Radiation Hard SiPM Development for CEPC

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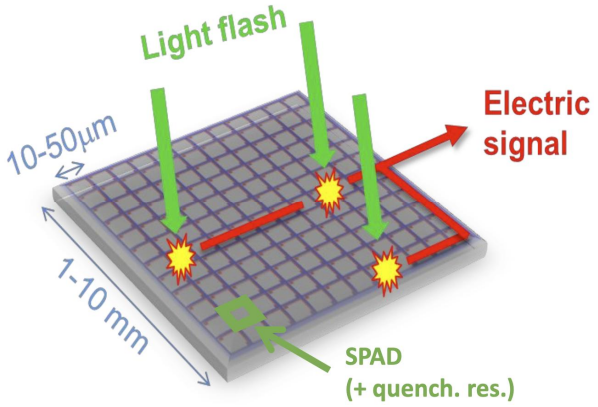
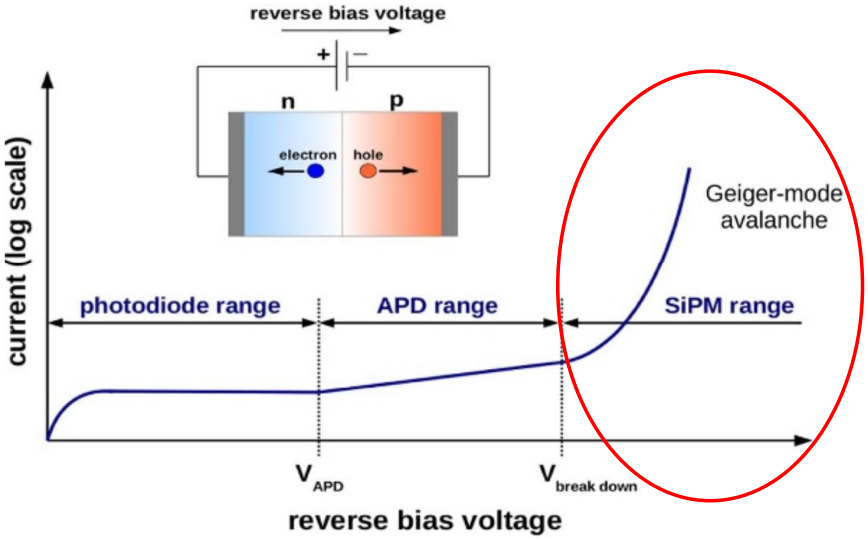
Outline

- Background of SiPM
- SiPM simulation and design
- SiPM samples and weak light tests
- SiPM neutron irradiation experiment and analysis
- Introduction to SPAD and preliminary experiments
- Summary

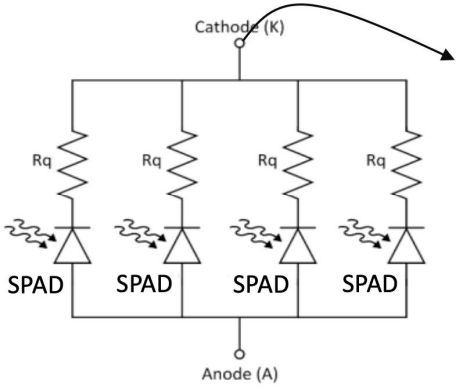
SiPM(Silicon Photomultiplier)

- **Composed of a single photon avalanche diode (SPAD) array in parallel**
- **Working above avalanche break voltage, with avalanche quenching mechanism**
- **Excellent photon number resolution and high single photon detection sensitivity**

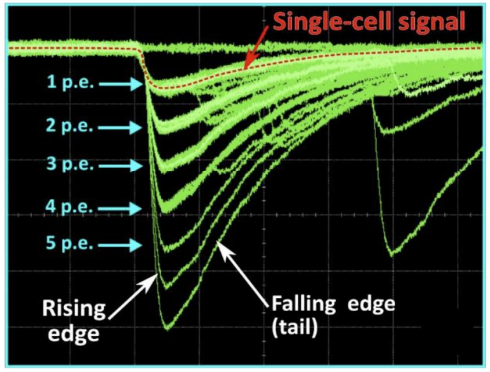




Operating Voltage of SiPM



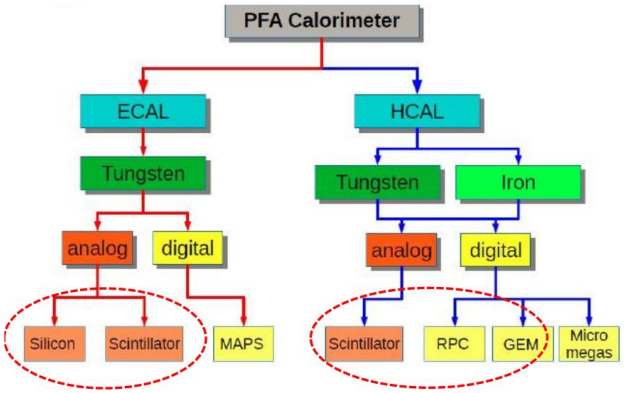
Equivalent circuit of SiPM



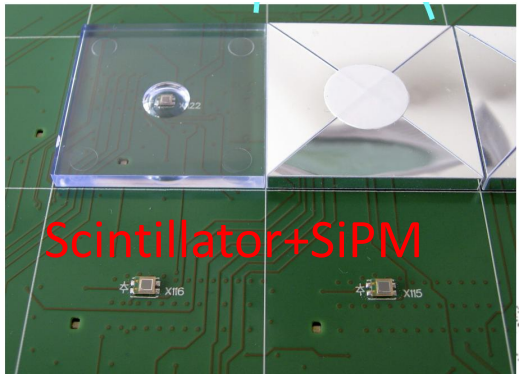
Typical waveform of SiPM

The application of radiation hard SiPM

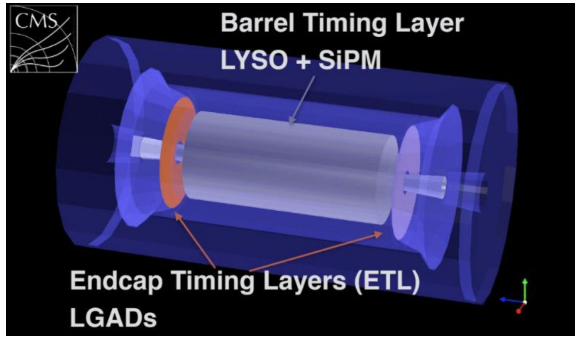
CEPC calorimeter, Space station scientific experiment (Herd …)



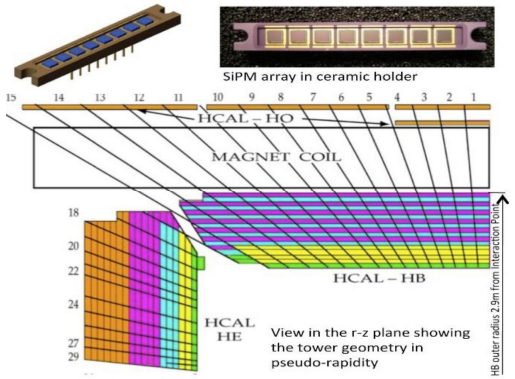
CEPC PFA
AHCAL prototype

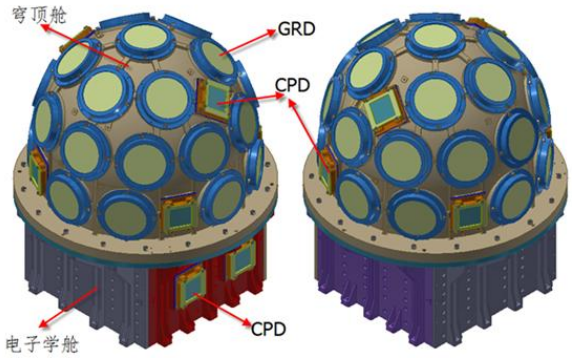


CMS Barrel Timing Detector

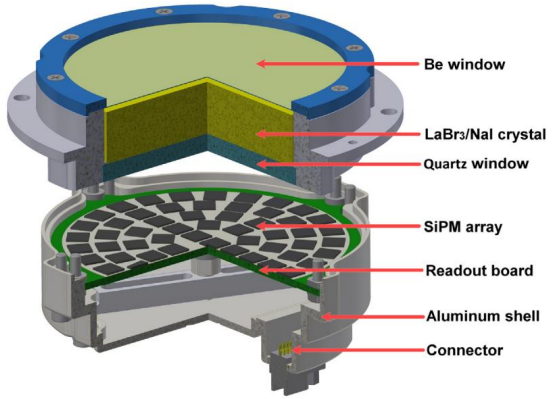


CMS-ECAL upgrade





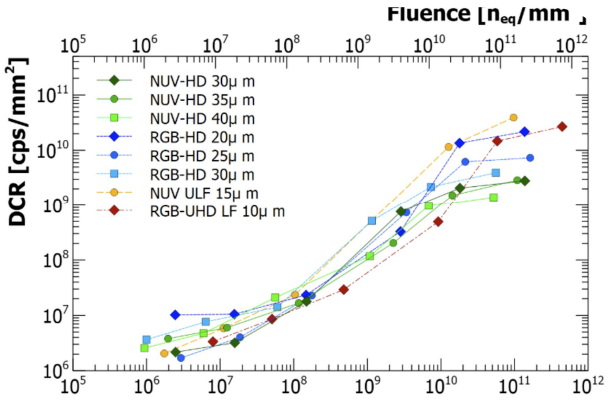
GECAM

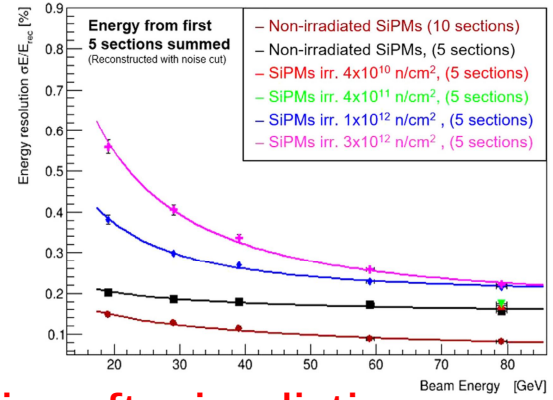


The requirements for radiation hard SiPM

After 10^{10} n_{eq}/cm^2 or 10Krad dose

- Signal gain decrease
- Energy resolution decrease
- Dark count increase





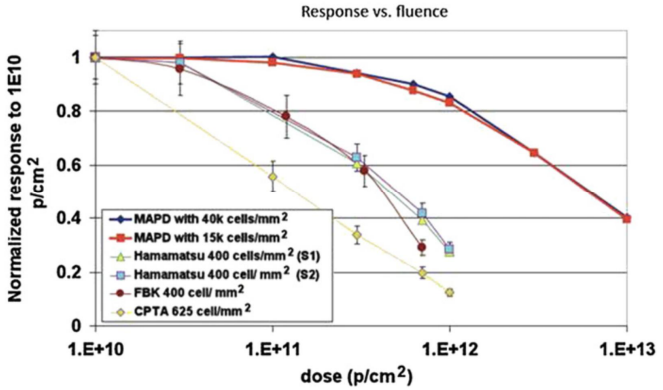
Energy resolution after irradiation

Urgent requirement 1: excellent radiation resistance

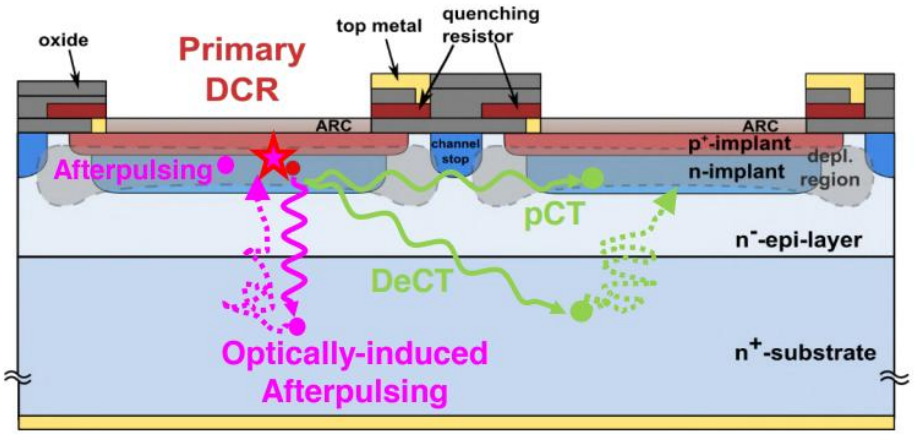
Urgent requirement 2: Low dark count

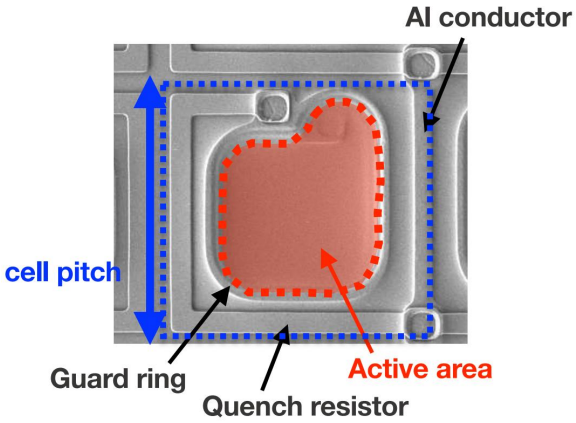
	Long term Satellite or Space station application	CEPC requirement
TID does	100 krad	>100 krad
Fluence	~10^{10} n_{eq}/cm^2	>10^{13} n_{eq}/cm^2

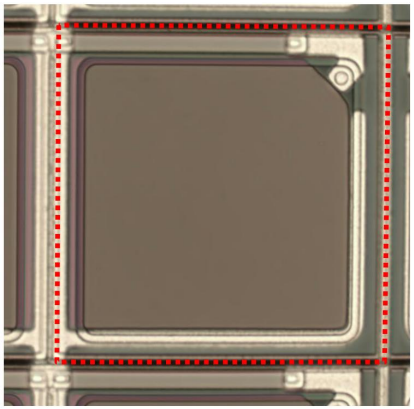
SiPM Signal VS Fluence



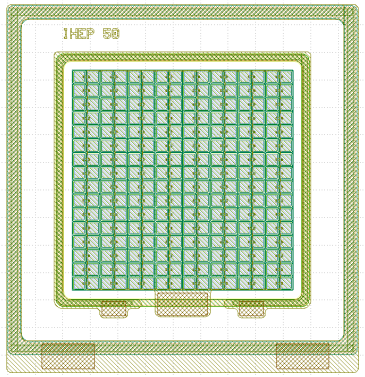
IHEP SiPM-V0

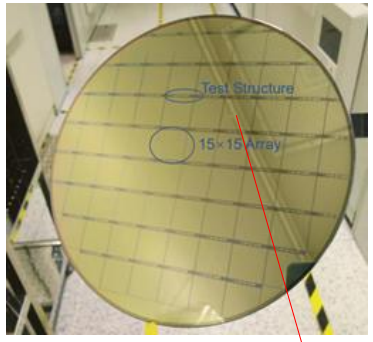


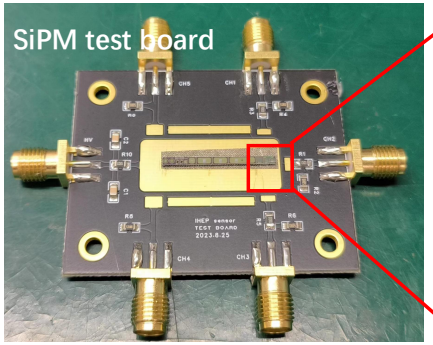


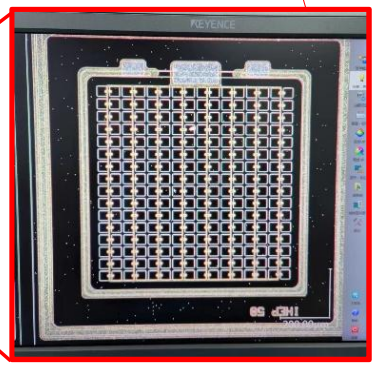


Fraction of active area, typically 50-70%





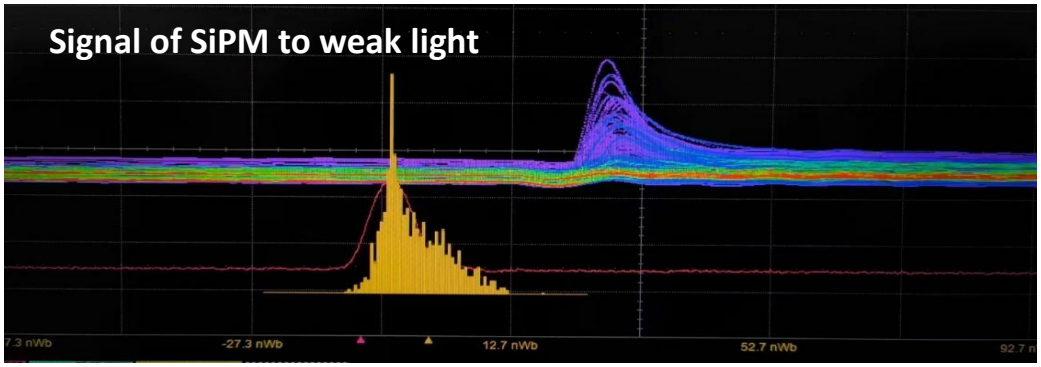


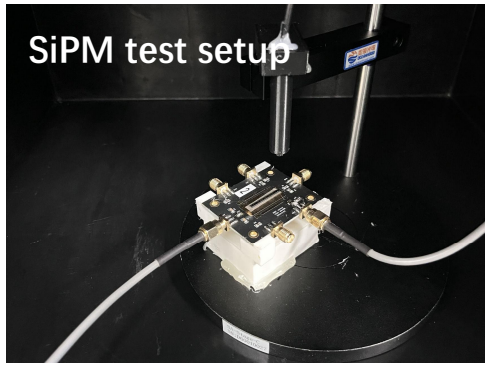


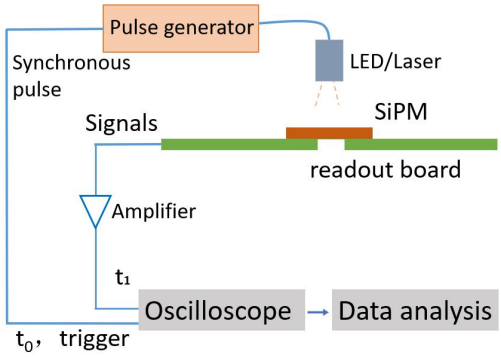
SiPM sample produced along with LGAD pre-production

- **Pixel size： 50μm**
- **16 x 16 pixels**

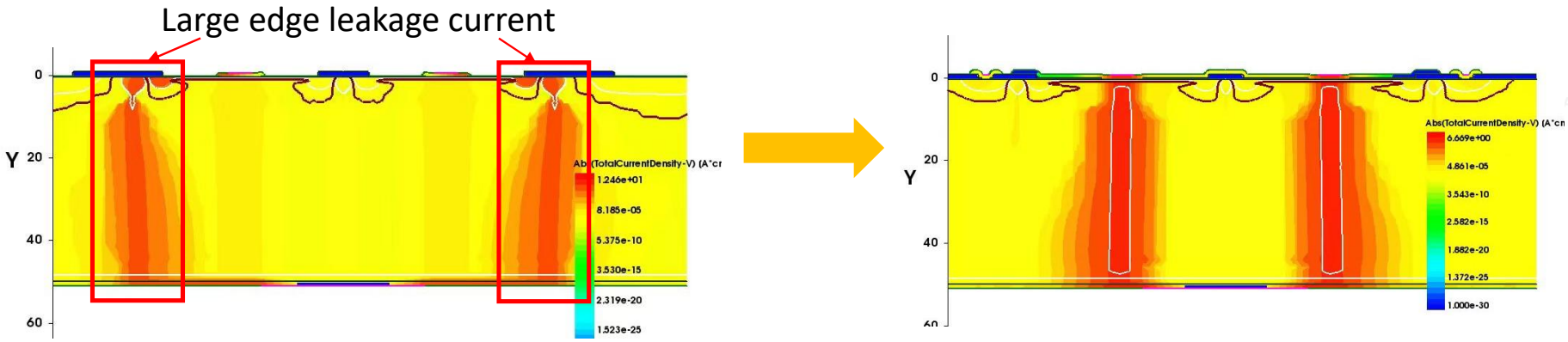
Weak light experiment and TCAD simulation of SiPM





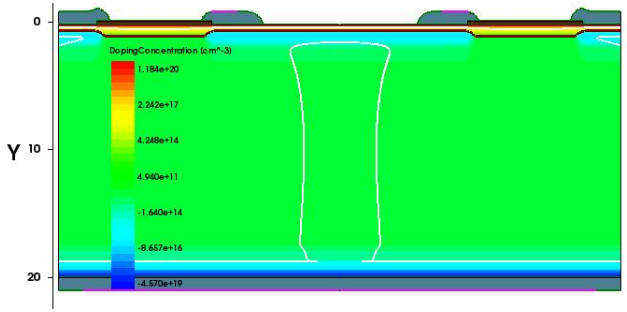


- The structural design and some processes of SiPM have been validated.
- Energy resolution needs to be optimized.

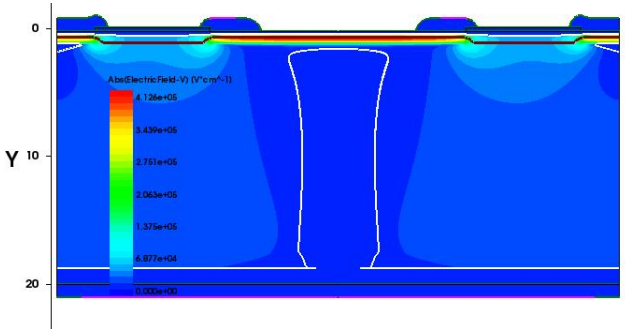


Optimize the Pstop and GR structures through simulation to reduce the leakage current of the edge Pstop;

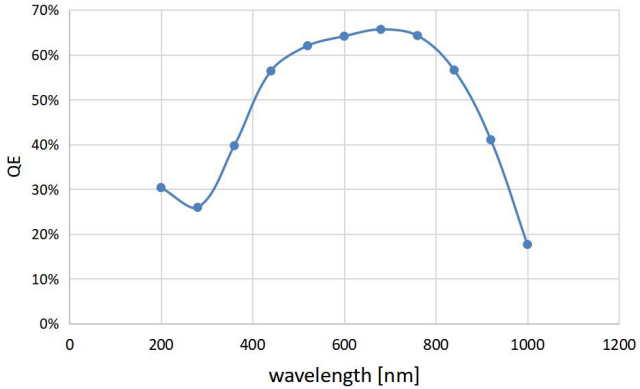
TCAD simulation of radiation hard SiPM



Doping profile

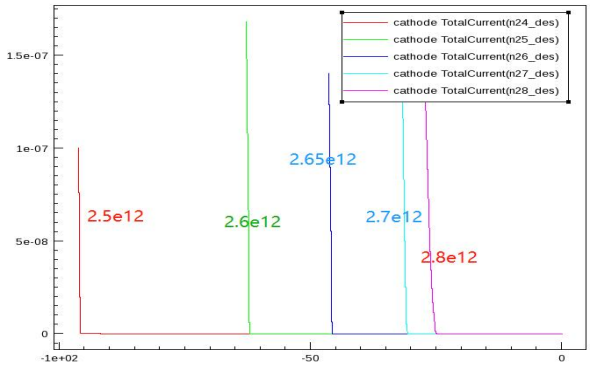


Electric field distribution



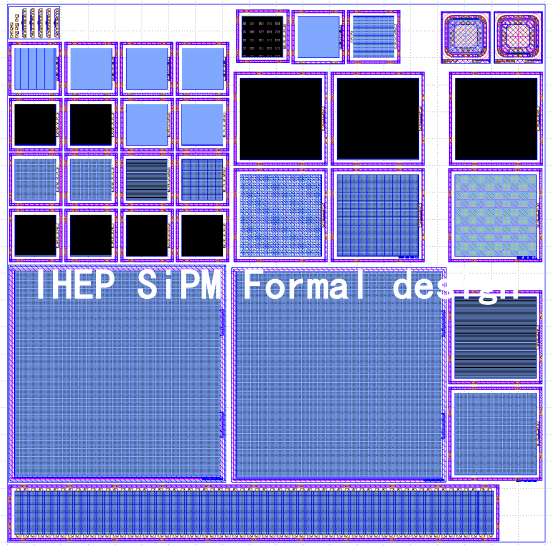
QE vs. Wavelength

Quantum Efficiency > 50% @ 420nm



I-V

Break Voltage 30V-100V

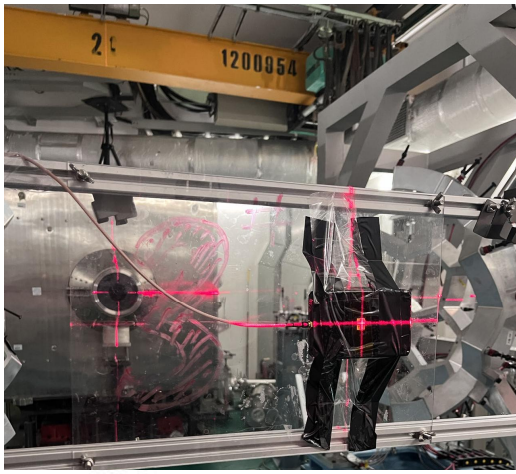


SiPM size:
- 7.6mm×7.6mm
- 3.0mm×3.0mm
- 1.5mm×1.5mm

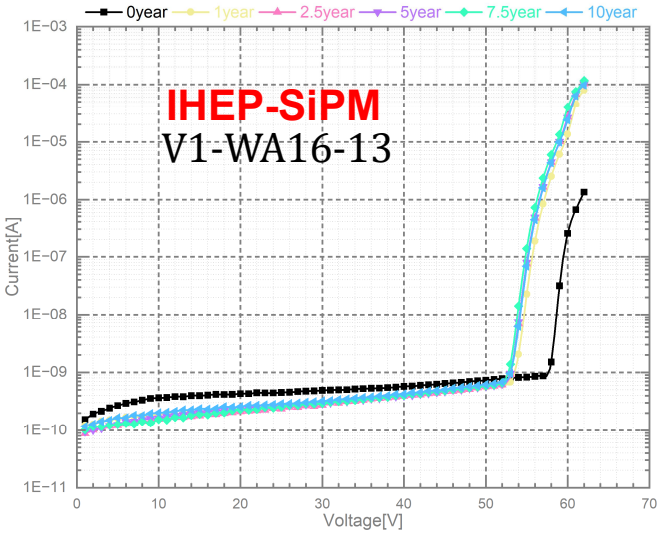
Pixel size:
100μm、50μm、20μm、10μm

Formal tape-out plan:
- Submit the official design layout at the end of January
- Complete the first version of streaming by the end of April

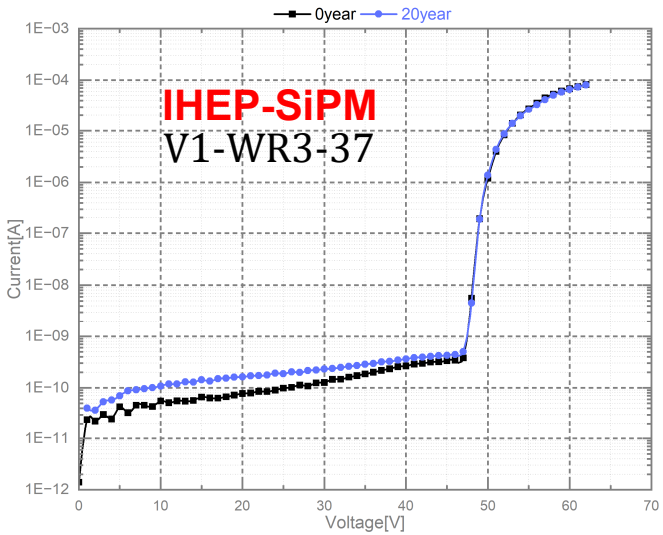
Neutron irradiation of SiPM-V0 in collaboration with CSNS



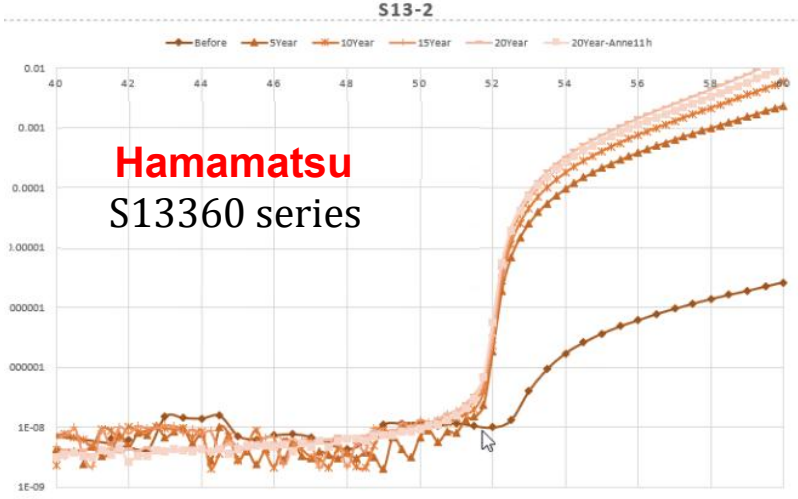
- Under the same irradiation conditions, SiPM is compared to the Hamamatsu S13360 series. At operating voltage, the leakage current of S13360 is $0.2778\mu\mathrm{A/cm}^2$, the leakage current of SiPM is $0.1094\mu\mathrm{A/cm}^2$.
- When the irradiation dose reaches $2.17 \times 10^{10} n_{eq}/cm^2$, the break voltage of SiPM maintains, and the leakage current remains basically unchanged(0.1nA);
- When the irradiation dose reaches $1.09 \times 10^{10} n_{eq}/cm^2$, the break voltage of SiPM decreases by 5V and the leakage current remains basically unchanged(0.2nA).



Dose: $1.09 \times 10^{10} n_{eq}/cm^2$



Dose: $2.17 \times 10^{10} n_{eq}/cm^2$



Dose: $2.17 \times 10^{10} n_{eq}/cm^2$

SiPM Test Plan

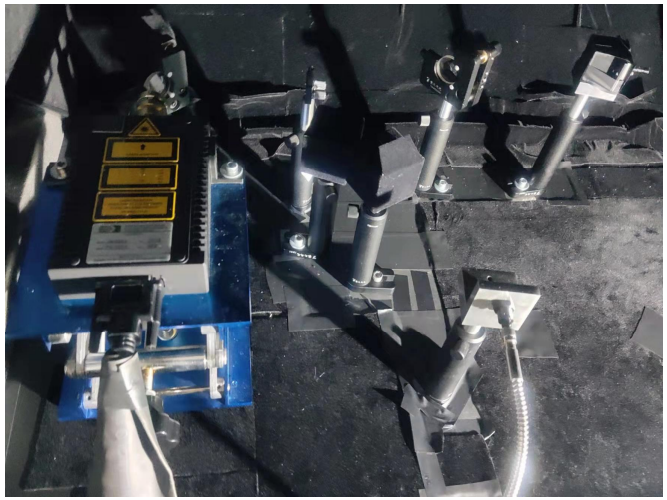
- Performance test plan:

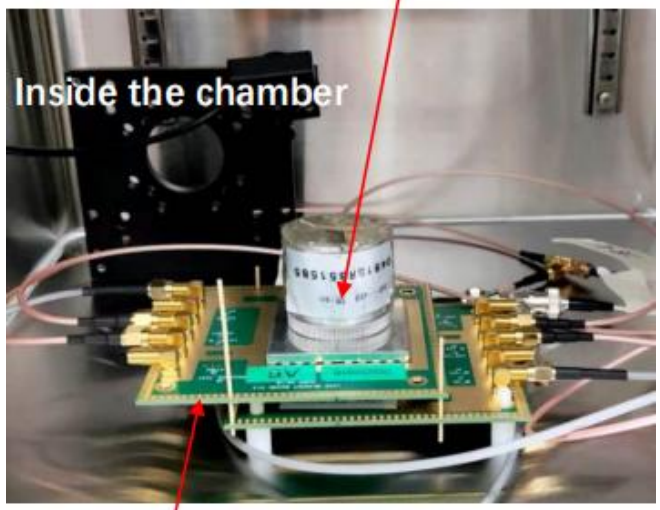
Existing single photon testing platforms and low-temperature testing platforms

- Irradiation test plan:

Plan to collaborate with the Dongguan spallation team to conduct proton irradiation of SiPM

Single photon testing platform
(based on picosecond lasers)

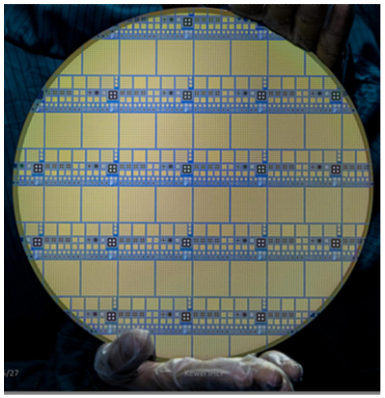




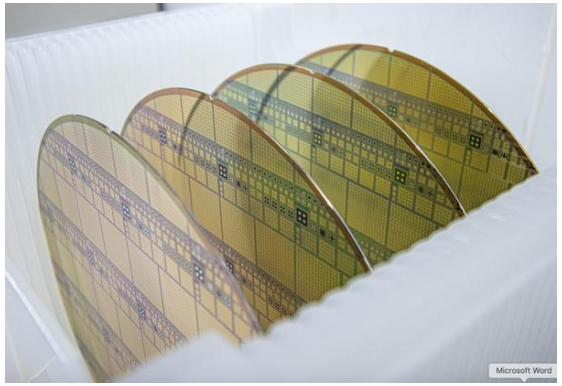
CSNS proton irradiation site

Time line for radiation hard SiPM

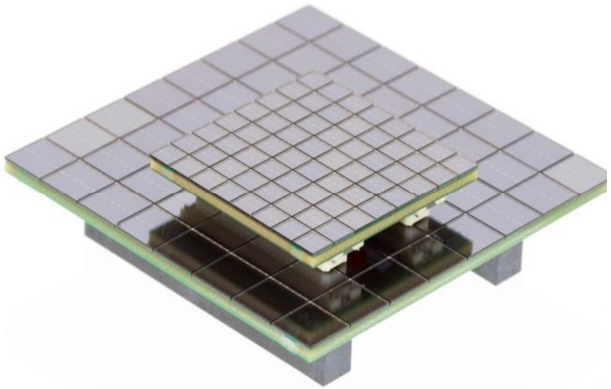
- 2023 1st half: SiPM irradiation hard design validated in LGAD engineering run
- 2023 2nd half: 1st Dedicated SiPM engineering run submission
- 2024: 1~2 more dedicated SiPM engineering run ||Attempt multiple laminations to ultimately determine SiPM process parameters and radiation resistance performance
- 2025: more dedicated SiPM engineering run ||Further optimization for specific projects



Simulation and exploration of various process parameters

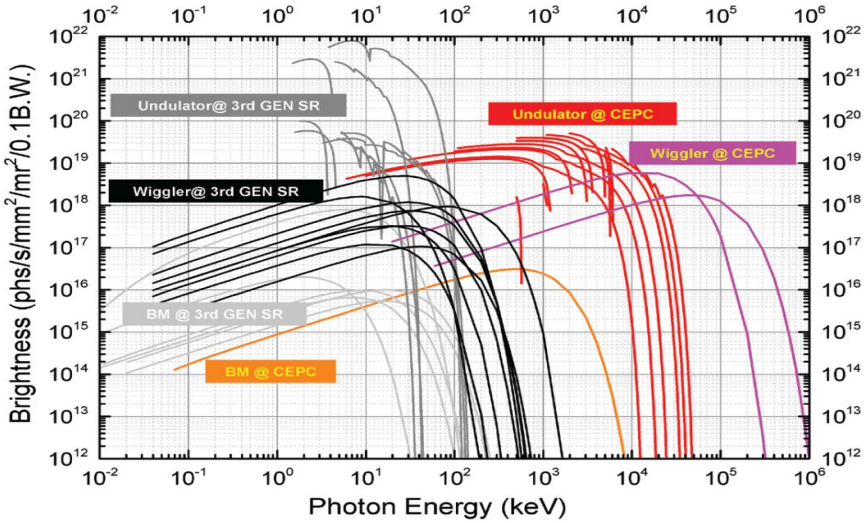


SiPM multiple flow sheets to determine process parameters



2023 2024 2025

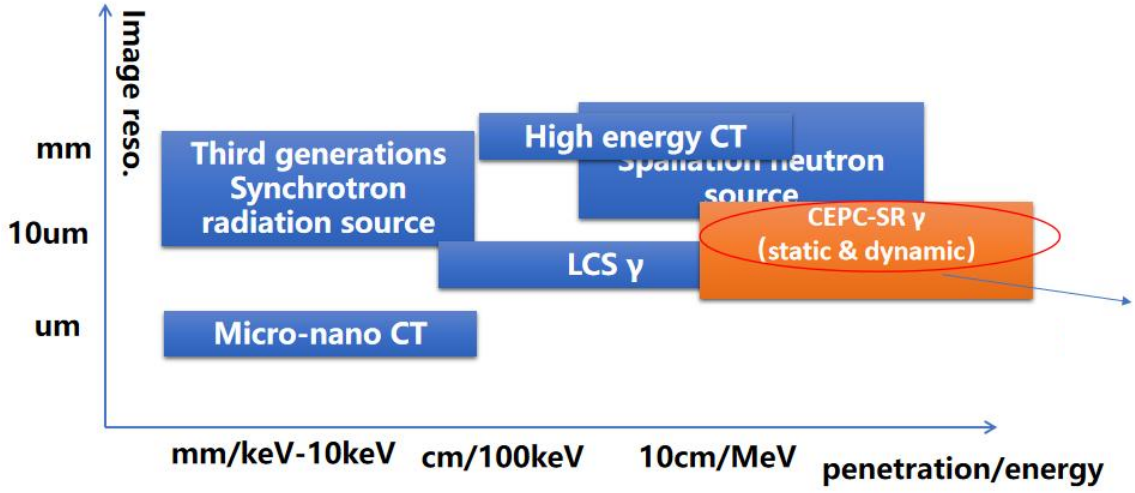
Background of SPAD R&D



Nuclear physics research (wiggler): The characteristics energy of γ-Ray is 17.2MeV, and the radiation energy can reach 300 MeV at high flux.

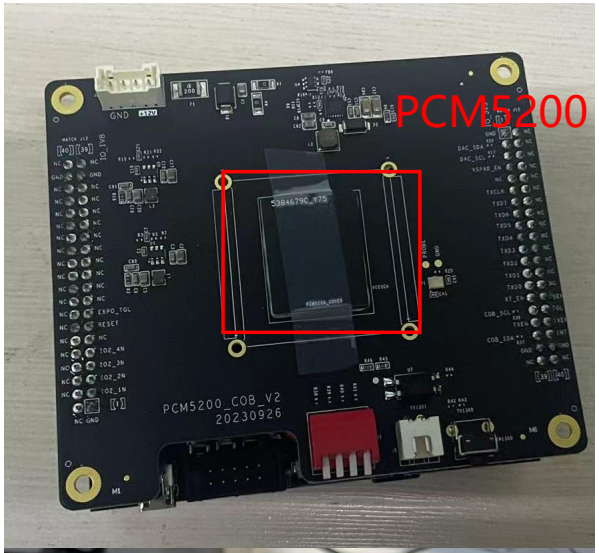
High energy γ: The radiation penetration is strong, but the imaging resolution is only at the millimeter level.

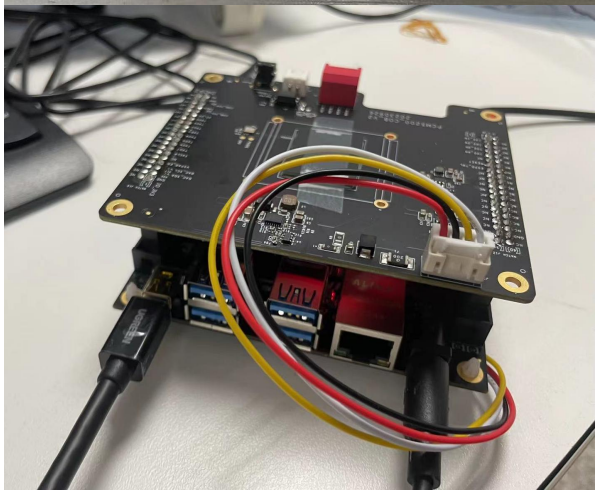
Our goal is to achieve imaging position resolution ~10 micrometre at high energy.



High energy, High-resolution

Introduction and Application of SPAD





Spad Parameter:

Size of photosensitive area: 12.816mm×9.856mm
Number of pixels: 260 × 200
Pixel Size: 49.28μm × 49.17μm

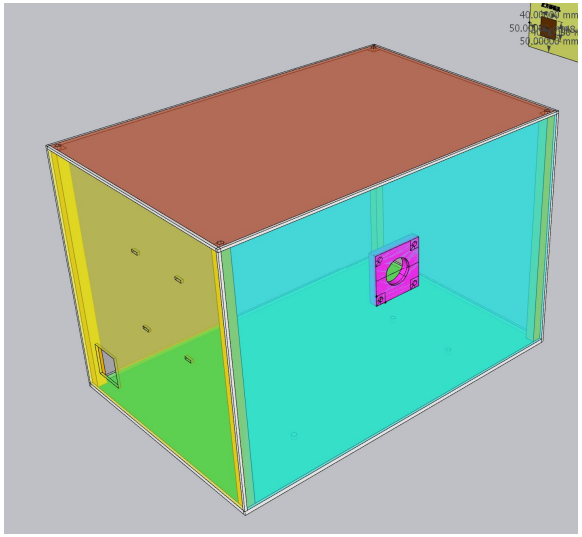
Advantage:

- Adopting high sensitivity SPAD sensors with single photon detection capability;
- High dynamic range, up to 156dB.

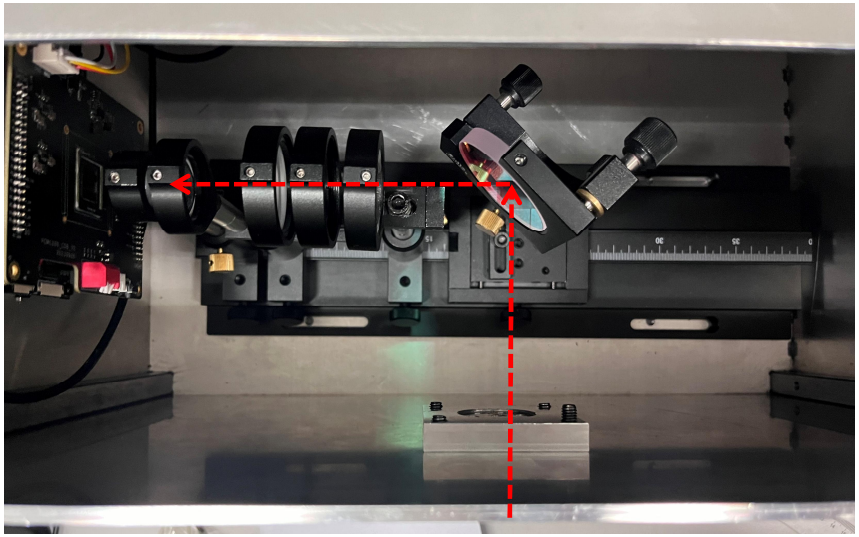
Application:

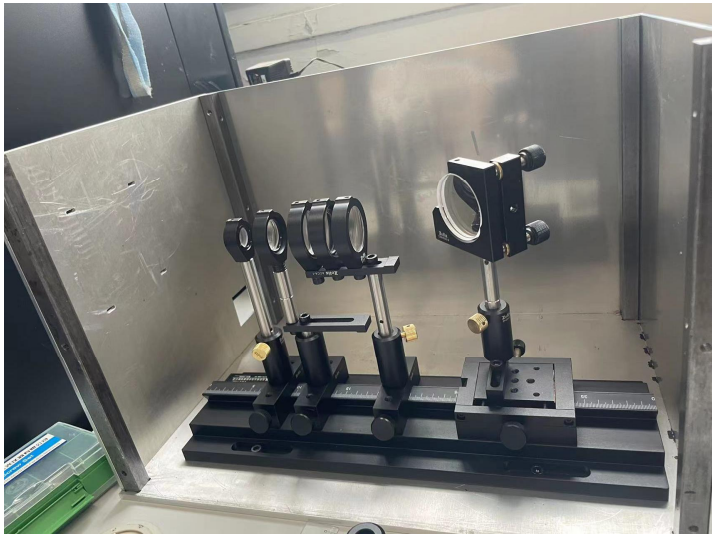
- Radiation imaging
- Weak light imaging
- Fluorescence analysis
- High speed imaging
- Medical equipment

Test Setup



Dark Box





Lens group：

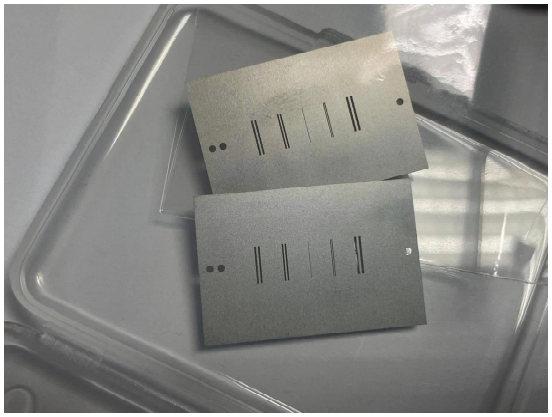
Energy loss efficiency：30%,

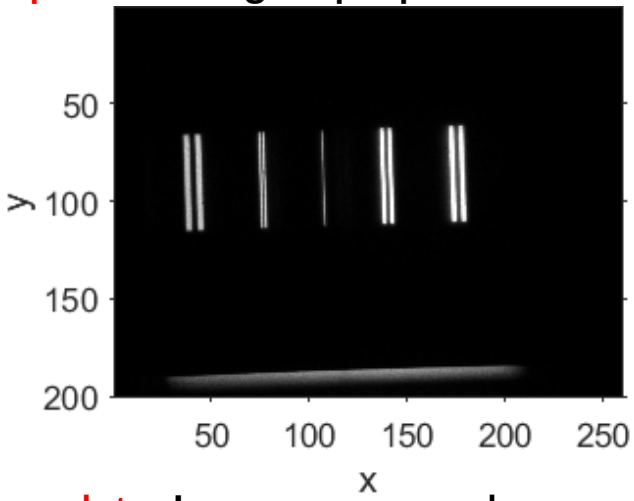
4π solid angle loss rate：98%

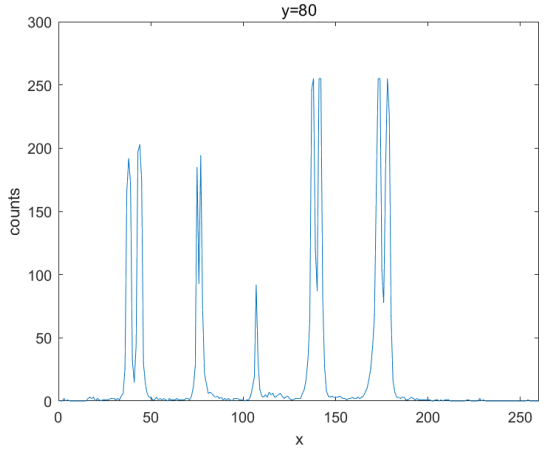
Reduce image size by 2 times

Resolution plate test

Visible light source-Metal resolution plate-Lens group-spad

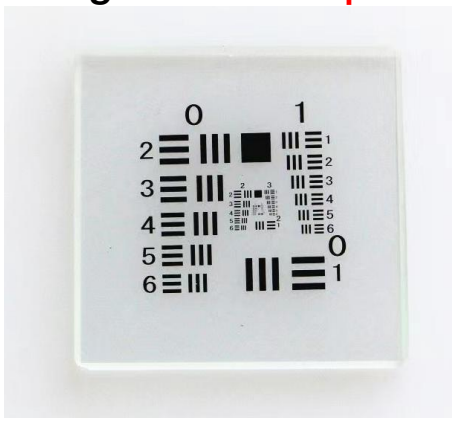




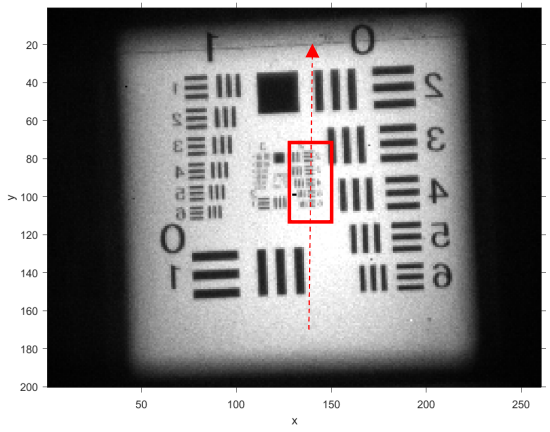


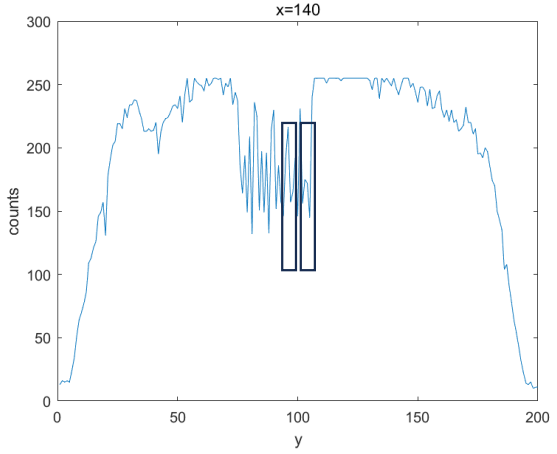
resolution ratio:
300um 100um 50um 200um 250um

Visible light source-Optical resolution plate-Lens group-spad



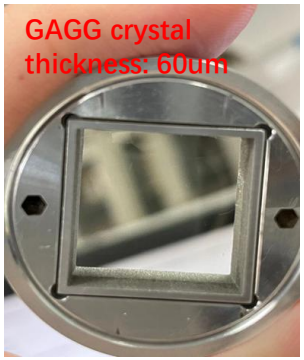
Thickness: 0.1mm



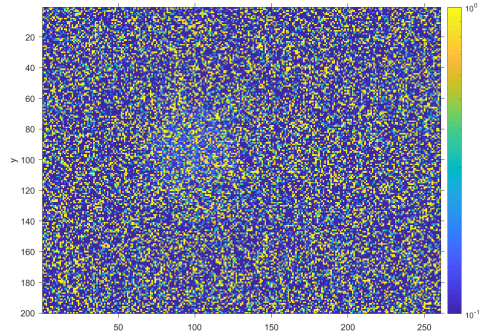


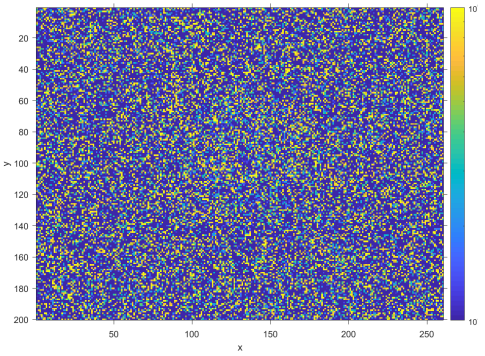
resolution ratio:99um

Scintillator+SPAD Preliminary test results (lensless)

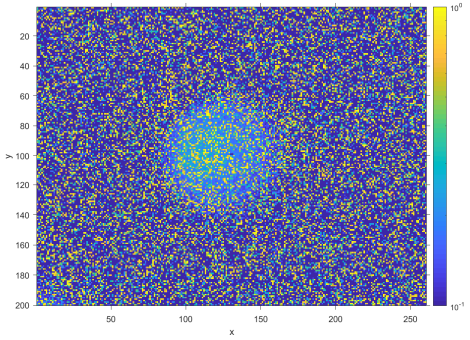


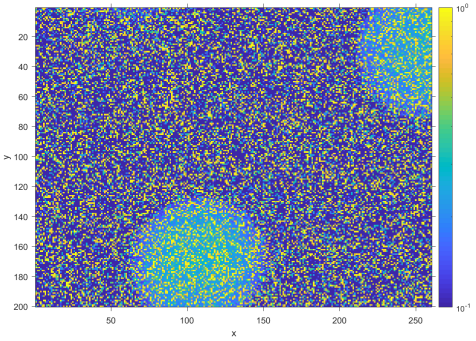
Exposure Time: 1e7us, Sr^{90}

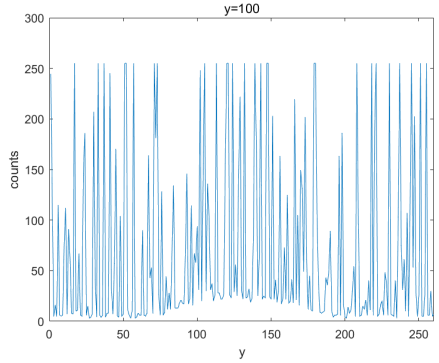


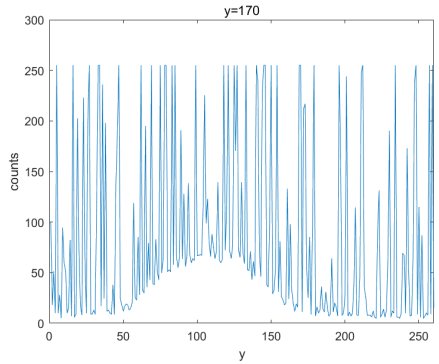


Exposure Time: 1e7us, Am^{241}









Summary

- **Development for radiation hard SiPM**
  - Aim for CEPC and Astrophysics application
- **Key technology has been validated in ATLAS HGTD detector project**
  - Radiation hard LGAD sensor developed by IHEP team
  - At operating voltage, SiPM has a smaller leakage current compared to the Hamamatsu S13360 series.
- Radiation SiPM R & D project
  - **Formal tape-out plan will be submitted in this month**
  - Dedicated engineering run by the end of this year
- SPAD Preliminary test results
  - **Imaging position resolution ~ 100μm**

Thanks for Your Attention

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