大型强子对撞机上ATLAS实验高颗粒度时间探测器

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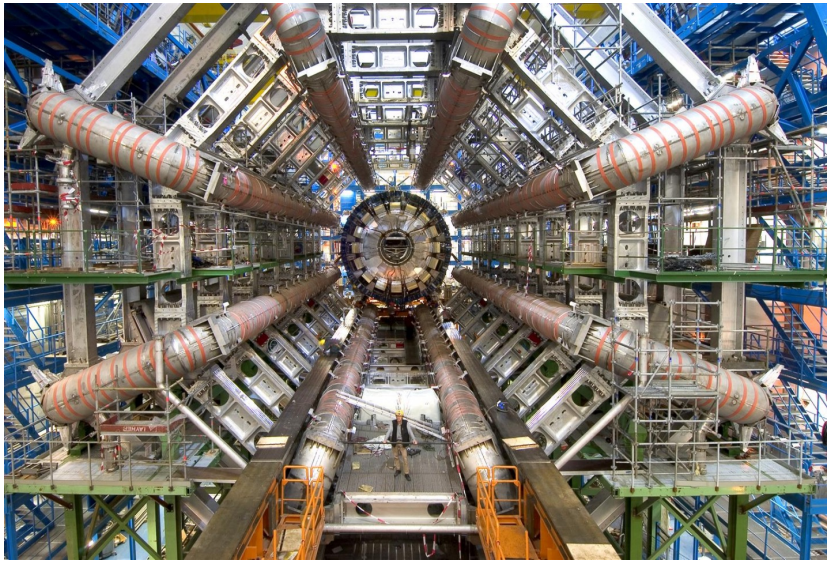
大型强子对撞机与ATLAS实验

大型强子对撞机



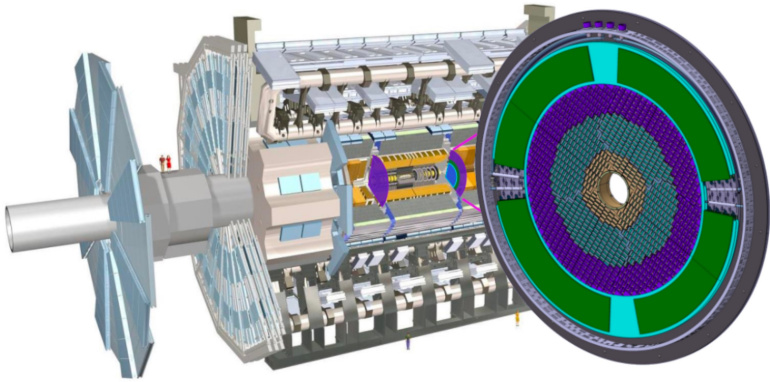
ATLAS探测器

- 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（14×10^{12}eV）
- 位于瑞士与法国边境

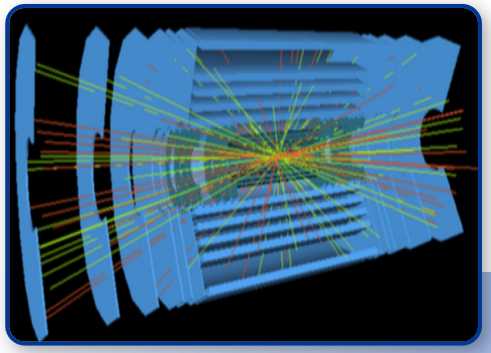
- 大约3000人的一个实验组
- 6层楼高（25米）的大型探测器
- 探测对撞产生粒子能量与动量

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

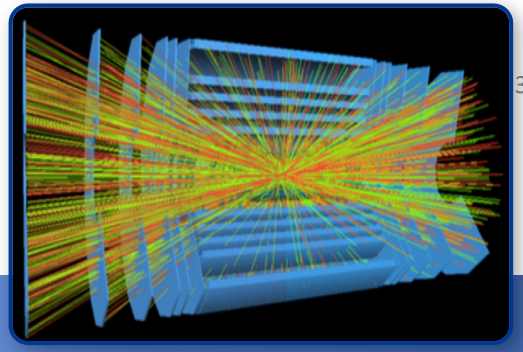
- 把粒子到达时间的测量精度提高2个数量级（数纳秒→30皮秒）
- 解决高亮度LHC对撞事例堆积问题
  - 6.4**平方米**的硅探测器， 30**皮秒**的时间分辨
  - **毫米级的颗粒度，超过三百万个读出通道**
  - **能承受**2.5×10^{15} n_{eq}/cm^2**的等效中子通量的辐照**
- 中国组主导探测器研制
  - 45%探测器组装（34% 高能所，11%科大）
  - 100%抗辐照高时间分辨传感器（90% 高能所-微电子所，10%科大-微电子所）
  - 100%前端电子学（高能所，南大）， 50% ASIC晶圆测试 （高能所，山大，科大）
  - 34%柔性电路尾板（山大），>16% 高压电子系统(山大，高能所)



目前的ATLAS探测器



高亮度LHC升级后的ATLAS探测器

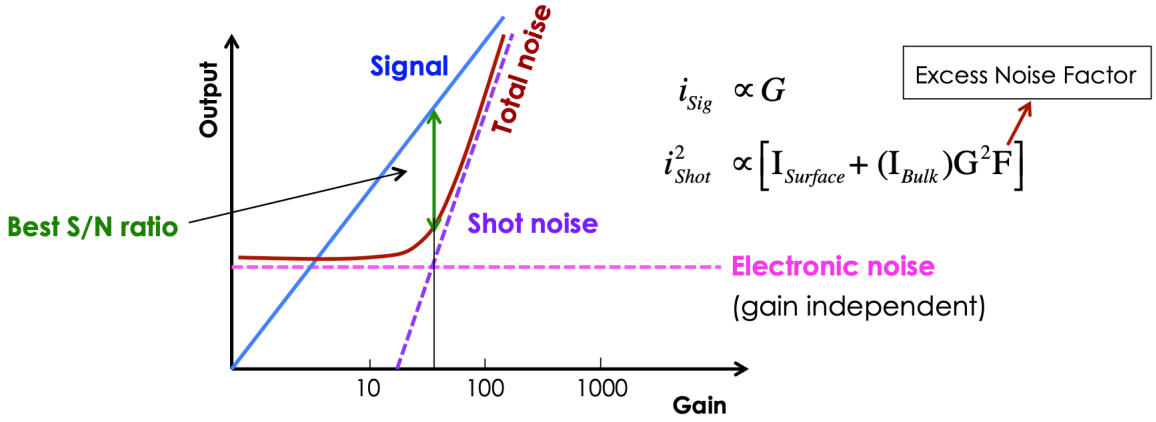


Low Gain Avalanche Detectors (LGAD)
低增益雪崩硅传感器

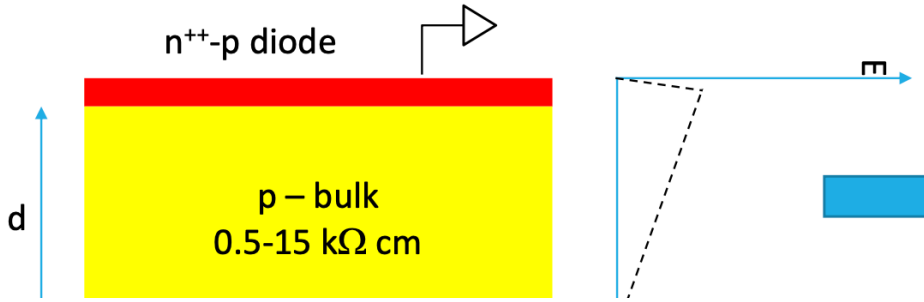
- LGAD是近年出现新型硅传感器，可以高精度测量时间（20-30皮秒）
- 与APD 和 SiPM比较, LGAD has 适中的增益 (~50)
  - 信噪比高，无自触发
  - 减薄耗尽区，提高电子漂移速度

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

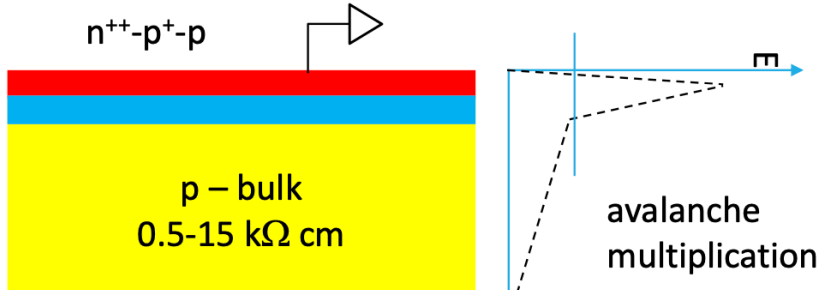
- **Modest gain to increase S/N**
- **Need thin detector to decrease**



一般的 PiN结传感器



低增益雪崩硅传感器
P+ gain layer on top of PIN diode



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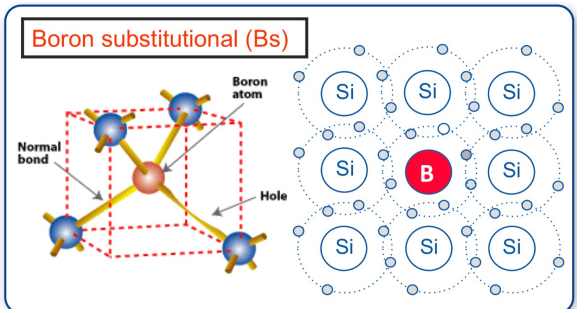
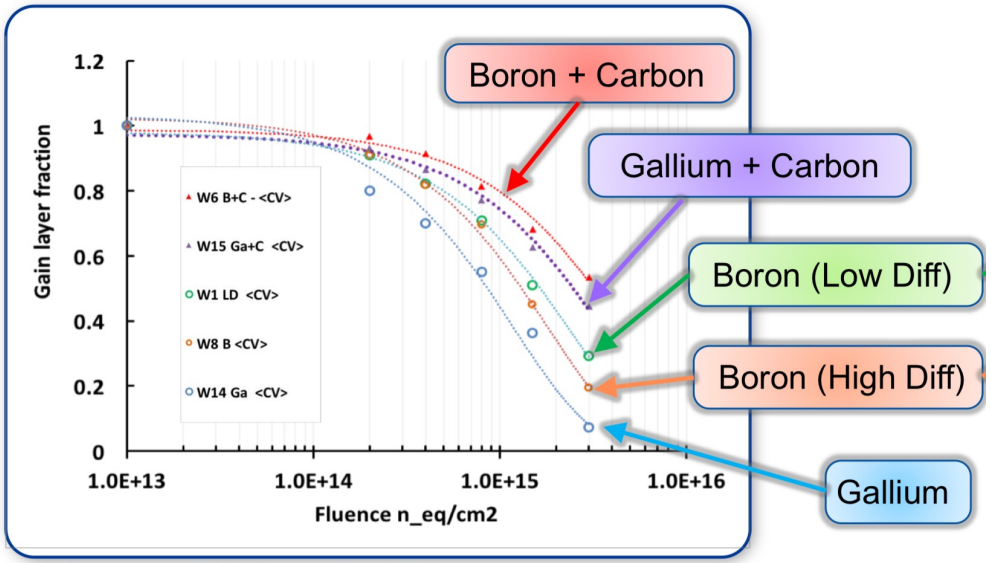
LGAD传感器辐照后硼掺杂移除 (Acceptor removal)

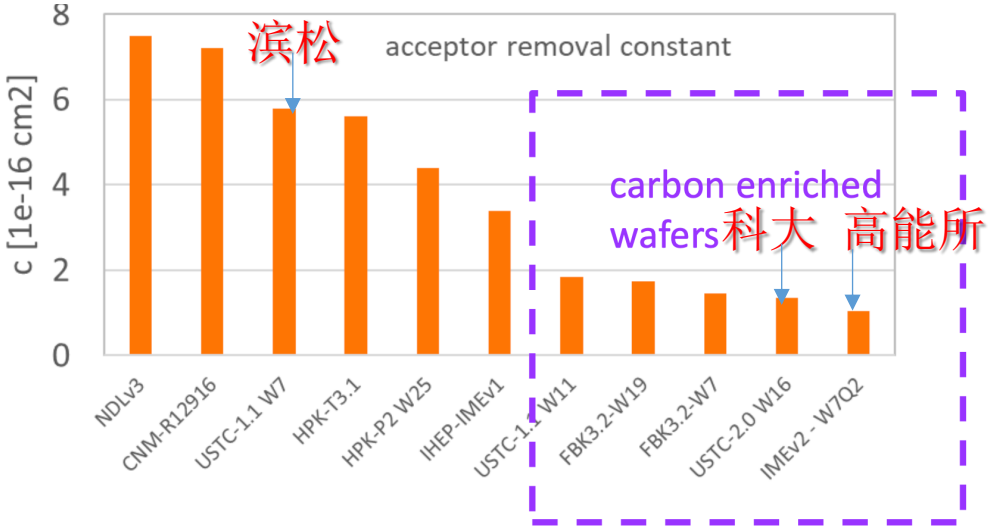
- 辐照后，硼掺杂失去活性，LGAD传感器增益下降(Acceptor removal)
- 高能所、科大等国产LGAD采用掺碳工艺
  - 显著减低辐照后损伤（减低硼移除率）
  - 抗辐照性能显著提高
  - 目前抗辐照性能优于滨松



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）



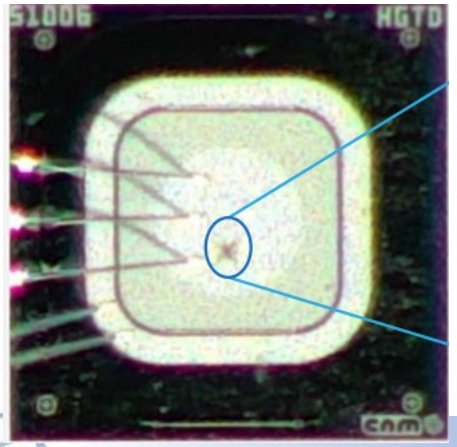
[G.Paternoster, FBK, Trento, Feb.2019]

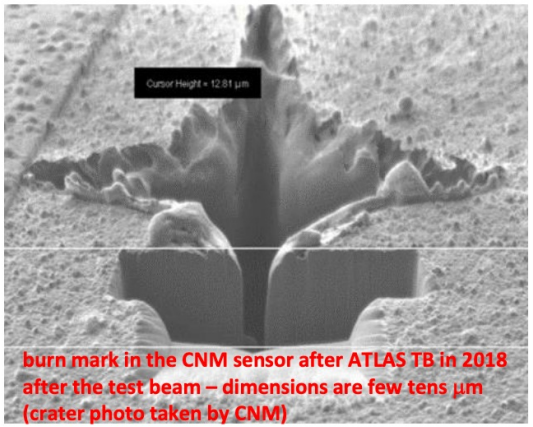


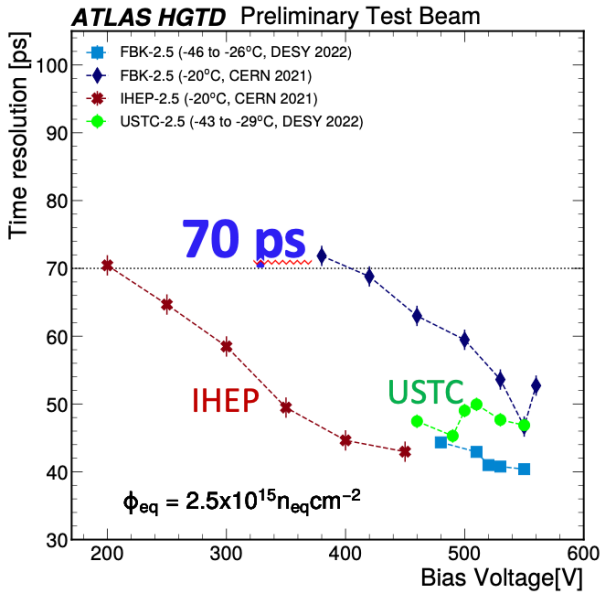
硅传感器的单粒子烧毁风险 Single Event Burnout (SEB)

- 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
  - 国产掺碳的LGAD基本能通过测试（高能所，中科大），无烧毁
    - 在2.5*10^{15} n_{eq}/cm^2的强辐照下，时间分辨率仍达到40皮秒

单粒子烧毁后LGAD（滨松/CNM）





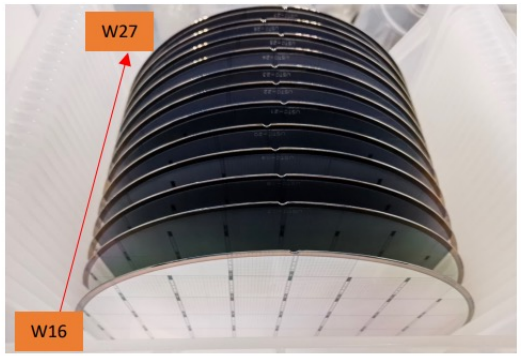


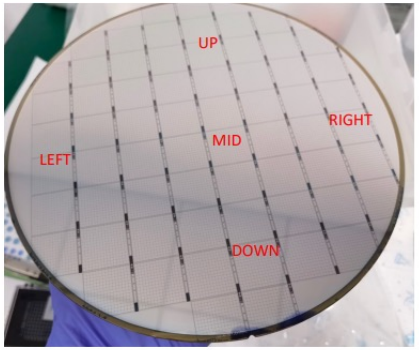
LGAD传感器的量产

详见赵梅的报告

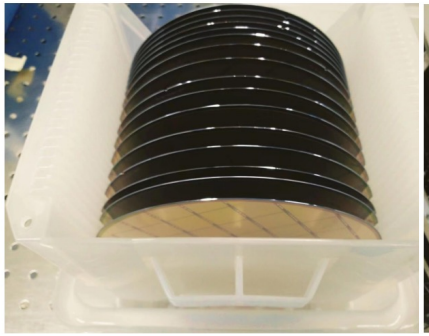
- 2023年高能所-微电子所赢得CERN的LGAD招标订单（>1.5万个传感器）
  - 在日本滨松、意大利FBK等竞争下，高能所-微电子所赢下招标
  - 欧洲核子中心（CERN）首次采购中国产的硅传感器
  - 象征着国产硅传感器国际地位显著提升
- 各单位在该项目LGAD传感器的贡献比重
  - 高能所-微电子所： 90%（66% CERN采购+ 24%实物贡献）
  - 中科大-微电子所：10% 实物贡献

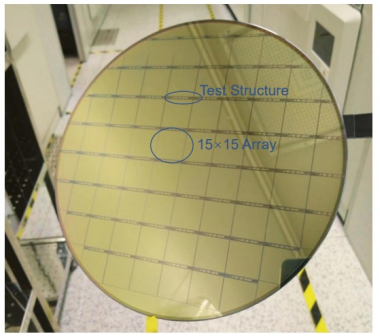
中科大-微电子所LGAD预生产





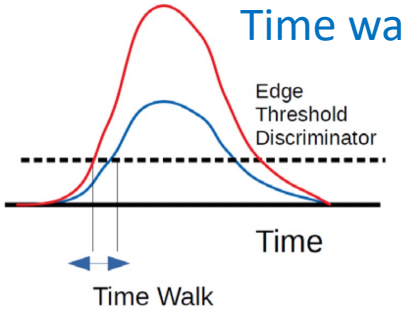
高能所-微电子所LGAD预生产



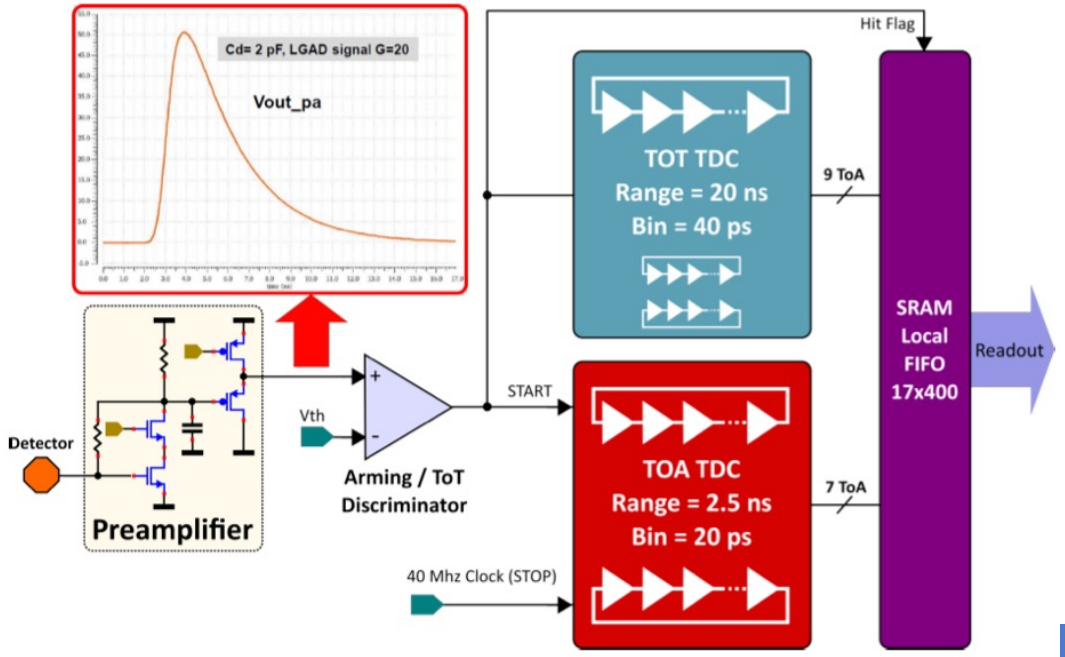


ALTIROC : 超快读出ASIC

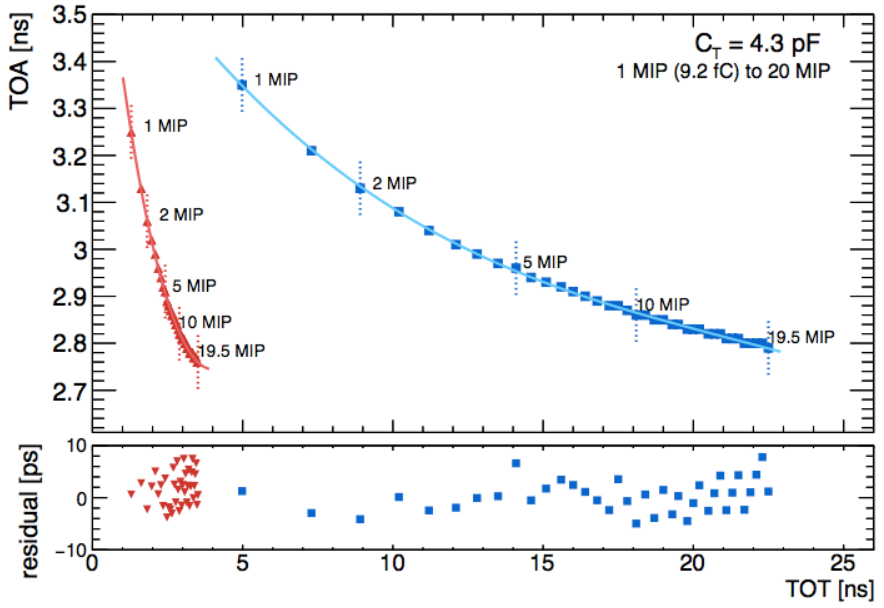
- ATLAS时间探测器研发超快读出ASIC芯片，多个单位参与
  - 高能所参与ASIC中数字电路部分的设计，承担50%的晶圆测试
- 225通道，每个通道有一个前端放大器，甄别器，两个TDC:
  - Two TDC (Time to Digital Converter) to provide digital **Hit data**
    - Time of Arrival (TOA) : Range of 2.5 ns and a bin of 20 ps (7 bits)
    - Time Over Threshold (TOT) : range of 20 ns and a bin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



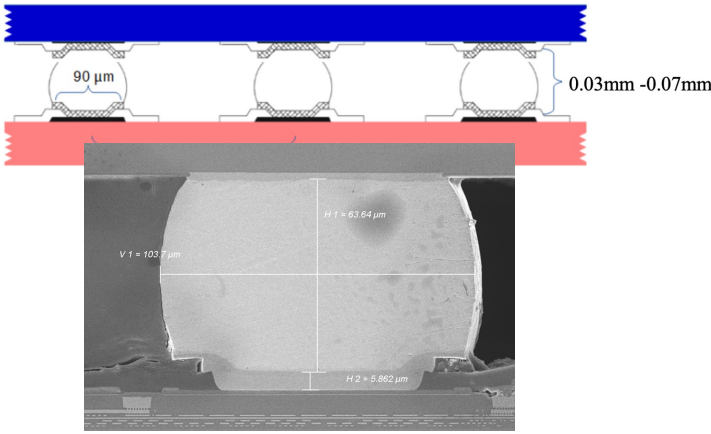
ALTIROC timing ASIC in nutshell



Time walk correction with TOT

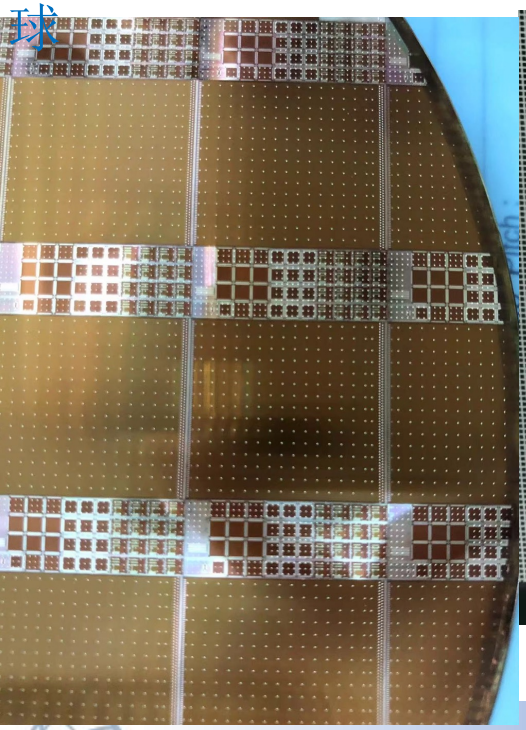


探测器模块：倒装焊封装

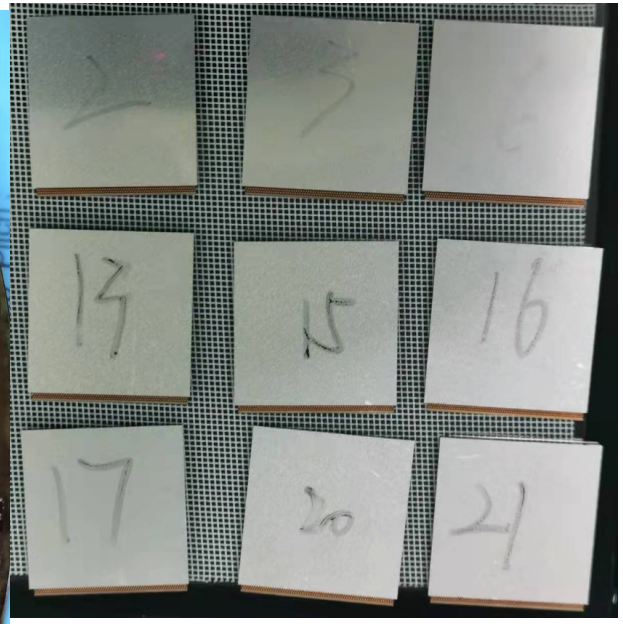


- 高能所承担项目中50%的倒装焊封装任务
- 高能所在国内已经研制出200+倒装焊模块
  - ALTIROC读出芯片 + 高能所-微电子所LGAD

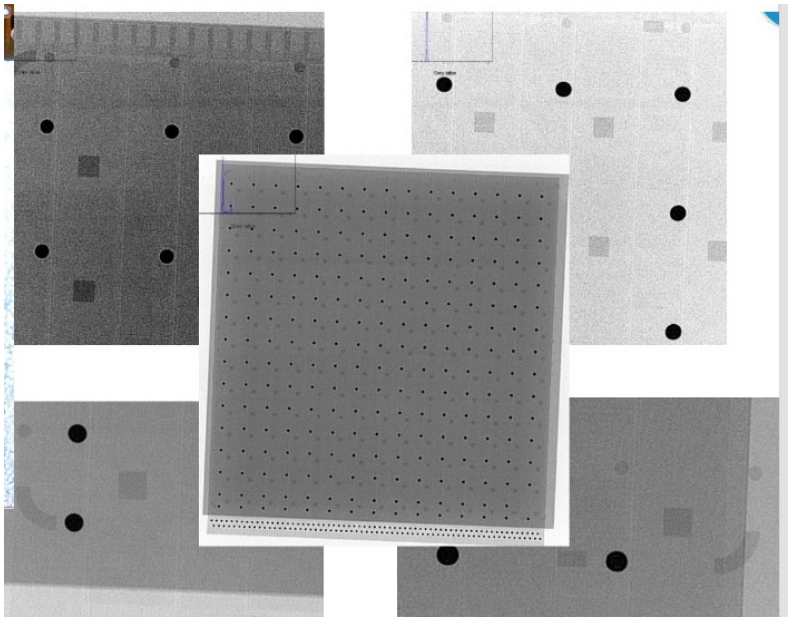
ALTIROC2 芯片晶圆植球



倒装焊模块后的模块



X-ray image of full-size hybrid

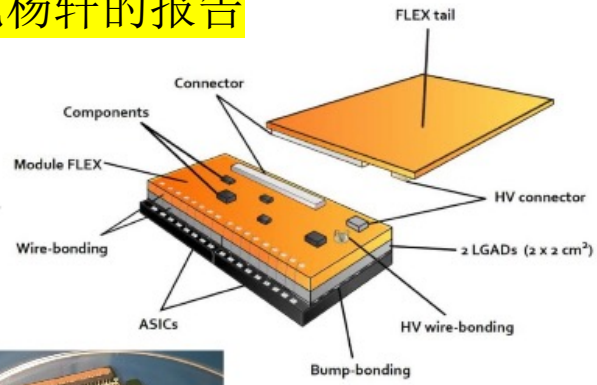


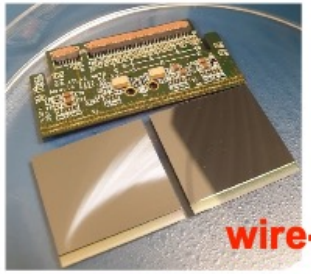
详见杨轩的报告

ATLAS时间探测器模块组装

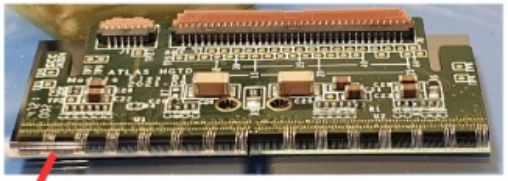
- HGTD项目总共需要8032个探测器模块
- 6个模块组装生产中心
  - 高能所，科大，德国，法国，西班牙，摩洛哥
  - 高能所是最大的生产中心，组装34%的模块
  - 中科大承担11%的模块组装
- 高能所与国内公司研制国产自动组装系统
  - 有高分辨图像系统，做芯片图像识别
  - 自动芯片组装、点胶
  - 位置组装精度达到微米级

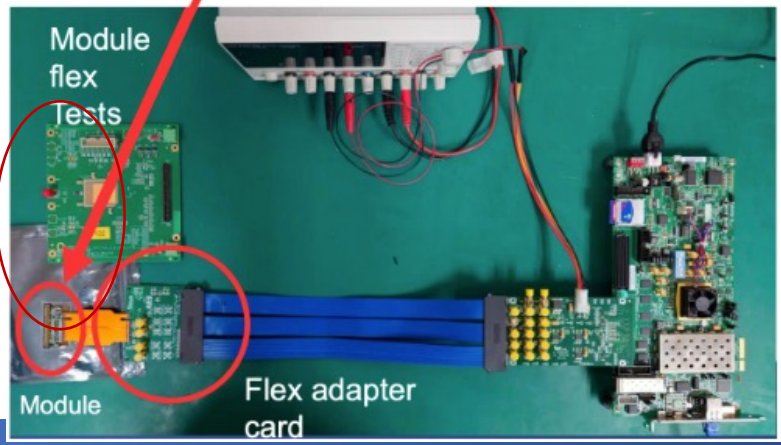
详见杨轩的报告

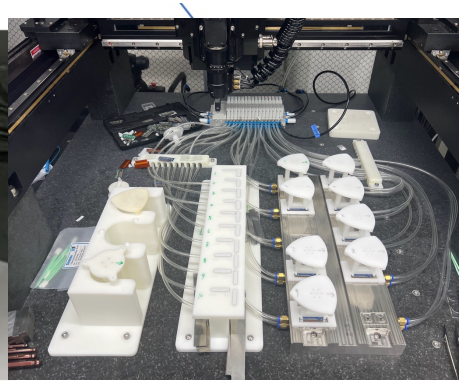




glue+
wire-bonds



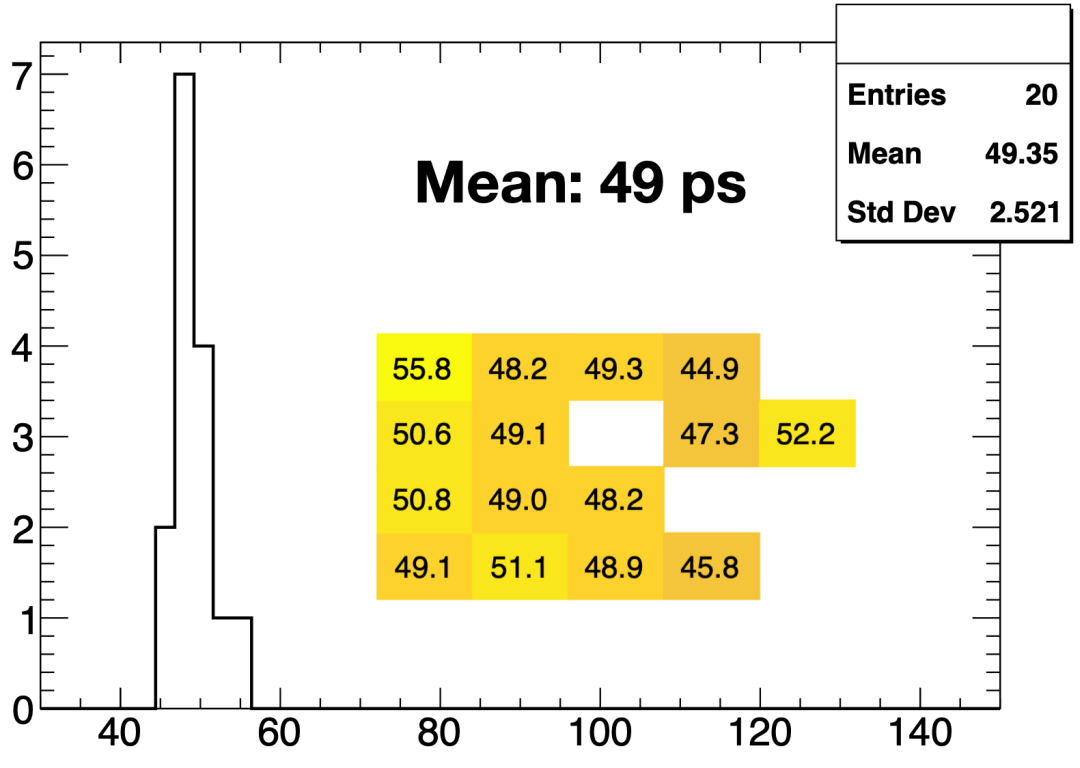




Picking tool Picking dummy sensor Placing dummy sensor Picking flex

探测器模块级别的测试

- 探测器模块级束流测试
  - 用高能所预生产的LGAD与ALTIROC3芯片
  - Individual channels can reach ~50ps level timing resolution
  - 未来数年，ATLAS时间探测器将实现300万像素同时实现50皮秒的时间分辨率

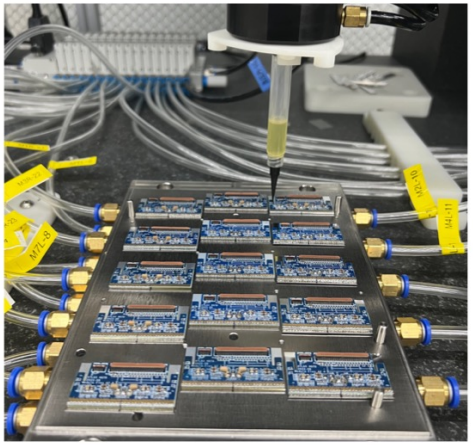


ATLAS时间探测器模块组装

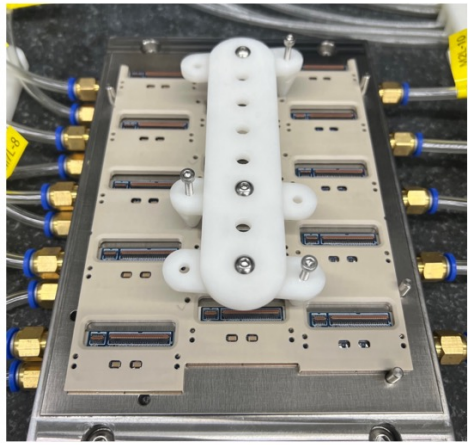
详见杨轩的报告

- 高能所研制第一个 基于高能所LGAD+ALTIROC3 芯片的探测器单元
  - 用自动组装机器人，实现大面积多模块的组装与点胶

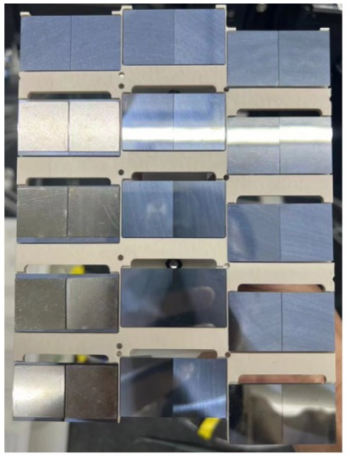
Dispensing with GluingTool



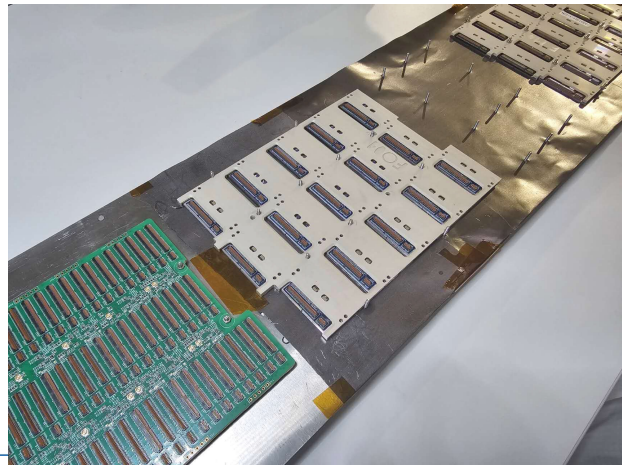
Put the support unit



Backside view after removal

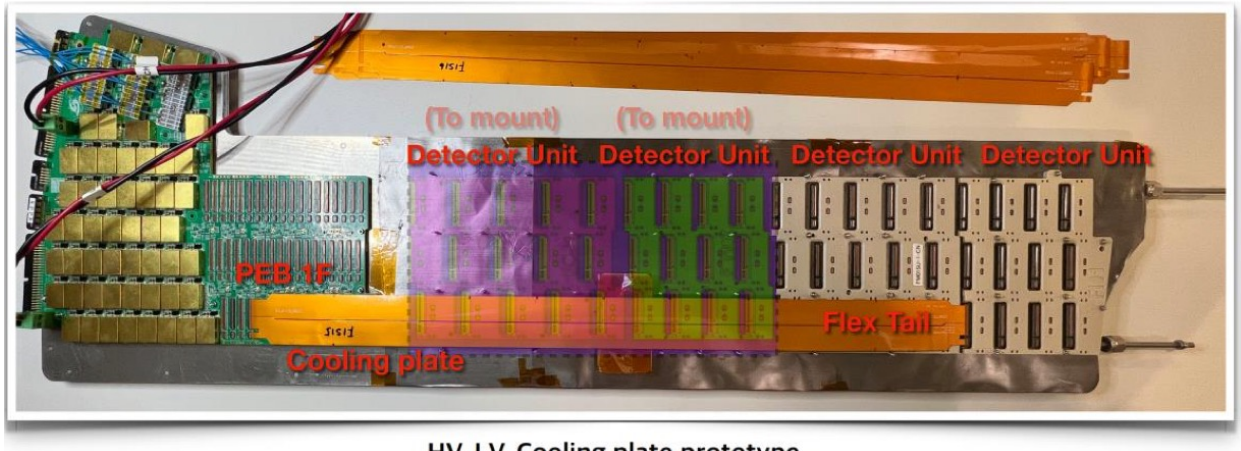


Detector unit shipped to CERN

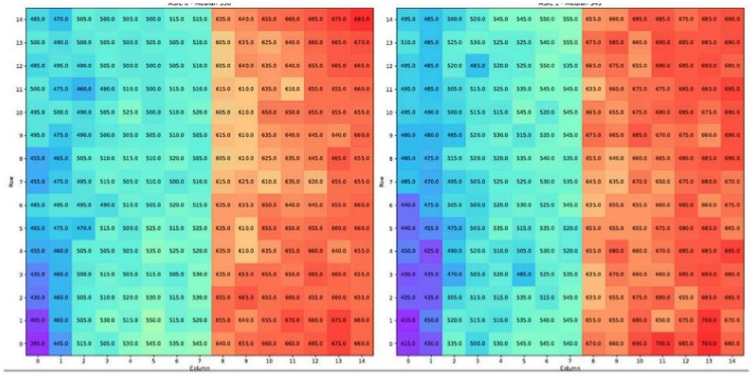


时间探测器系统级测试系统

- 高能所和南大在系统级电子学系统调试中发挥重要作用
  - 张杰（高能所）、葛振武 （南大）主导HGTD时间探测器系统级测试
  - 首次实现数十个模块的系统级电子学读出与校准



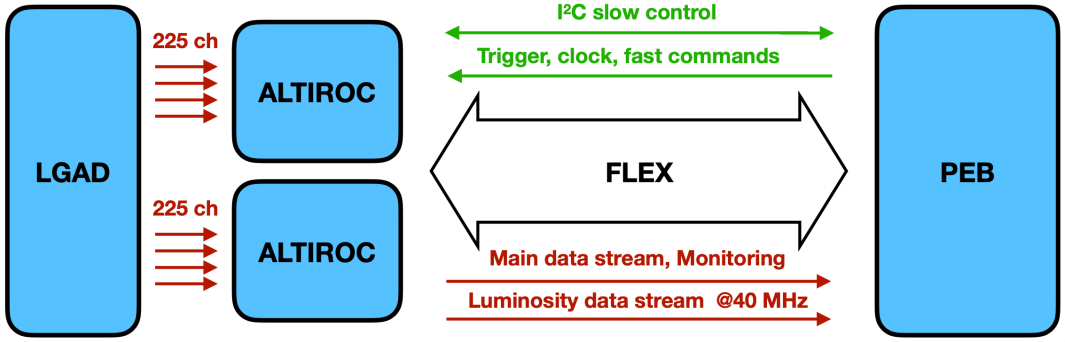
HV, LV, Cooling plate prototype
Electronics : PEB 1F + flex tails + 54 modules mounted on 4 support units (detector unit)



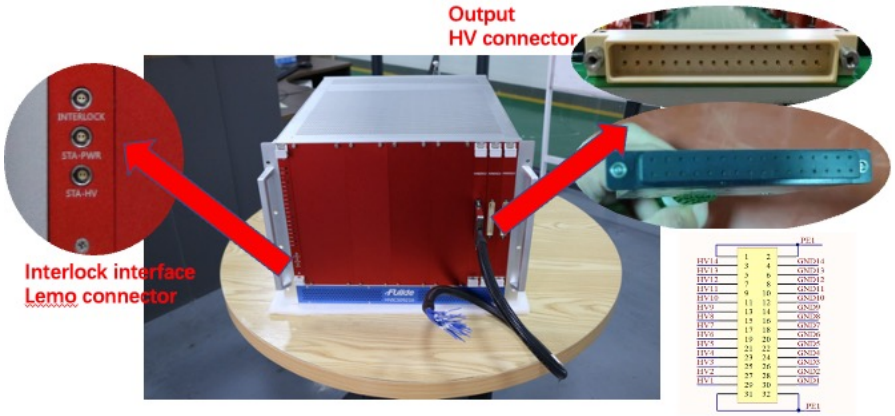
Module threshold scan obtained in demonstrator test

时间探测器电子学系统

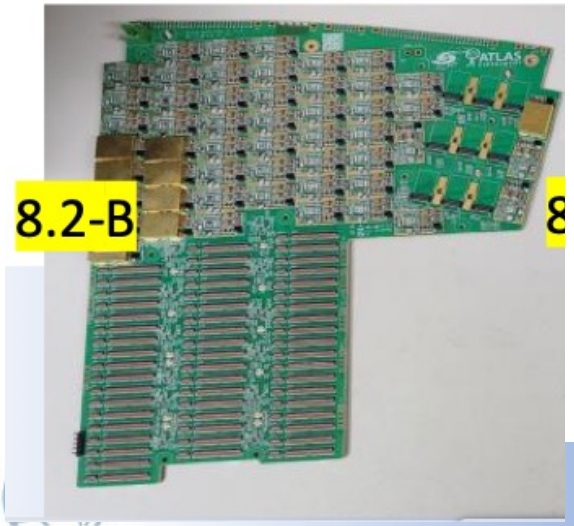
- 高能所与南大负责前端电路板的研发
- 山大负责研发超长的柔性电路尾板（~75cm）
- IHEP developed high voltage power supply prototype



High voltage power supply prototype



Modular Peripheral Electronics Boards prototype



Long Flex tail prototype (75cm)

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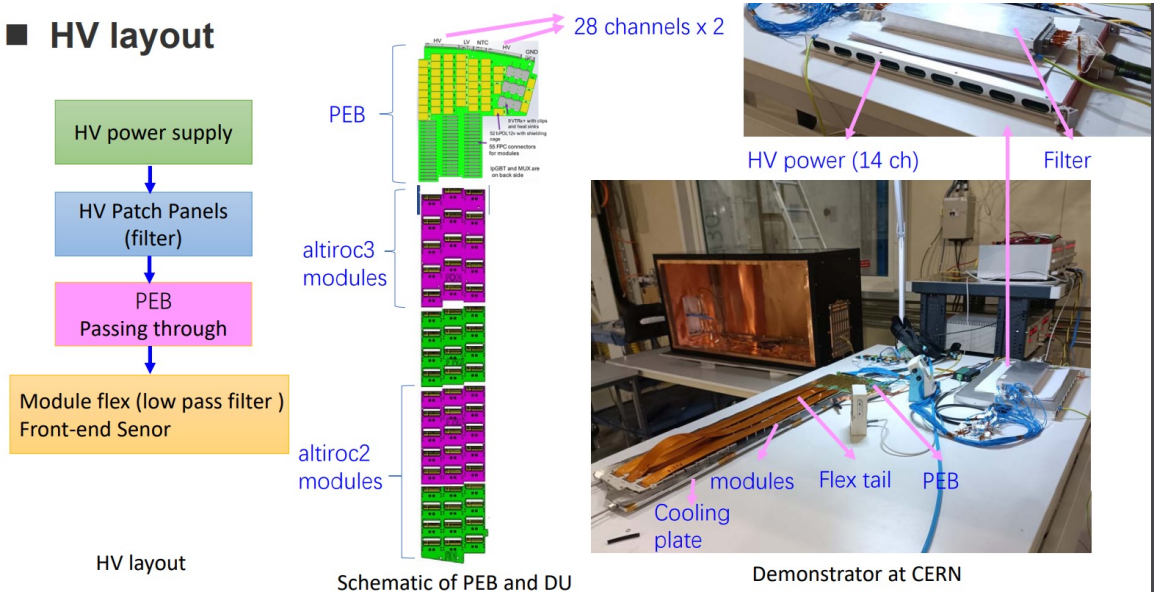
前端电路板研制

- 挑战
  - 不规则形状的二十多层电路板
  - 集成多个高速数据传输与电源模块，需要同时与数十个模块通讯
  - 欧洲核子中心在 2023年对LHC升级项目P2UG评审意见
  - It is comparable with the most difficult boards manufactured for HEP projects
- 最新进展
  - 高能所与南大完成第一个前端电路板样机设计
  - 南大、高能所与国内4个公司合作，都分别研制出前端电子学板的样机

高压电源系统

- 挑战：
  - 高压电源系统对漏电流测量精度达到百纳安级，需要8000多路独立高压
  - 面临CANE等国际公司的强力竞争

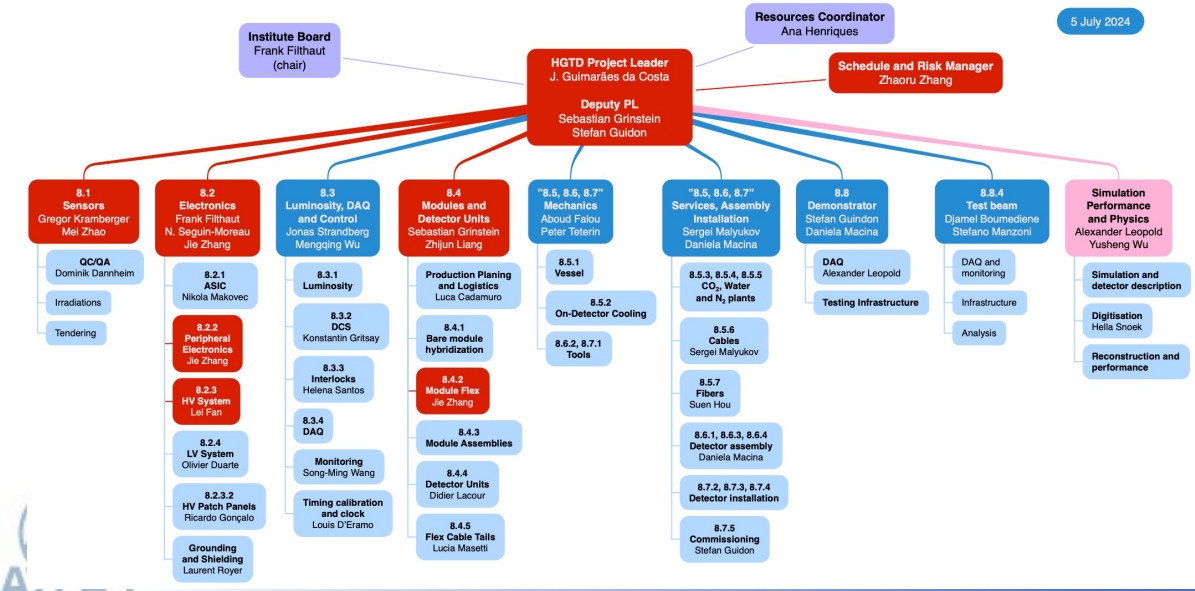
- 最新进展
  - 高能所、山大与国内公司合作研制高压电源，优化漏电流监测部分的电路
  - 主导ATLAS实验HGTD项目电子学设计，测试不同接地方案对探测器的影响

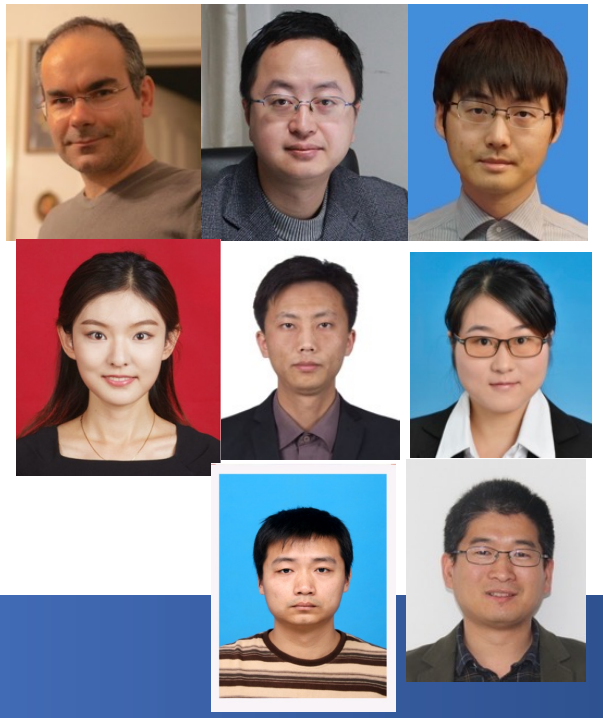


ATLAS高时间分辨探测器： 重要管理职位

- 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Level-2召集人 （梁志均，赵梅，张杰，张照茹、吴雨生）
  - 2人担任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



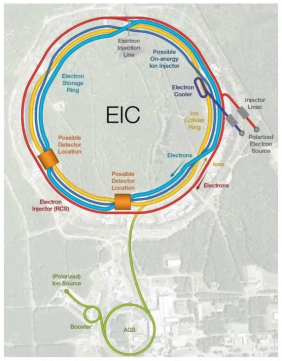


小结: ATLAS实验高颗粒度时间探测器

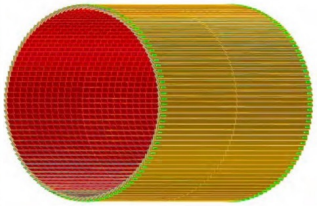
- 中国组在项目中占主导地位，担任项目经理等多个领导职务。
- LGAD传感器：
  - 高能所赢得欧洲核子中心（CERN）国际招标采购的订单
    - CERN首次采购中国产的硅传感器
  - 高能所、科大承担100%传感器研制（高能所90%，科大10%）
- 外围电路：
  - 高能所，南大主导了100%外围电路板的设计与研制工作
  - 研制出电路板读出系统原型机。
- 探测器模块：
  - 中国组（高能所，科大）将组装～4000个模块，占项目45%
- 高压系统：高能所、山大研制出高压电源原型
- 柔性尾板：山大研制出首批原型

未来发展： LGAD探测器的未来应用

Electron-Ion Collider (EIC)： Timing-tracker

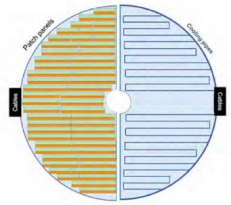


Barrel AC-LGAD detector



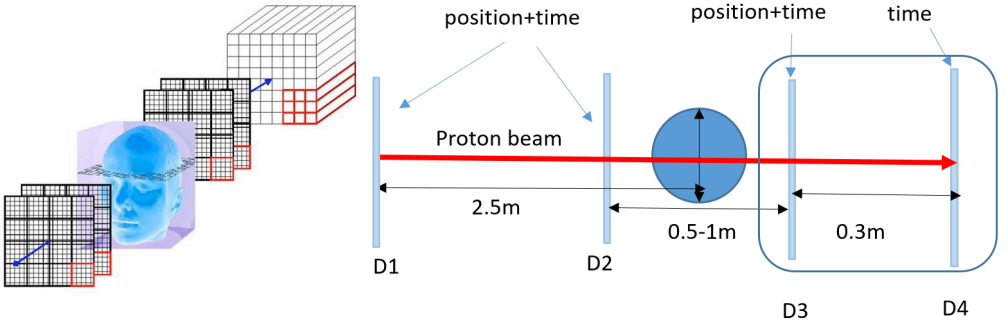
10.9 m^2

Hadron endcap AC-LGAD detector

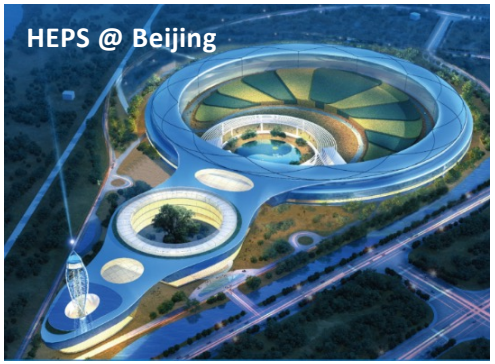


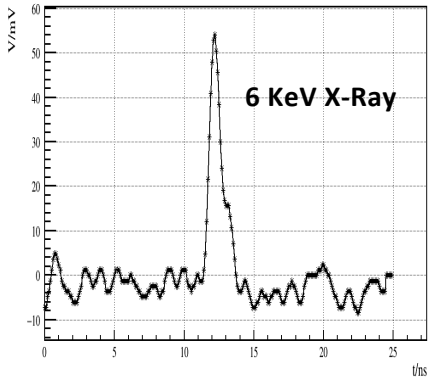
2.22 m^2

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
- …

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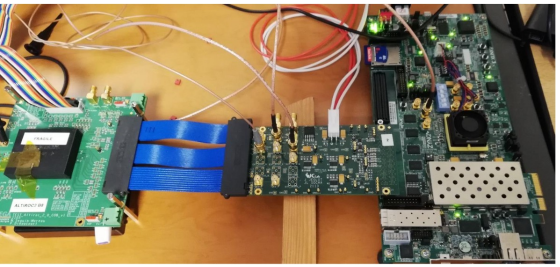
backup

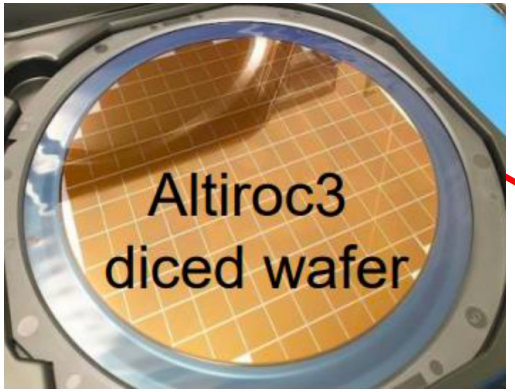
ALTIROC R & D

- 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)

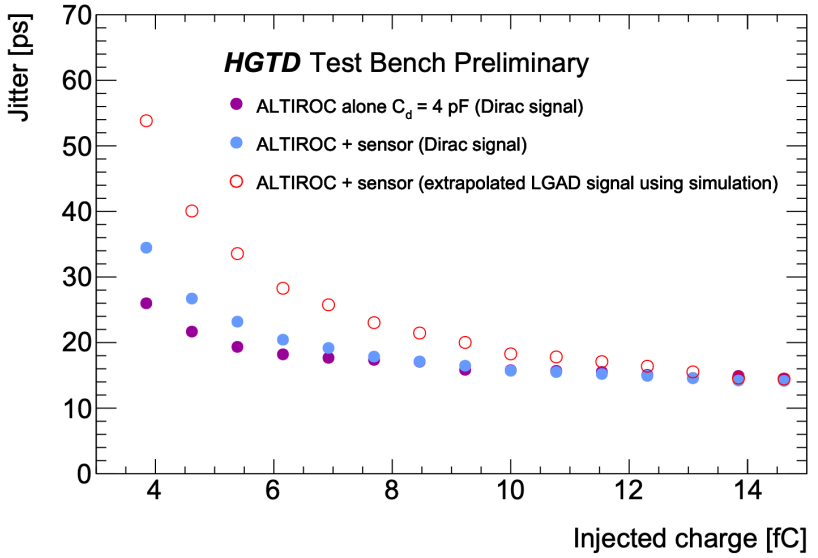
ALTIROC and test boad



ALTIROC3 wafer@IHEP

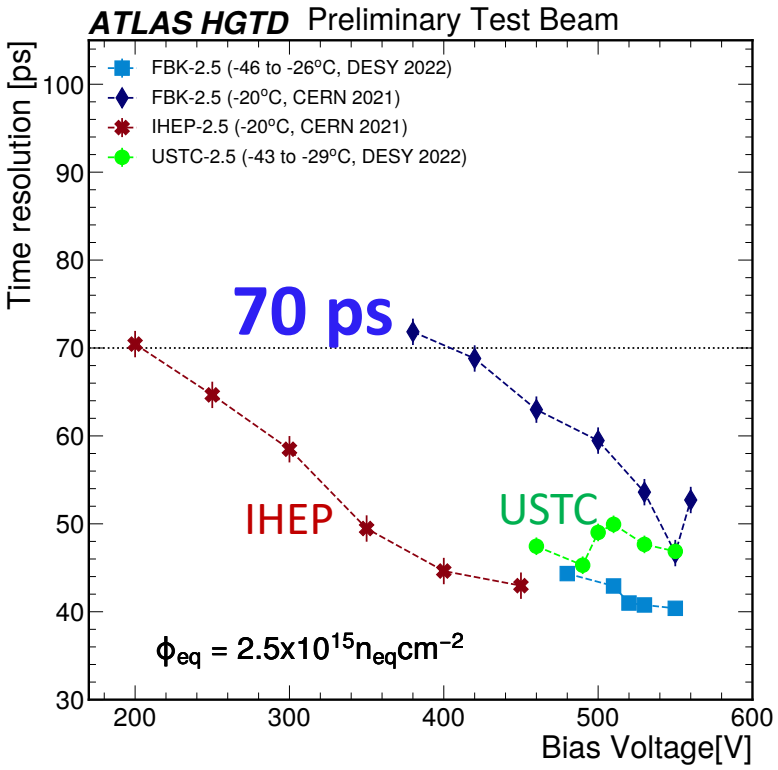


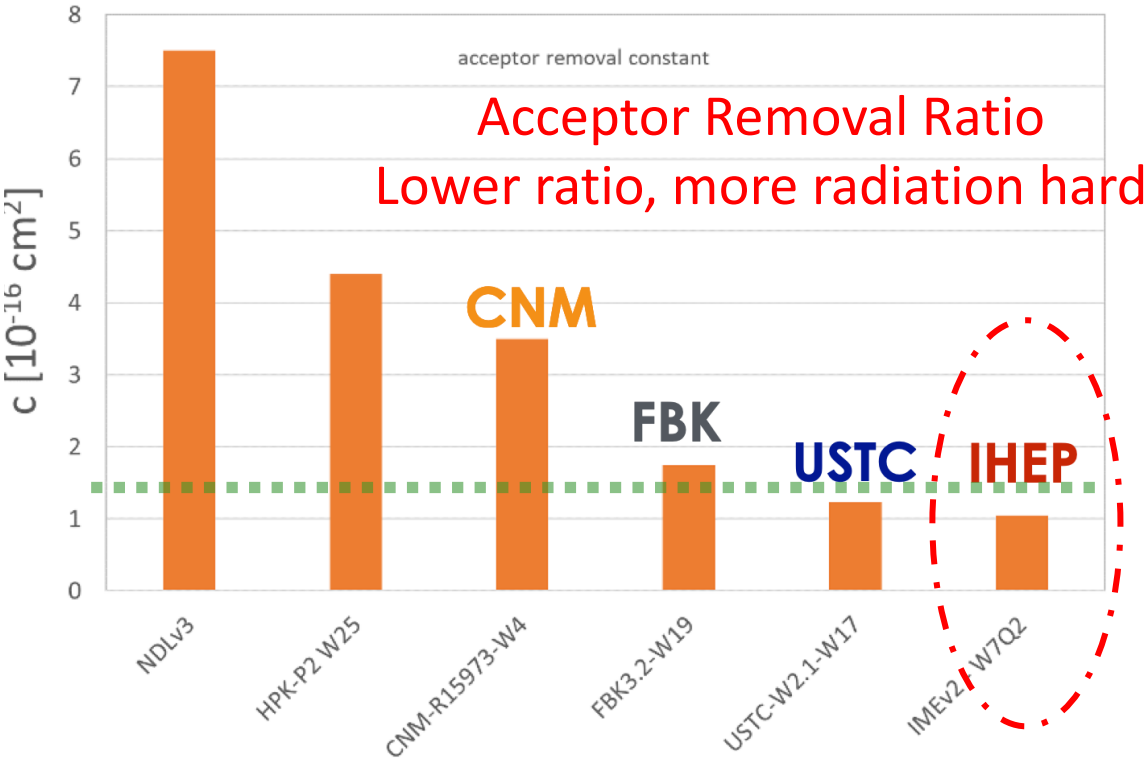
Injected charge Vs jitter



LGAD sensor after Irradiation

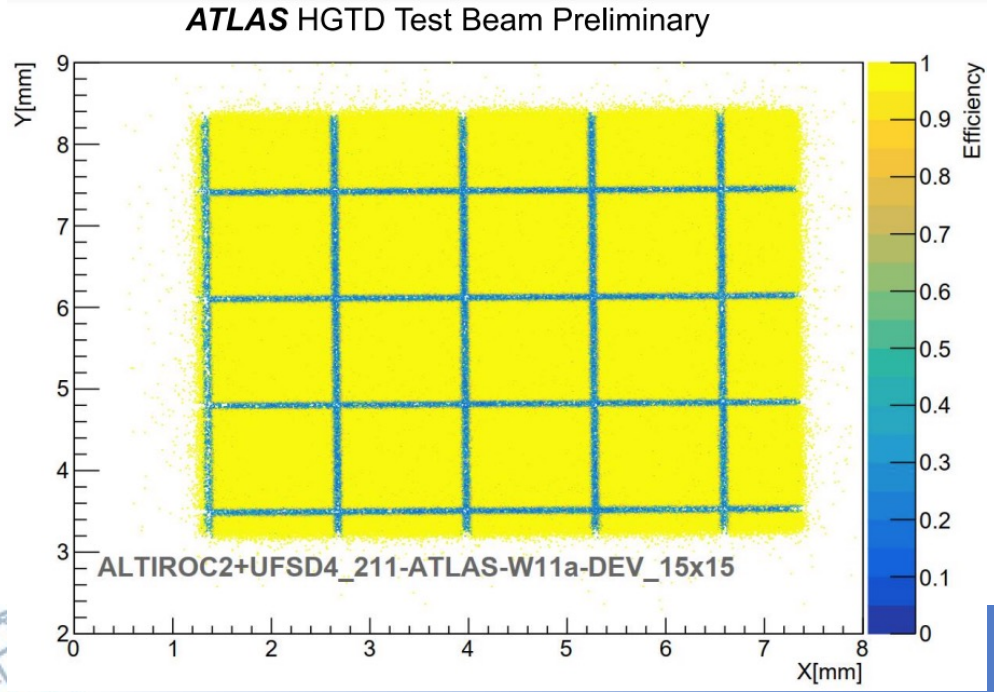
- Lots of prototypes R&D in LGAD in last few years, active vendors includes:
  - IHEP-IME (China), USTC-IME (China), IHEP-NDL(China), FBK (Italy), CNM (Spain), HPK (Japan) …
- IHEP-IME and USTC-IME LGAD with carbon-enriched doping
  - Significantly lower acceptor removal ratio, the most radiation hard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

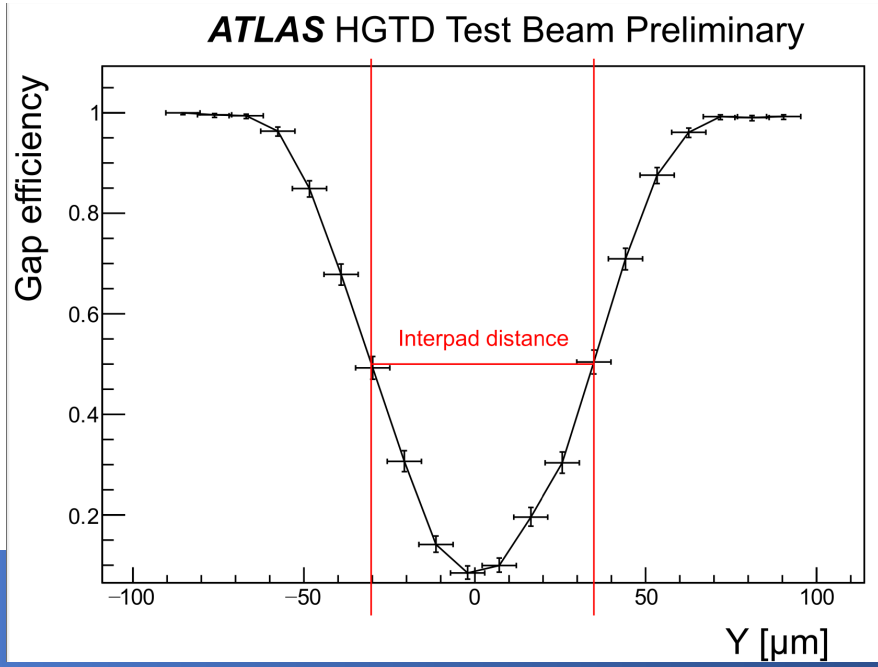




Hybrid test beam result

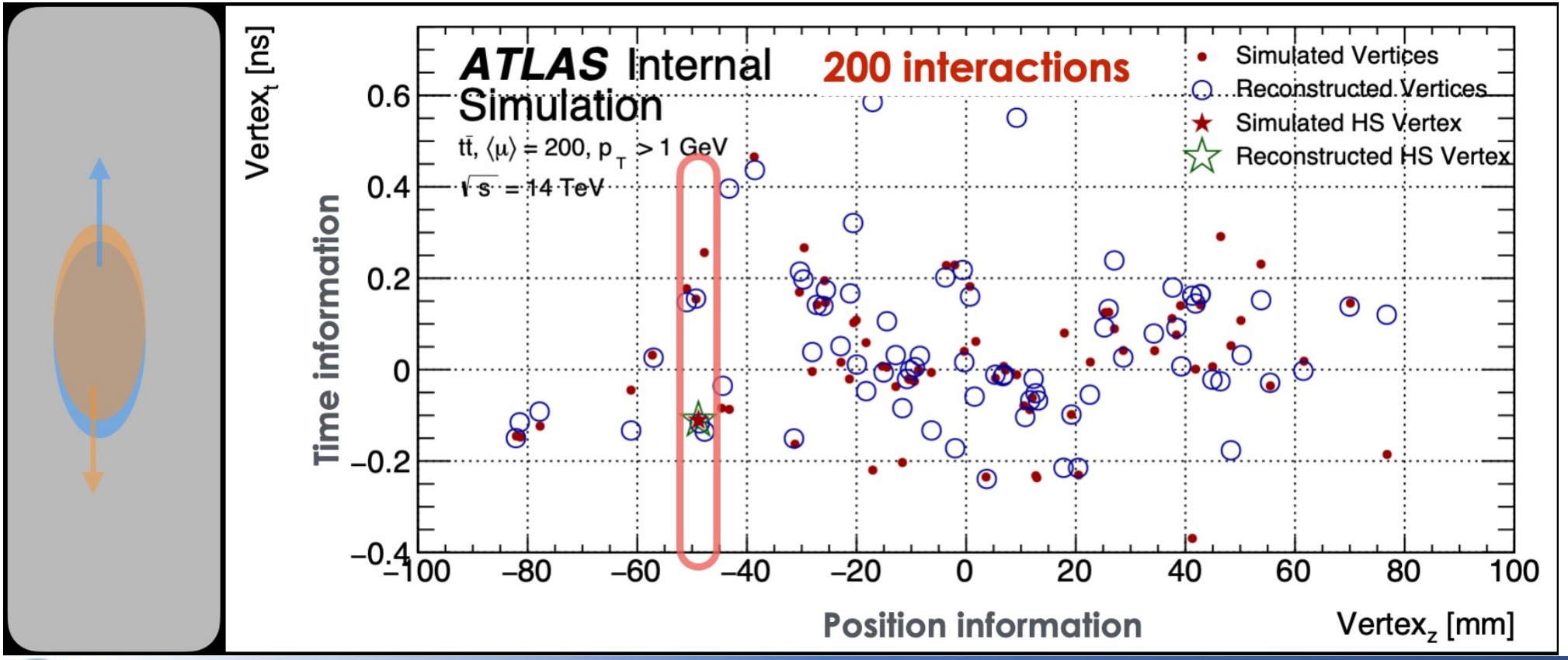
- Hybrid functionality was validated by test beam
  - The EUDET telescope is used for track reconstruction
  - Sensor bias voltage is -180 V, corresponding to a charge of ~20 fC
  - ASIC threshold 4.8 fC
- Close to 100% efficiency in the center of the pixel (pad)
  - The gap between pixels (pads) is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



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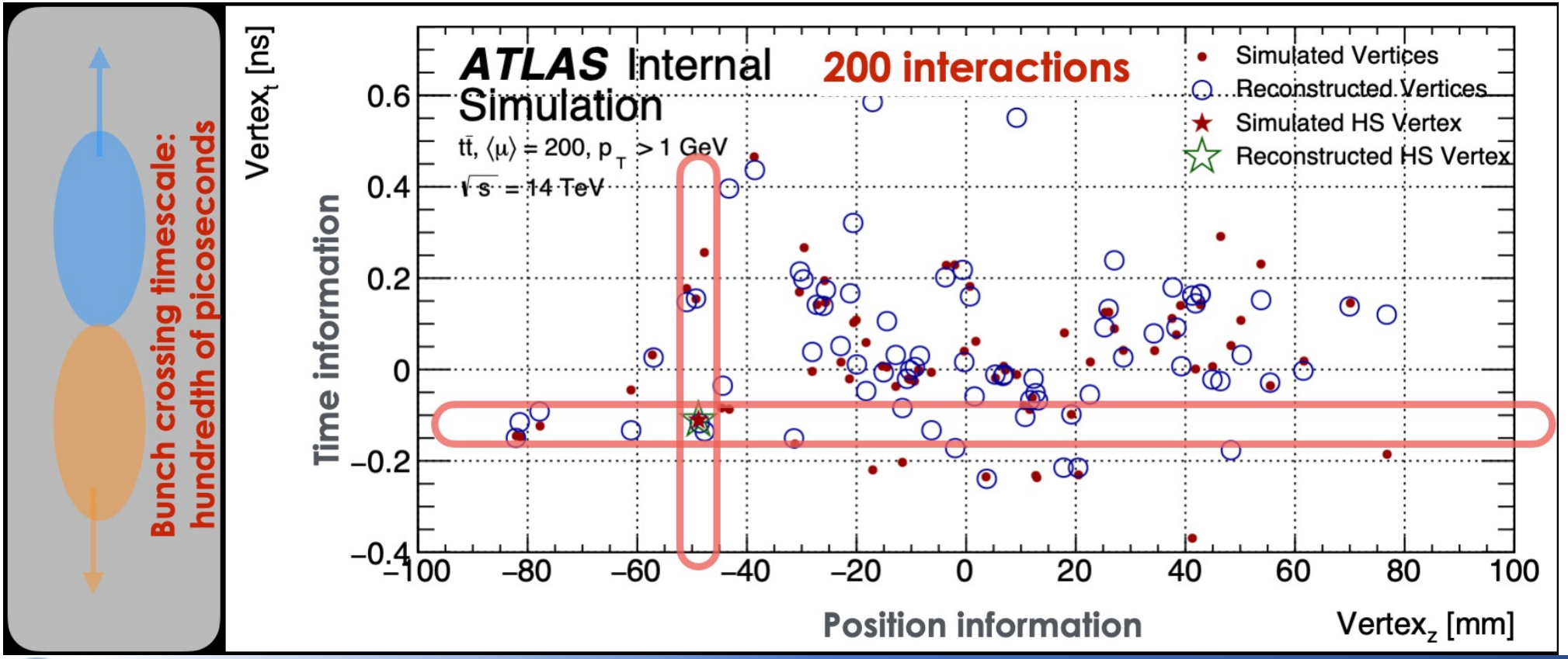
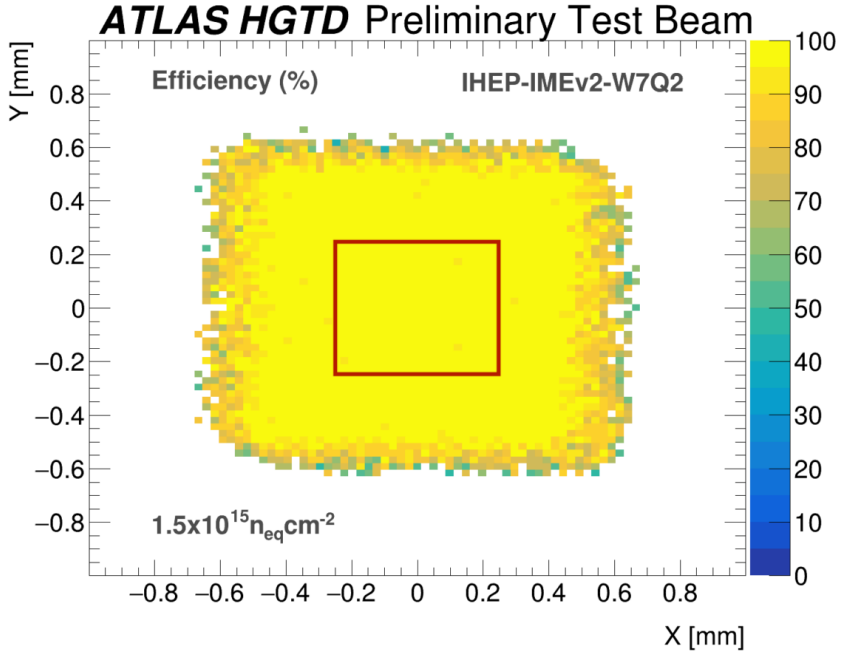


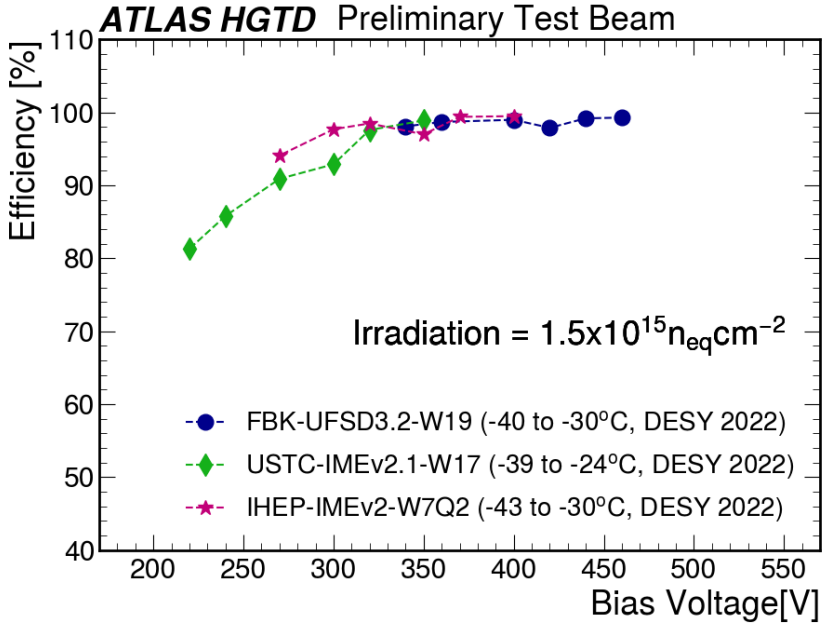
辐照后LGAD传感器在束流测试的性能

- 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

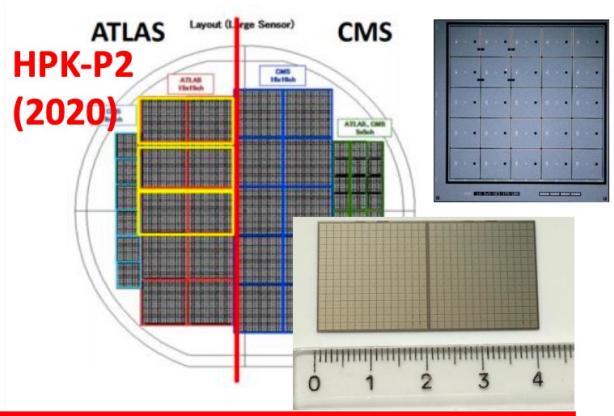


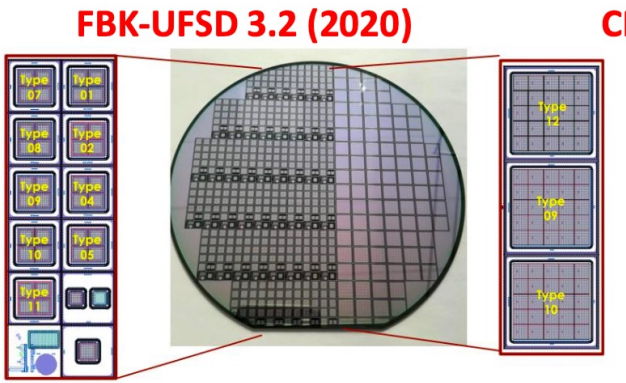
探测效率 VS 偏置电压

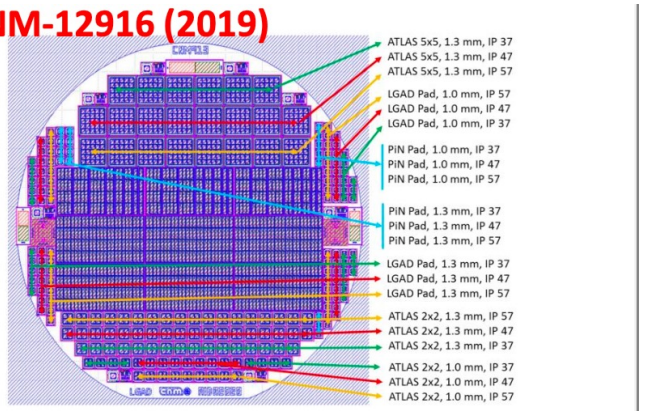


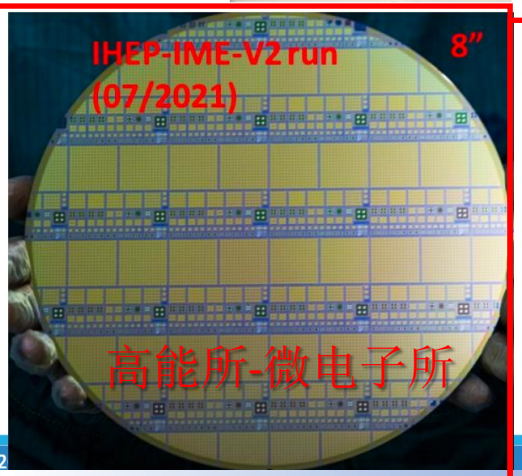
LGAD低增益雪崩硅传感器： 国内外形势

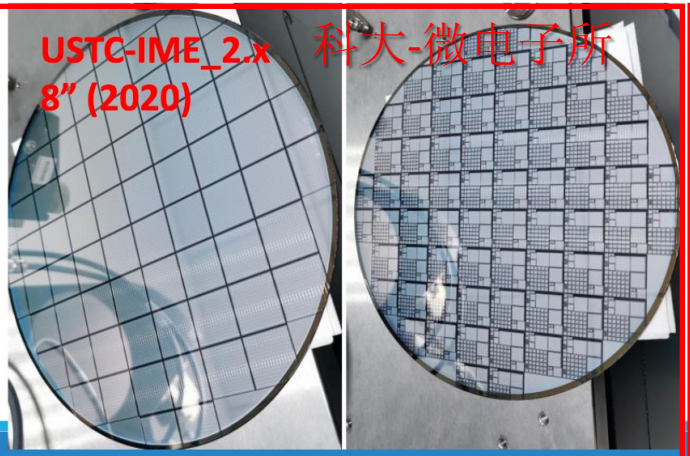
- 近年来，全世界范围涌现出很多研制LGAD硅传感器的单位
  - 国内：IHEP-IME (高能所-微电子所), USTC-IME (科大-微电子所), NDL(高能所-北师大)
  - 国际：滨松HPK (Japan)， FBK (意大利), CNM (西班牙）…
  - 高能所和科大分别独立设计传感器版图和工艺，在微电子所8寸晶圆工艺流片

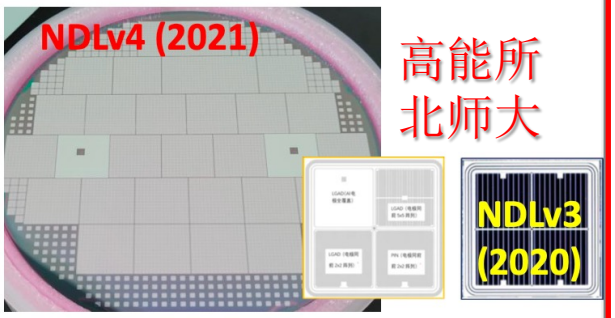










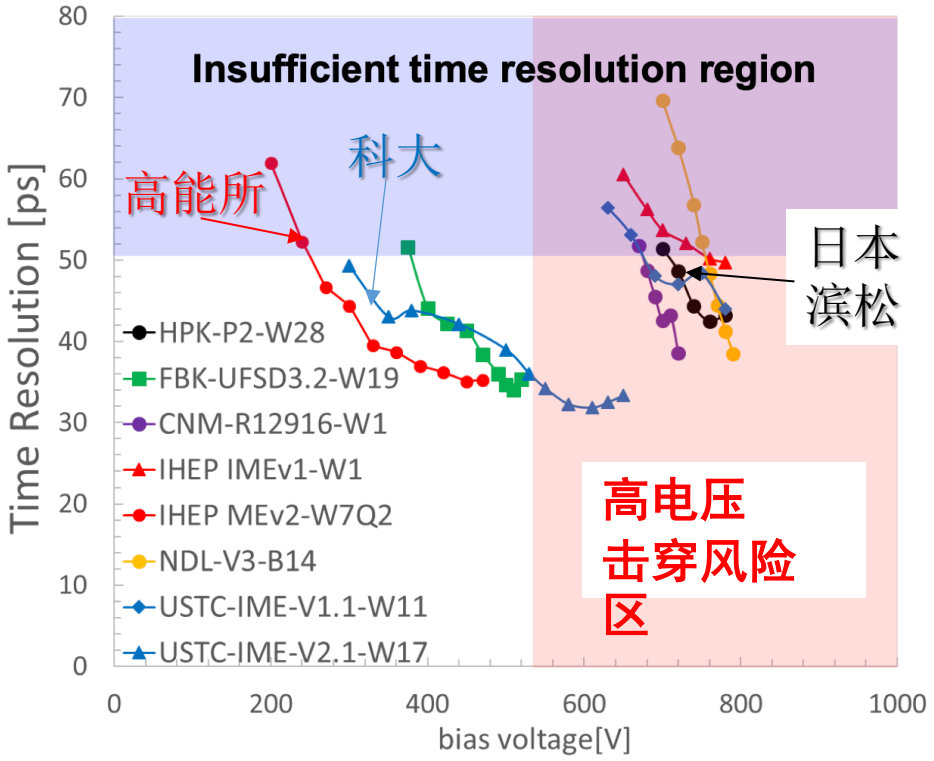


PLANAR TECHNOLOGY – more vendors
(e2V, BNL, Micron …)

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