SiC Timing Pixel Detector for Fusion Reactor and Beyond

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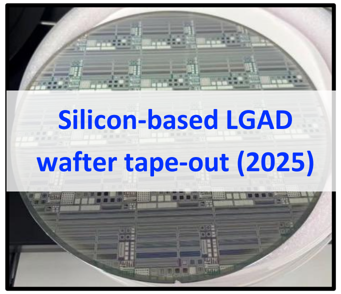
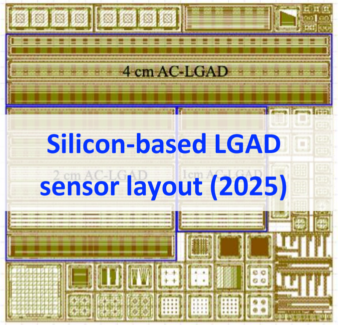
4th International Symposium on the Proton-Boron Fusion Sciences and Applications (ISPBF 2026)

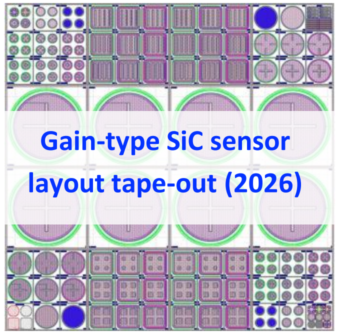
Research Group Activities



Silicon-based LGAD wafter tape-out (2025)



Silicon-based LGAD sensor layout (2025)



Gain-type SiC sensor layout tape-out (2026)

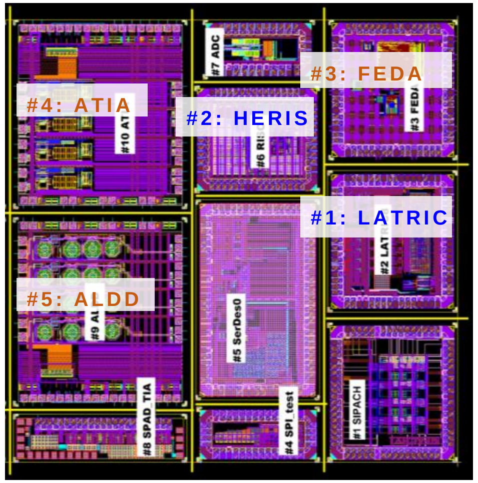
Developing advanced silicon-based and multi-material, multi-type sensor technologies

❑ **Semiconductor Detector Sensors:**

- **Silicon-based sensor**: The first large-area silicon-based sensor with both timing resolution ≤40 ps and spatial resolution of ~10 μm.
- **SiC sensor:** The first 4H-SiC sensor achieving a timing resolution of ~30 ps, for operation in high-temperature and high-radiation environments.

❑ **Readout Integrated Circuits:**

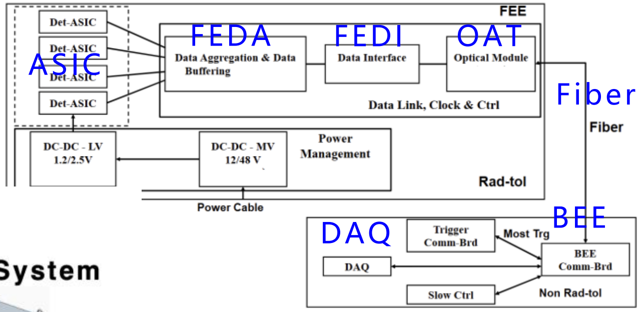
- **LATRIC:** A readout ASIC featuring high timing precision (≤30 ps), high spatial resolution (compatible with 10 μm), low power consumption, and high integration.
- **HERIS:** The first RISC-V system-on-chip (SoC) developed for particle physics applications.



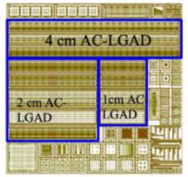
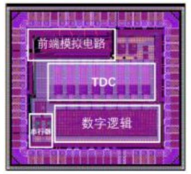
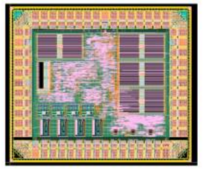
❑ **Other High-Speed Data Transmission ASICs:**

- **FEDA:** A 10.24 Gb/s data aggregation ASIC.
- **FEDI:** A data interface ASIC.
- **ATIA:** A photonic signal receiver ASIC.
- **ALDD:** A laser diode driver ASIC.

Readout architecture for future detector electronics



Developing Advanced Silicon Tracker Detector System

Sensor	ASIC	SoC	DAQ	Mechanics	Cooling System
					
The first sensor with 10 μm position resolution and ≤40 ps timing resolution	The ASIC with high timing precision (≤30 ps) and high spatial resolution	The first RISC-V SoC dedicated to HEP applications (taped out in 2025)	DAQ system	The first carbon fiber truss manufactured at IHEP in 2026	The first two-phase CO_2 cooling system in China for HEP (2026-10)

Personal Background

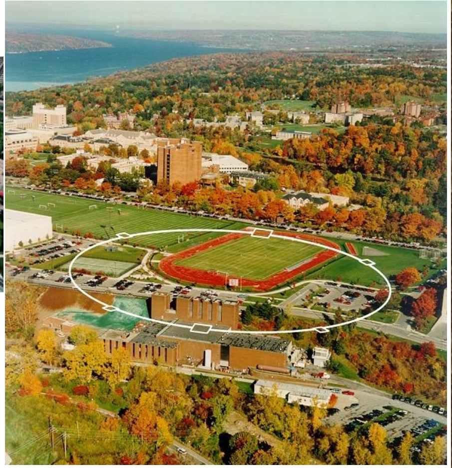
SDU 2001 PKU 2004 Cornell 2008 2011 NTU 2013 Purdue 2015 IHEP 2026

BEPC

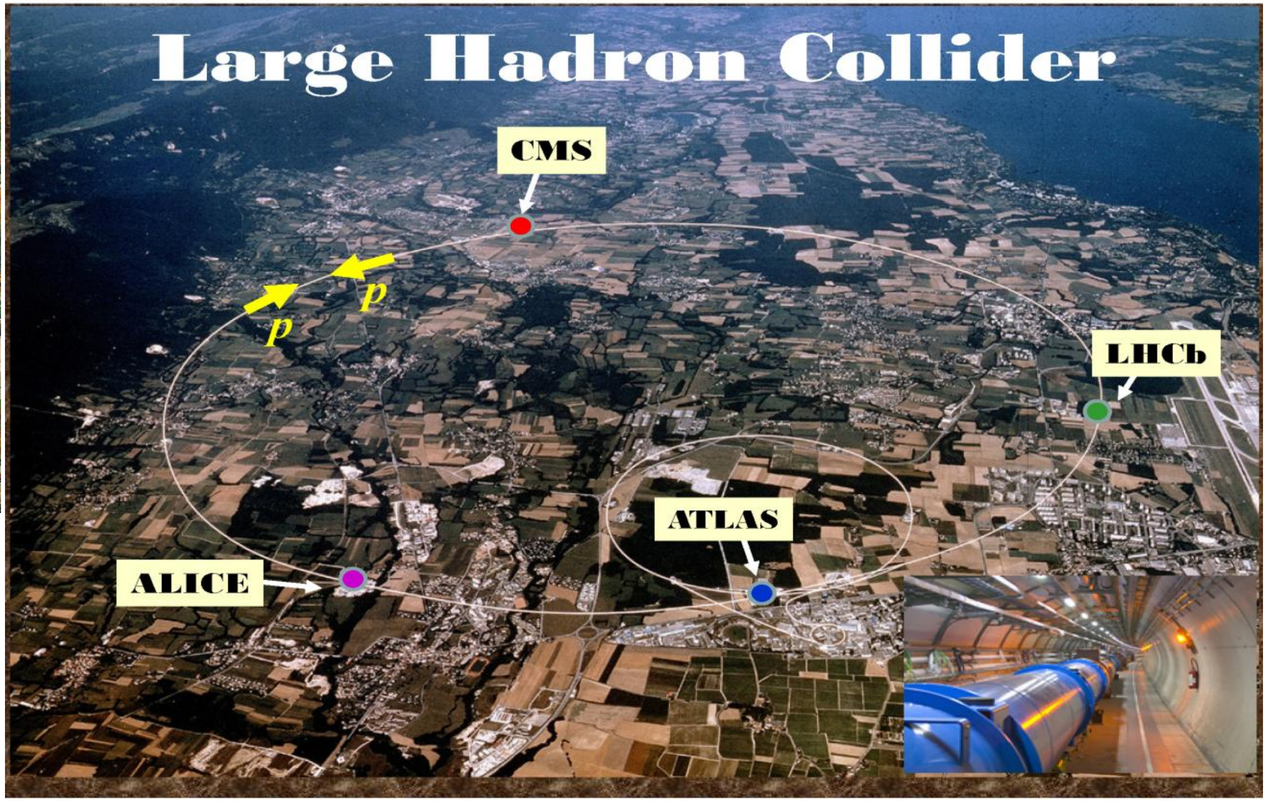
CESR

LHC@CERN

240m
e+e-
2-5GeV

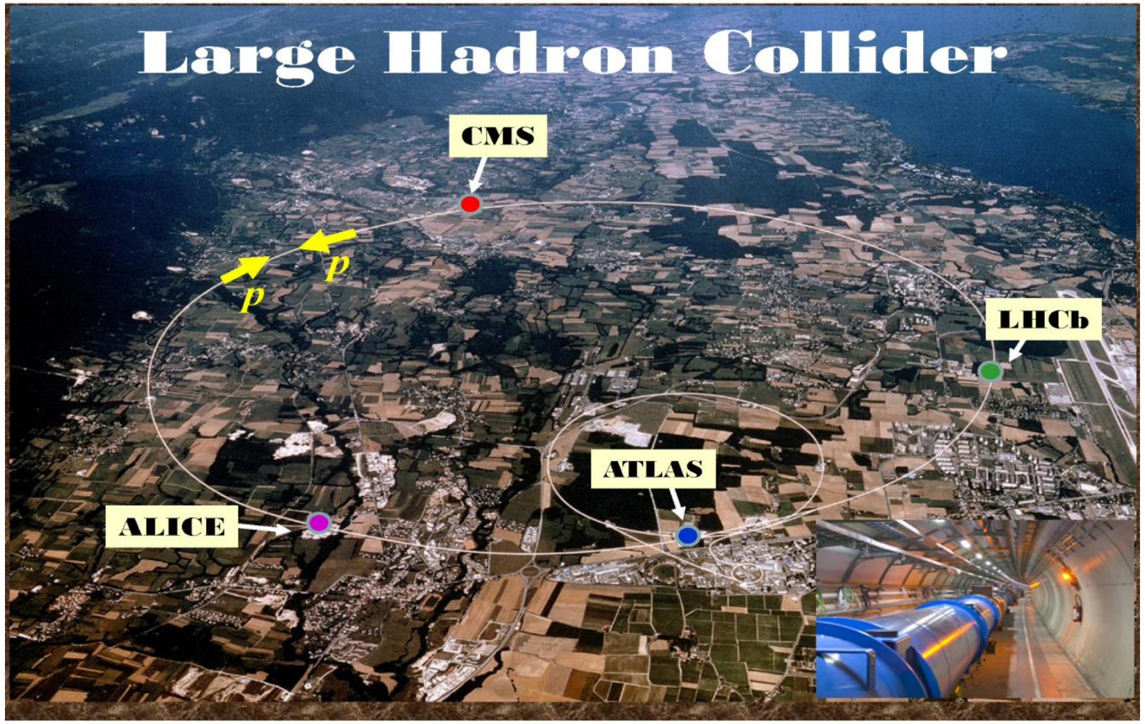


768m
e+e-
3-12GeV



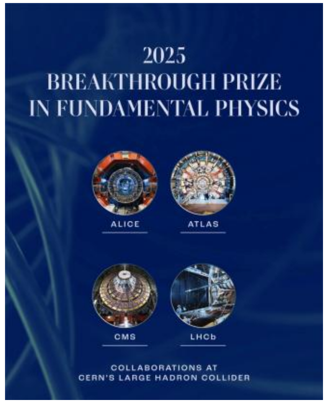
27km, pp, 14TeV

CERN – Large Hadron Collider and DRD3

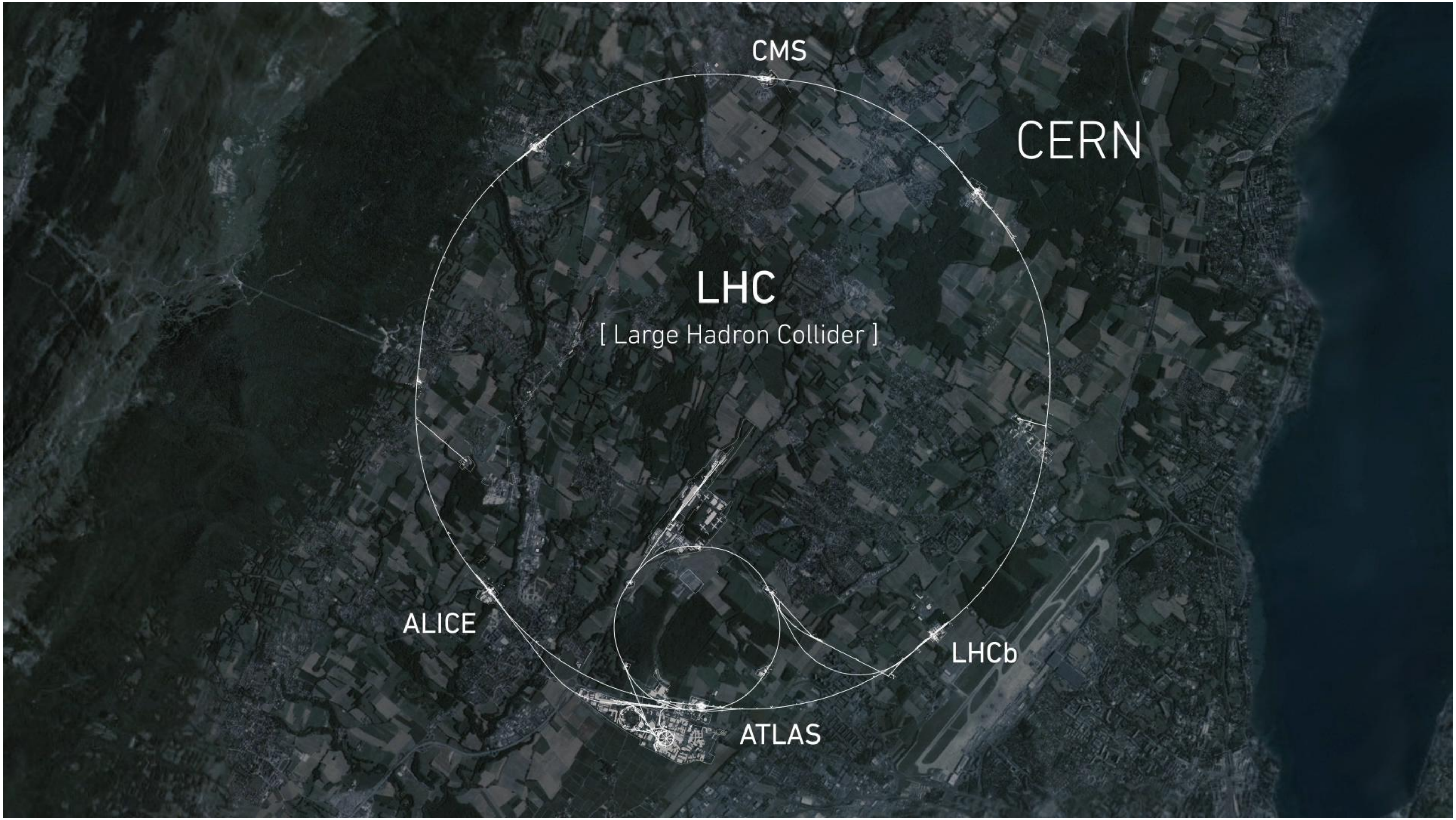


- Largest Particle Experiment in the world
- Over 10 000 scientists
- Four major experiments
  (ATLAS, CMS, ALICE, LHCb)
- 2012 Higgs discovery
  2013 Nobel Prize

2025 Breakthrough Prize in Fundamental Physics

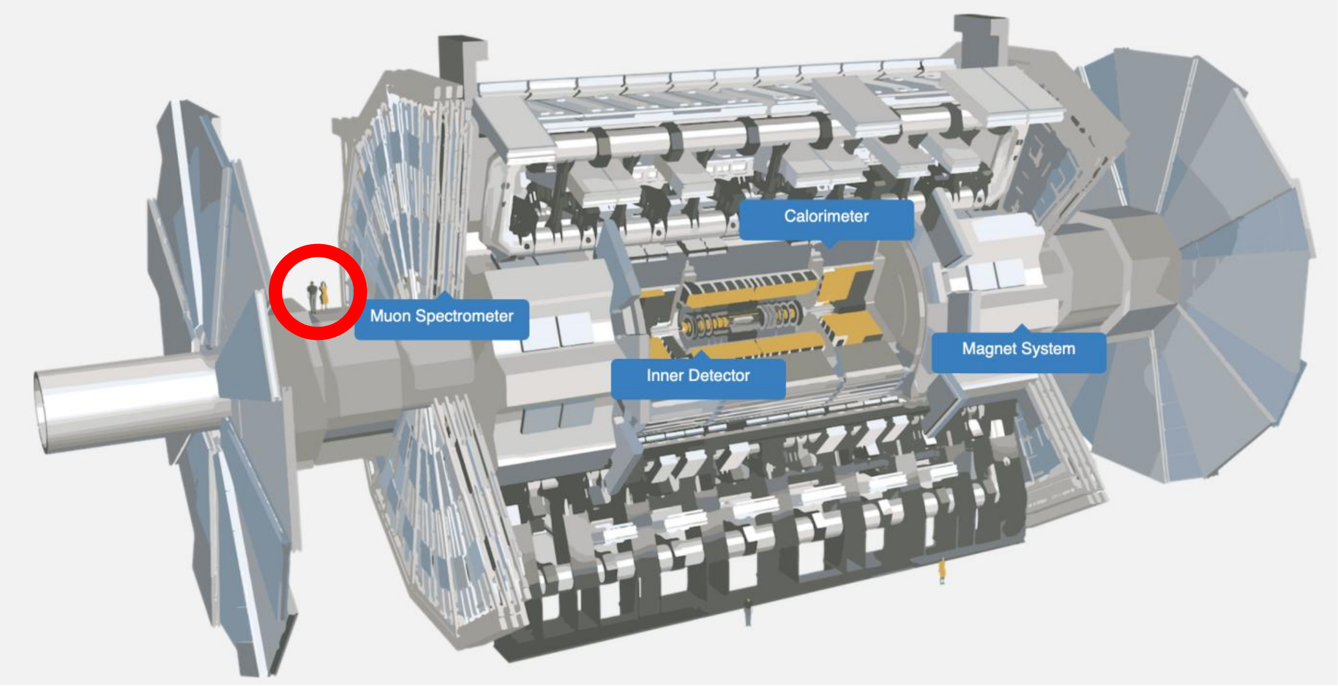


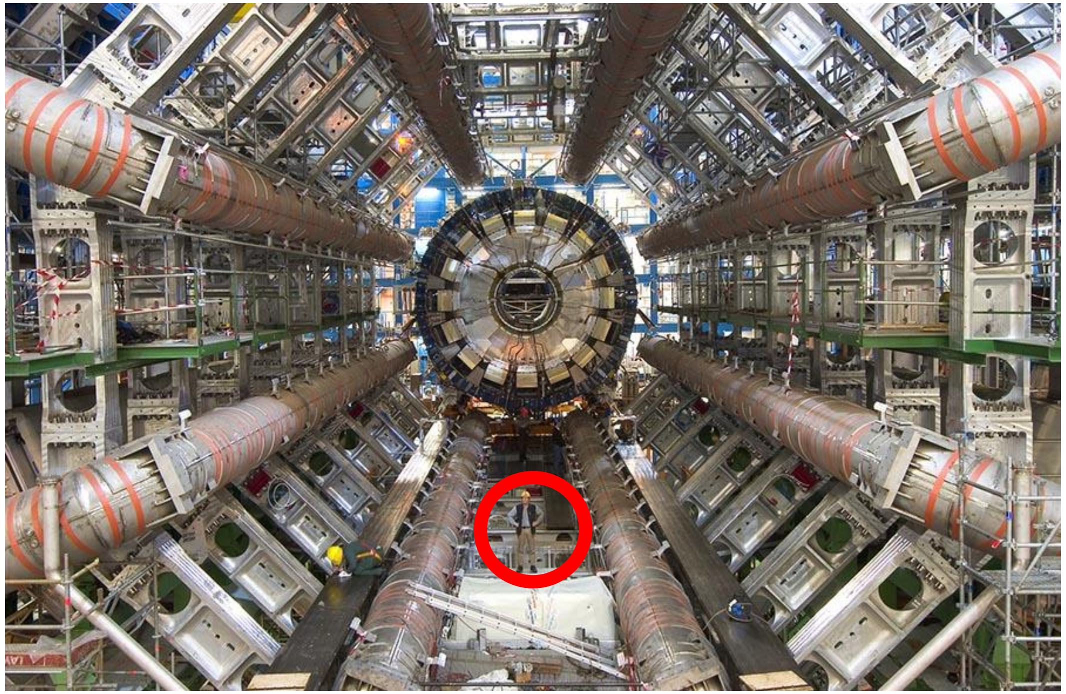
- DRD3 – R&D on Semiconductor Detectors (2024 – Now)
  - Convenor of WG6: Wide Bandgap and Innovative Sensor Materials


CMS
CERN
LHC
[Large Hadron Collider]
ALICE
LHCb
ATLAS

ATLAS EXPERIMENT

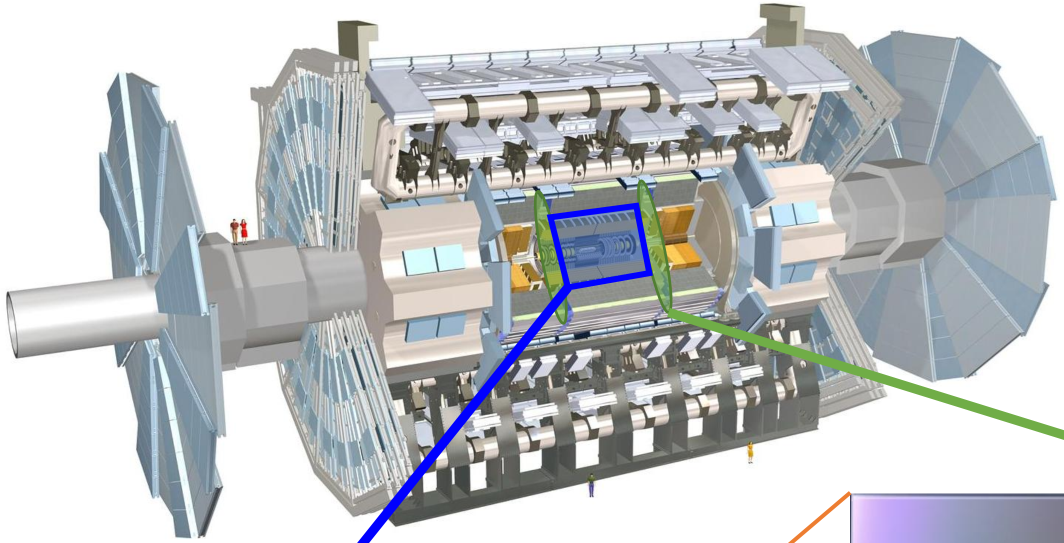
https://atlas.cern

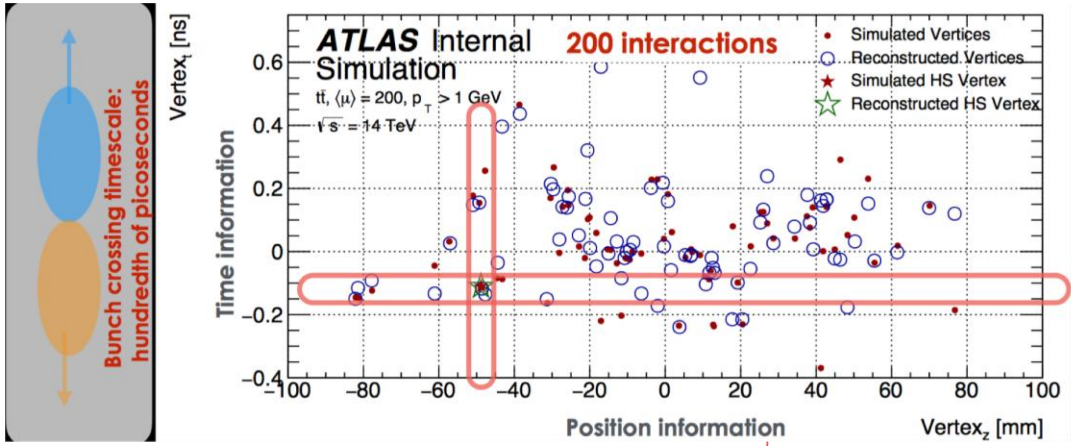




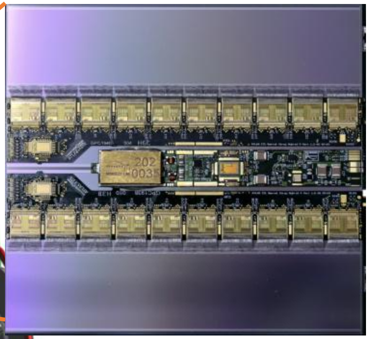
- Largest detector ever constructed for a particle collider
- Long: 46 m / diameter: 25 m / 7000 t

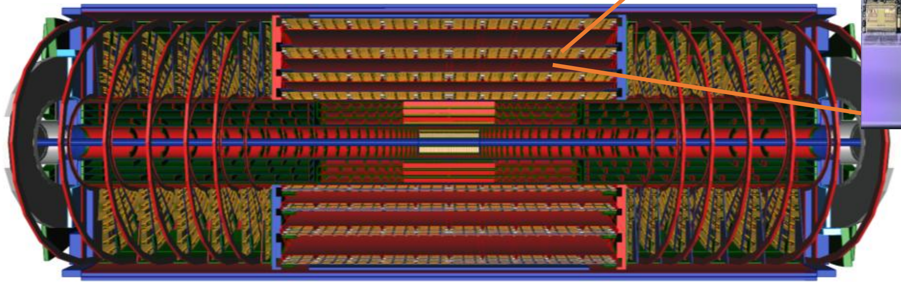
ATLAS Detector Upgrade – Silicon





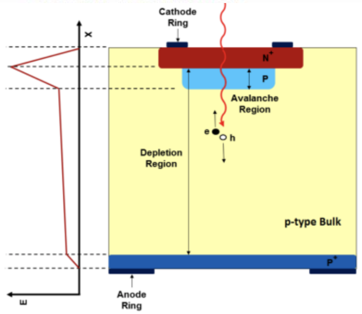
Inner Tracker

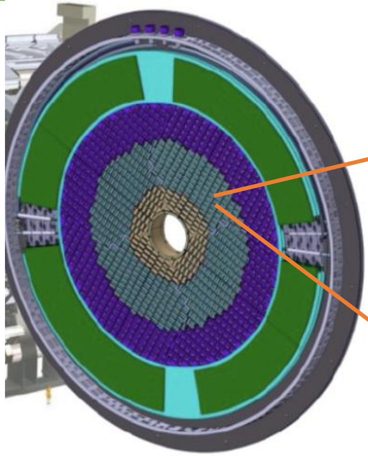


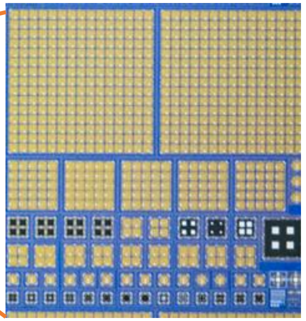


1.8k modules / 60 M channels / 165m^2

High Granularity Timing Detector

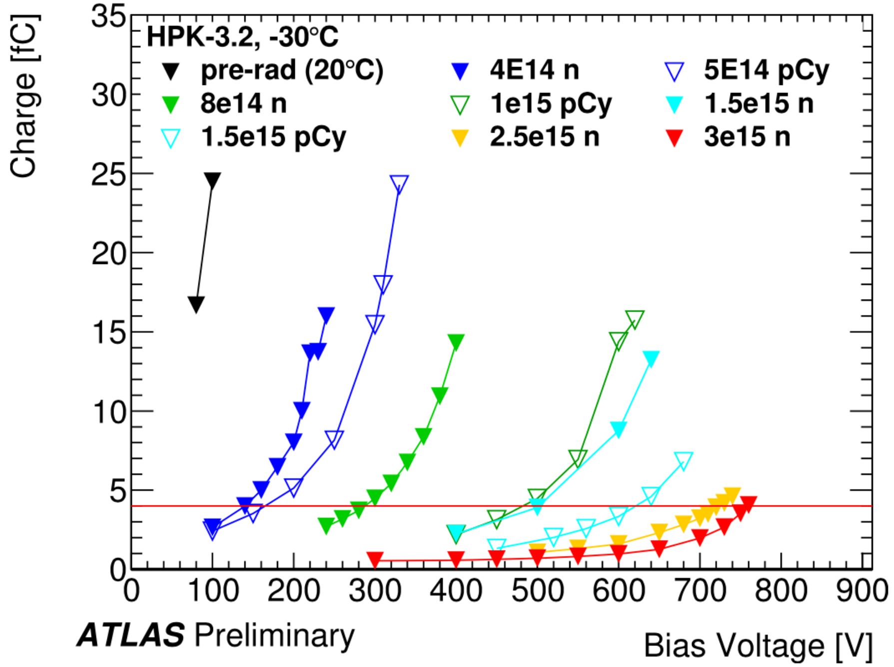


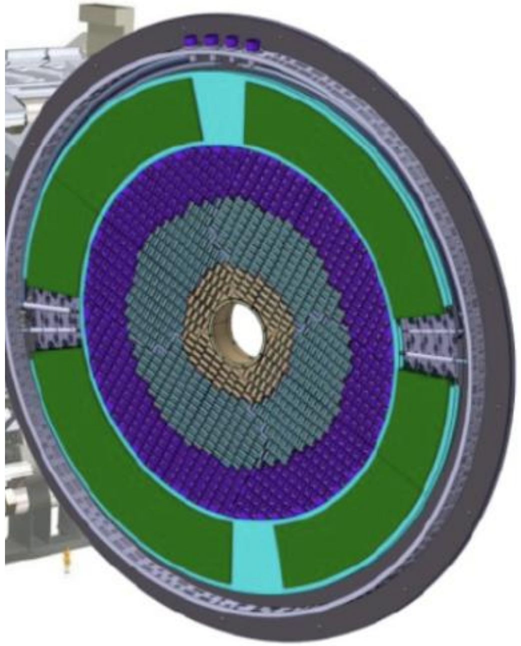


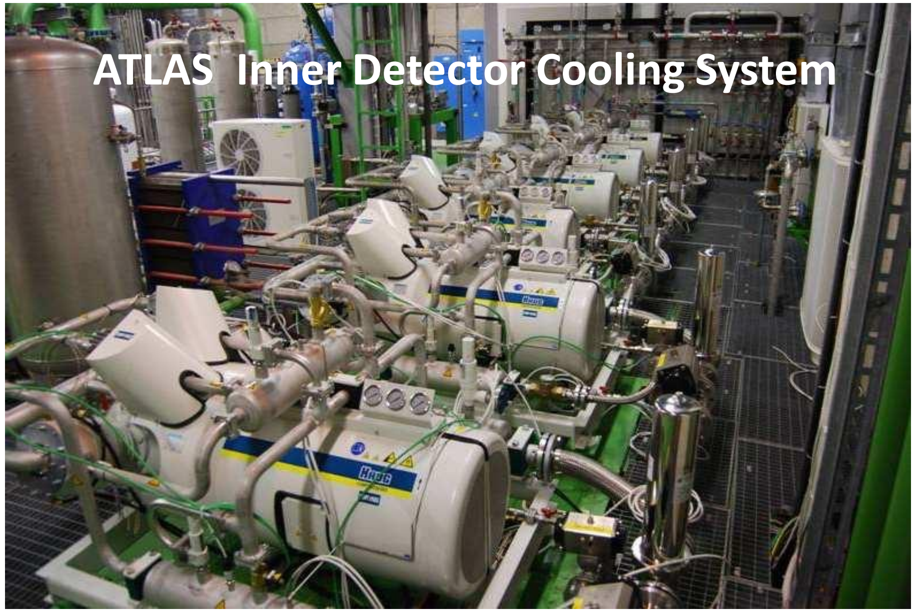


Limitations of silicon detector

- Silicon detector is well-established in HEP experiment but with limitations
  - Less radiation hard ⇒ need to replace the inner rings
  - Leakage current increase after irradiation ⇒ need to operate under low temperature



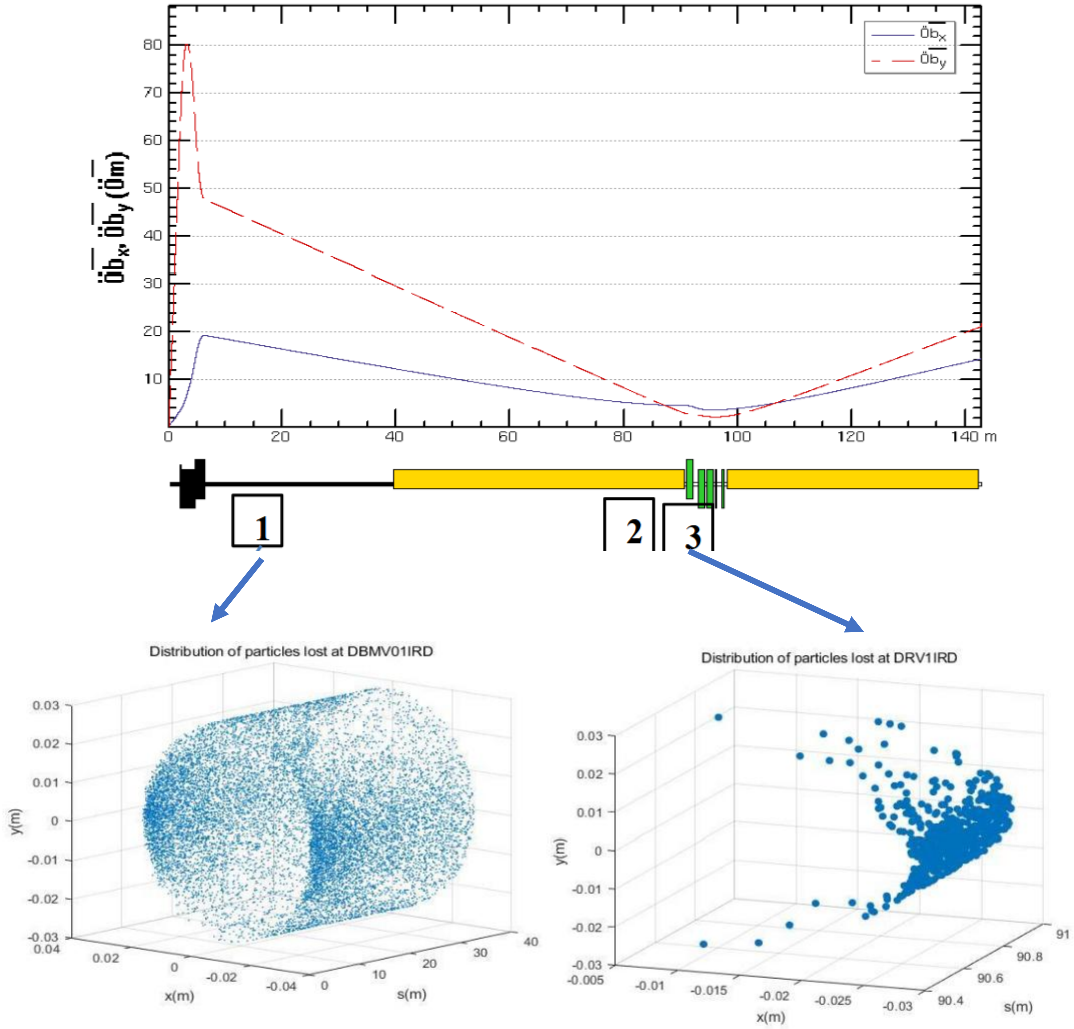




SiC for CEPC Fast Luminosity Monitor

- CEPC MDI —— Fast Luminosity Detector
  - Detects small-angle Bhabha showers to track horizontal IP offsets
  - Realize the real-time luminosity feedback and monitor the collision quality and efficiency
  - Employ the radiation-hard detector to ensure long-term stable operation

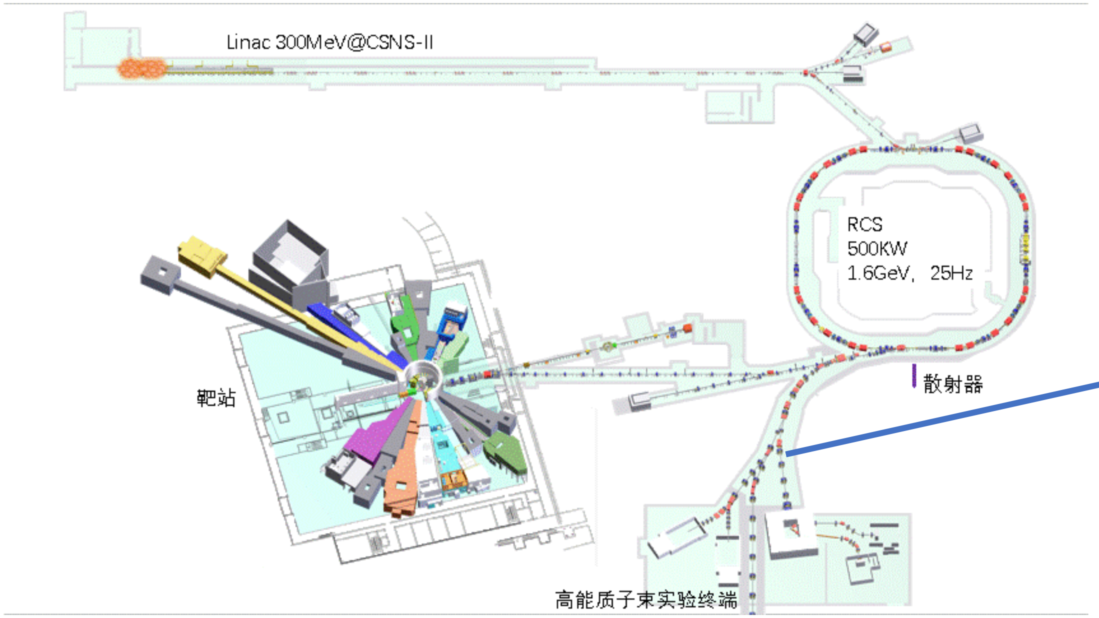
- SiC listed in the CEPC TDR as a fast luminosity detector
  - The FLM is positioned at two locations, 10 m and 90.5 m away from the IP
  - Precision requirement: ν ≤ 2% @1khz
  - Number of detected Bhabha electrons Nd >= 2500

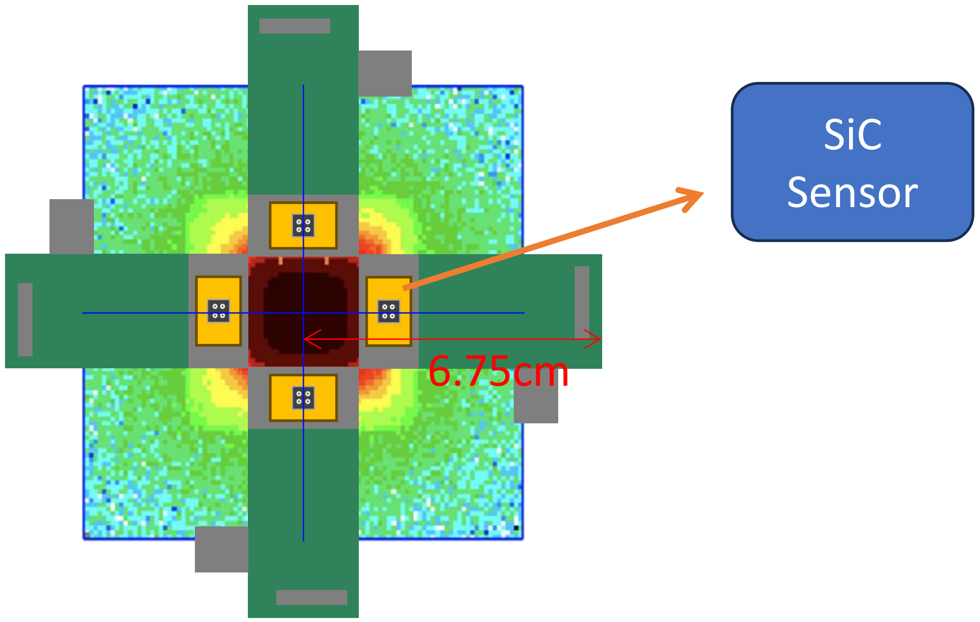


https://doi.org/10.1007/s41605-024-00491-8

SiC for BMOS in CSNS-II Upgrade

- High Energy Proton Experimental Station (HPES)
- China's first 1.6 GeV proton source
- A beam monitoring system to detect the proton flux
- Using SiC as the beam monitor system (BMOS)





Future High Energy Experiment: need for new material

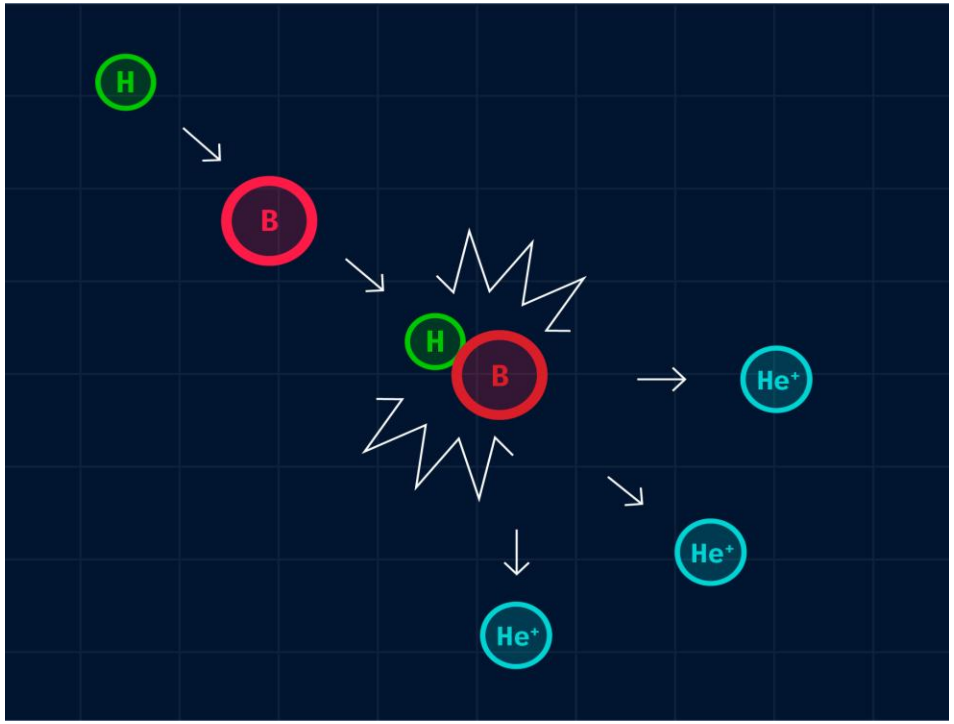
- Future proton-proton collision will introduce even harsh environment
- Need more radiation-hard and better timing capabilities
- Connection with the proton-boron process in Hydrogen-Boron fusion?

Hydrogen-Boron Fusion & Diagnostic Challenges

- The p–^{11}B reaction: a leading **aneutronic** energy pathway

- Extreme diagnostic environment:
  - **High temperatures**
  - **Mixed radiation fields**: protons, α-particles, and γ-rays

- Critical need: precise α-particle spectroscopy under these harsh conditions

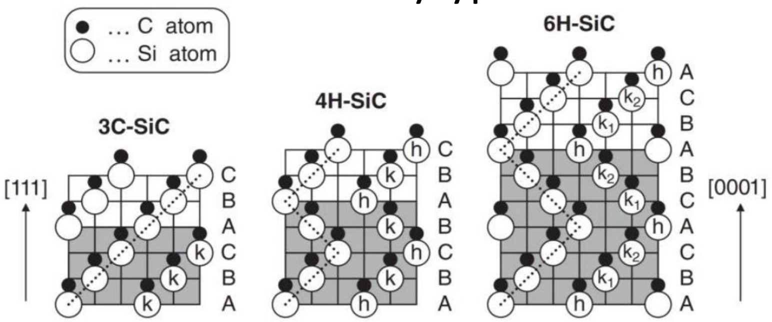


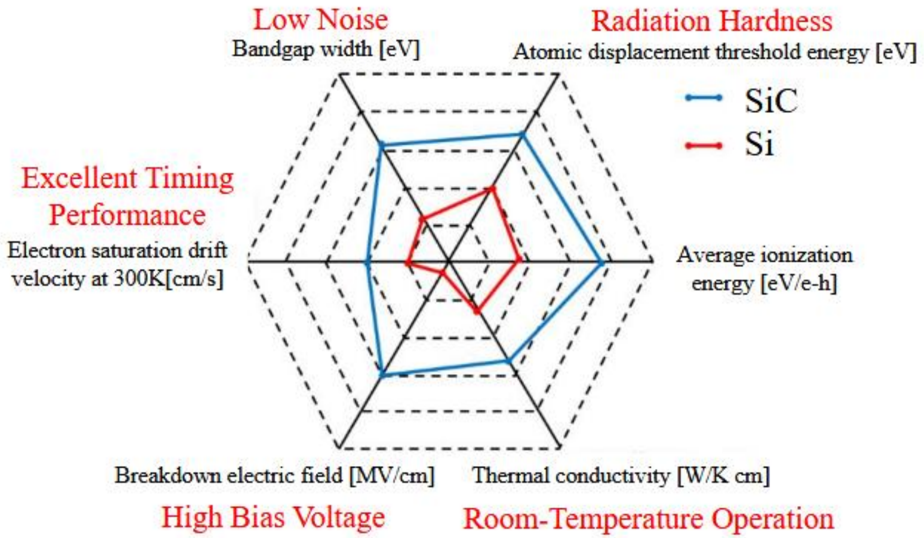
https://hb11.energy

Silicon Limitations vs. SiC Advantages

- **Conventional silicon detectors**: severe degradation in high-temperature, mixed-field environments
- **SiC (Silicon Carbide)** solution:
  - Wide bandgap → low leakage current
  - Superior radiation hardness → long-term stability
- Enables reliable operation where silicon fails
- SiC advantages:
  - Low noise, radiation hard, excellent timing,
  - High Bias Voltage, high-temperature operation

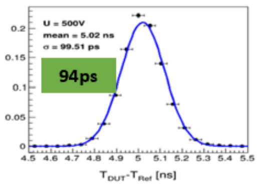
SiC Polytype





SiC development timeline by IHEP

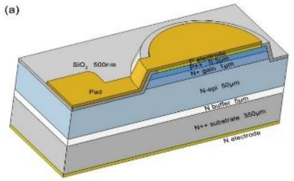
- Develop high temporal and spatial resolution SiC detectors, BJT, graphene as the goal
- Systematically Advancing Device Process Development and Performance Optimization



2022

SiC-PIN

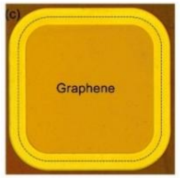
Time resolution:94ps



2024

SiC-LGAD

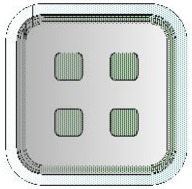
Gain factor:3



2025

Graphene-SiC-PIN

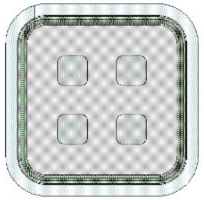
Time resolution:58ps



2026

BJT / LGAD

Aim： Gain factor: 90



2027

AC-LGAD pixel

Aim： pixel 2x2

2028

LGAD Multi-pixel

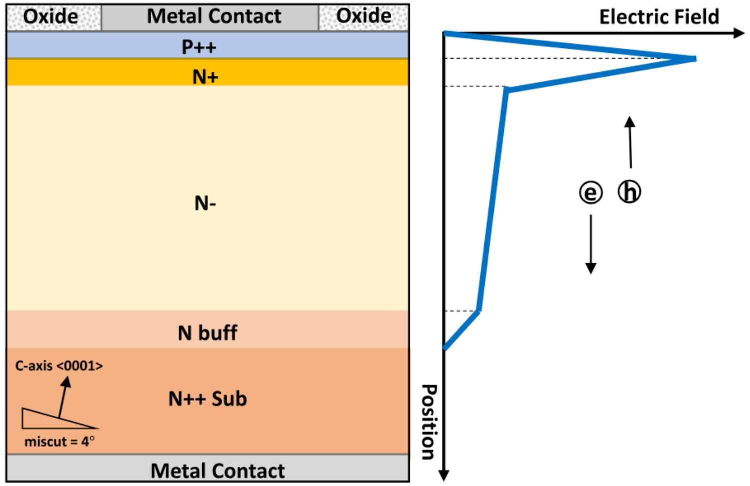
Aim： multi-pixel

Done

In progress

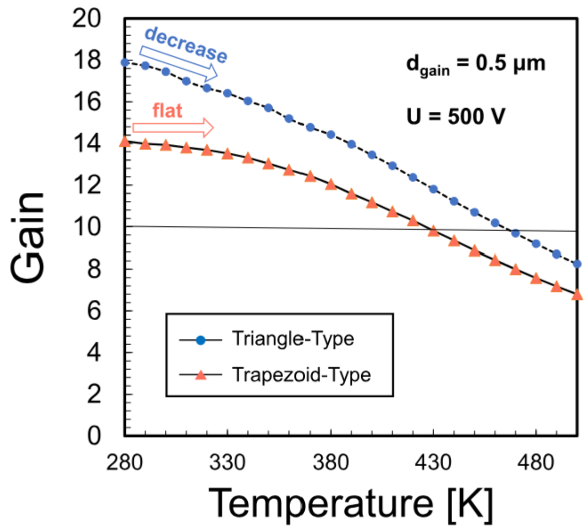
SiC LGAD + Pixelated Readout

- **SiC LGAD** structure:
  - Provides **internal gain** for charged particles
  - Enables **high timing precision ~50ps**



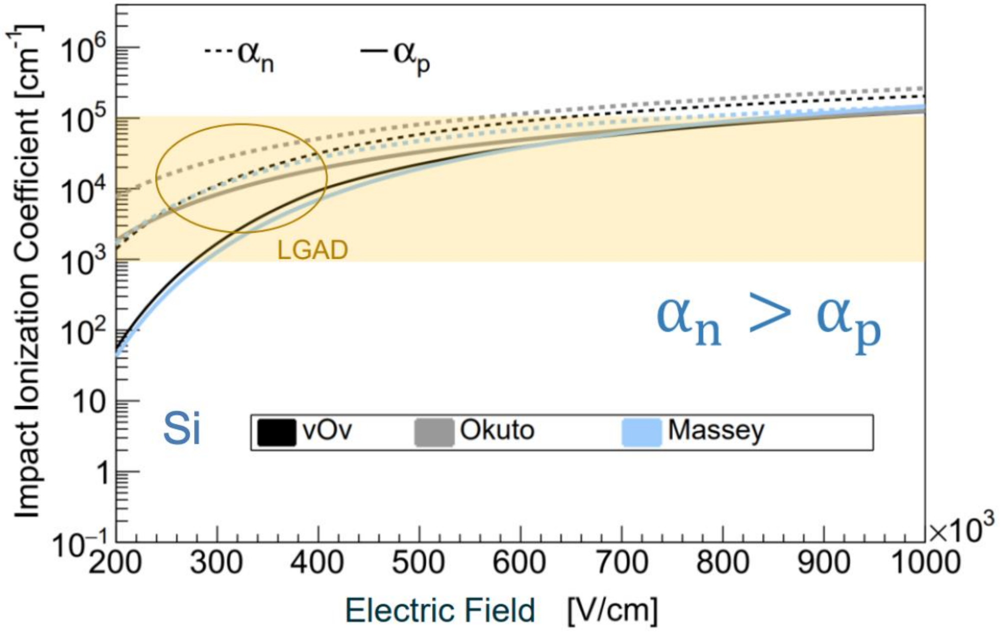
NIM A 1056 (2023) 168677

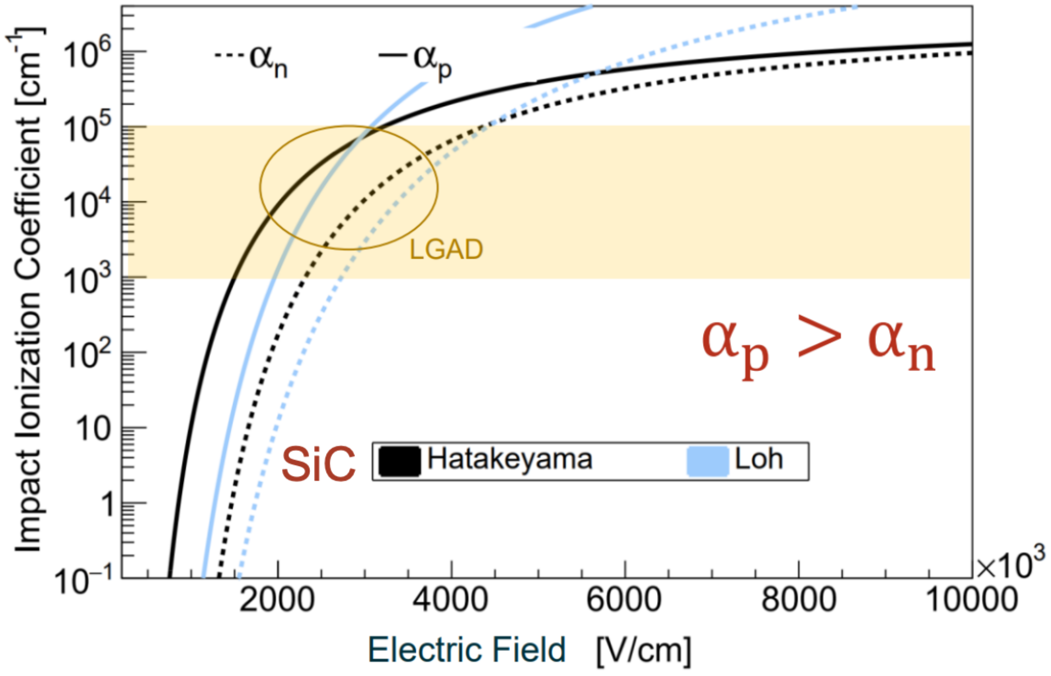
- **Pixelated readout**:
  - Adds spatial resolution
  - Essential for background rejection in plasma environments



- A dedicated time detector system for α-spectroscopy in H-B plasmas

4H-SiC LGAD – Impact Ionization Coefficient

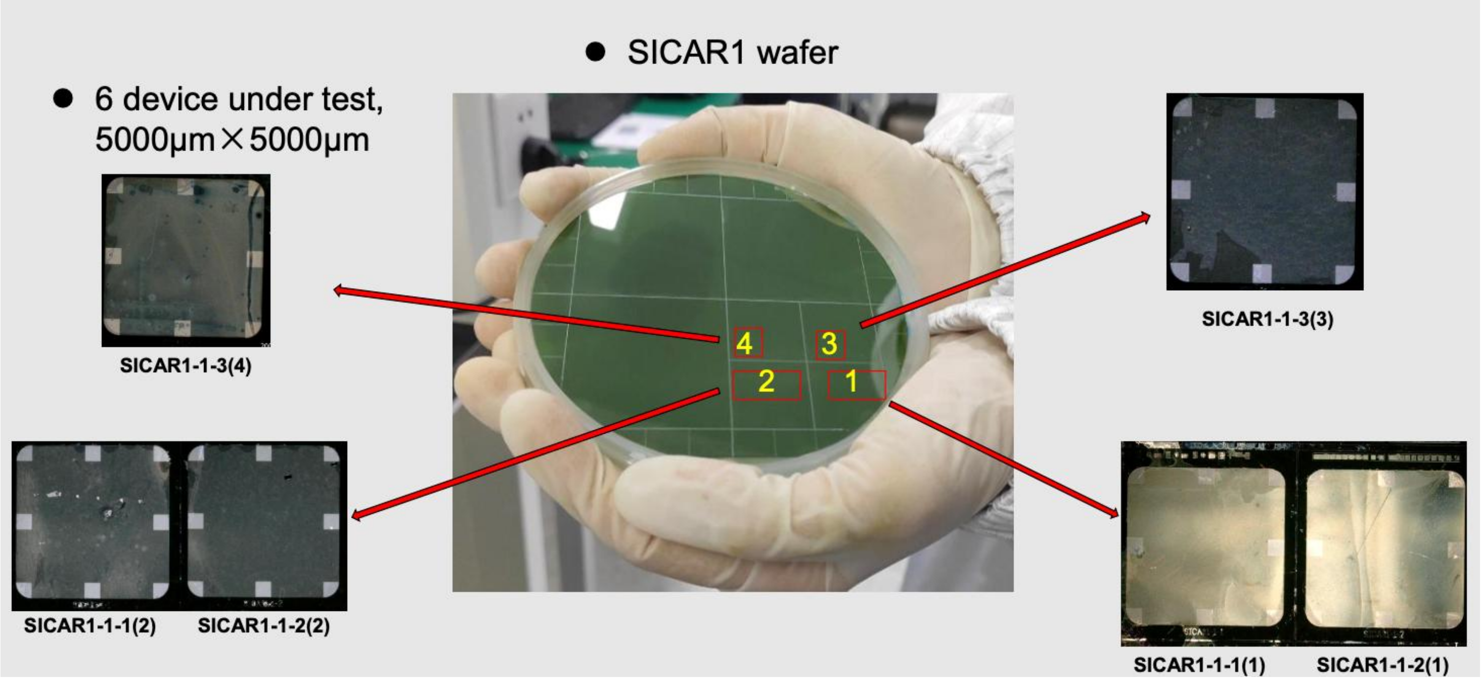


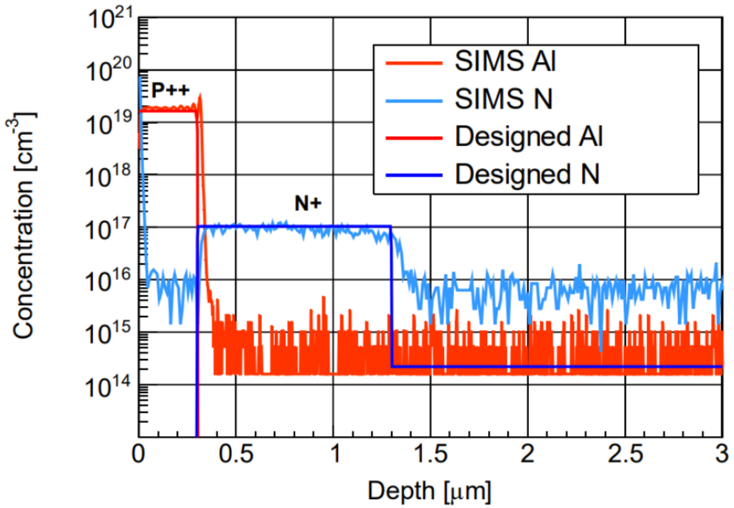


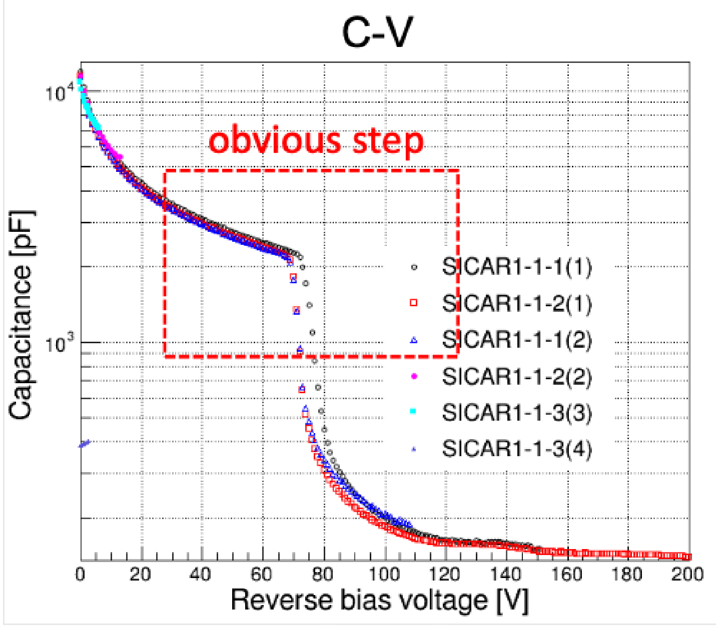
- Si LGAD: electron dominant avalanche P-type， electrical field strength 0.3 MV/cm
- 4H-SiC LGAD : hole dominant avalanche N-type， electrical field strength **2**MV/cm

SICAR1 – 4-inch wafer (2023)

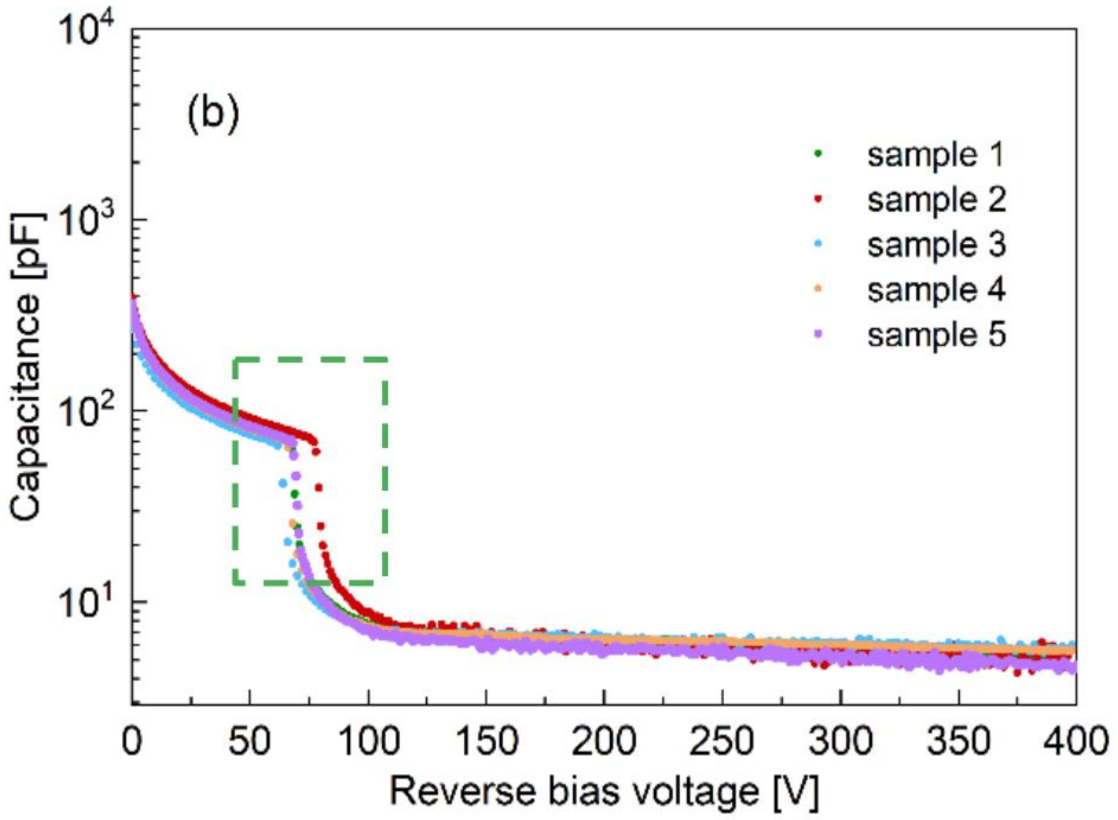
- The first version indicates the gain layer structure

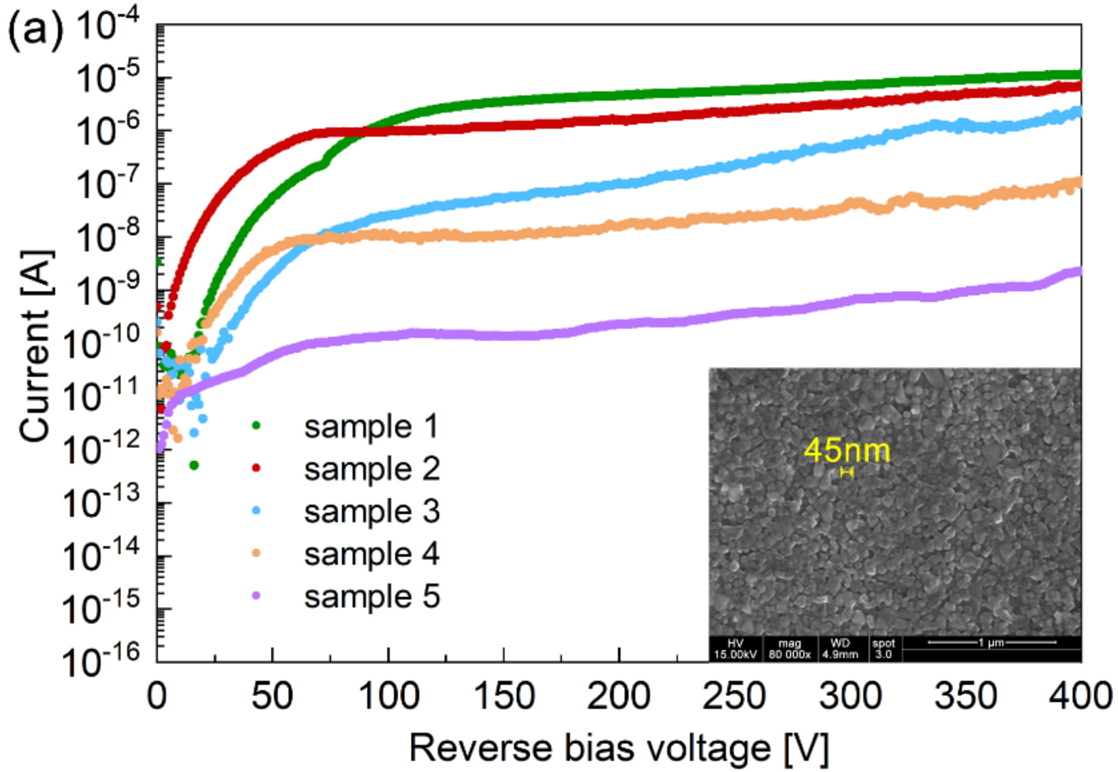






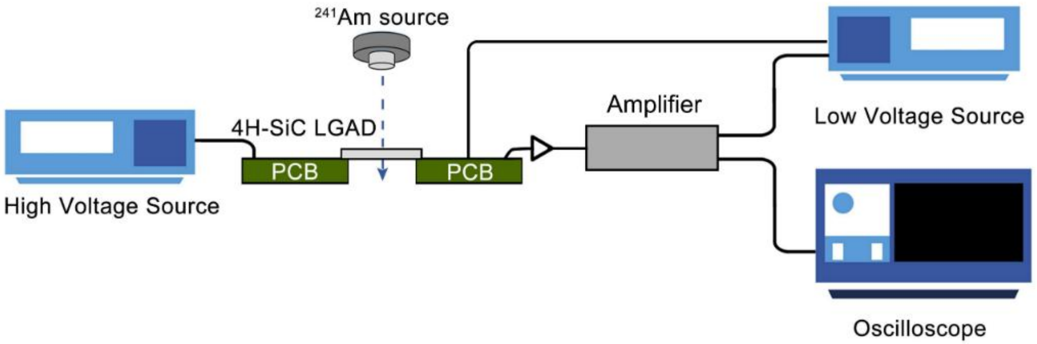
SICAR1 – IV & CV characteristics

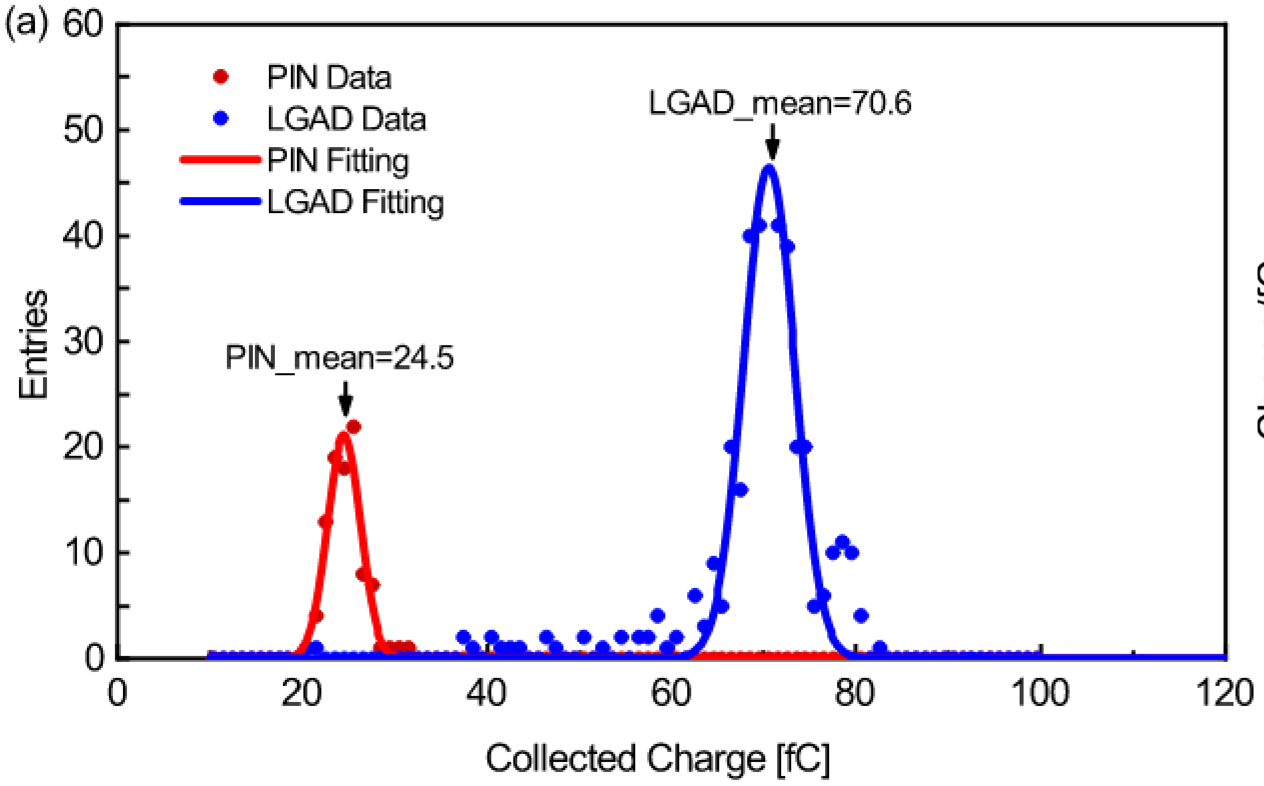


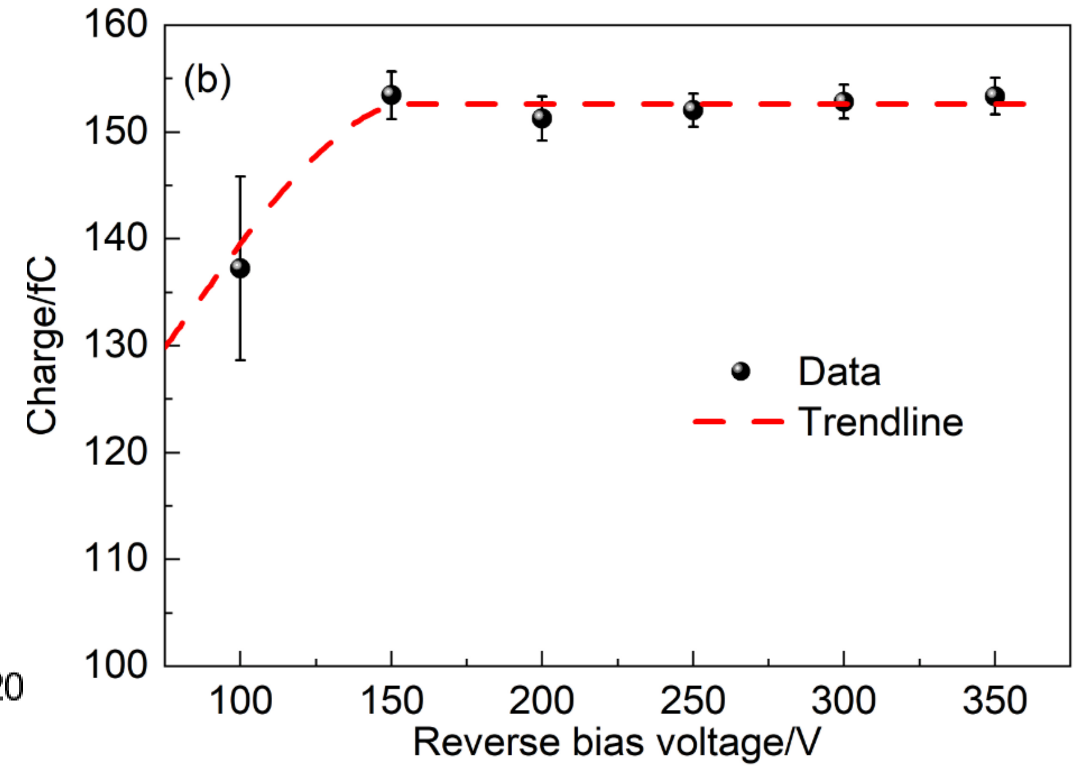


- V_{GL} ~ 75V, V_{FD} ~ 350 V
- Low leakage current ~ nA

SICAR1 – α particle test





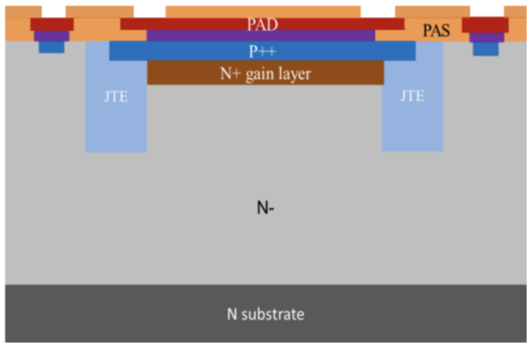


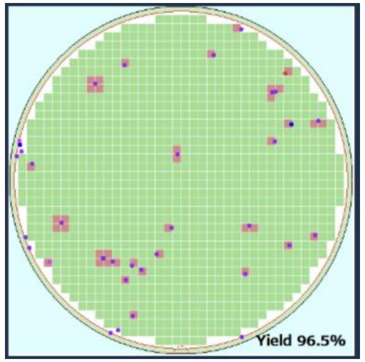
- Large charge collection compared with SiC PIN device
- Collected charge reached plateau 150V~ 350V

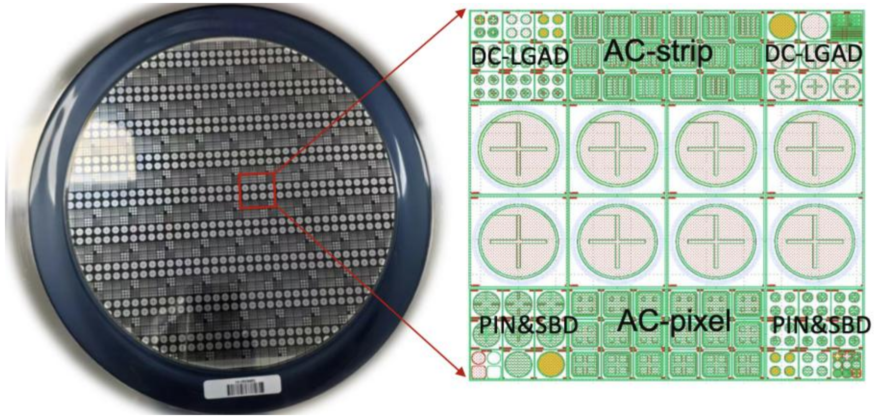
IEEE VOL. 71, NO. 11, 2024

SICAR3 status (2026)

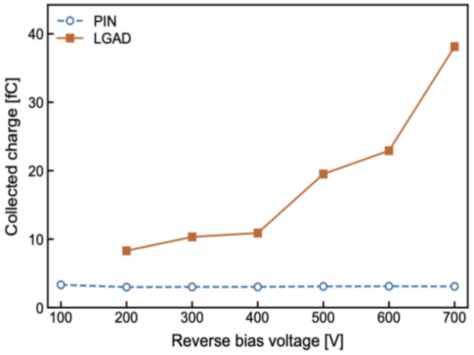
Joint effort with SDIAT

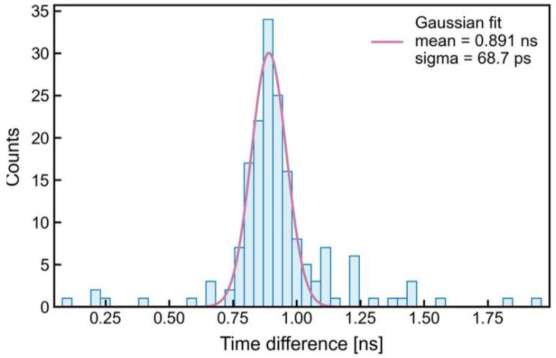






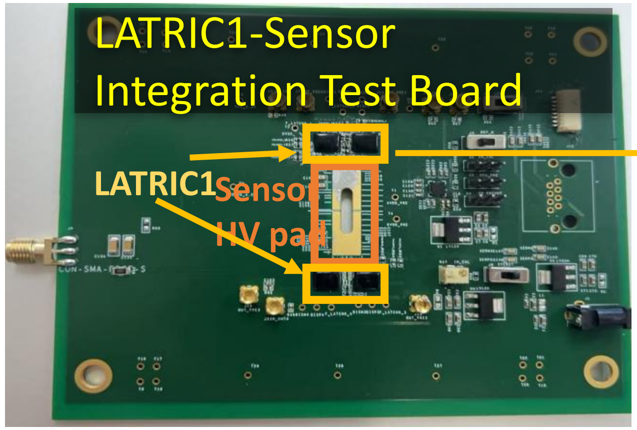
- 350nm MOSFET Process Platform
- High-energy ion implantation & High-temperature post-implantation annealing
  - N+ gain layer / P++ layer / JTE Termination
- 8-inch epi wafer / 96.5% yield
- Leakage current reaches ~1 μA at 1000V in LGAD
- Charge collection reaches ~12× that of the PIN @ 700V;
- Time resolution of SICAR3 ~55 ps (d~1.4mm) @ 400V

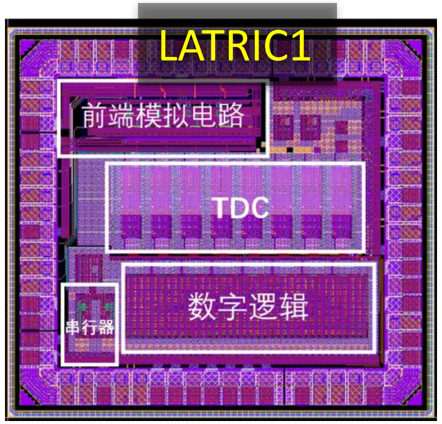


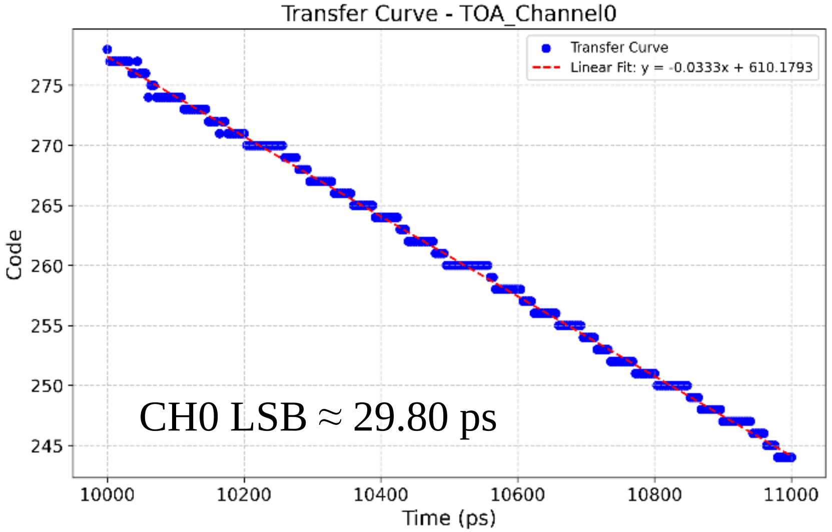


SiC LGAD Detector System

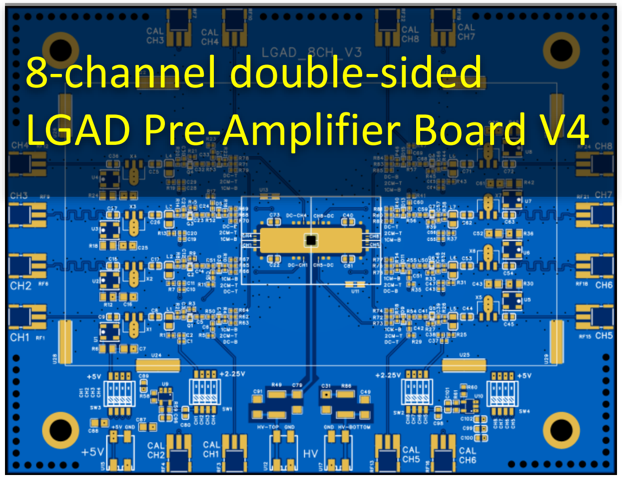
- Synergy with ASIC development for Si-LGAD (LATRIC)
  - LATRIC1 (Oct 2025): 8 channels, LSB ~30 ps

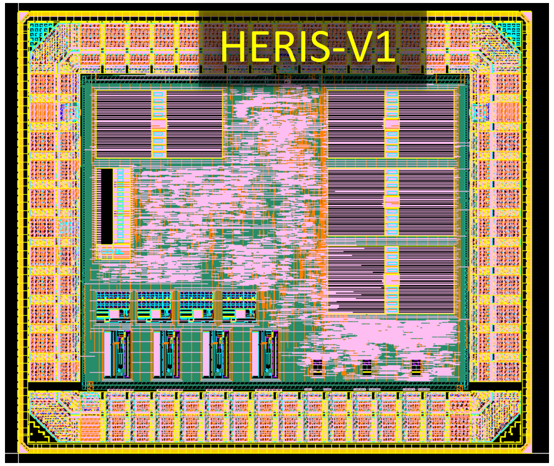






- Data Acquisition Framework

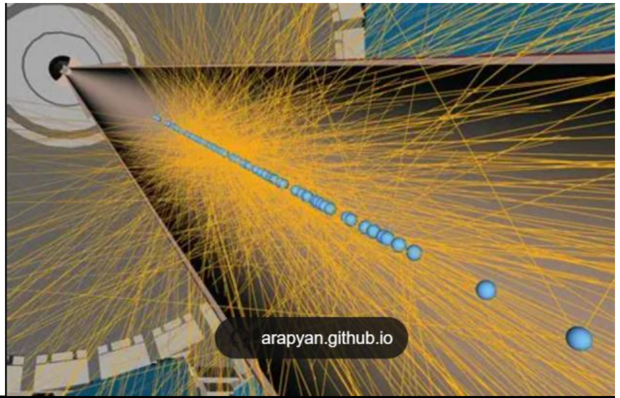


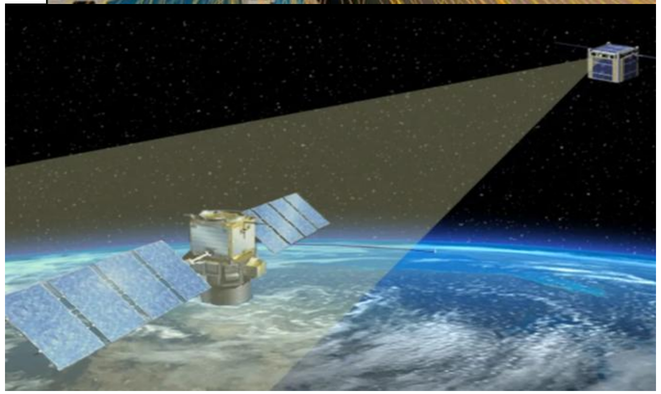


- System on Chip (SoP) based on RISC-V
- Received in Oct 2025
- 55 nm Process
- Working frequency: 50 MHz
- Area: 1.020 x 1.196 mm
- Voltage: 1.2 V

Beyond H-B Fusion – Broader Applications

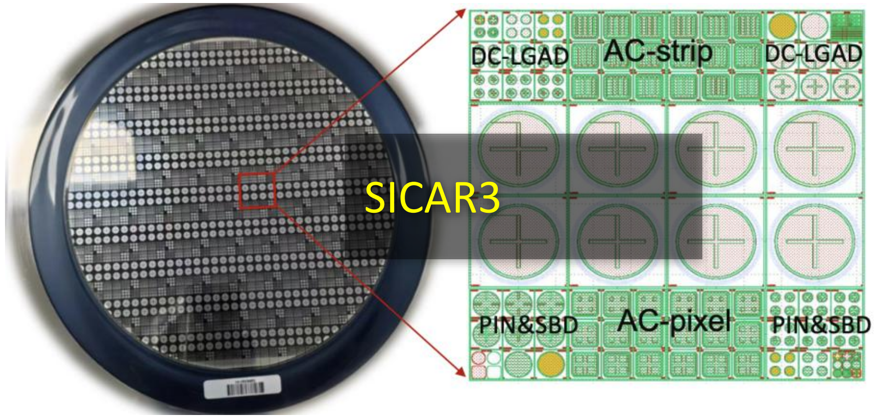
- **High Energy Physics (HEP)**:
  - 4D tracking in future colliders under extreme fluence
- **Space-Borne Radiation Monitors**:
  - SiC hardness ensures long satellite missions
- **Positron Emission Tomography (PET)**:
  - Fast timing for Time-of-Flight improves image quality

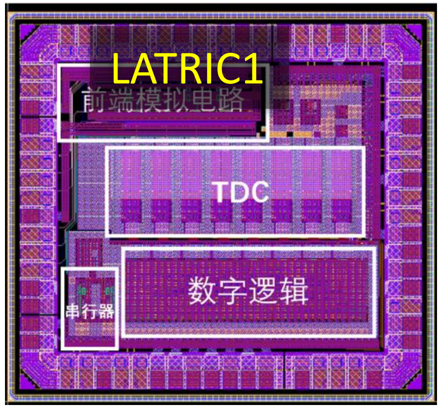


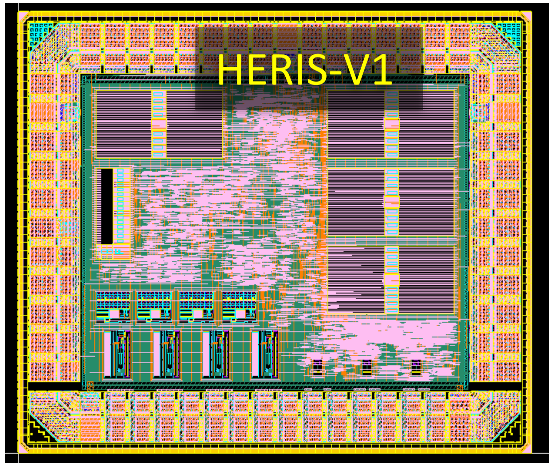


Summary

- H-B fusion diagnostics require detectors beyond silicon capability
- **Pixelated SiC LGAD + ASIC + DAQ** system is the proposed solution
- Delivers high timing precision, SNR, and radiation tolerance
- Enables reliable α-spectroscopy in extreme plasmas



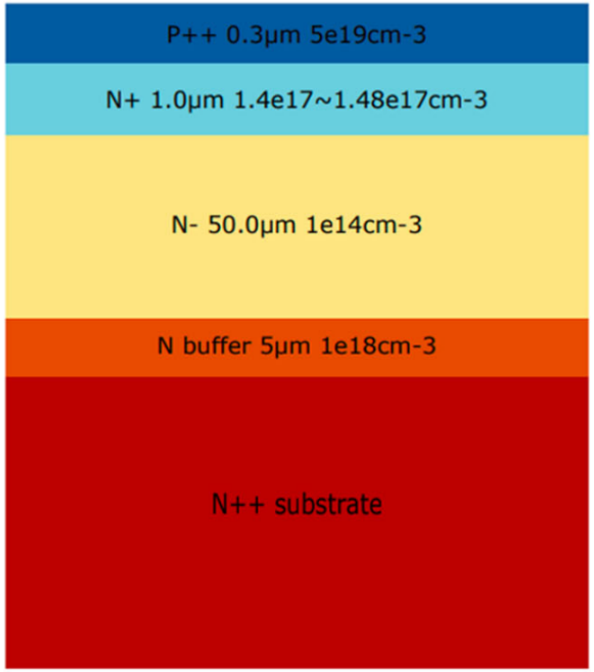


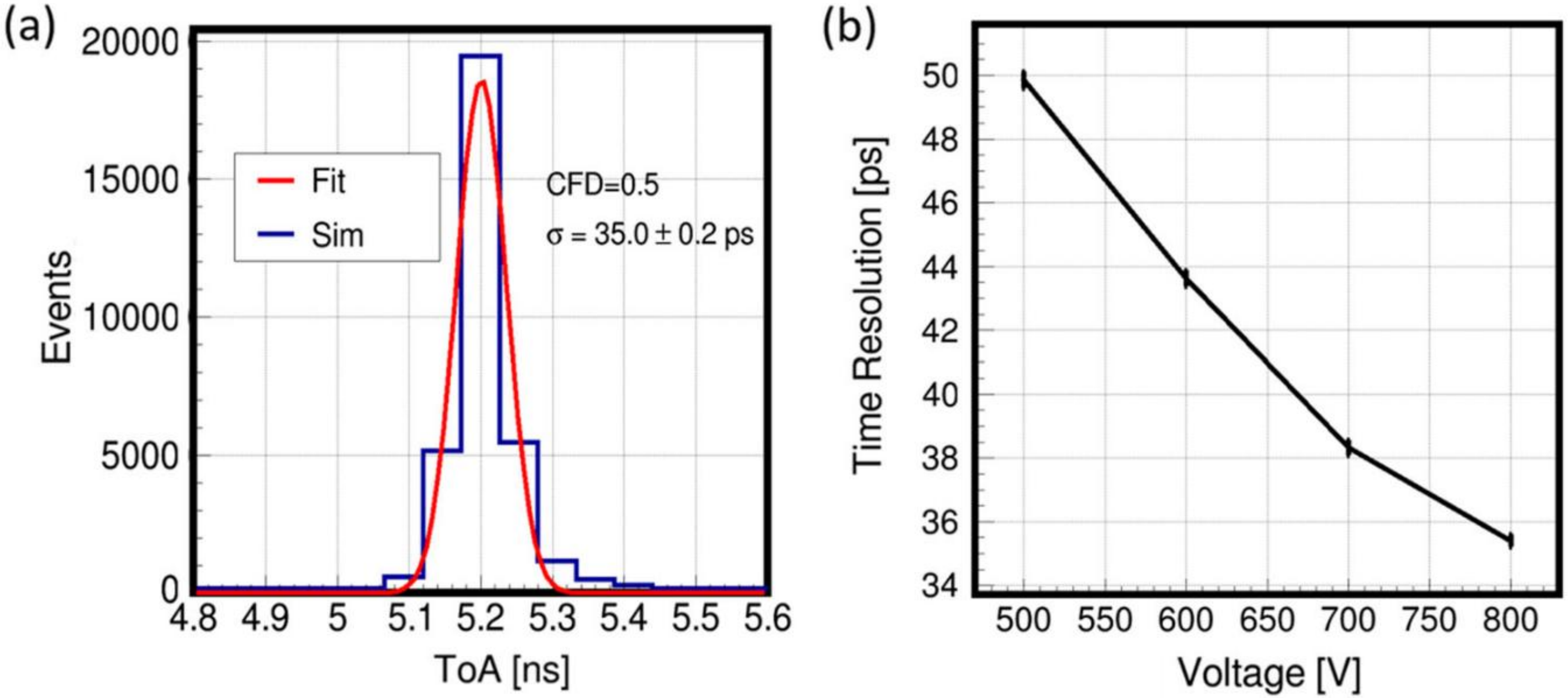


Welcome collaboration from HB fusion community!

Backup

Design of 4H-SiC-LGAD – SICAR1





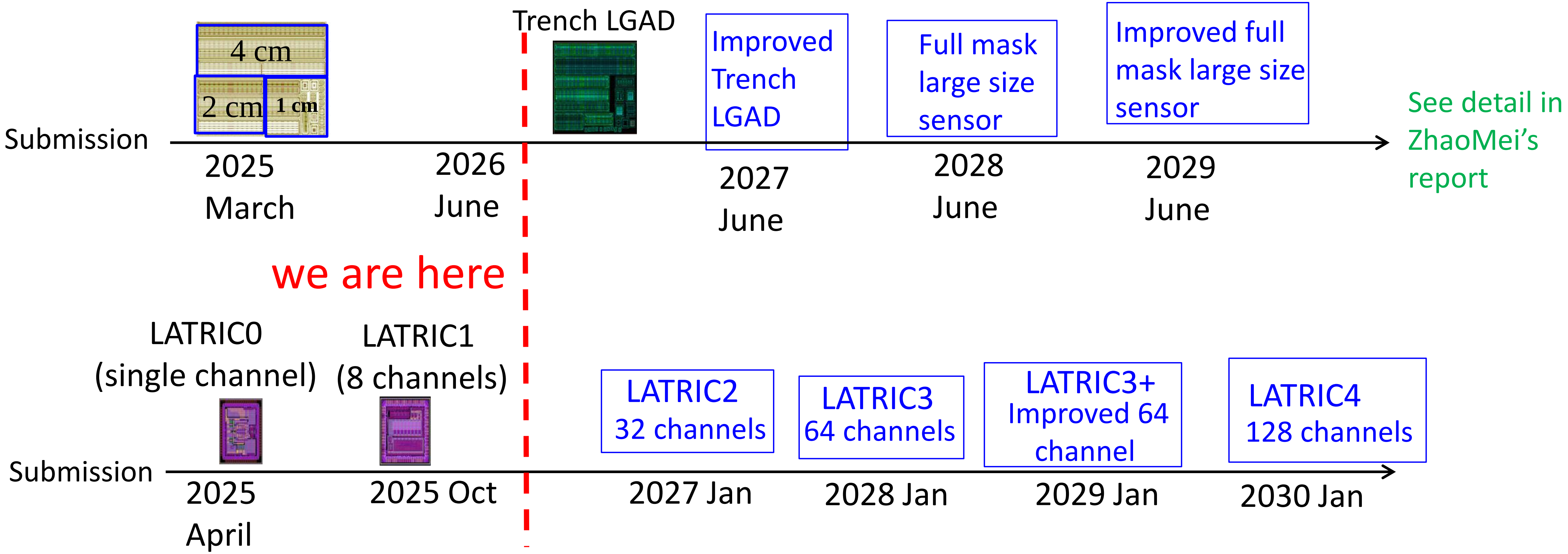
- Simulation with open-source software RASER
- Can reach 35ps @800V

https://pypi.org/project/raser/

https://doi.org/10.1007/s41605-023-00431-y

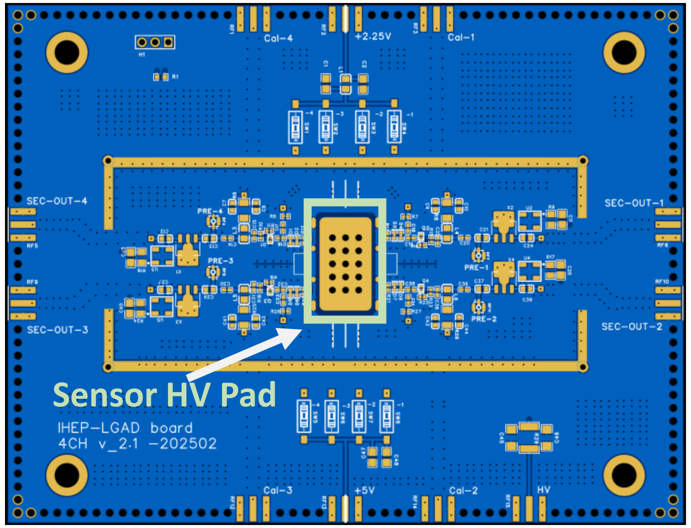
IHEP's AC-LGAD and LATRIC R&D Plan

- LGAD sensors are evolving toward improved process, larger size, higher performance, and lower power consumption



- LGAD readout ASIC, LATRIC, is being developed towards multi-channels

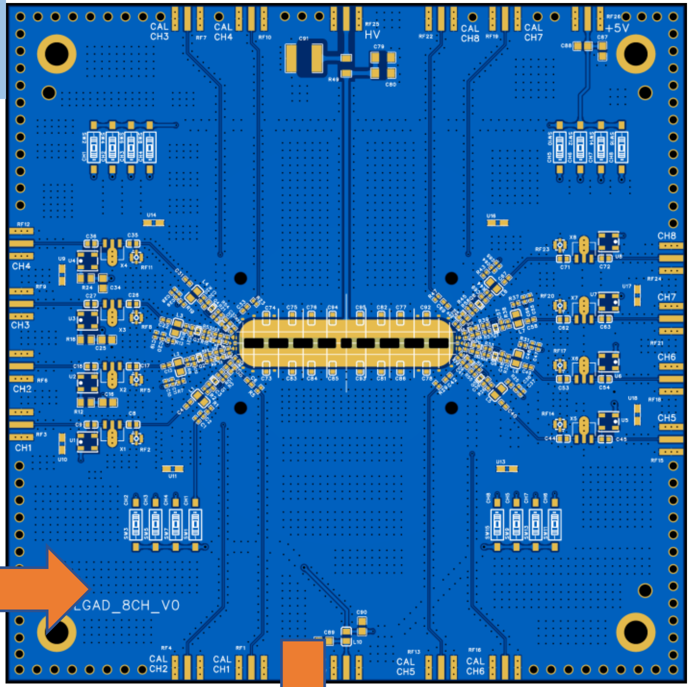
AC-LGAD Pre-Amplifier Board Optimization



10cm x 13cm

V1: 4-Channel LGAD Pre-Amplifier Board:

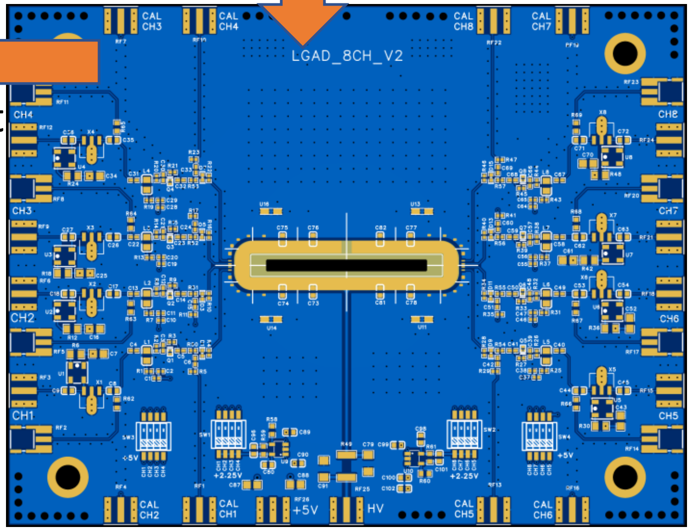
- Provides high-voltage bias for LGAD sensors.
- Four signal readout channels
- ~100× amplification per channel



13cm x 13cm

V2: 8-Channel LGAD Pre-Amplifier Board:

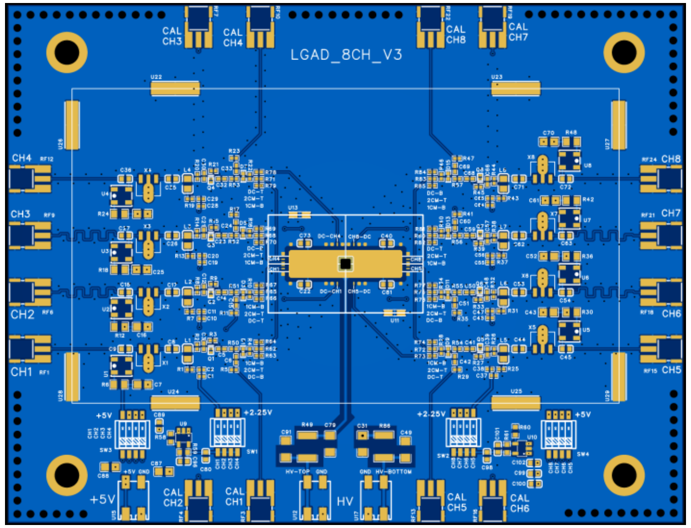
- **Increased number of channels**
- **Extended high-voltage pads** for better compatibility with strip sensors
- Optimized HV pad geometry with cut-outs to improve particle detection efficiency



10cm x 13cm

V3: 8-Channel LGAD Pre-Amplifier Board

- Reduced board size for better integration
- Simplified power connectors for easier cabling
- **Optimized HV pad cut-out geometry** to further enhance particle detection efficiency



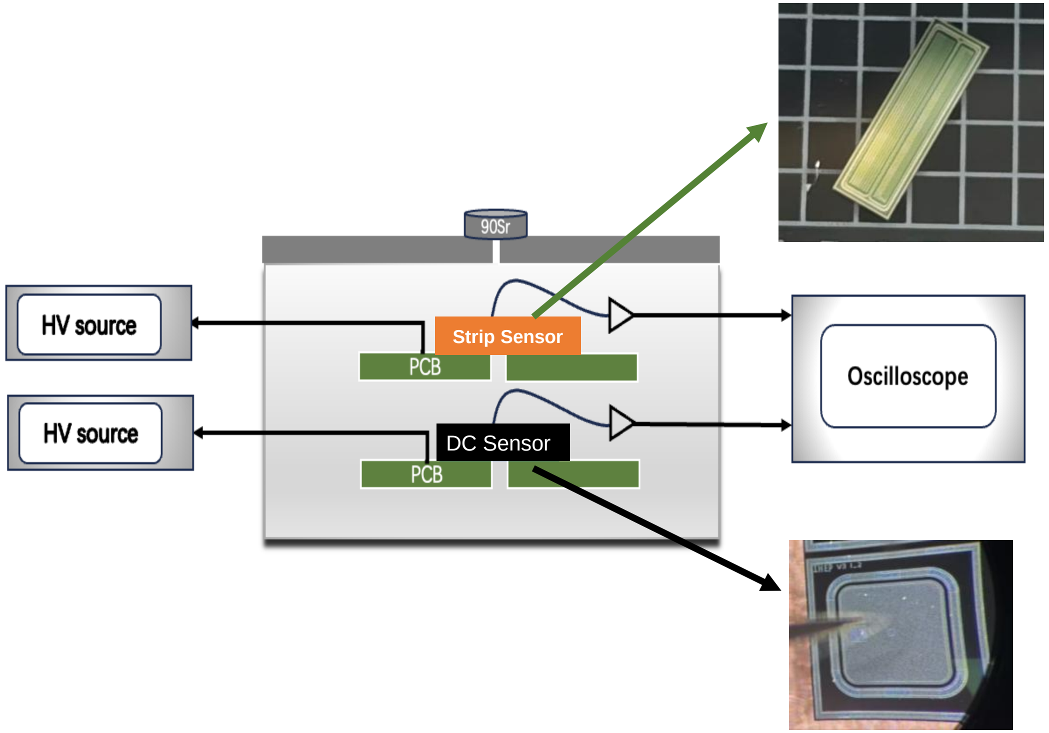
10cm x 13cm

V4: 8-Channel Double-Sided LGAD Pre-Amplifier Board:

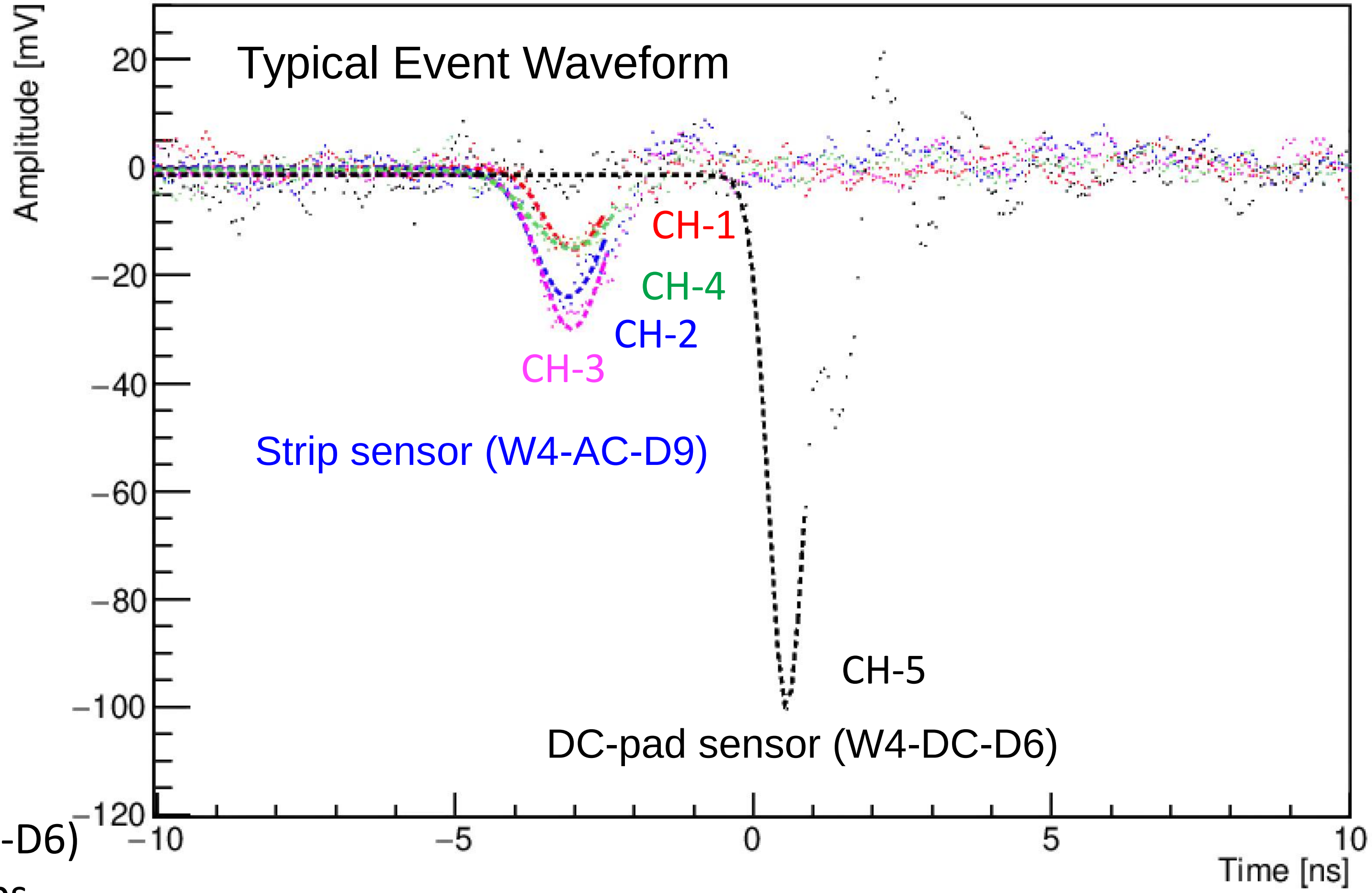
- Double-sided to support different LGAD types (pixel and strip)
- Optimized routing with equal-length traces for all 8 channels
- Reduced board thickness to ~5 mm

Sensor Characterization with a ^{90}Sr Beta Source

BUT Strip sensor (W4-AC-D9, 2 cm)

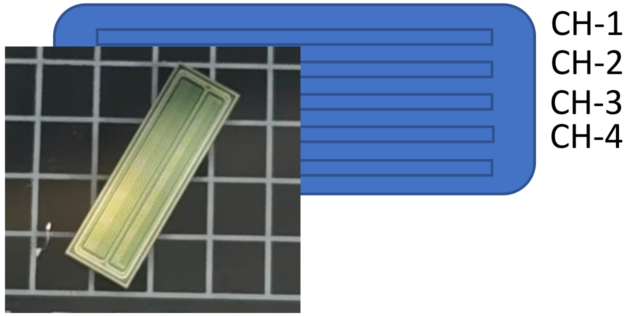


DC-pad sensor (W4-DC-D6)
Time resolution 36 ps

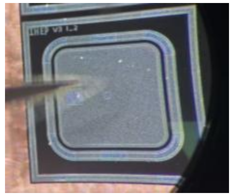


Strip Sensor Timing Resolution (β-Source Test)

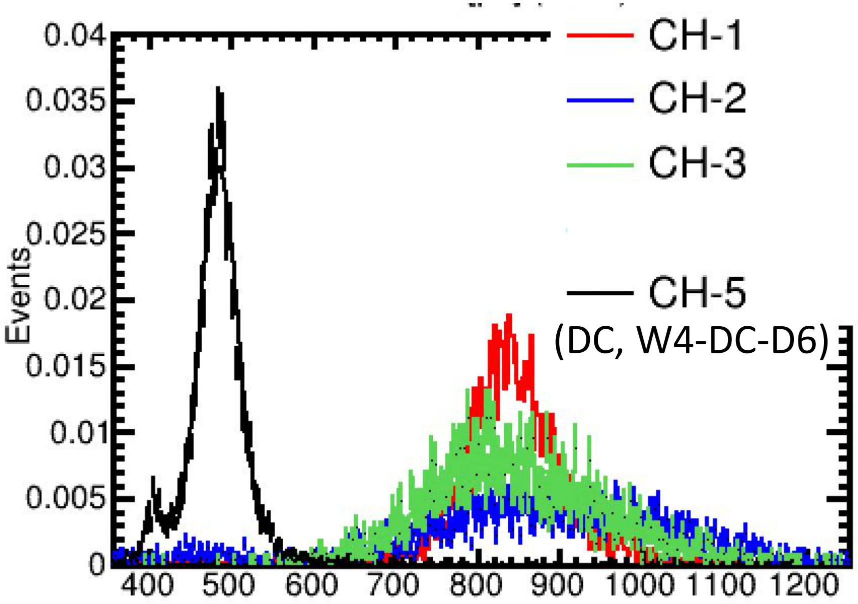
DUT sensor (AC-LGAD)



Ref sensor (DC)

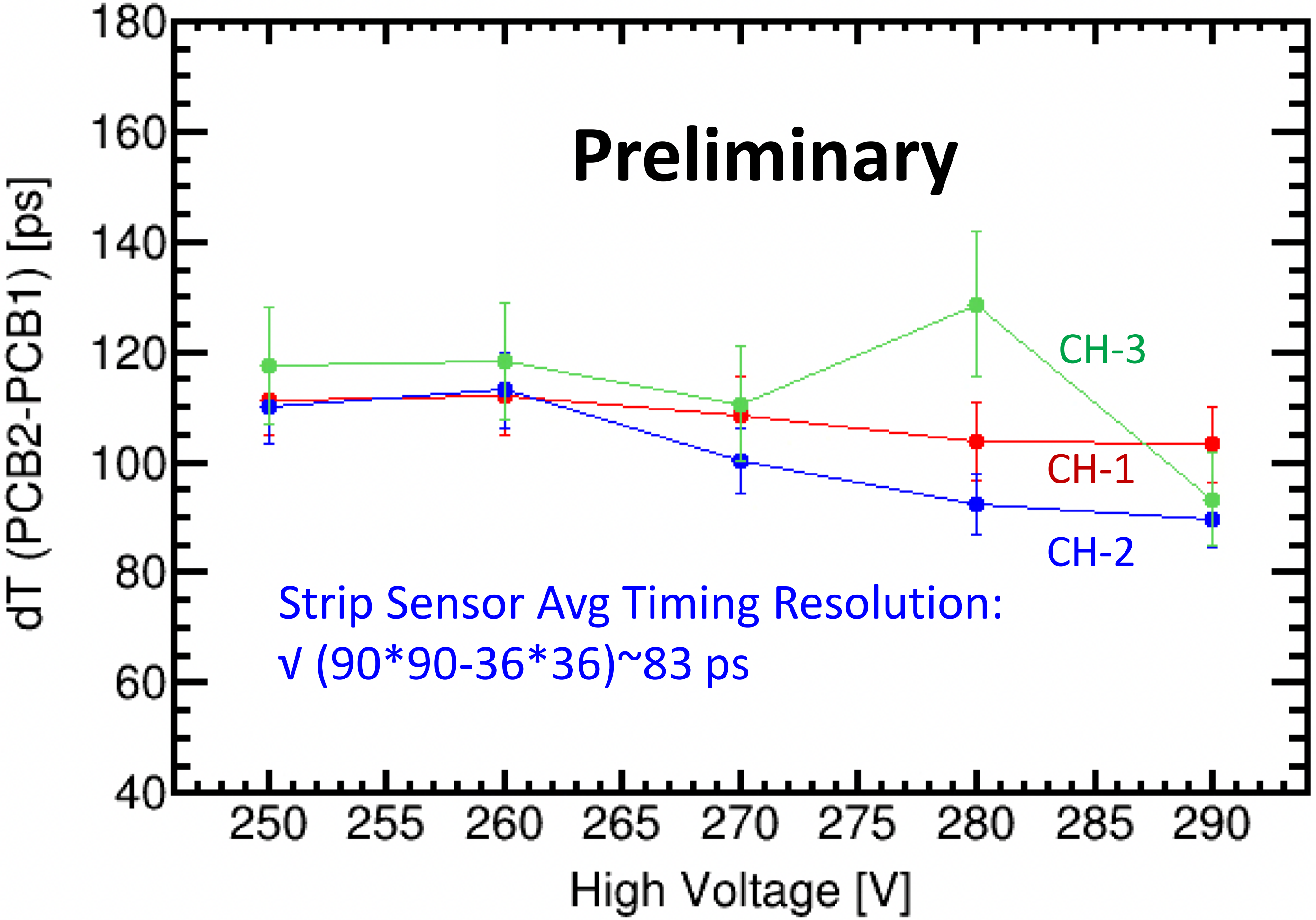


CH-5



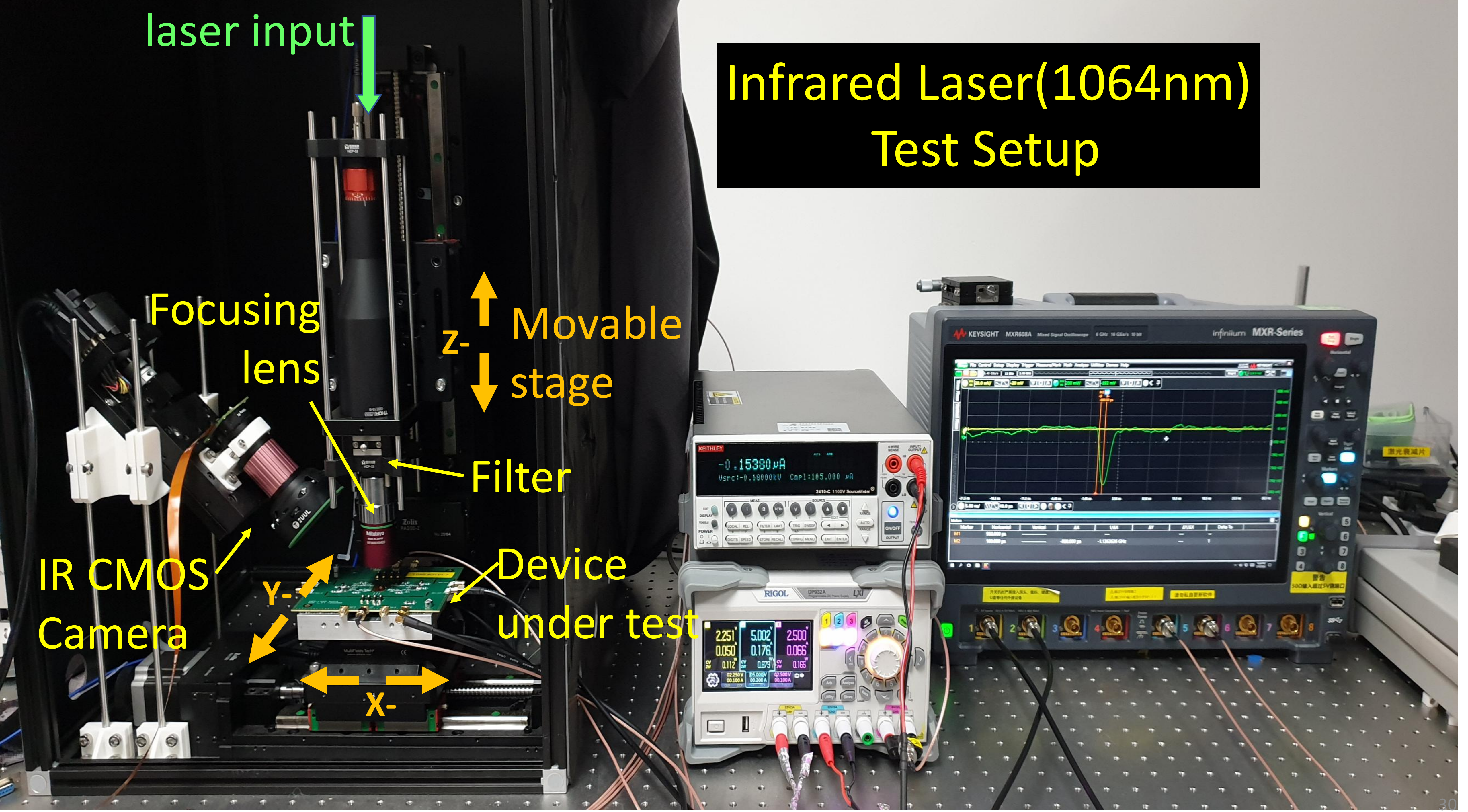
Rise time [ps]

W4-AC-D9, 2 cm, pitch 100um electrode width 50um

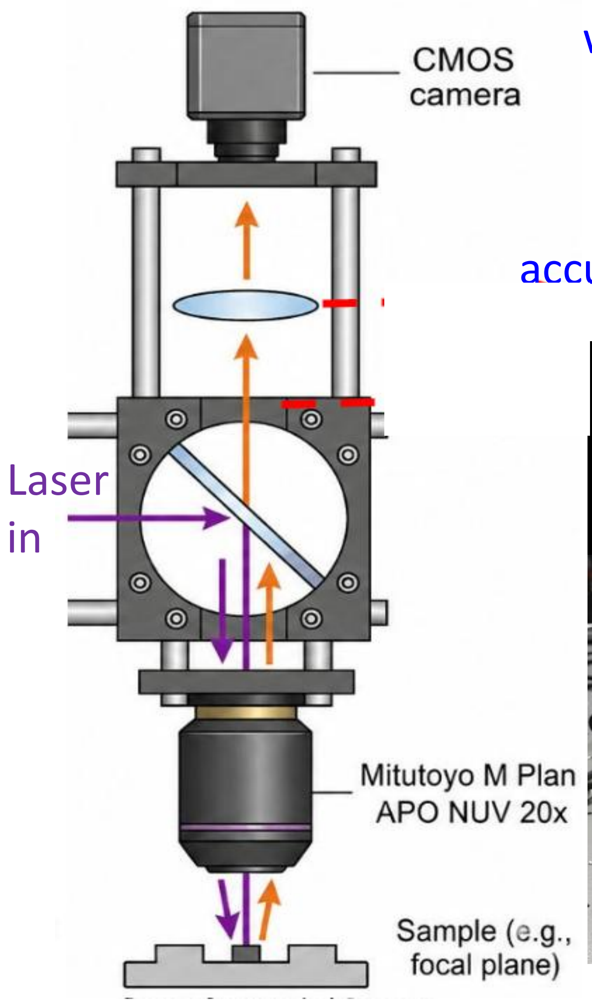


The signal rise time of strip sensors is substantially longer than that of pad sensors.

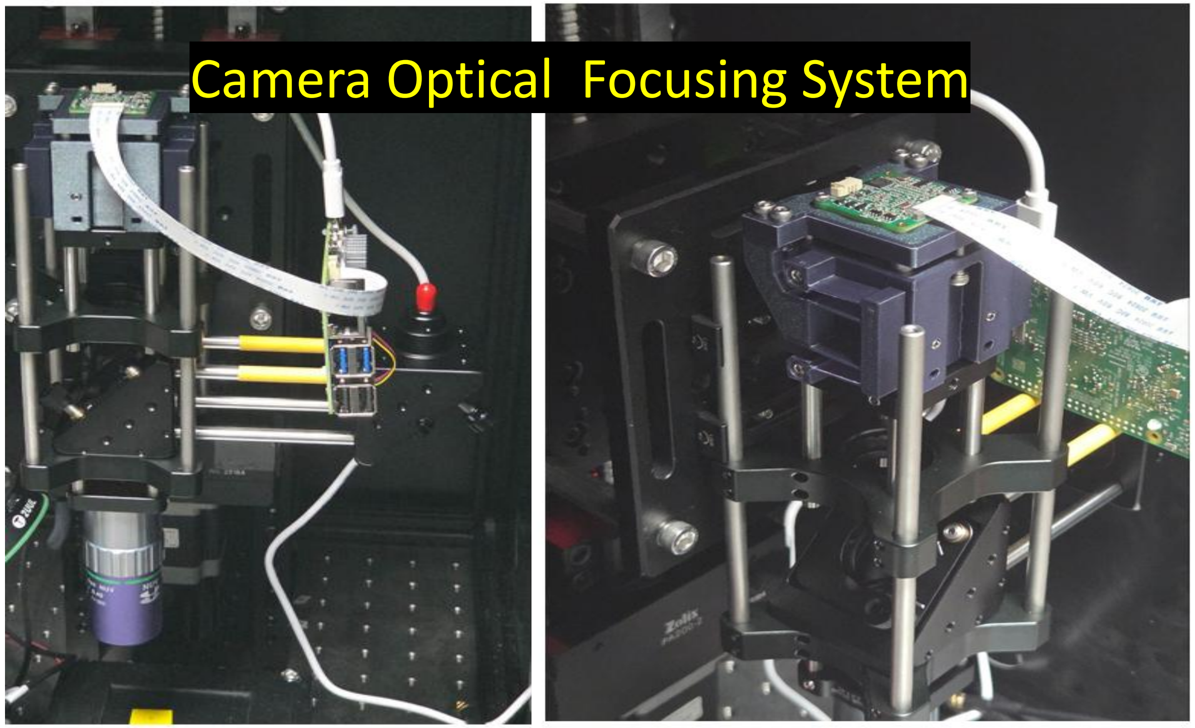
The strip sensor (2cm, pitch 100um electrode width 50um) achieved a timing resolution of ~83 ps.


Infrared Laser(1064nm)
Test Setup
laser input
Focusing
lens
Z-
Movable
stage
Filter
IR CMOS
Camera
Y-
X-
Device
under test
KEITHLEY
-0.15380 μA
2410-C 1100V SourceMeter
RIGOL
DP832A
KEYSIGHT
MXR608A
Infiniium MXR-Series

In addition to the infrared test system, a customized **UV laser test platform for SiC sensor** has been developed. Both Si and SiC sensor development activities share a unified R&D framework with common test infrastructure, front-end electronics, and system integration resources.



Stepper motor with magnetic encoder feedback: positioning accuracy <0.1 μm



- 355 nm UV laser
- Repetition rate: 1–10 Hz
- Pulse width: ~10 ns