Radiation hard SiPM development for CEPC calorimeter

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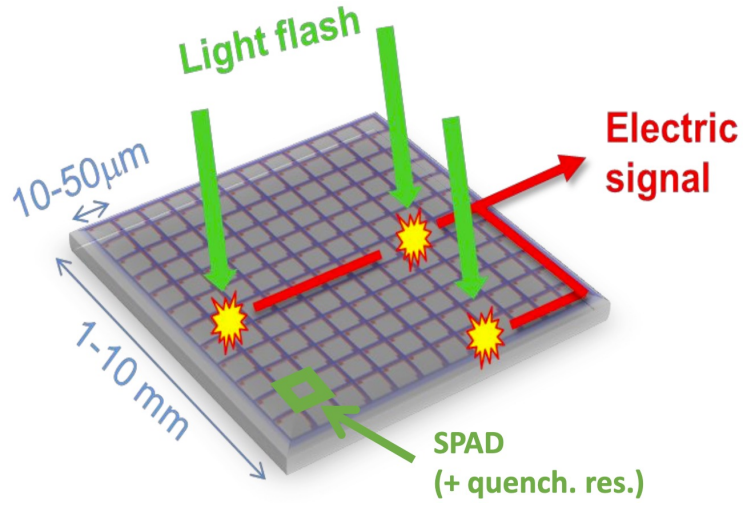
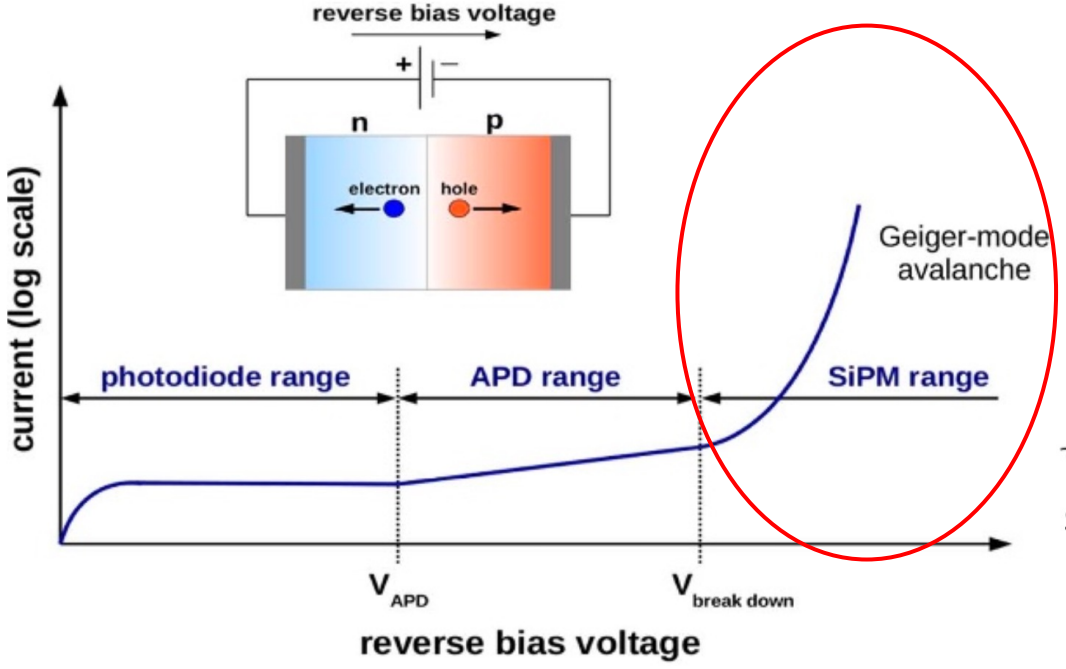
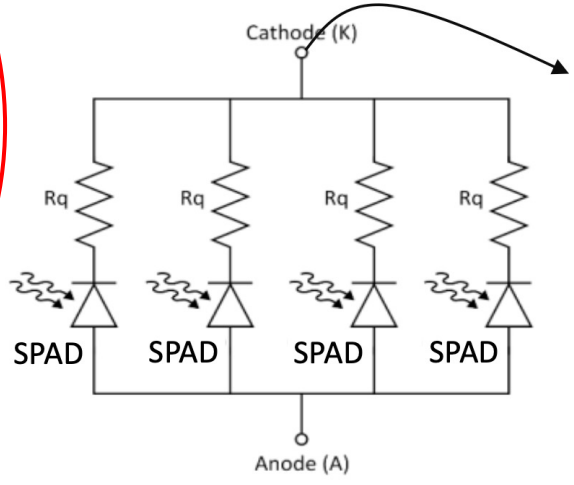
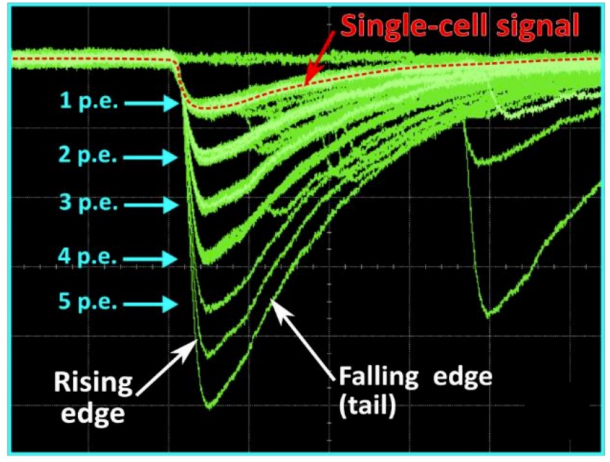
SiPM introduction

- SiPM--silicon photomultiplier: advantage:
  - High resolution
  - Single photon counting
- The goal is to develop Radiation hard SiPM





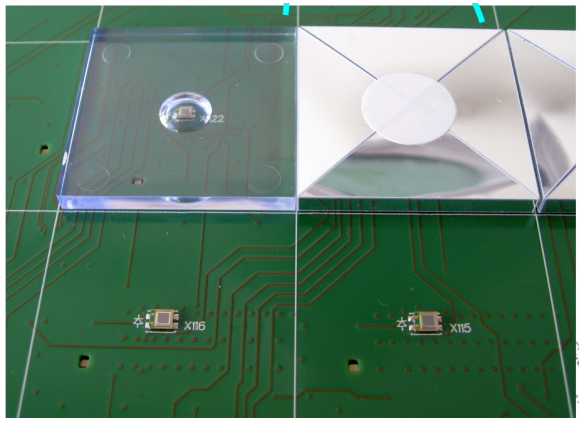




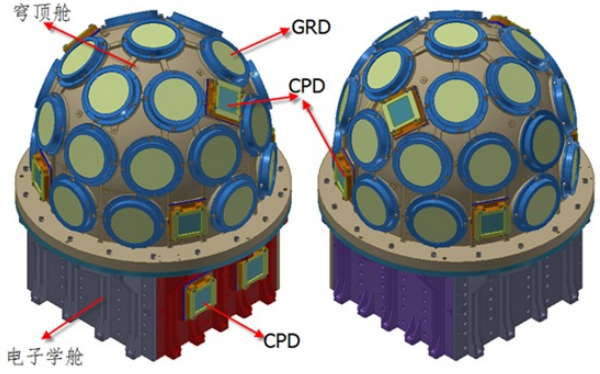
Radiation SiPM application

- Astrophysics: Space station scientific experiment (Herd …)
- Collider physics: calorimeter application
  - CMS timing layer, calorimeter
  - CEPC calorimeter and time of flight detector

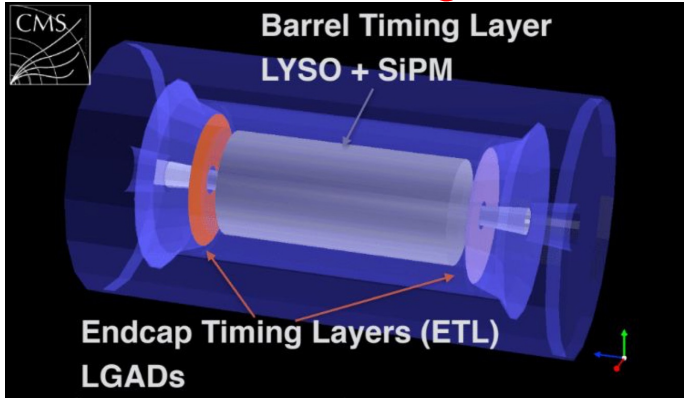
CEPC PFA calorimeter prototype



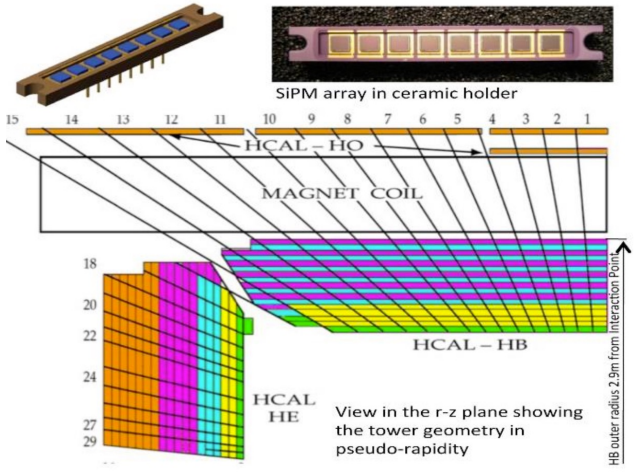
GECAM



CMS MIP timing detector

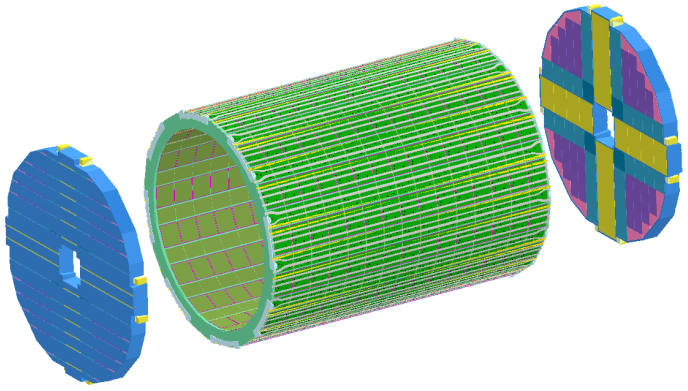


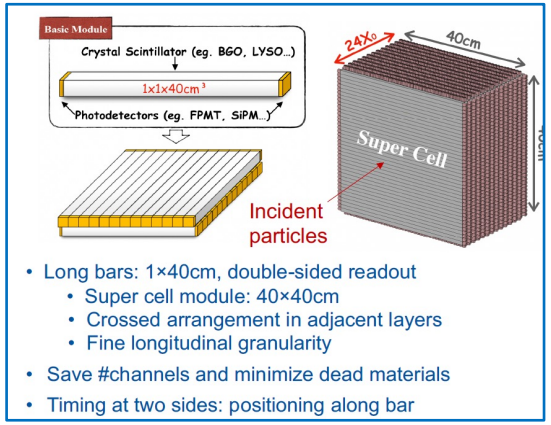
CMS Calorimeter

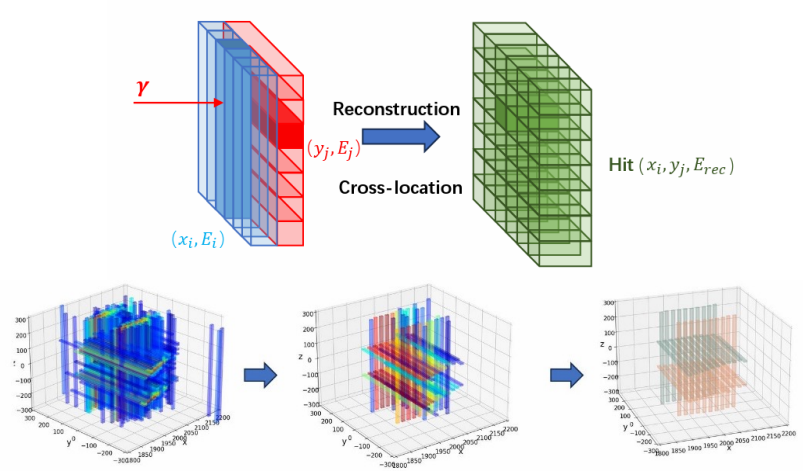


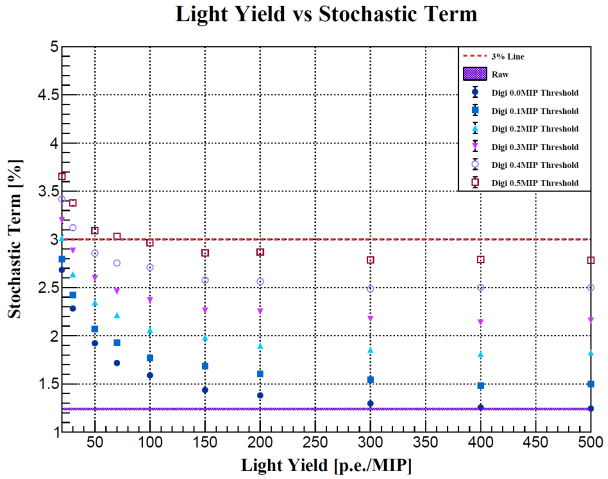
Example: CMS – ECAL upgrade

CEPC ECAL: High-granularity crystal calorimeter





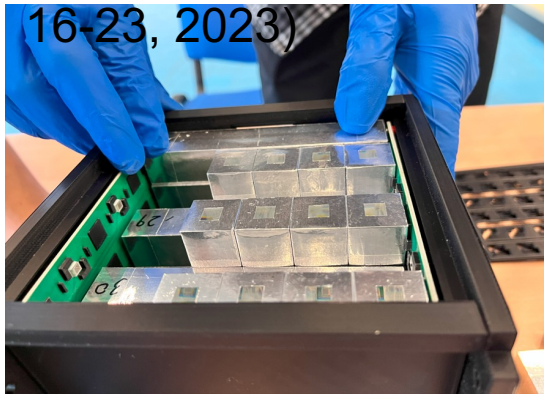


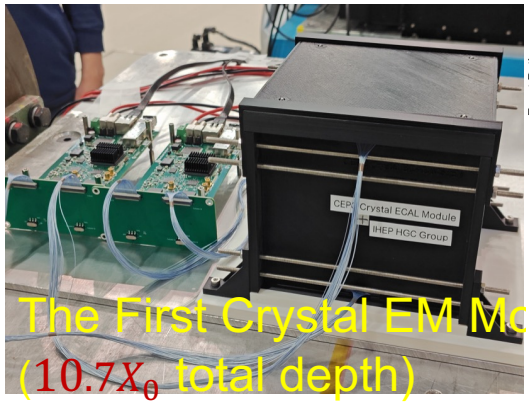


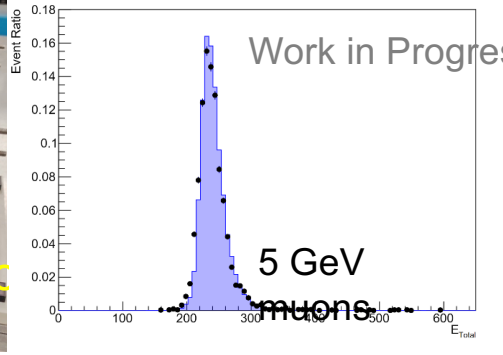
- Crystal ECAL with long-bar configuration
- Simulation studies on design specifications
- Dedicated reconstruction software under development
  - Pattern recognition for particle-flow
- Hardware developments: crystal-SiPM characterizations, crystal modules and beamtests

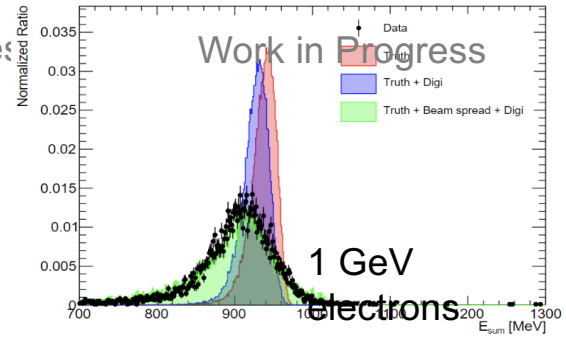
Crystal calorimeter prototypes and beam tests

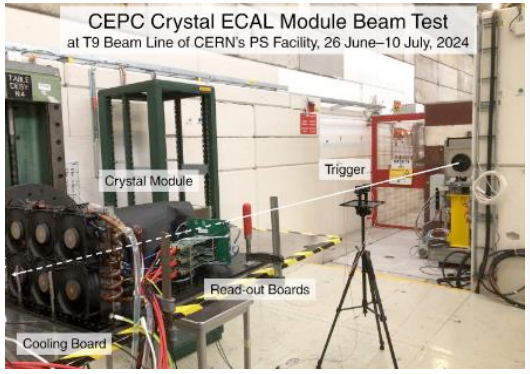
CERN beamtest: parasitic runs at PS-T09 (May 16-23, 2023)







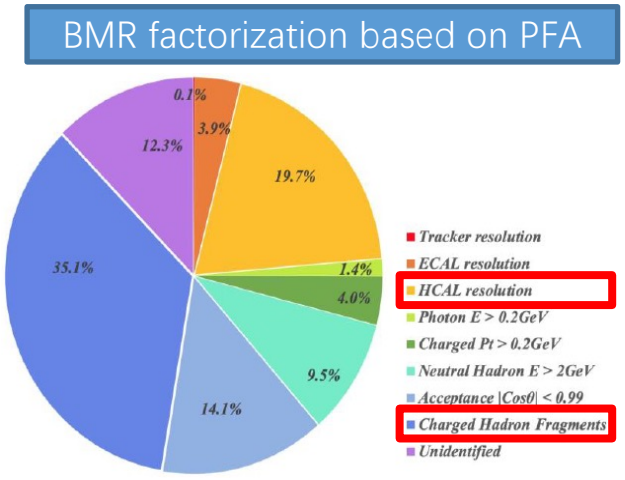




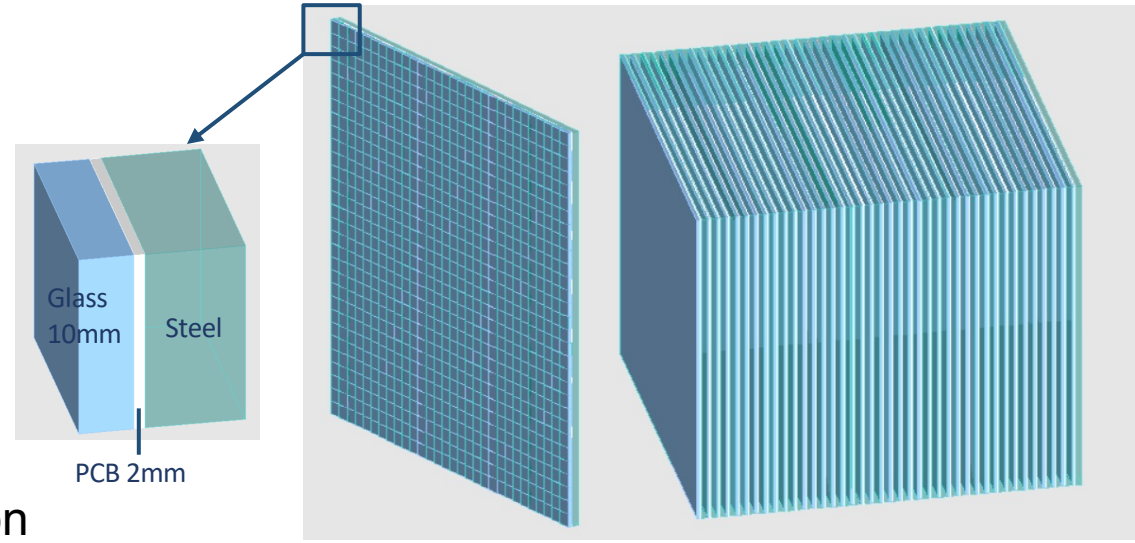
- Crystal calorimeter prototype: key issues
  - System integration and EM performance
- Extensive studies in beam tests at CERN and DESY
  - Muons for MIP calibration
  - Electrons for EM shower studies
  - Data sets for validation of simulation + digitisation

CEPC ScintGlass HCAL overview

- ScintGlassHCAL: PFA-oriented sampling hadron calorimeter
  - A variant option of CALICE-AHCAL: scintillator-SiPM, steel
  - Sensitive layer: dense and bright *scintillating glass* tiles
  - Aim to further improve hadron energy resolution, which is a major factor for precision jet energy measurements

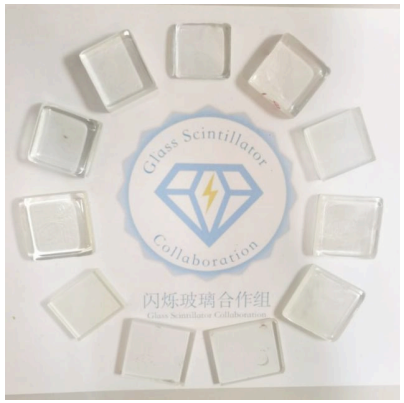


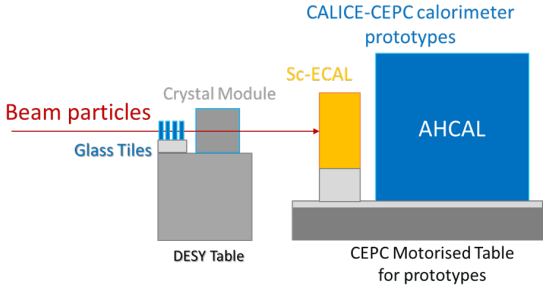
BMR=Boson Mass resolution

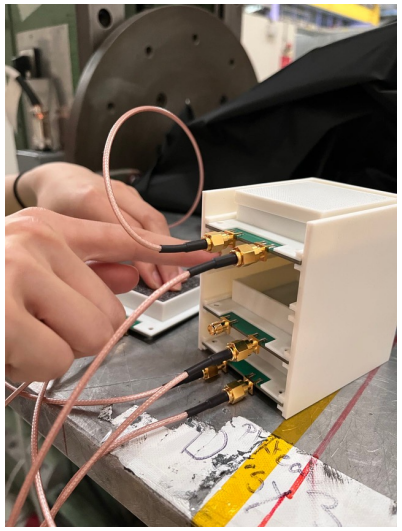


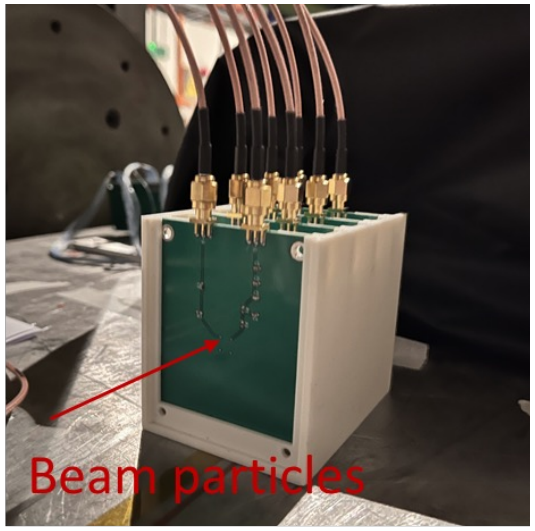
Scintillator glass tiles: CERN beamtest in 2023

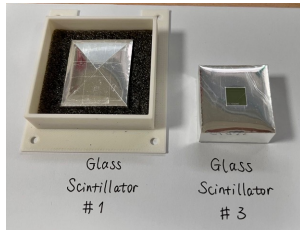
- Successful beamtest with scintillator glass tiles
  - Combined tests with CEPC calorimeter prototypes
  - 11 pieces of large-area glass tiles: the first batch produced by the “Glass Scintillator Collaboration”
  - Clear MIP signals in all 11 glass samples with 15 GeV muons
  - 3 glass tiles showed promising MIP response

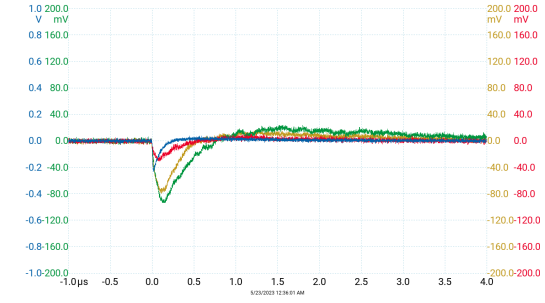


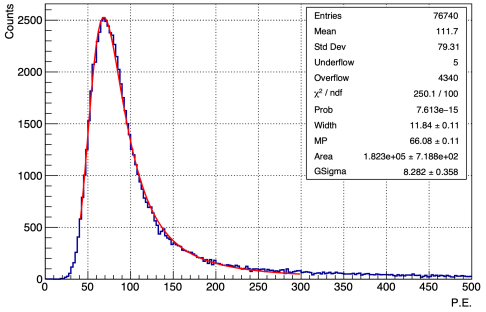












Glass scintillator (#3): 66 p.e./MIP ($29.8\times28.1\times10.2\ \mathrm{mm}^3$)

CEPC ECAL and HCAL: SiPM requirement

- ECAL : Small pixel size (6um*6um), large dynamic range
- HCAL: High PDE Sipm (PDE>60-70%)

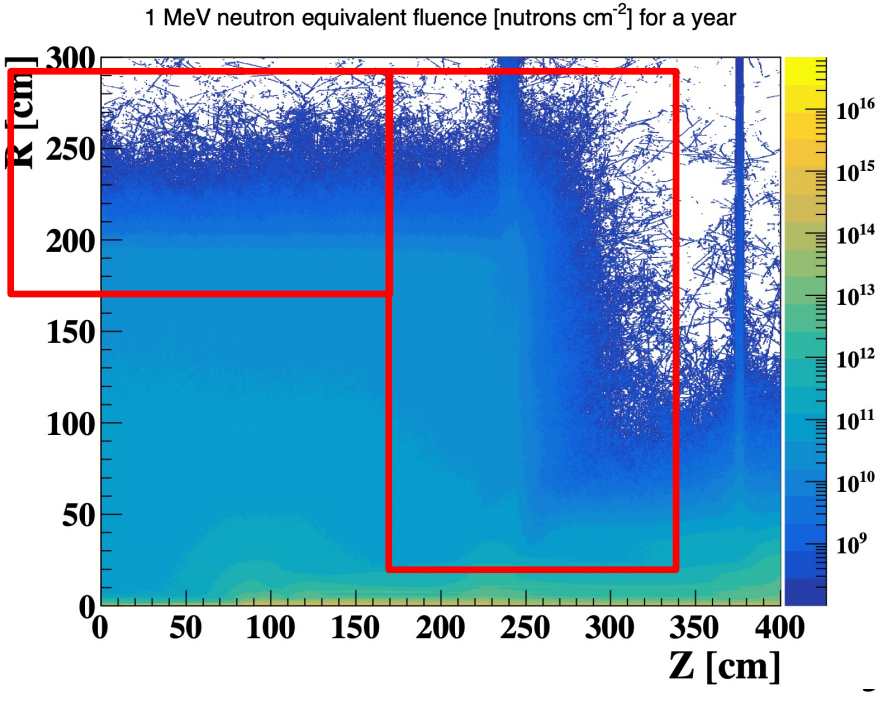
	SiPM for CEPC ECAL	SiPM for CEPC HCAL
Wavelength	350 – 600 nm	350 – 600 nm
Size	3 mm× 3mm	3 mm× 3mm
Pixel size	6 μm × 6 μm	50 μm × 50 μm or larger
PDE	>= 30% (at ~420nm)	>= 60% (at ~400nm)
Number of SiPM	~1 Million	~5 Million

SiPM radiation hardness challenge

- After 10 year operation of CEPC, fluence is above 10^{13} n_{eq}/cm^2
- SiPM typically work below 1krad or 10^9 n_{eq}/cm^2 fluence
  - Performance drop after 1krad or 10^9 n_{eq}/cm^2
  - In great need to develop radiation hard SiPM

	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

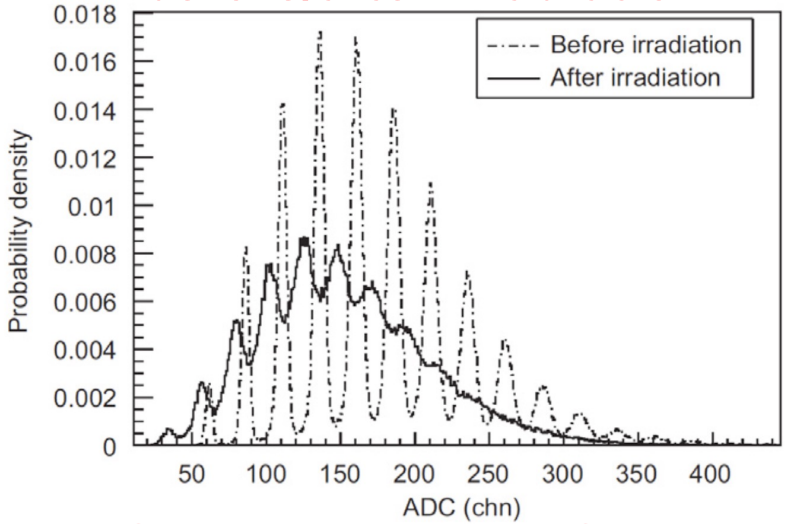
Fluence in ZH run （240GeV）



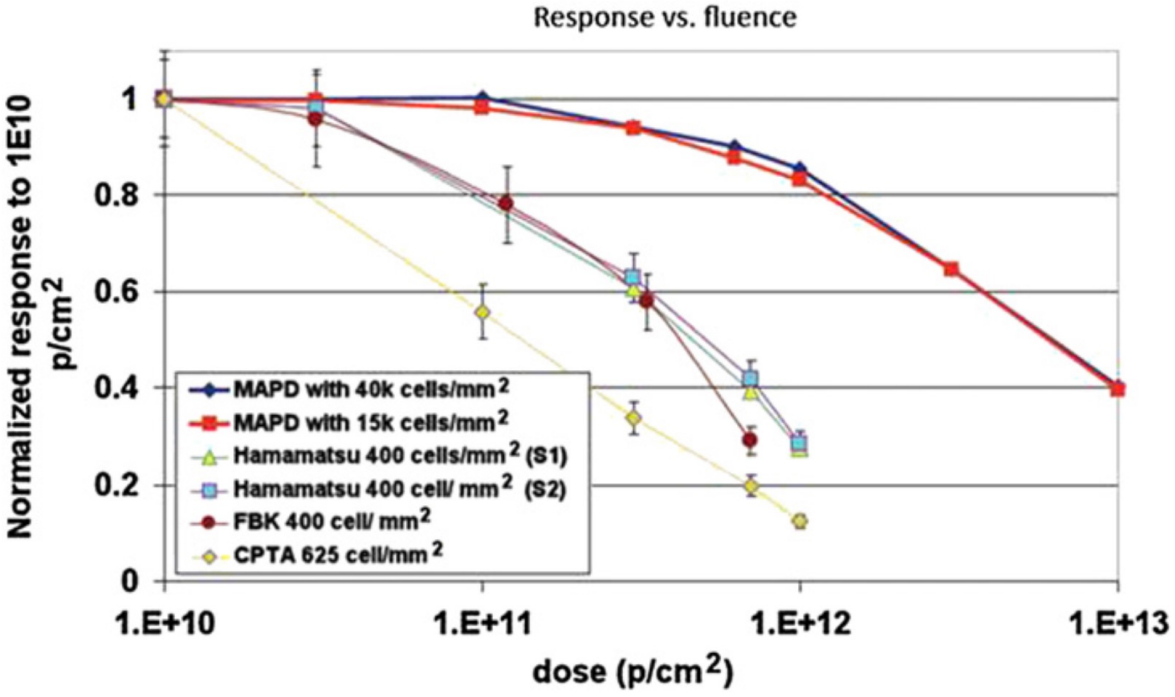
SiPM Radiation hardness

- After 10^{10} n_{eq}/cm^2 or 10Krad dose
  - Signal gain decrease
  - Energy resolution decrease
  - Dark count increase

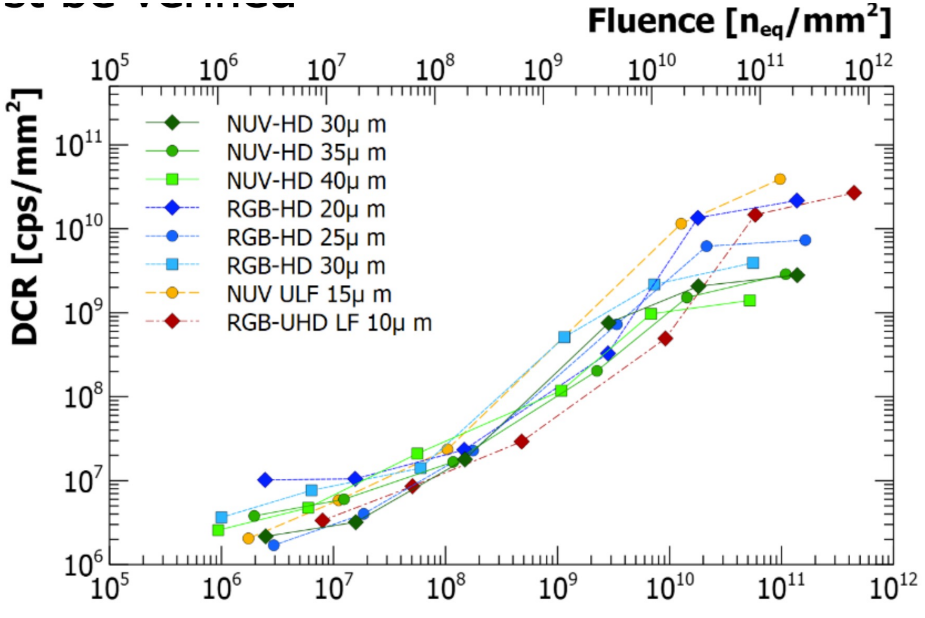
Energy resolution before/after irradiation



SiPM gain VS Dose

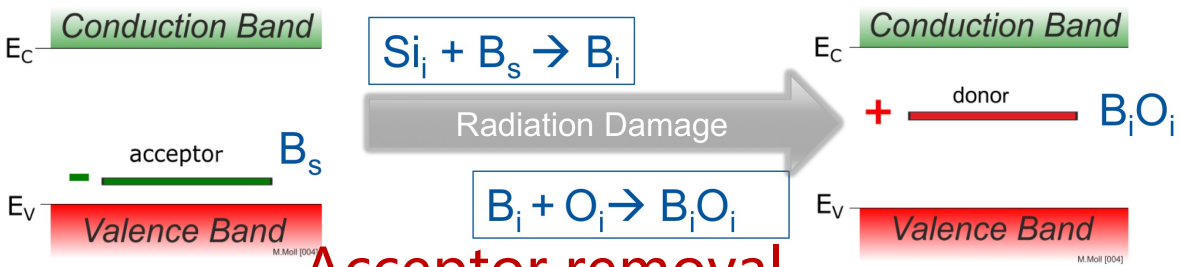


SiPM dark count VS Fluence

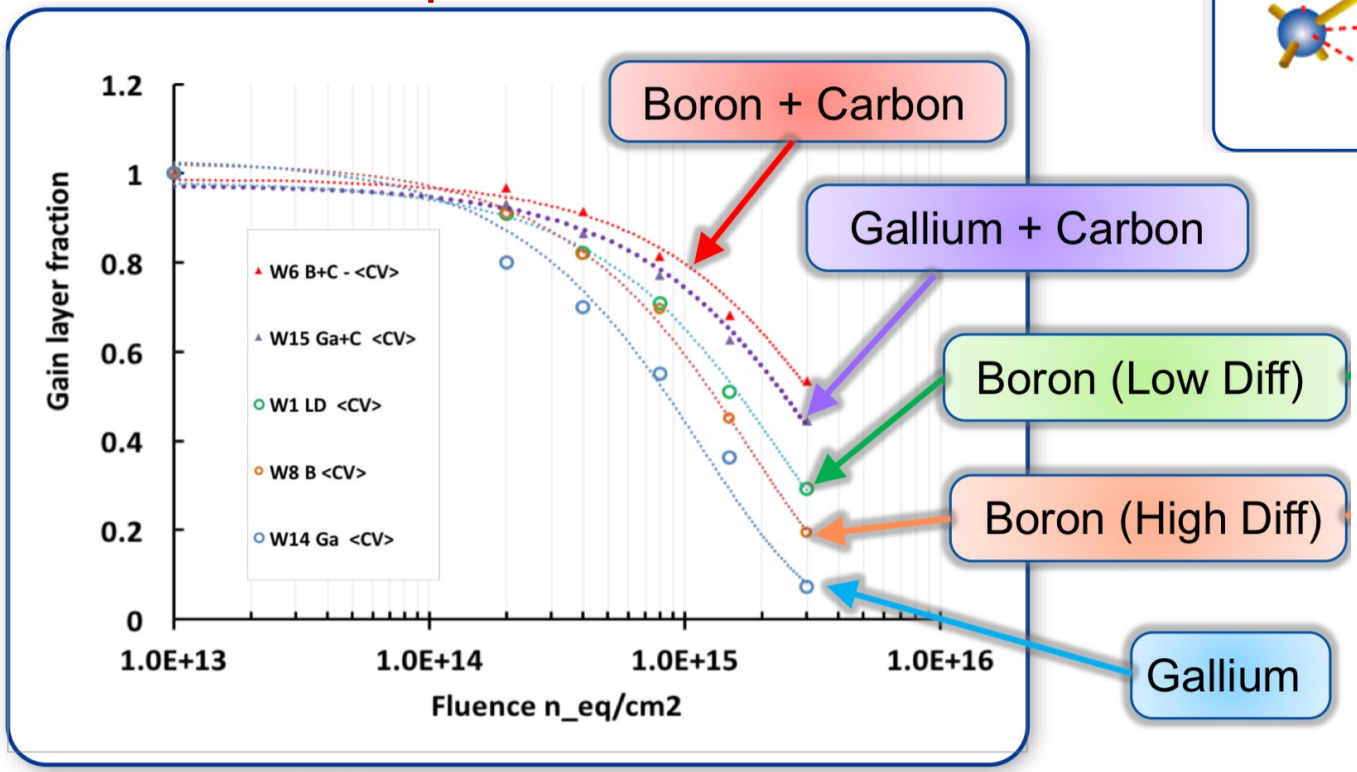


SiPM radiation hardness theory

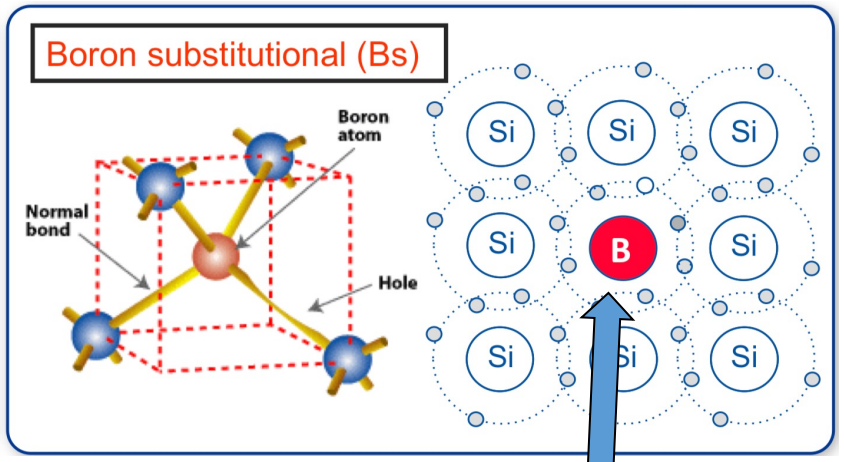
- SiPM signal gain decreased after irradiation （p+ acceptor removal）

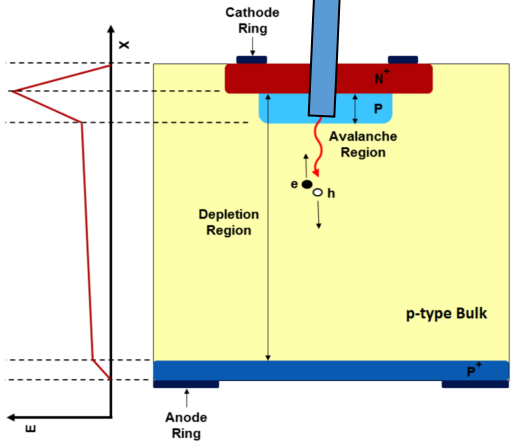


Acceptor removal



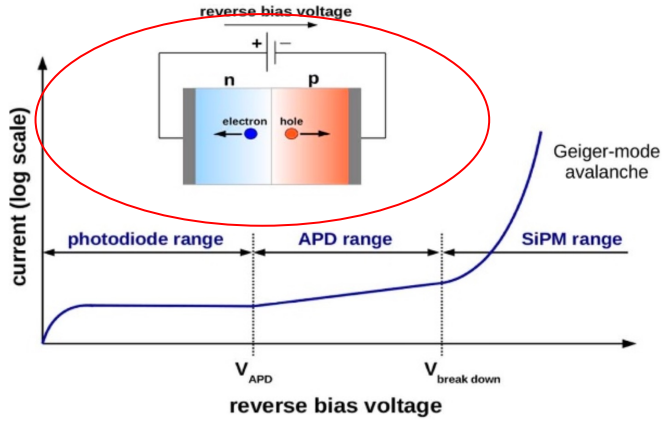
[G.Paternoster, FBK, Trento, Feb.2019]



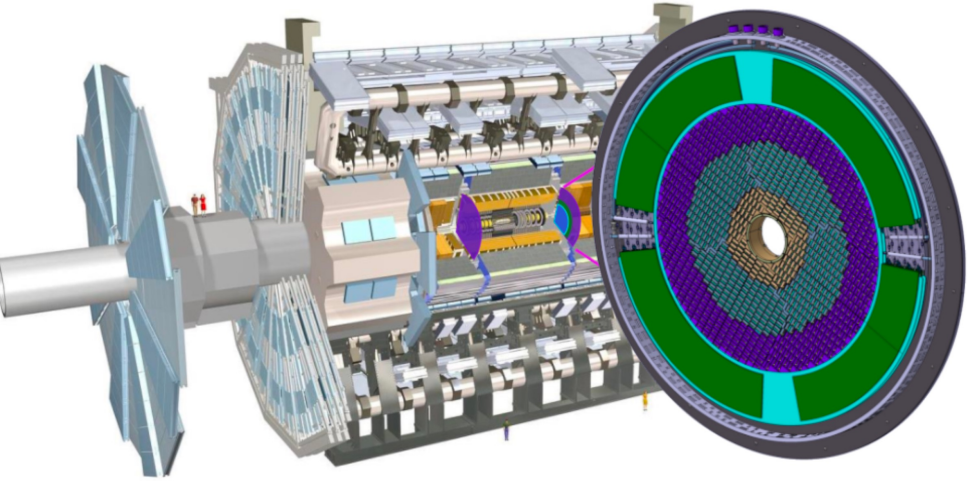


Radiation hard Low Gain Avalanche Detectors (LGAD)

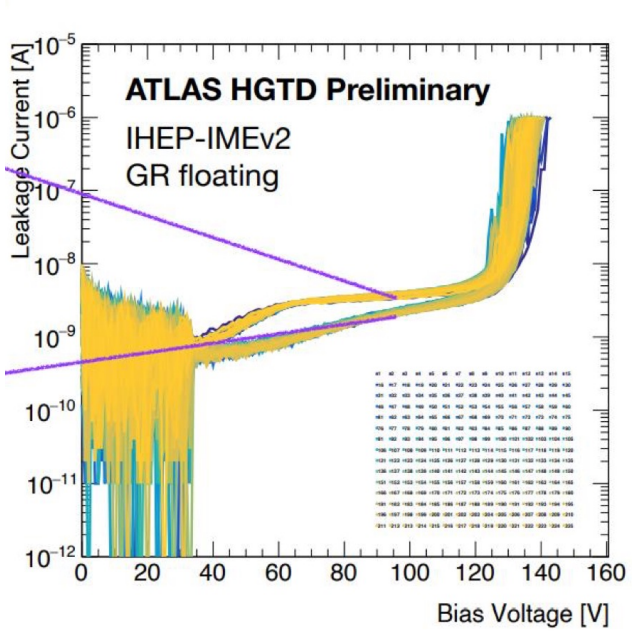
- IHEP developed radiation hard Low Gain Avalanche Detectors (LGAD)
- Developed for ATLAS high granularity timing detector
- LGAD and SiPM has similar structure
  - Good foundation for radiation hard SiPM development

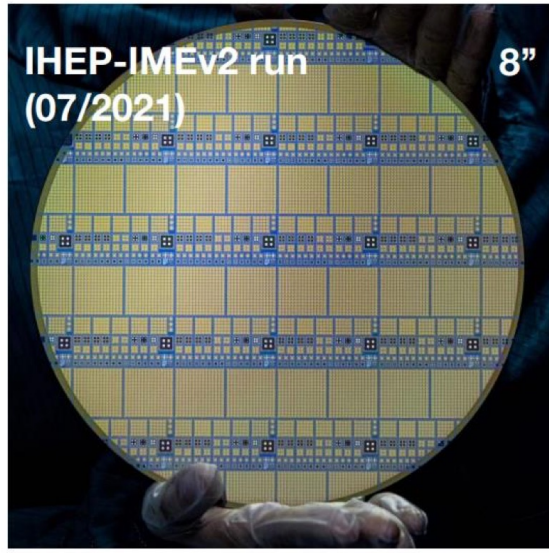


LHC ATLAS experiment
High granularity timing detector



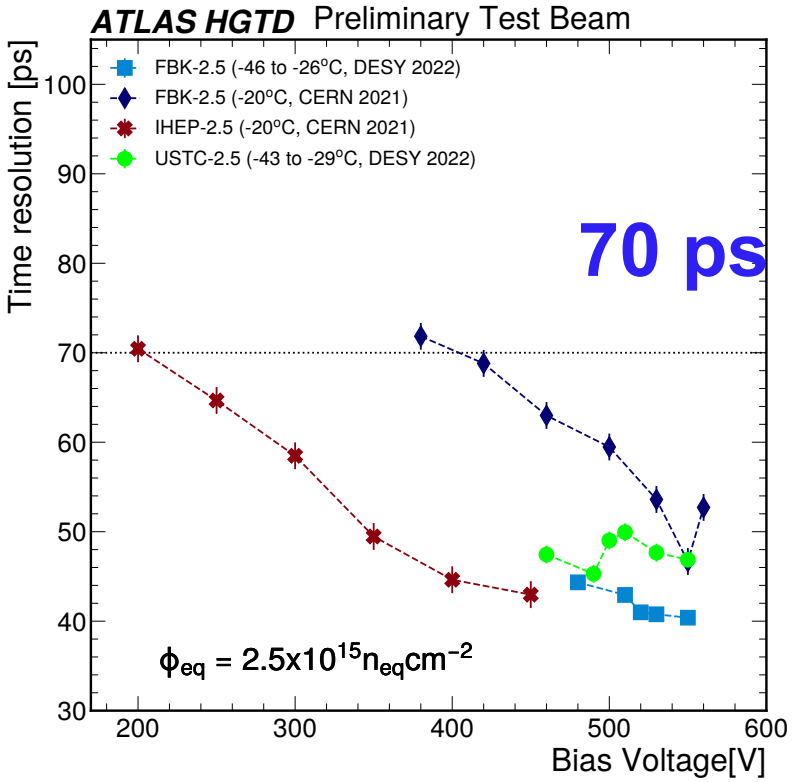
LGAD sensor developed by

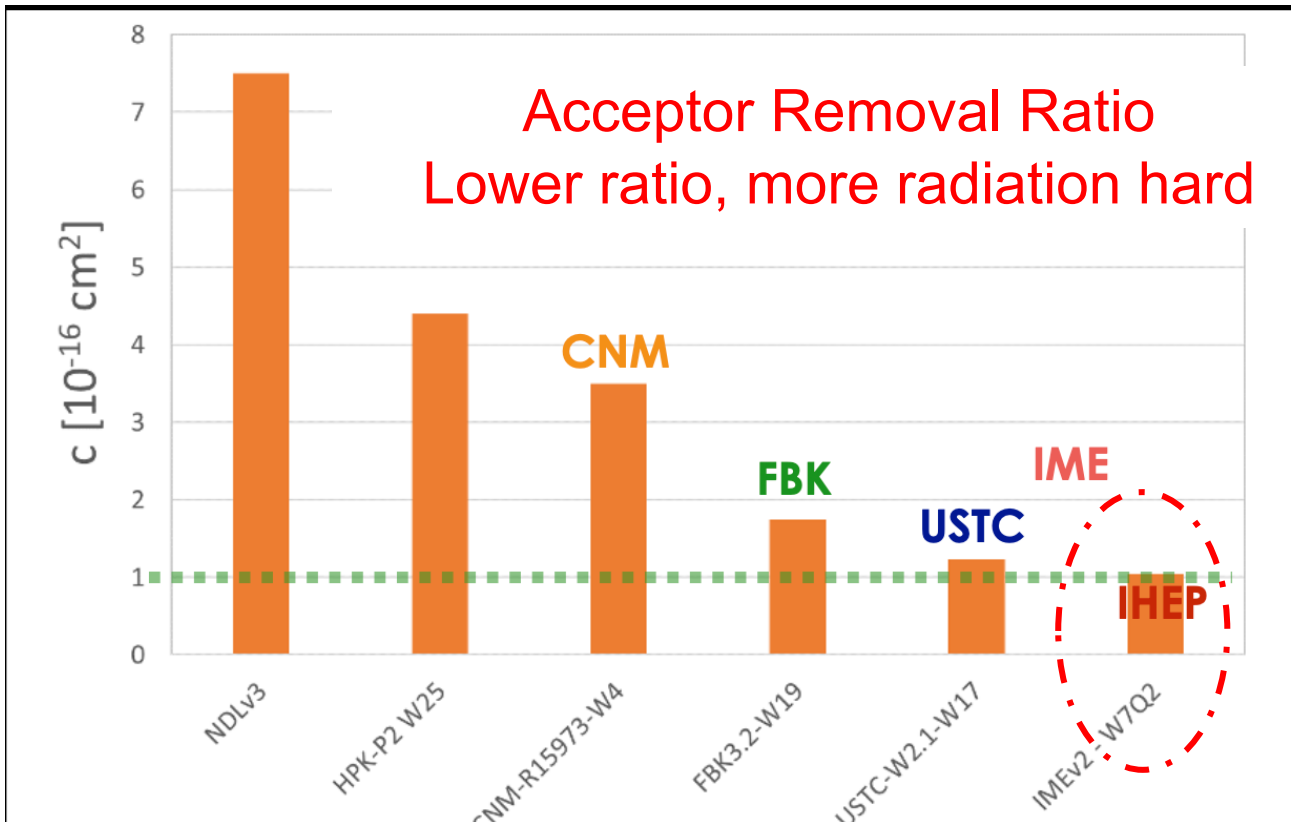




LGAD sensor after Irradiation

- IHEP-IME LGAD with carbon-enriched doping
  - Significantly lower acceptor removal ratio, the most irradiation hard LGAD sensor by far
- After 2.5×10^{15} n_{eq}/cm^2, IHEP LGADs were operated at voltages below 350 V, avoid HV breakdown
  - Test beams at CERN and DESY, confirm the feasibility of LGAD timing detector for HL-LHC
  - IHEP made a leading contribution to radiation hard LGAD sensors

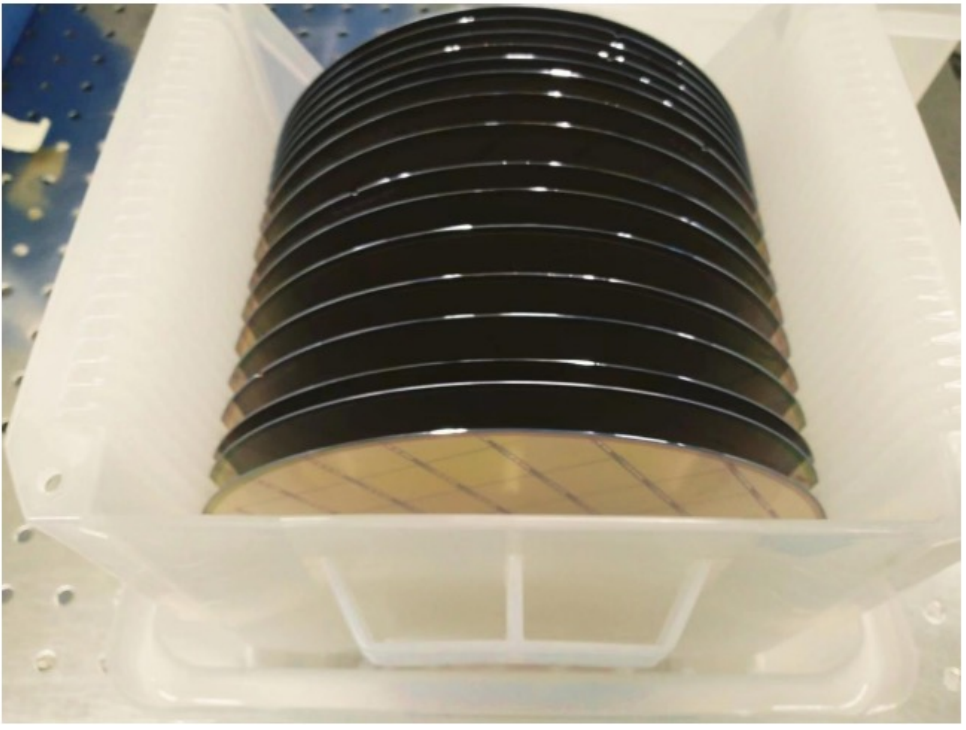


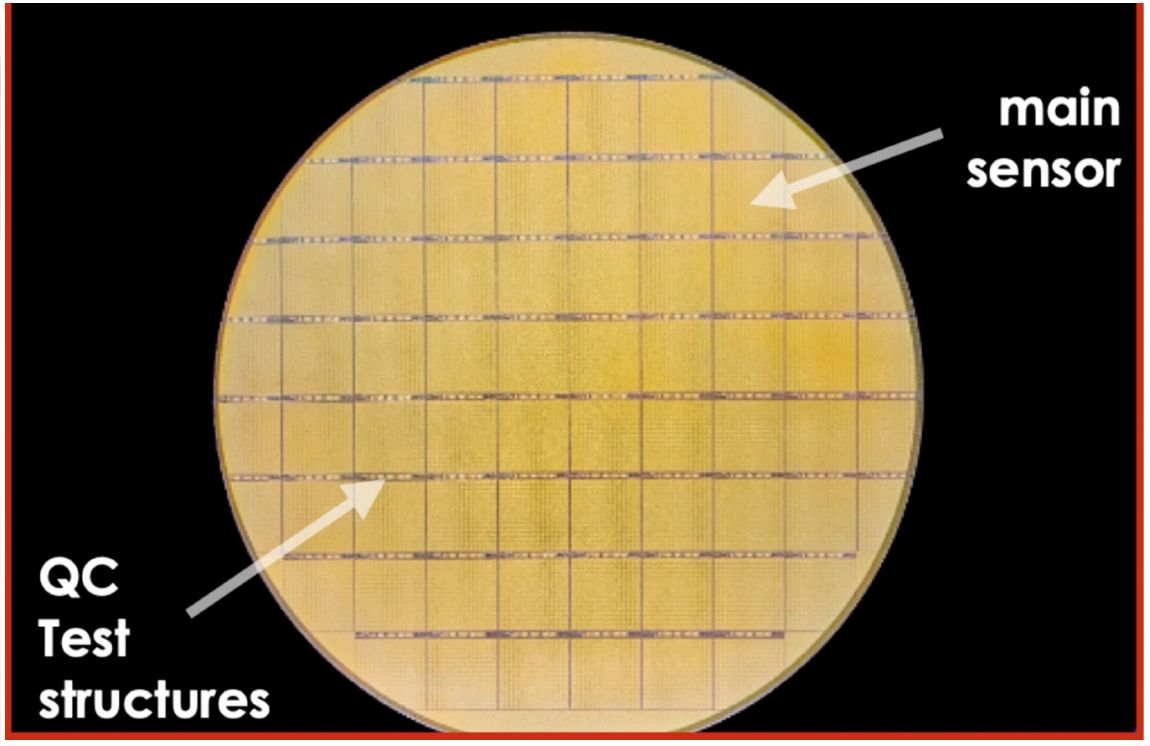


LGAD pre-production for ATLAS experiment

- IHEP-IME sensor Won CERN tendering for ATLAS timing detector
  - 1.7k good sensor fabricated in pre-production, PRR passed at July 25, 2024
  - Production contract signed in Feb 2025.
- The first time that Chinese irradiation hard sensor used at LHC experiment

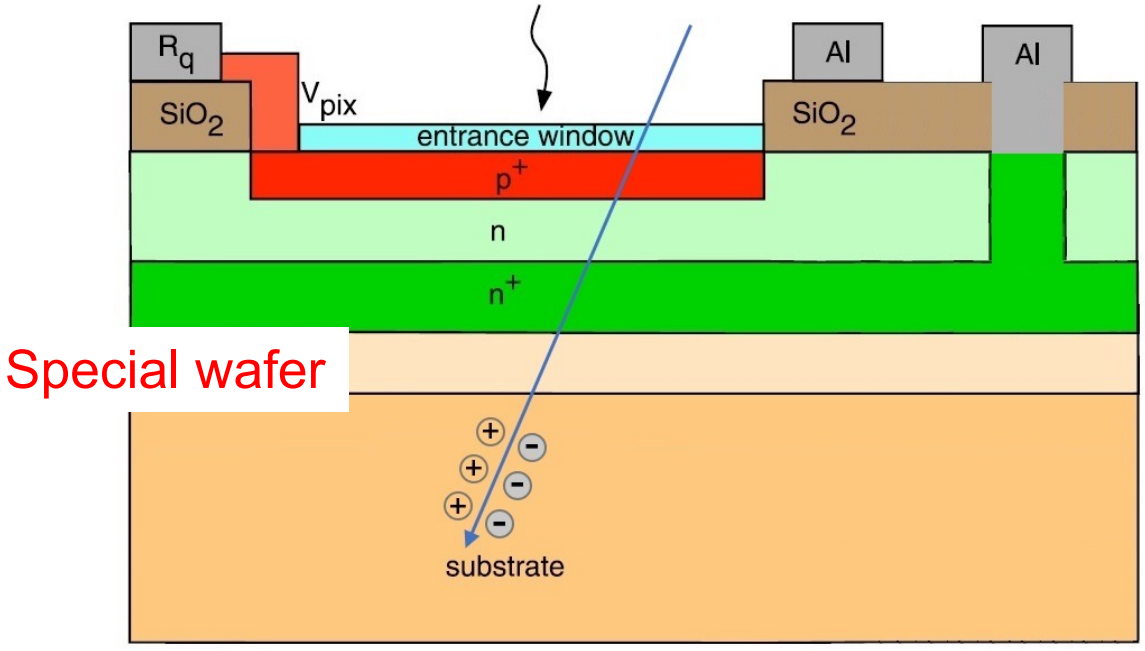
Pre-production LGAD sensors from China





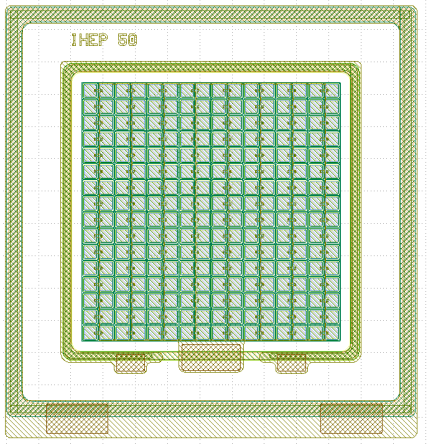
SiPM dark count after irradiation

- Bulk damage after irradiation → dark count increased
- Potential Solution:
  - Design a special wafer to isolate the dark current from bulk damage



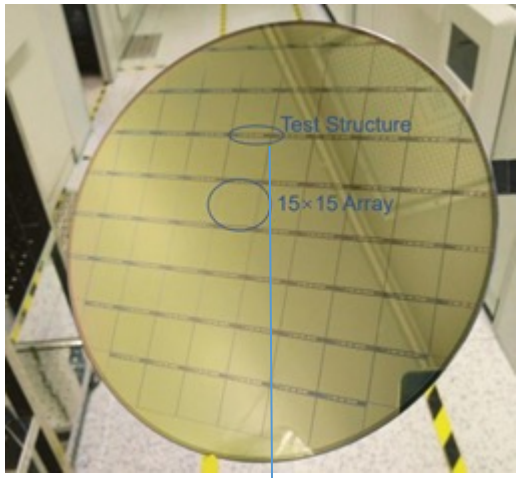
SiPM sample from 1st trial MPW run

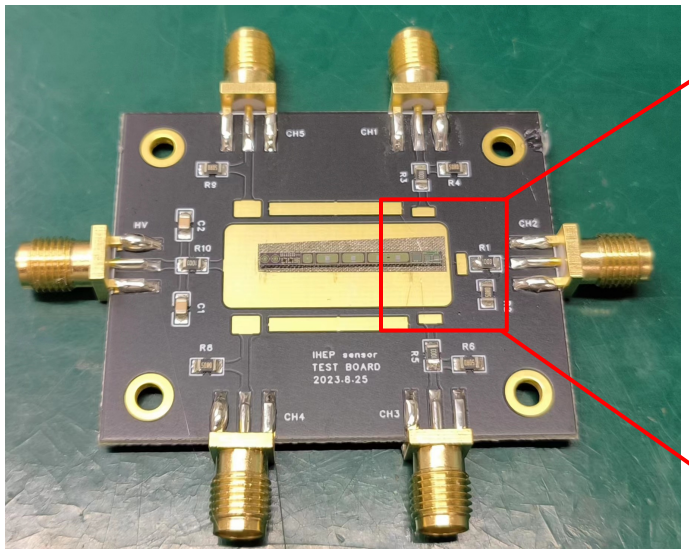
- We prototyped a small SiPM design

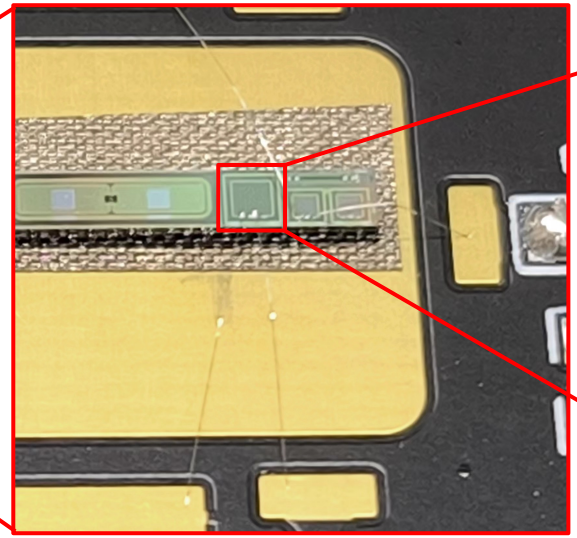


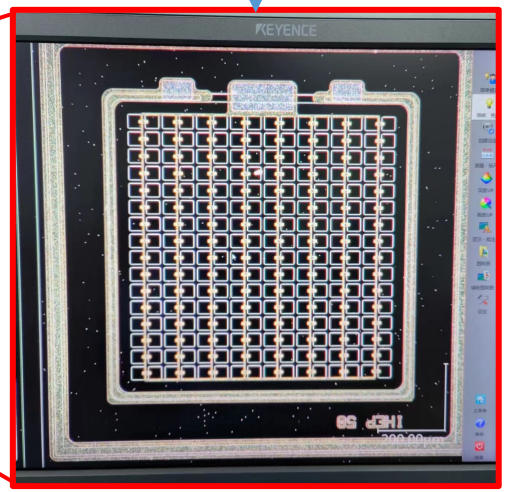
- **Pixel size： 50μm**
- **16 x 16 pixels**

SiPM

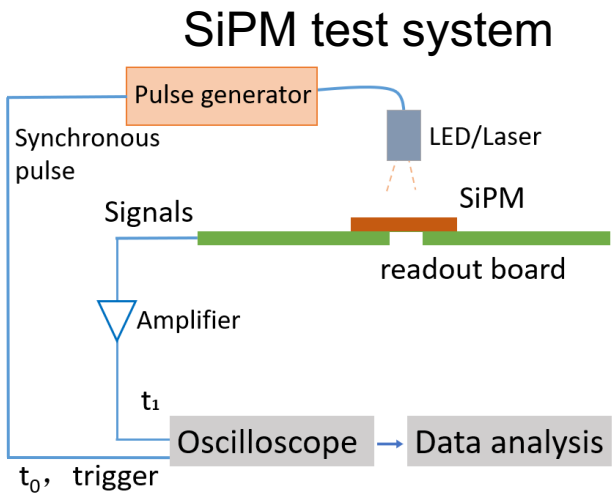


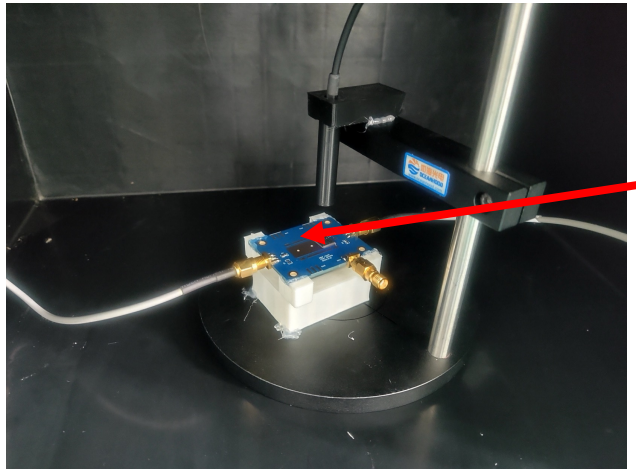


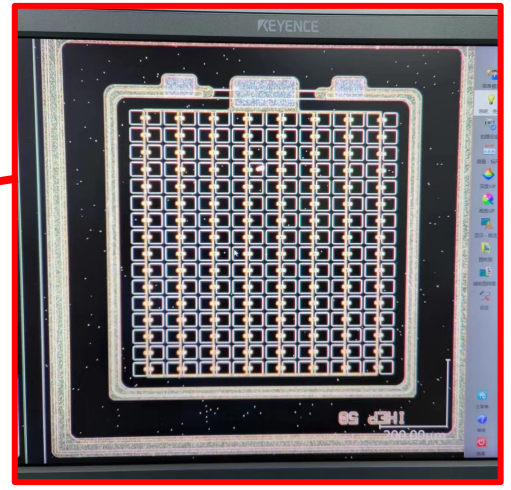


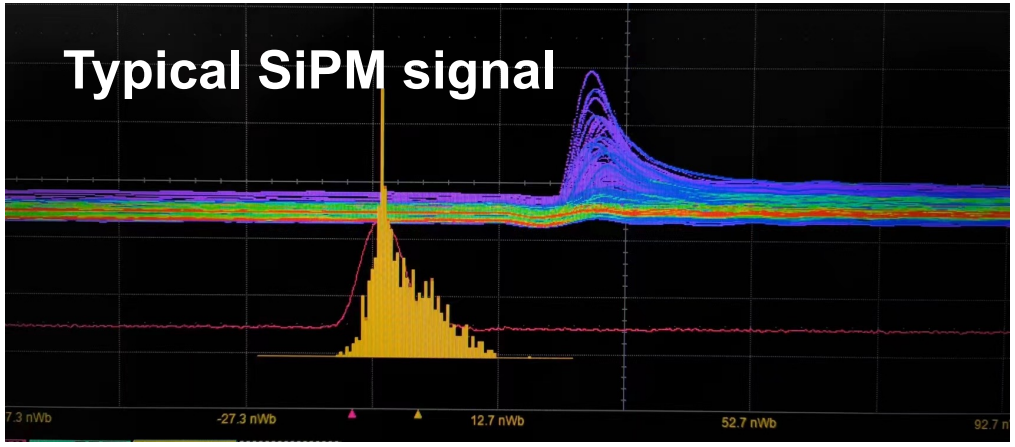


SiPM sample from 1st trial MPW run

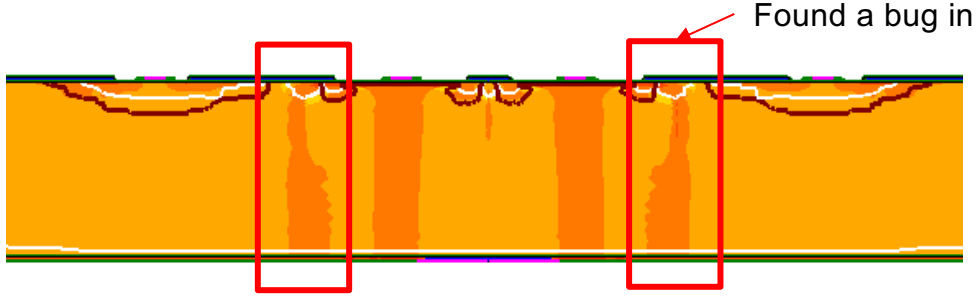








SiPM layout and process has been validated



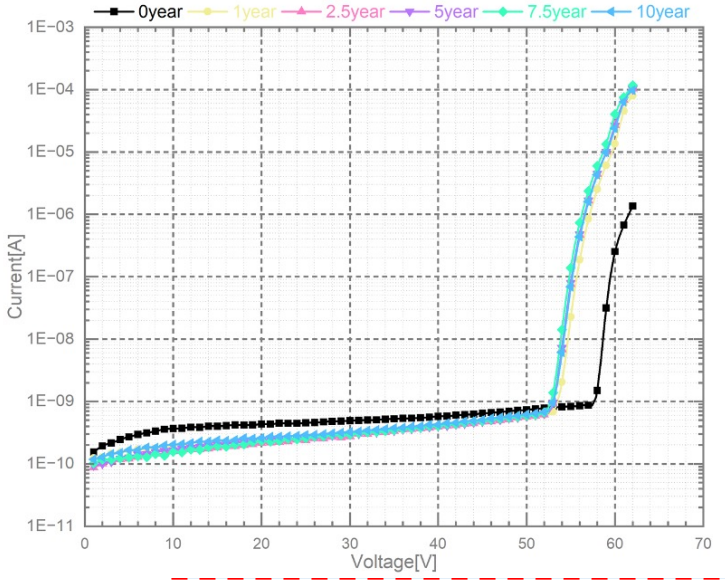
SiPM Leakage current is a bit high in 1st trial run

- **Pstop and GR design has some issue**
- **Optimized the design for engineering runs**

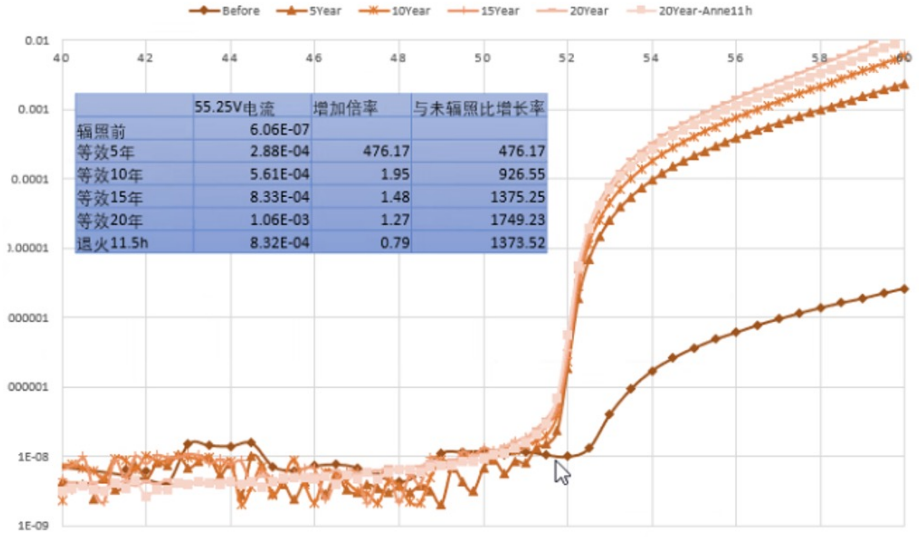
Leakage current of Sipm after irradiation

- First trial of this special wafer idea in LGAD development
- Indication that IHEP Sipm has potential to be irradiation hard
  - After 2E10 n_{eq}/cm2, IHEP SiPM leakage current increased by ~10
  - After 2E10 n_{eq}/cm2, HKP sipm increase by 2-3 order of magnitude

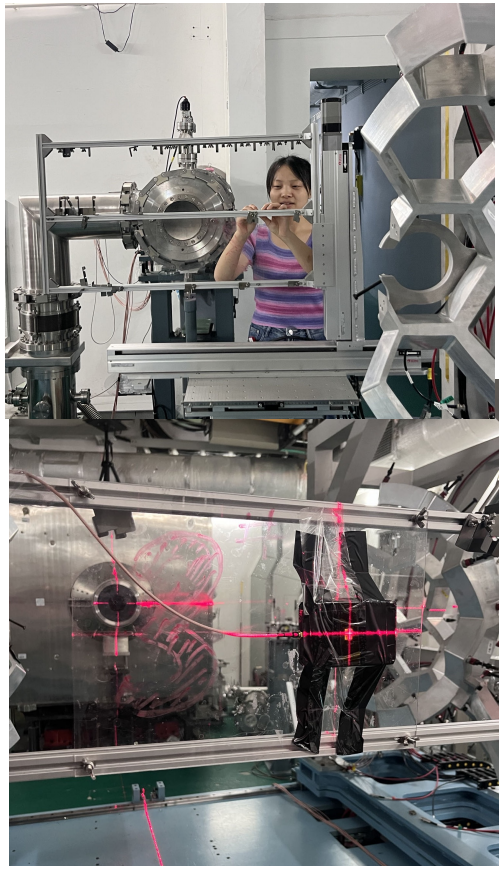
IHEP-SiPM



Hamamatsu -SiPM

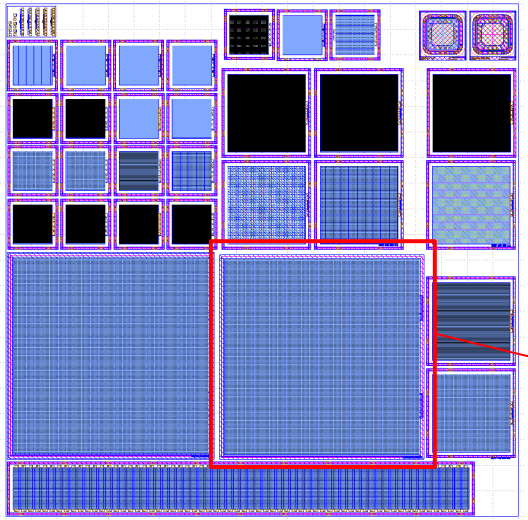


	55.25V电流	增加倍率	与未辐照比增长率
辐照前	6.06E-07		
等效5年	2.88E-04	476.17	476.17
等效10年	5.61E-04	1.95	926.55
等效15年	8.33E-04	1.48	1375.25
等效20年	1.06E-03	1.27	1749.23
退火11.5h	8.32E-04	0.79	1373.52



Dedicated SiPM engineering run

- Dedicated radiation hard SiPM run will be submitted next month
  - Various SiPM size: 1*1mm, 3*3mm, 5*5mm
  - Various Pixel size: 10um ,20um, 50um

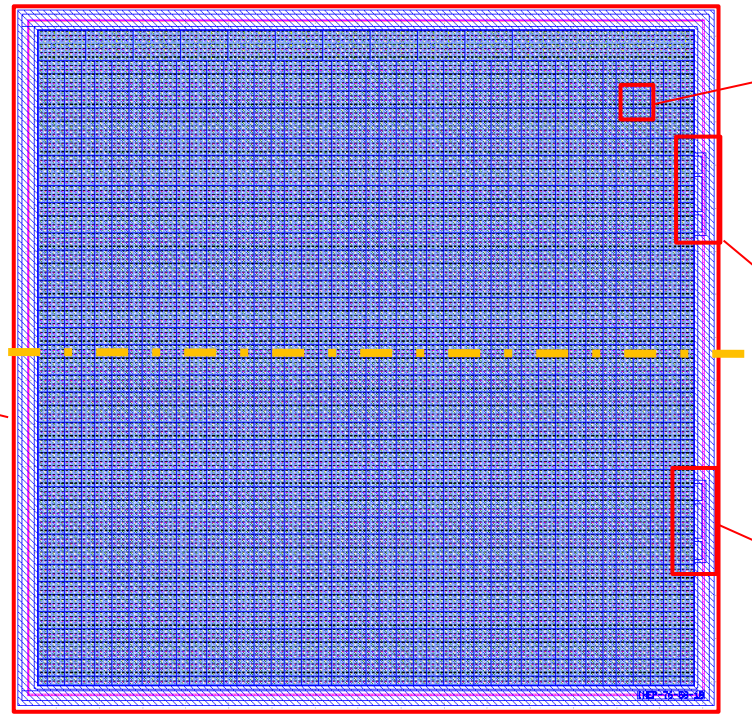


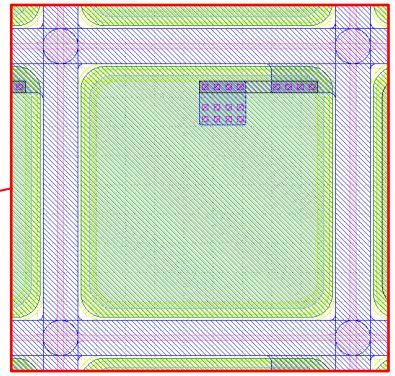
IHEP SiPM 版图

LACT 专用 SiPM:

- **7.6 mm X 7.6 mm**
- **152 x 152 pixels**
- **Pixel size： 50um**
- **Fill factor 64%**

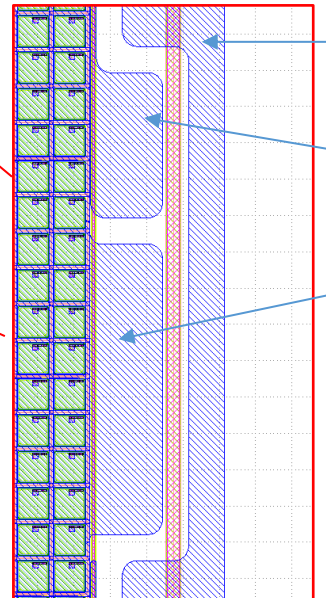
SiPM designed for LACT





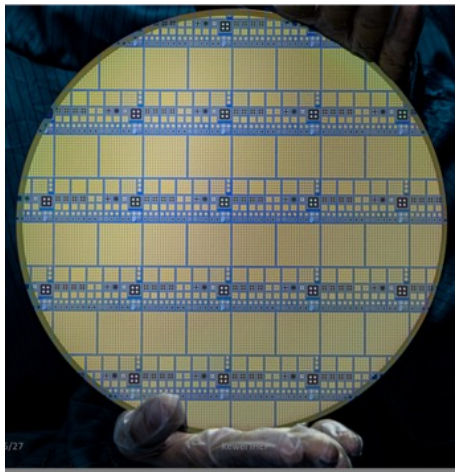
单像素参数:

- Pixel size 50um
- Quenching resistance 200KΩ

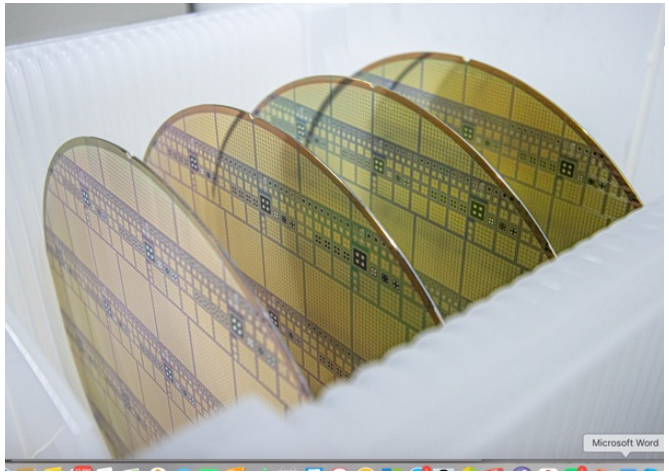


Time line for radiation hard SiPM

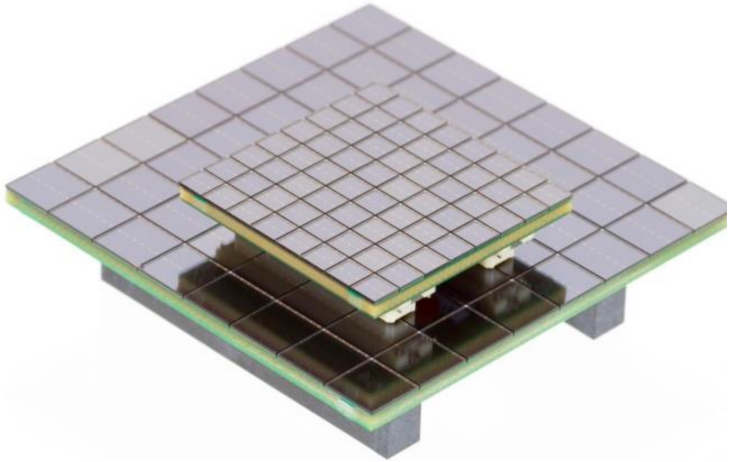
- 2025 :SiPM irradiation hard design validated in LGAD engineering run
  - Two type of radiation hard Sipm
  - ECAL : Small pixel size (6um*6um), large dynamic range
  - HCAL: high PDE Sipm (PDE>60-70%)
- 2026: built prototype for ECAL and HCAL



仿真与探索各种工艺参数



SiPM的多次流片，确定工艺参数



2023 2024 2025

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
  - First domestic Radiation hard silicon sensor used in LHC experiment
- Radiation SiPM R & D project
  - 1st trial run has been submitted, and preliminary result obtained
  - Dedicated engineering run by this year
  - Integrate into ECAL and HCAL prototyping in 2026