高时间分辨率硅探测器的研发现状与发展趋势

Zhijun Liang (IHEP)

梁志均

中国科学院高能物理研究所

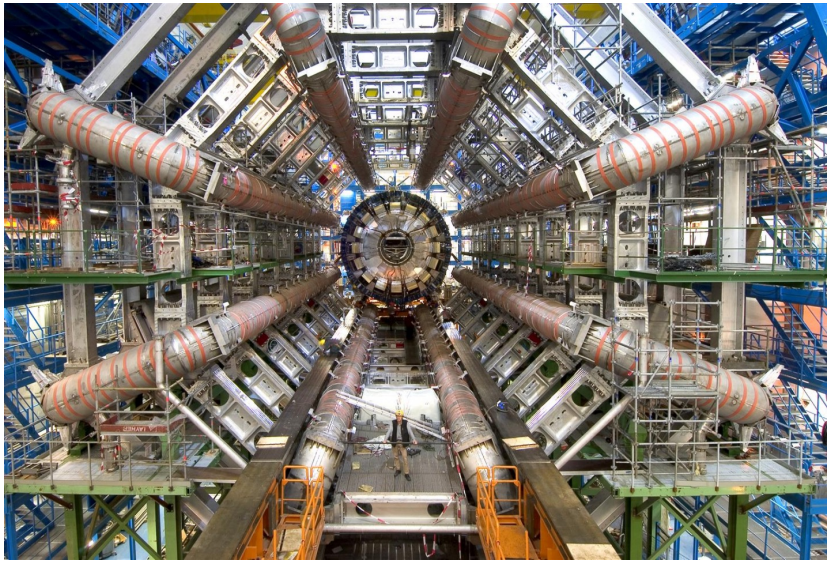
Outline

- 高时间分辨率硅探测器的研发现状
- 高时间分辨率硅探测器发展趋势

大型强子对撞机与ATLAS实验

大型强子对撞机

- 周长27km，总投资40亿美元
- 世界能量最高的加速器
- 质心系能14TeV（$14x10^{12}eV$）
- 位于瑞士与法国边境

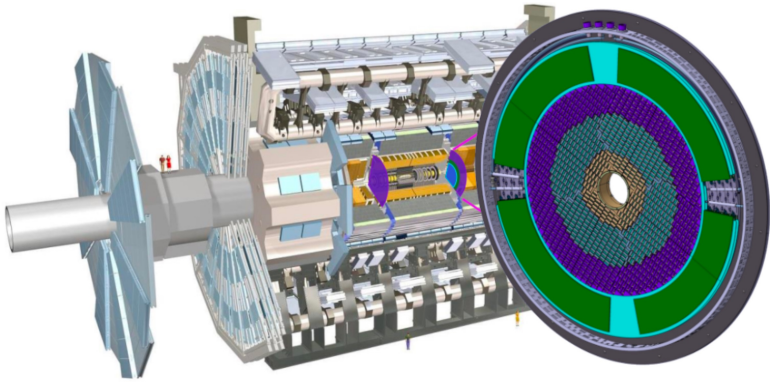


ATLAS探测器

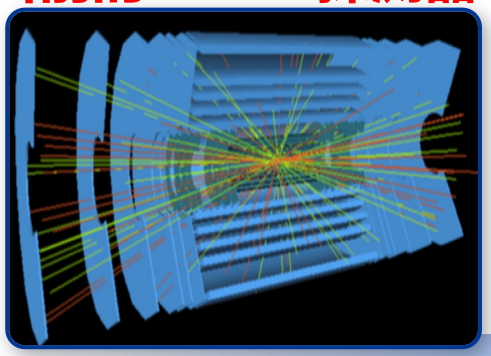
- 大约3000人的一个实验组
- 6层楼高（25米）的大型探测器
- 探测对撞产生粒子能量与动量

High Granularity Timing Detector (HGTD)
ATLAS实验高颗粒度时间探测器

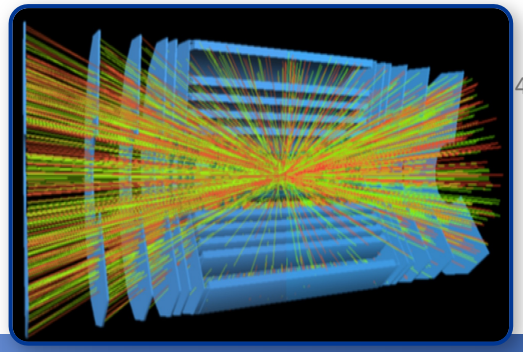
- 把粒子到达时间的测量精度提高2个数量级（数纳秒→30皮秒）
- 解决高亮度LHC对撞事例堆积问题
  - 6.4**平方米**的硅探测器， 30**皮秒**的时间分辨
  - **毫米级的颗粒度，超过三百万个读出通道**
  - **能承受**2.5×10^{15} n_{eq}/cm^2**的等效中子通量的辐照**
- 中国组主导探测器研制
  - 45%探测器组装（34% 高能所，11%科大）
  - >88%抗辐照高时间分辨传感器（78% 高能所-微电子所，10%科大-微电子所）
  - 100%前端电子学(高能所，南大)， 50% ASIC测试， >16% 高压电子系统



目前的ATLAS探测器

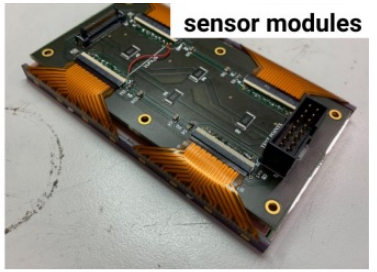


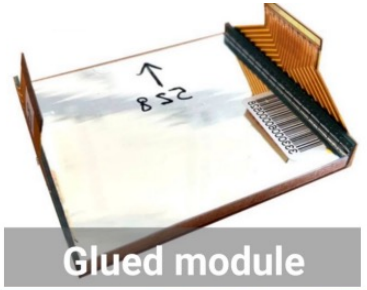
高亮度LHC升级后的ATLAS探测器

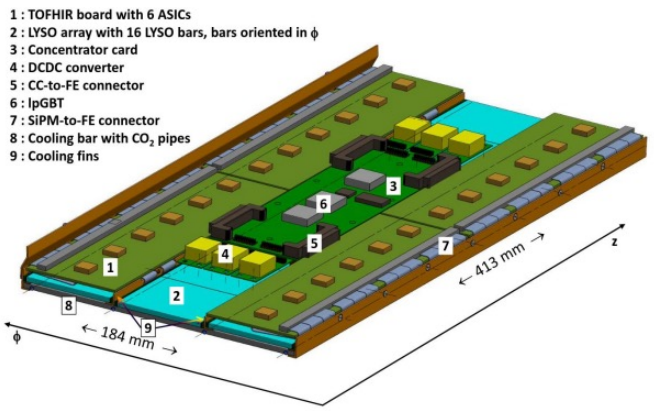


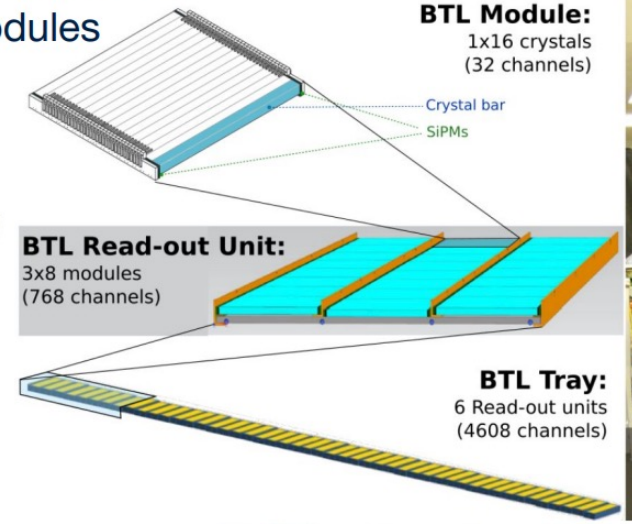
CMS实验的桶部时间探测器

- 16 LYSO bars+ 32 SiPM - 51x57 mm ^{2}
- 2 sensor modules per FE board
- 12 FE per CC - BTL Read-out unit
- 6 BTL RU per tray
- 72 trays (36 in ϕ × 2 in η) - 250 x 18 x 2.5 cm
- 331k readout channels, 10368 modules





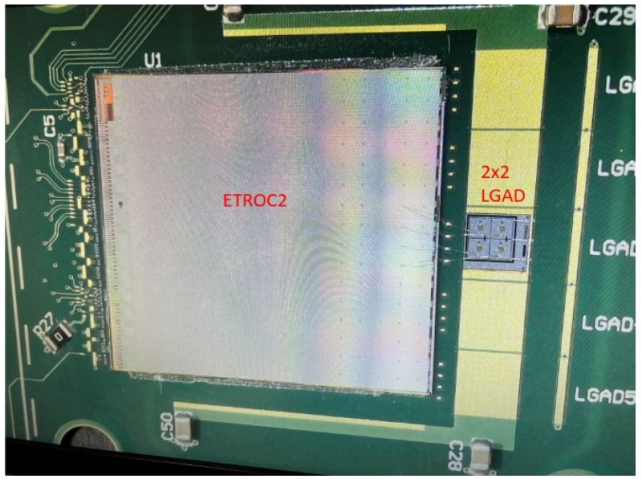


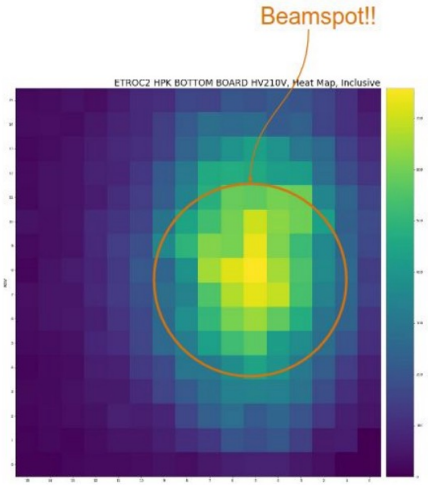


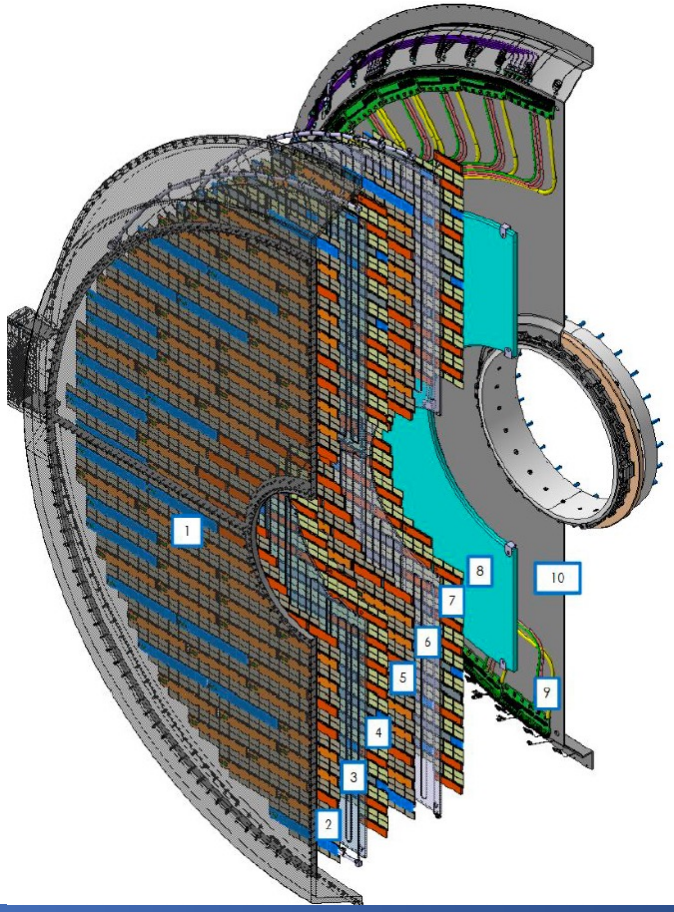
北京大学是其中一个模块组装站点

CMS端盖时间探测器

- Strong effort to combine inputs from studies into a complete detector design and layout: ~8000 modules (4 sensors each) on 2 EndCaps. ~8M channels in total
- Each detector consists of 2 disks with front and back face instrumented
- Modules + front end electronics and services need to fit in very tight mechanical envelope - total detector z < 99mm





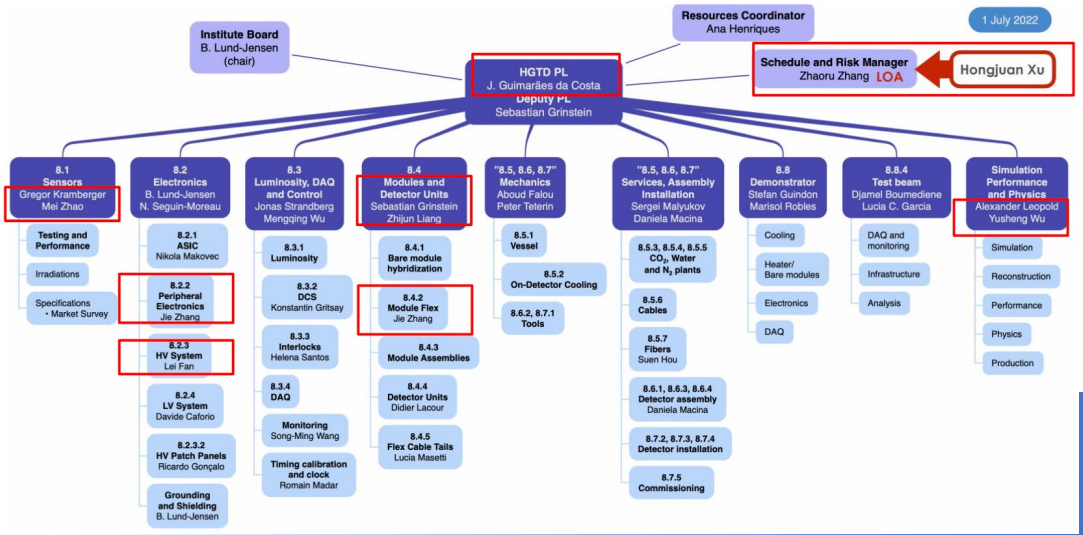


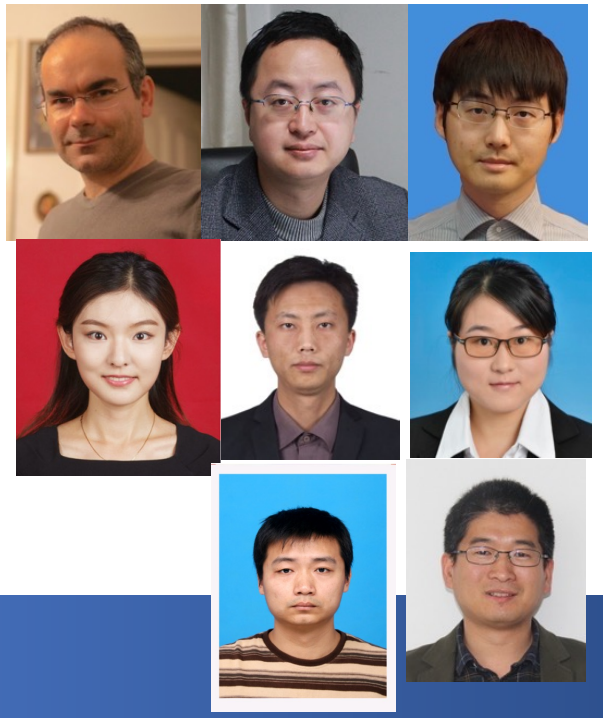
ATLAS高时间分辨探测器： 重要管理职位

- 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
  - 4人担任探测器Level-2召集人 （梁志均，赵梅，张照茹、吴雨生）
  - 2人担任探测器Level-3召集人 （张杰，樊磊）
  - 1人担任speaker committee（刘衍文）

HGTD项目的管理架构

Management architecture of HGTD projects



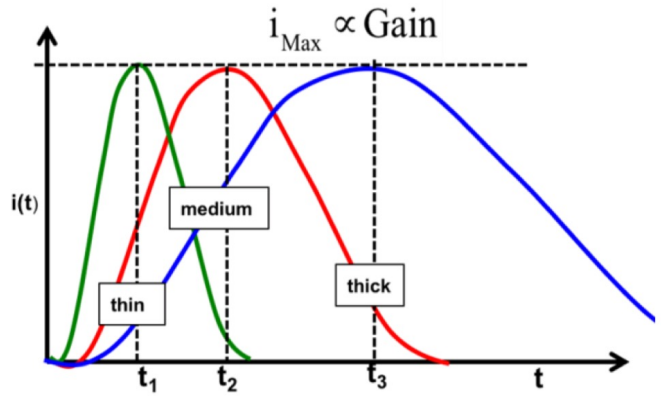


Low Gain Avalanche Detectors (LGAD)
低增益雪崩硅传感器

- LGAD是近年出现新型硅传感器，可以高精度测量时间（20-30皮秒）
- 与APD 和 SiPM比较, LGAD has 适中的增益 (10-50)
  - 信噪比高，无自触发
  - 减薄耗尽区（漂移区），提高电场与电子漂移速度

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

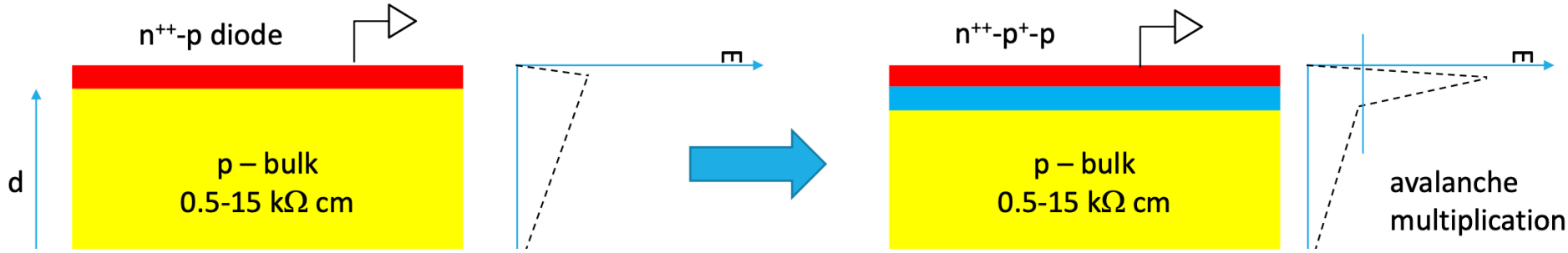
- **Modest gain to increase S/N**
- **Need thin detector to decrease t_{rise}**



低增益雪崩硅传感器

P+ gain layer on top of PIN diode

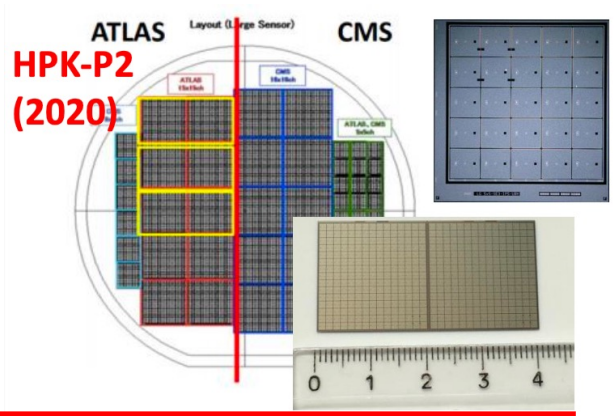
一般的 PiN结传感器

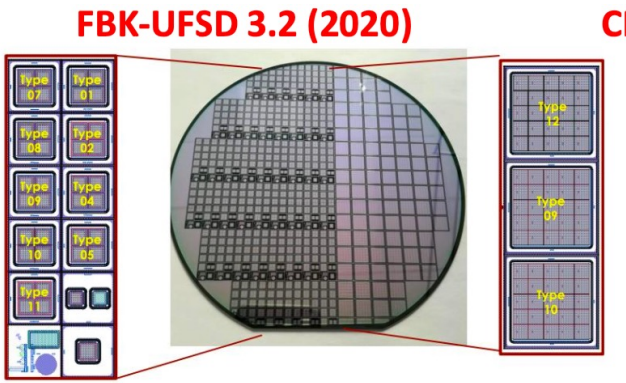


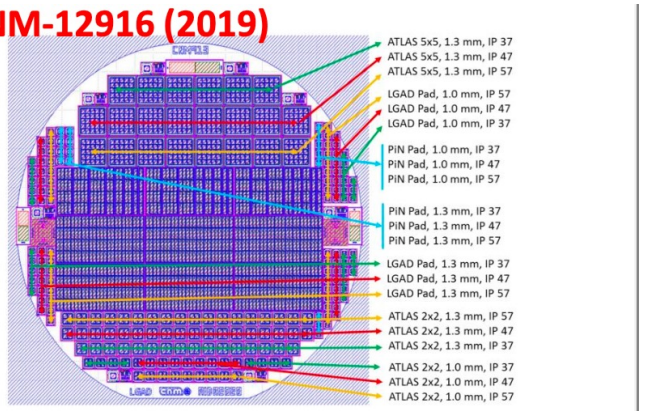
8

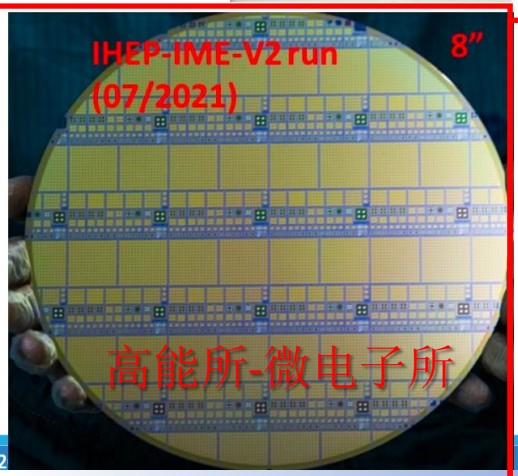
LGAD低增益雪崩硅传感器： 国内外形势

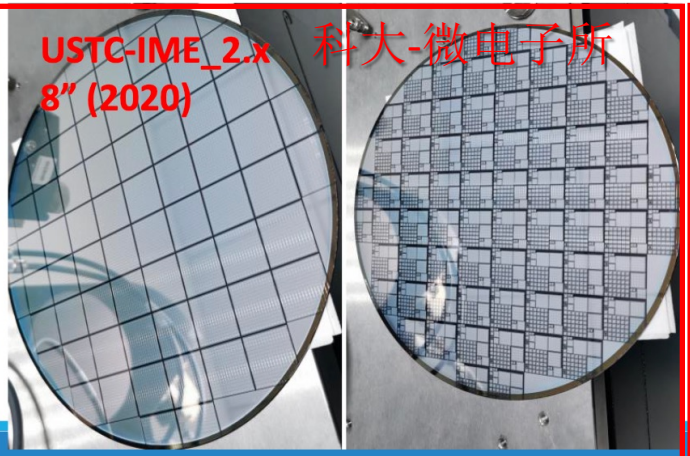
- 近年来，全世界范围涌现出很多研制LGAD硅传感器的单位
  - 国内：IHEP-IME (高能所-微电子所), USTC-IME (科大-微电子所), NDL(高能所-北师大)
  - 国际：滨松HPK (Japan)， FBK (意大利), CNM (西班牙）…
  - 高能所和科大分别独立设计传感器版图和工艺，在微电子所8寸晶圆工艺流片

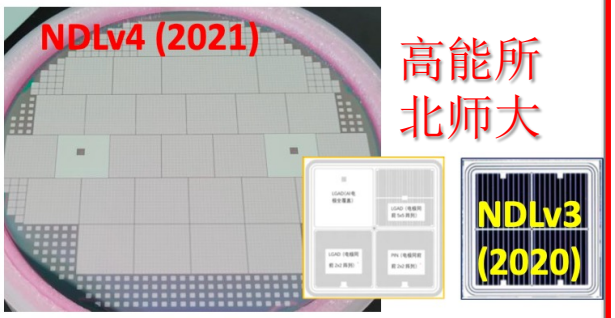








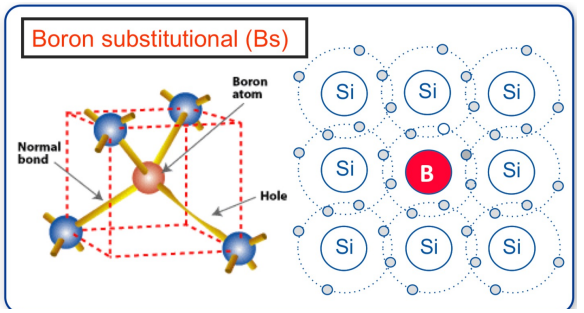




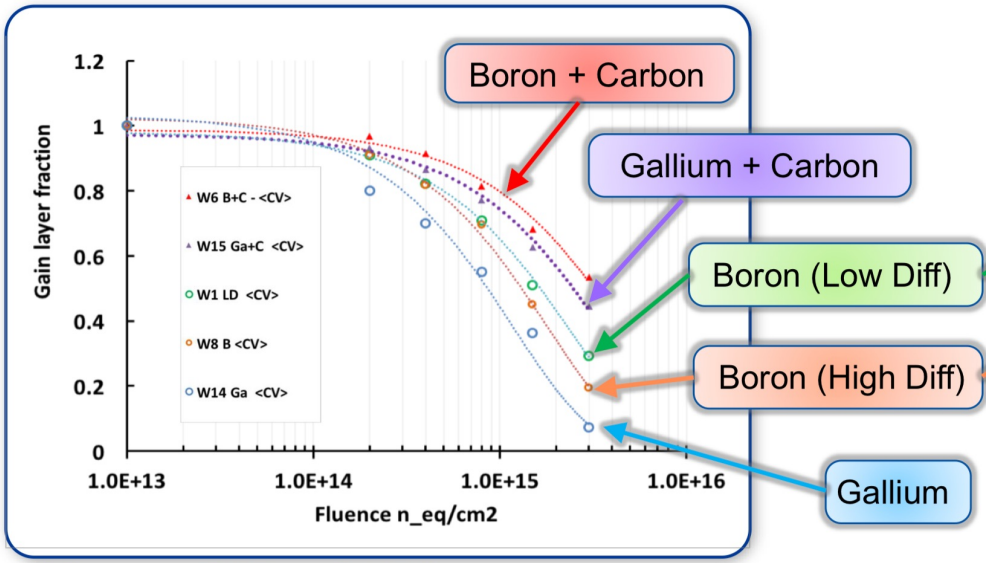
PLANAR TECHNOLOGY – more vendors
(e2V, BNL, Micron …)

LGAD传感器辐照后硼掺杂移除 (Acceptor removal)

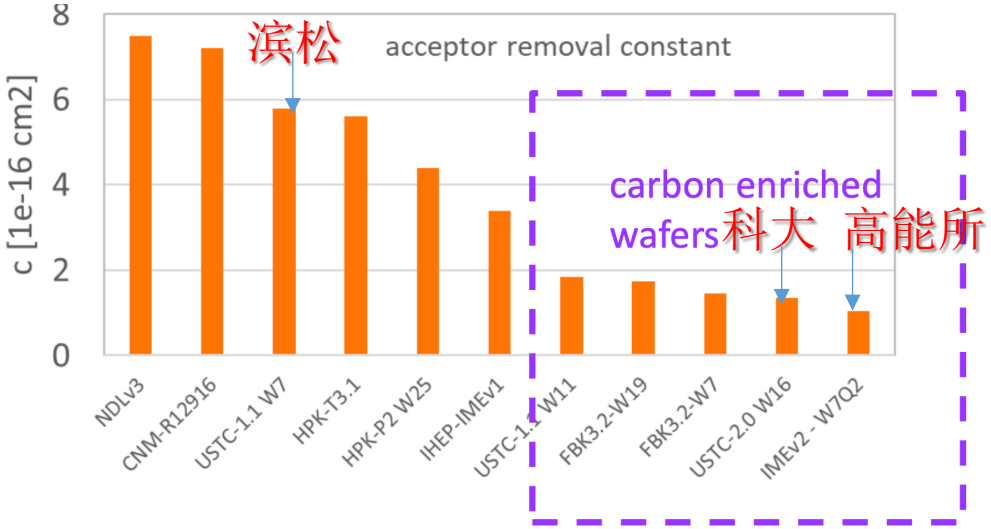
- 辐照后，硼掺杂失去活性，LGAD传感器增益下降(Acceptor removal)
- 高能所、科大等国产LGAD采用掺碳工艺
  - 显著减低辐照后损伤（减低硼移除率）
  - 抗辐照性能显著提高
  - 目前抗辐照性能优于滨松



高能所传感器、科大研发传感器
目前移除率最低（最佳抗辐照性能）



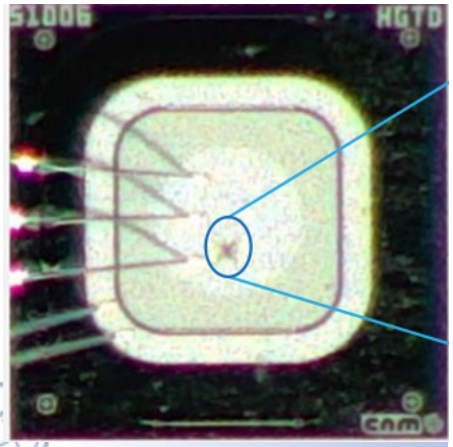
[G.Paternoster, FBK, Trento, Feb.2019]

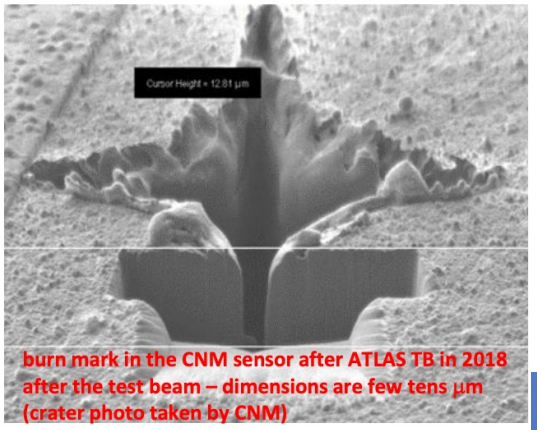


硅传感器的单粒子烧毁风险 Single Event Burnout (SEB)

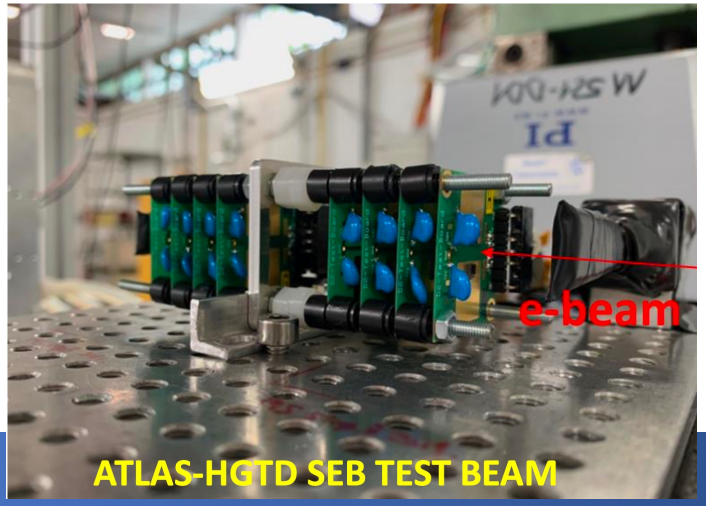
- RD50, CMS and ATLAS 合作组在2021年确认LGAD的单粒子烧毁风险
- 高电压与高电场导致烧毁，工作电压要控制到<550 V （50微米的硅传感器）
- ATLAS合作组开展欧洲核子中心（CERN）的高能质子流测试
  - 辐照后，不掺碳的LGAD（滨松，西班牙CNM）烧毁率较高
  - 掺碳的LGAD基本能通过测试（高能所，中科大，意大利FBK）
  - 高能所传感器辐照后，8个样品全部通过测试，无一烧毁

单粒子烧毁后LGAD（滨松/CNM）





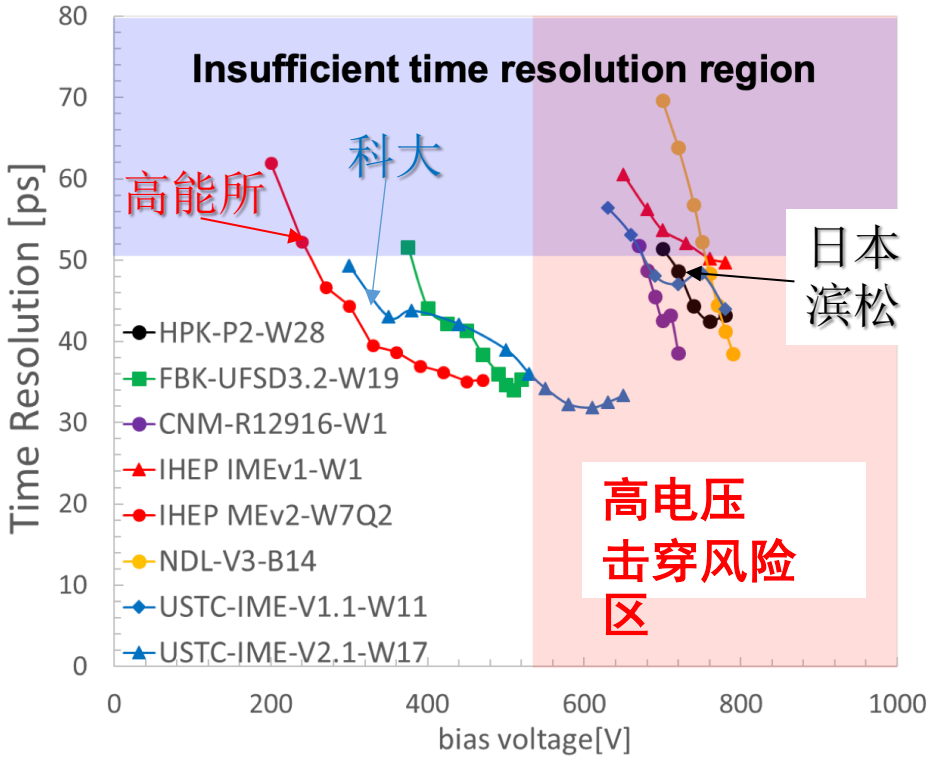
CERN test beam: 120 GeV 质子束流



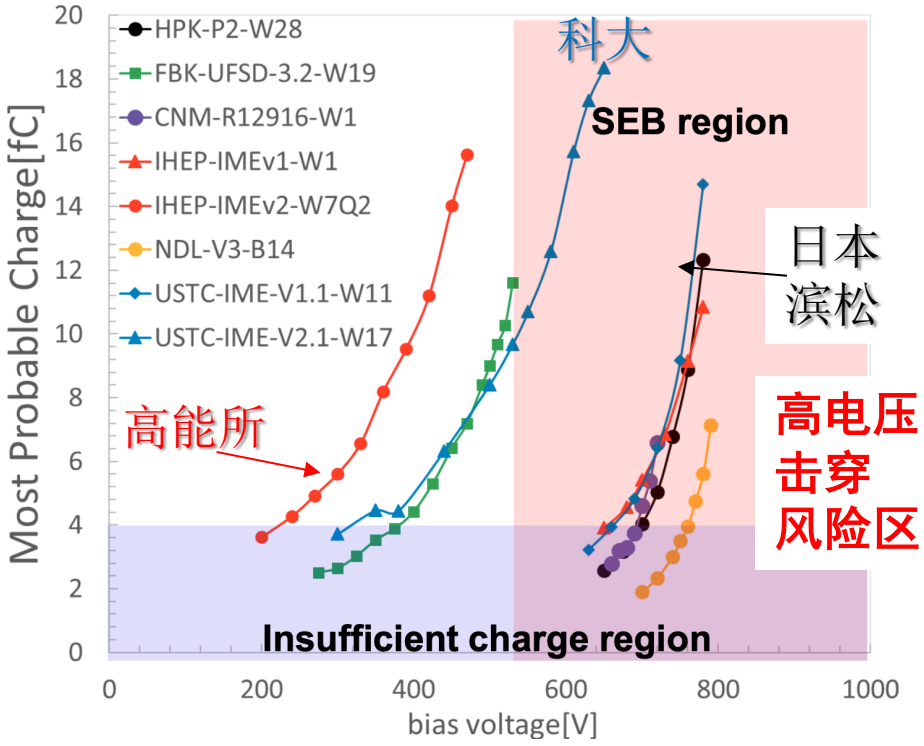
LGAD传感器在辐照后的性能 （ 2.5e15 cm^{-2} 等效中子通量）

- 掺碳的LGADs 满足ATLAS实验的 HGTD 要求（高能所，科大，意大利FBK）
  - 30-50皮秒的时间分辨率
  - 4fC以上的电荷收集，工作电压低于550V（避免烧毁）

时间分辨率 vs 偏置电压



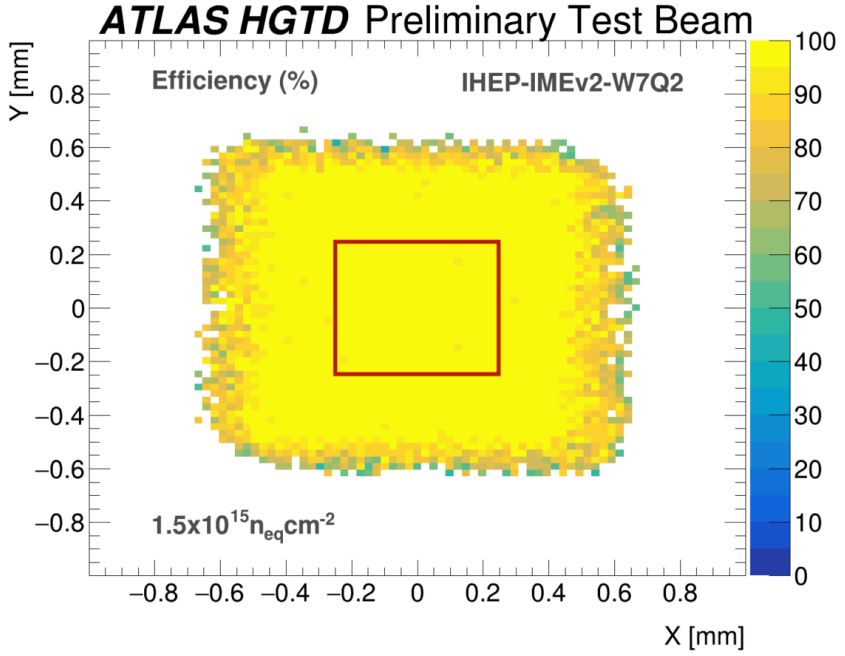
电荷收集 vs 偏置电压



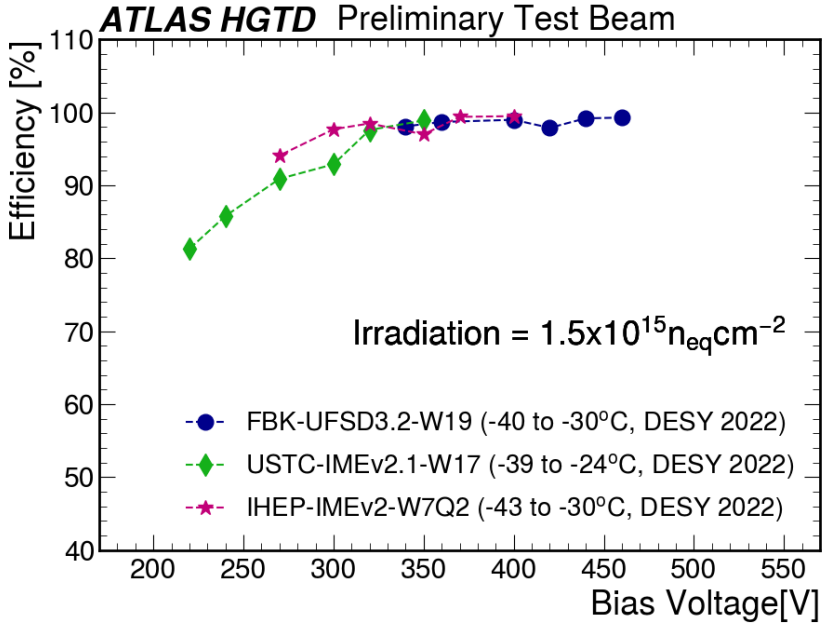
辐照后LGAD传感器在束流测试的性能

- 辐照后，掺碳LGAD传感器束流测试中有>99% 探测器效率
- 高能所、科大LGAD通过欧洲核子中心CERN的Market Survey
  - 国产硅传感器首次在LHC实验上得到应用

高能所传感器在束流测试中探测效率



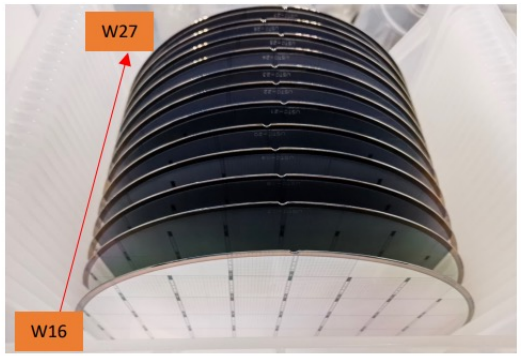
探测效率 VS 偏置电压

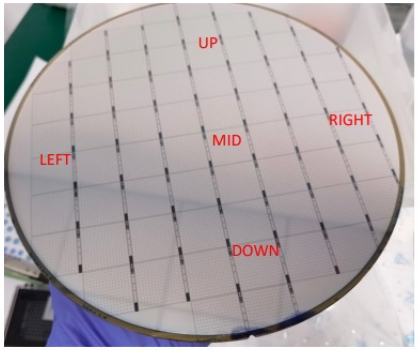


LGAD传感器的量产

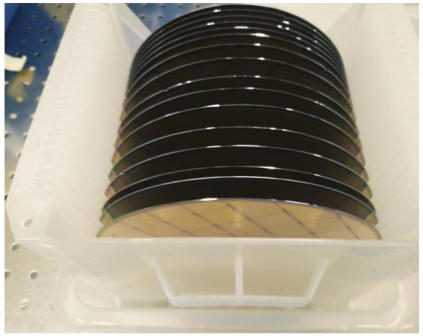
- 2023年高能所-微电子所赢得CERN的LGAD全额招标订单（>1.5万个LGAD）
  - 在日本滨松、意大利FBK等竞争下，高能所-微电子所赢下招标
  - 欧洲核子中心（CERN）首次采购中国产的硅传感器
  - 象征着国产硅传感器国际地位显著提升
- 各单位在该项目LGAD传感器的贡献比重
  - 高能所-微电子所： 90%（66% CERN采购+ 24%实物贡献）
  - 中科大-微电子所：10% 实物贡献

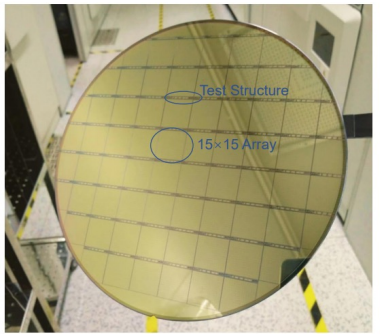
中科大-微电子所LGAD预生产





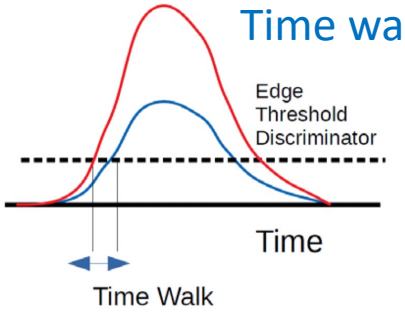
高能所-微电子所LGAD预生产



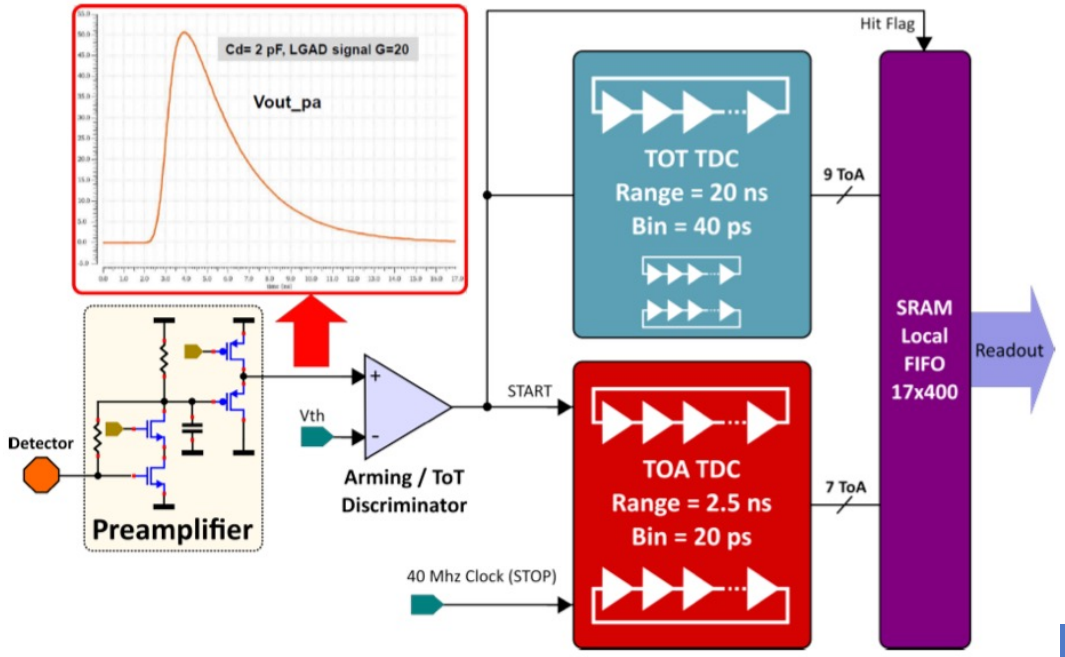


ALTIROC : 超快读出ASIC

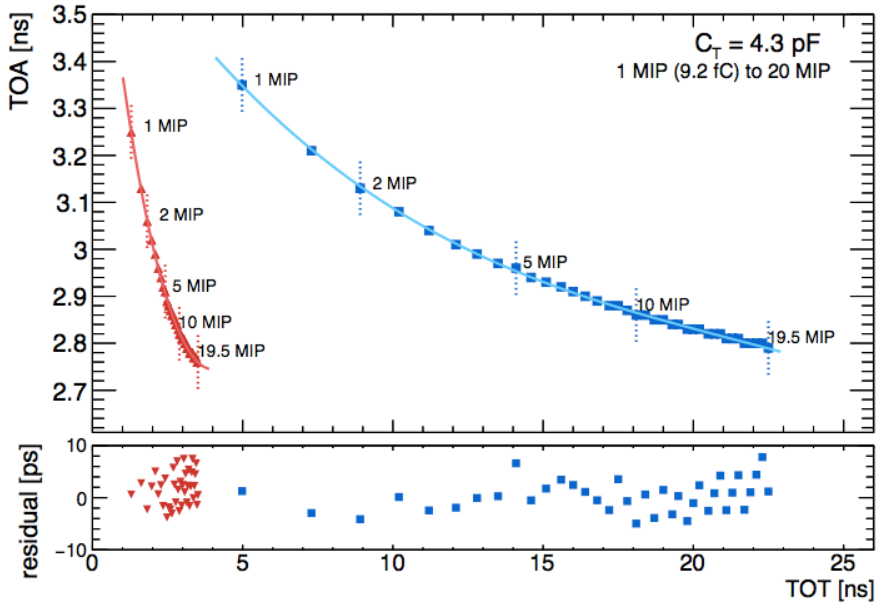
- ATLAS时间探测器研发超快读出ASIC芯片，多个单位参与
  - 高能所参与ASIC中数字电路部分的设计，承担50%的晶圆测试
- 225通道，每个通道有一个前端放大器，甄别器，两个TDC:
  - Two TDC (Time to Digital Converter) to provide digital **Hit data**
    - Time of Arrival (TOA) : Range of 2.5 ns and a bin of 20 ps (7 bits)
    - Time Over Threshold (TOT) : range of 20 ns and a bin of 40 ps (9 bits)
  - One Local memory: to store the 17 bits of the time measurement until L0/L1 trigger (~ 1 MHz)



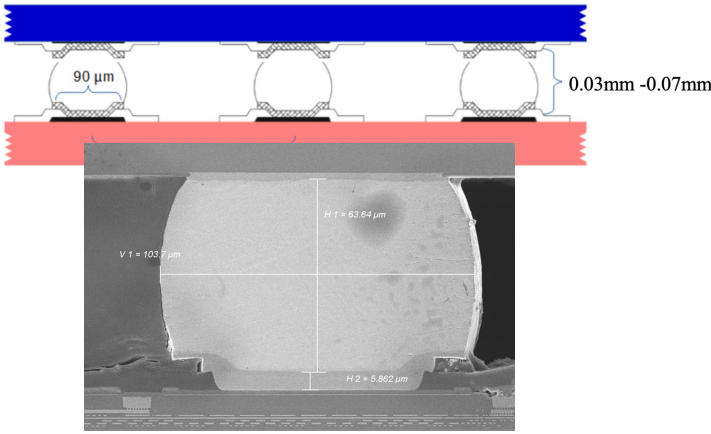
ALTIROC timing ASIC in nutshell



Time walk correction with TOT

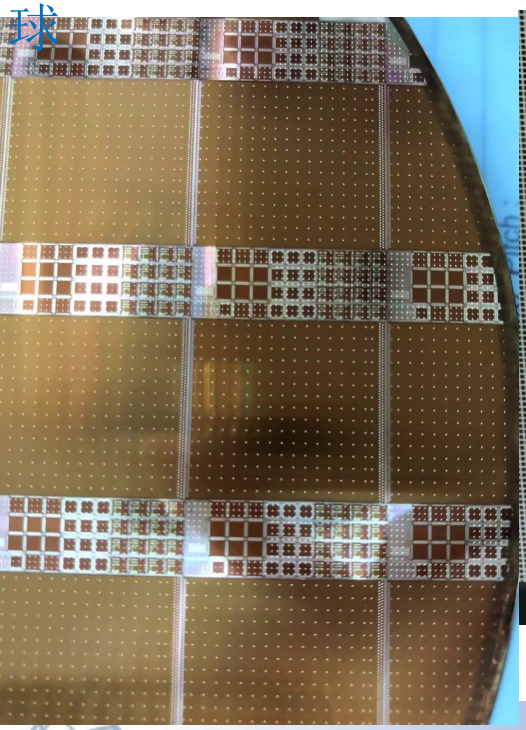


探测器模块：倒装焊封装

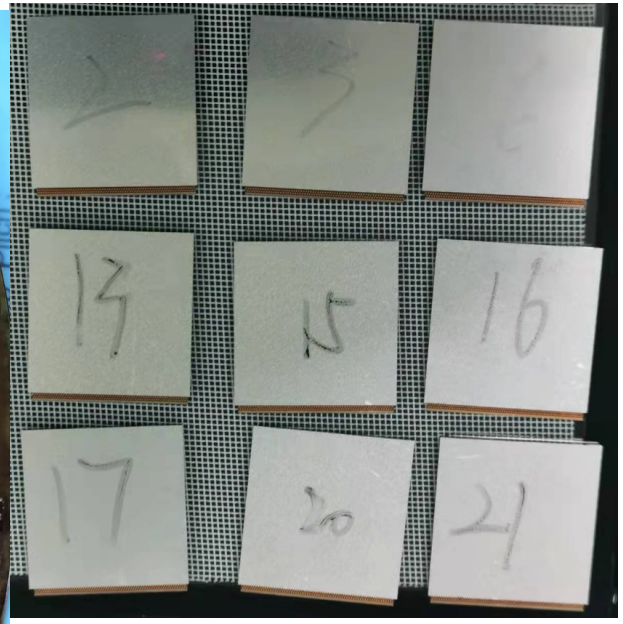


- 高能所承担项目中50%的倒装焊封装任务
- 高能所在国内已经研制出100+倒装焊模块
  - ALTIROC读出芯片 + 高能所-微电子所LGAD

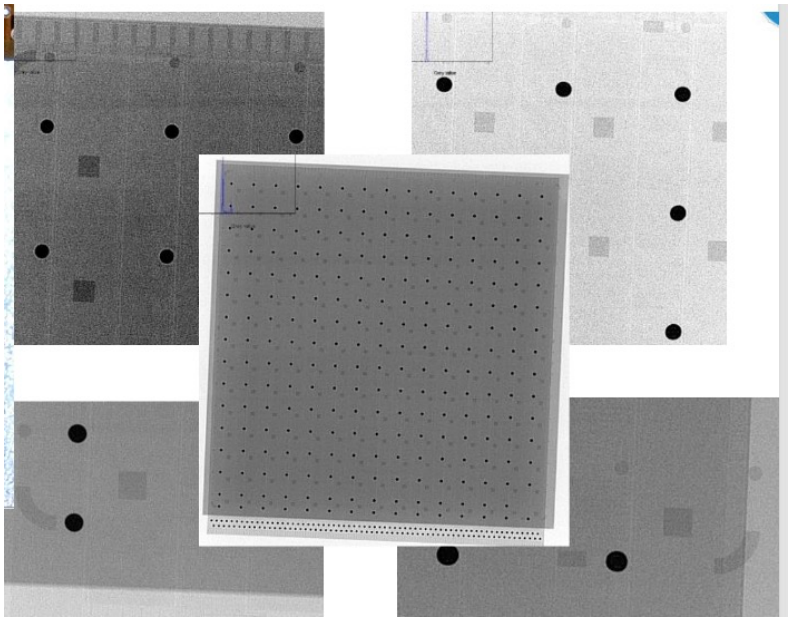
ALTIROC2 芯片晶圆植球



倒装焊模块后的模块

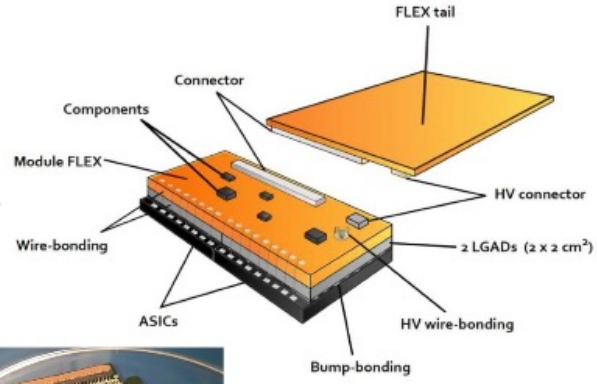


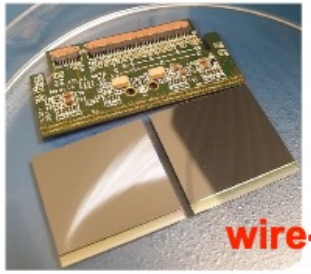
X-ray image of full-size hybrid



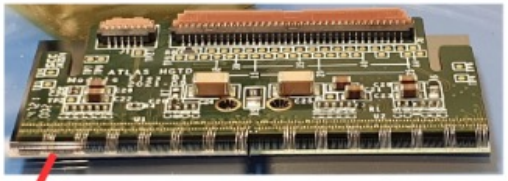
ATLAS时间探测器模块组装

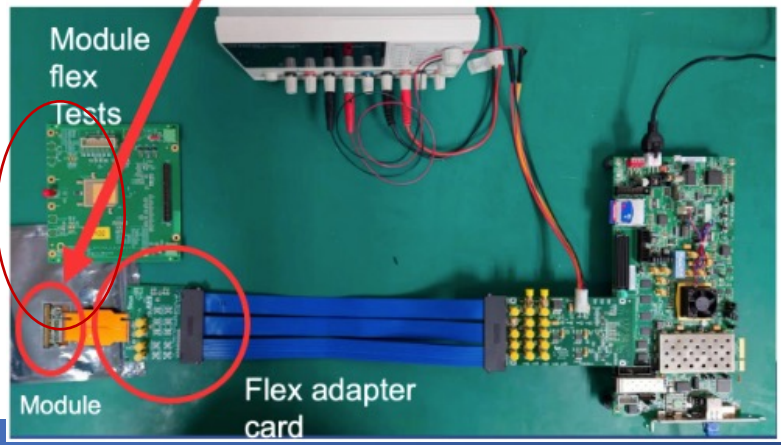
- HGTD项目总共需要8032个探测器模块
- 6个模块组装生产中心
  - 高能所，科大，德国，法国，西班牙，摩洛哥
  - 高能所是最大的生产中心，组装34%的模块
  - 中科大承担11%的模块组装
- 高能所与国内公司研制国产自动组装系统
  - 有高分辨图像系统，做芯片图像识别
  - 自动芯片组装、点胶
  - 位置组装精度达到微米级

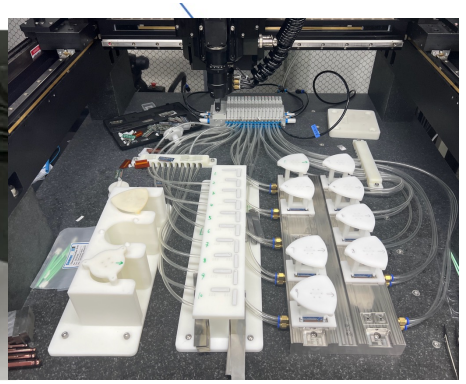




glue+
wire-bonds



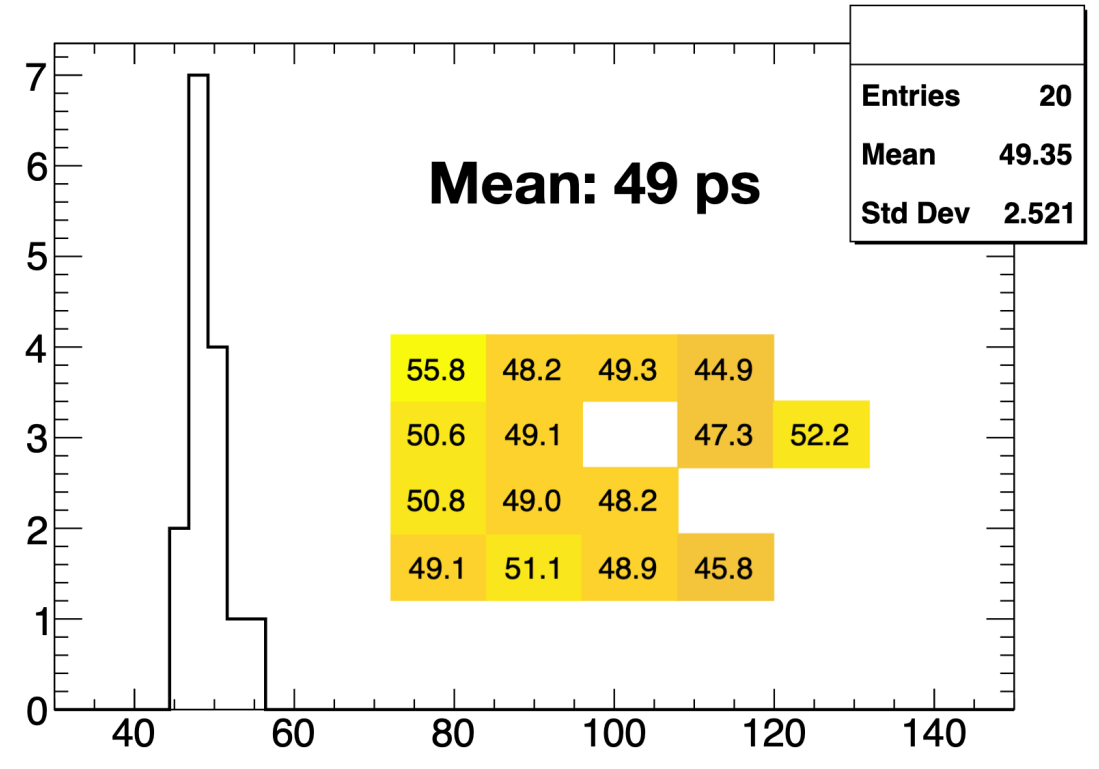




Picking tool Picking dummy sensor Placing dummy sensor Picking flex

模块级别的测试

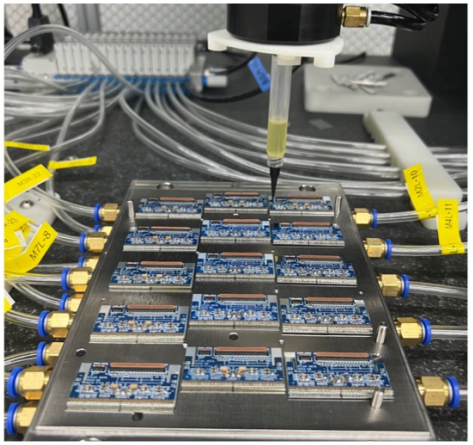
- Module level Test beam showed that
  - Individual channels can reach ~50ps level timing resolution
  - In next few years, HGTD will have 3M channels @ ~50ps resolution



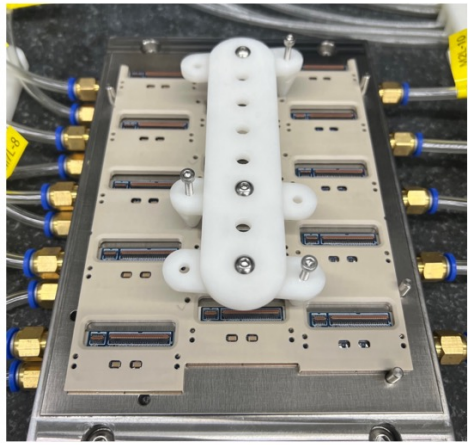
HGTD module loading

- IHEP loaded the first ALTIROC3 detector unit for HGTD demonstrator
  - Use Gantry system to position all 15 modules and glue dispending
  - Delivered to CERN, and passed reception tests

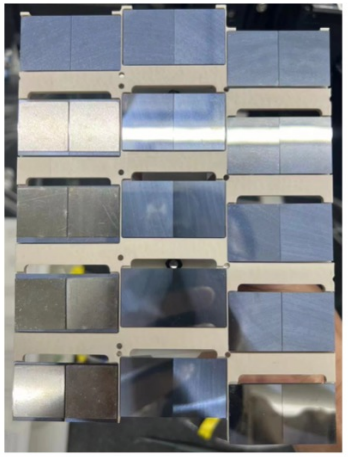
Dispensing with GluingTool



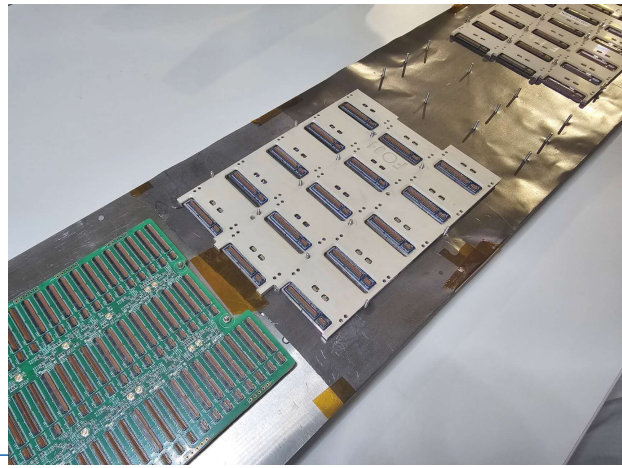
Put the support unit



Backside view after removal

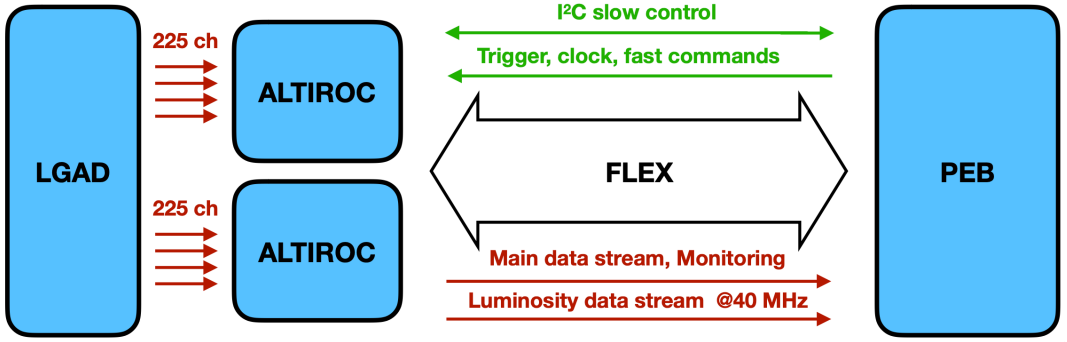


Detector unit shipped to CERN

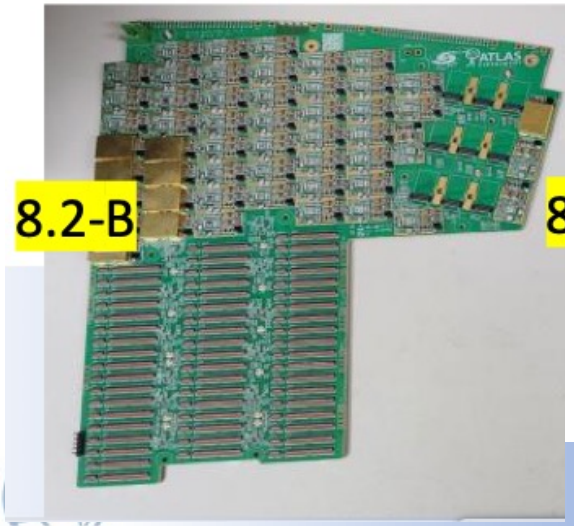


Peripheral Electronics Boards, flex tail, HV power supply

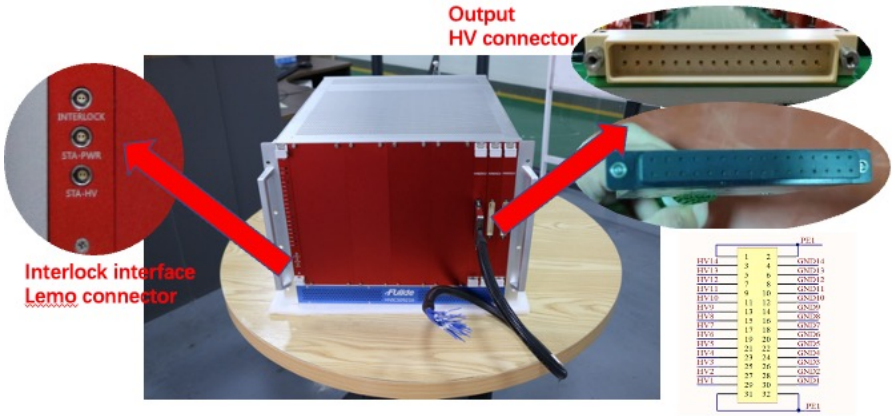
- IHEP and NJU developed Peripheral Electronics Boards prototype
- SDU developed long flex tail prototype (75cm)
- IHEP developed high voltage power supply prototype



Modular Peripheral Electronics Boards prototype



High voltage power supply prototype



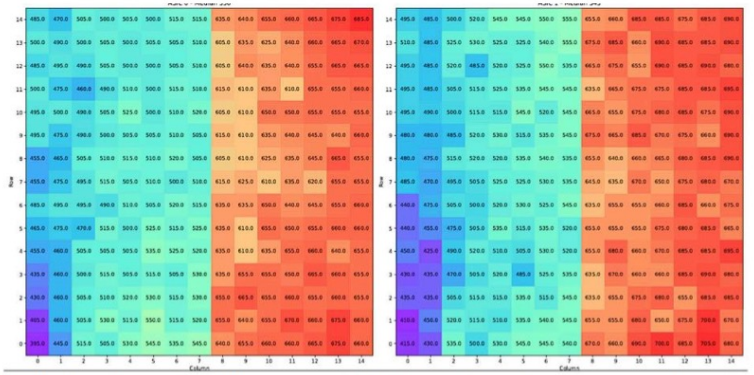
Long Flex tail prototype (75cm)

20

HGTD系统级测试系统

- IHEP and NJU played important role testing demonstrator system at CERN
  - Jie Zhang and Zhenwu Ge (NJU) played key role in demonstrator
    - Setting up the system early April
    - Noise levels were measured with 42 modules, no major problem
    - First time to demonstrate multi-module operation that in system level

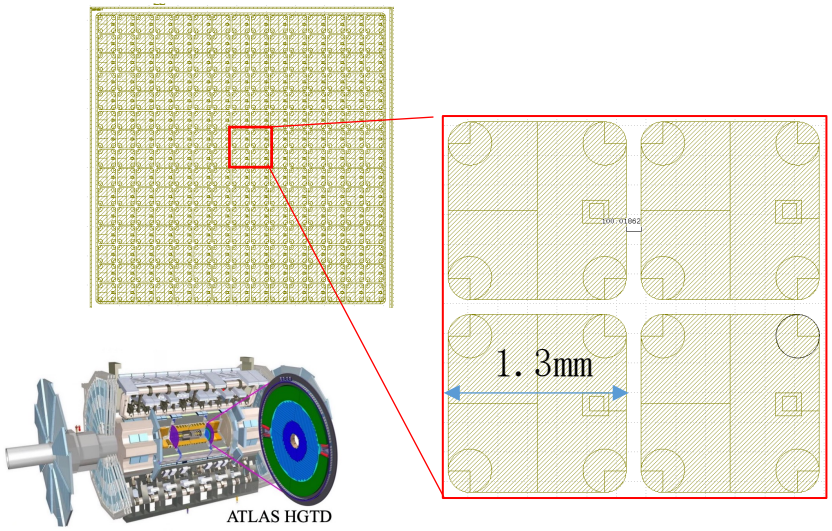
HV, LV, Cooling plate prototype
Electronics : PEB 1F + flex tails + 54 modules mounted on 4 support units (detector unit)



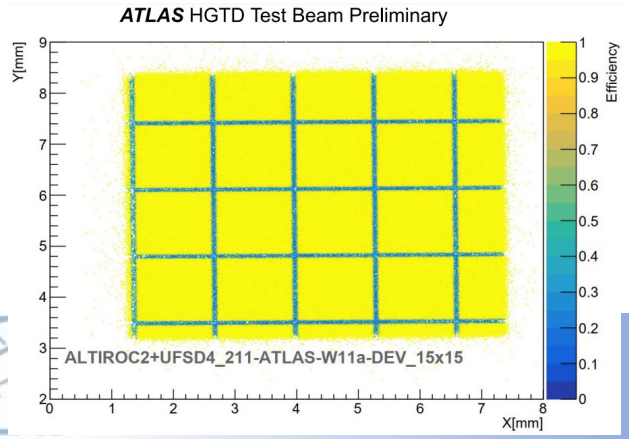
Module threshold scan obtained in demonstrator test

未来发展方向： AC耦合的LGAD探测器

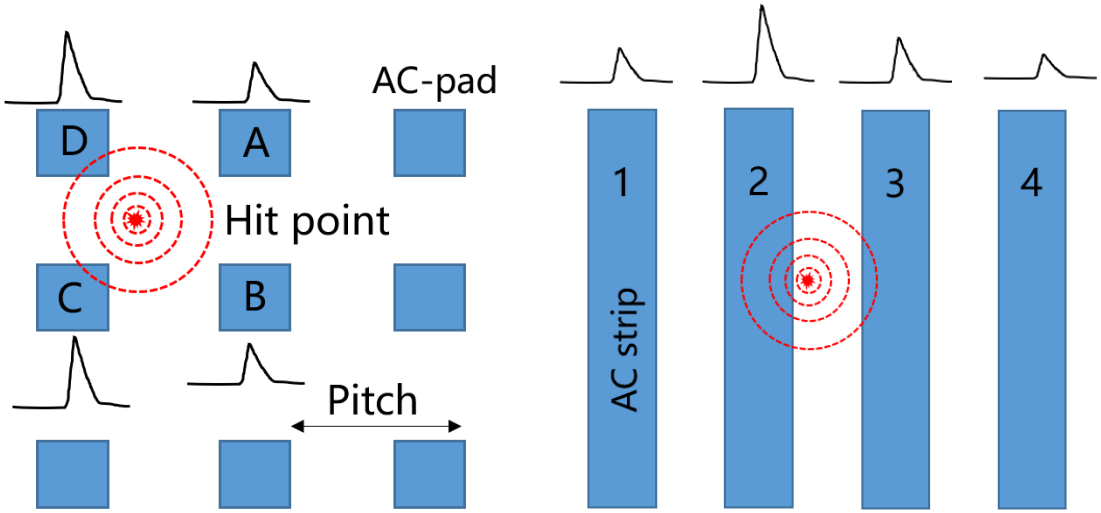
15×15 LGAD for ATLAS HGTD project



- Dead zone : ~0.1mm
- Pixel size: 1.3mm



AC-LGAD：two layout schemes for AC-pads



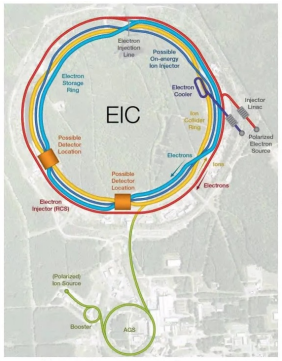
Pixels AC-LGAD:
- Position information：1 layer (x,y)
- Bump bonding

Strips AC-LGAD:
- Lower readout electronics，no bump bonding
- Position information：2 layers for (x,y)

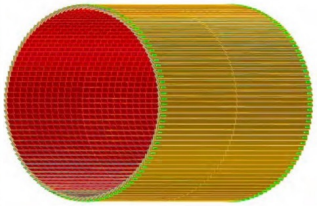
mzli@ihep.ac.cn

未来发展： AC耦合的LGAD探测器

Electron-Ion Collider (EIC)： Timing-tracker

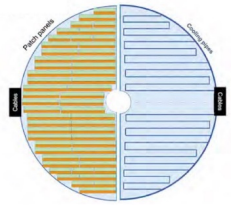


Barrel AC-LGAD detector



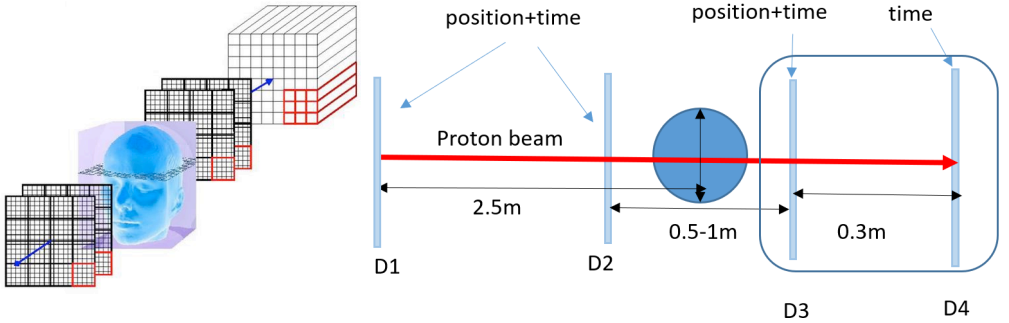
10.9 m^2

Hadron endcap AC-LGAD detector

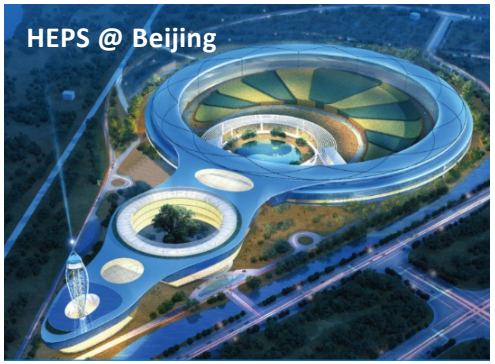


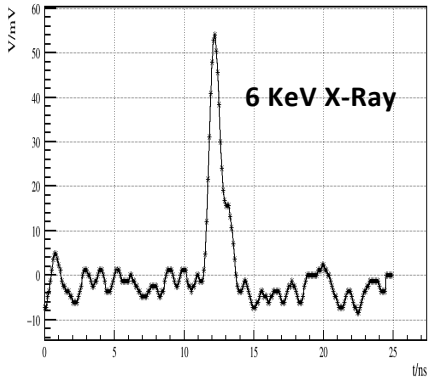
2.22 m^2

Nuclear Medicine Instruments：
Such as proton therapy and proton CT



X-ray detectors @ advanced light sources





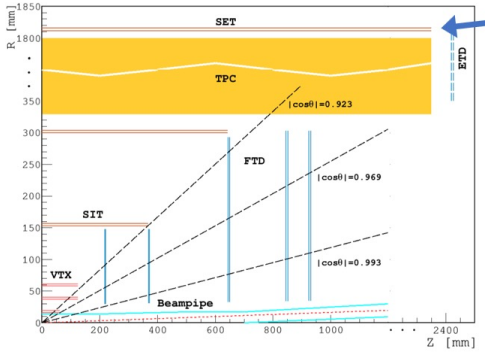
other applications

- Beam Telescope for Beam Test Platform
- LiDAR: Positioning and Navigation
- Track and time detectors in other particle physics and nuclear physics experiments
- …

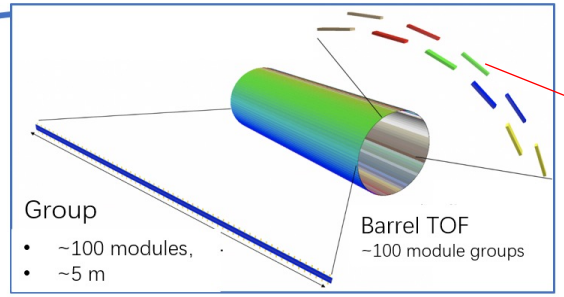
mzli@ihep.ac.cn

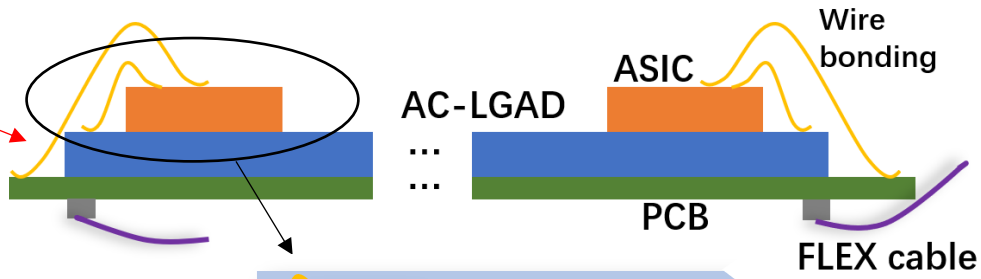
CEPC飞行时间探测器+外围径迹探测器

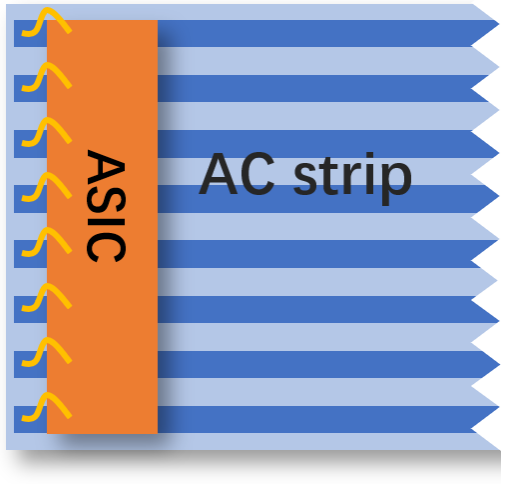
Baseline detector concept in CDR



LGAD timing detector in Barrel region







CEPC 4D outer tracker concept design：

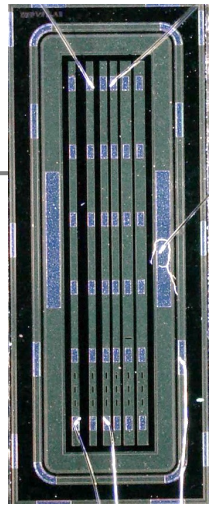
- Should be part of SET (silicon wrapper layer outside TPC or drift chamber)
- Serve as Timing detector and part of the tracker
- Barrel : 50 m^2 , Endcap 20 m^2 , **~ 10^6 channels**
- Strip AC-LGAD （each strip: **4 or 10 cm × 0.05cm**）
  - Timing resolution: 30-50 ps
  - Position resolution: ~ 10 μm @ R-phi direction

Strip AC-LGAD + ASIC：

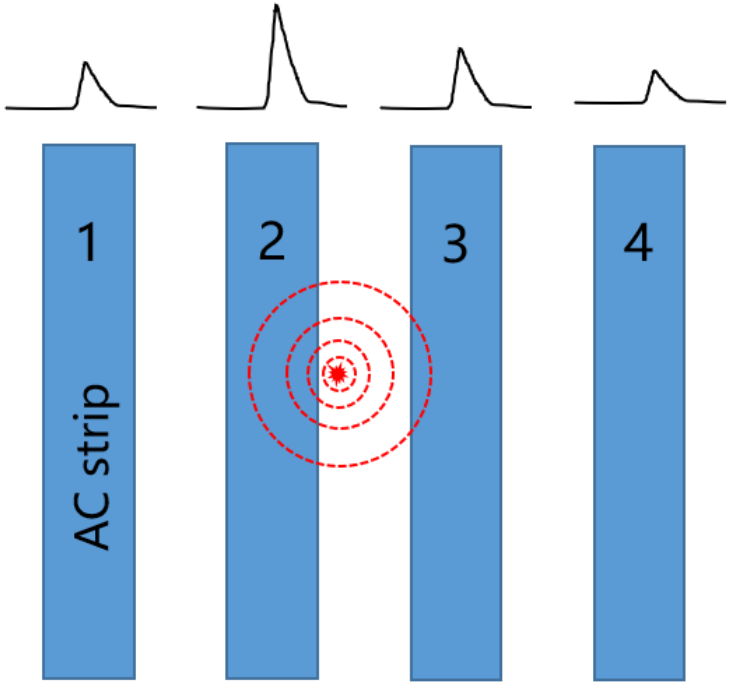
- TOT->amplitude->charge sharing->position
- TOA+TOT->timing (time–amplitude correction)

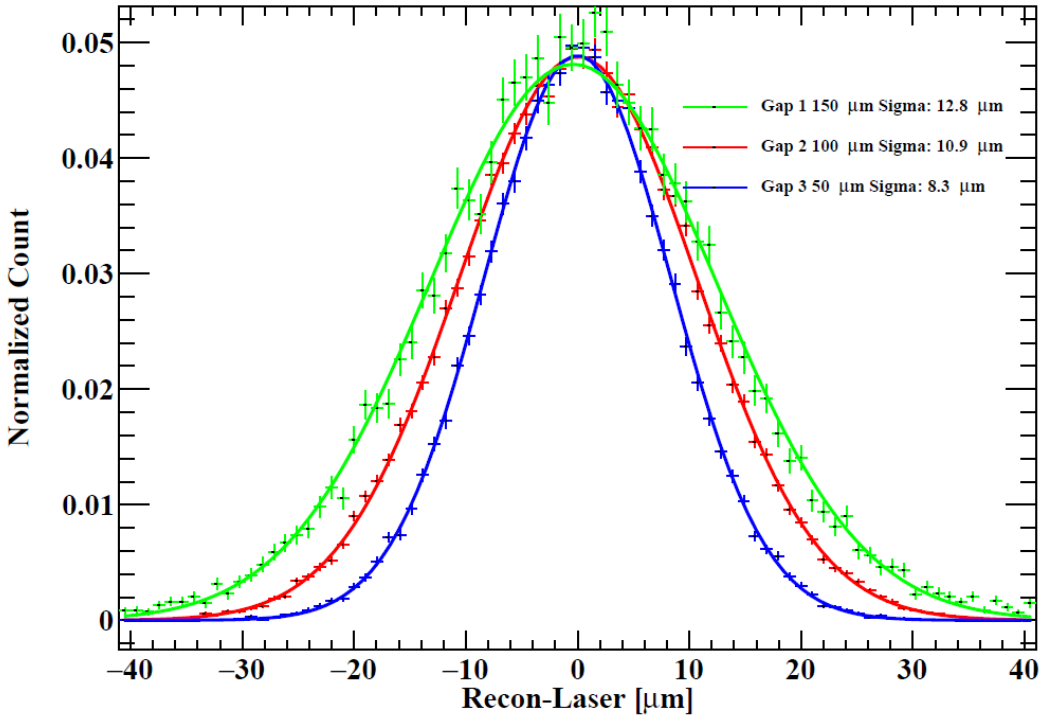
mzli@ihep.ac.cn

CEPC飞行时间探测器+外围径迹探测器



- Laser test result of strip AC-LGAD sensor
  - It can reach about ~10μm resolution with 150um pitch strip detector
  - While timing resolution of AC-LGAD is still can reach 30-50ps





小结: ATLAS实验高颗粒度时间探测器

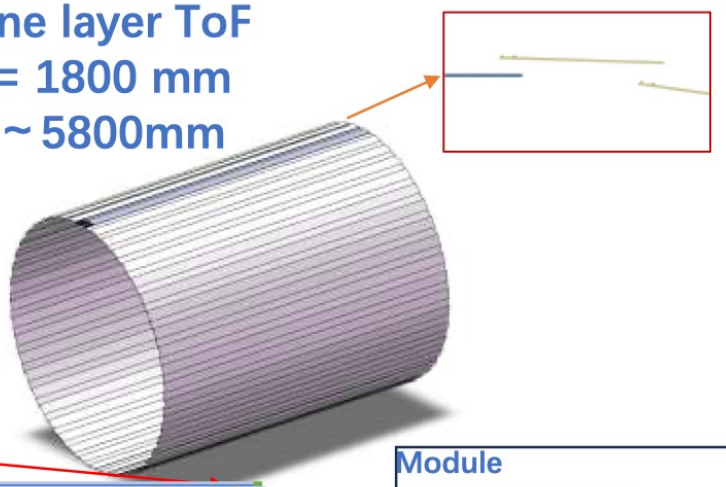
- 中国组在项目中占主导地位，担任项目经理等多个领导职务。
- LGAD传感器：
  - 高能所、科大自主研制国产超快硅传感器，获得重大进展
    - 高能所得到目前最佳抗辐照性能
    - 高能所赢得欧洲核子中心（CERN）国际招标采购的订单
    - CERN首次采购中国产的硅传感器
- 外围电路：
  - 高能所，南大主导了外围电路板的设计与研制工作
  - 研制出电路板读出系统原型机。
- 探测器模块：
  - 中国组主导模块研制，
  - 中国组（高能所，科大）将组装～4000个模块，占项目45%

Module level and system level design

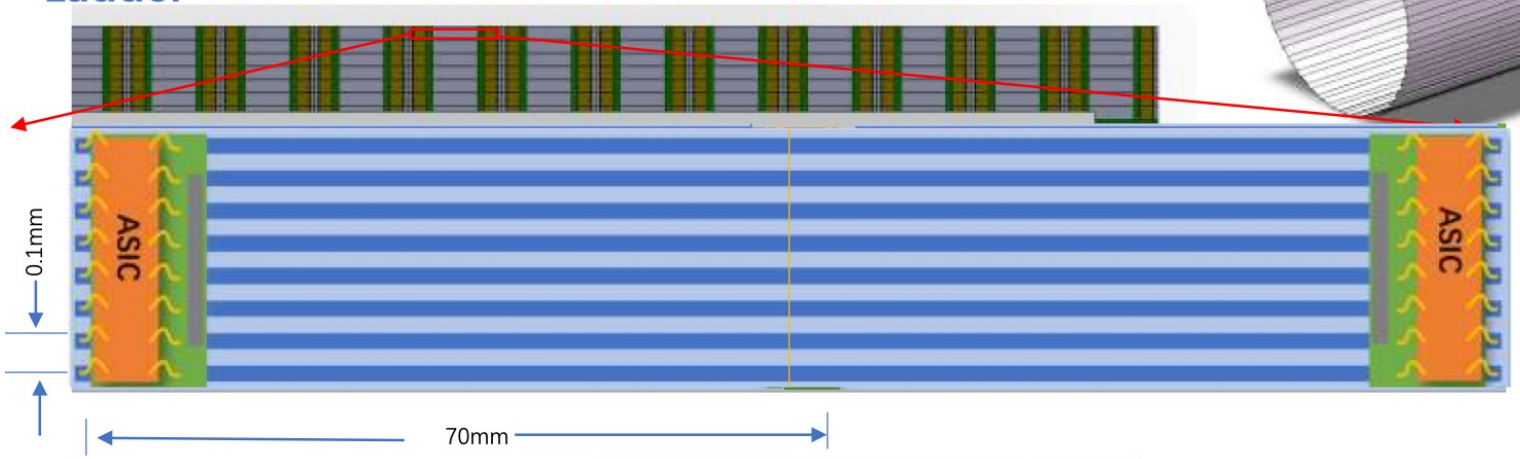
- One layer:
  - 90 ladders，45 ladders each side,
    - 42 modules/ladder
      - 22 ASIC/module
        - ✓ 128 channels/ASIC
- Total modules needed：

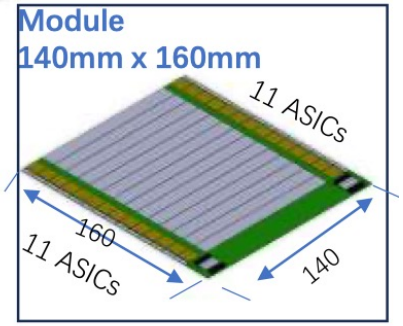
  45 *2*42 = 3780 modules

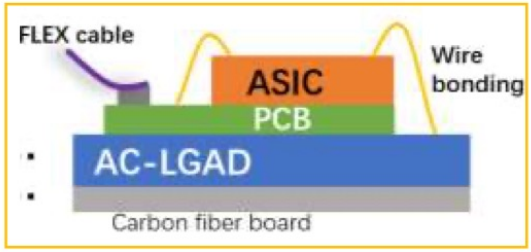
One layer ToF
R= 1800 mm
H ~ 5800mm



Ladder







LGAD development for CEPC time of flight detector: Motivation

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

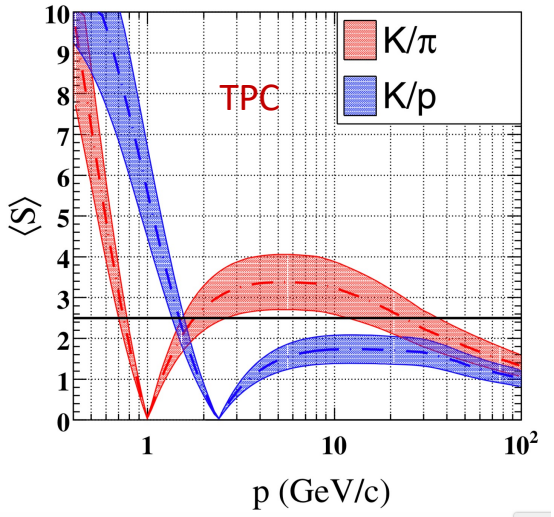
- **Particle separation problems** of Gas detector (dE/dx) for CEPC flavor physics:
  - **0.5-2 GeV for K/pi separation, >1.5 GeV for K/p separation**

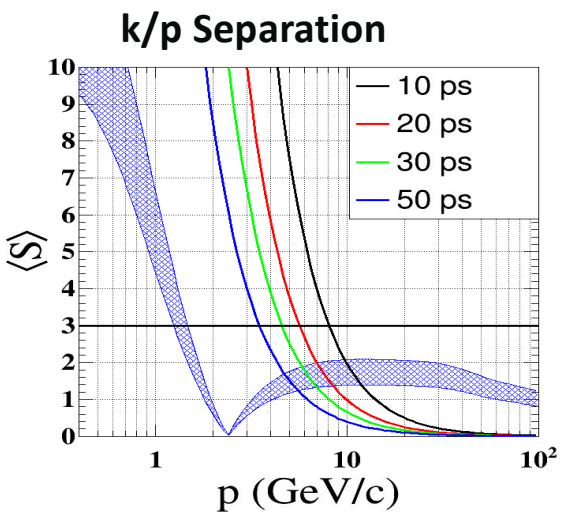
- **CEPC International Advisory Committee: one of the key recommendations**

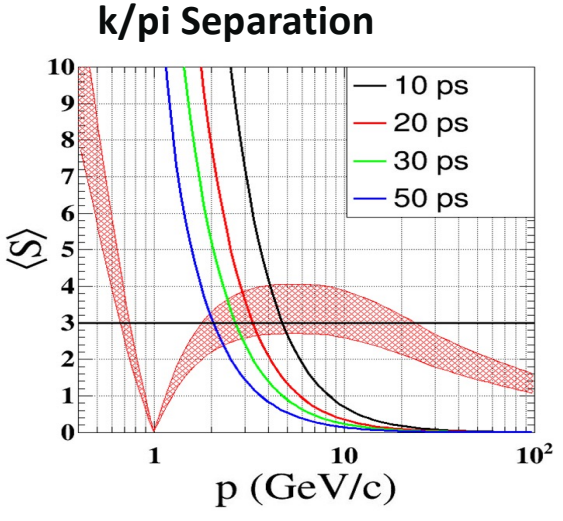
Precision timing detector should be determined as a matter of urgency (4D track)

- **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







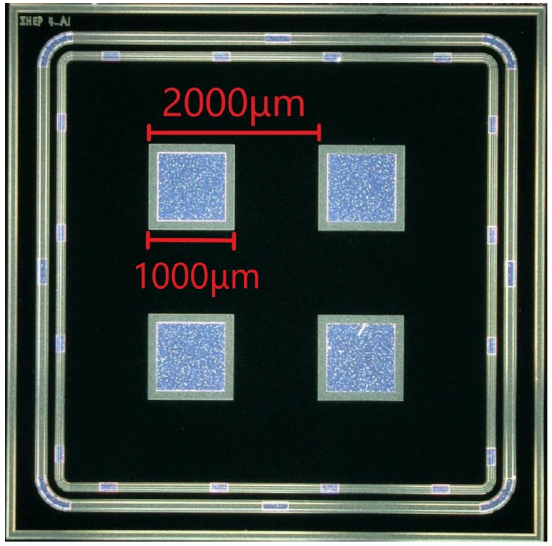
AC-LGAD sensors development

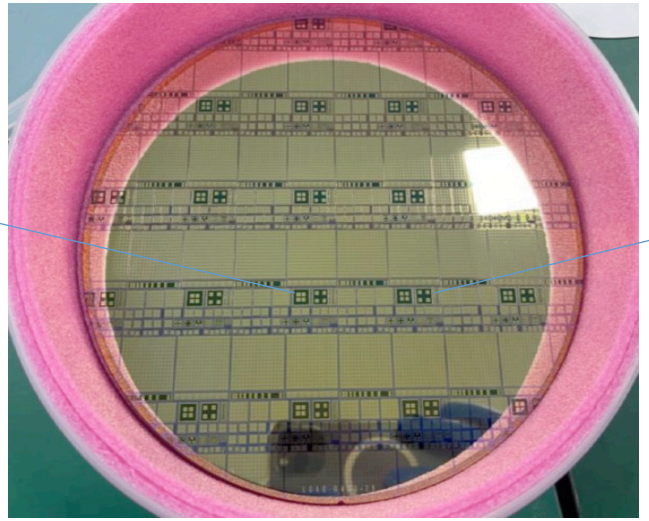
Pixels AC-LGAD：

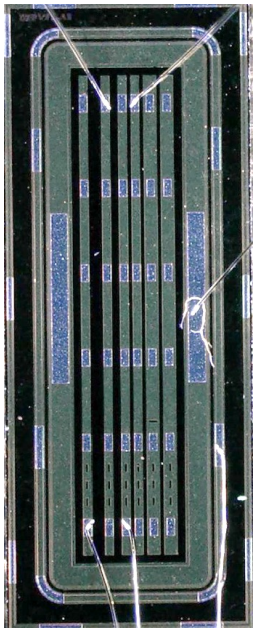
- Position information： 1 layer
- Pitch size 2000um, pad size 1000um
- Different N+ dose ：
  - **10P， 5P， 1P， 0.5P， 0.2P**

Strips AC-LGAD：

- Position information： 2 layer
- Strip length 5.6mm, width 100um
- Different Pitch size：
  - **150um、 200um、 250um**

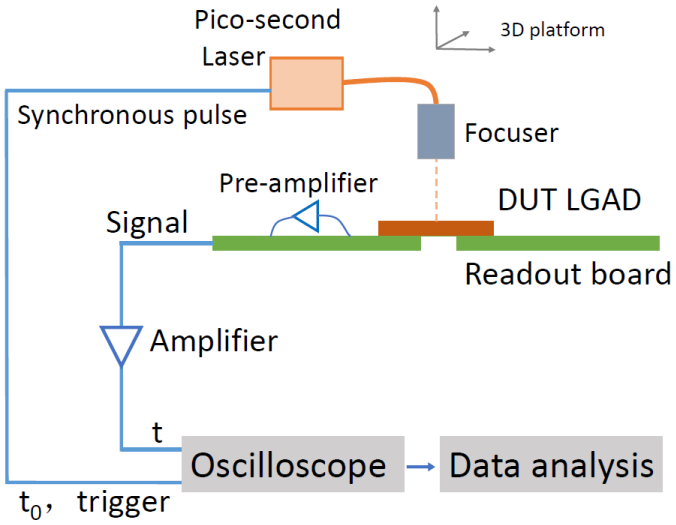


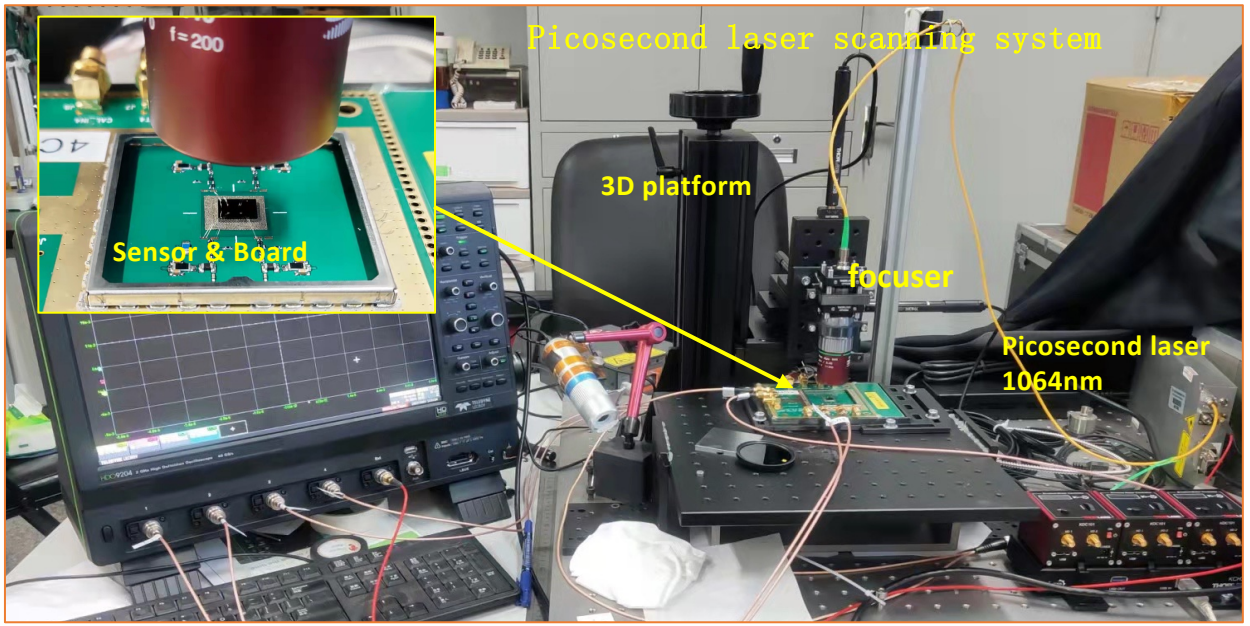


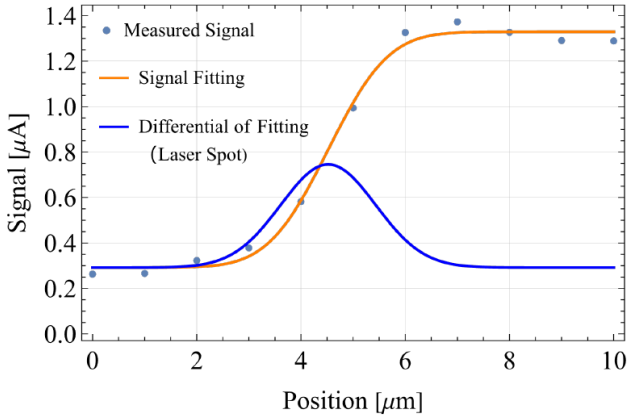


mzli@ihep.ac.cn

AC-LGAD sensors testing system

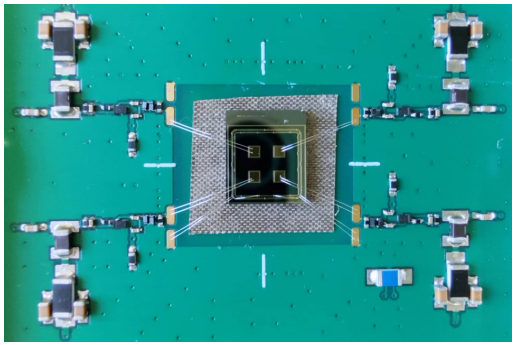






Picosecond laser scanning system

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

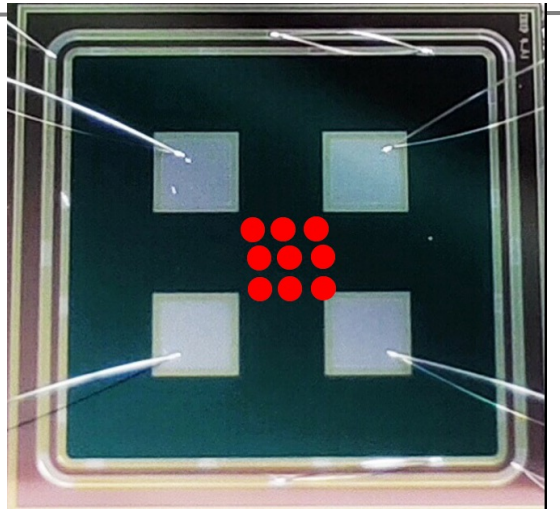


mzli@ihep.ac.cn

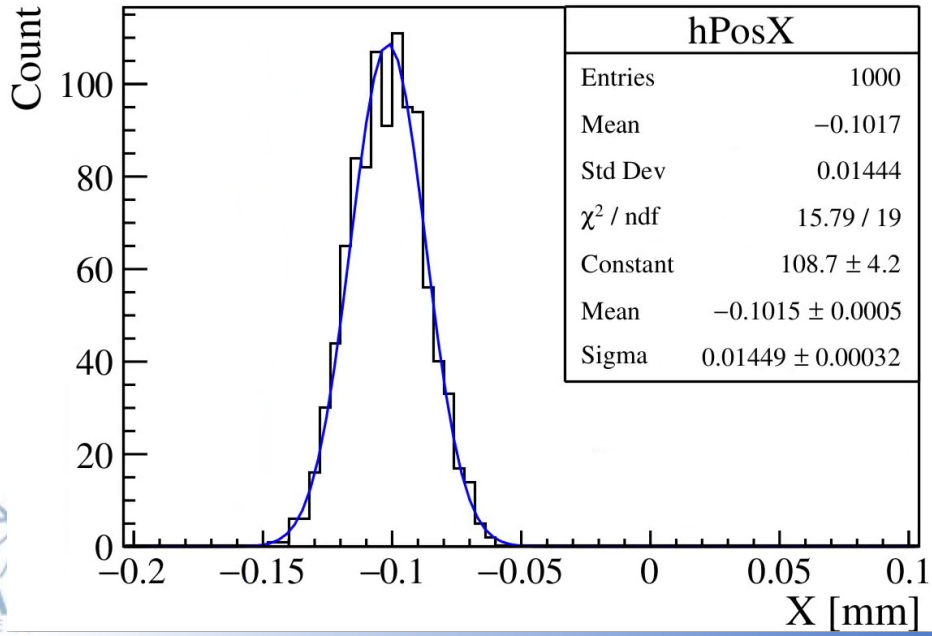
Spatial resolution of AC-LGAD pixel

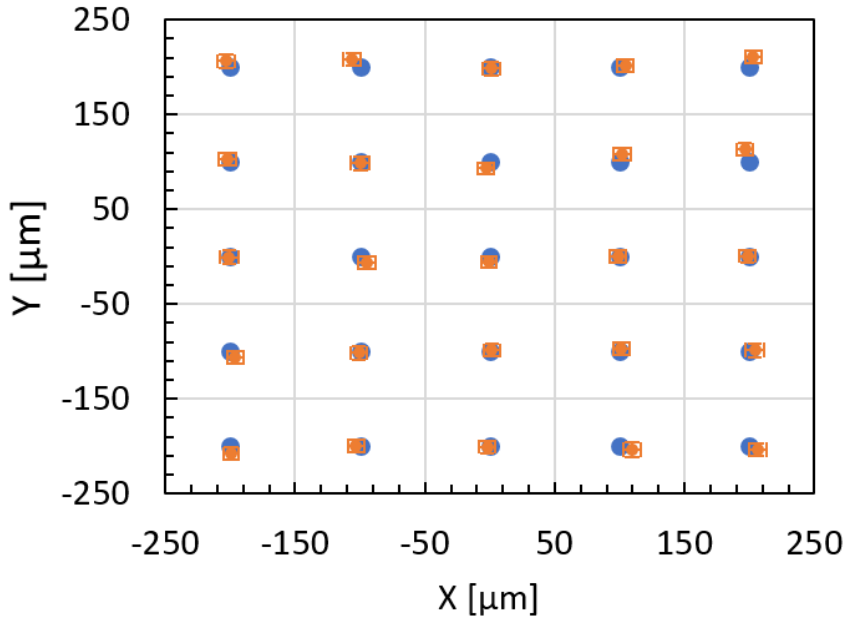
- Spatial resolution ～15um

Sensor size [μm]	pad size [μm]	Picth size [μm]
4000	**1000**	**2000**

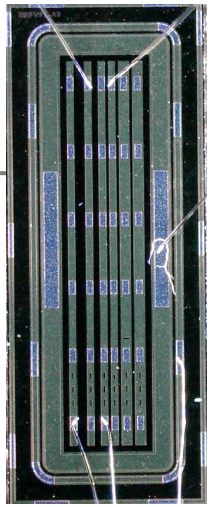


AC-LGAD
Spatial resolution ～15um

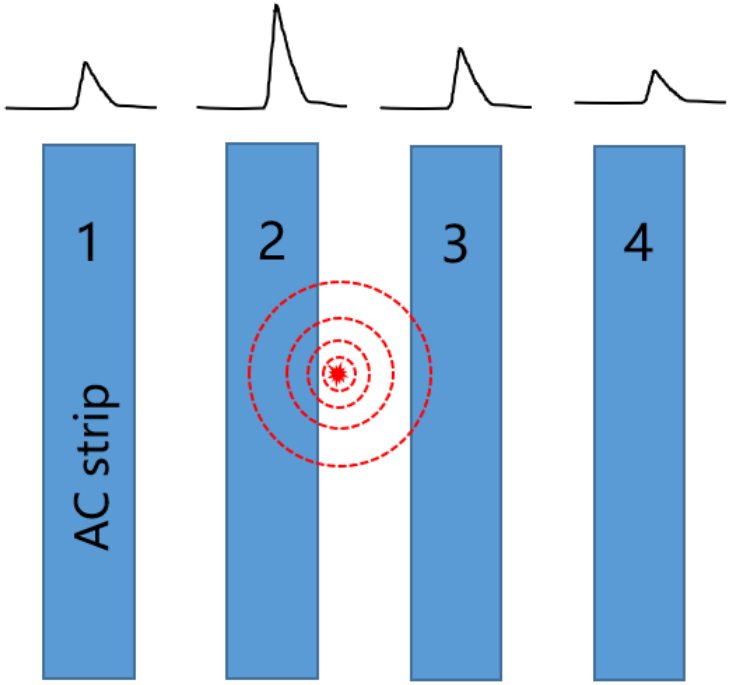


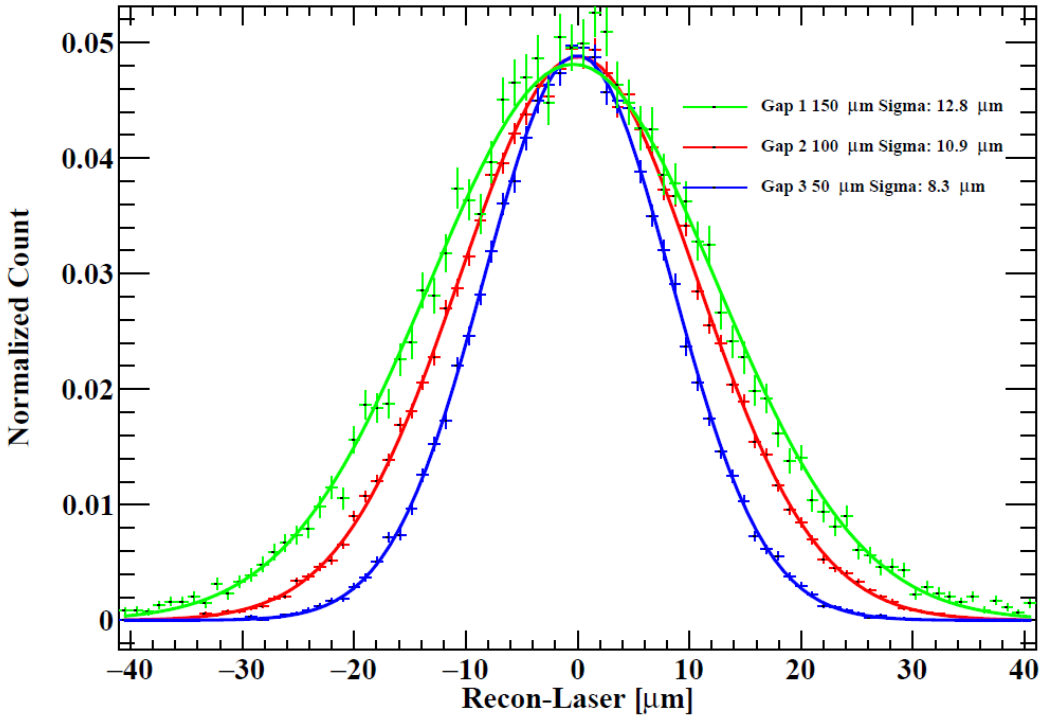


Spatial resolution of AC-LGAD strip



- Laser test result of strip AC-LGAD sensor
  - It can reach about ~10μm resolution with 150um pitch strip detector
  - While timing resolution of AC-LGAD is still can reach 30-50ps

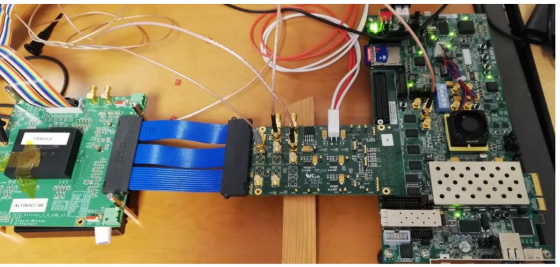




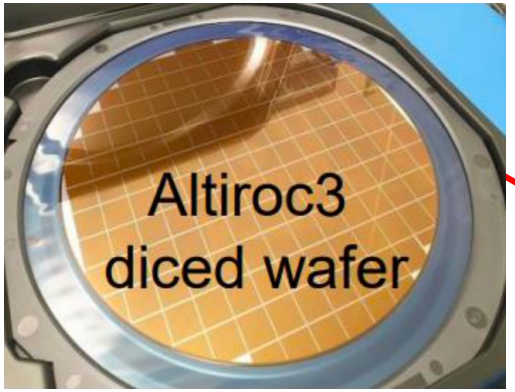
ALTIROC R & D

- IHEP is responsible for 50% of ALTIROC ASIC wafer testing
  - IHEP joined the digital part of ALTIROC ASIC design
- ALTIROC2/ ALTIROC3– 15x15 array with almost complete functionalities
  - ~15 ps jitter @ 15 fC, better than 70 ps jitter@ 4 fC
  - Full-size ASIC prototype ~2x2 cm^2 with 225 readout channels
  - Large amount of digital data, limited power consumption (1.2W/ASIC → 5.3 mW/ channel)

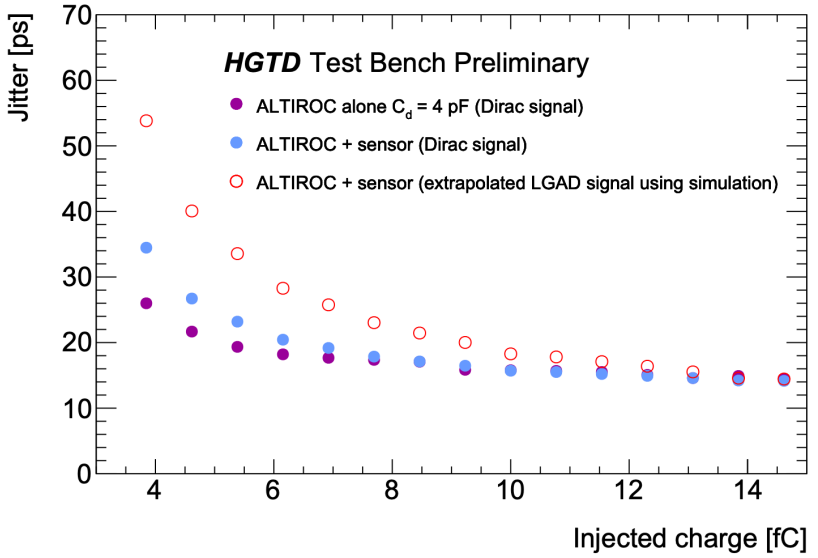
ALTIROC and test boad



ALTIROC3 wafer@IHEP

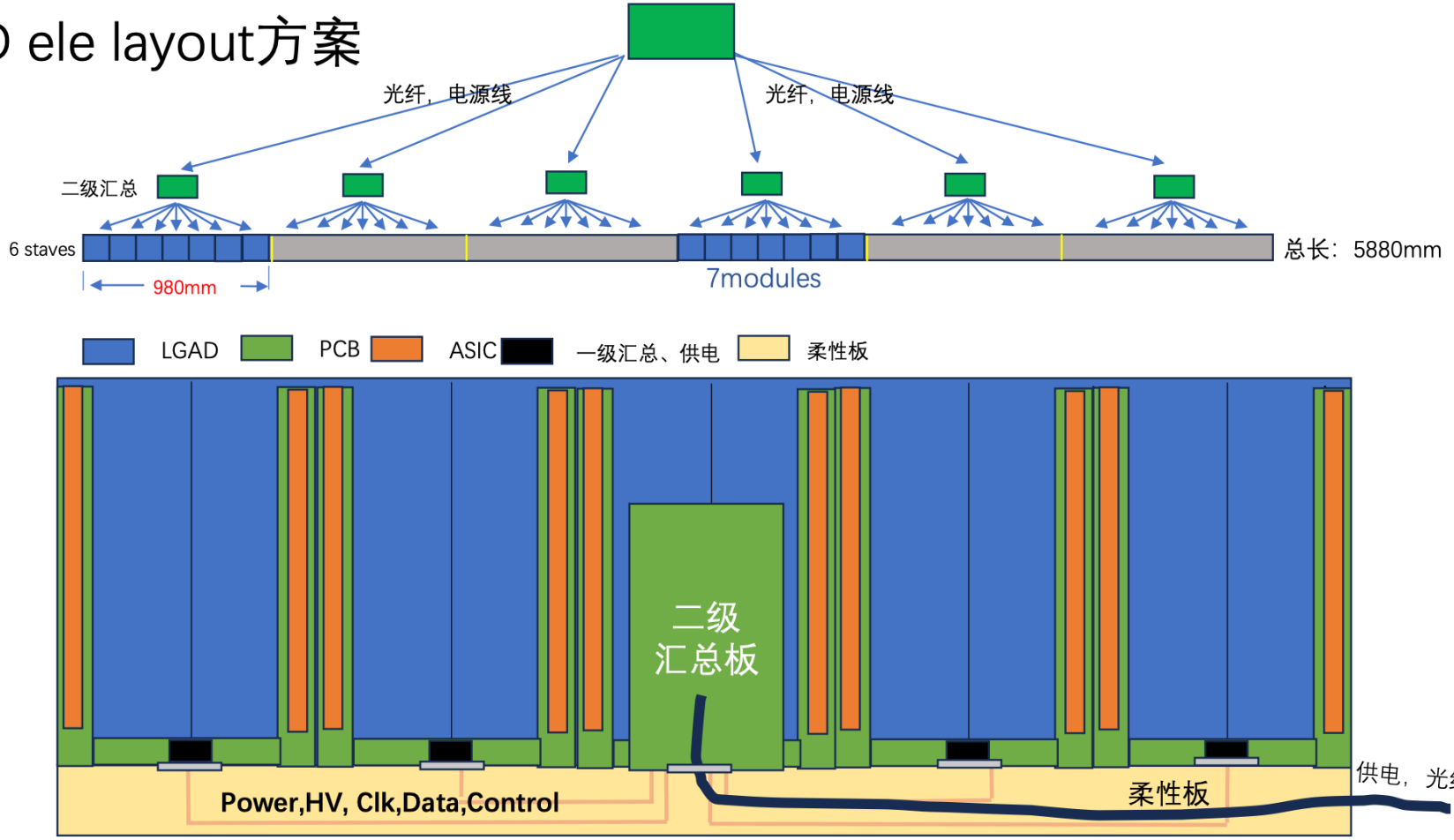


Injected charge Vs jitter



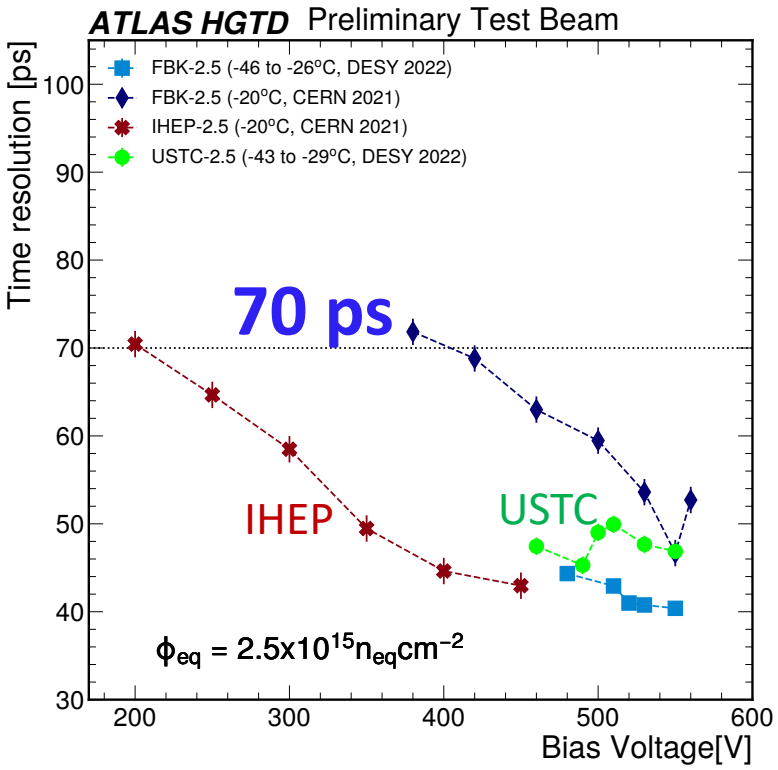
Electronics for CEPC LGAD based outer tracker

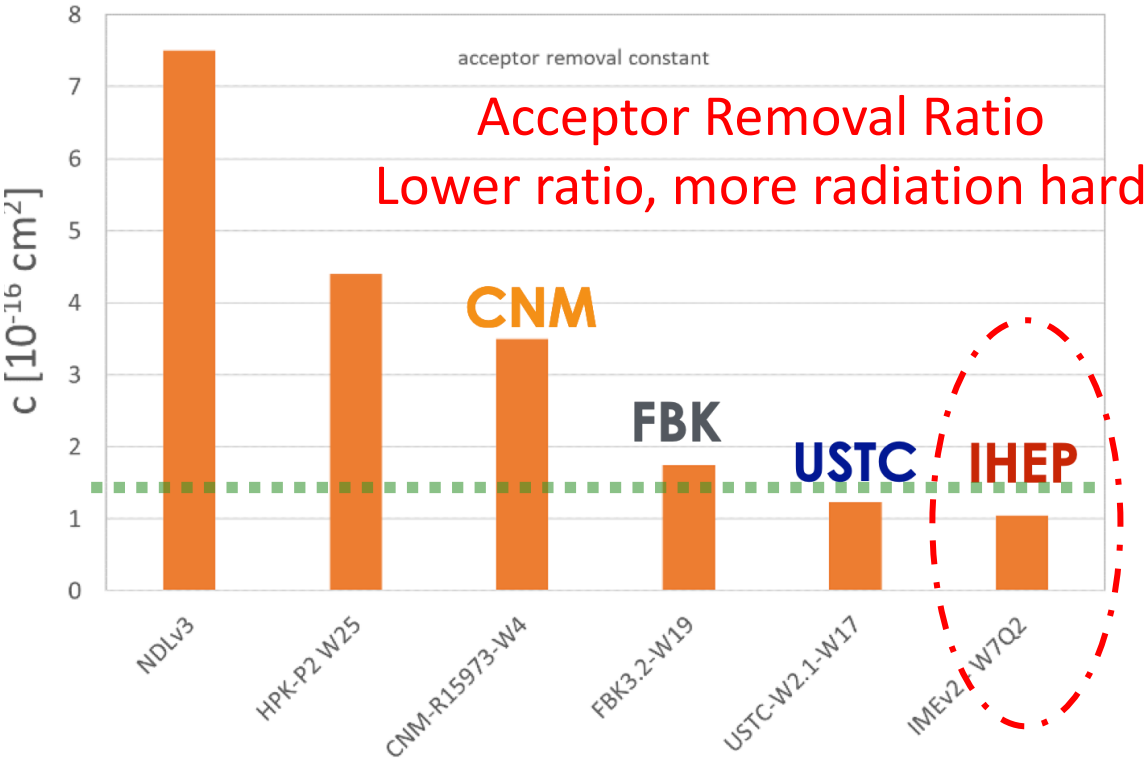
LGAD ele layout方案



LGAD sensor after Irradiation

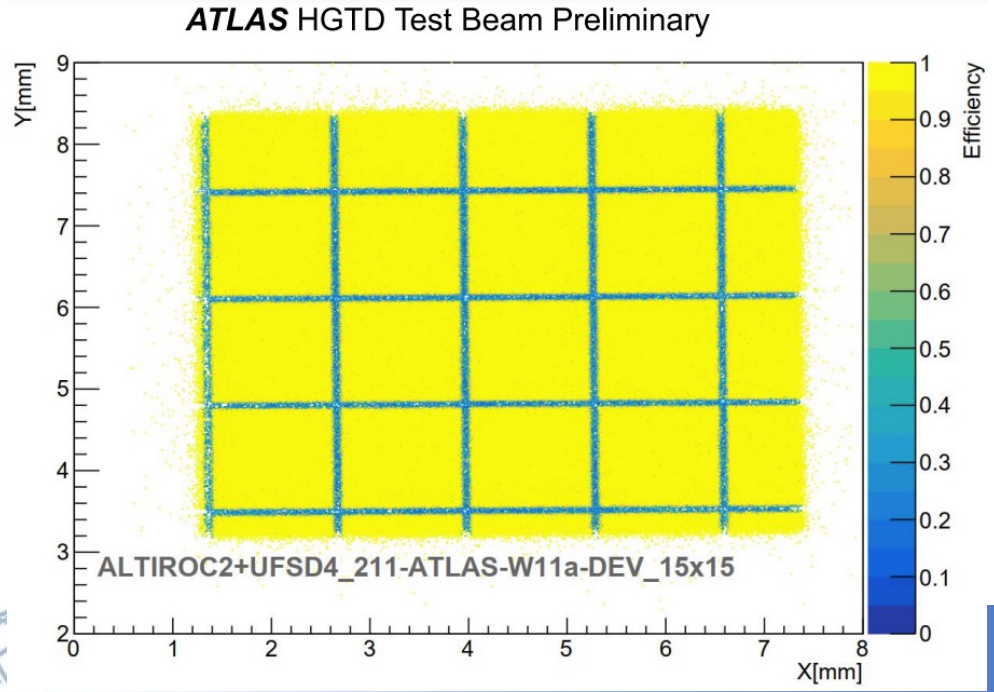
- Lots of prototypes R&D in LGAD in last few years, active vendors includes:
  - IHEP-IME (China), USTC-IME (China), IHEP-NDL(China), FBK (Italy), CNM (Spain), HPK (Japan) …
- IHEP-IME and USTC-IME LGAD with carbon-enriched doping
  - Significantly lower acceptor removal ratio, the most radiation hard
- After 2.5×10^{15} n_{eq}/cm^2, LGADs can operated below 550 V → avoid single event breakdown

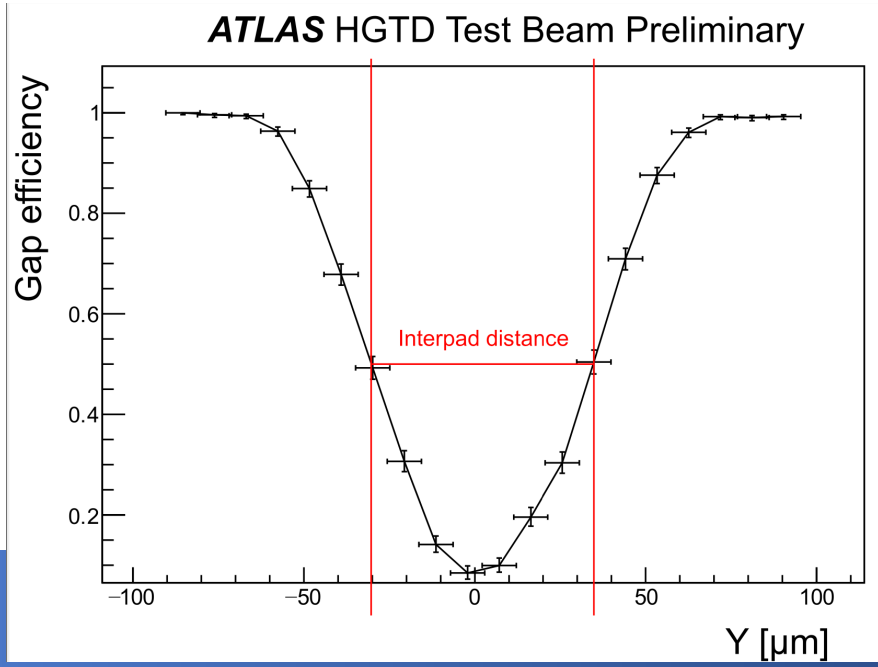




Hybrid test beam result

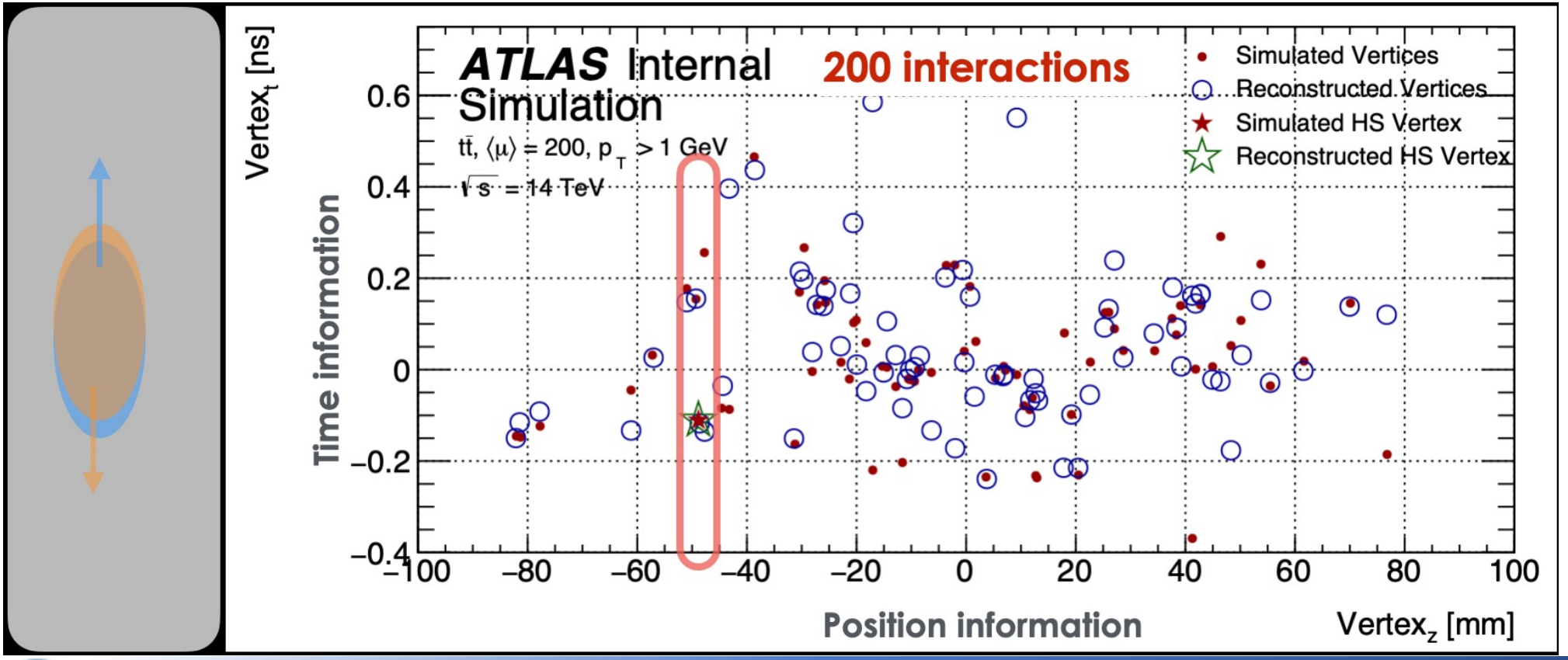
- Hybrid functionality was validated by test beam
  - The EUDET telescope is used for track reconstruction
  - Sensor bias voltage is -180 V, corresponding to a charge of ~20 fC
  - ASIC threshold 4.8 fC
- Close to 100% efficiency in the center of the pixel (pad)
  - The gap between pixels (pads) is about 50μm





Motivation

- Pileup background is major challenges at high luminosity LHC
- High precision timing info can reduce the pileup by one order of magnitude



Motivation

- Pileup background is major challenges at high luminosity LHC
- High precision timing info can reduce the pileup by one order of magnitude