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Institute of High Energy Physics
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# Research of AC-LGAD strip detector for 4D tracking

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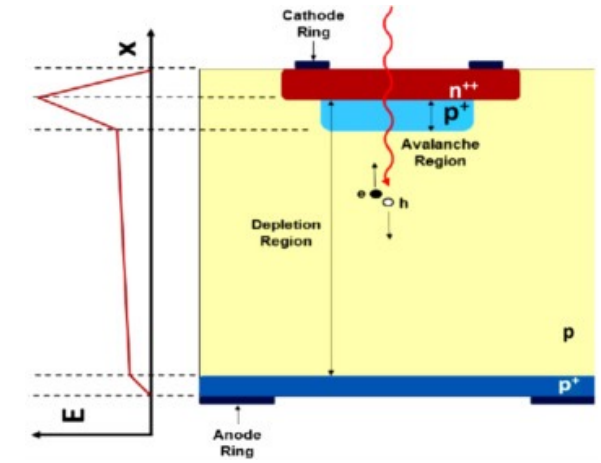
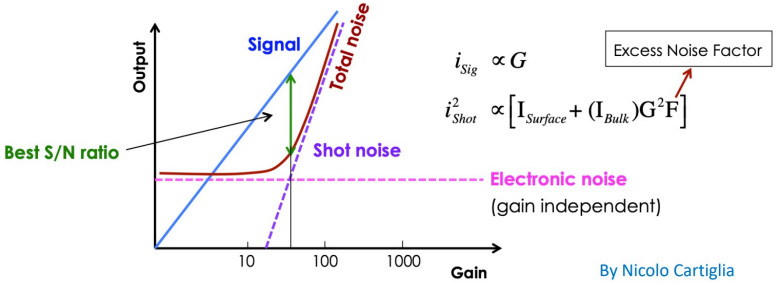
# LGAD and AC-LGAD

## LGAD: **Low-Gain Avalanche Diode**




- High electric field in the gain layer
- Multiplication
- Good SNR due to low gain




**Noise increases faster than then signal**

**→ the ratio S/N becomes worse at higher gain**

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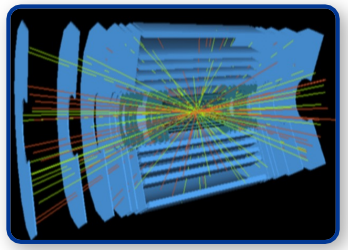
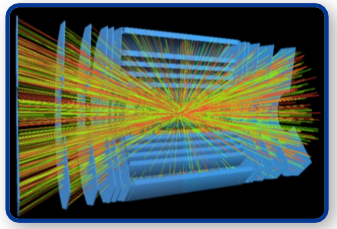
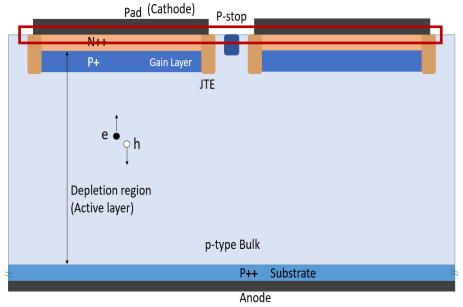
## ATLAS @ LHC



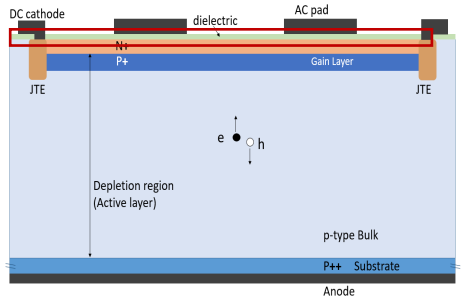
## ATLAS @ HL-LHC



HGTD based on LGAD:
Proposed to address severe pile-up in HL-LHC phase




*Dielectric*




**LGAD (Low-Gain Avalanche Diode)**

- Metal pads are 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)**

- Metal AC-pads are separated from the n+ layer by a thin dielectric ($Si_3N_4$, $SiO_2$)
- No dead zone (100% fill factor)
- Time resolution ~ 30ps
- Position resolution: 5~10 um
- Radiation hardness: $10^{15}$ ~$10^{16} n_{eq}/cm^2$

# Motivation

- LGAD based silicon sensors can provide precise timing information, while AC-LGAD as a new 4D detector, **can provide the position information at the same time**.

**DRDT 3.2 - Develop solid state sensors with 4D-capabilities for tracking and calorimetry**

Understanding the ultimate limit of precision timing in sensors, with and without internal multiplication, requires extensive research and developments to increase radiation tolerance and achieve 100% fill factors. New semiconductor and technology processes with faster signal development and low noise readout properties should also be investigated

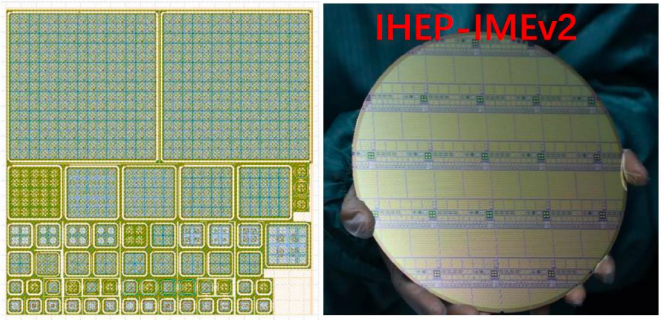
| WG2 research goals <2027 | |
|---|---|
| | **Description** |
| **RG 2.1** | Reduction of pixel cell size for 3D sensors |
| **RG 2.2** | 3D sensors for timing ($< 55 \times 55$ $\mu$m, $< 50$ ps) |
| **RG 2.3** | LGAD for 4D tracking $< 10$ $\mu$m, $< 30$ ps, wafer 6" and 8" |
| **RG 2.4** | LGAD for ToF (Large area, $< 30$ $\mu$m, $< 30$ ps) |

- **RG 2.3: LGAD Sensors with very high fill factor, and an excellent spatial and temporal resolution.**
  - 2024-2025: LGAD test structures of different technologies (TI-LGAD, iLGAD, AC-LGAD/RSD, DJ-LGAD), matching existing read-out ASICs.
  - 2026-2028: Large LGAD sensors based on the best-performing technology.
  - 2025-2028: Investigation of radiation hardness of LGAD technology beyond $\sim 2.5 \cdot 10^{15}$ $n_{eq}/cm^2$.
- **RG 2.4: LGAD sensors for Time-of-Flight applications**
  - 2024-2026: Production of LGAD sensors with large size for Tracking/Time-of-Flight applications to demonstrate yield and doping homogeneity. Study of spatial and temporal resolutions as a function of the pixel size.
  - 2026-2028: LGAD structures with 4D capabilities produced with vendors capable of large-area productions to demonstrate the industrialization of the process.

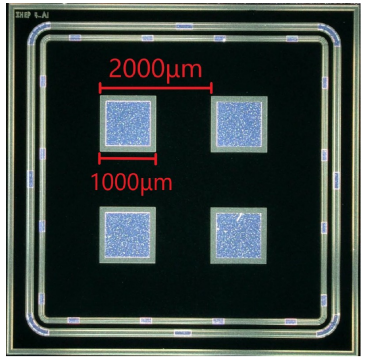
- The project has been proposed at 1st DRD3 meeting.

Develop LGAD based silicon sensors and detector modules for the outer tracker and time-of-flight layer in future colliders (CEPC, FCC-ee, ILC, CLIC, etc.)

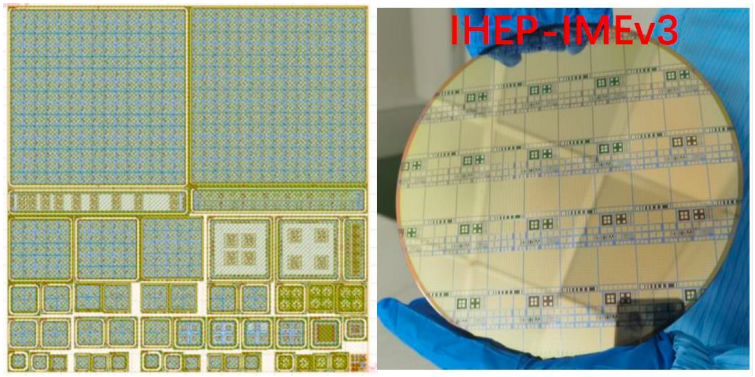
# AC-LGAD Research in IHEP



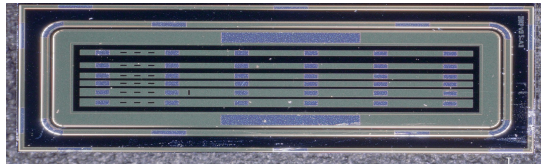

**AC-LGAD R&Dv1:**




Pixeled AC-LGAD
•With different pad-pitch size
1000-2000um
100-500um
100-200um
50-100um
•wafers: with different n+ dose: 10P to 0.2P
Process parameters have been studied.




**AC-LGAD R&Dv2:**

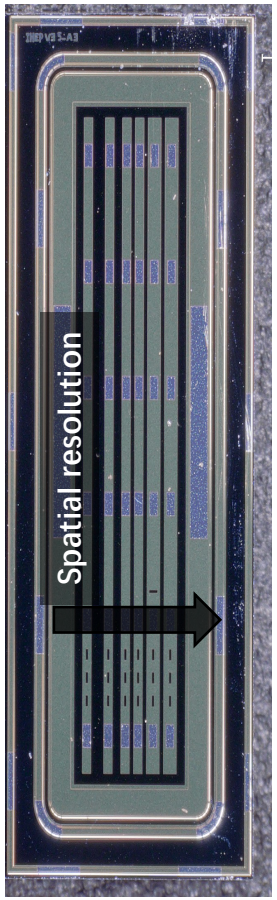


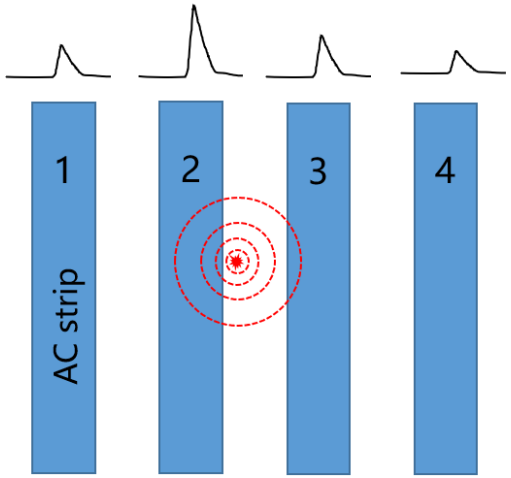
Pixeled and strip AC-LGAD
•With different pad-pitch size
1000-2000um pixel
100-250um strip
100-150um strip
50-100um strip
•wafers: with different n+ dose:0.2P to0.01P
First trial in AC-LGAD Strip

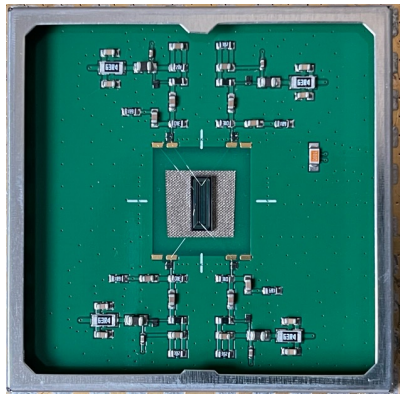
# AC-LGAD Strip

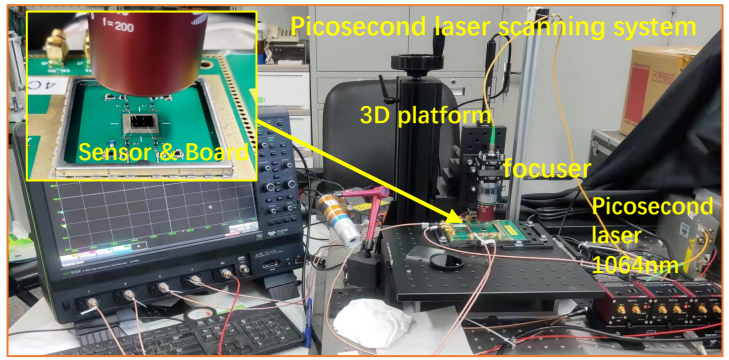
## AC-LGAD Strip：

- Position information： 2 layer
- Strip length 5.6mm, width 100um
- Different Pitch size：
  - **150um、200um、250um**



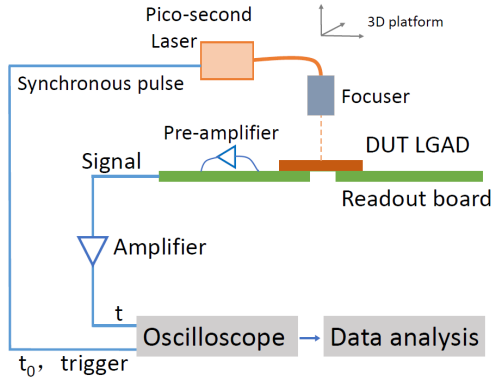



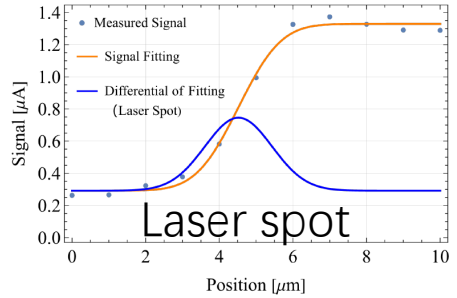



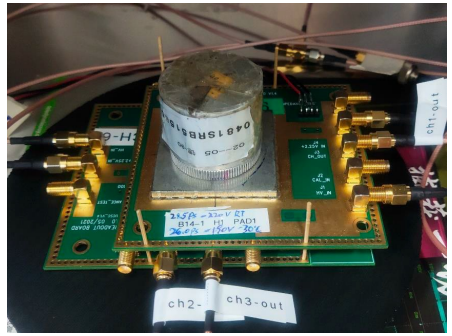



## Picosecond laser scanning system

- Displacement accuracy 1 μm
- Automated scanning
- Picosecond laser 1064nm
- Spot size 2~5 μm

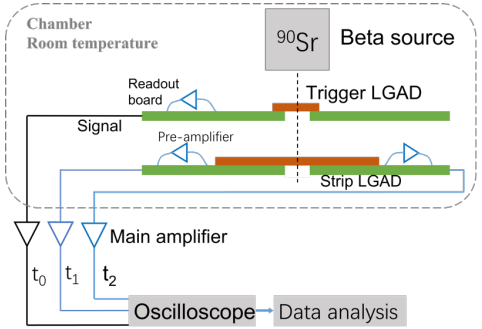


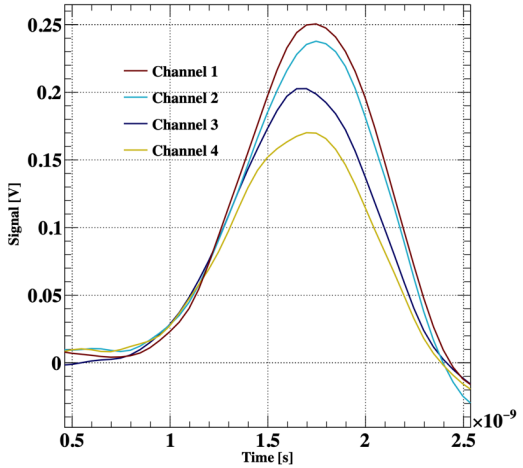



## Beta source test system

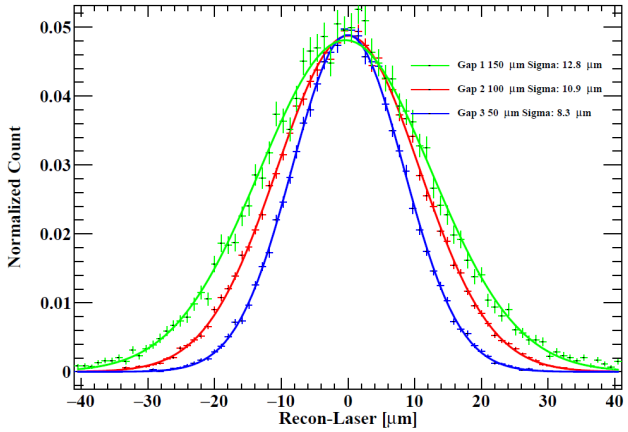
- Stronium-90 2MeV MIP
- With trigger LGAD



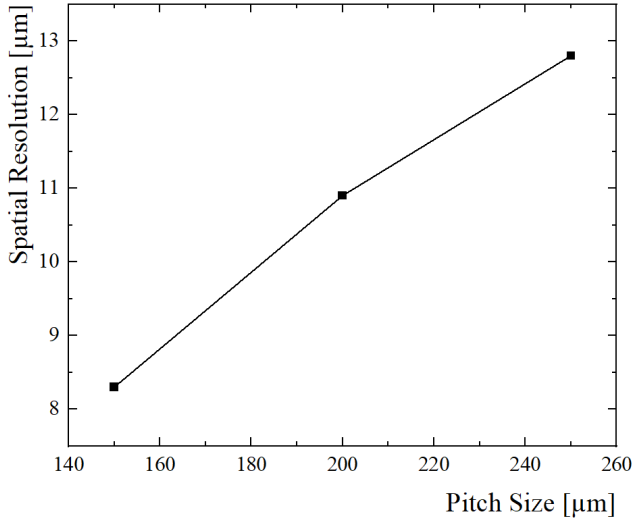
# Signal properties and spatial resolution

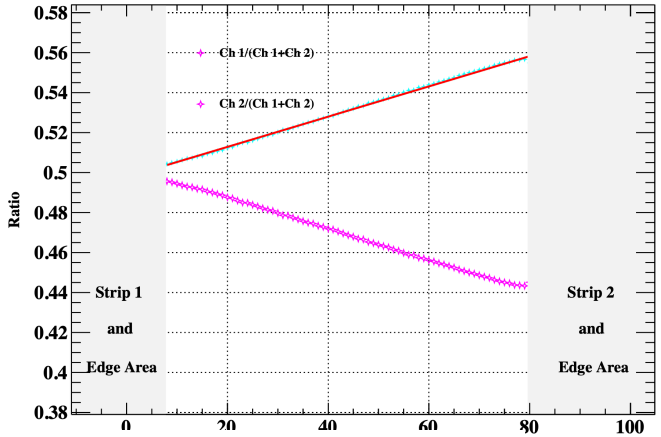



Waveforms on 4 strips of a laser hit




Distribution of difference between real and reconstructed laser hit position
Best spatial resolution: **8.3 µm**

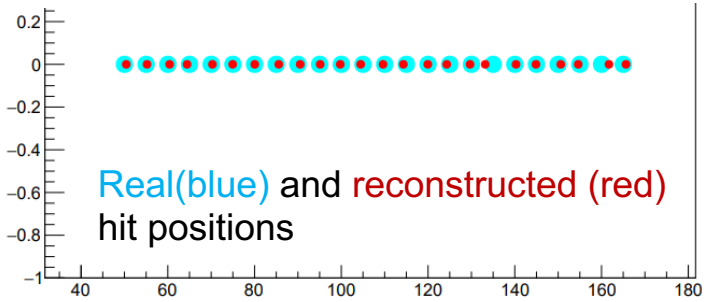



$$R = \frac{Amp_2}{Amp_1 + Amp_2}$$

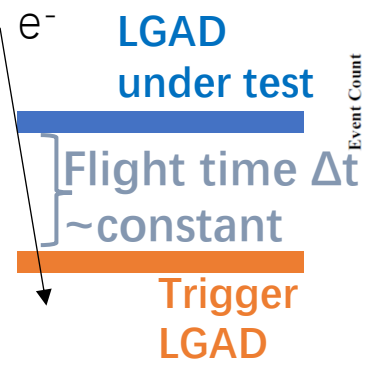
**Position reconstruction:**

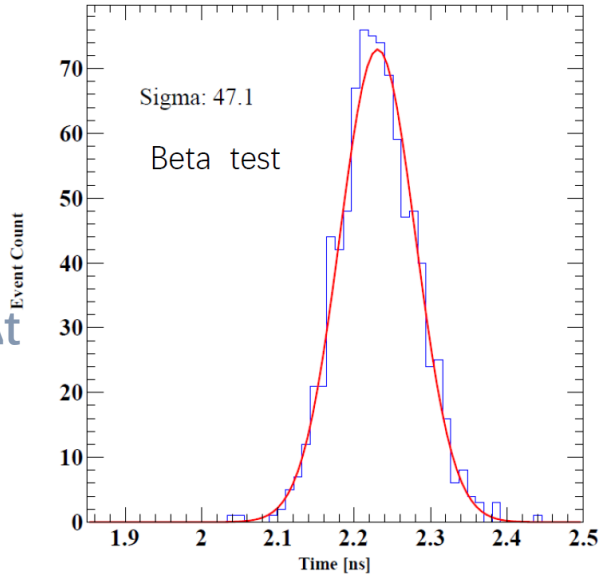
- Based on resistor networks, the fraction of the signal ($R$) changes linearly with laser position between gaps.
- Distortion observed at approach to edge region
- Better than 8.3 µm with 150 µm pitch, and approx. 12 µm with 250 µm pitch




- Good consistency between the reconstruction position and the laser position
- The smaller the pitch size, the better the spatial resolution
- The rise in spatial resolution values is slower than linear with increasing Pitch size

# Time resolution of AC-LGAD Strip



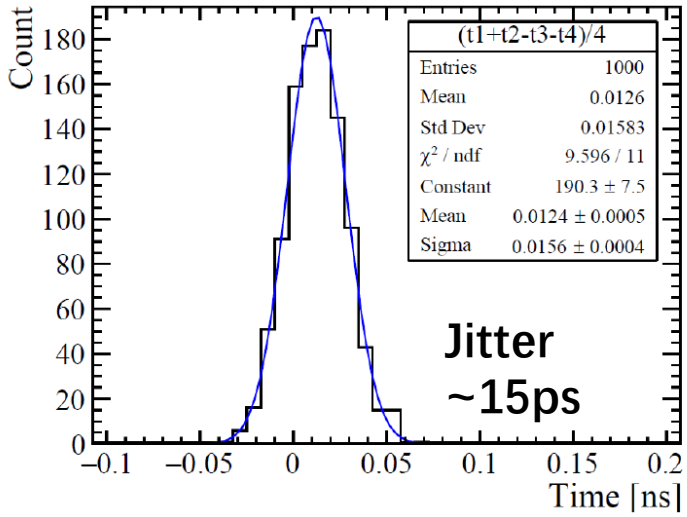




**Distribution of Δt**

**Sigma Δt = 47.1 ps**

**Time resolution: best 37.5 ps**

Jitter ~ 15ps

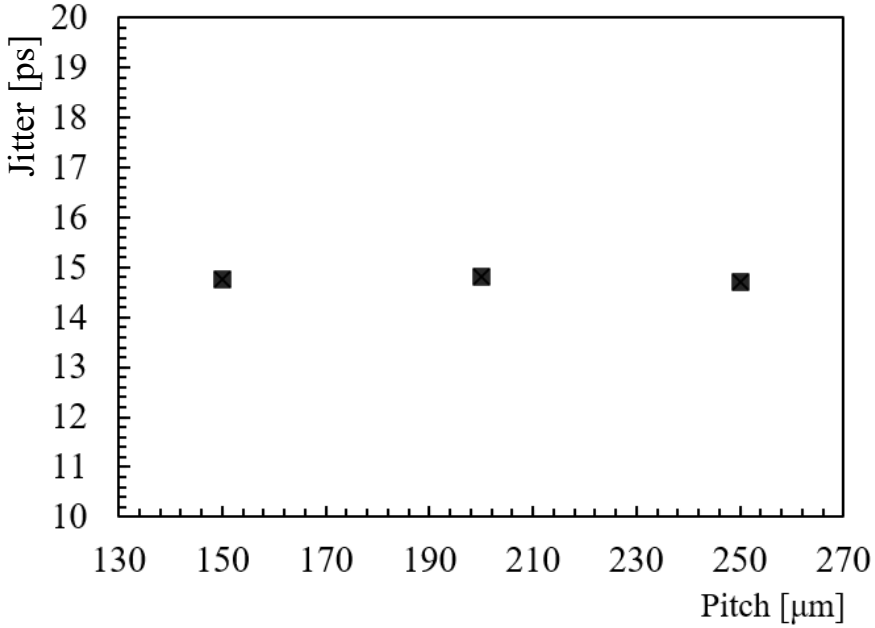



Time Resolution

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

Time resolution of trigger

Weighted time resolution of AC-LGAD

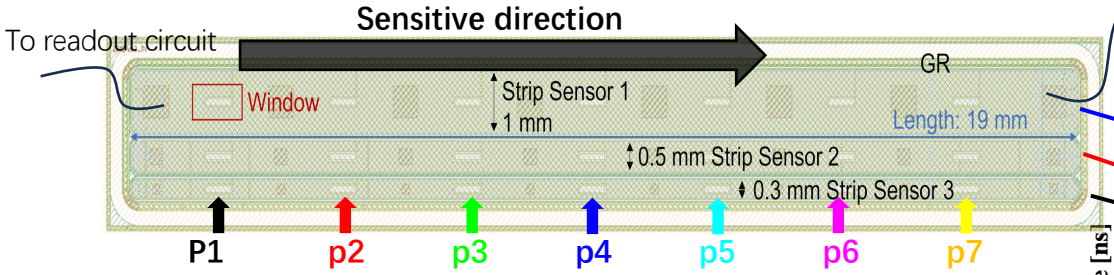



**Jitter Vs. pitch size** -*laser test*

- **~37 ps timing resolution AC-LGAD, via Beta source test.**
- **No significant change in timing resolution was observed among pixel，strip AC-LGADs**
- **Jitter, ~ 15 ps, not change with pitch**

$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{Landau}^2 + \sigma_{Jitter}^2$$

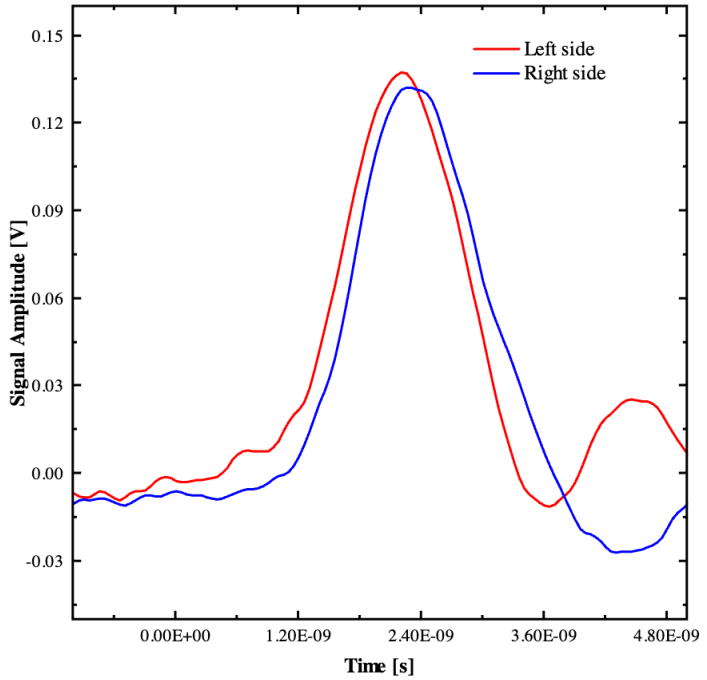
# LGAD-Strip Spatial resolution



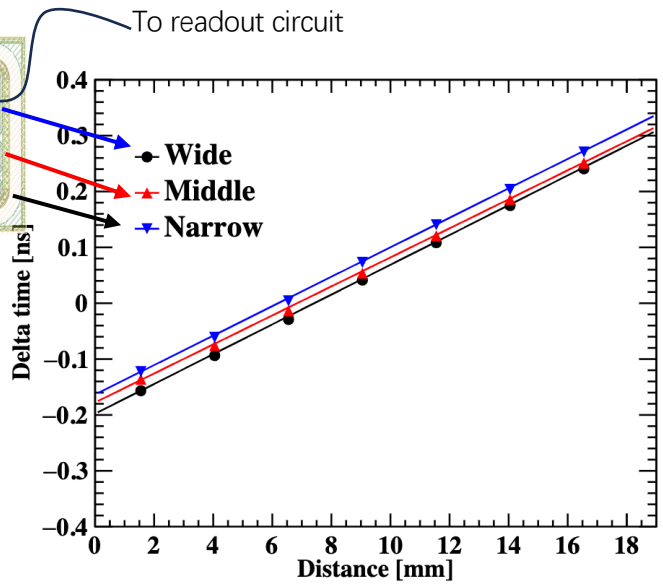

Double-end Readout of LGAD strip

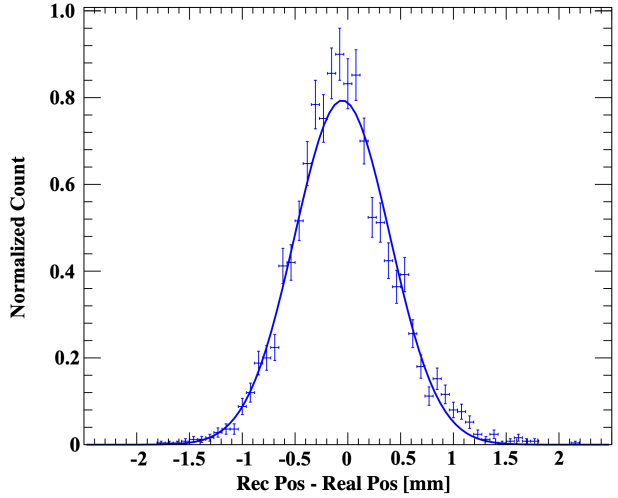
Length: 20mm with 0.3, 0.5 and 1 mm width

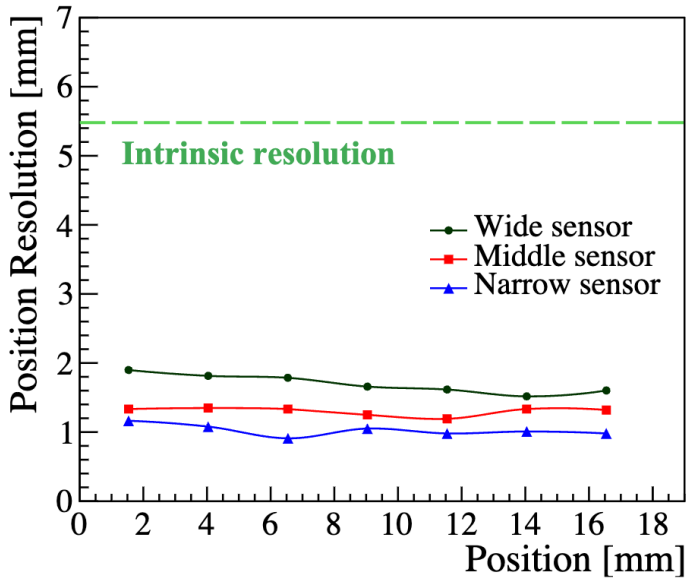
*LGAD-Strip，Not AC-LGAD*




Waveform Variation at two ends




**Position reconstruction:**

- Based on time-lag between two ends
- Good linearity

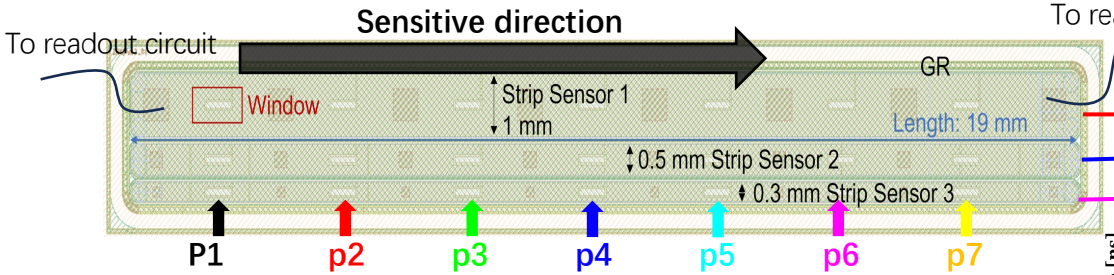
**Position resolution along Z**

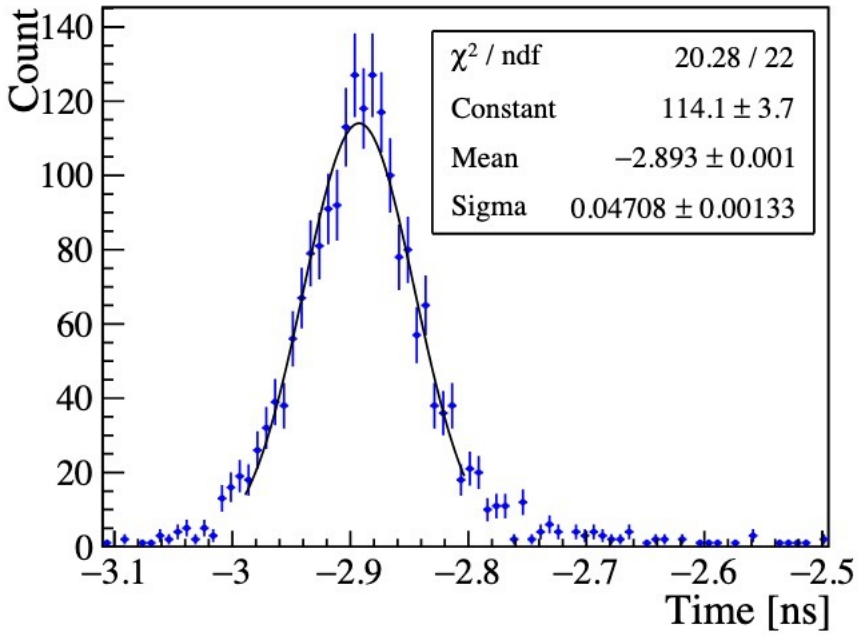
**0.9 mm**

**Intrinsic：5.5 mm**

**Total length：19mm**

# LGAD-Strip Time Resolution

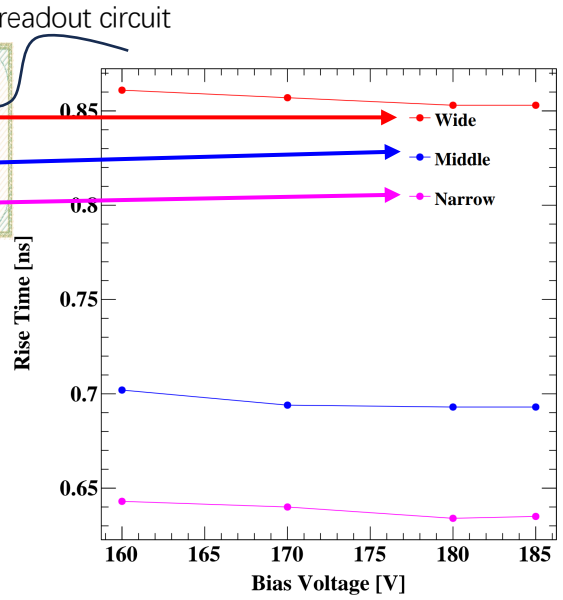


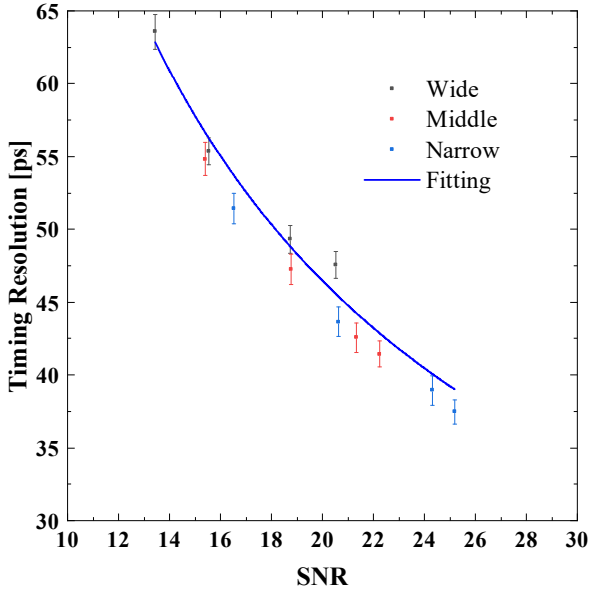



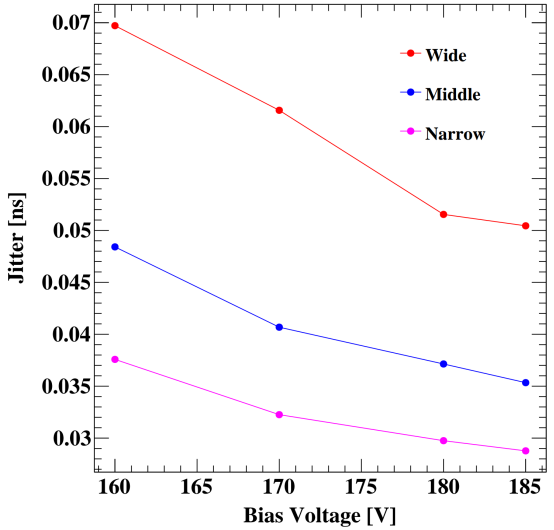

Time resolution of LGAD-strip :

best **37 ps** —double end readout

Similar method with AC-LGAD strip

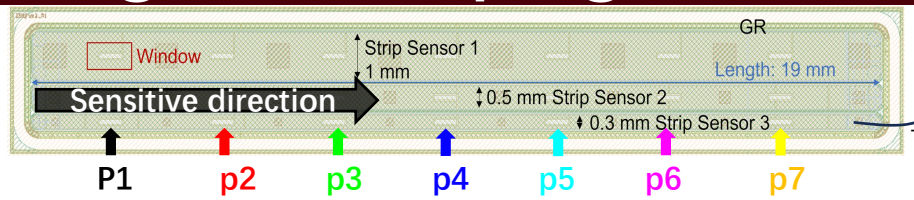


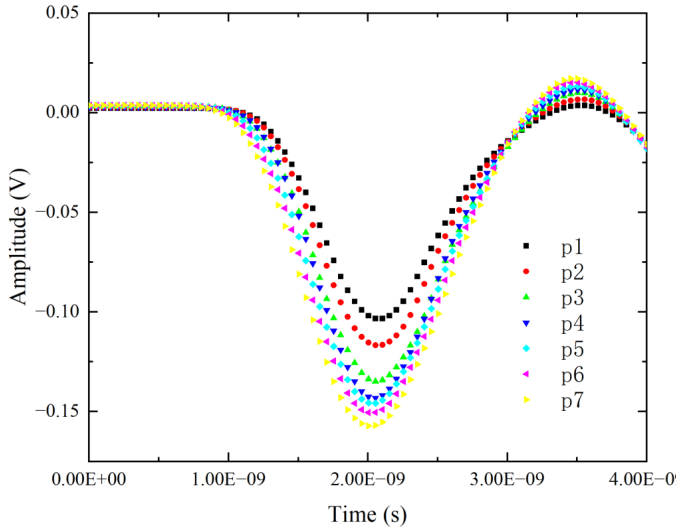




- Jitter decreases with decrease of sensor area
- Dominant of time resolution
- Rise time not change with bias voltage
- $Time\ resolution \approx \frac{Risetime}{SNR}$
- This holds for 2cm scale LGAD

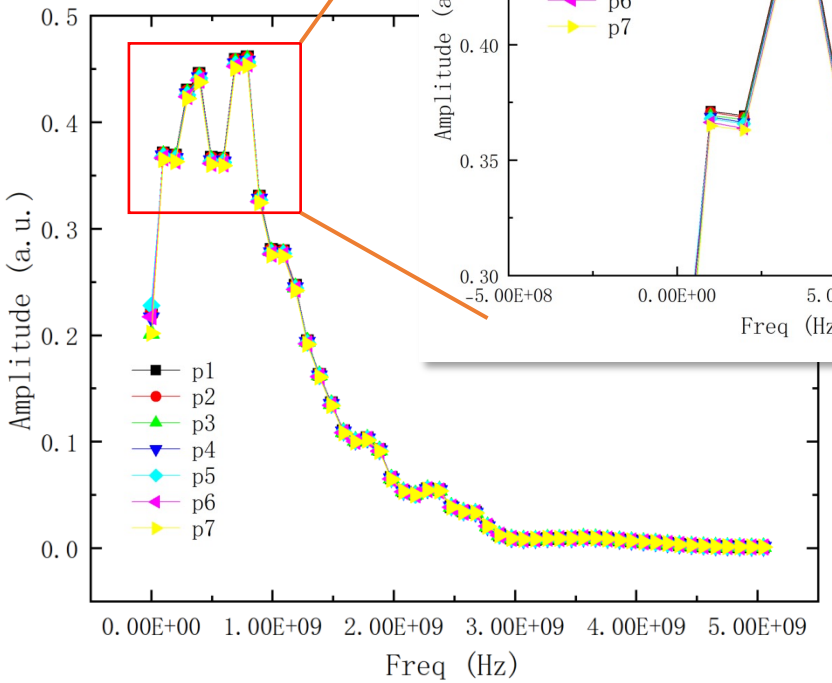
# Signal Propagation Properties—Transmission Line?



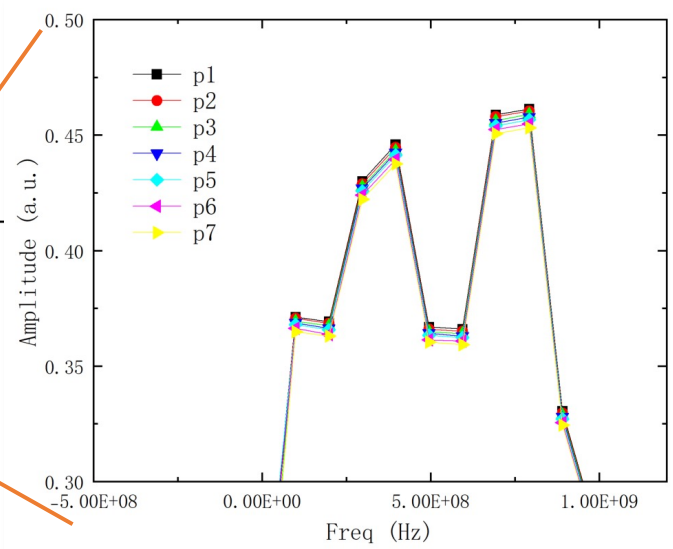

To readout circuit




**Waveform at different hit positions From P1 to P7**




Spectrogram of hit position P1-P7




- ➢ transmission line effect
- Skin effect:

Resistance variation with frequency, especially for high frequency signals

- Dielectric Loss:

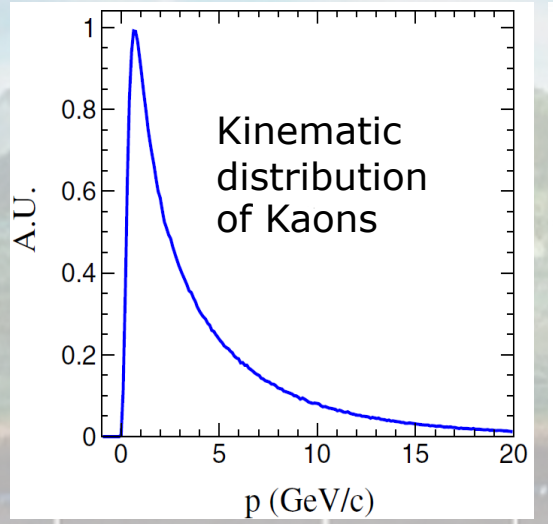
Lost due to dielectric materials

- ➢ **Total loss is related to frequency**

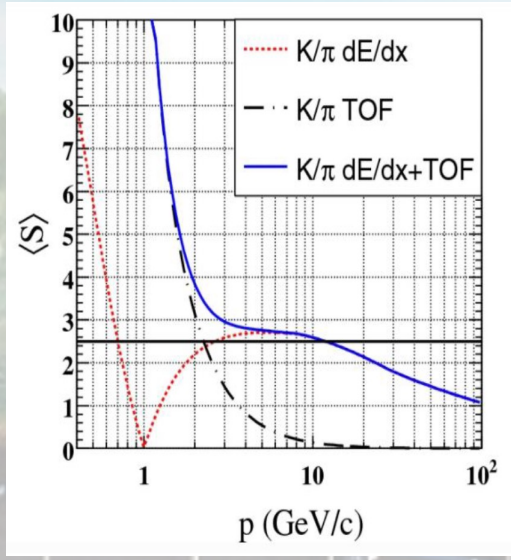
- Signal frequencies mainly in the range of 0.1 to 1.5GHz
- 1GHz dominant
- Amplitudes and areas of waveform (charge) of one end differ, but summation of two ends maintain the same
- In the spectrogram, no significant difference shows in the amplitude of the frequencies among P1-P7

- ➢ DC-LGAD with low n+ resistance
- ➢ For AC-LGAD and high resistance n+ device, things may change, still need to demostrate.

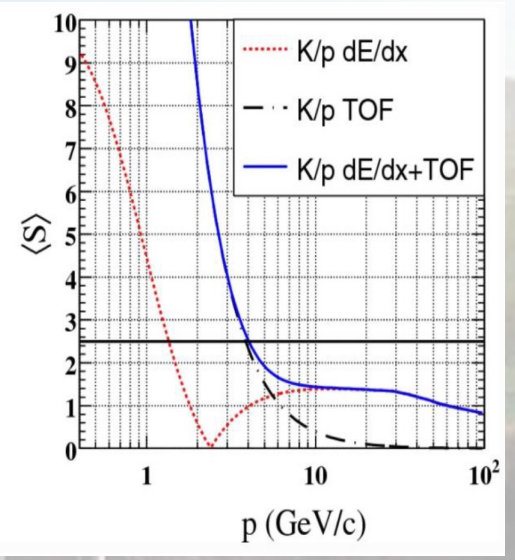
# Application—CEPC ToF


K/pi separation




K/proton separation




Circular Electron Position Collider (CEPC)—A Higgs factory to run at $\sqrt{S}$~ 240GeV.

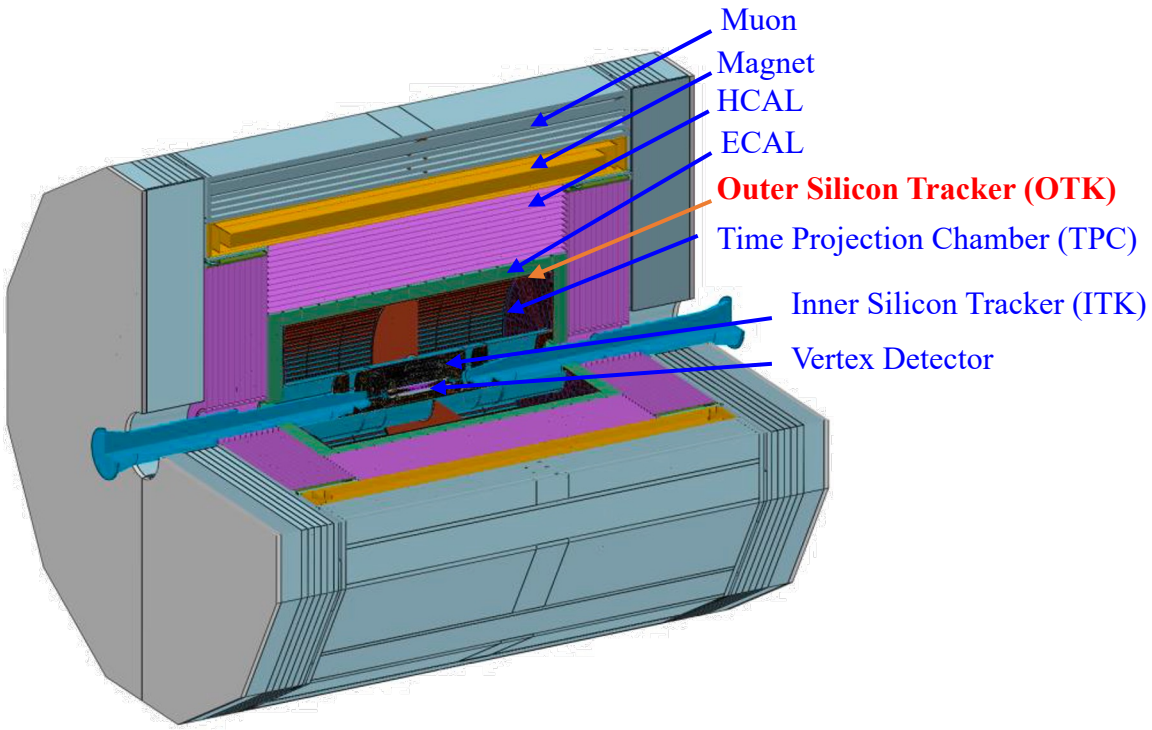
To produce above

1M Higgs at ZH mode

Tera Z at Z pole mode

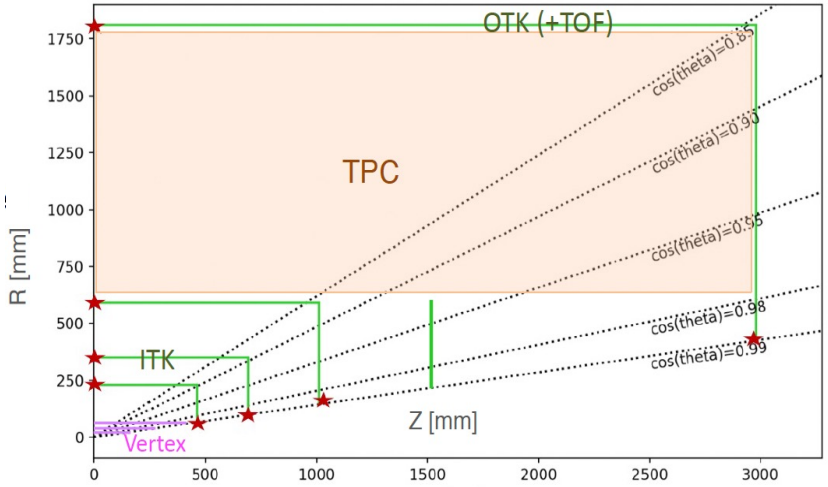
- Multi-targets—Higgs, electroweak, flavor physics……
- LGAD based OTK(+ToF) will be placed between TPC and ECAL
- Time detector is complementary to gaseous detector
- Improve particle separation ability:
  **--0-4GeV for K/Pi separation, 0-8 GeV for K/p separation**

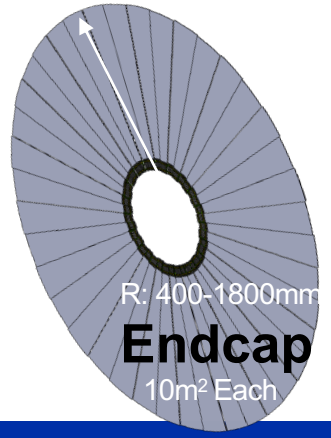
# Application—CEPC ToF

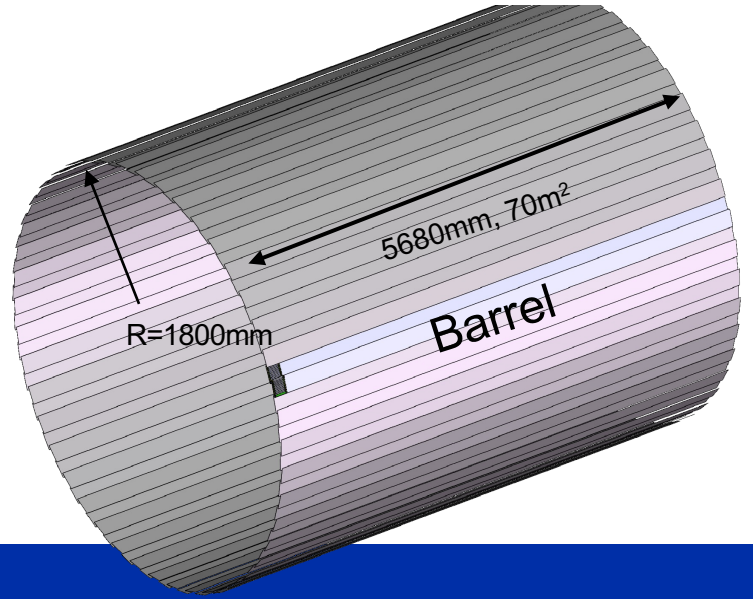



## Design target of CEPC ToF Barrel

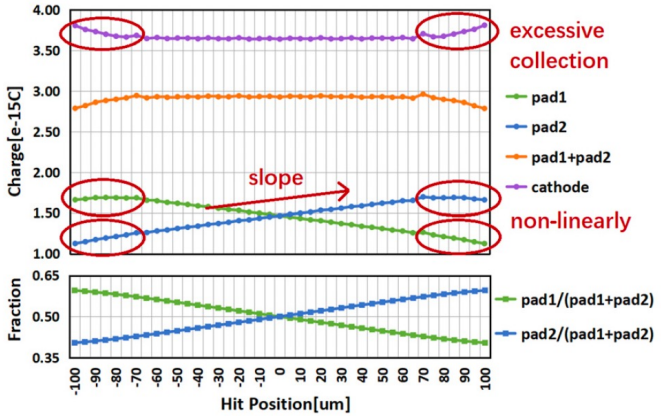
| | |
|---|---|
| Area | ~ 70 $m^2$ |
| Radius | 1.8m |
| Length | 5.8m |
| Strip Length | 20 mm (to be determined) |
| Strip Pitch | 100-500 μm (to be determined) |
| Channel number | ~ $10^7$ channels |
| MIP Time resolution | ~50 ps |
| Spatial resolution | ~ 10 μm (R-Φ) |



# New Trials



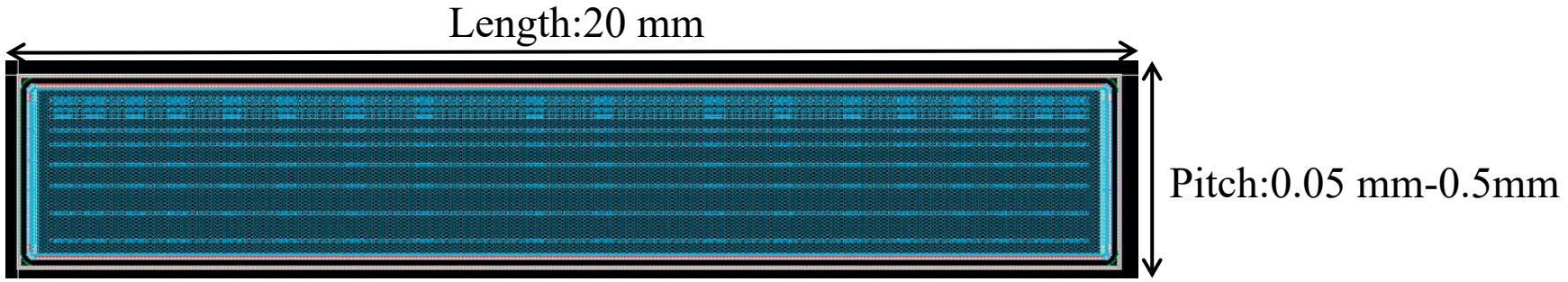

- Long strip AC-LGAD simulation ongoing
- Optimized structure design of AC-LGAD:
  - Pixelated AC-LGAD: different pixel size
  - Strip AC-LGAD:
    - Different strip length\different pad-pitch size(1cm, 2cm, 4cm long; pitch: 50um to 500um…)
    - Design for endcap region: Sectoral AC-LGAD strip sensors
    - Strip AC-LGAD with different p-stop isolation structure
- Strip DC-LGAD:

  Different strip length\different pad-pitch size(1cm, 2cm, 4cm long; pitch: 50um to 500um…)

…

- Process parameters design of AC-LGAD:
  - AC Coupling capacitor(insulating material)
  - N+ layer doping dose

…



# To do list……

## ➢(Ideal) Timetable of AC-LGAD:

2024

Submission 1: end of 2024

**--Verification of designing principles and key processes**

2025

Submission 2: September of 2025

(Testing: IV, CV, timing, spatial resolution, Test beam, radiation hardness)

**--Long strip and process optimization**

2026

Submission 3: June of 2026

(Testing: IV, CV, timing, spatial resolution, Test beam, radiation hardness, testing with ASIC)

**--Enhancement of irradiation hardness and formation of detection system**

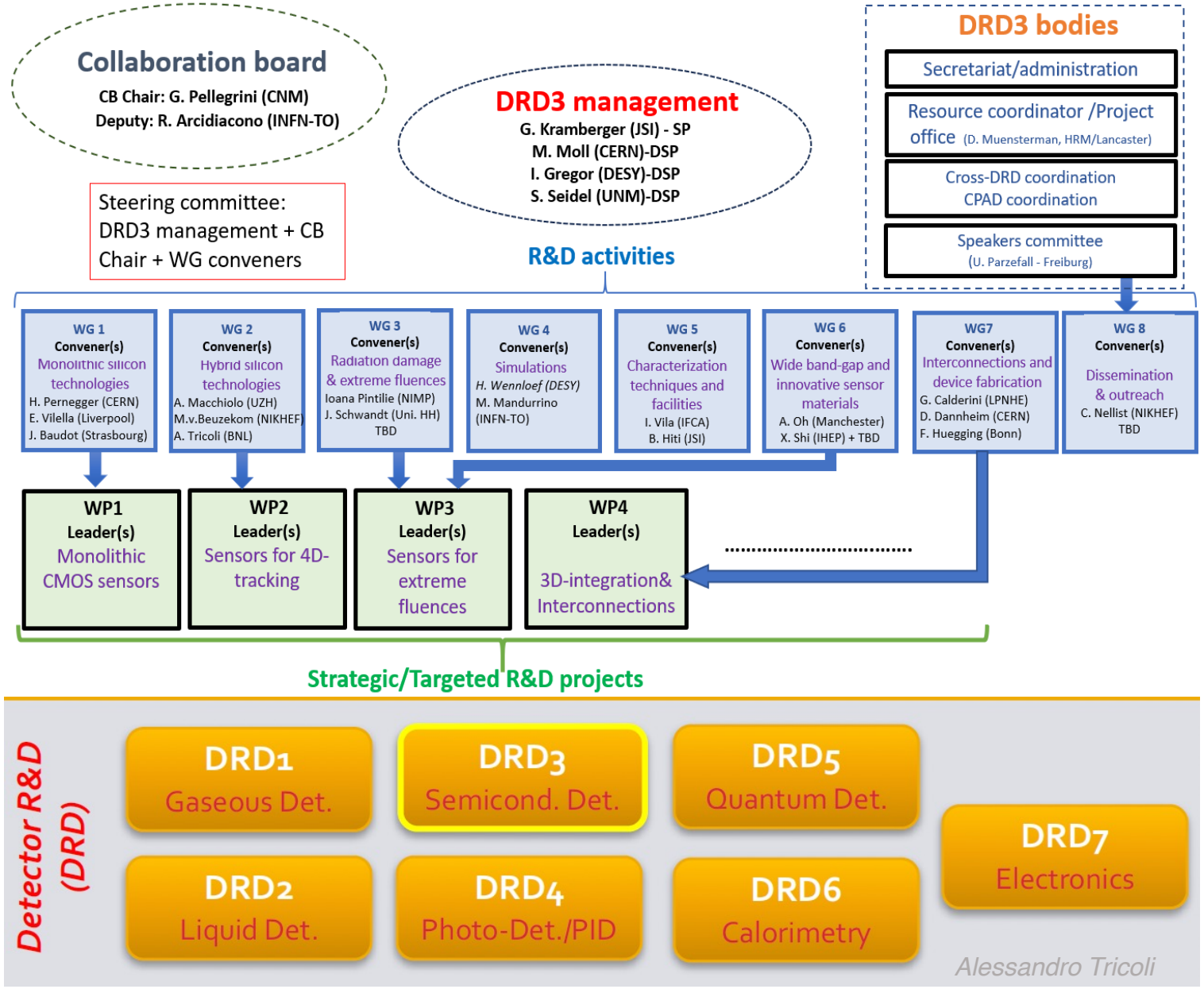
2027

Submission 4: June of 2027

**--Final version of AC-LGAD for 4D Tracking, achieving time resolution better than 50 ps and position resolution better than 10 μm with large sensitive area**

- Topic:
- 1、AC-LGAD simulation, design and fabrication
- 2、 AC-LGAD testing： IV, CV, timing, spatial resolution, gain, etc
- 3、AC-LGAD Test beam testing
- 4、Radiation performance（TID, neutron, proton）
- 5、Position reconstruction methods
- 6、Design optimization for electron collider
- 7、Sensor with ASIC(TDC board) testing on system level
- 8、 Application of AC-LGAD as 4D detector
- ……

# Collaborations




## Cross WG activities

- WG3- Sensor irradiation performance study
- WG4 - Simulation of process and structure parameters for fabrication of AC-LGAD
- WG5 – Beam test to check AC-LGAD timing and spatial performance
- WG6- sensor and ASIC connected methods

## Cross DRD collaborations

- DRD4, Photo-Det./PID, AC-LGAD's application as photo detector or X-ray detector
- DRD7, Electronics, AC-LGAD readout ASIC, providing TOA and TOT information, ASIC and sensor testing board

# Summery and Invitation

*Participants for now*

- Institute of high energy physics, Chinese Academy of Sciences(IHEP)
- Institute of Microelectronics, Chinese Academy of Sciences(IME)
- Jozef Stefan Institute, Ljubljana (JSI)
- University of Montenegro (UCG)
- Shanghai Jiao Tong University(SJTU)
- Shandong University (SDU)
- Nankai University (NKU)
- Zhengzhou University (ZZU)

- AC-LGAD has the potential to fulfill the requirements of DRD-3 4D tracker in terms of spatial and time resolution, sensitive area fill factor, etc.
- R&D of AC-LGAD has yielded promising results but still has a long way to go……

**You Are Warmly Invited to Join Us**

*Contact person:*
Prof. Mei Zhao (IHEP-CAS), zhaomei@ihep.ac.cn

Project plan: https://cds.cern.ch/record/2918306

--DRD3–Working Group2 *Hybrid Silicon Technologies*
--DRD3–Working Package2 *Sensors for 4D Tracking*

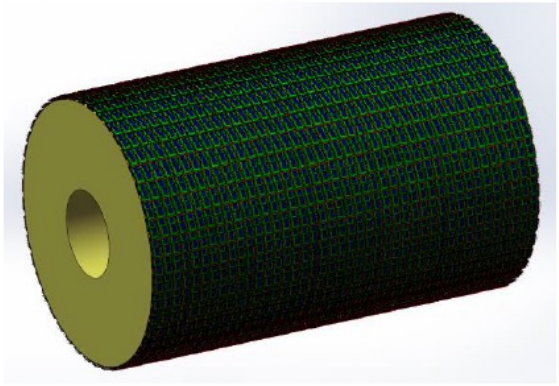
# Back up

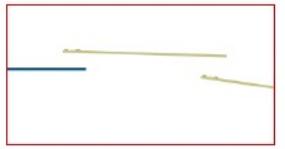
# Design of the OTK with the strip AC-LGAD: Barrel

- one layer: 70 m², 3780 modules

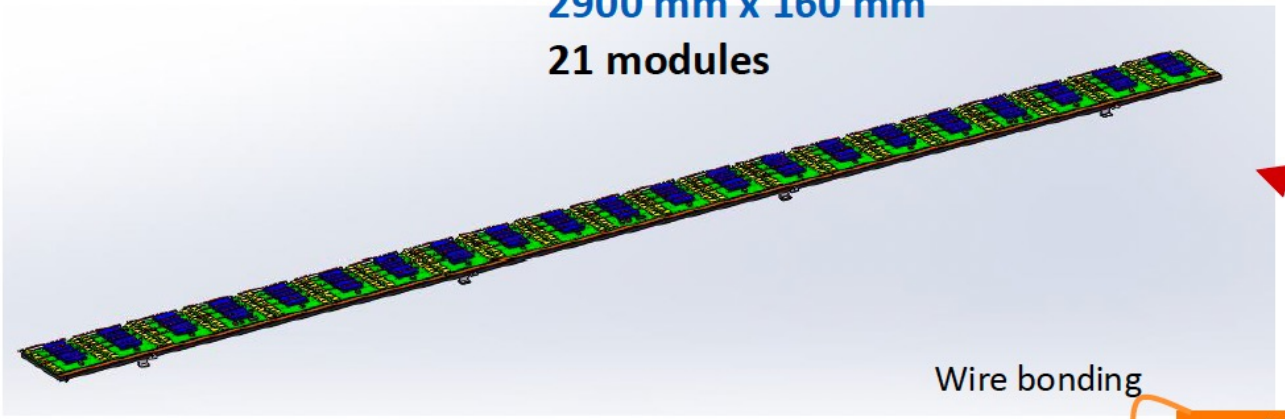
  R= 1800 mm ,H ~ 5800mm
  - overlap to decrease the dead area
  - 90 staves
  - 42 modules/stave

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

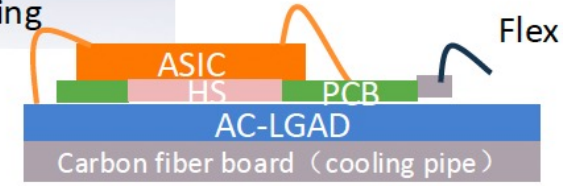




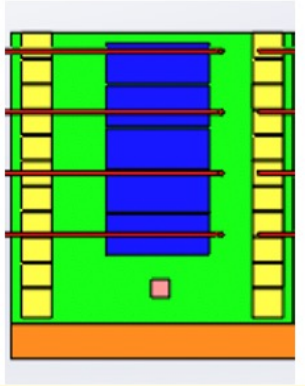
**Long half stave**
**2900 mm x 160 mm**
**21 modules**



**Module**
**137.8 mm x 160mm**
**22 ASICs**

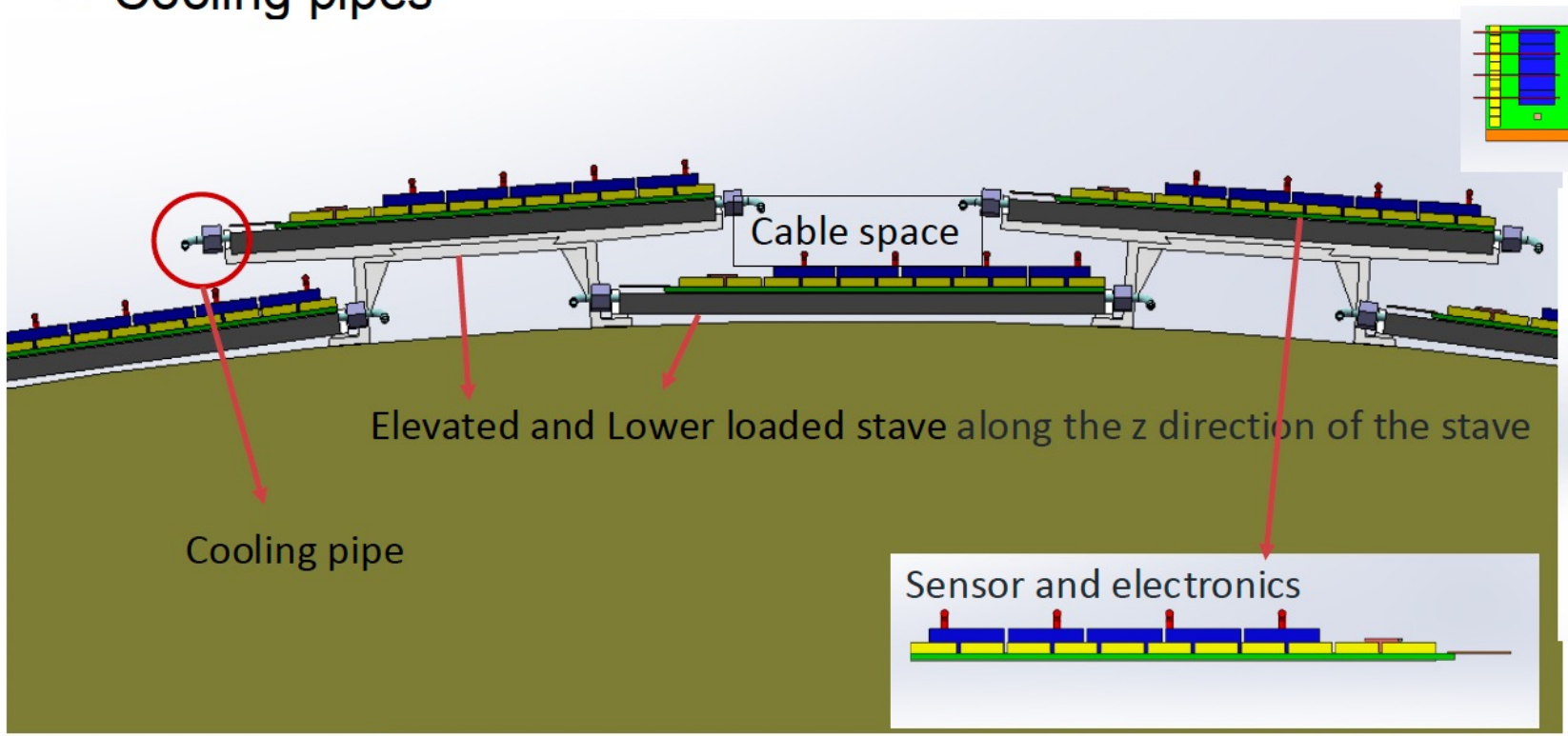


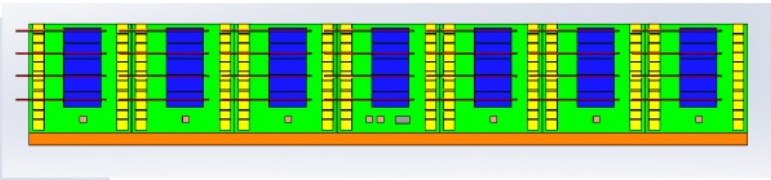

Heat sink(HS): Al;

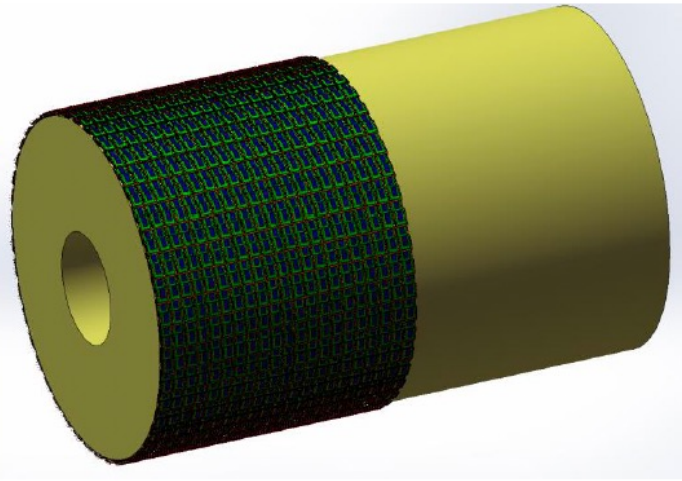


# Mechanical Design for LGAD ToF & OTK

- 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





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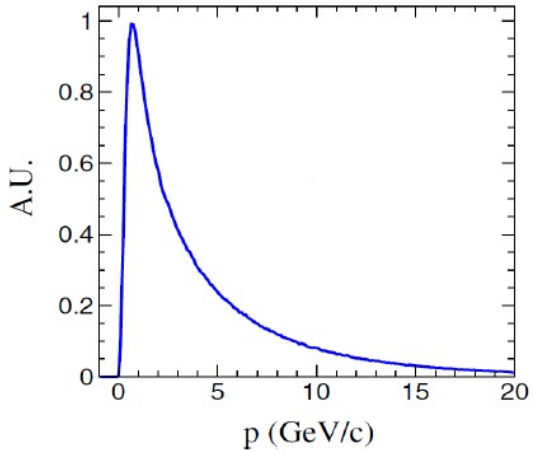
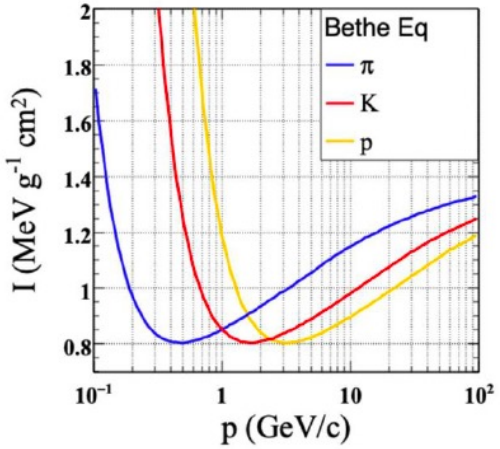
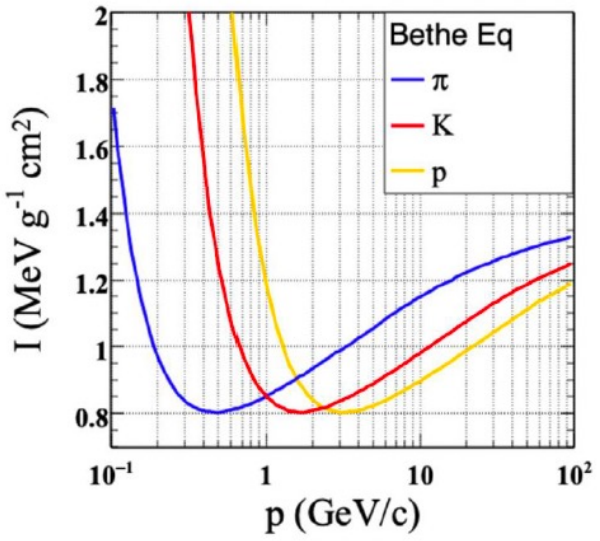
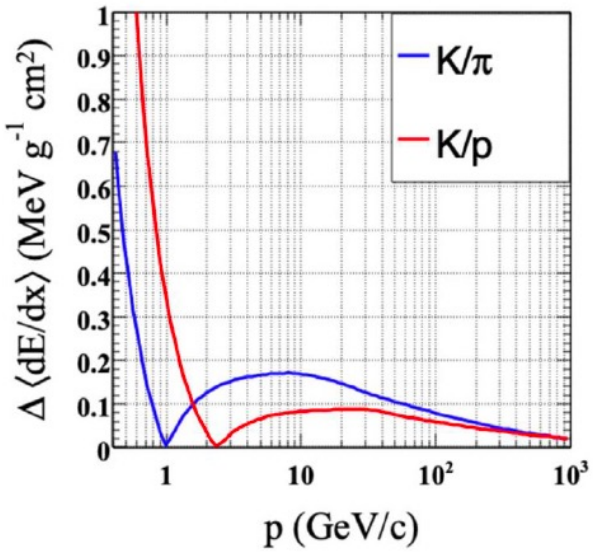
# TPC




(a)




(b)

**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).