AC-LGAD Timing Tracker Development for Future Colliders

with a focus on sensor & readout ASIC test

5th DRD3 week on Solid State Detectors R&D @ Bucharest

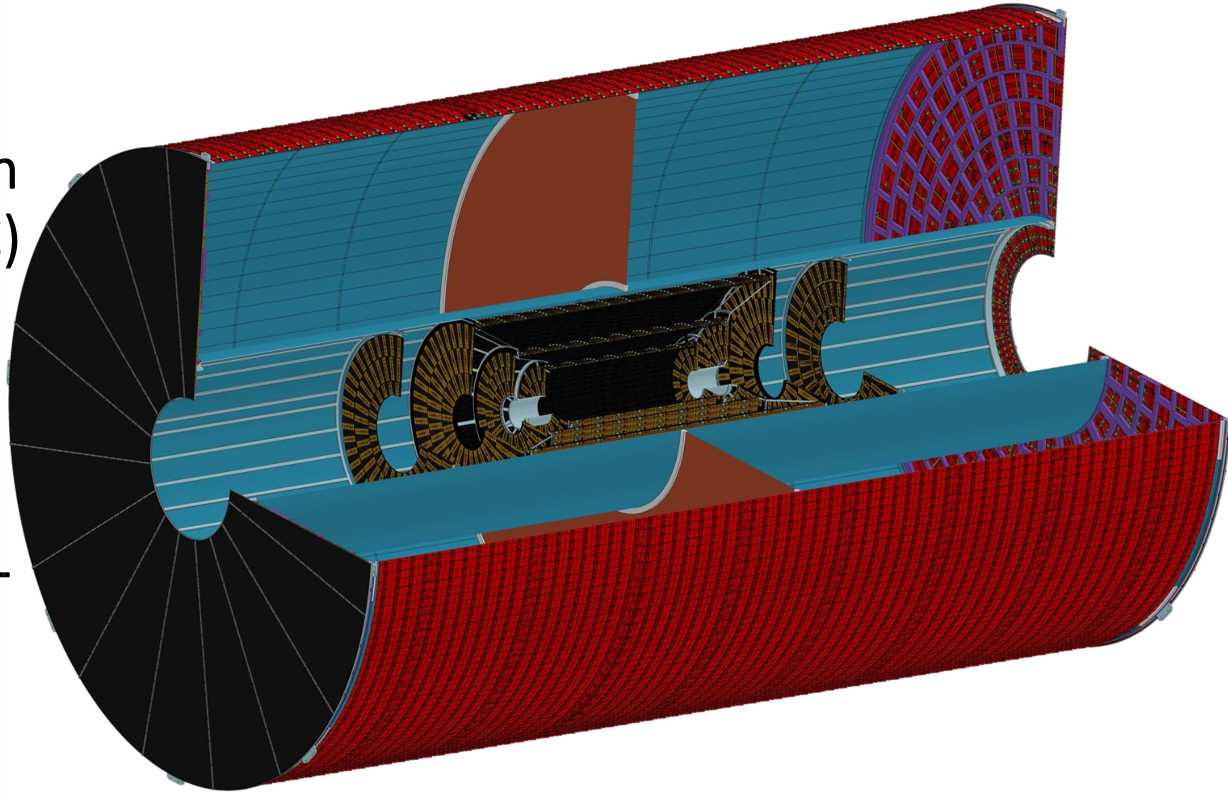
30 June 2026

JiaJian Teoh on behalf of CEPC OTK Group.

IHEP, CAS

CEPC OTK Detector

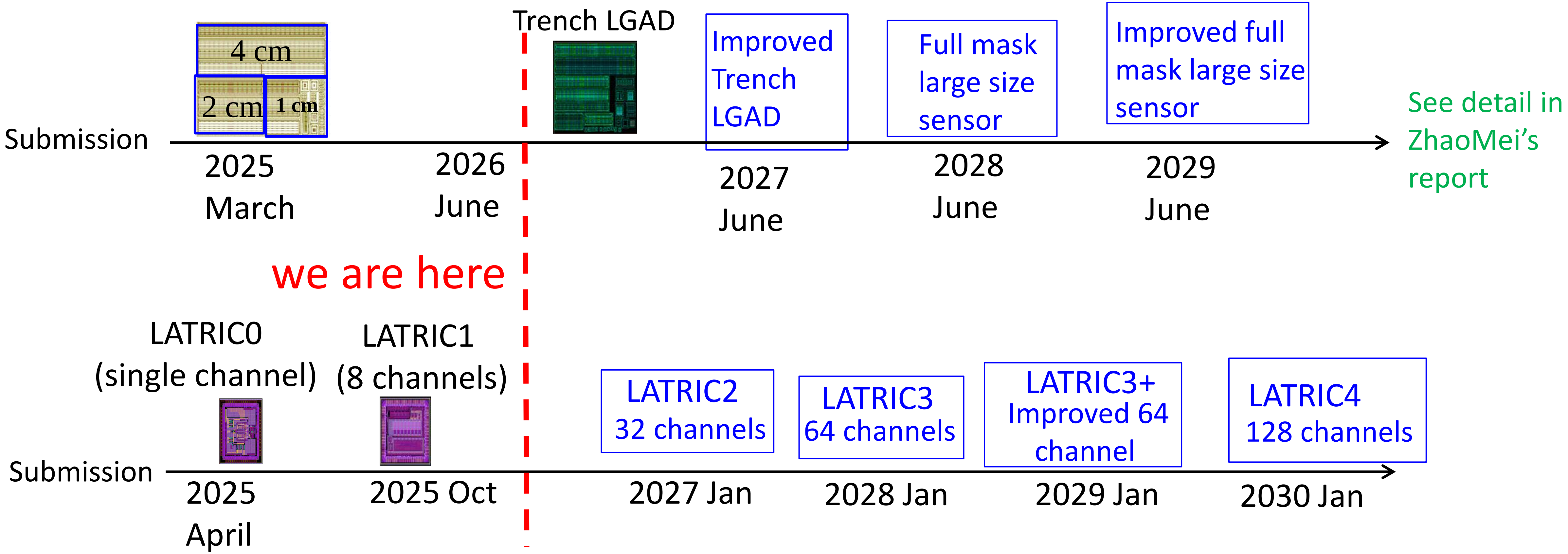
- The Outer Tracker (OTK):
  - outermost detector of the tracking system in the Circular Electron Positron Collider (CEPC) experiment [1].
- Provide precise spatial measurement to improve momentum resolution and precise timing measurement for Time-of-Flight (TOF) based particle identification.
- OTK employs AC-coupled Low-Gain Avalanche Detector (AC-LGAD)
  - simultaneously measures position (10 μm) and time (50 ps)



[1] **CEPC Technical Design Report -- Reference Detector**
https://doi.org/10.48550/arXiv.2510.05260

IHEP’s AC-LGAD and LATRIC R&D Plan

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

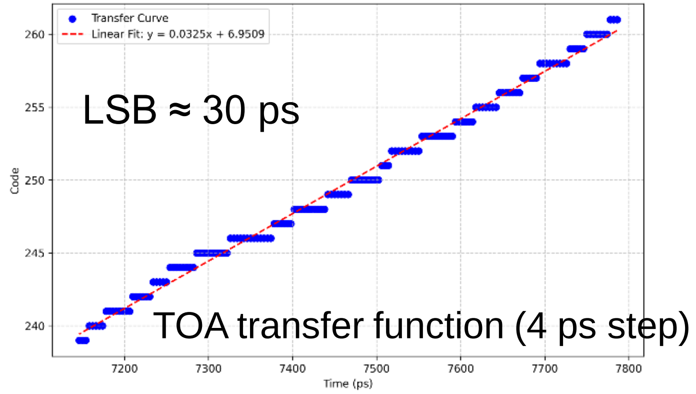


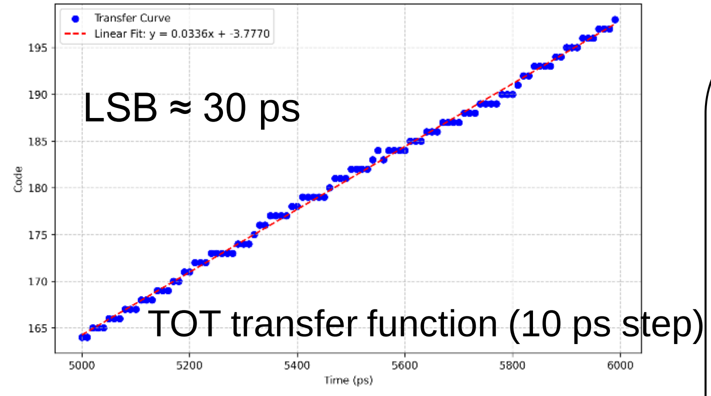
- LGAD readout ASIC, LATRIC, is being developed towards multi-channels

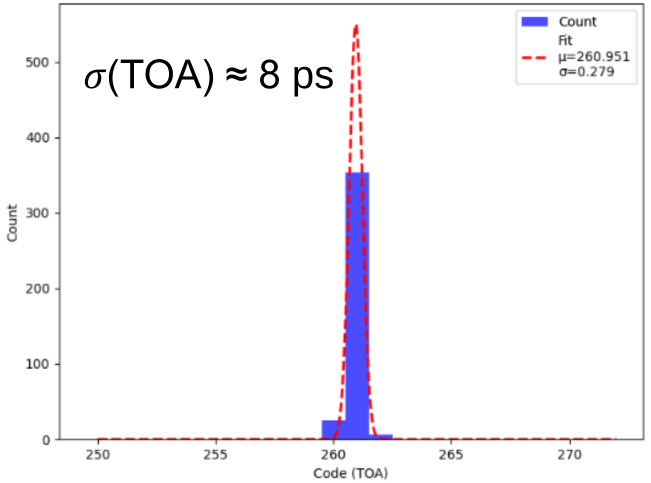
LGAD Readout ASIC, LATRIC

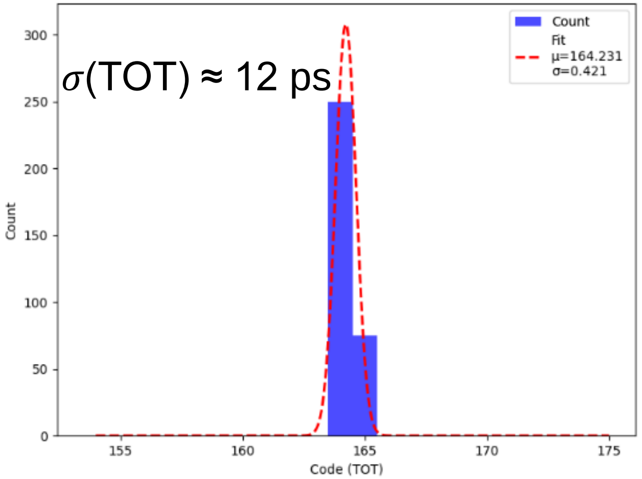
The first LATRIC prototype, LATRIC-V0, submitted for tape-out in April 2025, was delivered to IHEP in Aug 2025:

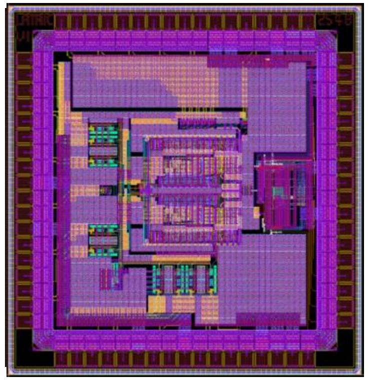
- The ASIC integrates a pre-amplifer, a discriminator, a TDC, and a serializer for data output.
- Tests find that the LSB is 29.8 ps, meeting the 30 ps design goal.
- The measured TDC power consumption is 0.1 mA (1.2 V) @ 0.5 MTPS (Mega-Trigger Per Second), 0.3 mA @ 1 MTPS, and 0.5 mA @ 2 MTPS, agreeing with the design.

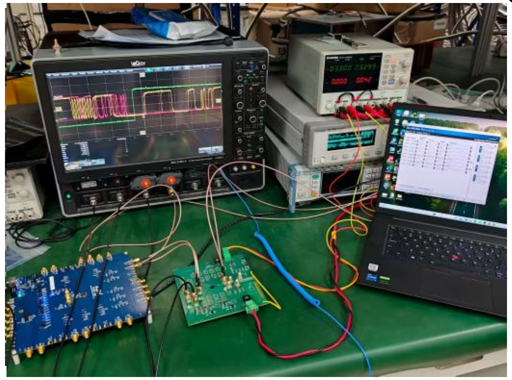


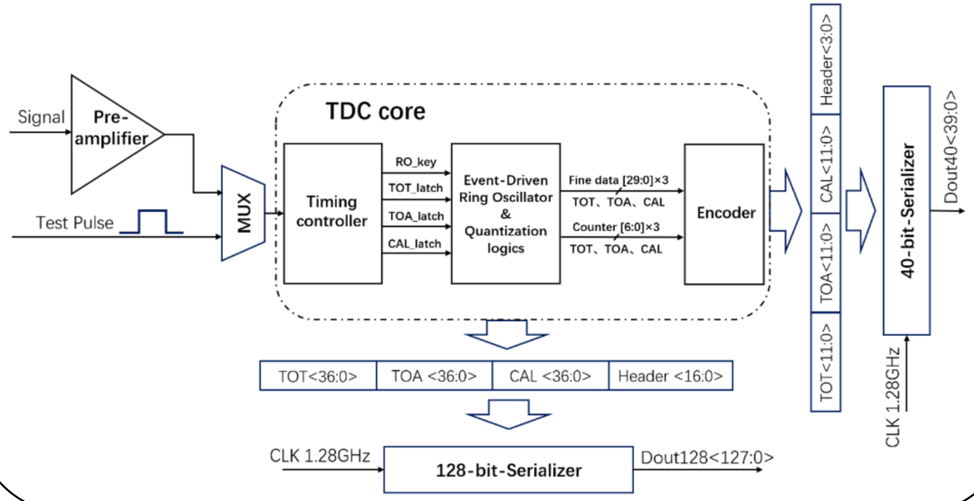








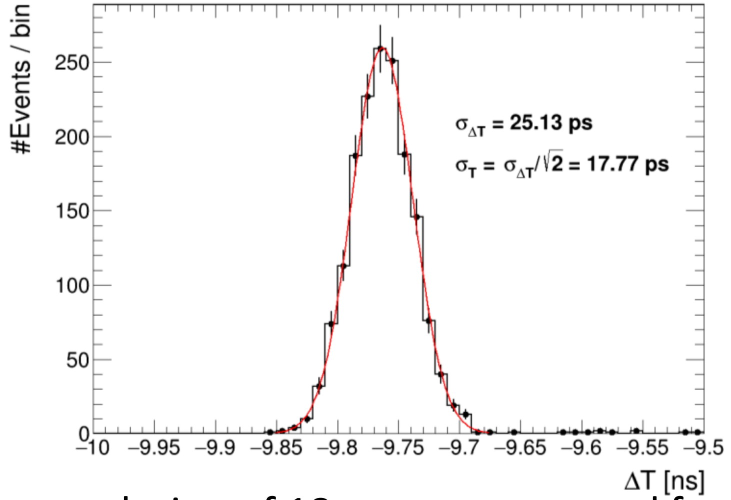




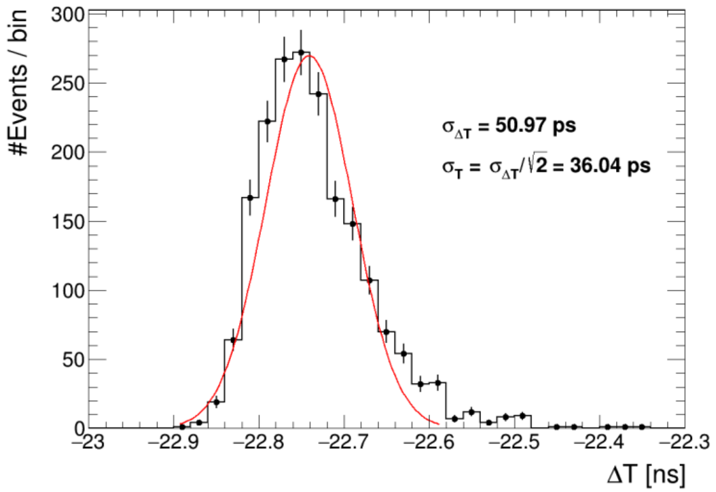
DOI 10.1088/1748-0221/21/04/C04028

LATRIC0 (Single Channel) and Sensor Combined Test

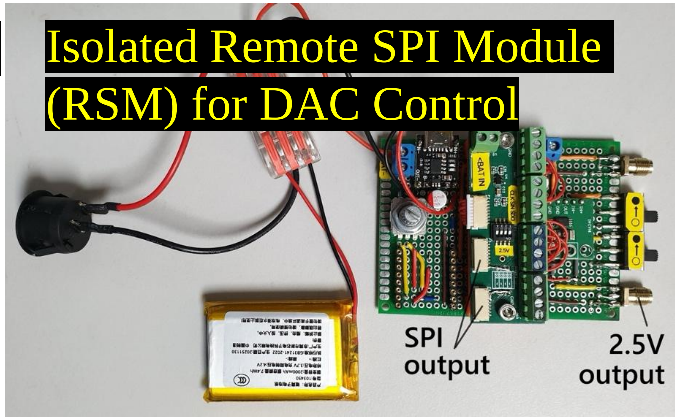
55 nm CMOS process



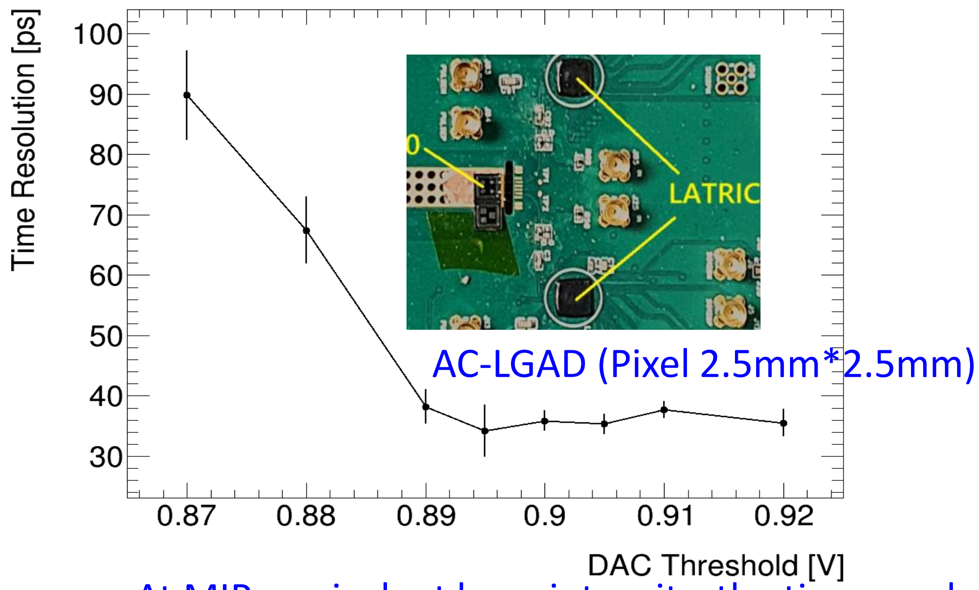
A time resolution of 18 ps was measured for the combined LGAD+LATRIC at 100% laser intensity.



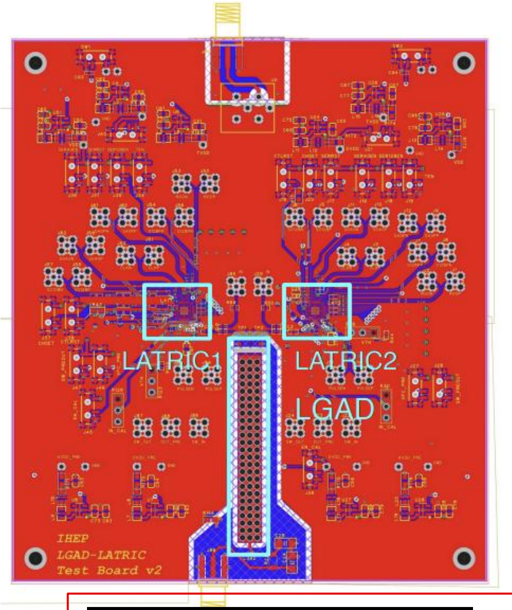
A time resolution of 36 ps was measured for the combined LGAD+LATRIC at a MIP-equivalent laser intensity (0.5%).



Time difference measured with two LATRIC0 chips



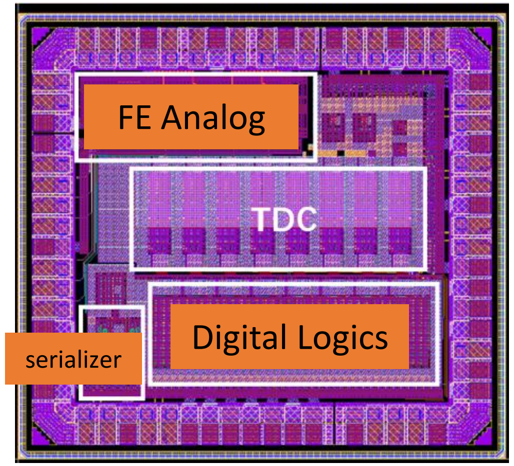
At MIP-equivalent laser intensity, the time resolution improves with increasing threshold and stabilizes at about 36 ps in the 0.89–0.92 V range.



Sensor–LATRIC0 Integrated Test Board

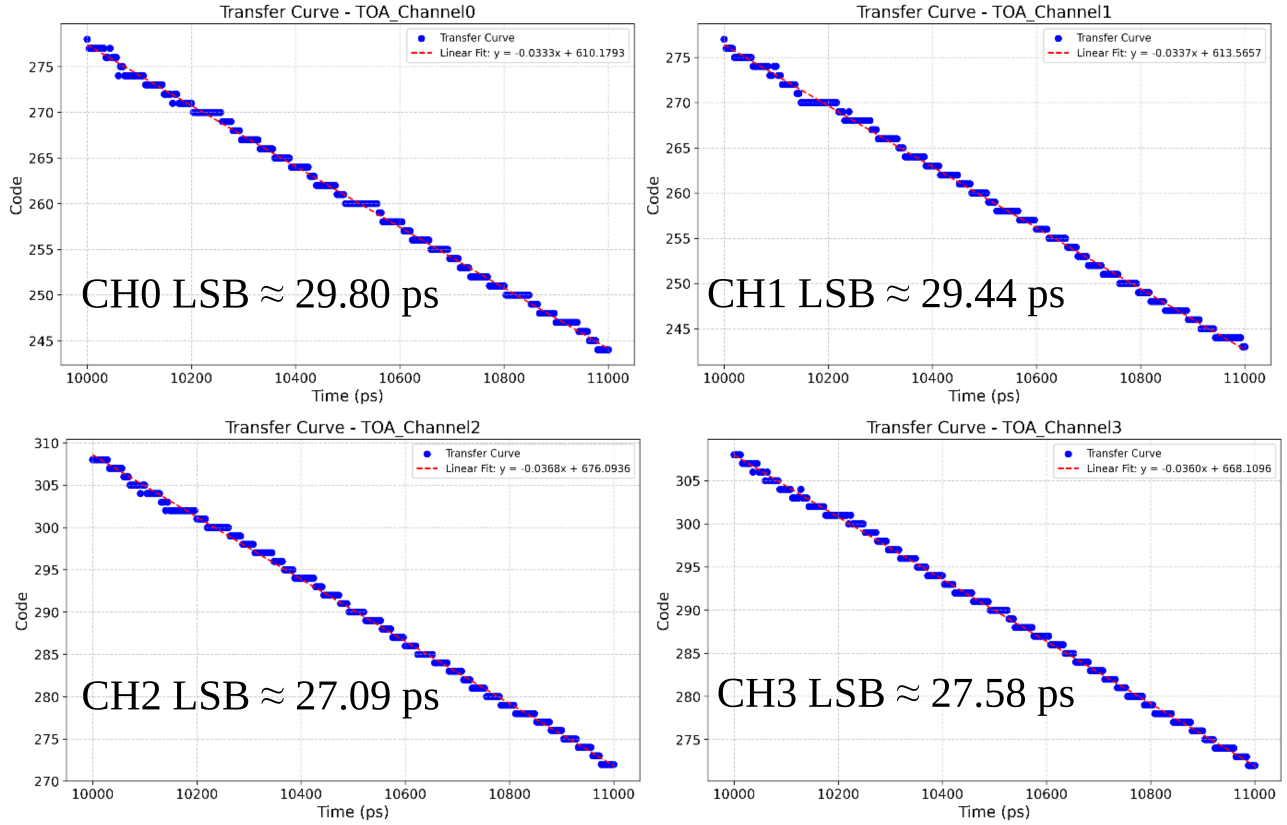
Latest Progress of the LATRIC1 (8 Channels) Readout ASIC

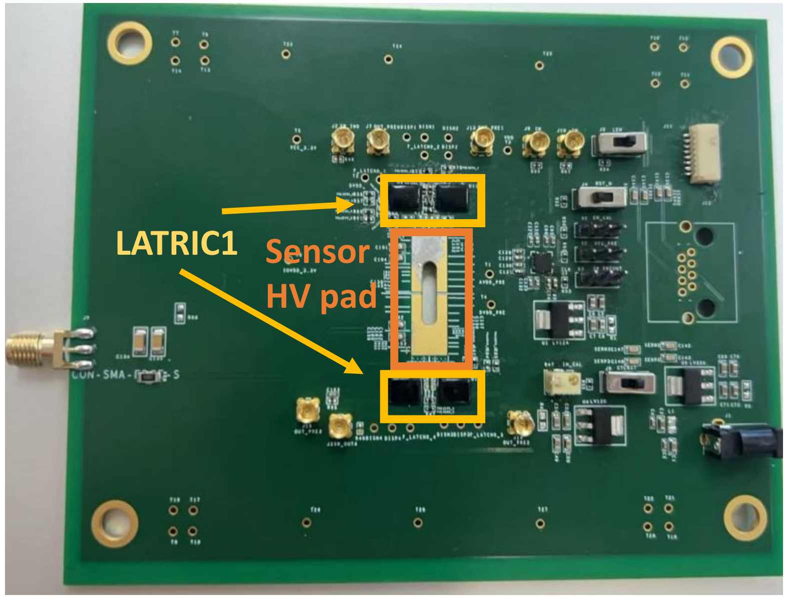
- The second version readout ASIC, LATRIC1
  - The channel pitch is **100 µm.**
  - **8 channels** Four channels integrate the analog front-end and TDC.
    The other four channels consist of TDCs connected to differential pulse receivers.
- Performance optimizations include:
  - An enhanced analog front-end with increased preamplifier gain to improve the signal-to-noise ratio.
  - Refined encoder logic. Addition of an event builder and timestamp functionality, etc.



LATRIC1 layout

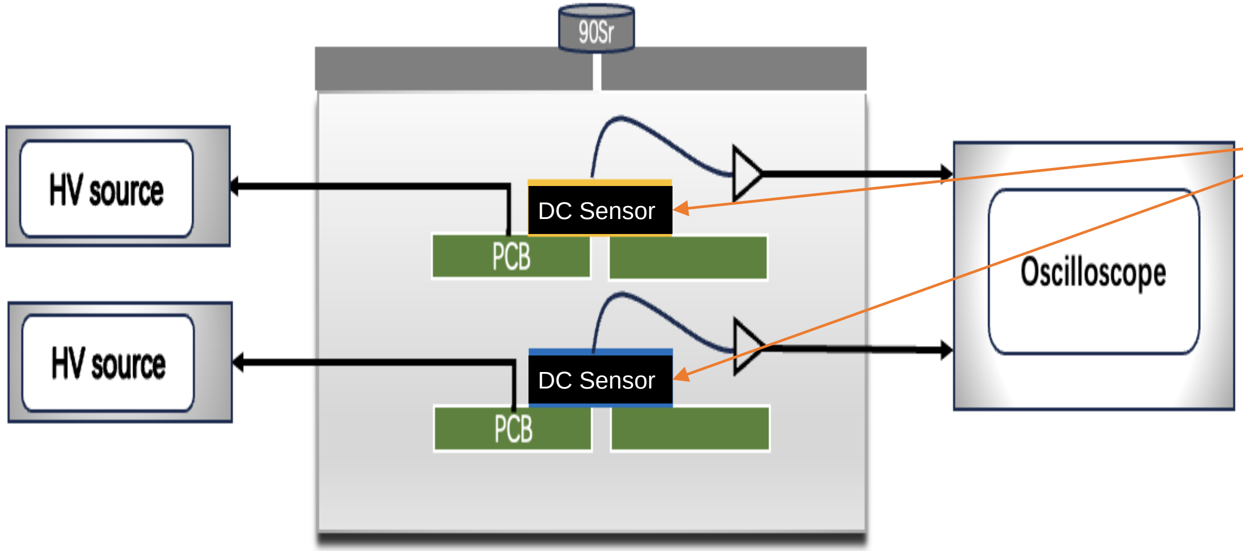
LATRIC1 TDC LSB

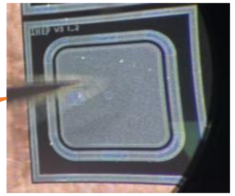




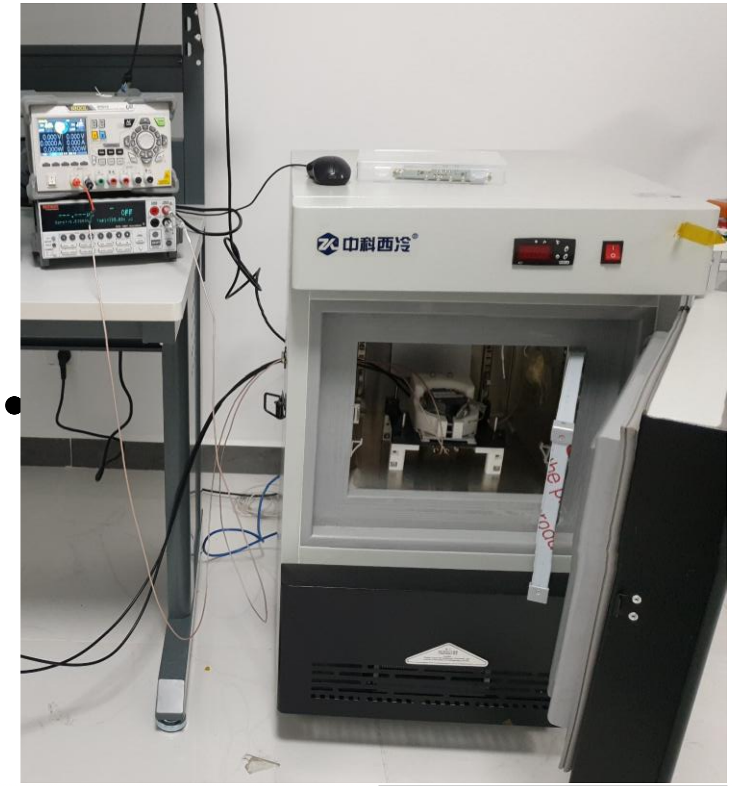
The latest designed LATRIC1-Sensor Integration Test Board

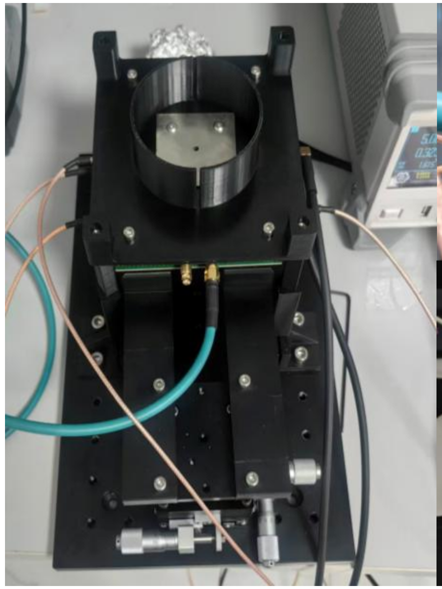
Sr-90 β-Source Test Setup

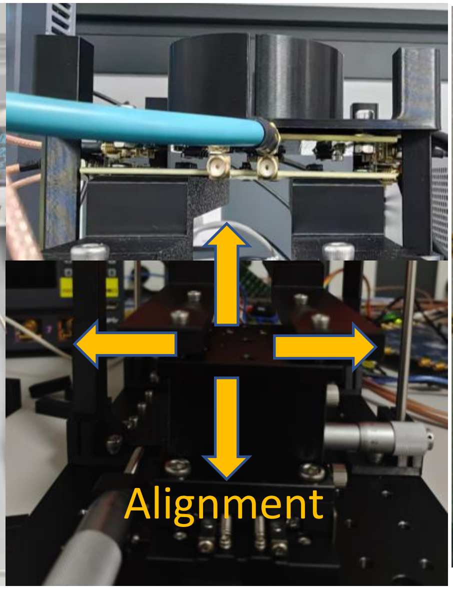


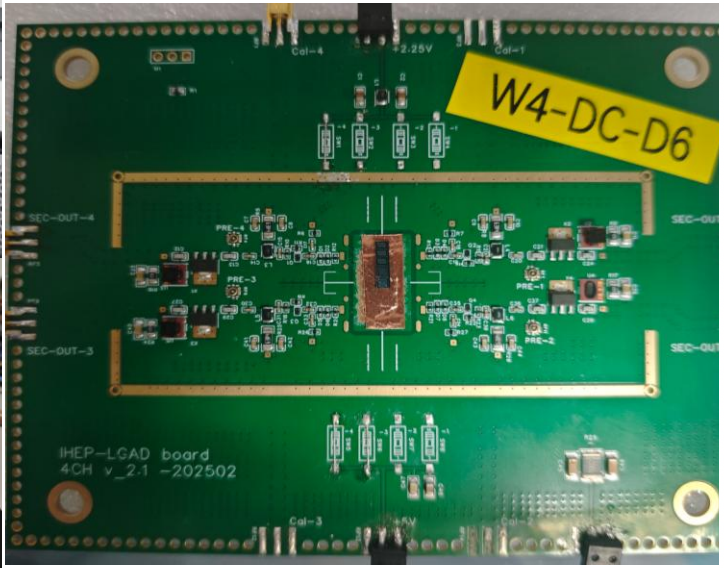


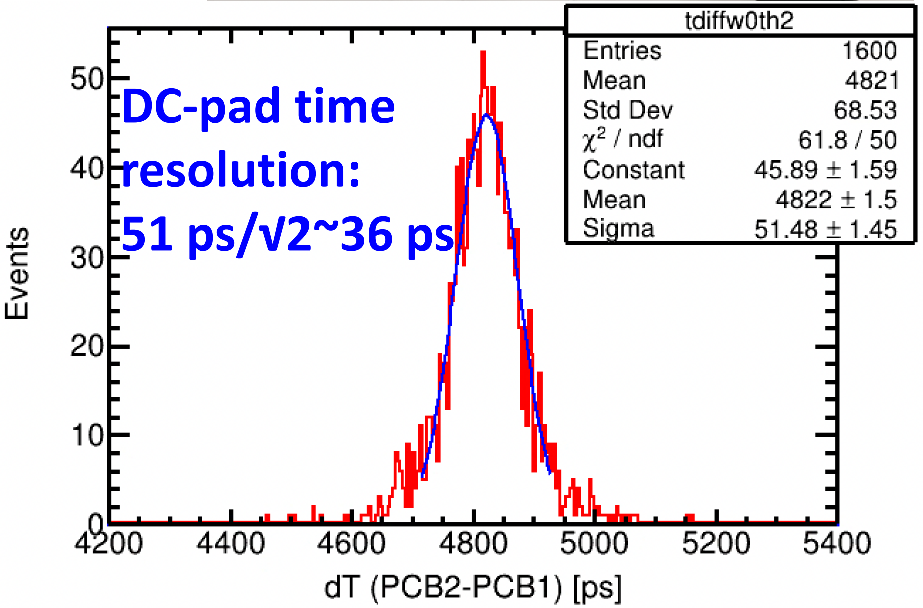
2 DC pads sensor
(W4-DC-D6,W4-DC-12):
1.5 mm*1.5mm



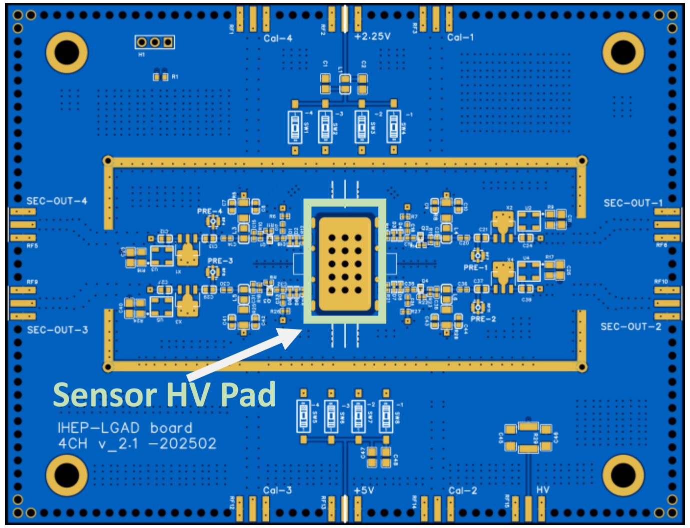








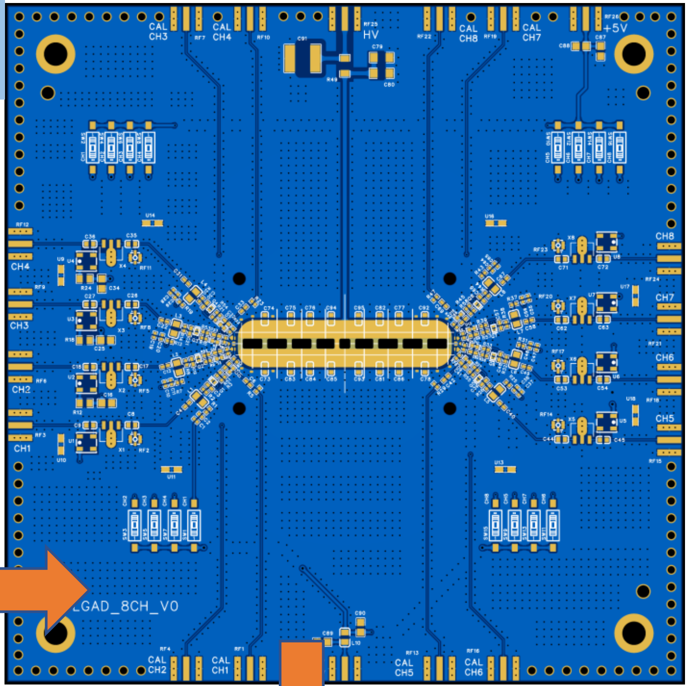
AC-LGAD Pre-Amplifier Board Optimization



10cm x 13cm

V1: 4-Channel LGAD Pre-Amplifier Board:

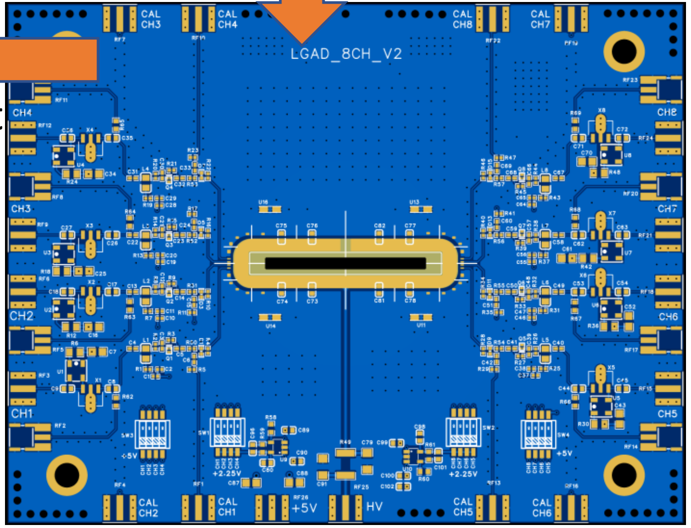
- Provides high-voltage bias for LGAD sensors.
- Four signal readout channels
- ~100× amplification per channel



13cm x 13cm

V2: 8-Channel LGAD Pre-Amplifier Board:

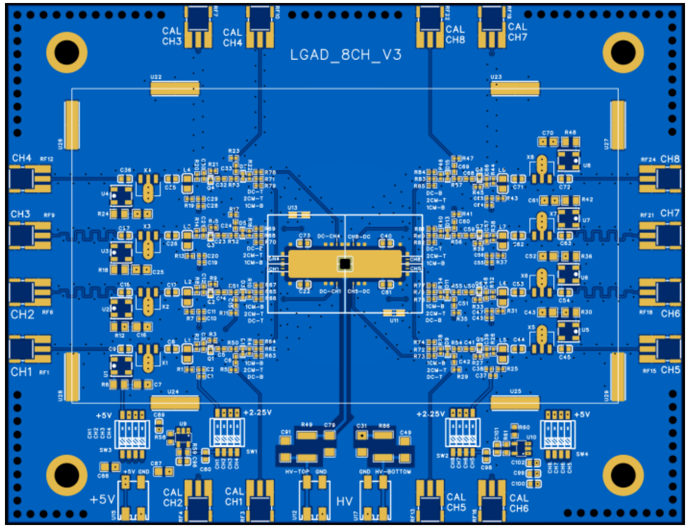
- **Increased number of channels**
- **Extended high-voltage pads** for better compatibility with strip sensors
- Optimized HV pad geometry with cut-outs to improve particle detection efficiency



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



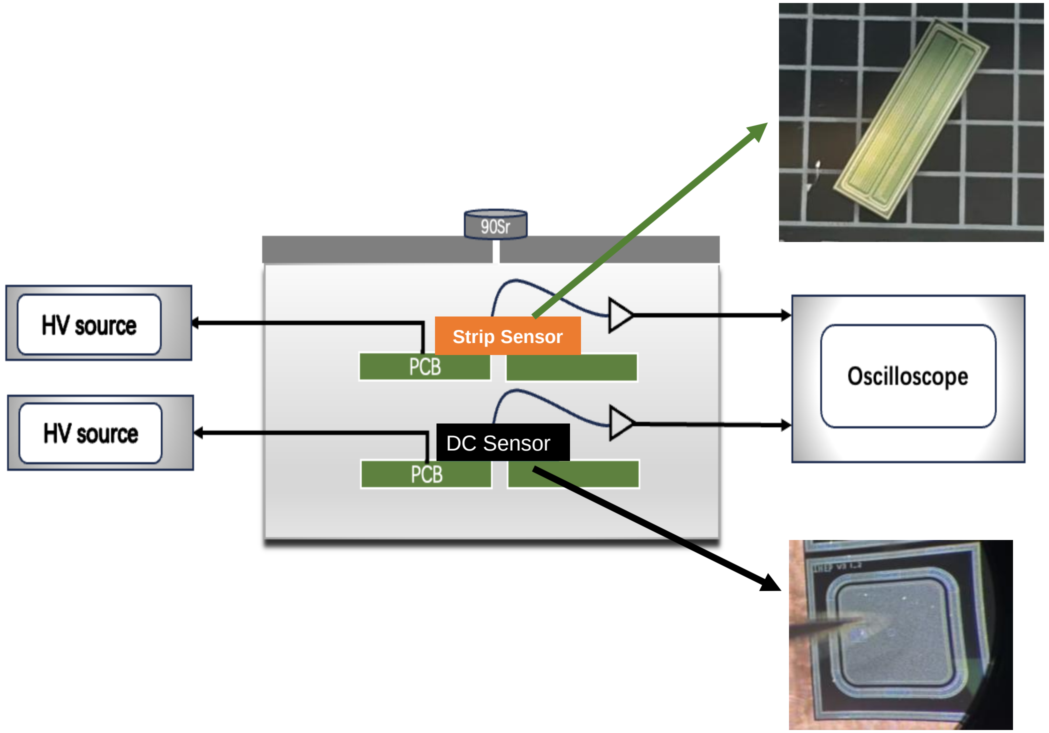
10cm x 13cm

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

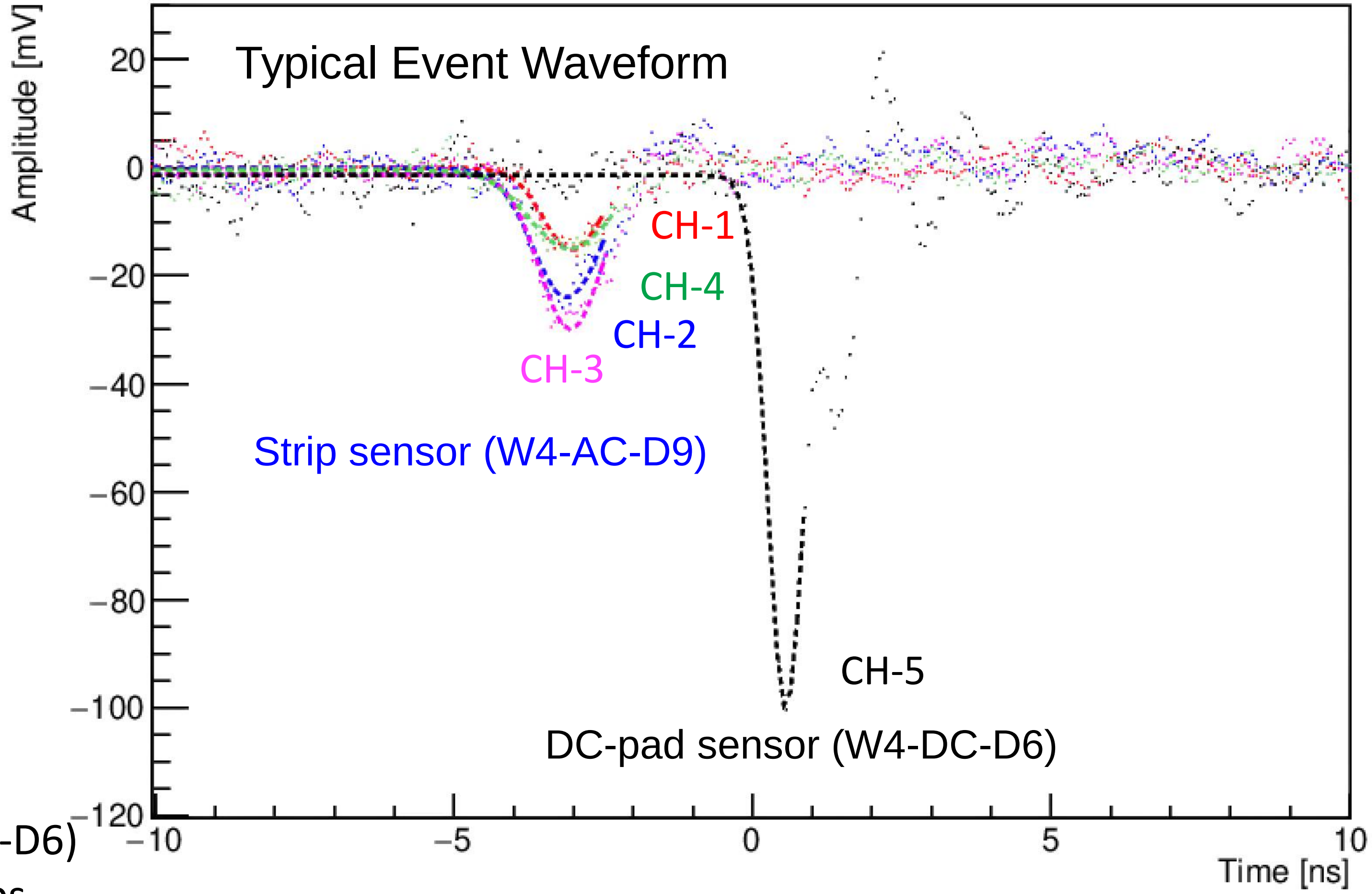
- Double-sided to support different LGAD types (pixel and strip)
- Optimized routing with equal-length traces for all 8 channels
- Reduced board thickness to ~5 mm

Sensor Characterization with a ^{90}Sr Beta Source

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

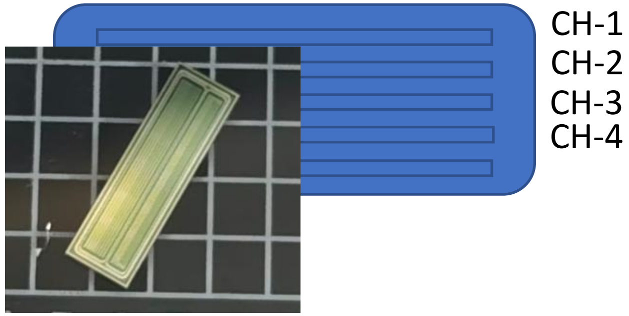


DC-pad sensor (W4-DC-D6)
Time resolution 36 ps

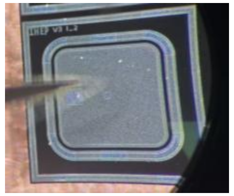


Strip Sensor Timing Resolution (**β-Source Test**)

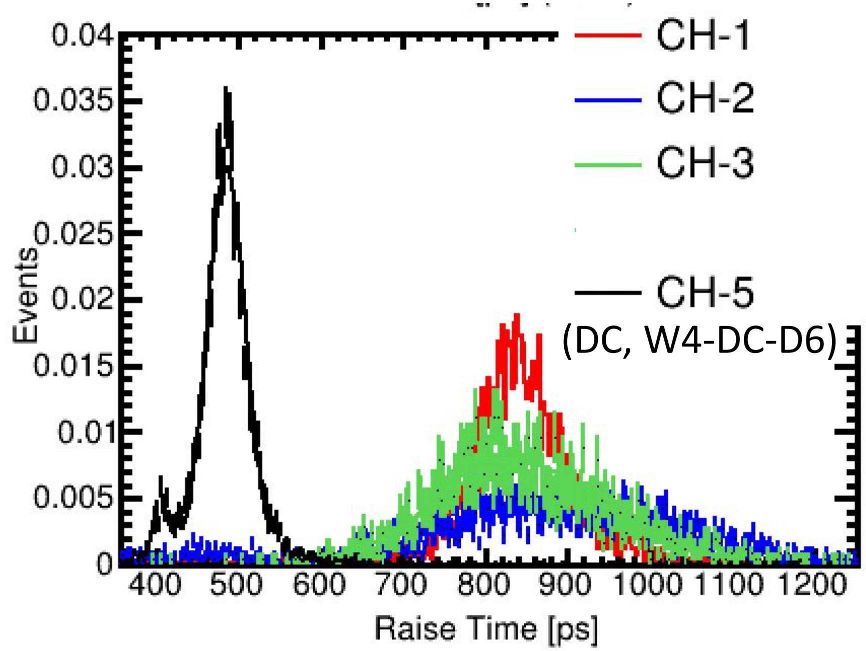
DUT sensor (AC-LGAD)



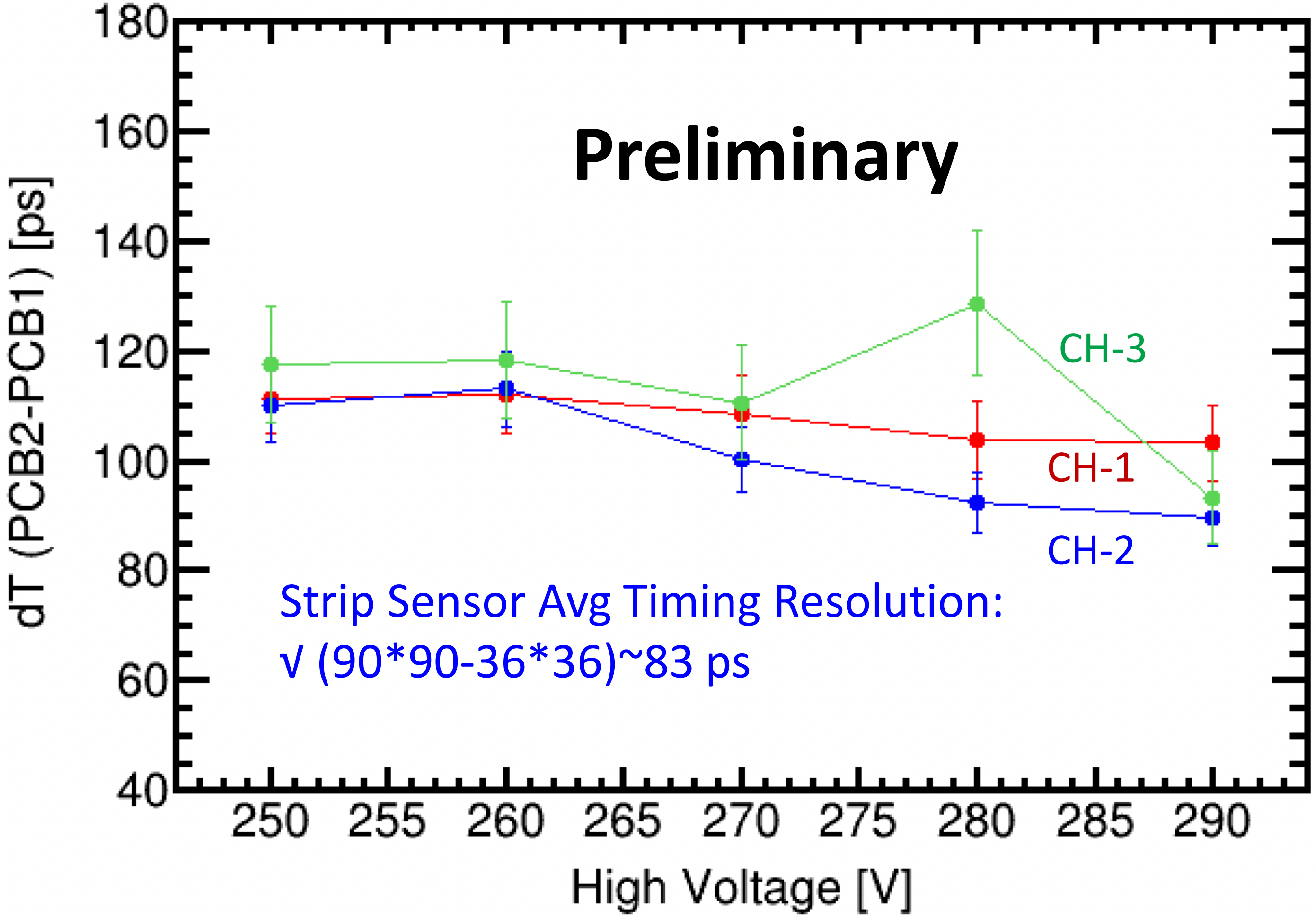
Ref sensor (DC)



CH-5



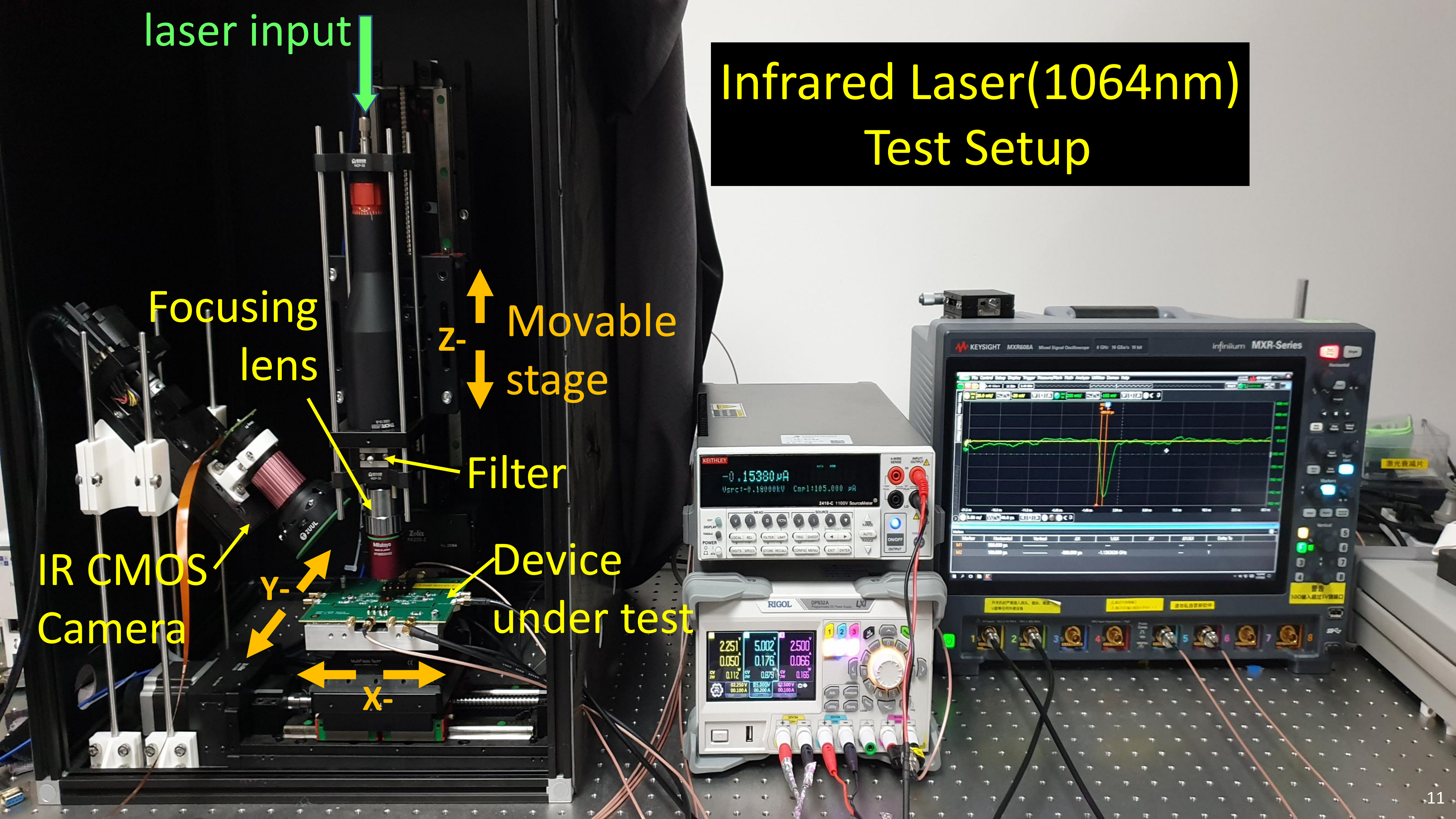
W4-AC-D9, 2 cm, pitch 100um electrode width 50um)



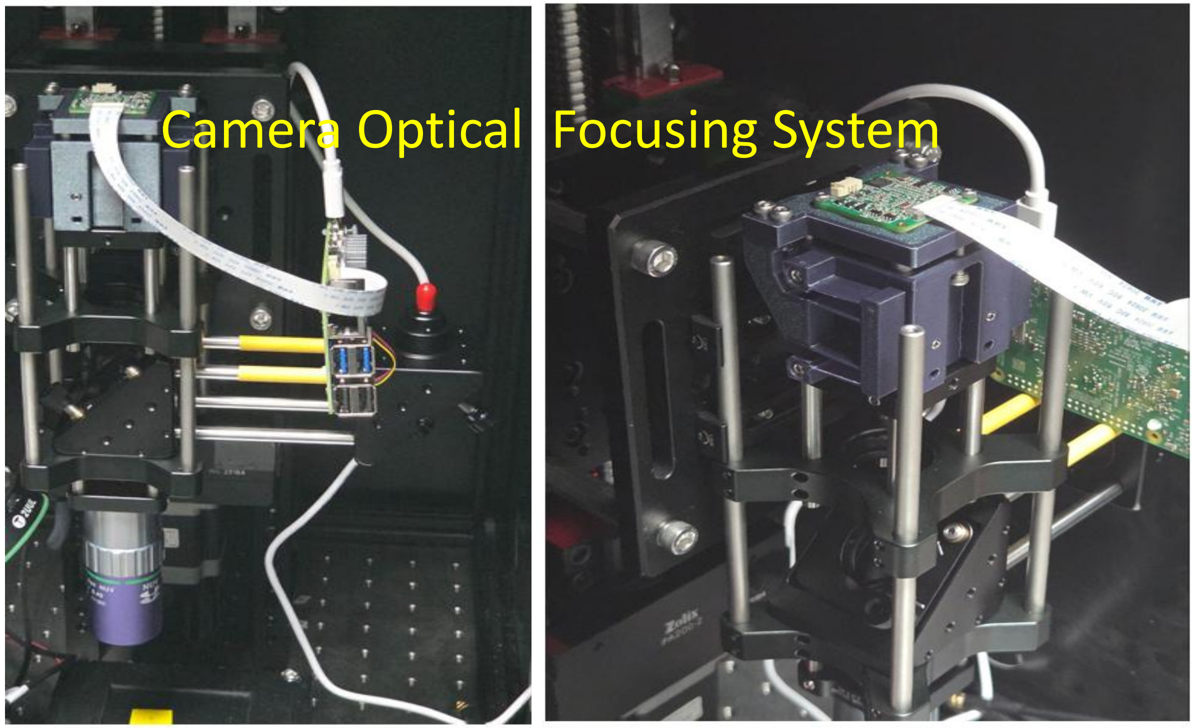
The signal rise time of strip sensors is substantially longer than that of pad sensors.

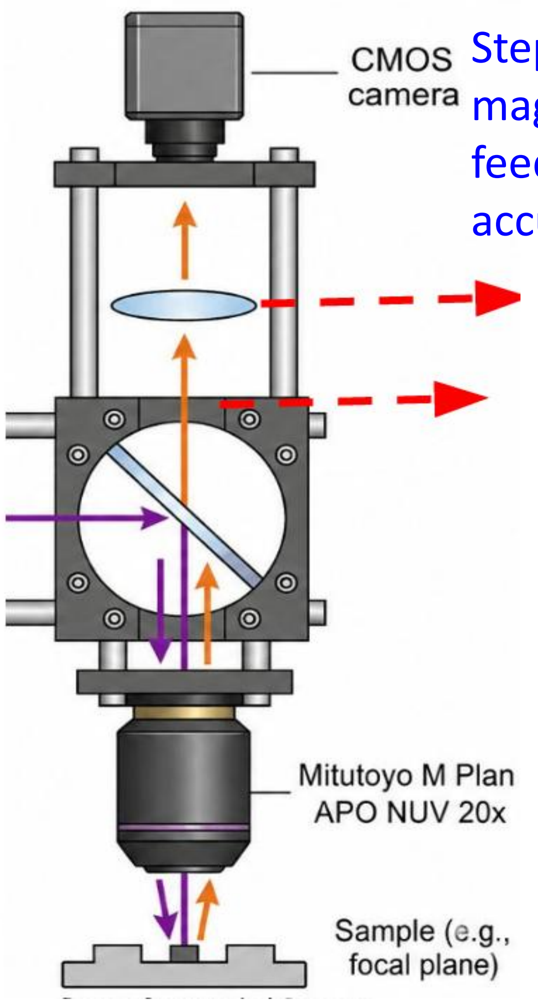
The strip sensor (2cm, pitch 100um electrode width 50um) achieved a timing resolution of ~83 ps.

Infrared Laser(1064nm) Test Setup

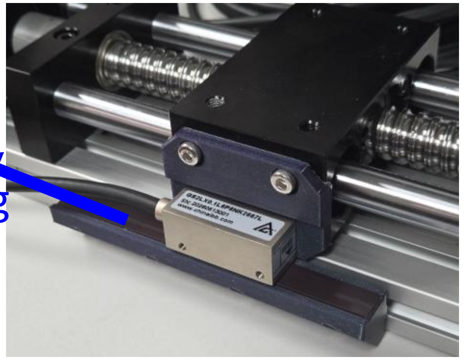


In addition to the infrared test system, a customized UV laser test platform for SiC sensor has been developed. Both Si and SiC sensor development activities share a unified R&D framework with common test infrastructure, front-end electronics, and system integration resources.

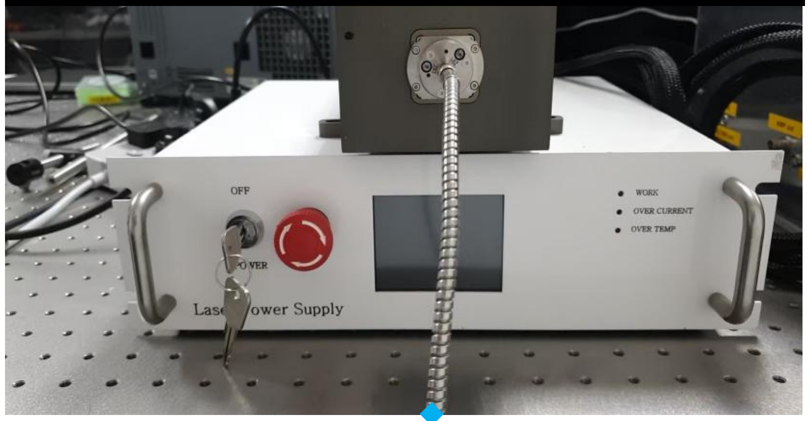


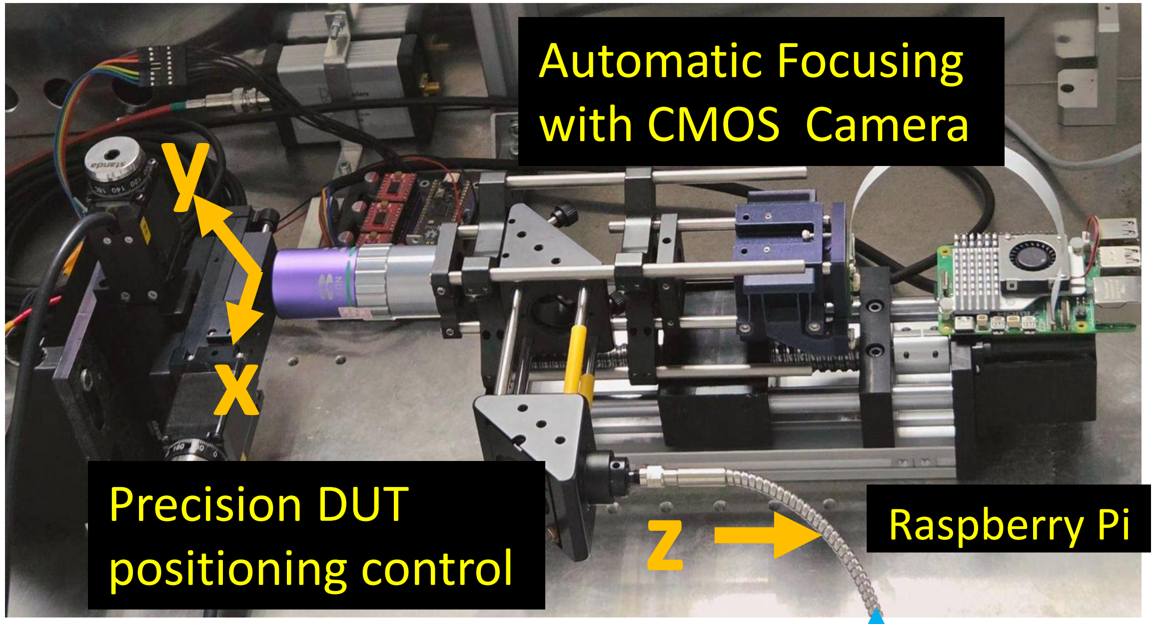


Stepper motor with magnetic encoder feedback: positioning accuracy <0.1 µm



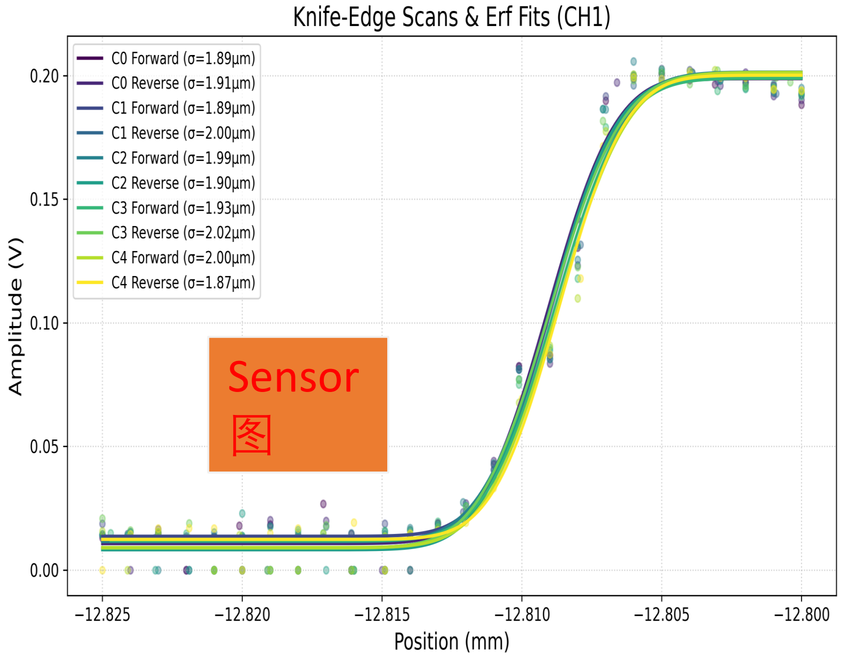
- 355 nm UV laser
- Repetition rate: 1–10 Hz
- Pulse width: ~10 ns

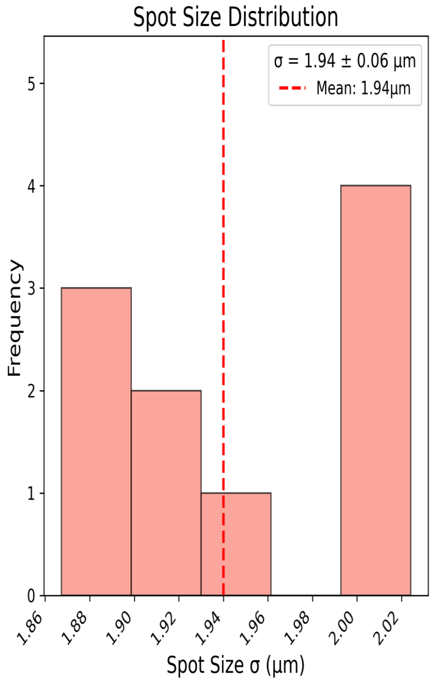




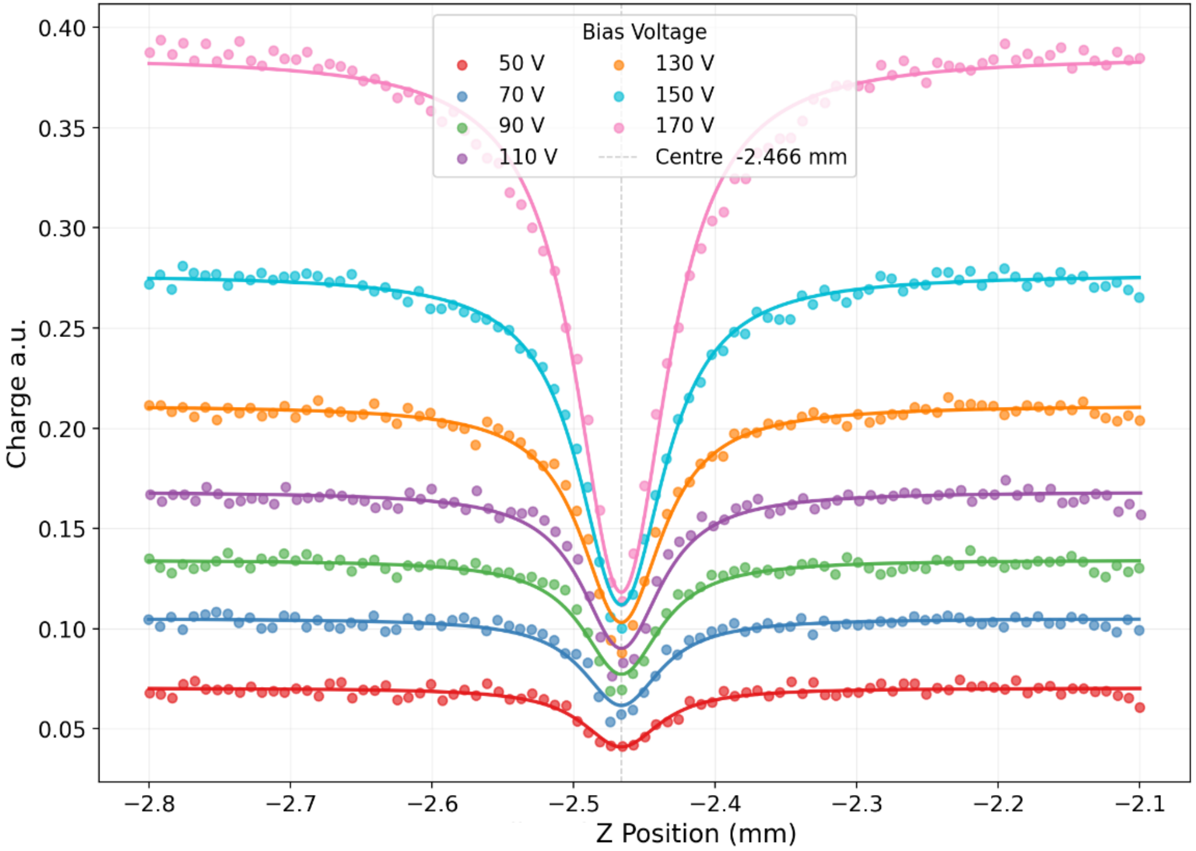
Minimizing Beam Spot Size

- Two independent methods for cross check:
  1. space charge effect→ scan Z position
  2. Knife-edge scan→scan across electrode edge for each Z-position





space charge effect

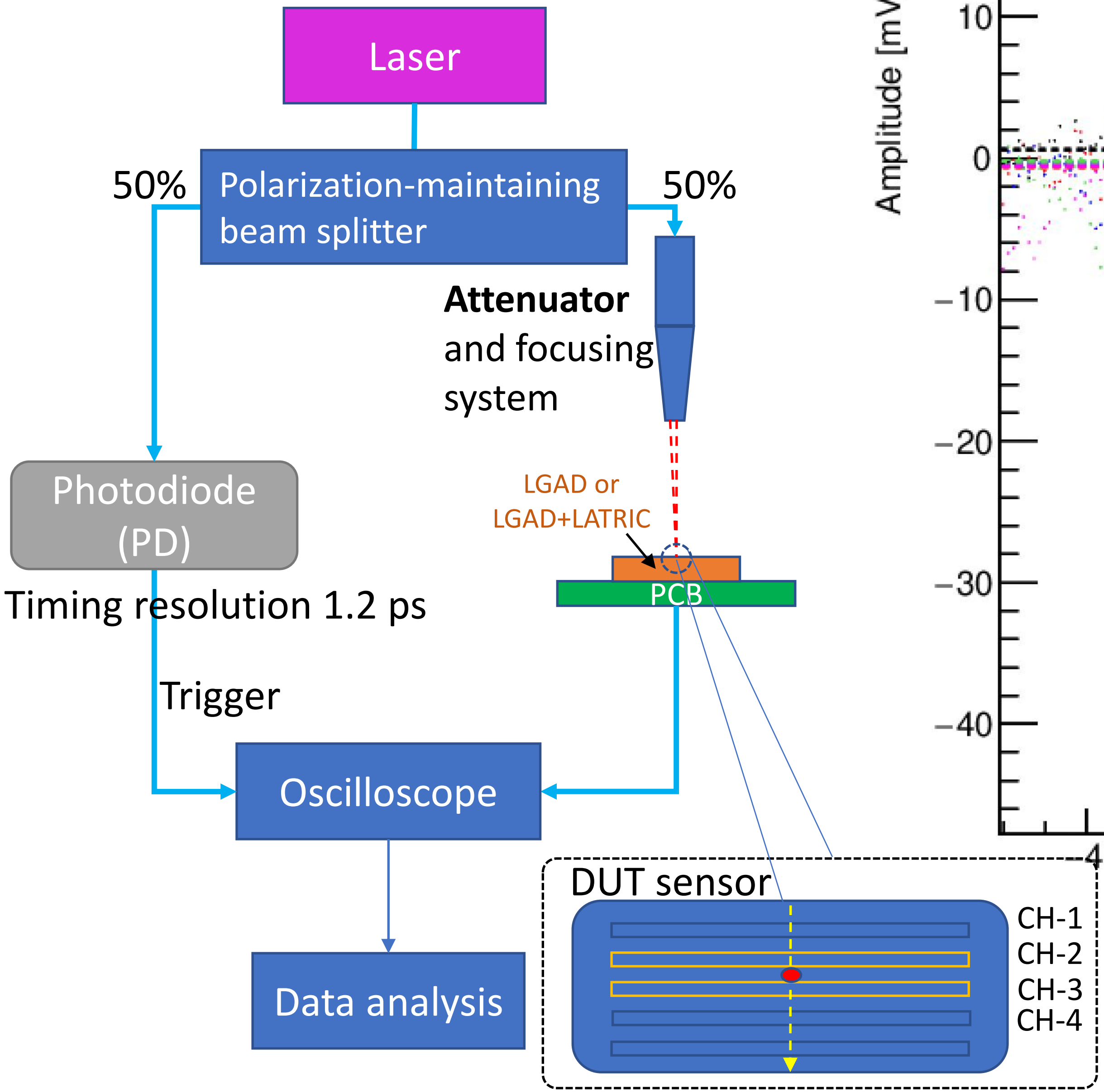


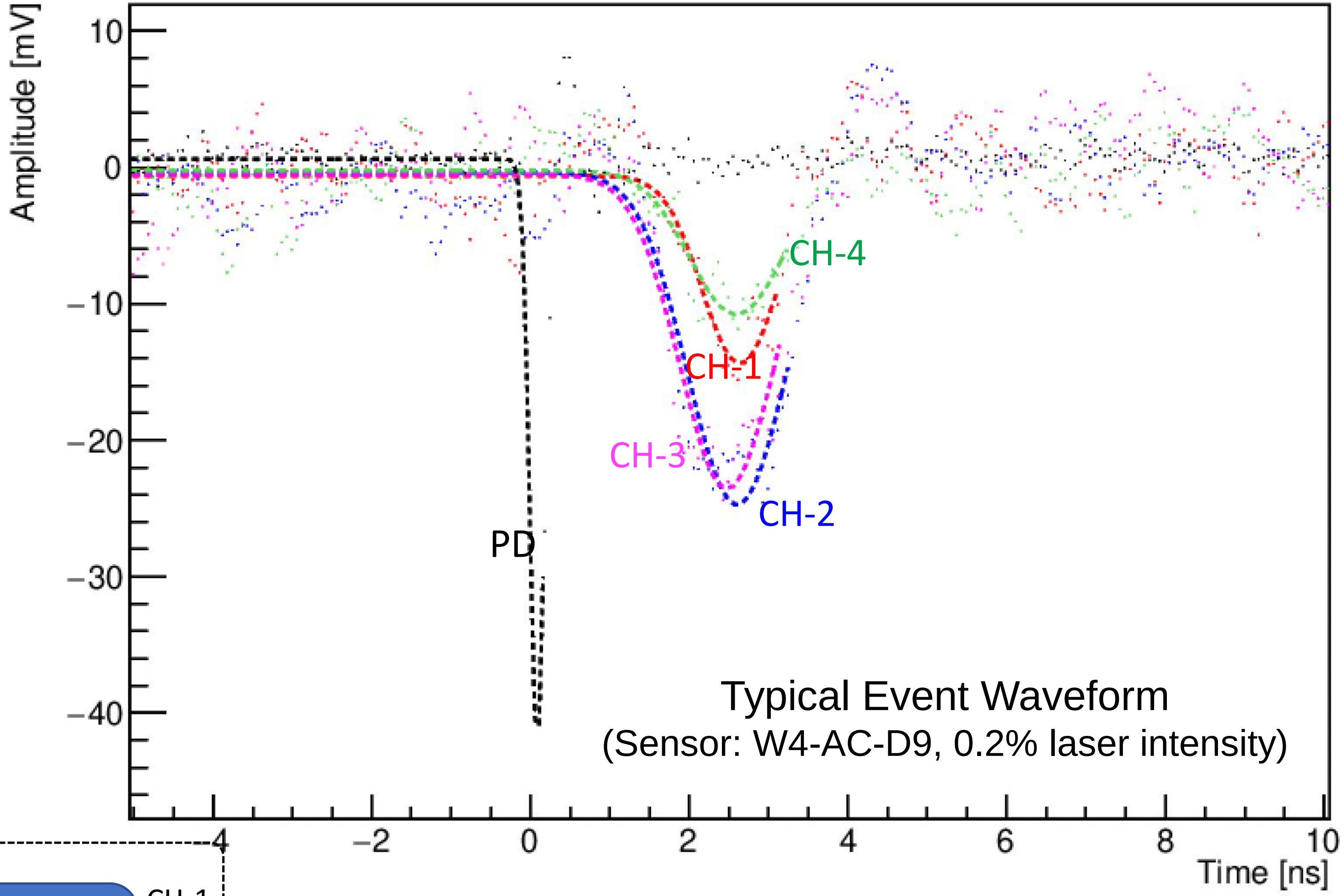
$$S(z) = S_{max} \exp\left(-\frac{A}{w_o^2\left[1+\left(\frac{z-z_o}{z_R}\right)^2\right]}\right)$$

- w_0: The beam waist (minimum radius).
- z_0: The focal point position.
- z_R: The Rayleigh length.

Validated beam waist: $\sim 2 - 3$um

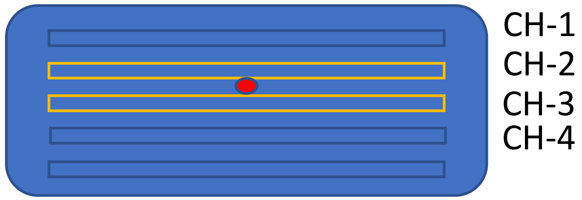
Sensor Characterization

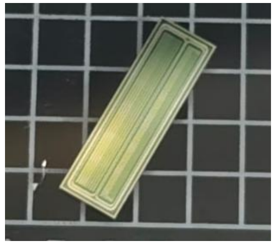




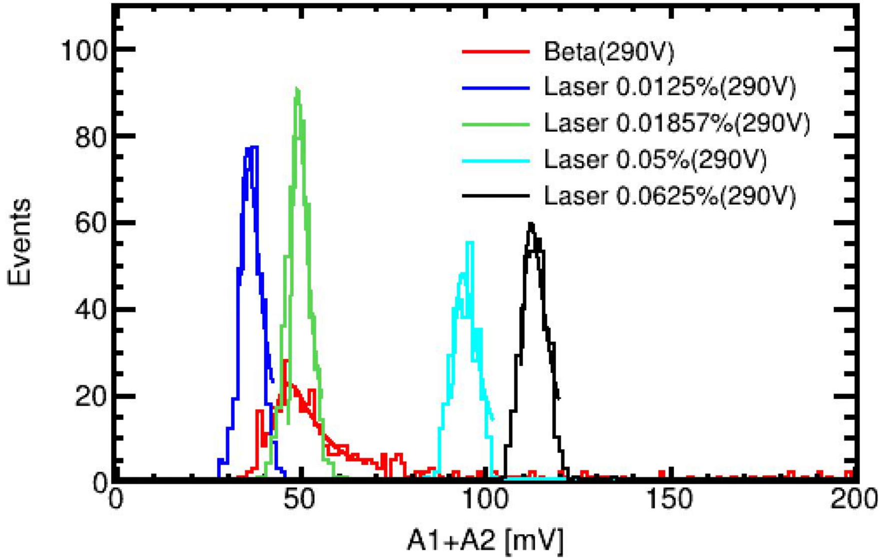
MIP-Equivalent Laser Intensity Tuning (i)

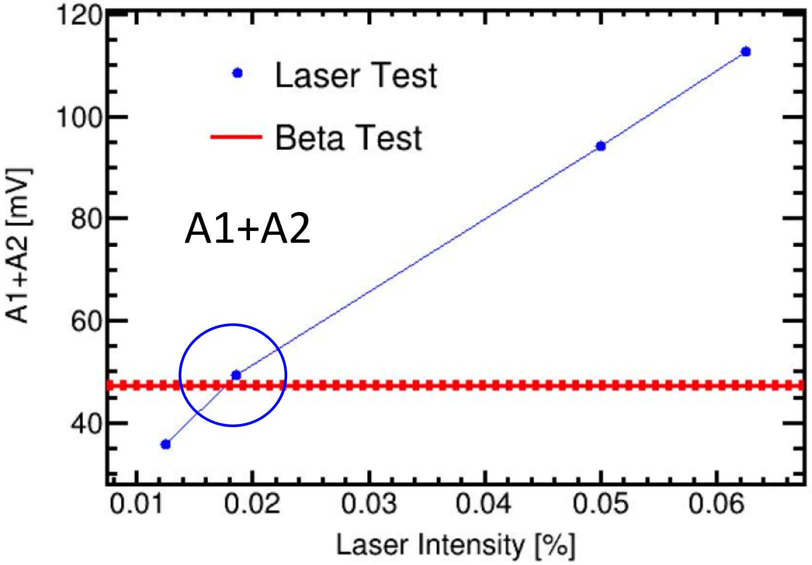
Strip sensor (W4-AC-D9, 2 cm)

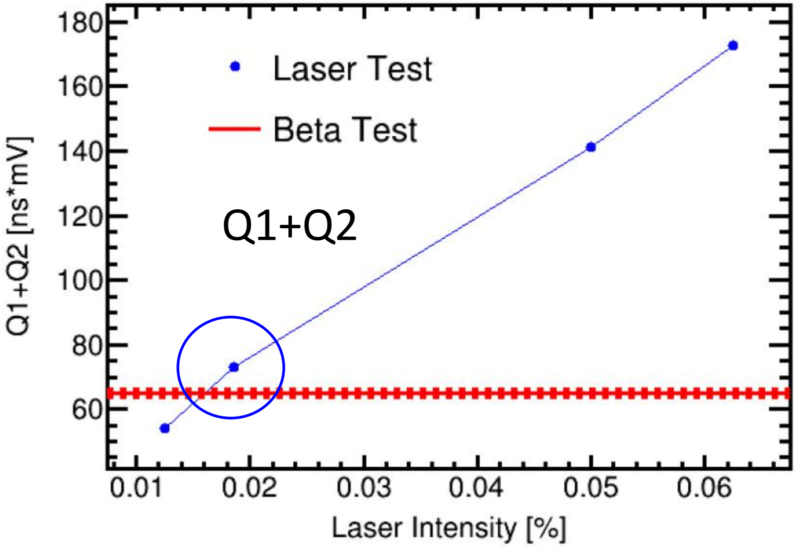




A1 and A2 are the waveform amplitudes of the seed (maximum amplitude) strip and the second strip, respectively.
Q1 and Q2 are the integral charge (negative polarity) of the corresponding waveforms.





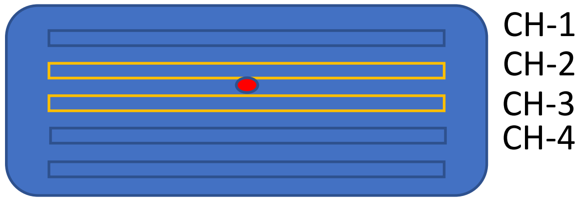


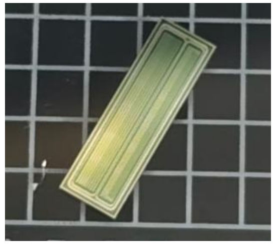
The laser intensity of 0.02% matches the MIP response in both amplitude and integrated charge.

15

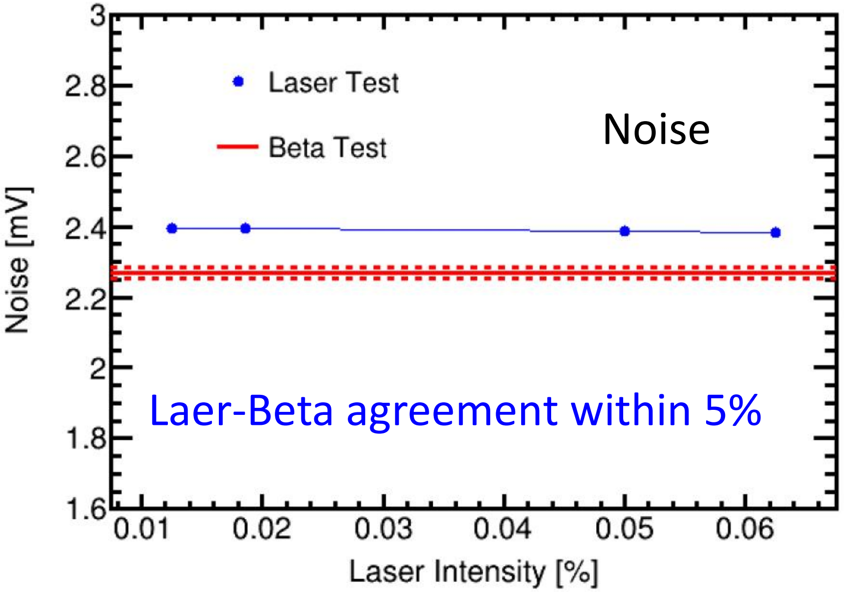
MIP-Equivalent Laser Intensity Tuning (ii)

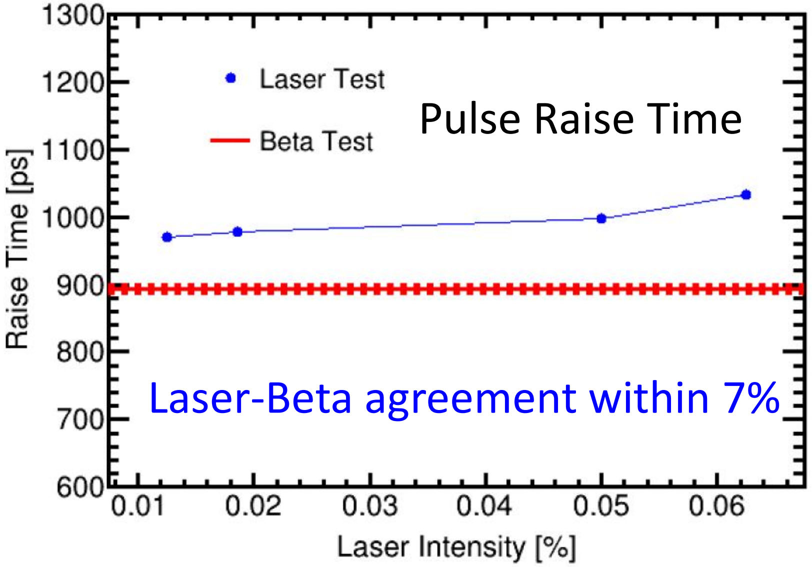
Strip sensor (W4-AC-D9, 2 cm)

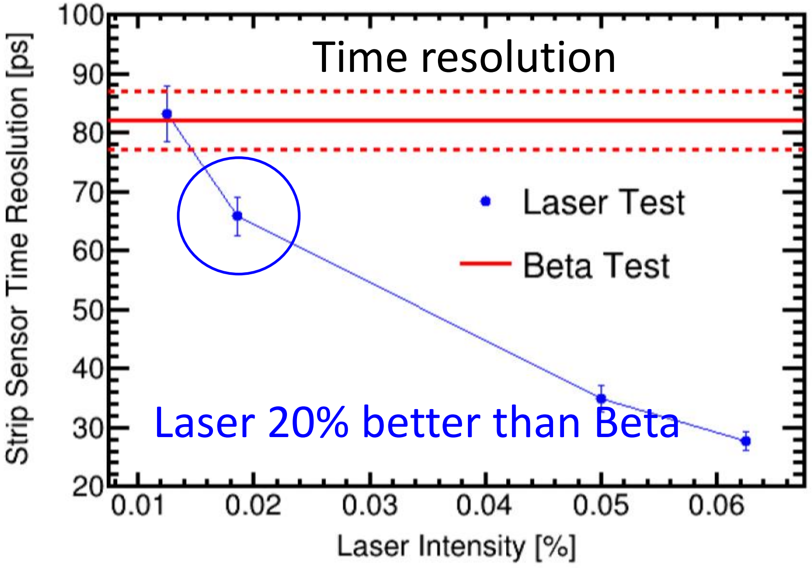




The tuned laser emulates the MIP amplitude, noise, and rise time well.







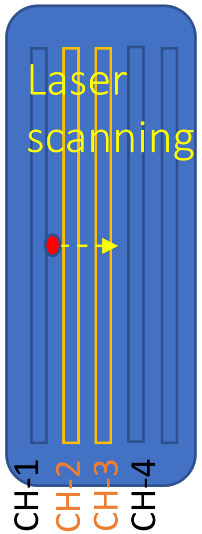
The time resolution of the strip sensor (W4-AC-D9, 2 cm) obtained from the laser test is ~65 ps, which is 20% better the beta test (~80 ps), as Landau fluctuations in dE/dx are absent in the laser measurements.

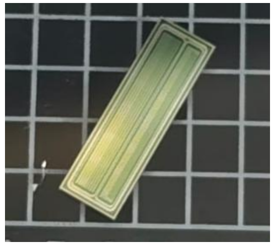
16

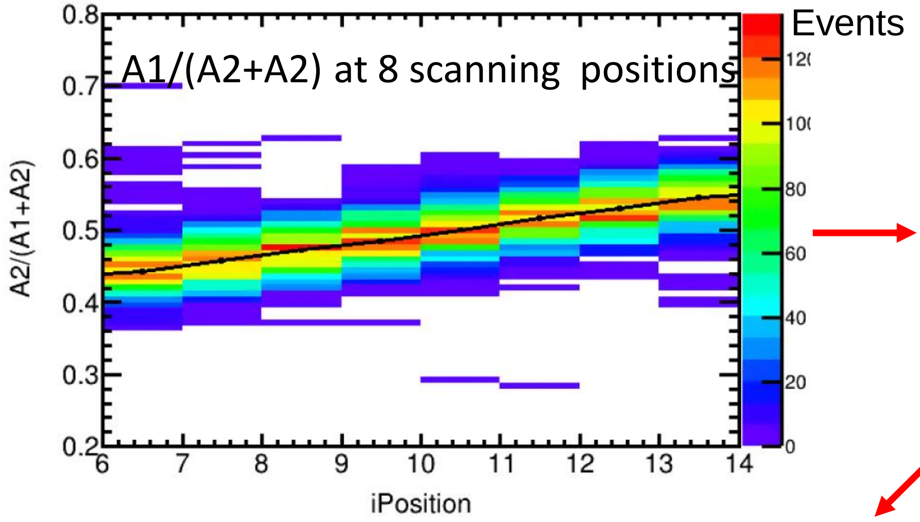
Strip Sensor Spatial Resolution with MIP-Equivalent Laser (0.02% Intensity)

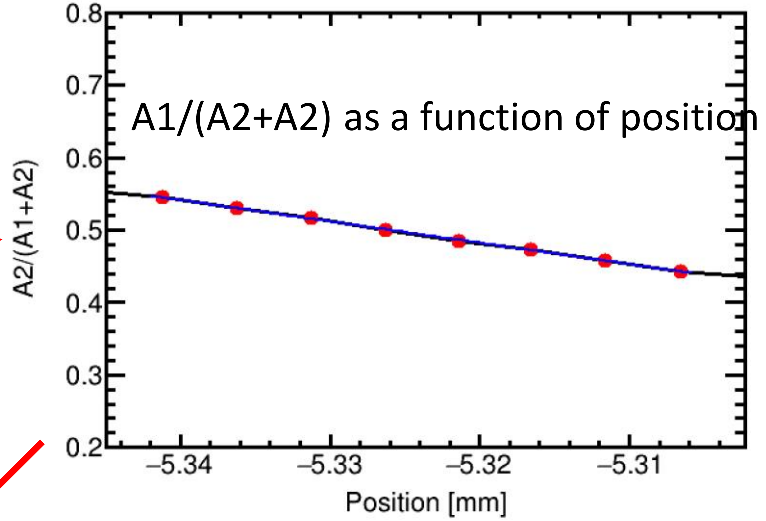
A_2 and A_1 are the waveform amplitudes of the seed (maximum amplitude) strip and the second strip, respectively.

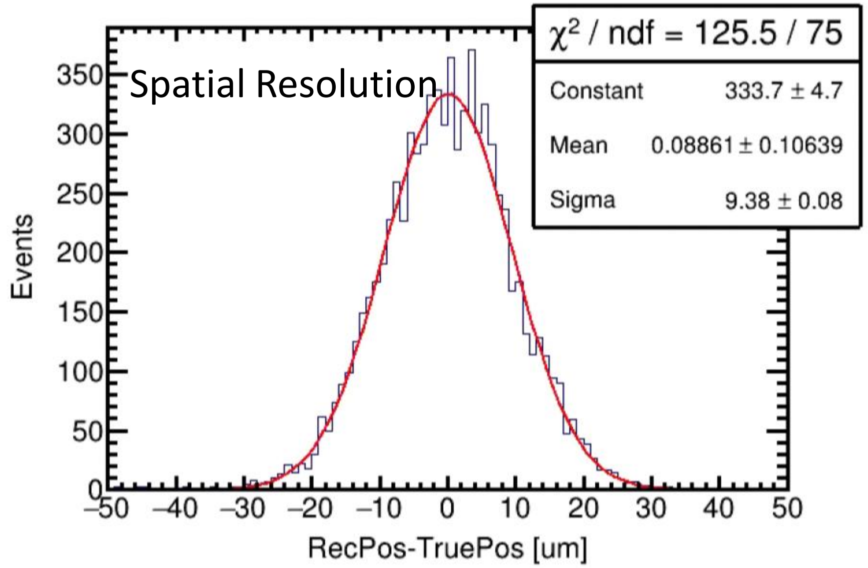
Strip sensor (W4-AC-D9, 2 cm):
Open window of 50 μm between 2 stirps





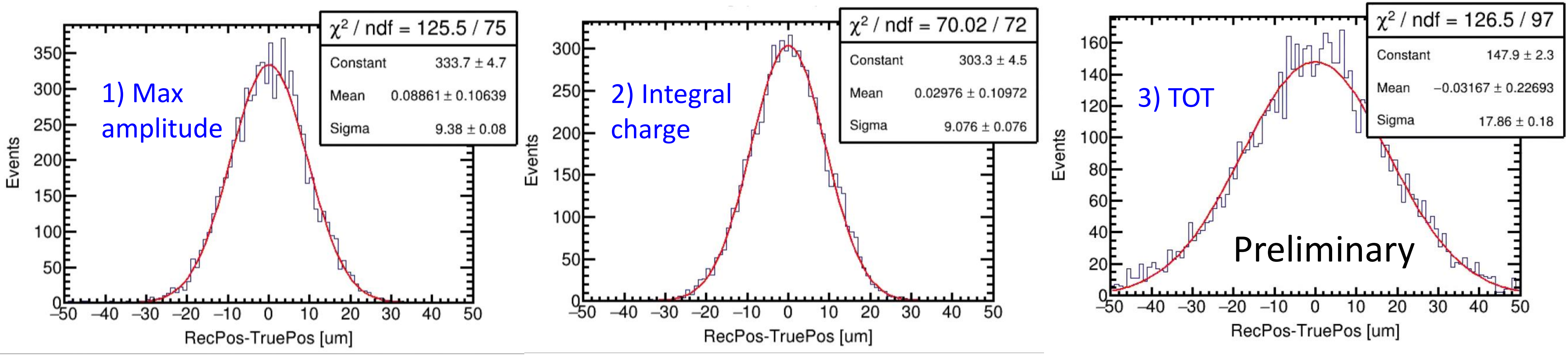






The latest tape-out optimized n^+ strip sensor (W4-AC-D9: 2 cm, pitch 100 μm, 50 μm electrode width, and n^+ dose = 0.1 p) achieved a spatial resolution of 9.4 μm.

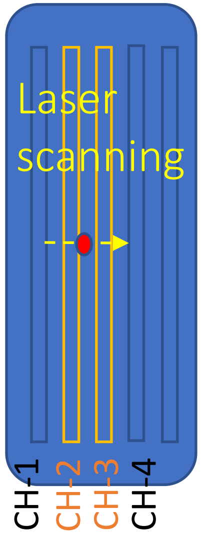
Sensor Spatial Resolution Using Different Amplitude Estimators



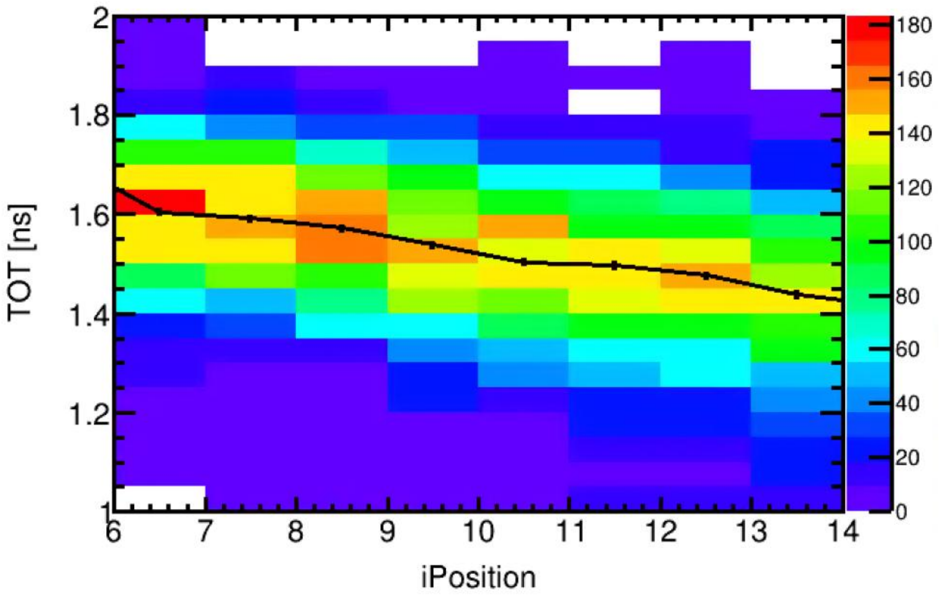
Achieving a spatial resolution below 10 μm using Time Over Threshold (TOT) information (LATRIC) with a 100 μm strip pitch appears to be challenging and may offer limited flexibility.

Sensor Spatial Resolution Measured Using TOT

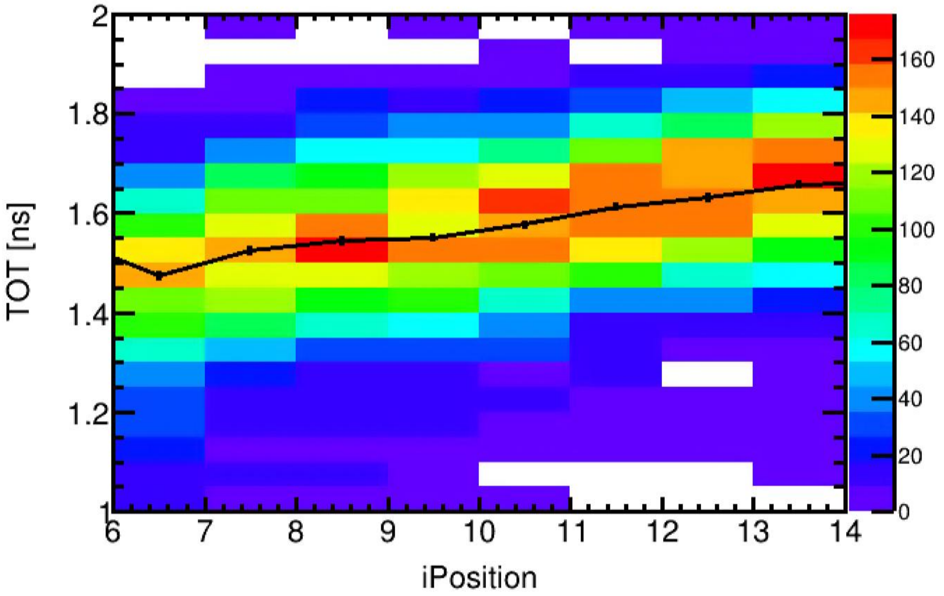
Scanning at 8 positions within the 50 µm open window between CH2 and CH3.



CH2 TOT



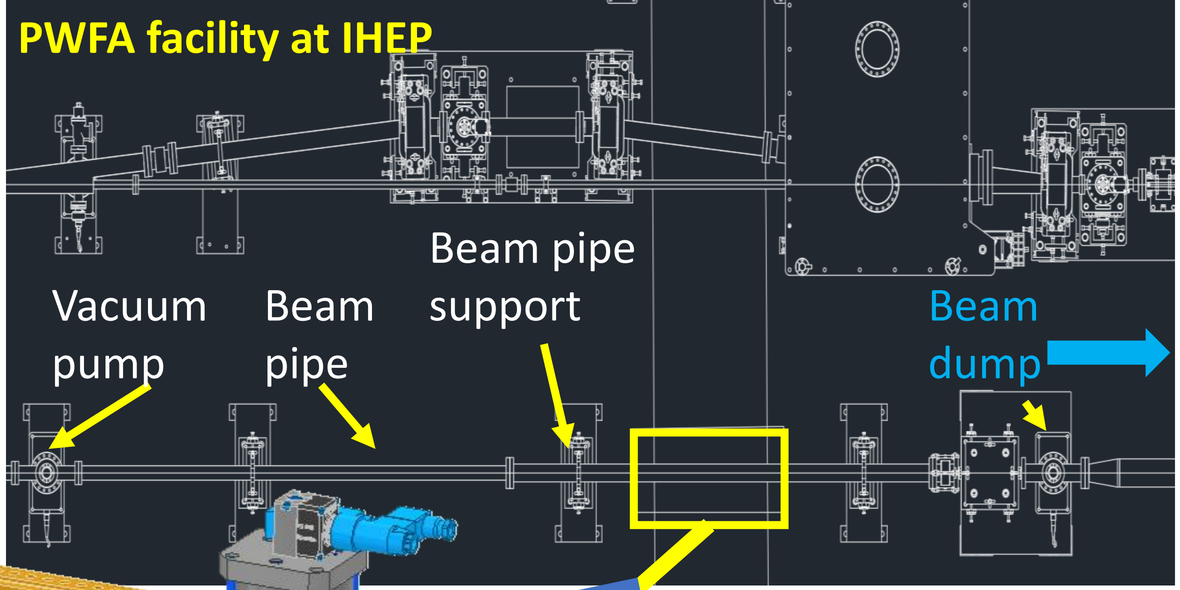
CH3 TOT

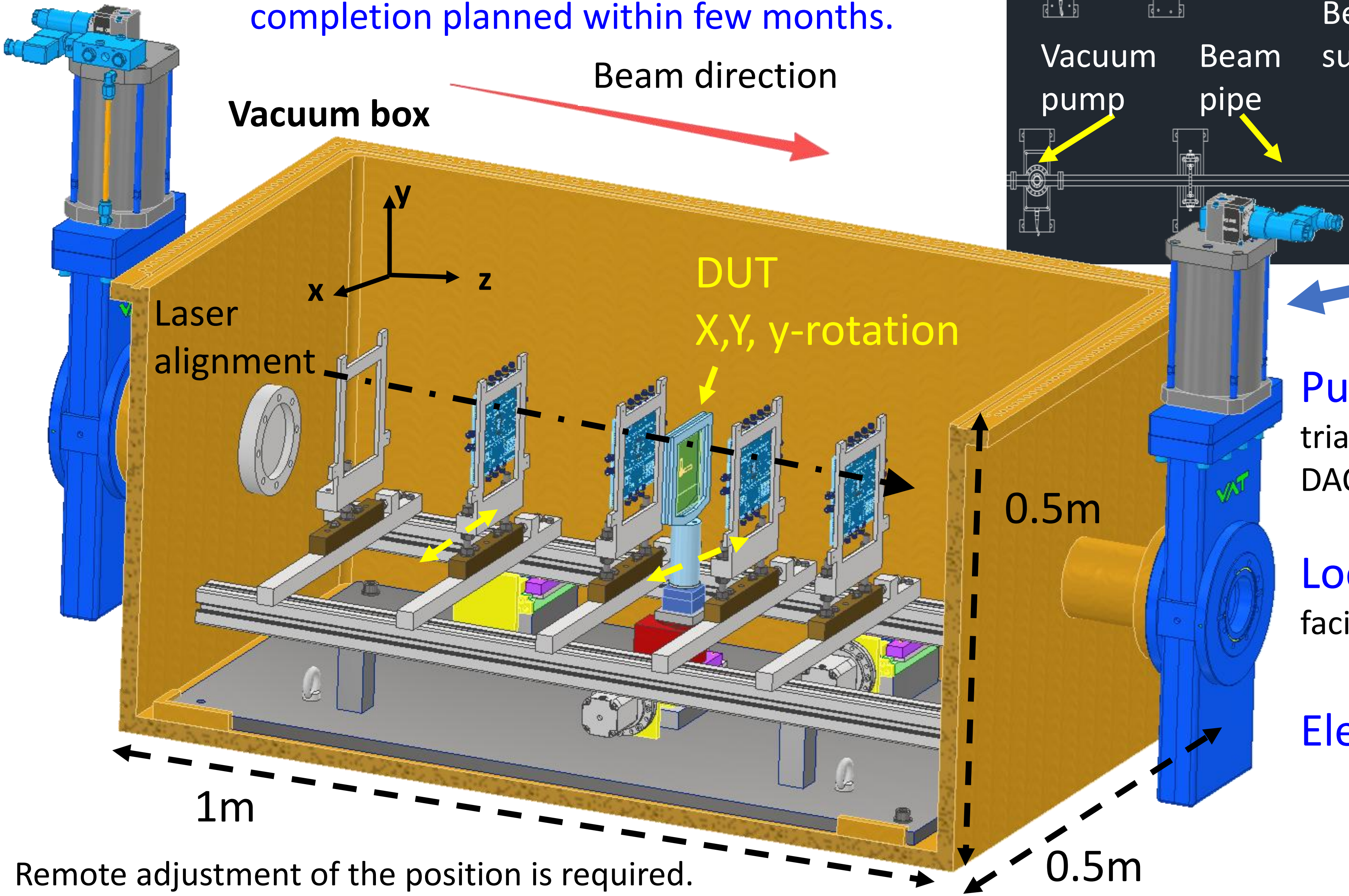


Achieving a spatial resolution below 10 µm using Time Over Threshold (TOT) information (LATRIC) with a 100 µm strip pitch appears to be challenging and may offer limited flexibility.

Beam Telescope

design is currently ongoing, with completion planned within few months.





Purpose: to facilitate initial beam trials and system evaluation (e.g., the DAQ) prior to higher-energy beam tests.

Location: Beam dump area at PWFA facility at IHEP.

Electron beam energy: ~2 GeV

Remote adjustment of the position is required.

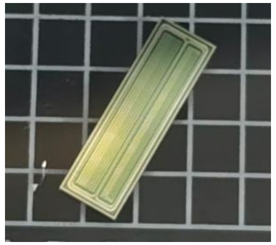
Summary

- Develop AC-LGAD and its readout ASIC, LATRIC.
- Laser and beta source test has been performed.
- Preliminary timing and position resolution studies with laser and beta source
  - Laser intensity tuned to beta (MIP) equivalent signal
- Developing IHEP in-house beam test facilities.

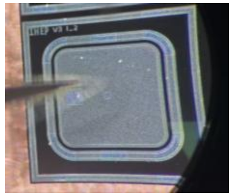
Additional Slides

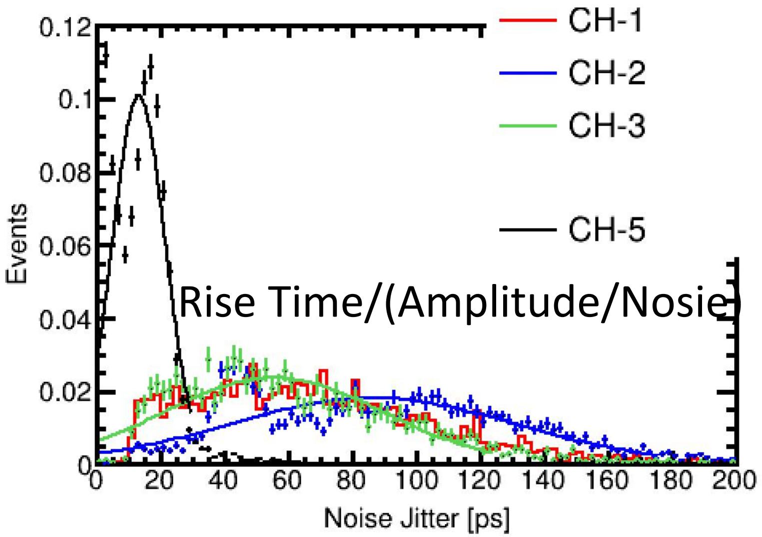
Noise Jitter=R_{rise} Time/(S/N)

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

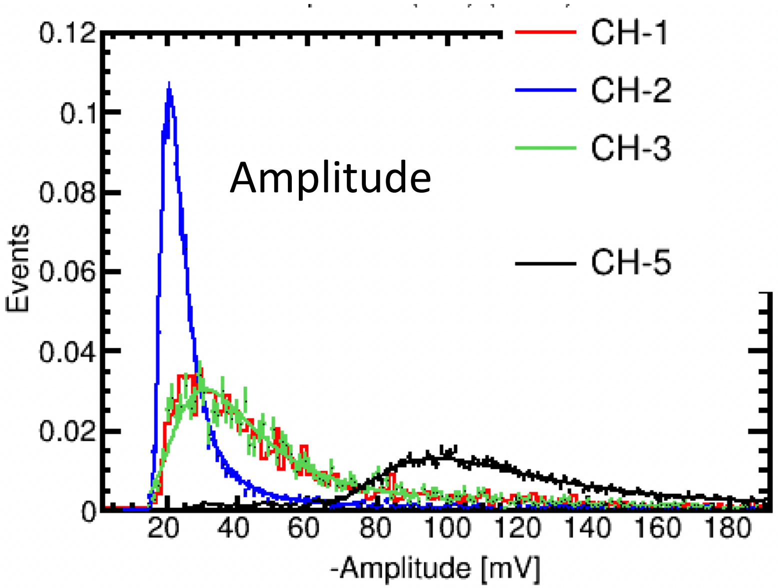


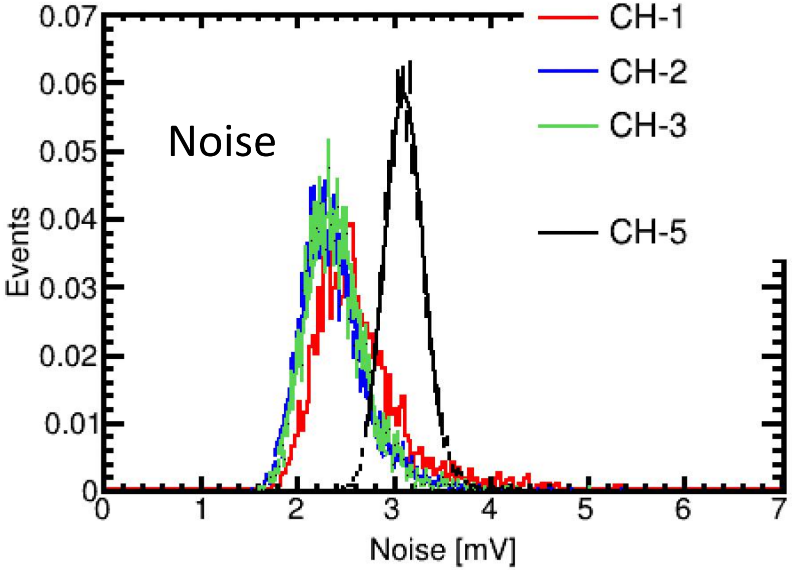
CH-5 (DC, W4-DC-D6)

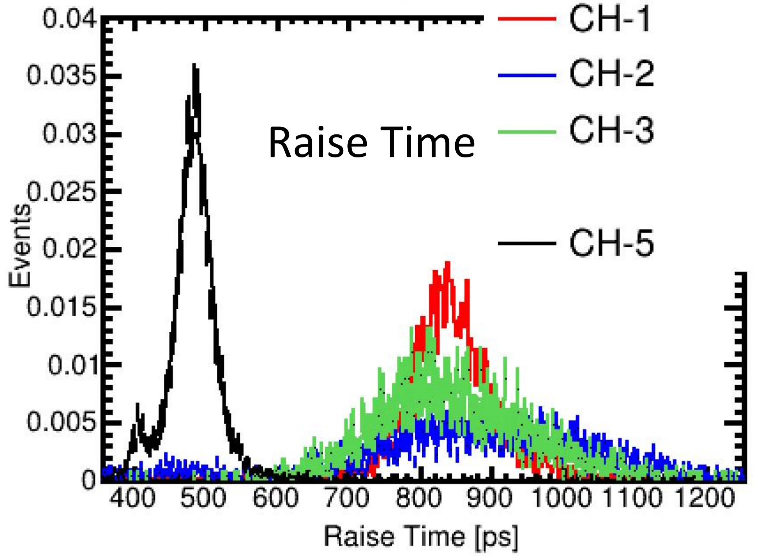




The pulse of strip sensor has substantially smaller amplitude and longer rise time than DC-pad sensor. The mean “noise jitter” is ~80 ps, consistent with the estimated time resolution from the beta test.





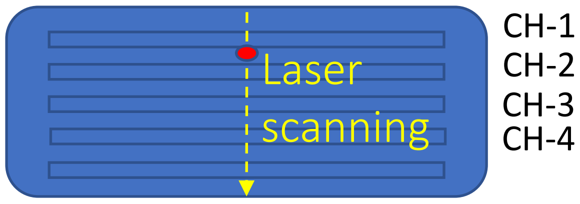


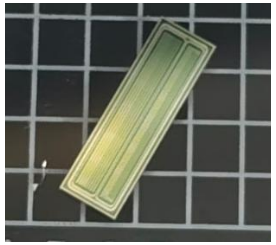
23

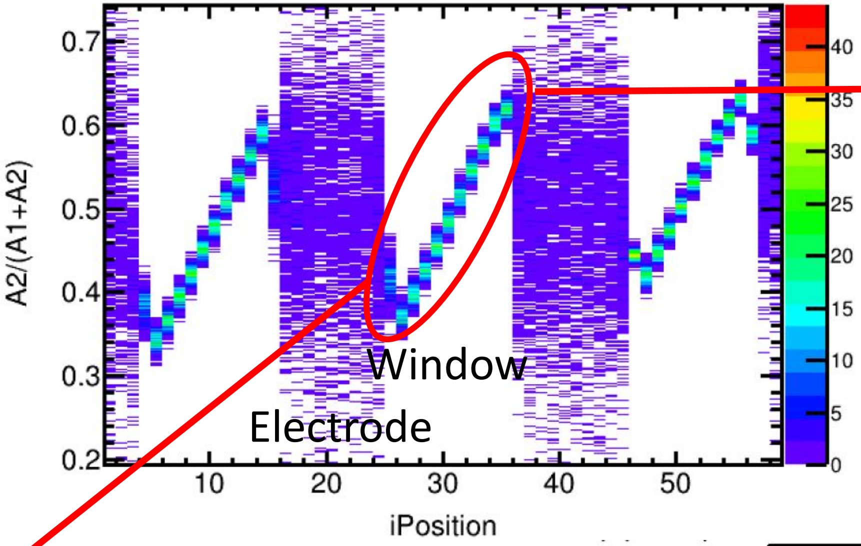
Strip Sensor Spatial Resolution (0.2% Laser)

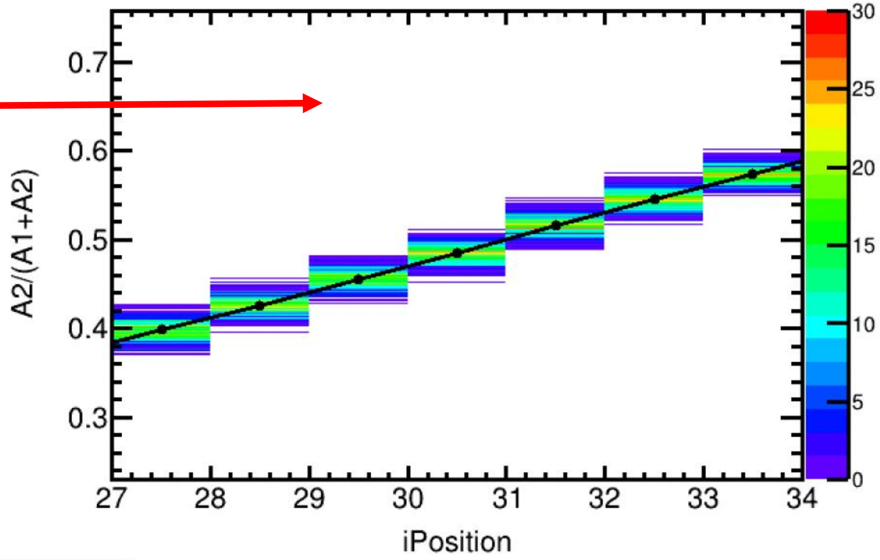
A_2 and A_1 are the waveform amplitudes of the seed (maximum amplitude) strip and the second strip, respectively.

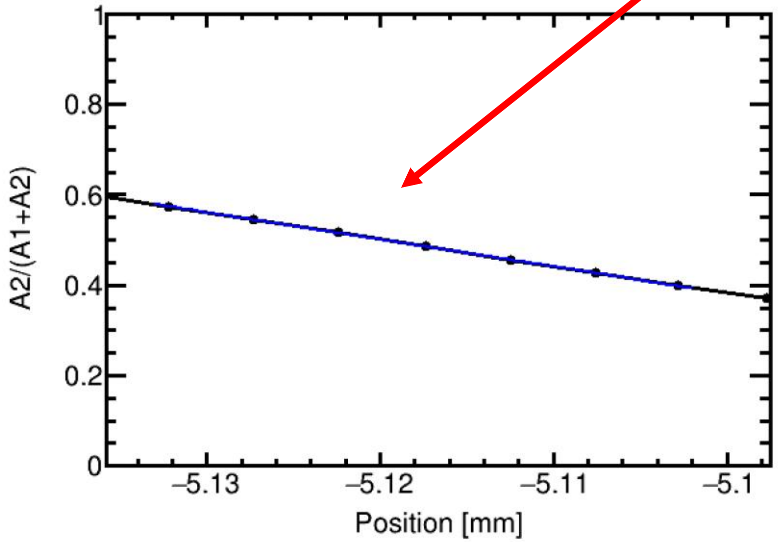
DUT sensor

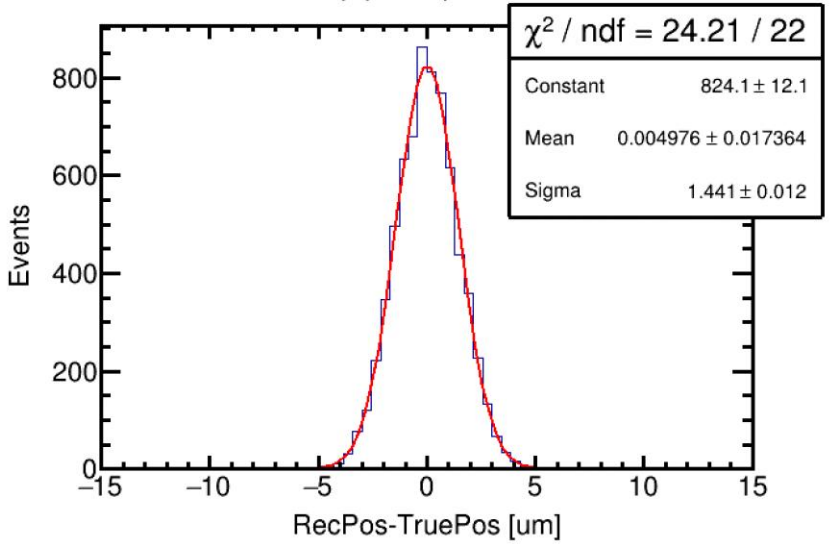




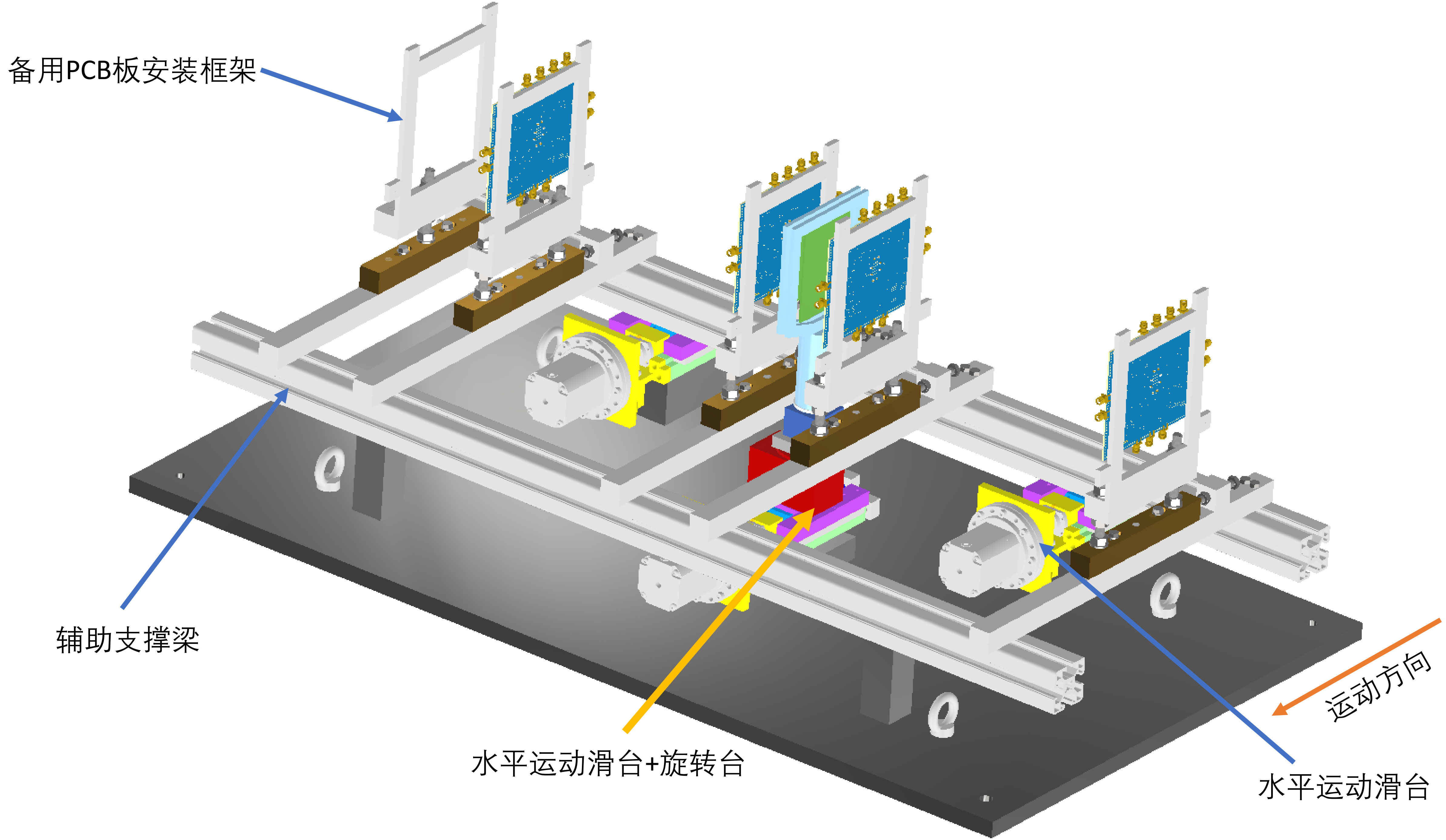


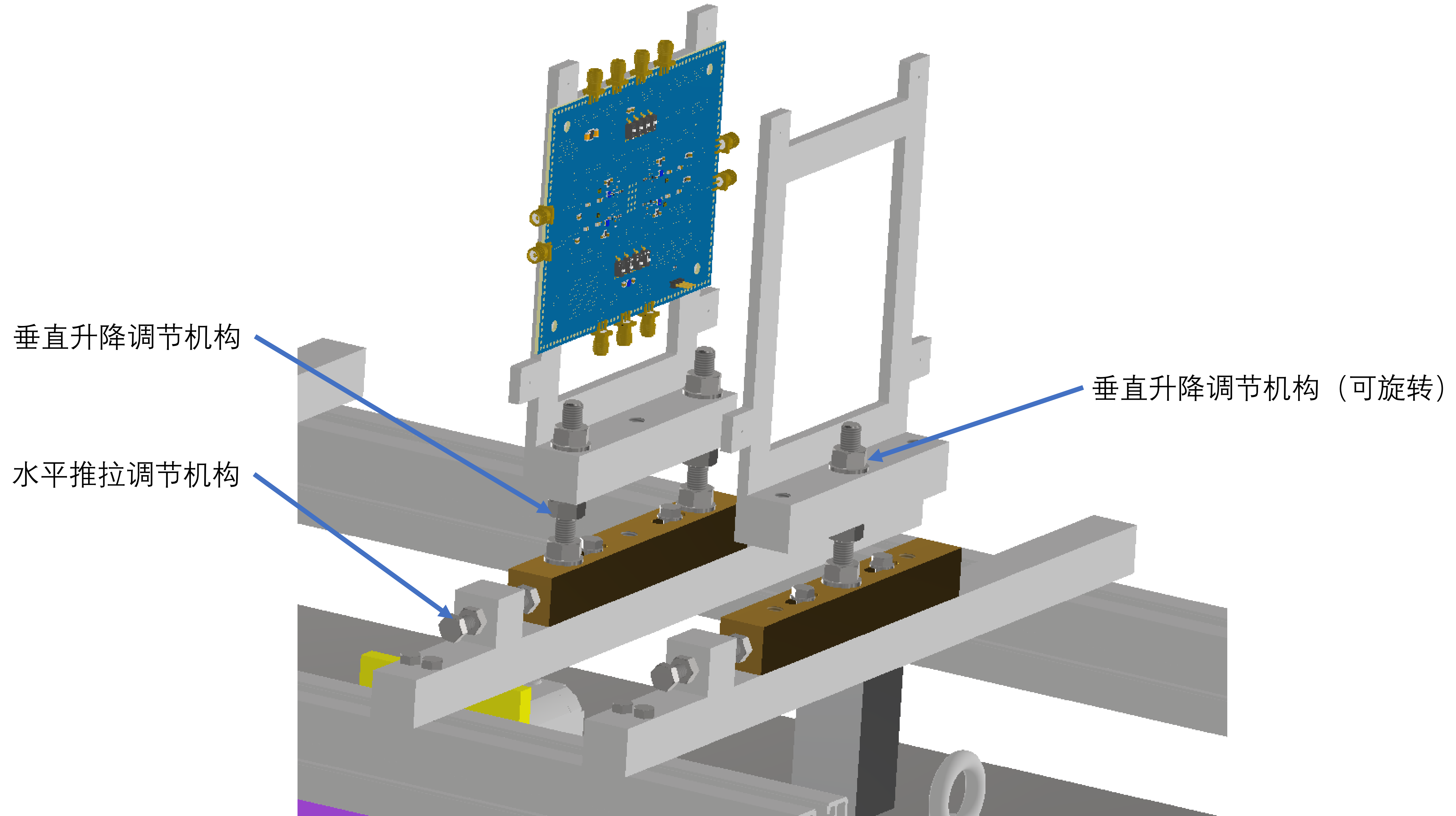




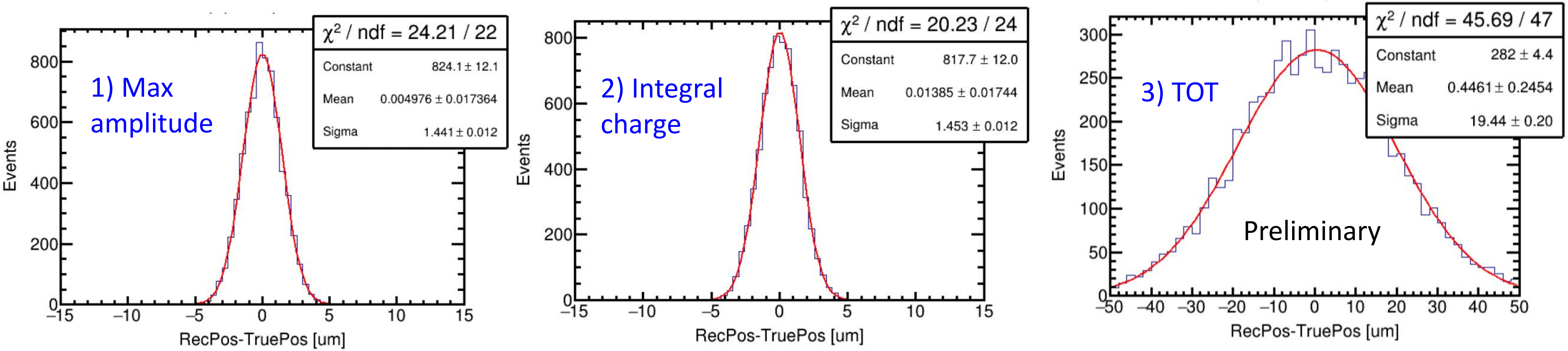


The latest tape-out optimized n^+ strip sensor (W4-AC-D9, 2 cm, n^+ dose = 0.1 p) achieved a spatial resolution of ~1.4 µm.


备用PCB板安装框架
辅助支撑梁
水平运动滑台+旋转台
运动方向
水平运动滑台

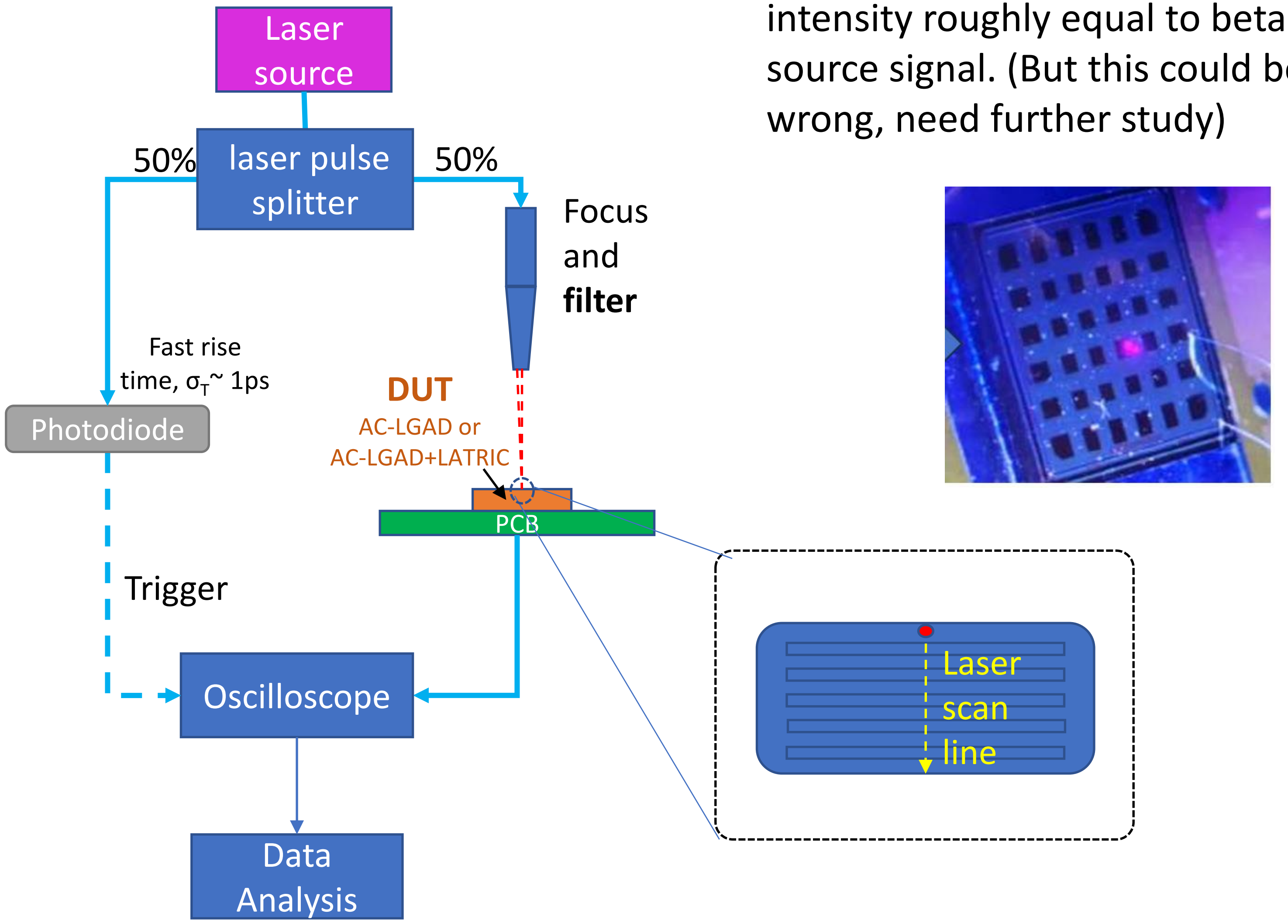

垂直升降调节机构
水平推拉调节机构
垂直升降调节机构（可旋转）

Sensor Spatial Resolution Using Different Amplitude Estimators

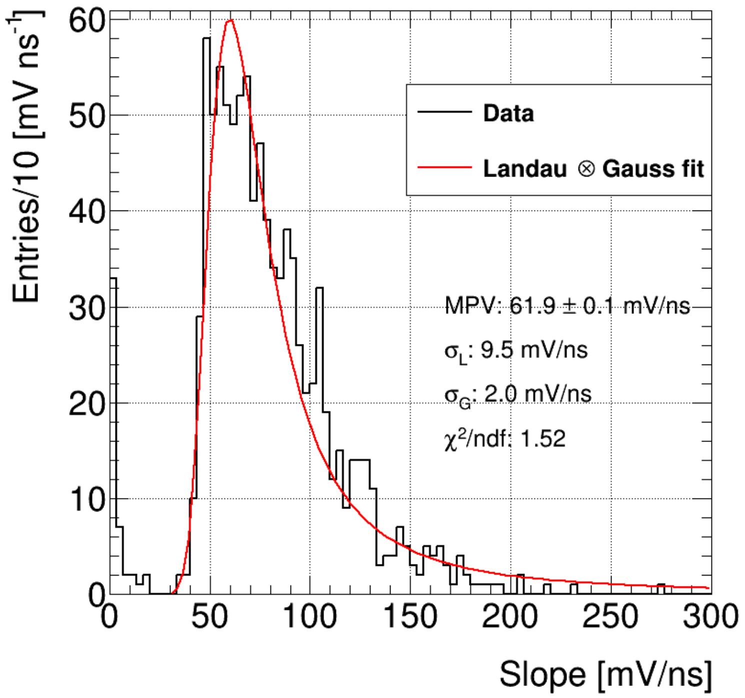


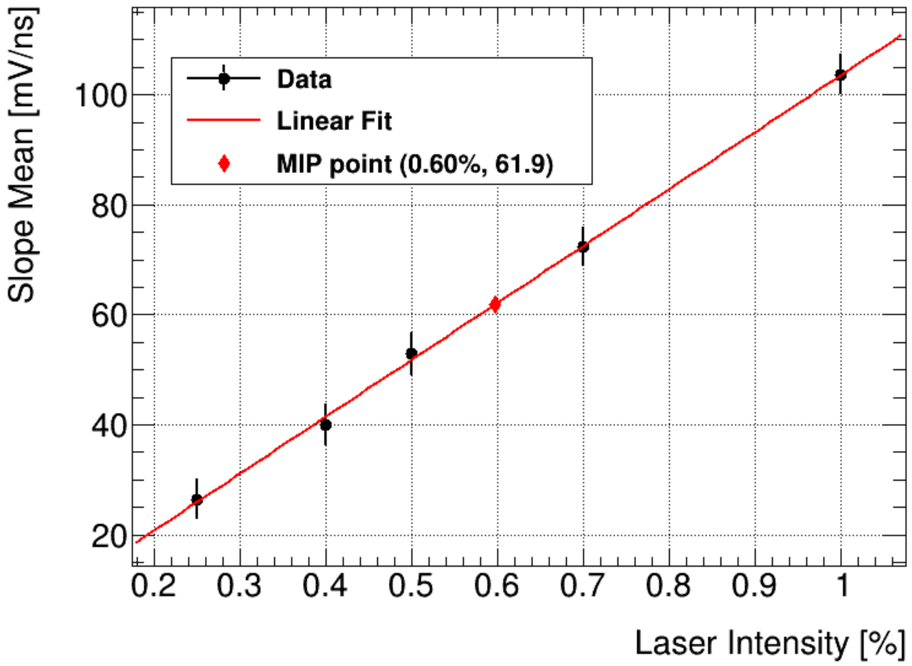
Achieving a spatial resolution below 10 μm using LATRIC's Time-Over-Threshold (TOT) information with a 100 μm strip pitch appears to be challenging and may offer limited flexibility.

Laser TCT Setup



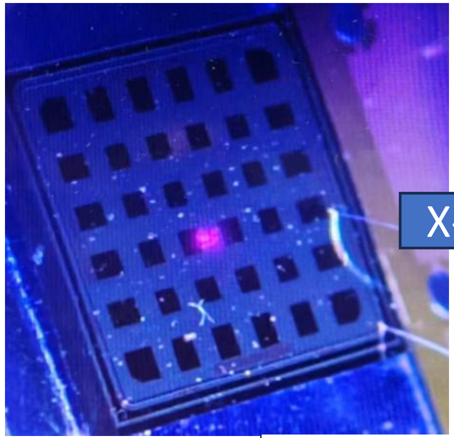
Earlier study with a DC sensor showed signal @ ~0.5% laser intensity roughly equal to beta source signal. (But this could be wrong, need further study)



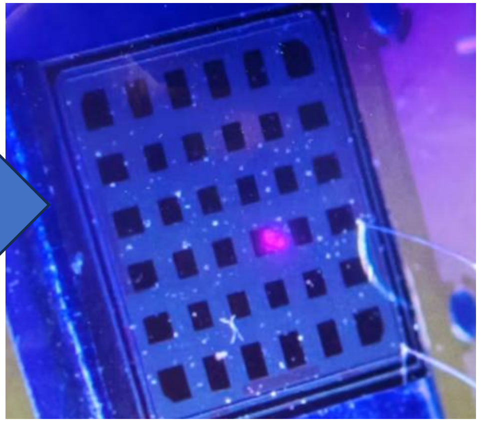


Hardware–Software Co-Designed Test System (Automated Knife-Edge Laser Scanning)

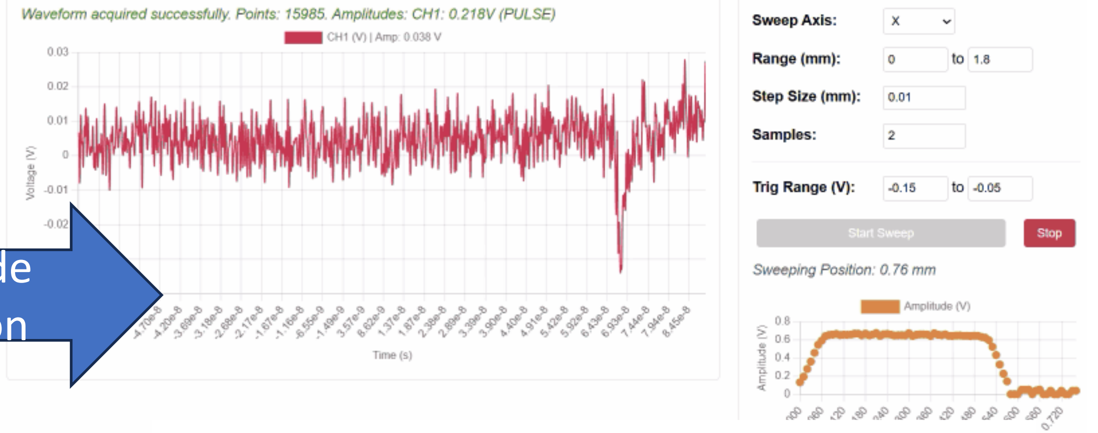
Automatic piezo-stage motion control → Data acquisition and transfer → Laser spot analysis → Automatic Z-axis adjustment → Iterative optimization of Z_0 (micron-level focusing precision) to minimize the laser spot size



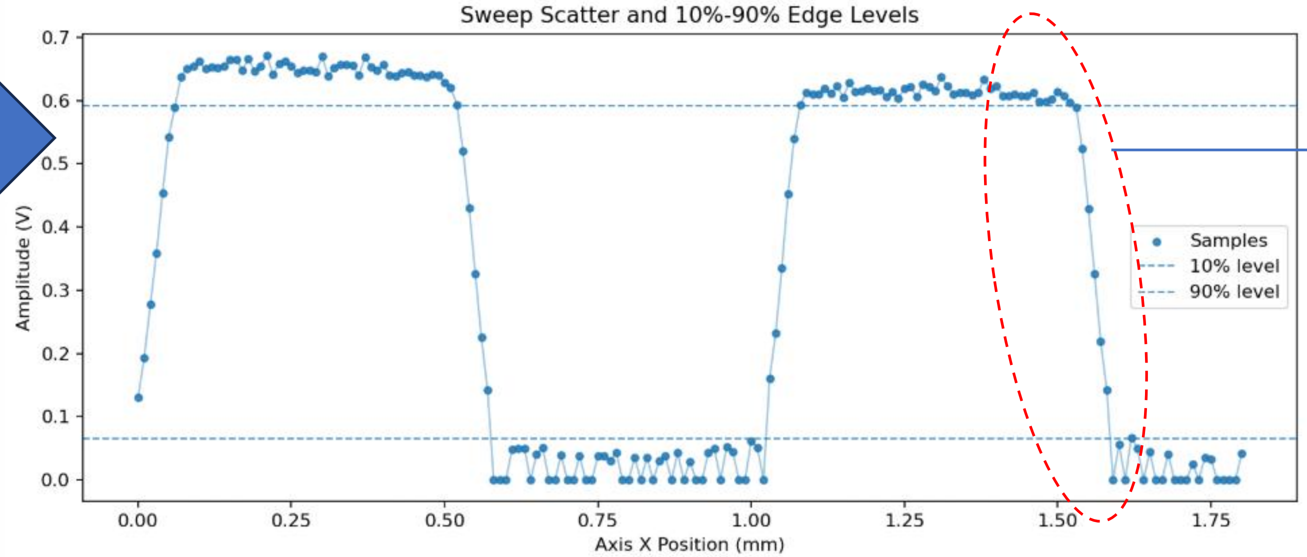
X-axis motion

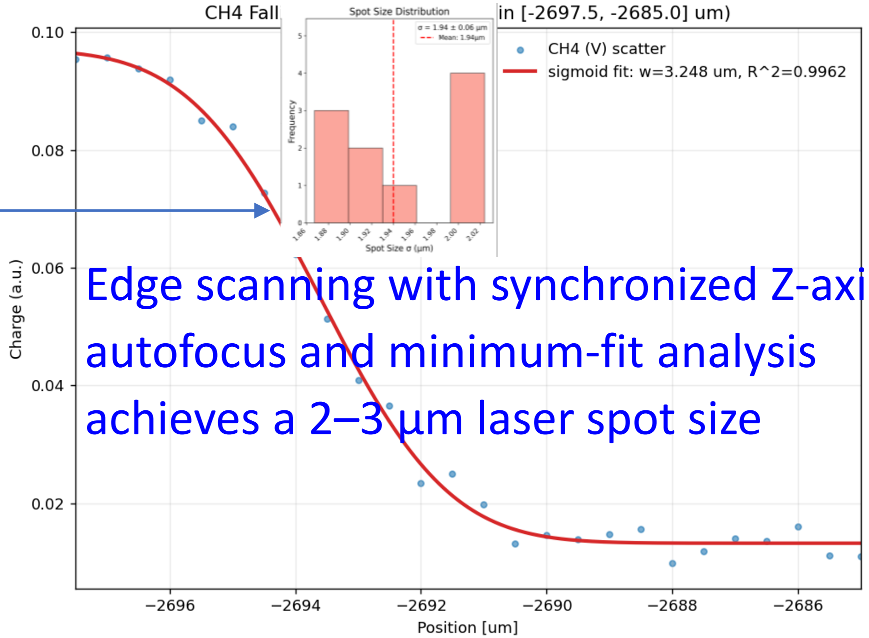


Amplitude extraction



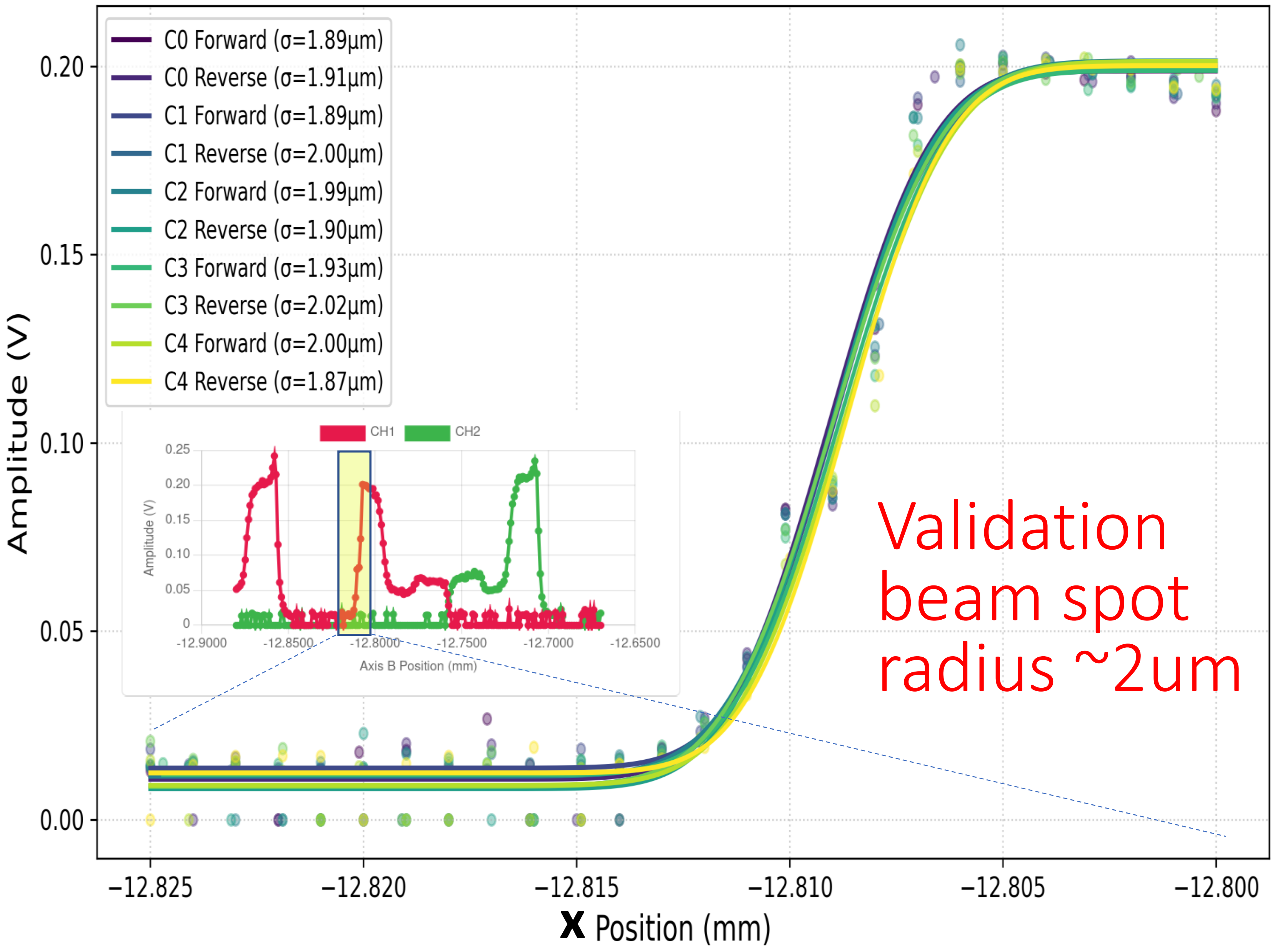
Scan output

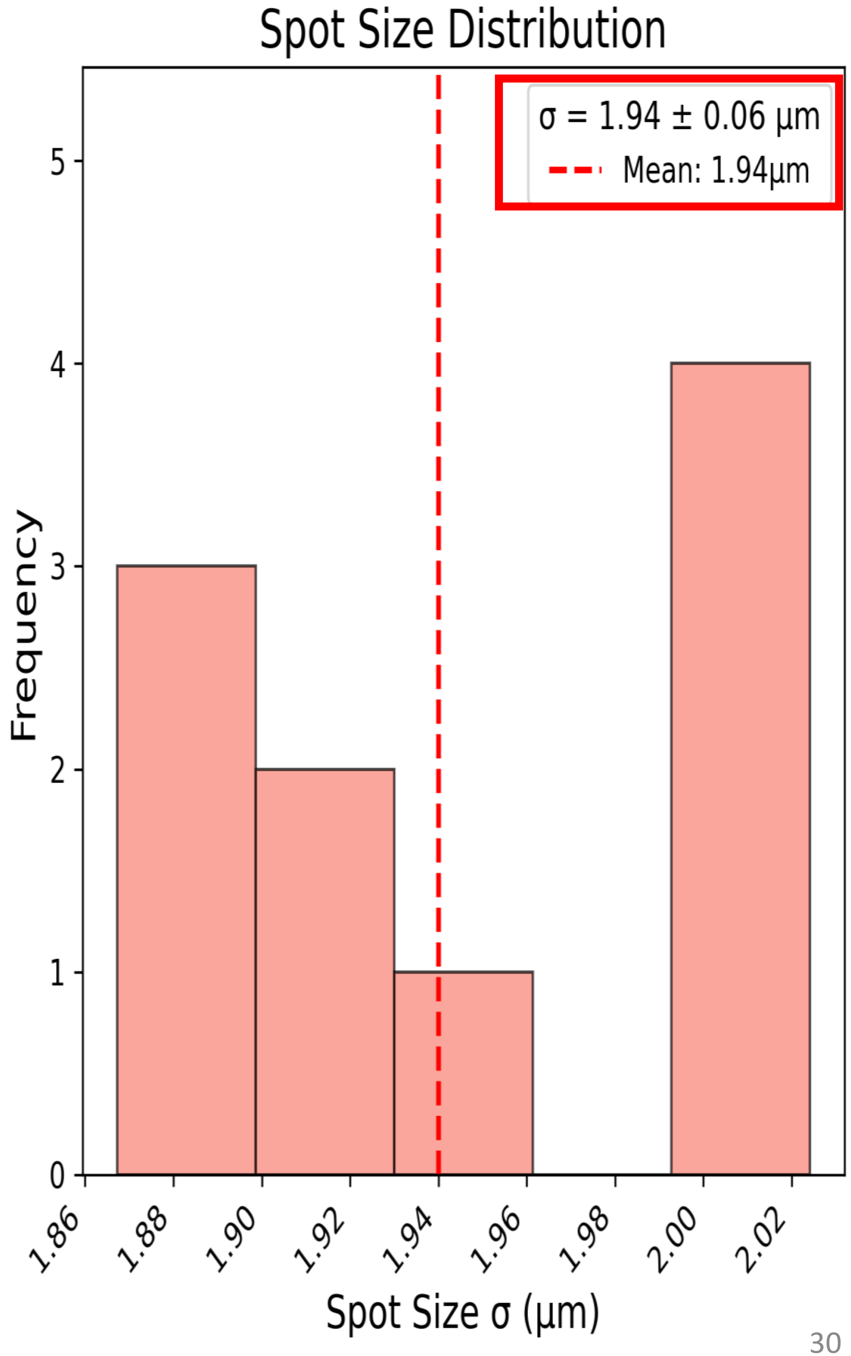




Edge scanning with synchronized Z-axis autofocus and minimum-fit analysis achieves a 2–3 μm laser spot size

At Z=0.295

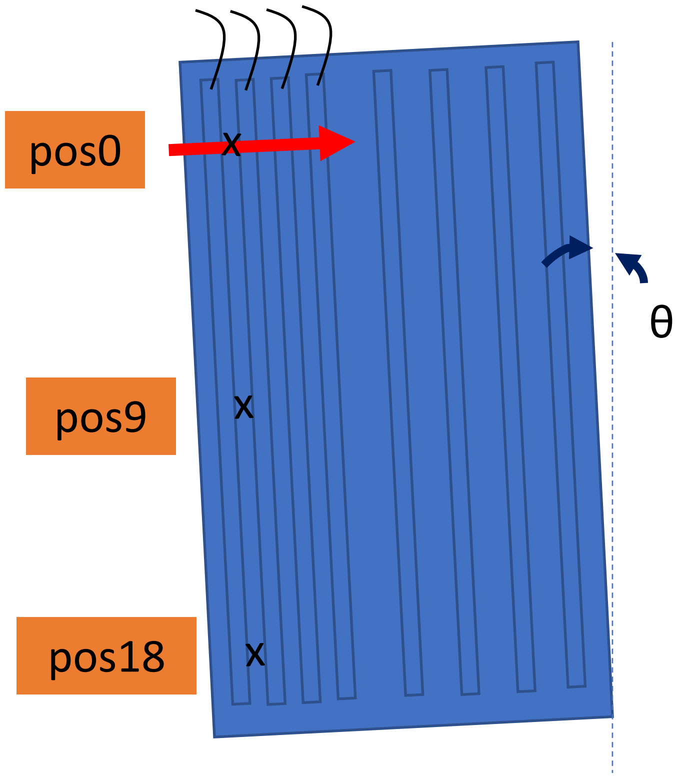

Knife-Edge Scans & Erf Fits (CH1)
C0 Forward (σ=1.89μm)
C0 Reverse (σ=1.91μm)
C1 Forward (σ=1.89μm)
C1 Reverse (σ=2.00μm)
C2 Forward (σ=1.99μm)
C2 Reverse (σ=1.90μm)
C3 Forward (σ=1.93μm)
C3 Reverse (σ=2.02μm)
C4 Forward (σ=2.00μm)
C4 Reverse (σ=1.87μm)
Amplitude (V)
X Position (mm)
CH1
CH2
Amplitude (V)
Axis B Position (mm)
Validation beam spot radius ~2um


Spot Size Distribution
σ = 1.94 ± 0.06 μm
Mean: 1.94μm
Frequency
Spot Size σ (μm)

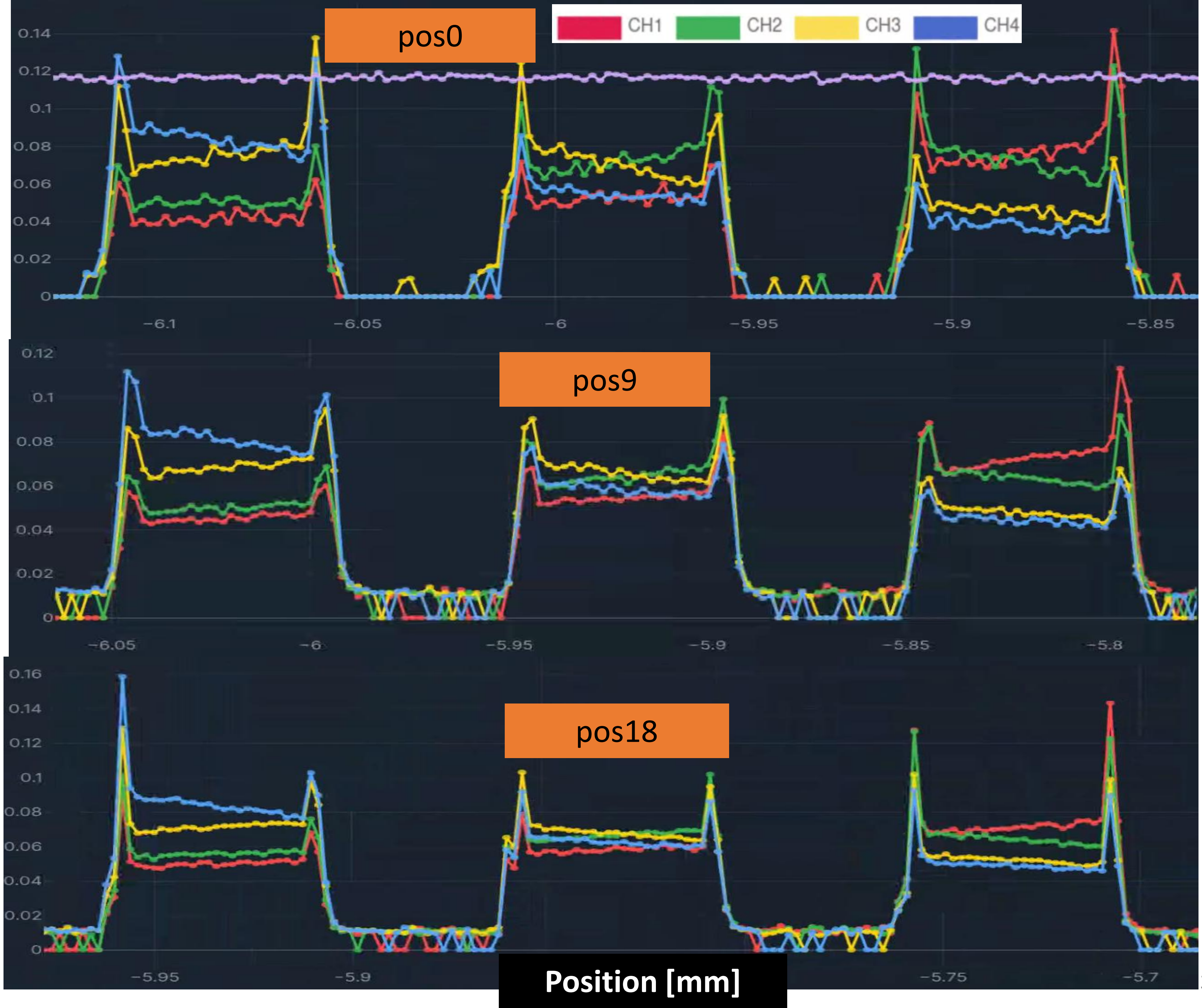
W4-AC-D7-2-1 (n^+ =1P)

Lateral scan (0.005/step)

x Longitudinal scan (3 points)



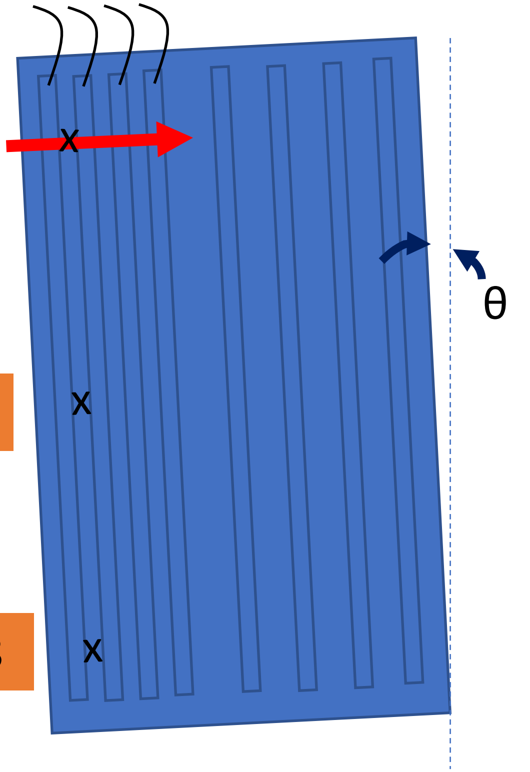
EPI thickness: 50 µm
Strip length: 2cm
Pitch: 100 µ m
Gap :50 µ m



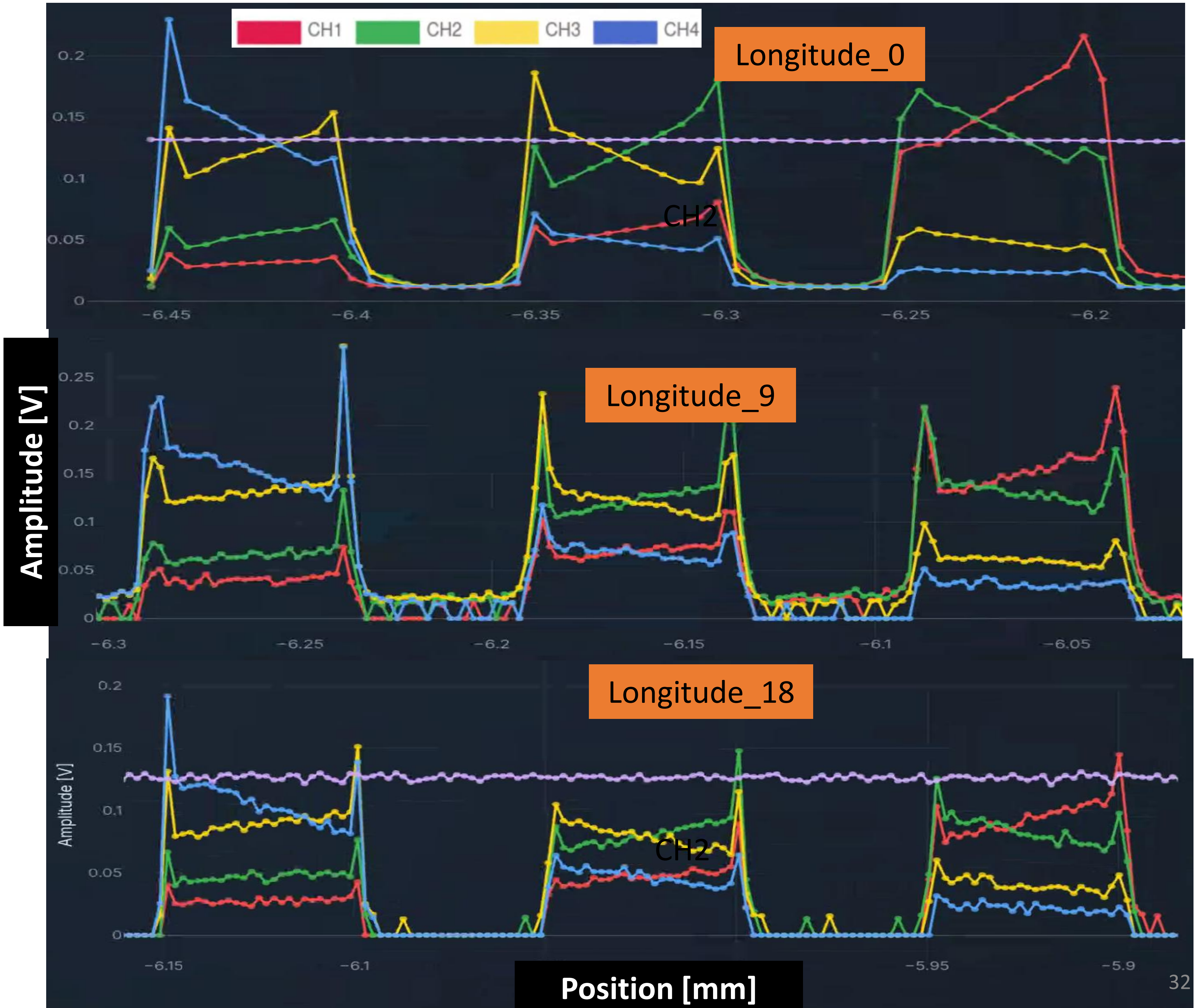
W4-AC-D9-2-1 ($n^+ = 0.1P$)

Lateral scan (0.005/step)

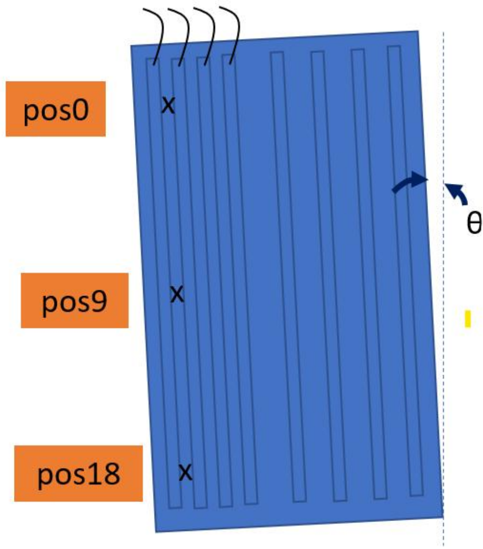
x Longitudinal scan (3 points)



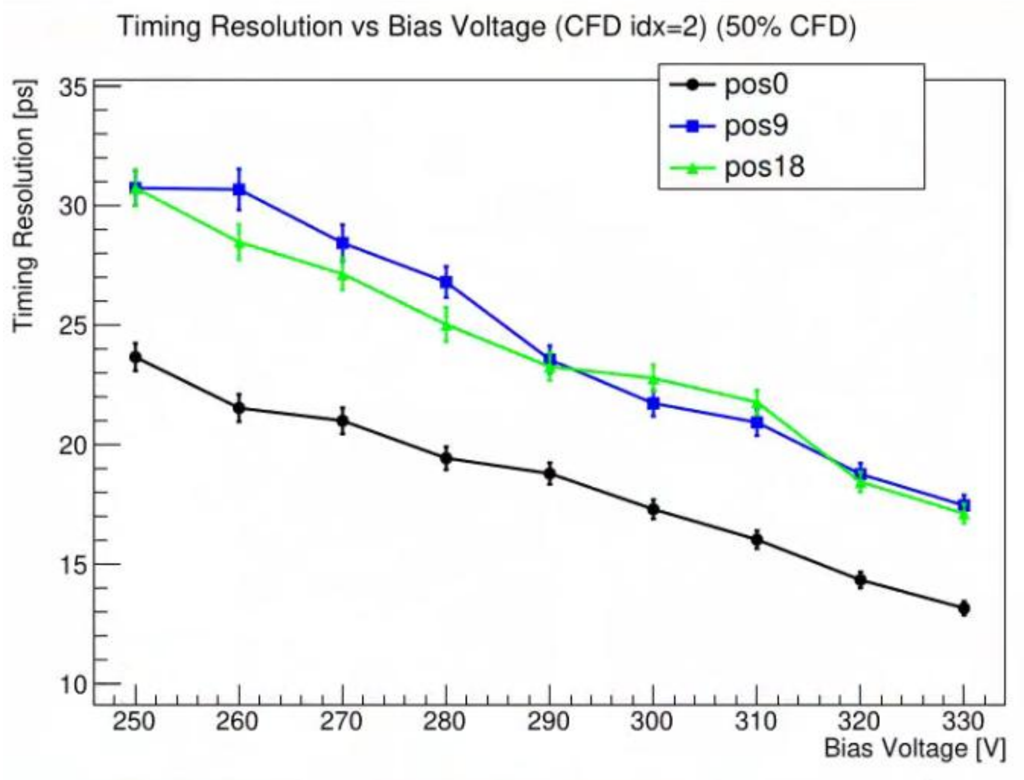
EPI thickness: 50 μ m
Strip length: 2cm
Pitch: 100 μ m
Gap :50 μ m



- Preliminary result: timing resolution versus bias voltage at different longitudinal position.
  - Still need to verify every step of analysis algo.



W4-AC-**D7**-2-1_-300V



W4-AC-D9-2-1_-270V