Radiation hard SiPM development

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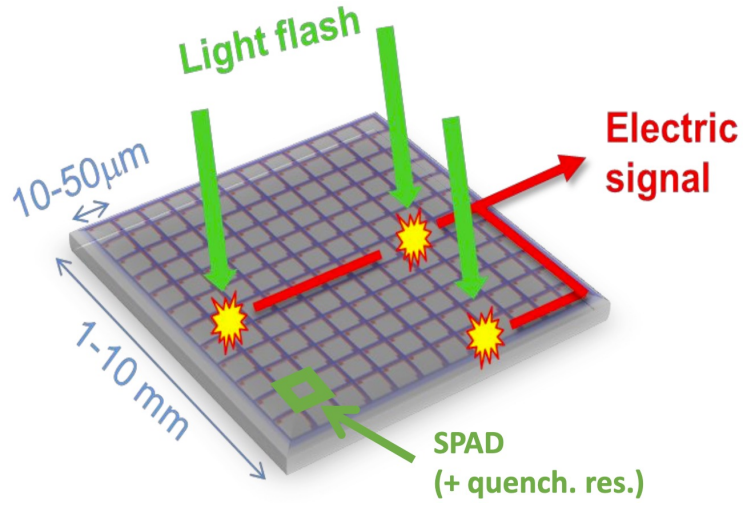
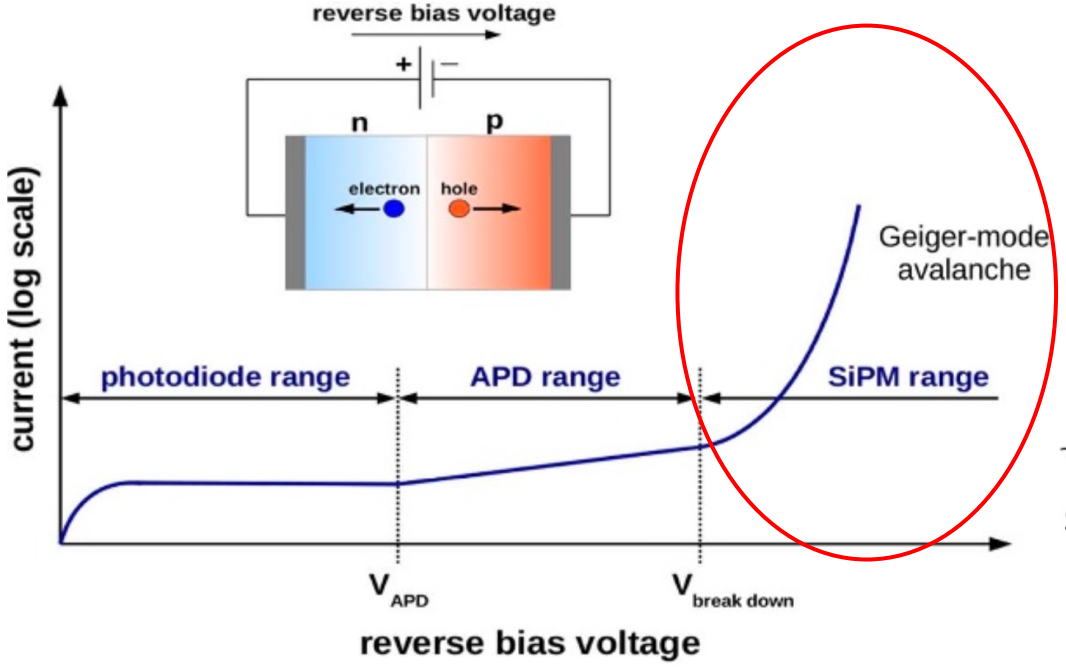
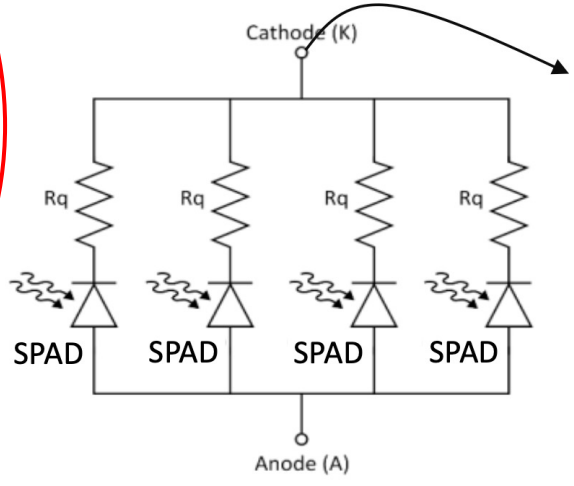
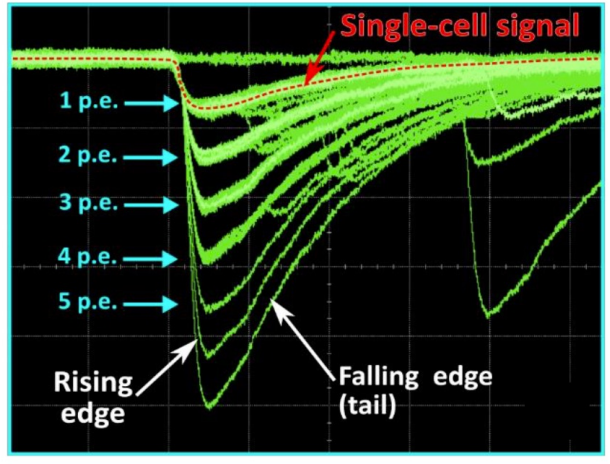
SiPM introduction

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





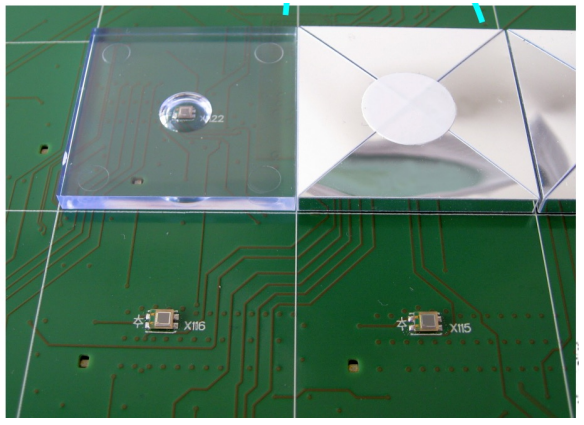




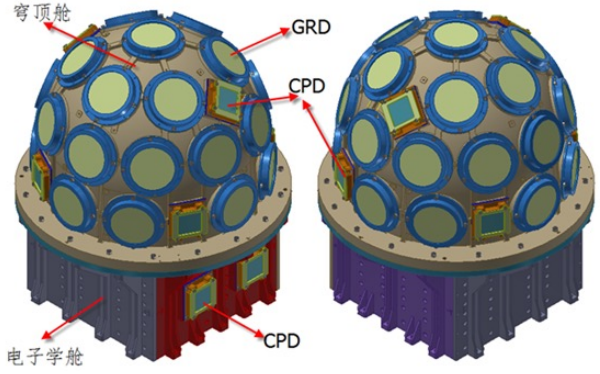
Radiation SiPM application

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

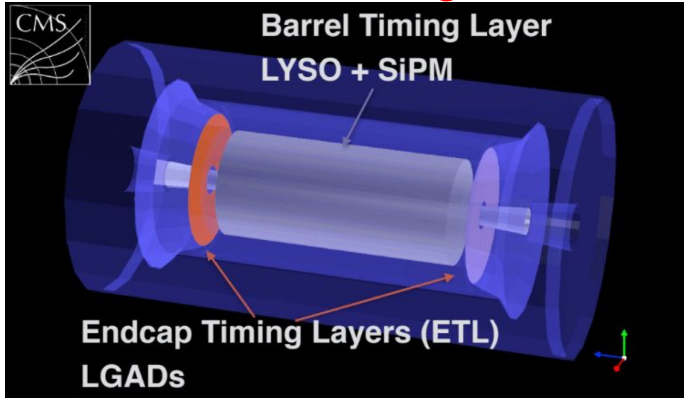
CEPC PFA calorimeter prototype



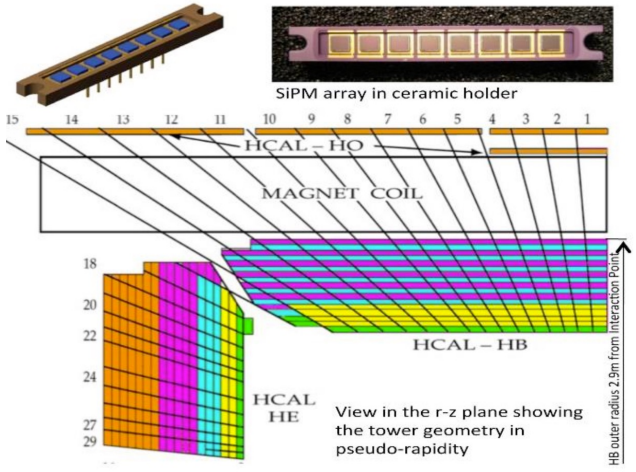
GECAM



CMS MIP timing detector



CMS Calorimeter



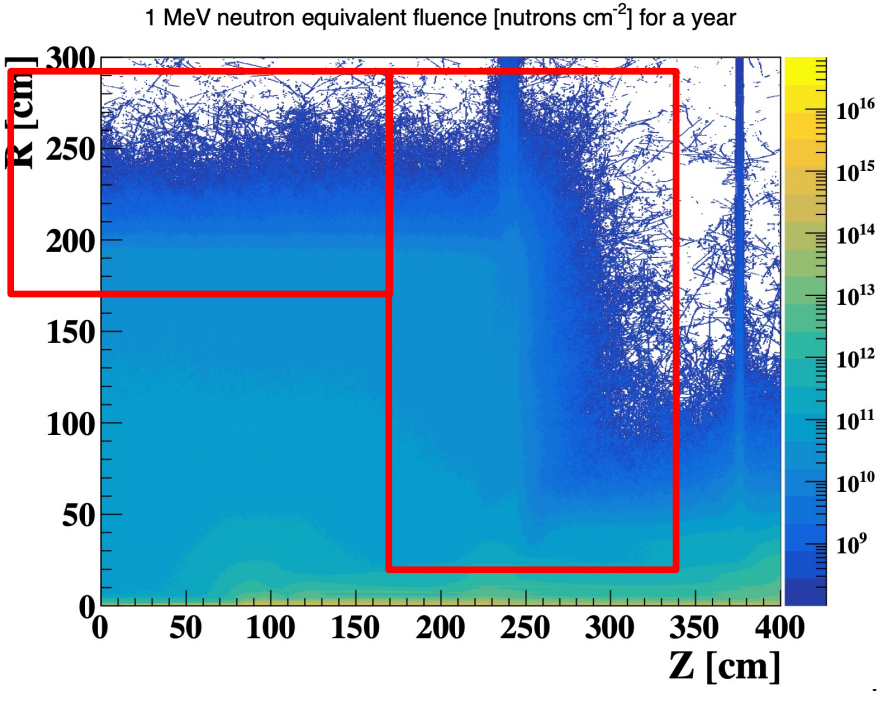
Example: CMS – ECAL upgrade

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

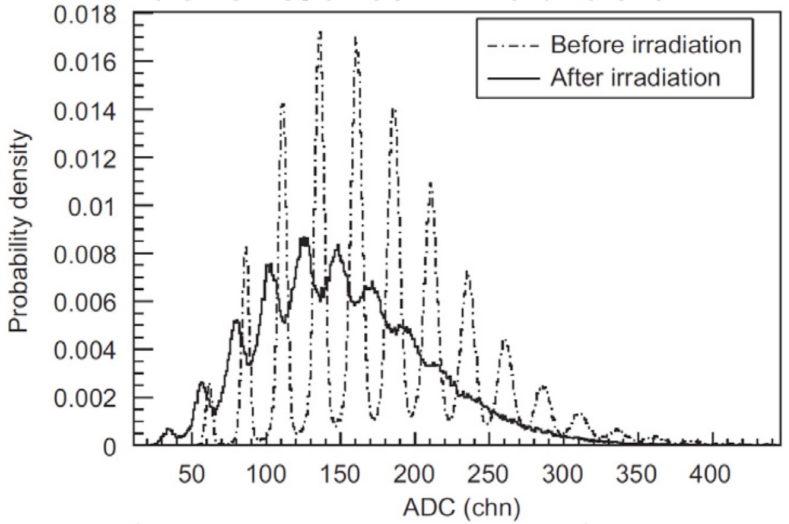
Fluence in ZH run (240GeV)



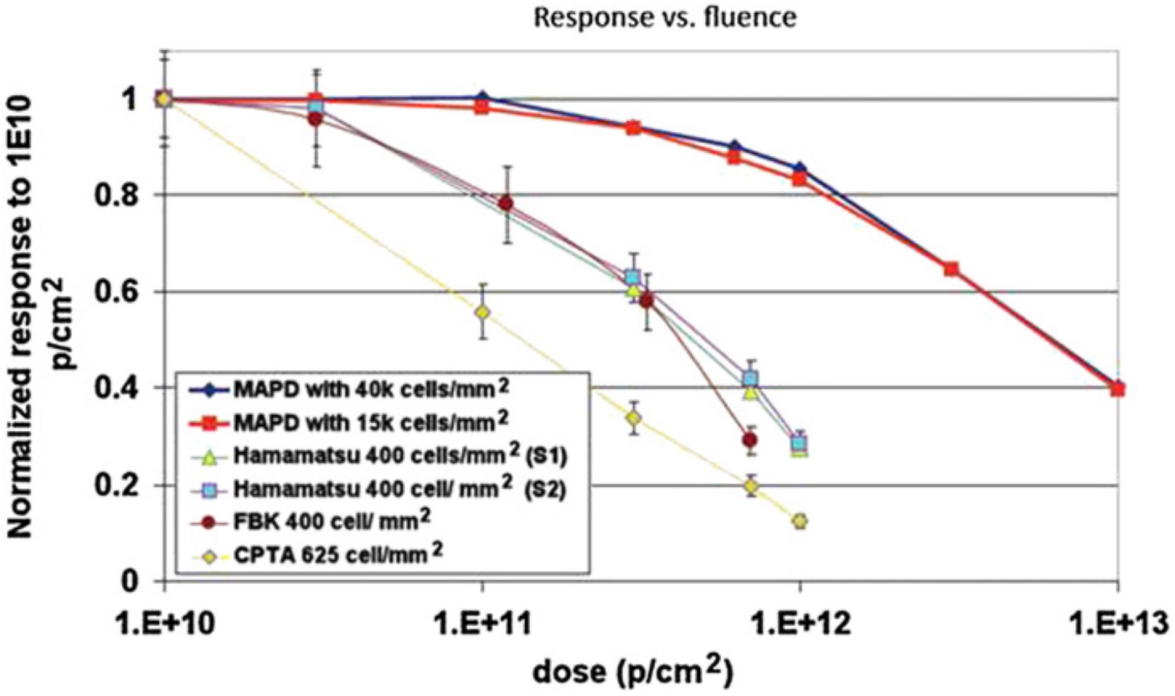
SiPM Radiation hardness

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

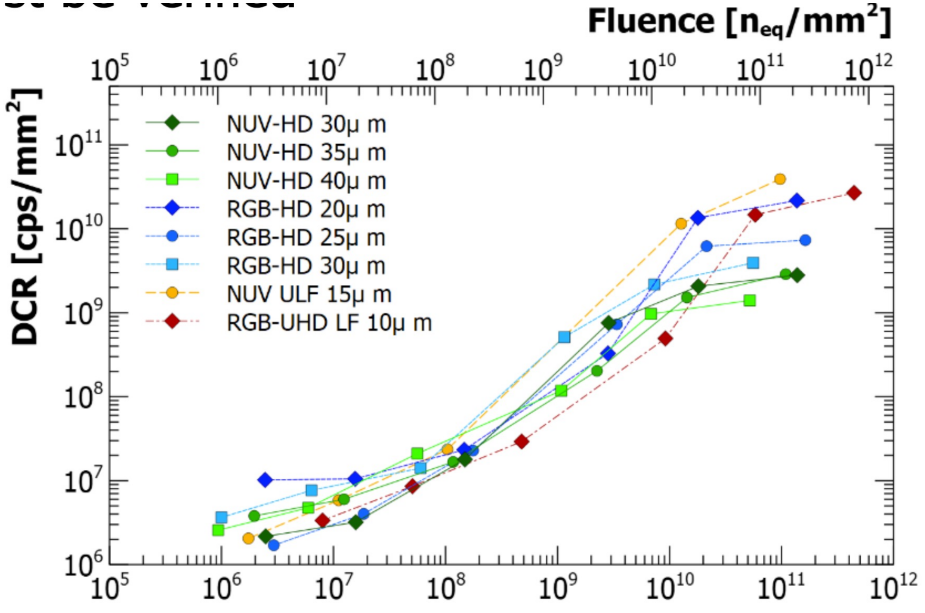
Energy resolution before/after irradiation



SiPM gain VS Dose

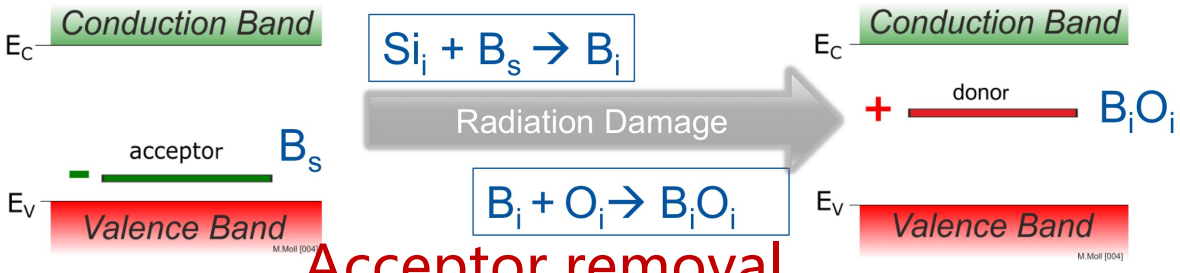


SiPM dark count VS Fluence

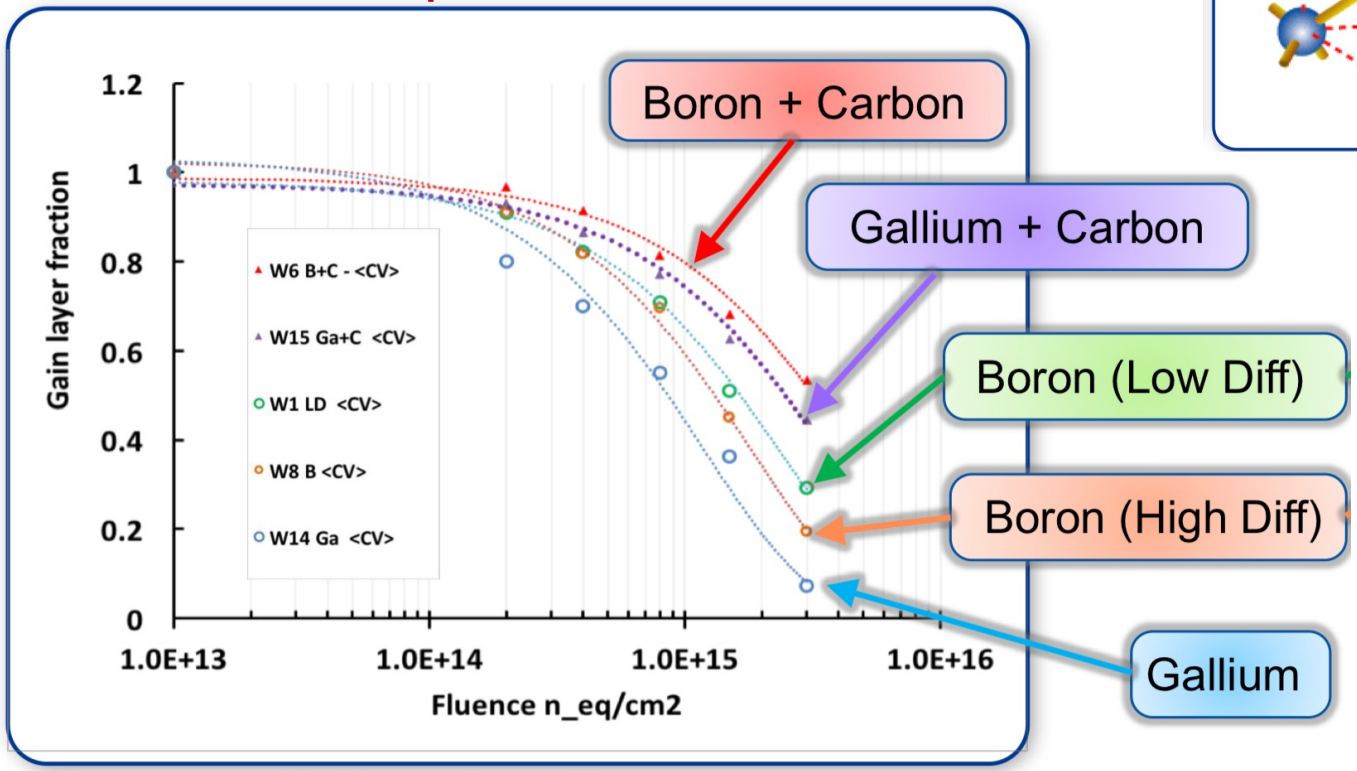


SiPM radiation hardness theory

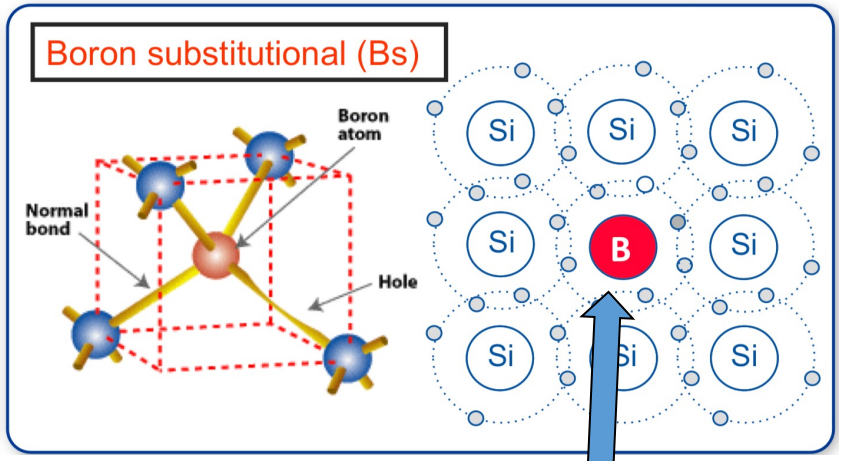
- SiPM signal gain decreased after irradiation （ p+ acceptor removal ）

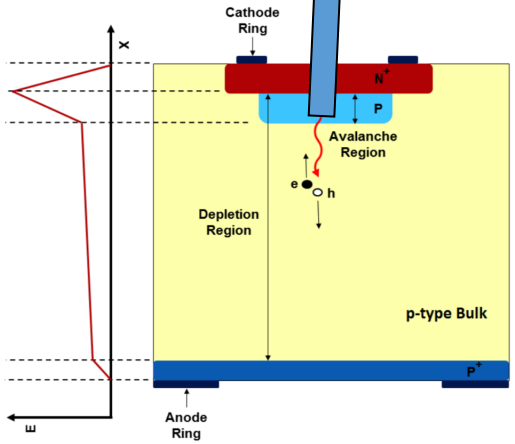


Acceptor removal



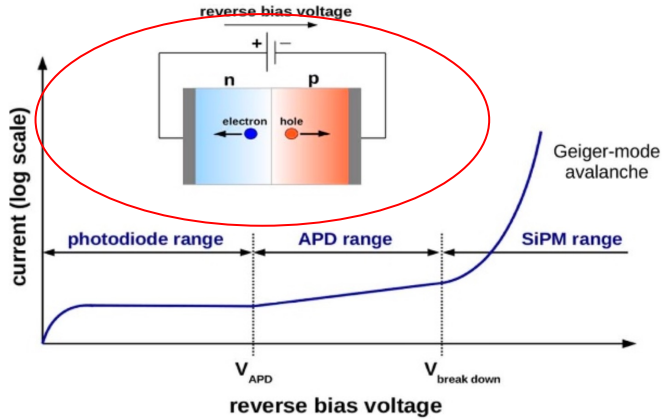
[G.Paternoster, FBK, Trento, Feb.2019]



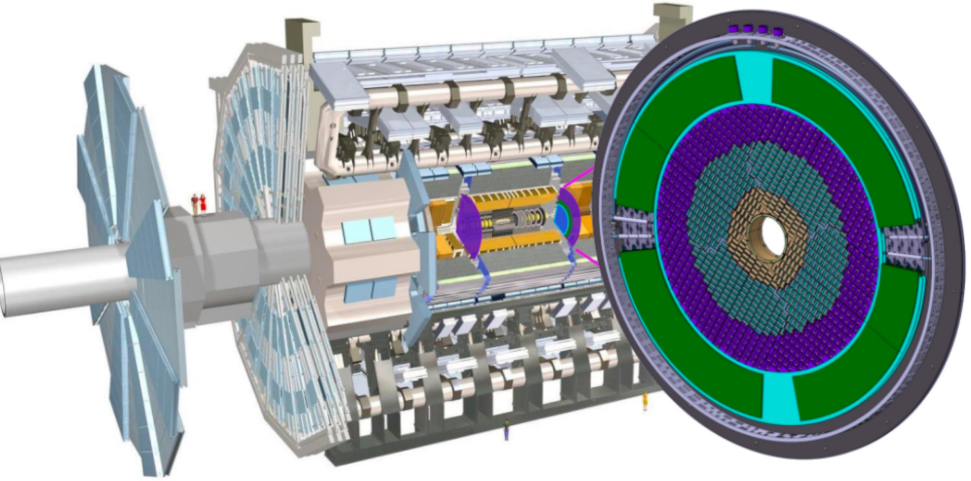


Radiation hard Low Gain Avalanche Detectors (LGAD)

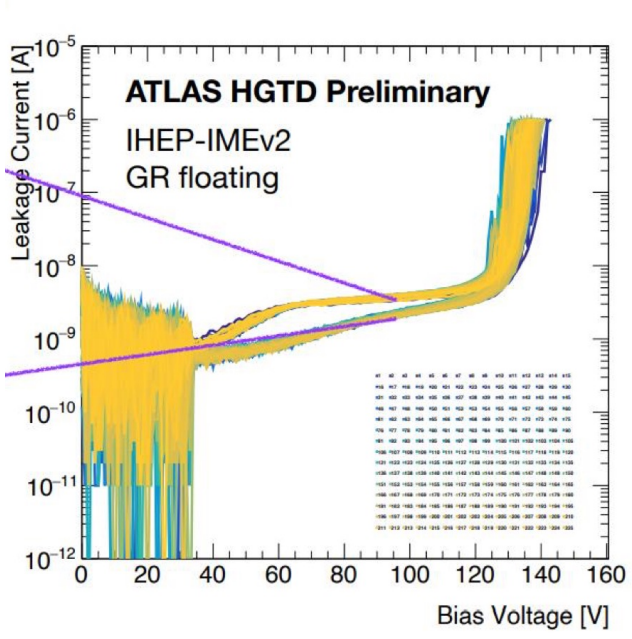
- IHEP developed radiation hard Low Gain Avalanche Detectors (LGAD)
- Developed for ATLAS high granularity timing detector
- LGAD and SiPM has similar structure
  - Good foundation for radiation hard SiPM development

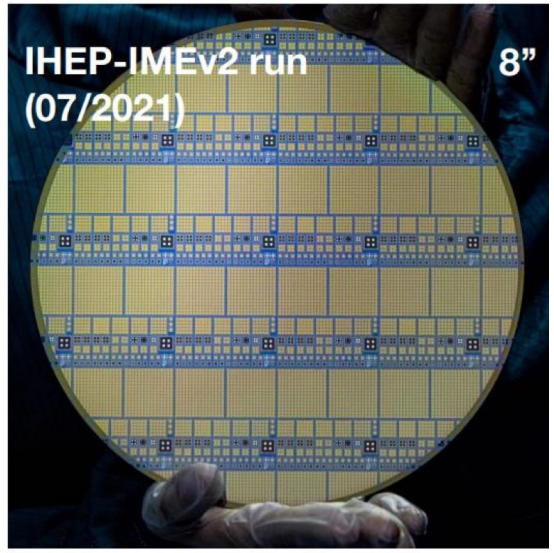


LHC ATLAS experiment
High granularity timing detector



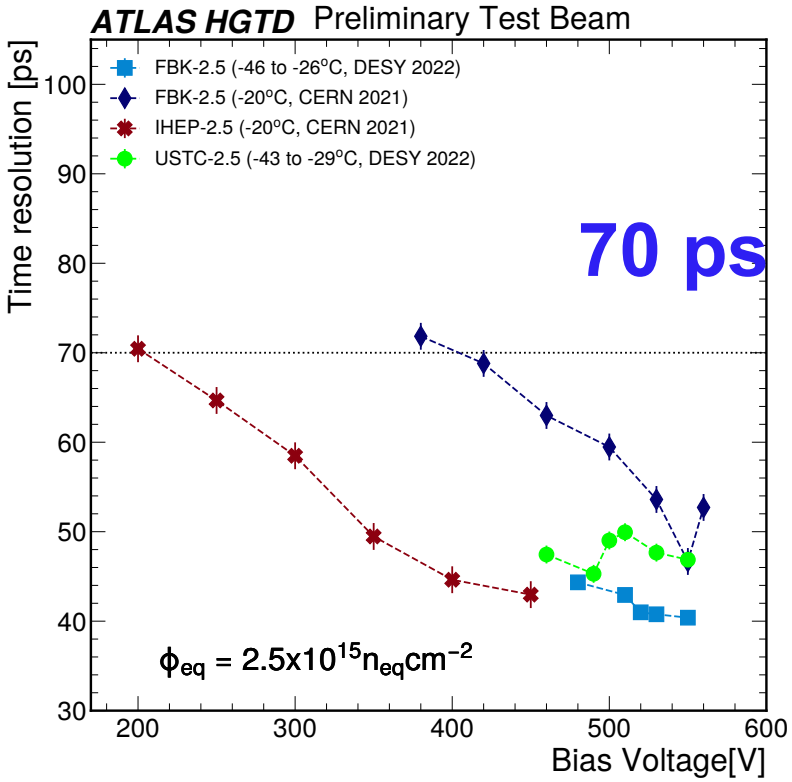
LGAD sensor developed by

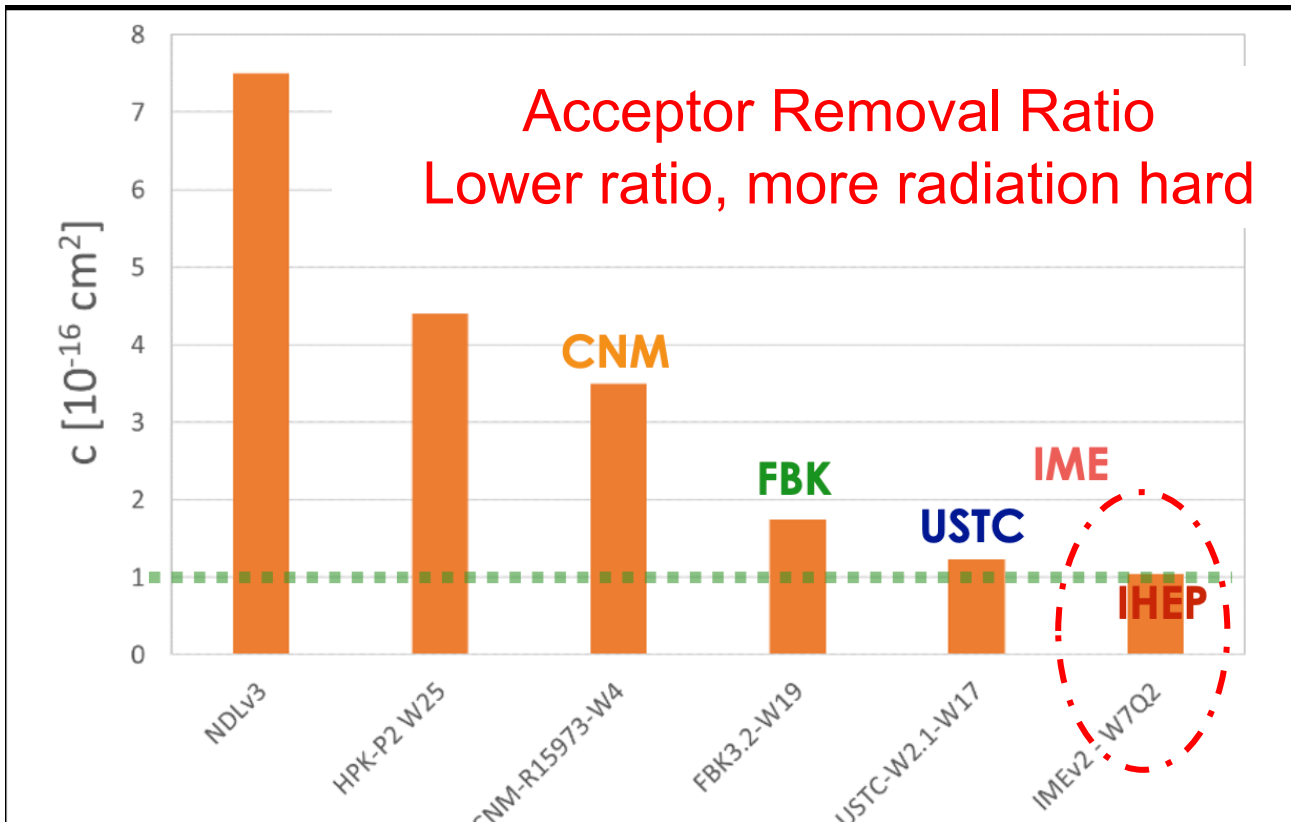




LGAD sensor after Irradiation

- 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

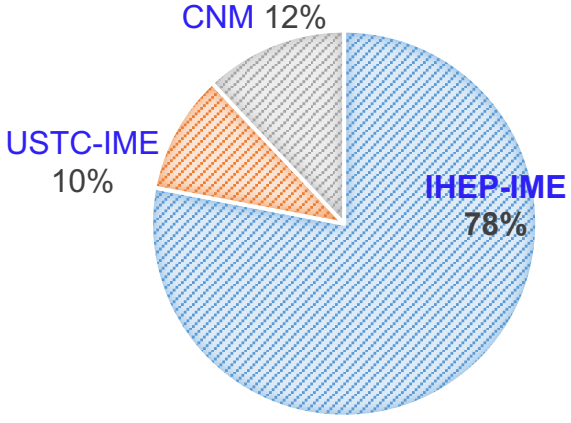




LGAD pre-production for ATLAS experiment

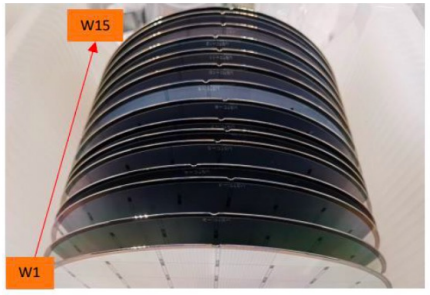
- IHEP-IME sensor Won CERN tendering for ATLAS timing detector
  - IHEP-IME: 78% (54% from CERN tendering+24% in-kind contribution)
  - CNM: 12% in-kind contribution
  - USTC-IME: 10% in-kind contribution
- The first time that Chinese irradiation hard sensor used at LHC experiment

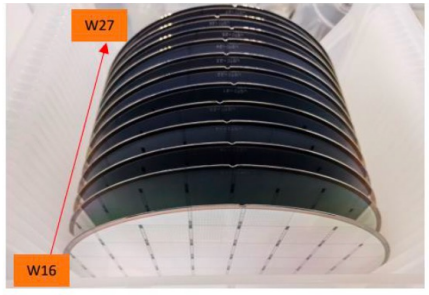
Share of production between vendors

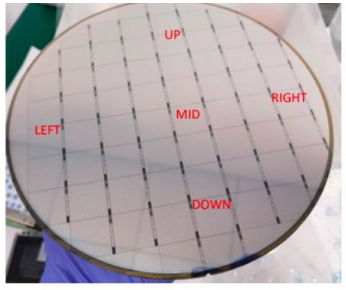


Pre-production LGAD sensors from China

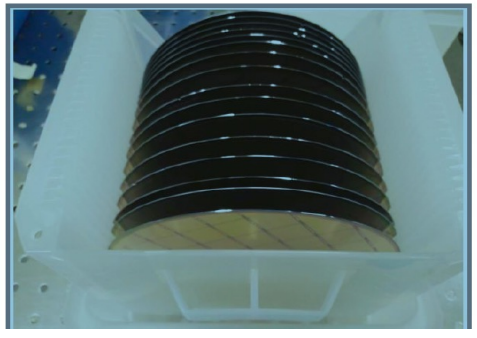
USTC-IME
Pre-production

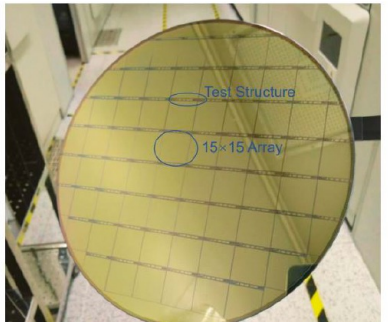






IHEP-IME
Pre-production

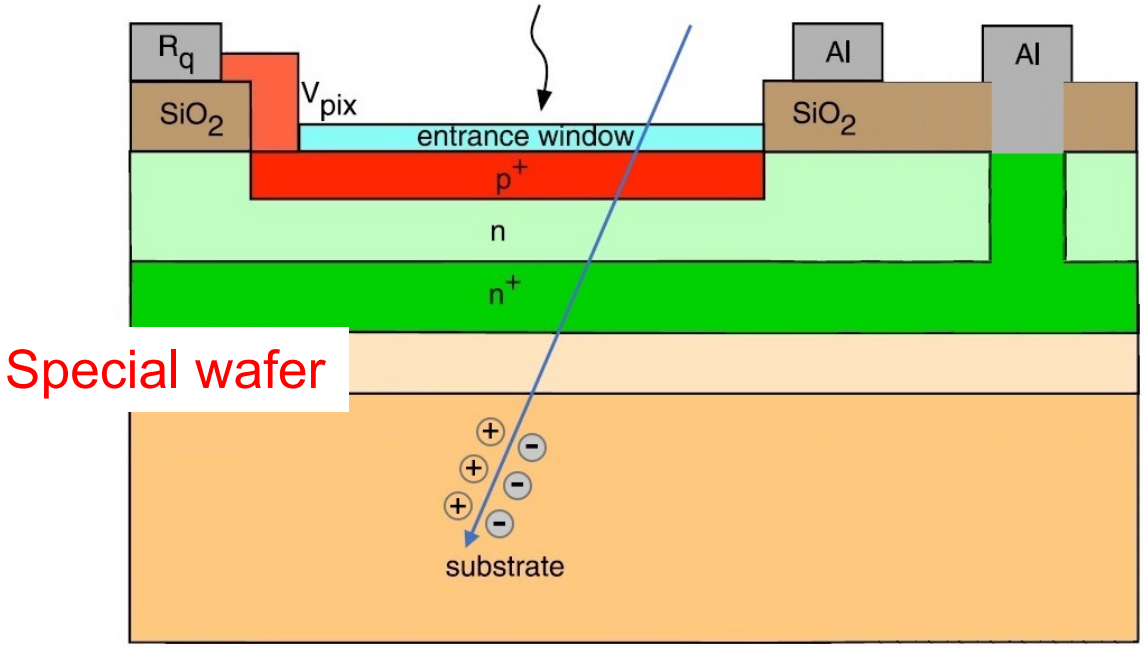




- 15x15 array sensors and test structure
- 52 sensors on one 8inch wafer

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

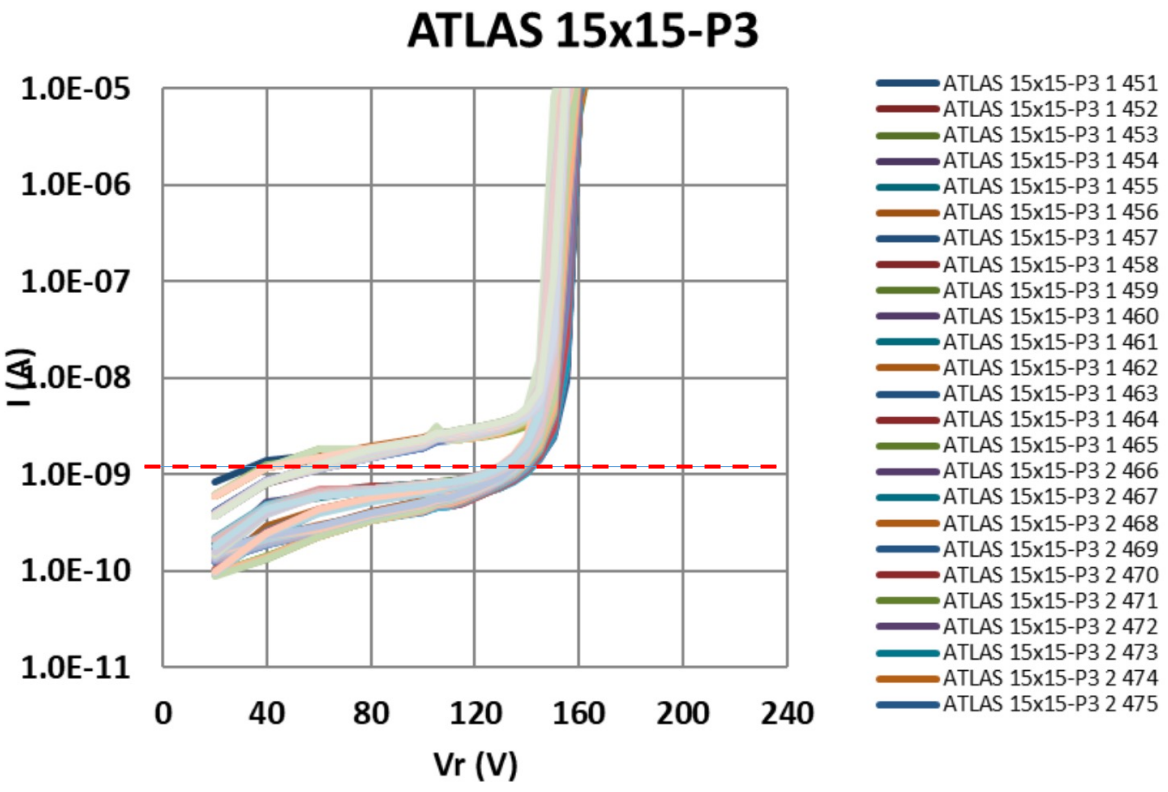


Leakage current of LGAD before irradiation

- First trial of this special wafer idea in LGAD development
  - The leakage current of IHEP LGAD is low before irradiation

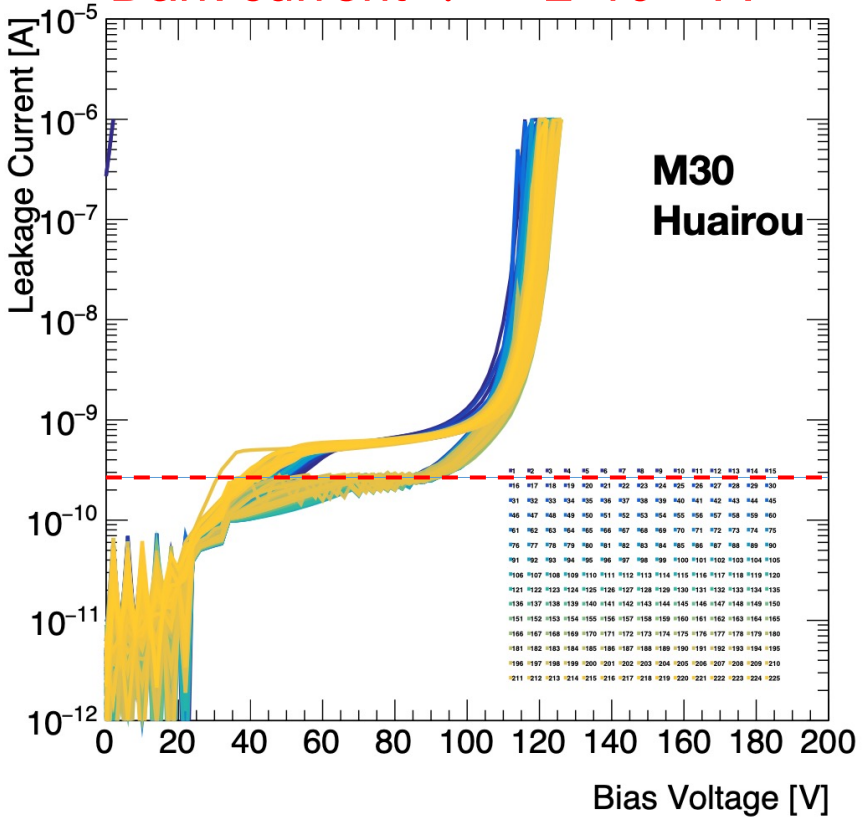
Bias voltage Vs Dark current (HPK LGAD)

Dark current ： ~ 10^{-9} A



Bias voltage Vs Dark current (IHEP LGAD)

Dark current ： ~ 2*10^{-10} A

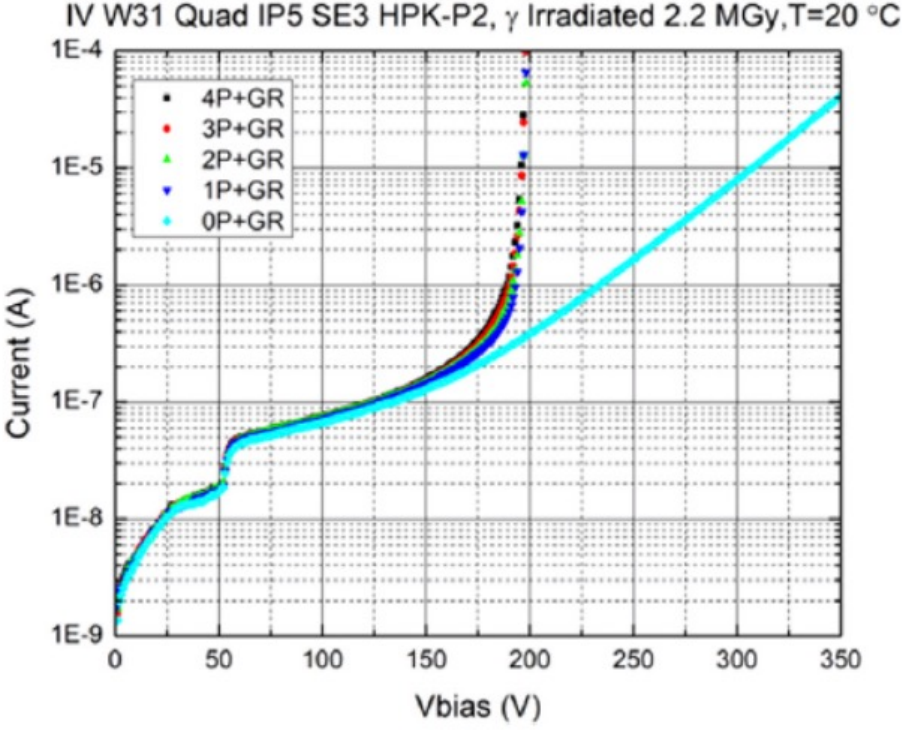


Leakage current of LGAD after irradiation

- After 200 MRad TID dose
  - IHEP LGAD showed a low leakage current
  - Validate the idea of special wafer

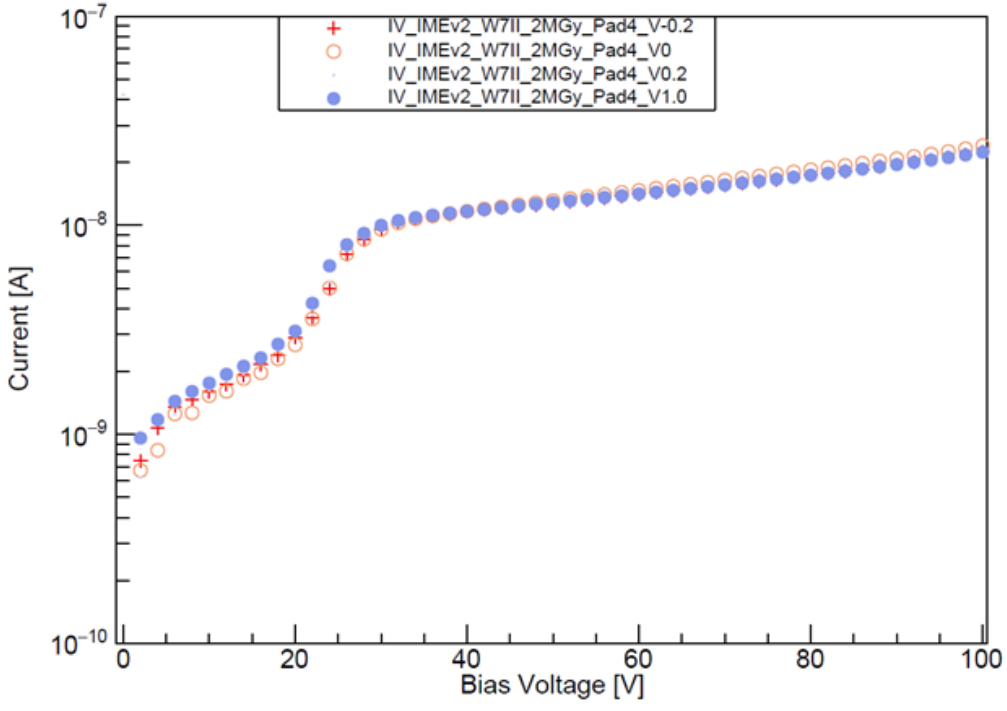
Bias voltage Vs Dark current (HPK LGAD)

Dark current ： ~ 10^{-7} A



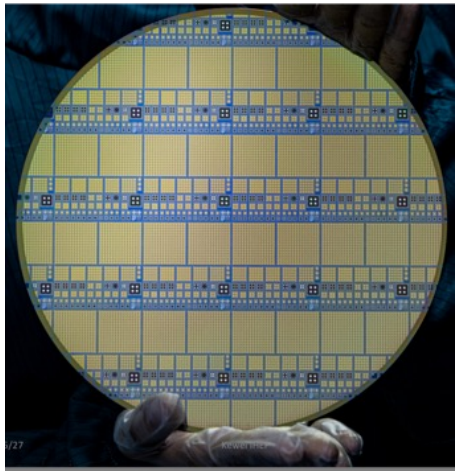
Bias voltage Vs Dark current (IHEP LGAD)

Dark current ： ~ $2*10^{-8}$ A

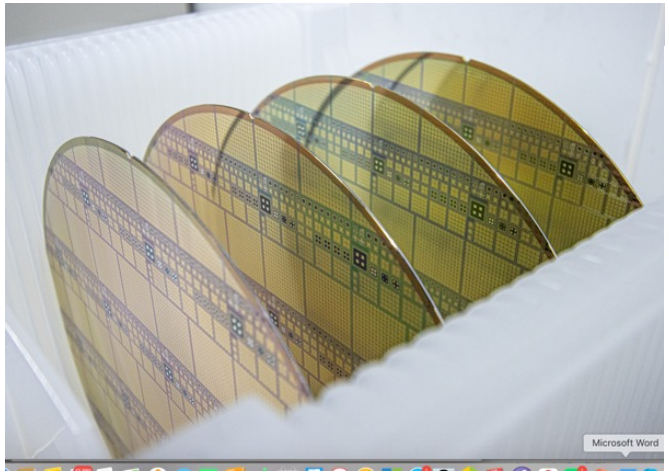


Time line for radiation hard SiPM

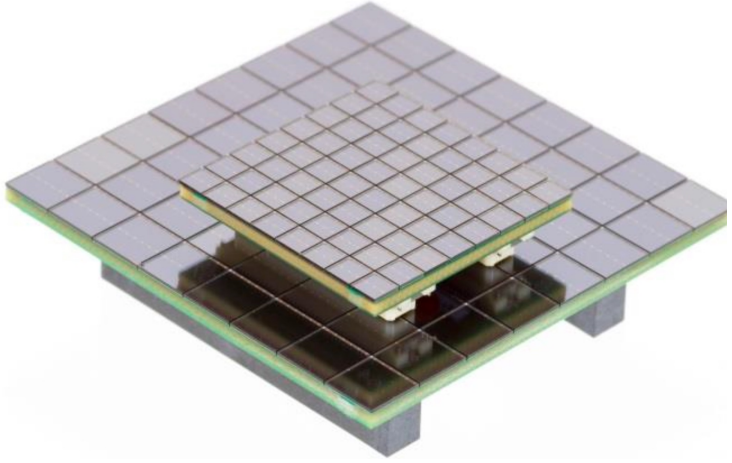
- 2023 1st half :SiPM irradiation hard design validated in LGAD engineering run
- 2023 2nd half ： 1st Dedicated SiPM engineering run submission
- 2024: 1~2 more dedicated SiPM engineering run
- 2025: built modules or working device based on radiation hard SiPM



仿真与探索各种工艺参数



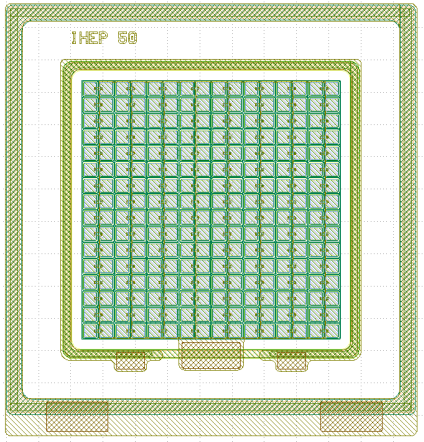
SiPM的多次流片，确定工艺参数



2023 2024 2025

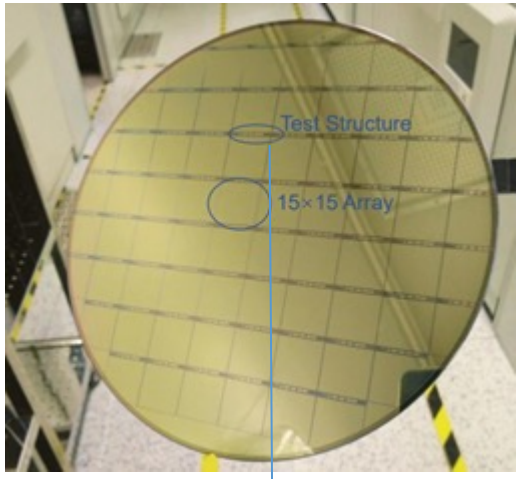
SiPM sample from 1st trial MPW run

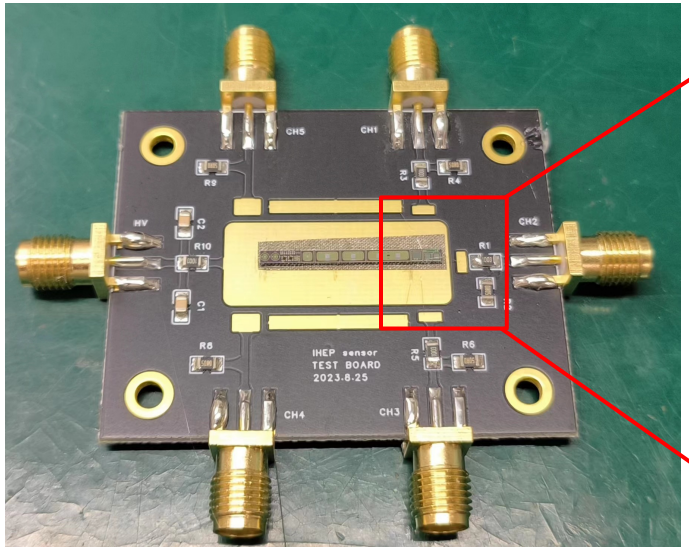
- We put a small SiPM design on LGAD prod

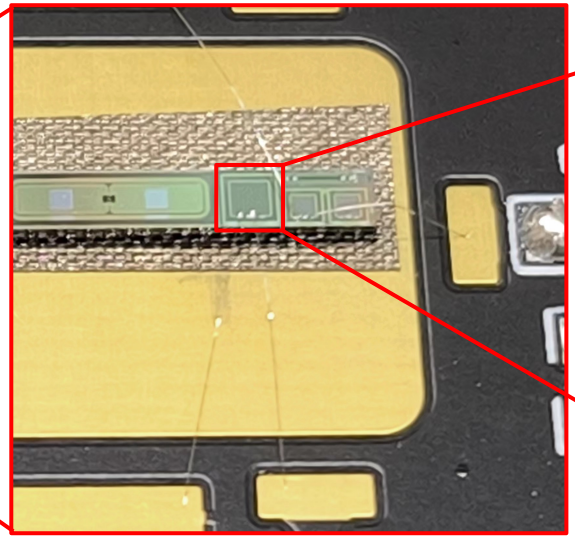


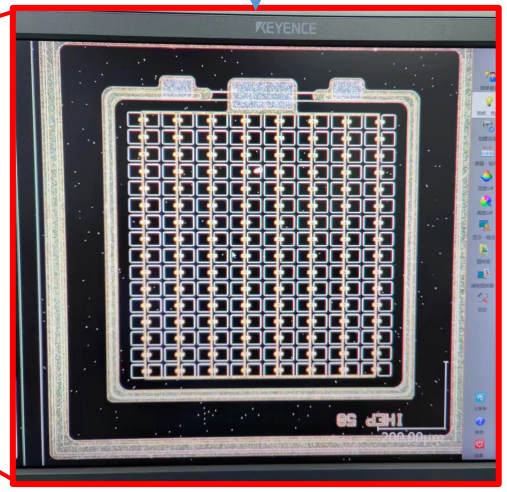
- **Pixel size： 50μm**
- **16 x 16 pixels**

SiPM

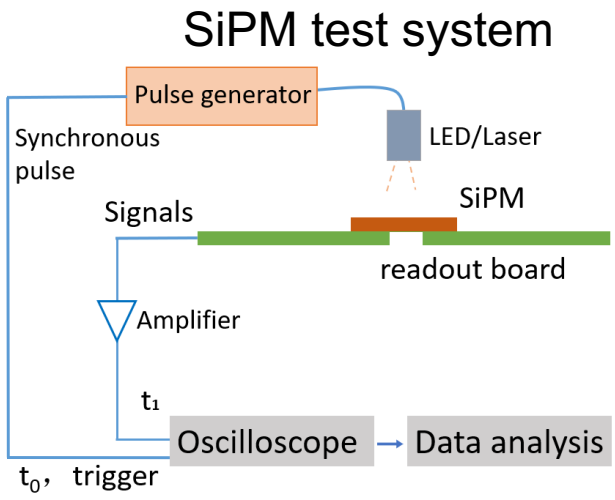


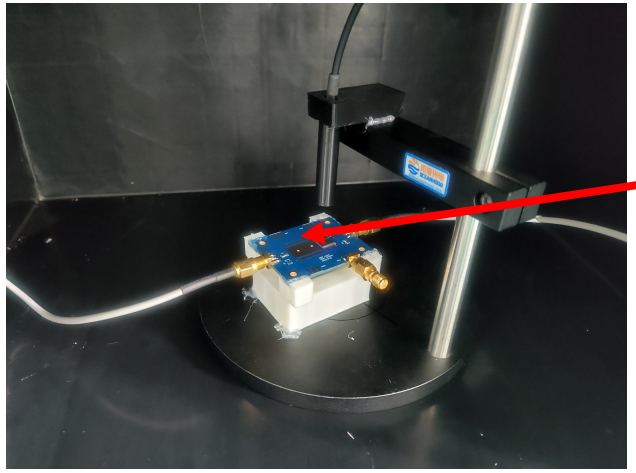


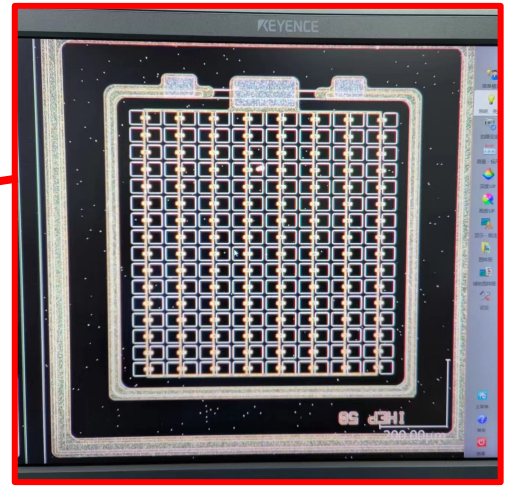


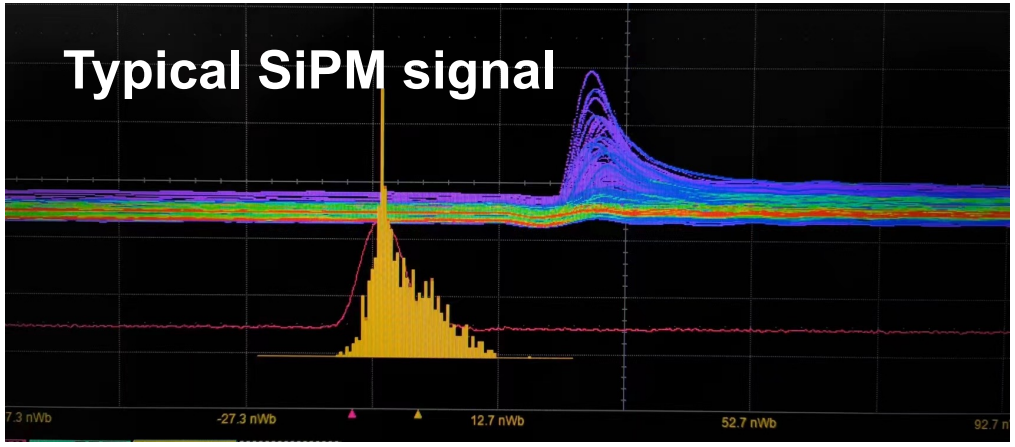


SiPM sample from 1st trial MPW run

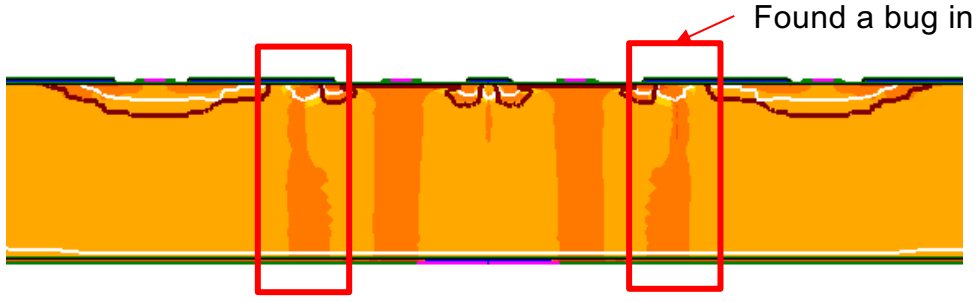








SiPM layout and process has been validated

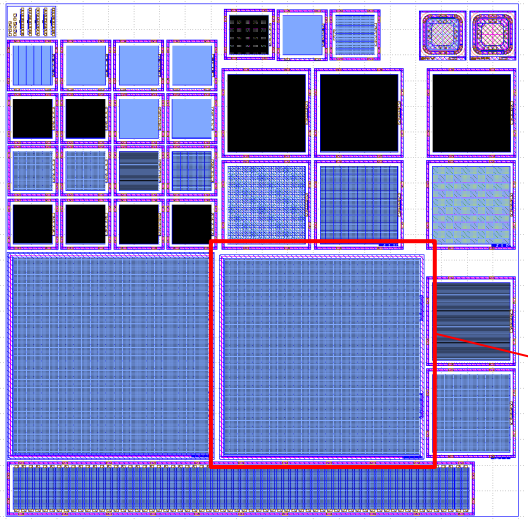


SiPM Leakage current is a bit high in 1st trial run

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

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

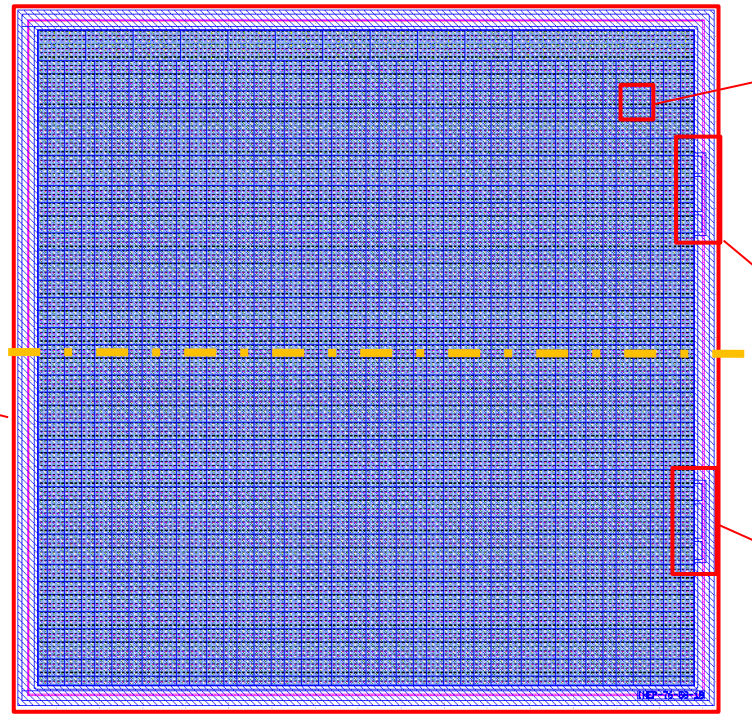


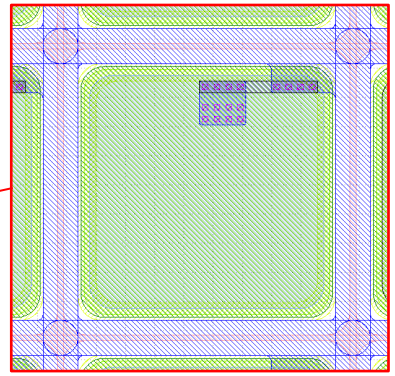
IHEP SiPM 版图

LACT 专用 SiPM：

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

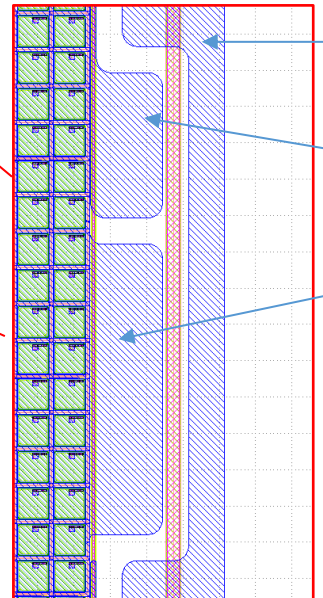
SiPM designed for LACT





单像素参数：

- Pixel size 50um
- Quenching resistance 200KΩ



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 the end of this year

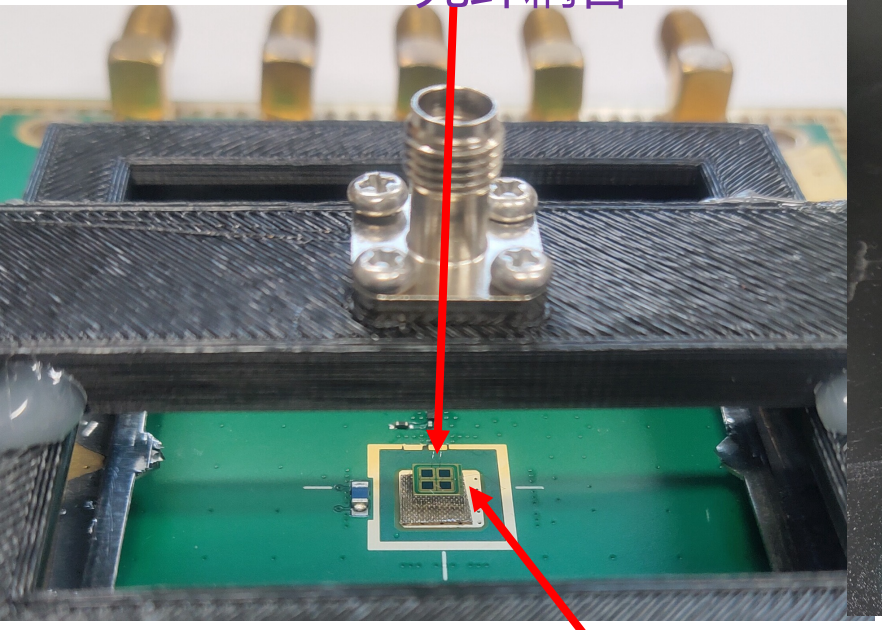
backup

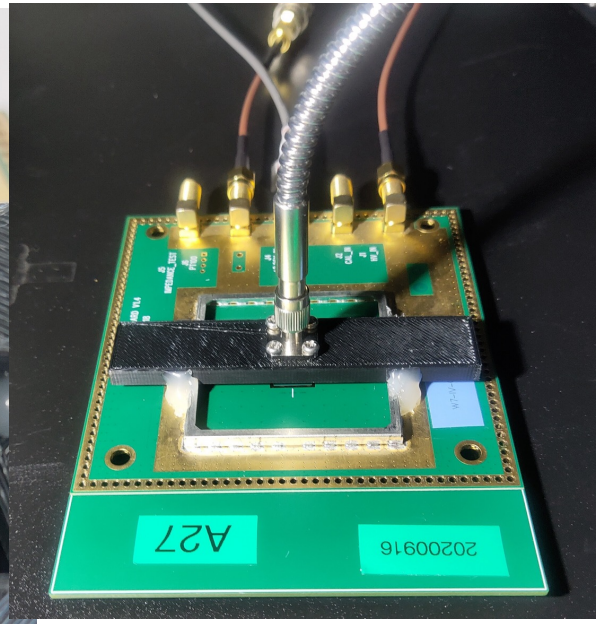
谢谢！

研究方案：测试方案

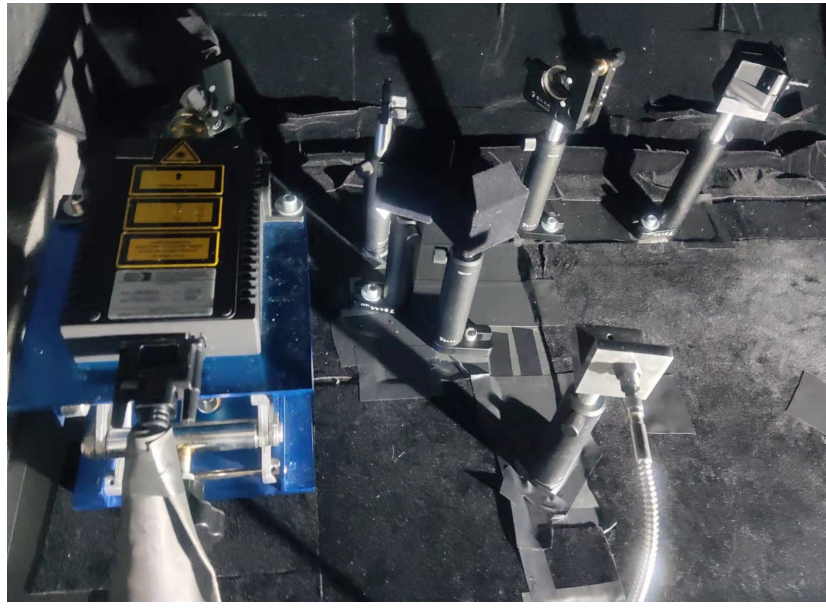
- 辐照测试方案：
  - 计划与东莞散裂团队合作，做SiPM的质子辐照
- SiPM性能测试方案：
  - 已有单光子测试平台与低温测试平台

目前基于LGAD传感器的弱光测试





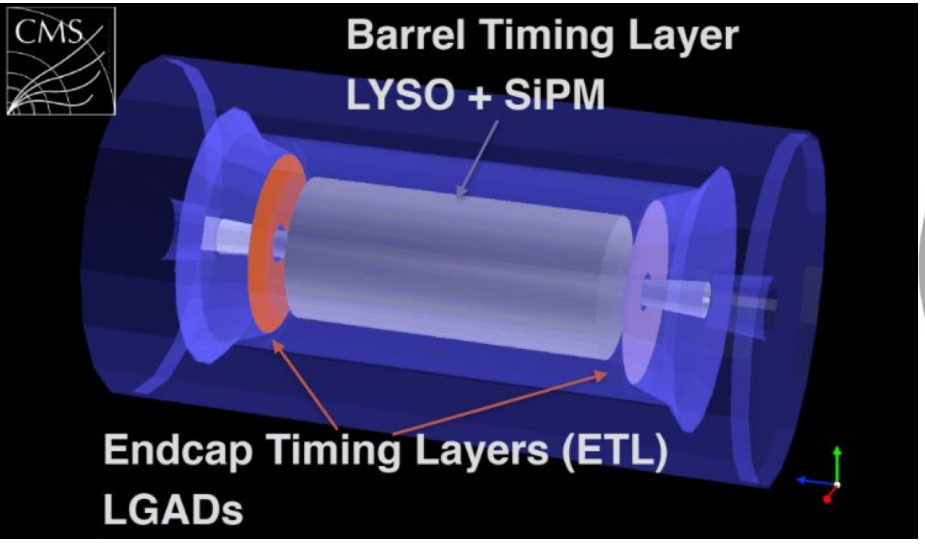
单光子测试平台（基于皮秒激光器）



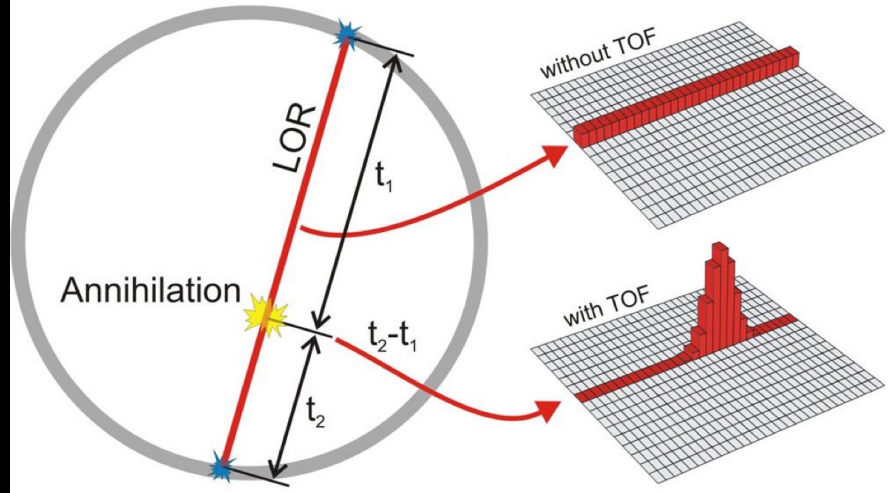
SiPM在时间测量上的应用

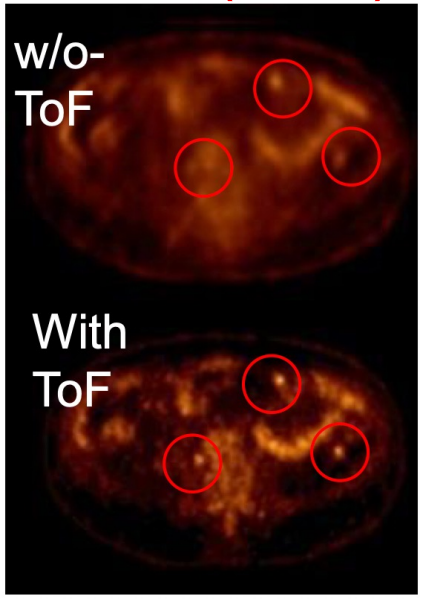
- 部分国外的SiPM有～30皮秒的本征时间分辨
- 未来有望用于各种时间探测器的应用中
  - 医学成像（TOF-PET），生物细胞成像
  - 飞行时间探测器

CMS的桶部时间探测器



超快SiPM在正电子发射型计算机断层显像（PET）





国内外形势：SiPM的暗计数

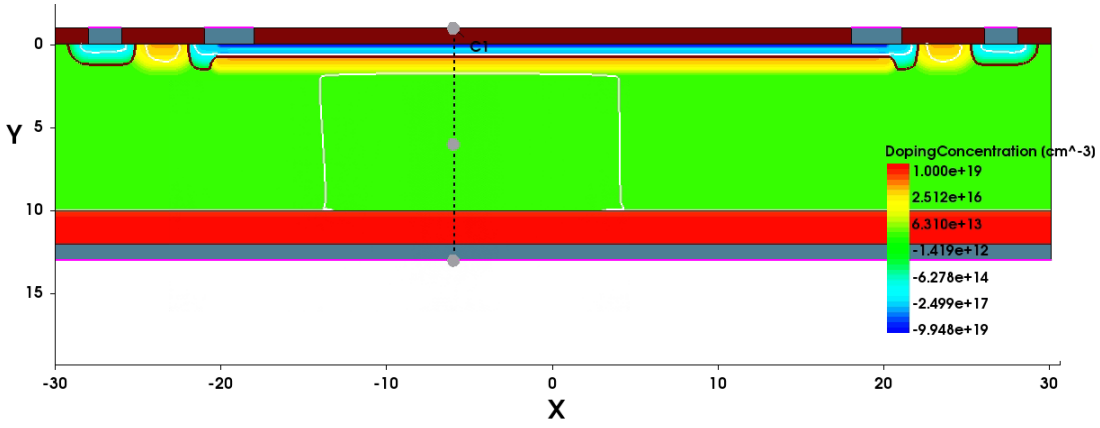
- 日本滨松与Sensl公司的SiPM是国际上领先的
- 国内以北师大的 SiPM为代表
  - 在小像素SiPM的量子效率上很有特点
  - 在暗噪声水平与工艺一致性方面（量产能力），与国际水平有差距

	日本滨松SiPM	Sensl SiPM	北师大NDL SiPM
面积	3.0*3.0 mm^2	3.0*3.0 mm^2	3.0*3.0 mm^2
常温的暗计数（kcps）	2000	860	~6000
Pitch	10 μm	28 μm	10 μm
Micro-cell Number	90000	10998	90000
Peak PDE	10%@470nm	24%@420nm	31%@420nm

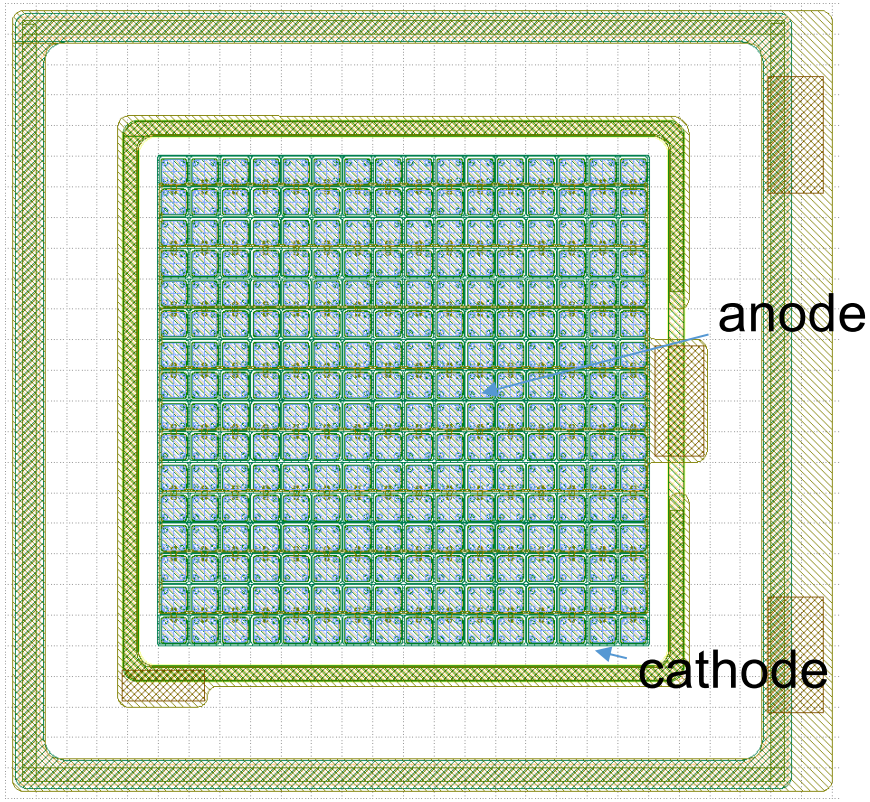
1st MPW runs for radiation hard

- 完成第一版的工艺流程设计、TCAD仿真与版图设计

SiPM simulation



SiPM design



9-layer mask

初步版图设计

- 器件面积：1 mm×1mm， 3 mm×3mm
- 像素尺寸：
  - 10 μm，15 μm，30 μm，50um