Development of LGAD for ATLAS HGTD and CEPC TOF out-tracker

应用于ATLAS HGTD和CEPC TOF out-tracker 的LGAD探测器研究进展

赵梅

ON BEHALF OF IHEP LGAD GROUP

中国科学院高能物理研究所

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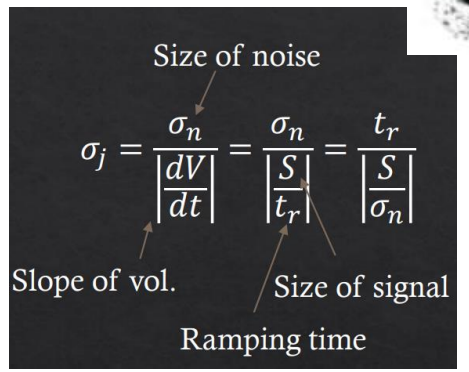
- LGAD 低增益雪崩二极管探测器
- 应用于ATLAS HGTD
- 应用于CEPC out-tracker
- 其他应用

LGAD 传感器

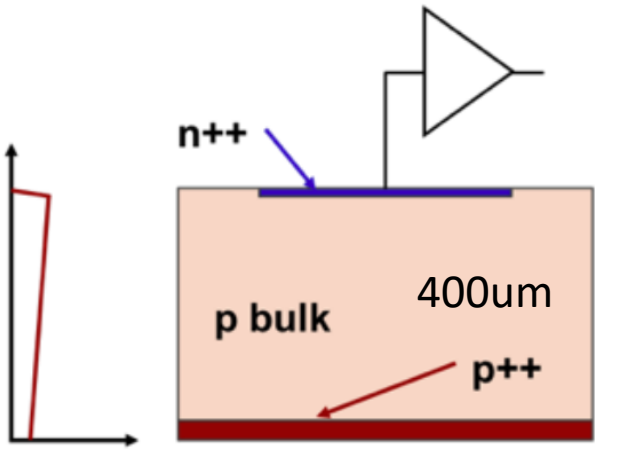
◆Low Gain Avalanche Detectors (LGAD)：低增益雪崩二极管

- 雪崩二极管，相比于传统的PIN，在n++和p衬底间具有P型的增益层（高电场区）
- 工作在线性区
- 增益: 10~50, higher signal as compared with PIN
- 薄耗尽层(~50um) to decrease t_{rise} (fast ramping time)
- 较好的信噪比Good Signal/Noise ratio， 相比于SiPM，无自触发(暗计数)

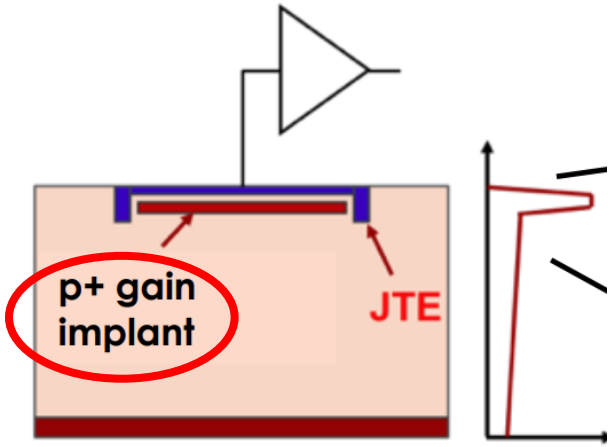


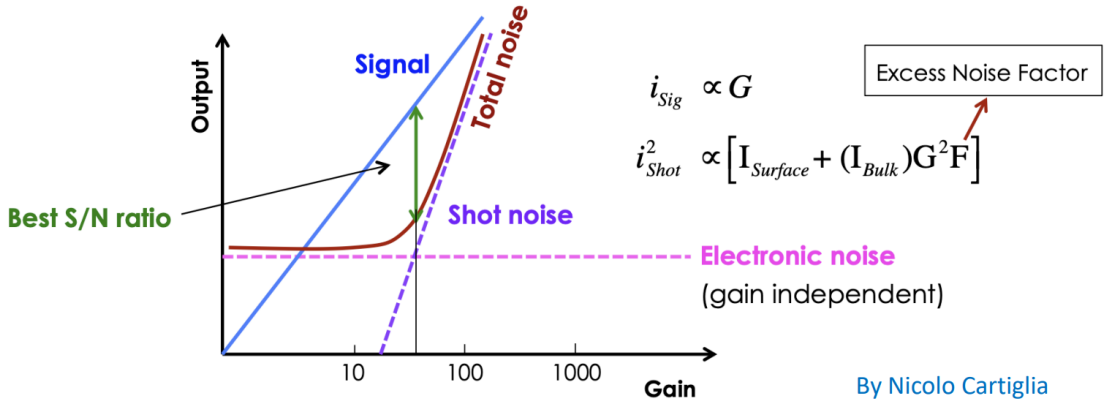
➢**good timing resolution(<30ps)**

PIN diode



LGAD sensor





Noise increases faster than then signal

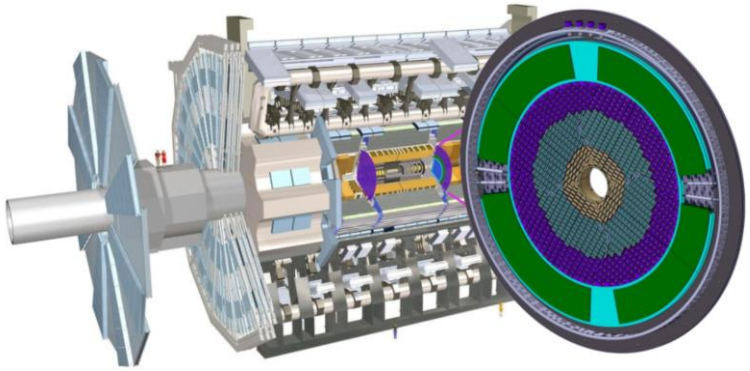
→ the ratio S/N becomes worse at higher gain

Koji Nakamura (KEK), https://indico.ijclab.in2p3.fr/event/9730/

https://doi.org/10.1201/9781003131946

应用于ATLAS HGTD

ATLAS HGTD高颗粒度时间探测器



- 欧洲核子中心，大型强子对撞机高亮度II期升级:

  ATLAS High Granularity Timing Detector (HGTD)

  - 把粒子到达时间的测量精度提高2个数量级（数纳秒→30ps）
  - 解决高亮度LHC对撞事例堆积问题

- HGTD探测器：

  6.4m²的硅探测器， 30ps的时间分辨

  毫米级的颗粒度，超过三百万个读出通道

  能承受2.5×10^{15} n_{eq}/cm^2的等效中子通量的辐照

- 两个disk：每个disk都是双面的， mounted on the cooling disk

  半径 120 *mm* < R < 640 *mm* corresponding to 2.4 < |η| < 4

- 模块：8032个

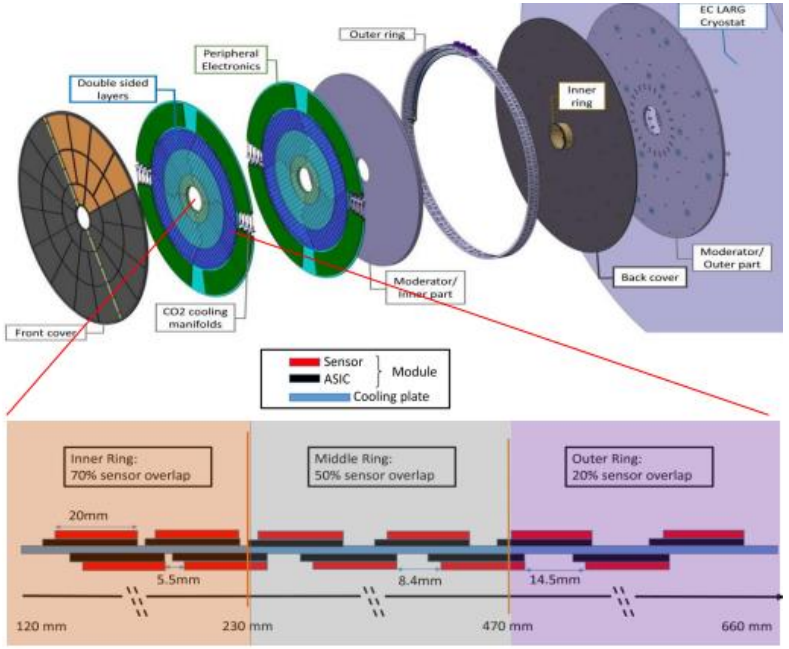
  2 LGADs (15x15 pads) + 2 ASIC (15x15 channel) + flex

- **HGTD探测器研制关键是LGAD探测器件**

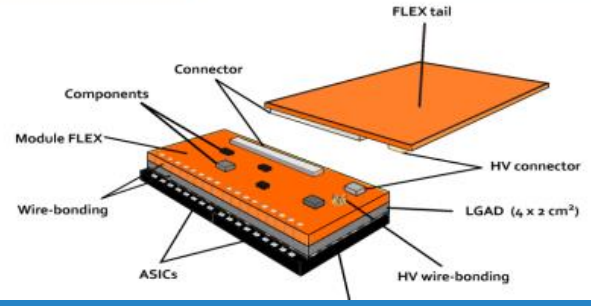
  时间分辨率可达30-50ps，从而提高区分堆积的能力，改进前向区域的粒子重建。

- HGTD 需求LGAD探测器：>2万颗

Disk



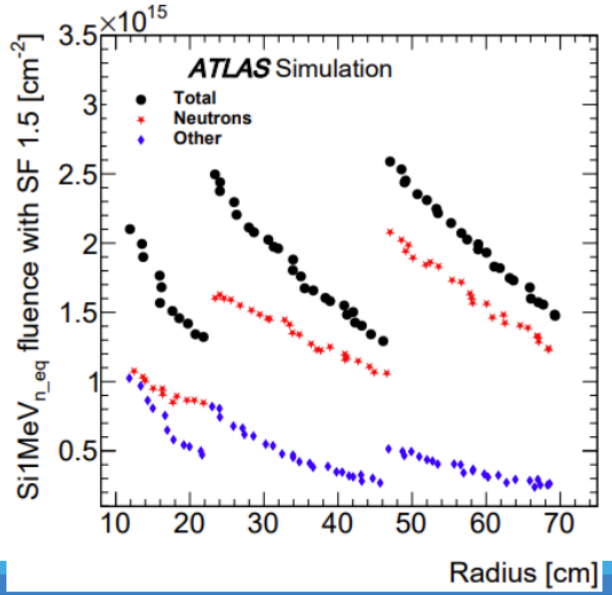
模块

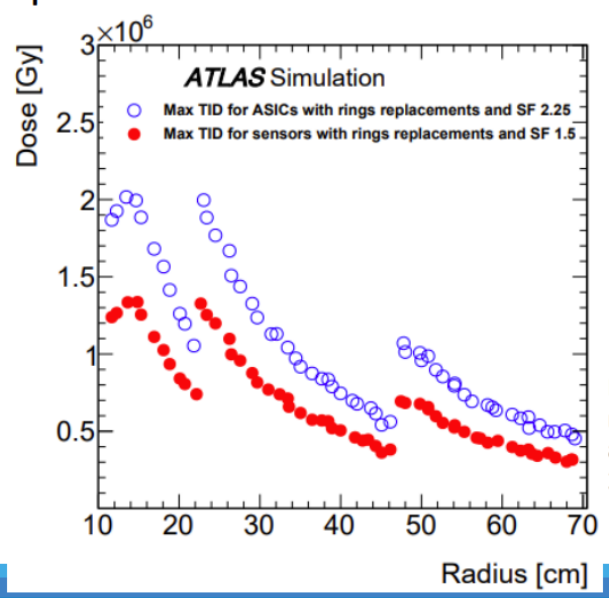


HGTD LGAD探测器性能要求

- Size: 15x15 array, 1.3x1.3mm^2 pixel size
- Active thickness: 50um(Thin: faster rise time, lower impact from radiation)
- LGAD sensor can withstand the lifetime of the HL-LHC running: irradiation requirement
  - Maximum n_{eq} fluences: 2.5×10^{15} n_{eq}/cm^2
  - Total Ionizing Dose (TID): 2 MGy at the end of HL-LHC (4000 fb^{-1})
- Time resolution: 35ps (start), 70ps (end) per hit, while 30ps (start), 50ps (end) per track
- Collected charge per hit >4fC (minimum charge needed by the ASIC to hold good time resolution)
- Hit efficiencies of 97% (95%) at the start (end) of their lifetime

Maximum fluence with replacements



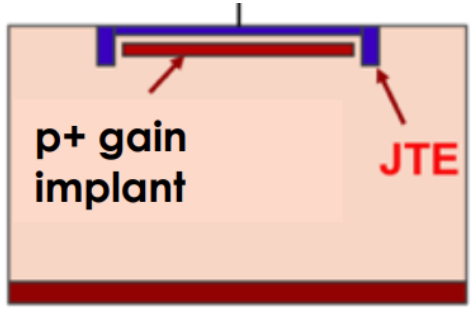


Replacement of inner ring every 1000 fb^{-1} and middle ring at 2000 fb^{-1}

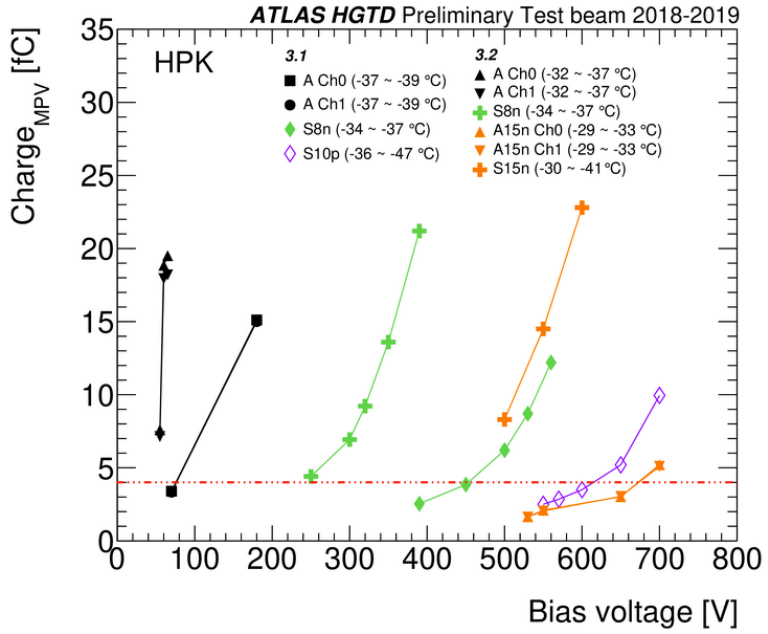
参数	指标
衬底材料厚度	50μm EPI /250μm silicon
像素尺寸	1.3mmX1.3mm
像素阵列	15X15
时间分辨率	<35ps(辐照前)，<70ps(辐照后)
收集电荷	>15fC(辐照前)，>4fC(辐照后)
辐照剂量	2.5e15 n_{eq}/cm^2, 2MGy
工作电压	<800V

HGTD LGAD探测器:抗辐照挑战

- 辐照后，增益区有效浓度降低，Boron这一受主移除效应

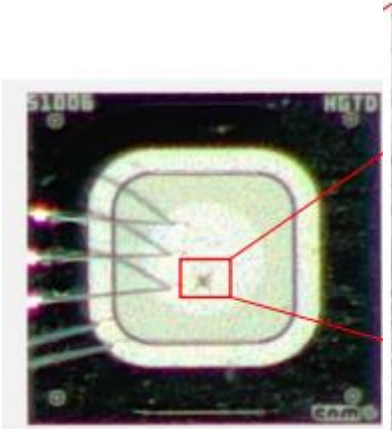


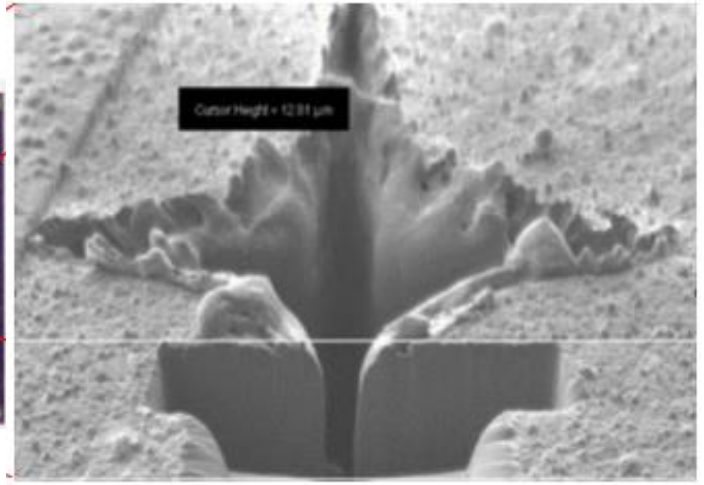
- 增益下降，收集电荷变少，时间分辨特性变差



4fC

- 增大工作电压后，在束流测试时出现单粒子烧毁的情况



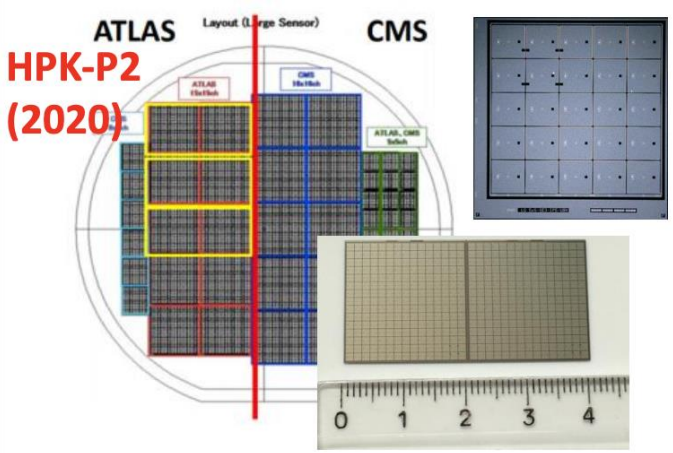


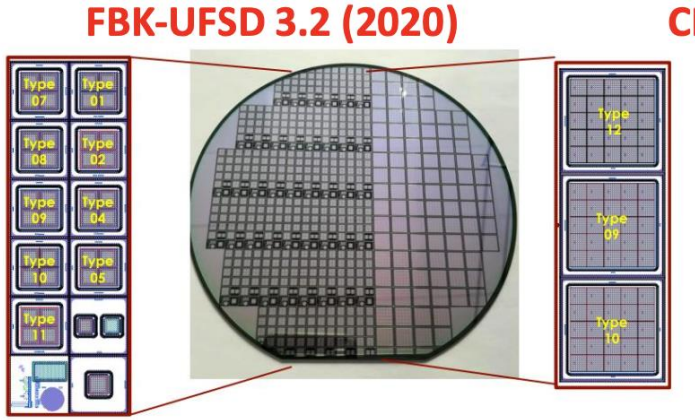
- SEB现象： CMS/ATLAS/RD50 均有报告

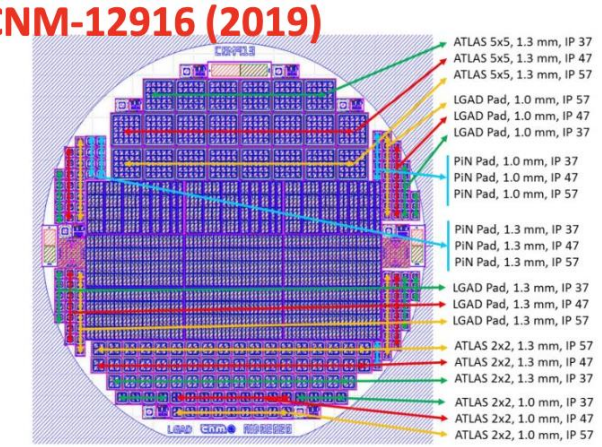
研究发现：高电压与高电场导致烧毁，工作电压要控制到<550 V （50微米的硅传感器），电场<12V/um, 可收集到足够的电荷

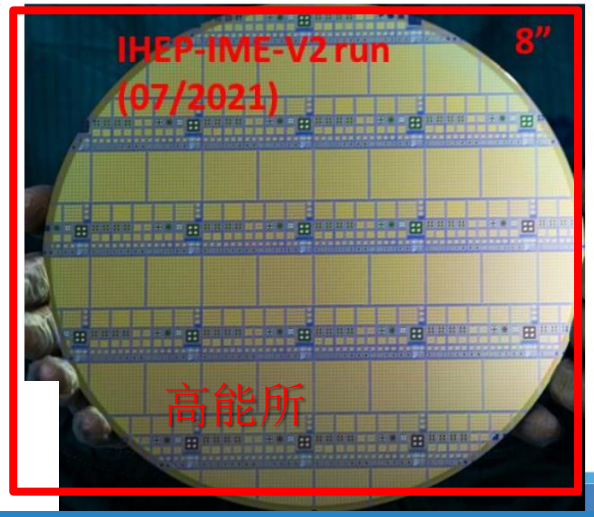
LGAD探测器： 国内外研究单位

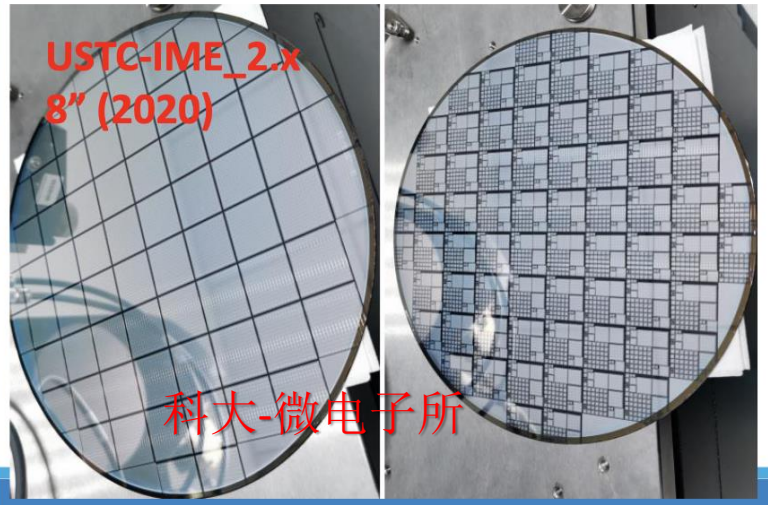
- 国内：高能所，科大，北师大
- 国际：滨松HPK (日本)， FBK (意大利)，CNM (西班牙)， BNL(美国)…
- 高能所自主设计LGAD探测器版图和工艺，在微电子所8寸工艺线流片

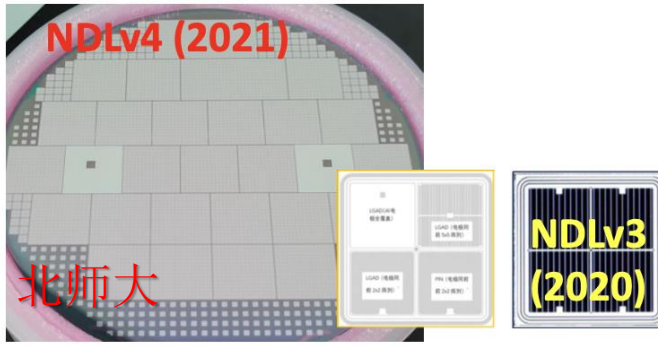










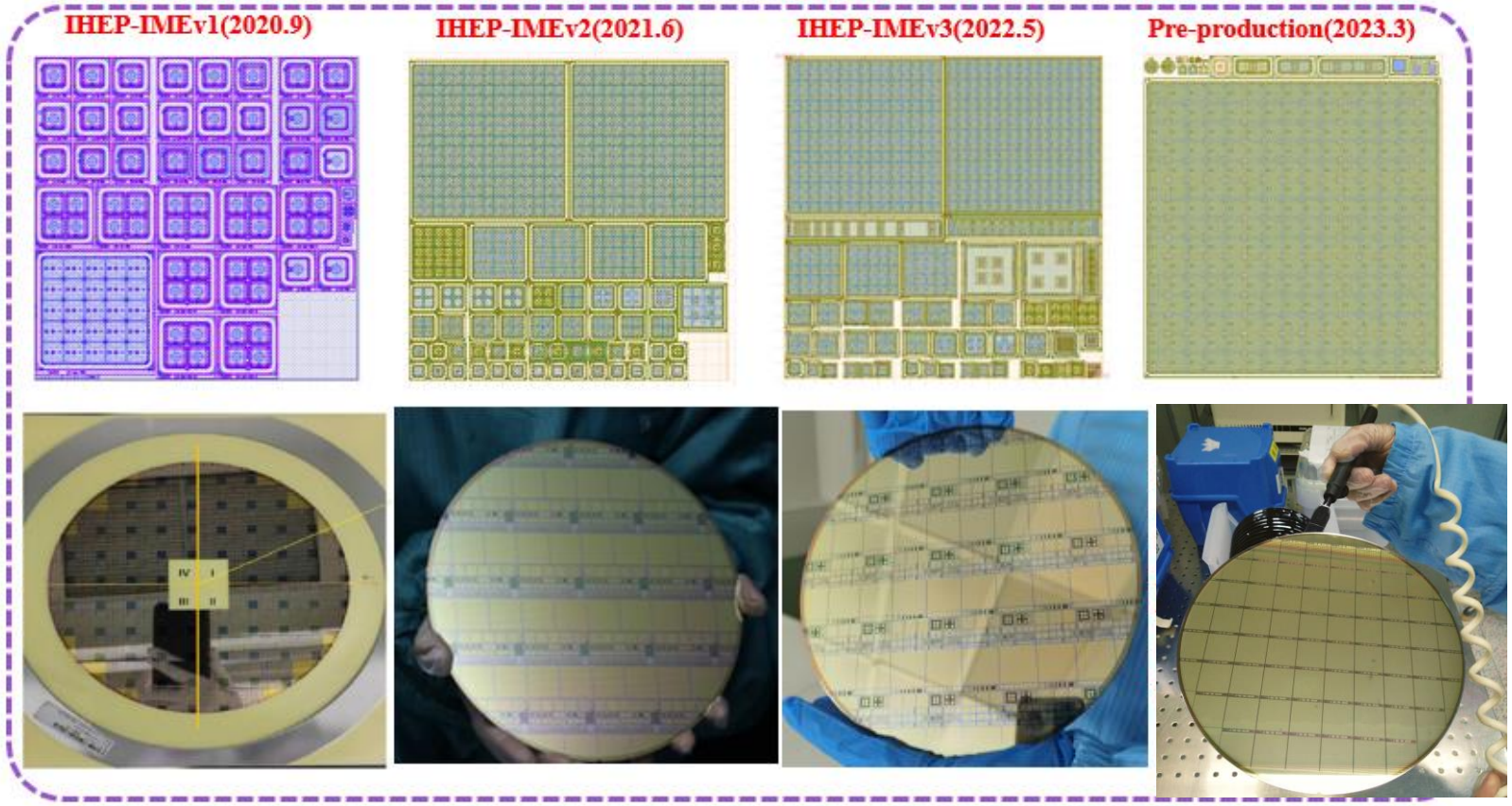


PLANAR TECHNOLOGY – more vendors
(e2V, BNL, Micron …)

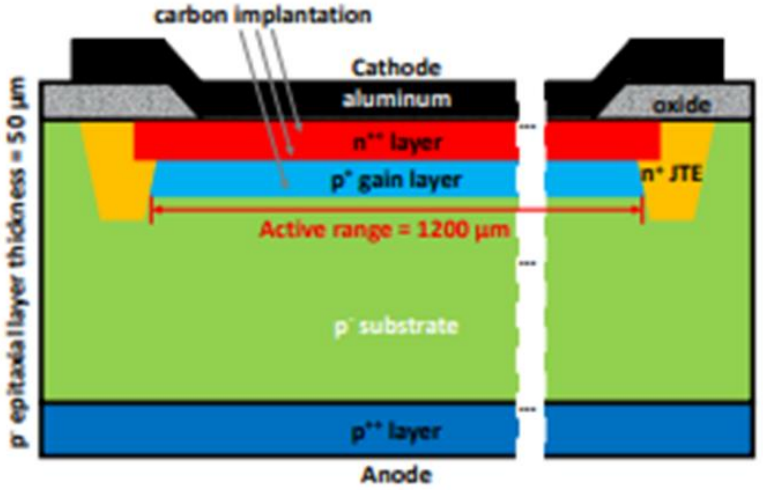
IHEP LGAD探测器研发进展

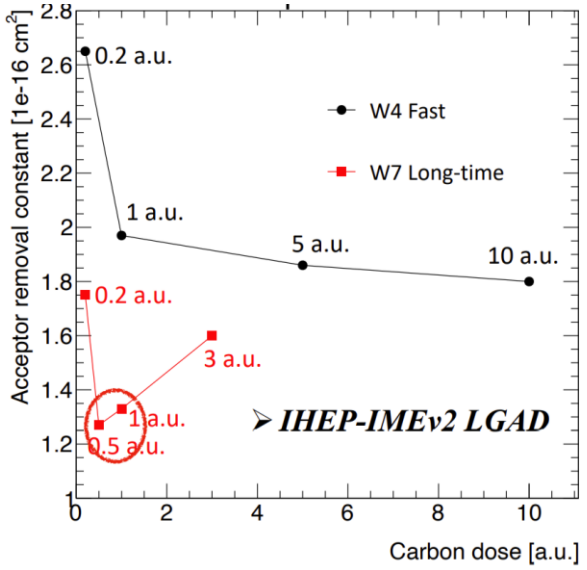
高能所从2018年起致力于LGAD探测器的研发，自主设计版图与工艺参数，多次流片迭代，成功研制出了具有良好时间分辨与抗辐照性能的国产LGAD探测器。

- **IHEP-IMEv1(2020.9)，性能满足HGTD项目要求**
- **IHEP-IMEv2(2021.6)，掺碳工艺优化器件抗辐照性能，大阵列器件**
- **IHEP-IMEv3(2022.5)，工艺重复性验证，优化大阵列器件设计**
- **2023年3月开始预生产（~1000颗）**
- **2024年8月开始正式生产（~20000颗）**



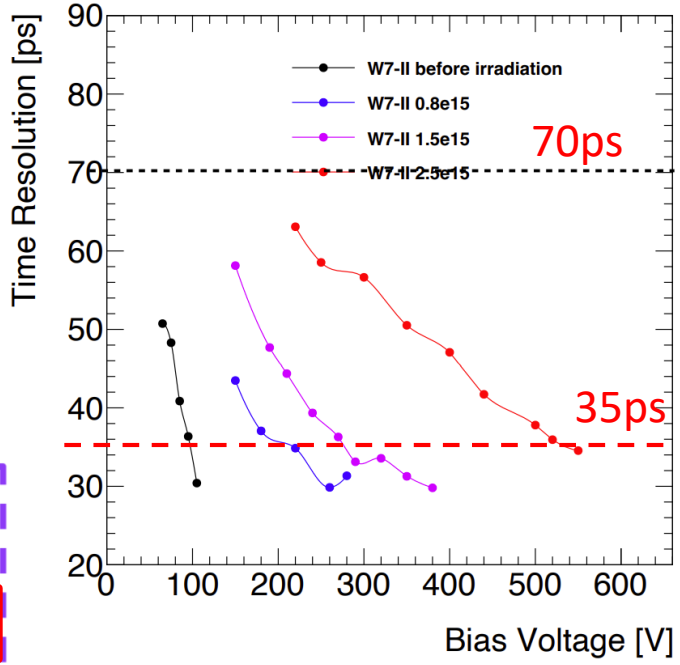
IHEP LGAD探测器：工艺优化与抗辐照性能





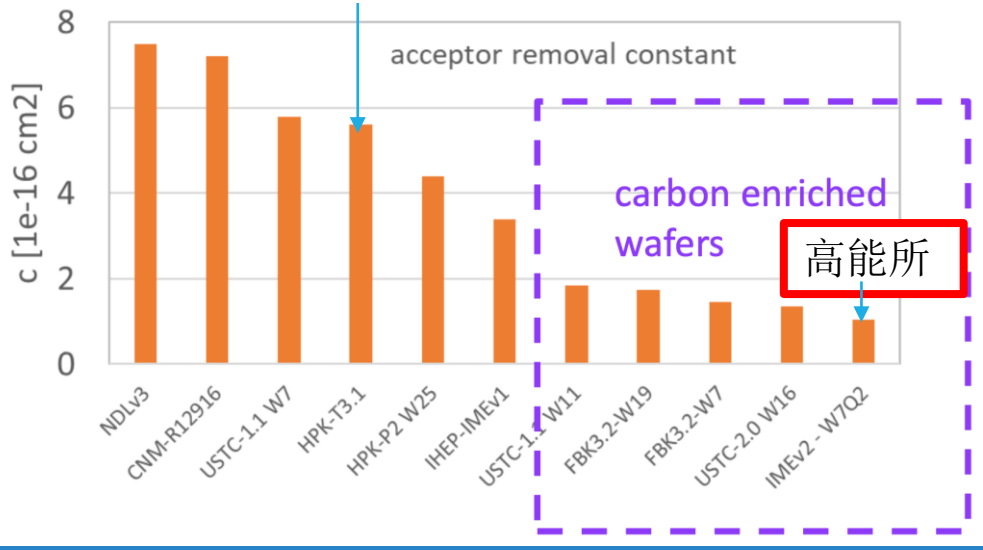
辐照前后，时间分辨均<35ps

时间分辨率 vs 偏置电压



- **掺碳LGAD器件性能研究：**
  不同的碳注入剂量和热处理条件
- 在不同的条件里，找到一个**最优**的碳注入剂量与退火条件。这个情况下，辐照后的器件具有最小的受主移除率（反映了器件的抗辐照性能）

日本滨松

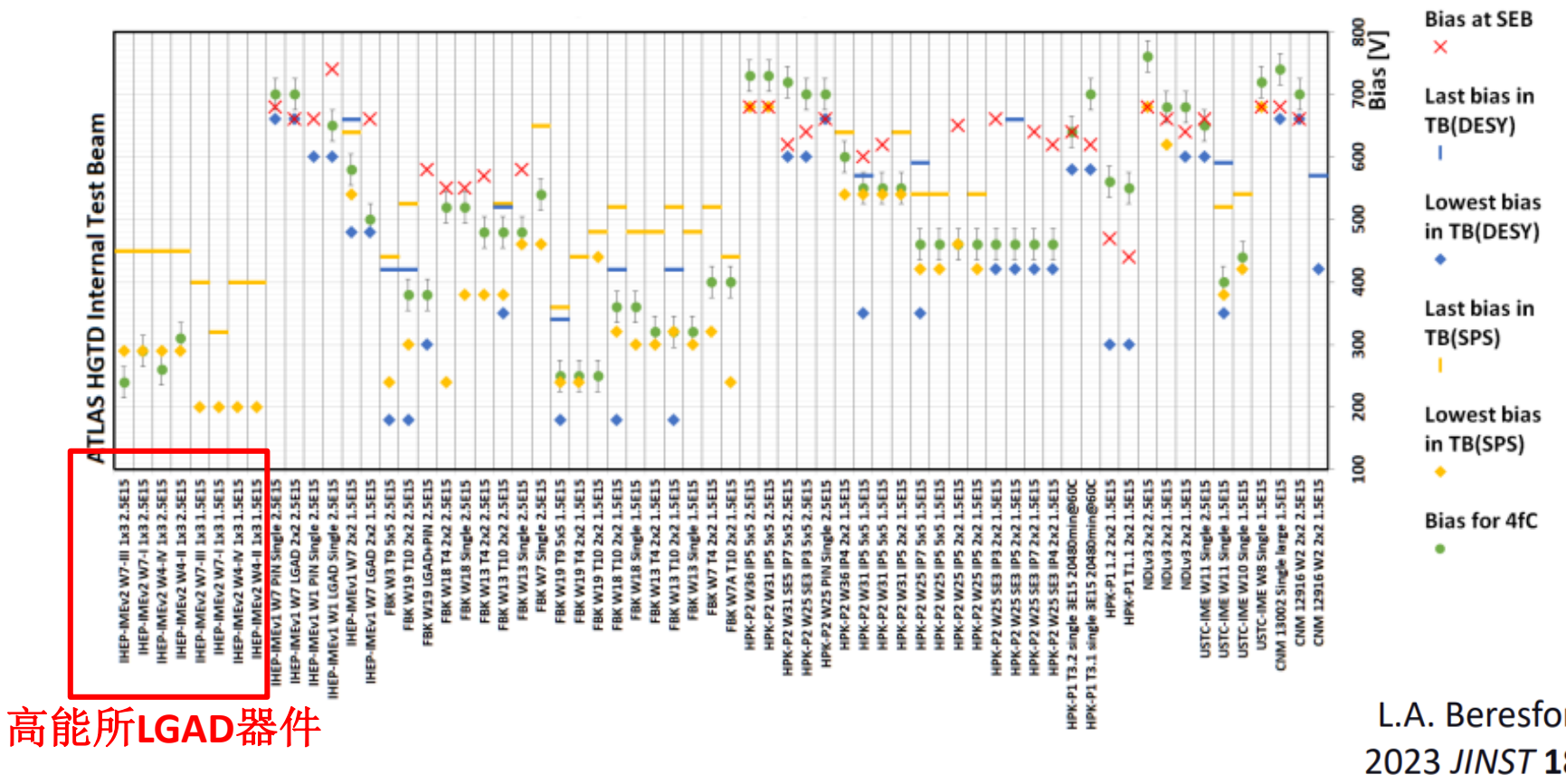


https://doi.org/10.1016/j.nima.2022.167697

IHEP LGAD探测器：束流测试

ATLAS合作组开展的欧洲核子中心（CERN）的高能质子流测试：

高能所掺碳LGAD器件辐照后均可在较低电压下收集足够的电荷（4fC），且在束流下长时间工作，无一烧毁



L.A. Beresford *et al*
2023 *JINST* **18** P07030

LGAD探测器：量产

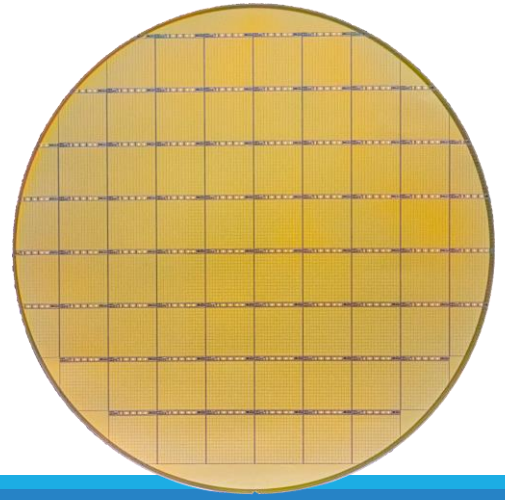
- 2023年高能所设计的LGAD探测器赢得CERN的全额招标份额
  - 在日本滨松、意大利FBK等竞争下，高能所设计的LGAD赢下招标
  - 欧洲核子中心（CERN）首次采购中国产的硅探测器
- HGTD项目LGAD探测器：21700颗
  - 高能所设计： 90% （54% CERN国际招标采购+ 24%实物贡献+12% Spain 贡献）
  - 中科大设计：10% 实物贡献

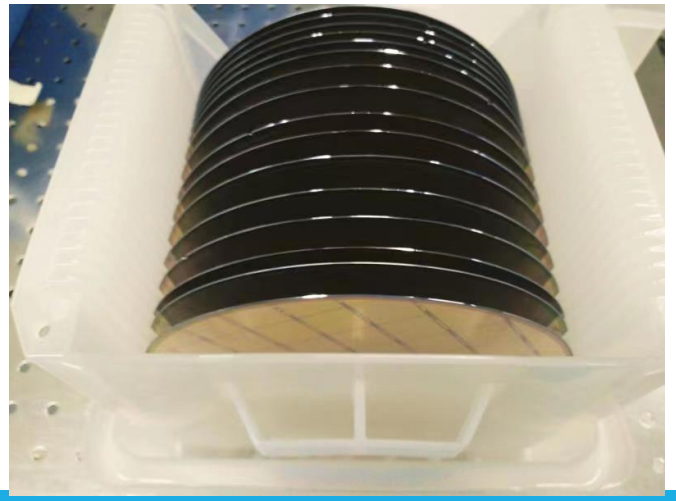
Vendor		Percent
IHEP-IME	CERN	54%
	China in-kind	24%
	Spain in-kind	12%
USTC-IME	China in-kind	10%

2023年3月开始HGTD项目LGAD器件批量预生产，目前高能所与科大已完成预生产，生产了~1900颗芯片（高能所：~1700颗，科大：~200颗），性能通过合作组的测试与评估，符合项目要求，并通过项目PRR评审。

于2024年8月开始正式生产。

单晶圆有52个
15x15 LGAD器件





预生产晶圆

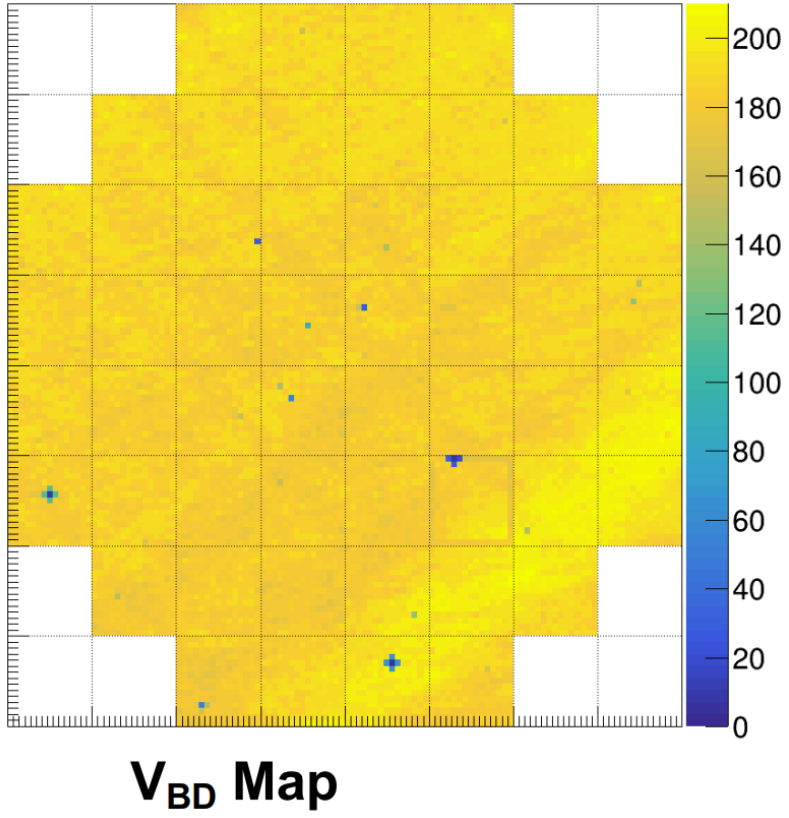
IHEP LGAD探测器：量产

- **成品率**：pad yield>99%, sensor yield: 64%
- **15x15 阵列器件性能一致性良好**

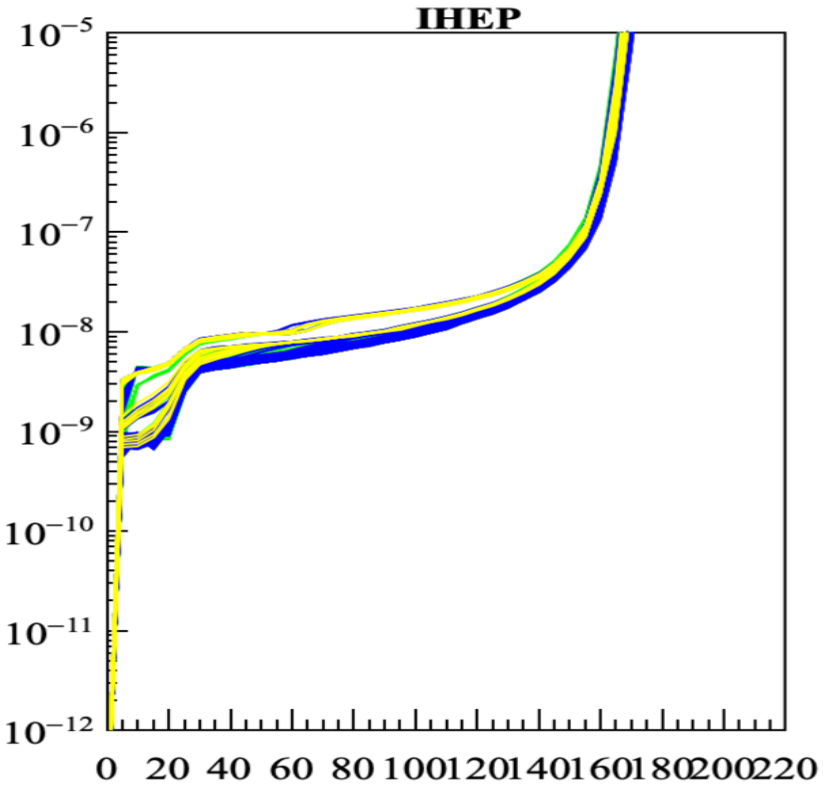
225个pad的击穿电压偏差小于5%：RMS($V_{bd,pad}$)/<$V_{bd,pad}$> <0.05

漏电流最大最小值的比值小于3，Pad leakage current spread at 0.8V_{bd}, peak to peak within a factor of 3X

晶圆上器件间Vbd分布图

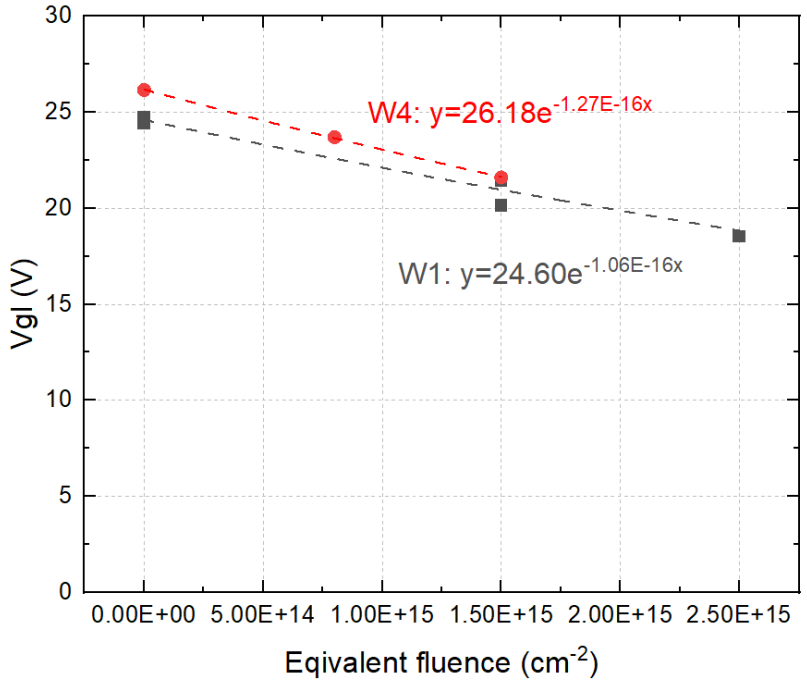


15x15器件上225个pad的IV图

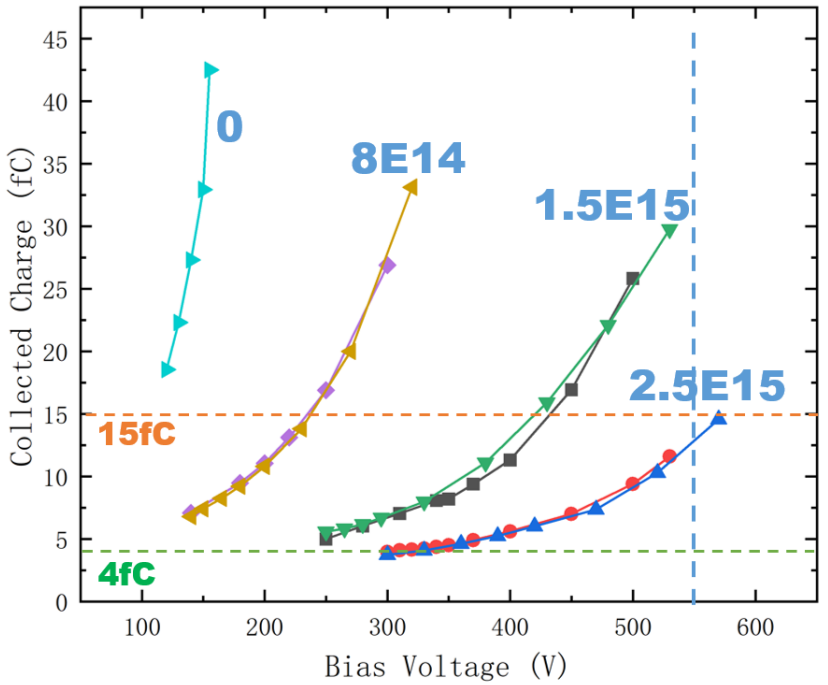


IHEP LGAD探测器： 预生产器件性能

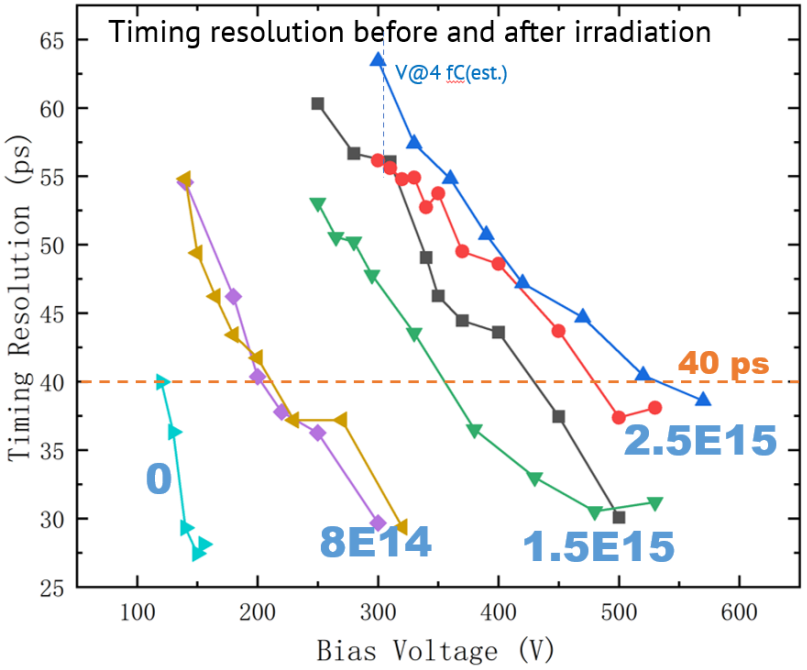
➢ 预生产器件抗辐照性能测试结果：中子辐照（JSI）



受主移除率低：1.06e-16
优于R&D run



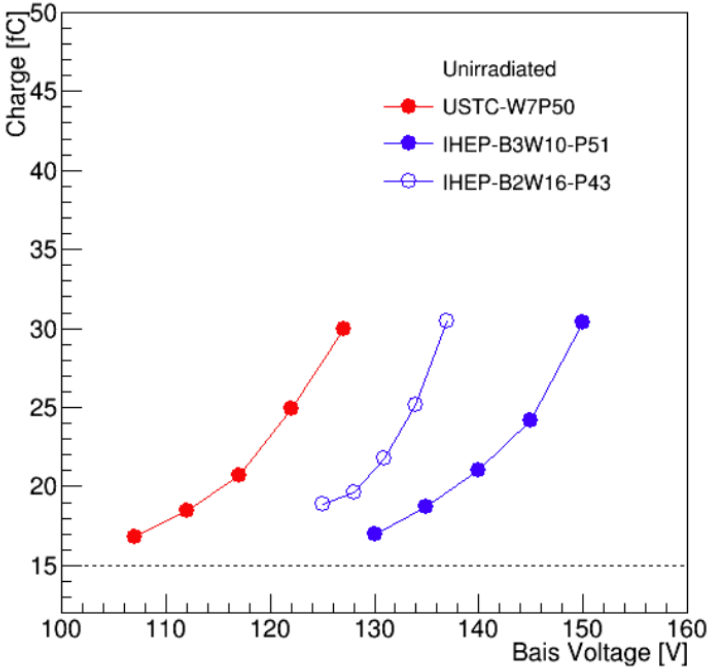
辐照后在<400V，可收集足够电荷



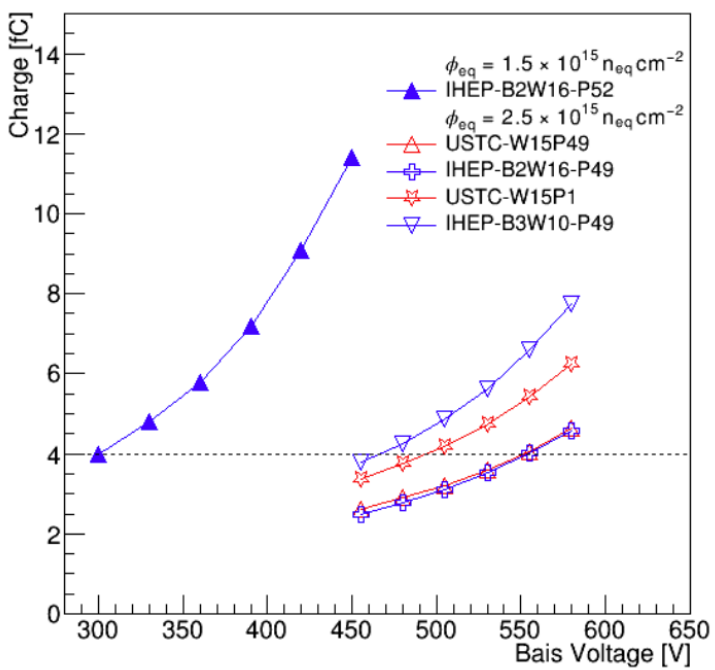
辐照前，时间分辨可达<30ps
辐照后，时间分辨可达<40ps

IHEP LGAD探测器：预生产器件性能

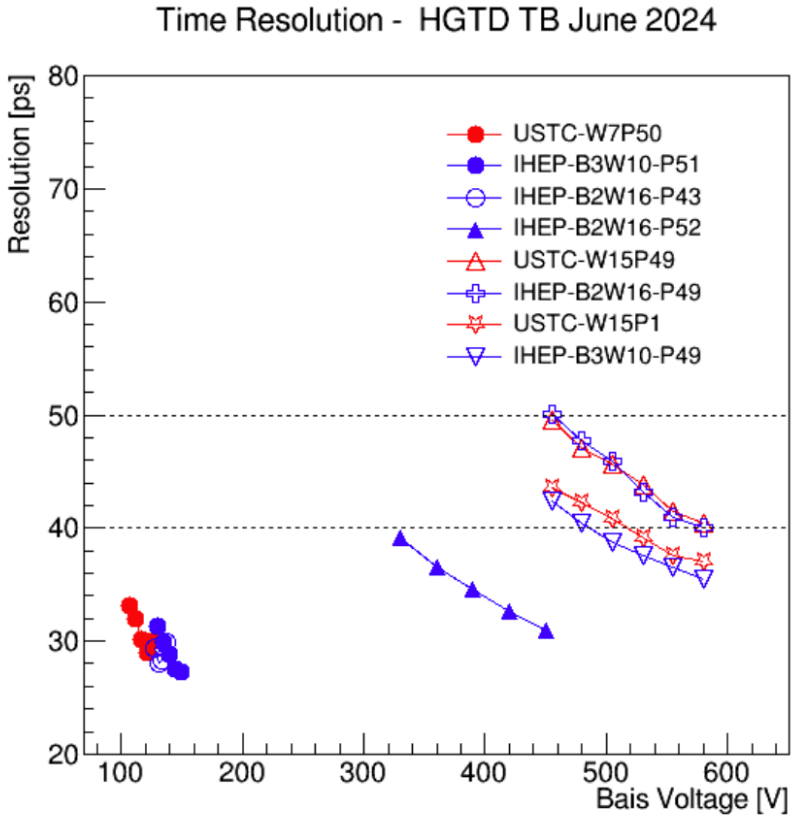
➢ 预生产器件抗辐照性能测试结果：辐照后single器件的束流测试结果



unirradiated sensor



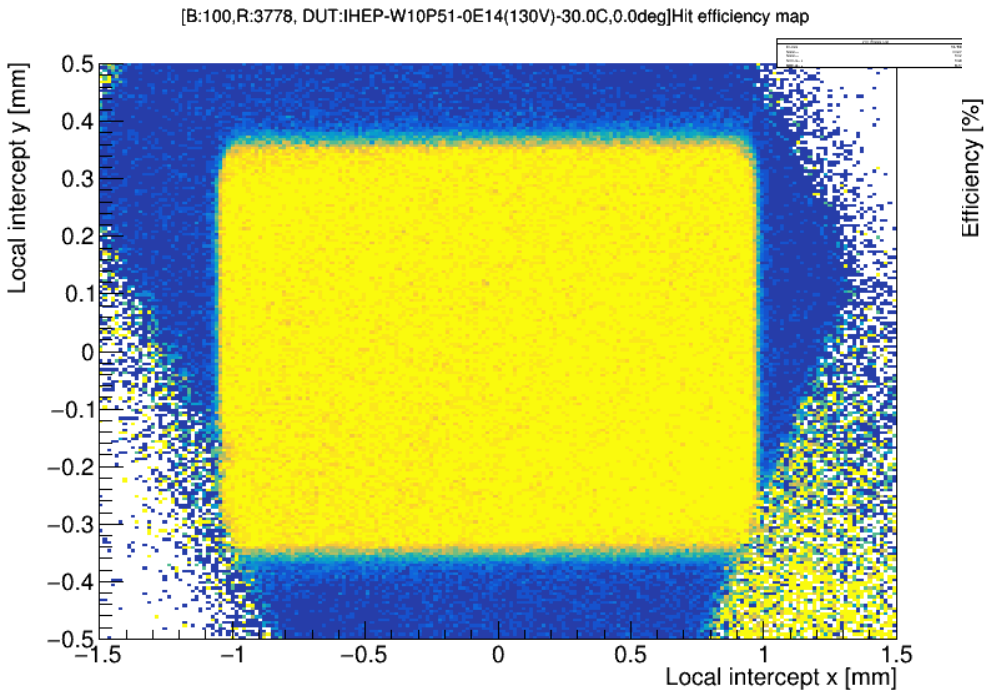
irradiated sensor

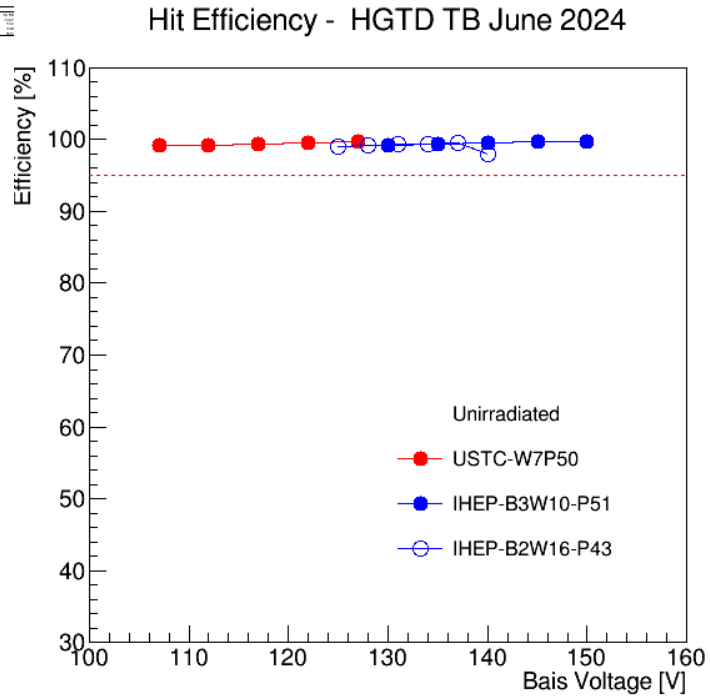


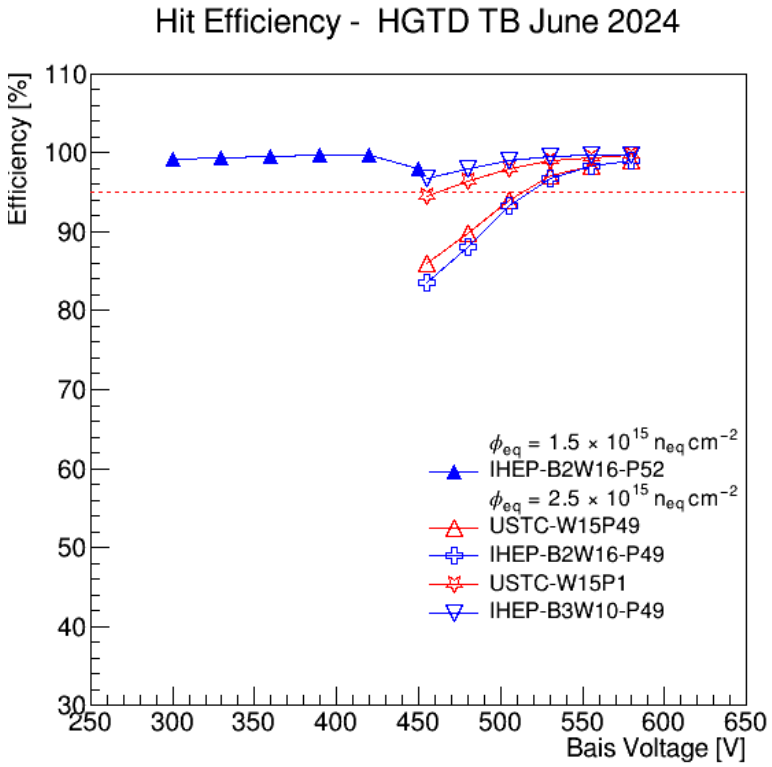
- 在低于550V的电压下收集足够的电荷（>4fC）
- 达到30-50ps的时间分辨特性
- 有效避免束流测试中的单粒子烧毁现象(SEB)，完全满足HGTD项目的应用要求。

IHEP LGAD探测器：预生产器件性能

- **预生产器件抗辐照性能测试结果：辐照后single器件的束流测试结果**







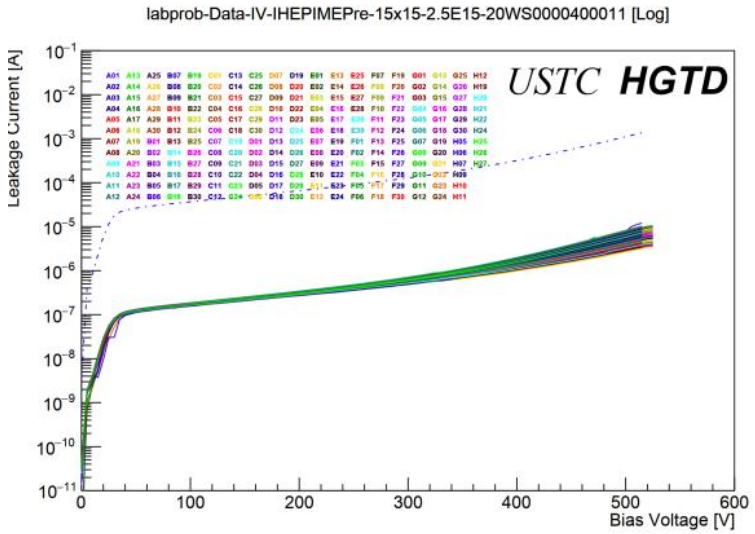
- 辐照前后均可达到95%~100%的探测效率，完全满足HGTD项目的应用要求。

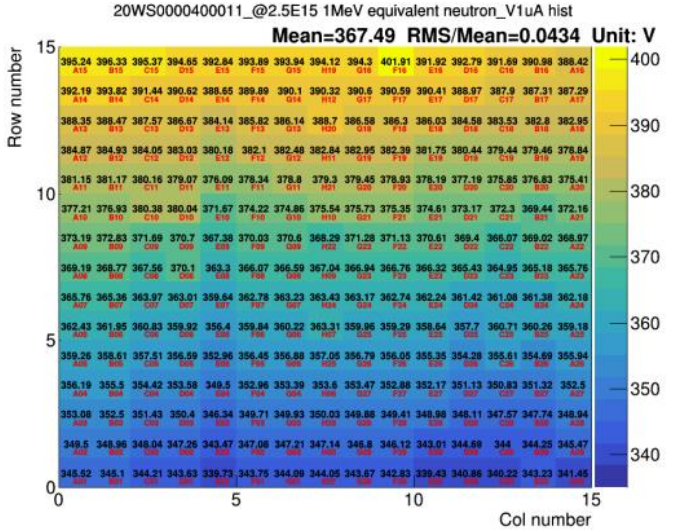
IHEP LGAD探测器：预生产器件性能

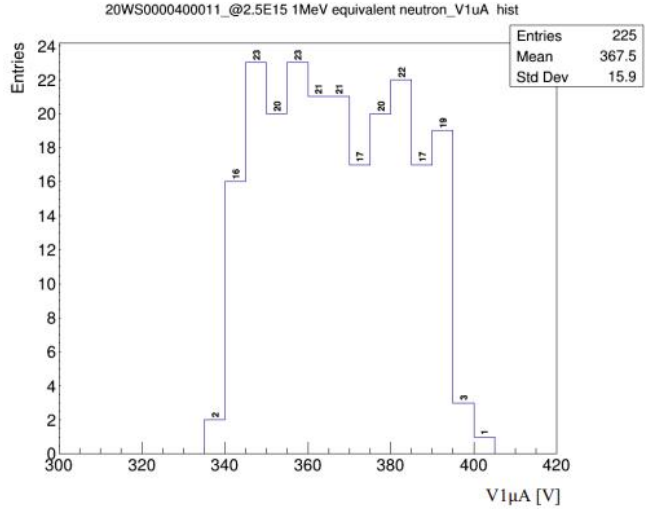
- **预生产器件抗辐照性能测试结果：**

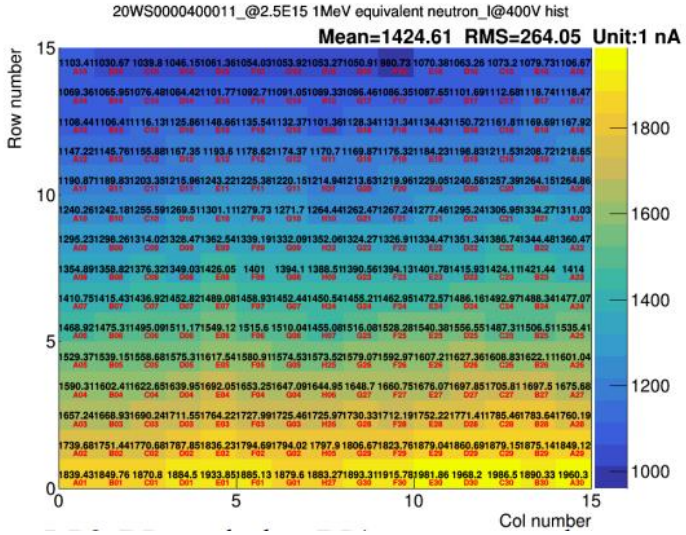
大阵列器件辐照后的IV特性

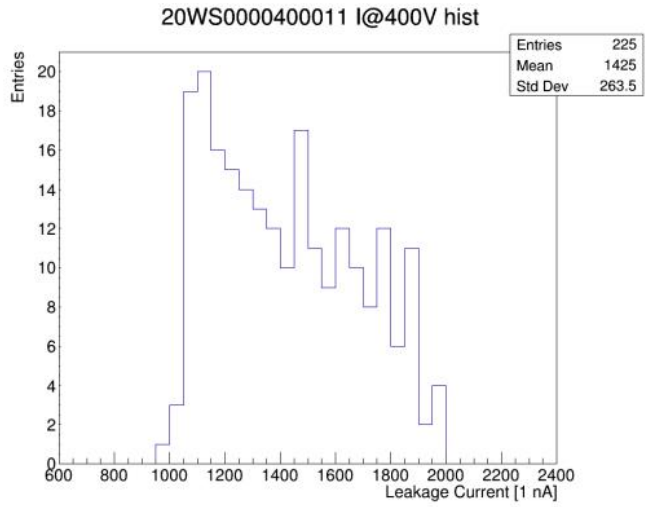
20WS0000400011@2.5E15 n_{eq}/cm^2







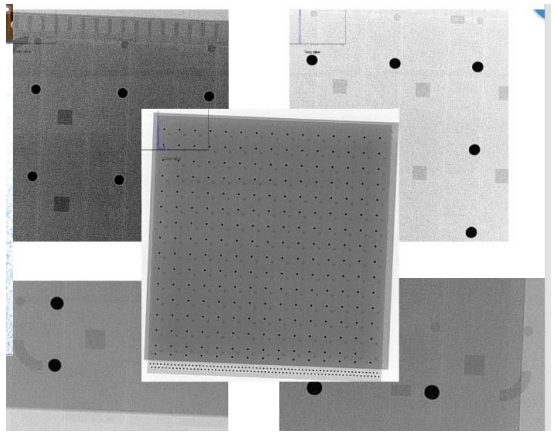


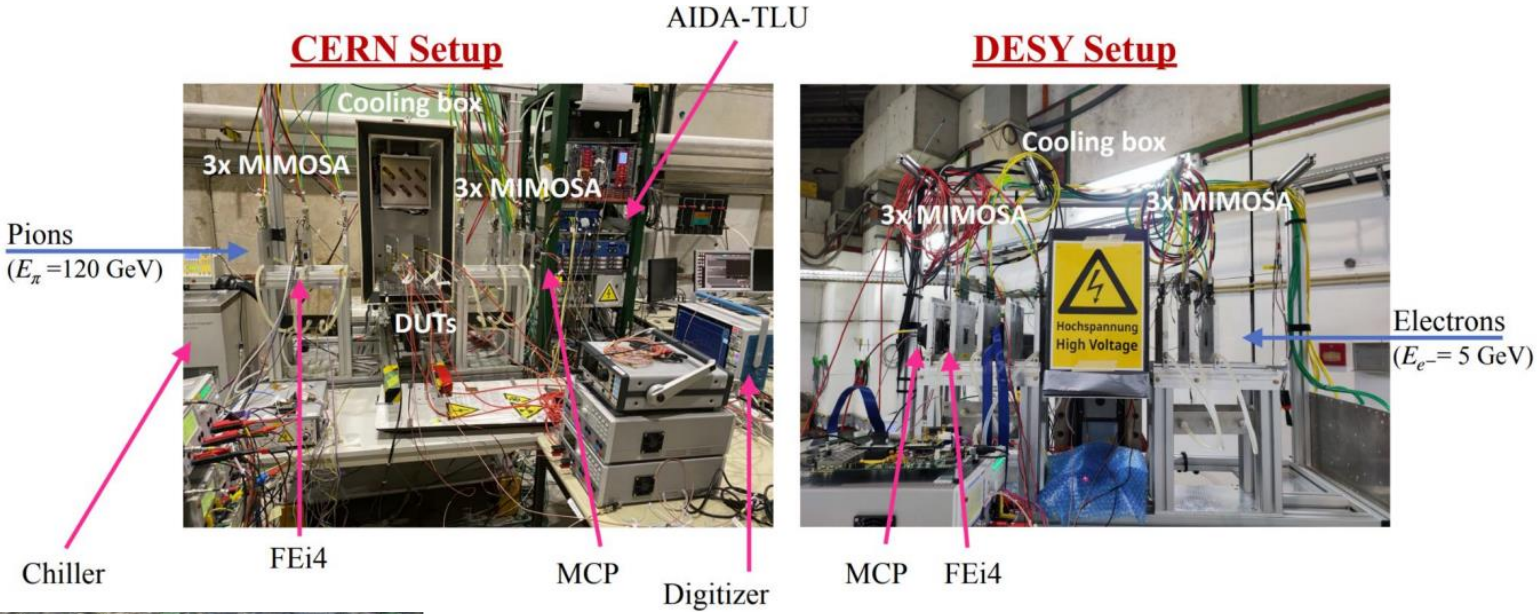


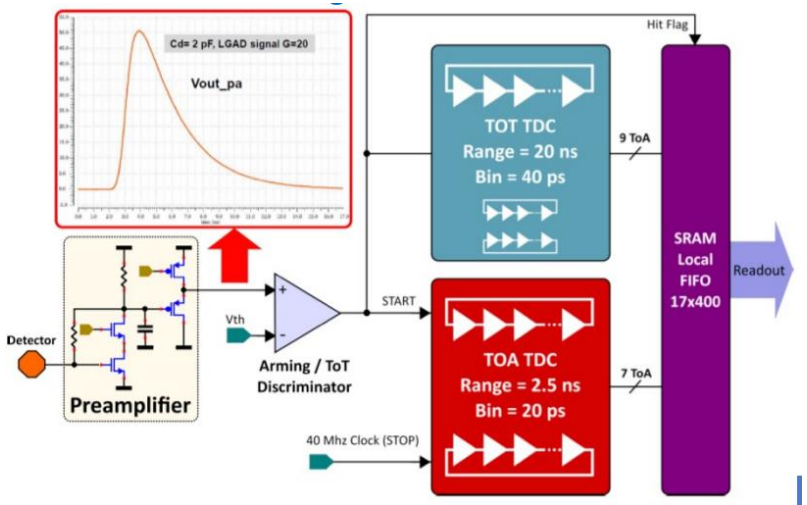
IHEP LGAD探测器：预生产器件

- LGAD 15x15探测器与ASIC通过倒装焊连接，之后对其性能进行测试。
- DESY和CERN SPS多次模组束流测试

- Oct 2023 / Nov 2023 / Feb 2024 DESY
- May 2024 SPS CERN

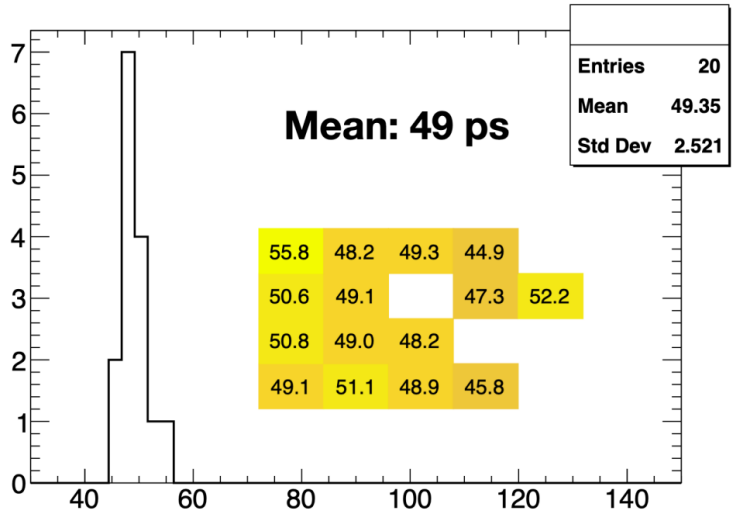


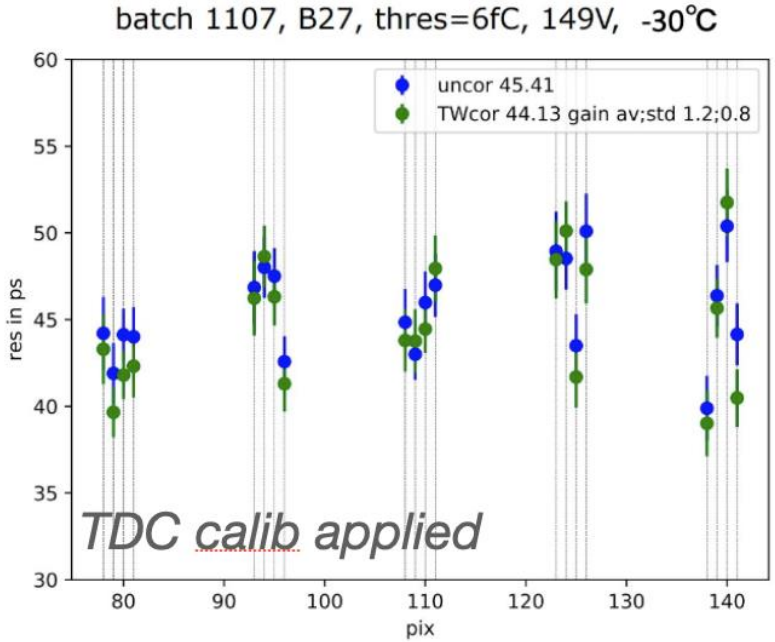




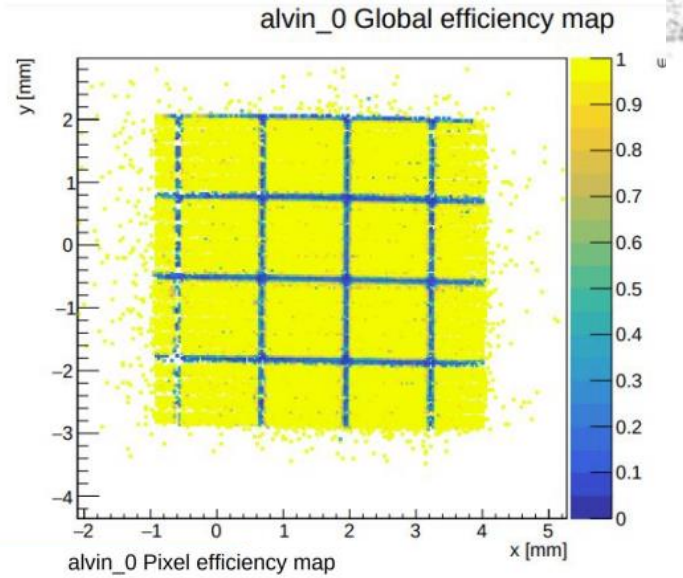
IHEP LGAD探测器：预生产器件

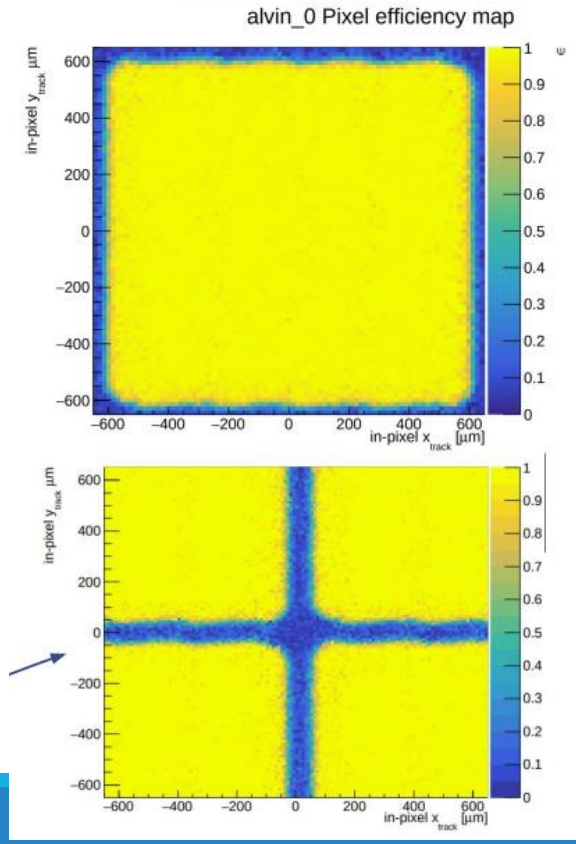
- 预生产器件抗辐照性能测试结果：与ASIC联合Beam测试
- 时间分辨率可达50ps
- 探测效率可>98%





~45 ps after calibration
and time walk correction





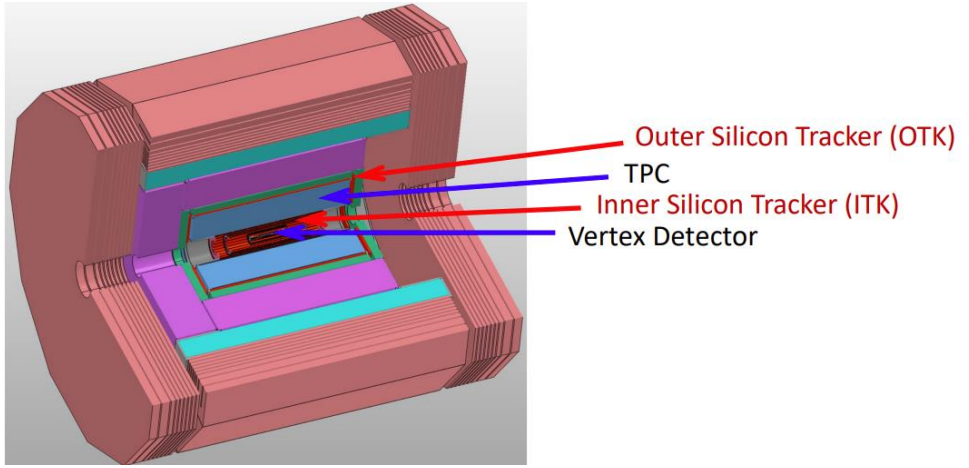
应用于CEPC TOF out-tracker

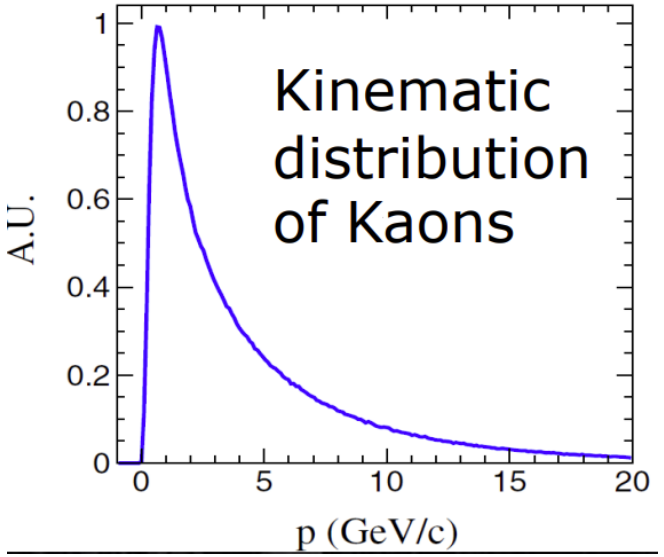
CEPC

- CEPC--huge measurement potential for precision tests of SM: Higgs, electroweak physics, flavor physics, QCD/Top
- Produce 10^{12} Z boson at Z pole: **Rich flavor physics program**
- Particle separation problems of Gas detector (dE/dx) :

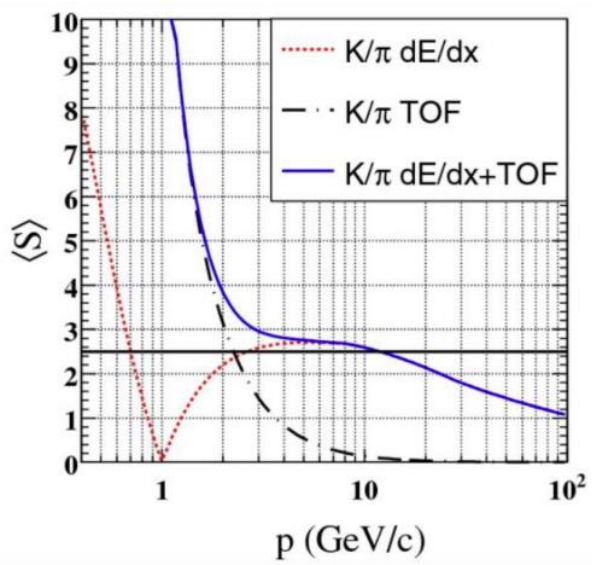
  0- 1 GeV for K/pi separation, 2 GeV for K/p separation
- Timing detector is complementary to gas detector:

  improves the separation ability: 0 - 4 GeV for K/pi separation, 0 – 8 GeV for K/p separation
- Outer layer adjacent to TPC， Barrel : 70 m^2 , Endcap 20 m^2

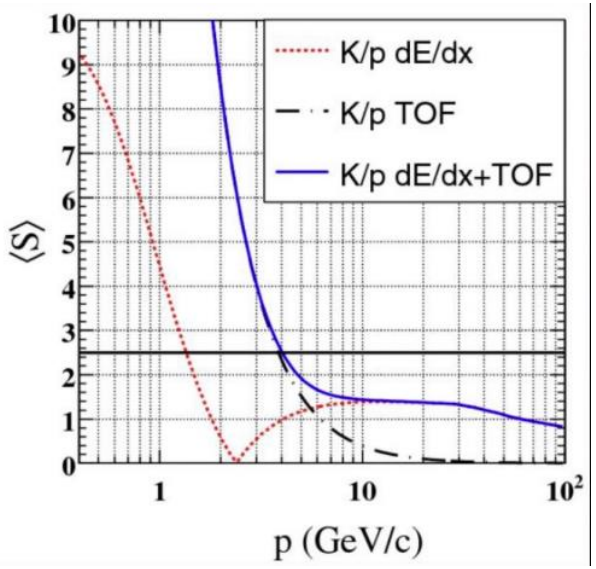




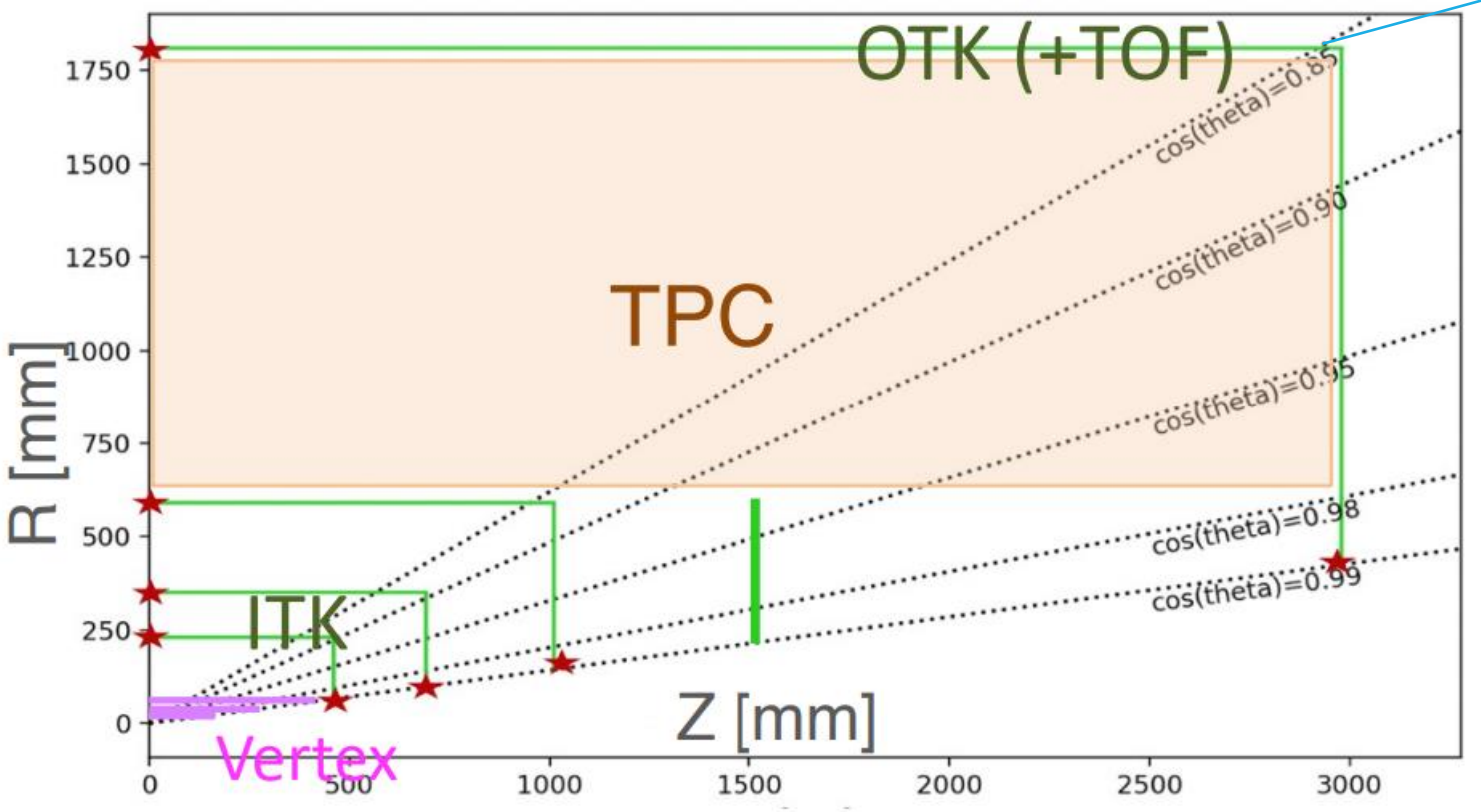
K/pi separation



K/p separation

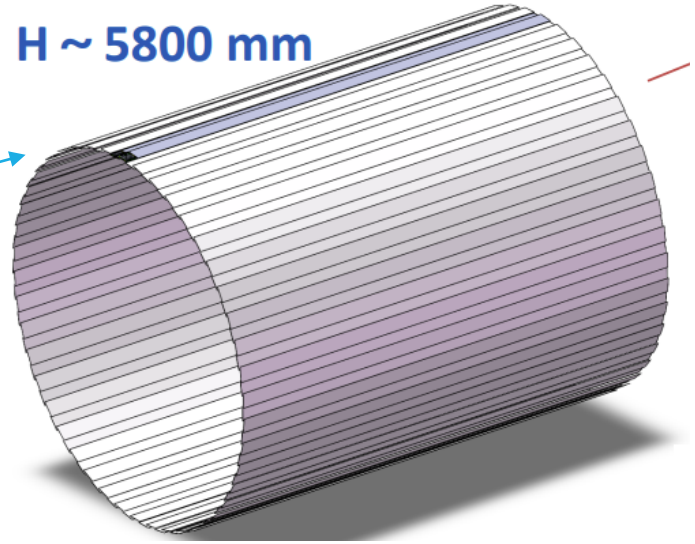


CEPC out-tracker

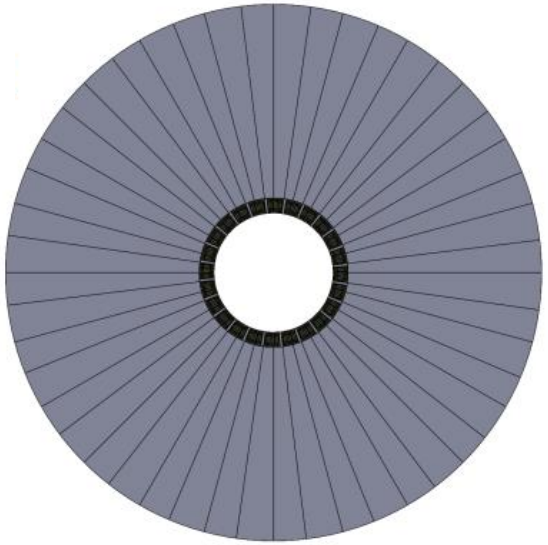


Barrel

R= 1800 mm
H ~ 5800 mm



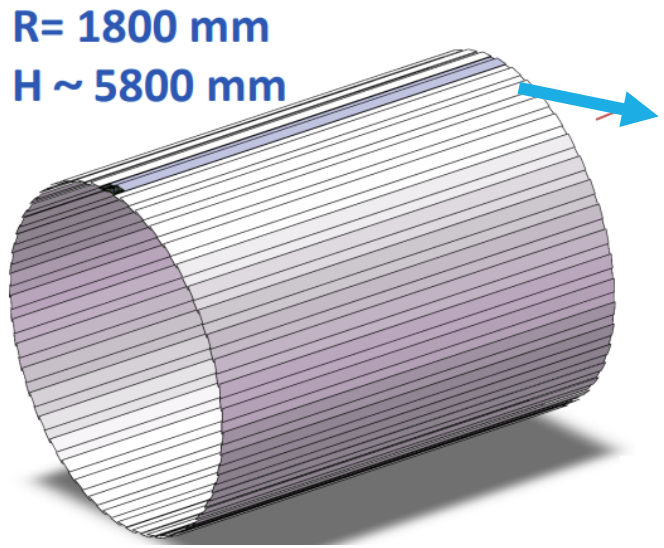
Endcap

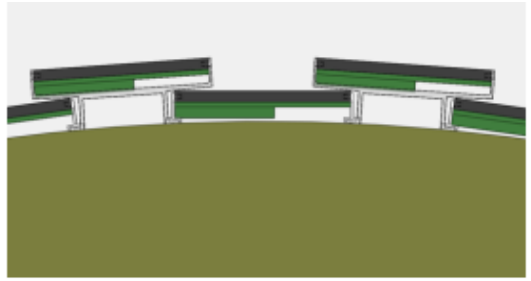


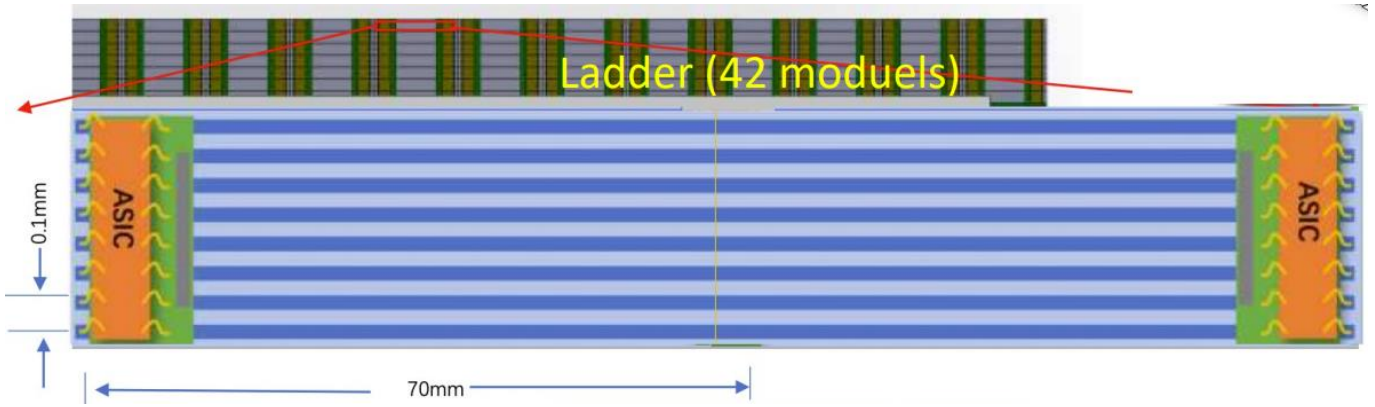
CEPC out-tracker结构设计

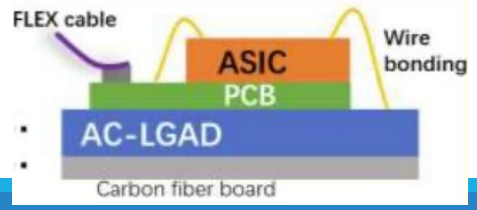
	Barrel
面积	~70 m^2
半径	1.8m
长度	5.8m
颗粒度	70mm x 0.1mm
通道数	~1x10^7
Ladder number	90
Module area	140mm x 160mm (2 sensors and 22 ASICs)
Module number per ladder	42
ASIC per module	22
Channel number per ASIC	128

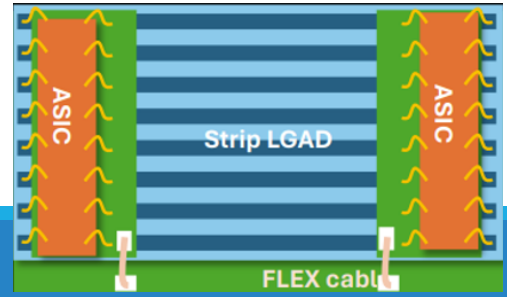
MIP Time resolution	~50 ps LGAD:37.5ps
Spatial resolution	~ 10 μm (R-Φ) LGAD:8μm ~ 1 mm (R-Z direction) LGAD:0.9mm







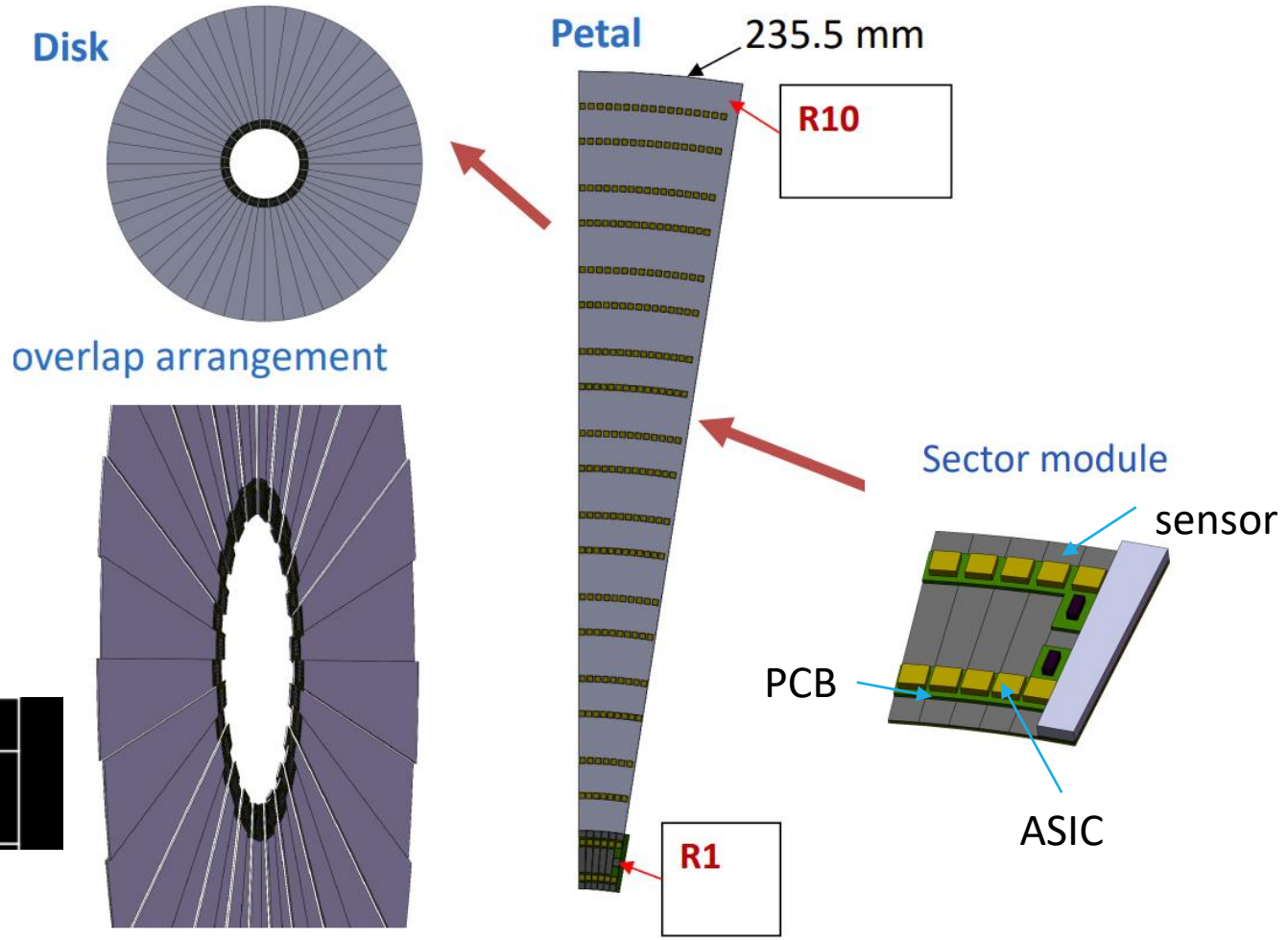




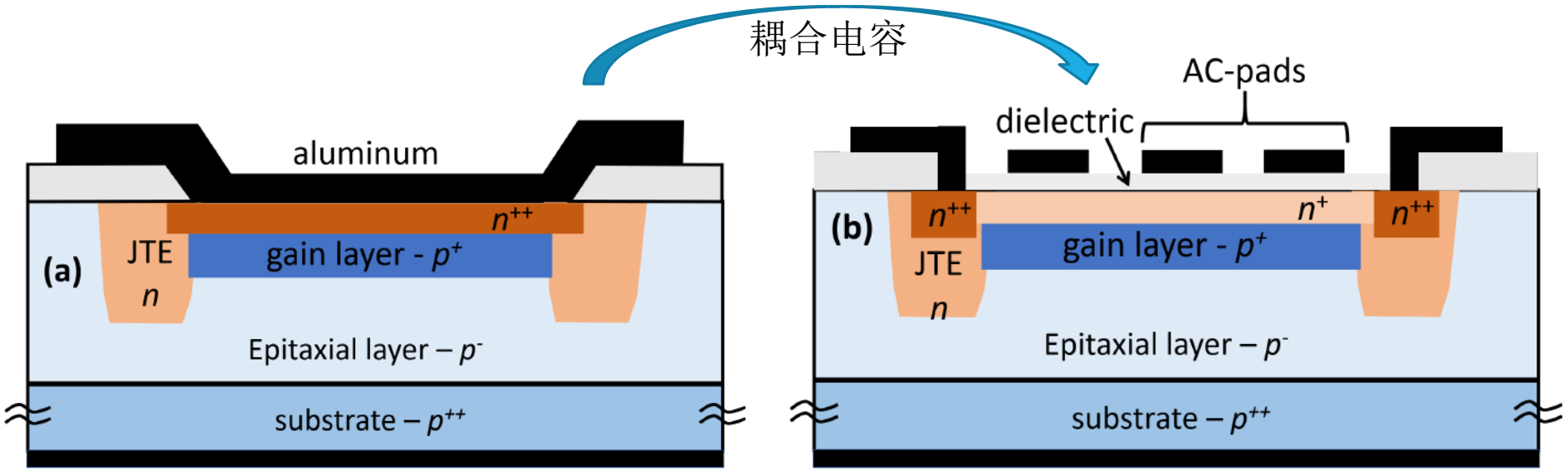
CEPC out-tracker结构设计

	Endcap
面积	~20 m^2
petal number	48
Sector module Number per petal	10

MIP Time resolution	~50 ps LGAD:37.5ps
Spatial resolution	~ 10 μm (R-Φ) LGAD:8μm ~ 1 mm (R-Z direction) LGAD:0.9mm



AC-LGAD



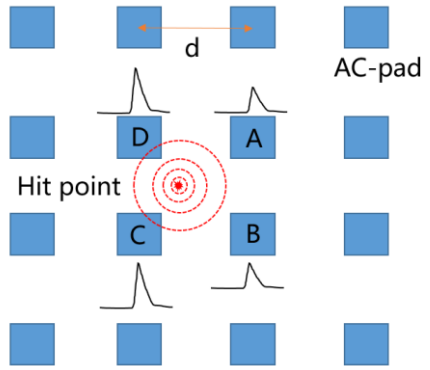
传统LGAD

- 直流读出
- 时间分辨~ 30ps
- 位置分辨:像素尺寸/√12
- 死区: JTE, Pstop, ~100um

AC-LGAD

- 电容耦合读出AC coupled readout electrode
  各个电极收集电荷的大小与粒子入射位置相关
- 时间分辨~ 30ps
- 位置分辨: <10um
- 死区 : 0 mm (no dead zone)

Signal of AC-LGAD



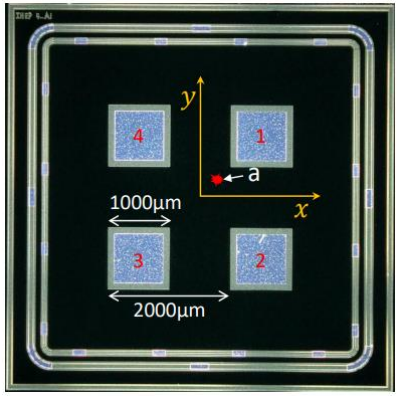
各耦合单元收集到的电荷数量与单元和粒子入射位置的相对距离有关。通过对耦合单元的电荷进行收集与分析，可重建出粒子入射位置，实现对粒子入射的位置信息进行分辨。

具有高的时间和位置分辨能力4D detector

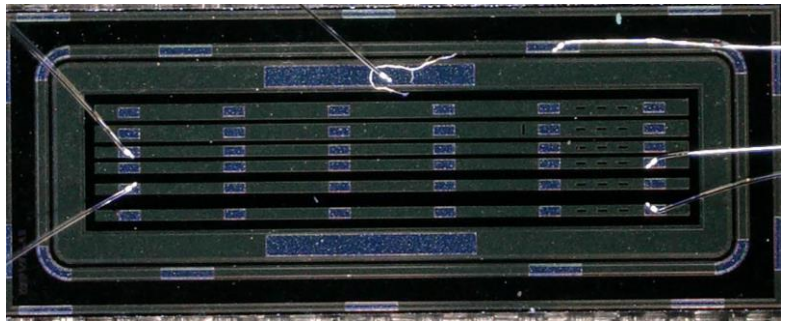
IHEP AC-LGAD

IHEP AC-LGAD 设计与工艺研究

Design of AC-coupled low gain avalanche diodes (AC-LGADs): a 2D TCAD simulation study
JINST，2022.9
DOI:10.1088/1748-0221/17/09/C09014

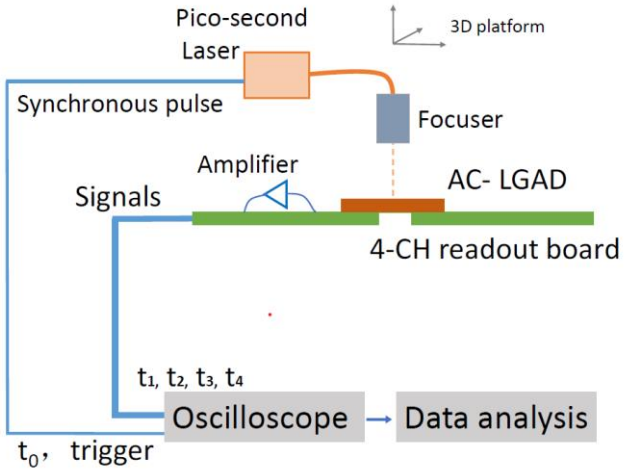


具有不同工艺参数的**pixel型AC-LGAD**

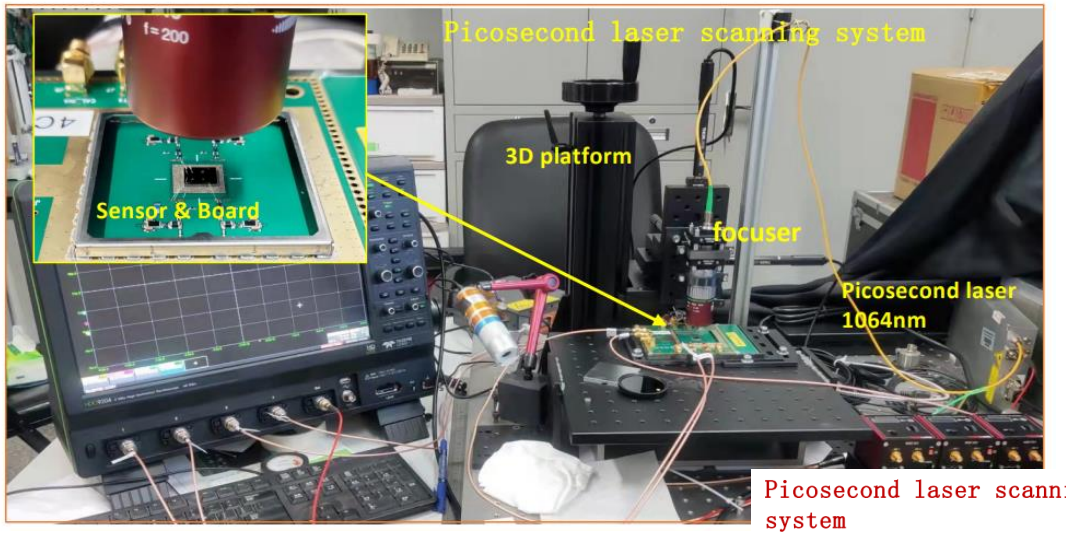


具有不同pad-pitch尺寸的Strip型AC-LGAD

IHEP AC-LGAD 激光测试系统

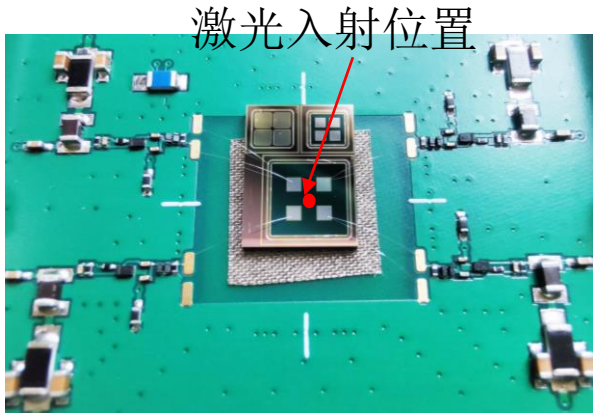


Picosecond Laser: 1065 nm



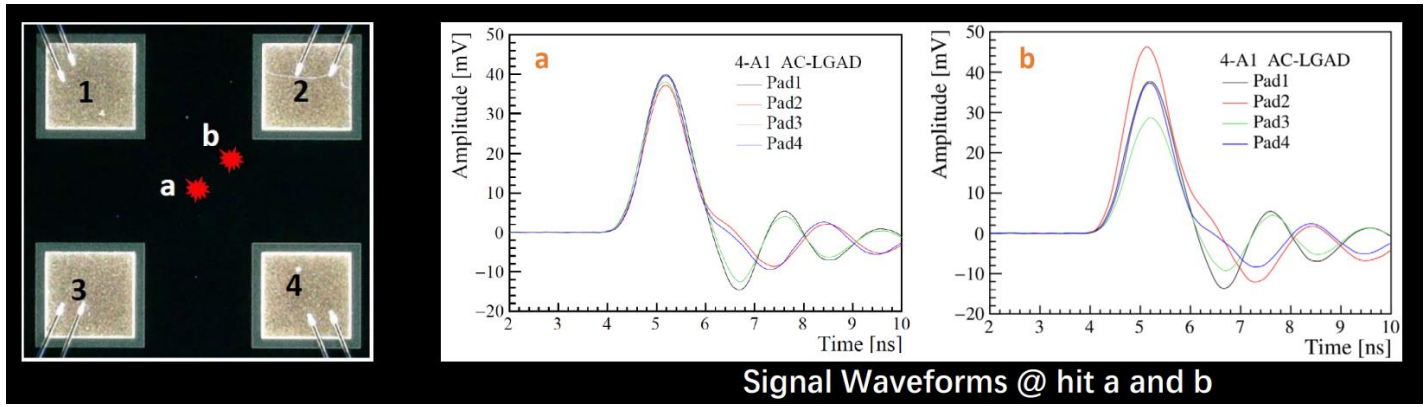
激光测试平台

Picosecond laser scanning system
- Displacement accuracy 1 μm
- Automated scanning
- Picosecond laser 1064nm
- Spot size 2~5 μm



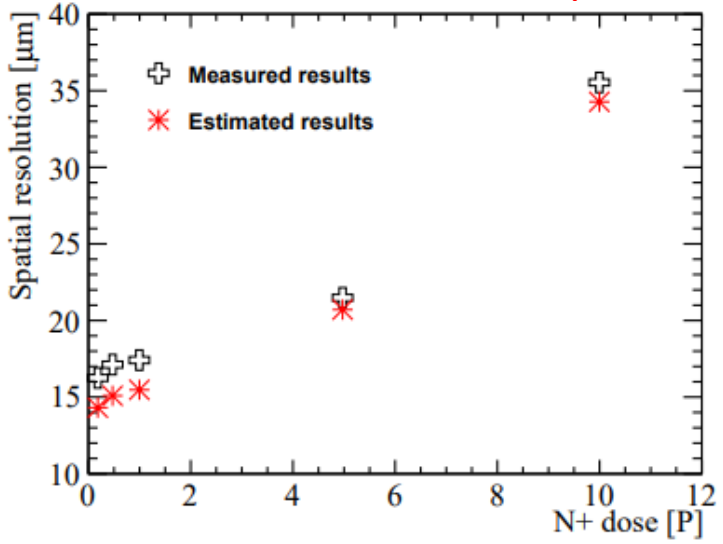
器件与四通道读出板引线连接

IHEP AC-LGAD



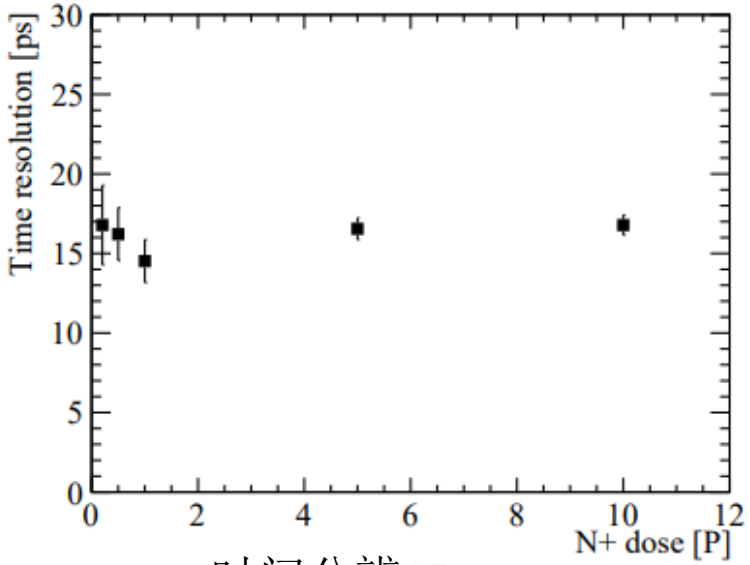
Pixel型的AC-LGAD

Pad-pitch：1mm-2mm

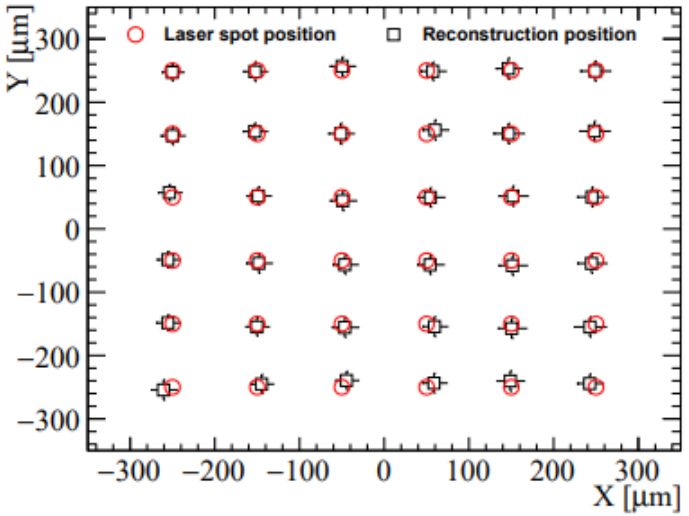


N++层浓度越低，位置分辨能力越优。

最优位置分辨15um



时间分辨15ps



入射36个点位置重建情况

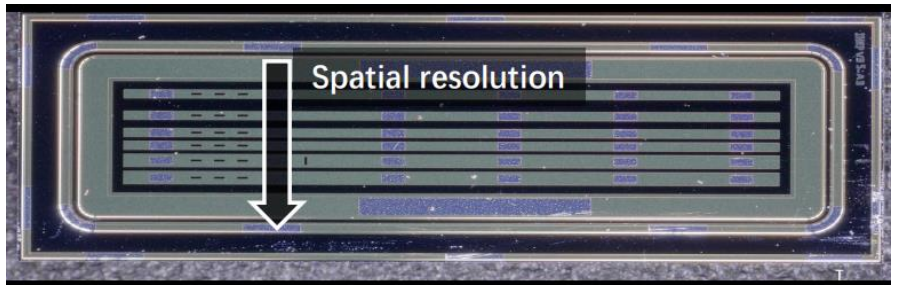
Pad-pitch尺寸器件
100-500um
100-300um
100-200um
50-100um

测试进行中

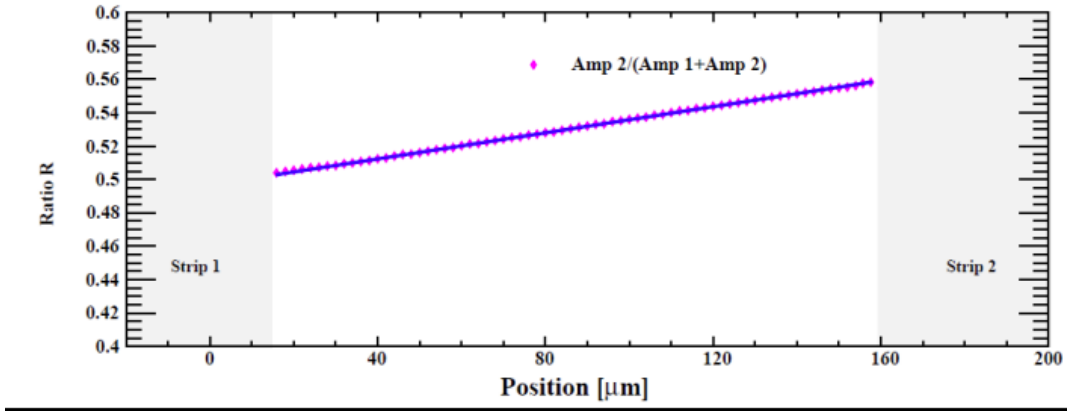
Paper：The performance of large-pitch AC-LGAD with different N+ dose，Trans. Nucl. Sci.，2023.6

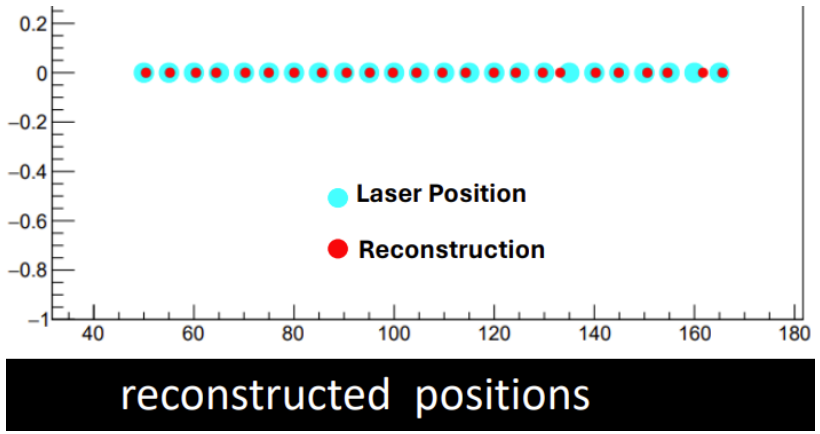
IHEP AC-LGAD

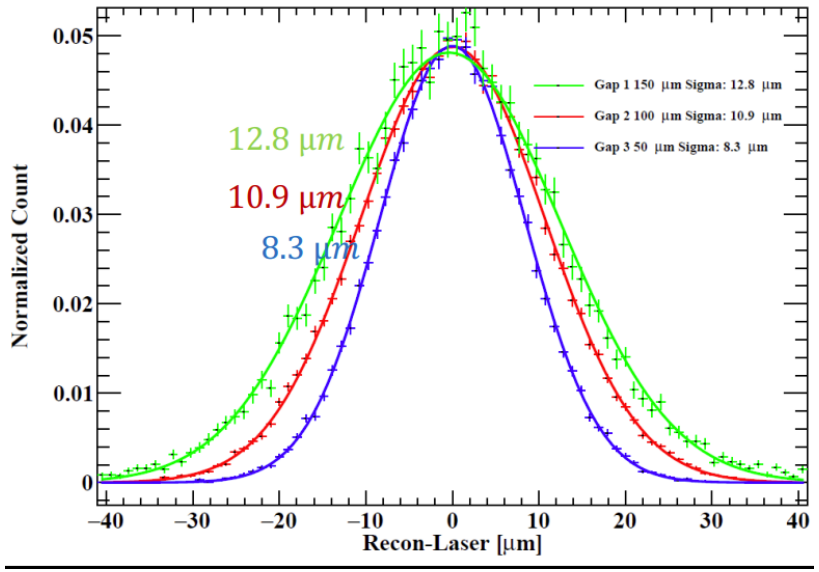
Strip型的AC-LGAD

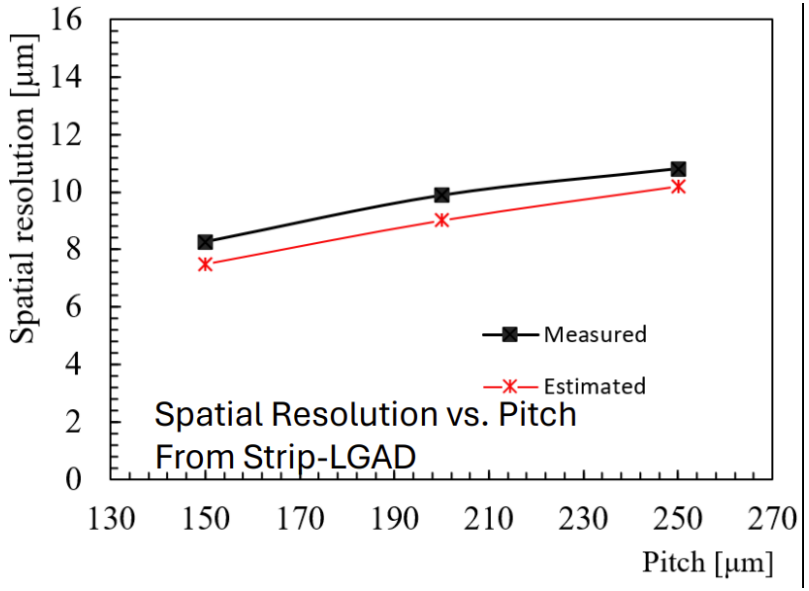


具有不同gap的Strip型AC-LGAD









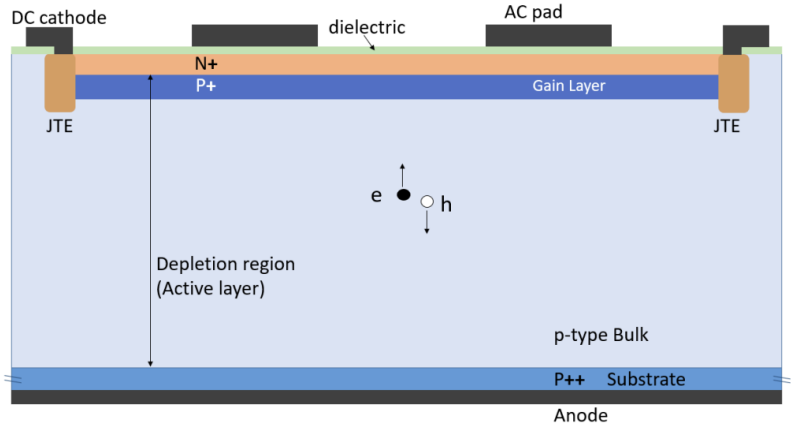
Gap 50um：最优位置分辨~8um

The performance of AC-coupled Strip LGAD developed by IHEP, NIMA, Volume 1062, May 2024, 169203

LGAD探测器发展与应用

- **传统LGAD → AC-LGAD，DJ-LGAD，inverse LGAD，Monolithic LGAD**

（a）

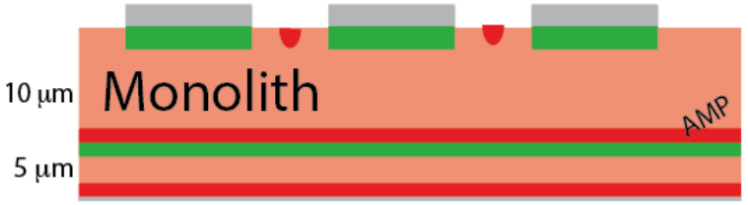


AC-LGAD: 耦合电极
同时实现时间和位置分辨，4D
位置分辨<10um，时间分辨<35ps

研究单位：高能所，科大，美国
BNL，欧洲FBK， INFN等

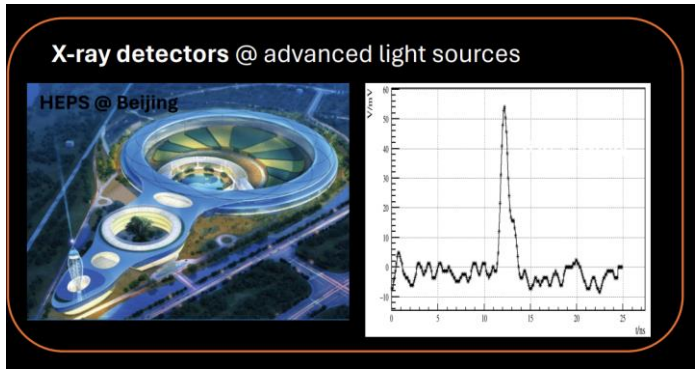
减少死区，低能X射线，PSI，巴西光源

（d）



LGAD上方做ASIC电路
费米实验室，日内瓦大学，
INFN，CNM，FBK等

LGAD探测器应用拓展



传统-LGAD：

- **ATLAS HGTD 项目：批量生产与质量监控**
- **CMS项目: Timing information, 参与市场调研，通过性能评估**
- **ATLAS BMA项目：束流检测Beam monitor**
- **东莞质子束流监测**
- **X射线探测：怀柔光源线站，空间X射线探测，低能X射线探测，优化设计进行中**

AC-LGAD：

- **CEPC outer-tracker and TOF：**
  prototype design：1cm，2cm，4cm length；扇形器件；8月底提交流片
- **暗光计划（Dark SHINE)**
- **激光、医学成像应用？**

Monolithic LGAD：单片式LGAD时间探测器，同时具备时间（<100ps）和位置分辨能力。