重离子碰撞实验中的硅像素探测器

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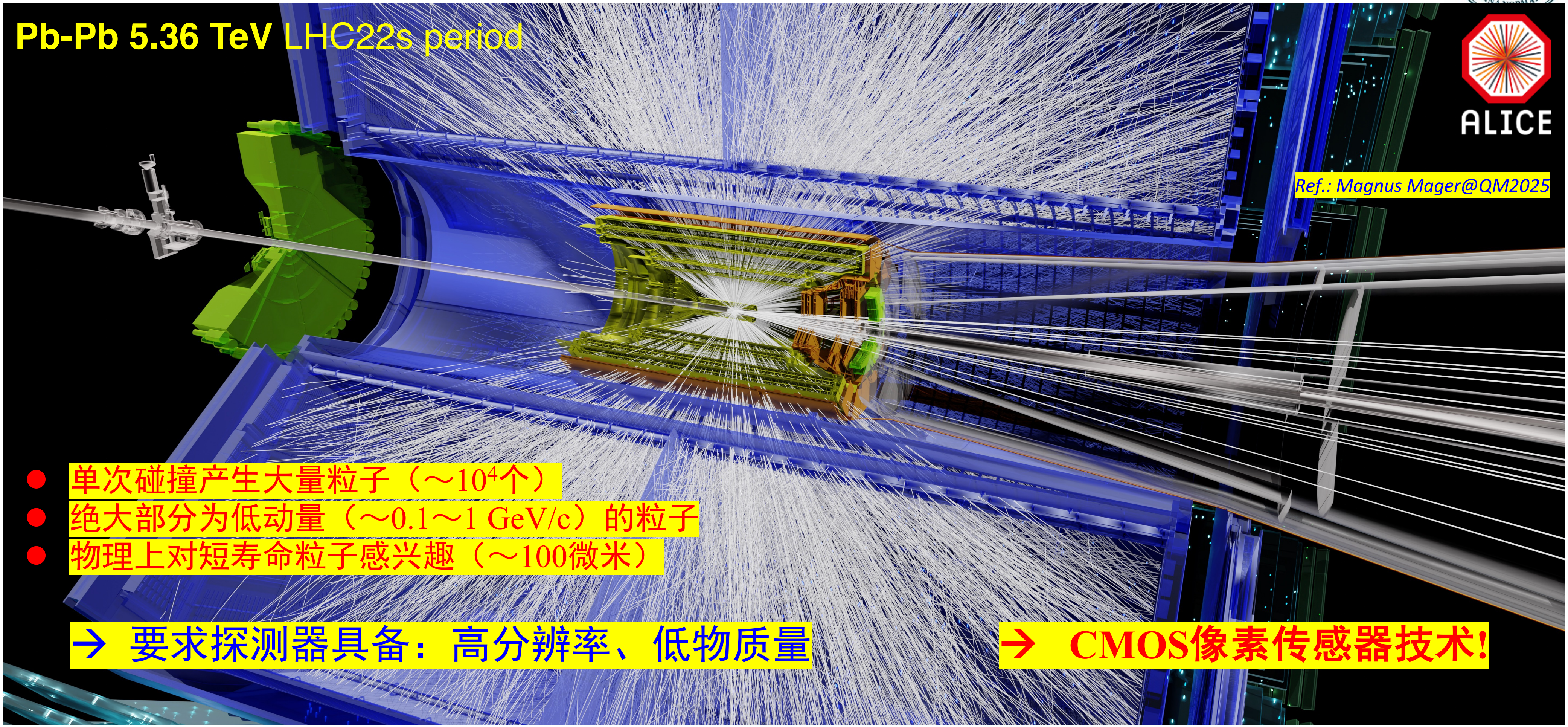
报告提纲

- 背景介绍
- CMOS单片有源像素传感器（MAPS）
- MAPS在重离子碰撞实验中的应用
  - ✓ STAR PXL
  - ✓ ALICE ITS2
  - ✓ ALICE ITS3
- MAPS探测器研发进展
- 总结

背景介绍 -- 高能重离子碰撞



- 单次碰撞产生大量粒子（～10^4个）
- 绝大部分为低动量（～0.1～1 GeV/c）的粒子
- 物理上对短寿命粒子感兴趣（～100微米）

→ 要求探测器具备：高分辨率、低物质量

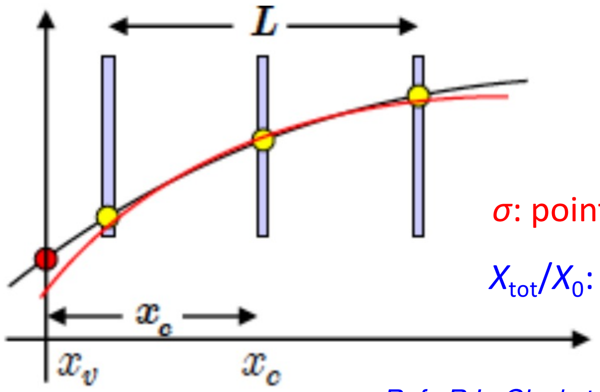
→ CMOS像素传感器技术!

背景介绍 -- 像素探测器关键参数

像素探测器的性能参数：

1. 碰撞参数分辨率
2. 动量分辨率
3. 寻迹效率

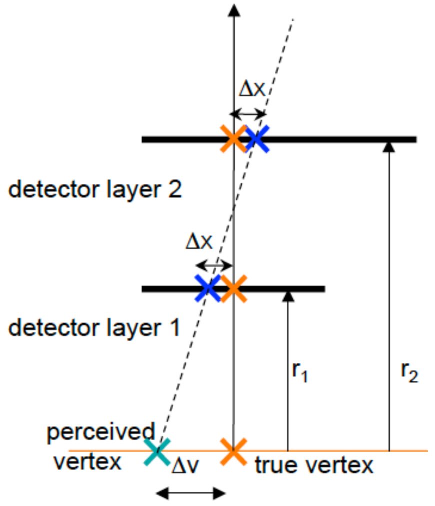
- 物质量
- 固有位置分辨率
- 到碰撞点的距离



σ: pointing resolution/plane

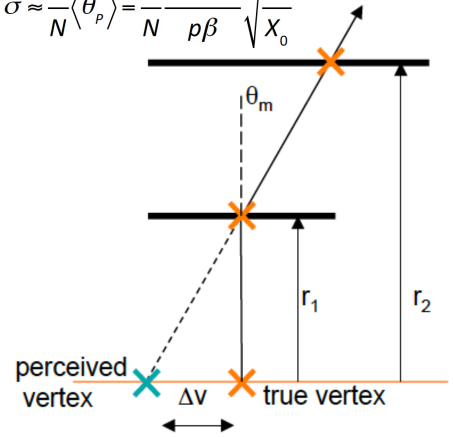
X_{tot}/X_0: total material budget

Ref.: R.L. Gluckstern, NIMA 24 (1963), 381-389



$$\Delta v = \Delta x \cdot \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}}$$

$$\sigma \approx \frac{L}{N}\langle\theta_p\rangle = \frac{L}{N}\frac{0.0136}{p\beta}\sqrt{\frac{x}{X_0}}$$



$$\Delta v = \theta_m \cdot r_1$$

Ref.: Luciano Musa@HP2023

$$\frac{\Delta p_t}{p_t} = \frac{\sigma[m]\,p[\mathrm{GeV/c}]}{0.3\,B[T]\,L^2[m^2]}\sqrt{\frac{720\,(N-1)^3}{(N-2)\,N\,(N+1)\,(N+2)}} \approx \frac{\sigma[m]\,p[\mathrm{GeV/c}]}{0.3\,B[T]\,L^2[m^2]}\sqrt{\frac{720}{N+4}}$$

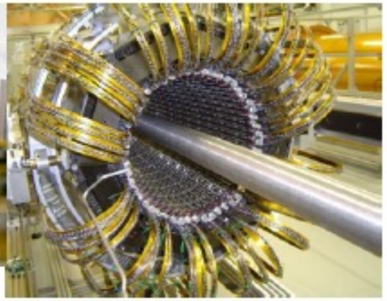
$$\frac{\Delta p_t}{p_t} = \frac{0.0136}{0.3\beta\,B[T]\,L[m]}\sqrt{\frac{X_{tot}}{X_0}}\sqrt{\frac{10}{7}\,\frac{12+(N-1)N^2(N+1)}{(N-2)N(N+1)(N+2)}} \approx \frac{0.0136}{0.3\beta\,B[T]\,L[m]}\sqrt{\frac{X_{tot}}{X_0}}\sqrt{\frac{10}{7}} \approx \frac{0.0542}{\beta\,B[T]\,L[m]}\sqrt{\frac{X_{tot}}{X_0}}$$

背景介绍 -- 像素探测器发展历史

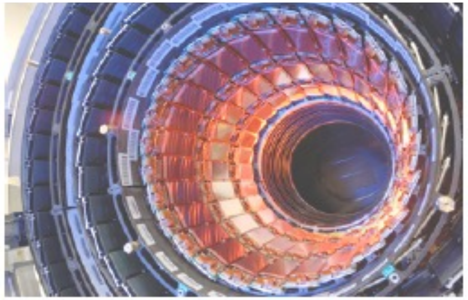
- 1995 – First Hybrid Pixel detector installed in WA97 (CERN, Omega facility)
- 1996/97 – First Collider Hybrid Pixel Detector installed in DELPHI (CERN, LEP)
- Complex systems operated in a challenging high track density environment
- Silicon pixel detectors were installed at the heart of LHC experiments since 2005

ALICE **Pixel** Detector

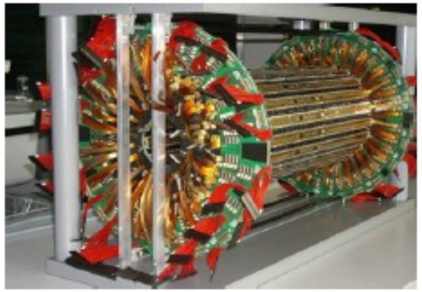
LHCb VELO



ATLAS **Pixel** Detector



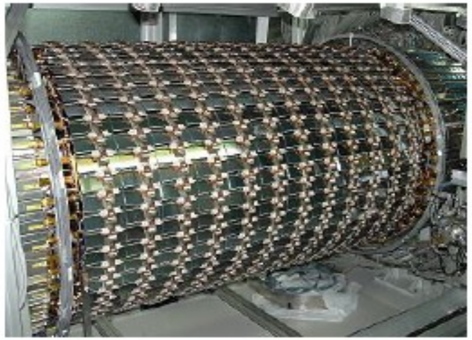
CMS Strip Tracker IB



CMS **Pixel** Detector

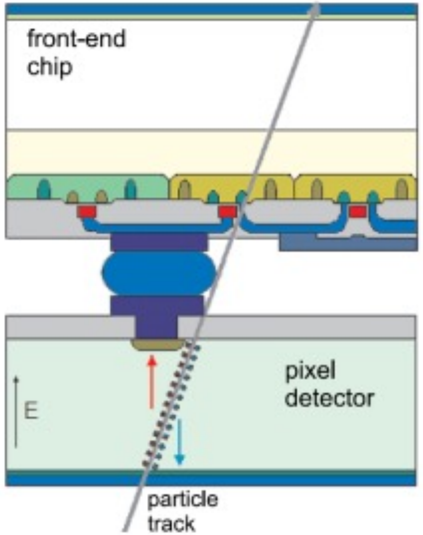
ALICE Drift Detector

ALICE Strip Detector

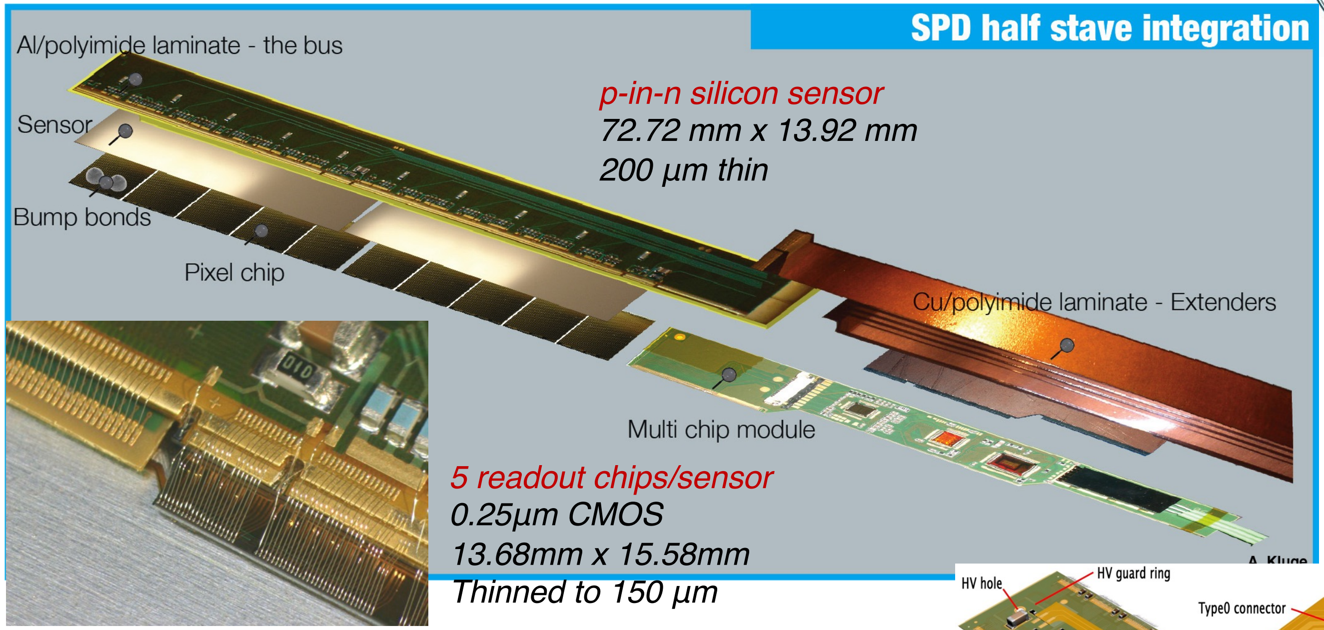


ATLAS SCT Barrel

背景介绍 -- 像素探测器发展历史

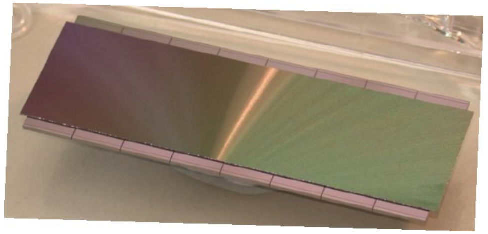


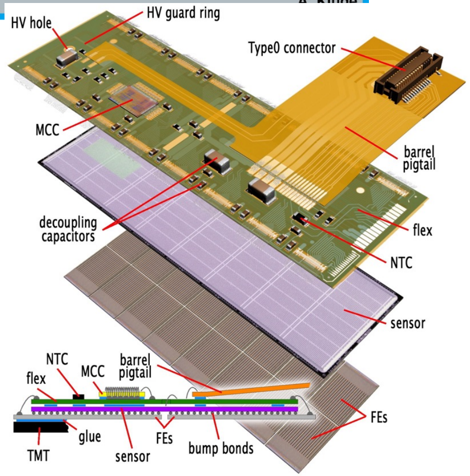
混合式像素传感器（Hybrid）



ALICE Silicon Pixel Detecor (SPD)

ATLAS Pixel Module





CMOS单片有源像素传感器（MAPS）

- Only in the early 2000s proposed for charged particle tracking in HEP
  - ➢ Need larger fill factor and better charge collection (higher resistivity substrate)

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 458 (2001) 677–689

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology

R. Turchetta[a,*], J.D. Berst[a], B. Casadei[a], G. Claus[a], C. Colledani[a], W. Dulinski[a], Y. Hu[a], D. Husson[a], J.P. Le Normand[a], J.L. Riester[a], G. Deptuch[b,1], U. Goerlach[b], S. Higueret[b], M. Winter[b]

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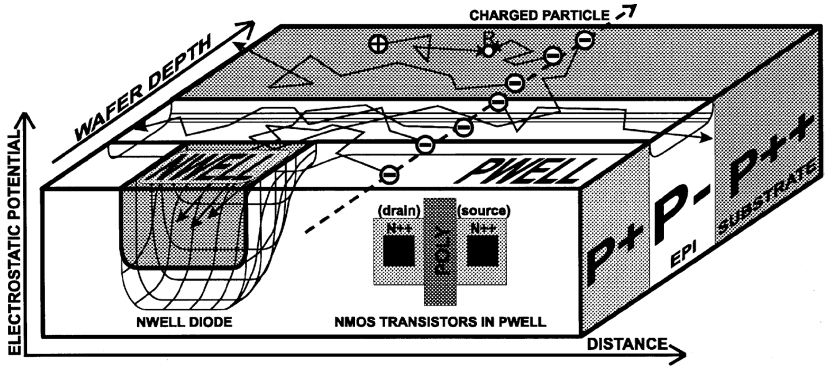
doi:10.1016/S0168-9002(00)00893-7



Integration of a sensor in 0.6 µm process

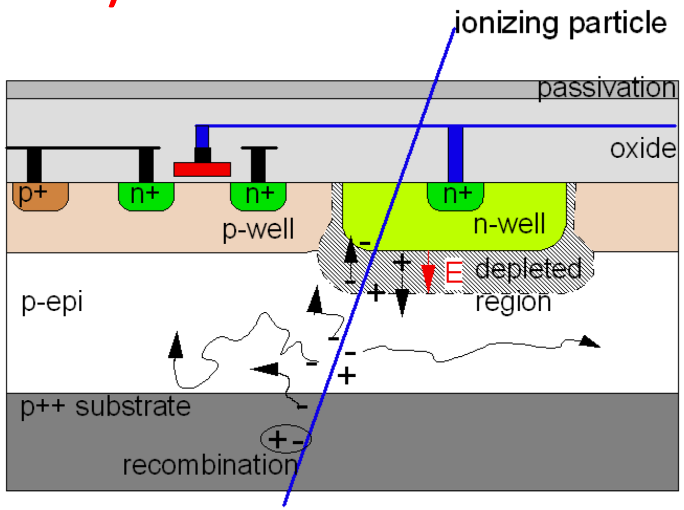
- Twin (P and N) wells
- Implanted in lightly doped (P^-) epitaxial layer
- Grown on top of the highly doped (P^{++}) substrate

Charge collection diode is made of the junction between the NWELL and P-type epitaxial layer

STAR PXL -- MIMOSA芯片

MIMOSA-family sensor developed for STAR/HFT (First application in HEP!)

- AMS 0.35 um CMOS, Twin-well process
- 'High' resistivity (≥ 400 Ω·cm) p-epi layer (~15 μm)
  - Reduced **charge collection time**
  - Improved **radiation hardness** (up to 10^{12} 1MeV N_{eq}/cm^2)
- Charge collection by diffusion (mostly) and drift
  - **Shallow depletion** region formed between n-well and p-epi
  - High-potential difference between lightly-doped epi and substrate



- NMOS only in pixel array
- **Rolling-shutter** readout architecture
- Clock distributed across the matrix, in-pixel amplifier

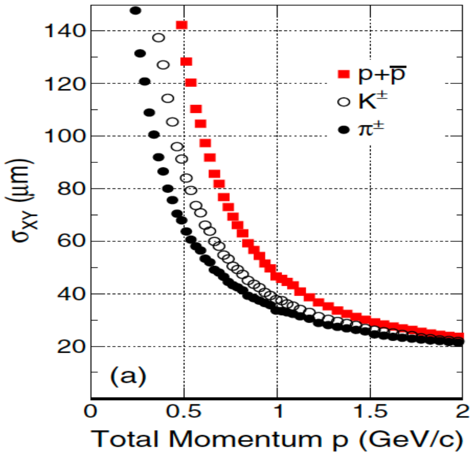
Key Features:

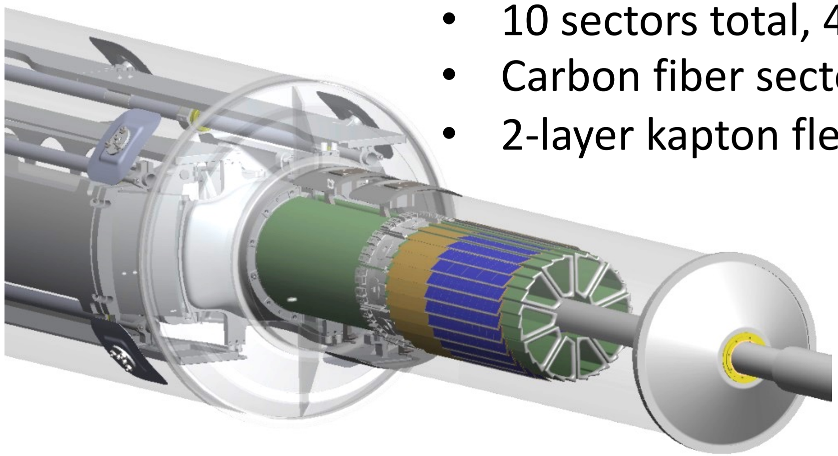
- **Dimensions:** 20mm x 22.7mm x 50μm
- **Pixel pitch:** 20.7μm x 20.7μm
- **Spatial resolution:** ~ 3.7 μm (3D)
- **Integration time:** ~185.6 μs
- **Ultra-low power (entire chip):** < 170mW/cm^2
- **Sensor efficiency:** ≥99% with accidental rate ≤10^{-4}

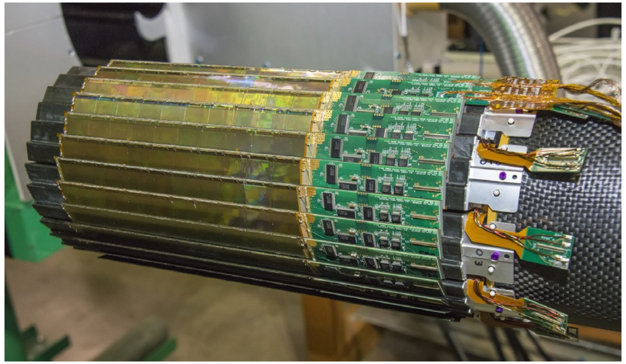
STAR PXL -- 探测器结构

Ladder with 10 MAPS sensors (~ 2 x 2 cm^2 each)

- 400 sensors (356M pixels, 0.16 m^2)
- 2 layers (2.8 cm and 8 cm)
- 0.4% X_0 per layer
- 10 sectors total, 4 ladders/sector
- Carbon fiber sector tubes (~ 200 μm thick)
- 2-layer kapton flex cable with AL traces







Mechanical support with kinematic mounts (insertion side)

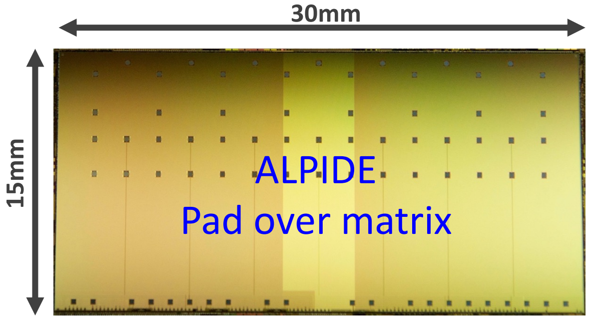
doi:10.1016/j.nima.2018.03.003

Ref.: L. Greiner (LBL) / CPIX-2014

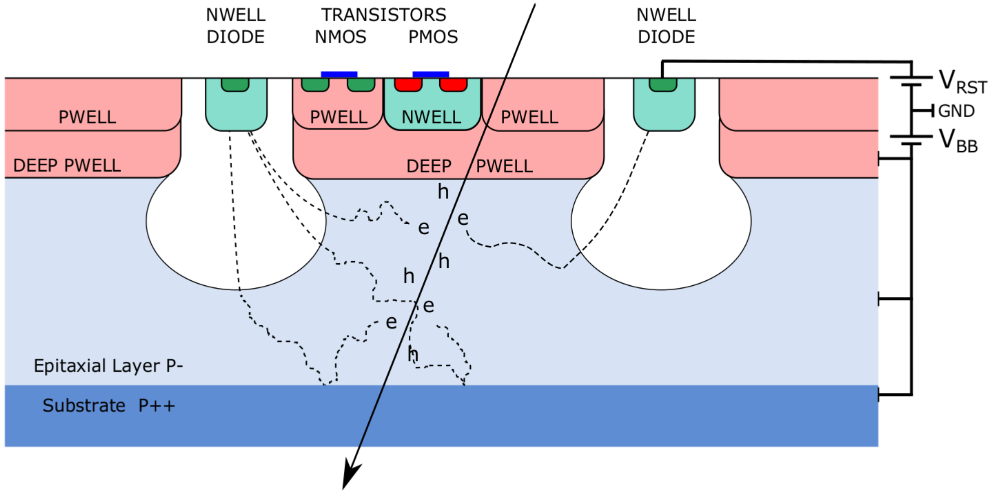
ALICE ITS2 -- ALPIDE芯片

ALPIDE produced using TowerJazz 180nm CMOS Imaging Sensor process

- ✓ Quadruple-well process
- ✓ High-resistivity (>1 kΩ·cm) p-type epi-layer (~25 μm)
- ✓ Small n-well diode (2 μm diameter)
- ✓ Deep PWELL shields NWELL of PMOS transistors, allowing for full CMOS circuitry within active area
- ✓ Reverse bias voltage to substrate to increase the NIEL tolerance beyond 10^{13} 1MeV N_{eq}/cm^2)
- ✓ Low-power hit-driven read-out



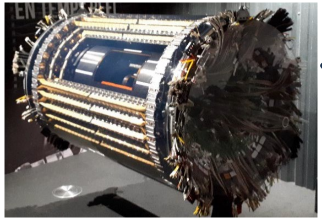
1024×512 pixels



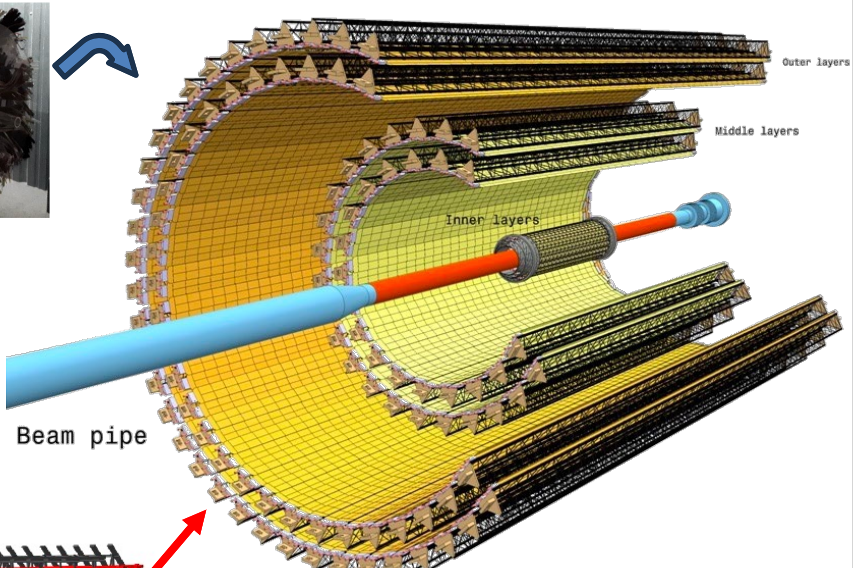
Key Features:

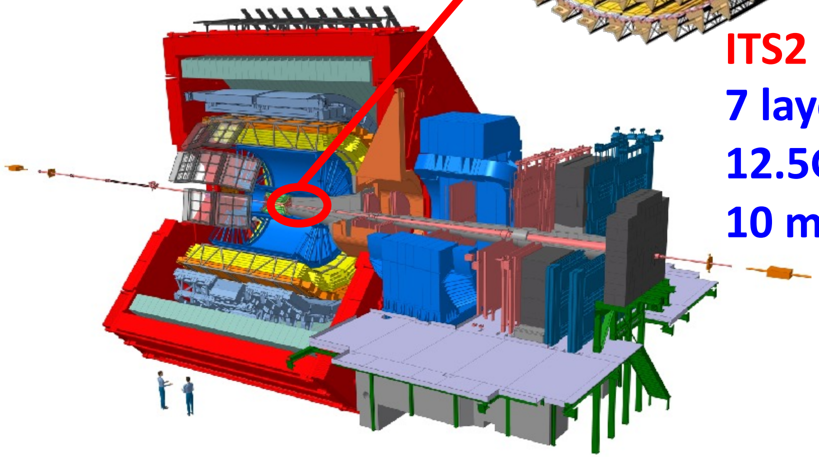
- ⊙ **Dimensions: 30mm x 15mm x 50 (100) μm**
- ⊙ **Pixel pitch: 29μm x 27μm**
- ⊙ **Spatial resolution: ~ 5 μm (3-D)**
- ⊙ **Fake-hit rate: ~10^{-10} pixel/event**
- ⊙ **Ultra-low power (entire chip): < 40mW/cm²**
- ⊙ **Global shutter: triggered acquisition (200 kHz) or continuous (integration time <4μs)**

ALICE ITS2



ITS1





ITS2

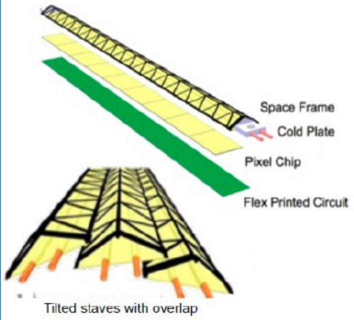
7 layers of MAPS

12.5G pixels

10 m^2 active area

- Monolithic Active Pixel Sensor (MAPS), **ALPIDE** (~24k chips)
- **5 μm** impact parameter resolution
- **7 cylinders** covering **~10 m^2** area
- Innermost radius: **23 mm**
- Inner Barrel (IB)
  - 3 Inner Layers (48x 9-chip Staves)
  - **~0.35% X_0** material budget
- Outer Barrel (OB)
  - 2 Outer Layers (90x 14-HIC Staves)
  - 2 Middle Layers (54x 8-HIC Staves)
  - **~0.8% X_0** material budget
- **100 kHz** trigger rate

ALICE ITS2 -- 探测器结构



Inner Barrel (IB)

Material thickness: ~ 0.35% X_0

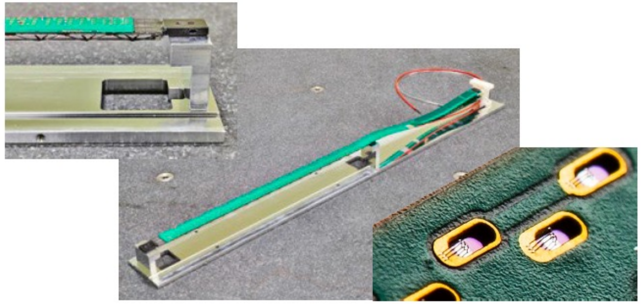
Readout speed: 1200 Mbps

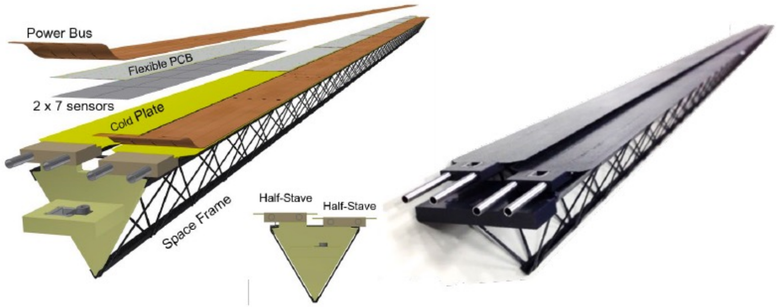
<radius> (mm): 23, 31, 39

Nr. staves: 12, 16, 20

Nr. chips: 432

Assembled and validated at CERN





Outer Barrel (OB) – Middle Layers and Outer Layers

Nr. modules/stave: 4 (ML), 7 (OL)

Material thickness: ~ 1% X_0

Power density ~ 40mW/cm^2

Nr. staves: 24, 30, 42, 48

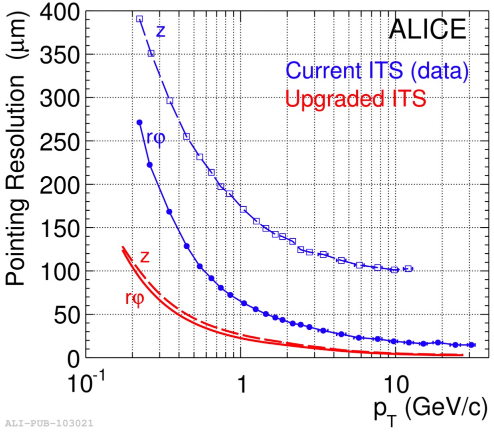
<radius> (mm): 194, 247, 353, 405

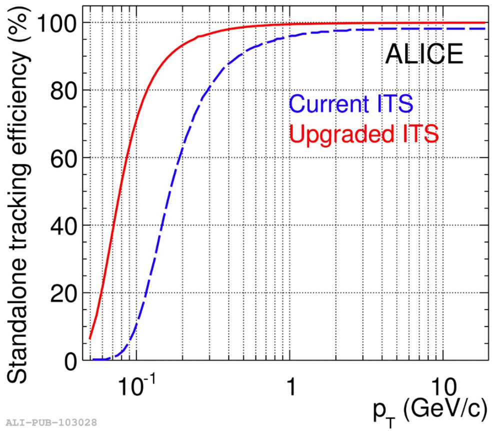
Readout speed: 400 Mbps

Length (mm): 844 (ML), 1478 (OL)

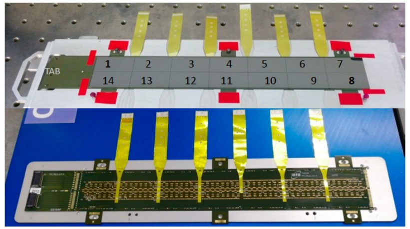
Nr. Chips: 6048 (ML), 17740(OL)

Assembled at Berkeley, Daresbury, Frascati, Nikhef, Torino, Bari, Liverpool, Pusan, Strasbourg and Wuhan





IB HIC模块

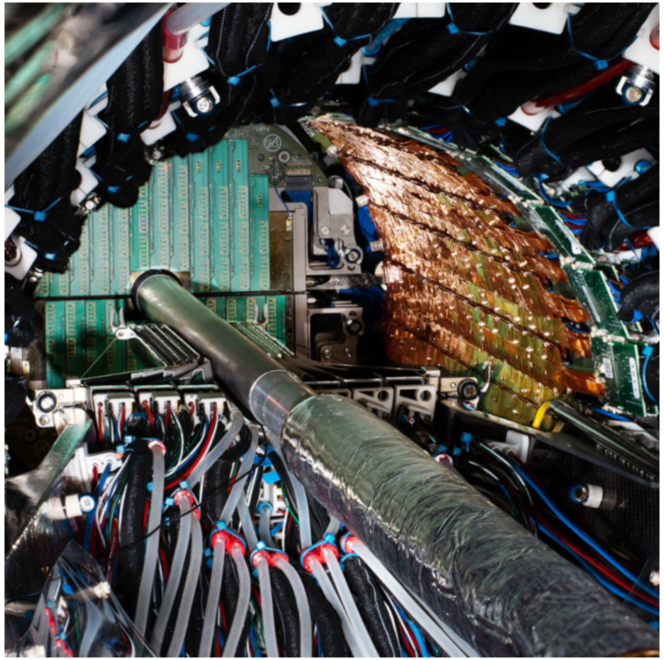


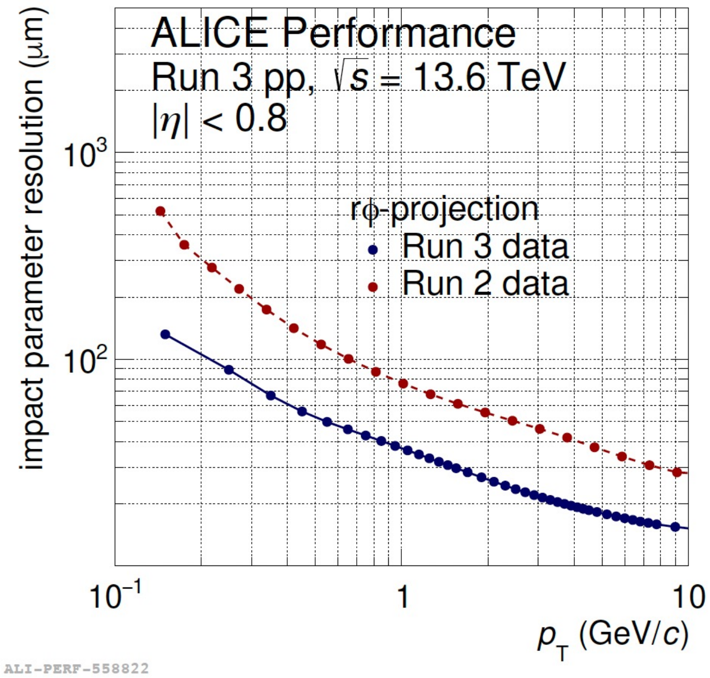
OB HIC模块

ALICE ITS2 -- 物理性能

Ref.: Magnus Mager@QM2025

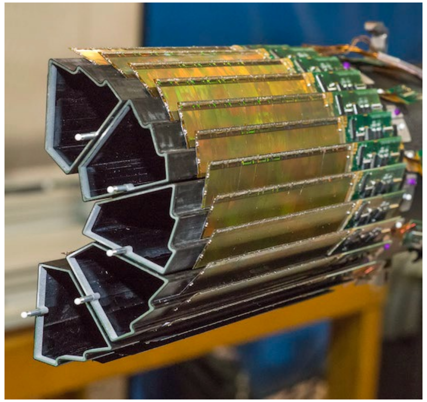
The outer barrel of ALICE ITS2 installed in March,2021





- ✓ Introducing the MAPS tracker, ALICE significantly improved its tracking performance
- ✓ improved several measurements and access new channels

Next development of MAPS pixel detector

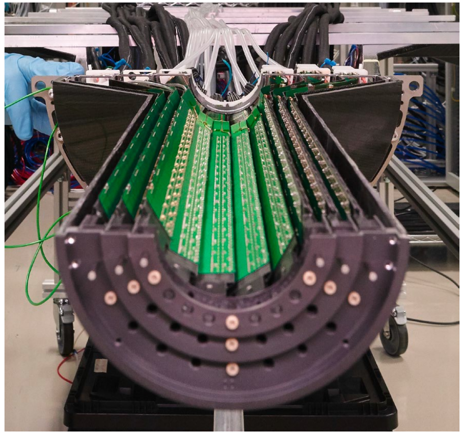


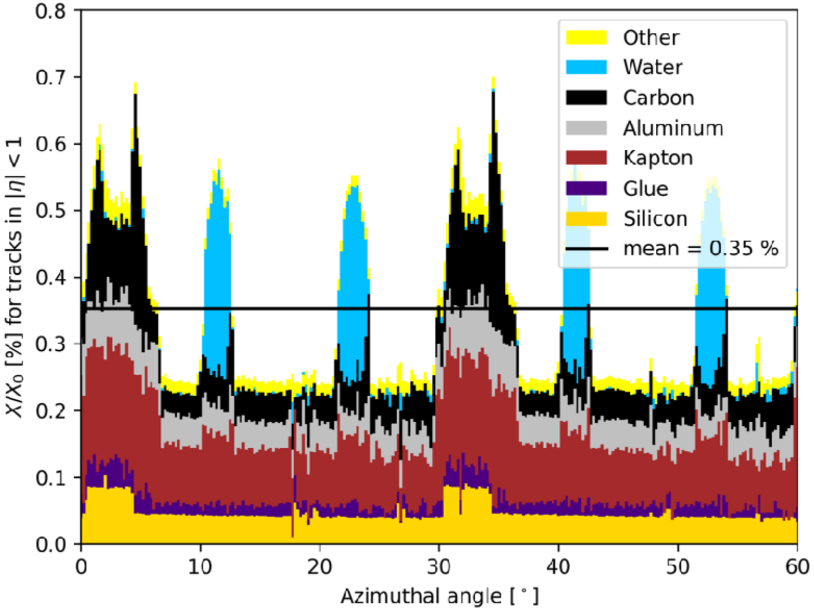
STAR HFT (2014-2016)

Material: 0.4% X_0
Minimum radius: 2.8 cm
Pixel pitch: ~ 21 μm

ALICE ITS2 (2021 -2025)

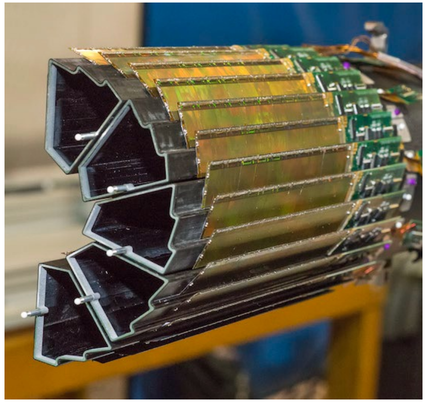
Material: 0.35% X_0
Minimum radius: 2.3 cm
Pixel pitch: ~ 30 μm





- **Can the material be further reduced?**
- **Can we get closer to the interaction point?**

ALICE ITS3: Stitching MAPS



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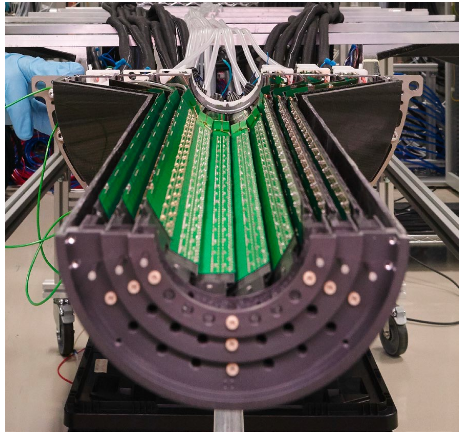
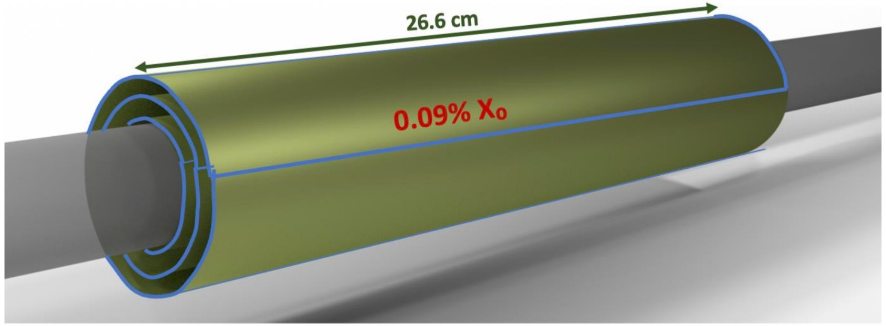


A truly-cylindrical, 'silicon-only' detector to achieve unprecedented tracking performance at low p_T

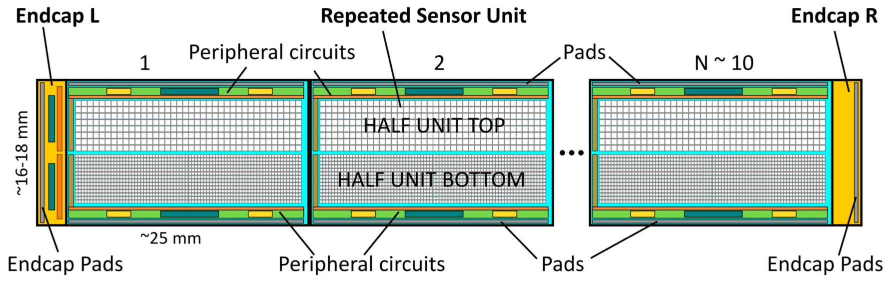


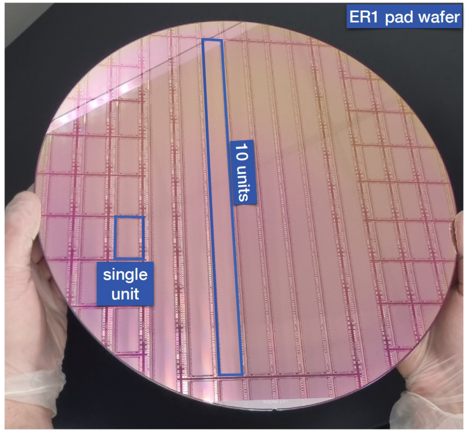
ALICE ITS3 (2027 - ?)

Material: 0.09% X_0
Minimum radius: 1.9 cm
Pixel pitch: < 25 µm

ALICE ITS3: Stitching MAPS

65nm CMOS Imaging process
MOSAIX





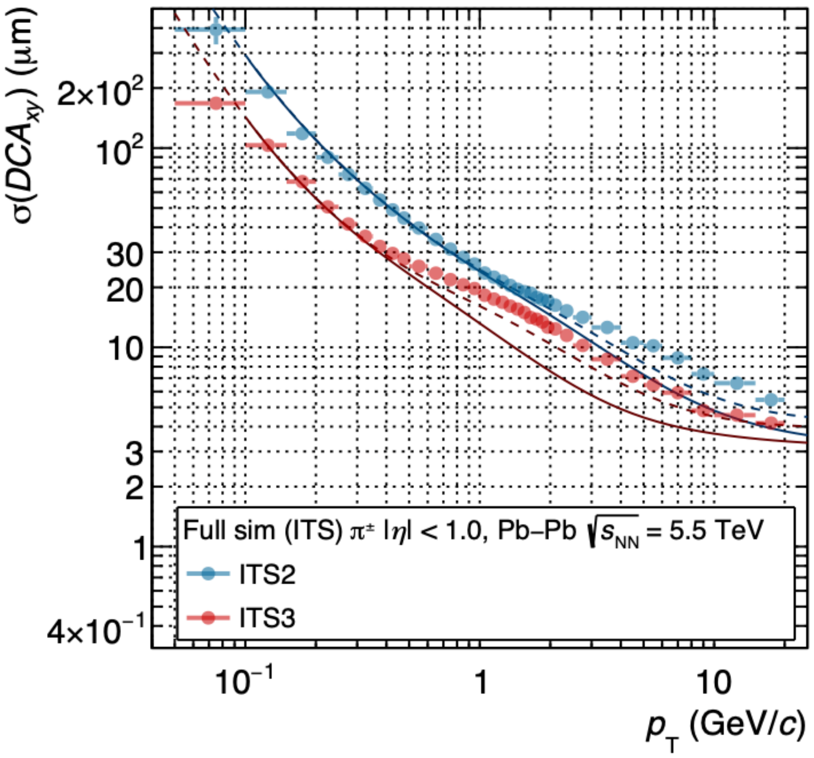
- Large wafer-scale ultra-thin sensor – 6 sensors
- Truly cylindrical – bent sensor
- No FPC for data, power – everything on silicon
- 0.09% X/X_0

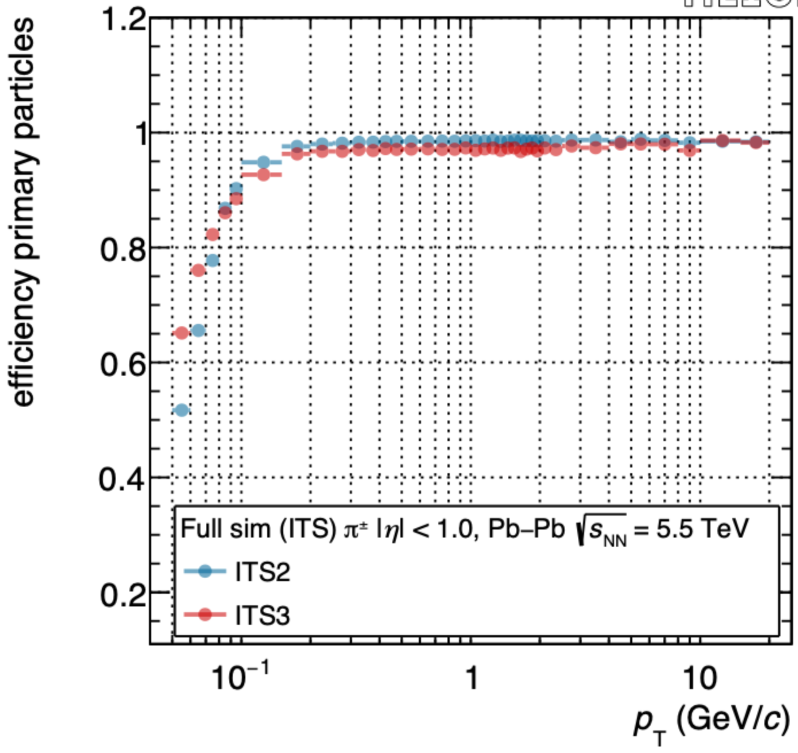
- Ultra-light self supporting mechanics
- No stave
- Air cooling

First time in a High Energy Physics experiment!

Ref. S. Siddhanta @ SQM 2026

ALICE ITS3: Performance





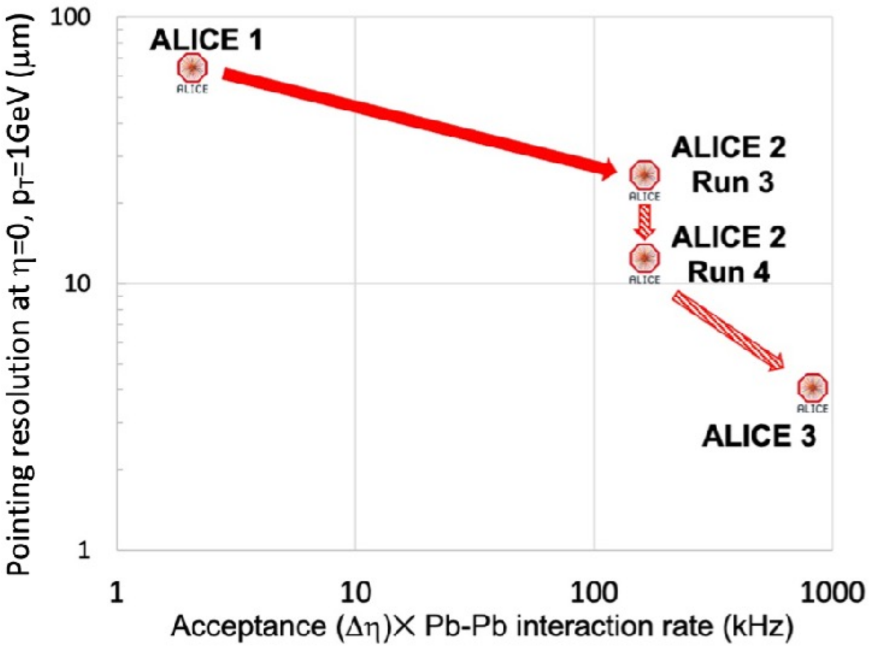
✓ improvement of factor 2 over all momenta

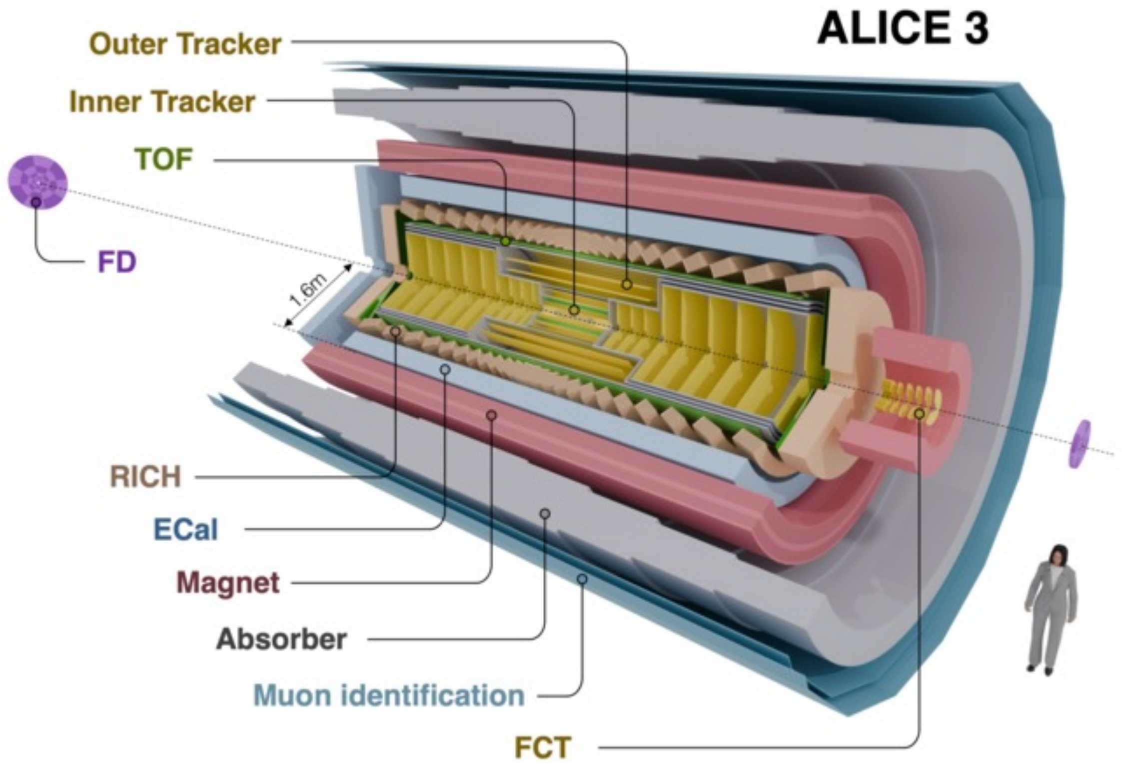
✓ large improvement for low transverse momenta

全硅探测器谱仪 -- ALICE 3 实验

- Compact, low mass, all-silicon detector, retractable vertex detector
- Super-conducting magnet system (2T)
- Extensive particle identification
- Continuous readout + online processing

下一代全硅实验

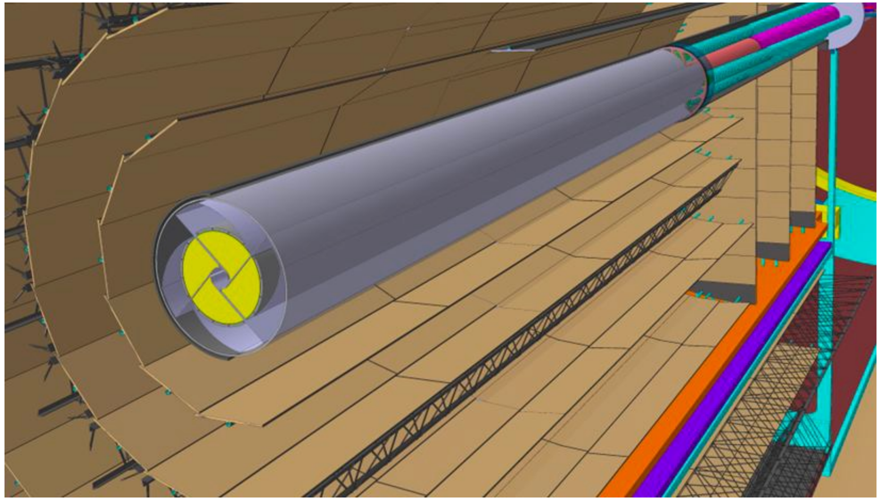


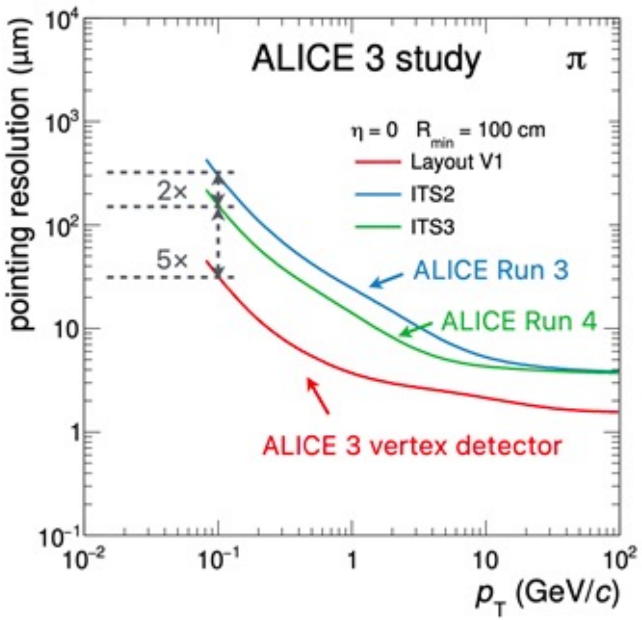


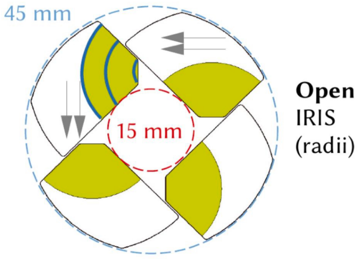
ALICE 3: Vertex Detector

Retractable vertex detector:

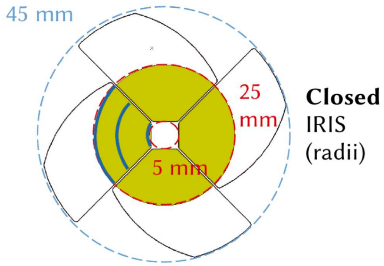
- ✓ Three layers within the beam pipe in secondary vacuum
- ✓ Stitching: Wafer-scale bent sensor (relying on ITS3 R&D)
- ✓ IRIS service system being developed
- ✓ Resolution: σ_{pos}~ $2.5\ \mu m$ → 10 μm pixel pitch
- ✓ Material: ~0.1% X/X_0 per layer
- ✓ 100 ns time resolution







Beam injection



Beam stable

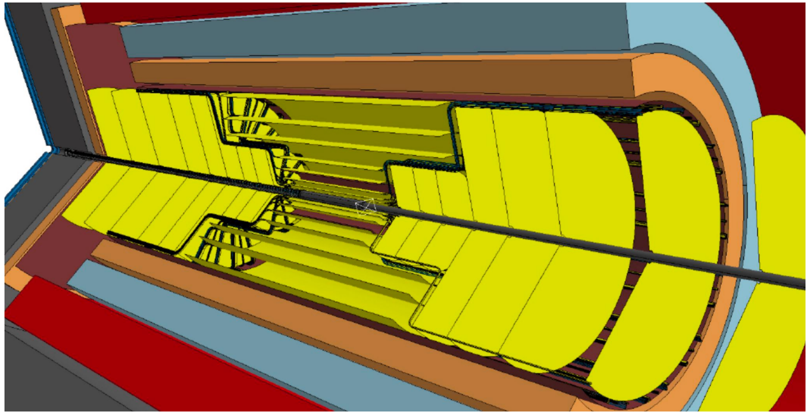
ALICE 3: Middle & Outer tracker

Requirements

Material: ~1% X/X_0 per layer

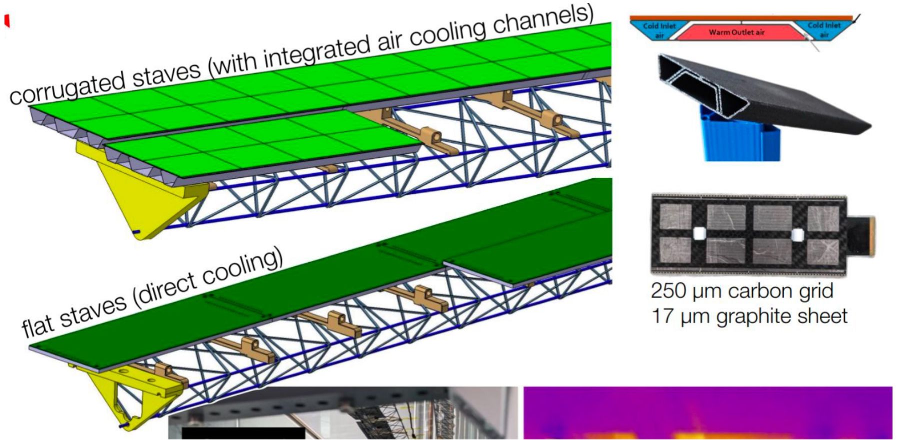
Spatial resolution: ~10 µm ➔ pixel pitch < 50 µm

Power consumption ≦ 20 mW/cm^2



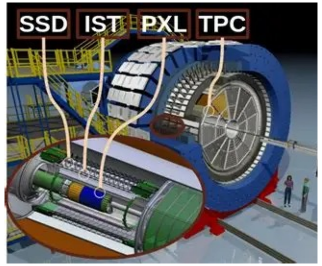
Implementation

- Four (middle) layers at 7-20 cm + 3x2 endcap disks
- Four (outer) layers at 30-80 cm+ 6x2 disk layers
  - 60 m^2 active detection area
  - CMOS MAPS are foreseen as the sensor technology.
  - The integration scheme is based on ITS 2 experience, with sensors assembled into modules and then into staves.

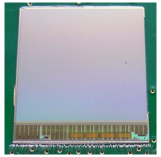


MAPS探测器研究进展

1st generation MAPS

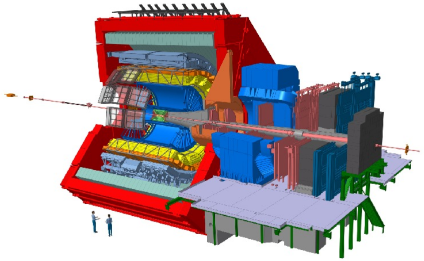


STAR PXL

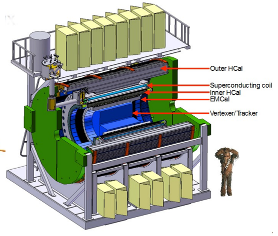


MIMOSA

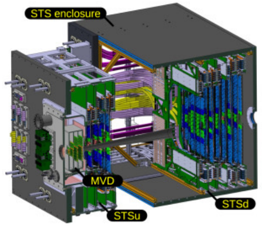
2nd generation MAPS



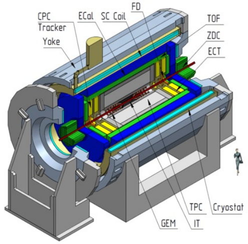
ALICE ITS2



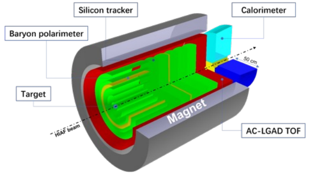
sPHENIX MVTX



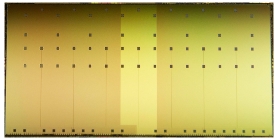
CBM STS



MPD IT

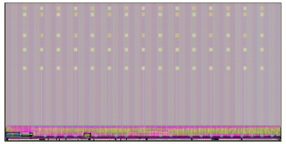


H-NS Tracker



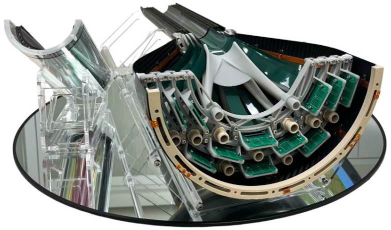
ALPIDE

MIMOSIS

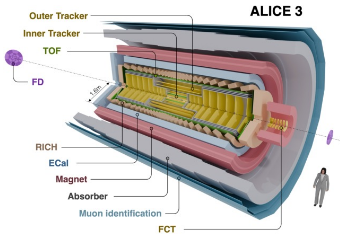


MIC6

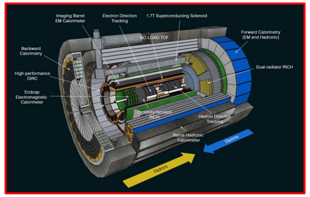
2nd + 3rd generation MAPS



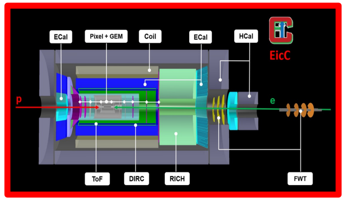
ALICE ITS3



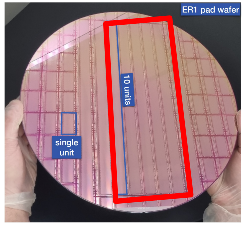
ALICE 3 Tracker



EIC/ePIC SVT

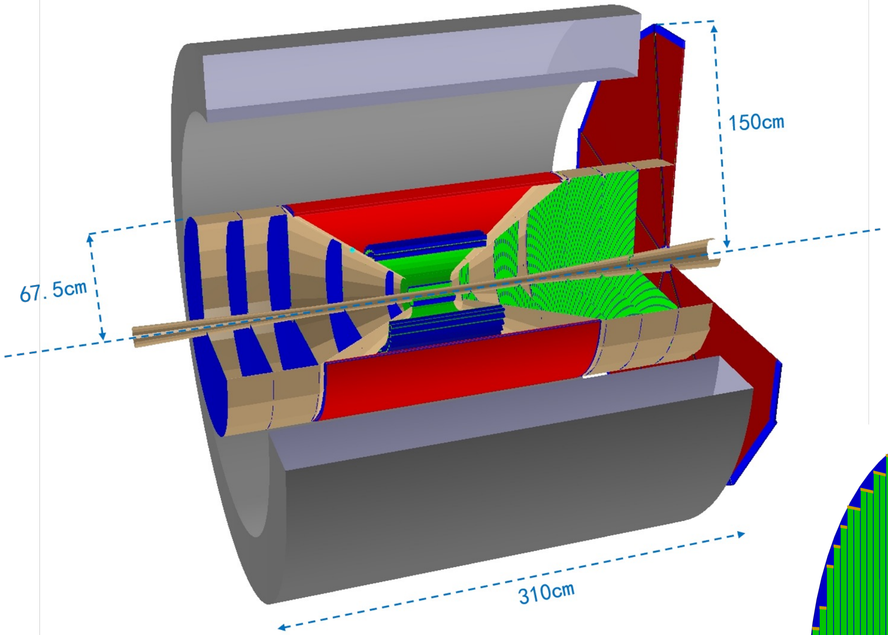


EicC Tracker

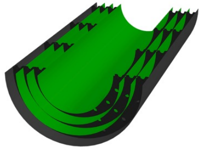


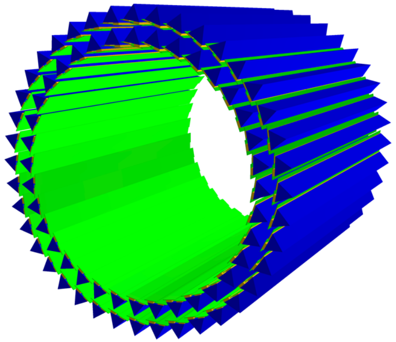
Stitching-based MOSAIX

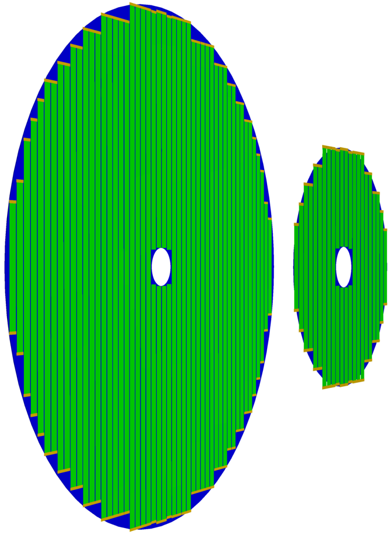
EicC径迹系统

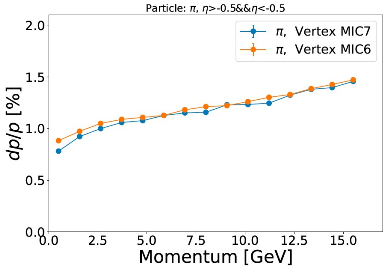


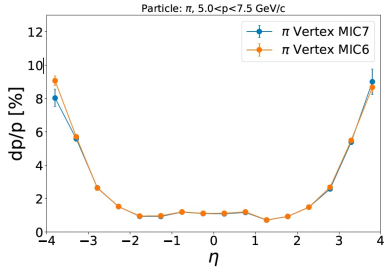
R(cm)	Length(cm)	Pitch Size(μm)	$X/X_0\%$		Tech.
3.3	28.0	20	0.09		MIC7
4.4	28.0	20	0.09	ITS3-like	MIC7
5.5	28.0	20	0.09		MIC7
27.5	73.42	30	0.85	ITS2-like	MIC6
30.0	80.01	30	0.85		MIC6
65.5	174.88	$150(r-\phi)$x150(z)	1.50		MPGD
67.5	174.88	$150(r-\phi)$x150(z)	1.50		MPGD

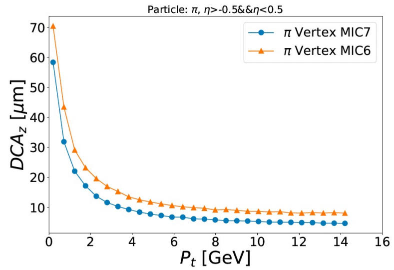


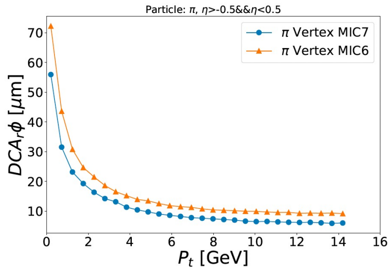




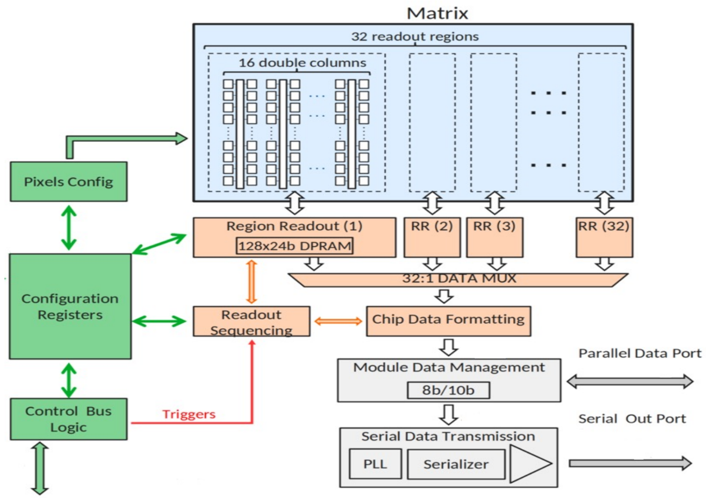




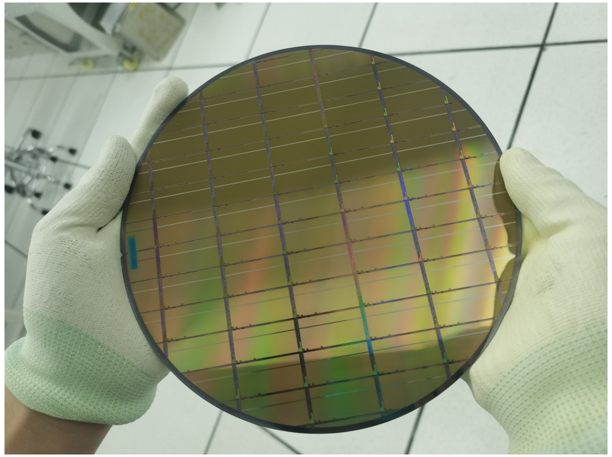


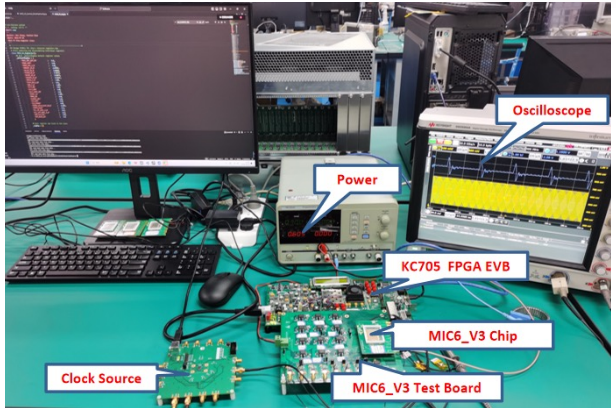


MIC6_V3 block diagram

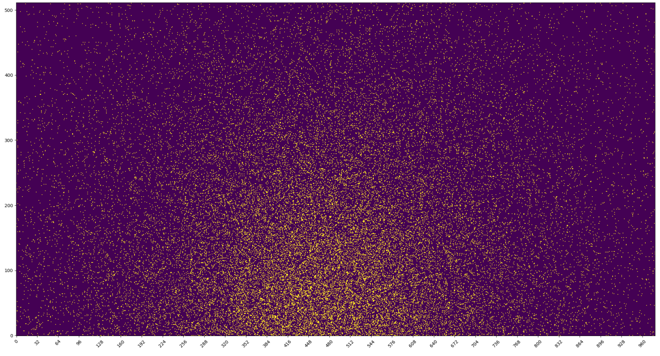


参数	ALPIDE	MIC6 原型
工艺	TowerJazz 180nm	GSMC 130nm
核心电压	1.8V	1.2V
芯片尺寸	30 mm × 15 mm	30 mm × 15.48 mm
像素阵列	1024 × 512	980 × 512
像素尺寸	29.24 um × 26.88 um	30.53 um × 26.8 um
像素达峰时间	2 us	1 us
积分时间	5~10 us	5~10 us
数据压缩读出	采用 AERD 方式读出	采用 AERD 方式读出
高速串行输出	1.2Gbps （8B10B 编码）	1.1Gbps （8B10B 编码）
功耗	40 mW/cm^2	32 mW/cm^2

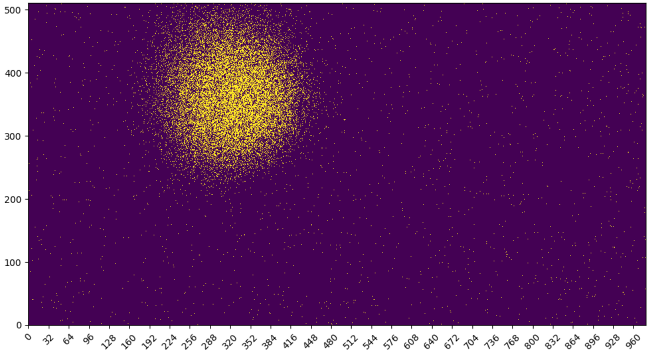




MIC6_V3芯片及测试系统

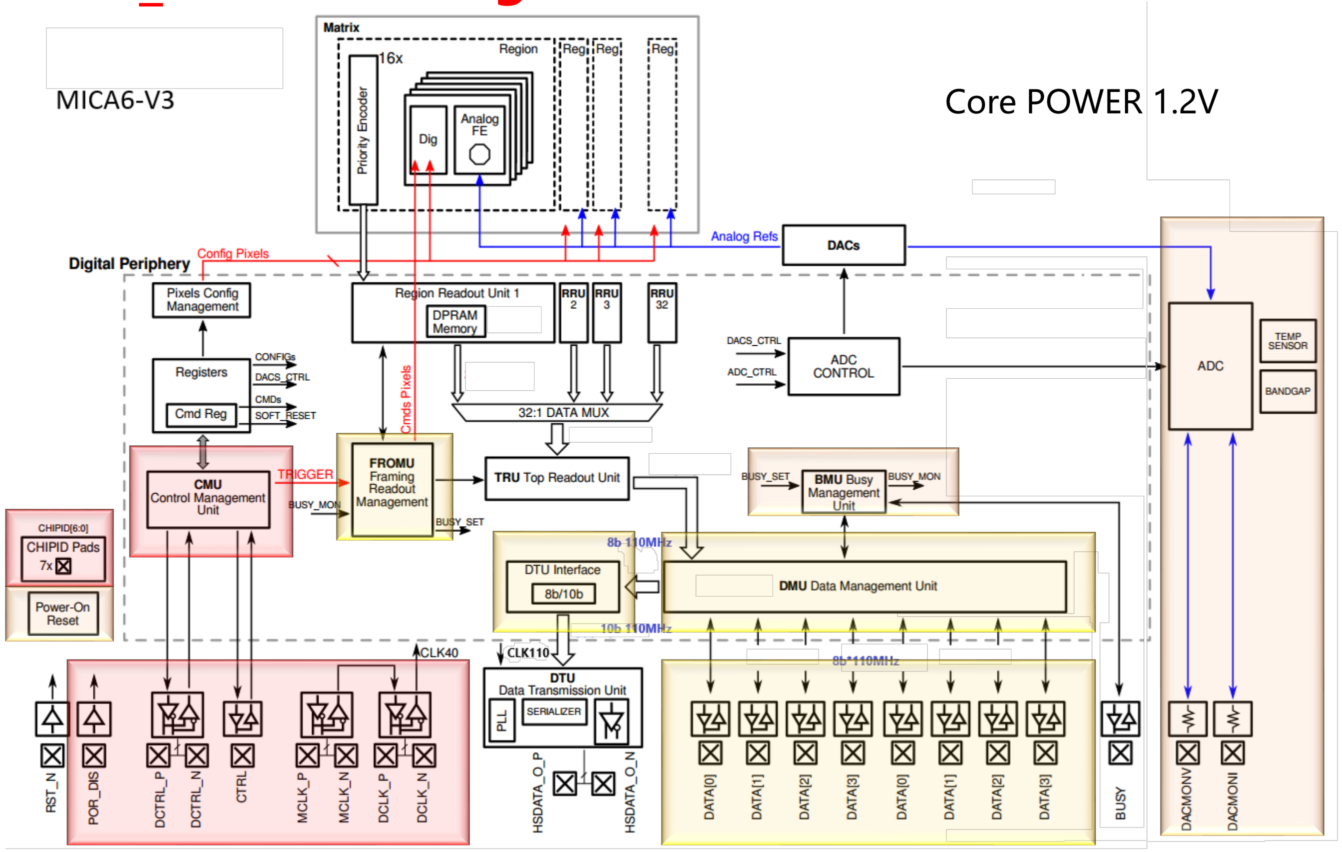


^{90}Sr测试



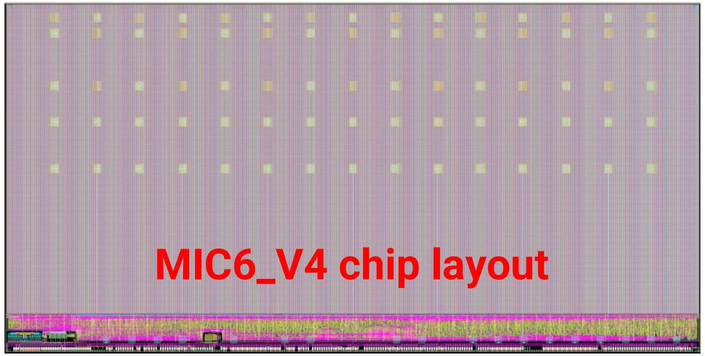
^{241}Am测试

MIC6_V4 block diagram



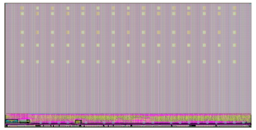
Add Red Parts **Modify Yellow Parts**

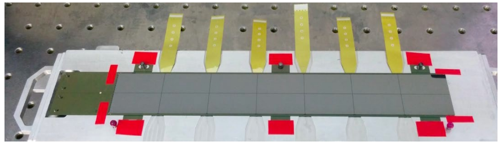
Features	MIC6_V4
Process Technology	GSMC-130 nm
Core Voltage	1.2V
Chip Size	30 mm×15 mm
Pixel Array	980×497
Pixel Size	30.53 um×26.8 um
Zero Suppression Readout	AERD
High-Speed Serial Output	1.2Gbps
Encoder	8B10B
Slow Control	MLVDS Control Bus
Parallel Data Interface	master-slave data aggregation and transmission

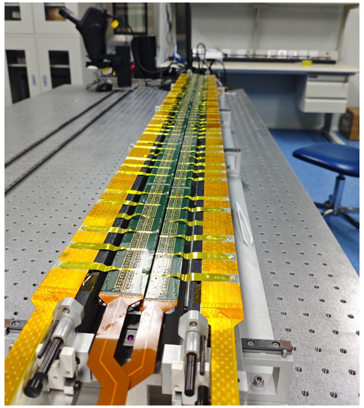

MIC6_V4 chip layout

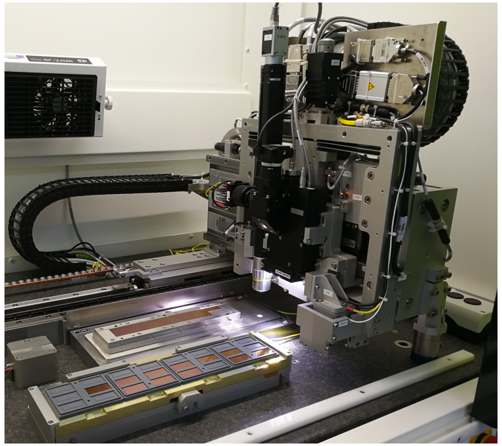
EicC径迹系统 – 探测器组装与集成

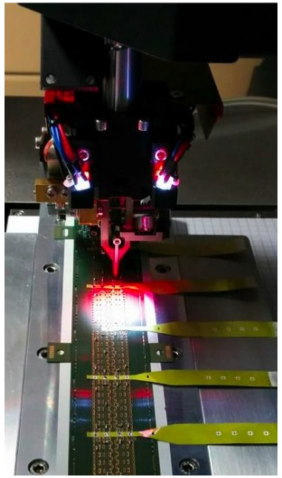
- 掌握从芯片集成到探测器模块组装的关键技术，建立组装与测试产线
- 围绕硅像素探测器研制，开展低物质量碳纤维复合材料结构设计与联合制备



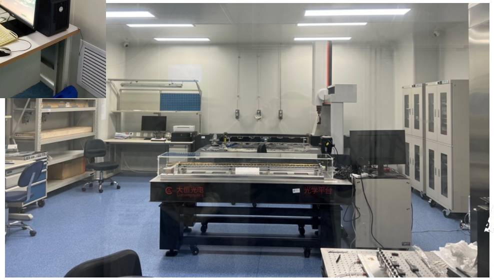




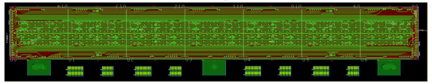




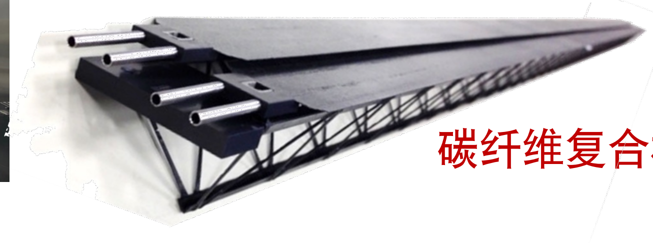
芯片集成千级净室



探测器模块组装万级净室



柔性PCB板



碳纤维复合材料结构

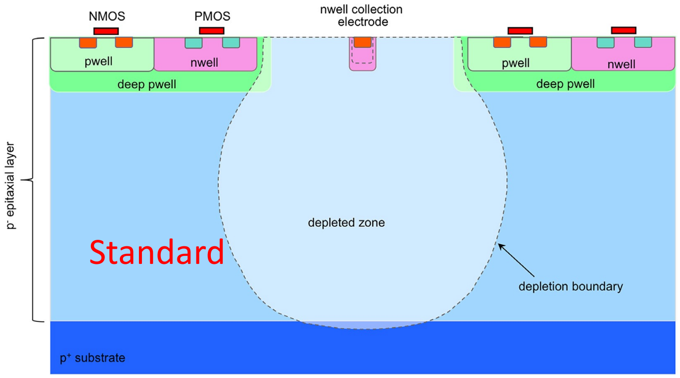
总结

- **自2001年提出CMOS MAPS概念以来，已先后成功应用于RHIC/STAR、LHC/ALICE和RHIC/sPHENIX等重离子碰撞实验;**
- **在建和拟推动建设的国内外大科学装置实验（NICA/MPD、EIC/ePIC、ALICE 3、H-NS和EicC、CEPC和STCF等）均将硅像素探测器作为其核心径迹探测器;**
- **近年来，硅探测器技术在国内发展非常迅速，中国研究团队积极参与并推动硅像素探测器在等国内外核物理和粒子物理实验的应用;**
  - ✓ MAPS: JadePix (IHEP&CCNU), MIC6 (CCNU), SuPix (SDU), STCF pix (USTC), TaiChuPix (IHEP), …
  - ✓ 读出电子学: USTC, IHEP, CCNU, SDU, …
  - ✓ 探测器组装与集成: CCNU, IHEP, IMP, CIAE, …
- **国内团队已完成EicC实验硅像素探测器系统的概念设计！**

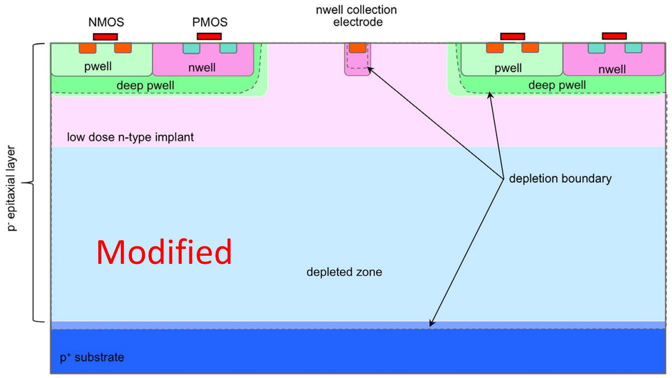
谢谢大家！

Full depleted MAPS

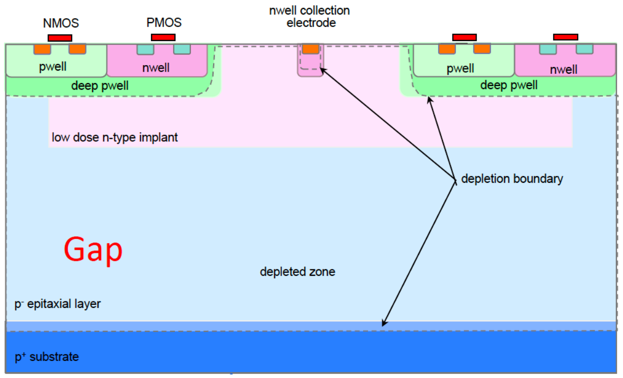
- ➢ A process modification developed as side activity of ALICE R&D
- ➢ Doping profiles of MAPS have been repeatedly improved to reach full depletion



https://doi.org/10.1016/j.nima.2017.07.046 (**ALICE R&D**)



https://iopscience.iop.org/article/10.1088/1748-0221/14/05/C05013 (**ALICE R&D**)



- Partially depleted epitaxial layer
- Charge collection time < 30 ns
- Operational up to 10^{14} 1 MeV n_{eq}/cm^2

- Fully depleted epitaxial layer
- Charge collection time < 1 ns
- Operational up to 10^{15} 1 MeV n_{eq}/cm^2