Time of Flight and tracker based on LGAD Technology

-Status and Plan

惠州强子谱仪HHaS合作组2025年年会

Huizhou，2025.11.28-2025.11.30

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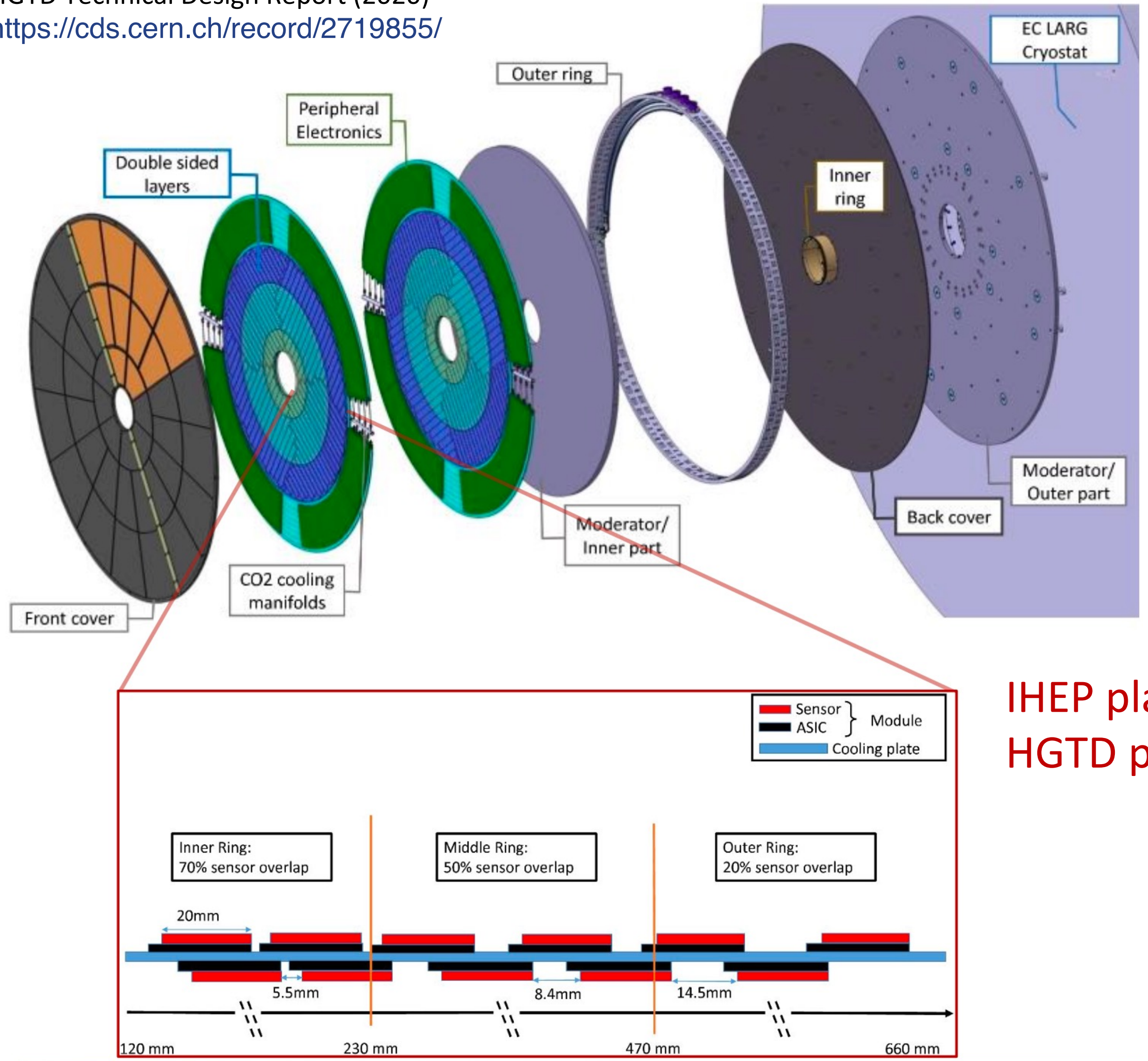
Outline

- **Updade for the timing performance of the LGAD at HGTD**
  - From the sensor to the system
  - Contributions of the time precision
  - Performance study from the sensor to the system
    - Sr90 and laser tests
    - Test beam facility

- **Status for the R&D for strip AC/DC-LGAD and ASIC status at IHEP**

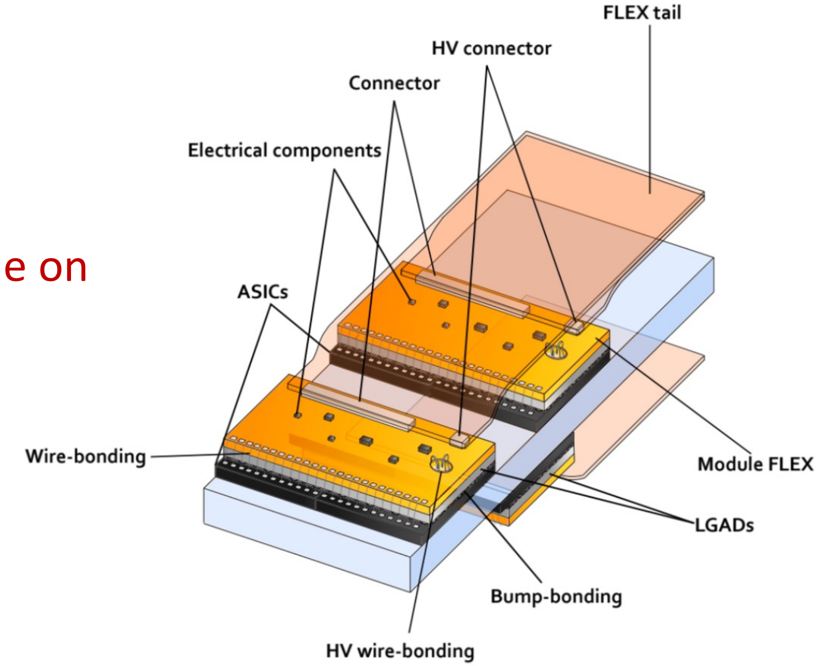
From the sensor to the system

HGTD Technical Design Report (2020)
https://cds.cern.ch/record/2719855/



- **Timing layer for phase II upgrade:**
  - CMS ETL detector，ATLAS HGTD detector
- **High Granularity Timing Detector (HGTD):**
  - 50 ps for the whole system
  - 3.6 M channels for ~6 m^2
  - Double sided wheel to reduce dead area
  - CO2 cooling….

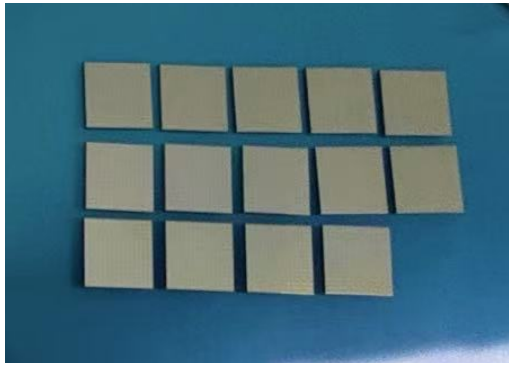
IHEP plays leading role on HGTD project



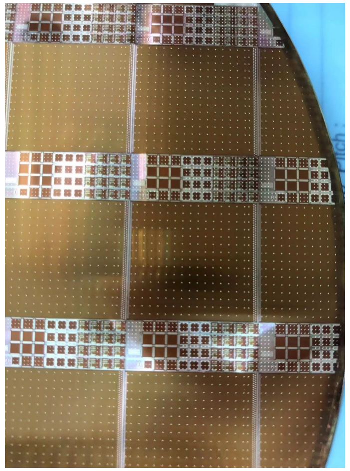
3D maps for the modules of HGTD

From the sensor to system

LGAD

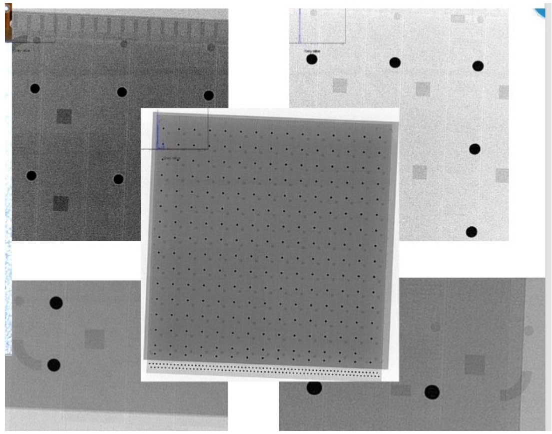


ALTIROC

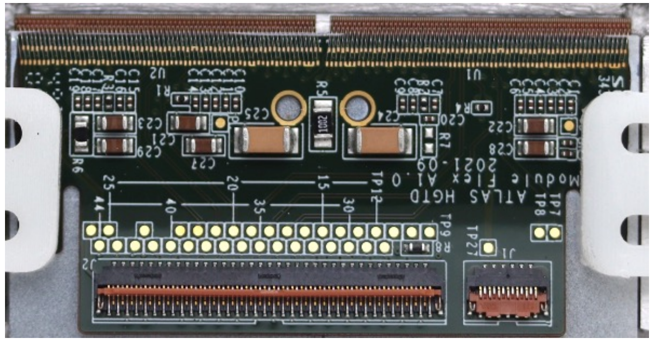


Hybrid
= (LGAD+ASIC)

X-ray image of hybrid



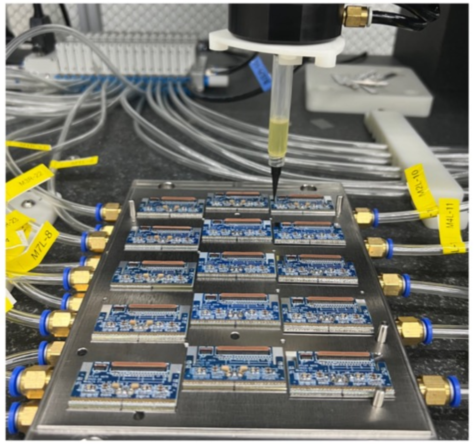
Module flex



Module

Detector Unit

Dispensing with GluingTool



Detector Unit and Peripheral Electronics

Peripheral Electronics

How to face the chanlleges of the Time precision

- **Contribution of the timing precision**

$$\underbrace{\sigma^2_{T_{hit}}}_{\sim 39\ \text{ps}} = \underbrace{\sigma^2_{Landau} + \sigma^2_{TW}}_{\text{Sensor}\ \sim 30\ \text{ps}} + \underbrace{\sigma^2_{jitter} + \sigma^2_{clock} + \sigma^2_{TDC}}_{\text{Read-out electronics}\ \sim 25\ \text{ps}} + \ldots(\sigma^2_{t_o})$$

Other souces

Landau: Fluctuations of energy deposition + charge transport in the sensor

- ✓ Mitigation: thinner the active thickness, satureated drift velocity

Timewalk effect:
Signal amplitude affects the Time-of-Arrive(ToA)

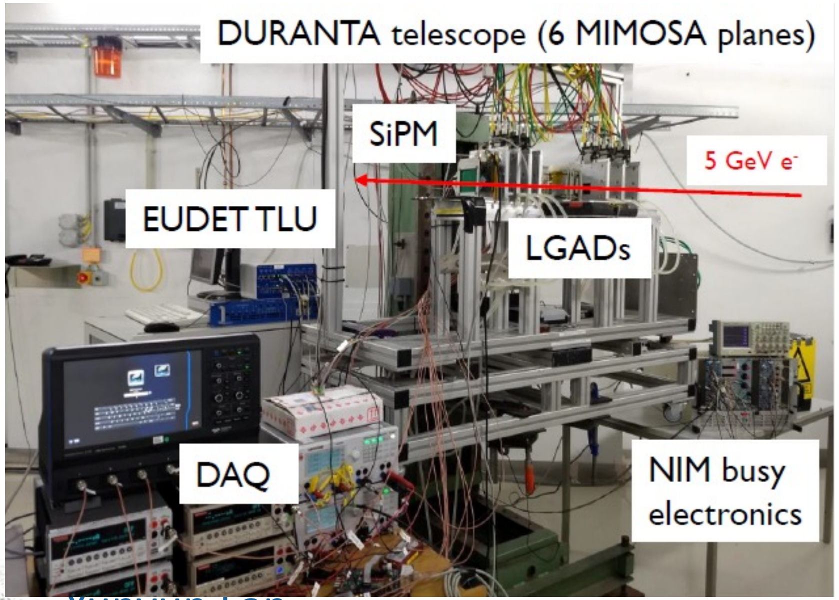
- ✓ Could be reduced with CFD method(ToT)

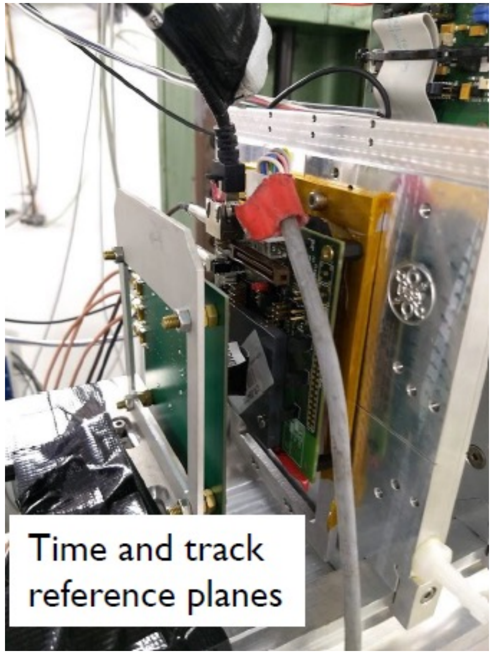
TDC:
TDC binning/non-linearity

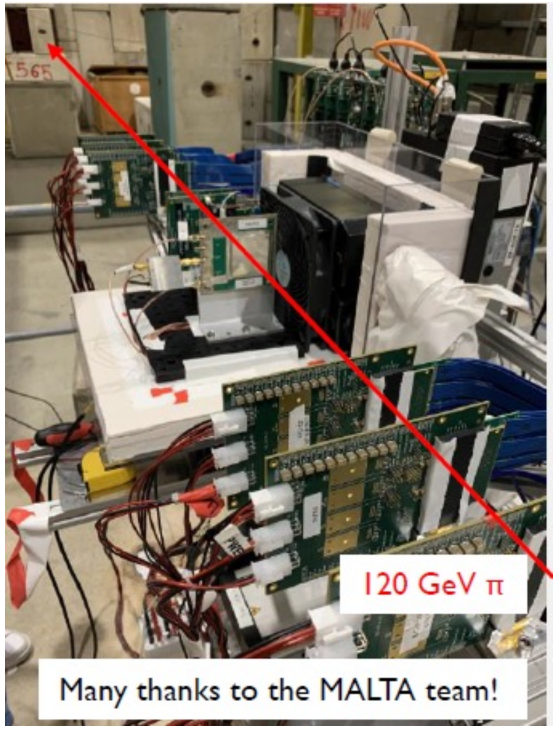
Clock:
Jitter from the clock of the system

Performance Study

- **Sr90 source and laser tests**
- **Test beam @DESY and @SPS (setup)**
  - CERN North Area SPS H6A beamline (120 GeV pion beam)
  - DESY T22 beamline (5 GeV e-beam)
  - Tracking Use of beam telescopes for tracking (EUDET-type 10 um/MALTA 5um)
  - Time reference：LGAD (CNM 0) used as a time reference in some tests (CERN SPS) as well as a SiPM device (DESY)



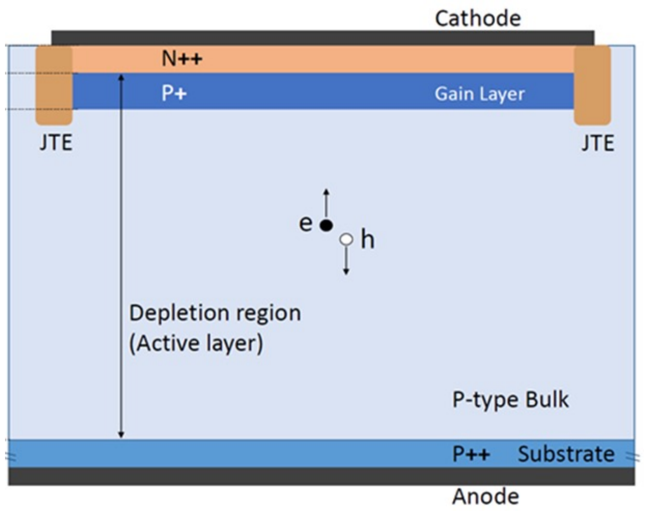




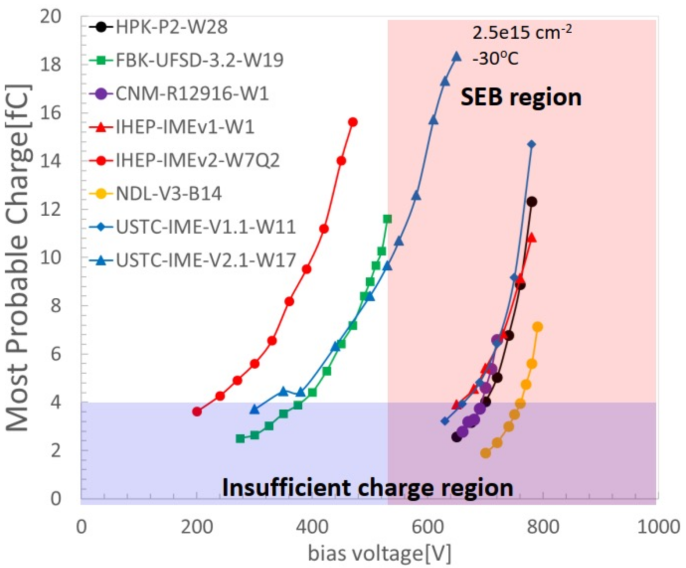
LGAD Sensor

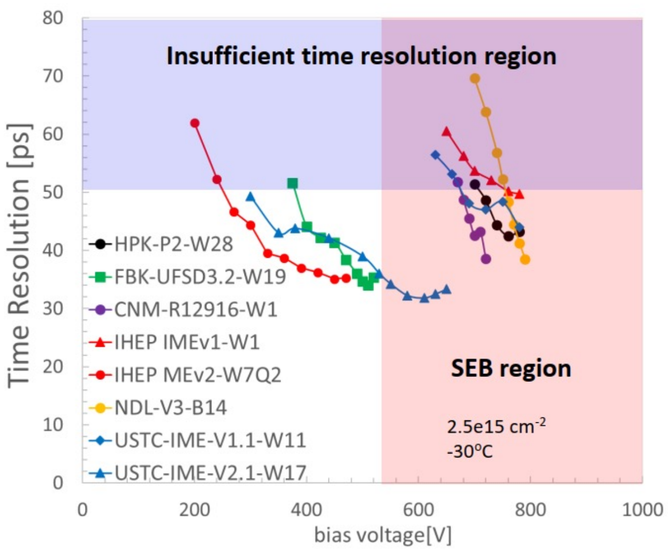
- **Carbonated LGAD sensor designed by IHEP and produced at IME**
  - Radiation hardness： 2MGy， $2.5\times10^{15}\ n_{eq}/cm^2$

Carbon implantation



	Before irradiation	After irradiation
Time resolution	~ 30ps -40 ps	50 ps
Collected charge per hit	10 fC	4 fC
Hit efficiency	97%	95%

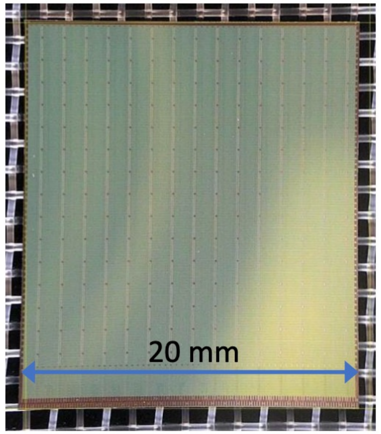




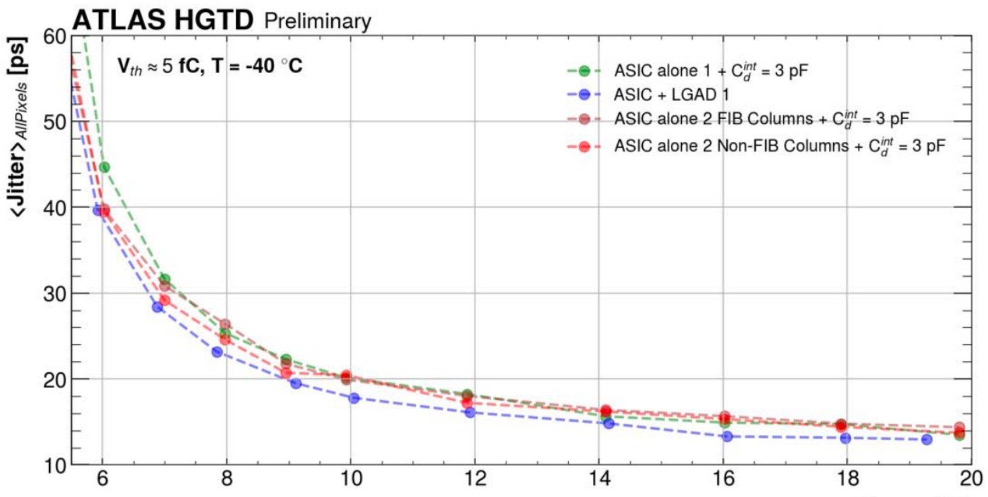
The ALTIROC readout ASIC

- **ATLAS LGAD Timing Integrated Read-Out Chip (ALTIROC)**
  - 225 channels
  - 130 nm CMOS from TSMC
  - **Jitter: < 25 ps at 10 fC (<65 ps at 4 fC)**
  - TDC: 20 ps binning
  - Discriminator threshold >= 2 fC
  - Radiation hard > 2 MGy
  - Also in preproduction…

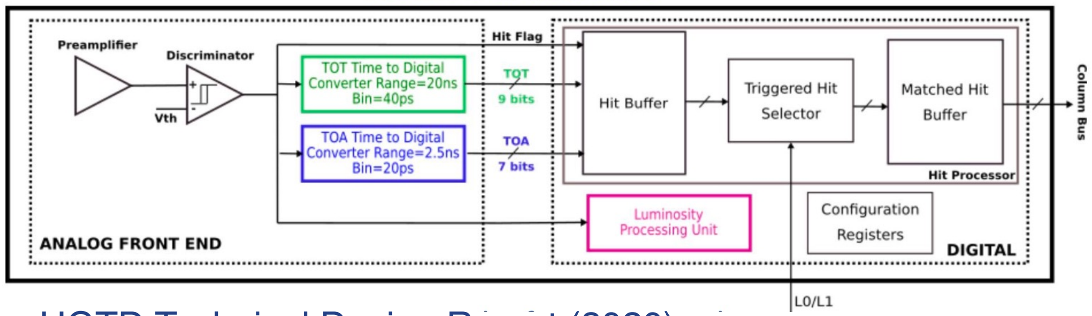
ALTIROC-A



Jitter vs. charge for ALTIROC-A, detection threshold: 5 fC



ALTIROC architecture



HGTD Technical Design Report (2020)

https://cds.cern.ch/record/2719855/

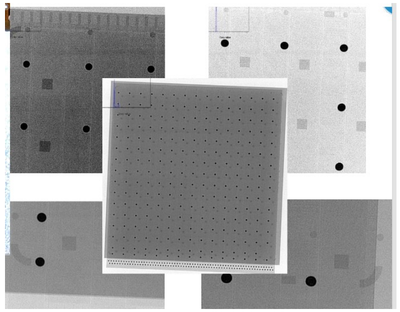
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HGTDPublicPlots

Test-beam performance for the Hybrid

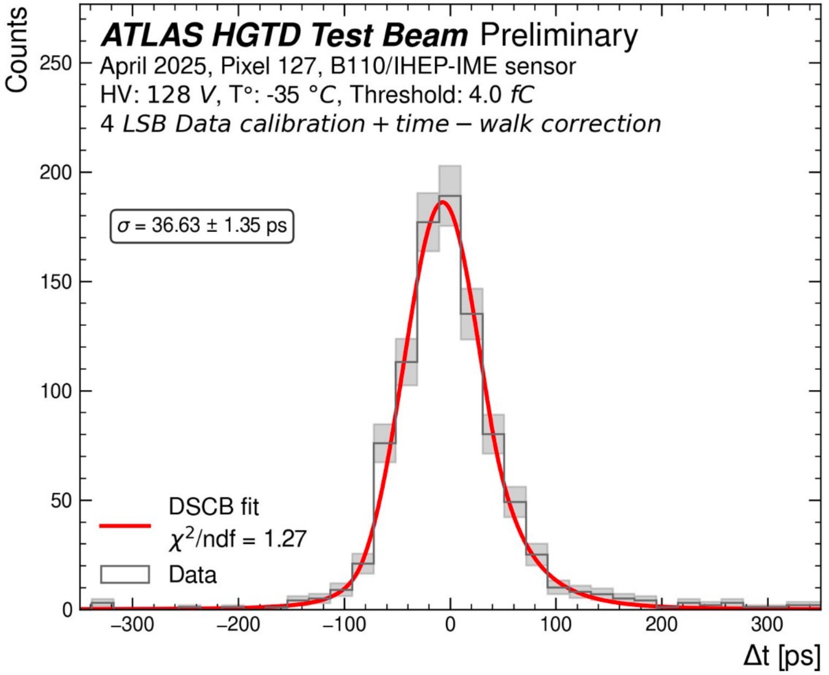
- **Performance measurement conditions:**
  - Low tem. (-35 °C)
  - High bias voltage (> 120V)
  - Low thre.(4 fC)

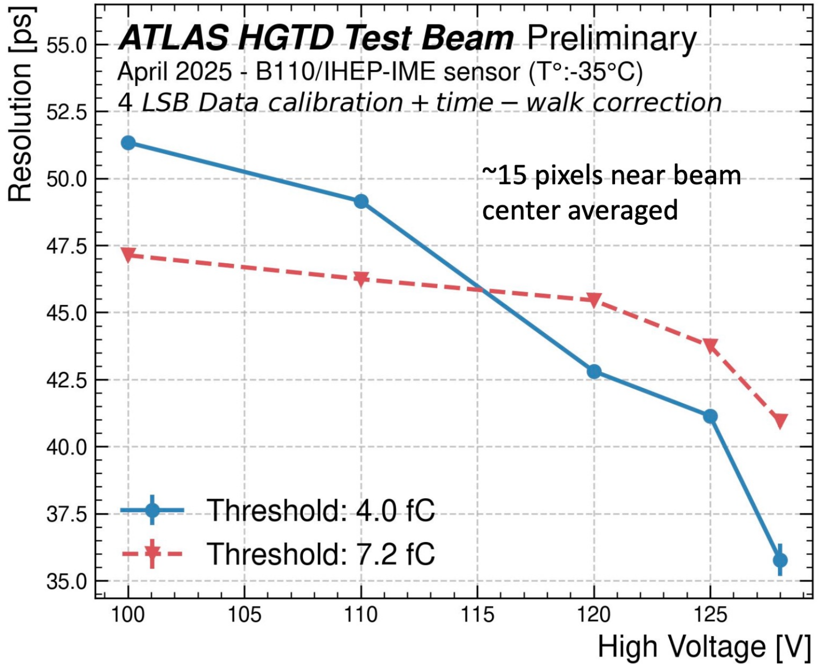
Hybrid: ~36 ps

Hybrid = LGAD + ASIC



Beam test was done at DESY and CERN

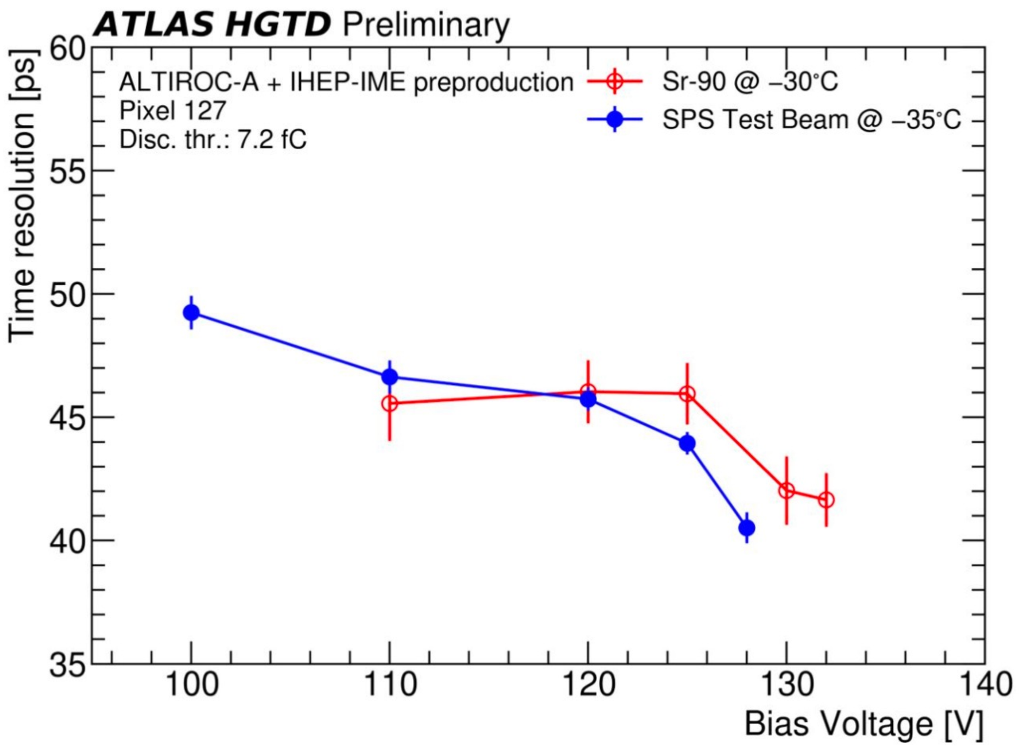




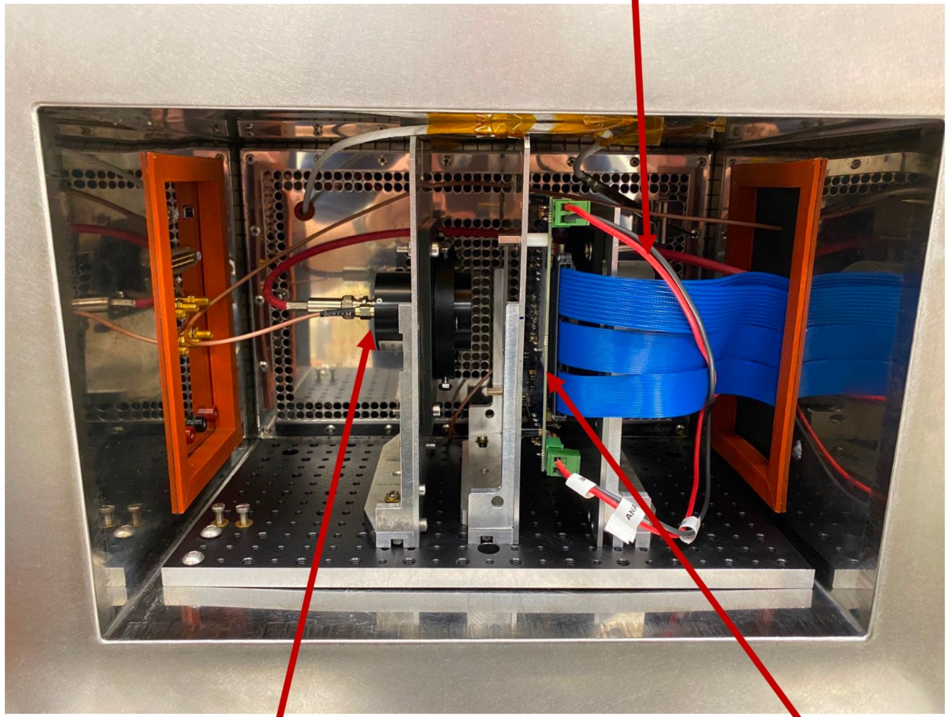
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HGTDPublicPlots

β-source time performance for the Hybrid

- **Time rsolution: ~45 ps with 7 fC threshold**
  - ✓ Consistent with test-beam threshold



Sr-90 source (~ 30MBq)



MCP-PMT(time reference) ALTIROC-A + LGAD test board

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HGTDPublicPlots

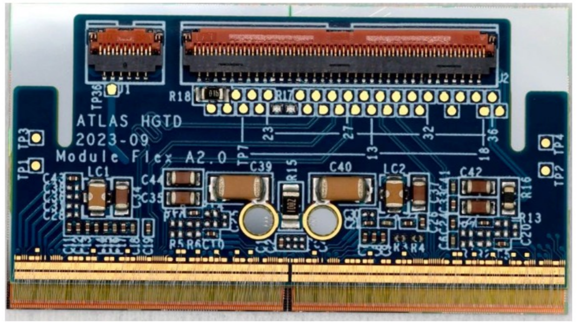
Least Significant Bit (LSB) calibrated to 20 ps

Module test-beam performance

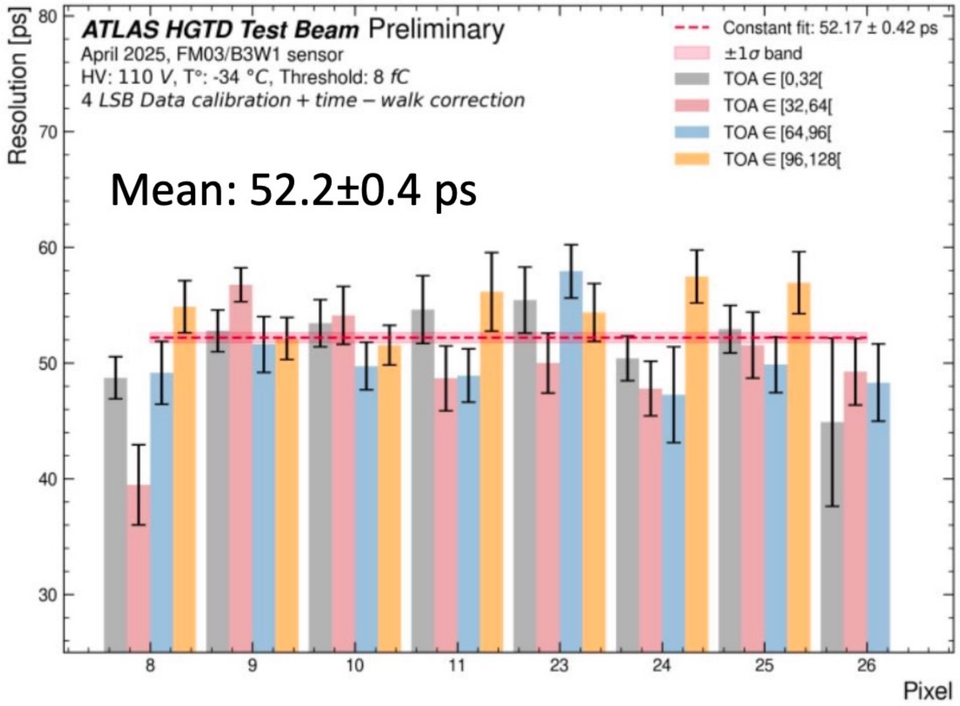
- **2 ALTIROC chips + 2 LGAD sensors + module flex**
  – < 50 ps timing resolution in test team
  – with time-walk correction and substracting 4 ps contribution from bad clock jitter of about 20 ps

Module = LGAD + ASIC + Peripheral electronics

Wire-bonded HGTD module



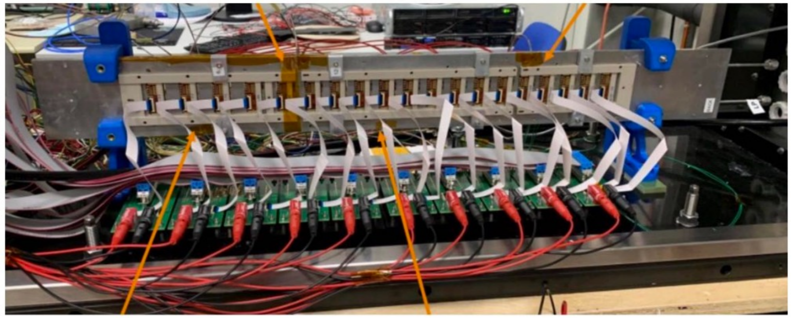
Module test-beam time resolution



System level tests to be done

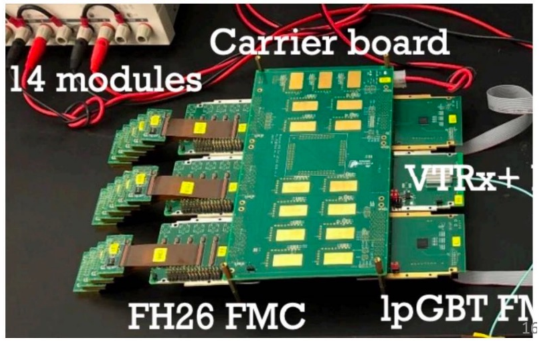
- **Test the time performance at the system level**

Thermal demonstrator



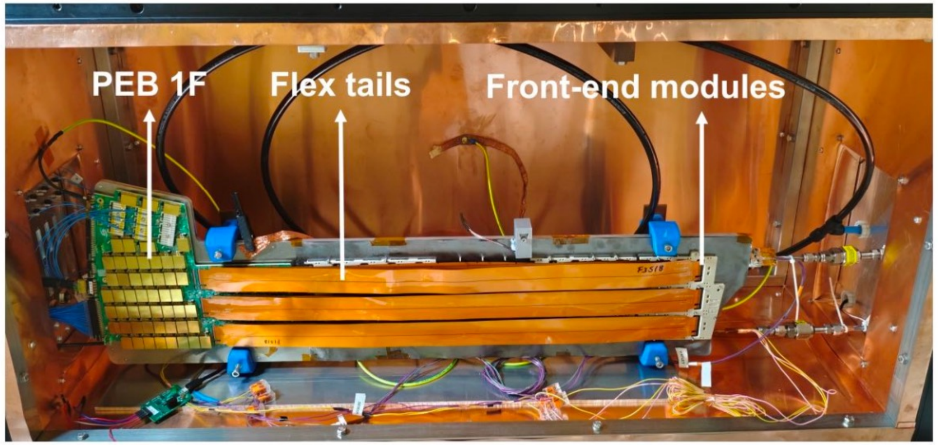
→ CO_2 cooling tests with realistic heat load

DAQ demonstrator

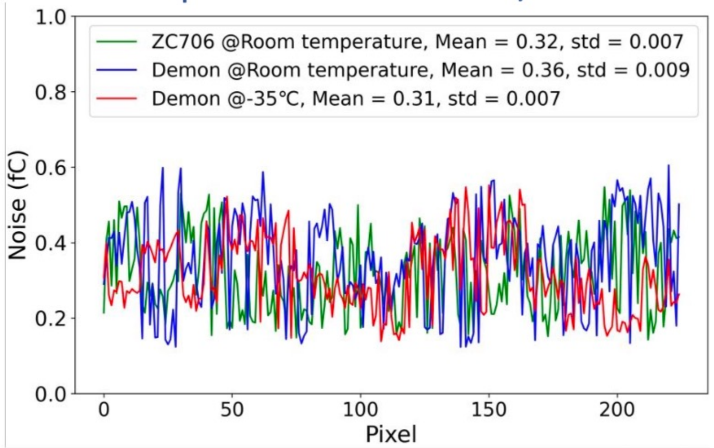


→ Testing readout path from module to FELIX FPGA DAQ cards, using final components of the peripheral electronics boards (PEBs)

Full demonstrator - 1 peripheral electronics board (PEB) connecting 54 modules on 4 support units + cooling



Noise comparison demonstrator / test bench



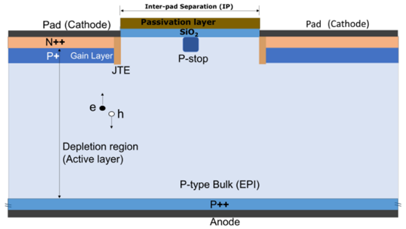
JINST 19 (2024) C12012

- **Status for the R&D for strip AC/DC-LGAD and ASIC status at IHEP**

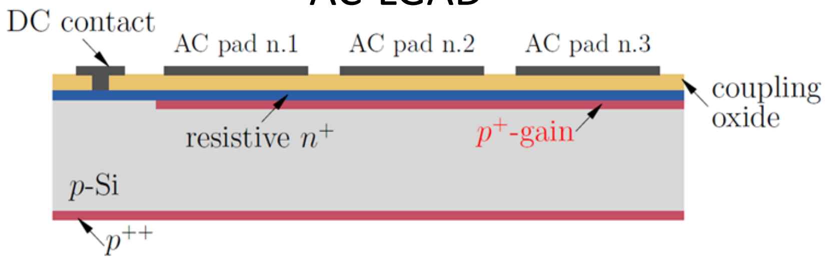
Design and Production of AC-LGAD

- **Aim to 4D track：30 ps， 10 µm**
- **AC-LGAD:** no dead region

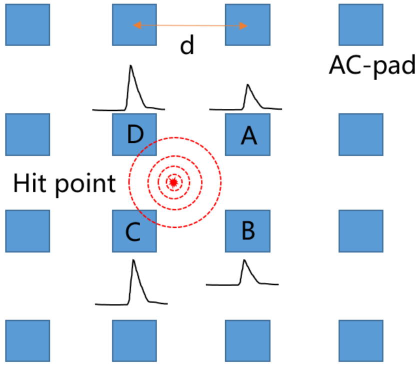
LGAD



AC-LGAD

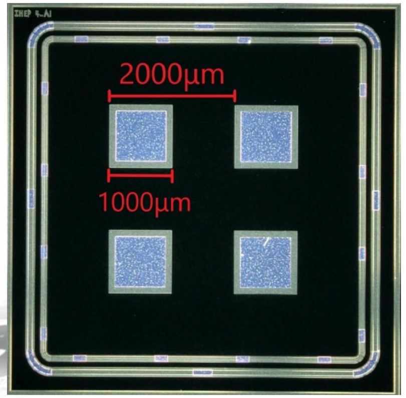


Signal of AC-LGAD

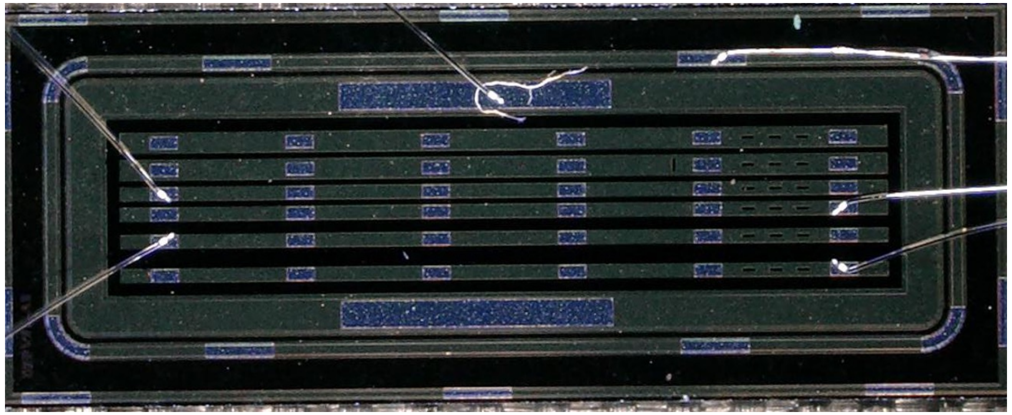


- **Different designs of AC-LGAD in IHEP**
  - ✓ **Pixels AC-LGAD：** reduce the material budget
  - ✓ **Strip AC-LGAD：** no bump bonding， easy to produce

Pixel LGAD

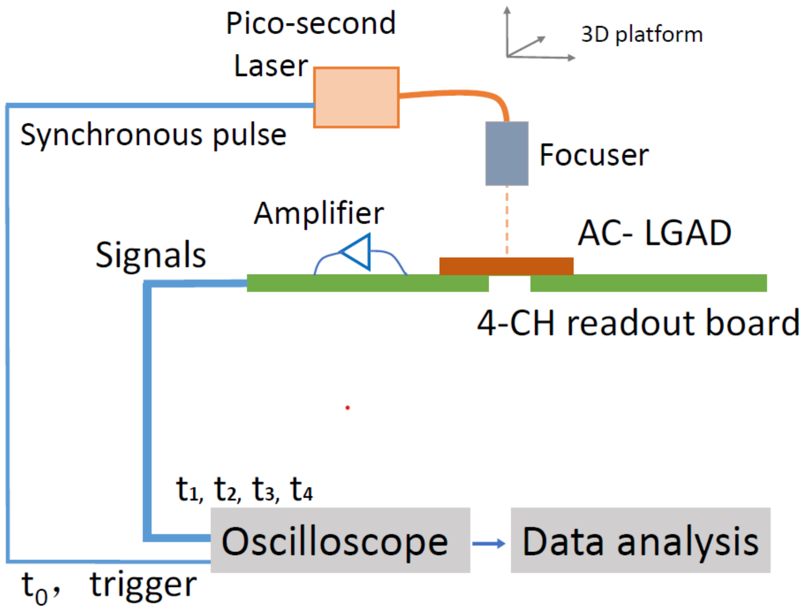


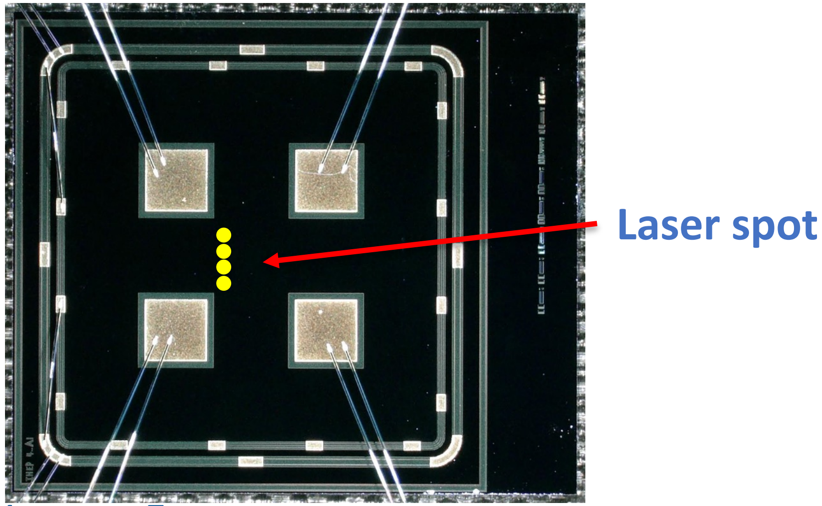
Strip AC-LGAD



Performance Test Setup of AC-LGAD

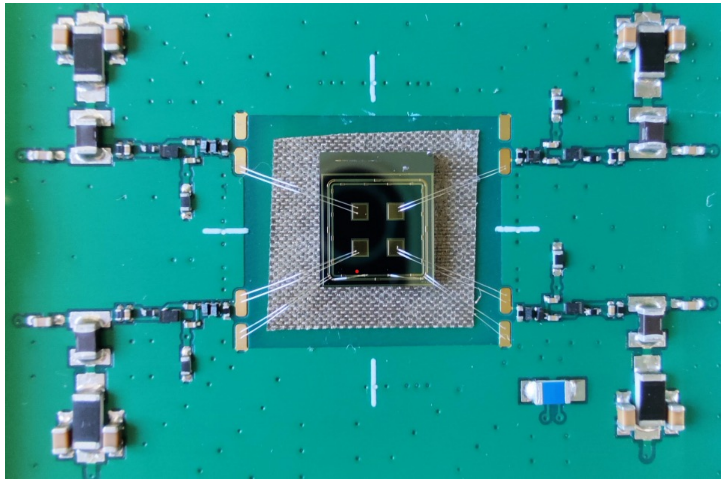
- **Timing and spatial resolution test of AC-LGAD**
- **Transient current technique (TCT)**
- Picosecond Laser: 1065 nm， spot size10 μm (3σ)
- **4 channels readout board designed by IHEP**
  - 470 Ω Broadband inverting trans-impedance amplifier
  - Reference of 1 channel board designed by UCSC





Yunyun Fan

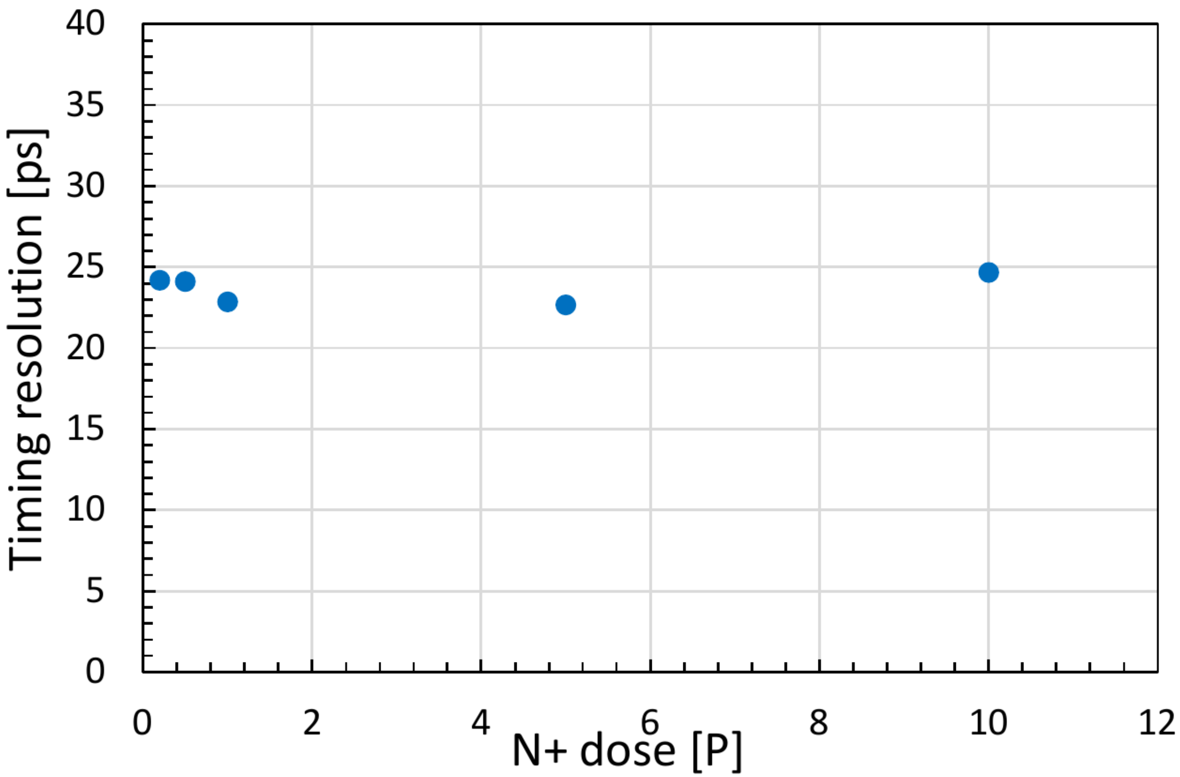
4 channels readout board designed by IHEP



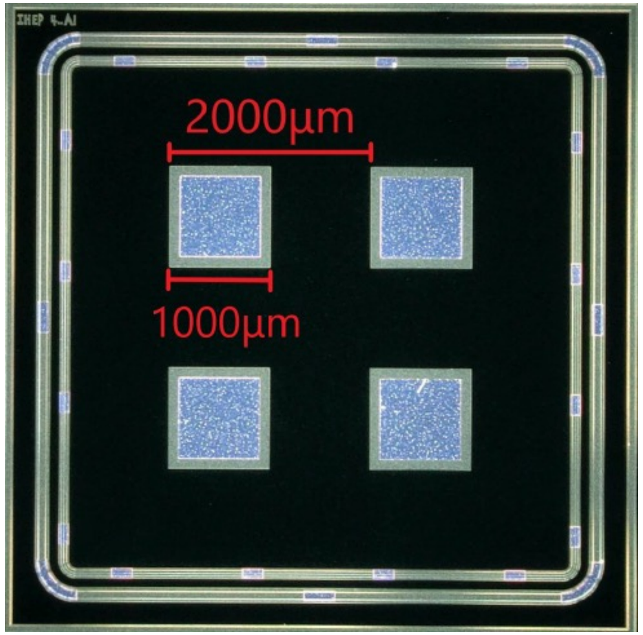
Timing resolution of AC-LGAD

- **Timing resolution of AC-LGAD with different N+ dose**
  - **22~25 ps**
  - N+ very slightly affects the time performance

Timing resolution of AC-LGAD with different N+ dose



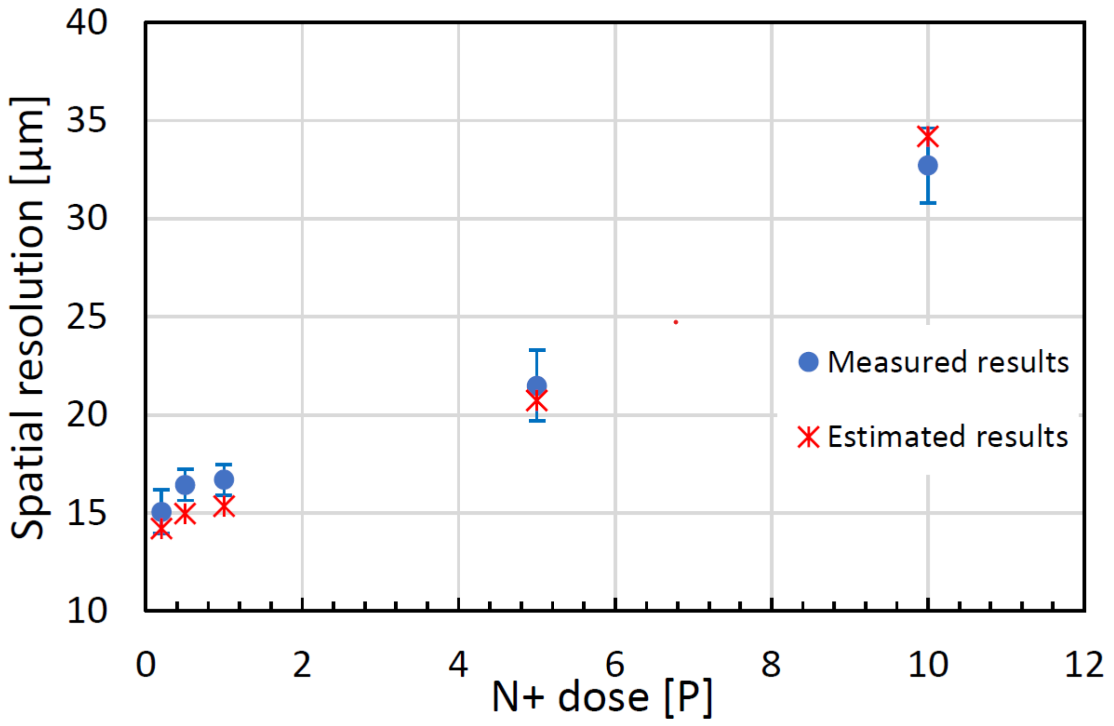
Tested AC-LGAD



Spatial resolution of AC-LGAD

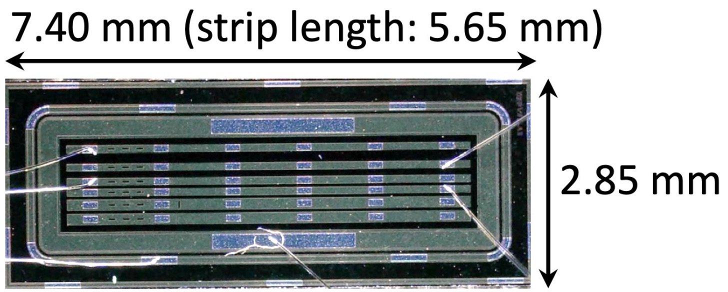
Spatial resolution vs N+ dose

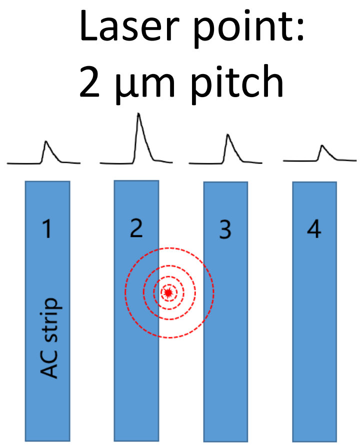
- 10 P → 0.2 P, spatial resolution ↑ 15 μm (minimum)
- Estimated laser point positions fit the measured well
- **Better than the FBK design** even with 2 times larger pitch

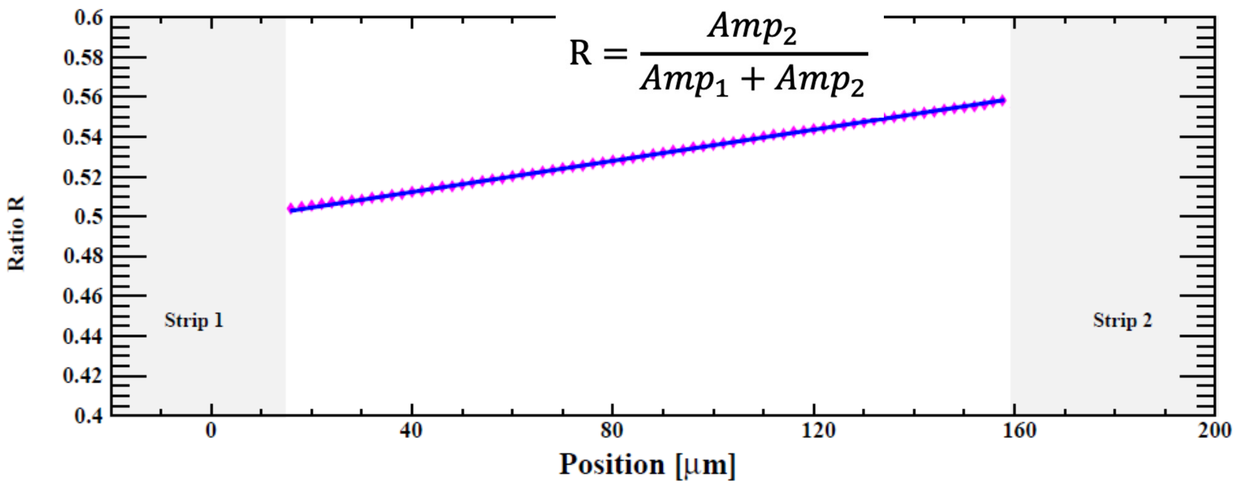


Sensors	Pitch size [μm]	Spatial resolution [μm]	Time resolution [ps]
IHEP AC-LGAD	2000	15	22 （laser）
FBK AC-LGAD	500	11	32 （laser）
BNL AC-LGAD	100	-	45 （beta source）

Performance of AC-LGAD： Spatial Resolution





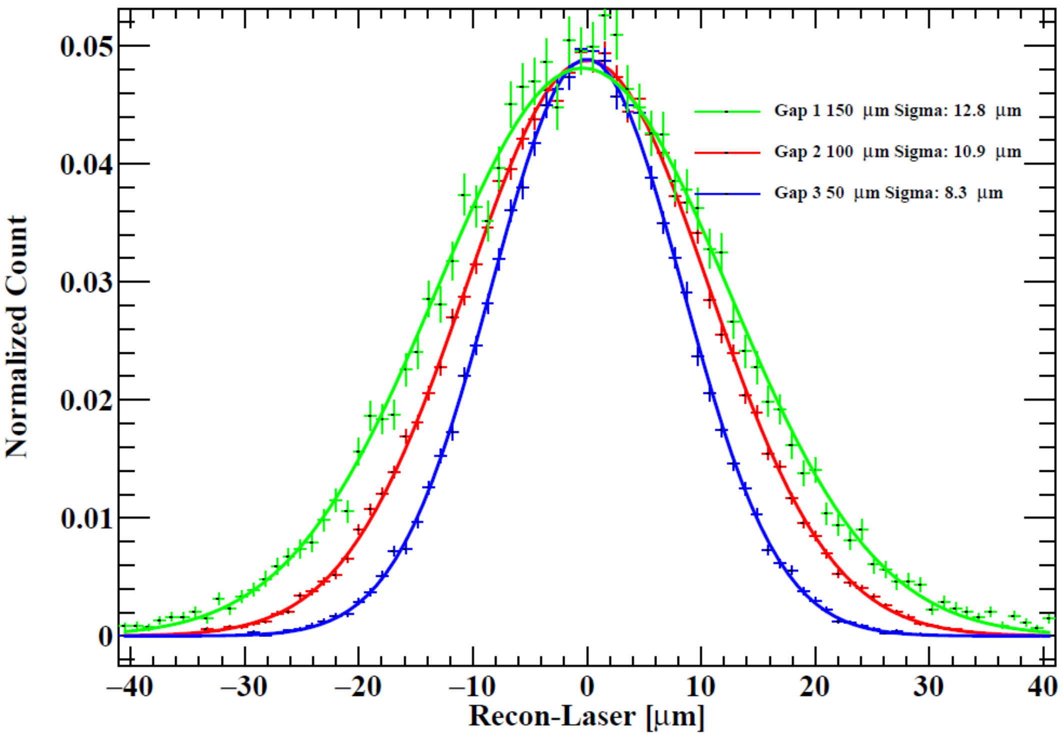


Position reconstruction:

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

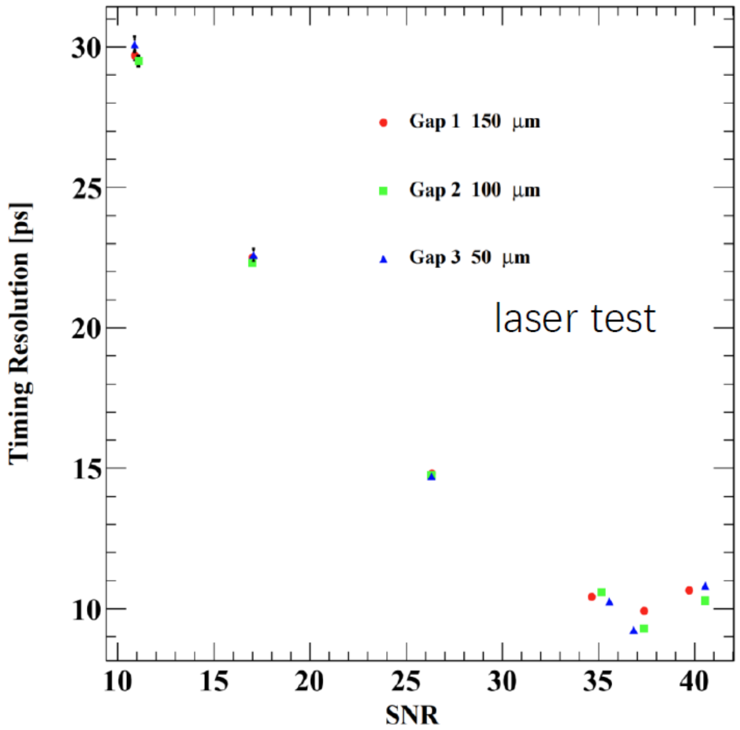
Spatial resolution：

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

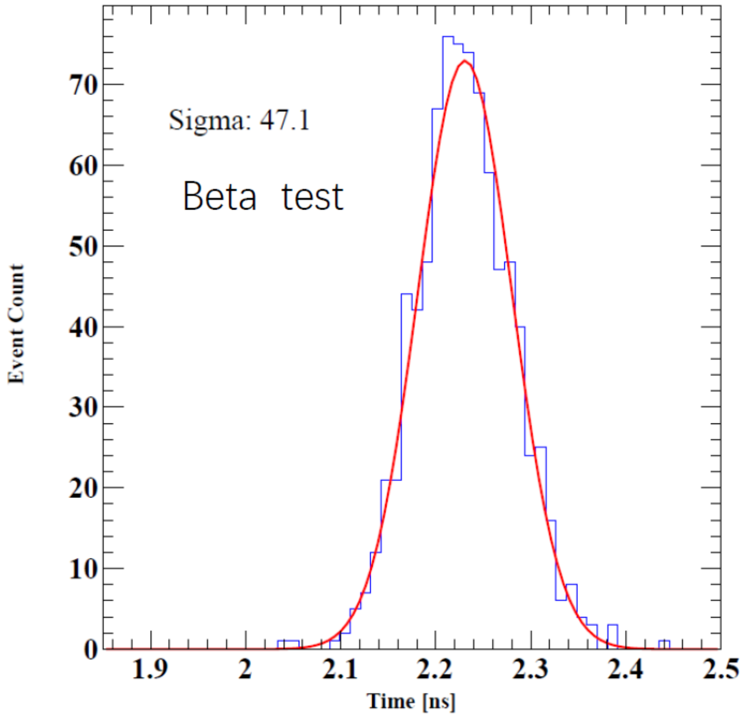


Performance of AC-LGAD： Time Resolution

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.**

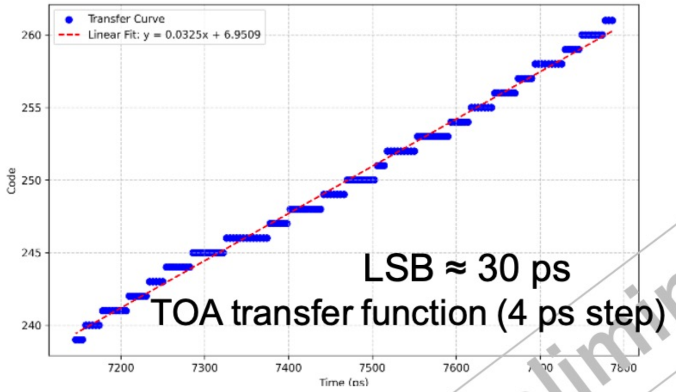
Recent Progress on LATRIC test

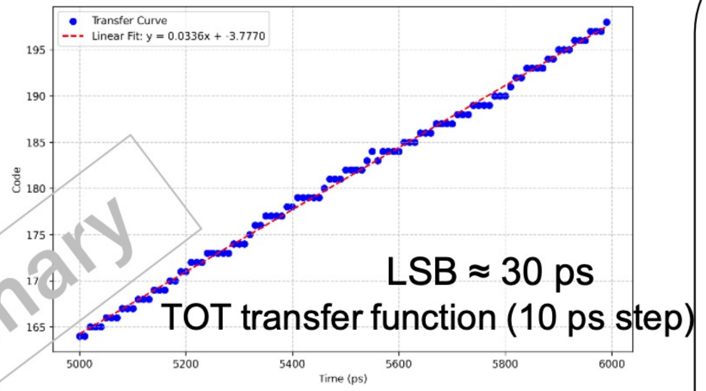
R&D new progress
Not in TDR

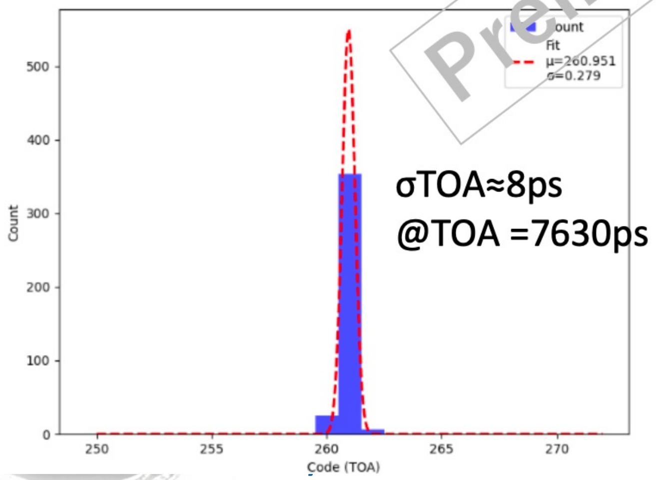
The latest tap-out chip (with wire bonding) for testing was returned on Aug 25th.

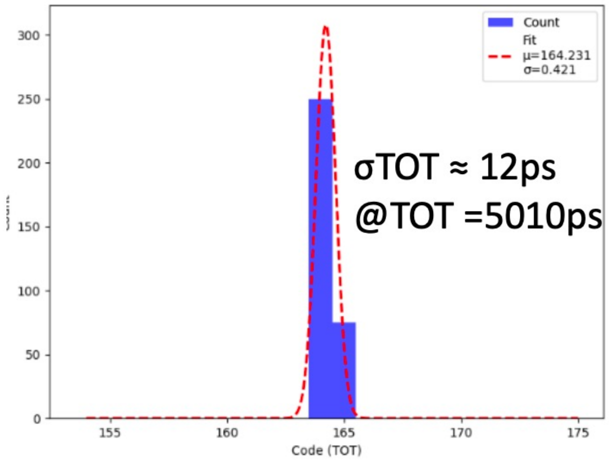
- It integrates Preamplifer, Discriminator, TDC, and Serializer.
- LATRIC-V0, with LSB of 29.8 ps, has been verified.
- Some bugs were identified and require further debugging (e.g. unstable data latch).

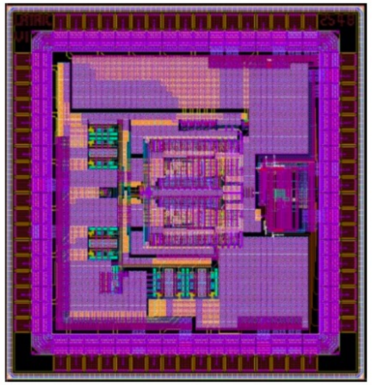
The next 8 channel version chip is scheduled for tape-out in October.

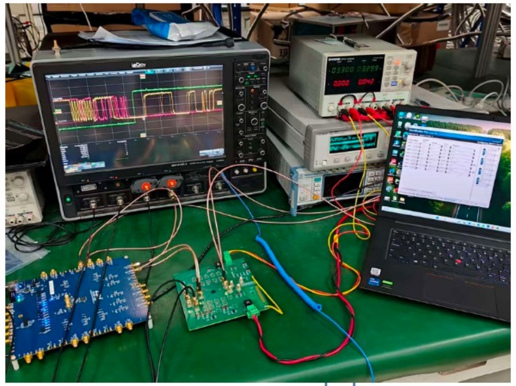




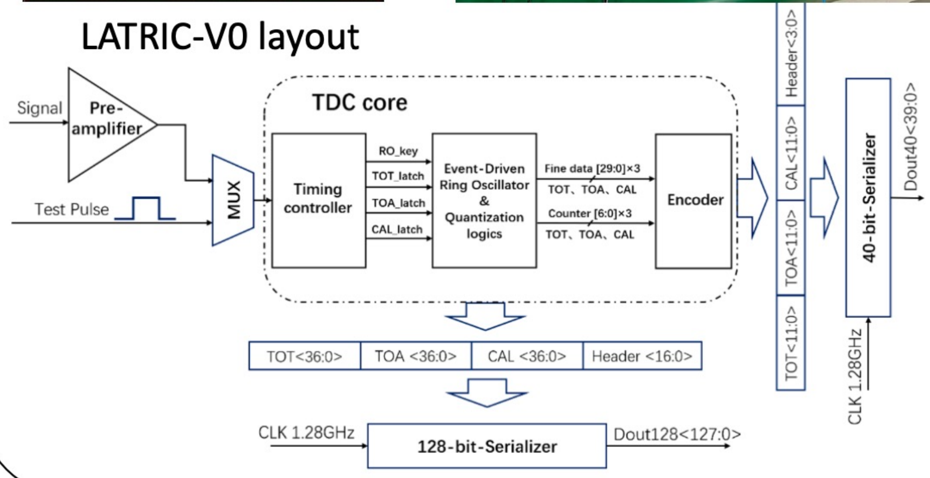








LATRIC-V0 layout



From Xiongbo Yan

Summary and Plan

- **Extensive testing of LGAD sensors, test structures, hybrids and modules**
  - Sensors meet requirements for timing, charge, and uniformity
  - Hybrids and modules show good performance after calibrations, down to ~40 ps

$$\sigma^2_{T_{hit}} = \sigma^2_{Landau} + \sigma^2_{TW} + \sigma^2_{jitter} + \sigma^2_{clock} + \sigma^2_{TDC}$$

- **strip AC/DC-LGAD and ASIC**
  - ✓ **Aim 30 ps, 10 μm**
  - ✓ **Present results of current 5 mm prototype :22~40ps (Beta) and 15 μm （laser results）**
    - ✓ **Plan focus on centimeter long strip AC-LGAD，reduce the capacitance by increase the pitch et .al. , charge sharing by reducing the n+**
  - ✓ **First engineer run has been tested recently**
- **Future Application of the ToF and Tracker based on LGAD technology**
  - EIC（25-35ps,30 μm ）, FCCee, Belle (IHEP joined recently)….

Thank you for your attention！

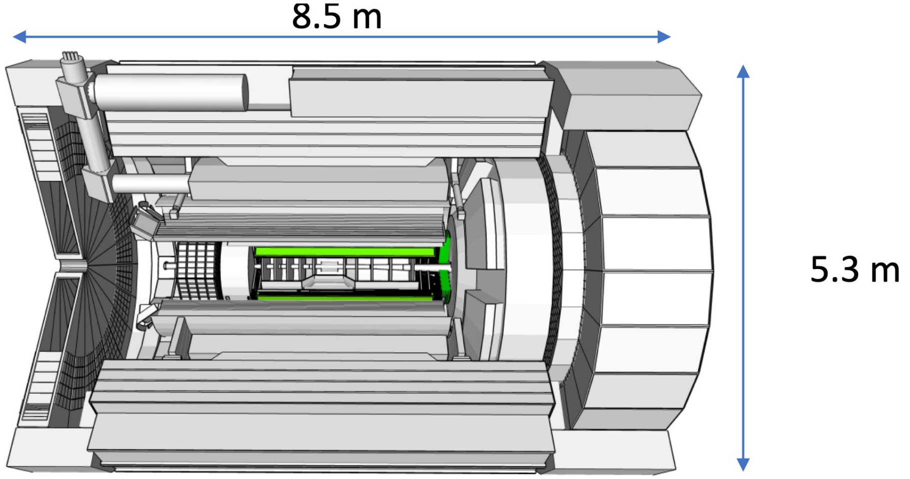
- **Back up**

Current application

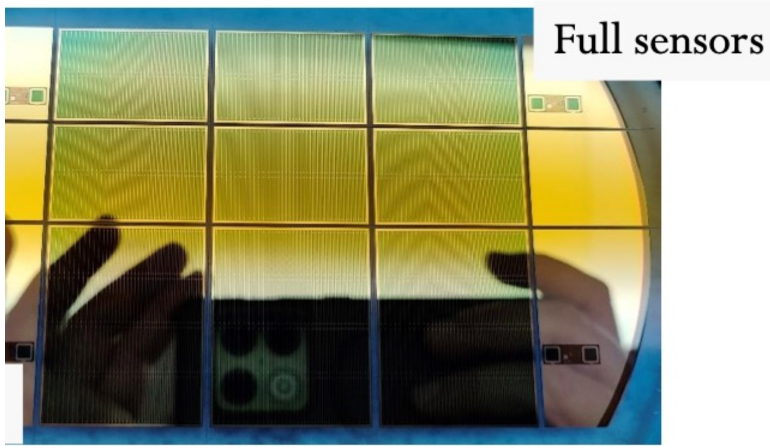
- **AC-LGAD would be applied at EIC， also other experiments (such as Pioneer, FCC-ee et all)**
  - EIC barrel strip：25/35 ps， 30 μm
  - TOF-PID， tracker

Preliminary Design Report in 2025 for EIC

Subsystem	Area (m^2)	dimension (mm^2)	channel count	timing σ_t (ps)	spatial σ_x (μm)	material budget (X/X_0)
Barrel TOF	12	0.5*10	2.4M	35	30 ($r \cdot \phi$)	3%
Forward TOF	1.1	0.5*0.5	3.2M	25	30 (x, y)	5%



Production in 2024



LGAD飞行时间探测器-性能参数需求

以下性能指标基本按重要性排列

From： 仇浩 – 中科院近代物理所

- Δt~30ps，越小（精确）越好
- 单层效率（~= 1 - 死区比例）> 90%，越高越好
  - 外层考虑做成2层，总效率>99%
- 像素尺寸 * 单像素死时间 ~< 1 mm^2 * μs，越小越好
  - 事例率100MHz，每事例4条径迹情况下，最内层占有度~10^{-2}
- 抗辐照剂量~>100kGy，等效中子通量~>1×10^{14} n_{eq}/cm^2
- 厚度X/X_0 ~<2%
- 功耗 < 20 mW/cm^2

- 以上是最初步的starting point，需要结合硬件实现难度（拐点）迭代
- 上述有实在难以实现或兼顾的指标，还可以调整
- LGAD在该谱仪中认为是比较成熟的技术，希望~2年完成研发，可以上工程

4维探测器广泛应用在各个加速器实验中

- **4维高精度探测器广泛应用于未来对撞机核物理实验中**
  – 高亮度LHC实验，正负电子对撞机（CEPC），美国EIC，中国惠州HIAF….
- **10-50皮秒高精度时间信息加入，给加速器物理分析带来了新的维度**
  – 如可极大提升Long Live particle 的探测敏感度 **Gotti, C., et al. (2022)**
  – 背景压缩
  – 带时间信息重建径迹/Trigger
  – 对低能0.5 GeV-3 GeV的粒子分辨能力提升…

Table 1. Table listing all the LGAD-based devices cited in the text, with main properties. In this example, pitch is taken to be 100 μm (except for LGADs) and thickness 50 μm (except for i-LGADs).

Device	Spatial Resolution	Timing	CR Process
LGAD	~mm	~30 ps	std
TI-LGAD	~10s μm	~30 ps	trenches
i-LGAD	~10s μm	~60 ps	std
AC-LGAD	< 10 μm	~30 ps	std
DL-LGAD [1]	< 10 μm	~30 ps	epi layer
DC RSD [1]	~10s μm	~30 ps	std
DJ-LGAD [1]	~10s μm	~30 ps	epi layer

[1] For DC RSD and DJ-LGAD, spatial and timing resolutions need to be confirmed when actual devices are fabricated and tested.

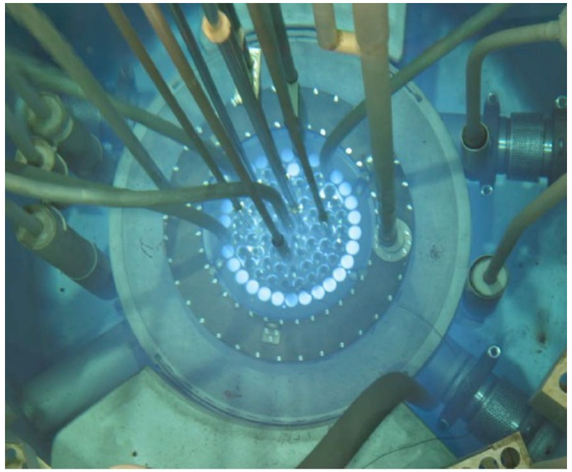
国产LGAD的体损伤辐照实验

辐照研究：质子辐照、中子辐照、x光辐照

IHEP高能所和 欧洲JSI及日本CYRIC合作进行质子和中子辐照实验

- HGTD主要的损伤为量能器反射的中子
- 质子辐照用来模拟HGTD的带电重离子的辐照效应

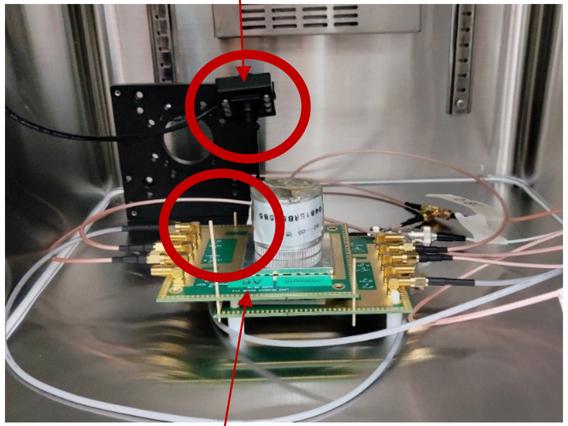
欧洲JSI，反应堆中子辐照

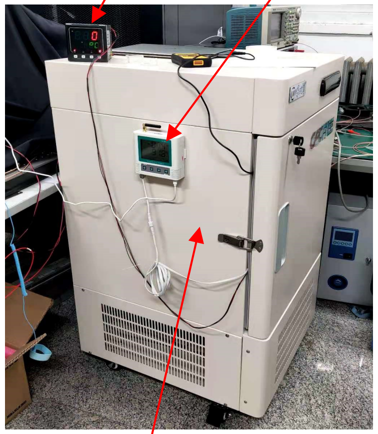


日本CYRIC，70MeV 质子辐照

测试平台搭建

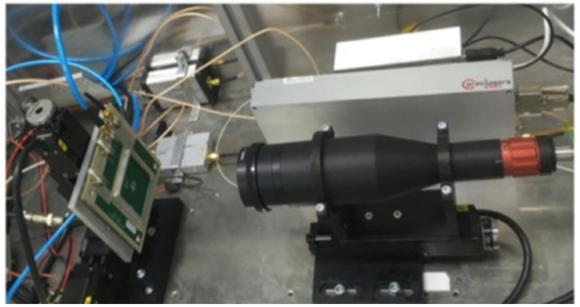
- **低温Beta辐照测试平台：**
  - 时间分辨率、电荷收集等
  - 为了降低噪音，- 30 C°低温
  - Sr90 Beta放射源
  - 二级放大器带宽 >1GHz





- **激光测试平台：**
  - 研究电子学噪音jitter对时间分辨率的影响
  - 排除Beta测试Landau项
  - 不同于传统测试平台，首次使用皮秒激光器

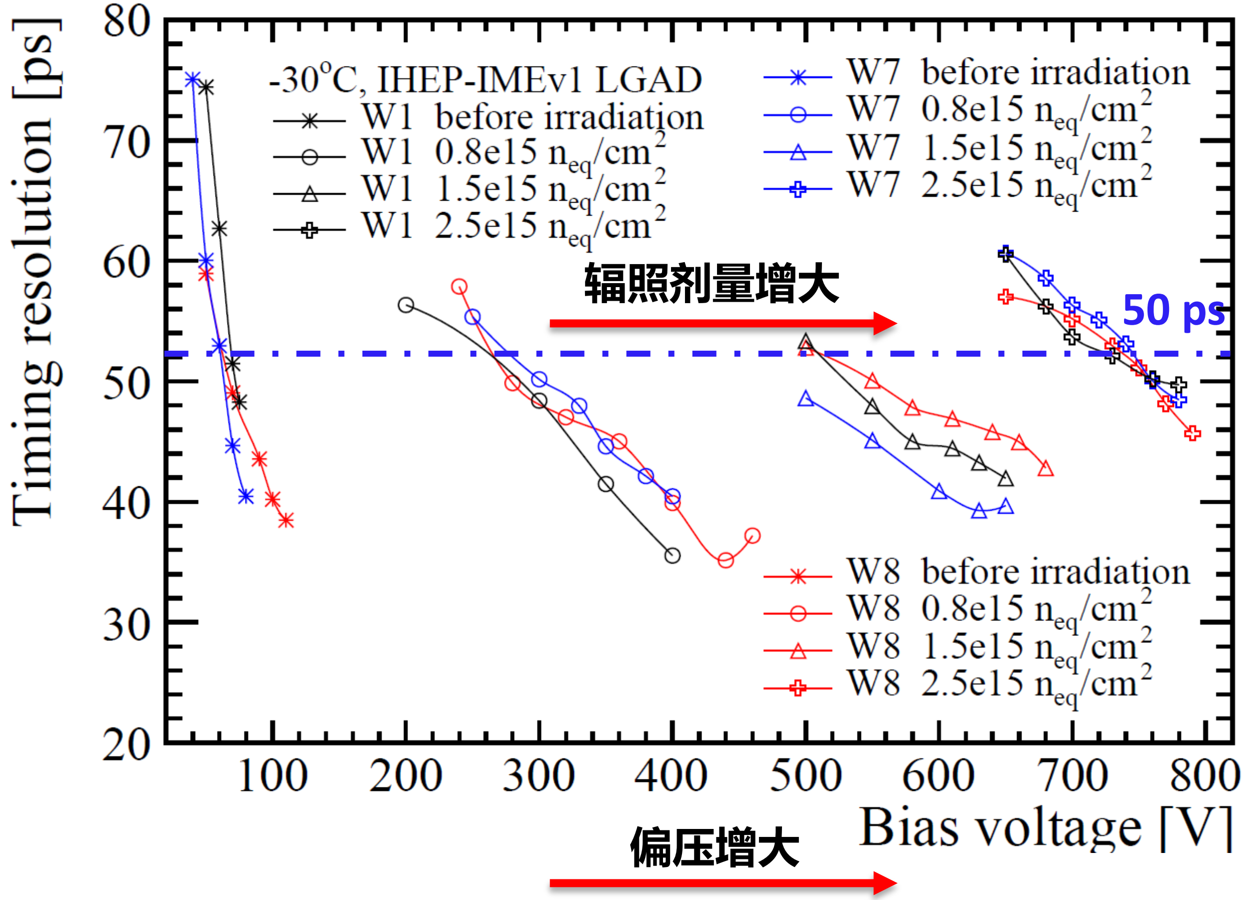
$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{timewalk}^2 + \sigma_{distortion}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2$$



超快硅LGAD的辐照损伤研究

- **辐照实验发现国产LGAD 辐照损伤和国外相同：**

Beta 测试结果



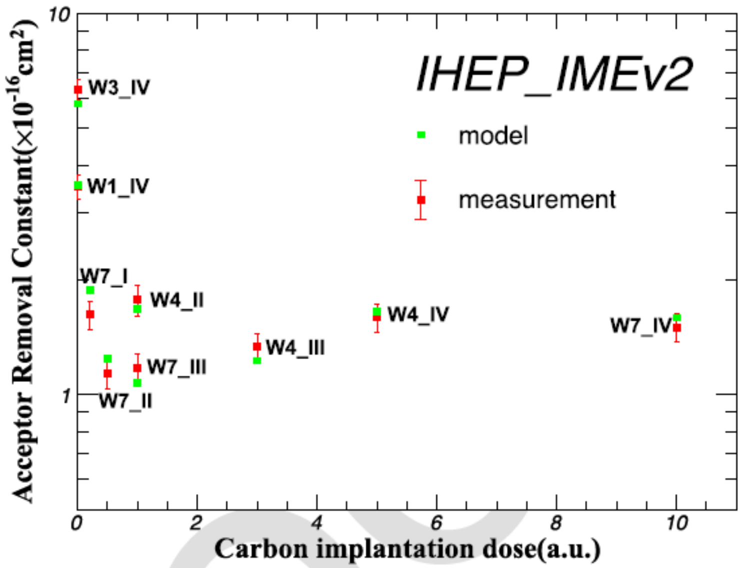
- **时间分辨率退化**
- **需 >600V 高压达到好的时间分辨率**

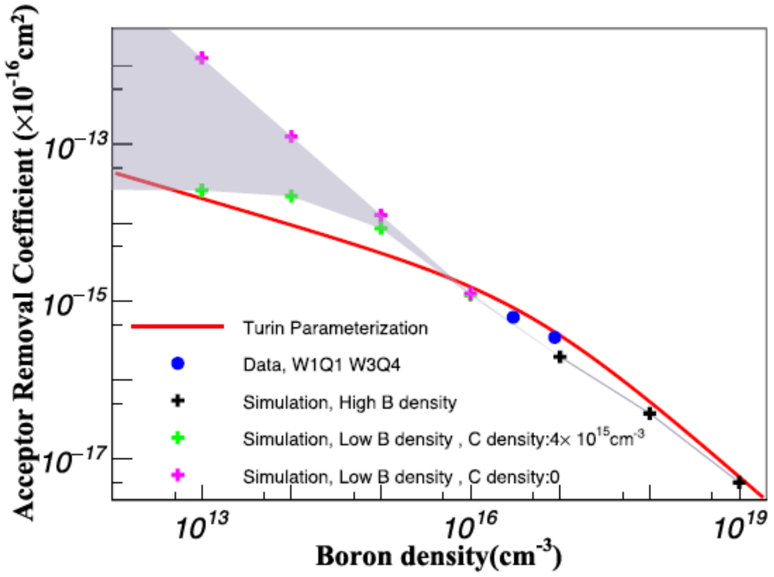
相关结果发表在SCI期刊：NIMA和JINST上

掺碳抗辐照模型

可以准确预估IME国产工艺掺碳后抗辐照的特性。对国外未掺碳的LGAD器件的抗辐照能力也可以有较好的预测。

”

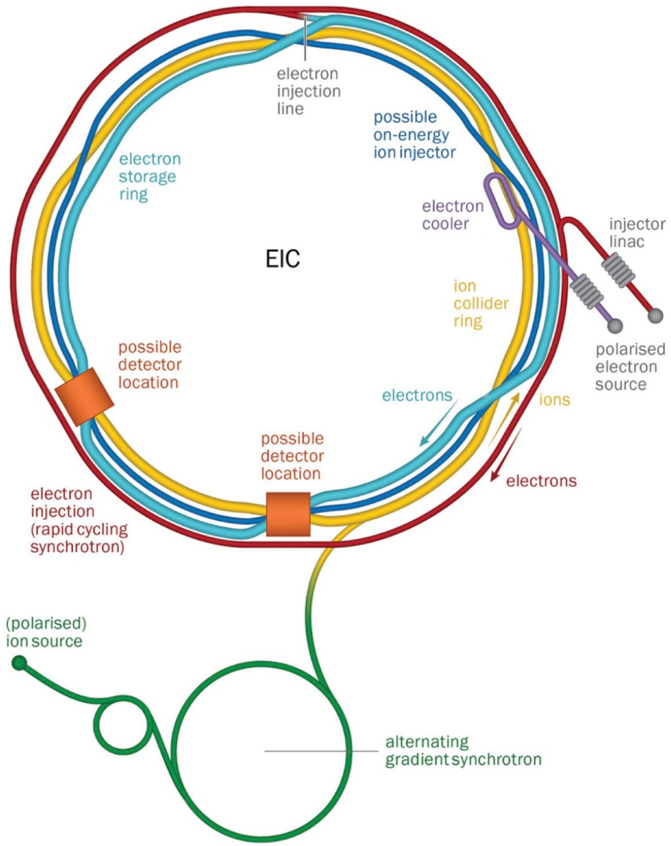




作为通讯作者发表IEEE 文章 “Y. Feng *et al.*, "Study of the acceptor removal effect of LGAD," in *IEEE Transactions on Nuclear Science*, 2022, doi: 10.1109/TNS.2022.3221482.”

The Electron-Ion Collider

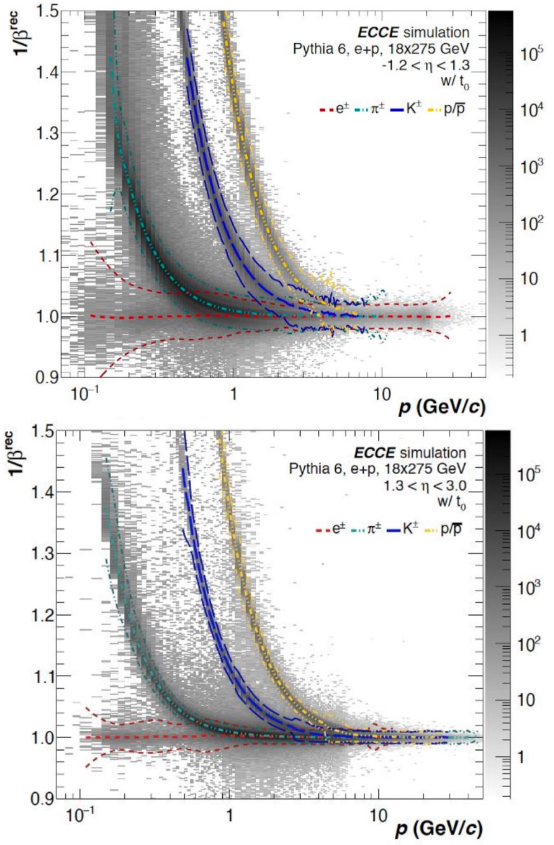
- Flagship Nuclear Physics Collider Experiment constructed at Brookhaven National Laboratory
  - Protons/nuclei 40-275 GeV ($Z/A \times E_p$)
  - Electrons up to 18 GeV
  - Up to 80% polarized beams
  - Luminosity up to 10^{34} cm^{-2}s^{-1} (100-1000x HERA)
- Two interaction regions
- First beams in early 2030s



AC-LGAD Detectors at EIC

AC-LGAD TOF in EPIC

- Target: 25ps detector resolution
- <20ps event t_0 determination
  - Machine clock + X-t correlation
  - Scattered e^- timing, fitted hadron timing
- Serves as additional tracking layer
  - Barrel: 0.5mm x 10mm strips
  - Hadron endcap: 0.5mm x 0.5mm pixels



OAK RIDGE National Laboratory

Current application

- **AC-LGAD would be applied at ePIC， also other experiments (such as Pioneer, FCC-ee et all)**
  – ePIC barrel strip requirement：25/35 ps， 30 μm
  – TOF-PID， tracker

Preliminary Design Report in 2025 for EIC

Subsystem	Area (m^2)	dimension (mm^2)	channel count	timing σ_t (ps)	spatial σ_x (μm)	material budget (X/X_0)
Barrel TOF	12	0.5*10	2.4M	35	30 ($r \cdot \phi$)	3%
Forward TOF	1.1	0.5*0.5	3.2M	25	30 (x, y)	5%