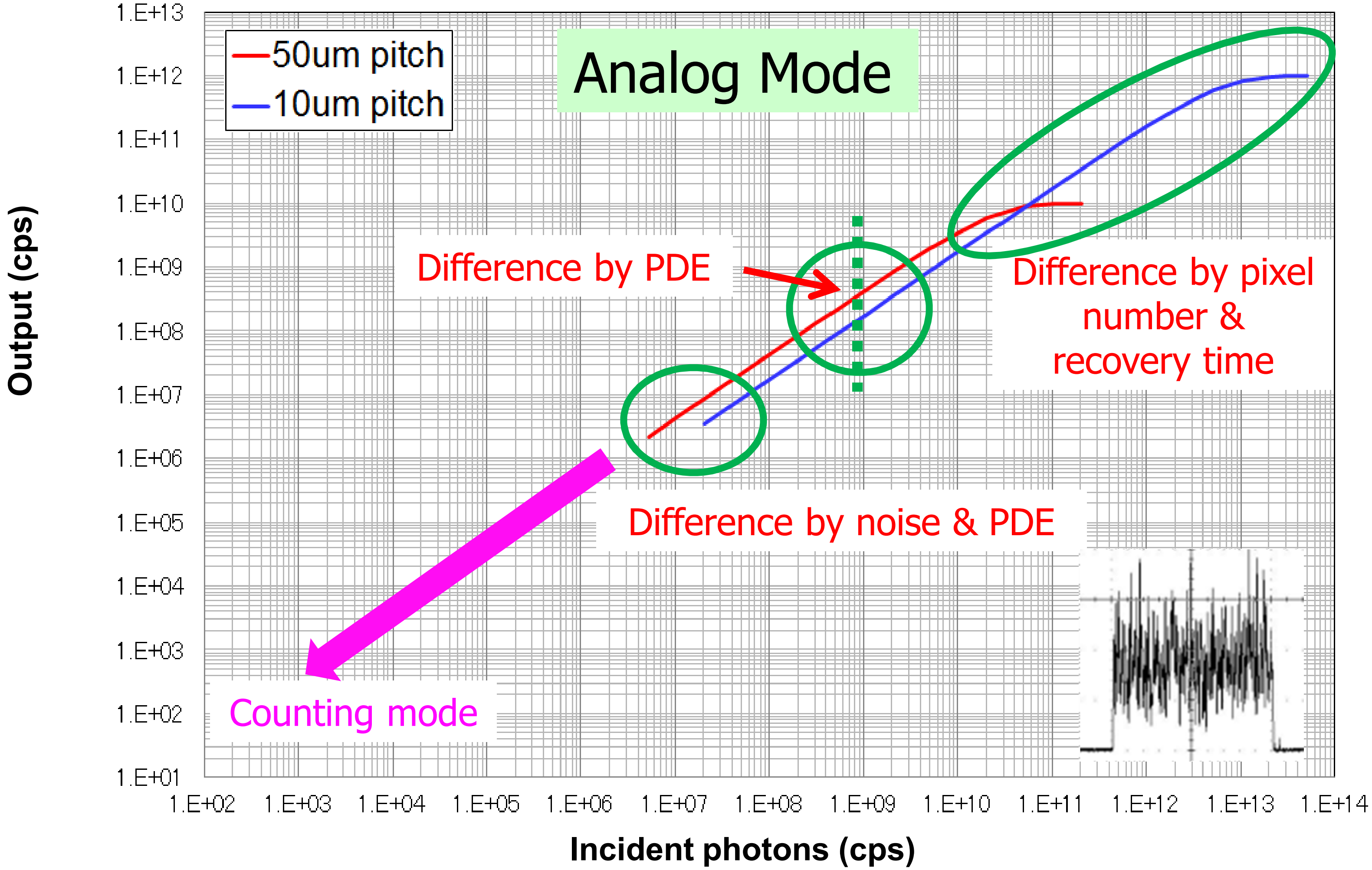
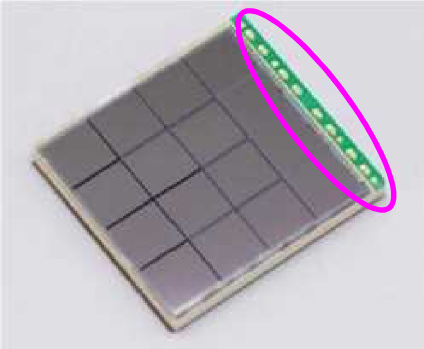
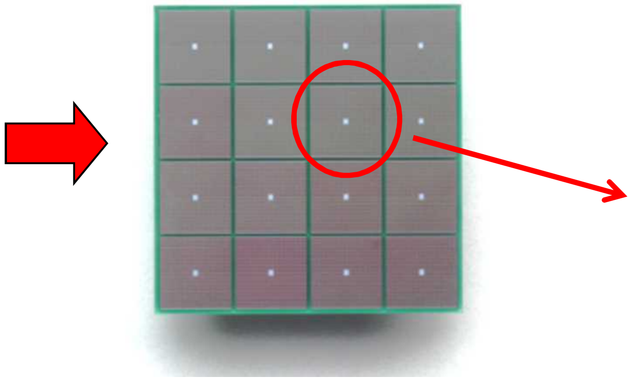
Photosensitive area : 3x3mm



MPPC® array with TSV(Through Si Via)



4x4ch monolithic array
with wire bonding
S11828 series

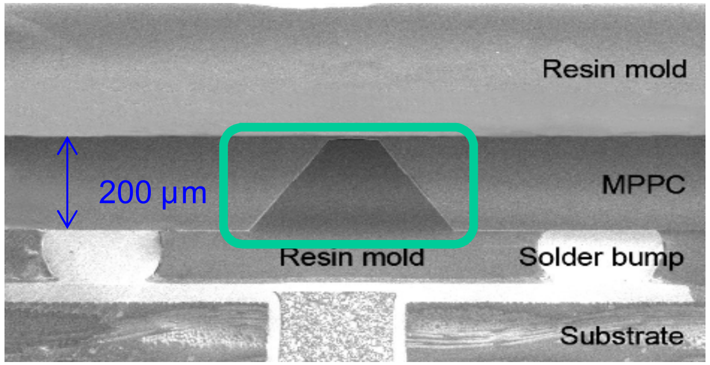


4x4ch discrete array
with TSV
S13361-3050 series

3x3mm Single 50mmp
with TSV

The TSV process requires small non-sensitive area (200mm sq.).

This area is corresponding to 0.44% of total active area, and it is hardly affected to the PDE (photon detection efficiency).

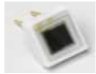


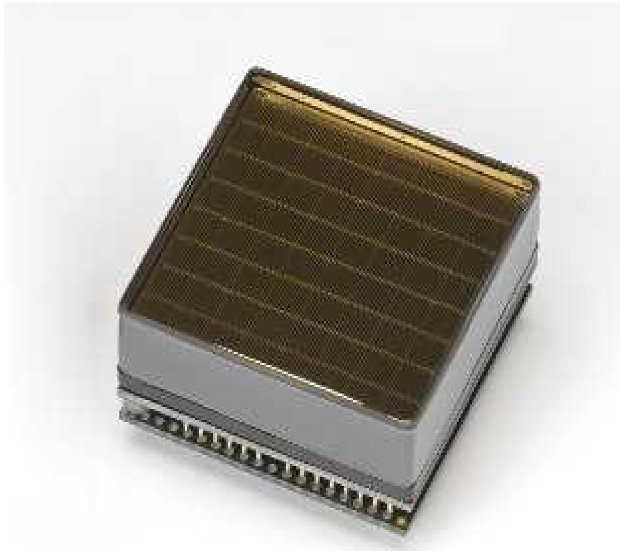
Cross section of TSV

1. Development and production history of Hamamatsu SSD (Silicon Strip Detector)
2. Our technology for SSDs
3. SSD and APD(Avalanche Photo Diode) for LHC
4. Development and characteristic of MPPC® (Multi Pixel Photon Counter)
5. **MPPC® for HEP application**

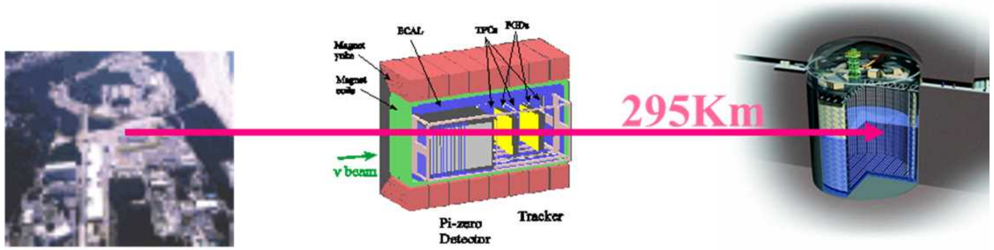
Characteristics of MPPC and PMT

	MPPC	PMT
GAIN	10^5～10^6	10^5～10^7
Operation Voltage	60～80	～1000
Active area	10 mm^2	≧10000 mm^2
Dark count	△	◎
Detection effi.	◎	○
Timing reso.	◎	○
Energy reso.	○	○
Compact	◎	○
Magnetic resist.	◎ (7 T)	× (1.5 T)





MPPC® for T2K Experiment (2008)

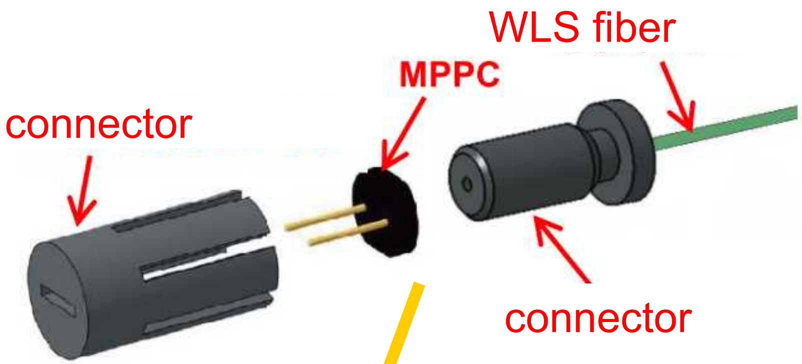


J-PARC in Tokai-mura

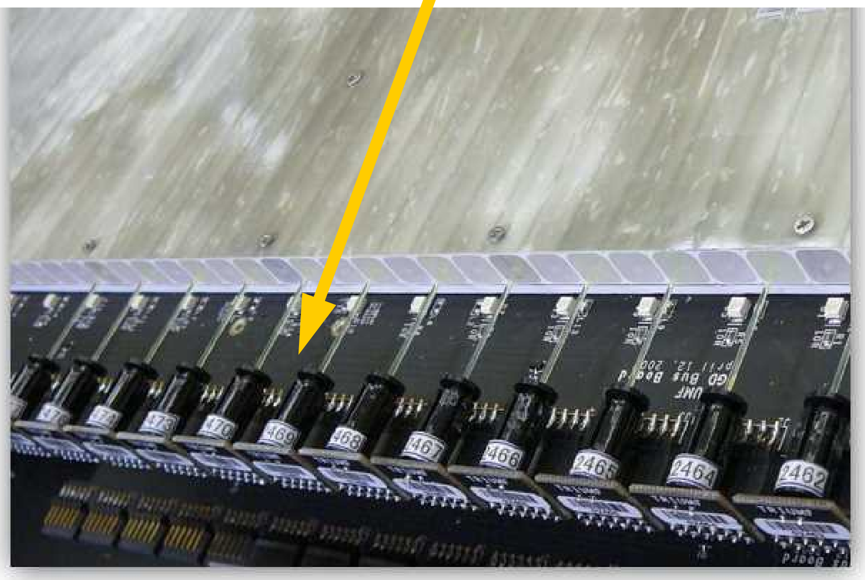
Fronting Detector in J-PARC

Super KAMIOKANDE

INGRID, FGDのコネクタ



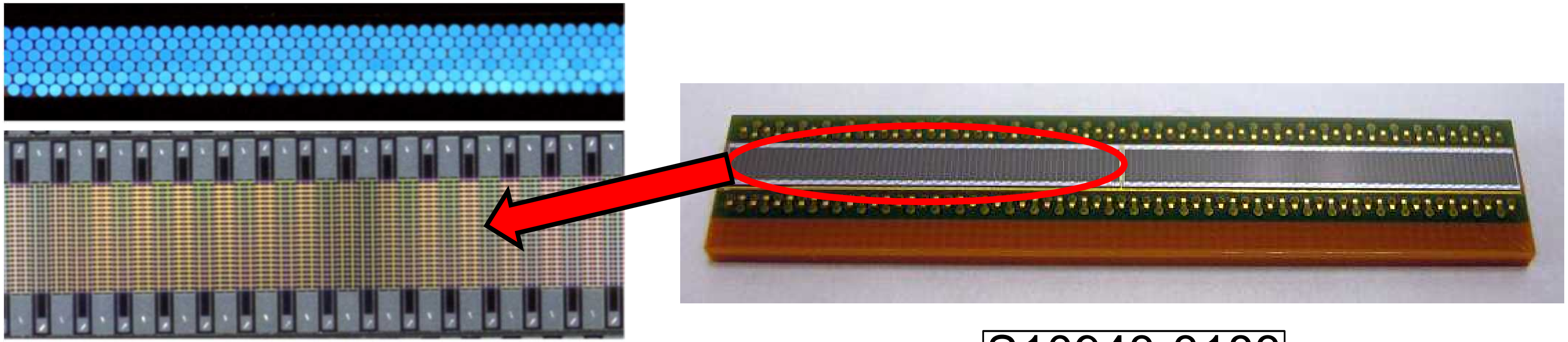
S10362-13-050C
Installed 56kpcs.



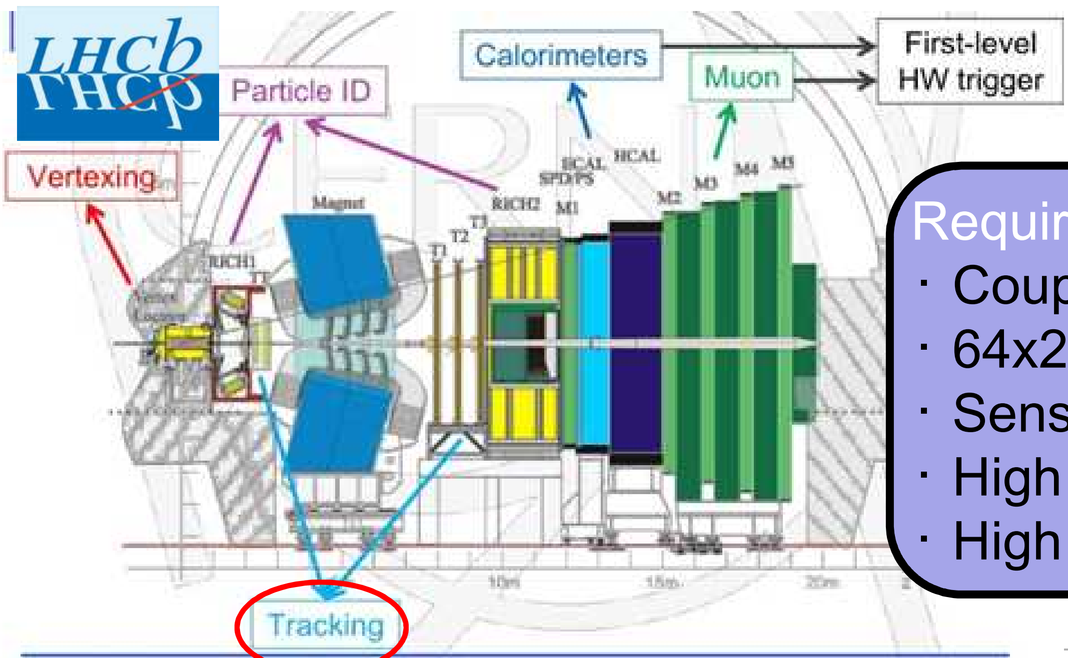
(Provided from Kyoto University)

Required properties
- Good coupling to φ1mm fiber
- High PDE for 525nm
- Withstand high magnetic field
- Low dark count

MPPC® for LHCb SciFi Tracker



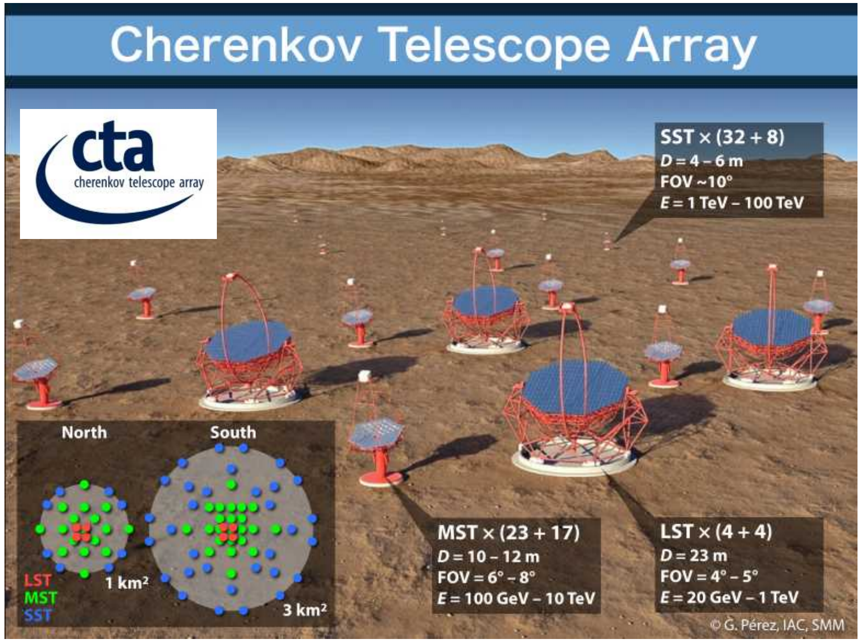
S10943-3183

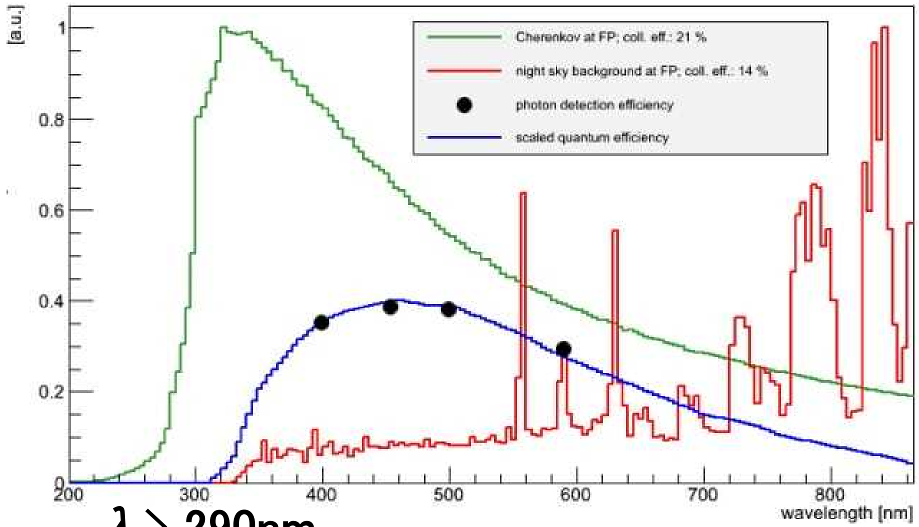


Required properties

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

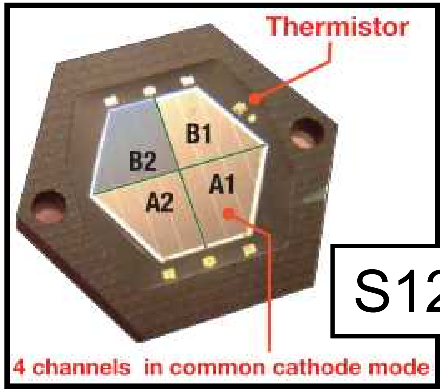
MPPC® for Cherenkov Telescope Array





$\lambda > 290$nm

Light guides



S12516

Required properties
- High PDE @300nm
- High Gain
- Low cross talk
- Low dark count
- Large sensitive area
- Sensitive area: 6mm 4ch Hexagonal

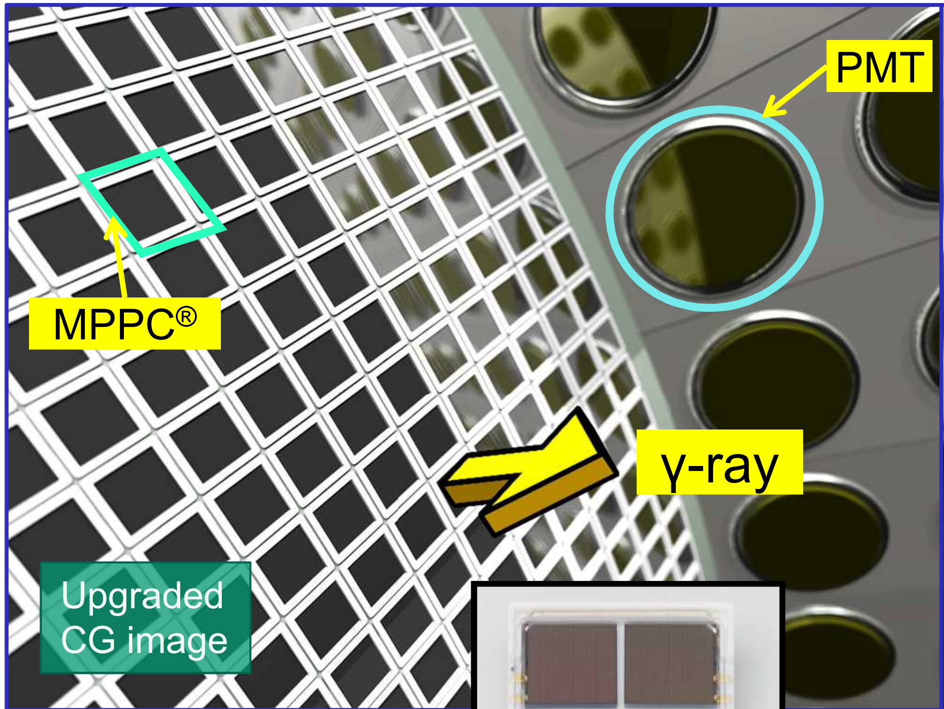
MPPC® for MEG Upgrade

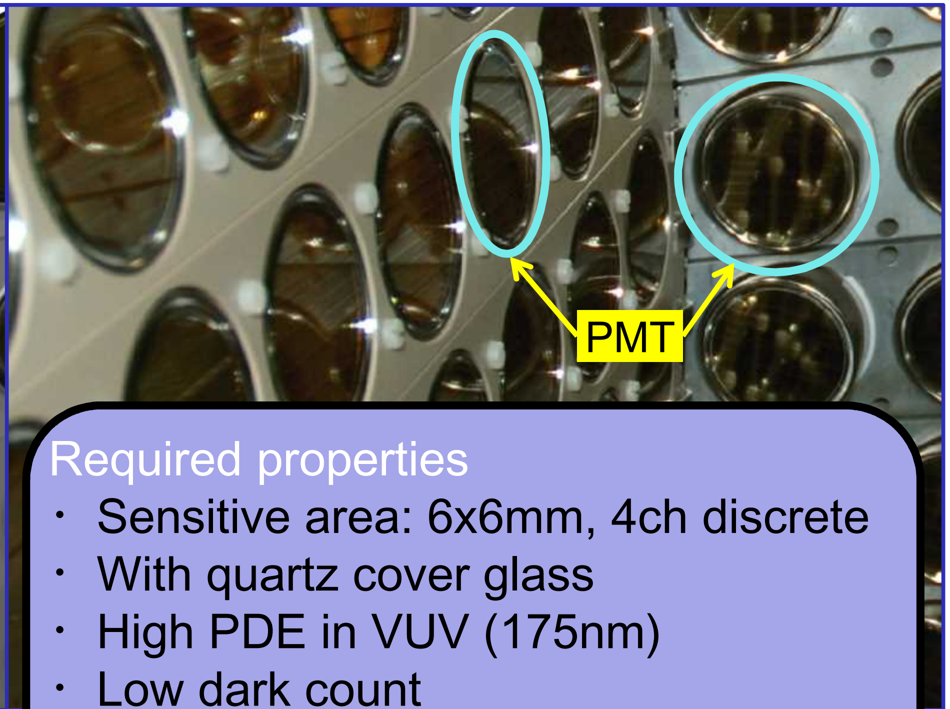
MEG experiment : searching for $\mu^+ \rightarrow e^+ + \gamma$ decay

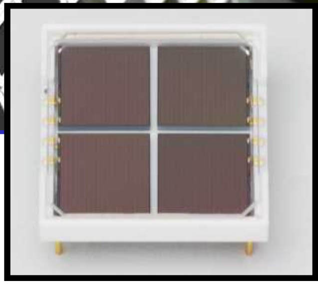
Liquid xenon γ-ray detector will be upgraded

2” PMT → MPPC® for VUV (175nm) total 4,000pcs.

(Pictures from Tokyo University)







S10943-3186

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℃)

Summary

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

2. **We have enough capability to design, process, and inspection of Si detectors for HEP.**

3. **We have developed and delivered SSDs and APDs for LHC-ATLAS and CMS experiment.**

4. **MPPC® characteristics for example after-pulses, cross-talk, pulse height distribution and dynamic range have been improved.**

5. **T2K experiment adopted MPPC®s and is using 56,000 pieces of 1.3x1.3mm-MPPCs. MPPC® will be expected and evaluated for HEP experiments.**

Closing

We Hamamatsu are proud that our Si-detectors are used
for many physical experiments.
We continually make efforts to provide a better sensor, and contributes
to the development of physics.

Photo of Ichino factory with beautiful cherry blossom

Awards received from the LHC experimental groups

Thank you for your attention !

jp.hamamatsu.com