
ATLAS实验高颗粒度时间探测器/ CEPC顶点探测器的研发

梁志均

中国科学院高能物理研究所

Outline

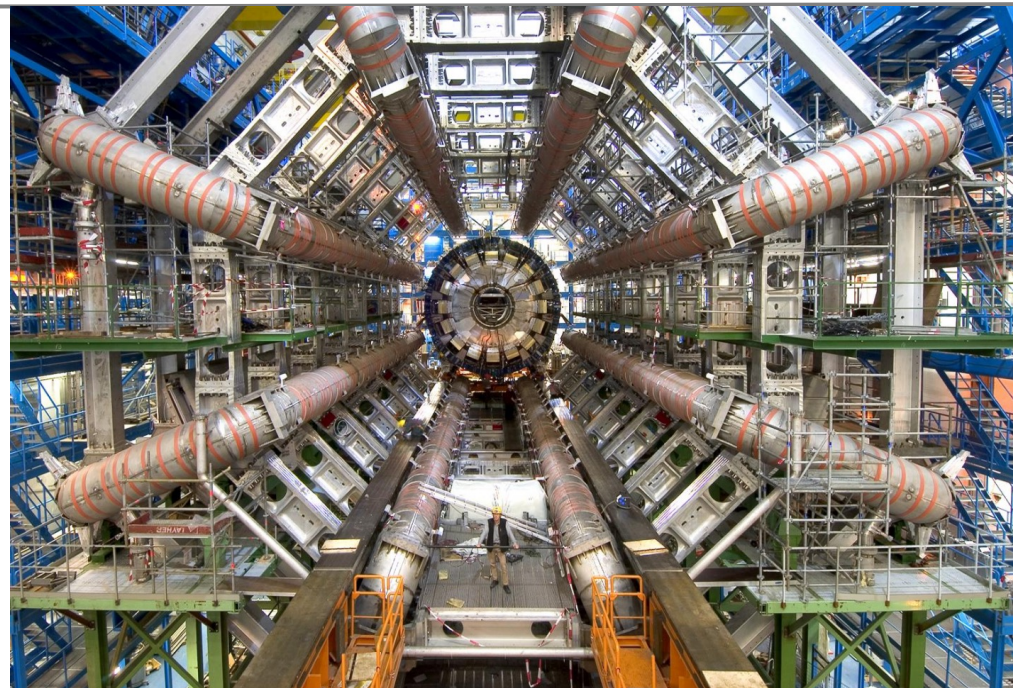
- 大型强子对撞机ATLAS实验高颗粒度时间探测器
- CEPC的物理与硅探测器研发

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** (**$14 \times 10^{12} \text{eV}$**)
- 位于瑞士与法国边境



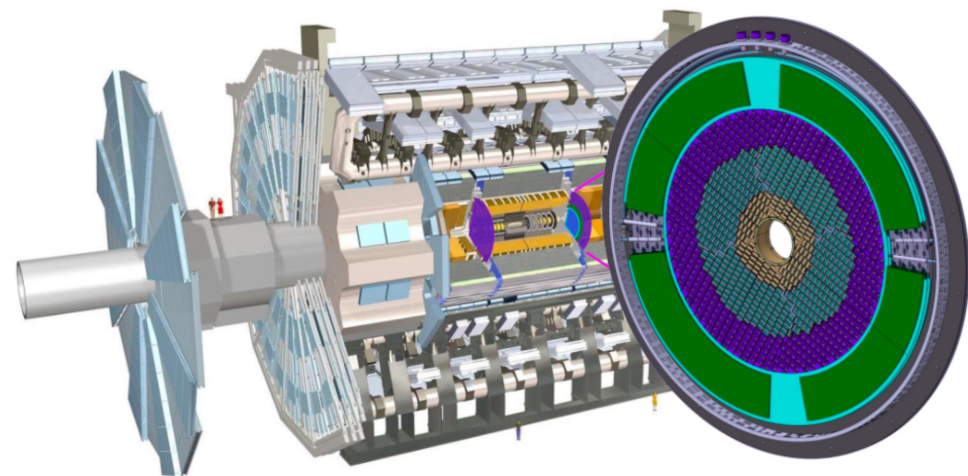
ATLAS探测器

- 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

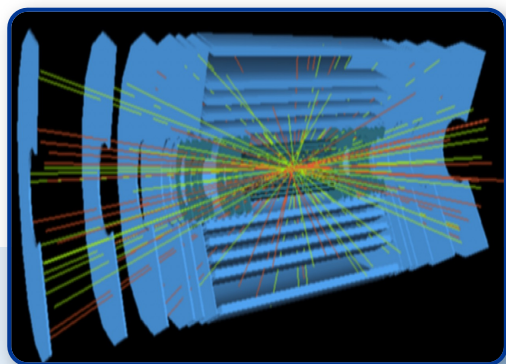
ATLAS实验高颗粒度时间探测器

High Granularity Timing Detector (HGTD)

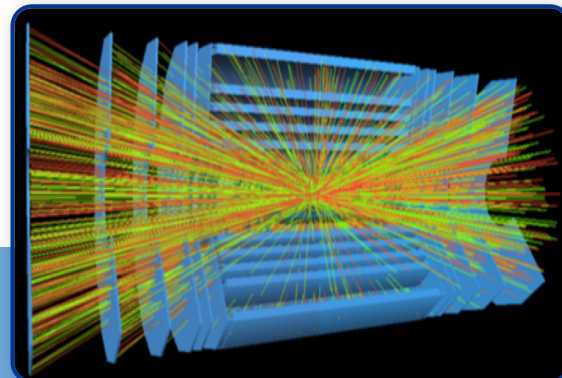
- 把粒子到达时间的测量精度提高2个数量级(数纳秒→30皮秒)
- 解决高亮度LHC对撞事例堆积问题
 - 6.4平方米的硅探测器, 30皮秒的时间分辨
 - 毫米级的颗粒度, 超过三百万个读出通道
 - 能承受 $2.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ 的等效中子通量的辐照
- 中国组主导HGTD探测器研制
 - 100%抗辐照高时间分辨传感器(高能所, 科大)
 - 100%前端电子学(高能所, 南大), 50% ASIC测试(高能所, 上交大, 山大)
 - 44%探测器组装(高能所, 科大, 山大, 南开, 上交大)
 - 100%柔性电缆(山大), >18% 高压电子系统(高能所, 交大)



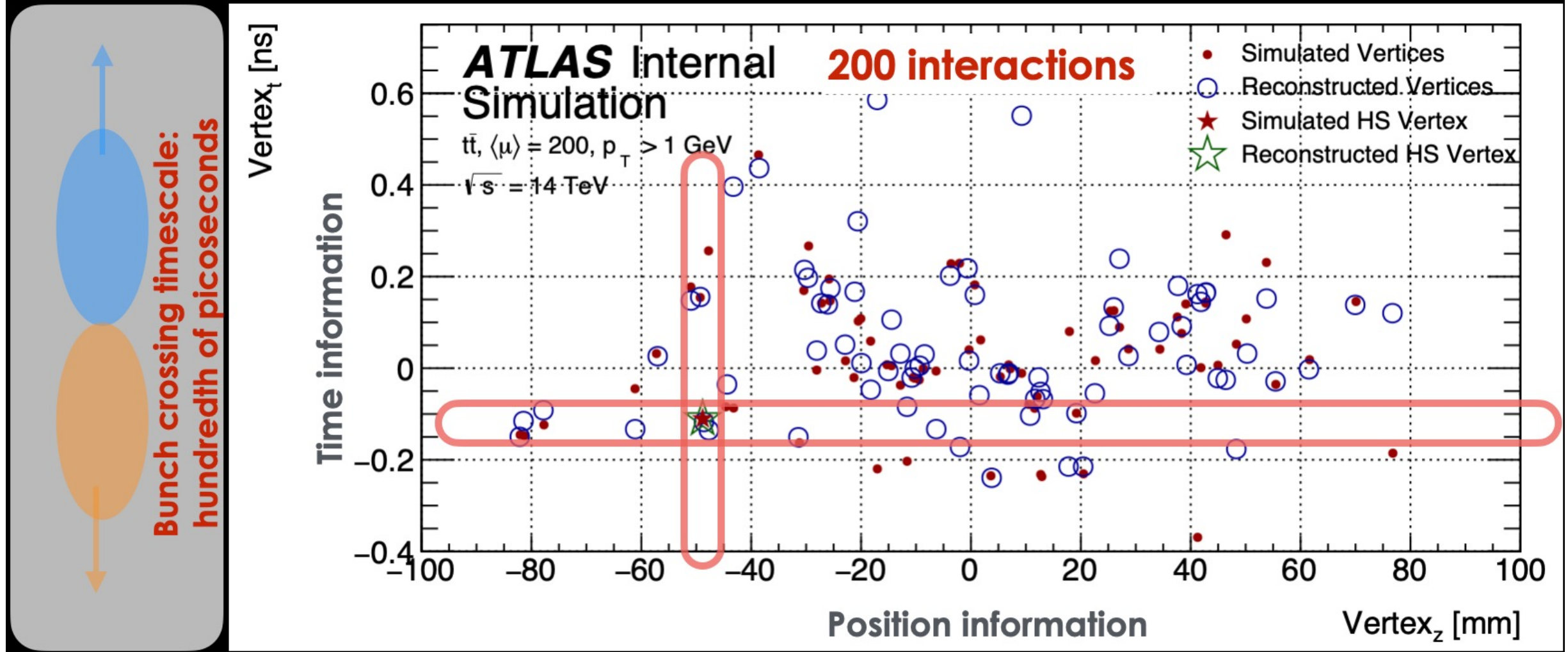
目前的ATLAS探测器



高亮度LHC升级后的ATLAS探测器



ATLAS实验高颗粒度时间探测器工作原理



中国团队在ATLAS实验HGTD探测器的管理职位

- 中国团队在HGTD项目中发挥主导作用，有多个重要管理职位
 - 2025年3月到2027年2月，高能所梁志均 担任HGTD探测器的项目副经理
 - 2021年3月到2025年2月，高能所Joao 曾担任HGTD探测器的项目经理
 - 6人现担任或曾担任L2 召集人 (张杰、赵梅、梁志均、张照茹、徐来林、吴雨生)
 - 3人现担任L3 召集人 (樊云云、樊磊、张杰)
 - 1 人曾担任 HGTD speaker committee (刘衍文)

Institute Board
Chair: Frank Flithaut

Project Leader: Stefan Guindon
Deputy Project Leader: Zhijun Liang

Resource Coordinator:
Laurent Serin

Schedule and Risk Manager:
Zhaoru Zhang

Latest HGTD management

L2 Coordinators

8.1: Sensors
Gregor Kramberger
Mei Zhao

8.2 Electronics
Jie Zhang
Nathalie Seguin-Moreau
Frank Flithaut

8.3: DAQ and Controls
Jonas Strandberg

8.4: Module
Assembly
Sebastian Grinstein
Zhijun Liang

8.4: Detector Unit
Loading and Testing
Lucia Masetti
Luca Cadamuro

8.5: Mechanics
Aboud Falou

8.5 + 8.6 + 8.7: Services,
Assembly, Installation
Sergei Malykov
Daniela Macina

8.8: Demonstrator
Daniela Macina
Stefano Manzoni

8.8.4: Testbeam
Djamel Boumdeiene
Xiao Yang
Stefano Manzoni

Simulation Performance
and Physics
Alexander Leopold
Louis d'Eramo



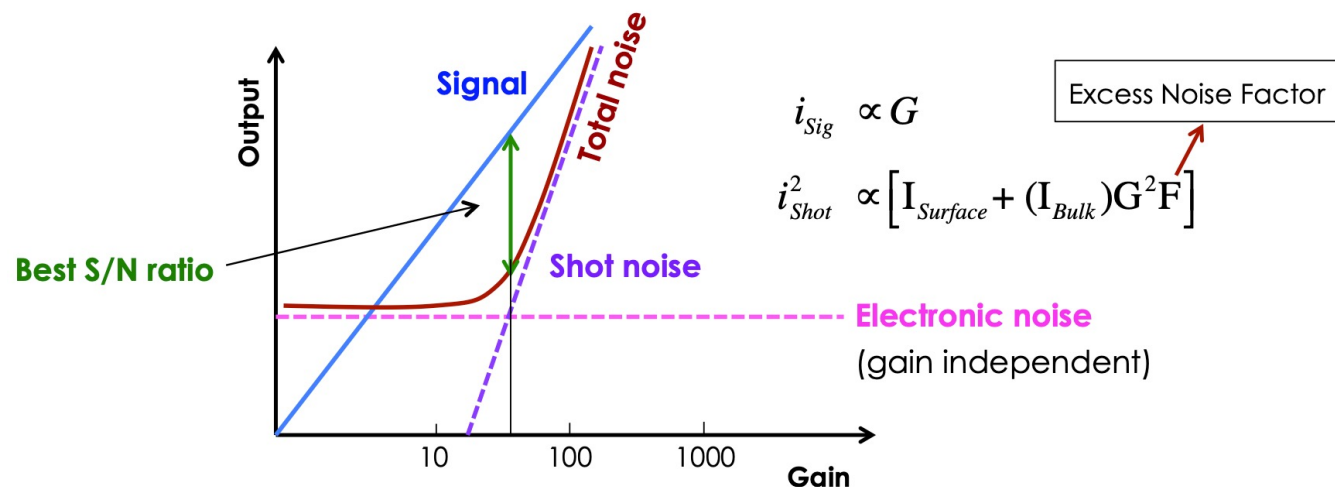
Low Gain Avalanche Detectors (LGAD)

低增益雪崩硅传感器

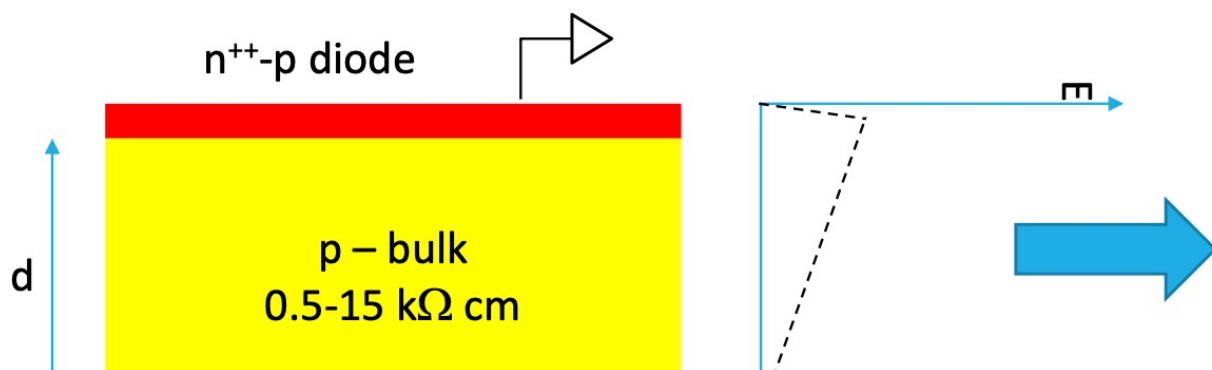
➤ 与APD 和 SiPM比较, LGAD has 适中的增益 (10-50)

- 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

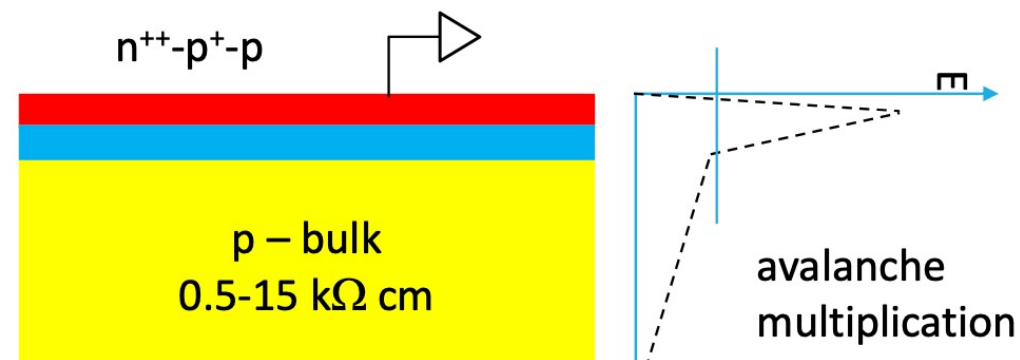
$$\sigma_{jitter}^2 = \left(\frac{t_{rise}}{S/N} \right)^2$$



一般的 PiN结传感器

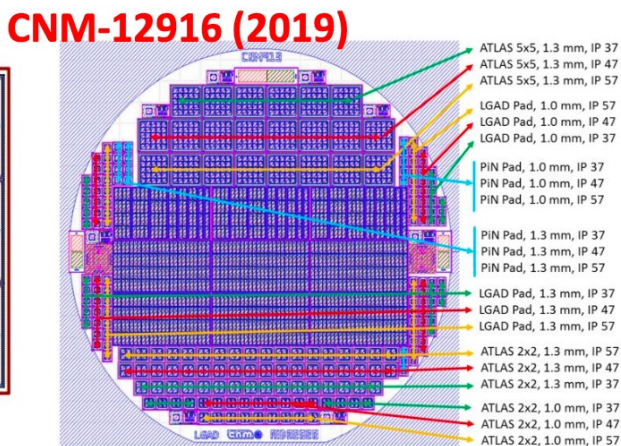
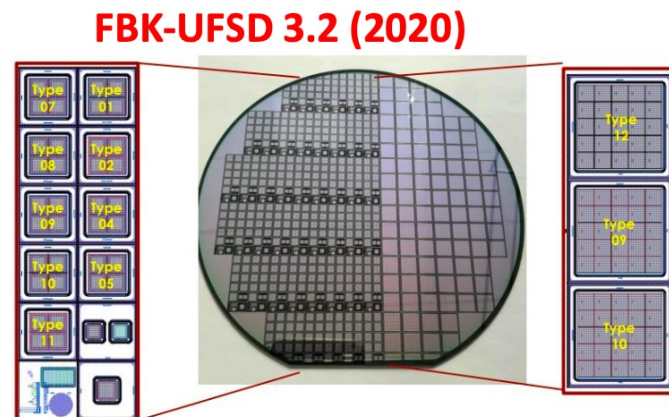
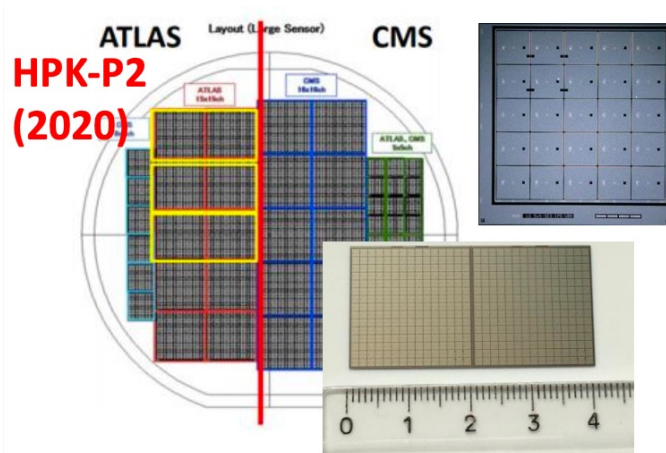


低增益雪崩硅传感器
P+ gain layer on top of PIN diode



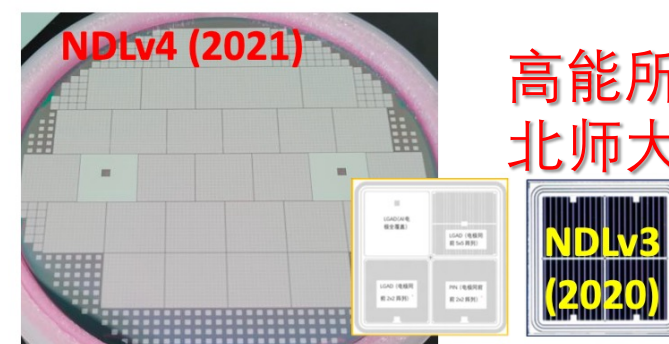
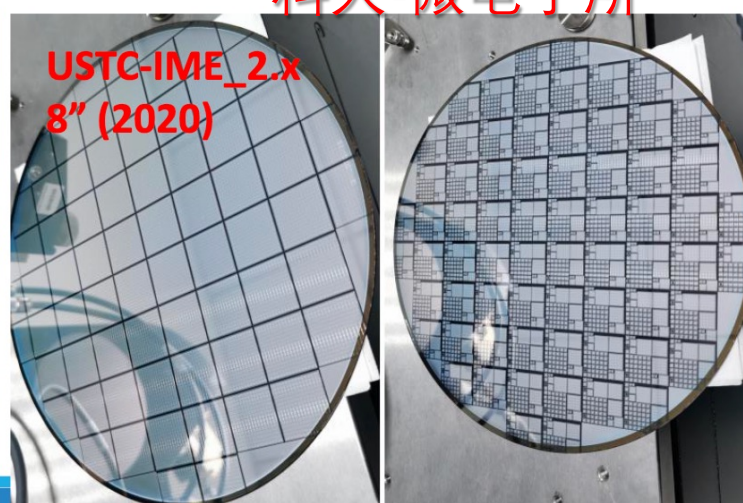
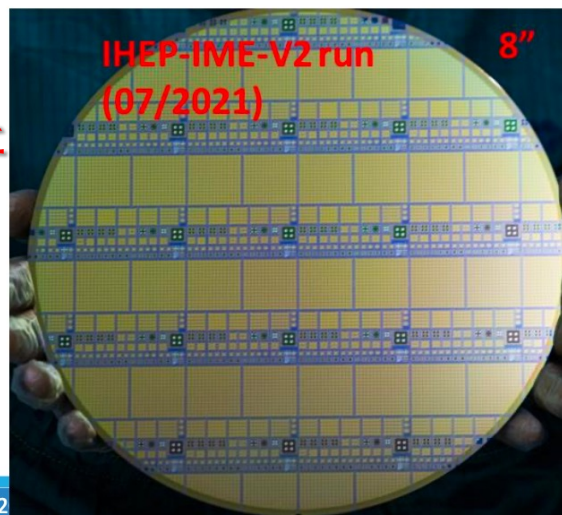
LGAD低增益雪崩硅传感器：国内外形势

- 2015年后，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) ...



科大-微电子所

高能所-
微电子所



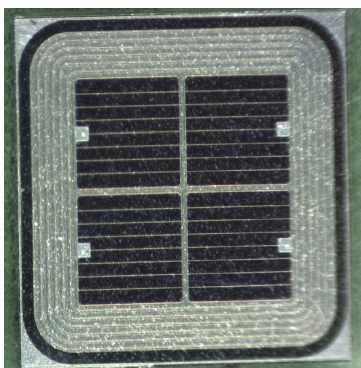
高能所
北师大

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

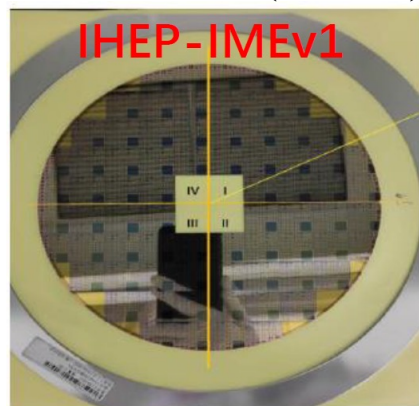
高能所LGAD 传感器的研发历程

- 2019年，高能所开始发展LGAD传感器技术，先后与多家单位合作研发
 - 北京师范大学(NDL), 清华大学微电子学院, 中科院微电子所(IME)
 - 与IME的合作中，高能所负责器件设计与测试，微电子负责流片

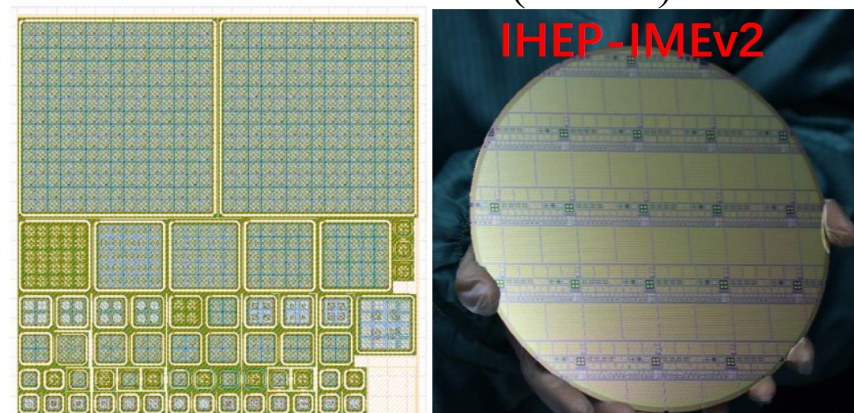
IHEP-NDL(2019)



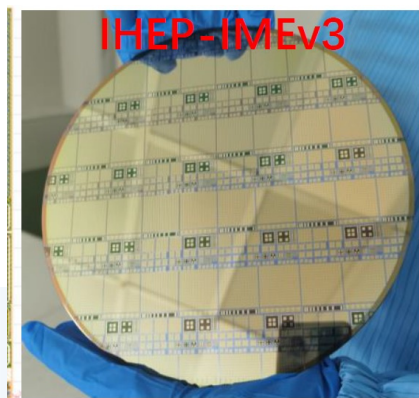
IHEP-IMEv1(2020.9)



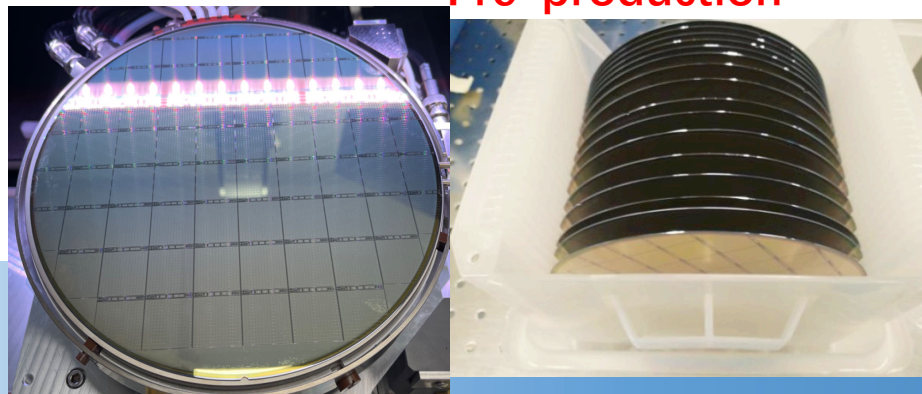
IHEP-IMEv2(2021.6)



IHEP-IMEv3(2022.5)



Pre-production for ATLAS (2023.7)
Pre-production

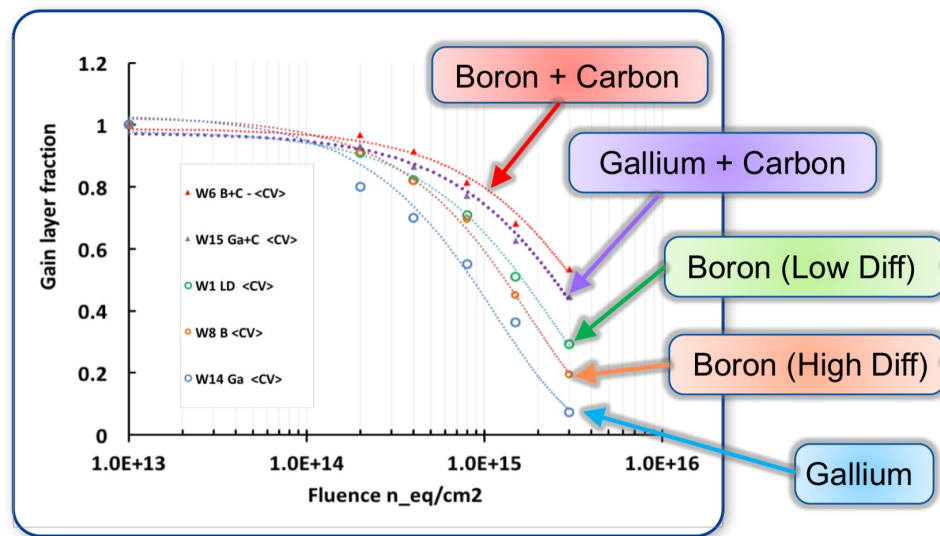


Mass production
for ATLAS (2024.6)

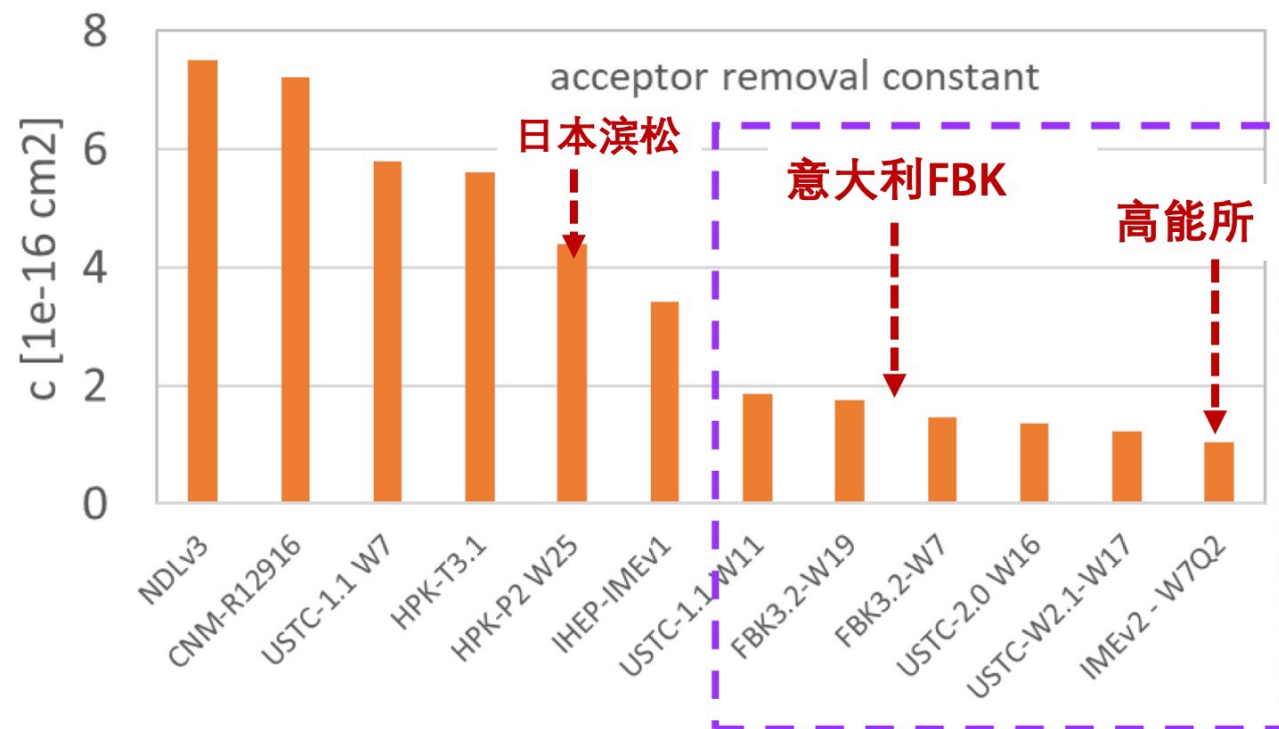
LGAD传感器辐照后硼掺杂移除 (Acceptor removal)

- 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）
 - 目前抗辐照性能优于滨松

高能所传感器
目前移除率最低（最佳抗辐照性能）



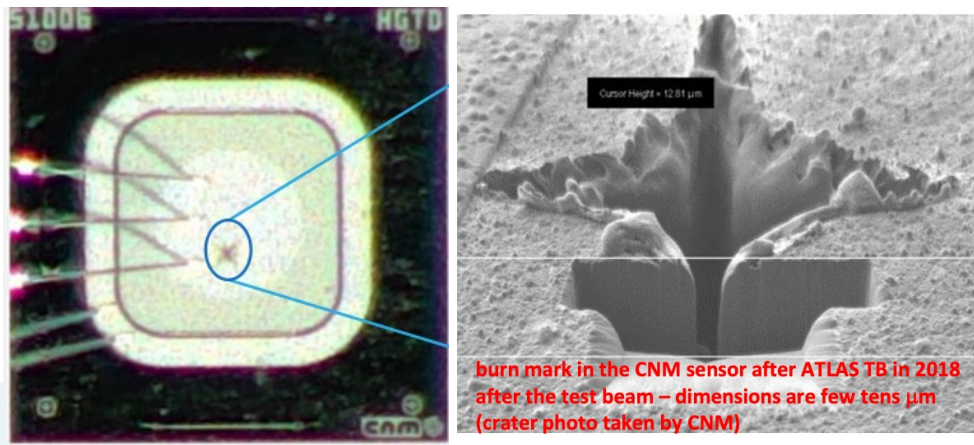
[G.Paternoster, FBK, Trento, Feb.2019]



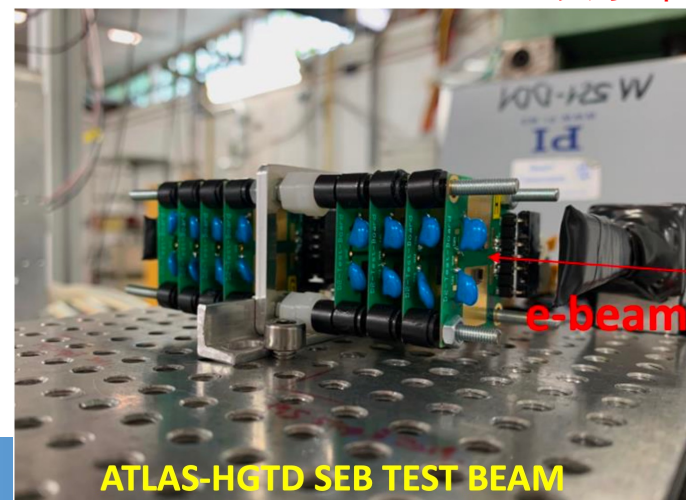
传感器的单粒子烧毁风险 Single Event Burnout (SEB)

- RD50, CMS and ATLAS 合作组确认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) 烧毁率很高
 - 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，数十个样品全部通过测试，无一烧毁

单粒子烧毁后LGAD (滨松/CNM)



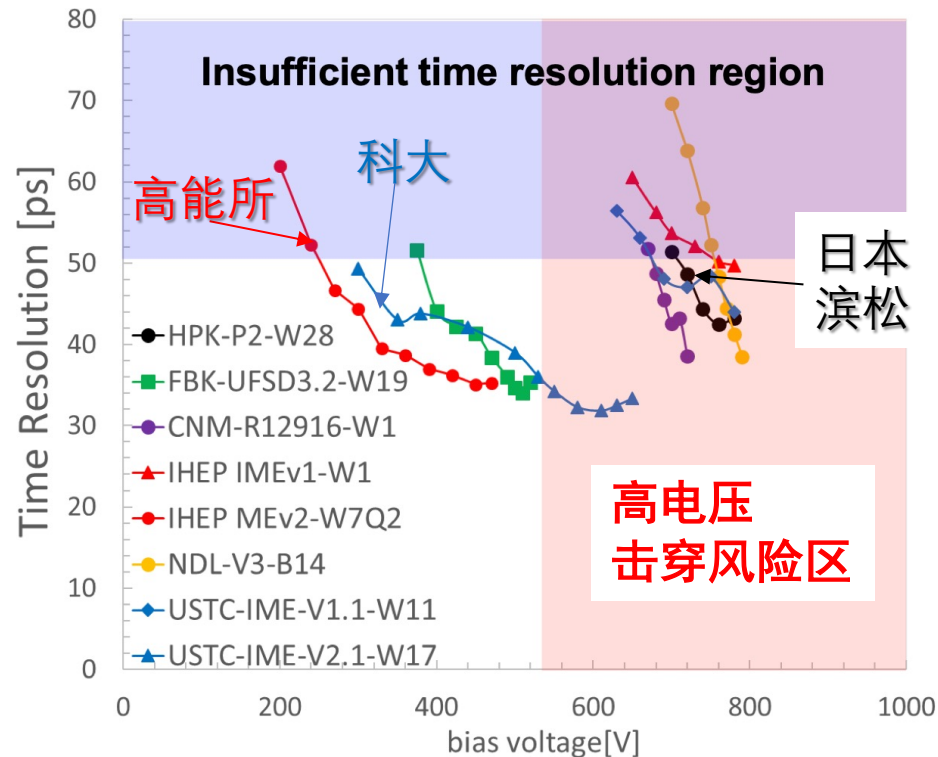
CERN test beam: 120 GeV 质子束流



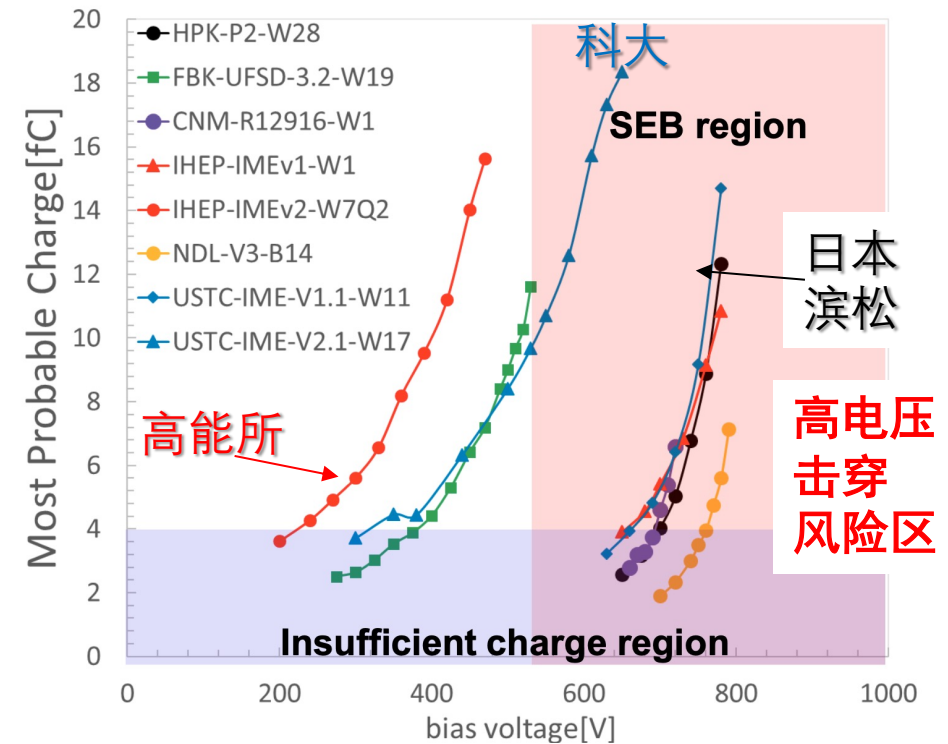
LGAD传感器在辐照后的性能

- 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



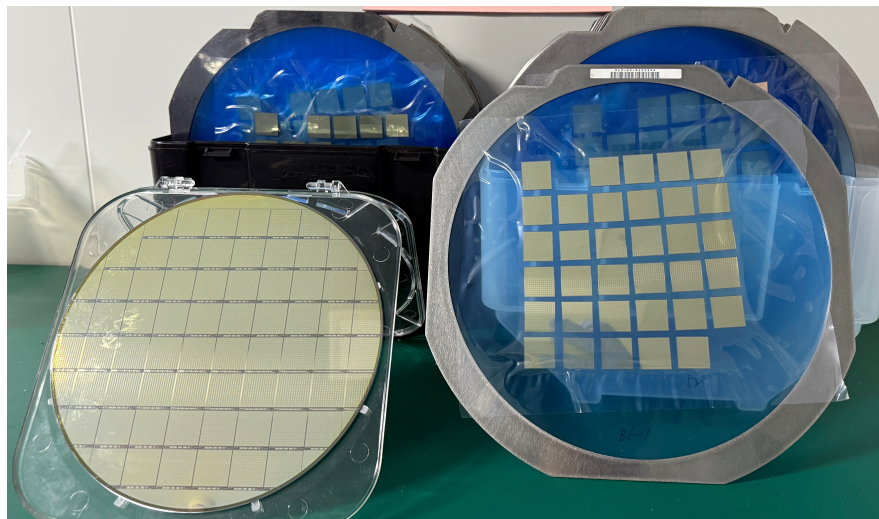
电荷收集 vs 偏置电压



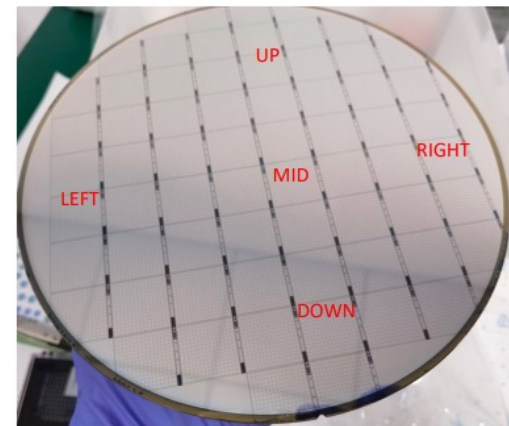
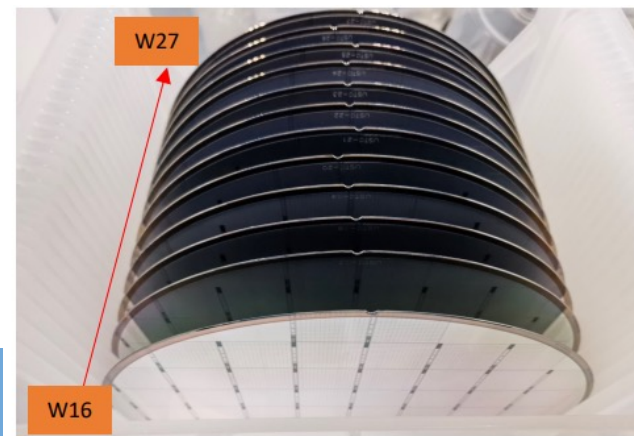
LGAD传感器的量产

- 2023年，**高能所-微电子**所赢得CERN的招标订单。今年初签订正式合同
 - 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**
- 各单位在该项目LGAD传感器的贡献比重，总共需要2.1万个传感器
 - 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

高能所-微电子所LGAD量产晶圆



中科大-微电子所LGAD预生产

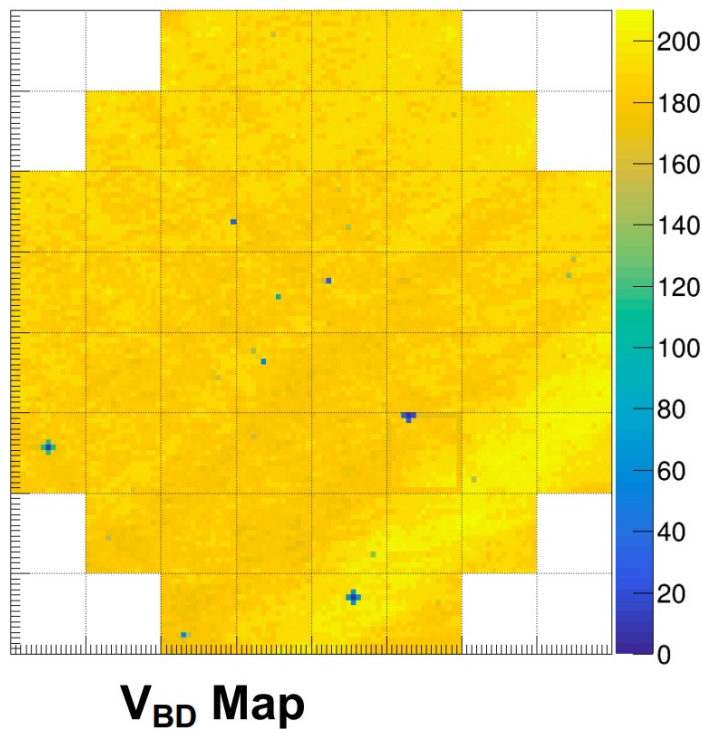
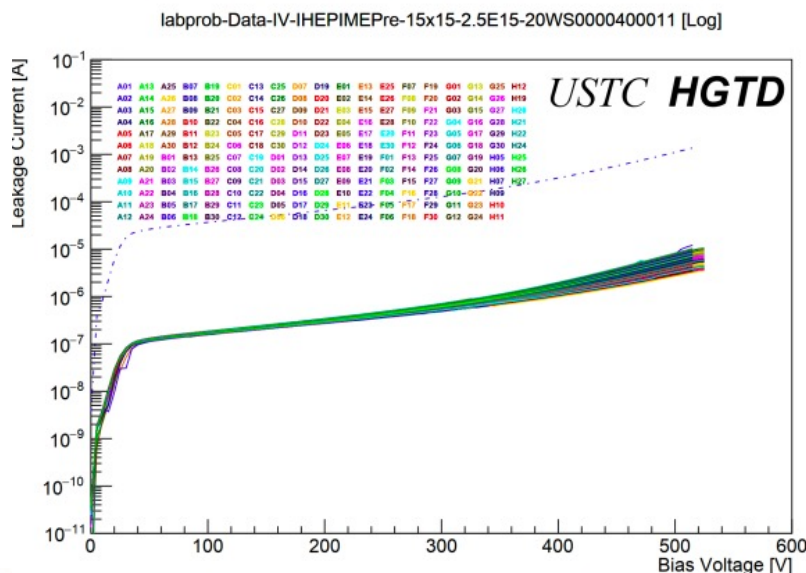


LGAD传感器的预量产

- 高能所与中科大分别已经完成1702个与208个LGAD，接近总量~10%
- LGAD传感器有225个像素，辐照前后的漏电流与击穿电压都非常均匀
- 辐照前后，时间分辨率都可以达到30~40皮秒

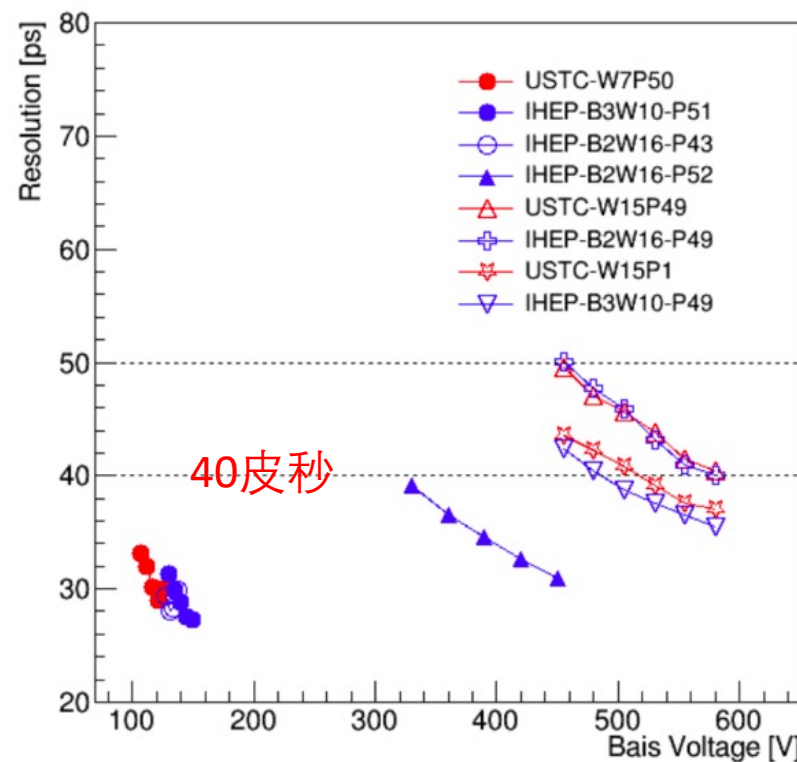
辐照后LGAD的漏电流与击穿电压

20WS0000400011@2.5E15 n_{eq}/cm²



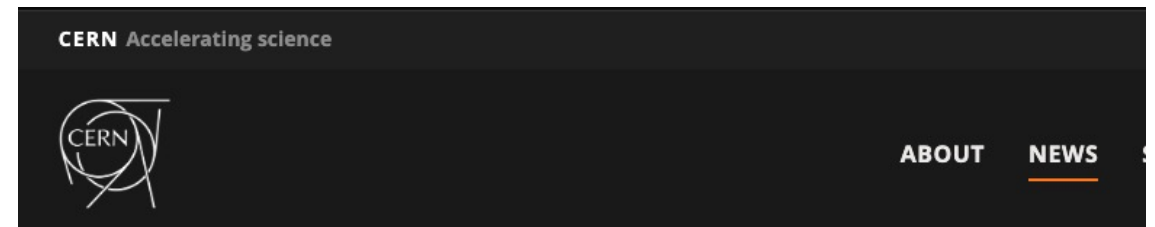
辐照后LGAD的时间分辨率

Time Resolution - HGTD TB June 2024



ATLAS 杰出贡献奖 (Outstanding Achievement Award)

- 3名高能所成员与1名科大成员获得2025年ATLAS实验杰出贡献奖
 - 由于他们在LGAD传感器研发的贡献
 - The list of ATLAS award for HGTD project: Bojan Hiti (Ljubljana), Alissa Howard (Ljubljana), Xuewei Jia (Munich MPI), **Mengzhao Li (Beijing IHEP)**, Chihao Li (Michigan), **Kuo Ma (Hefei)**, Theodoros Manoussos (CERN), **Weiyi Sun (Beijing IHEP)**, Guilherme Tomio Saito (Sao Paulo), Iskra Velkovska (Ljubljana), Xiao Yang (CERN), **Mei Zhao (Beijing IHEP)**



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Celebrating the outstanding achievements of the ATLAS collaboration

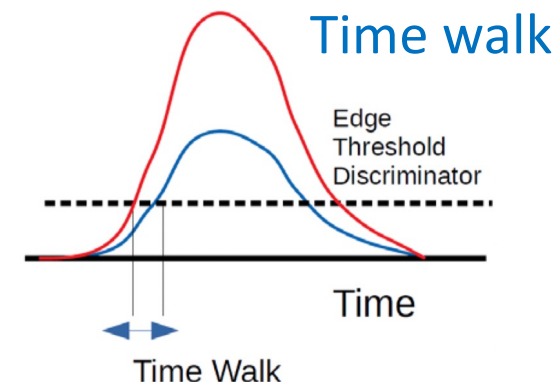
The ATLAS collaboration celebrated the dedication, ingenuity and collaborative spirit of its members at the 8th Outstanding Achievement Awards

8 JULY, 2025 | By [ATLAS collaboration](#)

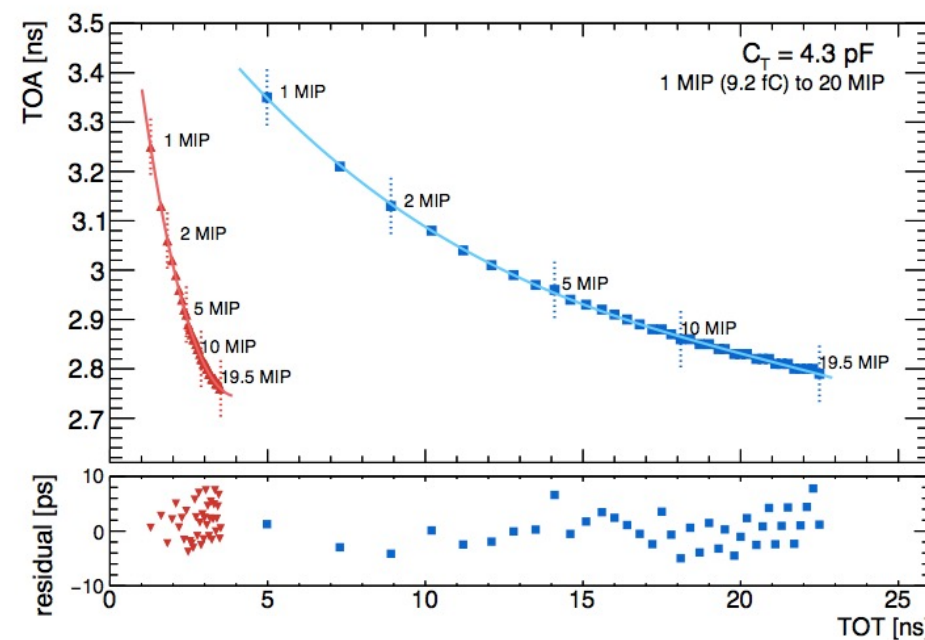
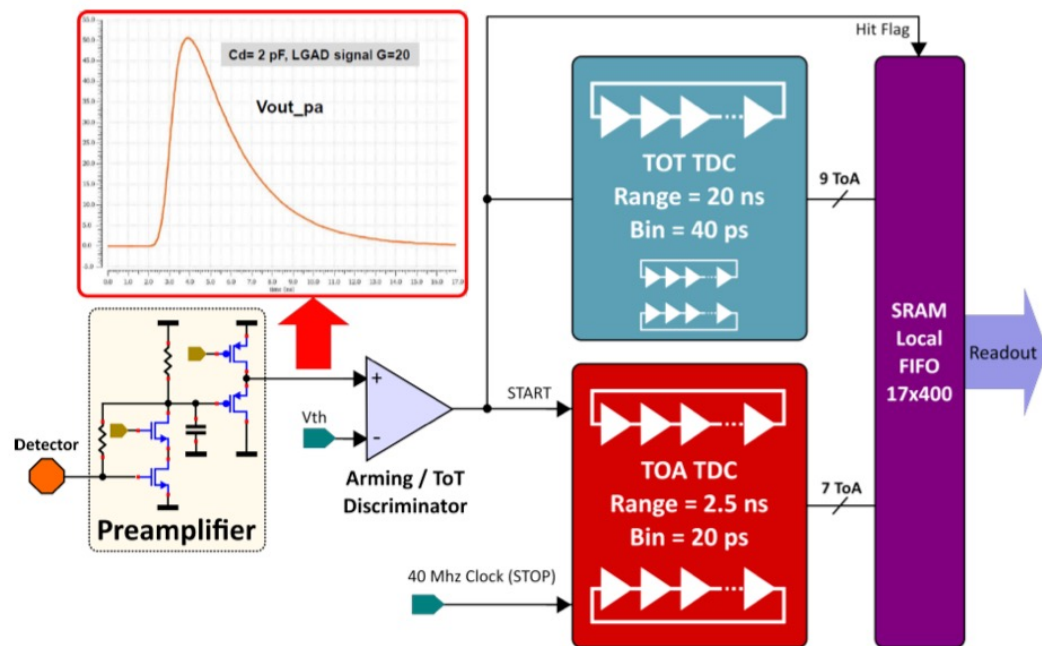
ALTIROC : 超快读出ASIC



- 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:
 - 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)



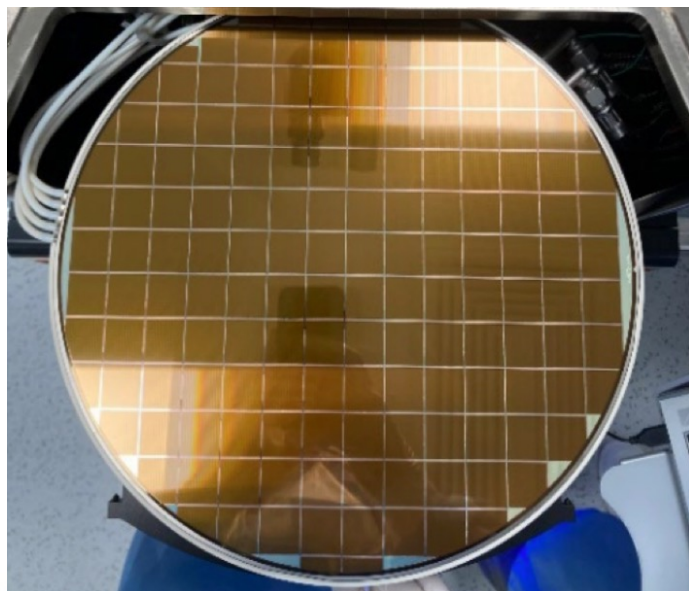
ALTIROC 芯片原理图



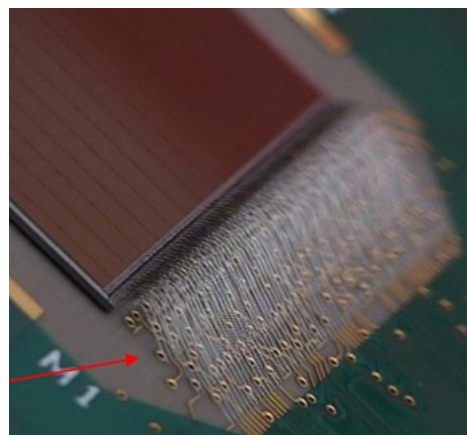
ALTIROC 超快读出芯片的晶圆级测试

- 中国组与法国IJClab各承担50%的超快ASIC晶圆测试任务
- 高能所完成了晶圆级测试的平台，是皮秒级芯片测试任务，有很大挑战
- 高能所，上海、山大已经完成预量产ALTIROC晶圆的晶圆测试任务，并通过CERN的评审
 - 已经测试了超过14个晶圆（~2000个ASIC芯片）
 - 测试进度大幅度领先于法国单位。ATLAS决定把100%测试任务放到中国。

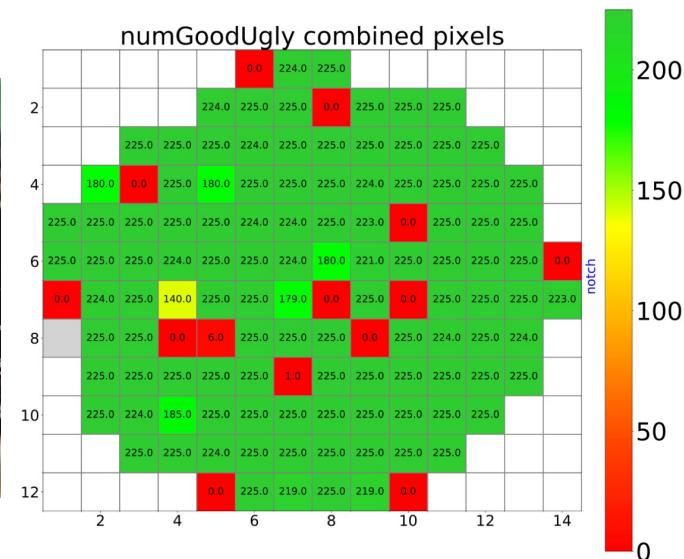
ALTIROC-A wafer



ASIC chip testing in test board

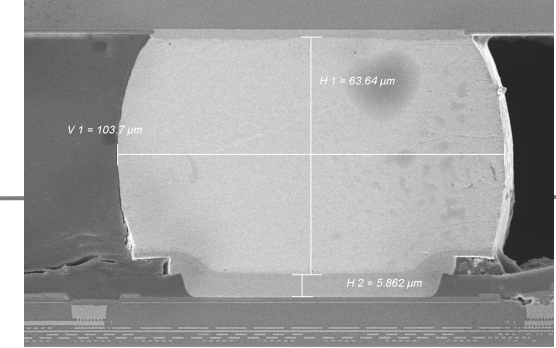


ASIC wafer test result

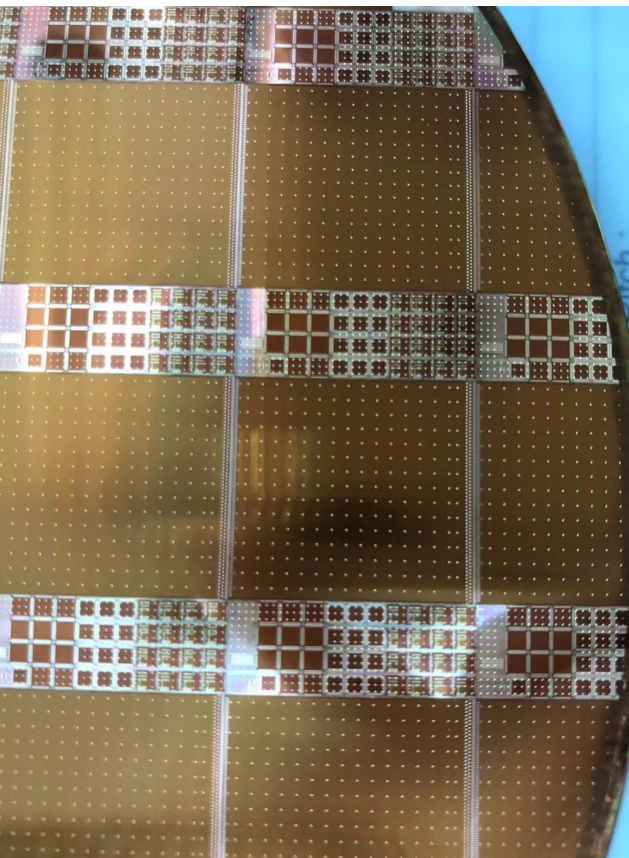


探测器模块：倒装焊封装

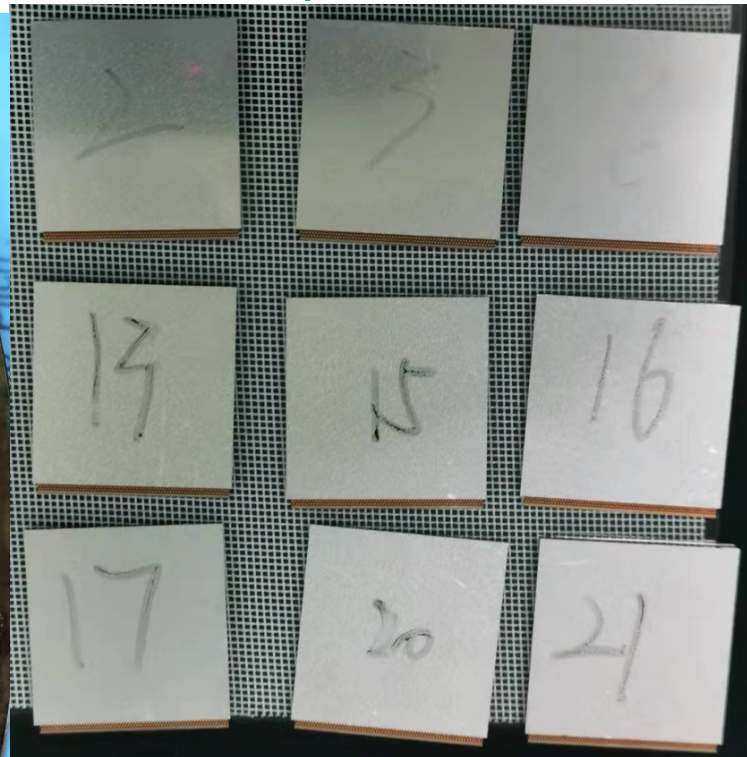
- 高能所承担项目中**50%的**倒装焊封装任务
- 高能所在国内已经研制出100多个倒装焊模块



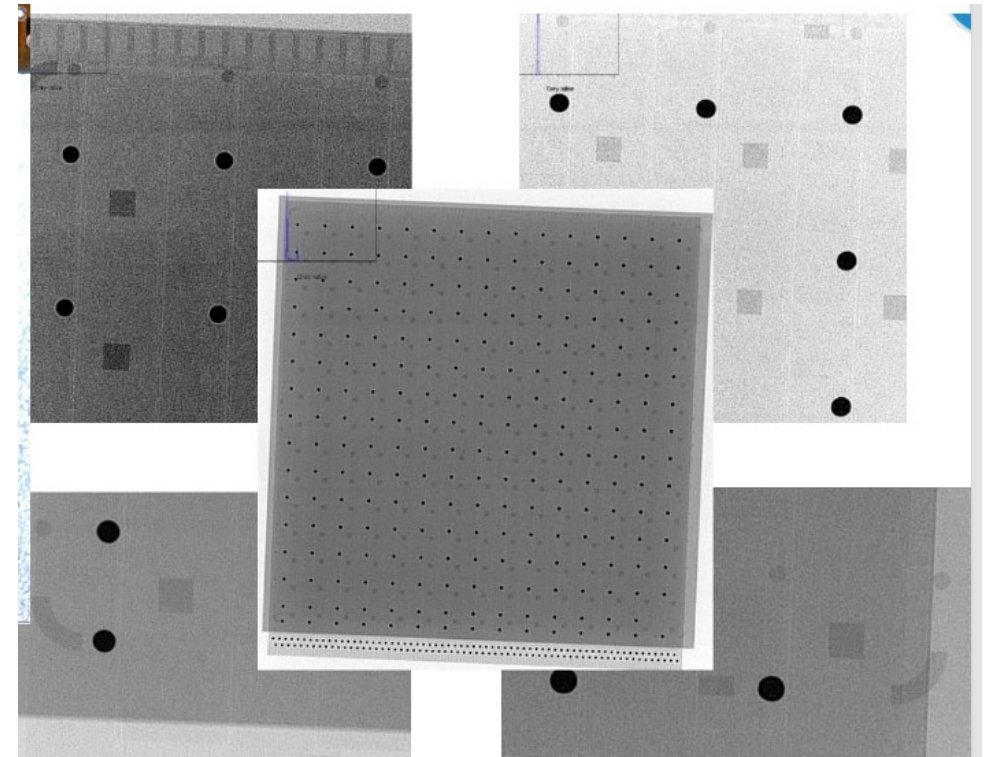
ALTIROC 芯片晶圆植球



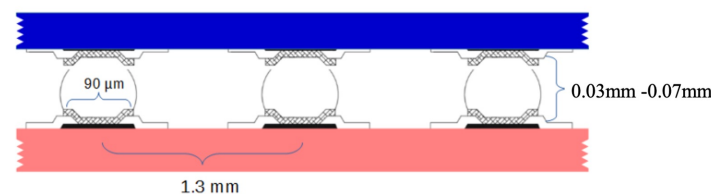
倒装焊模块后的模块



X-ray image of full-size hybrid

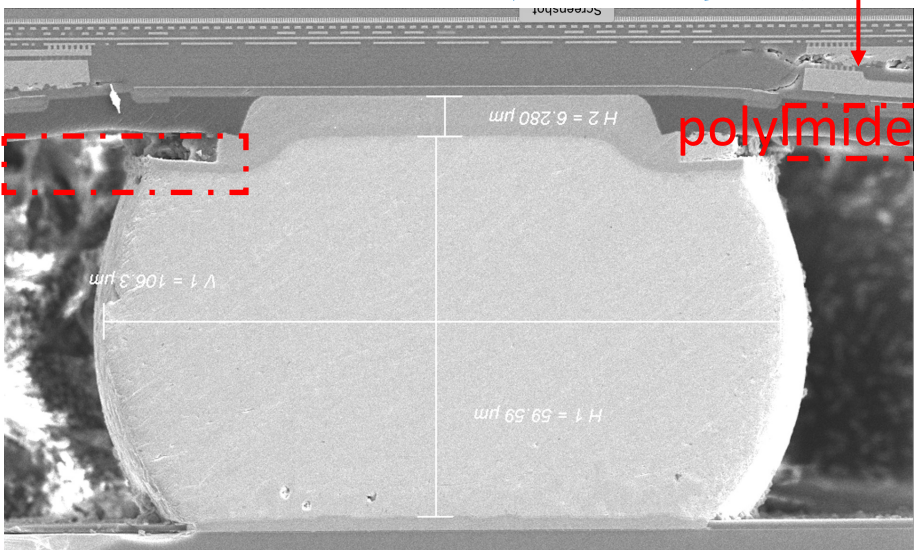


传感器与ASIC的倒装焊封装

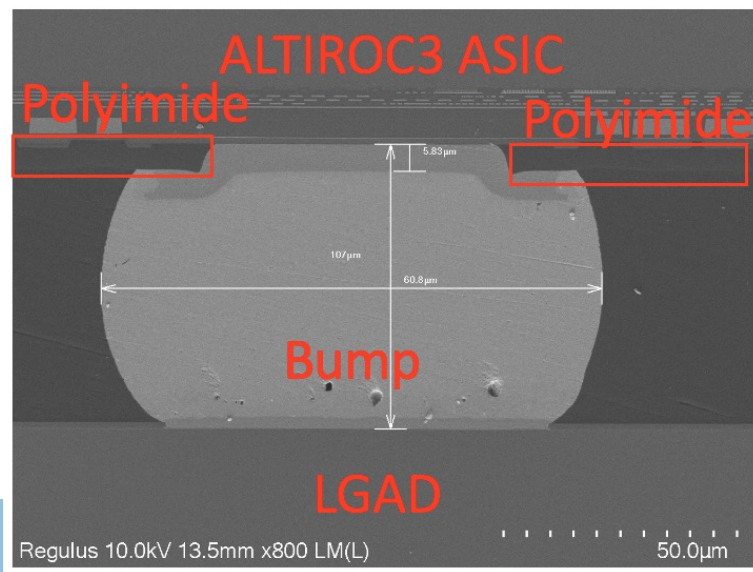


- 2023年末，HGTD项目遇到探测器模块的倒装焊热稳定性问题
 - 45度到40度热循环后，倒装焊脱落，ITK Pixel项目发现该问题，推迟LHC升级项目两年
 - HGTD探测器中，ASIC晶圆中台积电的polyimide保护层有问题（开窗尺寸与材质）
- 高能所攻关解决了HGTD探测器中的封装问题，通过CERN的评审
 - 用了更软的保护层材料吸收应力，使用更厚的LGAD传感器

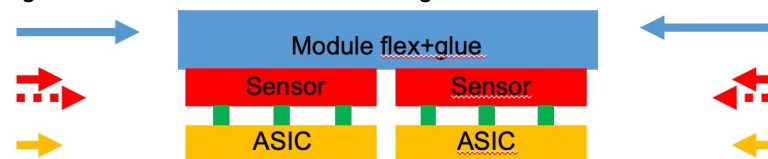
旧倒装焊 热循环后，应力导致芯片的开裂



新倒装焊

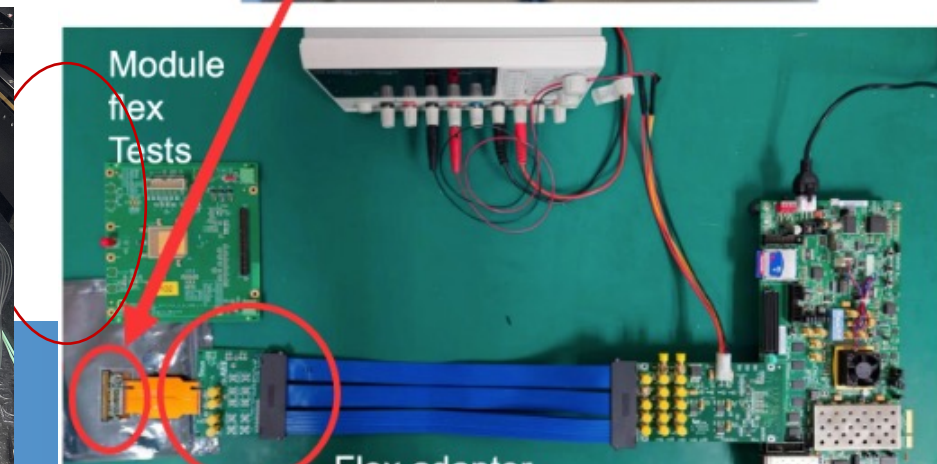
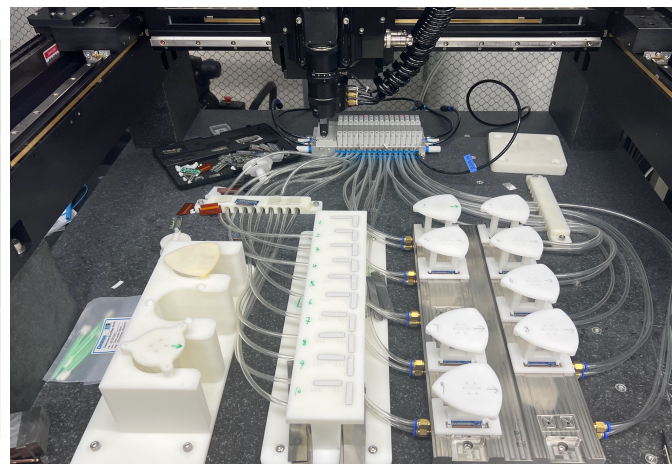
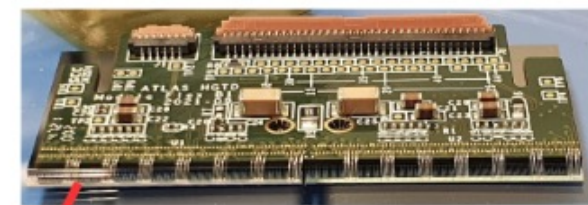
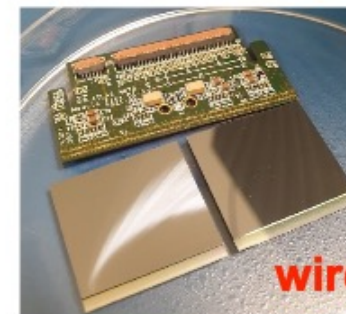
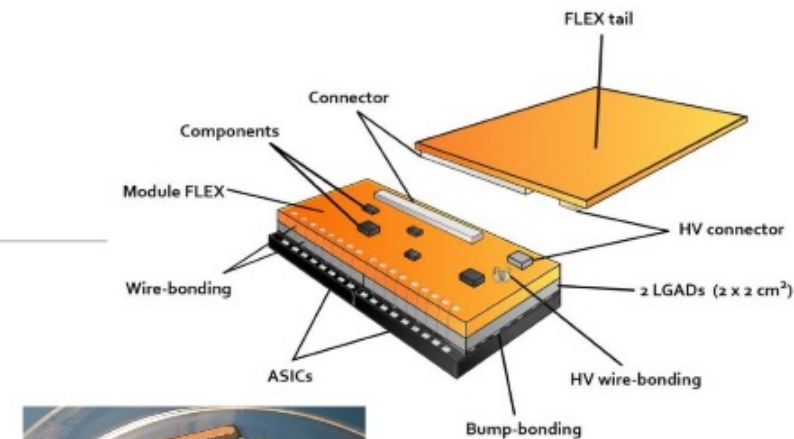


Consider low temperature (shrinking) situation
Length of arrow means deformation magnitude



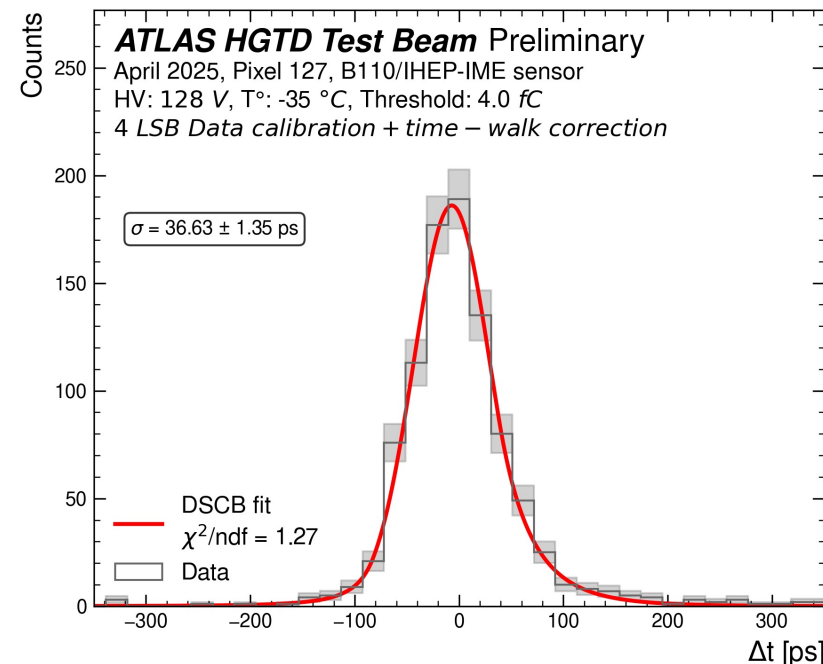
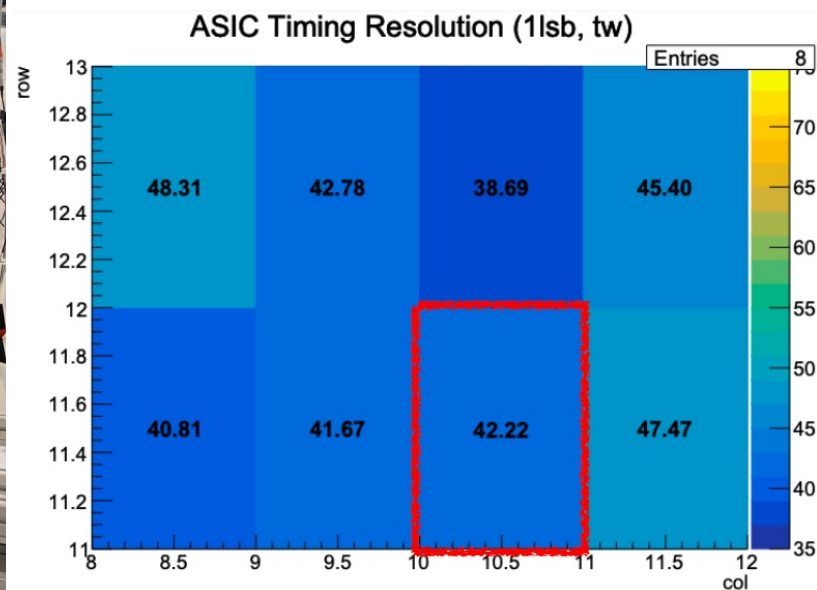
ATLAS时间探测器模块组装

- HGTD项目总共需要8032个模块 (6.4平方米)
- 5个模块组装生产中心
 - 中国, 德国, 法国, 西班牙, 摩洛哥
 - 中国组是最大的生产中心, 组装**44%**的模块
 - 高能所、科大、山大、上交、南开将合作完成
- 高能所、科大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



探测器模块的束流测试

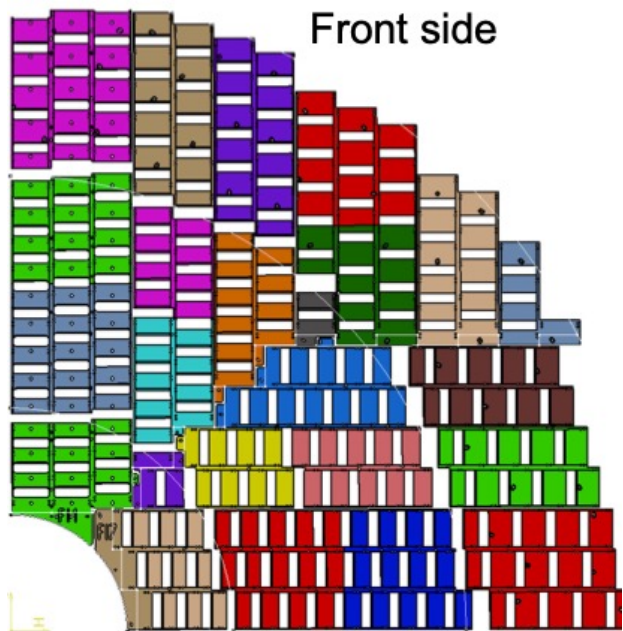
- HGTD的模块在CERN和DESY束流测试
 - 探测器模块是15*15像素阵列，225通道
 - 模块级别，每个像素的时间分辨达到~40皮秒
 - 未来几年，将会有超过3百万通道的HGTD探测器系统



HGTD探测器单元

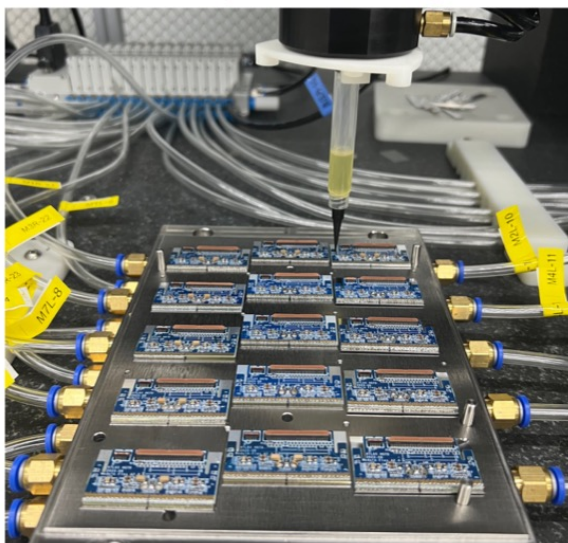
- 高能所研制项目首批两个ALTIROC3大面积探测器单元
 - 每个探测器单元有15个模块，约~500平方厘米面积。
- 高能所与科大合作，在大面积龙门机器人上做探测器单元量产的准备

Front side

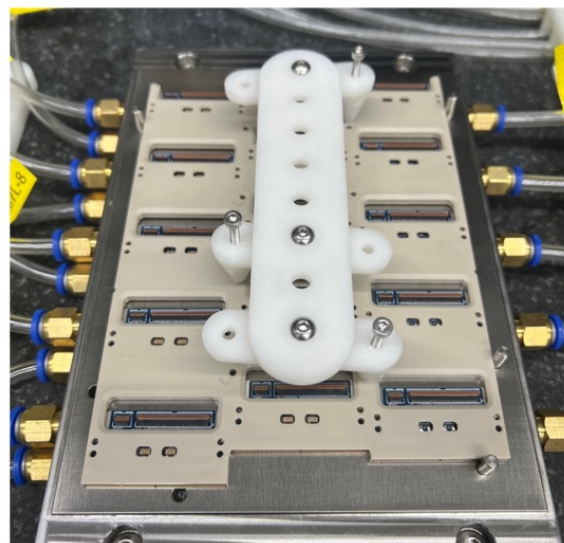


自动定位与点胶

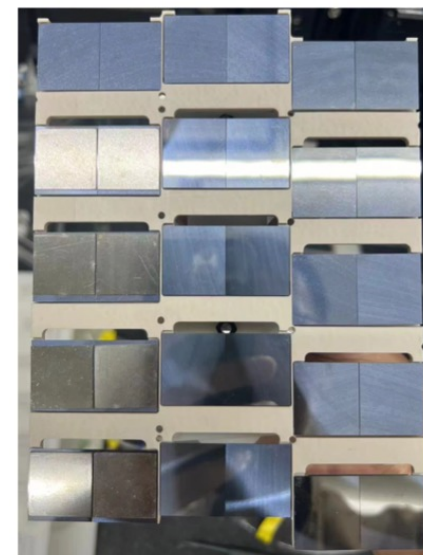
Dispensing with Gluing Tool



Put the support unit

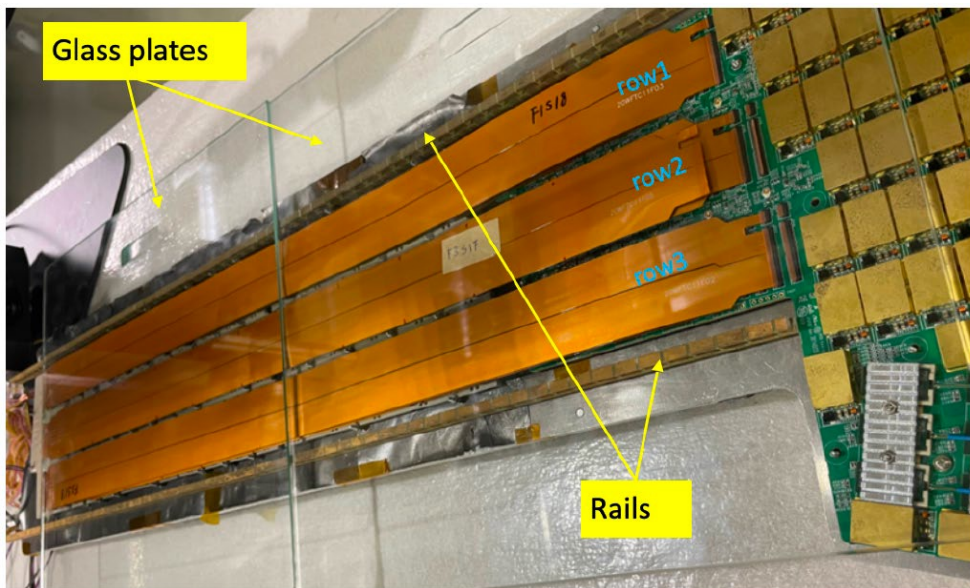
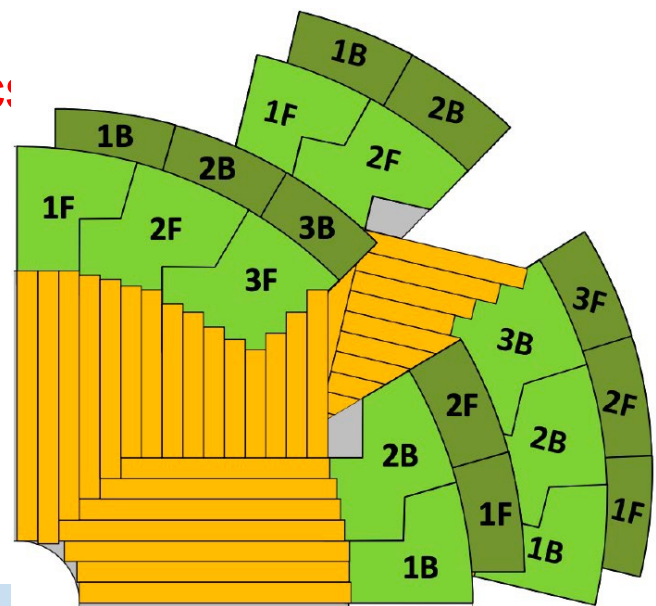
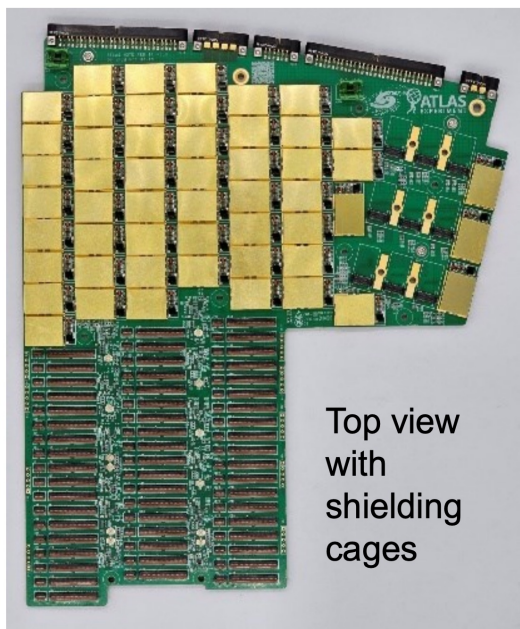


Backside view after removal



外围电路板

- 高能所与南大合作设计出HGTD项目首个外围电路板
 - 同时与55个模块通讯，二十多层金属层，52个电源，12个IpGBT模块
 - ❑ CERN P2UG 评委认可这个板子的研发难度非常大
 - ❑ It is comparable with the most difficult boards manufactured for HEP projects
- 山大研发柔性电缆，解决阻抗匹配、高速传输等问题，满足实验上厚度要求



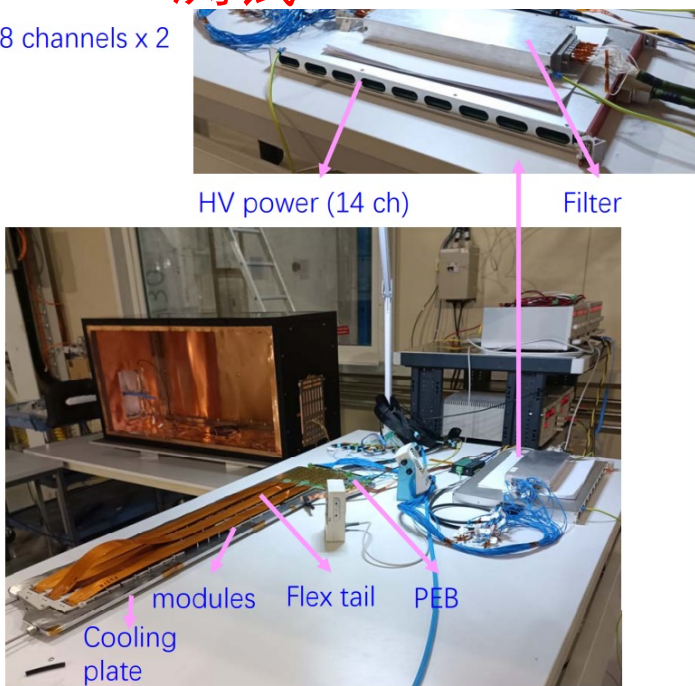
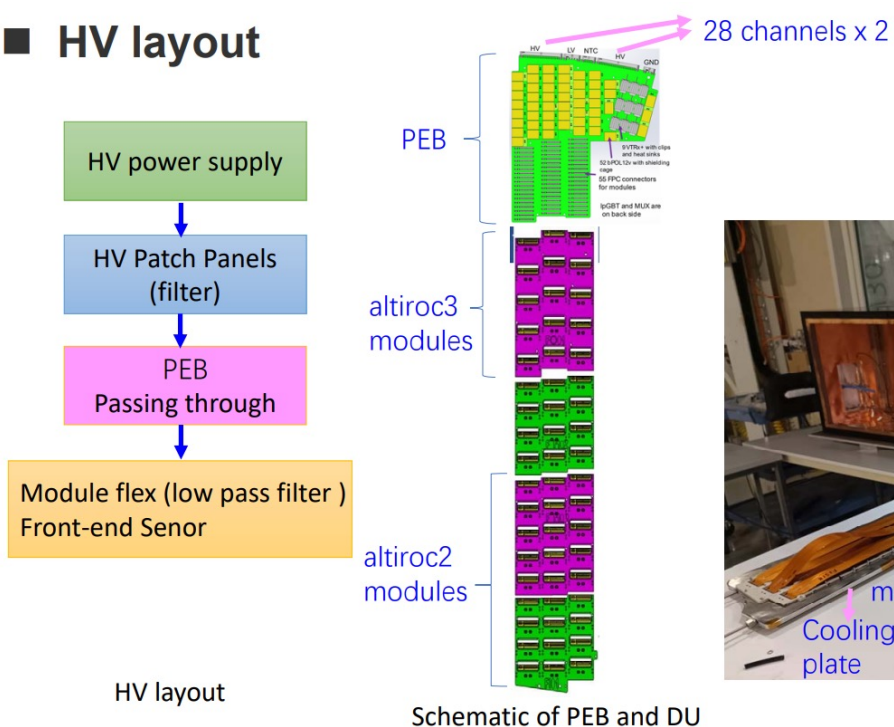
高压电源

- 高能所、山大承担18%的高压电源研制任务
 - 与国内福德公司研发出高压系统样机，实现高精度100nA的漏电流测量
 - 通过CERN的评审，开始预量产
 - 山大承担了在CERN的量产电源测试任务

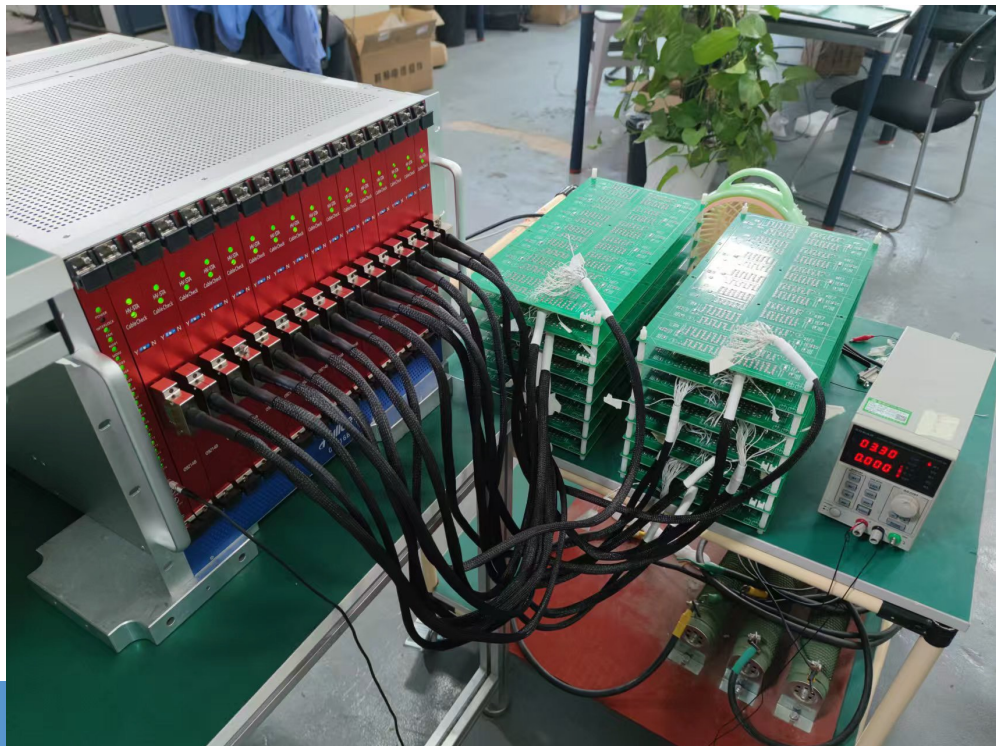
高压电源样机预量产

高压电源样机在CERN测试

■ HV layout

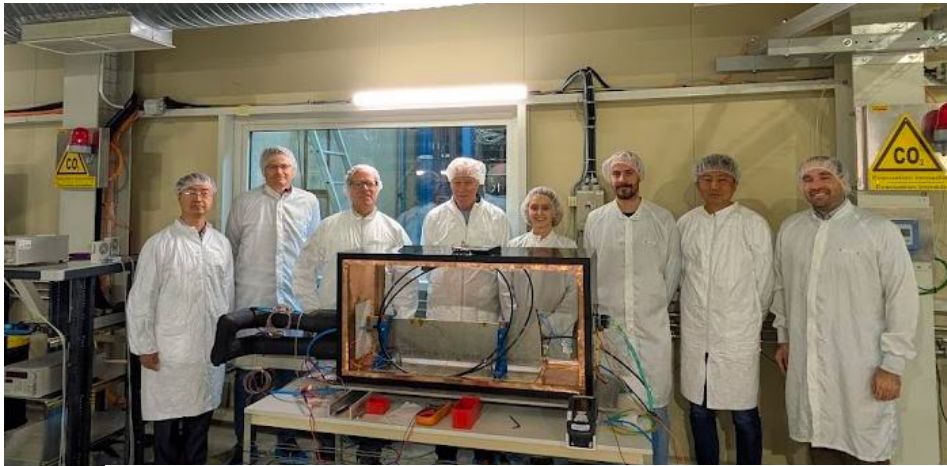


Demonstrator at CERN

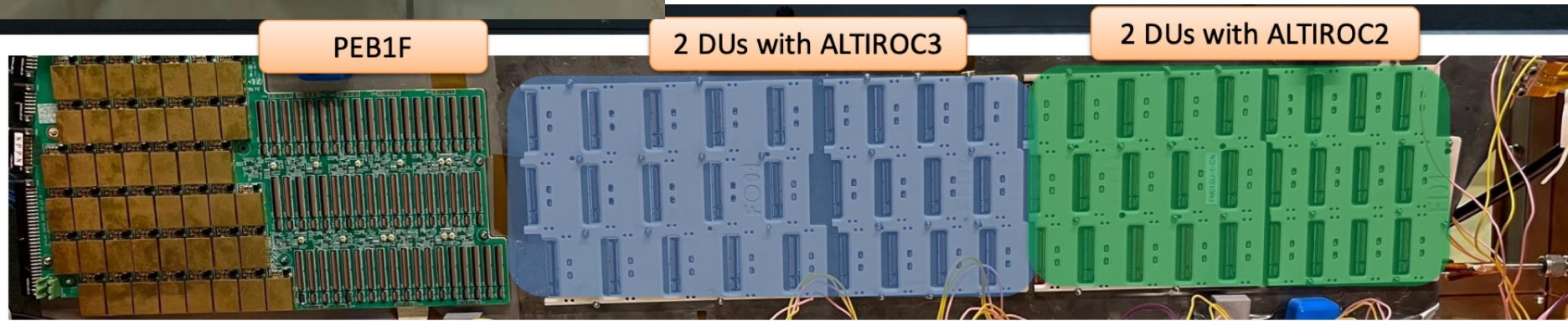
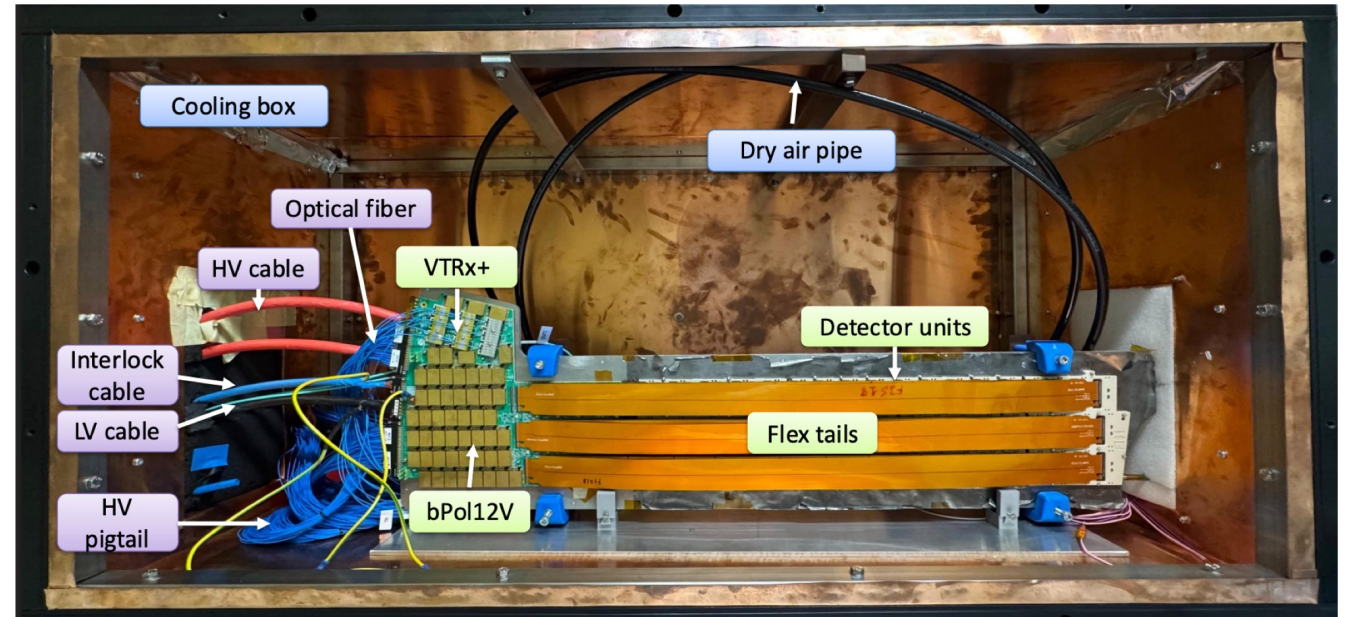


HGTD探测器大型样机

- 中国组在研制54模块的大型样机研发起主要作用
 - 首次验证数十个模块，上万个通道的高时间分辨探测器系统

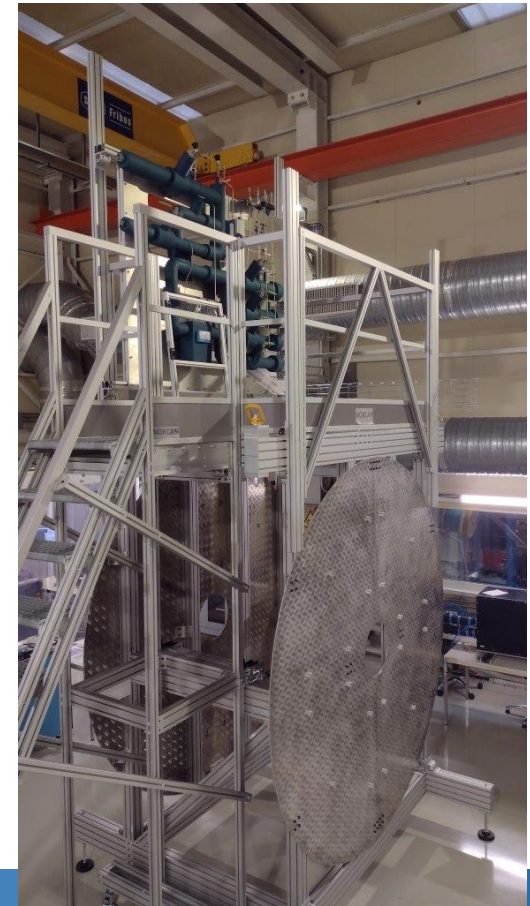
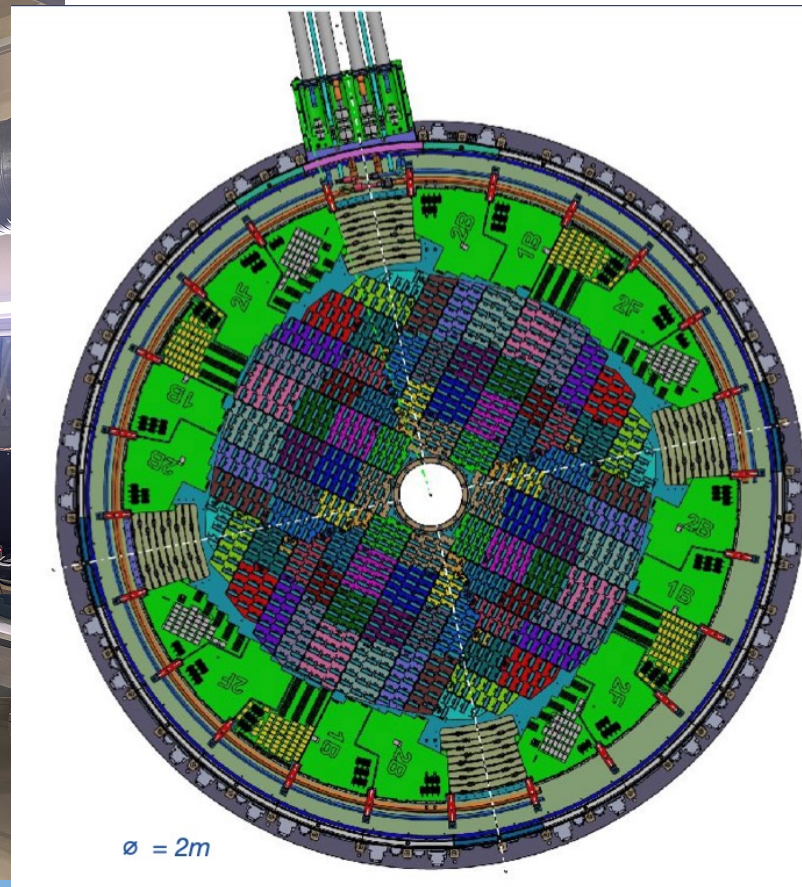
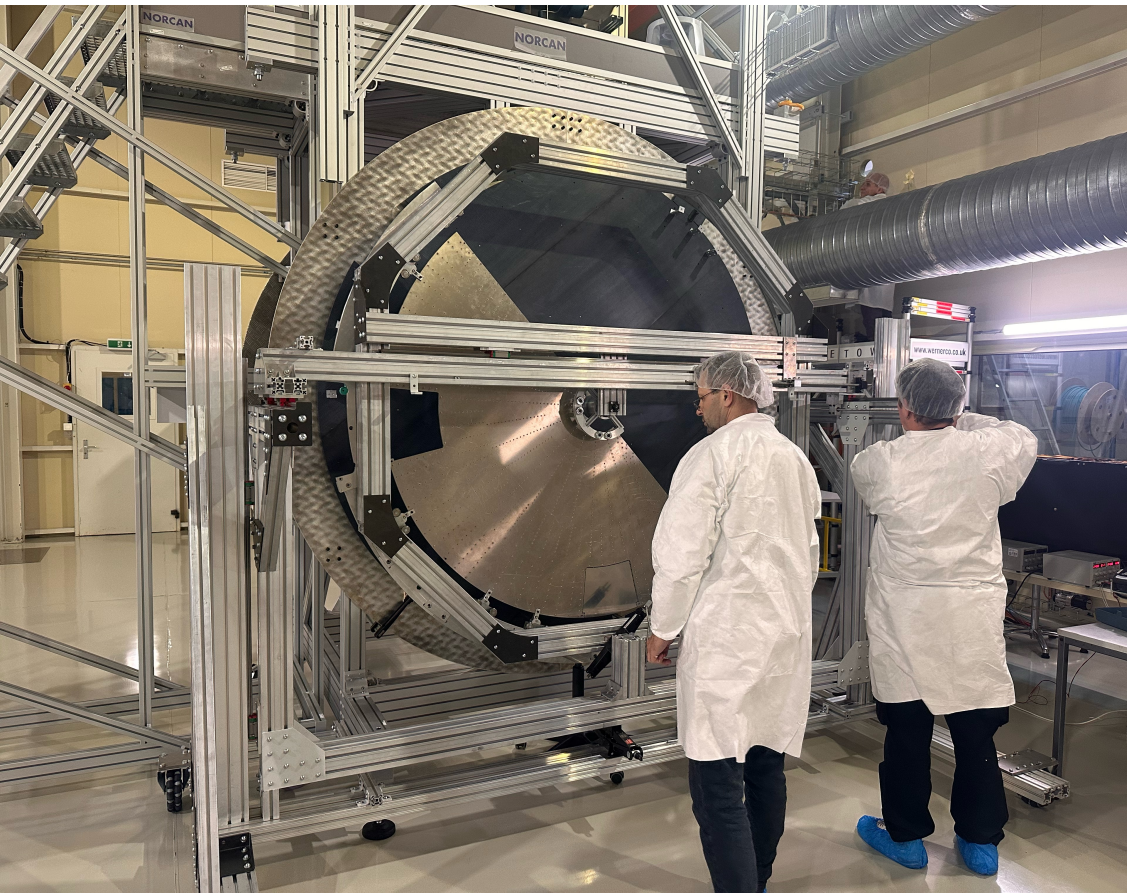


2025 ATLAS探测器升级的评审会
项目组与评委合照



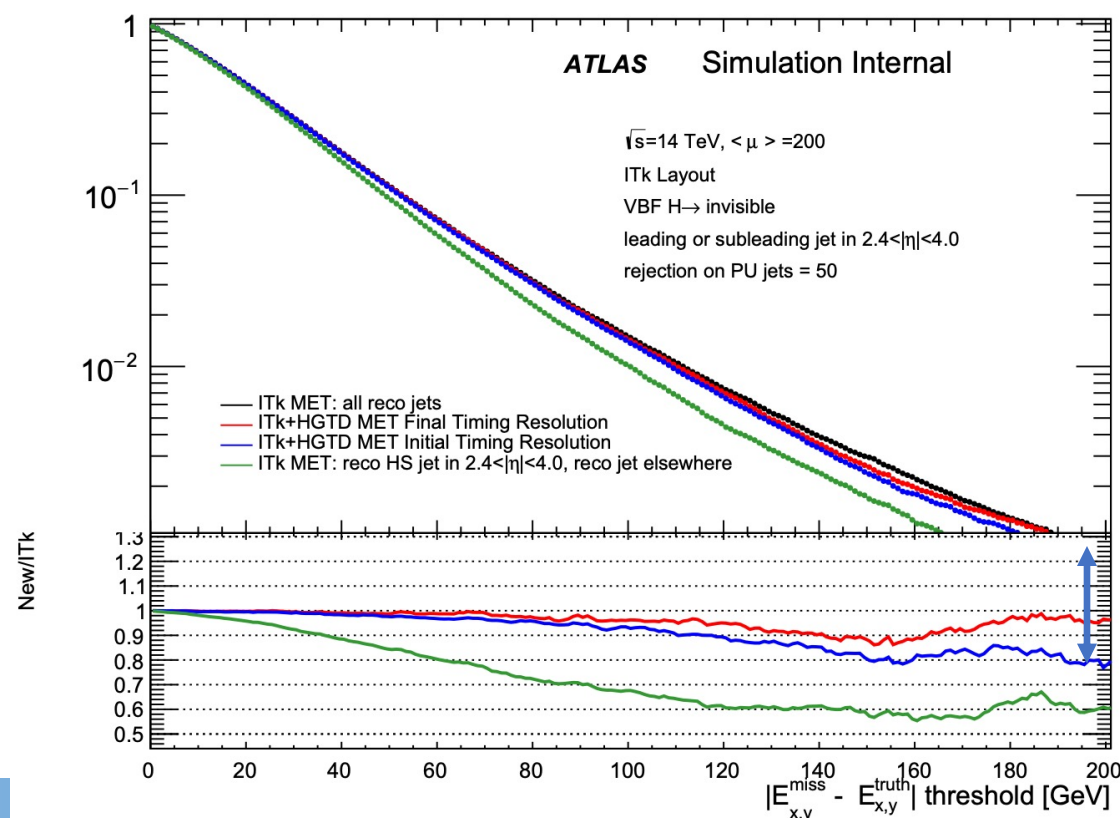
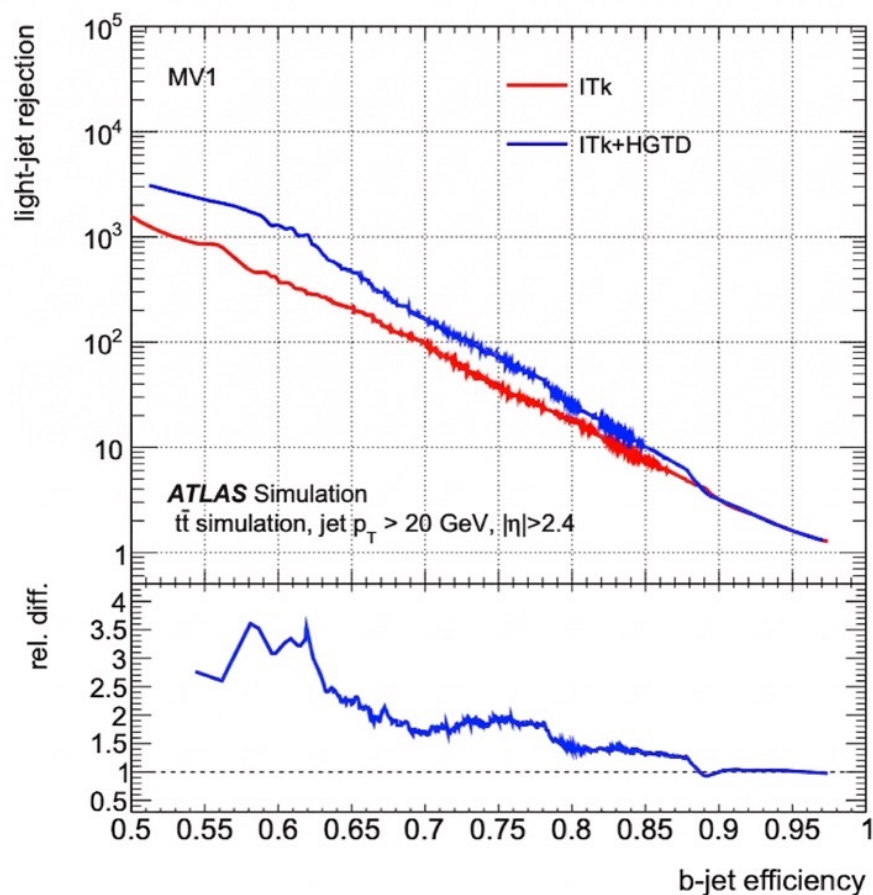
HGTD探测器总体组装

- 未来3-4年，HGTD探测器将完成量产与总体组装。
- 整体探测器安装的工装与二氧化碳冷却系统完成试制



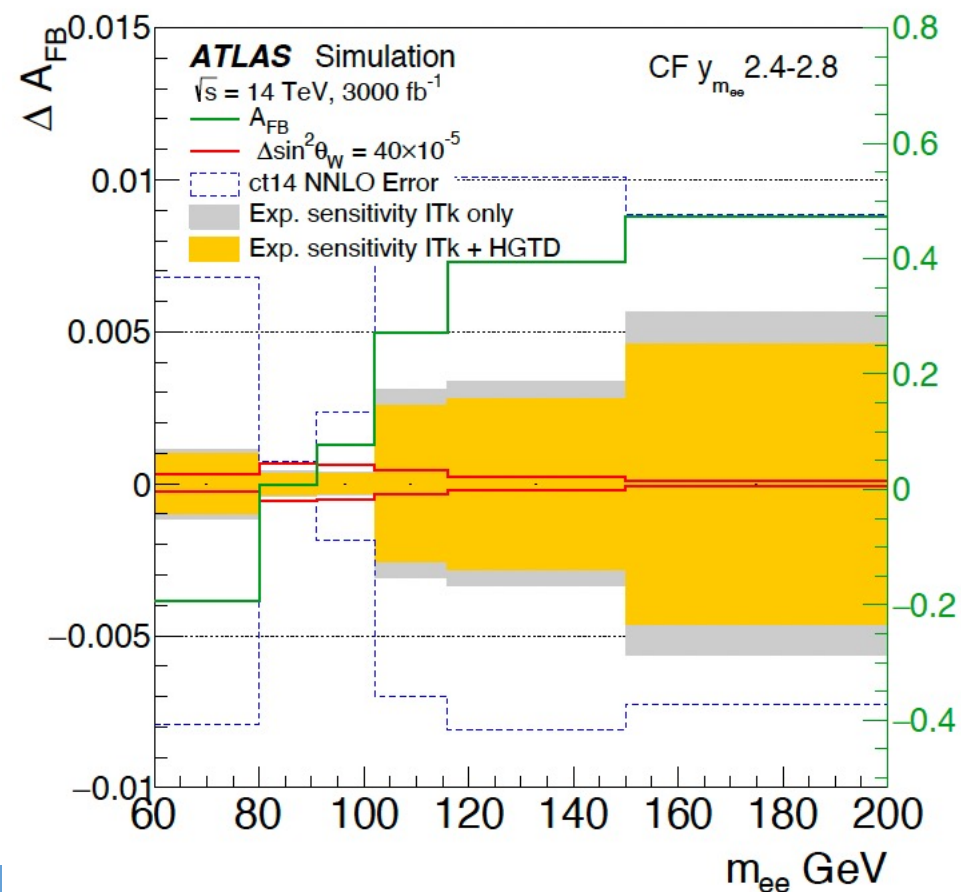
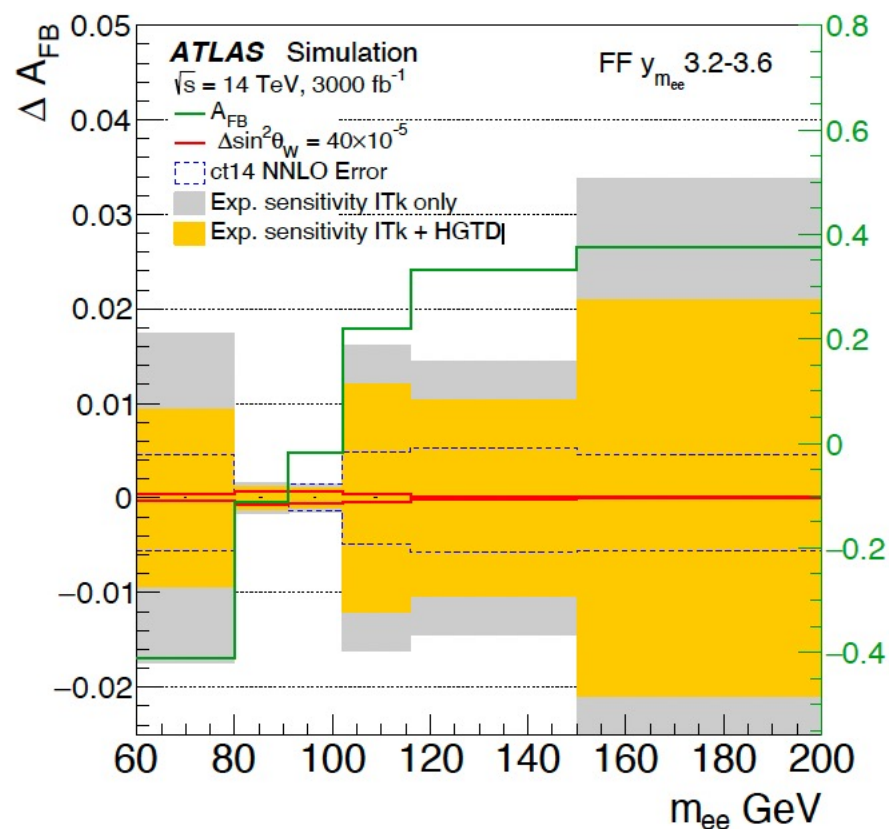
HGTD探测器预期物理性能

- Significant Pileup suppression in VBF jet
- Improve forward b jet tagging performance, Missing ET performance
- Expect **20-30%** improvement in VBF Higgs analysis



HGTD探测器预期物理性能

- Significant improvement in Z AFB and weak mixing angle analysis
 - Both in forward-forward and central forward category

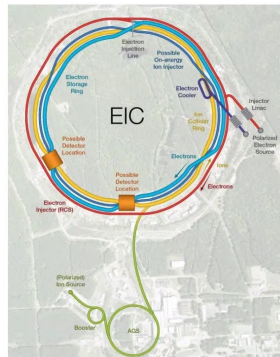


小结: ATLAS实验高颗粒度时间探测器

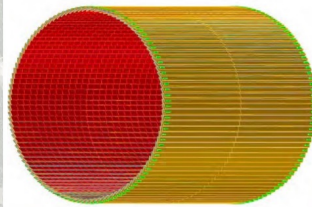
- 中国组在项目中占**主导地位**，担任等**项目经理**等多个领导职务。
- LGAD传感器，共需要2.1万个传感器，目前已经研制约2000个：
 - **高能所-微电子所赢得欧洲核子中心（CERN）国际招标**
 - 高能所将提供**90%**的LGAD，科大将提供**10%**的LGAD
- ASIC：高能所、上交大、山大将承担**50%**晶圆测试
- 探测器模块：中国组将组装~4000个模块，**占项目45%**
- 外围电路与电源：
 - 高能所、南大研制了首个外围电路板样机，山大研制柔性电缆
 - 高压电源：高能所、山大承担**18%**的高压电源，已经研制出样机

未来发展：LGAD探测器的未来应用

Electron-Ion Collider (EIC) : Timing-tracker

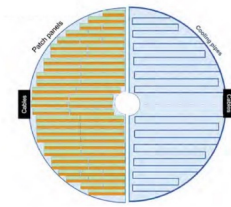


Barrel AC-LGAD detector



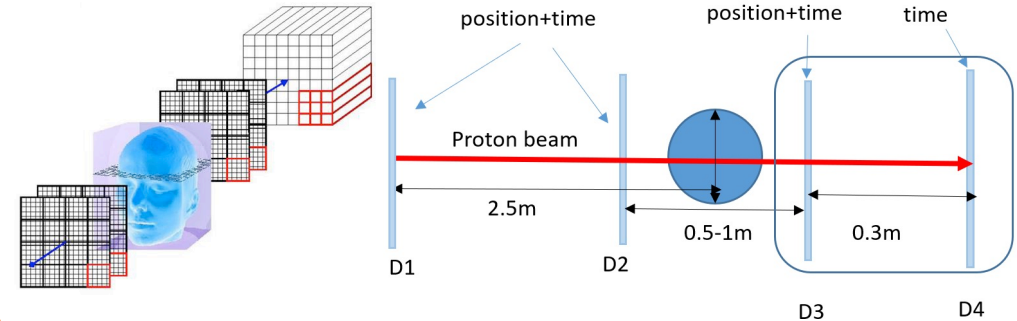
10.9 m²

Hadron endcap AC-LGAD detector

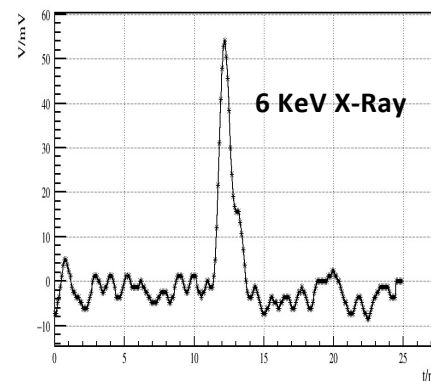


2.22 m²

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
- ...

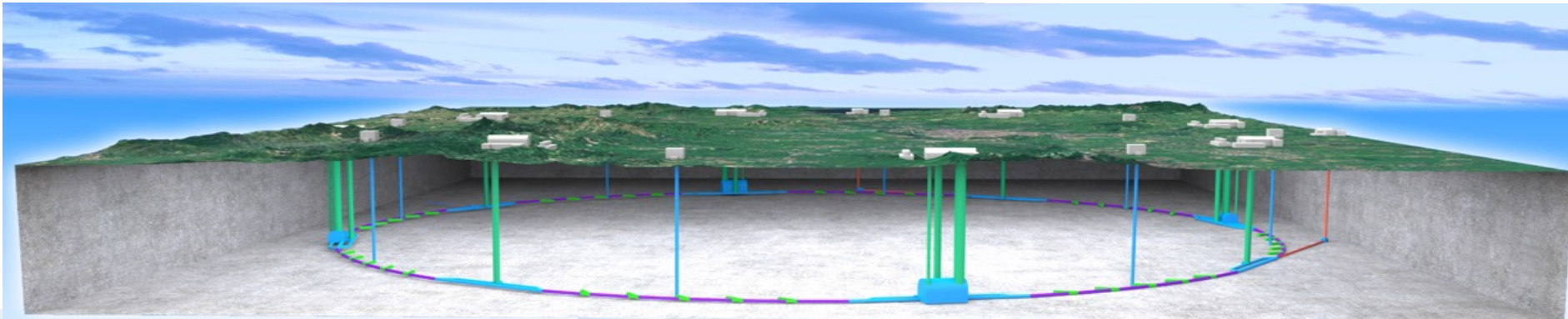
Outline

- 大型强子对撞机ATLAS实验高颗粒度时间探测器
- CEPC的物理与硅探测器研发

Circular Electron Positron Collider (CEPC)

- 2012年希格斯粒子发现后，中国科学家提出粒子物理发展路线：CEPC
 - 100公里周长的双环正负电子对撞机
- 240GeV：大量产生希格斯粒子(4×10^6 个)
- 在90GeV：产生Z玻色子($> 4 \times 10^{12}$ 个)
- 在160GeV：产生W玻色子($\sim 10^8$ 个)
- 360GeV: ttbar threshold

CEPC Operation mode		ZH	Z	W ⁺ W ⁻	ttbar
$\sqrt{s}$ [GeV]		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	-
CDR (30MW)	L / IP [$\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	3	32	10	-
	$\int L dt$ [ab^{-1} , 2 IPs]	5.6	16	2.6	-
	Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	-
Run time [years]		10	2	1	5
Latest TDR (50MW)	L / IP [$\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	8.3	191.7	26.6	0.8
	$\int L dt$ [ab^{-1} , 2 IPs]	20	96	7	1
	Event yields [2 IPs]	4×10^6	4×10^{12}	5×10^7	5×10^5

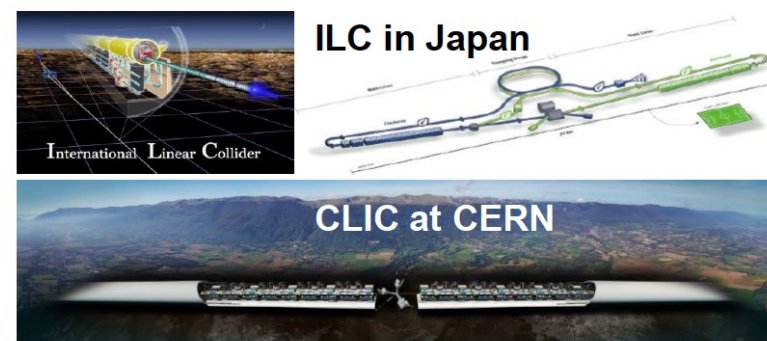
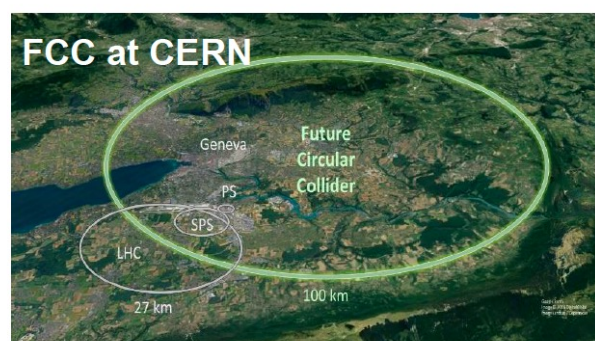


高能正负电子对撞机：希格斯工厂



- ❑ 2013和2016年，香山会议：**CEPC**是我国基于加速器高能物理发展的最佳途径和重大历史机遇
- ❑ 2020年，欧洲粒子物理战略规划：**正负电子希格斯工厂**是优先级最高的下一代对撞机
"An electron-positron Higgs factory is the highest-priority next collider"
- ❑ 2022年，国际未来加速器委员会 ICFA 重申：**希格斯工厂**是实现粒子物理科学目标的最优先任务
"A Higgs factory as the highest priority for realizing the scientific goals of particle physics"

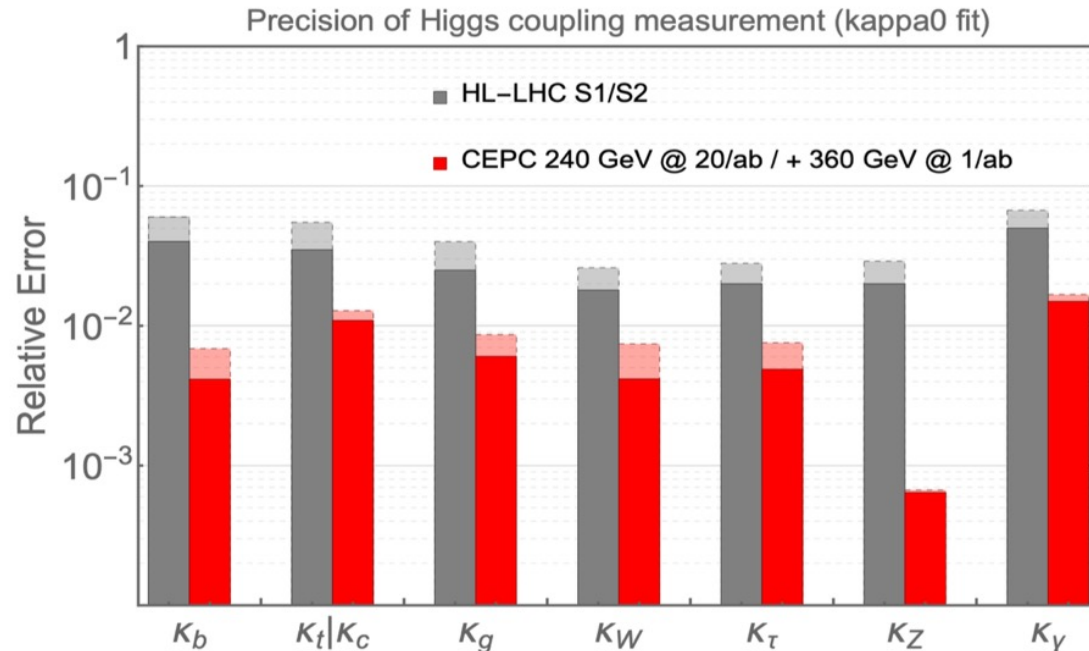
国际共识：正负电子希格斯工厂是优先级最高的下一代对撞机项目



CEPC 物理：希格斯精确测量

❖ CEPC希格斯性质的预期测量精度比CERN的HL-LHC预期精度提升约1个数量级

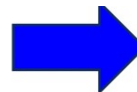
Higgs		
观测量	HL-LHC 预期精度	CEPC 预期精度
M_H	20 MeV	3 MeV
Γ_H	20%	1.7%
$\sigma(ZH)$	4.2 %	0.26%
$B(H \rightarrow bb)$	4.4%	0.14%
$B(H \rightarrow cc)$	-	2.0%
$B(H \rightarrow gg)$	-	0.81%
$B(H \rightarrow WW^*)$	2.8%	0.53%
$B(H \rightarrow ZZ^*)$	2.9%	4.2%
$B(H \rightarrow \tau^+\tau^-)$	2.9%	0.42%
$B(H \rightarrow \gamma\gamma)$	2.6%	3.0%
$B(H \rightarrow \mu^+\mu^-)$	8.2%	6.4%
$B(H \rightarrow Z\gamma)$	20%	8.5%
$B_{upper}(H \rightarrow inv.)$	2.5%	0.07%



《Precision Higgs Physics at CEPC》
Chinese Physics C, 43 (2019) 043002
荣获中国物理学会2020年度最有影响论文奖

CEPC 物理：味物理

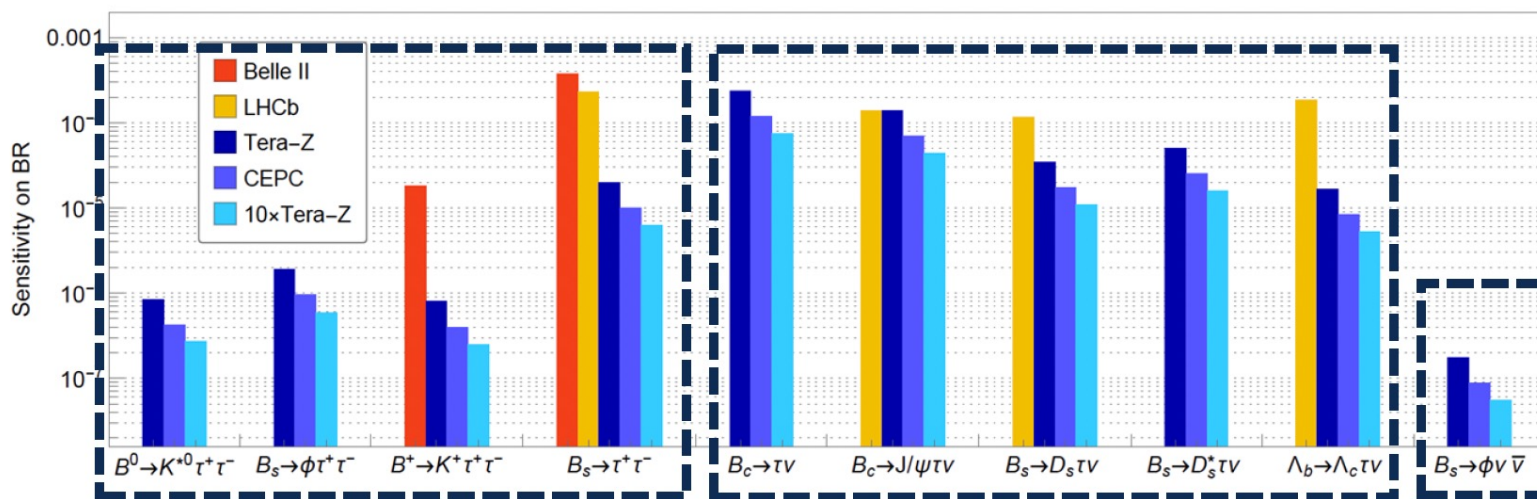
Tera-Z: Z工厂 + 味物理工厂



Mode	LEP bound (95% CL)	LHC bound (95% CL)	CEPC/FCC-ee
$\text{BR}(Z \rightarrow \mu e)$	1.7×10^{-6} [2]	7.5×10^{-7} [3]	$10^{-8} - 10^{-10}$
$\text{BR}(Z \rightarrow \tau e)$	9.8×10^{-6} [2]	5.0×10^{-6} [4, 5]	10^{-9}
$\text{BR}(Z \rightarrow \tau \mu)$	1.2×10^{-5} [6]	6.5×10^{-6} [4, 5]	10^{-9}

b -hadrons	Belle II ($50+5 \text{ ab}^{-1}$)	LHCb (300 fb^{-1})	Tera-Z
$B^0, \bar{B}^0$	5.4×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	1.2×10^{11}
$B^\pm$	5.7×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	1.2×10^{11}
$B_s^0, \bar{B}_s^0$	6.0×10^8 (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	3.1×10^{10}
$B_c^\pm$	-	1×10^{11}	1.8×10^8
$\Lambda_b^0, \bar{\Lambda}_b^0$	-	2×10^{13}	2.5×10^{10}
$c(\bar{c})$	2.6×10^{11}	$\gtrsim 10^{14}$	2.4×10^{11}
$\tau^\pm$	9×10^{10}	-	7.4×10^{10}

轻子味破坏检验 (LFV)



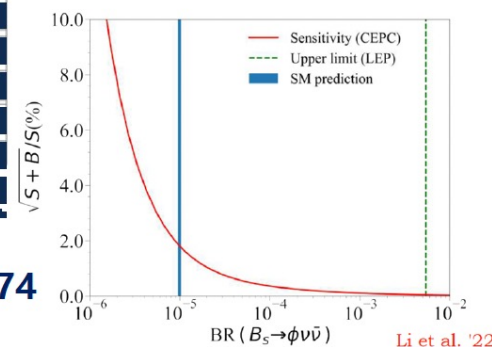
轻子味普适性检验 (LFU)

$B \rightarrow s \tau \tau$ 测量

轻子味普适性检验 (LFU)

$B_c \rightarrow \tau \nu$ 测量

Tera-Z 对 $B_s \rightarrow \phi \nu \bar{\nu}$
分支比的测量在标准模型预期值时达2%的精度，可间接探索反常B物理的影响！



2201.07374

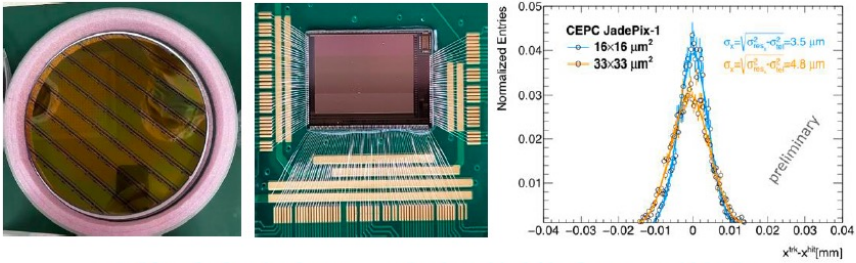
Li et al. '22

CEPC 探测器关键技术

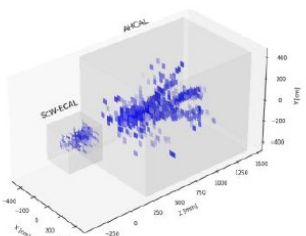
➤ 开展CEPC探测器关键技术预研、样机研制和束流实验分析等，全面覆盖各子探测器系统。

表 3.2：CEPC 各子探测器的关键技术与指标

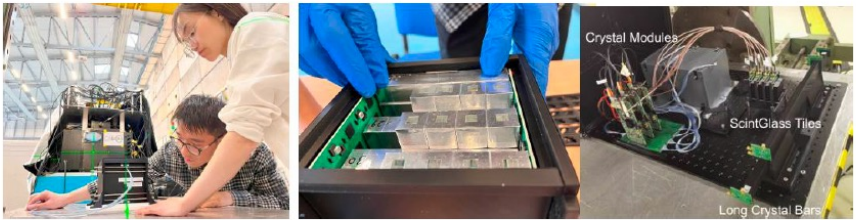
探测器系统	关键技术	关键指标
硅顶点探测器系统	单片集成硅像素芯片 低物质探测器结构	空间分辨率 ~3 微米 物质质量 <0.15% X_0 (每层)
硅径迹探测器系统	大面积硅探测器	粒子动量分辨率 $\sigma(\frac{1}{p_T}) \sim 2 \times 10^{-5} \oplus \frac{1 \times 10^{-3}}{p \sin^{3/2} \vartheta} (\text{GeV}^{-1})$
气体径迹探测器系统	高精度 dE/dx (dN/dx) 的测量	~2%
时间探测器	高时间分辨的硅探测器	时间分辨率 ~30 皮秒
电磁量能器	4D 晶体量能器，高精度的能量与位置测量，支持粒子流重建	电磁能量分辨率 ~ $3\%/\sqrt{E(\text{GeV})}$ 三维等效颗粒度约 $2\text{cm} \times 2\text{cm} \times 2\text{cm}$
磁铁系统	低质量的高温超导磁铁	磁场强度 2-3 T 磁体径向厚度 < 150 毫米 物质质量 <1.5 X_0
强子量能器	基于闪烁玻璃的高精度强子量能器	单强子能量分辨率 ~ $40\%/\sqrt{E(\text{GeV})}$ 支持粒子流喷注分辨率 ~ $30\%/\sqrt{E(\text{GeV})}$



硅像素探测器，空间分辨率3-5微米



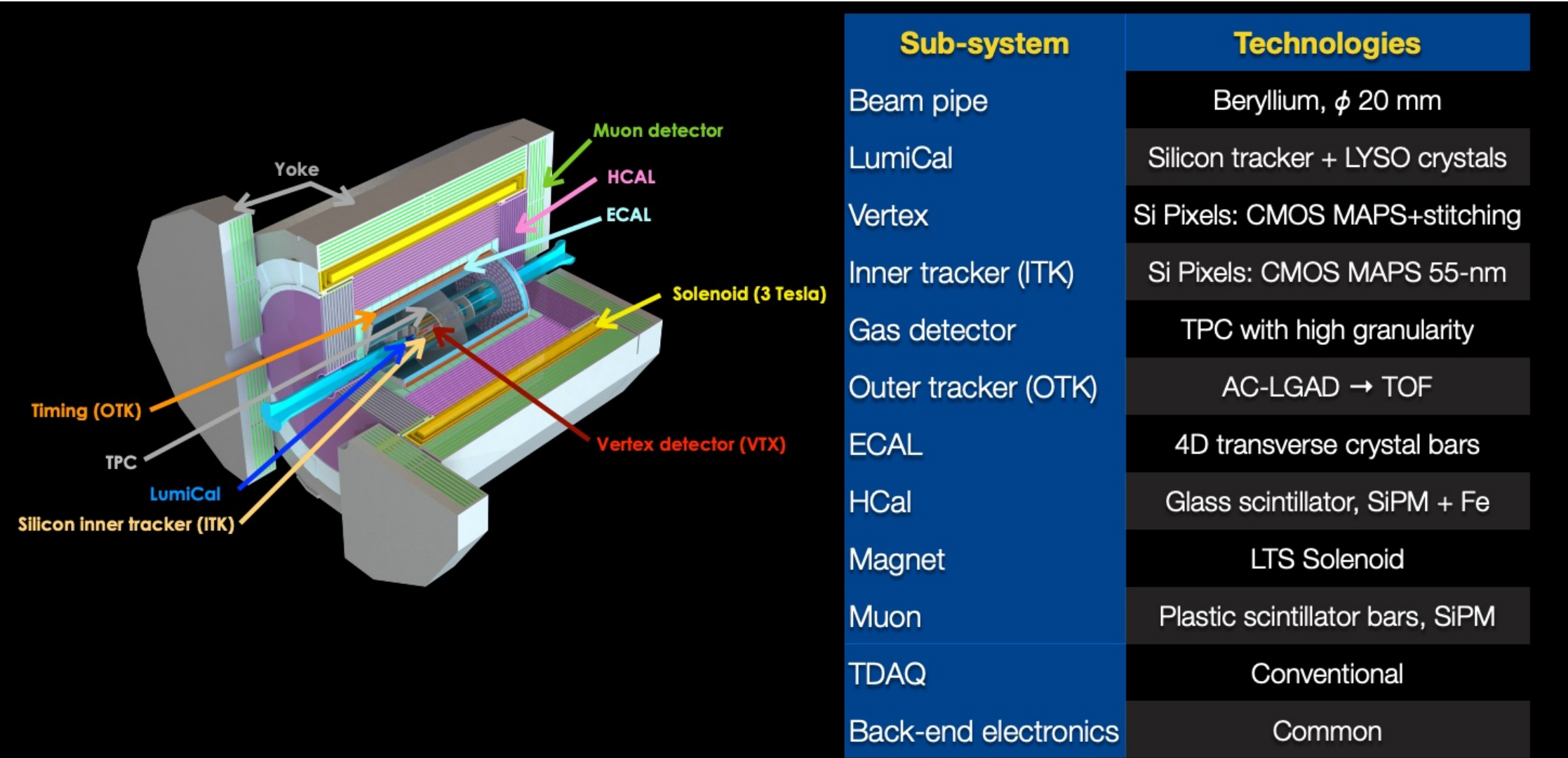
基于粒子流算法的电磁和强子量能器样机



晶体量能器样机和闪烁玻璃束流实验

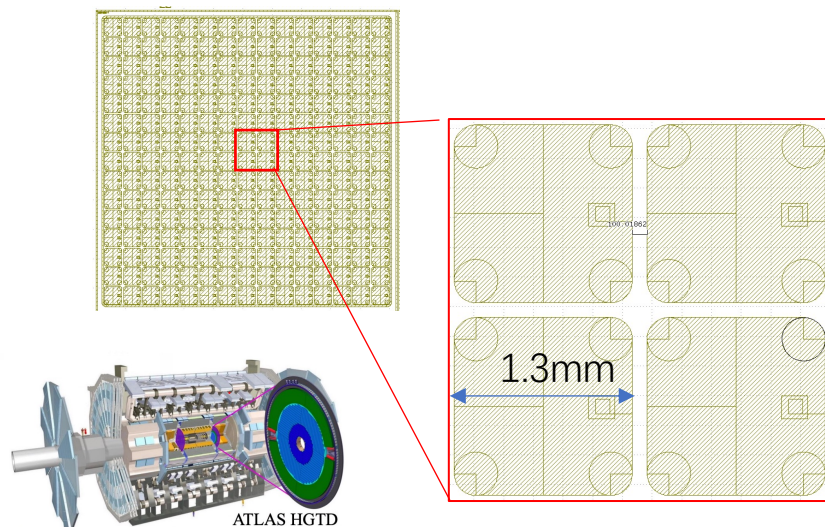
CEPC reference detector technical design report (Ref-TDR)

- CEPC在2025年末发布探测器与物理的ref-TDR (arXiv:2510.05260)

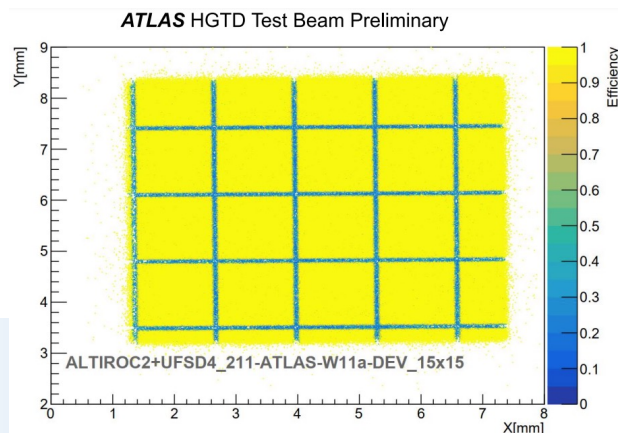


LGAD探测器未来发展方向：AC耦合的LGAD探测器

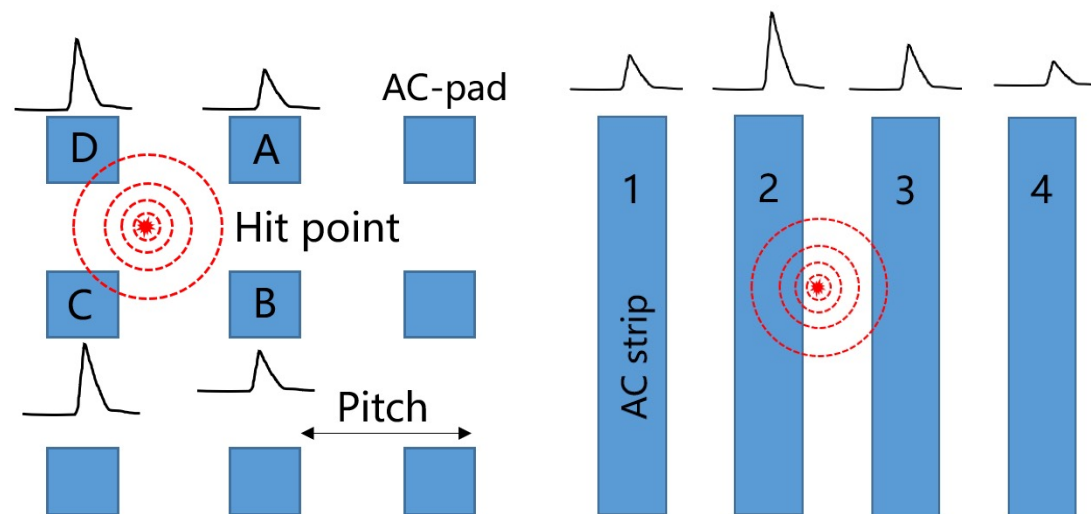
15×15 LGAD for ATLAS HGTD project



- Dead zone : $\sim 0.1\text{mm}$
- Pixel size: 1.3mm



AC-LGAD : two layout schemes for AC-pads



Pixels AC-LGAD :

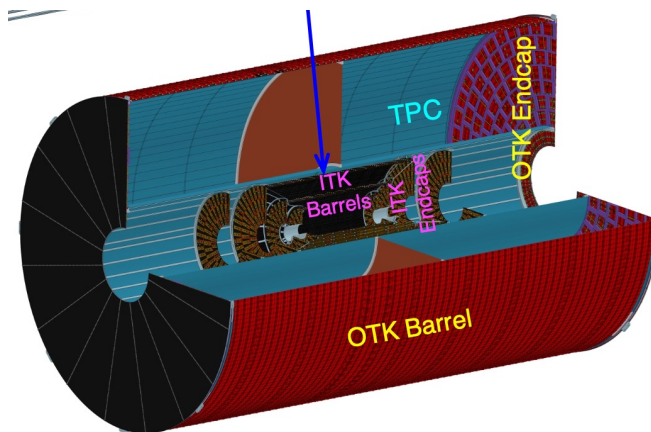
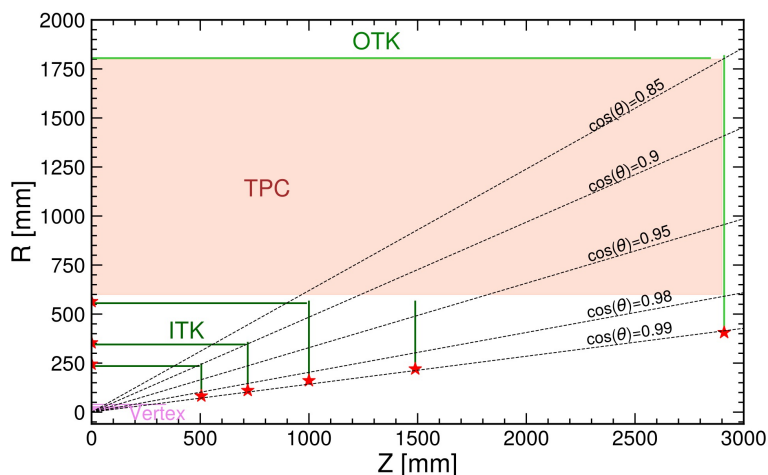
- Position information : 1 layer (x,y)
- Bump bonding

Strips AC-LGAD :

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

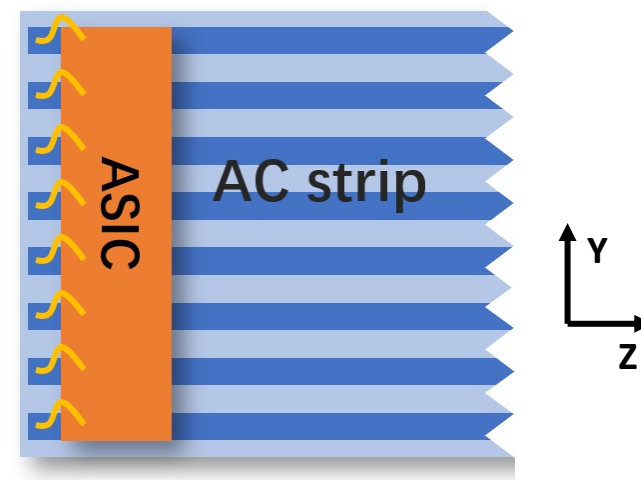
mzli@ihep.ac.cn

CEPC飞行时间探测器+外围径迹探测器



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 : $\sim 50 \text{ m}^2$, Endcap $\sim 20 \text{ m}^2$, $\sim 10^6$ channels
- Strip AC-LGAD (each strip: $\sim 4 \text{ cm}$)
 - Timing resolution: 30-50 ps
 - Position resolution: $\sim 10 \text{ }\mu\text{m}$ @ R-phi direction

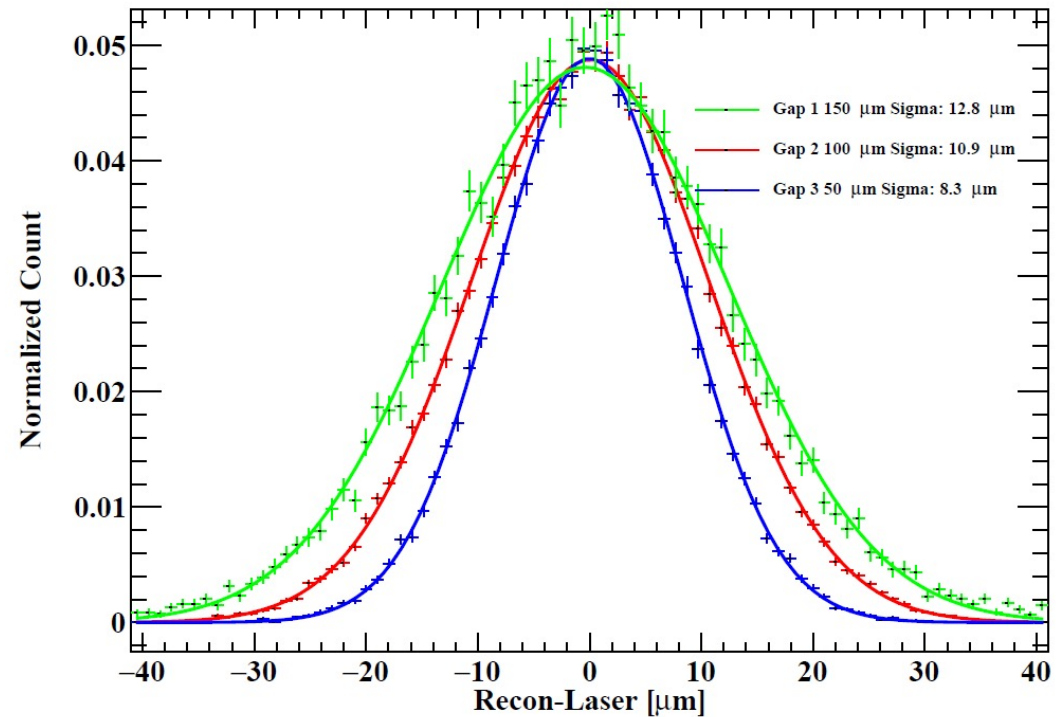
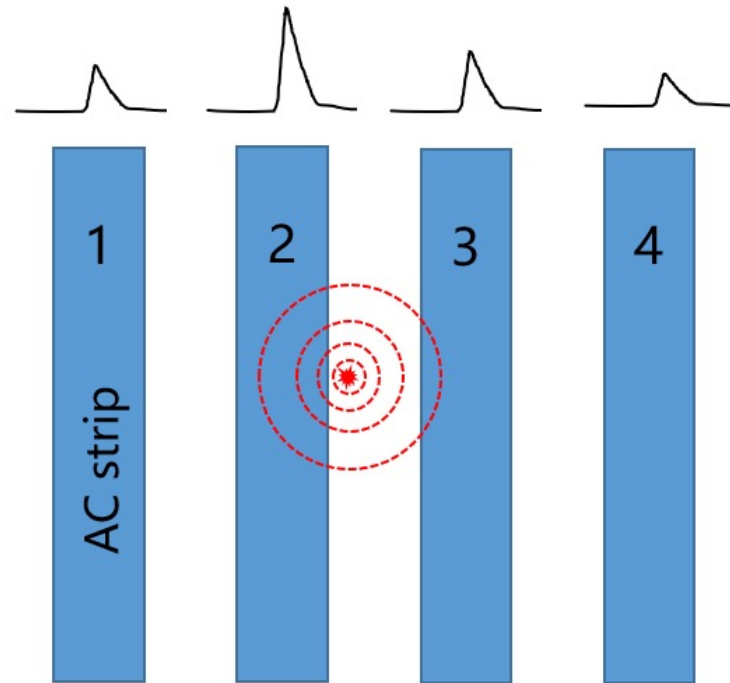
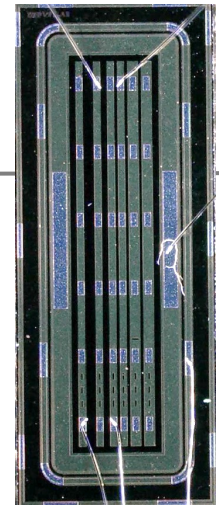


Strip AC-LGAD + ASIC :

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

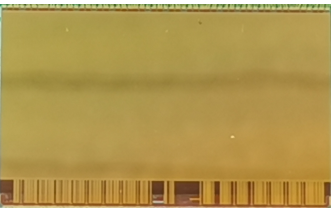
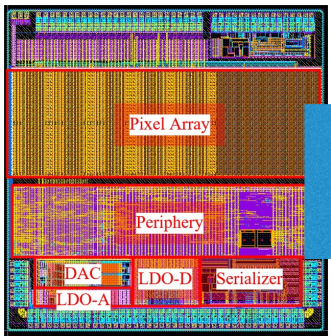
CEPC飞行时间探测器+外围径迹探测器

- Laser test result of strip AC-LGAD sensor
 - It can reach about $\sim 10\mu\text{m}$ resolution with $150\mu\text{m}$ pitch strip detector
 - While timing resolution of AC-LGAD is still can reach 30-50ps

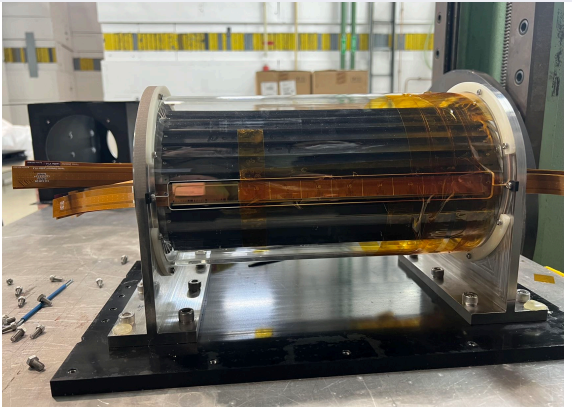
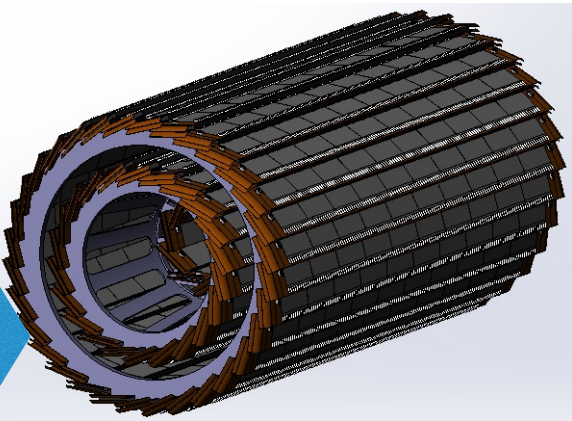
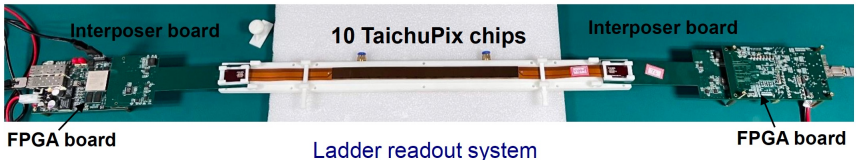
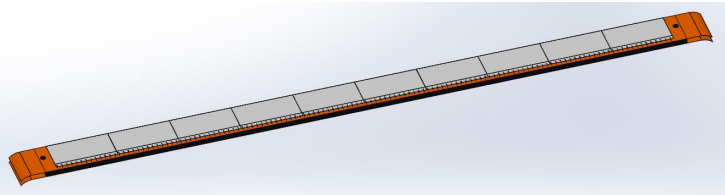


顶点探测器样机研发

芯片研发



探测器模块研发



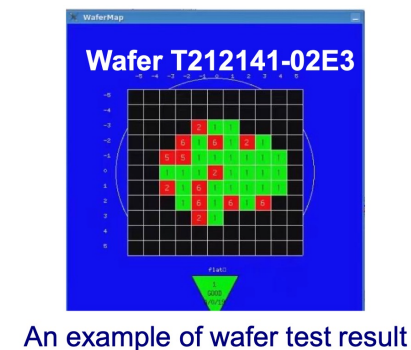
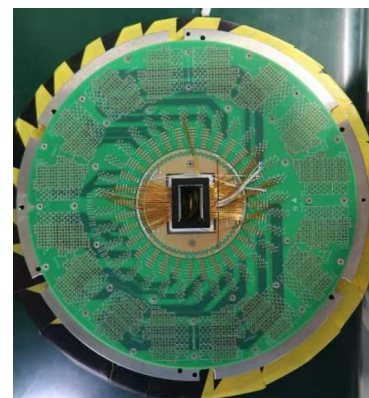
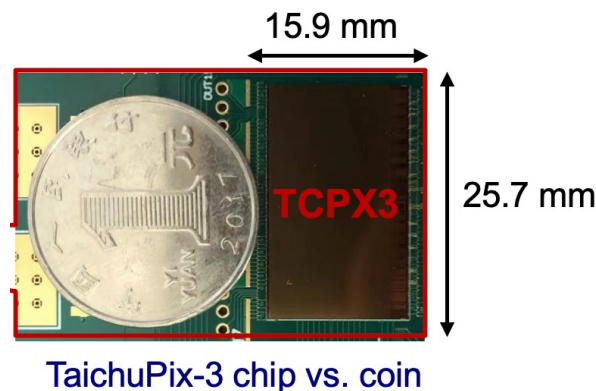
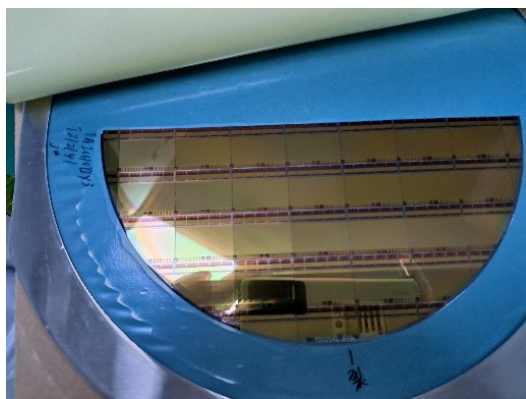
CEPC顶点探测器的研发需求

- 现有的单片集成型CMOS 传感器芯片不能满足CEPC要求
 - 像素尺寸小→ 高空间分辨率(3-5 μm)
 - 抗辐照能力: >1 Mrad (per year)
 - 高计数率-> CEPC Z pole 高亮度运行 (40MHz 的对撞频率)

	ALPIDE	ATLAS-MAPS (MONOPIX / MALTA)	MIMOSA
Pixel size	✓	X	✓
Readout Speed	X	✓	X
TID	X (?)	✓	✓

太初3高空间分辨率芯片

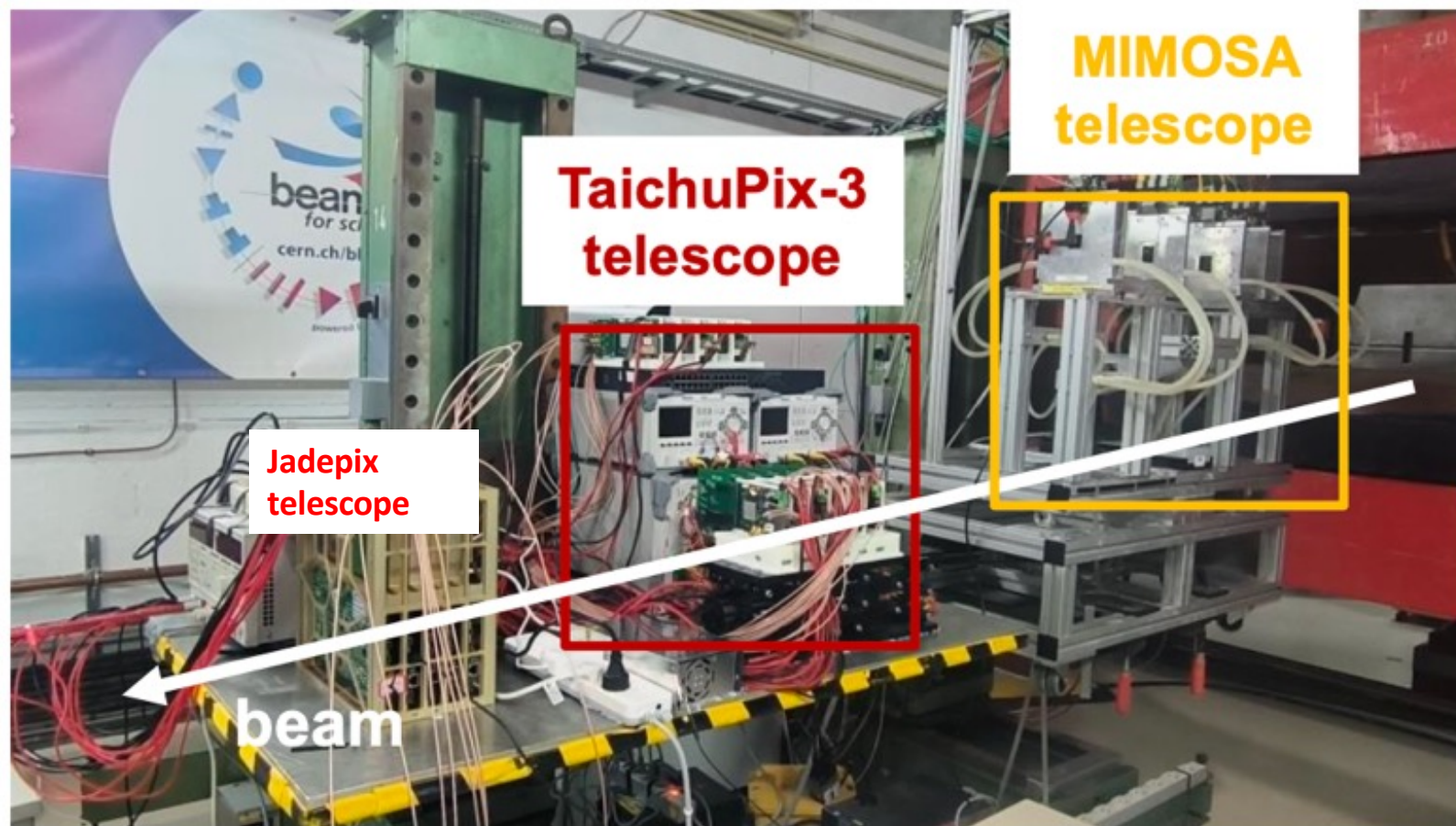
- 全尺寸 CMOS 像素探测器，单片集成型MAPS芯片，工艺: Towerjazz 180nm CIS process
 - 1024×512 像素阵列 芯片尺寸：15.9×25.7mm
 - 25μm×25微米 像素尺寸
 - 快速优先级读出，25ns的time stamp 精度，可以用在Z runs上 (~40MHz clock)



	Status	CEPC Final goal
CMOS chip technology	Full-size chip with TJ 180nm CIS	65nm CIS

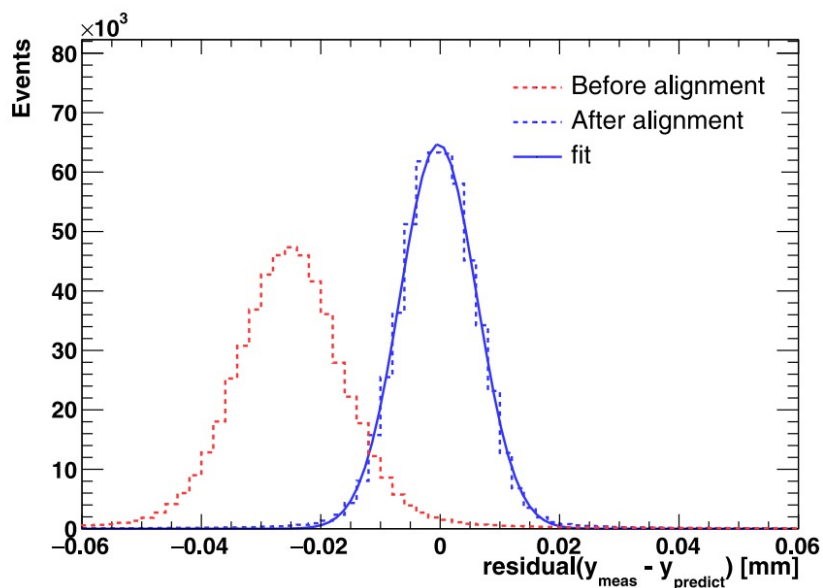
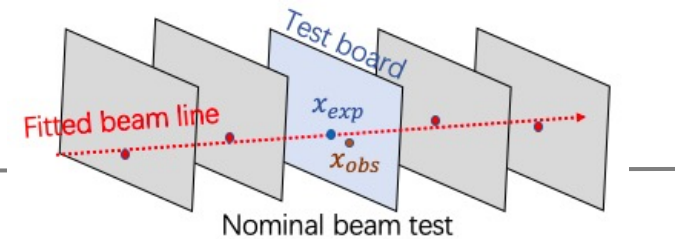
太初束流望远镜在DESY的束流测试

- 2022年底在DESY束流测试情况,测试太初和jdepix束流望远镜

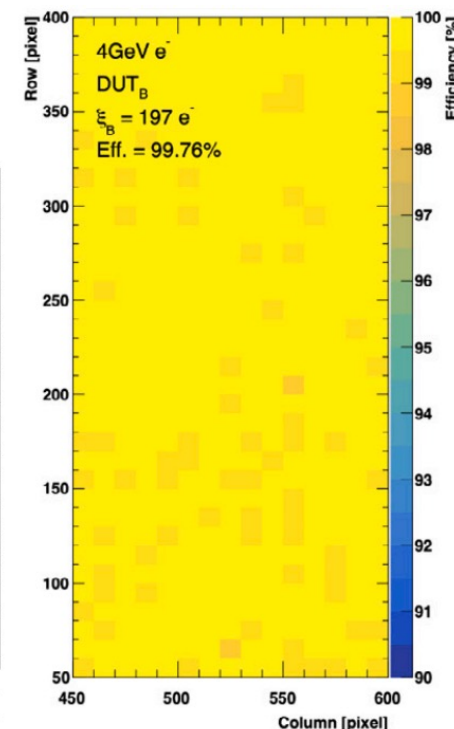
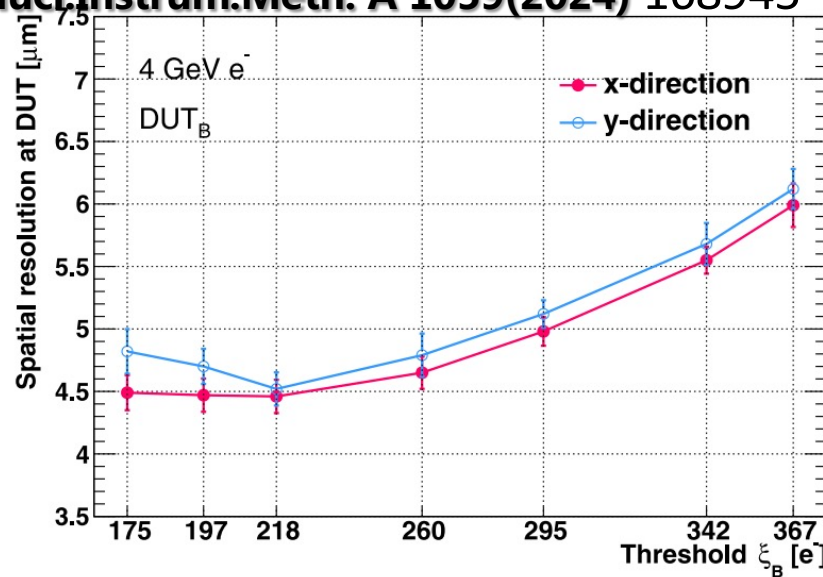


太初束流望远镜：空间分辨率

- 目前太初芯片在DESY束流测试的空间分辨率
 - 空间分辨率达到4.5微米，像素尺寸25*25微米
 - 带电粒子探测效率超过99.7%
 - 时间分辨率：30ns（测试时钟20MHz）



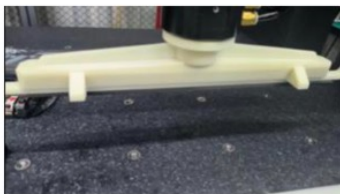
Nucl.Instrum.Meth. A 1059(2024) 168945



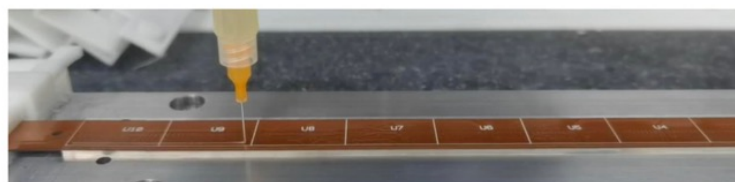
太初顶点探测器原型机的搭建

国内第一个硅顶点探测器原型机

New pickup tools



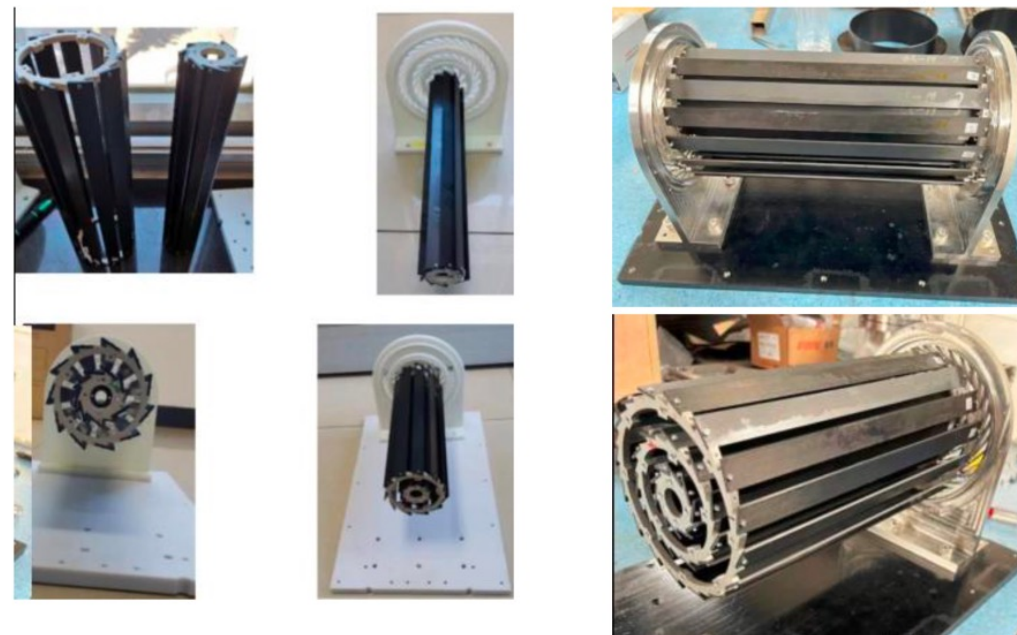
Dummy ladder glue automatic dispensing using gantry



Ladder on wire bonding machine



Dummy Ladder on holder



Ladder support tools



Ladder loaded on vertex detector



Wei Wang

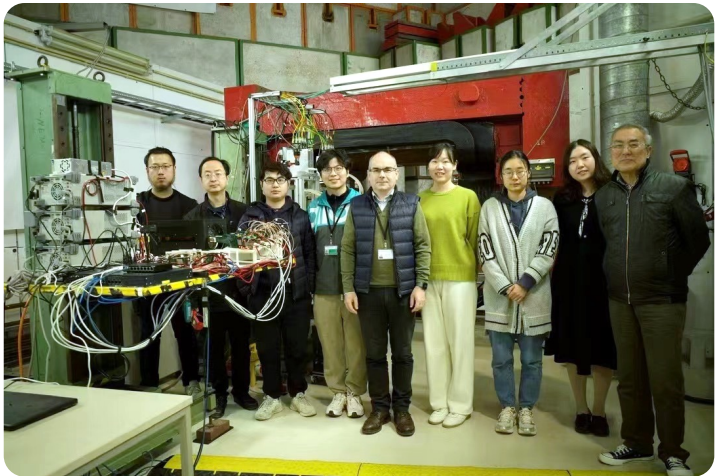
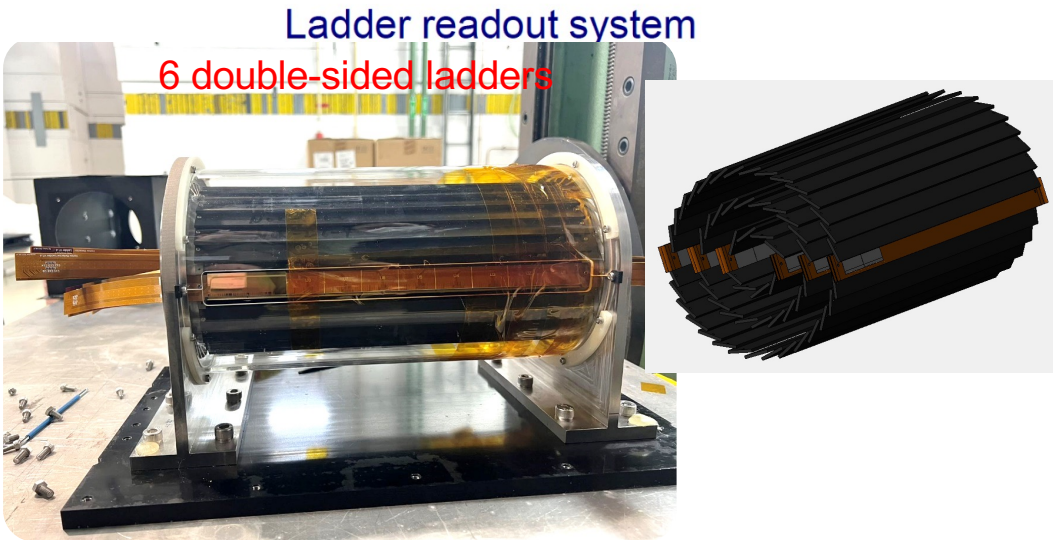
太初顶点探测器原型机与其性能测试

国内第一个硅顶点探测器原型机



TaichuPix-based prototype detector tested at DESY in April 2023

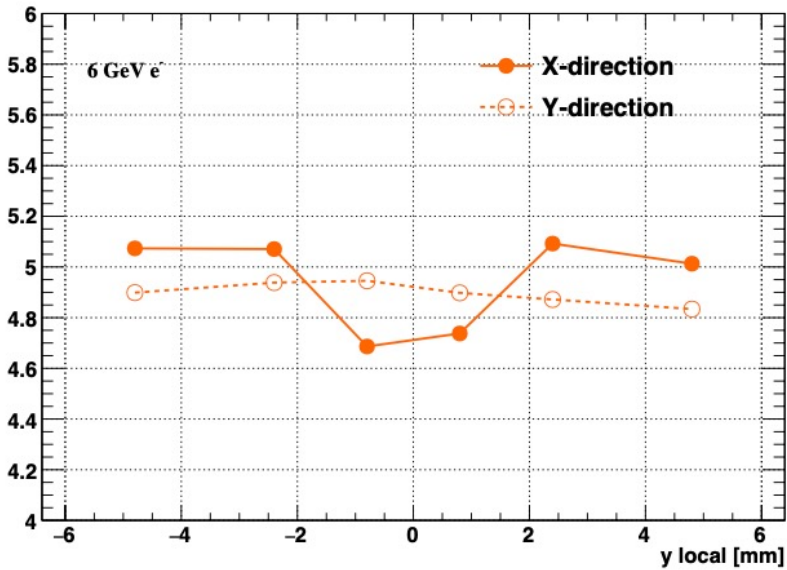
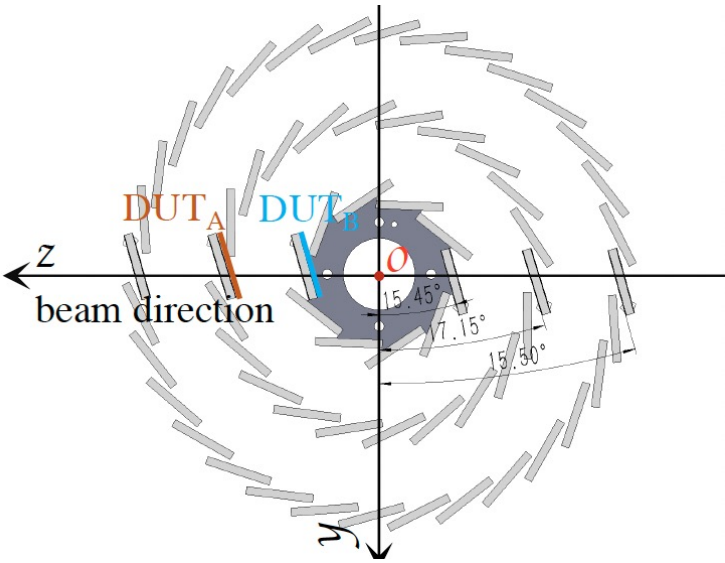
Spatial resolution ~ 4.9 μm



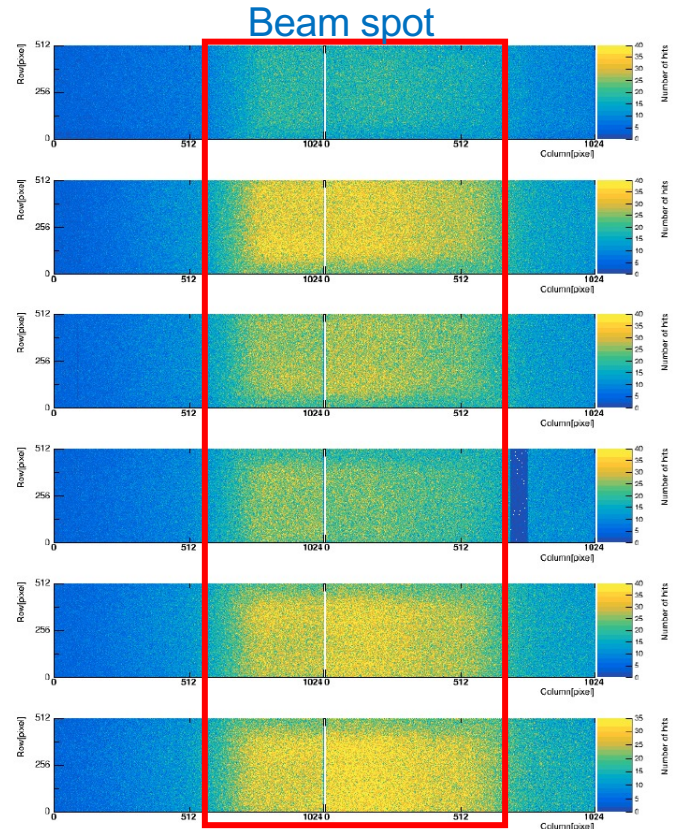
	Status	CEPC Final goal
Detector integration	Detector prototype with ladder design	Detector with bent silicon design

太初顶点探测器原型机的性能

- DESY电子束流测试，6个双面的ladder，可以产生12个hits，空间分辨率达到~ 5 μm



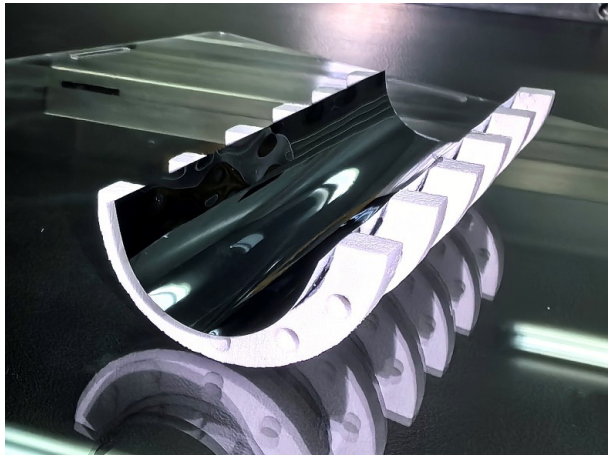
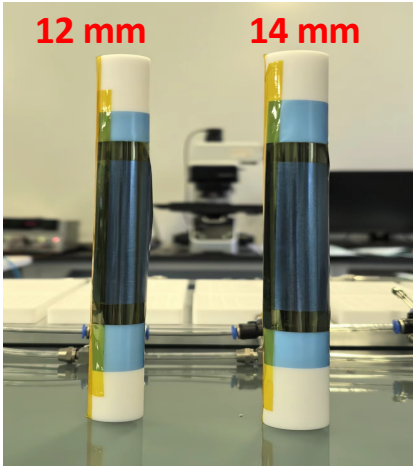
Hit maps of multiple layers



	Status	CEPC Final goal
空间分辨率	4.9 μm	3-5 μm

CEPC ref-TDR中的顶点探测器研发

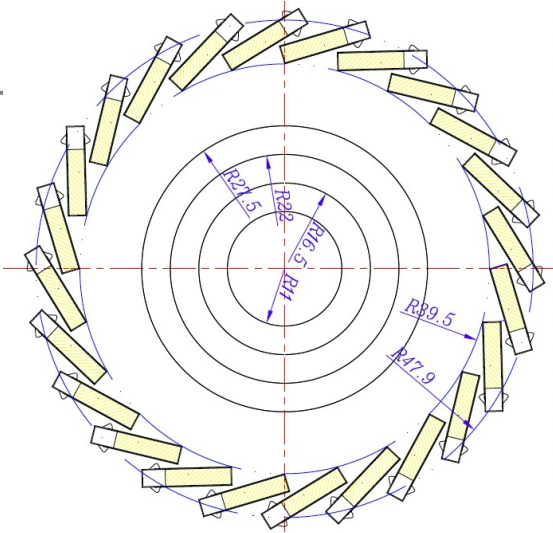
- CEPC b-layer radius (11mm) smaller compared with ALICE ITS3 (radius=18mm)
- Feasibility : Mechanical prototype with dummy wafer can curved to a radius of 12mm
 - The dummy wafer has been thinned to 30-40μm



	Status	CEPC Final goal
Bent silicon with radius	Bent Dummy wafer radius ~12mm	Bent final wafer with radius ~11mm

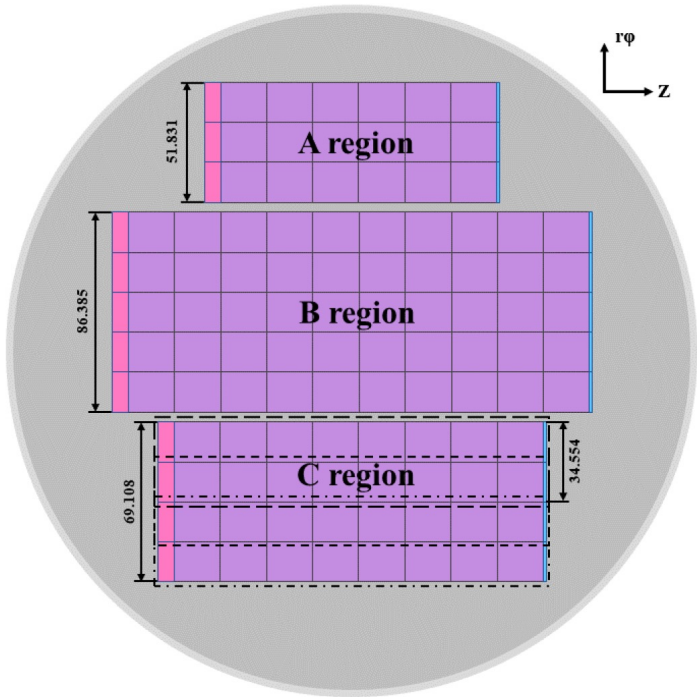
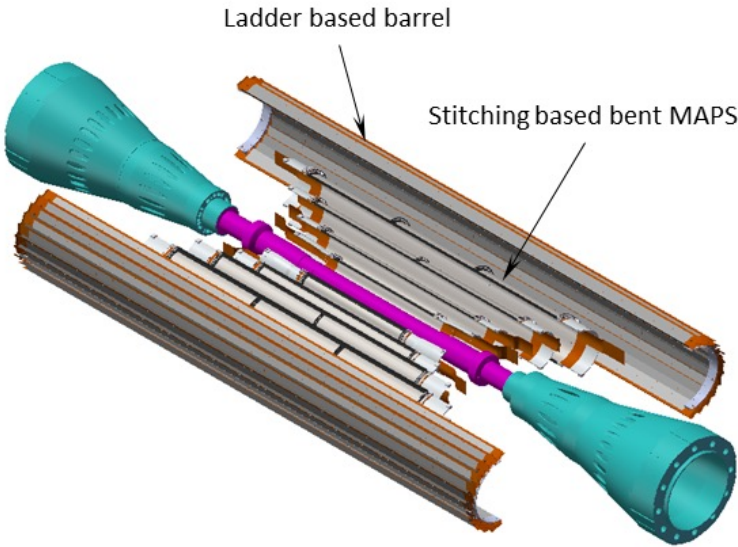
CEPC ref-TDR中的顶点探测器的基准方案：弯曲的MAPS方案

- 4 single layer of bent MAPS + 1 double layer ladder
 - Material budget is much lower than alternative option
- Use single bent MAPS for Inner layer ($\sim 0.15\text{m}^2$)
 - Low material budget 0.06%X0 per layer
 - Different rotation angle in each layer to reduce dead area



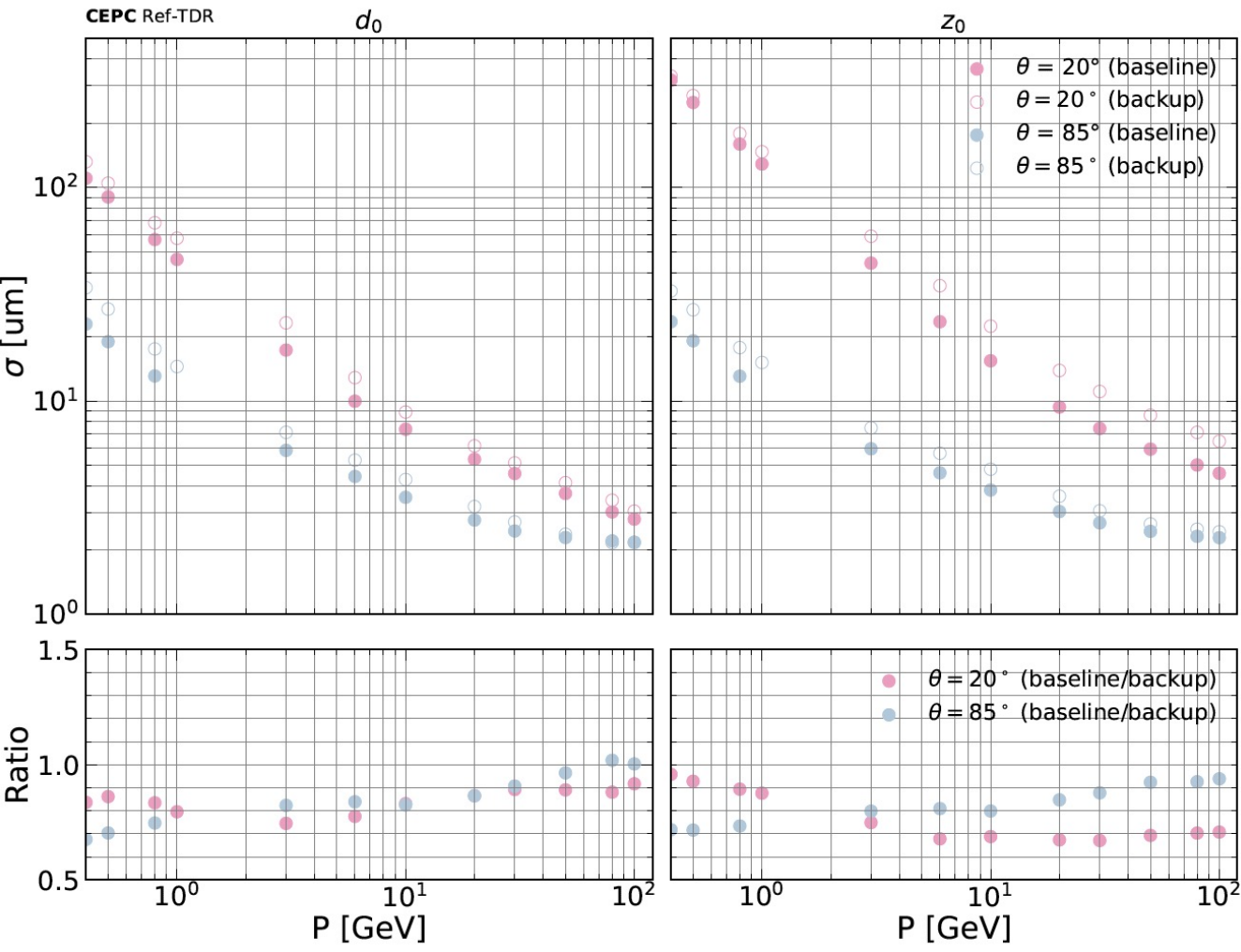
Long barrel layout (no endcap disk)
to cover $\cos \theta \leq 0.991$

layer/VXD X	radius .mm	length .mm
layer 1	11.06	161.4
layer 2	16.56	242.2
layer 3	22.06	323.0
layer 4	27.56	403.8
VXD 5	39.50	682.0

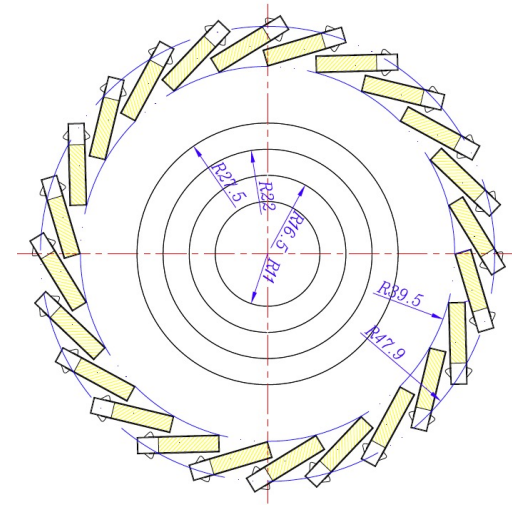


Performance: impact parameter resolution

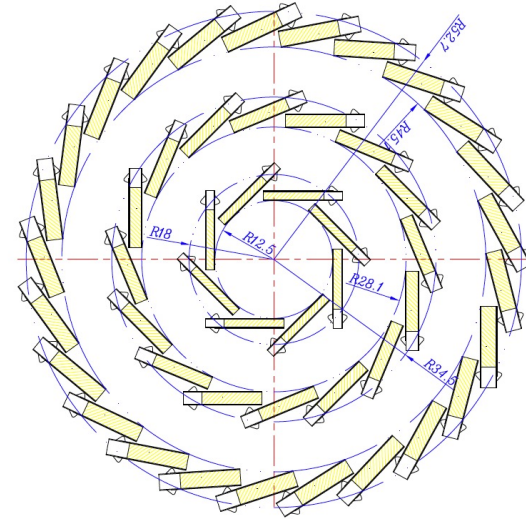
- Baseline has better resolution than alternative (ladder) (25-40%) in low momentum
d0 resolution: Baseline Vs backup layout



Baseline layer
4 stitching +
1 double layer ladders



Backup layout
3 double layer ladders



30%

小结

- **CEPC探测器与物理的ref-TDR已经发布（arXiv:2510.05260）**

- 基于全尺寸太初芯片初步研制了内层硅顶点原型样机

- 国内首个硅顶点探测器样机，空间分辨率好于5微米，关键指标达到国际水平

- 下一步研制基于stitching技术的顶点探测器原型机

- AC-LGAD技术成为CEPC外层探测器的baseline方案

- 初步原型传感器验证了其空间分辨率好于10微米，时间分辨率好于30皮秒

