

LGAD探测器研究进展

中科院高能所
赵梅

基于HIAF集群的高精度测量和新物理前沿研讨会

2023-7-6

报告内容



- LGAD探测器研究背景
- LGAD探测器研发进展
- 高能所LGAD探测器辐照前后性能
- 高能所LGAD探测器束流测试结果
- 新型AC-LGAD探测器
- 总结

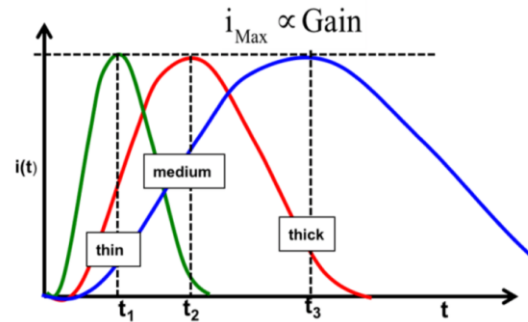


低增益雪崩二极管

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

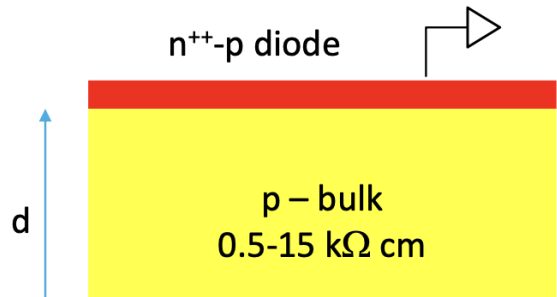
➤ 工作在击穿电压之下 (线性区), 增益>10, 具有良好的时间分辨特性(20-30ps)

- 相比于普通的PIN器件, 在P和N之间多了一层额外的增益区
- 与APD 和 SiPM比较, LGAD具有适中的增益 (10-50)
 - 信噪比高, 无自触发
 - 薄的耗尽区 (漂移区), 提高电场与电子漂移速度

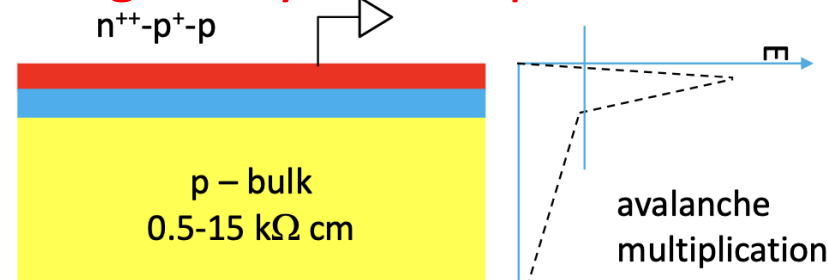


$$\sigma_{jitter}^2 = \left(\frac{t_{rise}}{S/N} \right)^2$$

一般的 PIN结探测器



低增益雪崩硅探测器
P+ gain layer on top of PIN diode



LGAD探测器研究背景

➤ 欧洲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

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 $2.5 \times 10^{15} n_{eq}/cm^2$ 的等效中子通量的辐照

- Two double-side layers mounted on the cooling disk
radius $120\text{ mm} < R < 640\text{ mm}$ corresponding to $2.4 < |\eta| < 4$

- 模块: 8032个

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

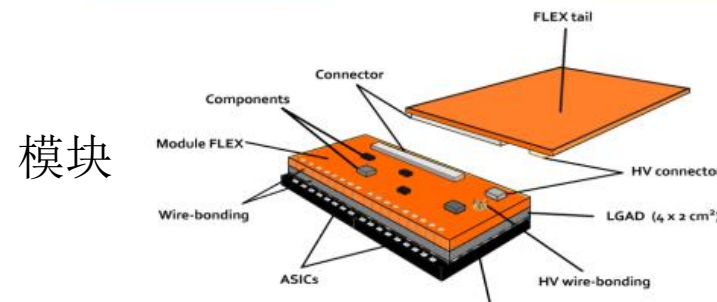
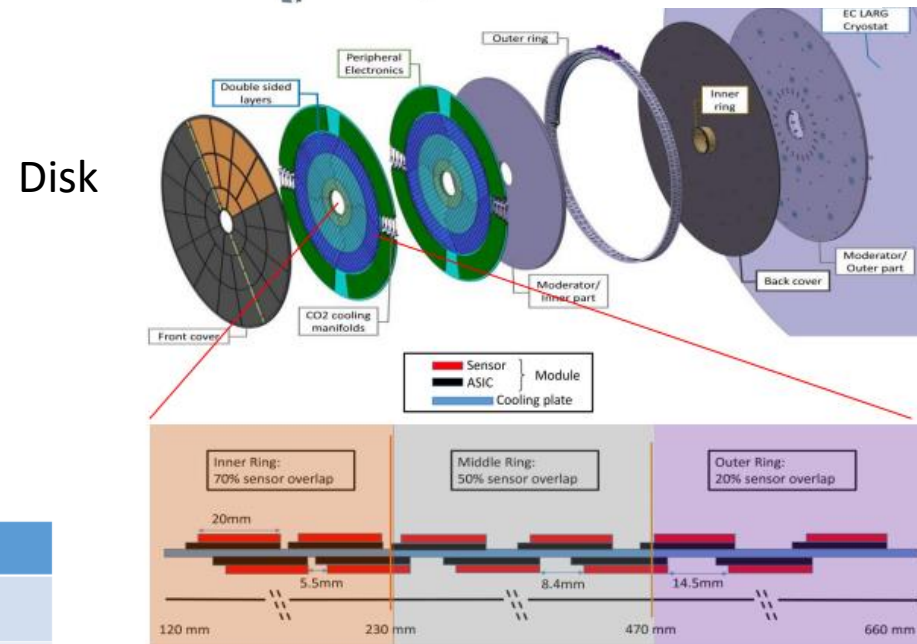
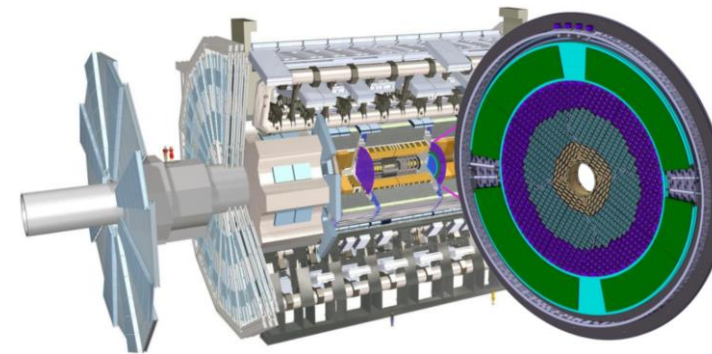
- HGTD探测器研制关键是LGAD探测器。
时间分辨率可达30-50皮秒, 从而提高区分堆积的能力, 改进前向区域的粒子重建。

- **HGTD 需求LGAD探测器: >2万颗**

- **CMS 需求LGAD探测器: ~4万颗**

- **HIAF 上的高能谱仪?**

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

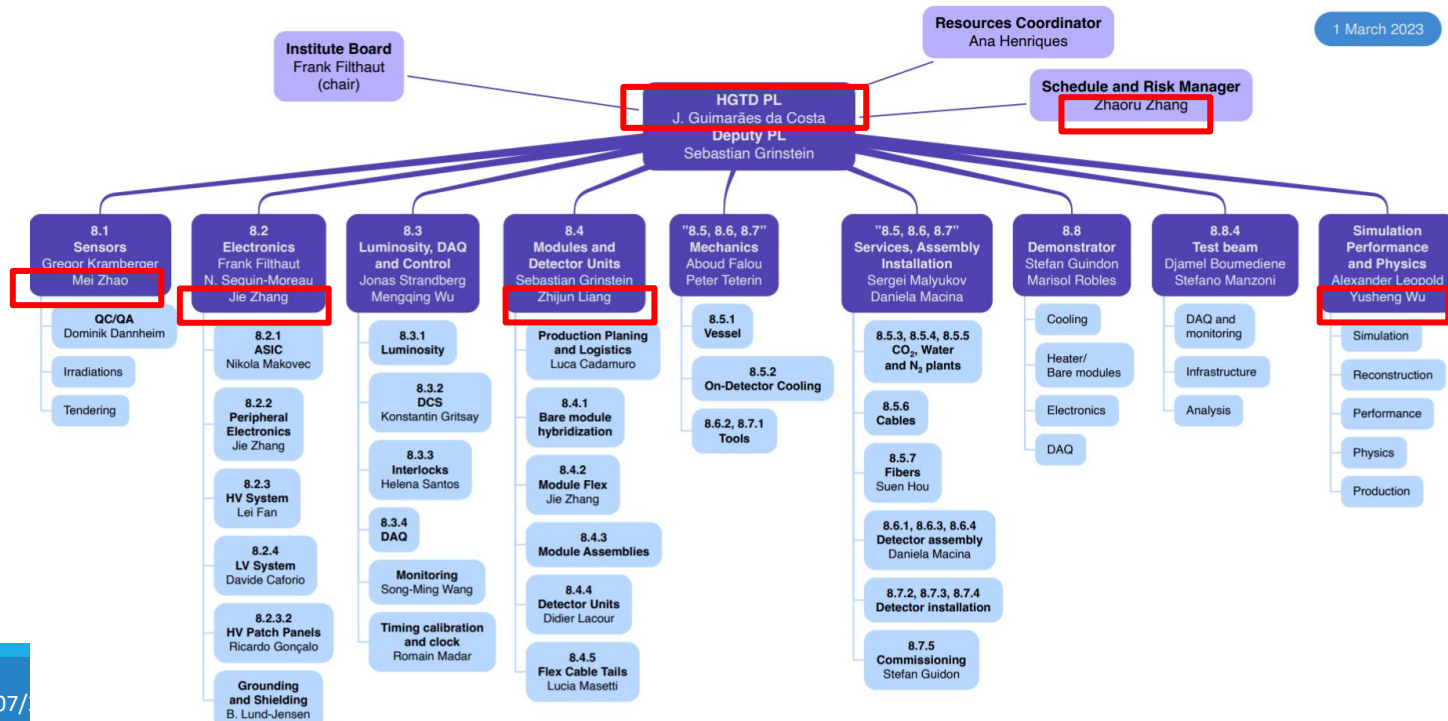




ATLAS高时间分辨探测器：重要管理职位

- 中国组在ATLAS高颗粒的时间探测器项目（HGTD）中起主导作用
 - 高能所Joao担任HGTD项目经理，ATLAS实验Level-1管理职位
 - 中国组首次在LHC实验子探测器担任项目经理
 - 5人担任探测器Level-2召集人（赵梅，张杰，梁志均，张照茹，吴雨生）
 - 1人担任探测器Level-3召集人（樊磊）
 - 1人担任speaker committee（刘衍文）

HGTD项目的管理架构





LGAD探测器：国内外研究现状

- 国内：IHEP-IME (高能所-微电子所), USTC-IME (科大-微电子所), NDL(北师大)
- 国际：滨松HPK (日本)，FBK (意大利)，CNM (西班牙) ...

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

ATLAS HPK-P2 (2020) CMS

FBK-UFSD 3.2 (2020)

CNM-12916 (2019)

- ATLAS 5x5, 1.3 mm, IP 37
- ATLAS 5x5, 1.3 mm, IP 47
- ATLAS 5x5, 1.3 mm, IP 57
- LGAD Pad, 1.0 mm, IP 57
- LGAD Pad, 1.0 mm, IP 47
- LGAD Pad, 1.0 mm, IP 37
- PIN Pad, 1.0 mm, IP 37
- PIN Pad, 1.0 mm, IP 47
- PIN Pad, 1.0 mm, IP 57
- PIN Pad, 1.3 mm, IP 37
- PIN Pad, 1.3 mm, IP 47
- PIN Pad, 1.3 mm, IP 57
- LGAD Pad, 1.3 mm, IP 37
- LGAD Pad, 1.3 mm, IP 47
- LGAD Pad, 1.3 mm, IP 57
- ATLAS 2x2, 1.3 mm, IP 57
- ATLAS 2x2, 1.3 mm, IP 47
- ATLAS 2x2, 1.3 mm, IP 37
- ATLAS 2x2, 1.0 mm, IP 37
- ATLAS 2x2, 1.0 mm, IP 47
- ATLAS 2x2, 1.0 mm, IP 57

IHEP-IME-V2 run (07/2021) 8" 高能所

USTC-IME_2.x (2020) 8" 科大-微电子所

NDLv4 (2021) 北师大

NDLv3 (2020)

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



高能所LGAD探测器研发进展

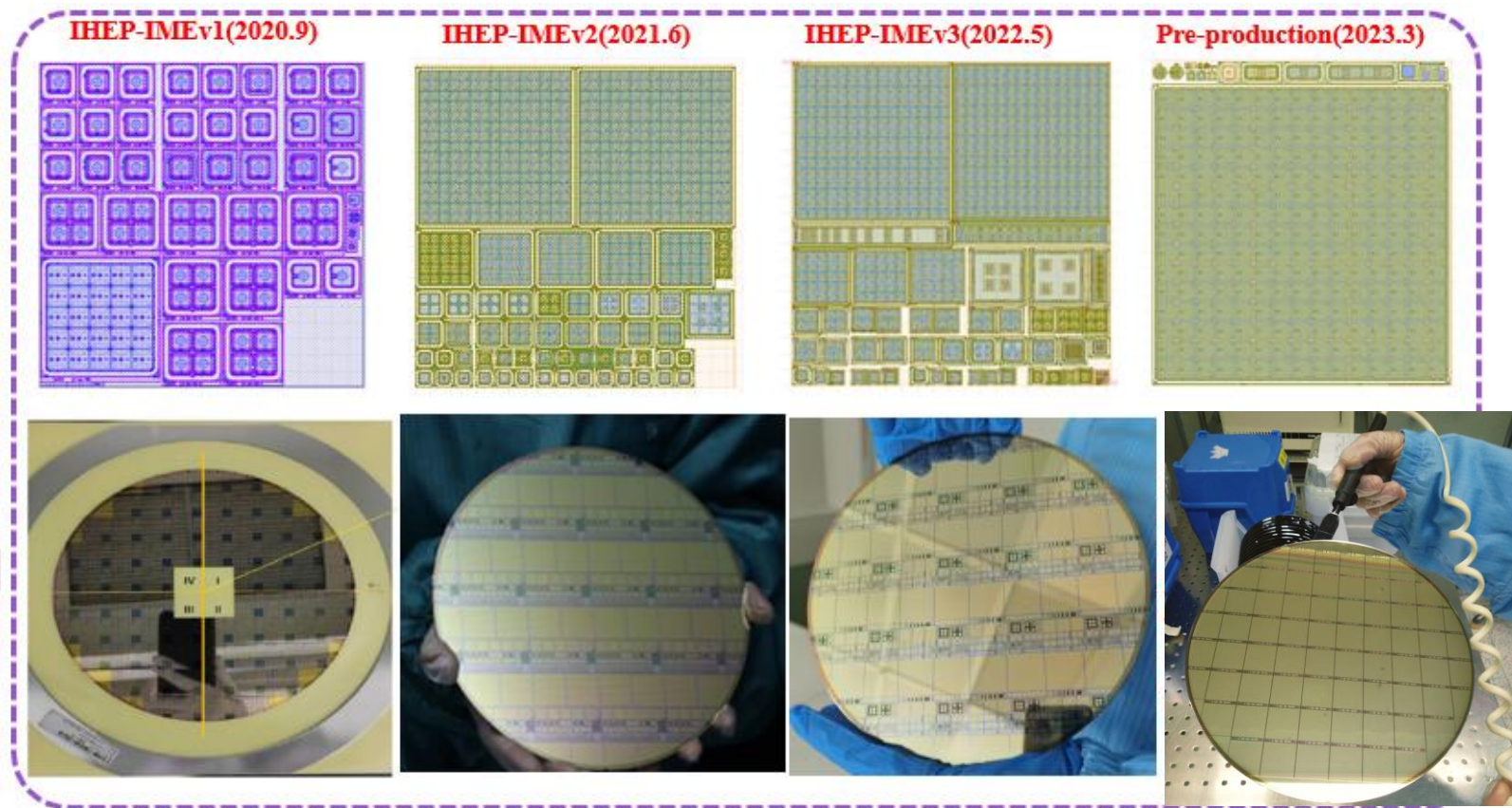
高能所从2018年起致力于LGAD探测器的研发，自主设计版图与工艺参数，并基于微电子所8寸工艺线多次流片，成功研制出了具有良好时间分辨与抗辐照性能的国产LGAD探测器。

- 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HGTD项目LGAD器件批量预生产，第一批已流片完成，初测性能符合预期

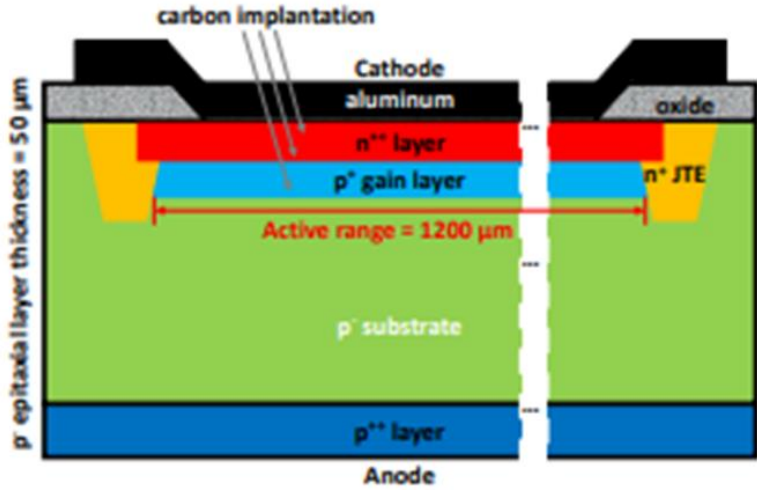
高能所自主研发的LGAD器件参与CERN HGTD项目 market survey，并获得项目CERN的全部市场份

参与CMS项目market survey





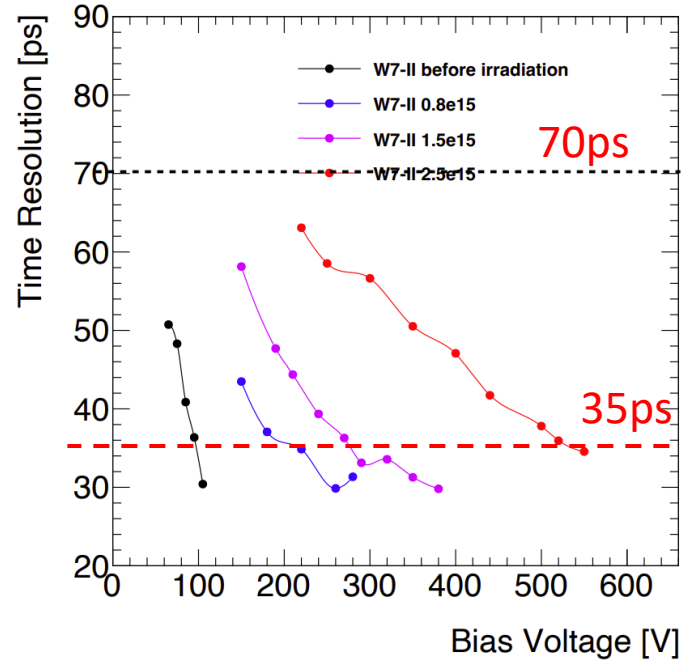
高能所LGAD探测器：性能



Sensor	Diffuse*	C dose(a.u.)	C factor (x10 ¹⁶ cm ²)	
W4	Q1	CLBL	0.2	2.57
	Q2	CLBL	1	1.77
	Q3	CLBL	5	1.60
	Q4	CLBL	10	1.50
W7	Q1	CHBL	0.2	1.62
	Q2	CHBL	0.5	1.14
	Q3	CHBL	1	1.18
	Q4	CHBL	3	1.34
W8	Q1	CHBL	6	1.30
	Q2	CHBL	8	1.32
	Q3	CHBL	10	1.23
	Q4	CHBL	20	1.29

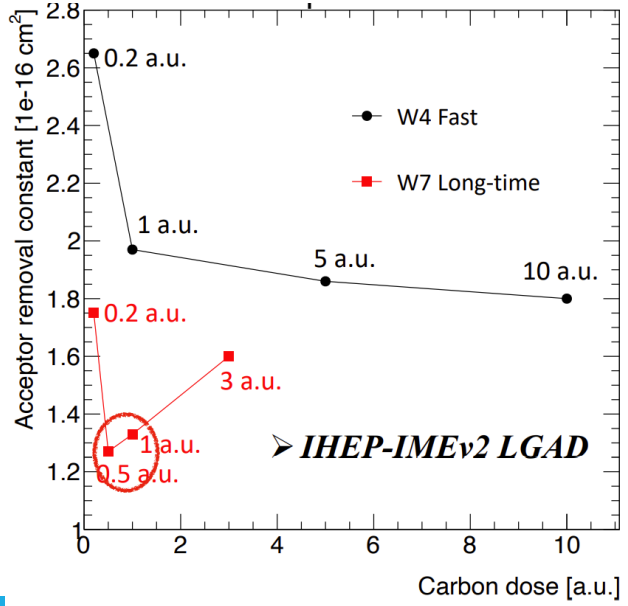
BEST

辐照前后
时间分辨率 vs 偏置电压



➤ 性能研究:

- 制备了12种不同的LGAD器件：不同的碳注入剂量和热处理条件
- 在不同的条件里，存在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）



➤ IHEP-IMEv2 LGAD

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

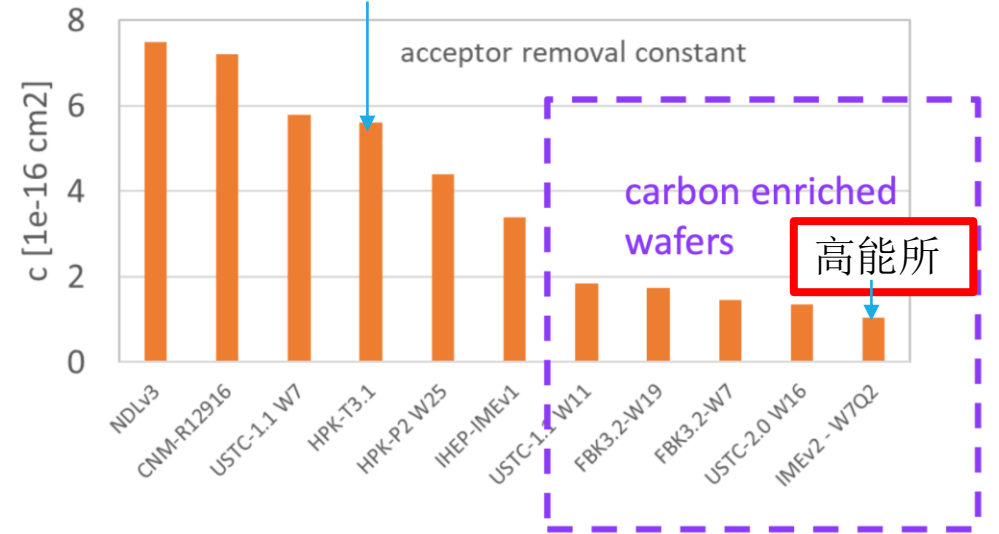
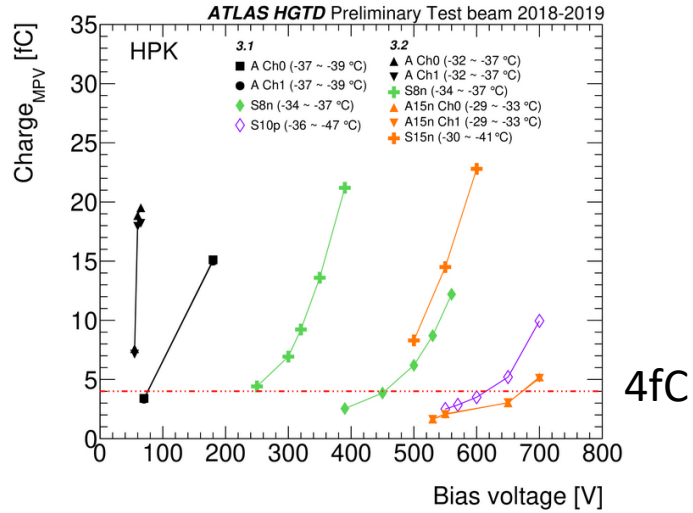


LGAD探测器抗辐照性能

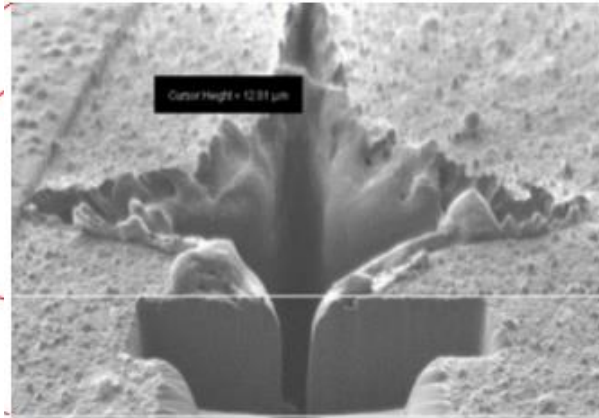
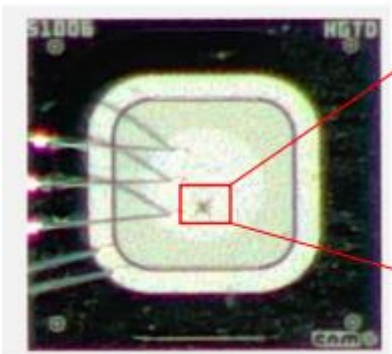
➤ 辐照后，受主移除效应（增益区有效浓度降低），增益下降，收集电荷变少，时间分辨特性变差

高能所自主研发的掺碳LGAD器件具有较小的受主移除率，抗辐照性能优于国内外LGAD探测器

日本滨松



➤ 增大工作电压后，在束流测试时出现单粒子烧毁的情况



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）

• SEB现象：Observed by CMS/ATLAS/RD50 teams



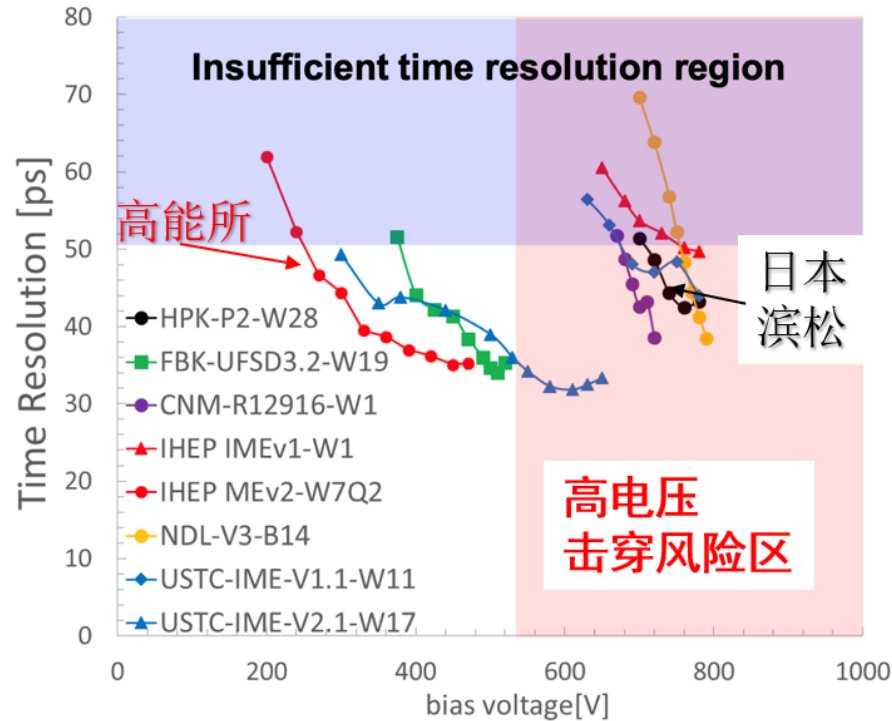
高能所LGAD探测器：性能

高能所LGAD器件辐照后（ $2.5e15cm^{-2}$ 等效中子辐照）：

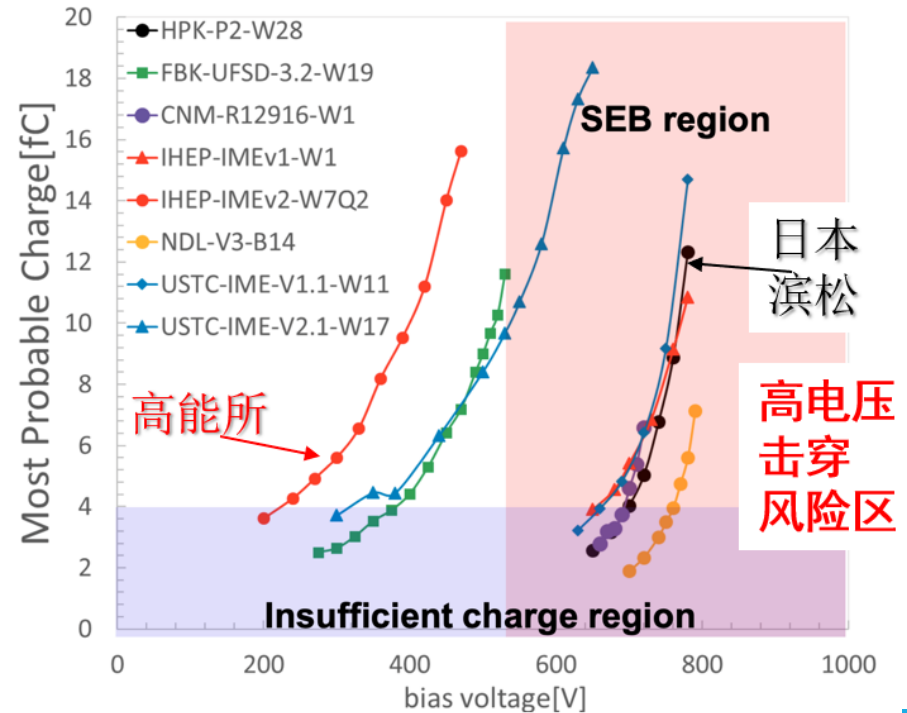
- 在低于400V的电压下收集足够的电荷（ $>4fC$ ）
- 达到30-50ps的时间分辨特性
- 有效避免束流测试中的单粒子烧毁现象(SEB)，完全满足HGTD项目的应用要求。

辐照后（ $2.5e15cm^{-2}$ 等效中子辐照）

时间分辨率 vs 偏置电压



电荷收集 vs 偏置电压



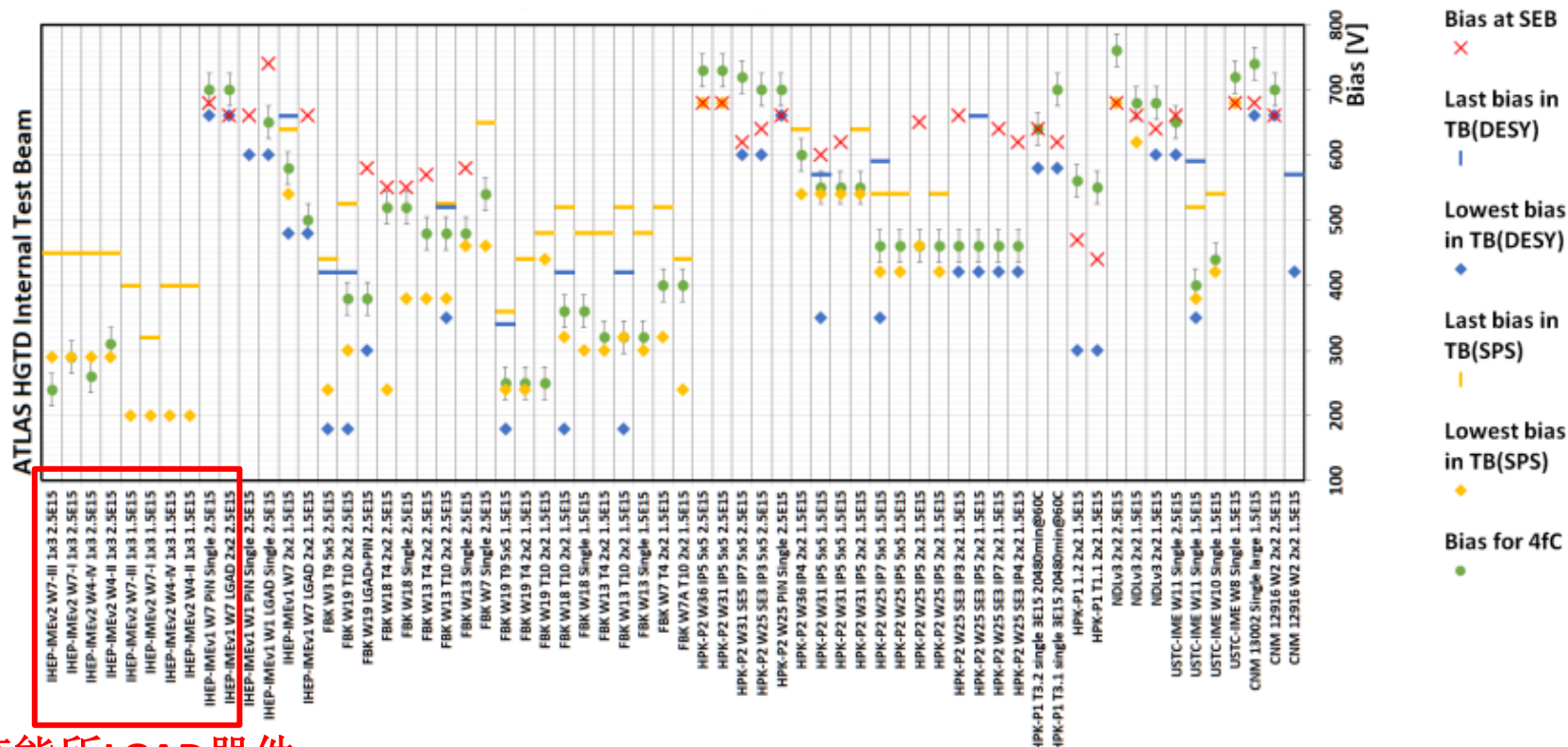


高能所LGAD探测器：束流测试

ATLAS合作组开展欧洲核子中心（CERN）的高能质子流测试：

辐照后，不掺碳的LGAD（滨松，西班牙CNM）烧毁率较高

高能所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



高能所LGAD器件

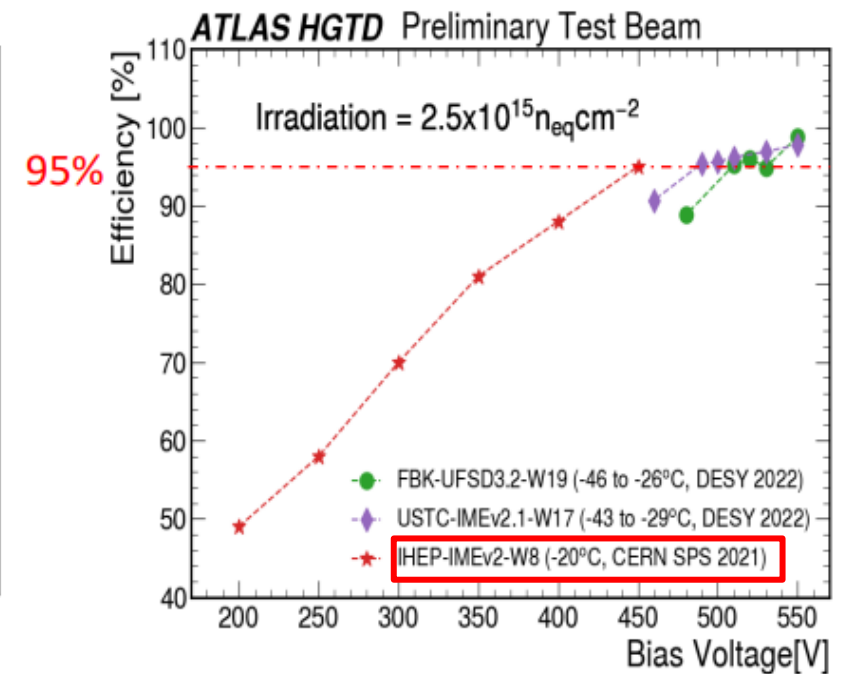
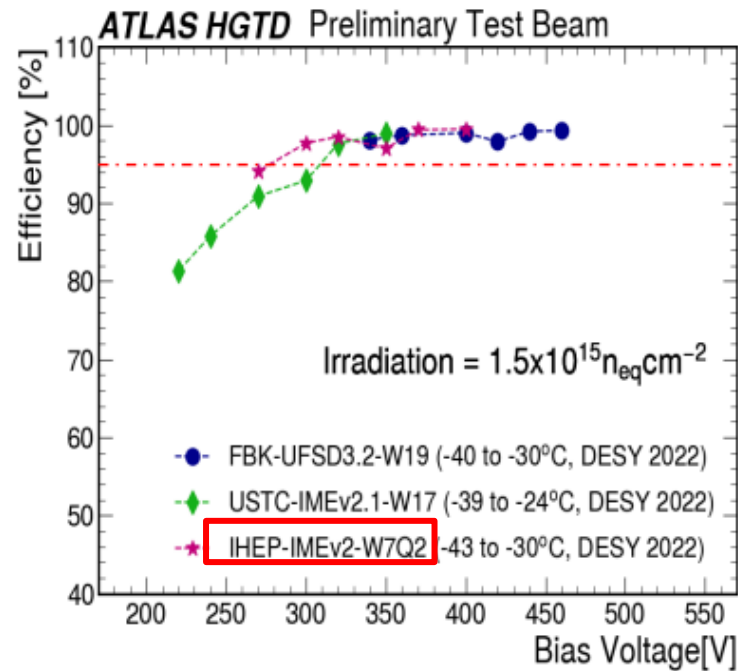
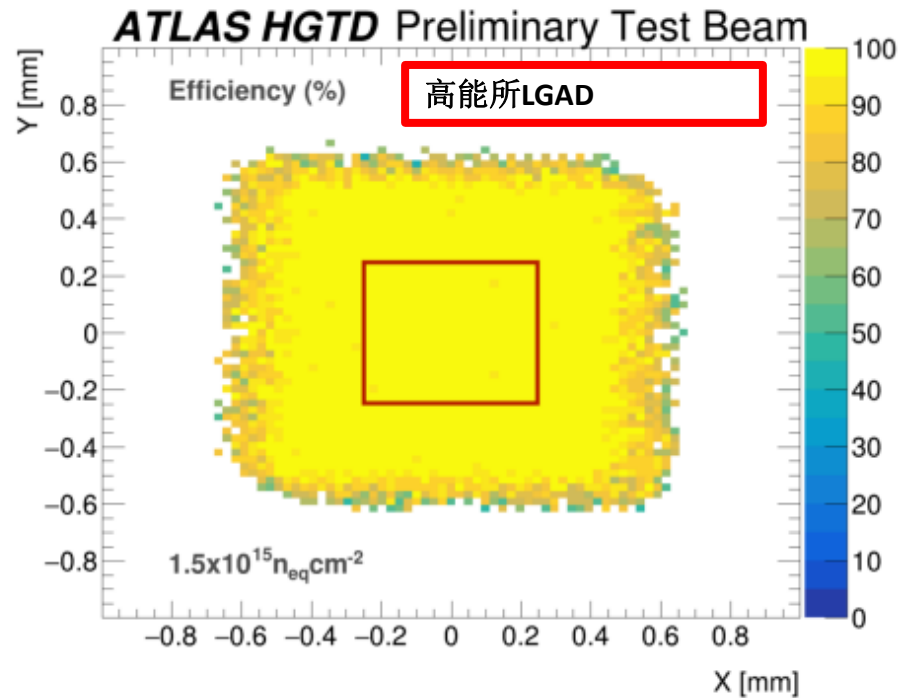
<https://arxiv.org/abs/2306.12269>



高能所LGAD探测器：束流测试

➤ ATLAS合作组DESY和CERN SPS束流测试：

高能所LGAD探测器辐照后的探测效率可达95%~100%

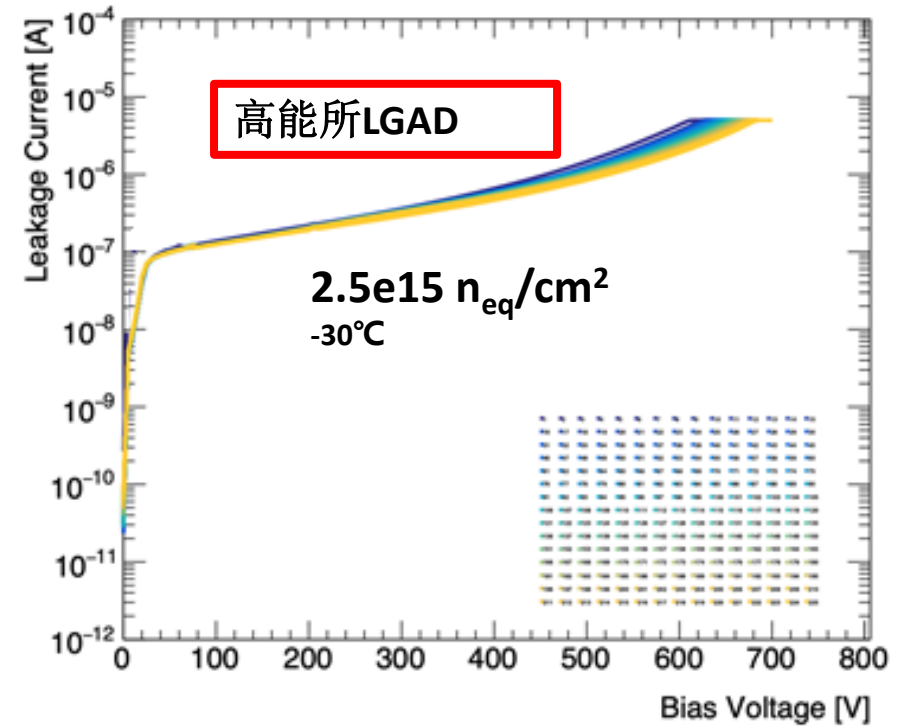
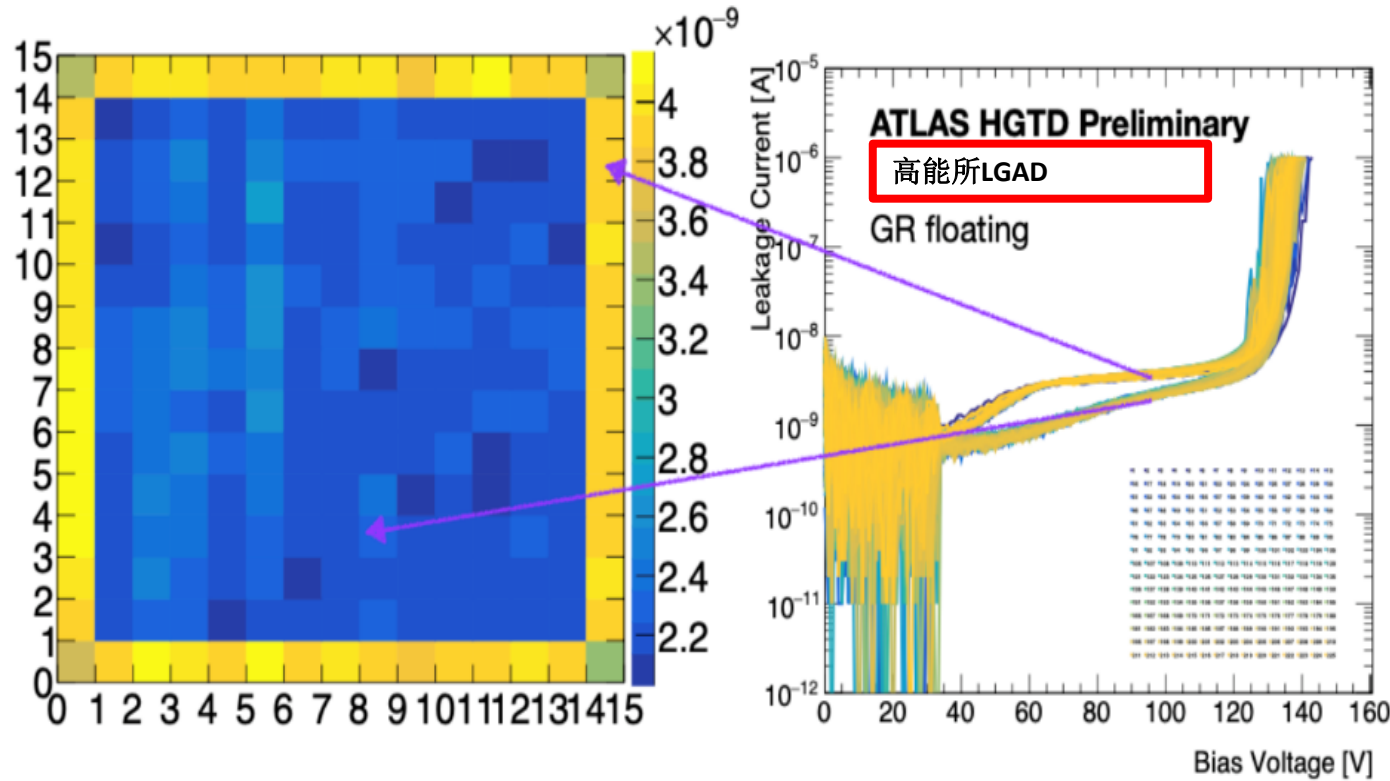


<https://doi.org/10.1088/1748-0221/18/05/P05005>



高能所LGAD探测器

- 高能所LGAD器件 15x15阵列具有良好的电压-电流一致性（辐照前后）
- 裸片测试pad成品率可到99%以上

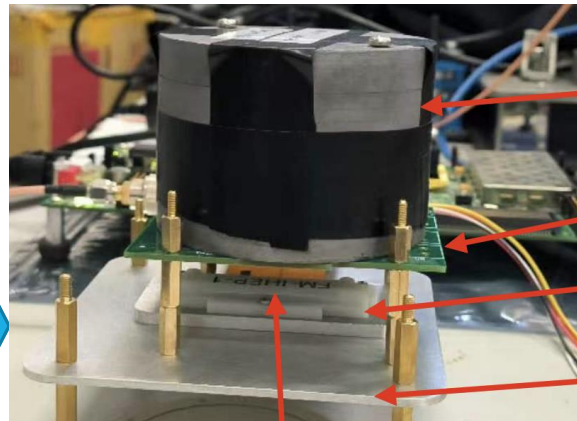




高能所LGAD探测器：模块测试

- ▶ 高能所LGAD 15x15探测器与ASIC通过倒装焊连接，之后对其性能进行测试。这也该项目首批探测器模块原型
- ▶ 在放射源功能测试中225个读出通道均正常工作

首个探测器
模块原型



Sr90

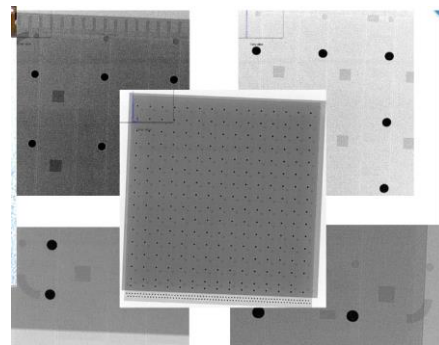
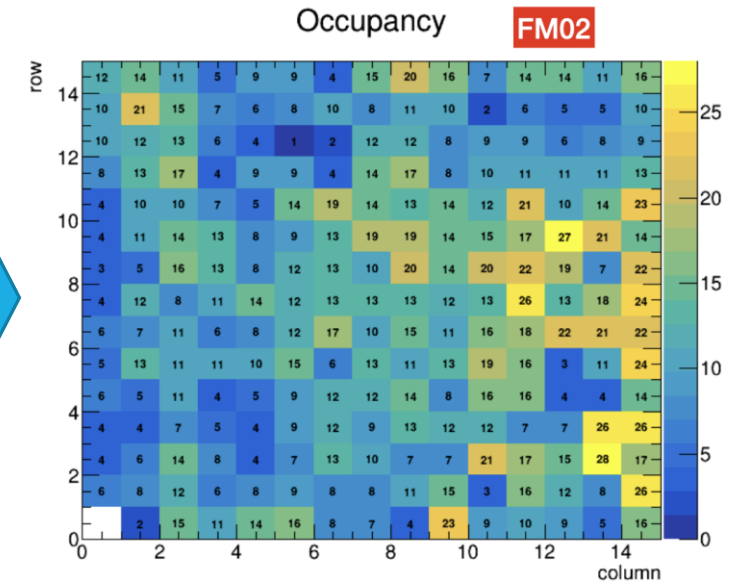
Holder

Full Module

Cooling plate



放射源测试的hit maps

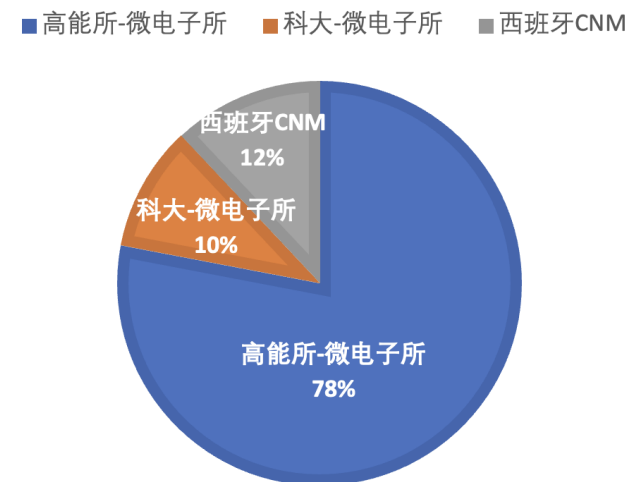


IHEP sensor bonding with Altiroc2



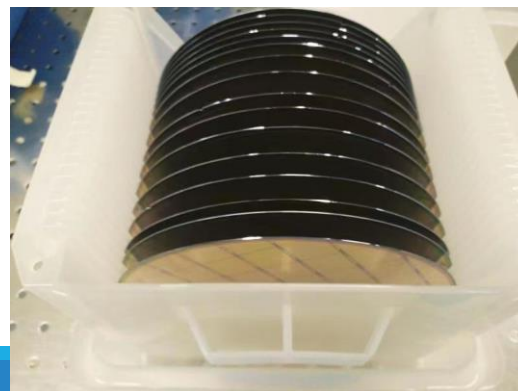
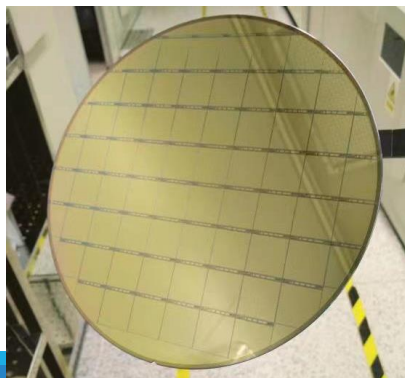
高能所LGAD探测器：量产

- ATLAS实验HGTD时间探测器项目需要>2万个LGAD探测器
- 2023年高能所设计微电子所制备的LGAD探测器赢得CERN的LGAD全额招标订单 (>1万个LGAD)
 - 在日本滨松、意大利FBK等竞争下，高能所-微电子所赢下招标
 - **欧洲核子中心（CERN）首次采购中国产的硅探测器**
- 各单位在该项目LGAD探测器的贡献比重
 - 高能所-微电子所：**78%**（54% CERN国际招标采购+ 24%实物贡献）
 - 中科大-微电子所：**10%** 实物贡献
 - 西班牙 CNM研究所：**12%** 实物贡献



目前处于预生产阶段 LGAD器件在制备中，明年初开始正式生产
第一批预生产器件已完成制备，晶圆级初步测试性能符合预期

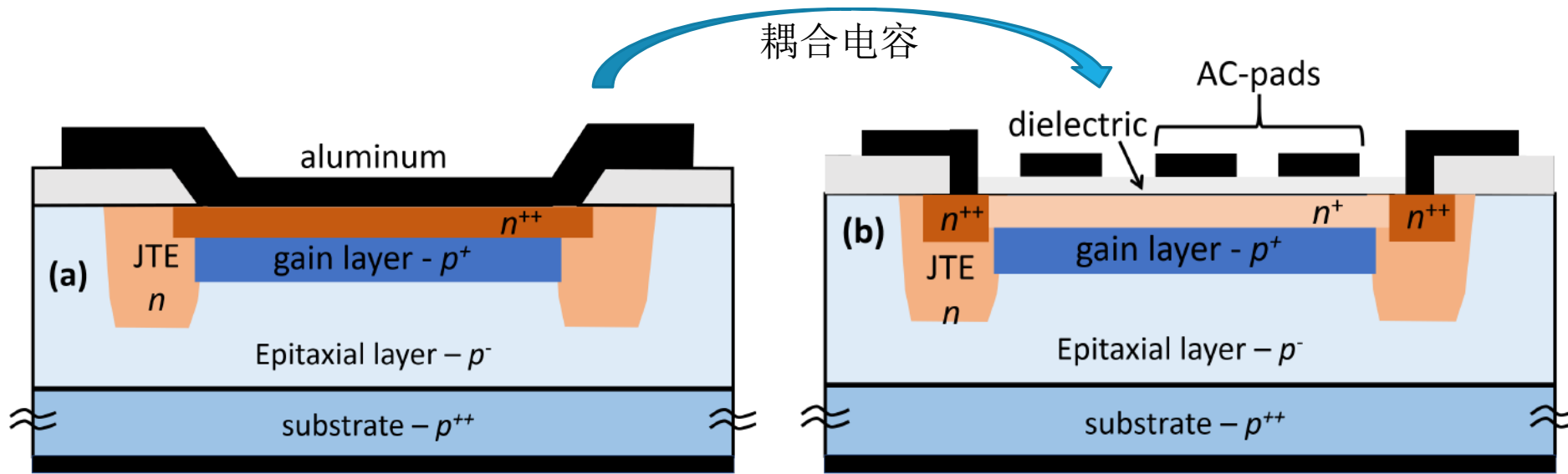
单晶圆有52个
15x15 LGAD器件



18个晶圆
制备完成



AC-LGAD



传统LGAD

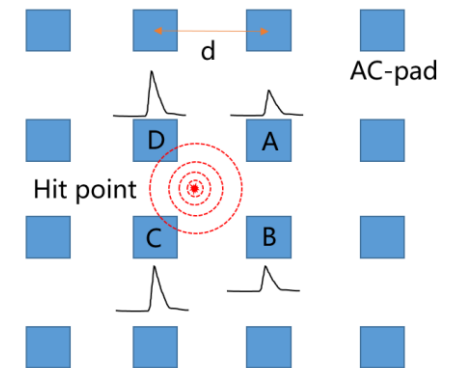
- 直流读出 DC readout electrode
- 时间分辨 Time resolution $\sim 35\text{ps}$
- 位置分辨 Position resolution: sensor size
- 死区 Dead zone: JTE, Pstop, $50\sim 100\mu\text{m}$

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 collected charge from each electrode is related with particle injection position.
- 时间分辨 Time resolution $\sim 35\text{ps}$
- 位置分辨 Position resolution: $<10\mu\text{m}$
- 死区 Dead zone : 0 mm (no dead zone)

4D detector

Signal of AC-LGAD

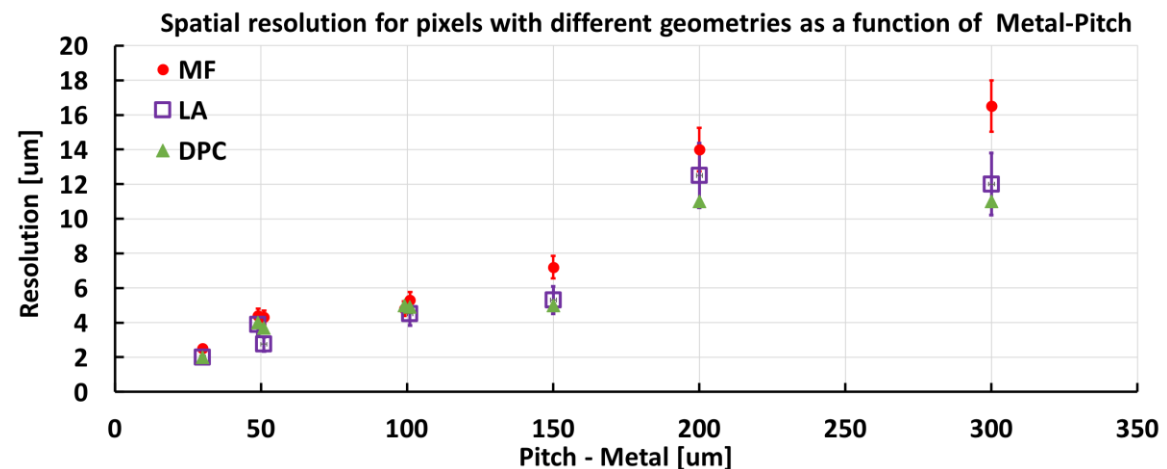


各耦合单元收集到的电荷数量与单元和粒子入射位置的相对距离有关。通过对耦合单元的电荷进行收集与分析，可重建出粒子入射位置，实现对粒子入射的位置信息进行分辨。



AC-LGAD研究现状与应用前景

国内外研究情况：美国BNL，意大利FBK、INFN，国内高能所等研究单位均于近年开展相关研究



[1] M. Mandurrino et al., "Demonstration of 200-, 100-, and 50- μm pitch Resistive AC-Coupled Silicon Detectors (RSD) with 100% fill-factor for 4D particle tracking", IEEE Electron Device Lett. 40(11), 1780-1783 (2019), DOI: 10.1109/LED.2019.2943242

[2] A. Apresyan, et al., Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam, Journal of Instrumentation, 15 (2020) P09038, 2020.

应用：可满足未来对撞机项目上的时间分辨率和空间分辨率的要求，且可用于PET与CT等辐射成像方面

CEPC: AC-LGAD 4D探测器：同时提供位置和时间分辨30ps, 5-10 μm (SET tracker 附近)

EIC: Central detector(ETTL, CTTL, FTTL), Far-Forward detector均采用AC-LGAD

REDTOP: Corrado Gatto, LGAD track: 4D track reconstruction for multihadron rejection

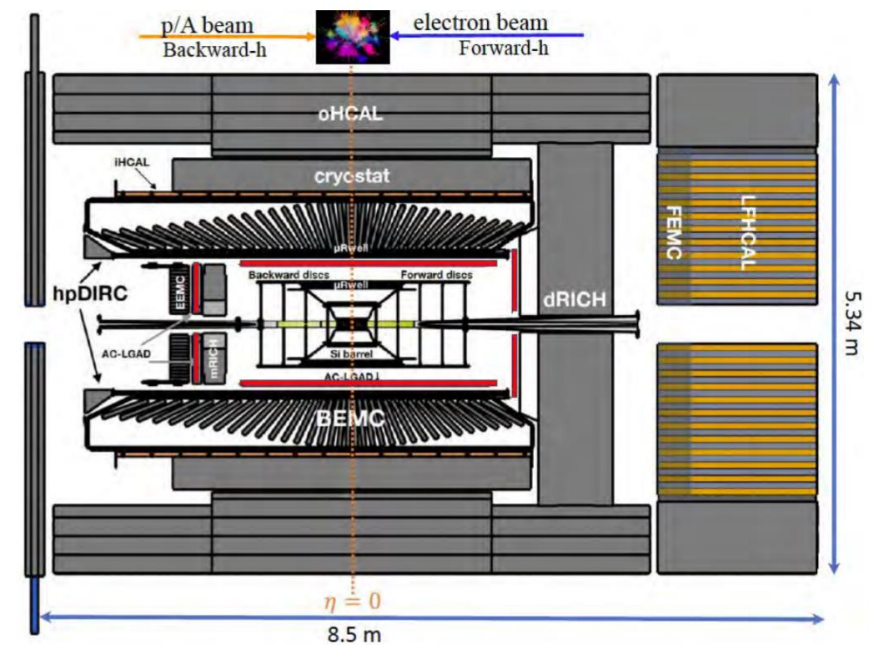


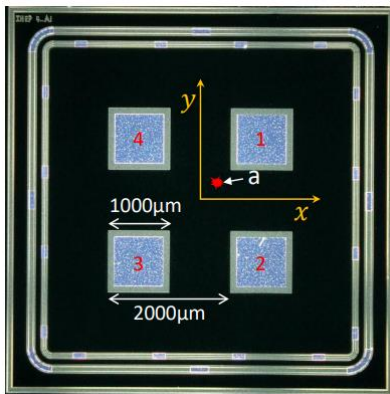
Figure 1: Layout of the central detector of the EPIC detector reference design, which includes a AC-LGAD Timing and Tracking Layer detectors (in red) in the backward, central, and forward directions.



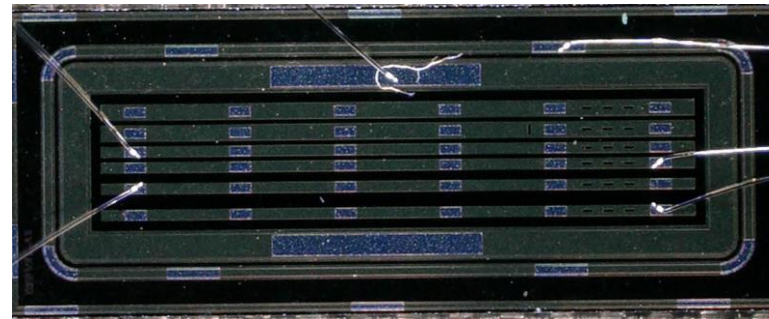
高能所AC-LGAD

高能所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

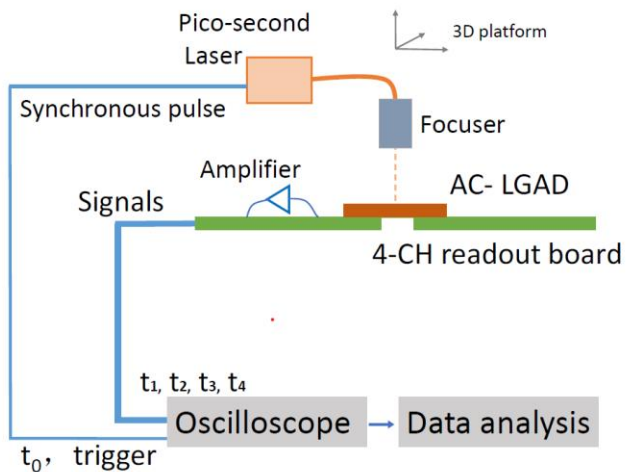


具有不同pad-pitch尺寸的**pixel型AC-LGAD**

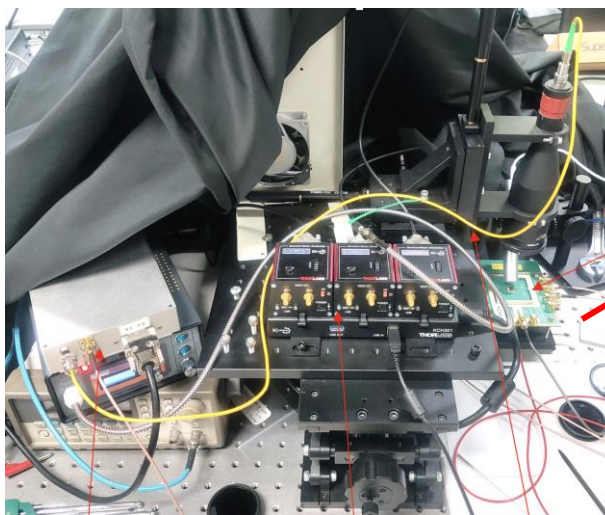


具有不同gap的**Strip型AC-LGAD**

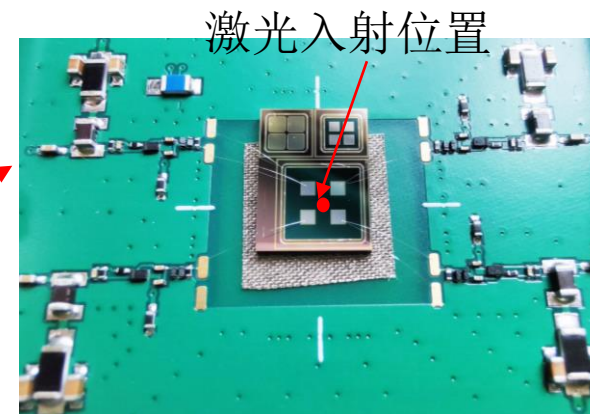
高能所AC-LGAD 测试系统



Picosecond Laser: 1065 nm



激光测试平台



激光入射位置

器件与四通道读出板引线连接

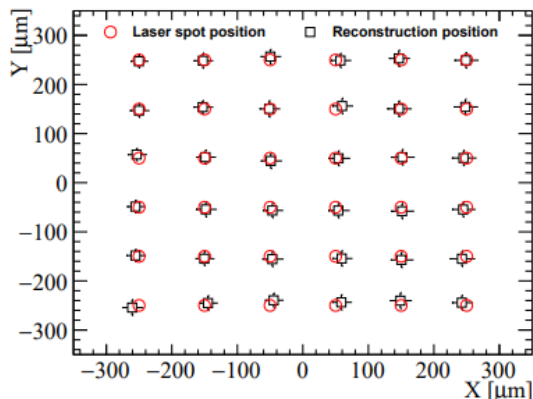
高能所AC-LGAD



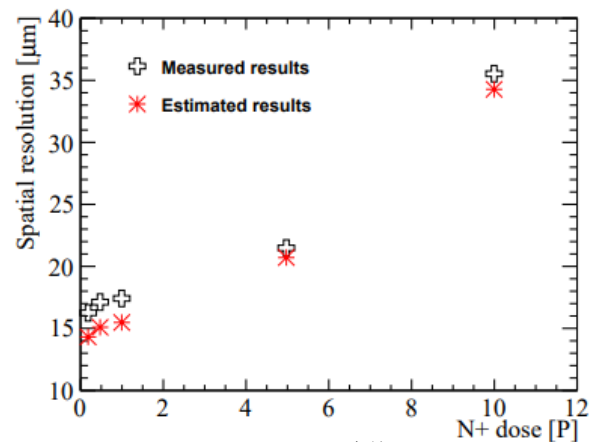
Pixel型的AC-LGAD

Pad-pitch: 1000-2000um

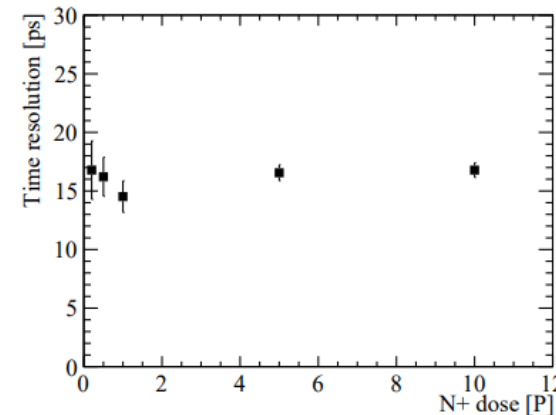
Paper: The performance of large-pitch AC-LGAD with different N+ dose, Trans. Nucl. Sci., 2023.6



入射36个点位置重建情况

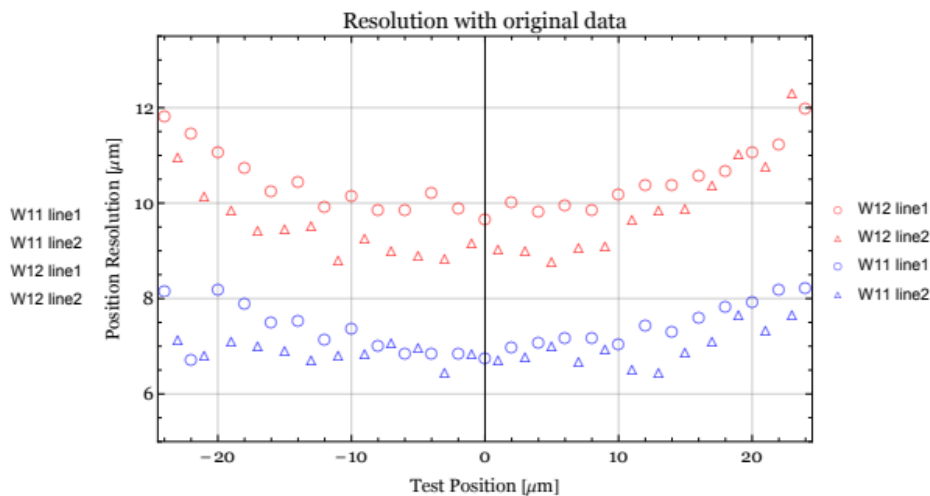


最优位置分辨15um

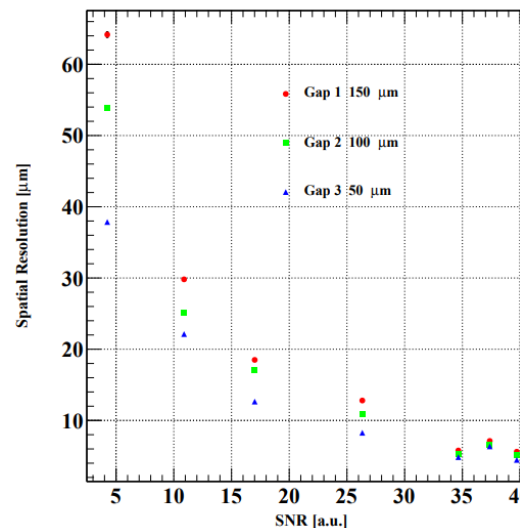


时间分辨15-20ps

Strip型的AC-LGAD



Gap 50um: 最优位置分辨<8um



提高信噪比后,
最优位置分辨
可达5um

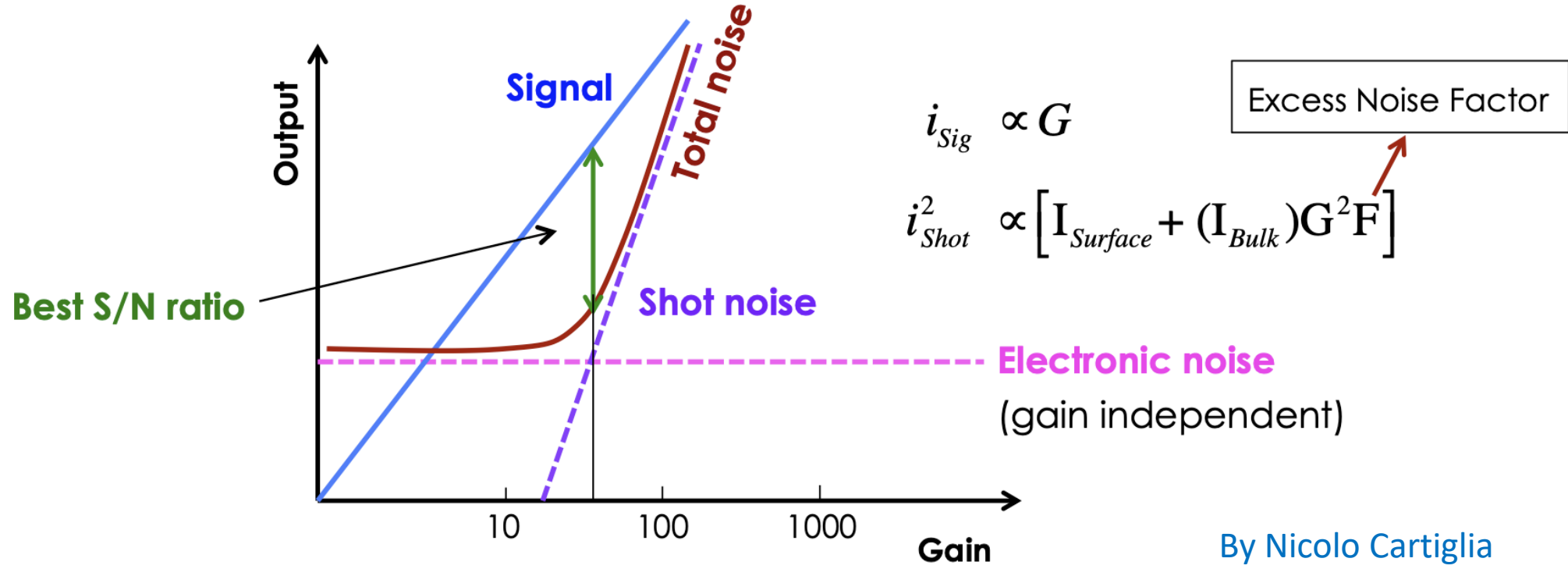
总结



- ▶ 基于国产工艺自主研发的LGAD探测器在ATLAS实验规定的超高辐照后其时间分辨率仍可达到35ps，并且可以工作在400V左右的低电压区（安全工作区），避免了器件的单粒子烧毁现象。
- ▶ 通过优化增益区碳注入工艺，高能所LGAD探测器的抗辐照性能超过日本滨松，意大利FBK等单位的器件，达到目前世界先进水平。
- ▶ 2023年高能所研制的LGAD探测器赢得欧洲核子中心的HGTD项目硅探测器公开招标，并获得其中100%的招标份额。欧洲中心将采购高能所研制的LGAD器件，这是欧洲核子中心首次采购国产硅探测器。
- ▶ 基于传统LGAD探测器工艺，高能所研发的新型AC-LGAD探测器，同时具备位置与时间分辨能力。位置分辨最优可达5um，时间分辨可达15-20ps（激光测试结果），有望应用于未来对撞机实验。



低增益雪崩硅探测器：增益 vs 信噪比



Noise increases faster than then signal

→ the ratio S/N becomes worse at higher gain

<https://doi.org/10.1201/9781003131946>



Introduction to HGTD(High Granularity Timing Detector)

Pixel detector with coarse spatial resolution but precise timing

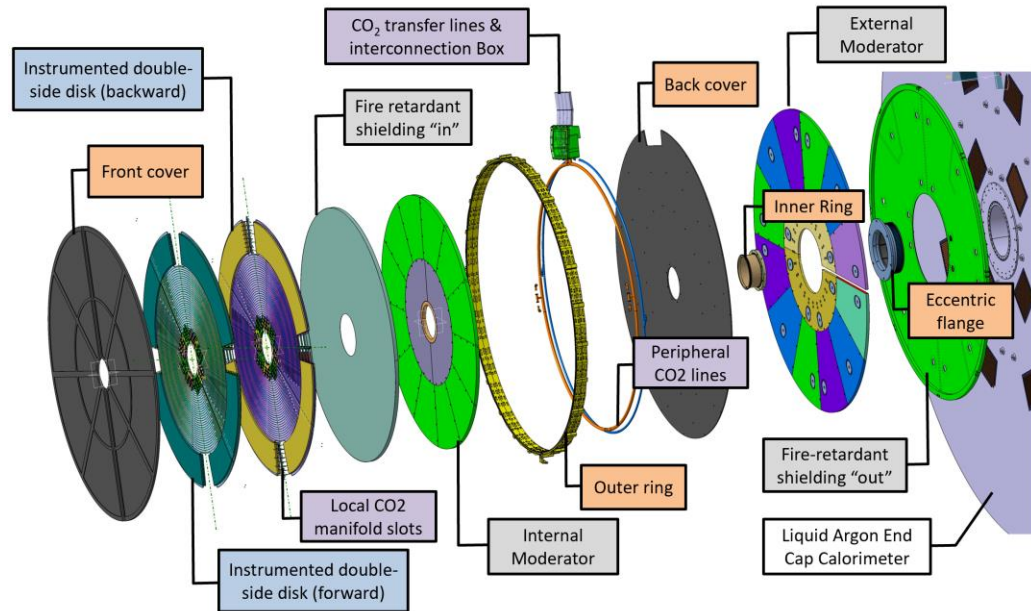
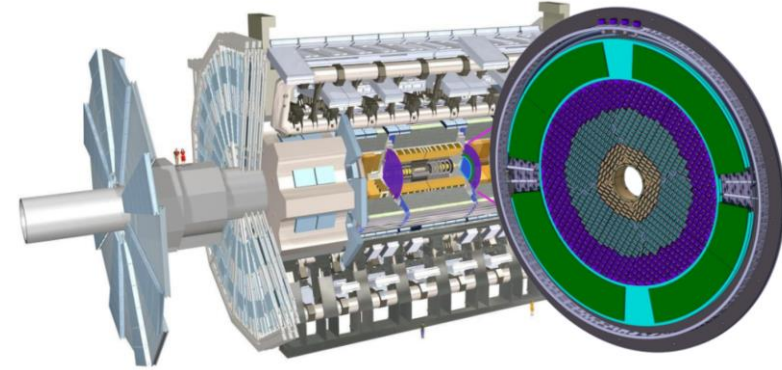
- ~ 3.6 million 1.3×1.3 mm² pixels(channels)
- 6.4 m² active area
- Time resolution target
 - 30-50 ps/track
 - 35-70 ps/hit up to 4000 fb⁻¹
- Luminosity measurement
 - Count number of hits at 40 MHz (bunch by bunch)
 - Goal for HL-LHC: 1% luminosity uncertainty

Two end-caps

- $z \approx \pm 3.5$ m from the nominal interaction point
- Total radius: $11 \text{ cm} < r < 100 \text{ cm}$
- Active detector region: $2.4 < |\eta| < 4.0$

Each end-cap

- Two instrumented disks, rotated by 15°





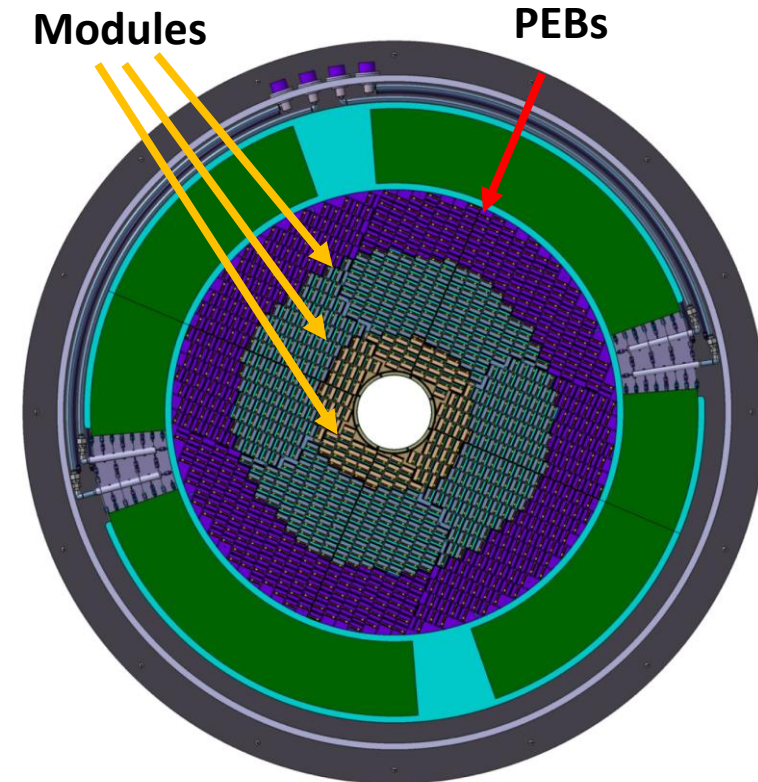
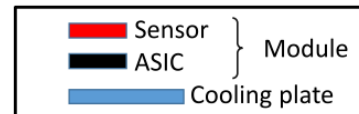
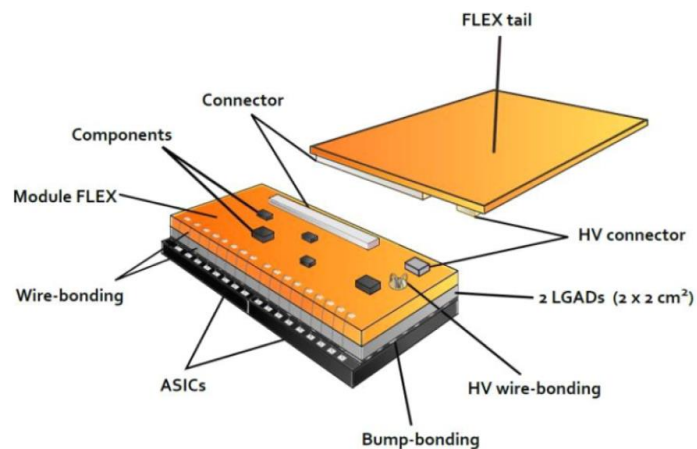
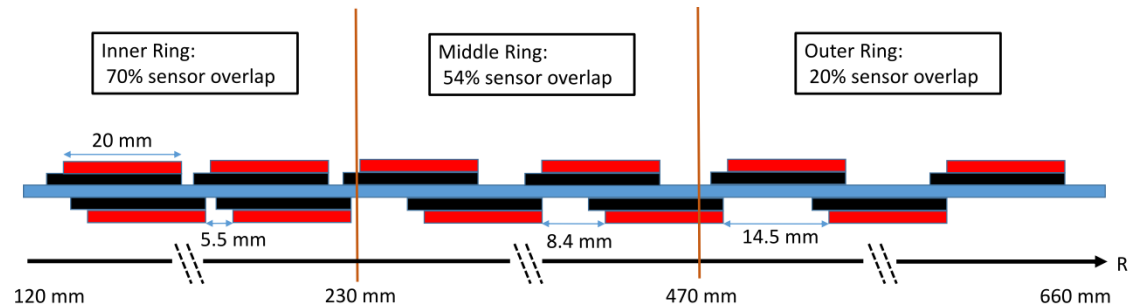
The instrumented disk

2 disks, each Disk:

- Double-sided layers mounted on a cooling plate
- 3 rings layout

8032 modules, each module:

- consists of two hybrids (2 sensors+ 2 ASICs)
- 2x4 cm², 15x30 channels



- Two hybrids be connected with one module Flex
- Module Flex be connected via Flex tails, arranged in rows, to the Peripheral Electronics Boards (PEB) @ $660 < r < 920$ mm



Motivation

CEPC will produce 10^{12} Z boson at Z pole: Rich flavor physics program

- **Particle separation problems of Gas detector (dE/dx) for CEPC flavor physics:**

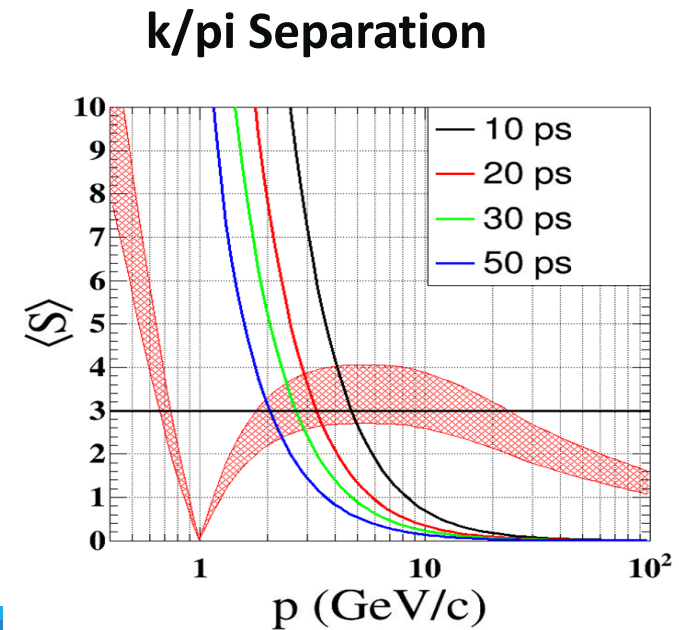
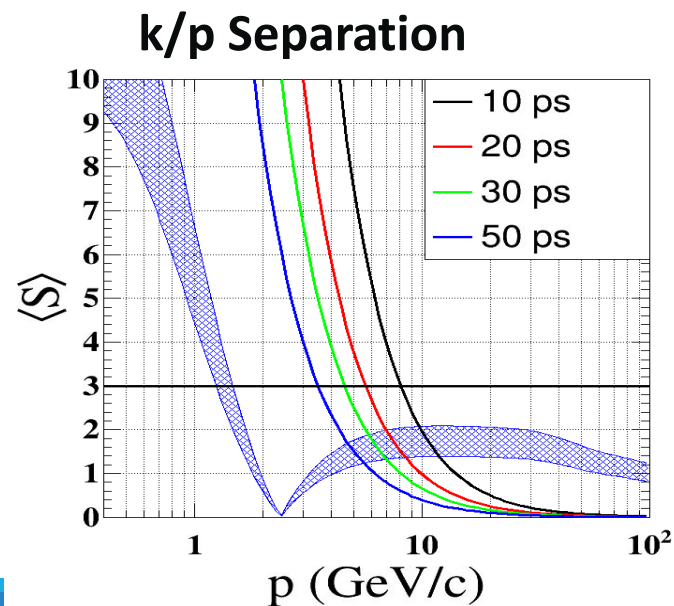
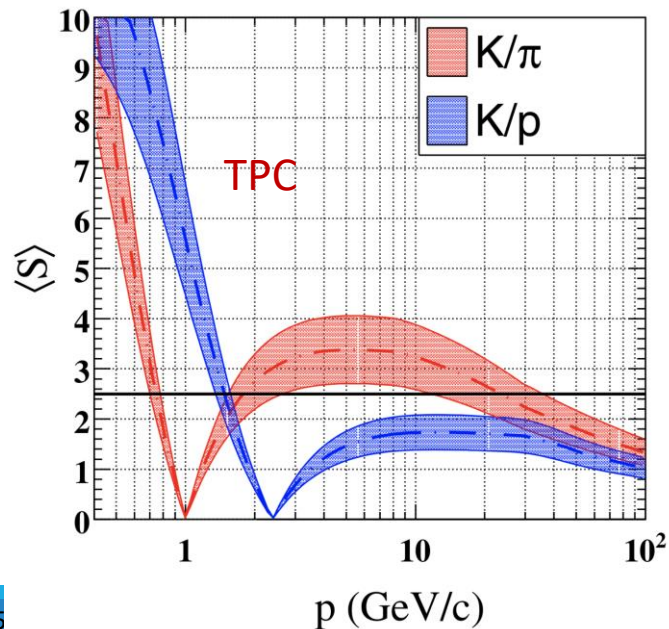
- **0.5-2 GeV for K/pi separation, >1.5 GeV for K/p separation**

- **CEPC International Advisory Committee: one of the key recommendations**

Precision timing detector should be determined as a matter of urgency (4D track)

- **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





CEPC timing detector: Concept

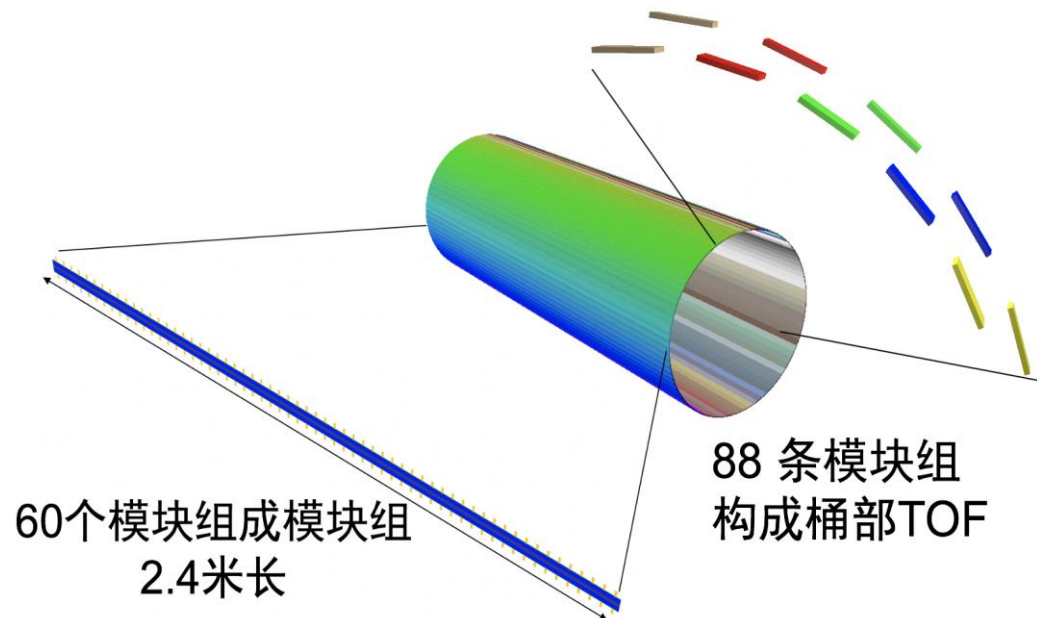
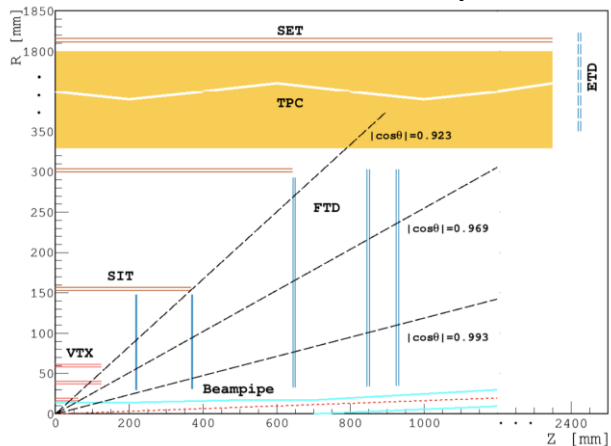
Two concept designs of the timing detector:

- I. Only offer the time information, between tracker and calorimeter
- ✓ **Large area LGAD**: high timing resolution (20 ps) serve as timing detector, low gain, high S/N, large pixel size to reduce the readout electronics, put near the SET
- II. Offer the time and spatial information (**4D track**) replace the SET
- ✓ **AC-LGAD**: 4 dimension detection (spatial and time resolution), 20 pico-second (ps), 7-10 μm

Close to SET tracker, Radius **~1.8 m**

Area of detector (**Barrel : 50 m² , Endcap 20 m²)**

Baseline detector concept in CDR





EIC

FY22 Report and FY23 Proposal on EIC AC-LGAD R&D - Frontend ASIC and Electronics -

eRD112

September 30, 2022

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- 1.1 AC-LGAD for the Central Detector 2
- 1.2 AC-LGAD for Far-Forward Detectors 3

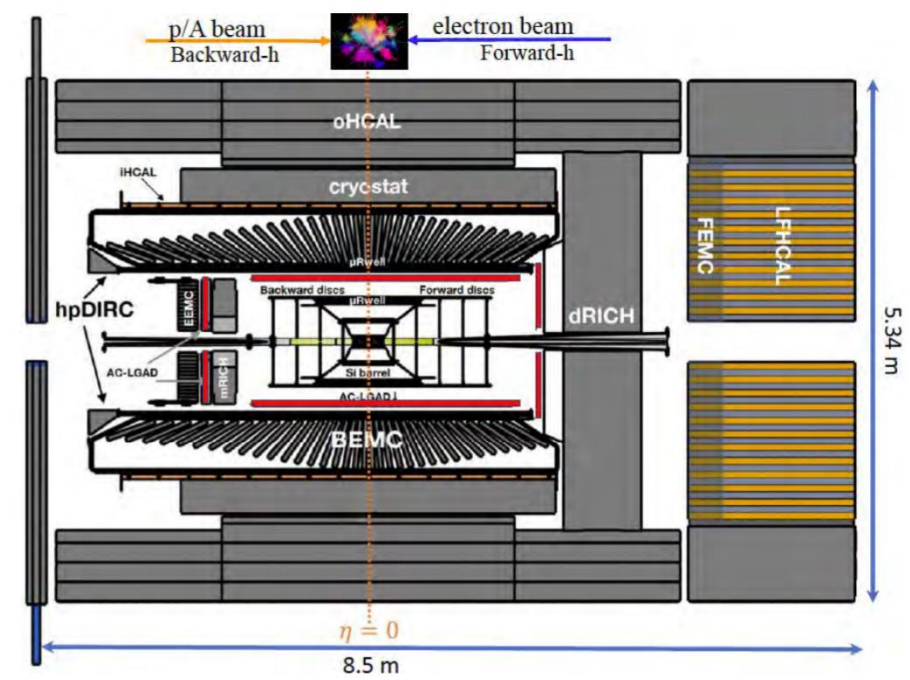


Figure 1: Layout of the central detector of the EPIC detector reference design, which includes a AC-LGAD Timing and Tracking Layer detectors (in red) in the backward, central, and forward directions.

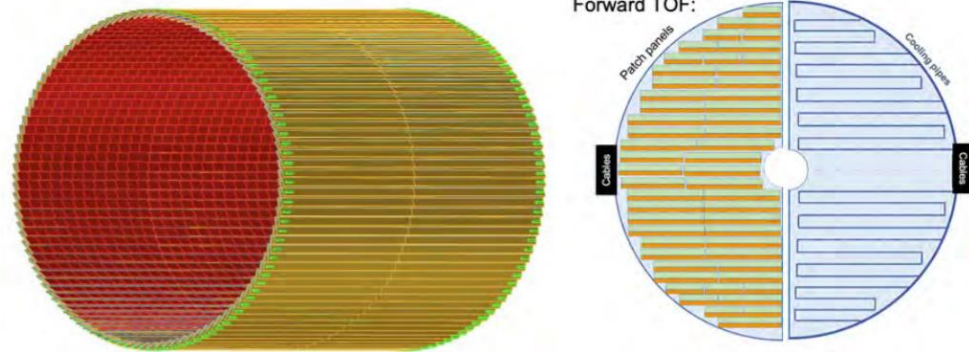


Figure 2: Layout of the EPIC AC-LGAD TTL detectors in the barrel (left) and endcap regions (right).

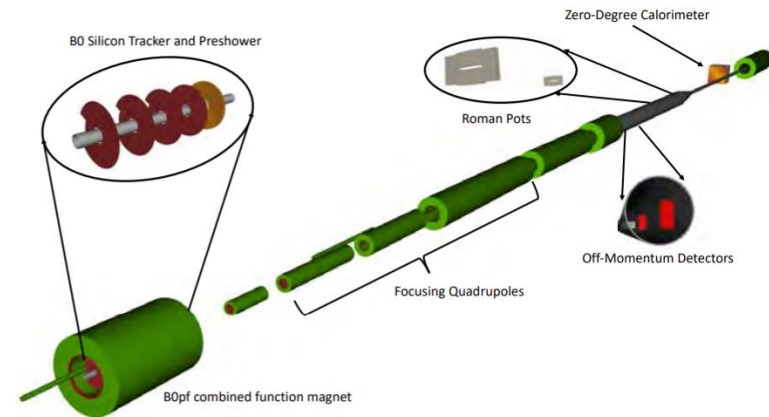


Figure 3: Layout of the EPIC far-forward detector systems, which include a tracking spectrometer and a silicon pre-shower embedded in an accelerator dipole magnet (the so-called “B0 detector”), silicon tracking detectors directly in the machine vacuum (Roman Pots and Off-Momentum Detectors), and a Zero-Degree Calorimeter with both hadronic and electromagnetic calorimetry capabilities.



REDTOP

REDTOP detector

