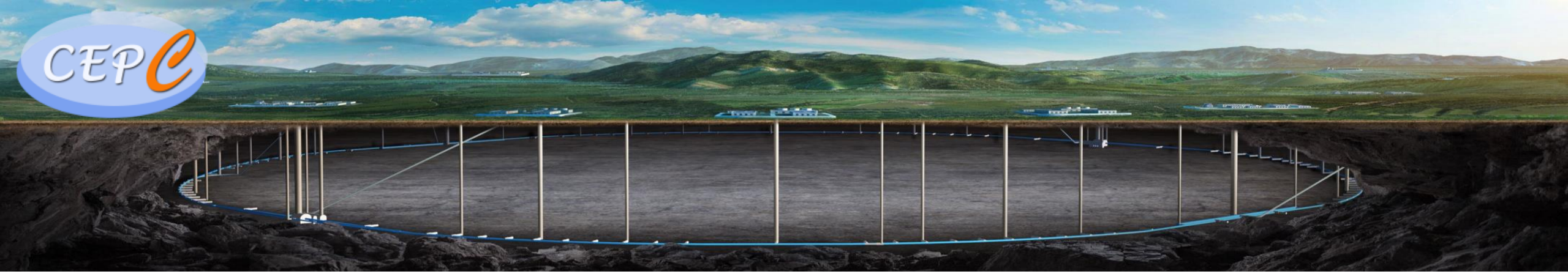


CEPC ToF & Outer Trakcer Detector

Yunyun Fan on behalf of ToF & Outer tracker detector group

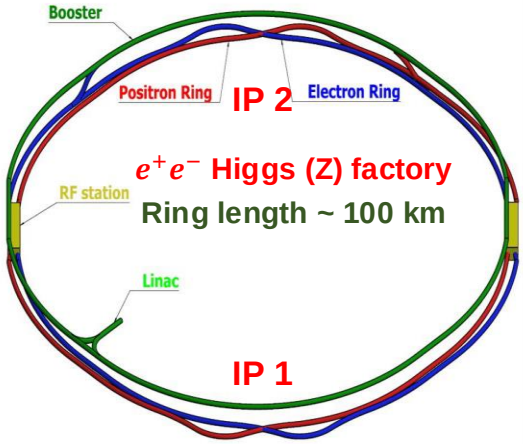
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Content

- Introduction
- Requirements
- Technology survey and our choices
- R&D efforts and results
- Detailed design including electronics, cooling and mechanics
- Readout electronics & BEC
- Research team and working plan
- Summary

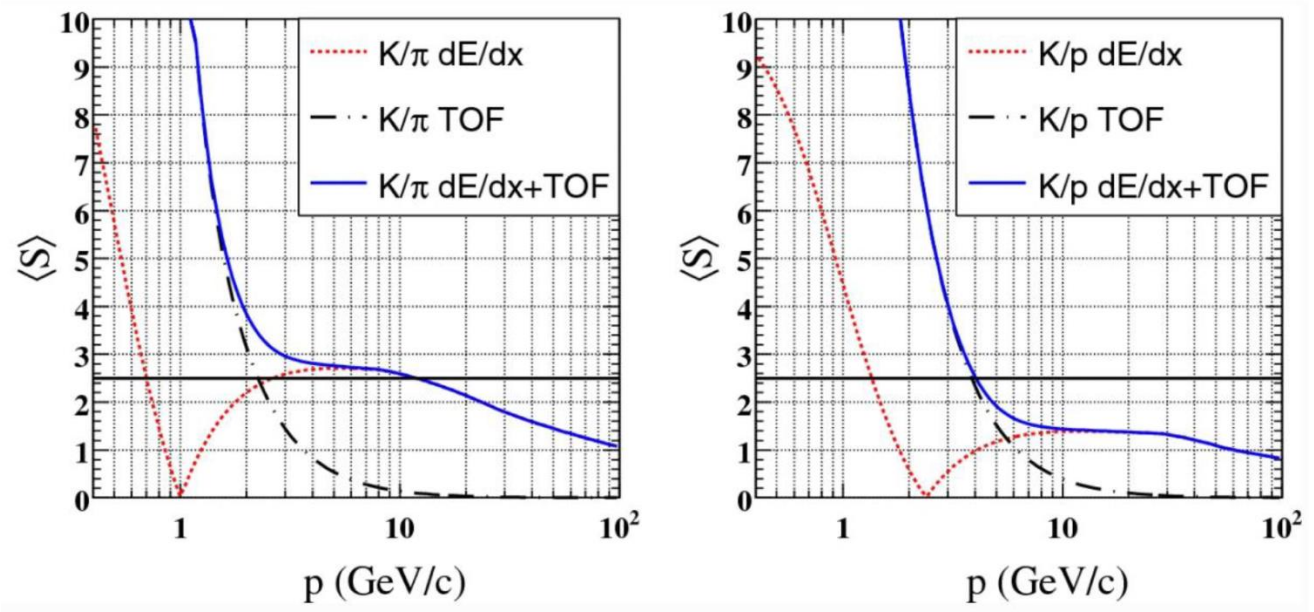
Introduction and requirement

- **CEPC: rich physics programs: Higgs, electroweak physics, flavor physics, QCD/Top**



- **Particle identification** of Gas detector (dE/dx) : insensitive region
  - ✓ **0.5-2 GeV for K/pi separation, 1.5-2.5 GeV for K/p separation**
- Precision timing detector is a matter of urgency (from IAC recommendation)
- **Timing detector is complementary to gas detector: 50 ps** could improves the separation ability

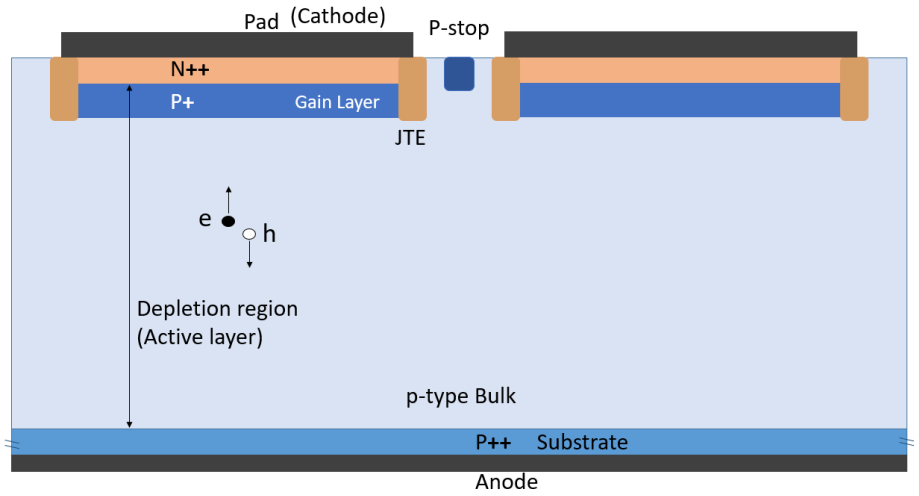
K/pi separation **K/proton separation**



Technology survey and our choices

LGAD (Low-Gain Avalanche Diode)

Segmented gain layer

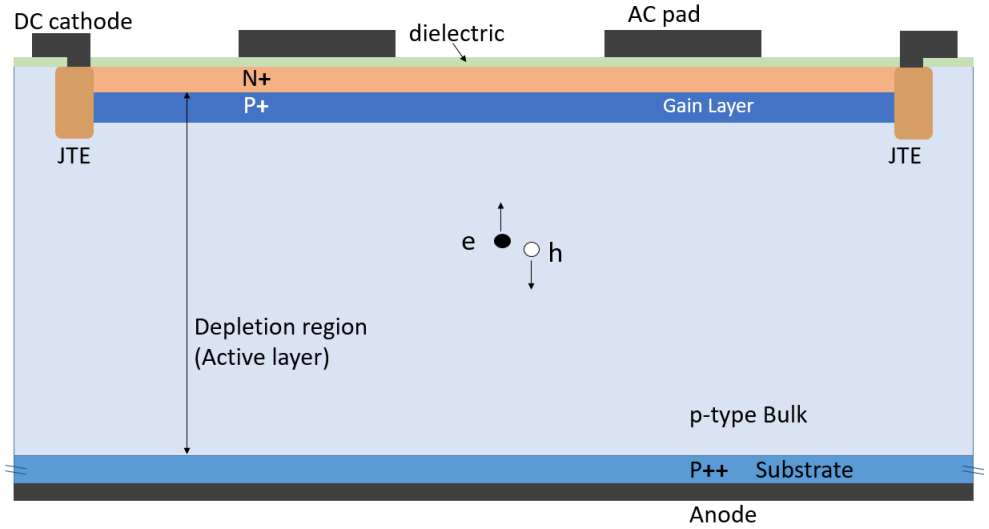


- The read-out electronics is connected to n++ layer
- Time resolution ~ 30ps
- Position resolution: pixel size/$\sqrt{12}$
- Radiation hardness： 10^{15} ~$10^{16}n_{eq}/cm^2$

AC-LGAD (AC-coupled LGAD)

Continuous gain layer

Less dead area， higher spatial resolution



- Metal AC-pads separated from the n+ layer by a thin dielectric (Si_3N_4, SiO_2)
- Time resolution ～30ps
- Position resolution: 5～10 um

4

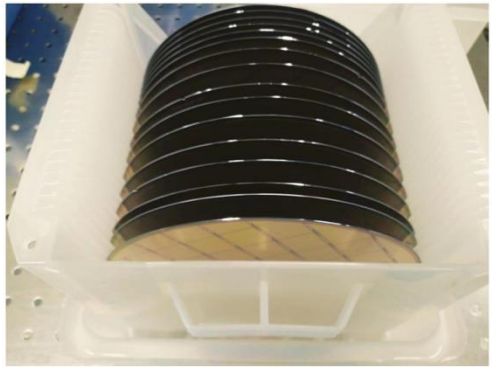
LGAD sensors pre-production at IHEP

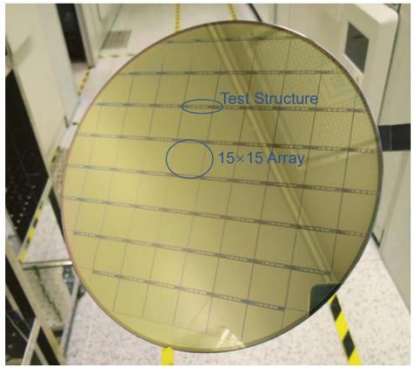
- In May 2023, IHEP-IME sensor was chosen for the ATLAS HGTD project.
  - **First time the silicon sensor designed and produced by China was chosen for an LHC experiment**

- The production plan:
  - IHEP-IME: 90% (66% from CERN tendering+24% in-kind contribution): ~8 m^2

Pre-production LGAD sensors from China

IHEP-IME Pre-production





[Details in Mei Zhao' talk]

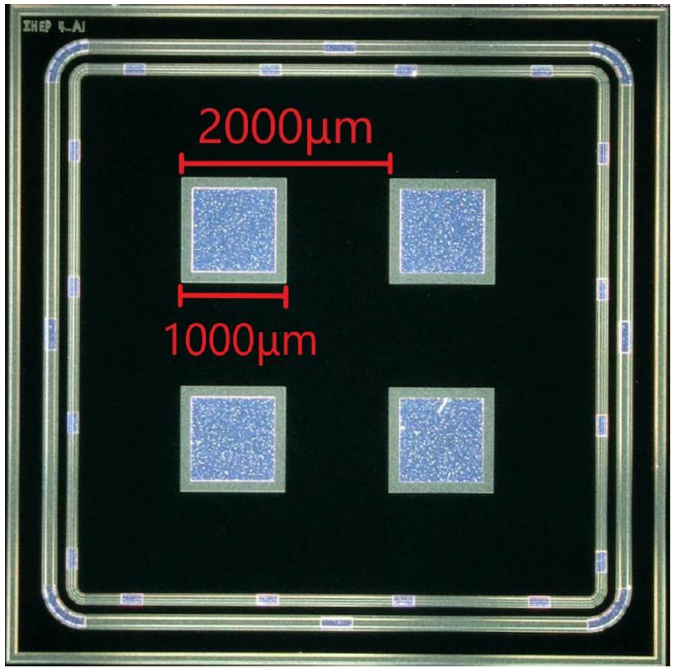
R&D： AC-LGAD sensors development at IHEP

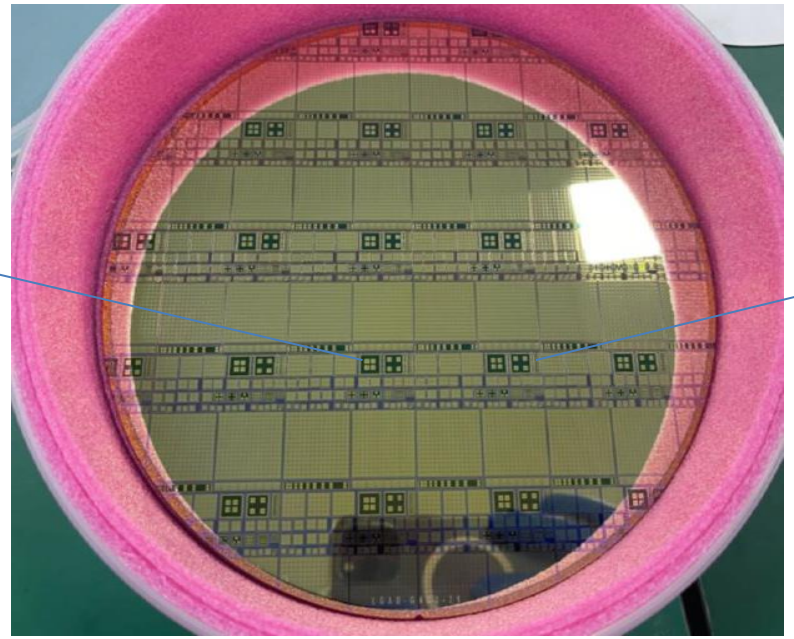
Pixels AC-LGAD：

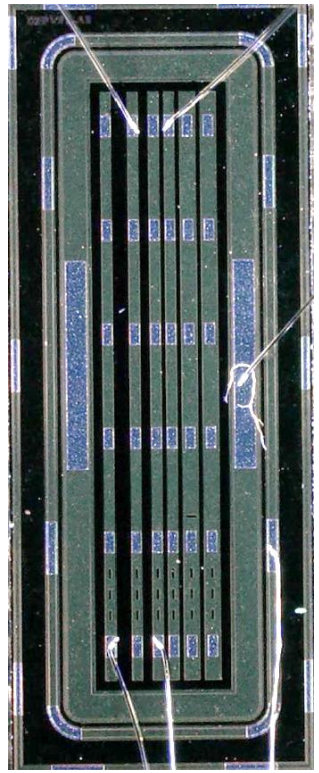
- Pitch size 2000um, pad size 1000um
- Different N+ dose：
  - **10P，5P，1P，0.5P，0.2P**

Strips AC-LGAD：

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



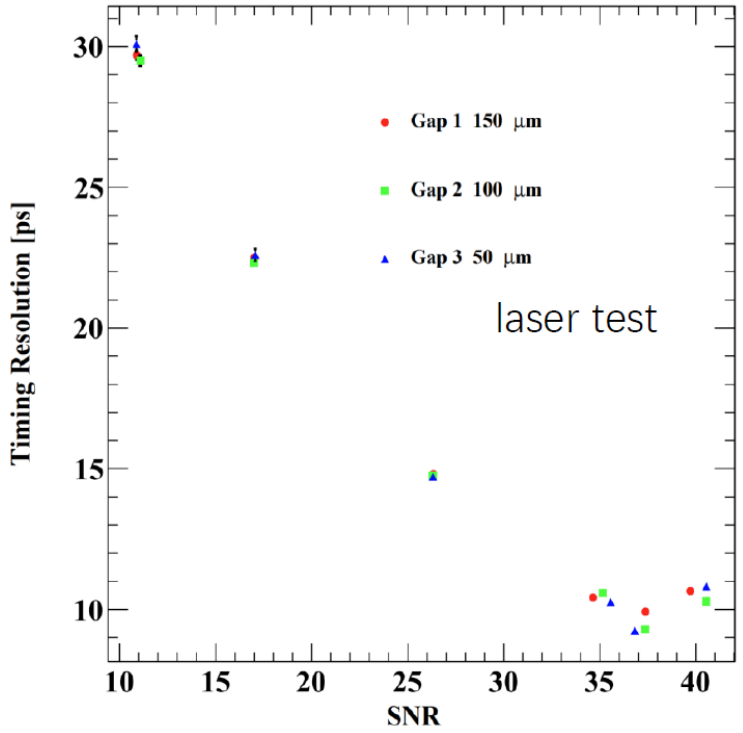




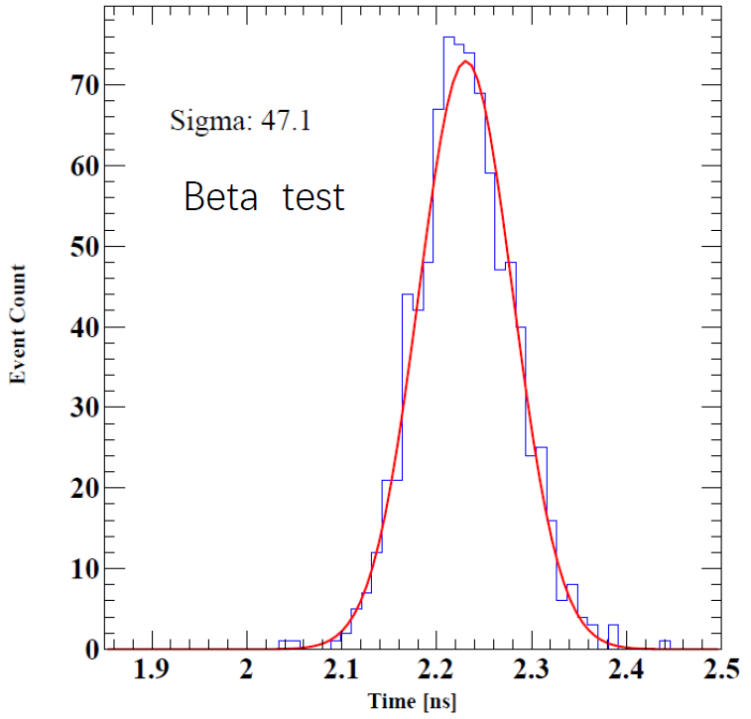
6

Performance of AC-LGAD: Time Resolution

Jitter tested by laser



Δt Distribution (Beta source)



Timing resolution of Trigger

$$\Delta T = T_{trigger} - \frac{\Sigma_i a_i^2 T_i}{\Sigma_i a_i^2}$$

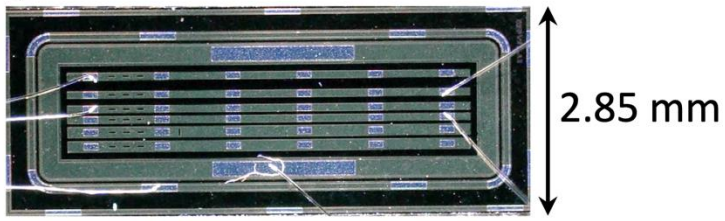
Weighted timing resolution of three strip electrodes

Sigma Δt = 47.1 ps
AC-LGAD strip : 37.5 ps

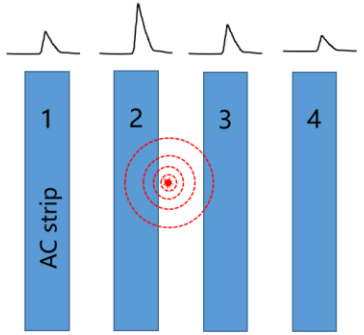
- **No significant change in timing resolution was observed for different pitches**
- **Saturation was observed： ~ 10 ps.**
- **37.5 ps timing resolution, via Beta source test.**

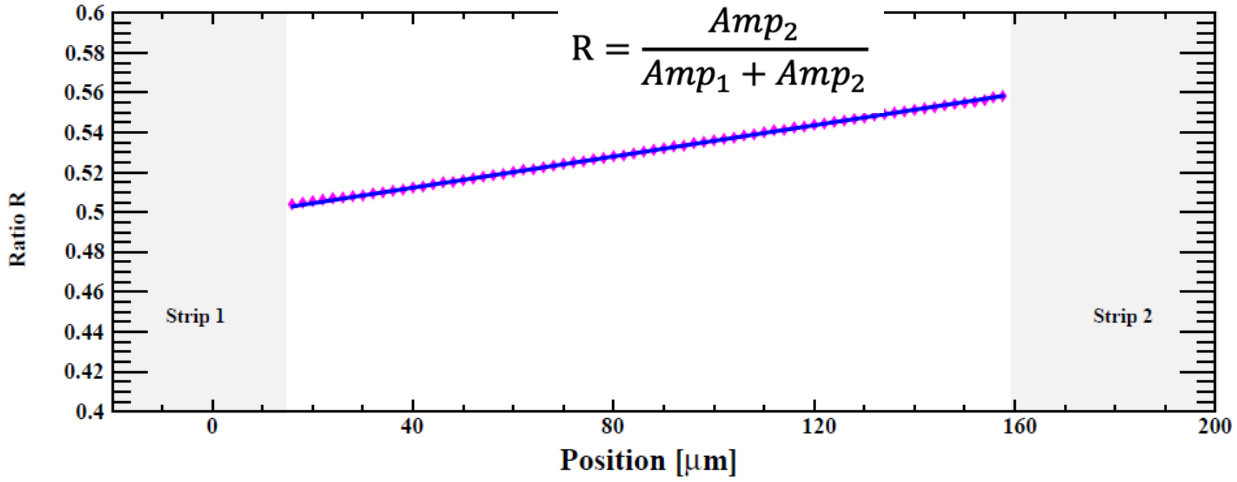
7

Performance of AC-LGAD: Spatial Resolution



Laser point:
2 μm pitch



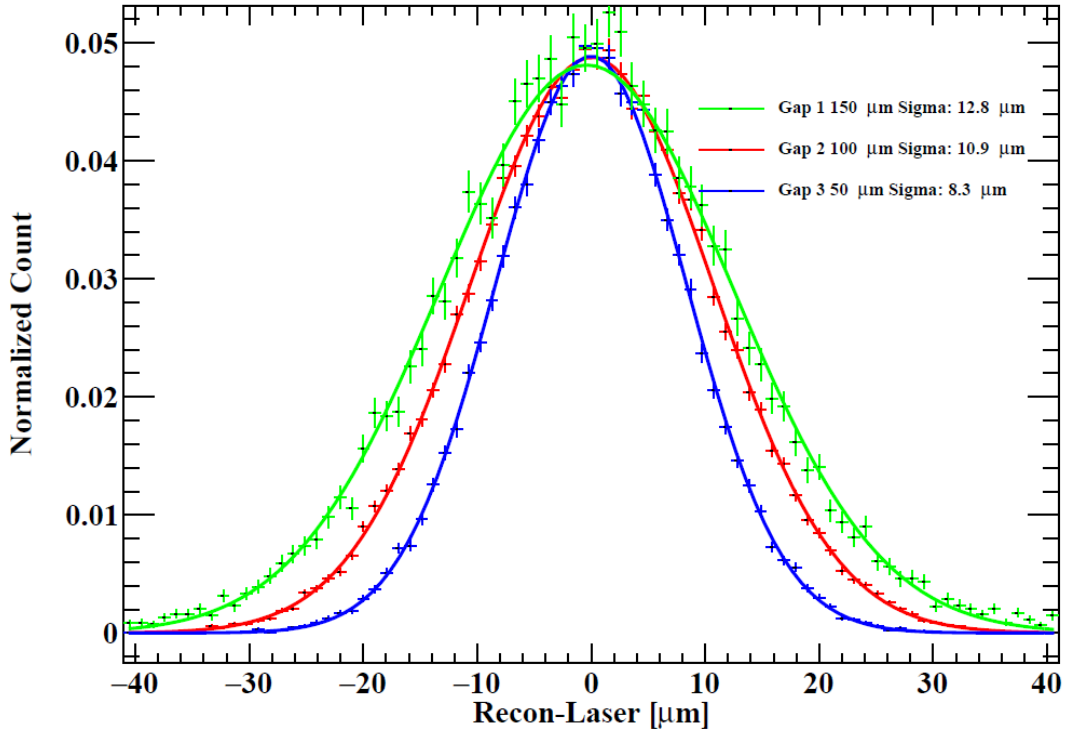


Position reconstruction:

The fraction of the signal (*R*) changes linearly with the move the laser.

Spatial resolution：

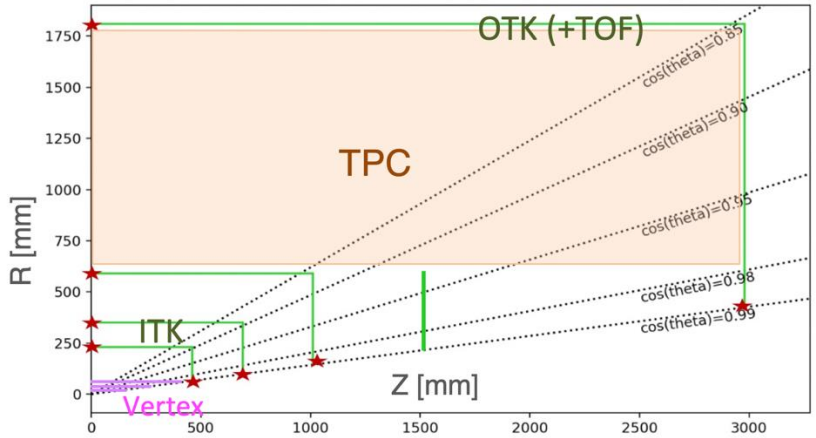
8.3 μm (150 μm pitch)
10.9 μm (200 μm pitch)
12.8 μm (250 μm pitch)



[Details in Weiyi Sun's poster]

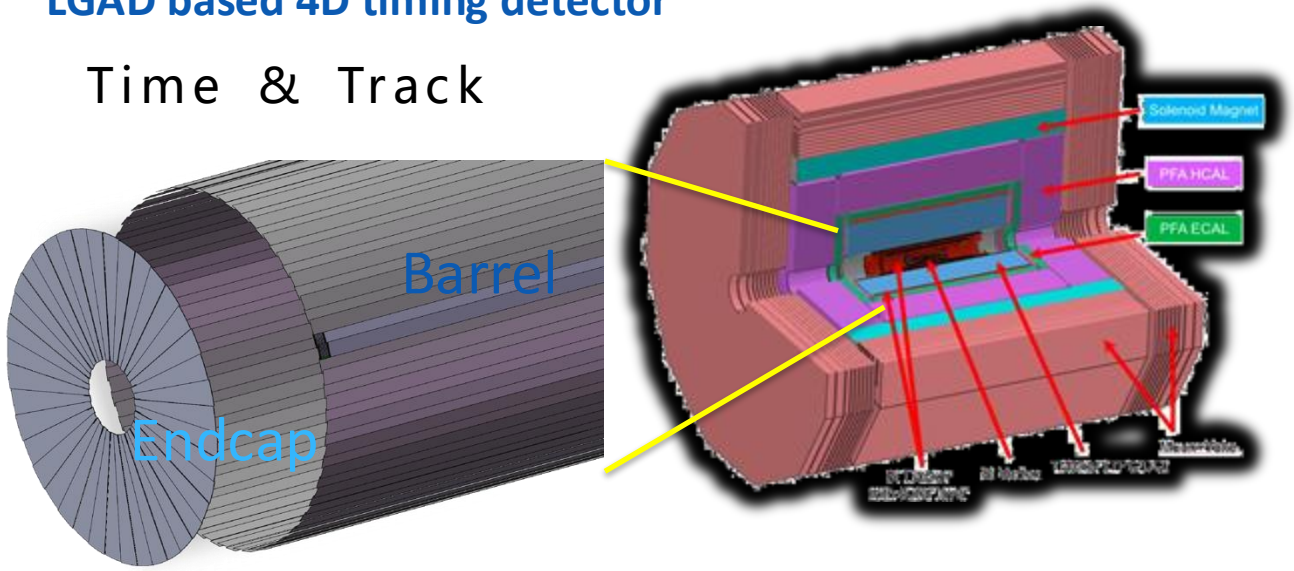
AC-LGAD Based ToF & Outer Tracker for CEPC

- Develop AC-LGAD strip silicon sensor for outer tracker
  - timing resolution **50 ps**
  - spatial resolution better than **10 μm** (Bending direction)



LGAD based 4D timing detector

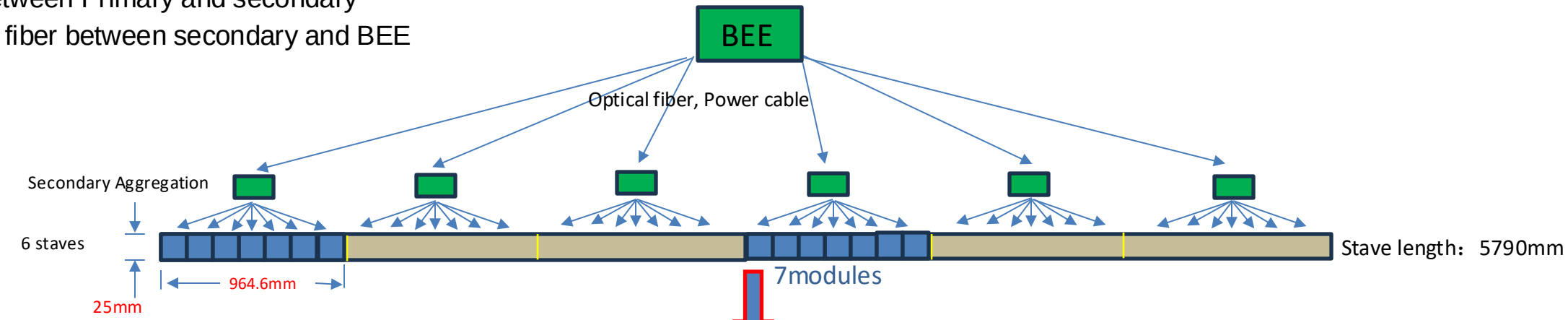
Time & Track



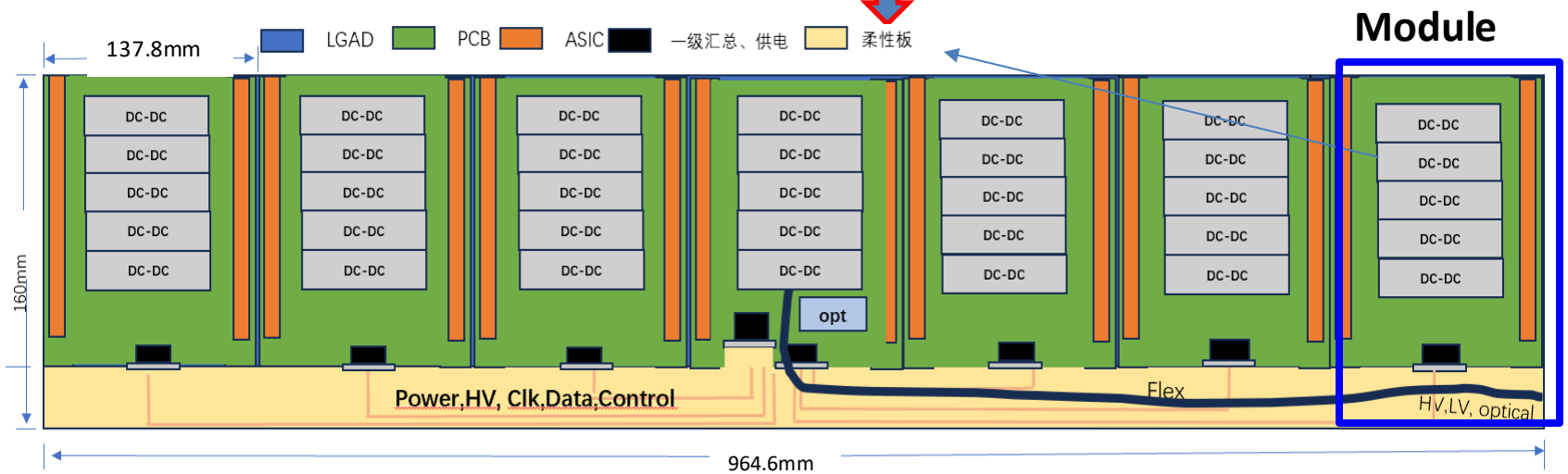
Reference TDR of CEPC

Electronics for ToF & Outer Tracker

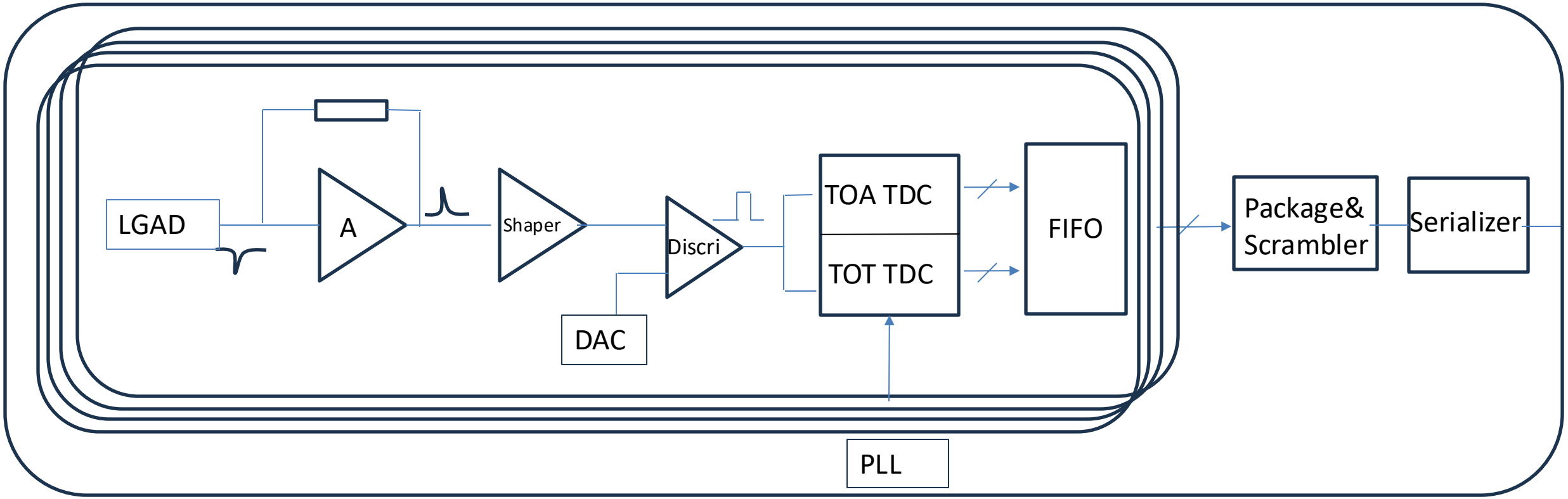
- **Four parts：Readout ASICs，Data aggregation，Data Link，BEE**
  - Provide LV and HV for module independently
  - Primary Aggregation adapts Data rate between ASIC and Data Link
  - Flex between Primary and secondary
  - Optical fiber between secondary and BEE



Ladder layout



AC-LGAD readout chip structure



16 bit (9 TOT, 7 TOA)

TOA for arrival time

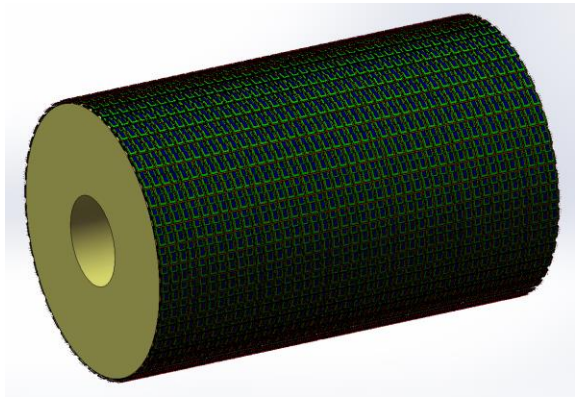
TOT for charge measurement and time walk correction

Design of the OTK with the strip AC-LGAD: Barrel

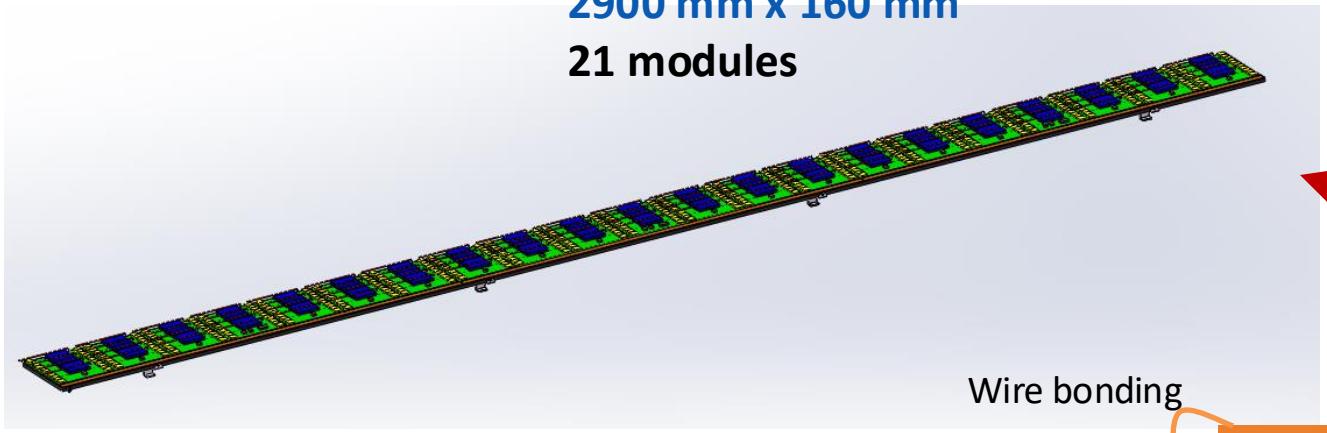
- one layer: 70 m^2, 3780 modules

  R= 1800 mm ,H ~ 5800mm
  - overlap to decrease the dead area
  - 90 staves
  - 42 modules/stave

One layer ToF+OTK
R= 1800 mm , H～5800mm
90 staves

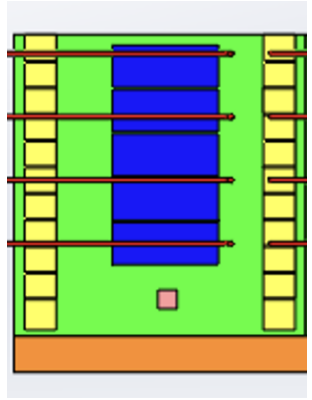


Long half stave
2900 mm x 160 mm
21 modules



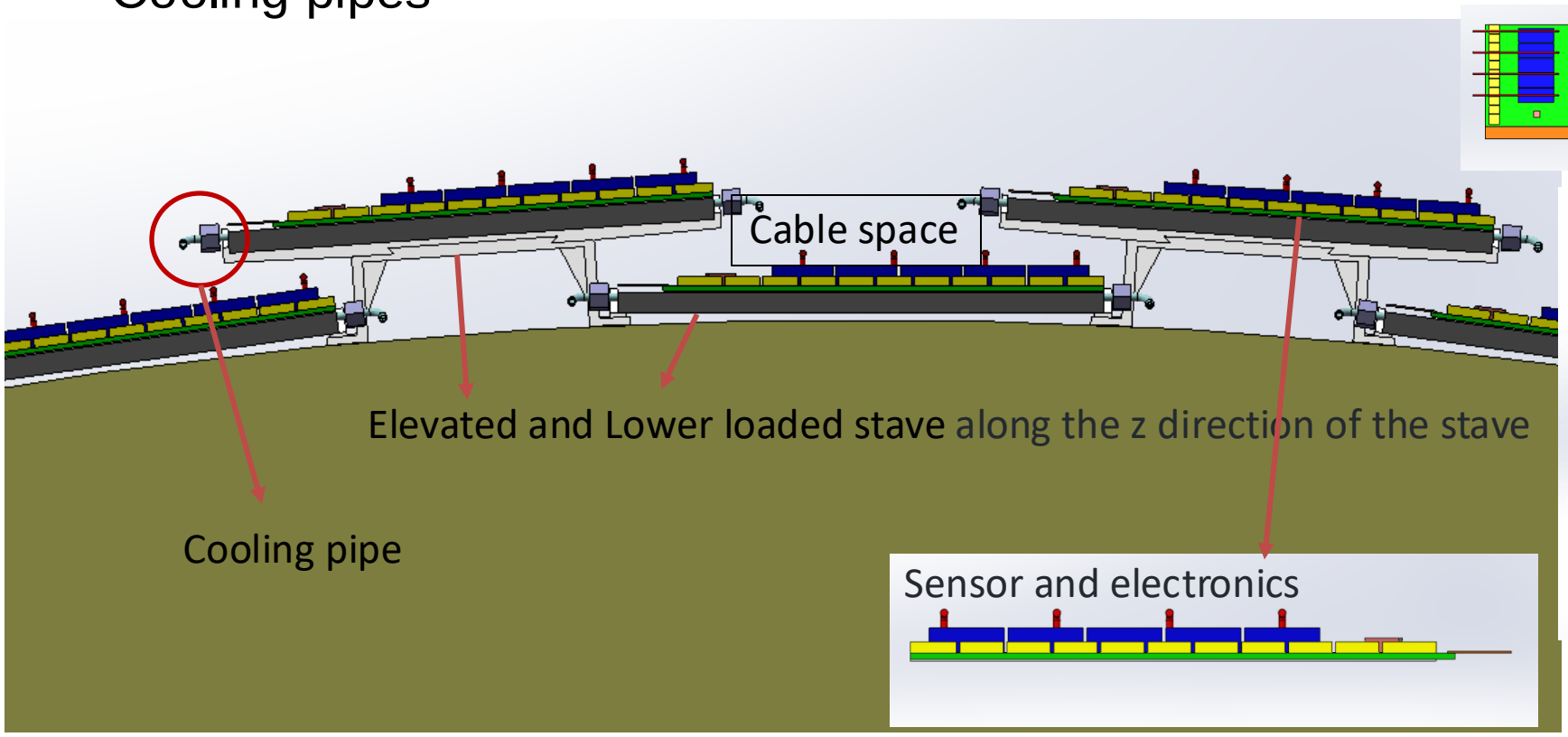
Module
137.8 mm x 160mm
22 ASICs

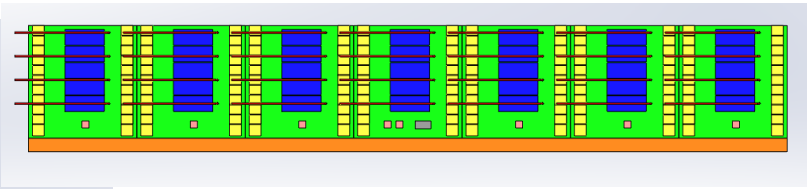
Heat sink(HS): Al;

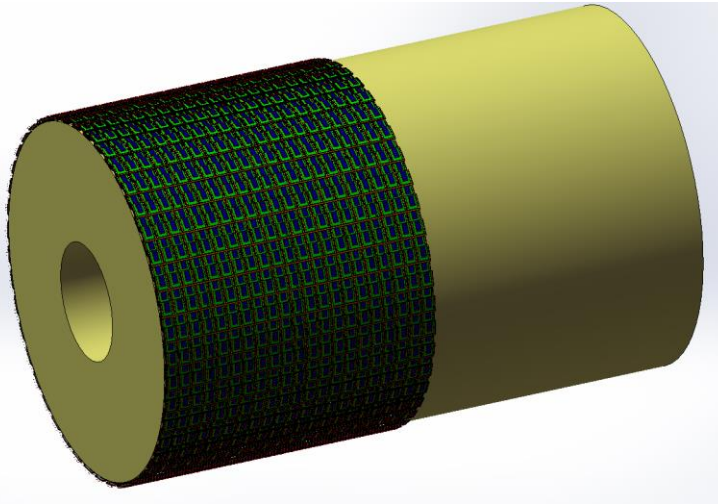


Mechanical Design for LGAD ToF & OTK

- Overlap staves for the barrel with detailed electronics design， cooling and installation
  - Sepcial support design to allow precise alignment of the AC-LGAD sensors
  - Extra space for cables
  - Cooling pipes



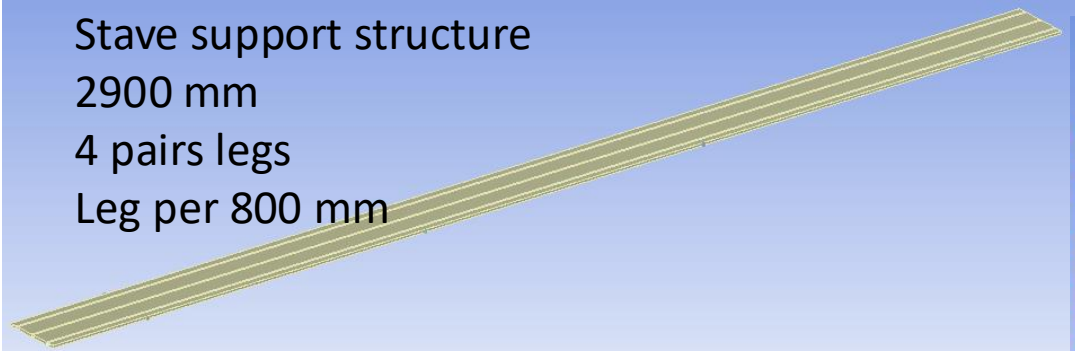


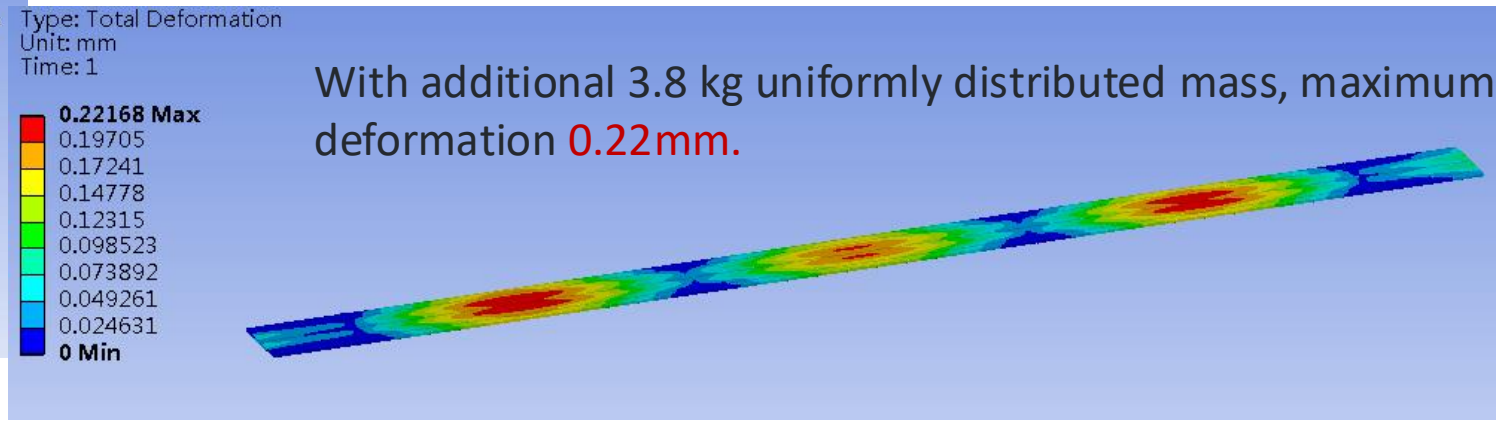


Deformation Analysis of ToF & OTK

- FEA analysis for the stave support structure
- Stave support structure： Equivalent thickness ~ 0.5mm CFRP.

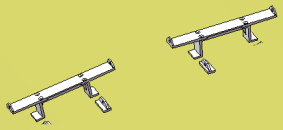
Stave support structure
2900 mm
4 pairs legs
Leg per 800 mm



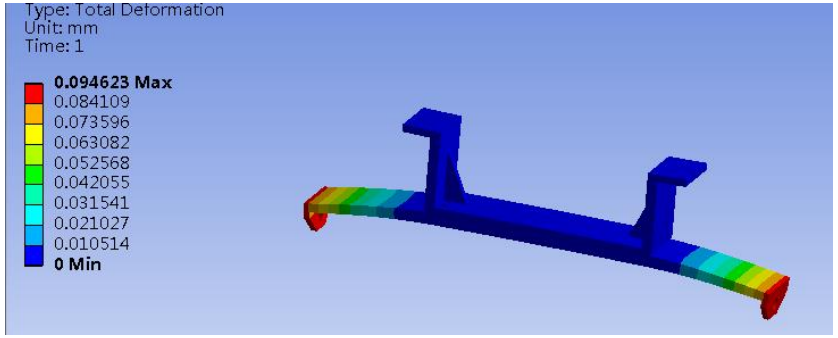


With additional 3.8 kg uniformly distributed mass, maximum deformation 0.22mm.

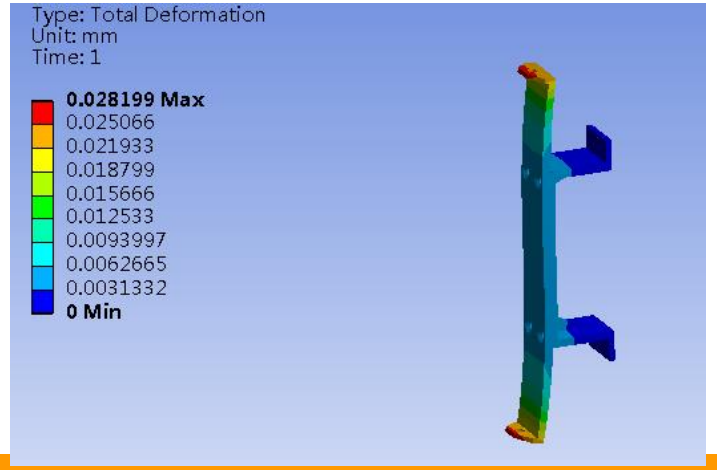
Legs



maximum deformation 0.1mm.

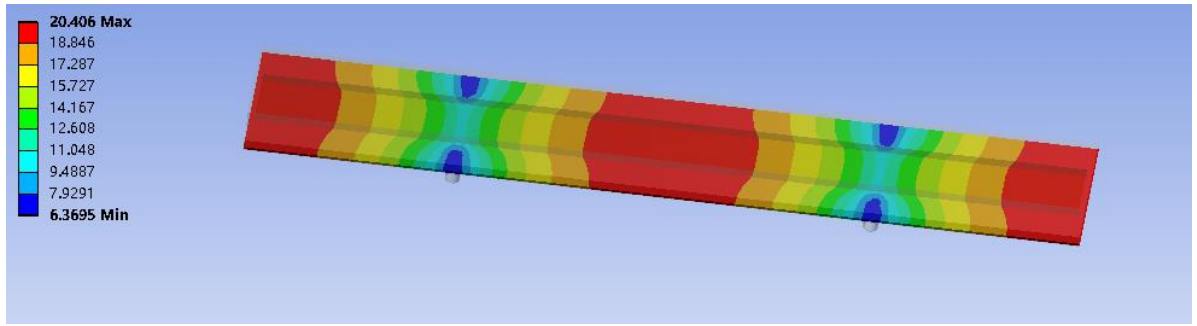


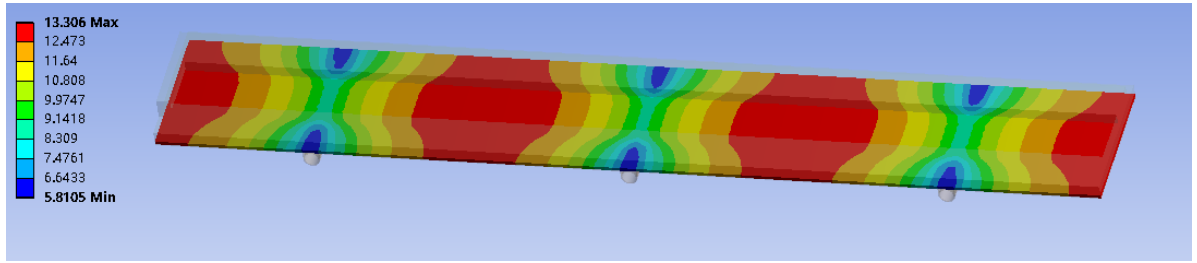
maximum deformation 0.03mm.



Thermal analysis for ToF & OTK

- Thermal analysis
  - Power：288mW/cm2
  - Cooling with two-phase CO2 heat pipe：isothermality temperature (**5°C),** feasible. (From Tsinghua University and Sun Yat-sen University)
  - Optimization of the temperature distribution （from 15 **°C** to 7 **°C** ）

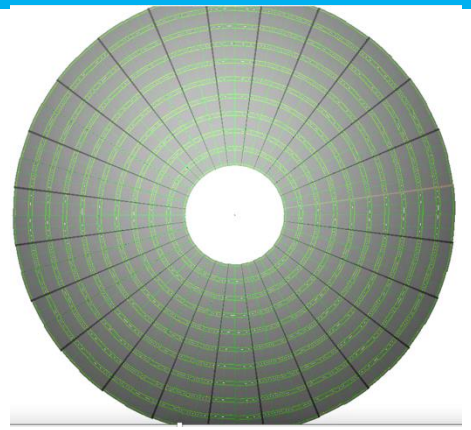




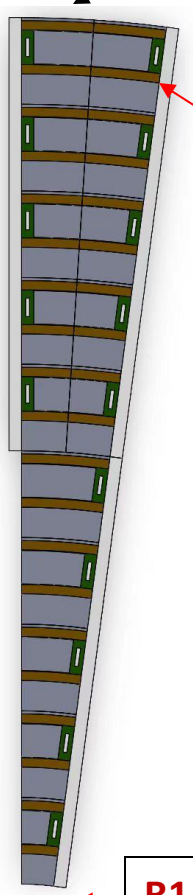
	H2O	CO2
Heat/W	1181.88	1181.88
Cooling Method	Single-phase cooling	Phase-change cooling
Heat transfer per unit mass (W/g)	21	214.98
Liquid Density (kg/m³)	1000	896
Required Mass Flow Rate (g/s)	56.28	5.5
Liquid Velocity (m/s)	17.91	1.95
Operating Pressure (MPa)	0.1	3.97

Endcap Design for ToF & OTK

Disk

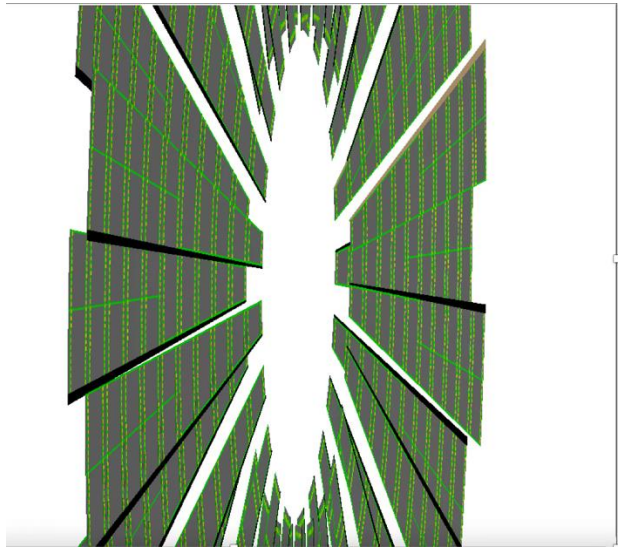


Petal

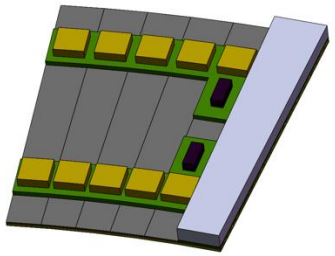


- One layer with 20 m^2
  - ✓ Radius from 400 mm to 1800 mm
  - ✓ Theta from 8º to 30o
- Overlap to reduce the dead area
  - ✓ 48 petals/layer
  - ✓ 10 rows/petal,
  - ✓ 7.5º per petal,
  - ✓ Overlap 0.5º/petal
- 140 mm / row at R direction

overlap petals to reduce the dead area



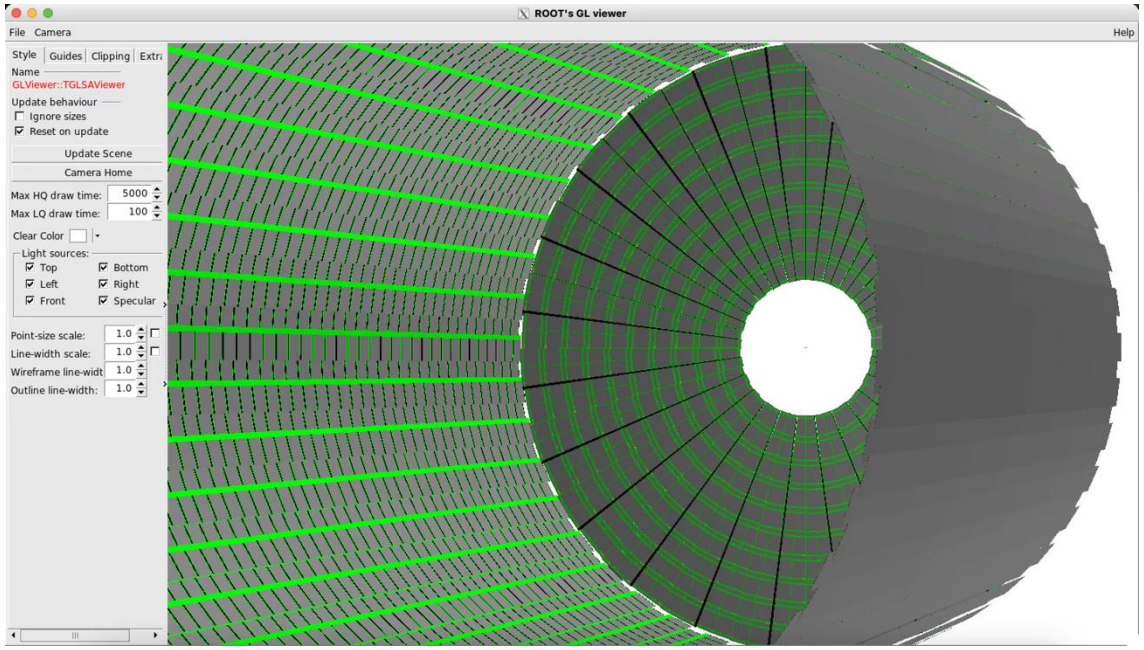
Sector Module per row



70 mm
R1: 52.36mm-70.69mm

CEPCSW Progress for ToF&out tracker

- Got the geometry of barrel and endcap into CEPCSW
  - Good for full simulation and future physics performance study
- Estimated the maximum occupancy: 0.35% at z pole, OK



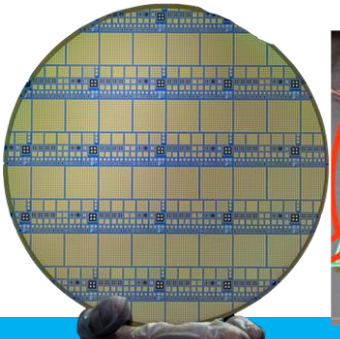
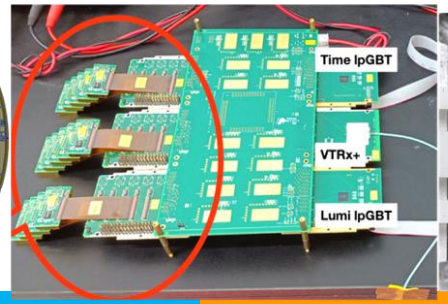
Details in Dian Yu's poster

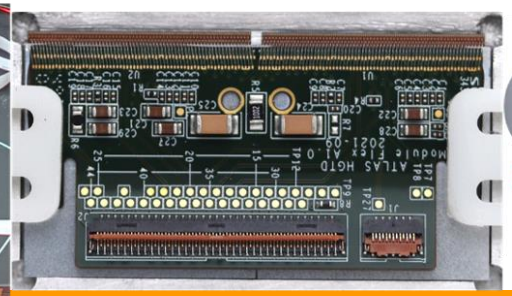
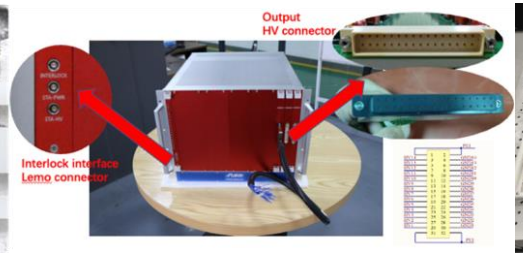
Research Team

- ToF & OTK: 9 universities and institutes，　~ 18 staffs + ~ 22 postdocs & students

- **Joined the DRD3 group**

- **International cooperation experiences:** **ATLAS China team played a leading role in HGTD**
  - Joao (IHEP) is re-elected as Project leader (2021-2025)，L1 manager
  - 4 Level-2 conveners (Module, Sensor, Electronics, Risk, Simulation)
  - 3 Level-3 conveners (PEB, high-voltage, module flex)


Technical Challenges and Working Plan

- ✓ **4D LGAD based sensor**
  - 40 ps and 10 μm for ~70 mm long strip
- ✓ **High precision and low power consumption ASIC**
  - 30 ps jitter
- ✓ **Large module：**
  - Long ladder： 2900 mm
  - ….

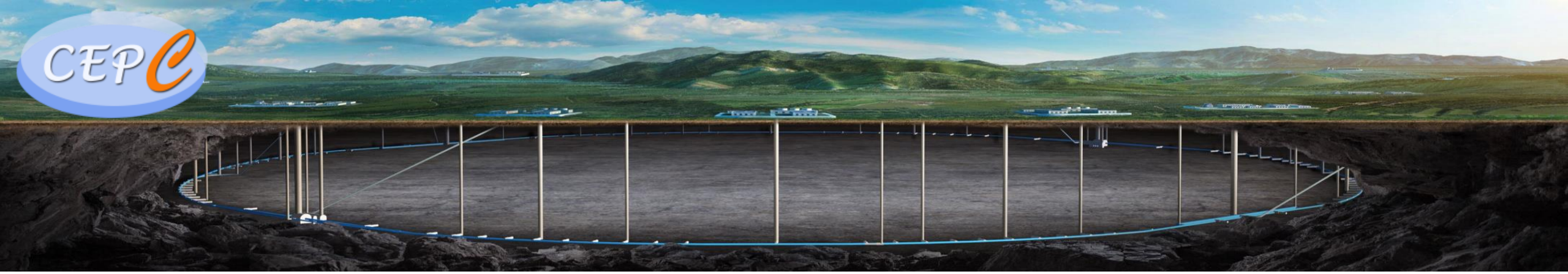
CEPC requirement for the sensor and ASIC

	CEPC TOF barrel	CEPC TOF endcap
Area (m^2)	~ 70	~19.4
Granularity	70mm × 0.1mm	70mm × 0.1mm
Capacitance	~10 pF	~10 pF
Charge	>15fC	>15fC
Channel number	**~ 1×10^7**	**~ 2×10^6**
Module assembly	Wire bonding at strip	Wire bonding at strip
MIP Time resolution	~30-50 ps	~30-50 ps
Spatial resolution	~ 10 μm	~ 10 μm （r -ϕ）
Number of channels per module	2816	2816
Data size	16 bit (9 TOT, 7 TOA) + channel(7bit, 128) +bunch ID(8bit) + chip ID (4-5 bit) ~40-48 bits	16 bit (9 TOT, 7 TOA) + channel(7bit, 128) +bunch ID(8bit) + chip ID (4-5 bit) ~40-48 bits

Summary and Working plan

- **Designed an AC-LGAD based detector as ToF + Outer Traker for CEPC**
  - **50 ps** time resolution and **10 μm** spatial resolution (4D detector)
  - aim to design **70 mm** long strip AC-LGAD
  - cover the barrel and endcap region: **~90 m²**
- **Prototype**: AC-LGAD sensor with **5.6mm** strip length and **150 um** pitch, timing resolution is **37.5 ps** (Beta test), spatial resolution is **8.3 μm** (laser test).
- **Working plan for ToF & Outer Tracker**
  - Optimized the barrel and endcap design
  - Test beam for the long strip AC-LGAD
  - Sensor design: 3 steps (20mm, 40mm, 70 mm) towards the large area, long strip, sector sensor
  - High precision electronics optimization, such as the power consumption
  - Design and Optimize the cooling system (cooling pipe et. al.)
  - Physics performance study
  - **A lot to be done…**

Welcome to join us !



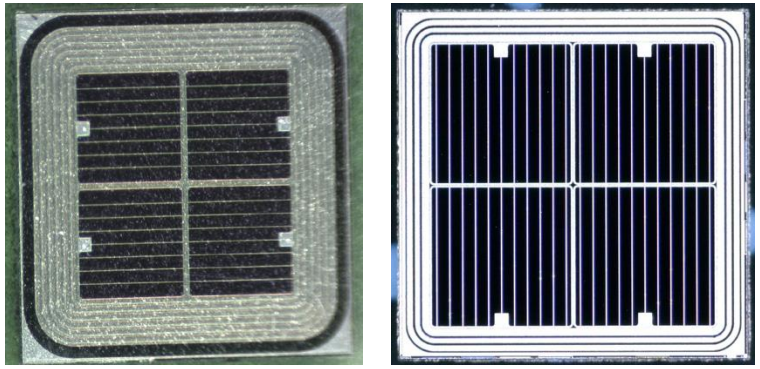
Thank you for your attention!

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

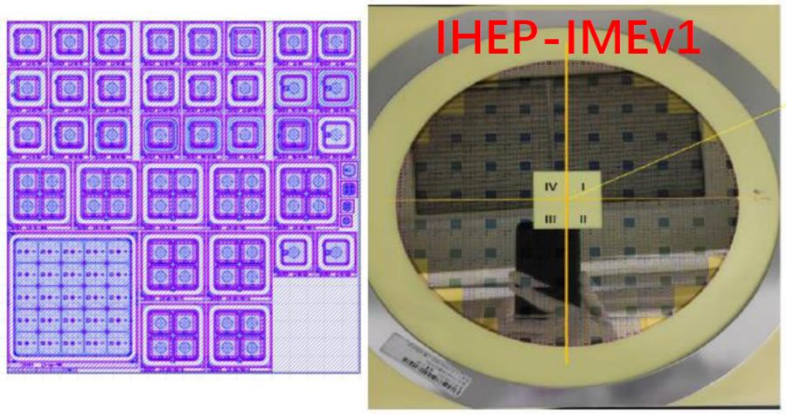
Backup

LGAD Development at LGAD

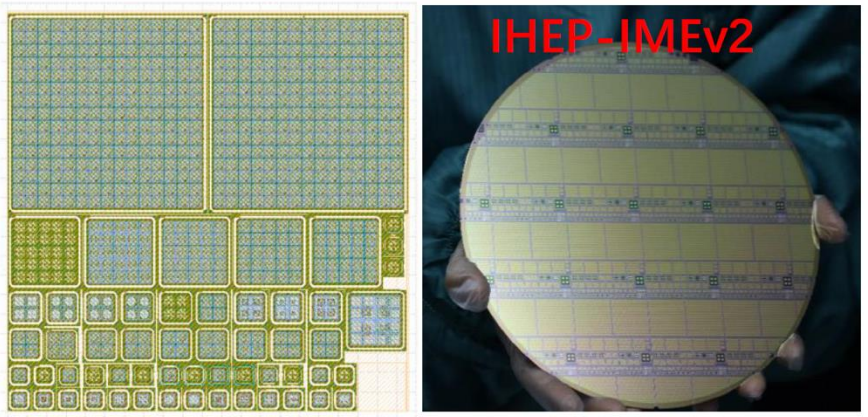
IHEP-NDL(2019)



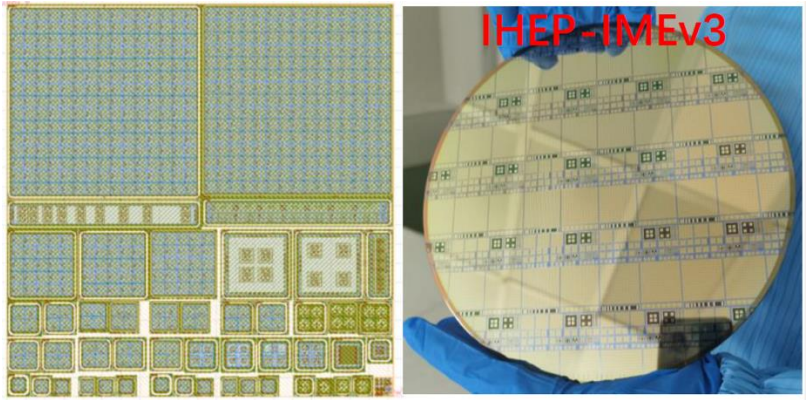
IHEP-IMEv1(2020.9)



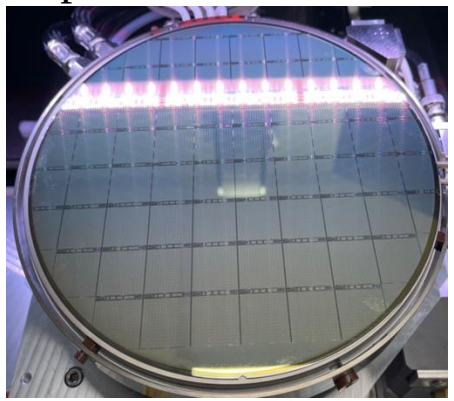
IHEP-IMEv2(2021.6)

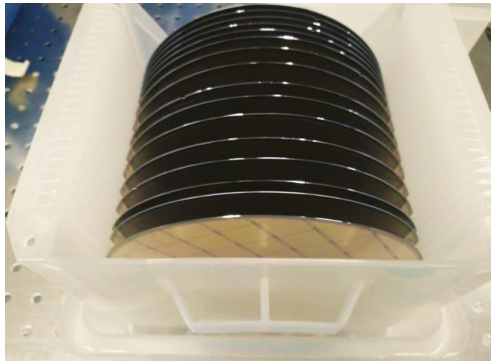


IHEP-IMEv3(2022.5)



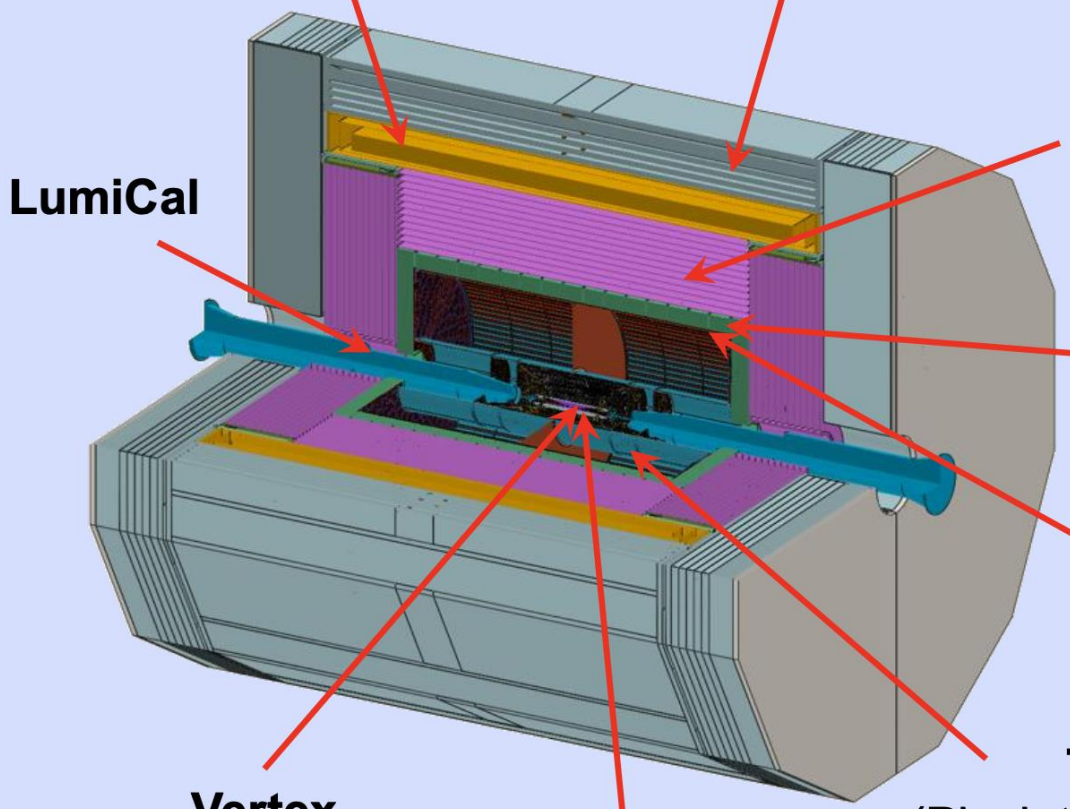
Pre-production for ATLAS (2023.7)





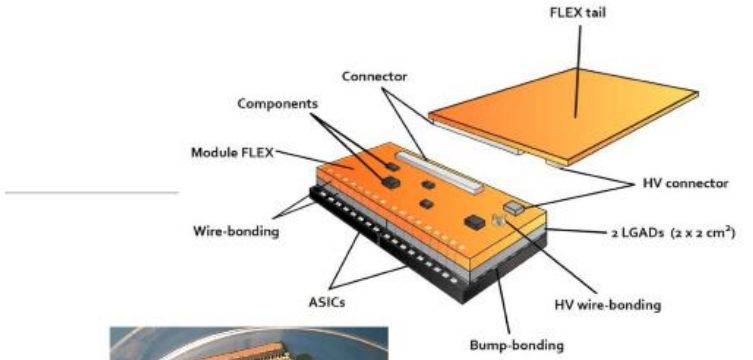
→ Mass production for ATLAS (2024.6)

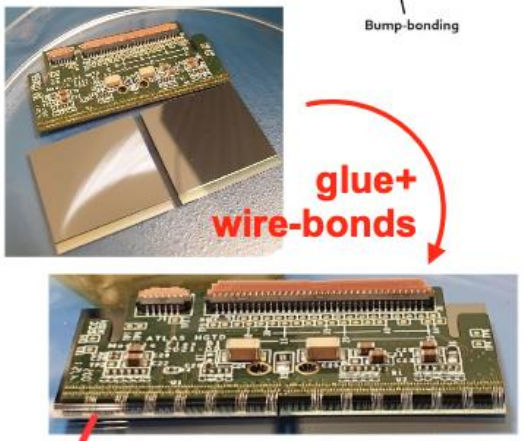
The 4th Concept

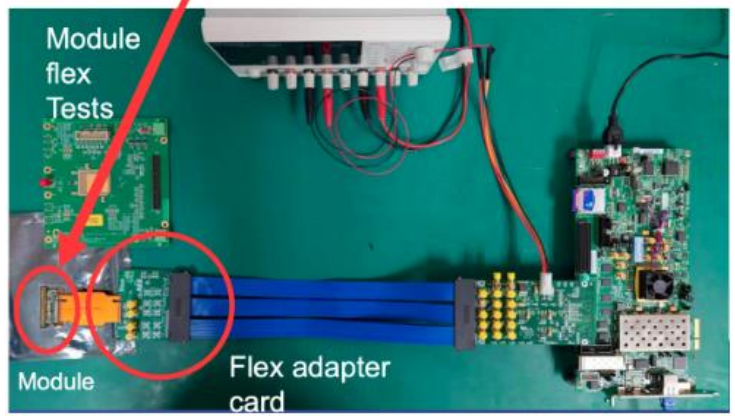


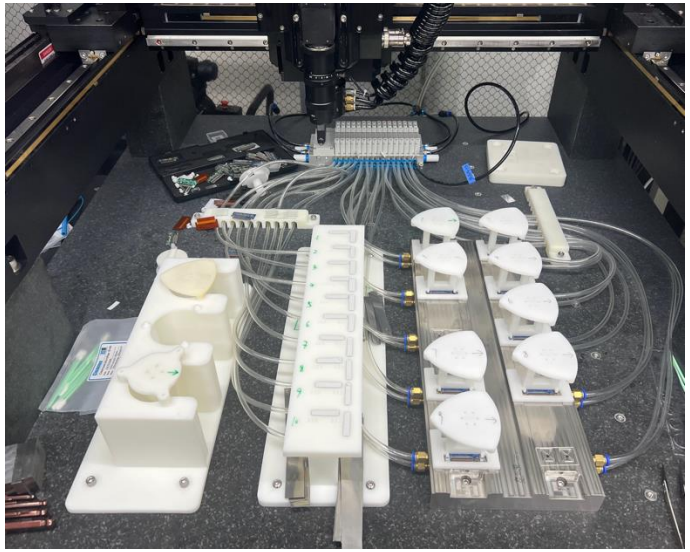
LGAD module assembly at IHEP

- 6 module assembly site at HGTD
  - IHEP, USTC, Mainz, France, IFAE, Morocco
  - **IHEP is largest site, 34% module assembly (~3000)**
- IHEP designed and fabricated module flex
- IHEP developed gantry system for assembly and loading
  - Pattern recognition, glue dispending and assembly
  - Plan to assemble 10 modules each time









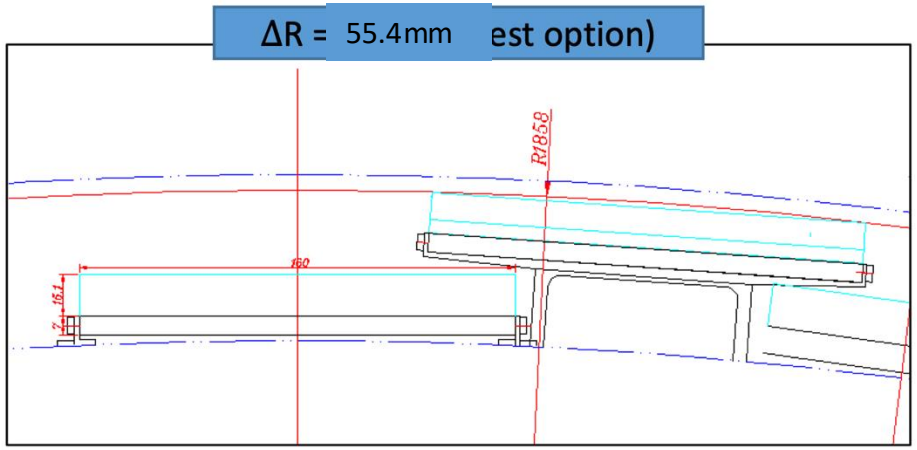
Mechanism: Optimization of the Barrel Design

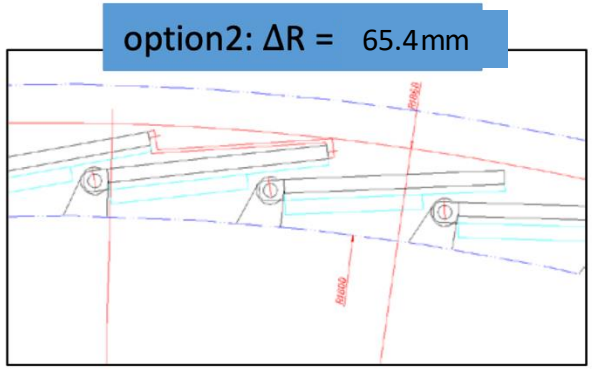
Three arrangement of the ladder

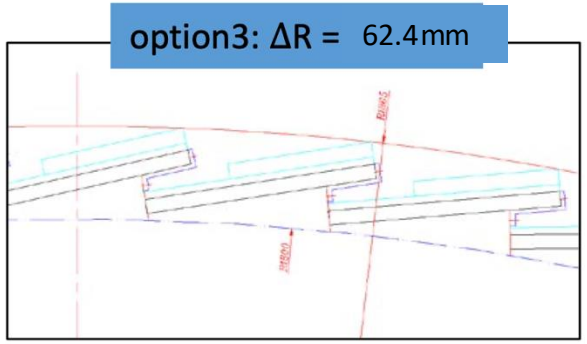
G1: ΔR = 55.4 mm （**The Best arrangement**）

The best option:

- minimum space required in R direction
  ΔR= 55.4 mm
- Sensors toward outside direction (update recently)

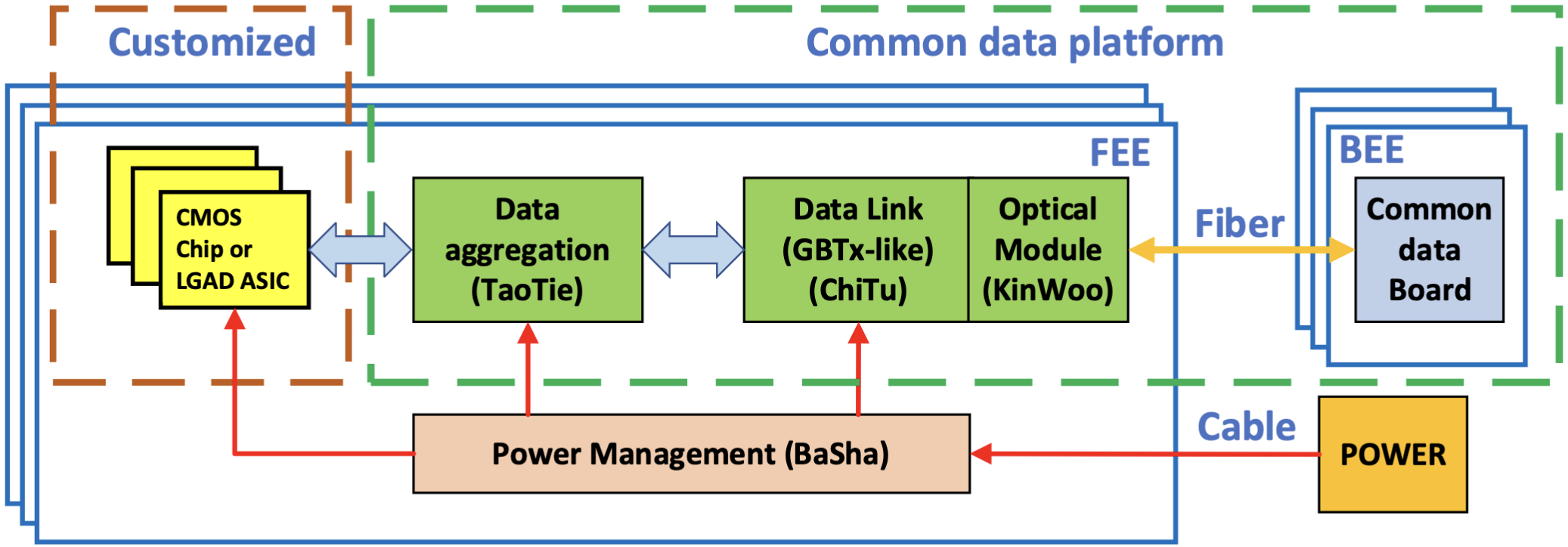




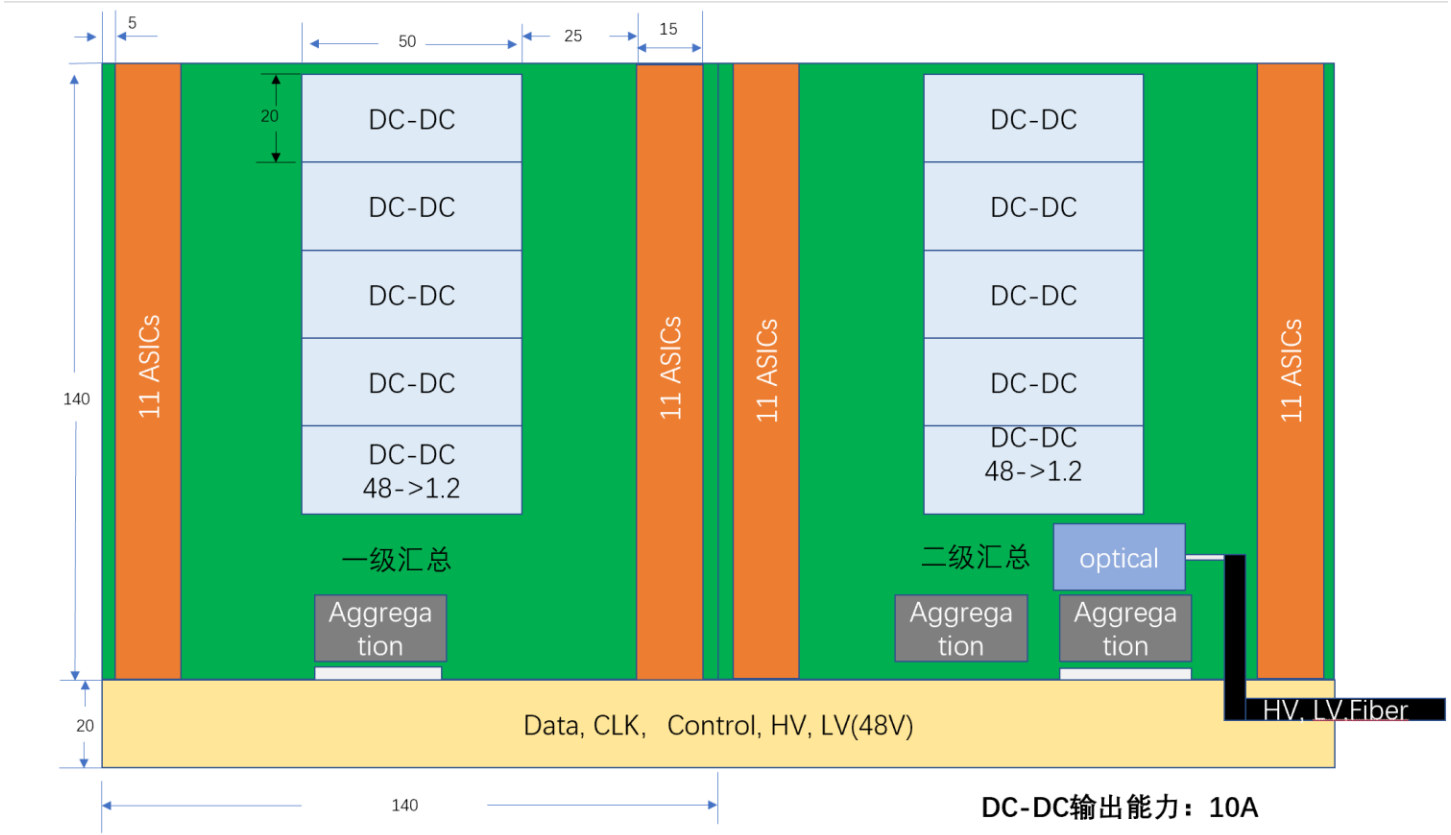


Sensor and electronics：
thickness 13.8 mm

Silicon Tracker Common Electronics



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


5
50
25
15
20
DC-DC
DC-DC
DC-DC
DC-DC
DC-DC
48->1.2
11 ASICs
11 ASICs
11 ASICs
11 ASICs
DC-DC
DC-DC
DC-DC
DC-DC
DC-DC
48->1.2
140
一级汇总
二级汇总
optical
Aggrega
tion
Aggrega
tion
Aggrega
tion
20
Data, CLK, Control, HV, LV(48V)
HV, LV Fiber
140
DC-DC输出能力：10A

Heat sink study

- PCB heat sink design should based on the standard manual
  - Experiences on 1.6 mm PCB with heat sink
  - Juno and AMS02 experiment applied the heat sink to cooling down

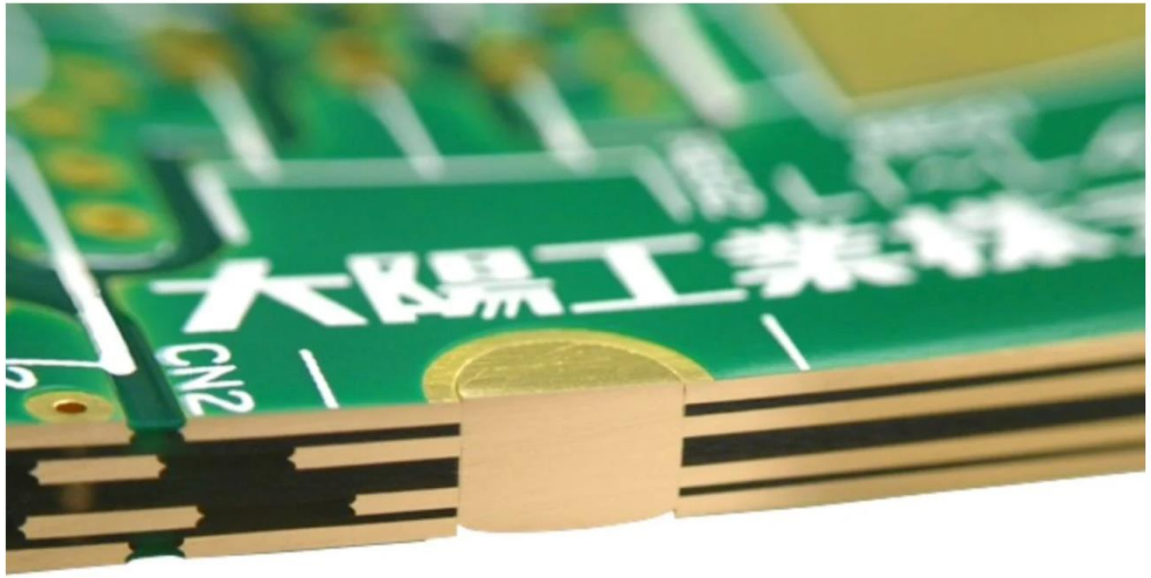


Figure 2: A PCB built with embedded copper coin.

Need to know how large the heat sink is?

Who can help to do the estimation?

https://www.proto-electronics.com/blog/design-hints-high-power-pcbs

AC-LGAD: Spatial Resolution

- Spatial resolution Vs. Pitch size
  - ✓ Pitch size 250um → 150um
  - ✓ Spatial resolution 11 -> 8 μm (Strip).
- **Smaller pitch sizes -> better spatial resolution**

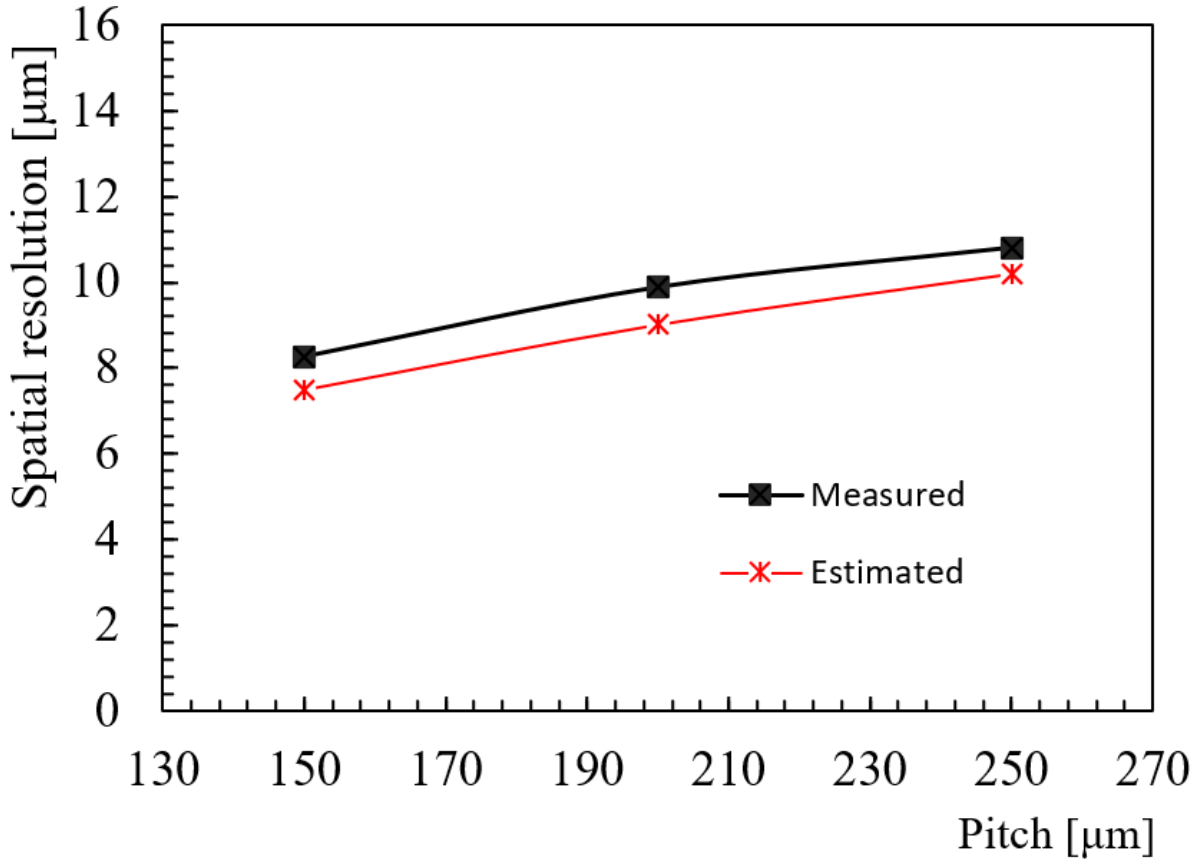
Resolution estimation:

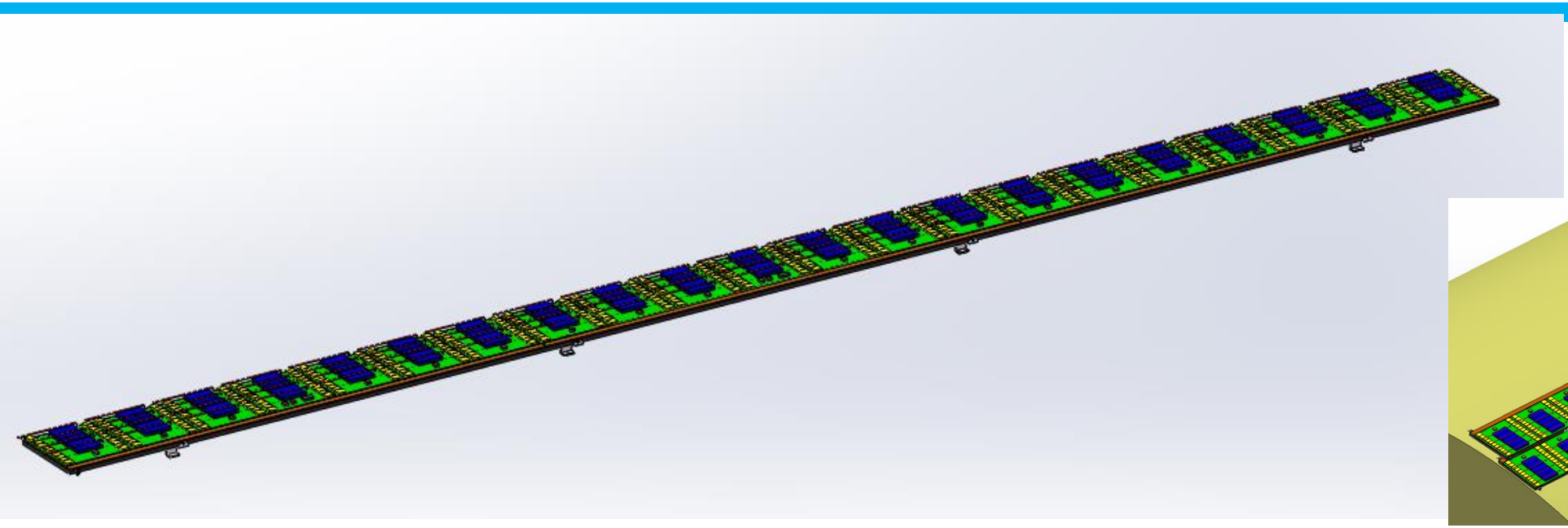
$$\sigma_{spatial} \approx \frac{N}{A}$$

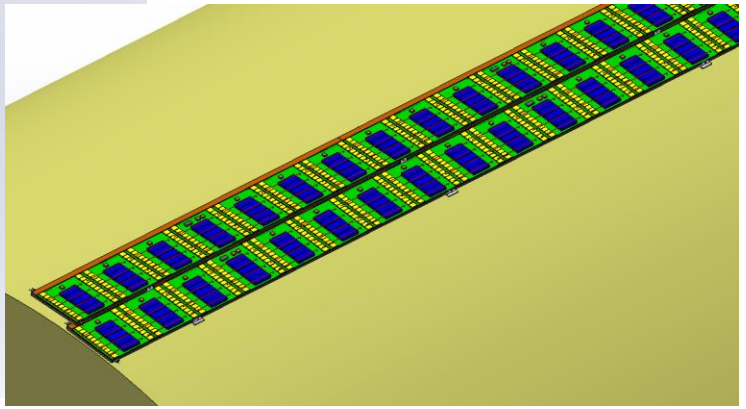
A: signal attenuation factor

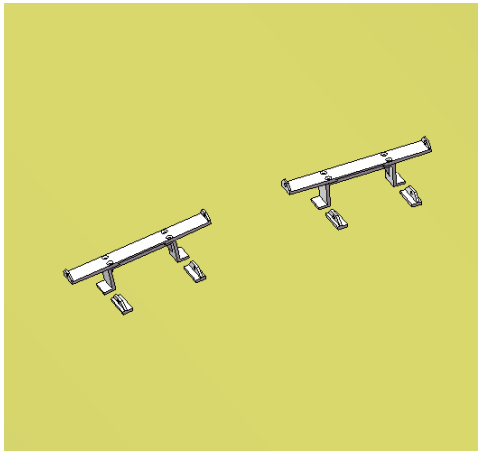
N: noise RMS (sensor + electronics)

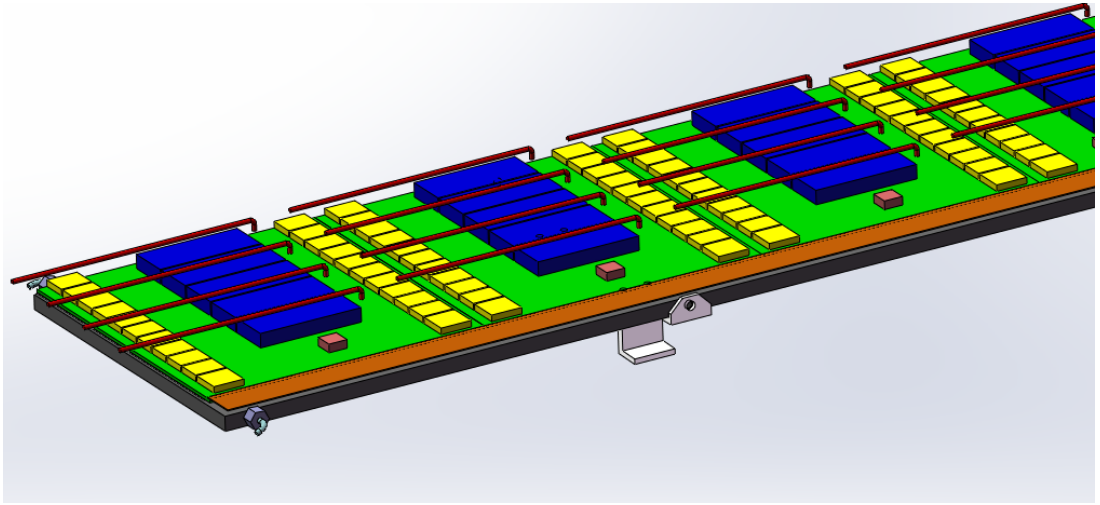
Spatial resolution Vs. pitch size



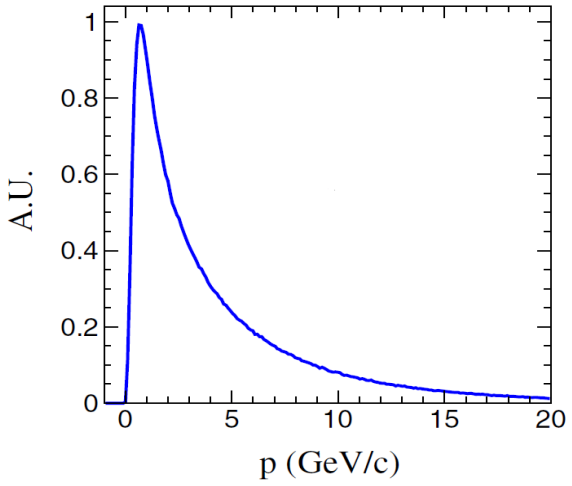


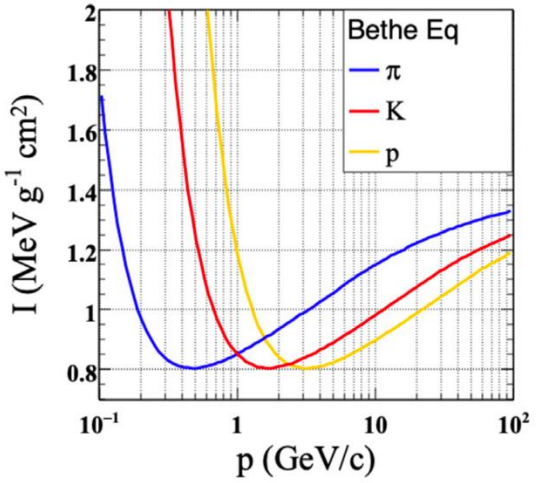






TPC





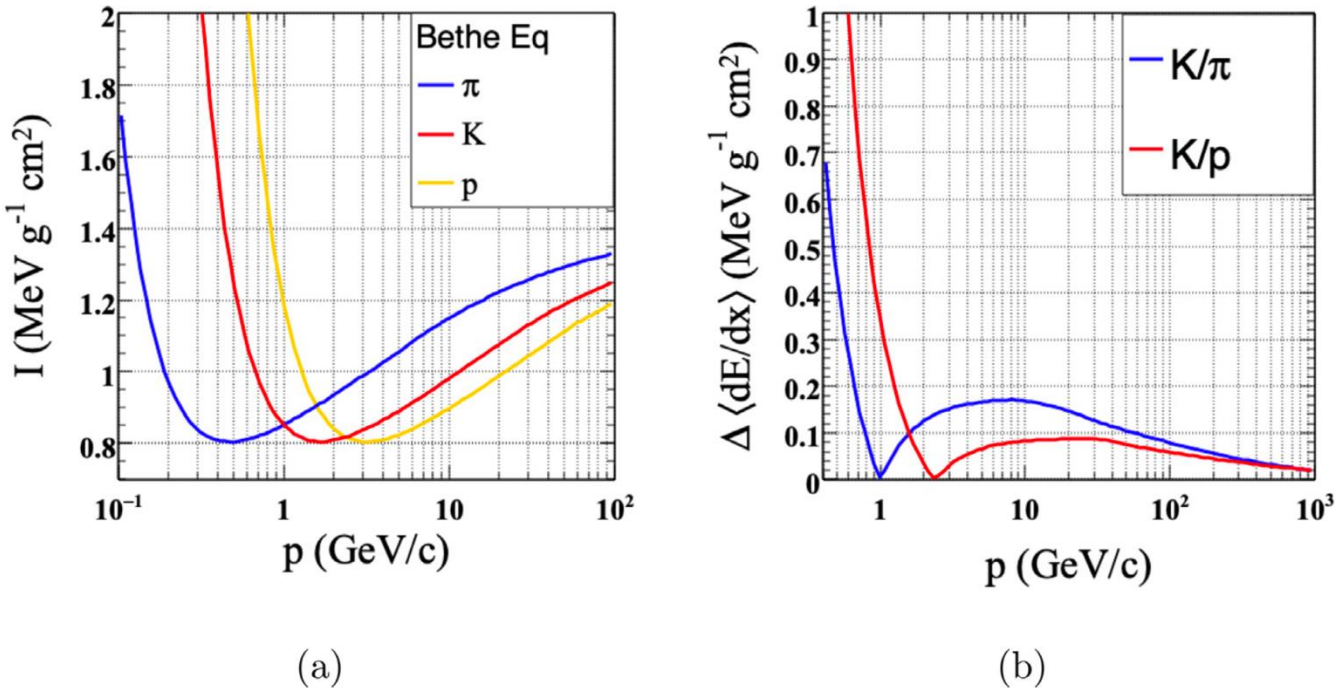


Fig. 4. The distribution of I as a function of momentum for $K^{\pm}/\pi^{\pm}/\overset{(-)}{p}$ (a) and the absolute difference of I for $K^{\pm}/\pi^{\pm}$ and $K^{\pm}/\overset{(-)}{p}$ (b).