Low Gain Avalanche Diode Detector

低增益雪崩二极管（LGAD）硅探测器

高能物理研究所：樊云云

fanyy@ihep.ac.cn

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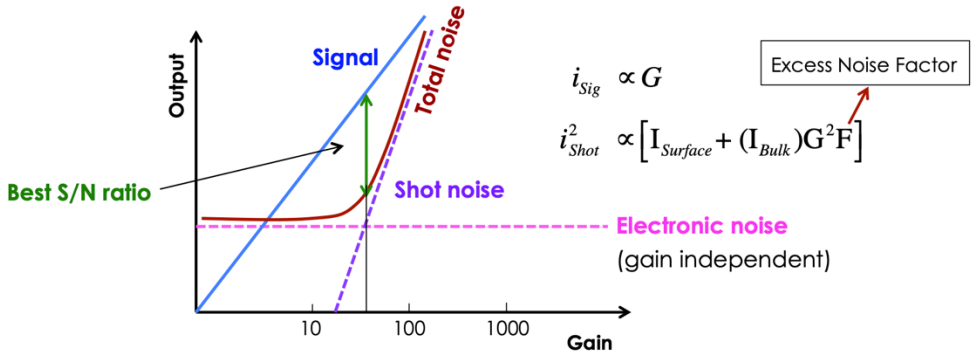
超快硅探测技术：低增益雪崩二极管探测器

- **超快硅探测技术,即低增益雪崩硅探测器(LGAD)近年来飞速发展**
  - 增益层的引入，低增益，10-50（对比APD 及SIPM）
  - 高信噪比 S/B, 无自触发，
  - 超薄零敏层，20～50 微米



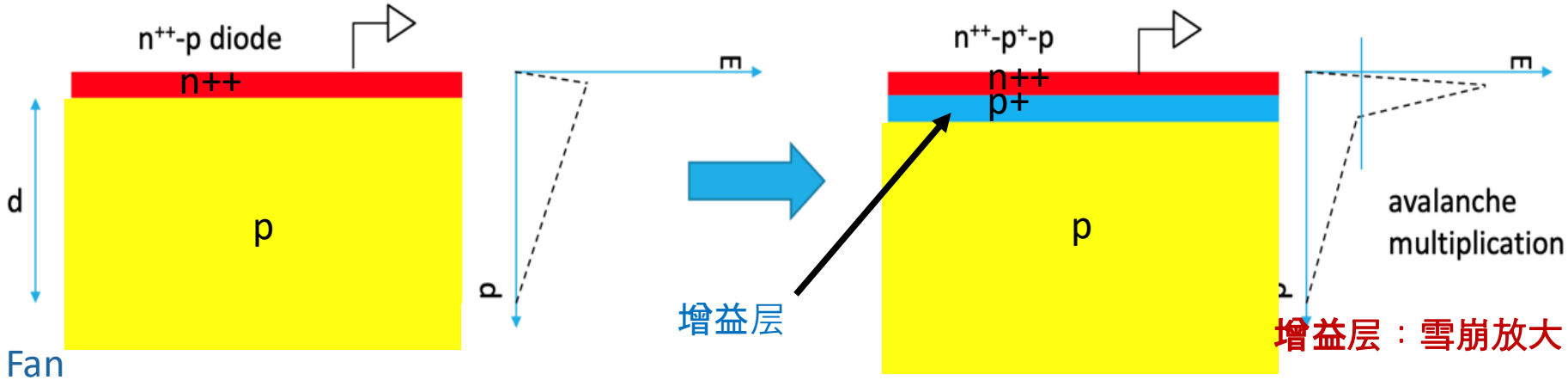
超快时间分辨率（MIP 20皮秒）

传统硅传感器: PN结

位置/能量测量

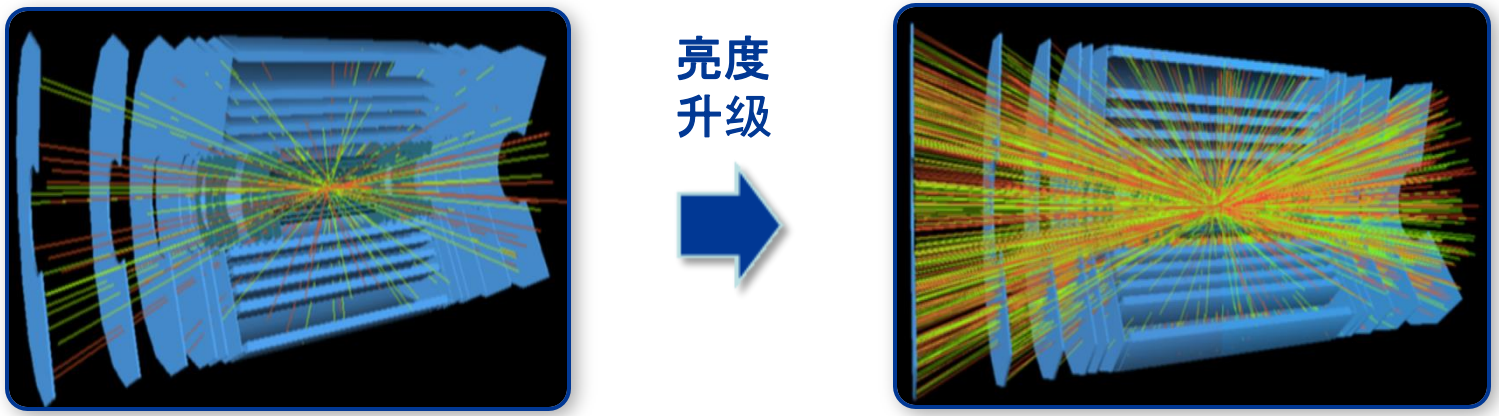
LGAD: PN结 + 增益层

时间测量

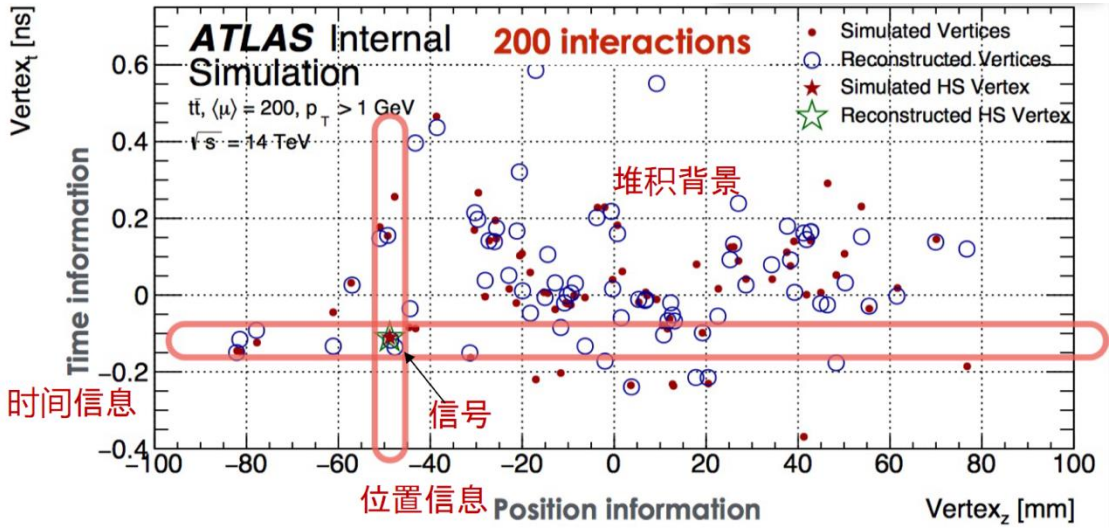


LGAD在大型强子对撞机升级中的应用

- 对撞机计划亮度升级：**精确测量希格斯玻色子**
- 高亮度→严重的**背景堆积**问题



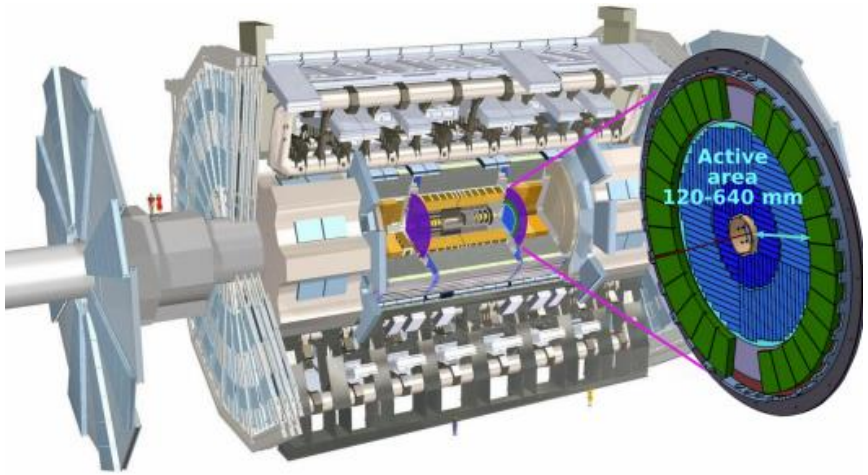
- 顶点探测器提供的**位置信息不足以区分堆积事例**
  - **研发时间分辨硅探测器势在必行**



HGTD项目介绍

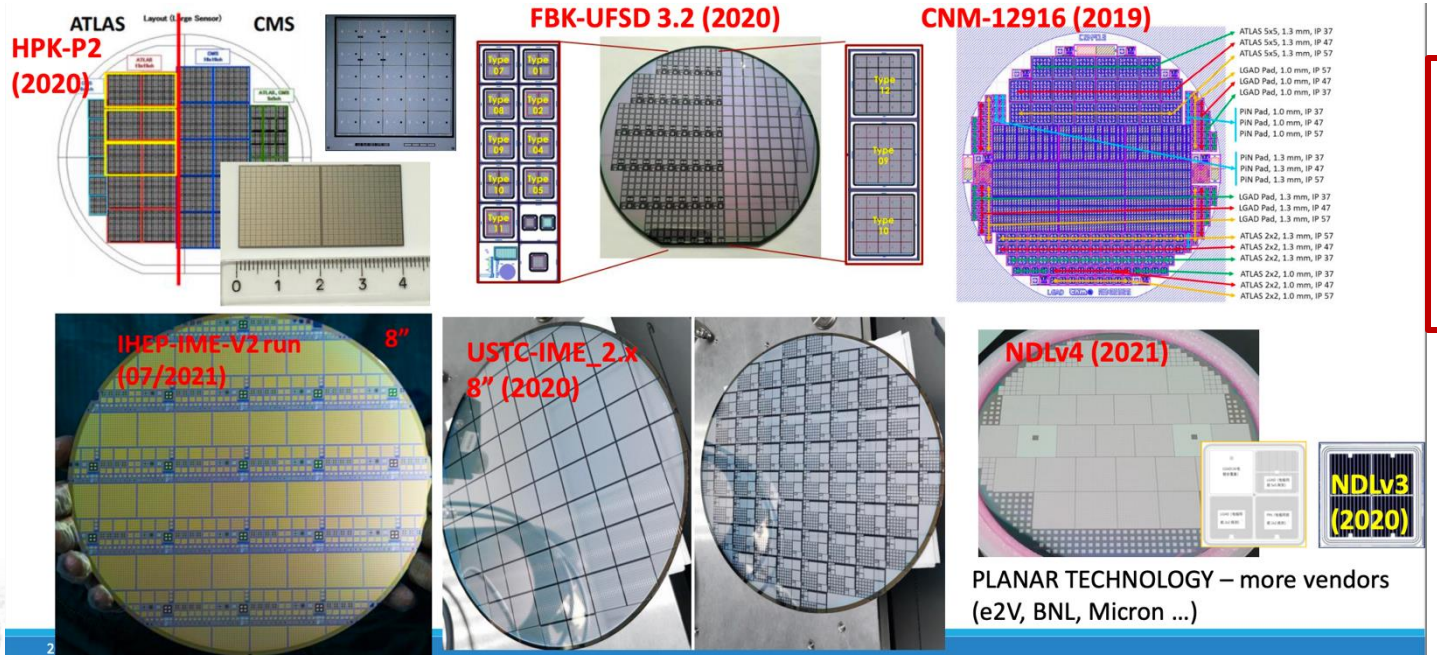
- **高颗粒度时间探测器(HGTD) 被CERN批准进入ATLAS phase-II 的升级**
  - 采用超快硅LGAD技术
  - 时间分辨率/径迹: < **50ps**
  - 减少5倍的顶点堆积
  - **6.4m^2** 探测器面积、~ **5x10^6** 读出道
  - 抗辐照要求: **2.5x10^{15} Neq /cm^2** and **2MGy**
  - 前向区域（2<|η|<4）

中国组占主导地位，高能所主导并负责1/3探测器的研制



LGAD抗辐照性能问题

- 成功应用于强子对撞机，**需解决超快LGAD的抗辐照问题**
- **国内外研究情况：**
  - 国外机构厂商研发，如日本滨松，西班牙CNM，意大利FBK等
    - **研发尚未成熟，时间性能退化严重**
  - 2019年后，中国组在国内开始从0到1的自主研发, 加入到国际竞争中
    - 高能所设计与微电子所流片（ IHEP-IME）， 北师大设计生产（IHEP-NDL）、高能所设计中环流片
    - 科大设计与微电子所流片（USTC-IME）



问题：如何利用中国国内的硅生产工艺，克服相关限制，实现抗辐照LGAD的国产化研究？

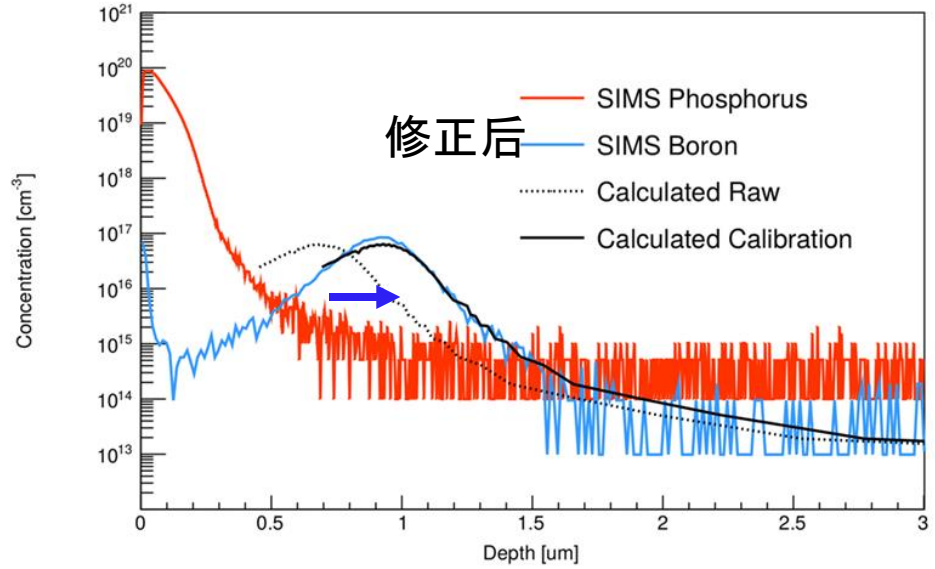
国产LGAD抗辐照设计

国产化设计初期解决问题：

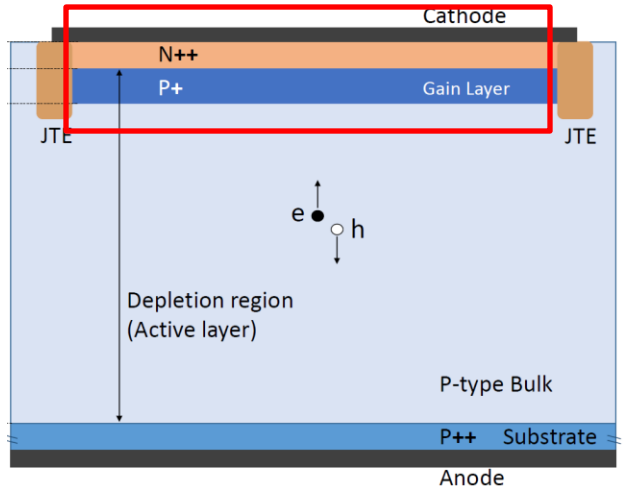
I. 辐照前，使用国内工艺达到设计时间分辨性能

- ✓ 34步工艺设计及优化，微电子所进行生产流片
- ✓ **退火突破注入能量限制、对比测试和仿真修正仿真模型等**
- ✓ PN结：P+硼的浓度和形状；N++的调整，磷的位置和浓度

修正仿真模型



优化pn结构，提高时间性能

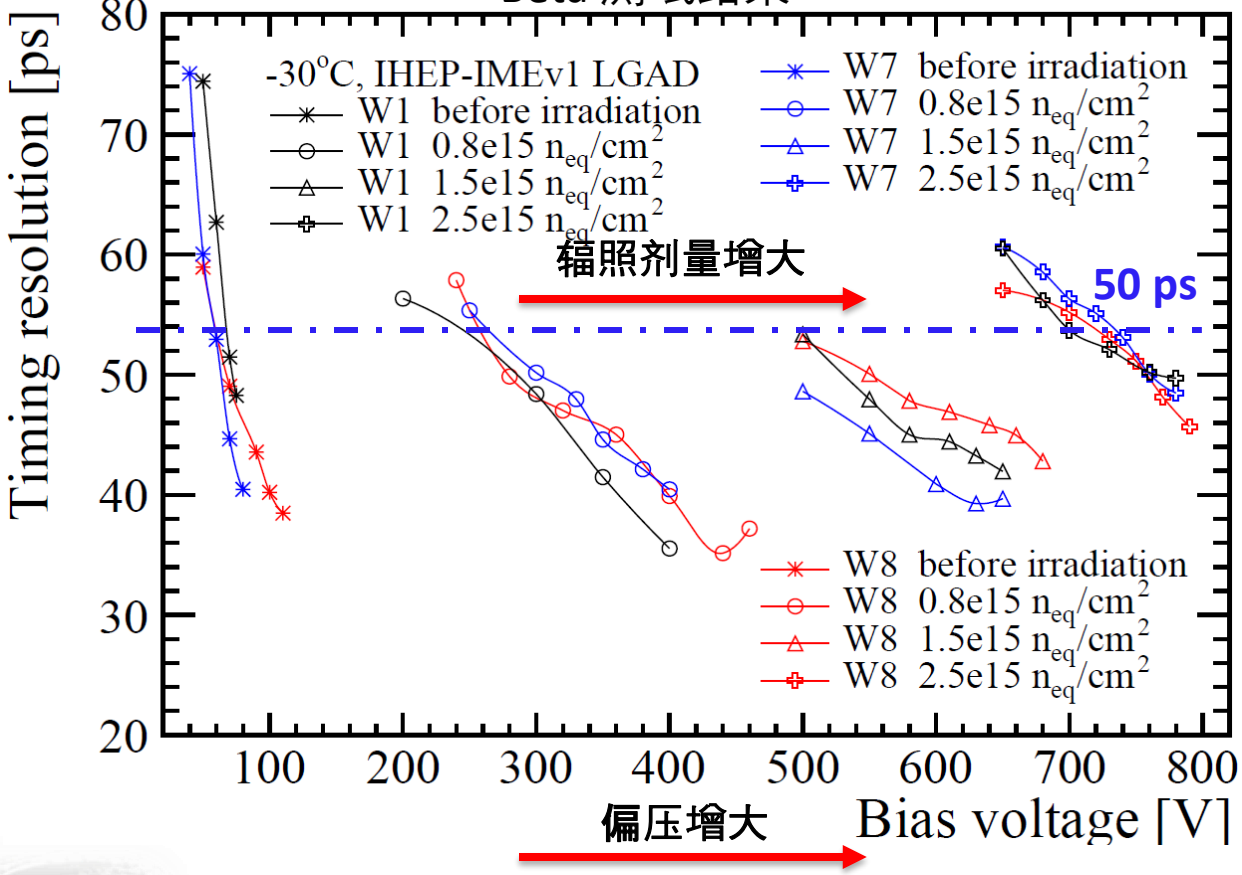


国产超快硅LGAD的辐照损伤

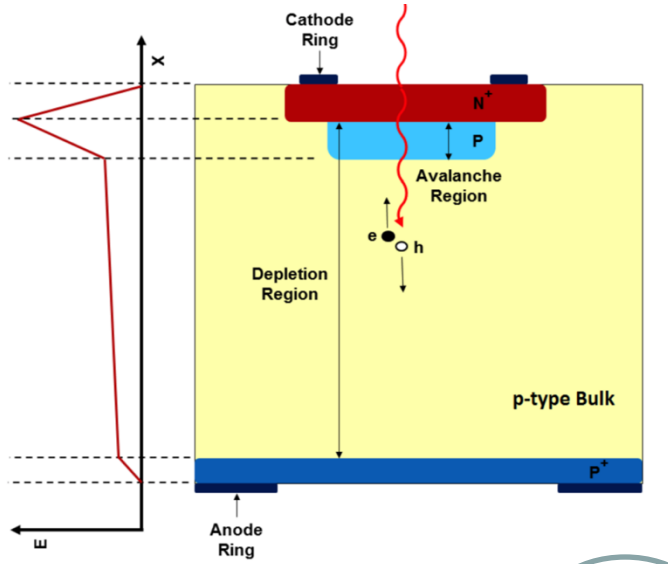
I. 增益层有效掺杂降低，受子移除的静态效应， 时间分辨严重退化

- 需 >600V 高压达到好的时间分辨率

Beta 测试结果



增益层退化



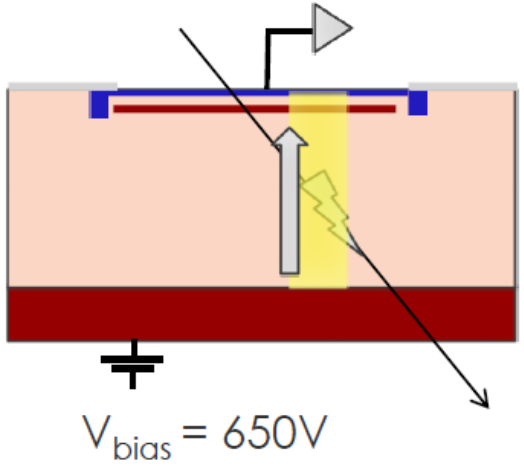
辐照后 $V_{gl} \propto N_{eff}$

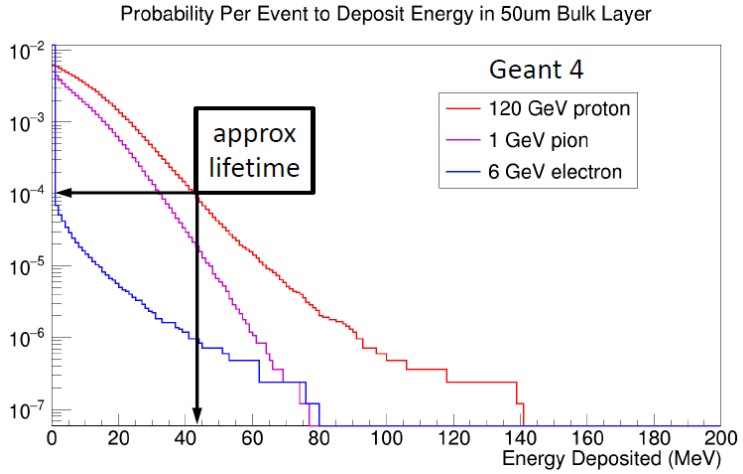
耗尽电压 ↓ 增益层有效掺杂浓度 ↓

LGAD的辐照损伤

II. 动态效应（单粒子烧毁，SEB）：探测器烧毁

高电压时(>600V)，束流测试发现单个高能带电粒子(GeV量级)经过可烧毁LGAD硅传感器





束流测试粒子在50um 硅中能量沉积

束流测试：

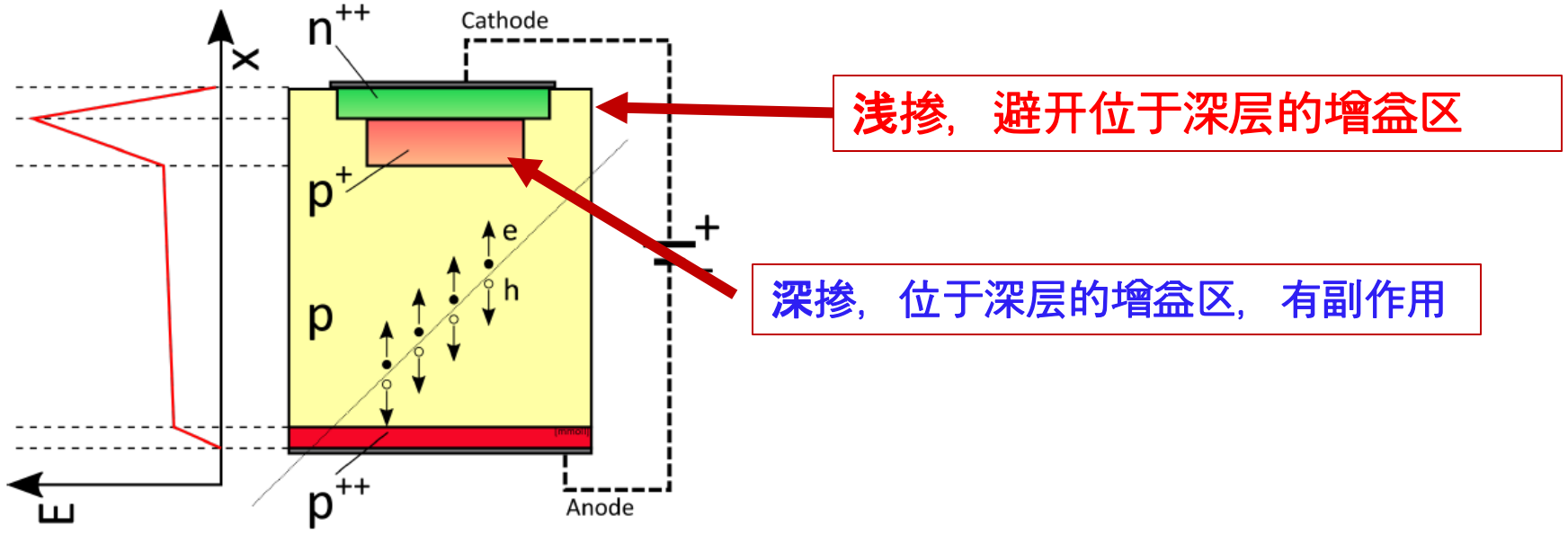
- 高电压下，40-50 MeV 能量沉积就可以产生150uJ的热量，融化50um厚、半径10um的硅
- LGAD存活时间和束流测试高能粒子的罕见、大能量沉积的概率一致

防止单粒子烧毁，需运行在600V电压之下

国产LGAD抗辐照新加固设计

- **新版国产LGAD的抗辐照加固新方案：浅掺碳设计**

1. 设计方面调整，如提高有效掺杂浓度，已达极限
2. 局部材料改性，即掺碳是最有希望的手段
3. **国外深掺碳存在副作用，对有增益层的保护不够好**
4. **创新提出浅掺碳方法，避免副作用，解决了国外面临的问题。**



LGAD抗辐照性能优化结果

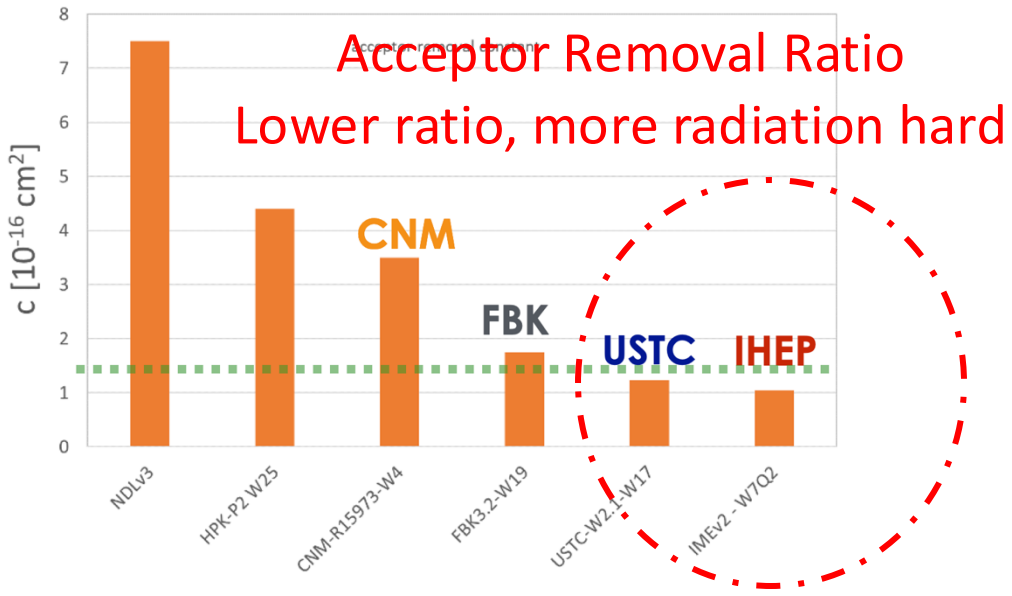
IHEP-IME 浅掺碳设计成功克服静态辐照效应影响

- 得到目前最低的受子移除速率
- 克服了国外深掺导致的硼失活效应
- **国际最优的LGAD抗辐照性能**

相关结果好于国际上一流的设计厂商， 日本滨松、意大利FBK

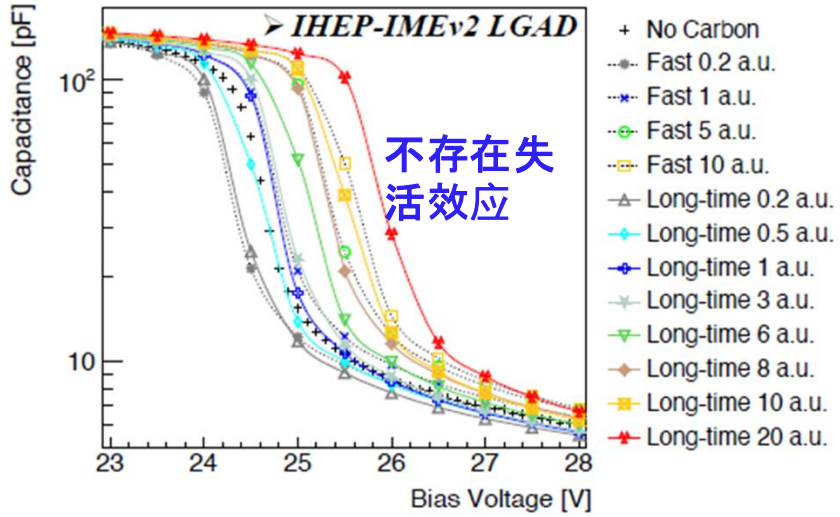
高能所IHEP-IME 传感器

得到最低受子移除速率，最优抗辐照性能



高能所IHEP-IME 传感器

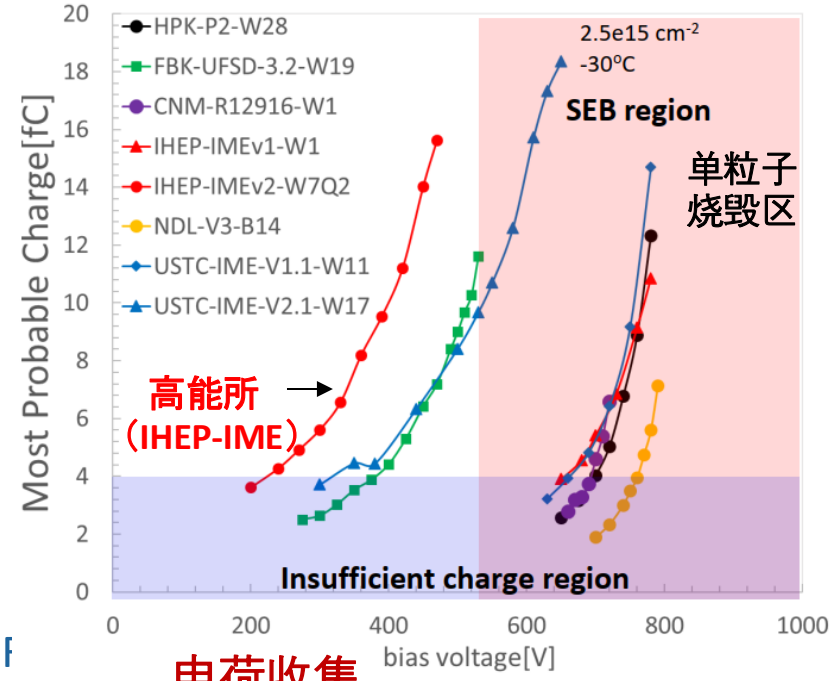
有效掺杂浓度 vs 浅掺碳浓度：



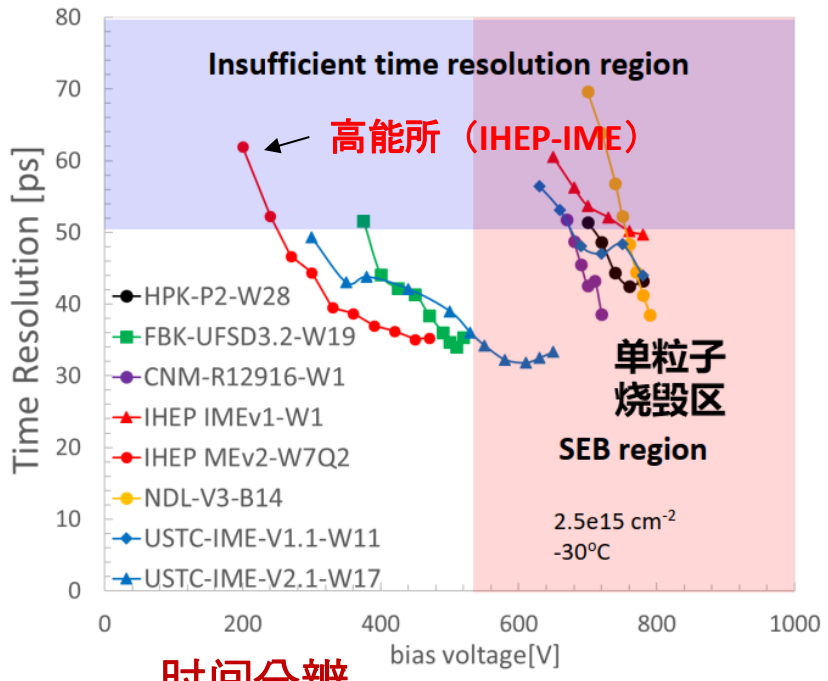
LGAD抗辐照性能优化结果

高能所设计的IHEP-IME传感器成功克服单粒子击穿效应影响

- 辐照后，可以工作在低电压区间（300V-400V左右、收集电荷>4fC，时间分辨30-50ps）
- 远低于 << 危险电压600V
- 国际上日本滨松HPK，西班牙CNM等都要工作在600V以上，烧毁风险非常高
- 意大利的FBK目前是中国组唯一竞争者（工作电压在500V-550V)



电荷收集



时间分辨

首个拿到欧洲核子中心硅传感器订单的国内单位

浅掺碳设计成功保护了增益层

降低时间性能退化

时间性能最优（35 皮秒）

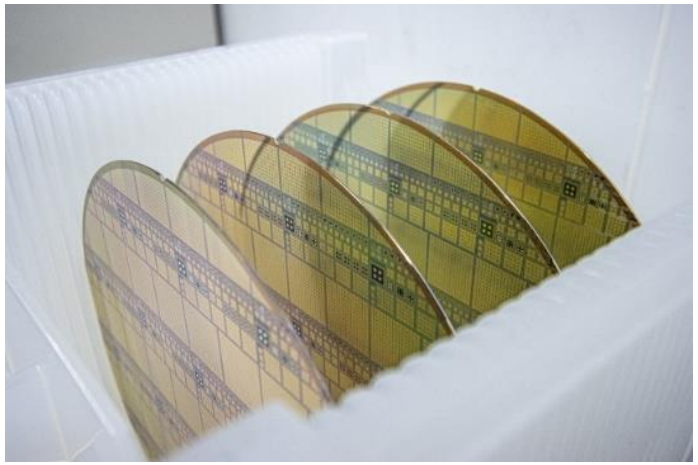
得到目前最低的受子移除率、**即最优抗辐照性能**

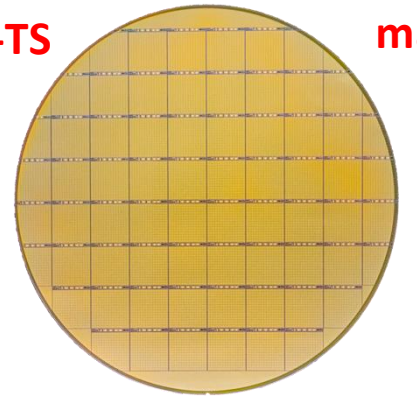
浅掺碳国产超快硅

占大型强子对撞机采购的100%

（取代日本滨松，打破垄断）

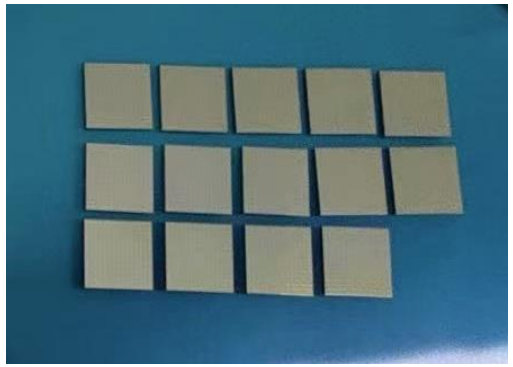
- LGAD sensors for HGTD project: ~21,000
  - ✓ Main sensor（15x15 array）, 1.3 mm x 1.3 mm pixel
- In 2023, IHEP design LGAD sensors be selected in the HGTD sensor tendering process.
- Pre-production started at June 2023.
- Sensor pre-productions finished in 2023 – produced comfortably enough sensors for HGTD needs.



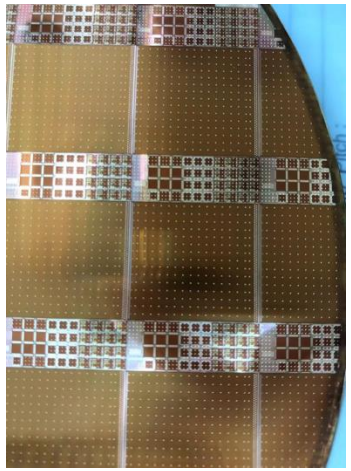


LGAD 探测器模块研发

LGAD

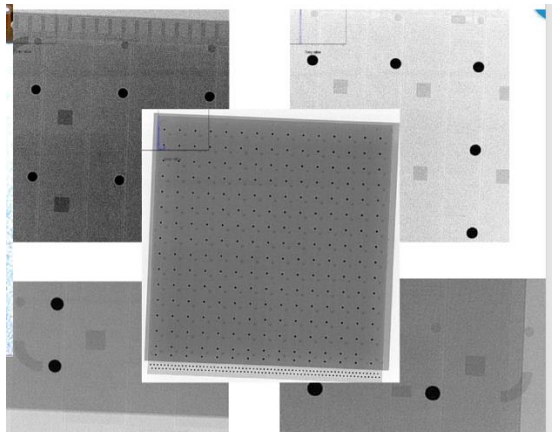


读出芯片

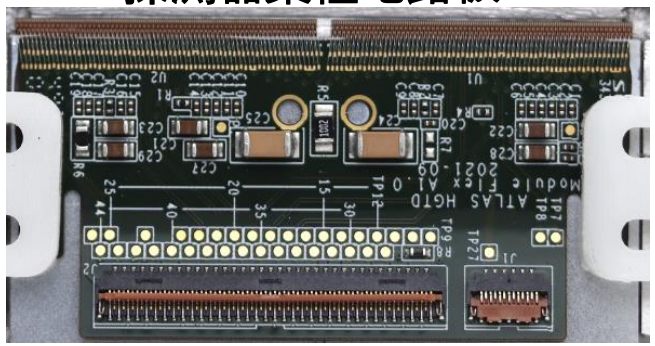


探测器hybrid
（LGAD+ASIC倒装焊）

X-ray image of hybrid



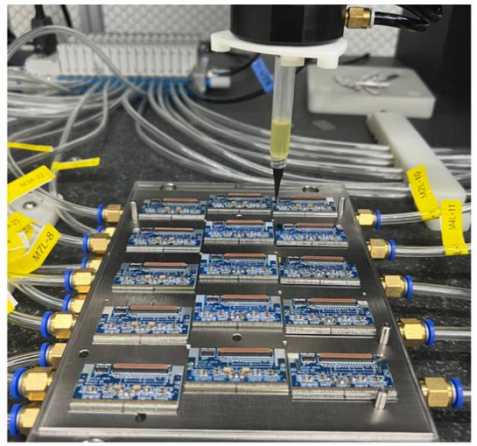
探测器柔性电路板



探测器单元

自动机器臂组装探测器摸块

Dispensing with GluingTool

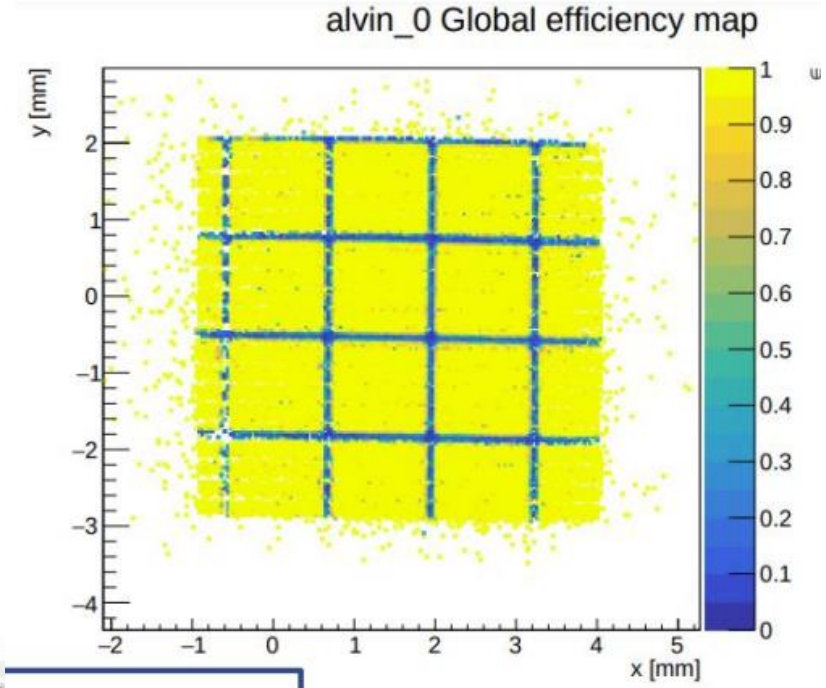


探测器模块及供电等周边电子学单元

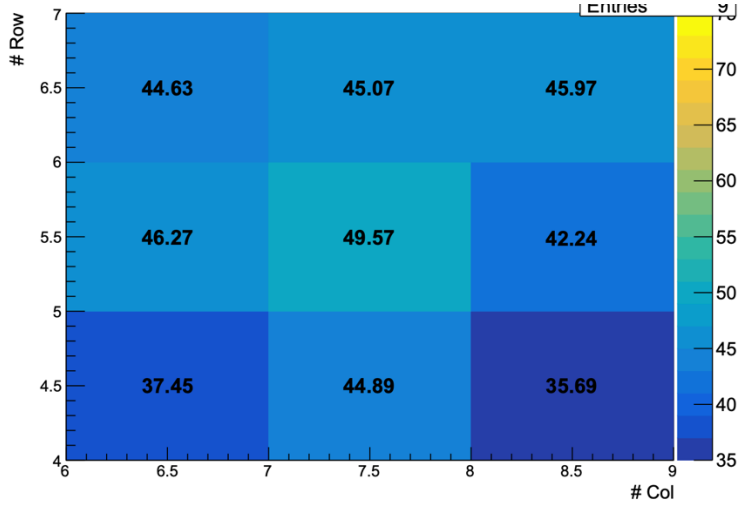
束流测试结果

- **探测器单元束流测试**
  - **50 ps** for the sensor/ASIC module
  - efficiency > 98%

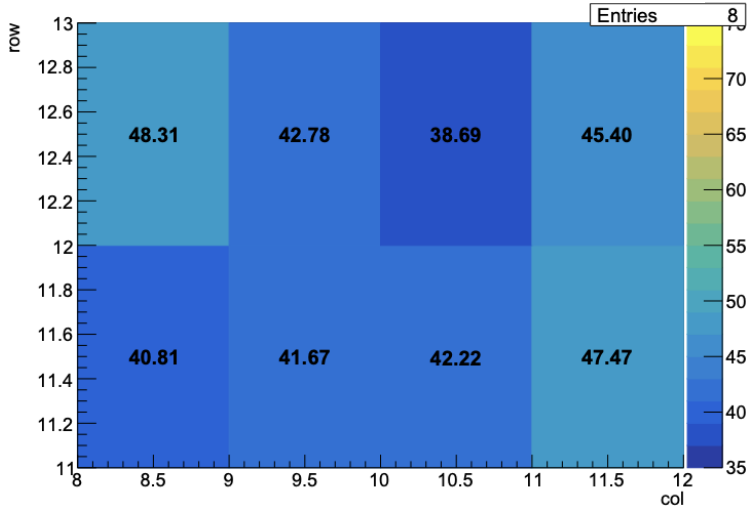
In next few years, HGTD will have 3M channels @ ~50ps resolution

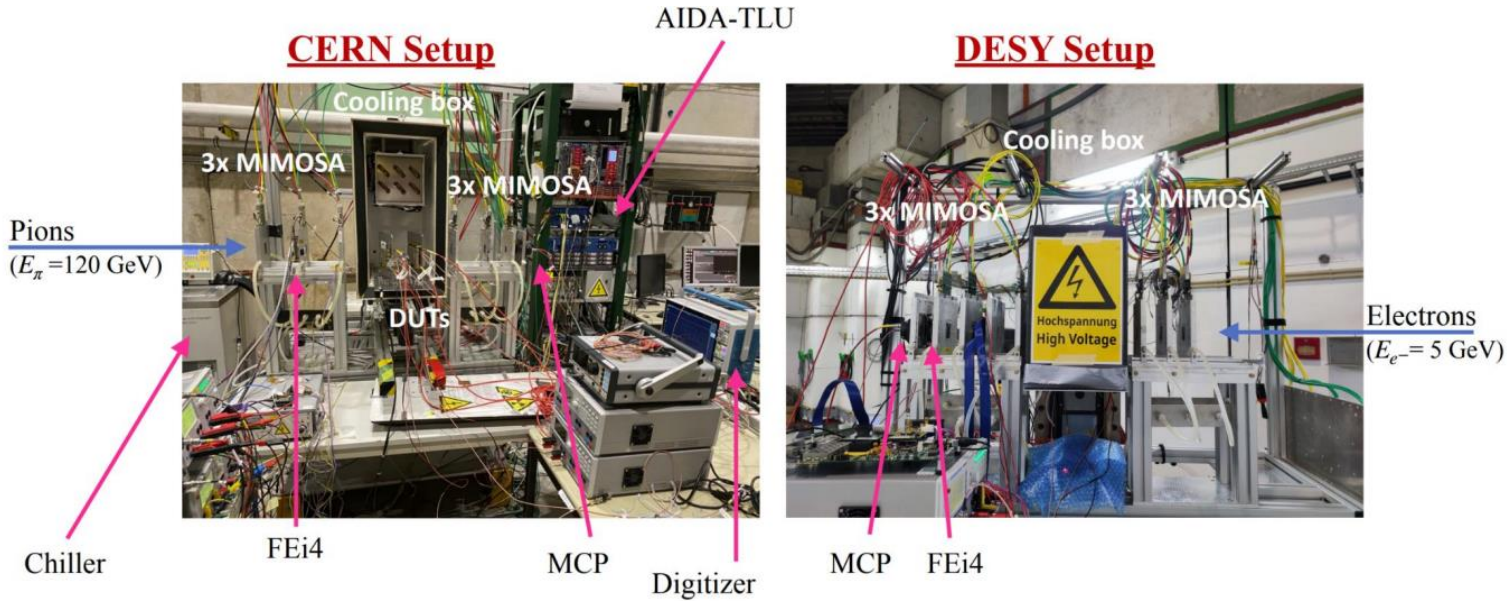


时间分辨：Non-irradiated



2.5E15 Neutron irradiation

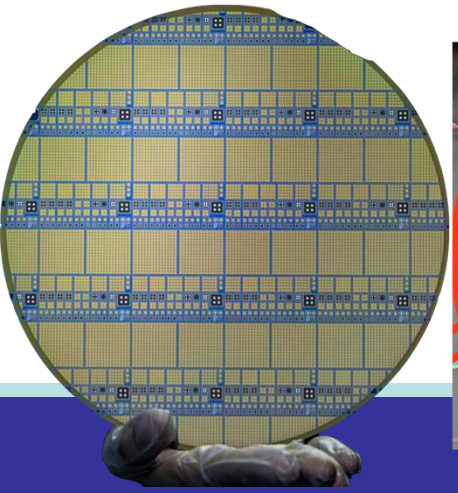




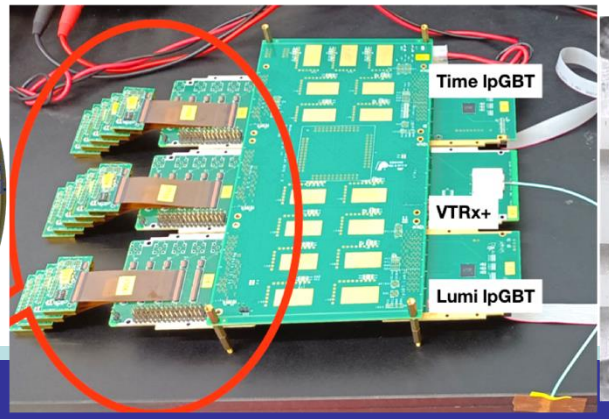
LGAD 应用于大型强子对撞机HGTD实验总结

- **目标**：压制堆积本底、对次顶点/长寿命粒子的探测， 亮度检测等
- 中国组承担其中数项核心工作（**高能所Joao为ATLAS项目经理**）
  - 100% LGAD传感器 (高能所 90%*， 科大10%)
    → **高能所、科大各自独立成功研发高性能传感器**
  - 44%探测器组装（高能所、科大）；
  - 100% 外围电子学（高能所， 南大）；
  - 16%高压电子系统（高能所， 山大）；33%柔性电缆（山大）
  - 束流测试、软件开发等

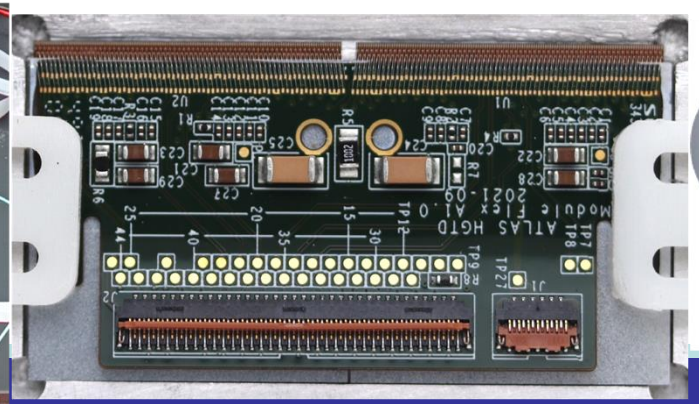
LGAD硅传感器



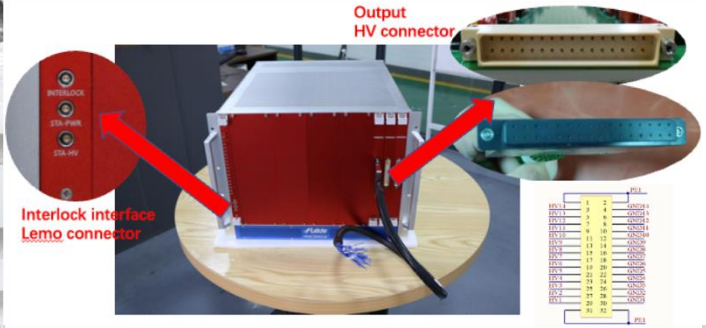
外围电子学



探测器模块
（LGAD+ASIC倒装焊）



高压电源



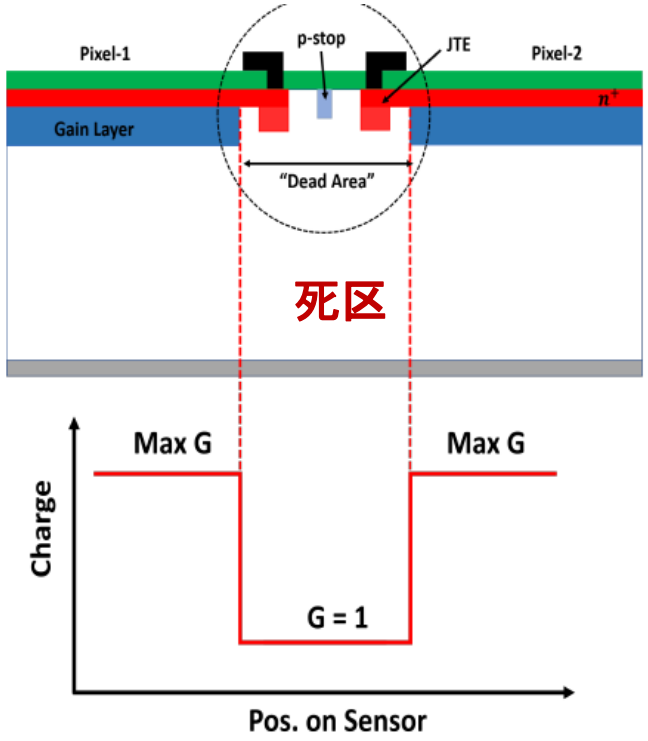
LGAD的新发展AC-LGAD：走向高精度4维探测

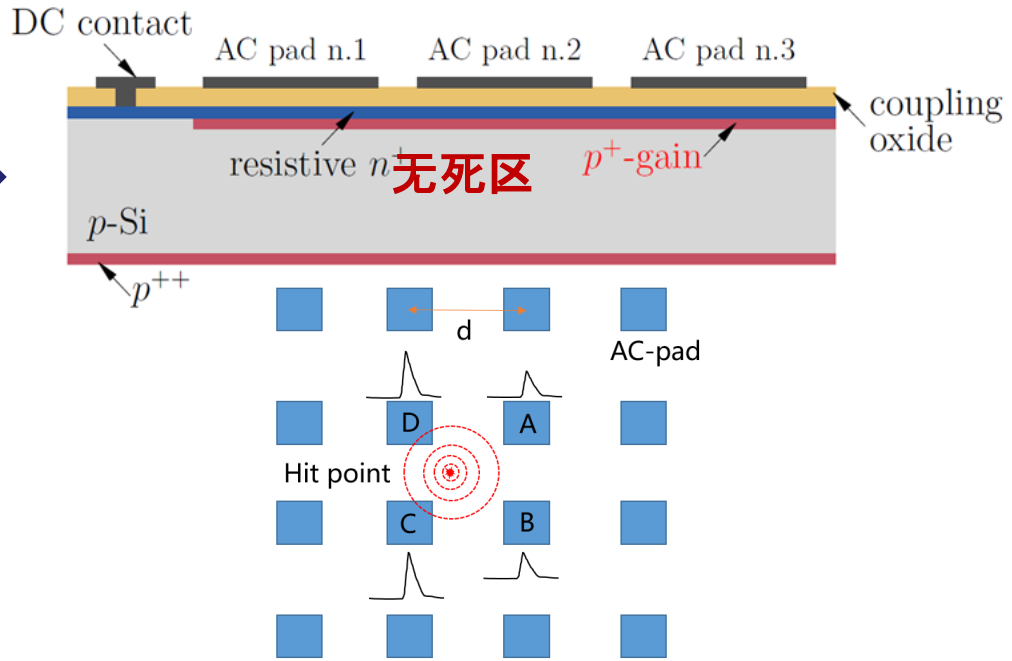
- **突破现有LGAD的限制**
  - 有死区，0.1mm
  - **毫米**级位置分辨

走向高精度4维探测

基于LGAD的AC-LGAD研究（2020发明）

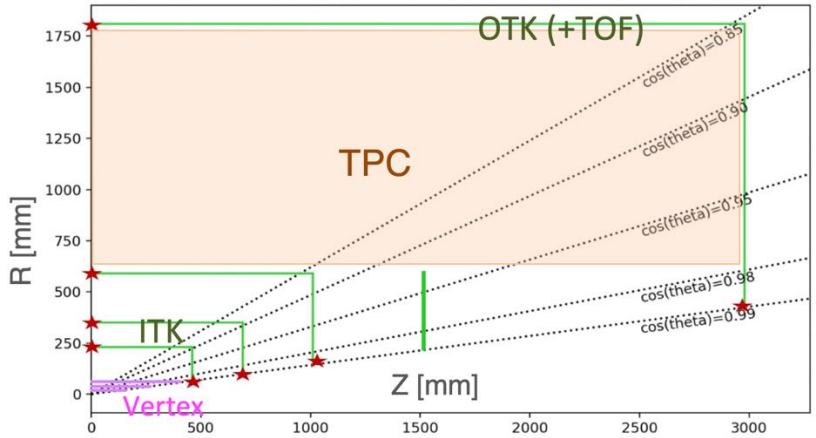
- 无死区、国内工艺可实现、读出通道少等
- 同时得到粒子的位置和时间信息，分辨理论可达**10微米**、20皮秒
- 应用前景广阔，CEPC（飞行时间探测器）、先进光源、核成像





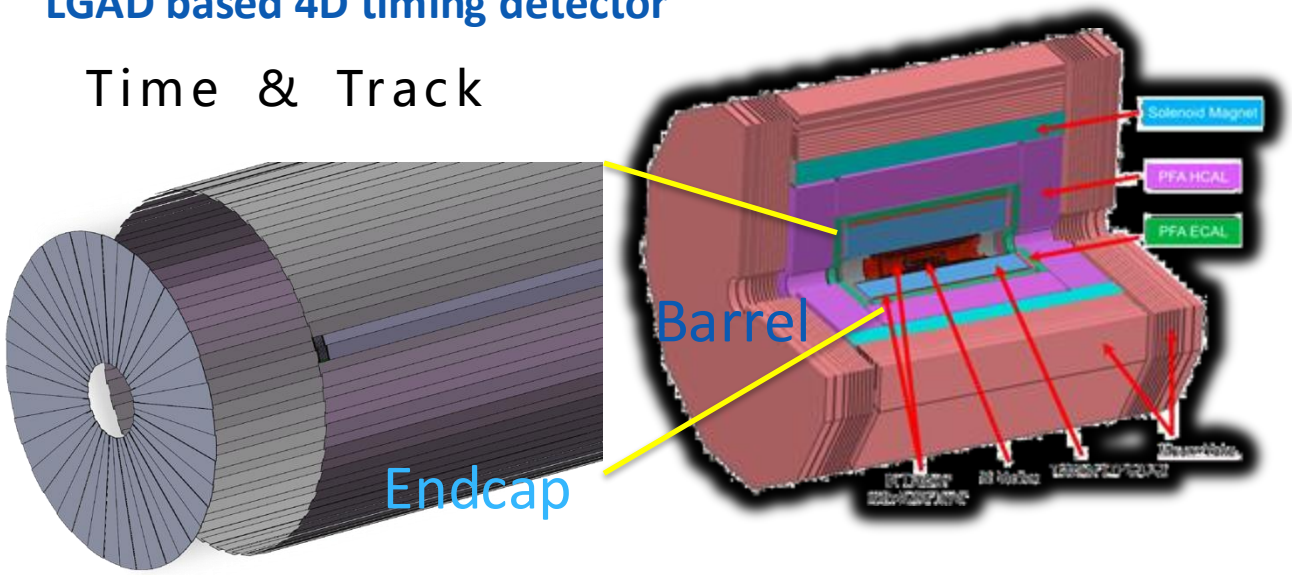
应用于CEPC的基于AC-LGAD 时间及径迹探测器研发

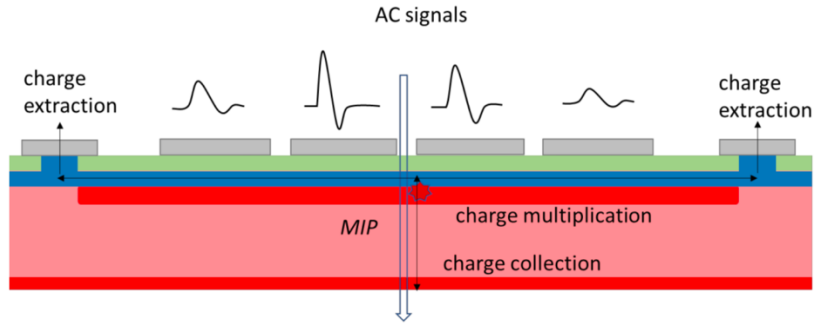
- **Develop AC-LGAD strip silicon sensor for outer tracker**
  - timing resolution **50 ps**
  - spatial resolution better than **10 μm** (Bending direction)
  - Strip AC-LGAD



LGAD based 4D timing detector

Time & Track





Reference TDR of CEPC

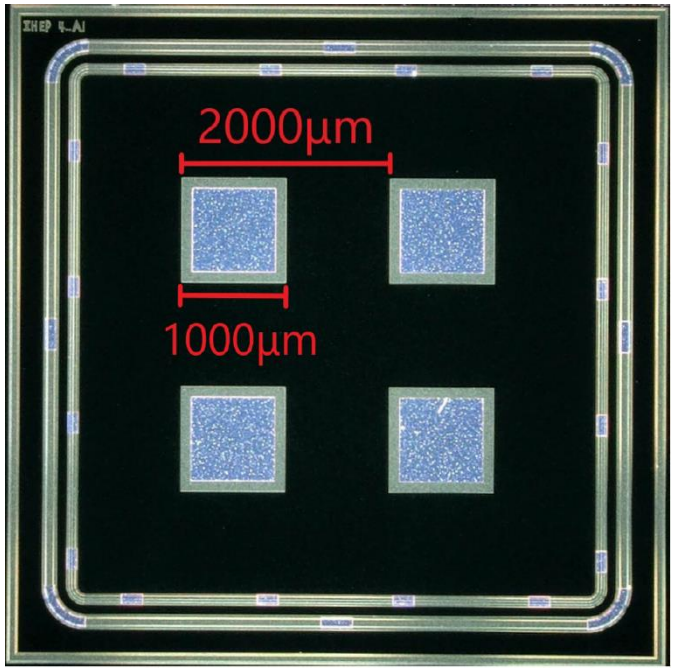
高能所研发的 AC-LGAD 传感器

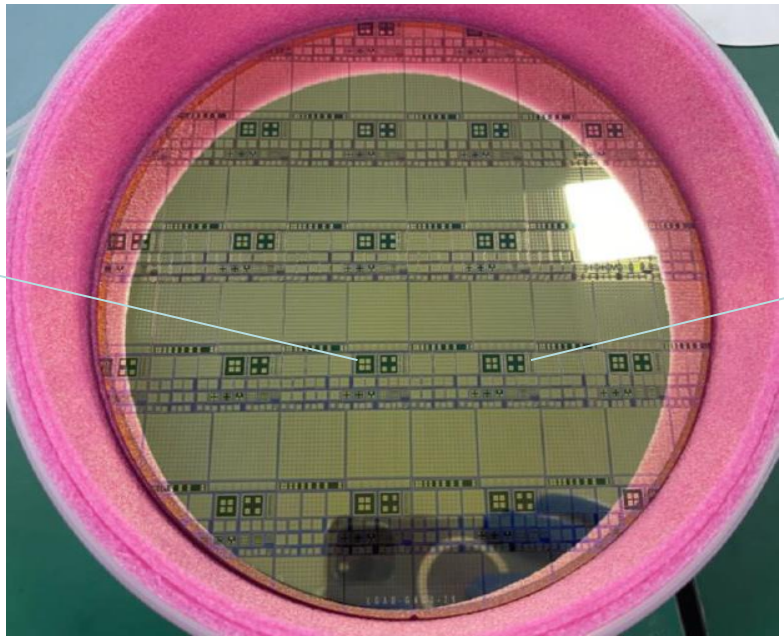
Pixels AC-LGAD：

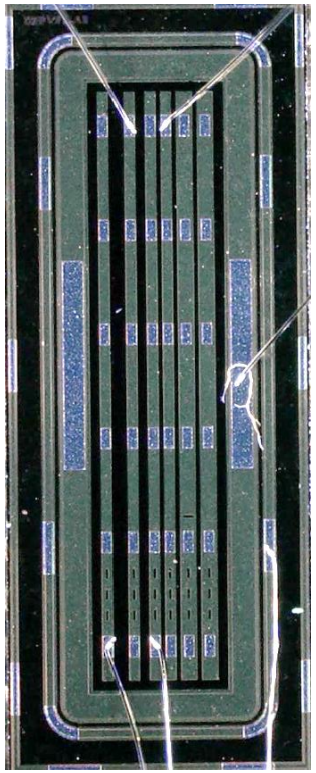
- Pitch size 2000um, pad size 1000um
- Different N+ dose ：
  - **10P，5P，1P，0.5P，0.2P**

Strips AC-LGAD：

- Strip length 5.6mm, width 100um
- Different Pitch size ：
  - **150um、200um、250um**

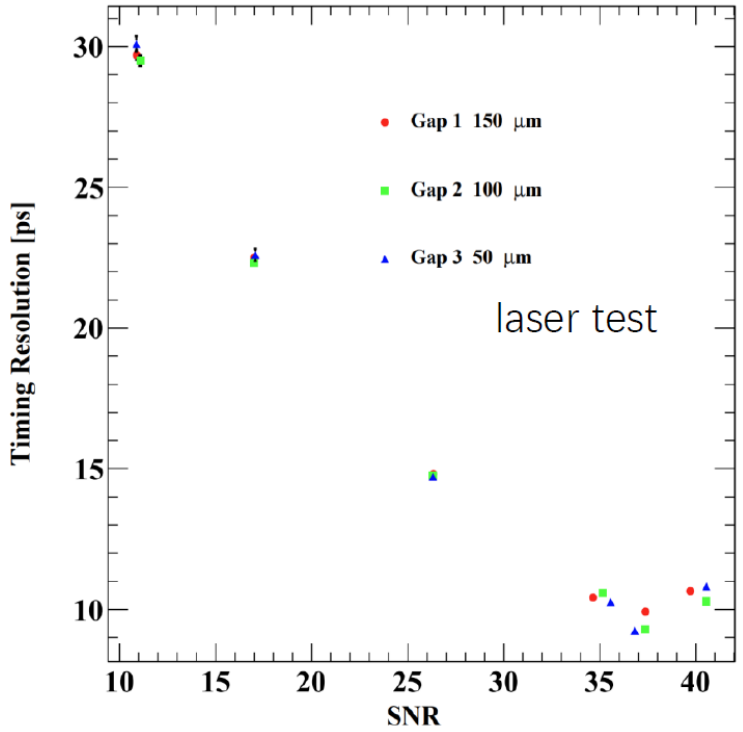




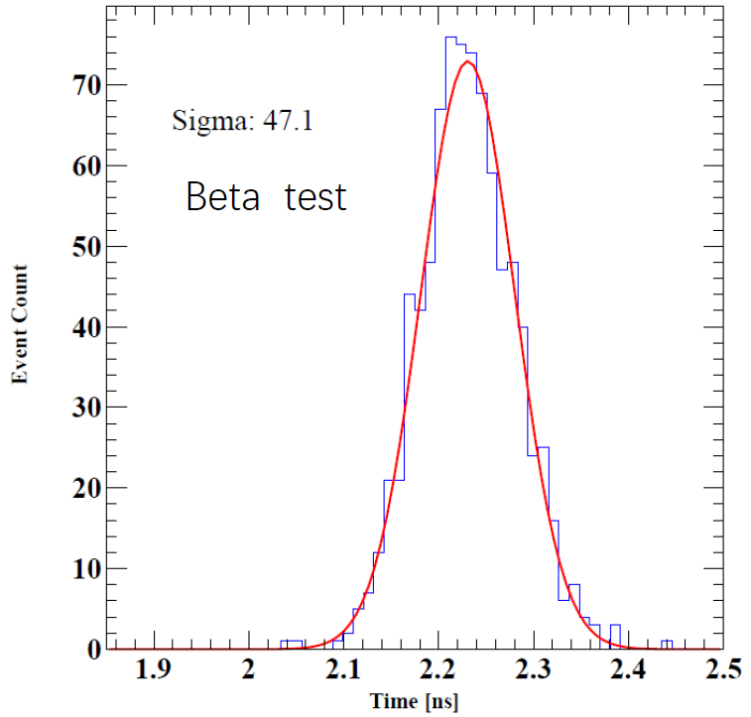


AC-LGAD的时间分辨

Jitter tested by laser



Δt Distribution（Beta source）



Timing resolution of Trigger

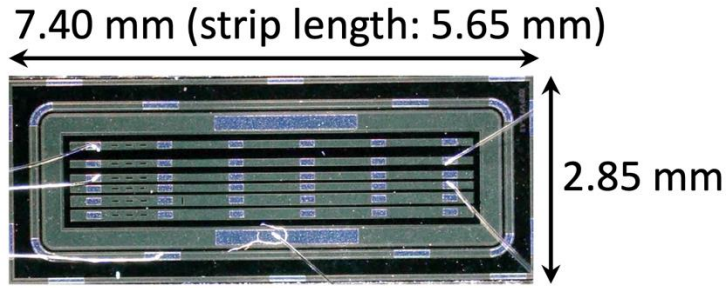
$$\Delta T = T_{trigger} - \frac{\Sigma_i a_i^2 T_i}{\Sigma_i a_i^2}$$

Weighted timing resolution of three strip electrodes

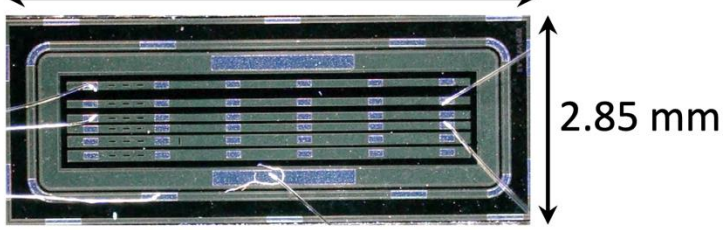
Sigma Δt = 47.1 ps

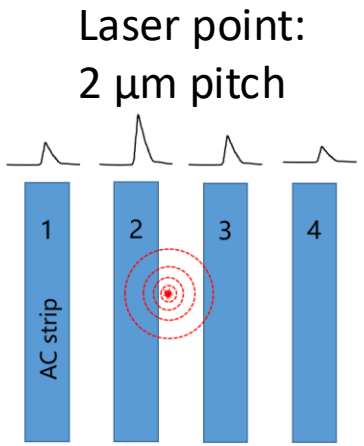
AC-LGAD strip ： 37.5 ps

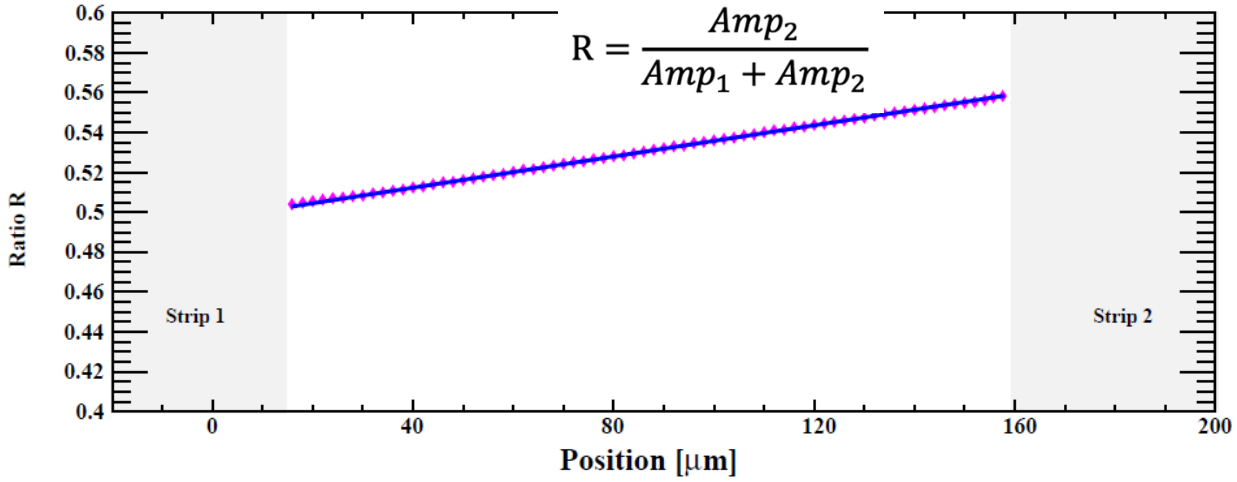
- **No significant change in timing resolution was observed for different pitches**
- **Saturation was observed ： ~ 10 ps.**
- **37.5 ps timing resolution, via Beta source test.**



AC-LGAD的位置分辨





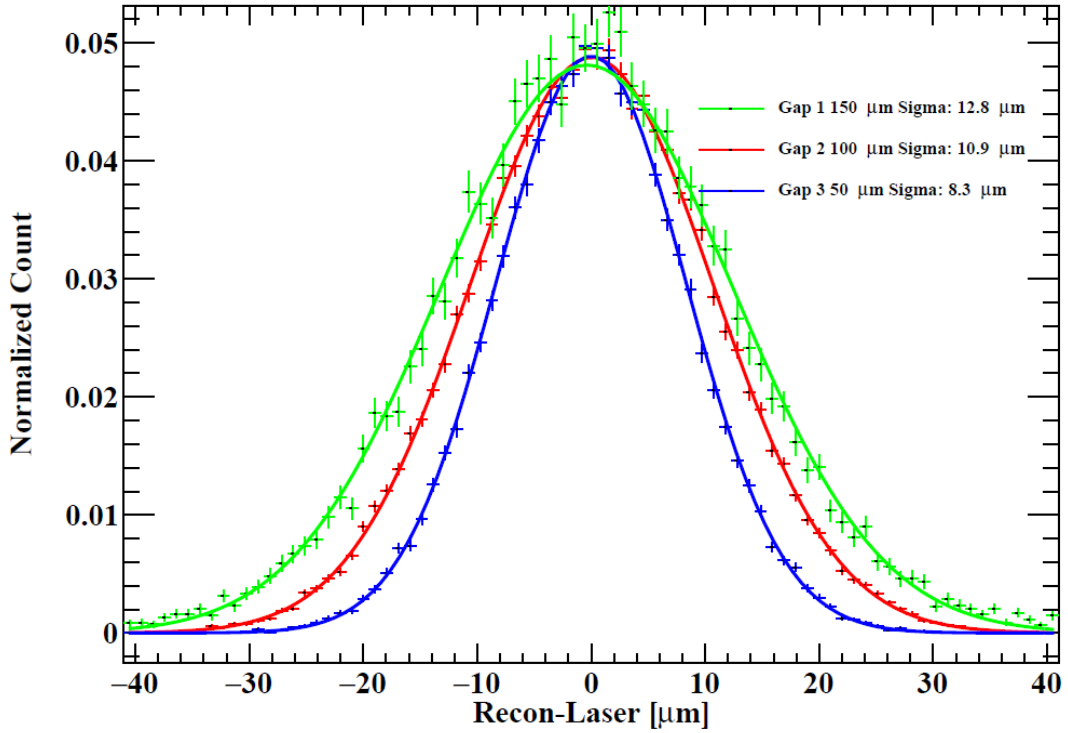


Position reconstruction:

The fraction of the signal (*R*) changes linearly with the move the laser.

Spatial resolution ：

8.3 μm (150 μm pitch)
10.9 μm (200 μm pitch)
12.8 μm (250 μm pitch)



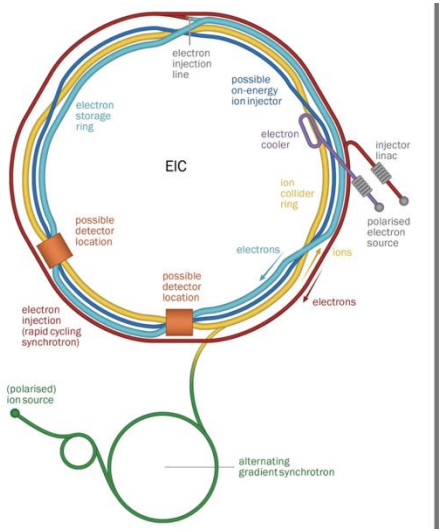
超快硅探测技术：低增益雪崩硅探测器

- **X光和带电粒子探测能力，抗辐照LGAD可应用于：**

  粒子物理探测，先进光源、核医学成像，航天航空探测等领域

美国EIC

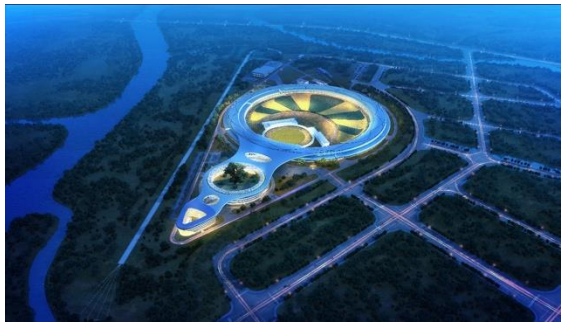
- ✓ **PID & ultra tracker**
- ✓ **Strip and pixel AC-LGAD**
- ✓ **10 m²**



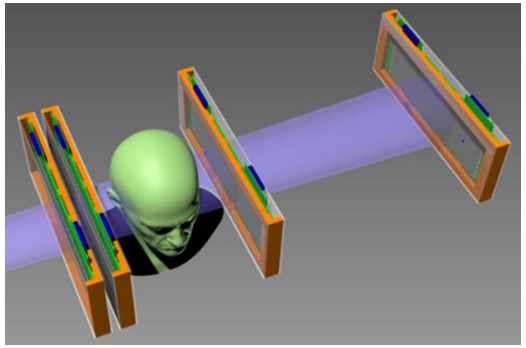
束流亮度测试
ATLAS 及SuperKEK

散裂中子源的质子测试束线

先进光源ps级成像



核医疗：质子治癌



总结

- **LGAD探测器将应用在大型对撞机的亮度升级中**
  - 高能所设计的LGAD将占CERN采购**90%**的份额
  - 模块级时间分辨在辐照后仍可达 **50 皮秒，位置分辨mm级**
  - **中国在探测器的各个关键方面起了主导作用**
- **AC-LGAD 应用在CEPC中**
  - 时间及径迹探测器
  - **时间分辨50皮秒，位置分辨10微米**
- **基于LGAD还广泛应用在其他的领域**
  - ATLAS束流亮度监测测试中表现良好，明年将安装在SuperKEK进行亮度测试
  - Track and time detectors in other particle physics and nuclear physics experiments，**such as EIC （pixel and strip AC-LGAD）**
  - **Space cosmic ray detecting**
  - **软x射线探测**
  - **…**

Thank you for your attention

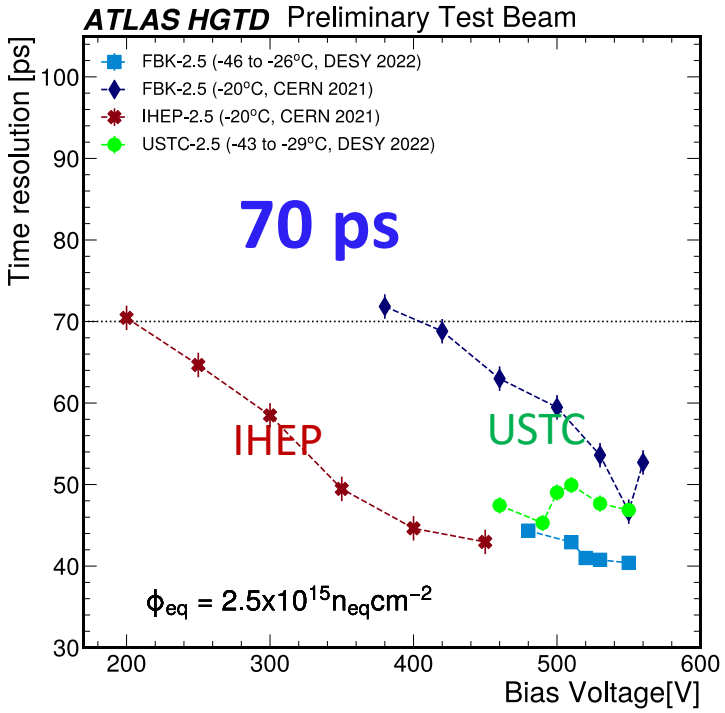
- **Back up**

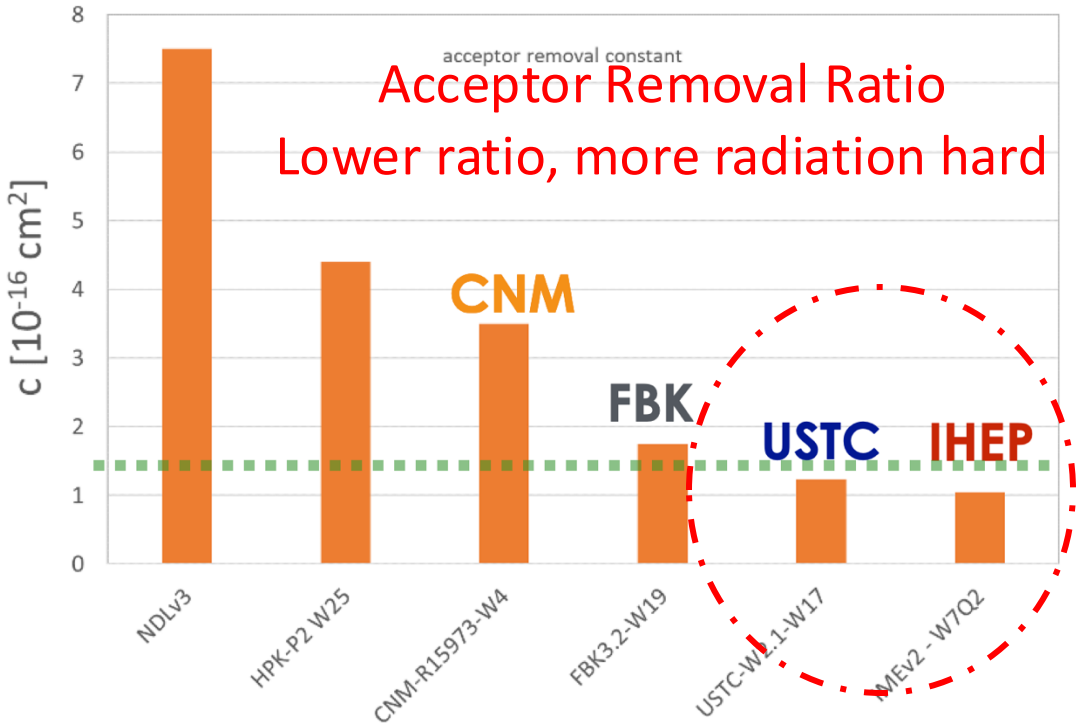
LGAD sensor after Irradiation

- **IHEP-IME LGAD with carbon-enriched doping**
  - 34 fabrication steps, all masks and processes designed by IHEP, fabricated at IME
  - Significantly lower acceptor removal ratio, the most radiation hard
- **After 2.5×10^{15} n_{eq}/cm^2 , IHEP LGADs can operated much below 550 V**

→ avoid single event breakdown

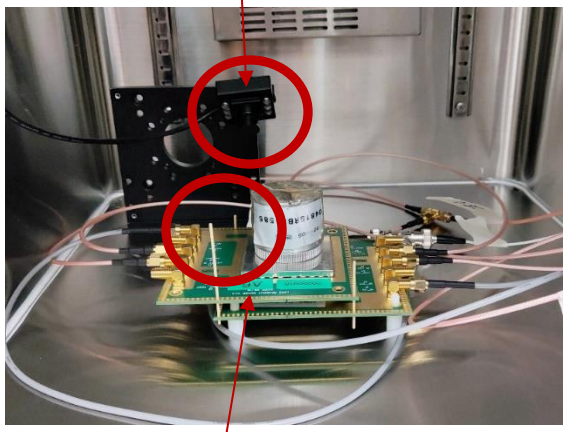
→ more than 20 sensors in test beam, no single event breakdown by far

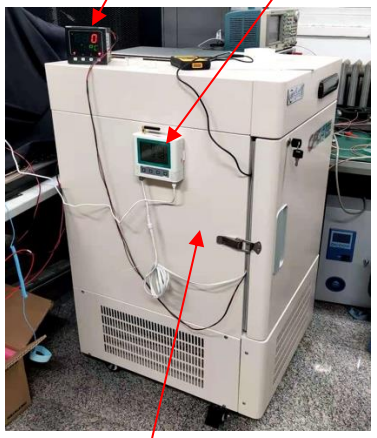




时间测试平台

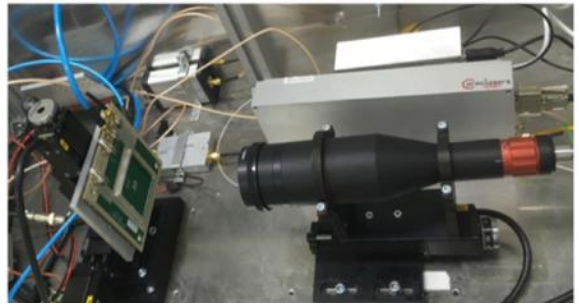
- **低温Beta辐照测试平台：**
  - 时间分辨率、电荷收集等
  - 为了降低噪音，- 30 C°低温
  - Sr90 Beta放射源
  - 二级放大器带宽 >1GHz





- **激光测试平台：**
  - 研究电子学噪音jitter对时间分辨率的影响
  - 排除Beta测试Landau项
  - 不同于传统测试平台，首次使用皮秒激光器

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{timewalk}^2 + \sigma_{distortion}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2$$



LGAD抗辐照性能优化结果

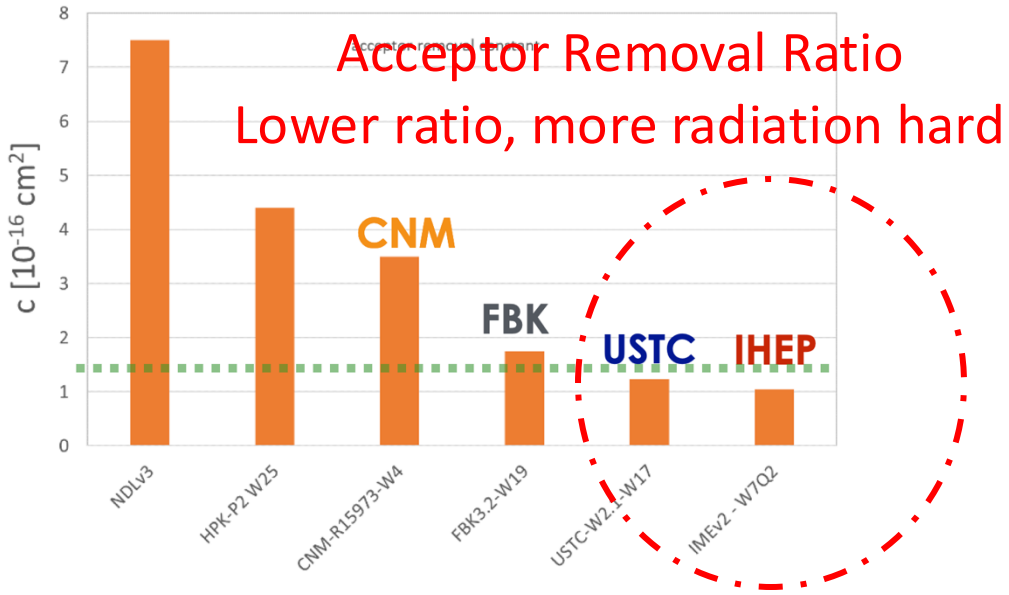
IHEP-IME 浅掺碳设计成功克服静态辐照效应影响

- 得到目前最低的受子移除速率
- 克服了国外深掺导致的硼失活效应
- **国际最优的LGAD抗辐照性能**

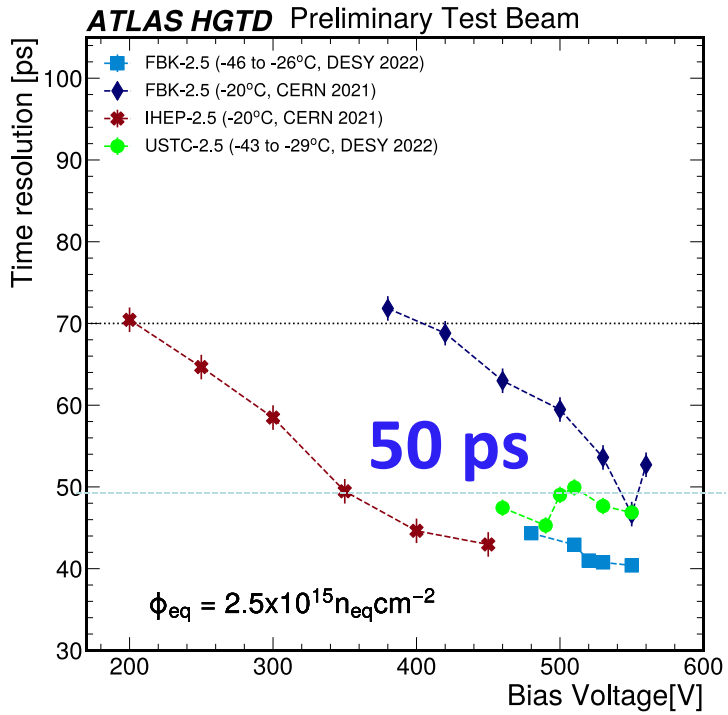
相关结果好于国际上一流的设计厂商， 日本滨松、意大利FBK

高能所IHEP-IME 传感器

得到最低受子移除速率，最优抗辐照性能



高能所IHEP-IME 传感器



LGAD sensor for HGTD

- ~21,000 LGAD sensors for HGTD project
- Requirements:

•Size: 15x15 array, 1.3x1.3 mm^2 pixel size

•Active thickness: 50 um(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})

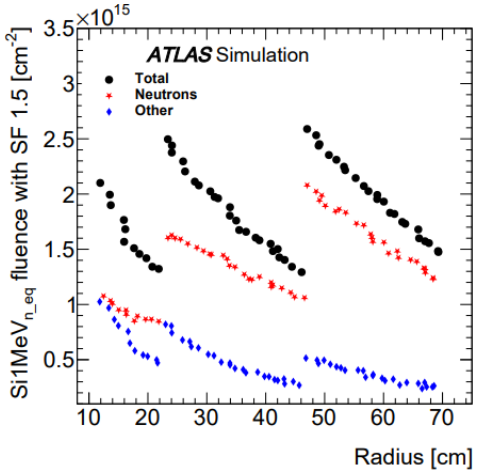
•Time resolution: 35 ps (start), 70 ps (end) per hit, while 30 ps (start), 50 ps (end) per track

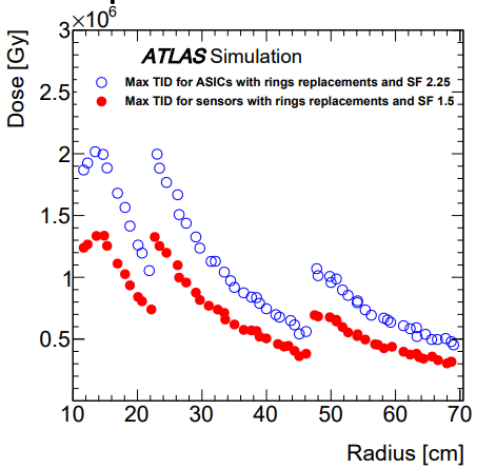
•Collected charge per hit >4 fC (minimum charge needed by the ASIC to hold good time resolution)

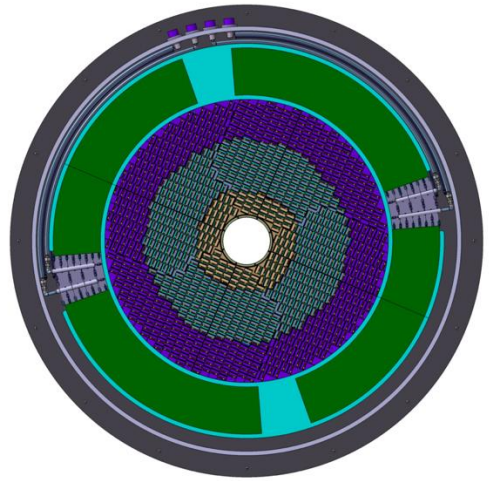
•Hit efficiencies of 97% (95%) at the start (end) of their lifetime

Replacement of inner ring every 1,000 fb^{-1} and middle ring at 2,000 fb^{-1}

Maximum fluence with replacements

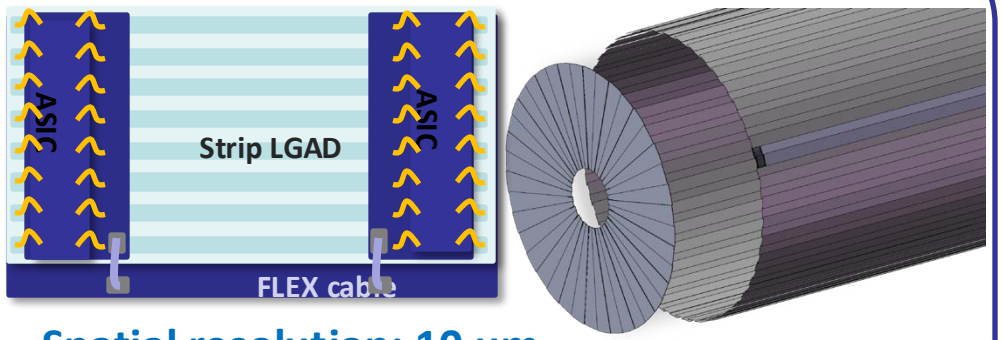






Other future Application of LGAD

CEPC : Outer Tracker+ TOF

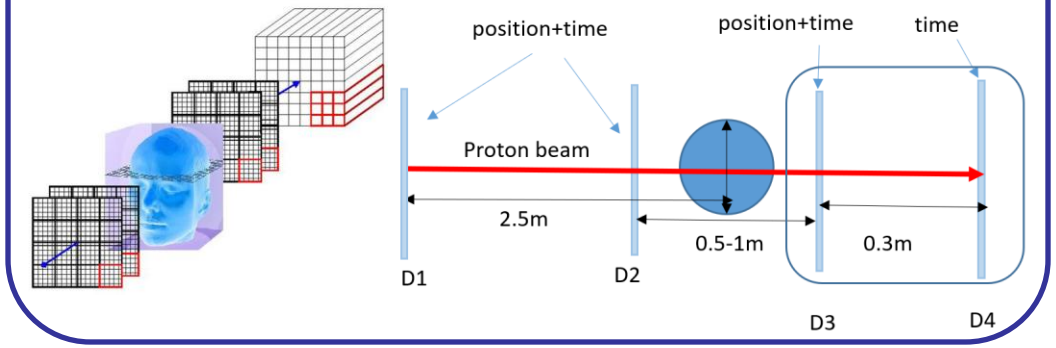


Spatial resolution: 10 um
Timing resolution: 30- 50ps

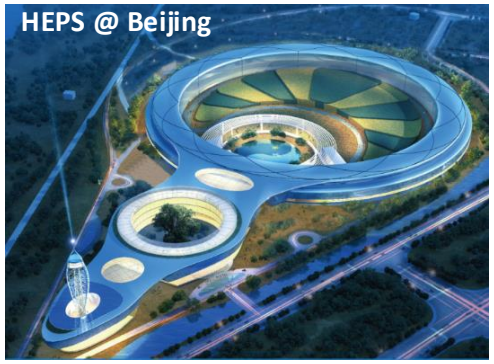
>70m^2 area

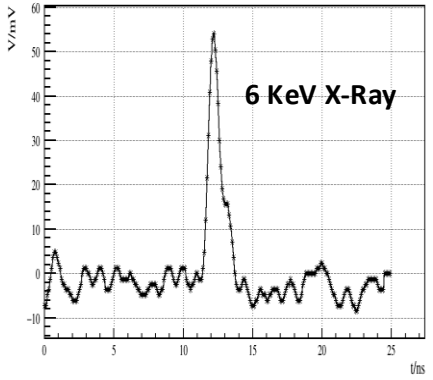
Nuclear Medicine Instruments :

Such as proton therapy and proton CT



X-ray detectors @ advanced light sources





other applications

- Beam Telescope for Beam Test Platform
- Track and time detectors in other particle physics and nuclear physics experiments, **such as EIC （pixel and strip AC-LGAD）**
- **Space cosmic ray detecting**
- …