

CEPC Silicon Tracker Detector

Qi Yan

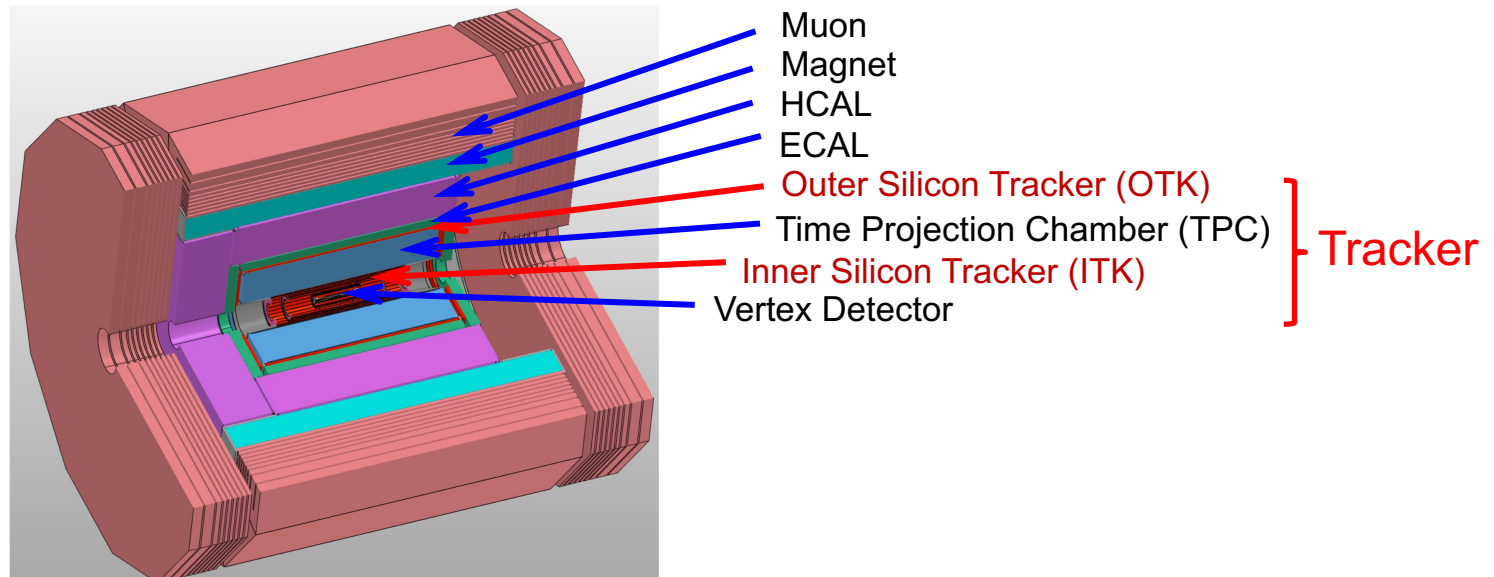
On Behalf of the CEPC Silicon Tracker Group



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Institute of High Energy Physics
Chinese Academy of Sciences

Introduction

- The CEPC tracker system includes several detectors: the Vertex Detector, Inner Silicon Tracker, Time Projection Chamber (TPC), and Outer Silicon Tracker. This presentation will focus on the Inner Silicon Tracker (ITK) and Outer Silicon Tracker (OTK).
- The ITK employs advanced sensor technologies, including HV-CMOS pixels and CMOS strips, to achieve precise position measurements for accurate particle trajectory determination.
- The Silicon Tracker measures particle's dE/dx . Additionally, the OTK incorporates the AC-LGAD semiconductor detector for precision time measurement of charged particles, significantly enhancing particle identification capabilities.



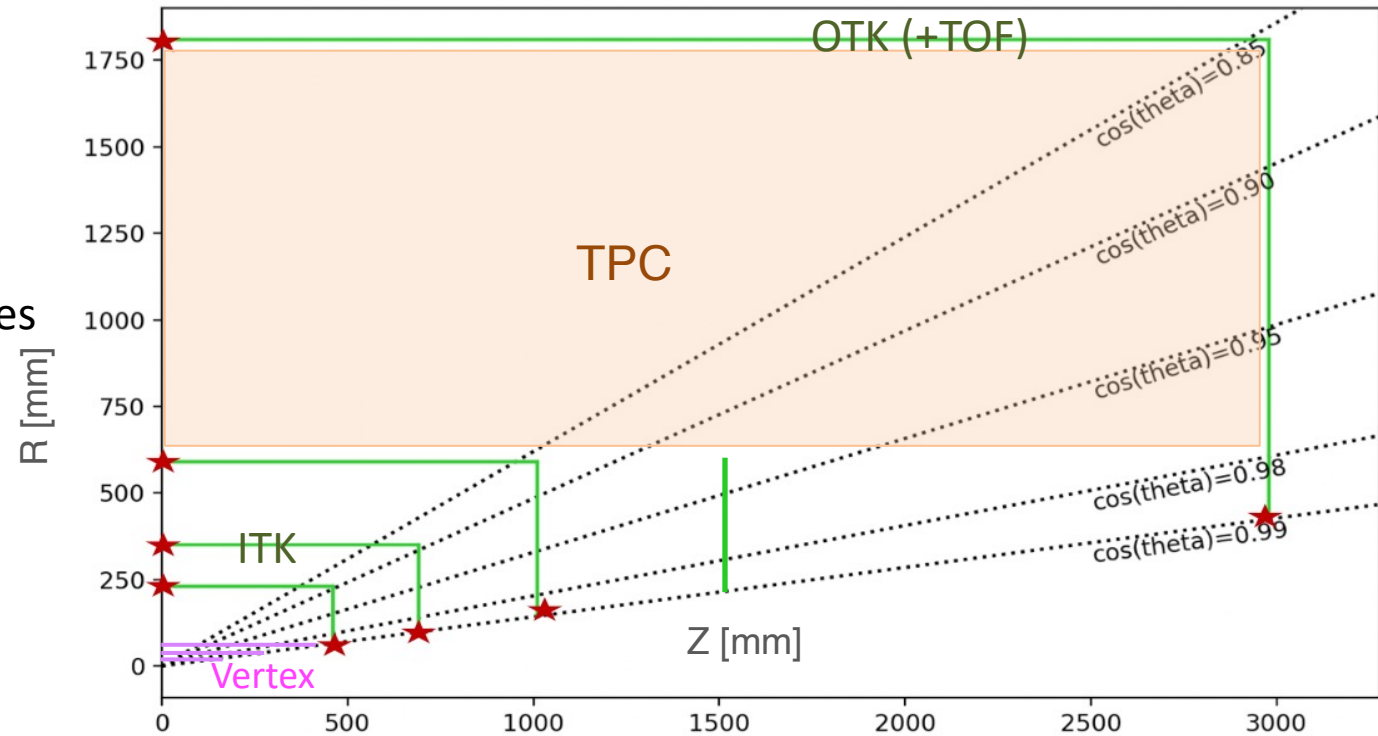
Requirements

■ Inner silicon tracker (ITK)

- Spatial resolution:
 - Barrel: $\sigma_\phi < 10 \mu\text{m}$ (bending), $\sigma_z < 50 \mu\text{m}$
 - Endcap: $\sigma_\phi < 10 \mu\text{m}$ (bending), $\sigma_r < 100 \mu\text{m}$
- Material budget:
 - $< 1\% X_0$ per layer
- Luminosity $\sim 115 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (Z-pole):
 - A few ns timing resolution to tag 23 ns bunches
 - Maximum hit rate $\sim 10^6 \text{ Hz/cm}^2$
- Cost effectiveness:
 - $\sim 20 \text{ m}^2$ area

■ Outer silicon tracker (OTK) with TOF

- Spatial resolution:
 - $\sigma_\phi < 10 \mu\text{m}$ (bending)
- Timing resolution:
 - $\sigma_t < 50 \text{ ps}$
- Cost effectiveness:
 - $\sim 85 \text{ m}^2$ area



The overall track momentum resolution requirement:
better than 0.3% for momenta below 100 GeV/c.

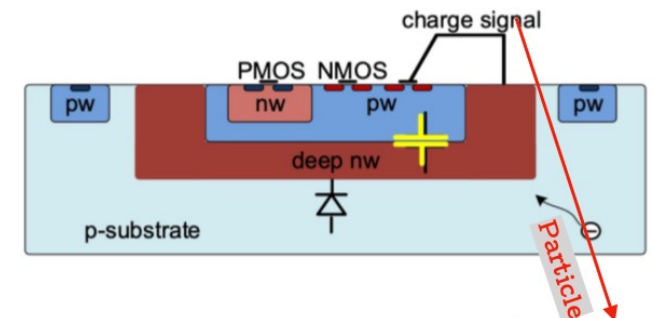
Technology Survey and Our Choice for ITK

■ CMOS sensor technology:

- Cost-effective: CMOS technology is widely used in the semiconductor industry, offering a unique opportunity for development of advanced semiconductor detectors for HEP.
- Simplified: The active detection layer and readout electronics are integrated into a single chip.

■ HVCMOS pixels:

- Large depletion depth (full depletion), large signal, and good time resolution.
- Radiation hard.
- Low materials.
- Relatively large capacitance, leading to increased noise and power consumption.



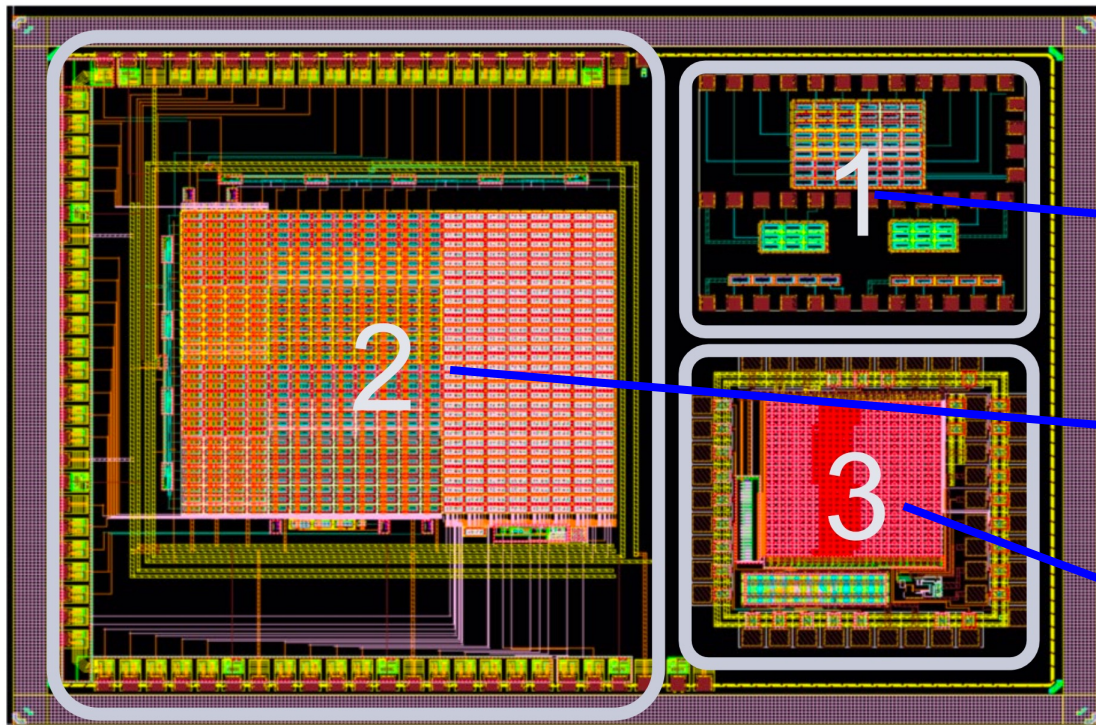
■ CMOS strips compared with CMOS pixels:

- Lower cost and power consumption per chip.
- Simpler readout with fewer technical barriers for chip development, as there is no interference between the readout circuit and sensor due to the detection distance.
- Comparable or even better spatial resolution, and negligible track ambiguity through specific detector layout design.
- **The CEPC ITK endcap is designed with strip sensors featuring a 22.5° cross angle between 2 half-layers.**
 - Advantages: Better intrinsic spatial resolution in bending direction ($\sim 3.6 \mu\text{m}$) and improved charge resolution for PID.
 - Disadvantages: Compared to pixel detectors, it requires twice the number of detector chips, along with a certain increase in materials budget.

R&D: CMOS Chip Development

CMOS pixels (COFFEE2): SMIC 55 nm CMOS process

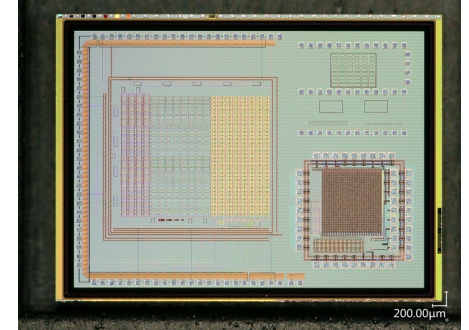
Submitted in Aug 2023, received in Dec 2023



CMOS SENSOR IN
FIFTY-FIVE NM PROCESS



COFFEE2



Three sections in the chip:

1: Passive diode arrays:

- Including 6 different signal collection structures for studying diodes and charge sharing.

2. Pixel arrays with diodes and in-pixel electronics:

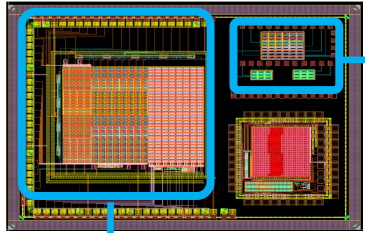
- Features 6 types of diodes and 3 types of in-pixel electronics.

3. Pixel arrays with peripheral digital readout:

- Used for validating readout strategies

The COFFEE2 chip test is progressing well, and the tape-out of the first CMOS strip chip (CSC1) for CEPC is scheduled for submission in 1-2 months.

HVCMOS (COFFEE2) Chip Test

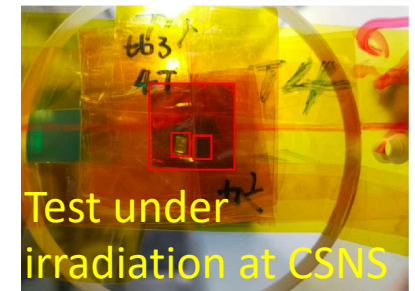
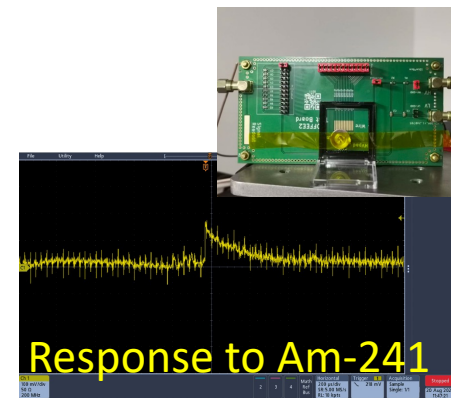
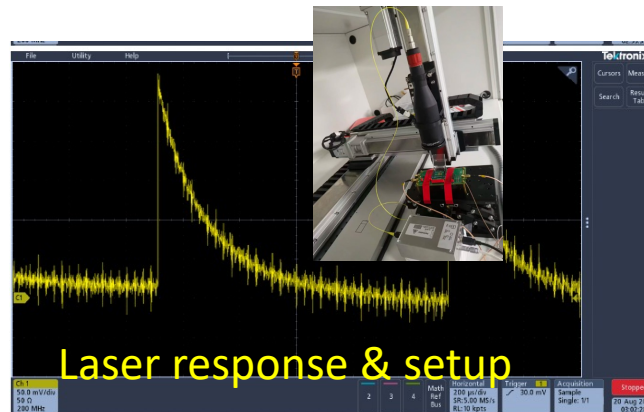
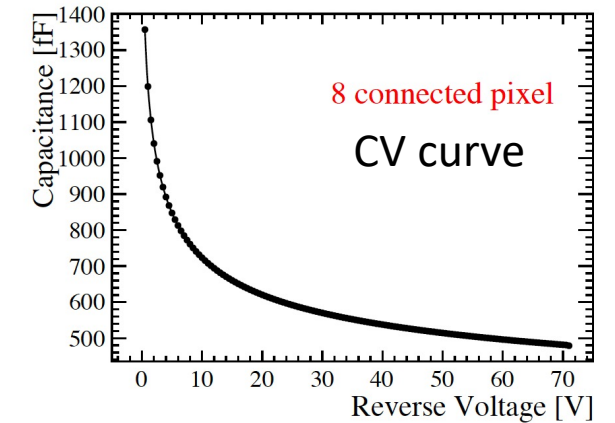
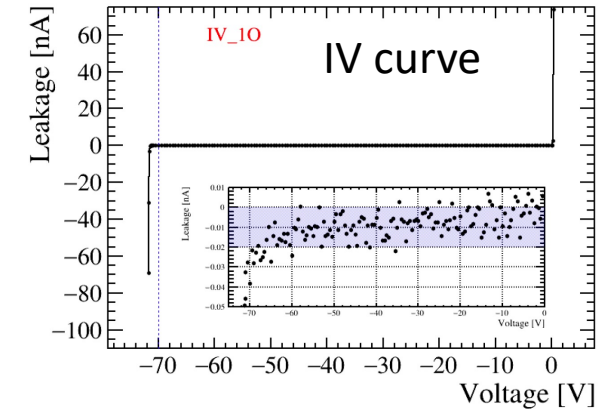


■ So far tests have been focused on passive diode arrays

- IV (breakdown at -70 V)
- CV (single pixel $\sim 30\text{-}40\text{ fF}$)
- Leakage current increased from 0.01 nA to $\sim 1\text{ nA}$ after $10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$ radiation
- Laser response observed
- Radioactive source observed

■ Circuit test almost ready

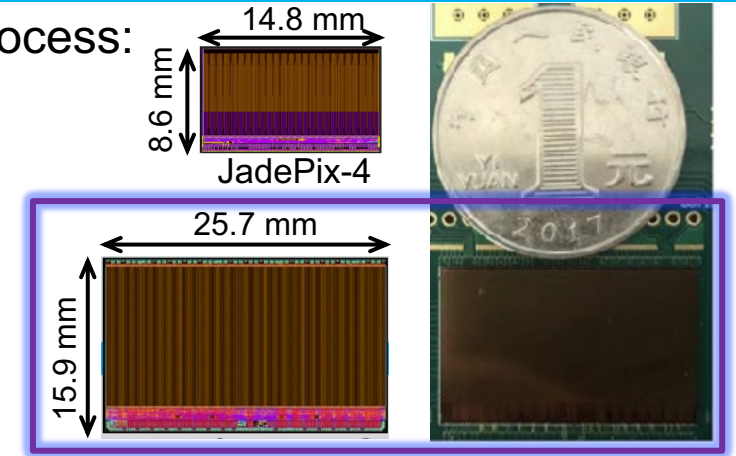
- Carrier board fabricated
- Caribou system installed, final firmware debugging



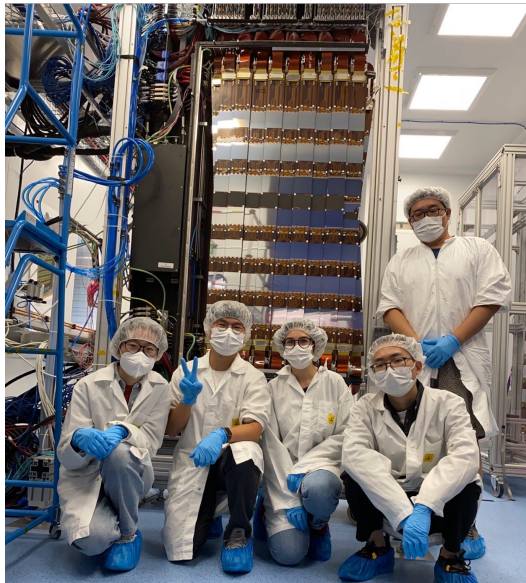
Experience in Silicon Detector Development

- The IHEP team has successfully developed several fully functional MAPS:
 - JadePix, TaichuPix, CPV, etc.
- Major contributions to silicon detector testing, integration and operation:
 - LHCb Upstream Tracker, AMS L0 upgrade, ATLAS ITK, ATLASPix, CHESS, etc.

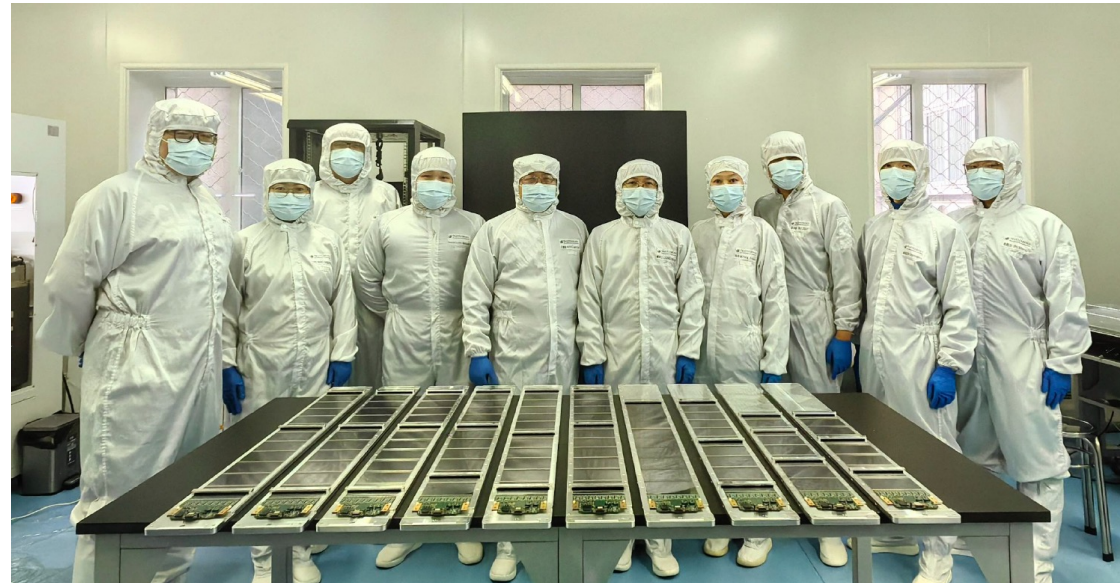
CIS process:



TaichuPix-3



LHCb UT A-side assembly



AMS L0 ladder production



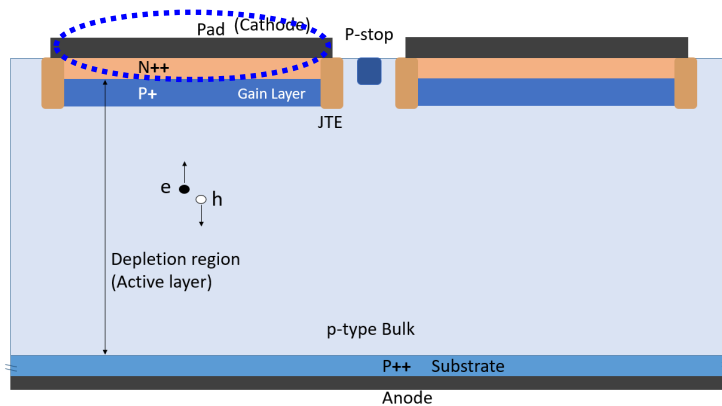
ATLAS ITK strip module

OTK (+TOF): Technology Survey and Our Choice

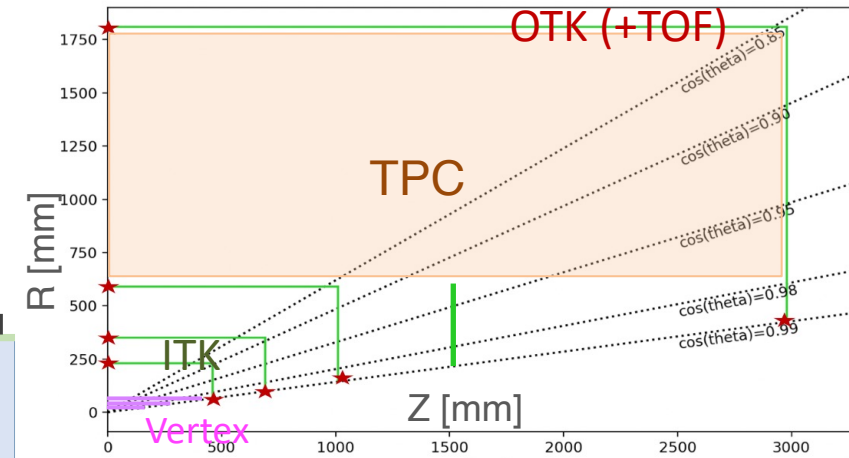
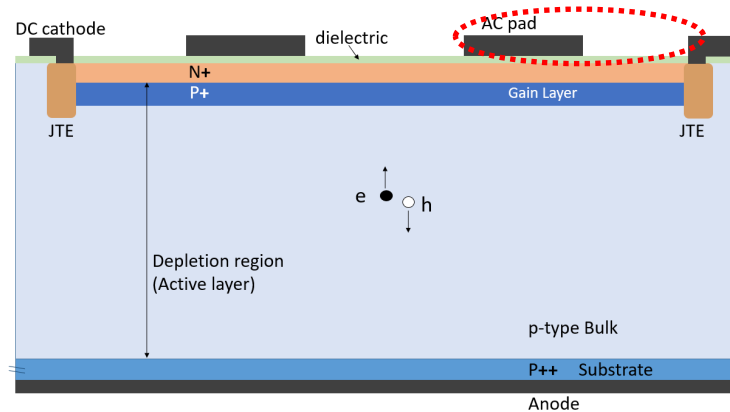
■ The outer silicon tracker (OTK) uses AC-LGAD microstrip sensor:

- Spatial resolution: 10 μm (with a strip pitch of 100 μm)
- Time resolution: 30-50 ps

LGAD (Low-Gain Avalanche Diode) Segmented gain layer



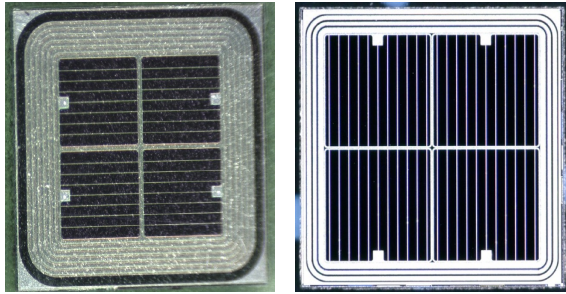
AC-LGAD (AC-coupled LGAD) Continuous gain layer



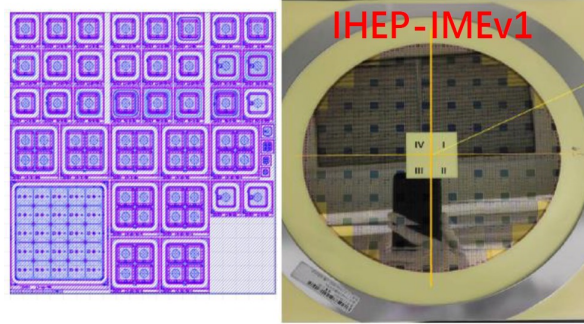
- The read-out electronics is connected to the N++ layer.
- A thin dielectric layer (Si_3N_4 , SiO_2) separates the metal AC pads from the N+ layer.
- Less dead area and better position resolution.

LGAD Development at IHEP

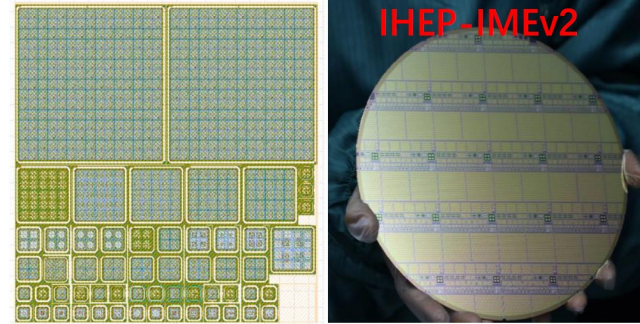
IHEP-NDL(2019)



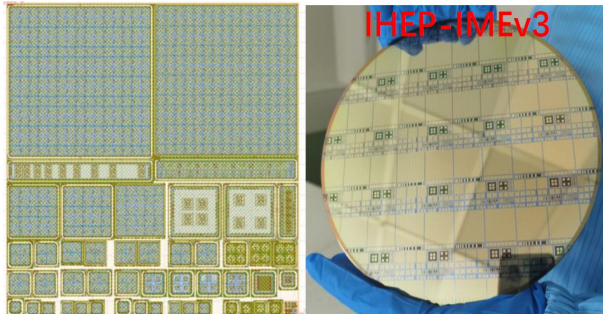
IHEP-IMEv1(2020.9)



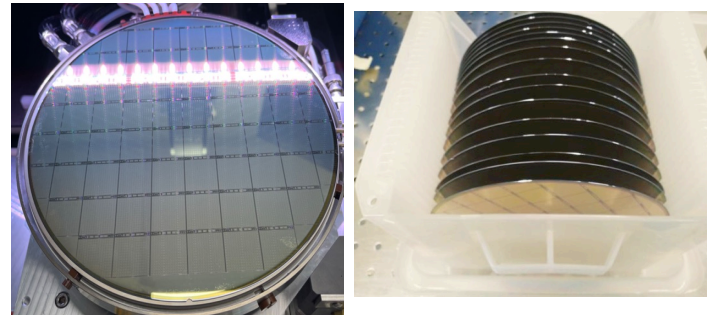
IHEP-IMEv2(2021.6)



IHEP-IMEv3(2022.5)



Pre-production for ATLAS (2023.7)

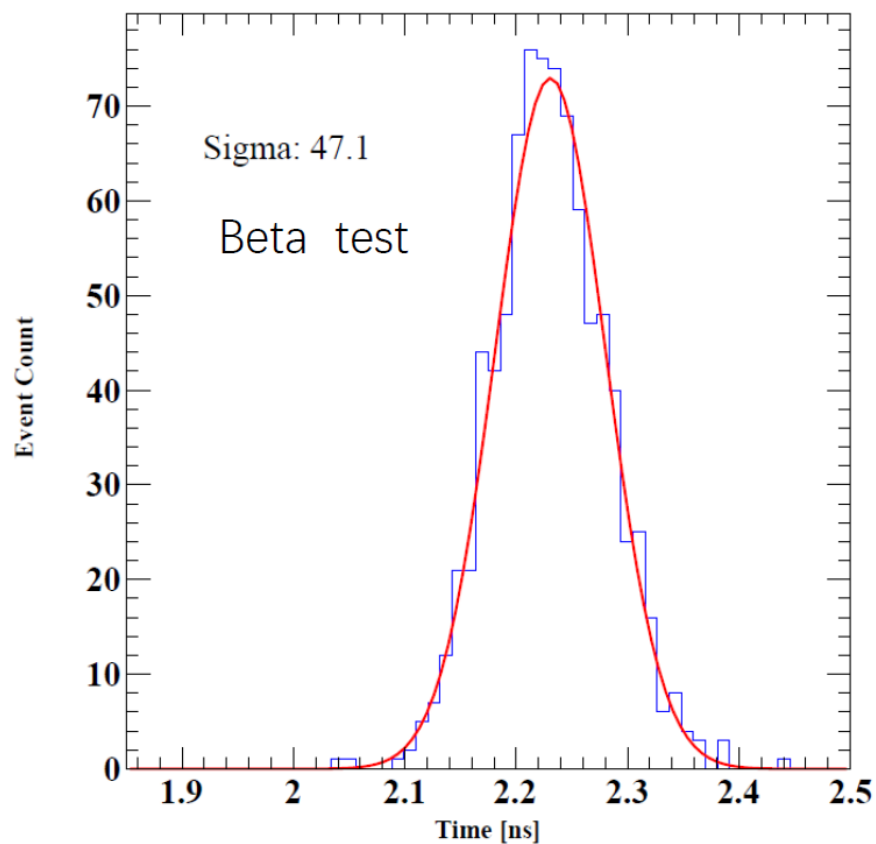


Mass production
for ATLAS (2024.6)



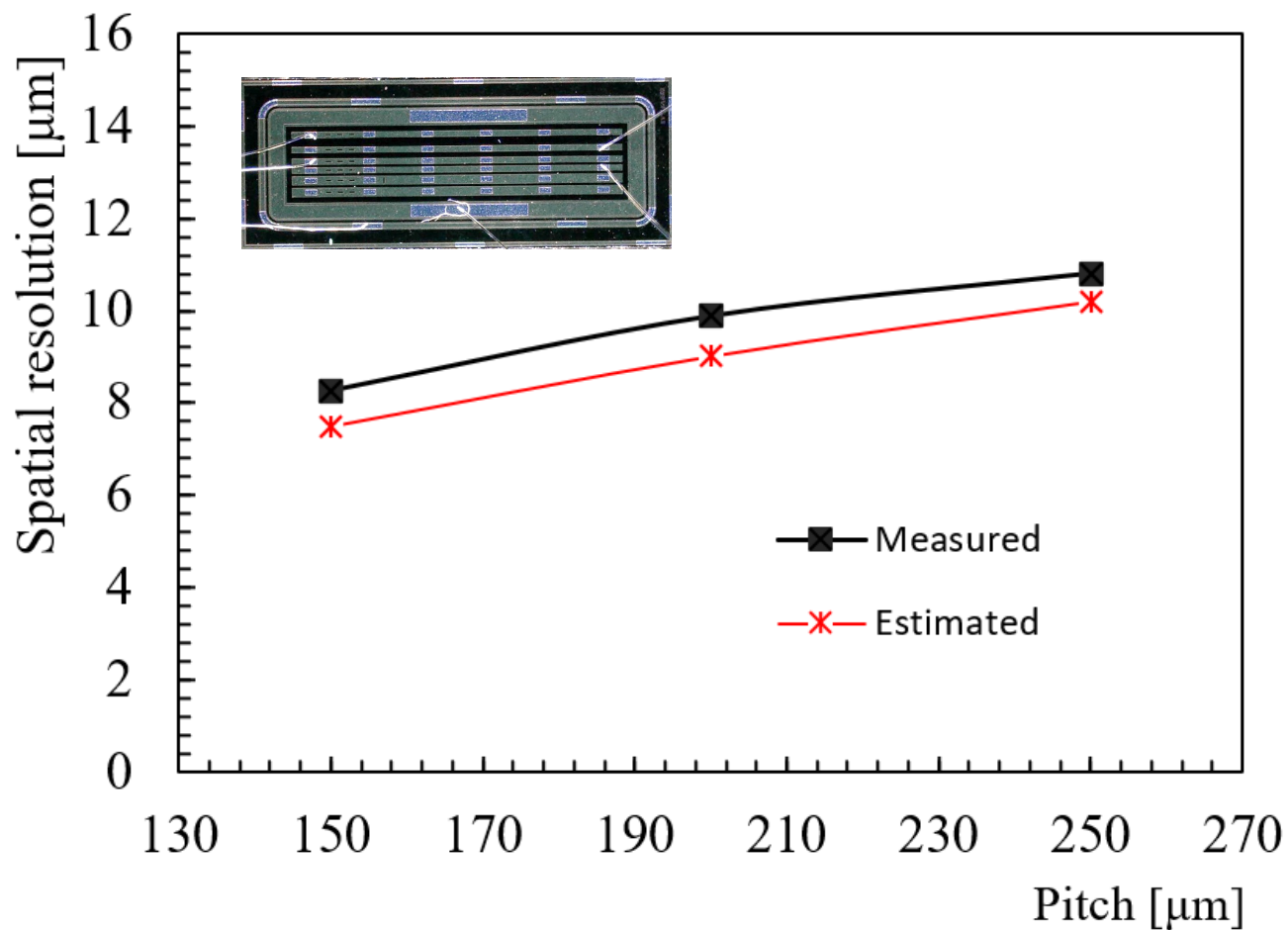
- In May 2023, CERN selected IHEP-IME in the HGTD sensor tendering process:
 - First time a domestic silicon sensor was chosen by CERN for an LHC experiment.
 - IHEP won the competition against Hamamatsu (Japan) and FBK (Italy).

AC-LGAD Performance: Time and Spatial Resolution



Time residual sigma: 47.1 ps

Time resolution: 37.5 ps



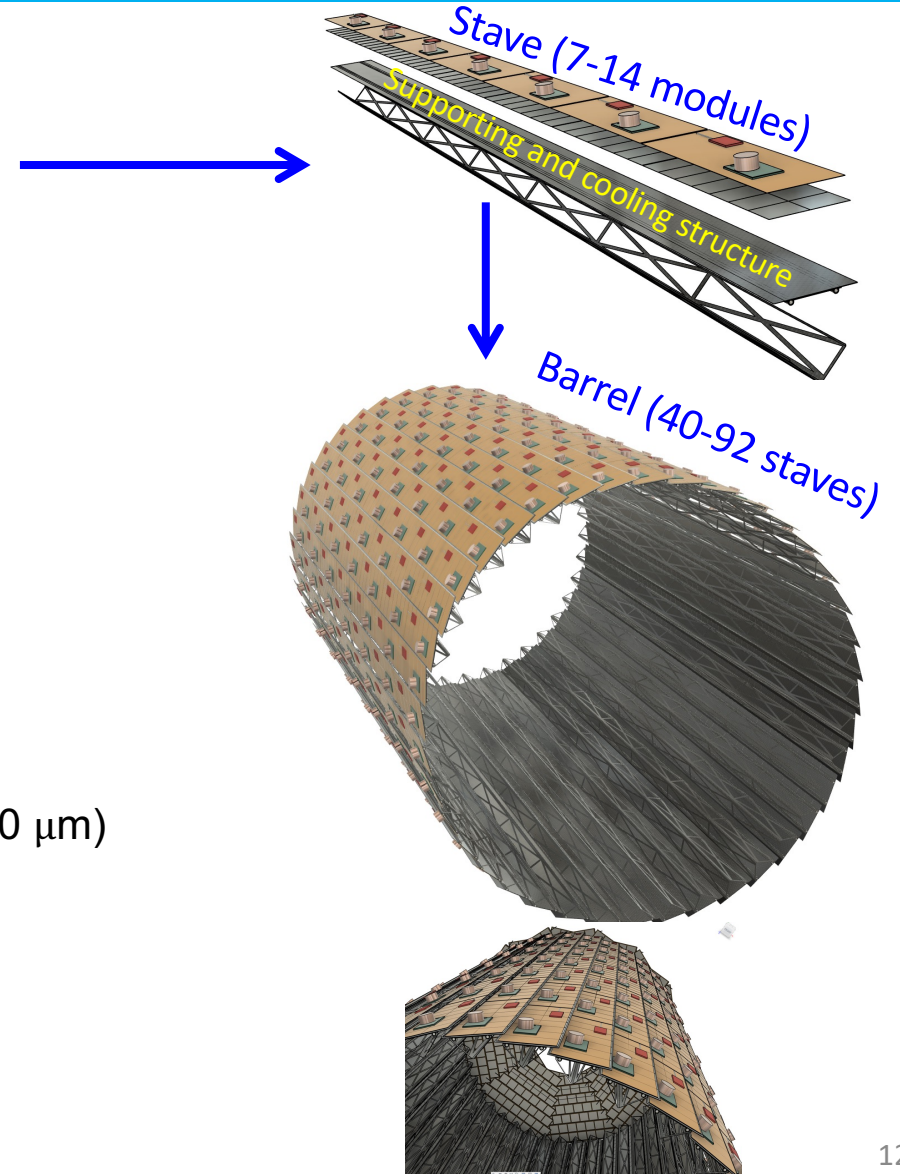
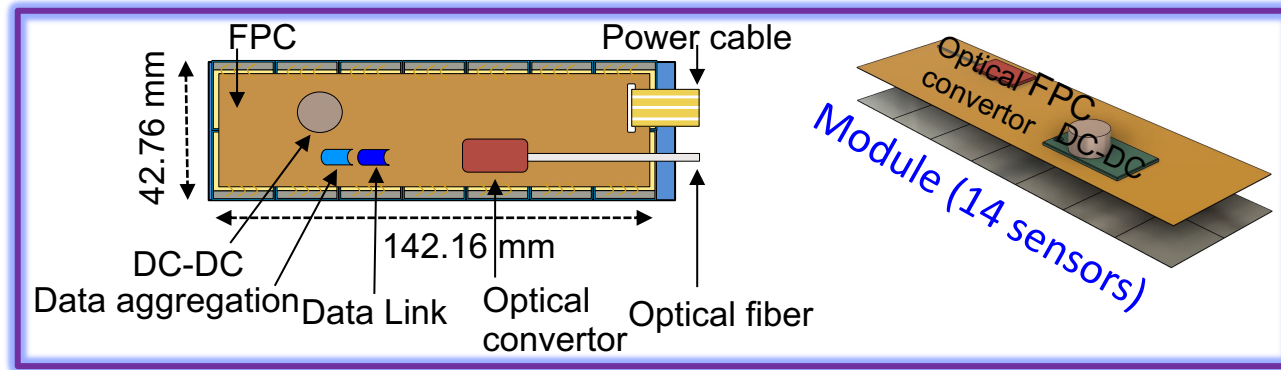
Spatial resolution: 8 μm for 150 μm strip pitch size

Summary of Sensor Parameters

	Monolithic HVCMOS pixels	Monolithic CMOS strips	Hybrid AC-LGAD strips
Pixel Size (Strip Pitch Size)	34 μm \times 150 μm	20 μm	100 μm
Sensor size	2 cm \times 2 cm (active area: 1.92 cm \times 1.74 cm)	2.1 cm \times 2.3 cm (active area: 2.05 cm \times 2.05 cm)	(6-9) cm \times (3-5) cm
Array size (Strip number)	512 rows \times 128 columns	1,024	384-512
Spatial resolution	σ_{ϕ} \sim 8 μm (bending), σ_z \sim 40 μm	σ \sim 5 μm	σ \sim 10 μm
Timing resolution	\sim 3-5 ns	\sim 3-5 ns	\sim 50 ps
Data size per hit (1 readout)	42 bits (14b BXID, 7b+9b address, 6b TOT, 5b fine TDC, 1 polarity)	32 bits (10b BXID, 10b address, 6b TOT, other 6 bits)	40-48 bits
Data rate per sensor	Maximum \sim 0.1 Gbps* (pair production)	Maximum \sim 0.2 Gbps* (pair production)	Maximum \sim 0.15 Gbps* (pair production)
LV / HV	1.2 V / 150 V	1.8 V / 150 V	1.2 V / 200 V

* Maximum hit rate: ITK barrel \sim 4.1×10^5 Hz/cm², ITK endcap \sim 7.5×10^5 Hz/cm², OTK barrel \sim 0.9×10^4 Hz/cm², OTK endcap \sim 3.5×10^4 Hz/cm²

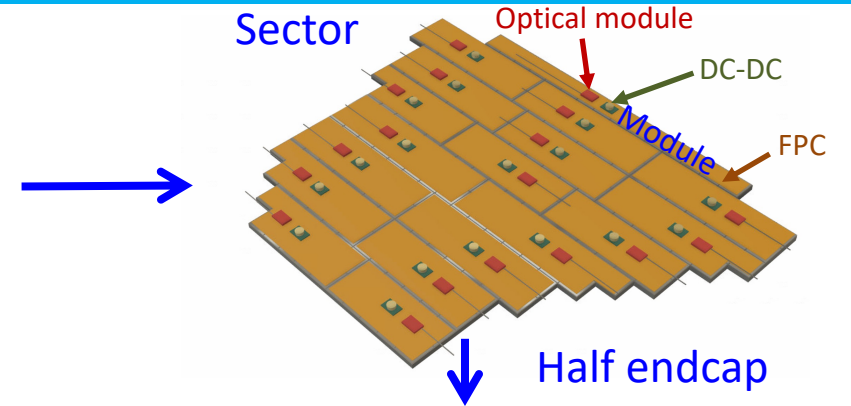
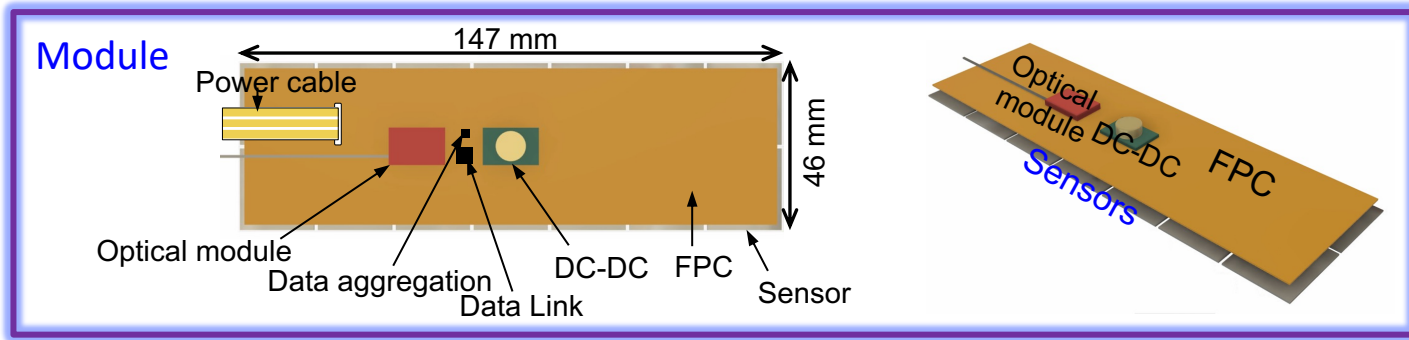
CEPC ITK Barrel Design (HVCMOS Pixels)



■ HVCMOS pixels for CEPC:

- Utilizes 55 nm process instead of the 180 nm used in ATLASPix3
More functionality and less power consumption
- Wafer resistivity: 1k-2k Ω -cm
- Chip size: 2 cm \times 2 cm
- Array size: 512 rows \times 128 columns
- Pixel size: 34 μ m \times 150 μ m (spatial resolution: 8 μ m \times 40 μ m)
- Time resolution: 3-5 ns
- Power consumption: \sim 200 mW/cm²

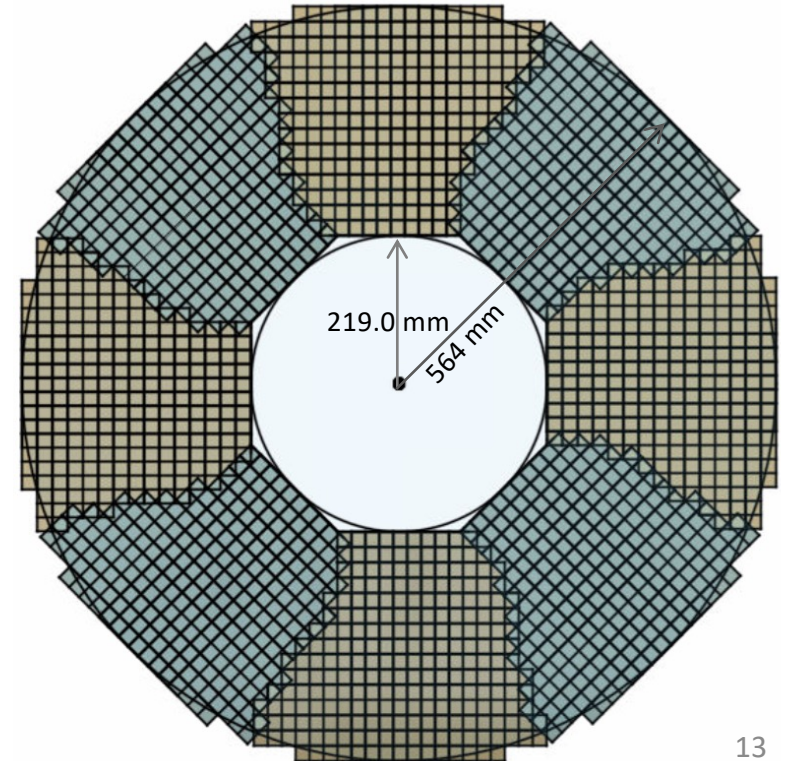
CEPC ITK Endcap Design (CMOS Strips)



■ CMOS Strip Chip (CSC) for CEPC:

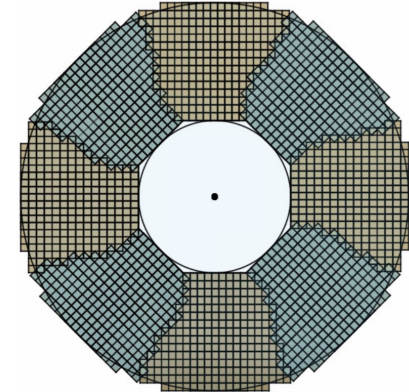
- Utilizes 180 nm process (CSMC, Wuxi Shanghua)
- Wafer resistivity: 2k Ω ·cm
- Chip size: 2.1 cm \times 2.3 cm
- Strip number per chip: 1,024
- Strip pitch size: 20 μ m (spatial resolution <5 μ m)
- Time resolution: 3-5 ns
- Power consumption: \sim 80 mW/cm²

Each half endcap is divided into 8 sectors, with each sector consisting of CMOS strip modules. The overlapping areas between the neighboring sectors are designed to be minimal.

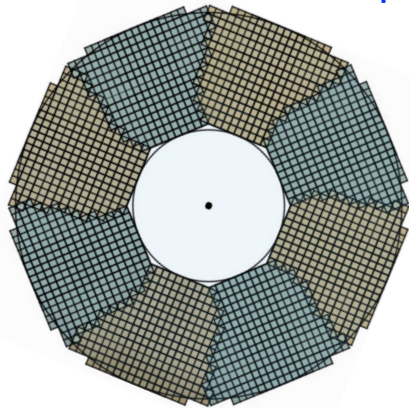


Two half endcaps are rotated 22.5° relative to each other to form one complete endcap:

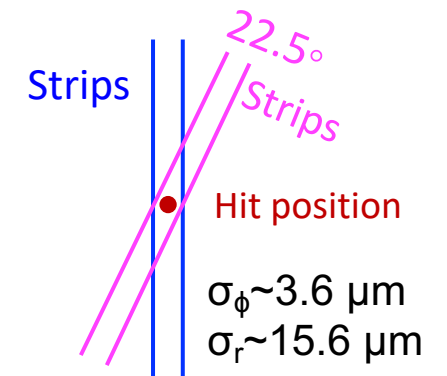
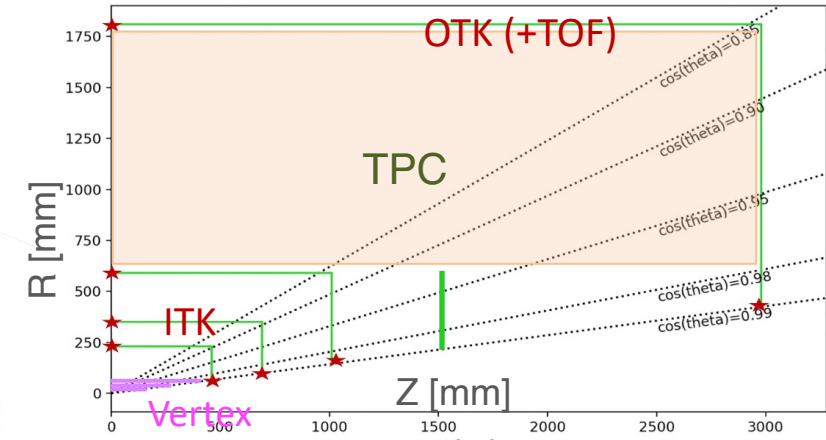
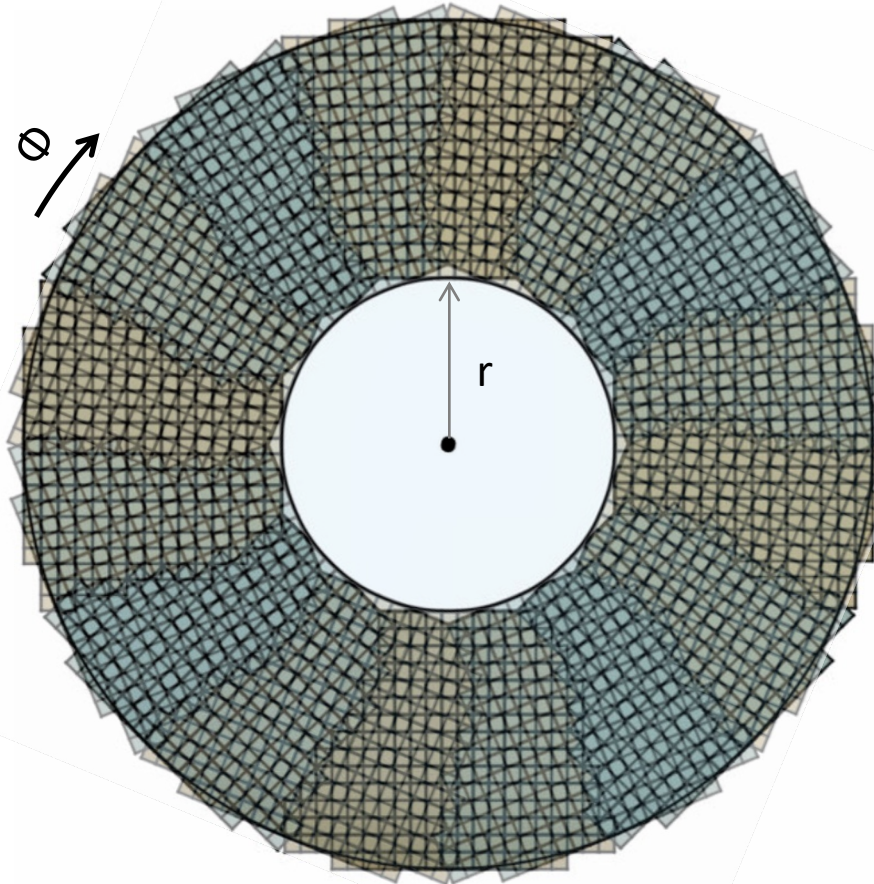
- Maximize track resolution in bending direction ϕ
- Minimize track ambiguity



Normal half endcap



22.5° half endcap

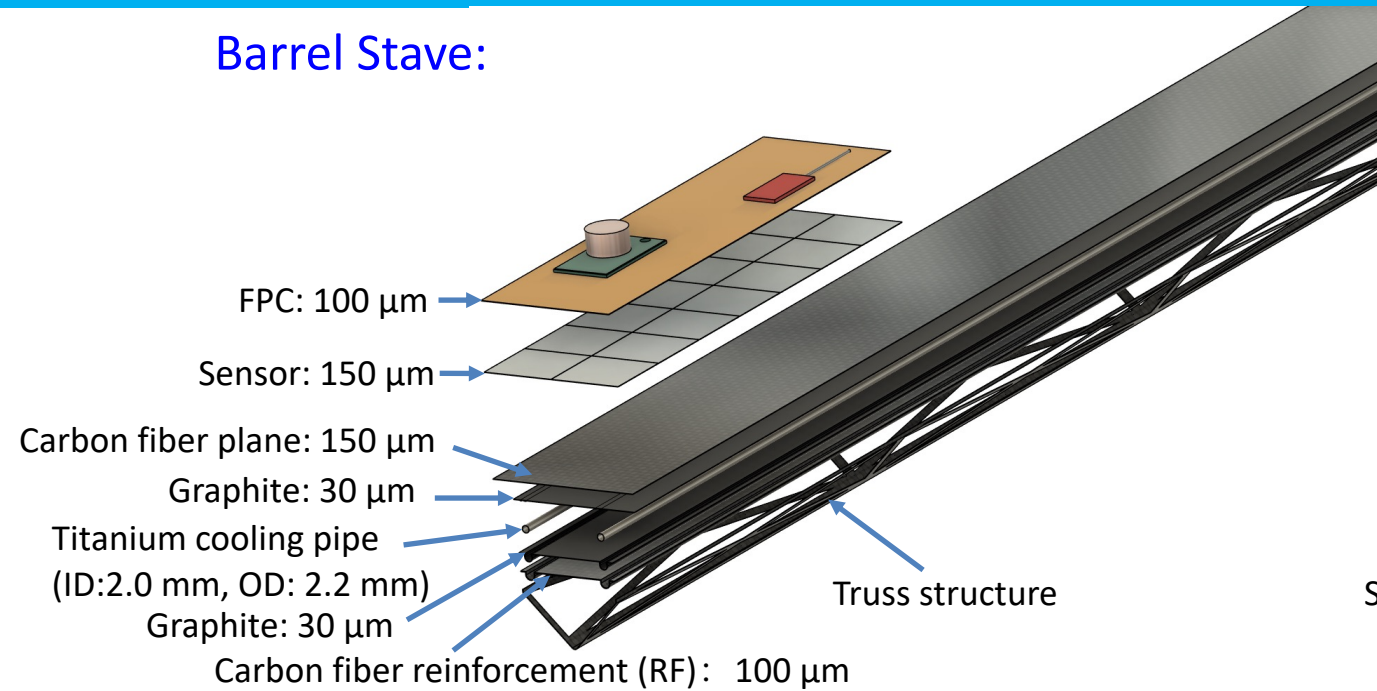


Detection precision using 20 μm pitch strips

The CEPC ITK barrels using pixels is considered for minimal material, while ITK endcaps using strips is optimized for high momentum measurement and particle identification (no TPC).

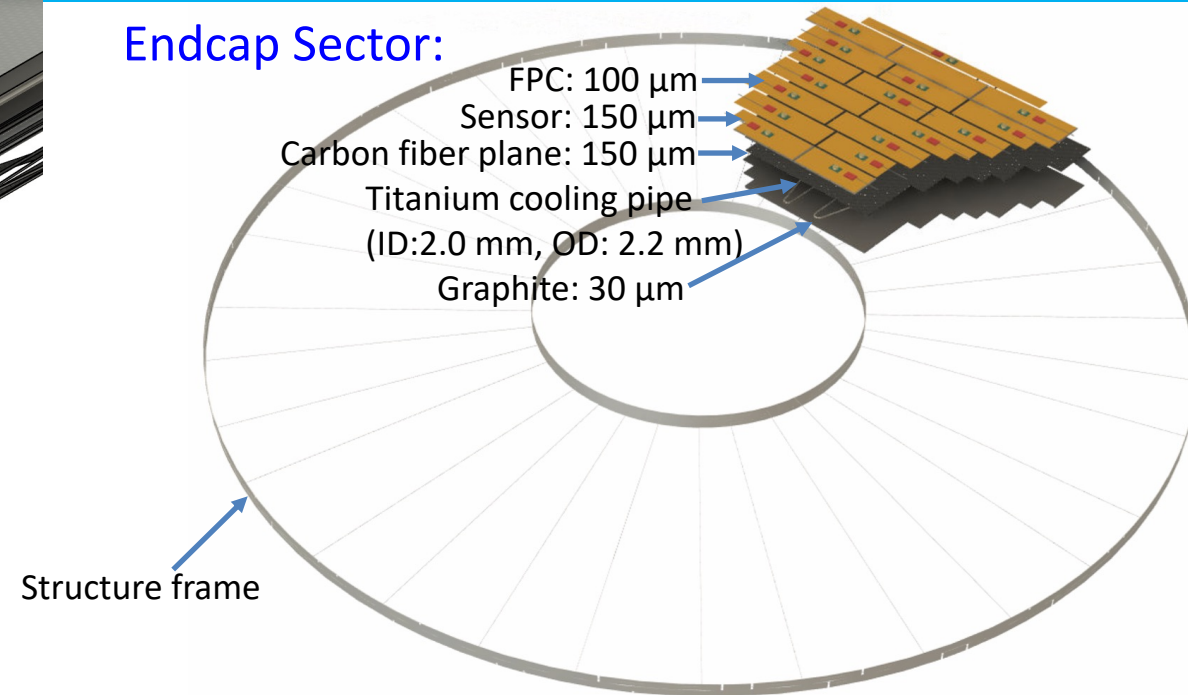
ITK Mechanical and Cooling Structure

Barrel Stave:



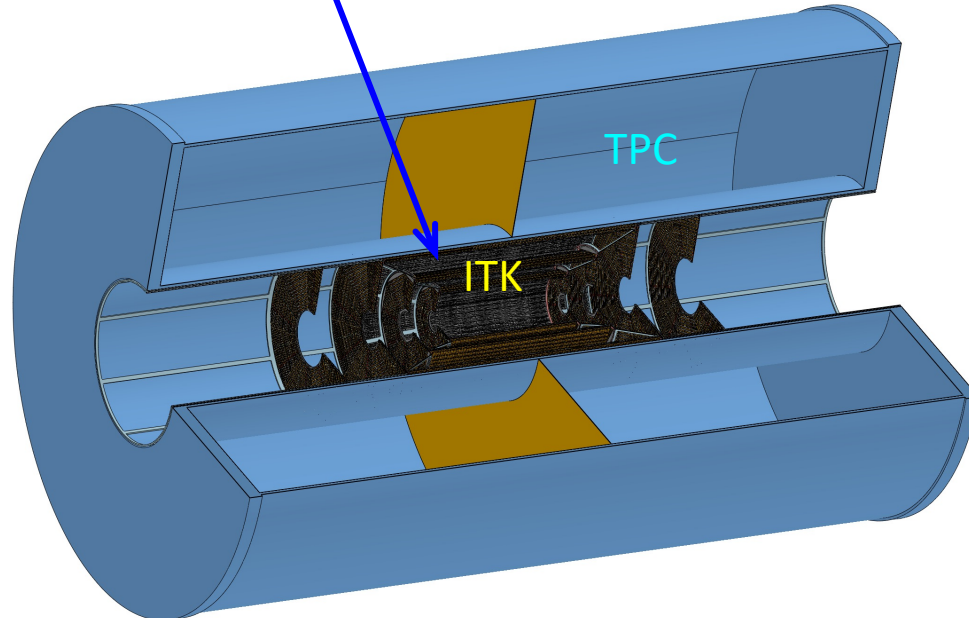
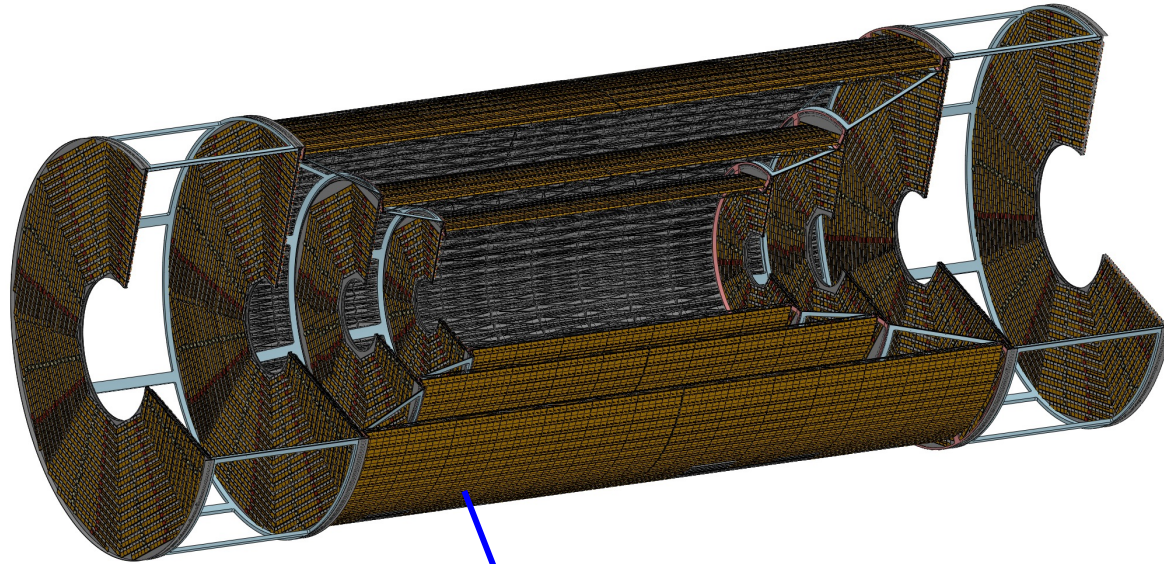
Materials	Thickness (mm)	Radiation Length [% X_0]
FPC	0.10	0.14
Sensor	0.15	0.18
Carbon fiber \times 2	0.25	0.10
Graphite \times 2	0.06	0.03
Others		0.05
Total		0.50

Endcap Sector:



Materials	Thickness (mm)	Radiation Length [% X_0]
FPC	0.10	0.14
Sensor	0.15	0.18
Carbon fiber	0.15	0.06
Graphite	0.03	0.02
Others		0.03
Total		0.43

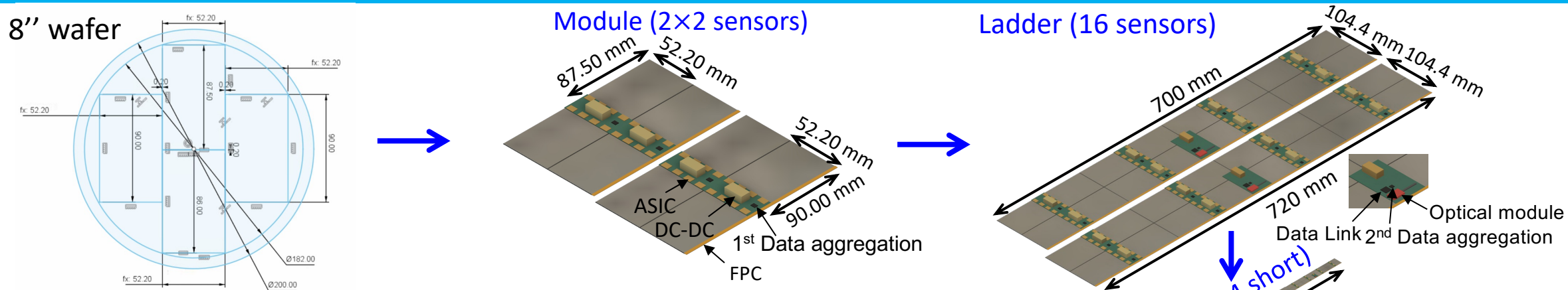
CEPC ITK Mechanics and Installation Design



	Sensors	Sensor area
Barrels		
ITKB1	3,920	1.6 m ²
ITKB2	7,840	3.1 m ²
ITKB3	18,032	7.2 m ²
Total	29,792	11.9 m ²

Endcaps		
ITKE1	1,536	0.74 m ²
ITKE2	3,136	1.51 m ²
ITKE3	8,288	4.00 m ²
ITKE4	7,520	3.63 m ²
Total	20,480	9.89 m ²

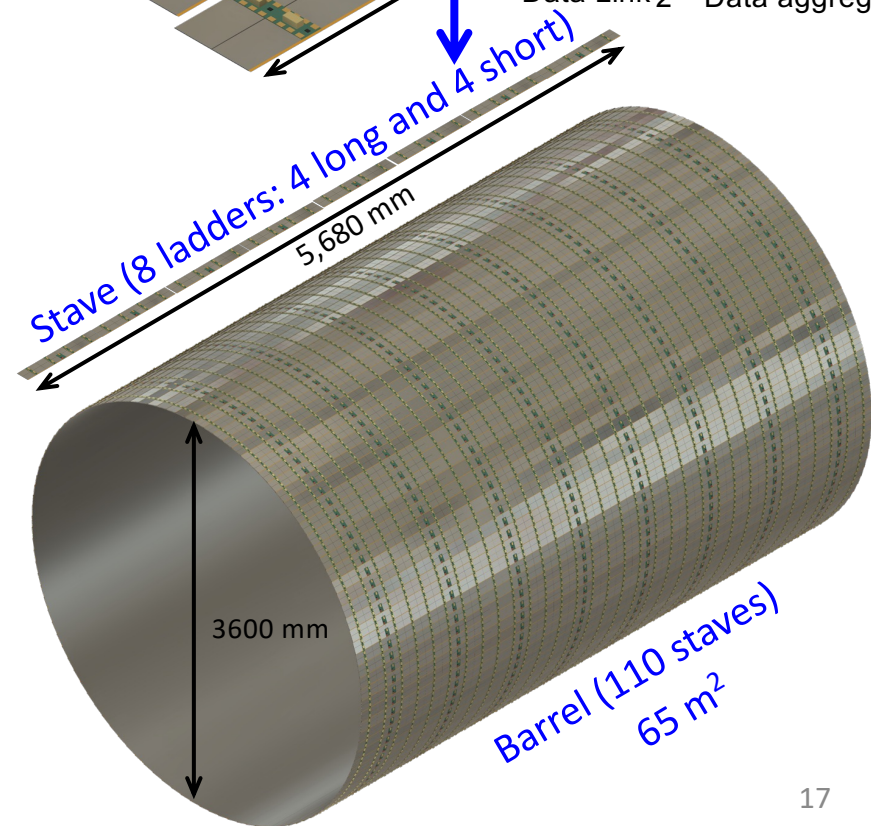
CEPC OTK Barrel Design (AC-LGAD Strips)



■ CEPC outer silicon tracker (OTK) utilizes AC-LGAD (Low Gain Avalanche Detector) developed by IHEP-IME:

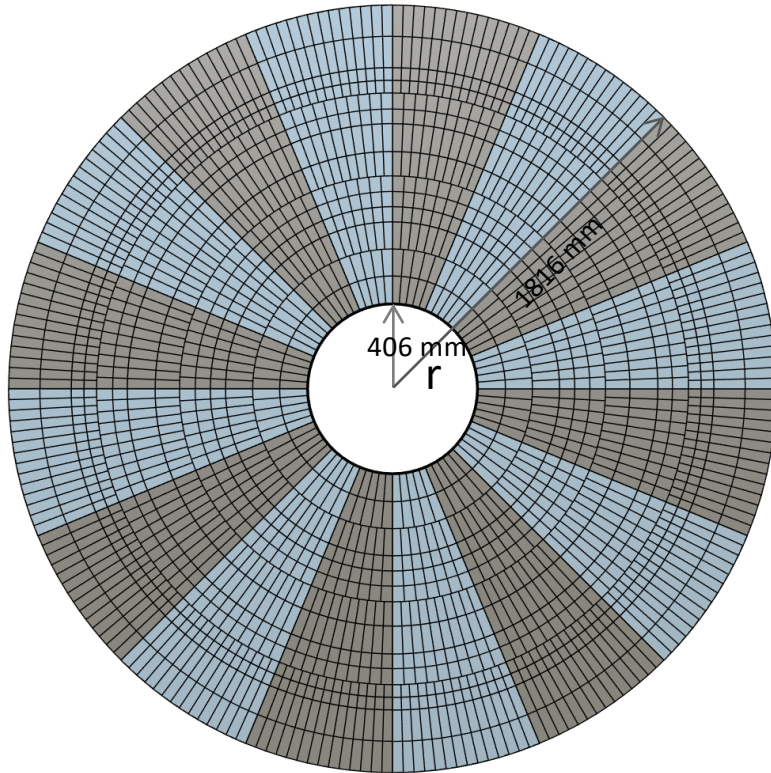
- Sensor size: 8.75 cm × 5.22 cm
9.00 cm × 5.22 cm
- Strip number per sensor: 512
- Strip pitch size: 100 μm
- Spatial resolution: 10 μm
- Time resolution: 50 ps
- Power consumption: ~300 mW/cm²

Maximum usage of silicon wafers for OTK barrel: a total 3,520 wafers, with 15% higher efficiency compared to a conventional single-piece sensor cut from a wafer.



CEPC OTK Endcap Design (AC-LGAD Strips)

Endcap (16 sectors, 10 m²):



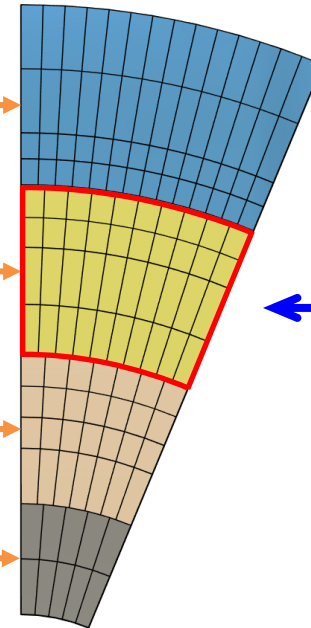
1/16 Sector:

Group D: 1400 mm-1816 mm

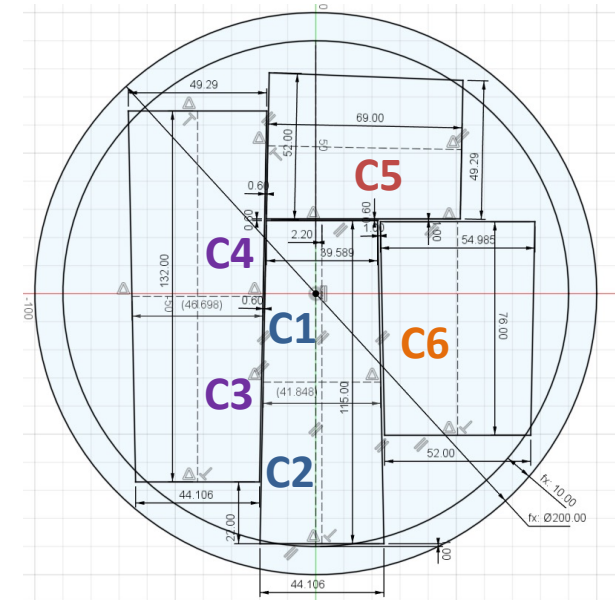
Group C: 1008 mm-1400 mm

Group B: 662 mm- 1008 mm

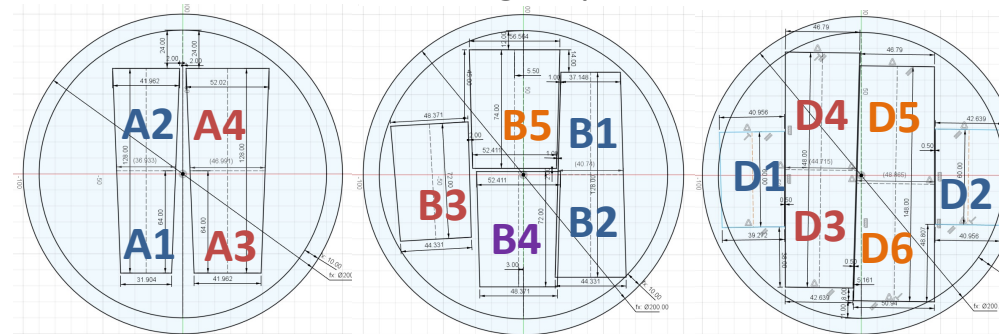
Group A: 406 mm- 662 mm



Sensor: 8'' wafer (group C sensors)



8'' wafer (group A, B, D sensors)

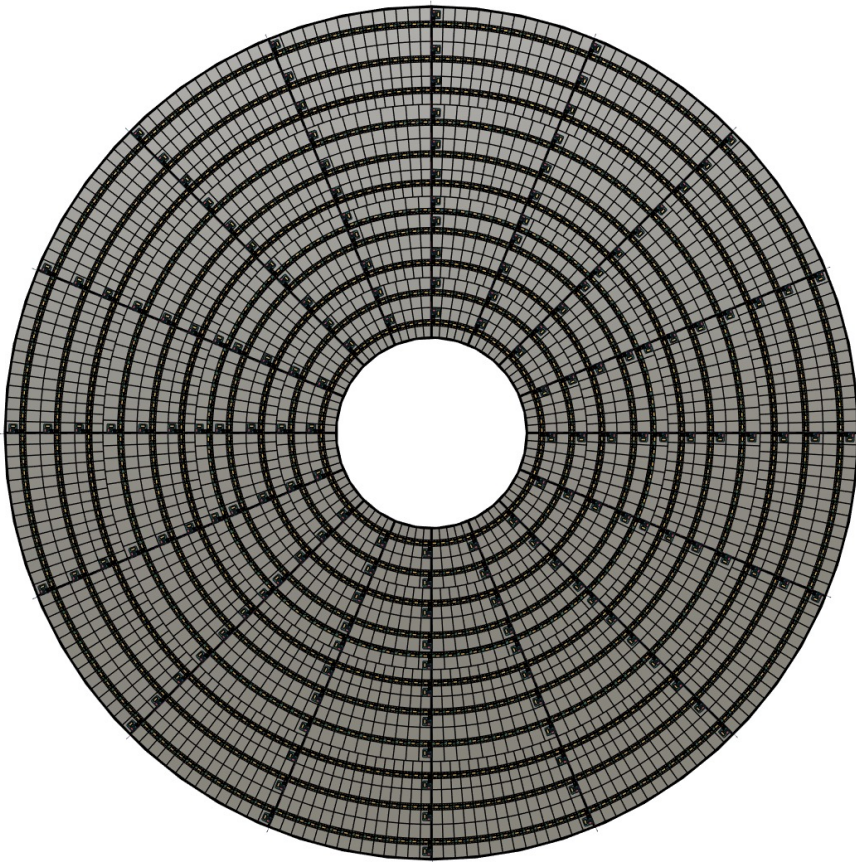


- OTK endcap consists of 14 rings, arranged into 4 groups.
- Each group contains 2-4 types of trapezoid sensors, which can be fitted to one 8'' silicon wafer.
- Each group of sensors is aligned to a 1/16 sector.
- The long sensor contains 2 sets of short-strip sensors.

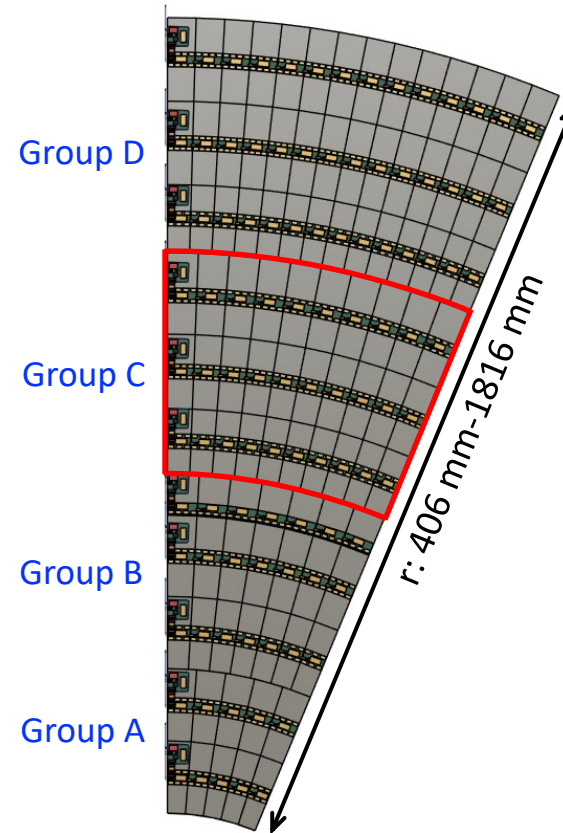
Maximize the use of silicon wafers and facilitate detector assembly.

CEPC OTK Endcap with Electronic Components

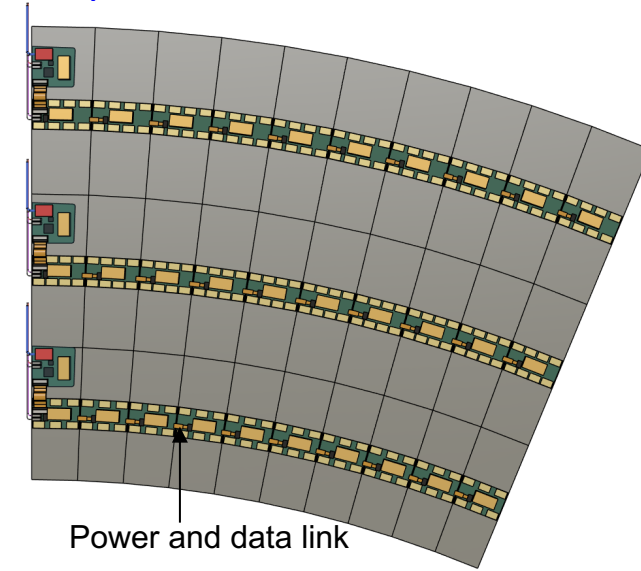
Endcap (16 sectors, 10 m²):



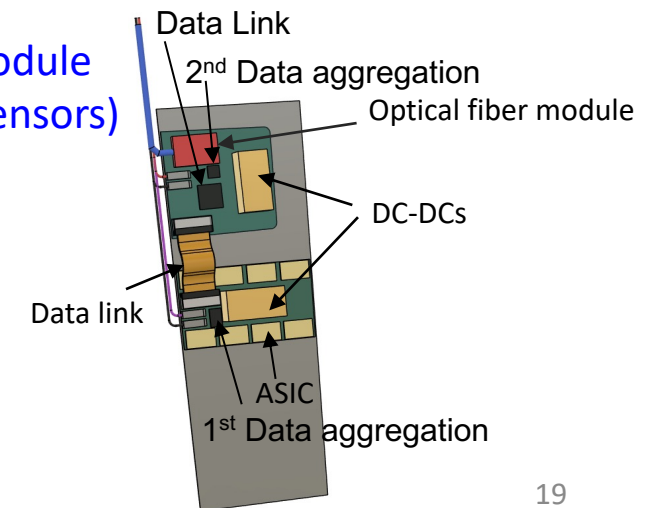
1/16 Sector:



Group C sensors:

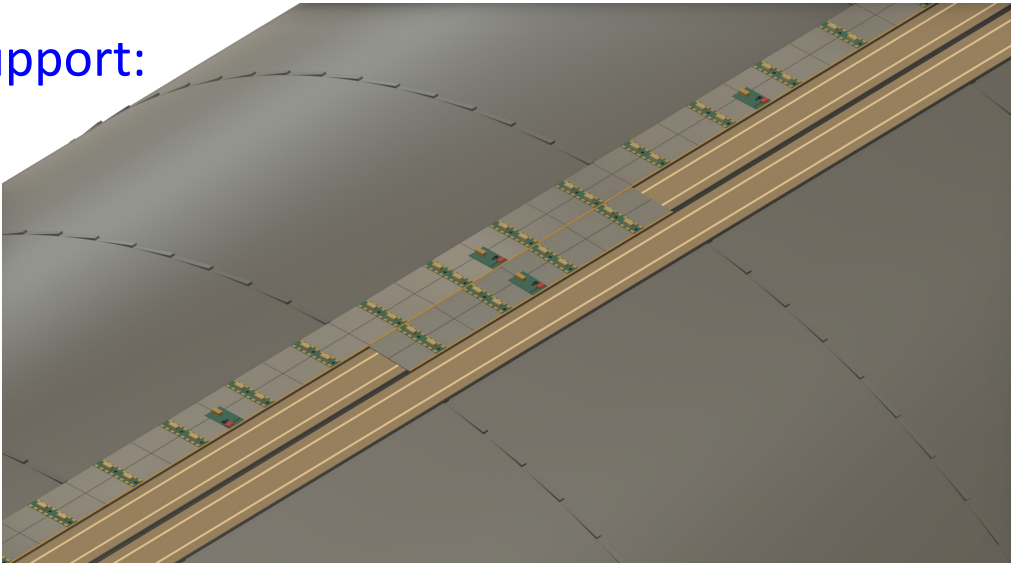


Module (2 sensors)



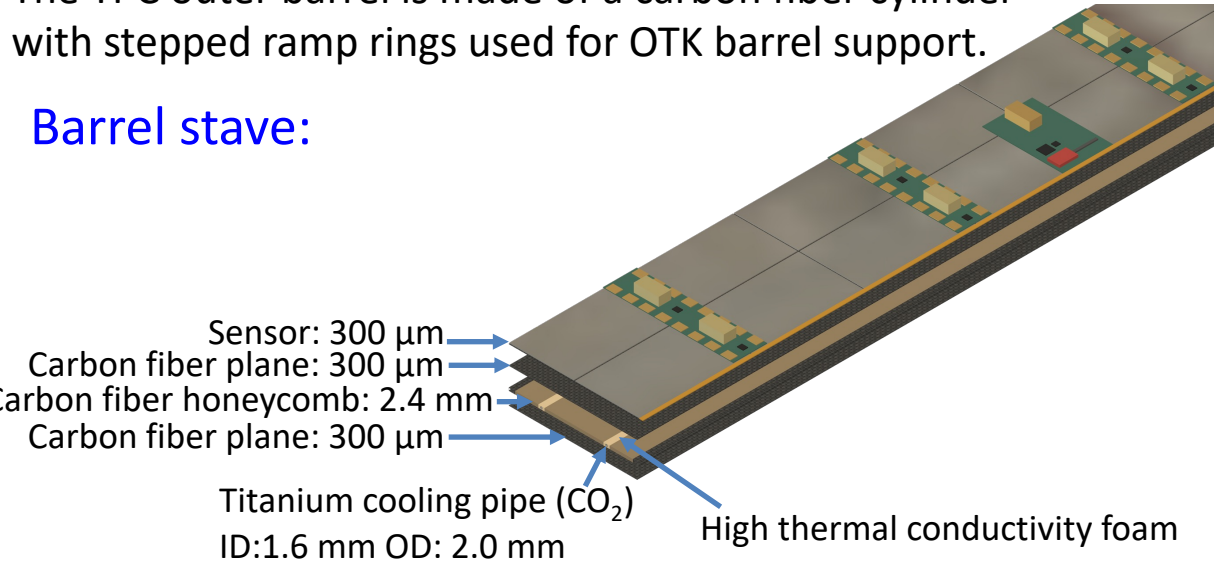
OTK Mechanical and Cooling Structure

Barrel support:

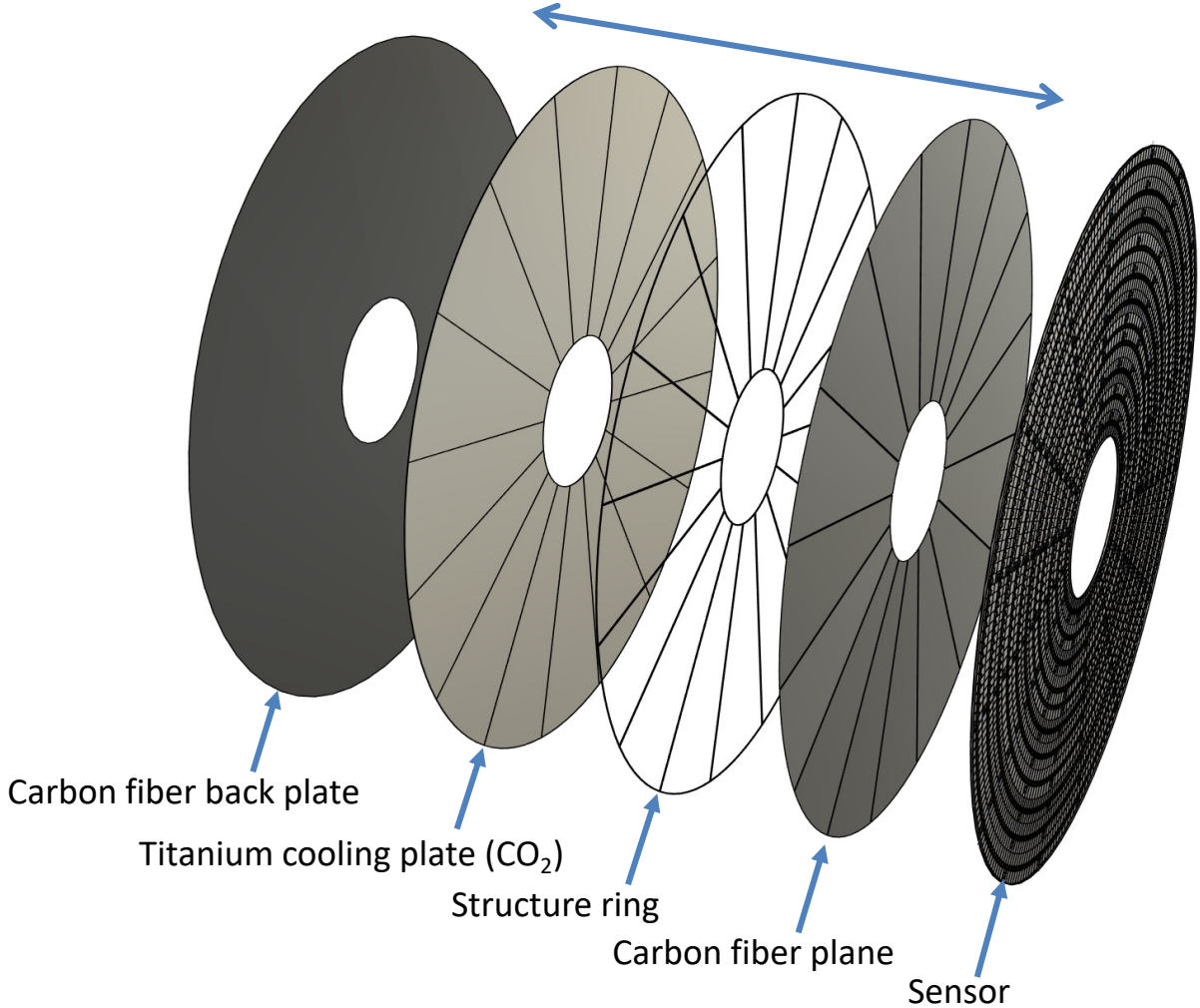


The TPC outer barrel is made of a carbon fiber cylinder with stepped ramp rings used for OTK barrel support.

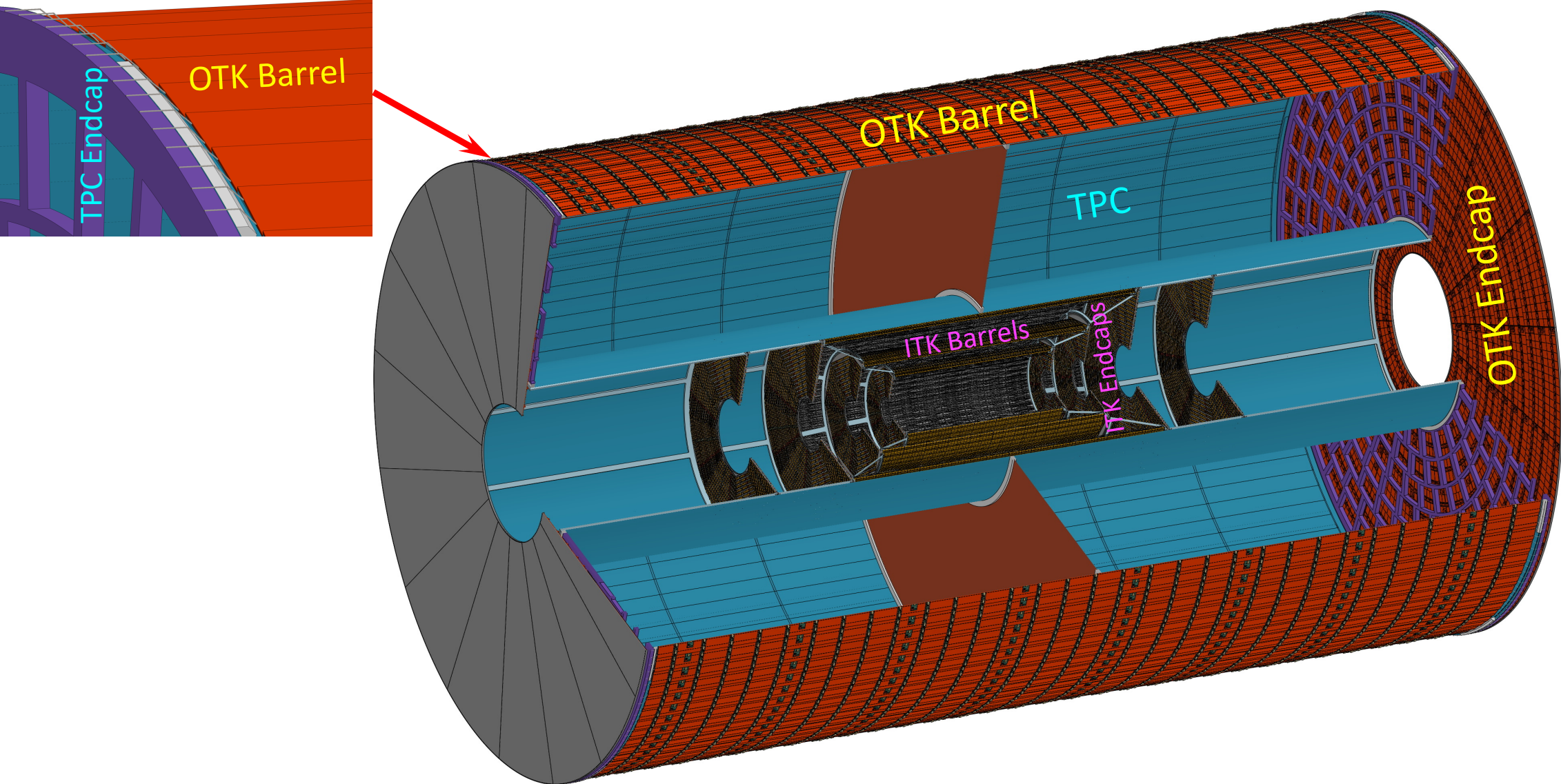
Barrel stave:



Endcap layout:

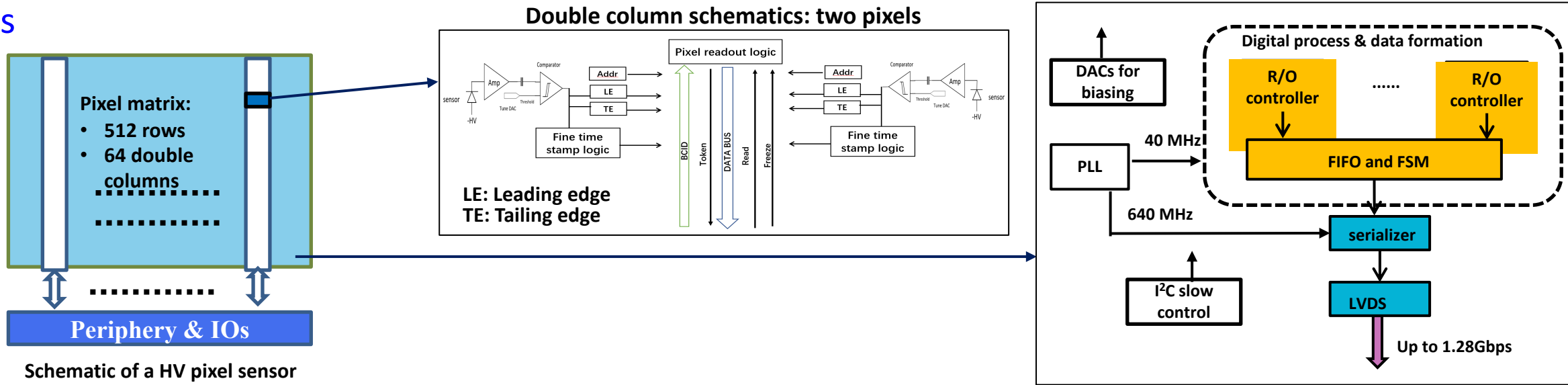


CEPC OTK Mechanics and Installation Design

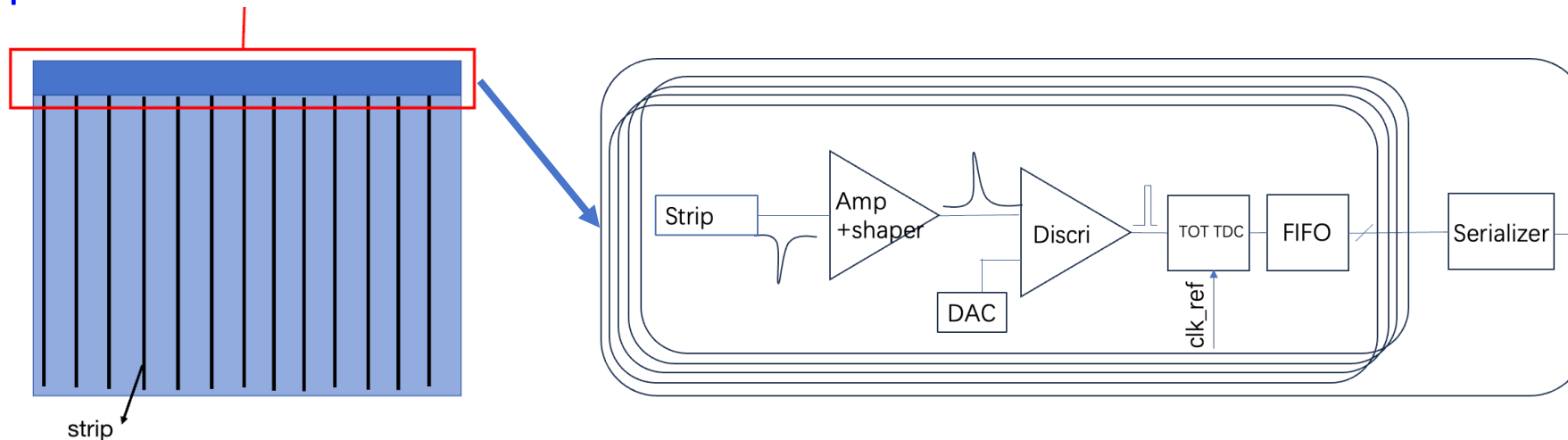


Front-End Readout: CMOS Circuit or AC-LGAD ASIC

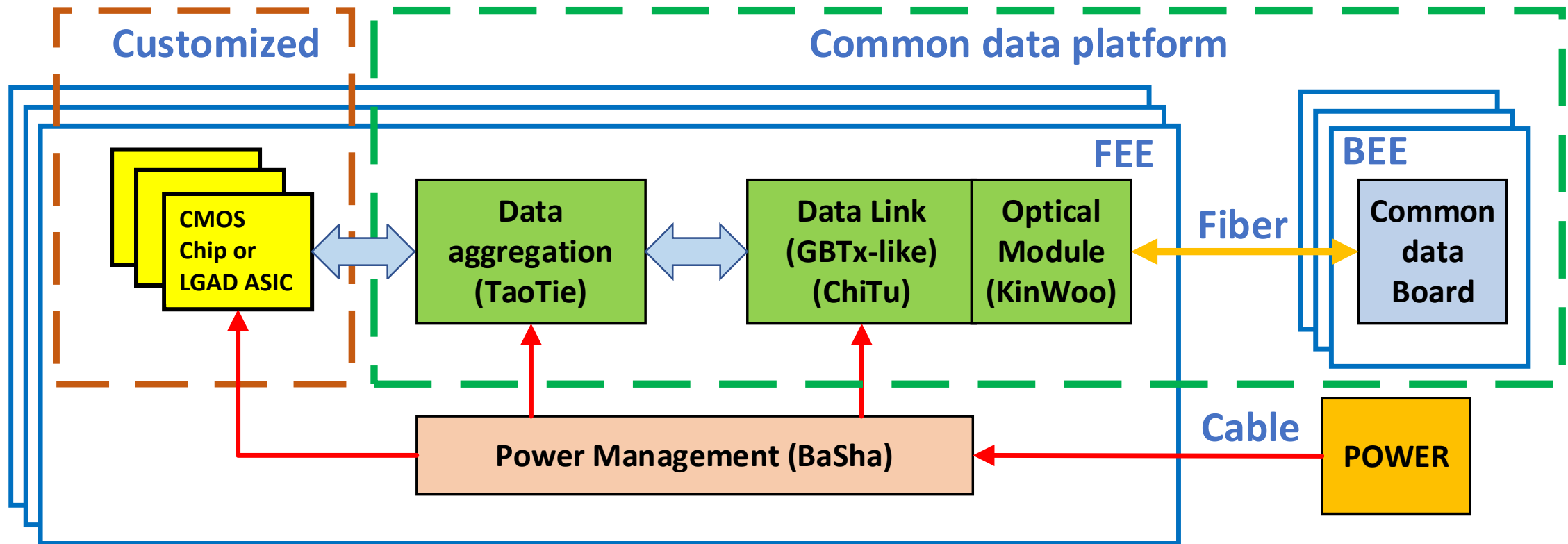
■ Pixels



■ Strips CMOS Circuit or AC-LGAD ASIC

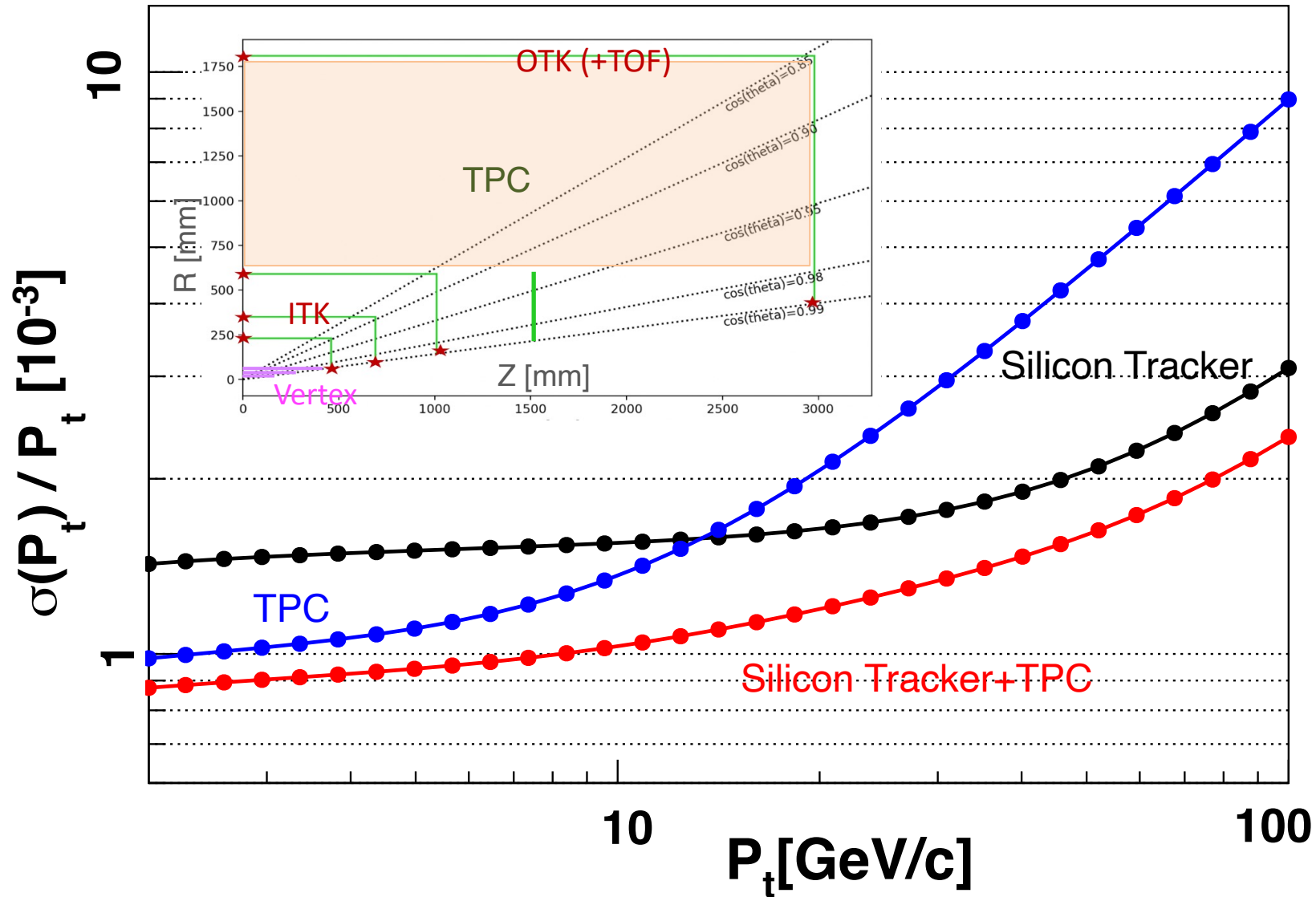


Silicon Tracker Common Electronics



- **Data transmission:** common data platform
- **Trigger mode:** triggerless

CEPC Tracker Performance from Simulation: Momentum Resolution



Our Research Team

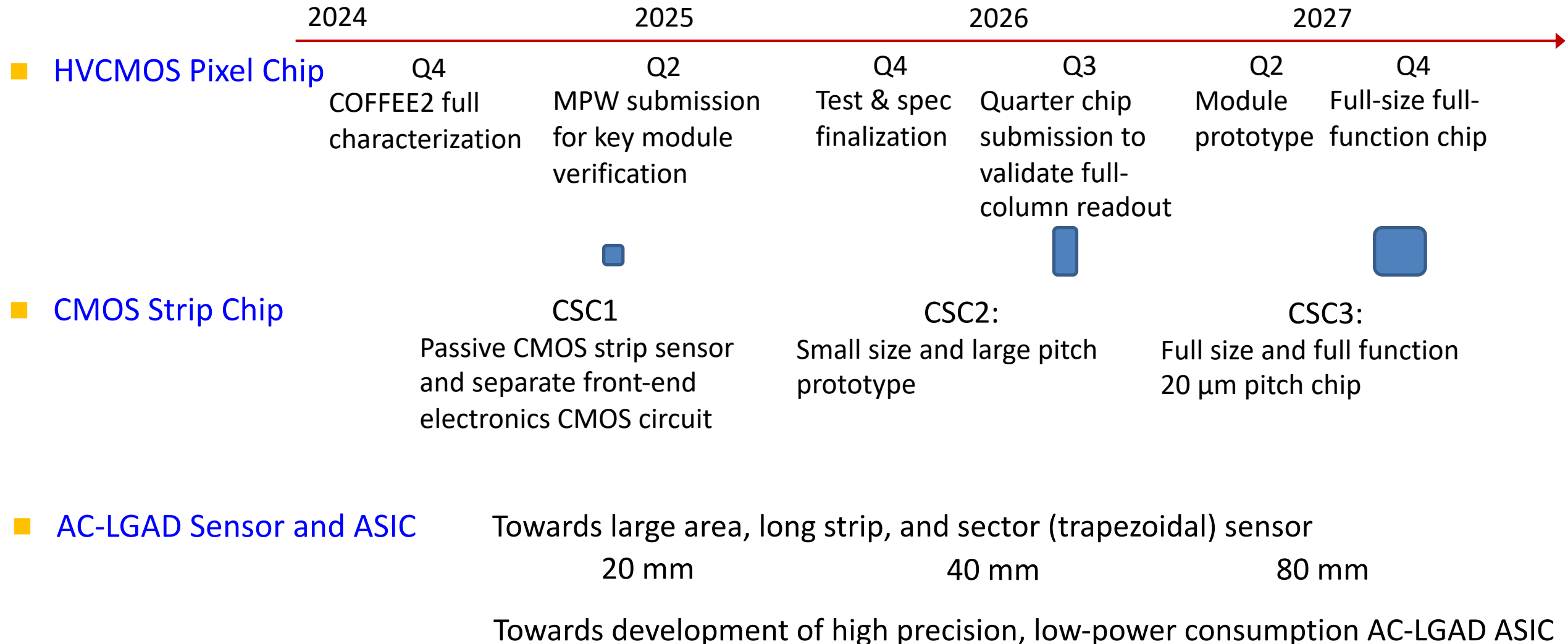
- ITK CMOS detector currently active: 16 institutes, 20 staff, 20+ postdocs & students



- OTK (+TOF) AC-LGAD currently active: 4 domestic and 2 international institutes, 12 staff, ~12 postdocs & students



Working Plan

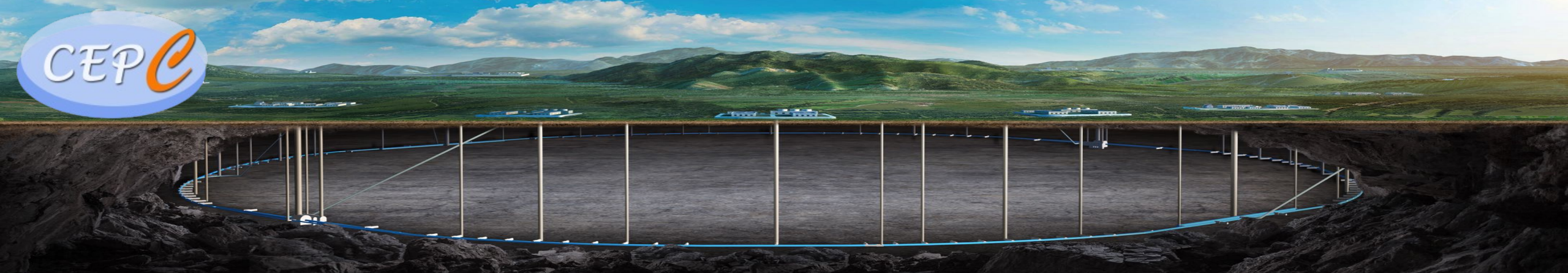


Summary

- CEPC incorporates the most advanced detector technologies while also having backup plan for construction.
- With the unique opportunity provided by CEPC to advance HEP semiconductor technology in China, we are steadily progressing in the development of forefront CEPC silicon tracker detector.



CEPC



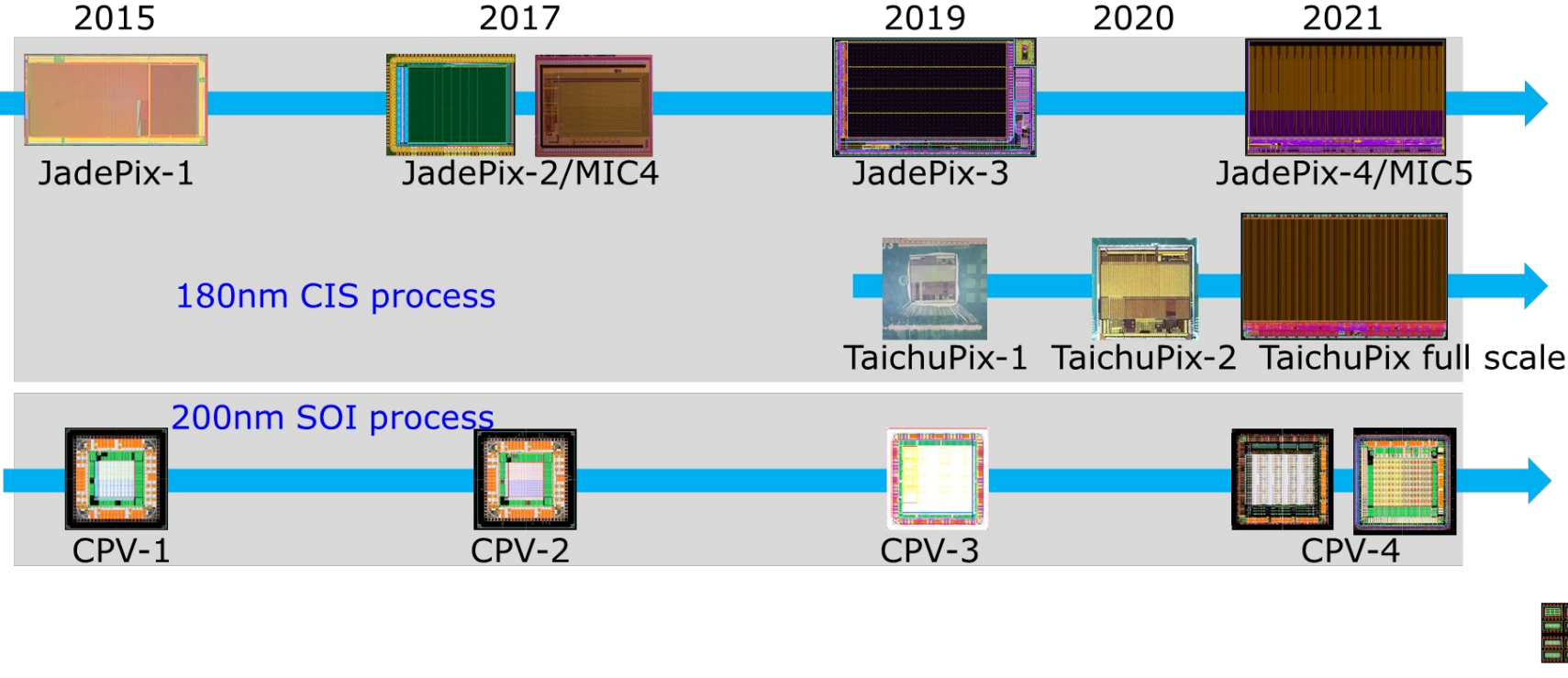
**Thank you for your
attention!**



中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Oct. 21st, 2024, CEPC Detector Ref-TDR Review

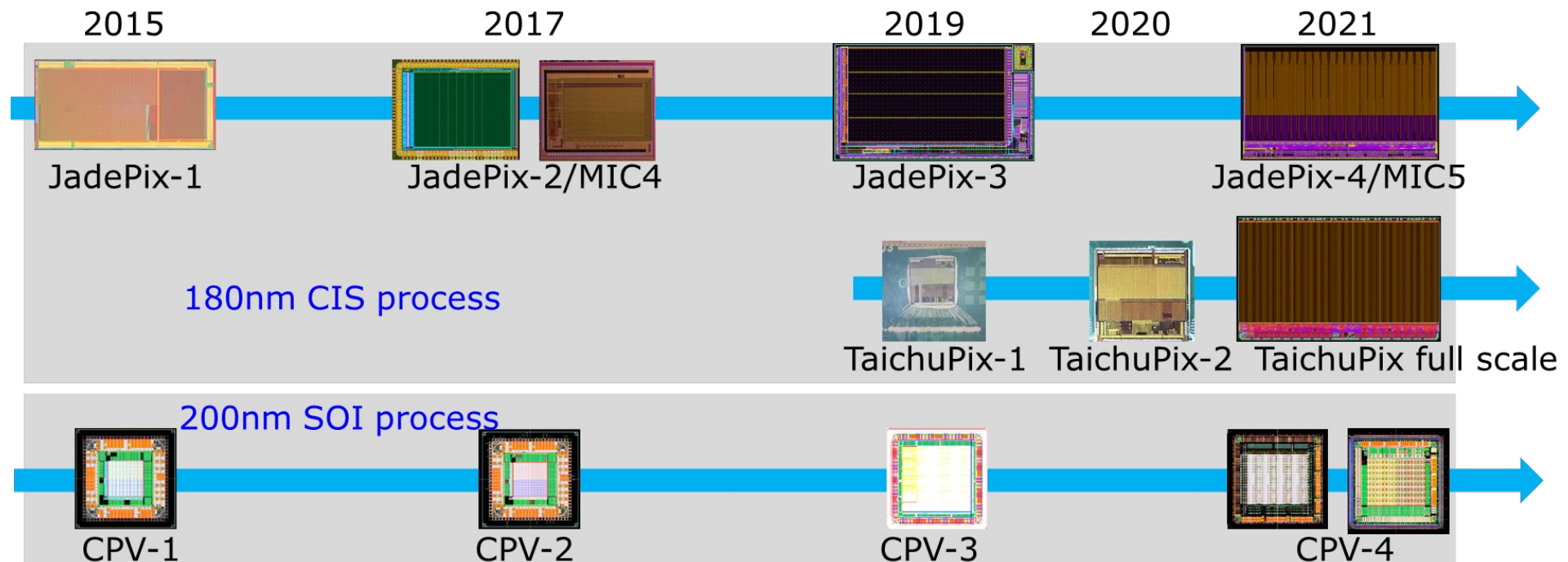
CMOS Chip Development in China



Overview of pixel sensors in China for CEPC VTX

- **Development of pixel sensors for CEPC VTX supported by**

- Ministry of Science and Technology of China (MOST)
- National Natural Science Foundation of China (NSFC)
- IHEP fund for innovation



Ref: "Status report on MAPS in China", 2021 CEPC workshop, Yunpeng Lu