IJCLab/IN2P3

KEK

Osaka

Tsukuba HEP

2026 Joint workshop of TYL/FJPPN and FKPPN

Design and characterization of very finely pixelated AC-LGAD sensors and readout electronics

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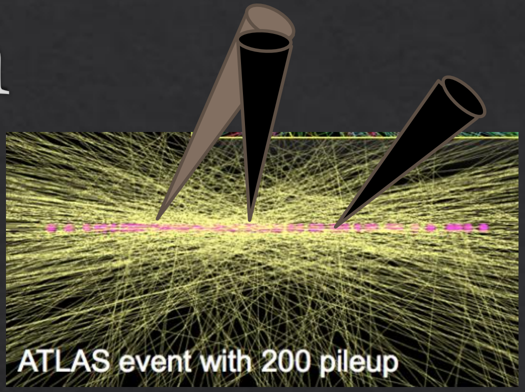
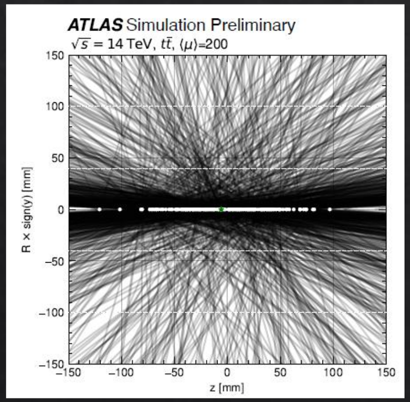
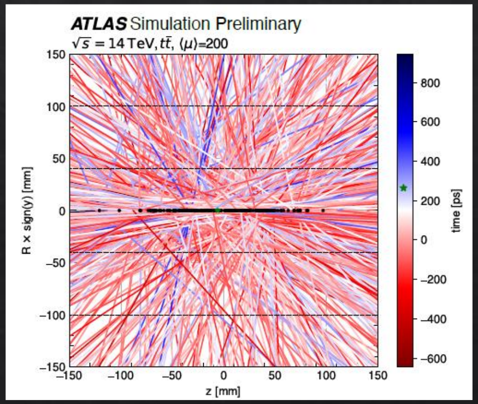
Impact for tracker with time resolution



- **Collider experiment gets high energy and high intensity.**
  →Future Tracking detector should have timing information for all hits!
- **Tentative Requirement**
  - **30ps timing resolution &~o(10)um spatial resolution**
  - **(hadron collider) ~o(10^{16})n_{eq}/cm^2 radiation tolerance**

4D tracking !





Solve pileup hits in an event

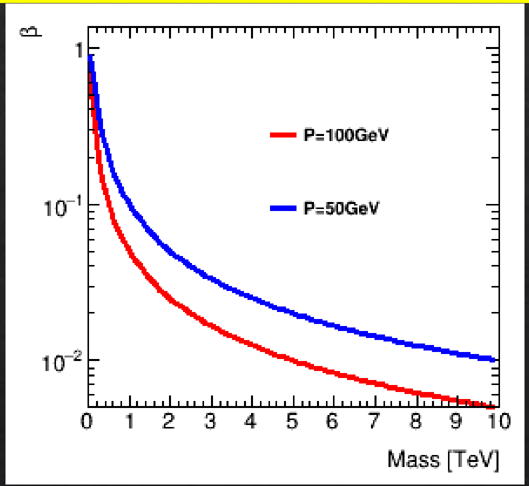
Particle identification

$\beta = 1$ $\beta = 0.95$

150ps difference at R=1m

K+ π+ separation

Mass spectrum for new particle

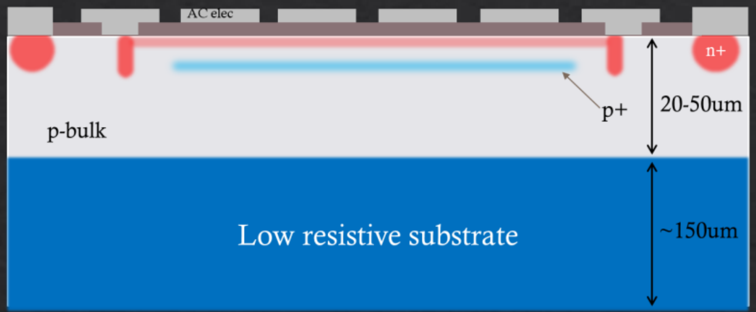


β measurement to obtain mass

e.g. Mass measurement for Long lived chargeno

History of timing silicon detector : AC-LGAD

- **We didn't have o(10)ps timing capability MIP particle detector 10 years ago.**
- World wide LGAD detector R&D started around 2015
  - **Low Gain Avalanche Diode (LGAD) detector**
  - Hamamatsu Photonics K.K. (HPK) can produce LGAD detector in Japan!



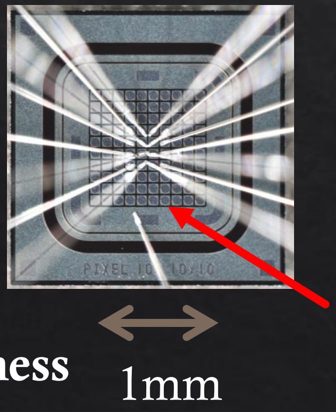
First prototype in 2015

remarkable improvement

- **Spatial resolution**
- **Timing resolution**
- **Understanding Radiation hardness**

Recent prototype (in 2022)

AC-LGAD pixelated detector



20ps timing resolution achieved

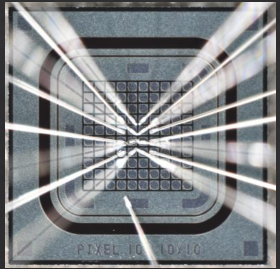
Pixel size :

100μm x 100μm

(50μm x 50μm)

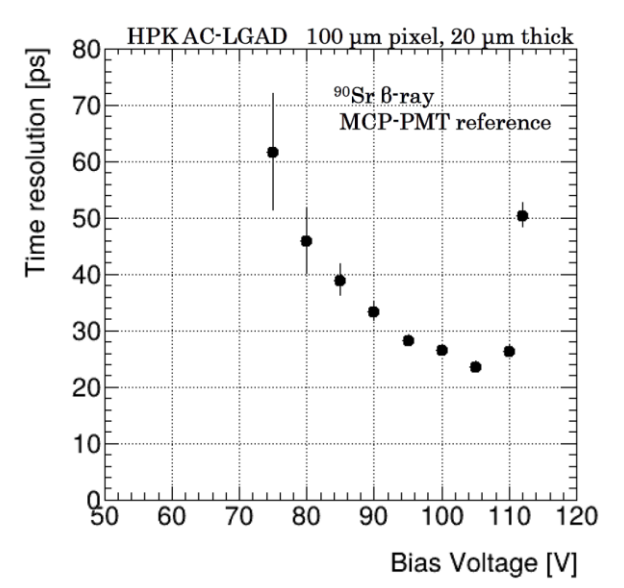
HSTD14(arXiv)

Time resolution measurement



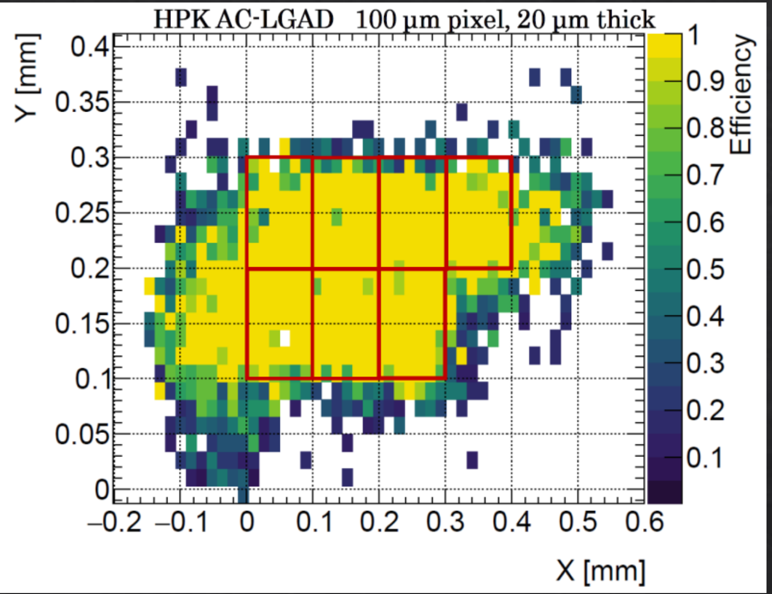
AC-LGAD with 100um x 100um pitch pixel
Measured by ^{90}Sr and 3 GeV electron beam.

■ Timing resolution (^{90}Sr beta-ray)



$$\sigma_t = 25.3 \pm 0.1 \text{ ps}$$

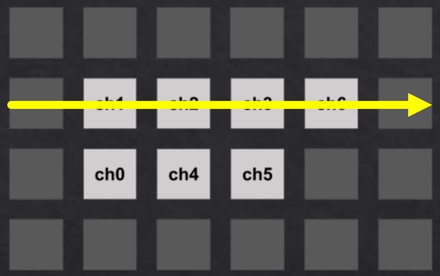
■ Efficiency Map

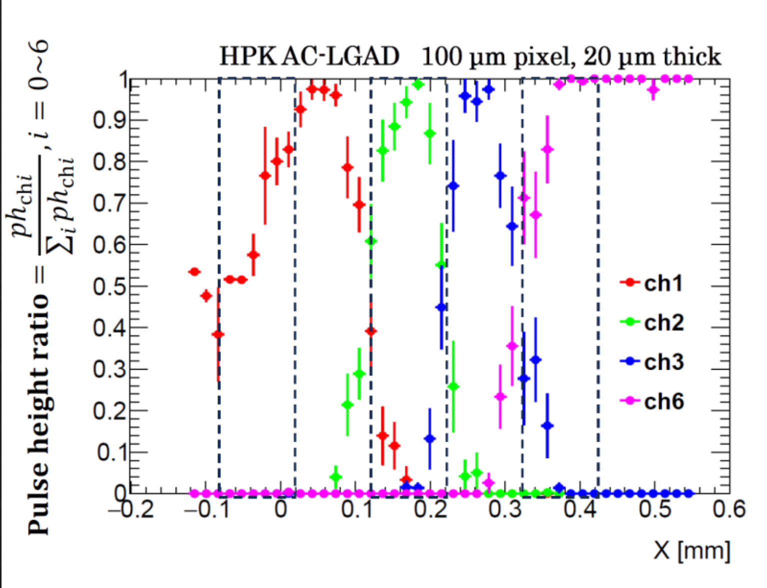


Spatial resolution

	$\sigma_{residual}$	σ_{track}	$\sigma_{detector}$
X	59.3±1.4 μm	54.3±1.4 μm	**23.8±4.7 μm**
Y	58.2±1.3 μm	52.6±1.2 μm	**24.9±4.0 μm**

■ Crosstalk feature





Achieved ~25ps timing resolution for 100um x 100um AC-LGAD pixel sensors

Concept of our project (RD_40)

- **World-leading sensor development in Japan**
  - **Pixelated AC-LGAD sensors developed with HPK**
    - Demonstrated **25 ps time resolution**
    - Achieved with **100 μm × 100 μm pixel electrodes**
  - A unique result enabling fine segmentation and precision timing
- **Key challenges toward detector applications**
  - **Dedicated readout ASIC for pixelated AC-LGAD**
  - **Optimization of radiation tolerance**
  - Sensor–ASIC integration and system-level performance
  - Validation under realistic experimental conditions

- **Complementary expertise from France and Japan**
  - **France: OMEGA / IJCLab**
    - **Strong ASIC development experience**
    - Contributions to **ATLAS HGTD** and **ePIC Roman pots/TOF**
  - **Japan**
    - **AC-LGAD sensor design and development**
    - Sensor characterization and beam/radiation tests
    - Close collaboration with HPK
- **Productive collaboration framework**
  - Mutual use of facilities and test infrastructures
  - Exchange of researchers and students
  - Sharing of design ideas and technical feedback
  - Focused discussions based on complementary expertise

Goal

Advance pixelated AC-LGAD from a world-leading prototype toward a realistic detector technology for future experiments

Readout ASIC development

- HL-LHC upgrade : ATLAS High Granular Timing Detector (HGTD)
  - Insert 2 disks of HGTD detector between Inner Tracker and Calorimeter.
  - ALTIROC ASIC : Targeting a 50ps time resolution
- ePIC detector : Roman Pots / TOF detectors at Electron Ion Collider (EIC)
  - EICROC ASIC : Targeting 500um sq pixel with 20ps jitter (<2mW/ch)

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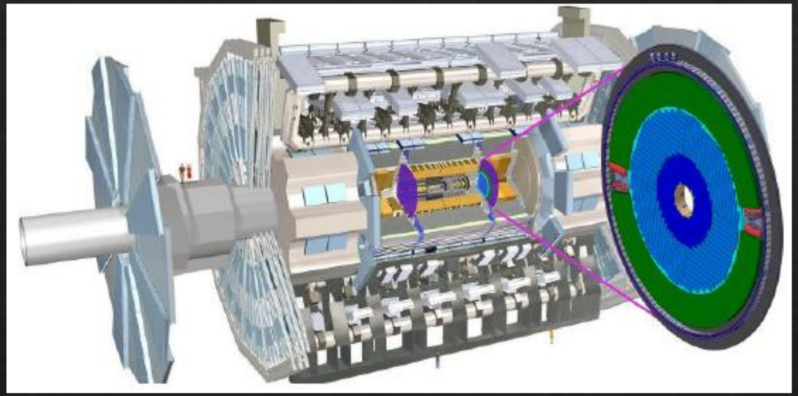
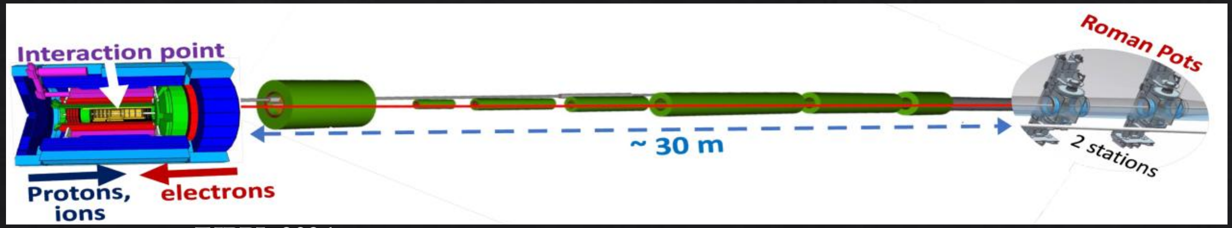
HGTD detector



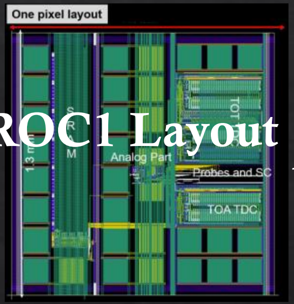
ePIC detector



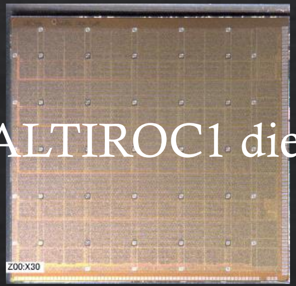
Plan : Application this technology to AC-LGAD pixel readout ASIC

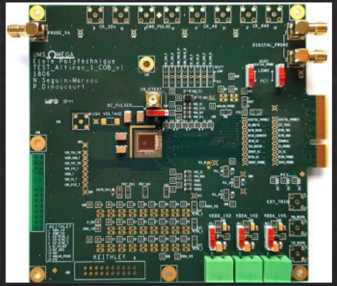
ALTIROC1 ASIC

ALTIROC1 Layout

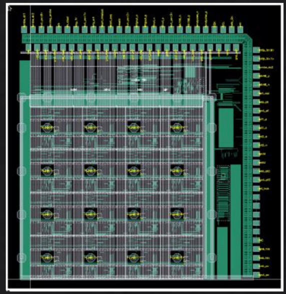


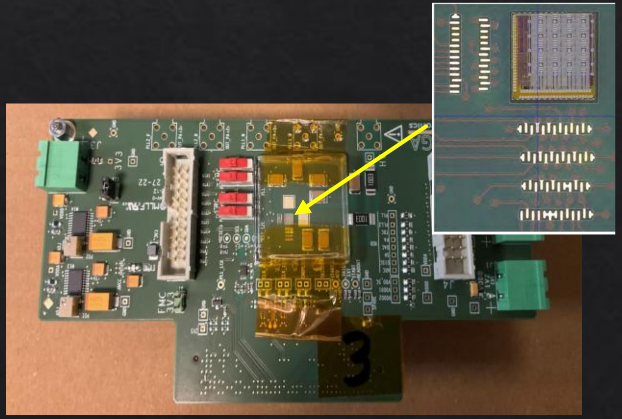
ALTIROC1 die



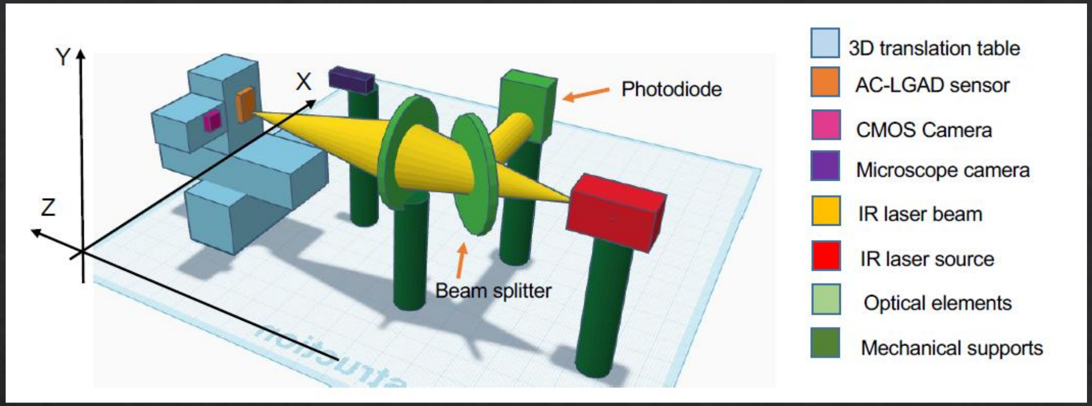


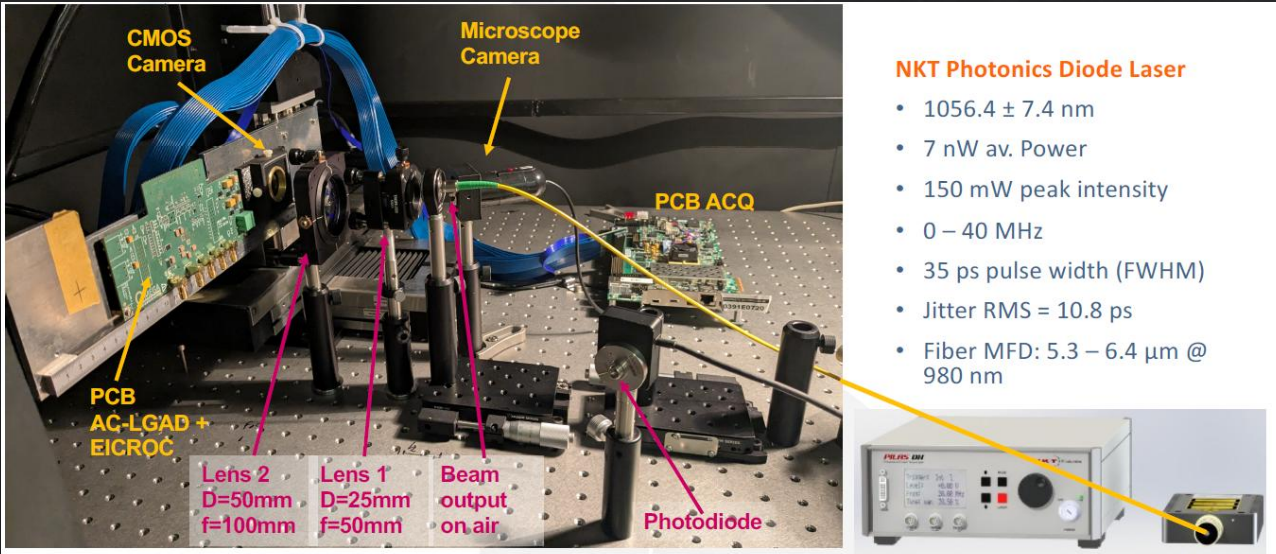
EICROC ASIC



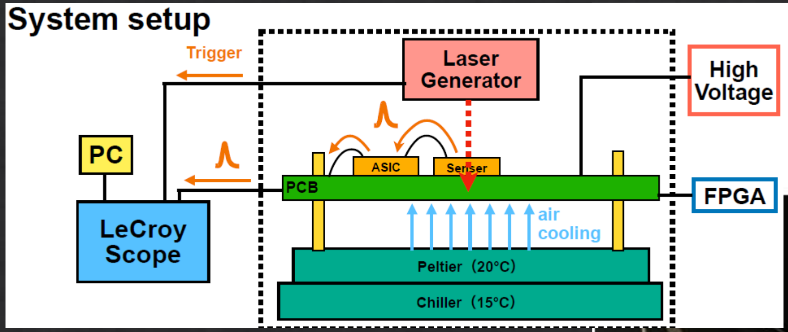


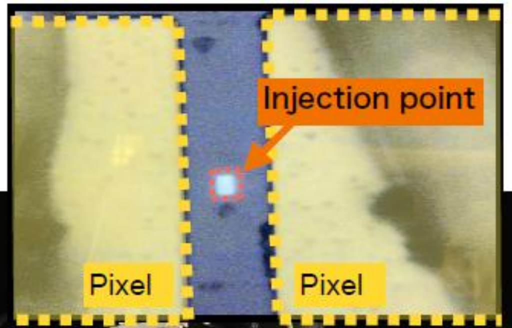
Laser testbench in France and Japan



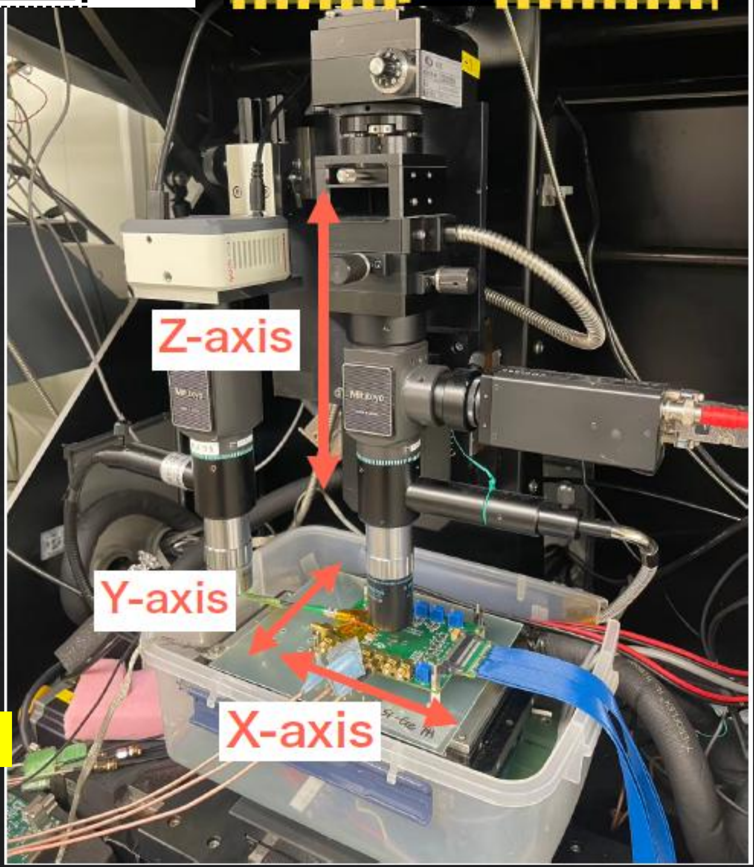


<8um spot size





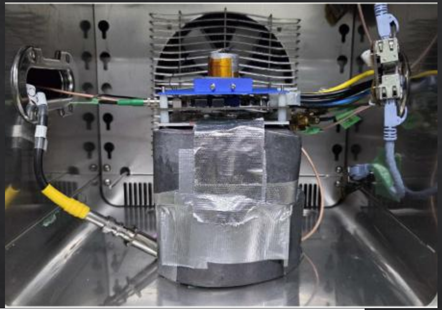
Infrared pulse laser :
Wavelength is 1064 nm.
2um spot size

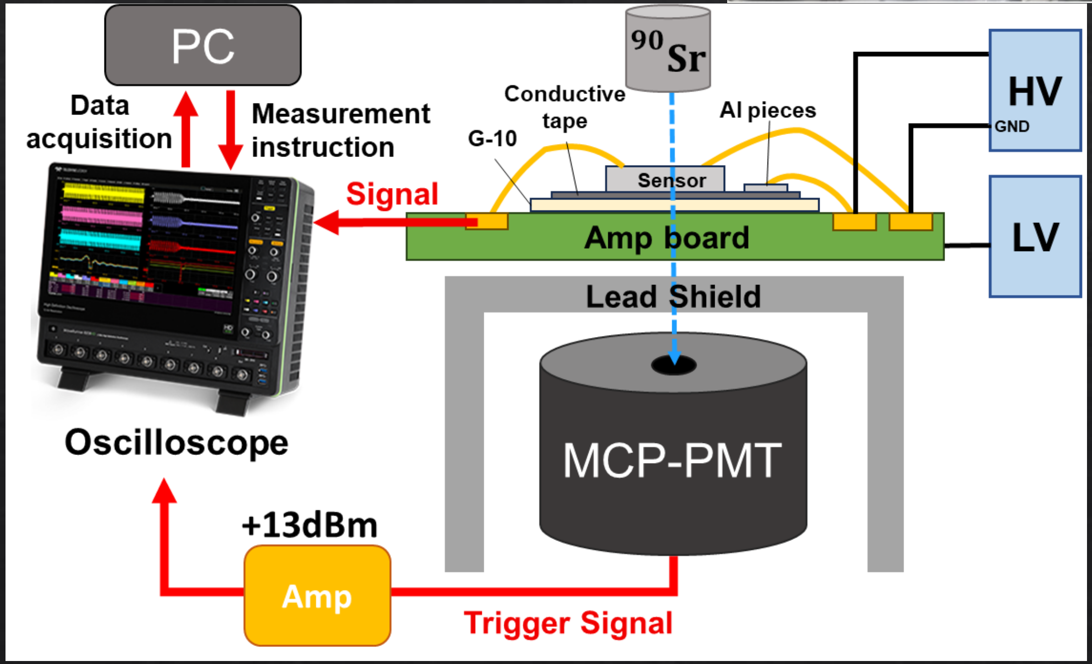


Complementary laser testbenches in France and Japan enable cross-checks, experience sharing, and optimized use of each setup depending on the sensor characterization needs.

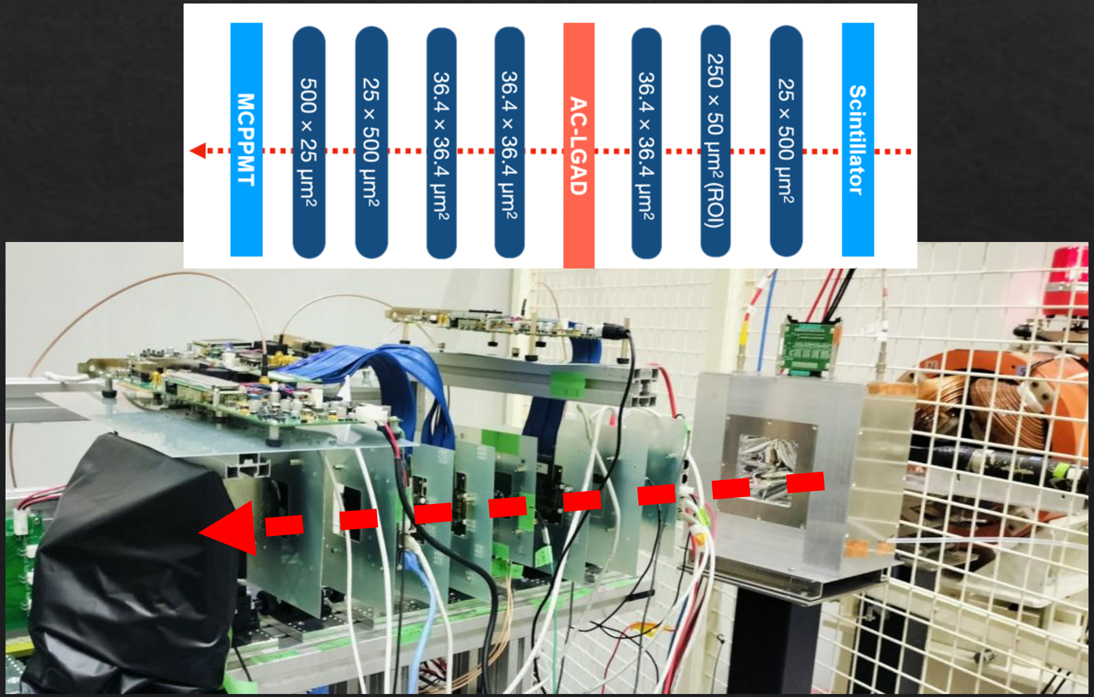
AC-LGADpix Timing resolution measurement

- ⟐ ^{90}Sr beta-ray measurement
  - ⟐ MCPPMT as timing reference (<10ps)





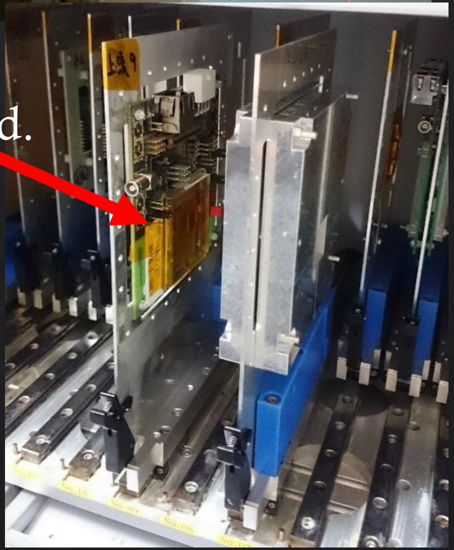
- ⟐ Testbeam measurement at KEK AR
  - ⟐ 3-5GeV electron beam
    - ⟐ Non-negligible multiple scattering
  - ⟐ FE-I4 + MALTA based Telescope
  - ⟐ MCPPMT as timing reference



RARiS : Irradiation Facility in Japan

- RARiS@Tohoku Univ.
  - An irradiation facility with 70MeV proton beam (~1μA beam current).
    - 3-5 hours for $3 \times 10^{15} n_{eq}/cm^2$ irradiation with (600nA beam)
  - This allows 2-3 pixel modules with Al plate at the same time(3% E loss/module).
  - Operated at -15^{o}C temprature with dry N_2 gas.
  - Scanning over full pixel range during irradiation.
  - Historically French prototype samples have been tested at CYRIC as a collaborative work.
- Facility for AC-LGAD development
  - Using this facility by sensor development very often (KEK)
  - In future, ASIC and module radiation tolerance test will be performed to develop AC-LGAD module (i.e. with sensor and ASIC)

Feb 2017
LAL's Pixel Mod.
(Active Edge)



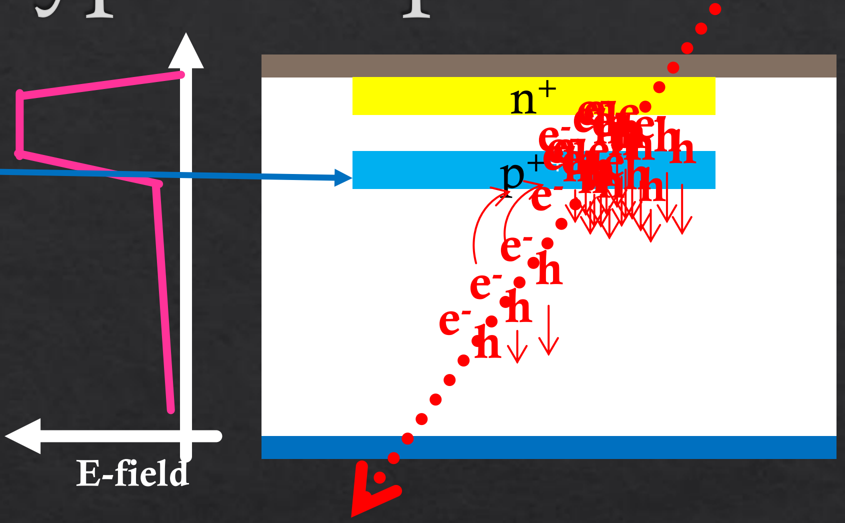
Rad hard paper (arXiv)

Rad hard evaluation and prototype samples

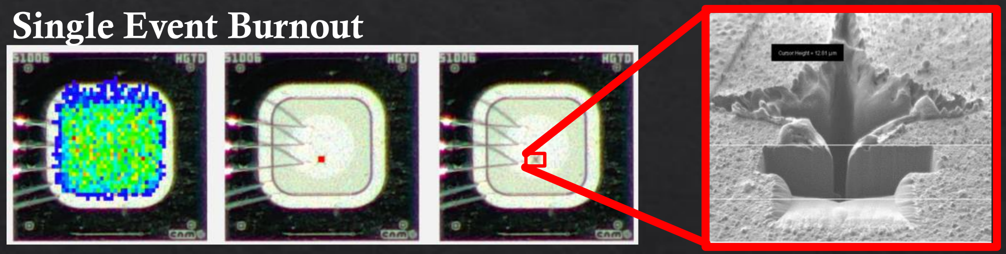
Radiation tolerance of gain layer

Electric field gets smaller by reducing p+ active impurity dope by acceptor removal. Higher Bias Voltage needed.

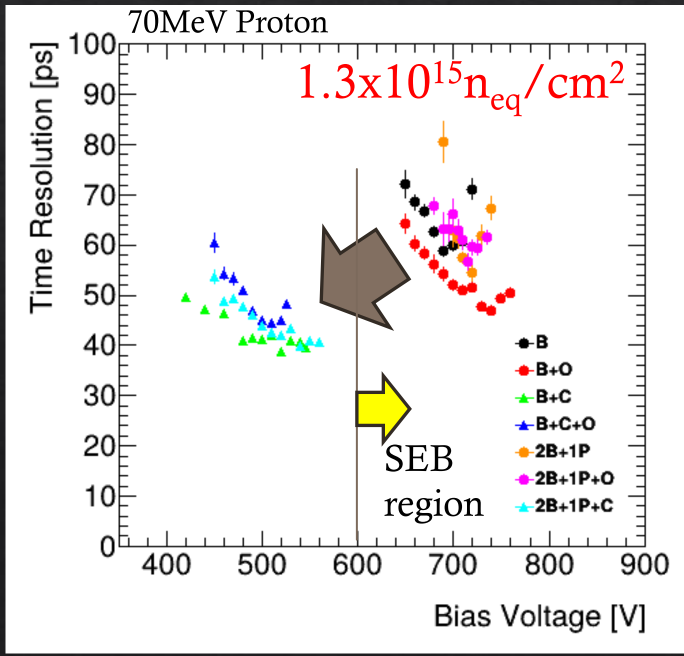
- ⟐ Single Event Burnout expected at 12V/um ave. e-field (600V for 50um)
- ⟐ Operation voltage increase (ΔV) should be smaller against fluence.



Single Event Burnout



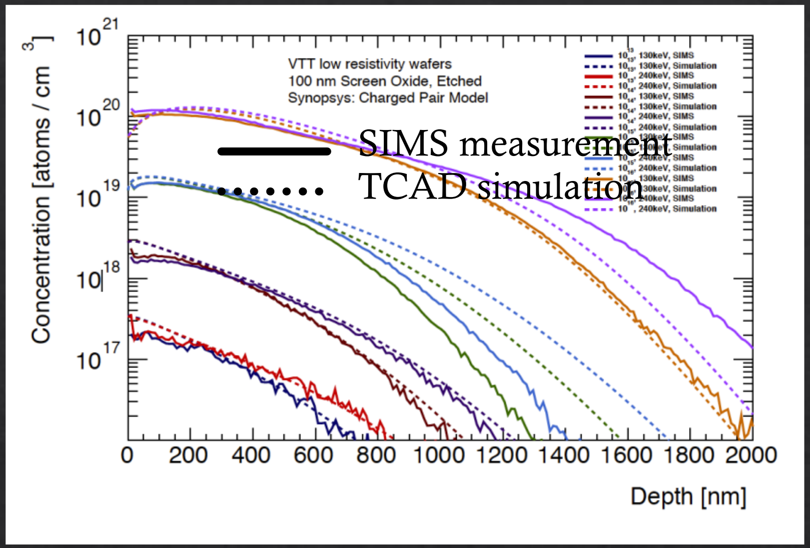
L.A. Beresford et. al.



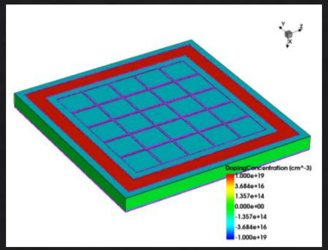
- Prototype samples
  - Oxygen enrich (B+O)
  - Carbon enrich(B+C)
  - Carbon and Oxygen enrich (B+O+C)
  - Boron + Phosphorus (2B+1P)
- Carbon enrich samples shows improvement
  - Reduction of Oxygen doesn’t help.
  - First observation of improvement of radiation tolerance in HPK LGAD samples

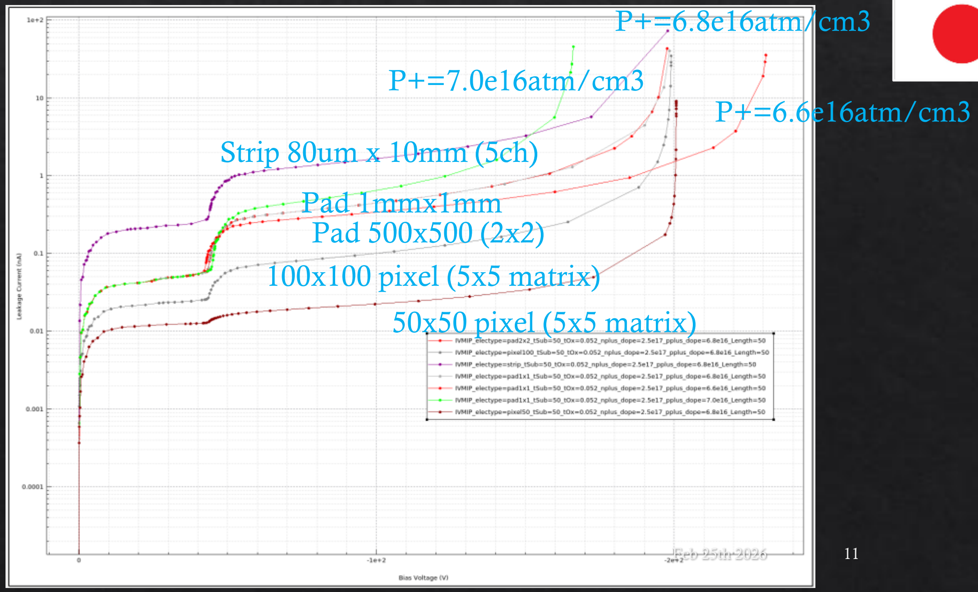
TCAD Simulation

- SILVACO TCAD simulation by France group
  - Process simulation:
    - Simulate implantation and resulting concentrations.
    - **Can compare to SIMS result.**
  - Device Simulation :
    - Simulate Electric field to understand the performance of silicon device.
    - Possible to perform simulation for charge correction of MIP signal.



- AC-LGAD simulation by Japan group
  - Device Simulation only :
    - Pixelated 3D device simulation
    - Avalanche break down has been demonstrated by different doping.
    - Heavily use this simulation for R&D





Exchange our experience and develop more advanced simulation framework.

MOSAIC facility at IJCLab

- **Unique facility for detector-material R&D**
  - Multidisciplinary ion-beam platform at **IJCLab / Université Paris-Saclay**
  - Ion implantation, irradiation, material modification, and surface/material analysis

Possible use of MOSAIC

We have started brainstorming how MOSAIC could contribute to AC-LGAD R&D.

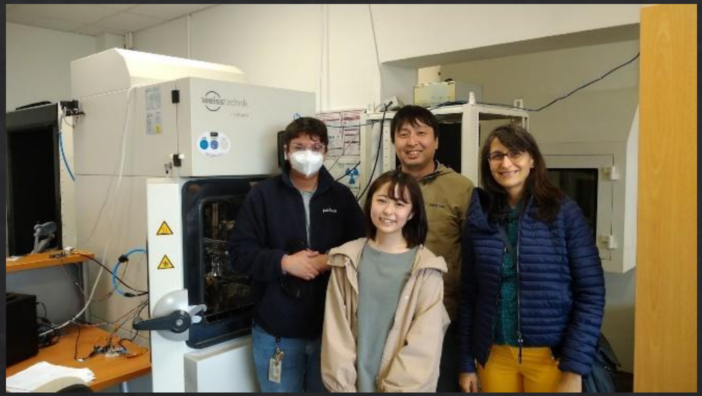
Possible directions:

- radiation-damage studies
- gain-layer degradation
- implant / process characterization
- link between material properties and sensor performance

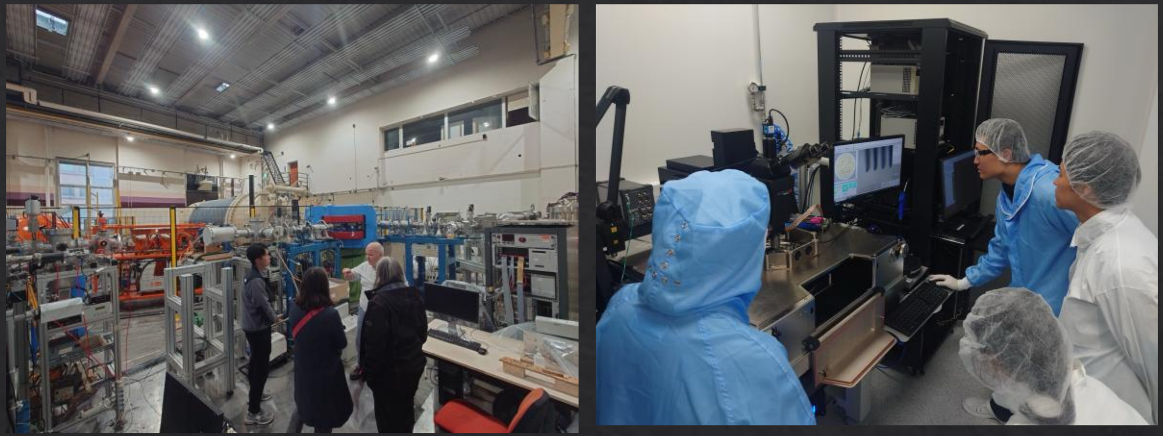
Other ideas can be explored through discussions with MOSAIC facility experts.

Exchange people and experience

Japanese team visiting IJCLab to discuss plan
and to exchange experience. 2022.9



Japanese team visiting IJCLab
also see MOSAIC 2024.11

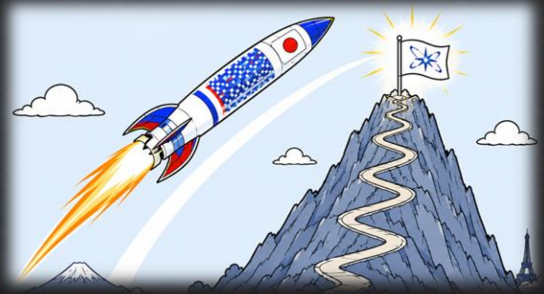


Japanese team visiting IJCLab and Omega lab
to learn and discuss electronics (ASIC) 2023.11

France team visiting KEK and Tateyama
to learn and discuss test facilitis 2025.11

Summary

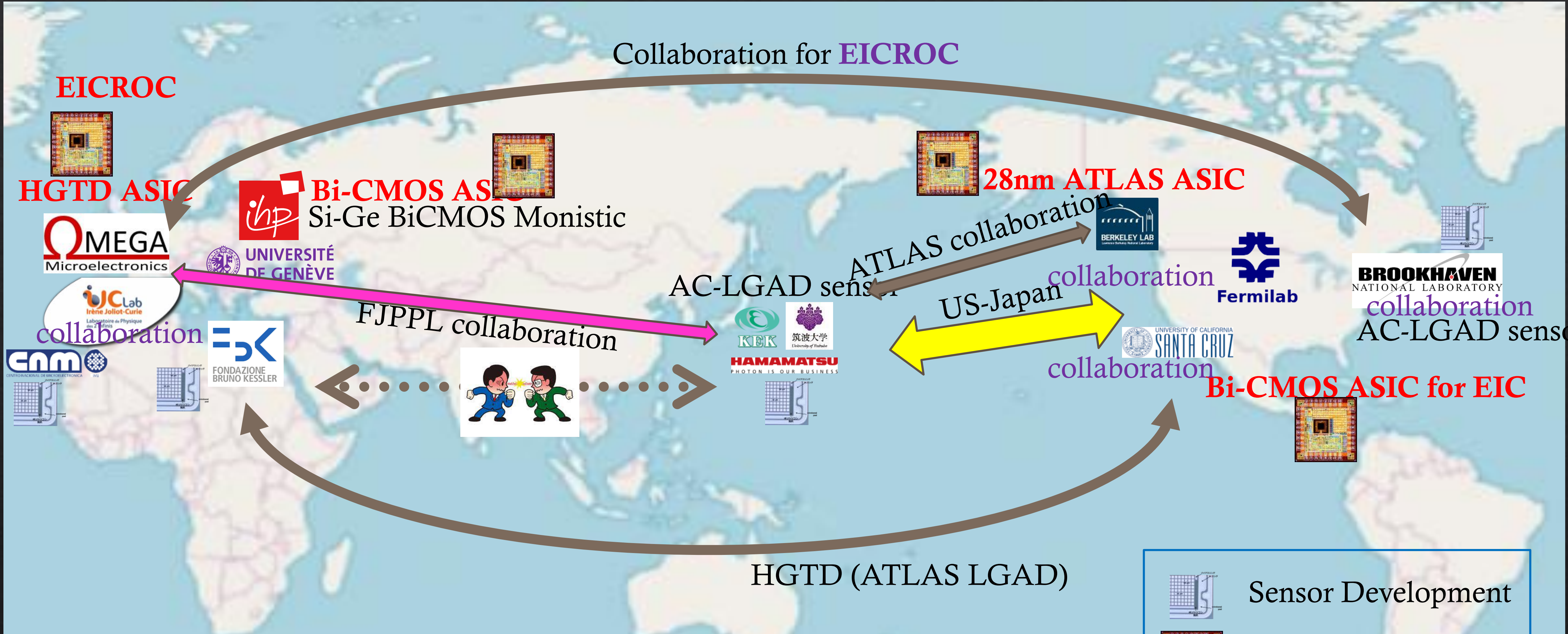
- **A complementary France–Japan R&D framework**
  - **Pixelated AC-LGADs** are a strong candidate for future 4D tracking detectors.
  - The project is driven by complementary strengths:
    - **Japan:** AC-LGAD sensor design, HPK fabrication, irradiation and testbeam experience
    - **France:** ASIC development, EICROC/ALTIROC expertise, laser and material-characterization facilities
  - Joint activities connect:
    - sensor development and readout electronics
    - performance measurements and material-level studies
    - laser/source/beam tests and system integration
  - Researcher exchange and shared facilities make the collaboration highly productive.



- **Goal:**
  Advance pixelated AC-LGADs from world-leading prototypes to practical detector technology through a complementary France–Japan collaboration.

Backup

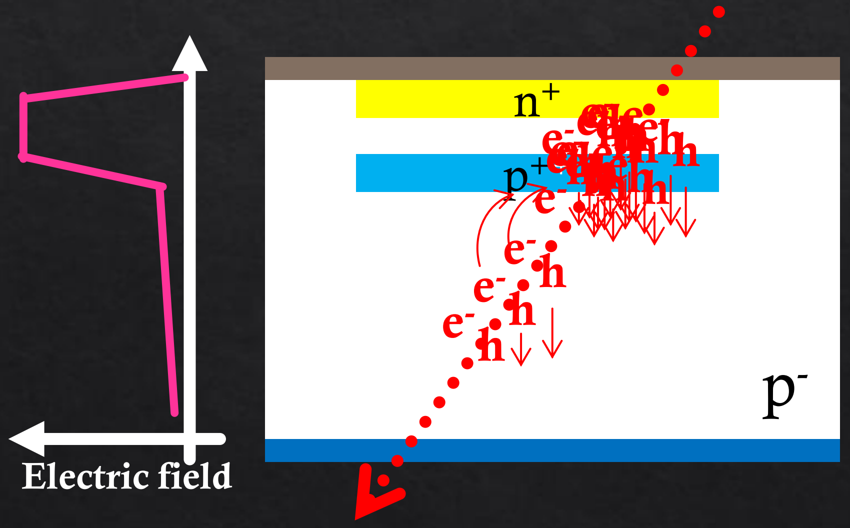
AC-LGAD collaboration



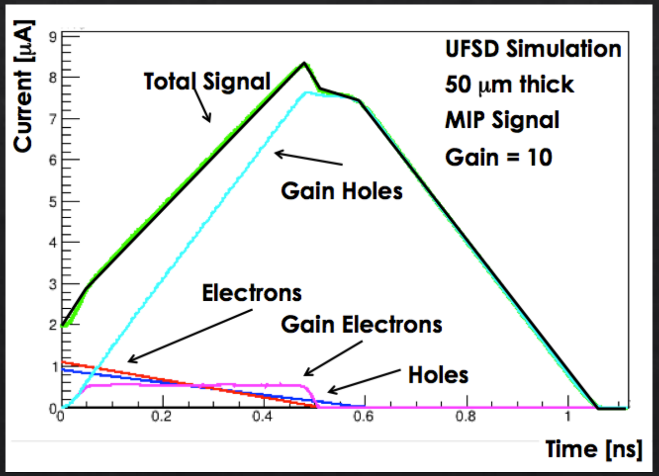
Will focus on HPK AC-LGAD in this seminar

Low Gain Avalanche Diode (LGAD)

- Low gain Avalanche Diode (LGAD)
  - General n^+-in-p type sensor with p^+ gain layer under n^+ implant to make very high Electric Field at the surface.
    → Good timing resolution.
  - **30ps timing resolution achieved already in 2015.**

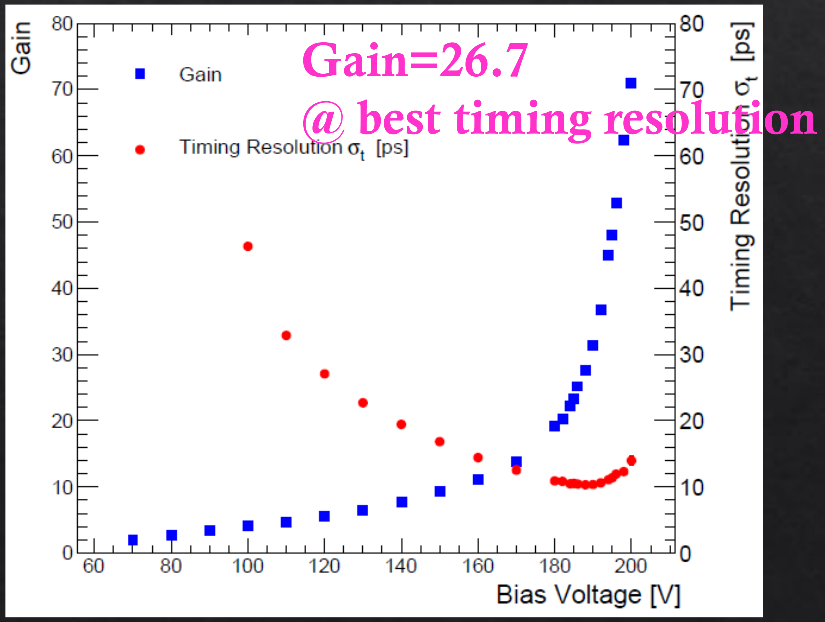


Signal drivers : **Gain Holes**



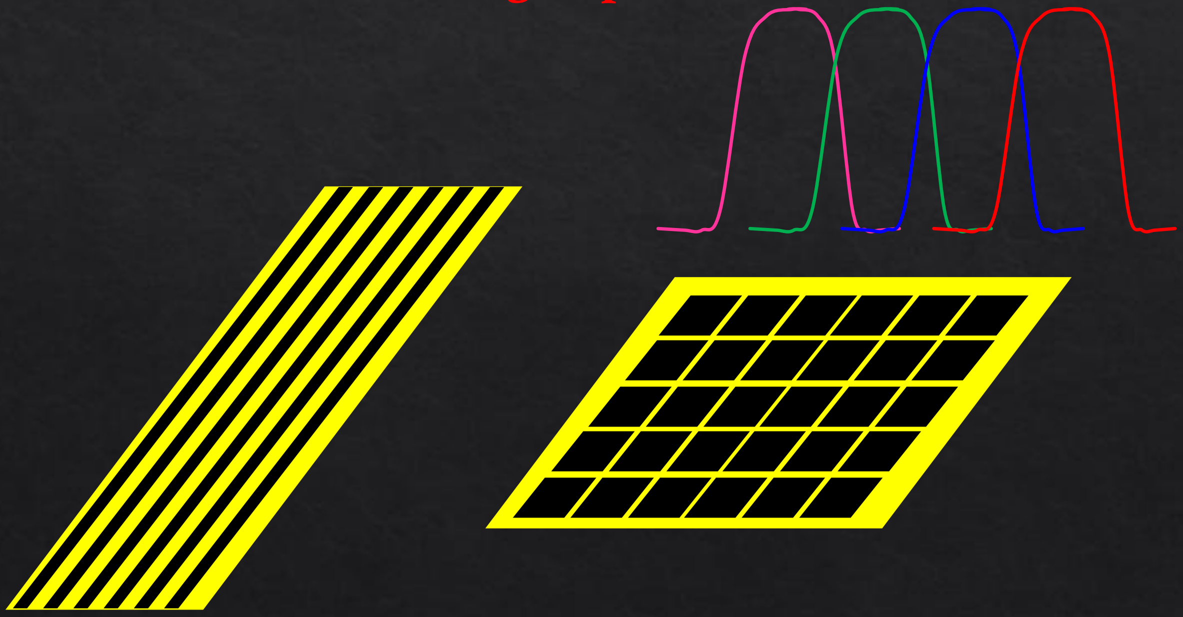
Cartiglia et al., NIMA 796, p141-148, 2015

Gain measurement (AC-LGAD):



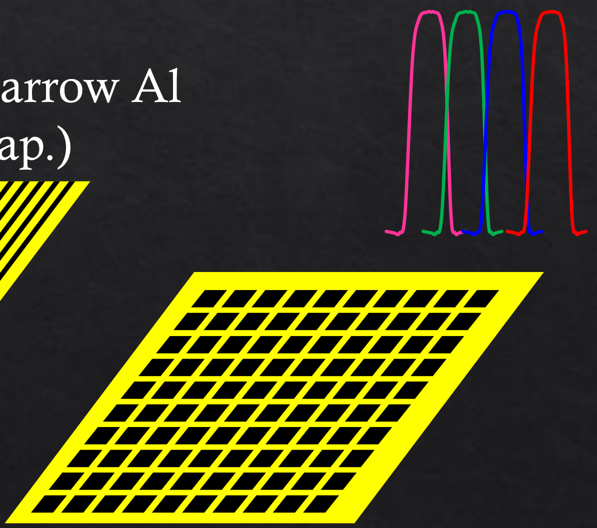
Two approaches for spatial resolution

- ***<u>Charge sharing approach</u>***
  - **For low occupancy colliders like lepton colliders or electron-ion collider.**
  - Reconstruct particle position using charge sharing (charge fraction to next channels)
    - Relatively low n+ implant resistivity
  - **Pros. : Smaller number of channel →Save ASIC power consumption.**
  - **Cons. : Large detector capacitance. Need high resolution ADC to get spatial resolution.**



- ***<u>Fine pitch electrode approach</u>***
  - **For High occupancy experiment like hadron collider.**
  - Reduce crosstalk (charge sharing)
    - High n+ implant resistivity
  - **Pros. : Smaller detector capacitance. Smaller ASIC power consumption per channel. Smaller occupancy per channel**
  - **Cons. : # of channels get huge…**

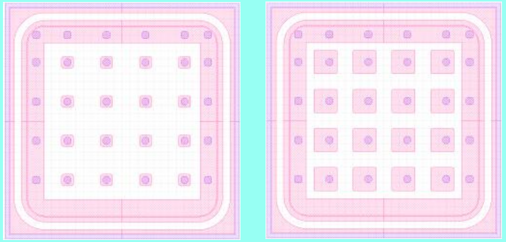
Fine pitch strip with narrow Al
(to reduce inter strip cap.)



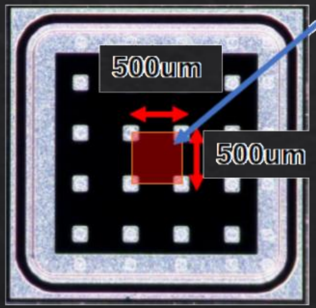
Two approaches for spatial resolution

- ***Charge sharing approach***

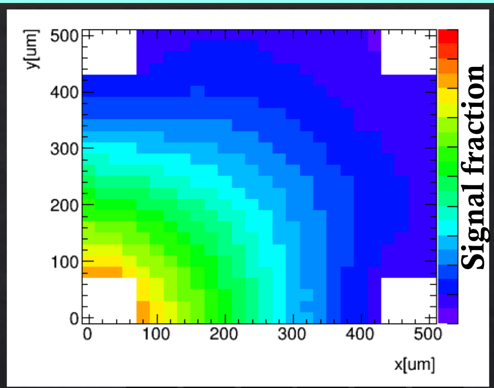
HPK EIC prototype
(500um pitch)

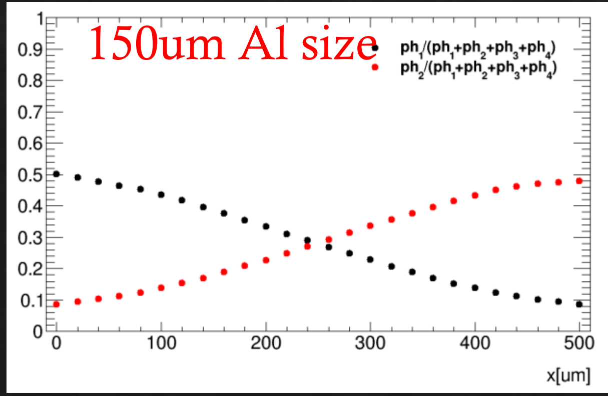


KEK-Tsukuba group with HPK produced
500um pitch pad/strip for future colliders (e.g. EIC)

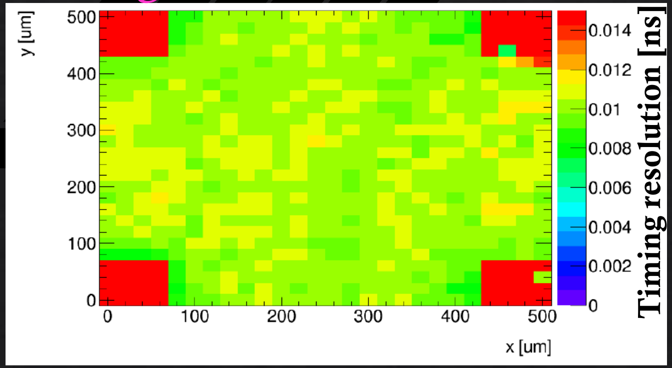


IR laser
Scan area



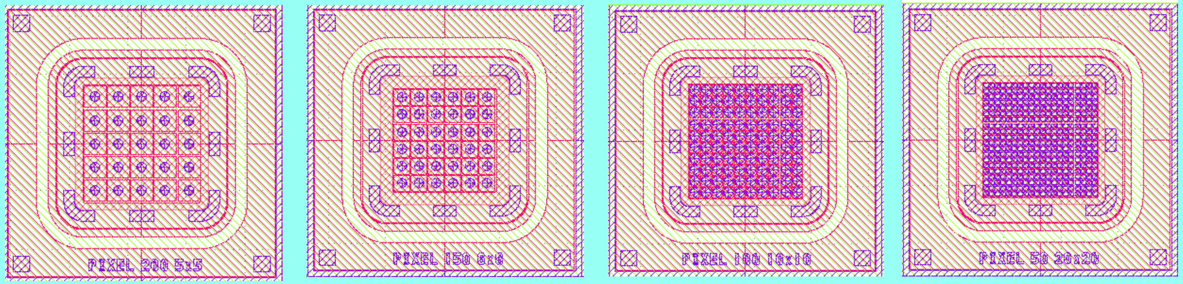


Timing resolution

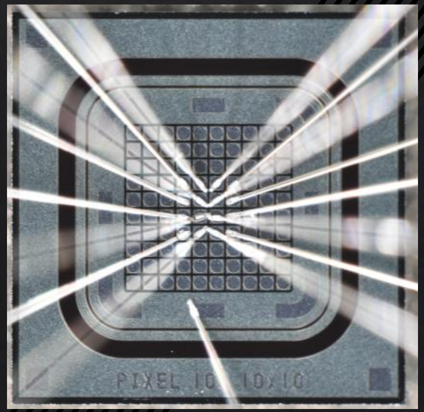


- ***Fine pitch electrode approach***

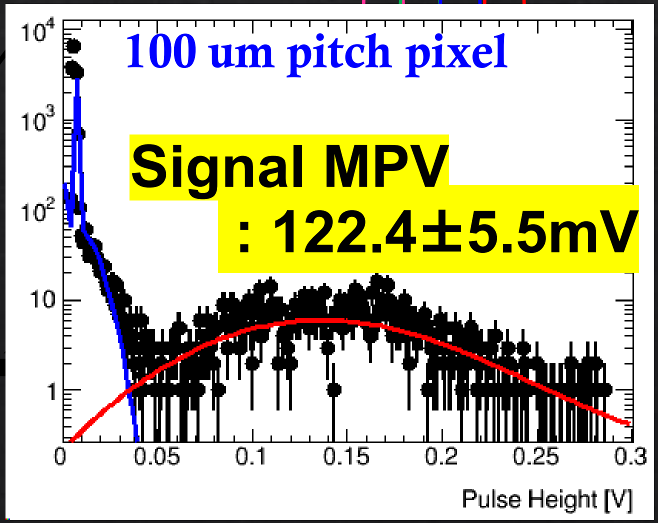
200um 150um 100um 50um



KEK-Tsukuba group with HPK successfully develop :
100um (50um) pitch Pixel detector
80um pitch Strip detector



JPS Conf. Proc. 42, 011030 (2024) VERTEX2022



Secondary Ion Mass Spectrometry and Simulation

- SIMS measurement
  - Analytical technique to characterize the impurities near surface(<30um) by ionized secondary particles.
  - Good detection sensitivity for **B, P, Al, As, Ni, O, Si** etc down to 10^{13} atoms/cm^3 with 1-5nm depth resolution.
- Synopsys TCAD simulation
  - Process simulation:
    - Simulate implantation and resulting concentrations.
    - **Can compare to SIMS result.**
  - Device Simulation :
    - Simulate Electric field to understand the performance of silicon device.
    - Possible to perform simulation for charge correction of MIP signal.

SIMS system at Analyseur ionique du GEMaC (CNRS/UVSQ, Université Paris-Saclay)