中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Preparation of the AC-LGAD test

Hanwen Wang
on behalf of the LGAD team

CEPC Silicon Tracker Group Meeting
2025.08.15

个人简介

- 王翰文，于**北京航空航天大学**（2016–2023年）和**布鲁塞尔自由大学**（2018–2023年）获得粒子物理学双博士学位。
- **博士期间**，我的研究主要集中在利用大型强子对撞机（LHC）上的紧凑型μ子线圈（CMS）探测器**测量希格斯玻色子性质**，作为H->ZZ->2l2v off-shell分析的主要贡献者，首次发现了希格斯粒子离壳产生的证据，并实现了迄今为止最精确的希格斯玻色子宽度测量 *Nature Physics vol. 18, p1329–1334 (2022)*。
- 自2023年2月起，我在中国科学院高能物理研究所（IHEP）从事**博士后工作**，研究方向起始于中微子物理领域的光探测器技术
- nEXO无中微子双β衰变实验：极低本底硅晶圆转接板的研发 *Neutrino 2024 id. 294*
- JUNO-TAO反应堆中微子实验：大规模（4000+ 片）**硅光电倍增管**（SiPM）的低温(-50℃)性能测试与表征、老化测试、质量验收、探测器能量分辨率估计及探测器集成与安装工作。*JINST 19 P07028*，*Neutrino 2024 id. 279*
- 从2025年6月起，参与CEPC硅径迹探测器项目，参加研制原理样机的研制工作，承担OTK LGAD全面测试的计划与筹备、以及基于双相CO_2的半导体探测器冷却技术的研发，未来也将参与生产线上AC-LGAD全工艺流程的验证与优化。

Low Gain Avalanche Detectors (LGAD)

For collider physics (GeV particle detection, not single photon)

- Keep charge information
- High timing resolution (20-30 ps)

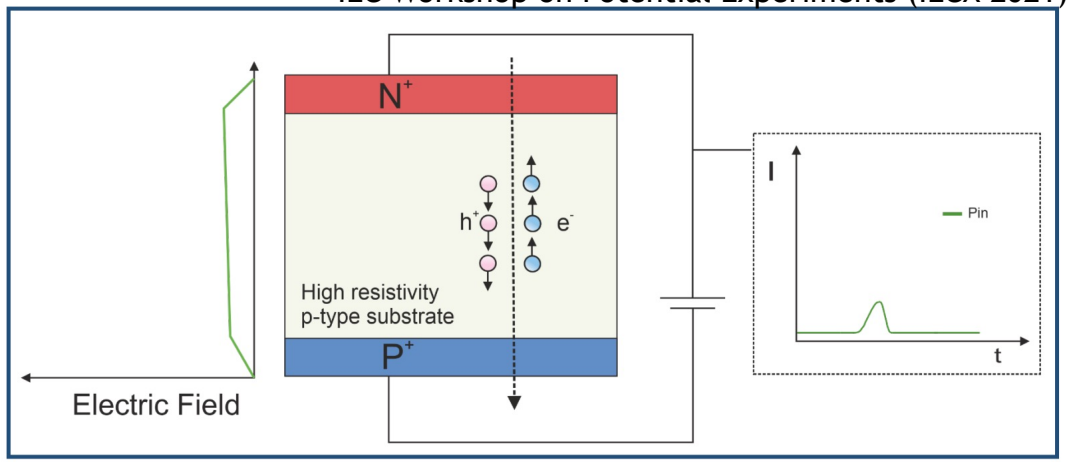
Low gain ‘APD’

⇩

LGAD

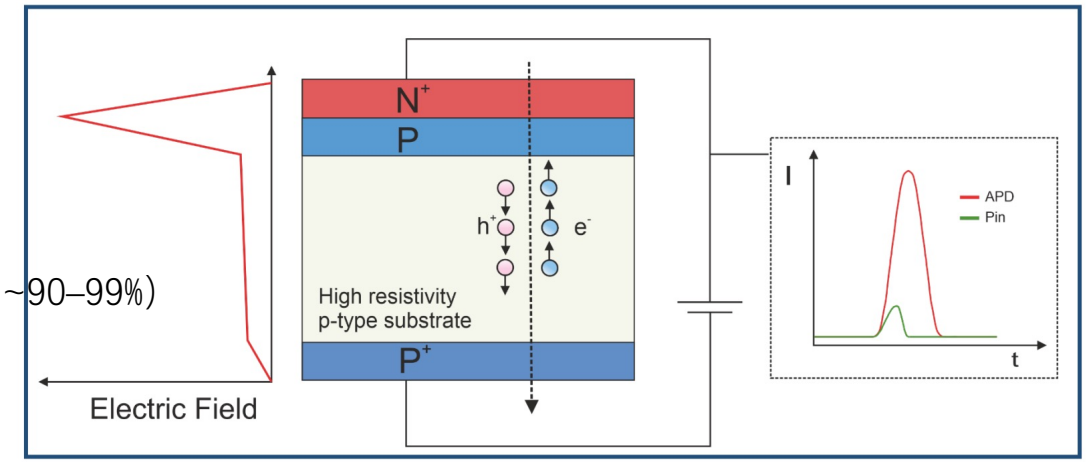
PIN
n^+-p

漂移时间分布宽，
时间分辨较差
（通常>100 ps）



APD
n^+-π-p

反偏接近雪崩击穿电压（~90–99%）
全漂移区形成高电场
时间分辨可以做到几百ps
但受限于增益 (1e2~1e3)
和SNR

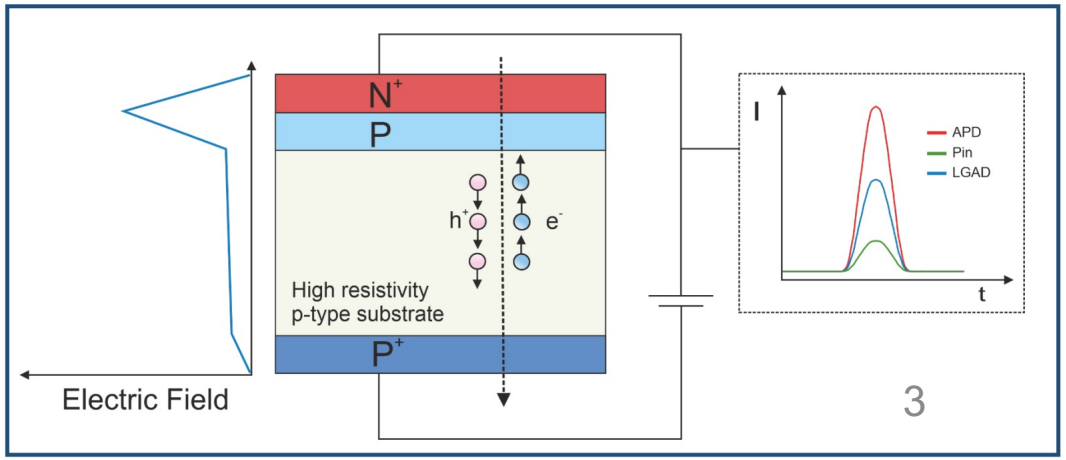


SAPD/SiPM

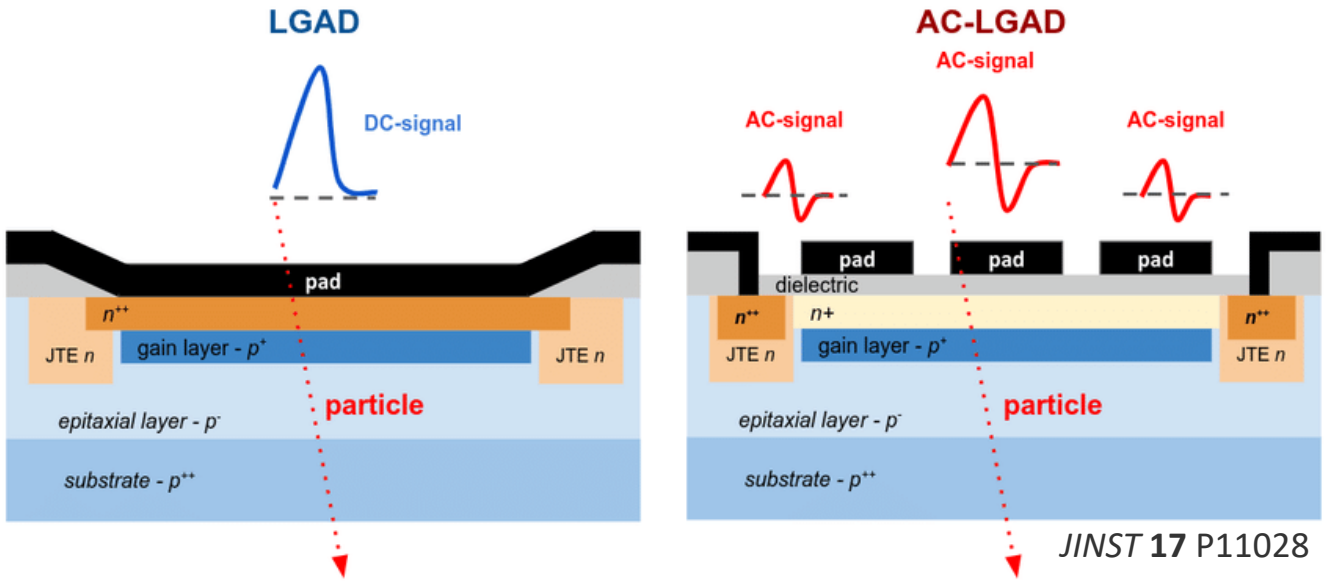
工作在击穿电压之上（盖革模式）
需要引入淬灭等方式停止雪崩
增益更大 1e6~1e7

LGAD
n^{++}-p^+-p

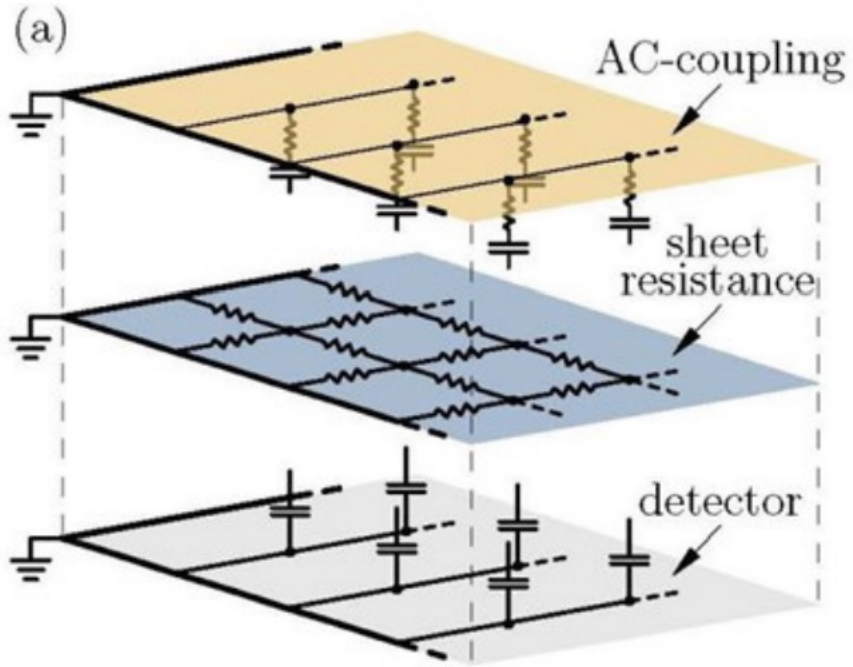
“低增益 APD”
工作低于击穿电压
（一般为 200–400 V）
高 SNR
高时间分辨（ps 级）



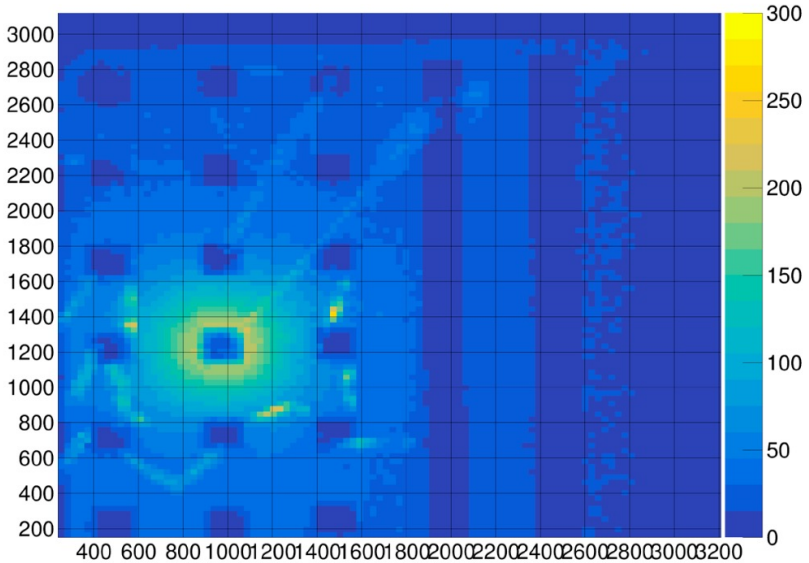
AC-LGAD



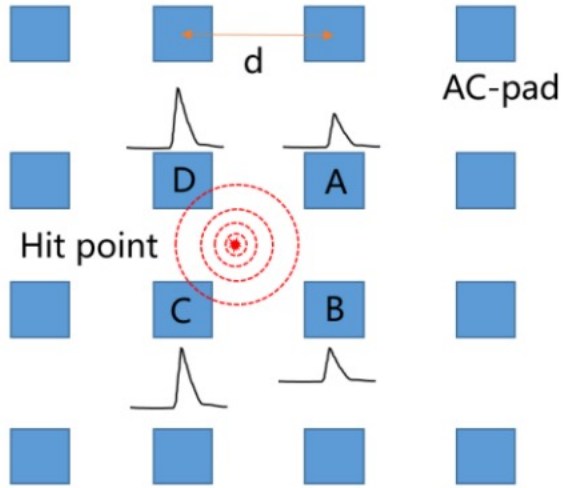
JINST **17** P11028



Sheet resistance of N⁺layer: signal spread a few 100 μm in a laser scan.



Signal of AC-LGAD

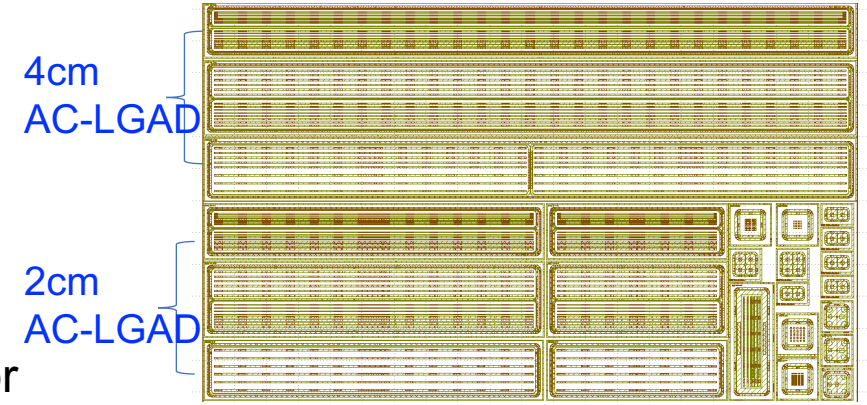


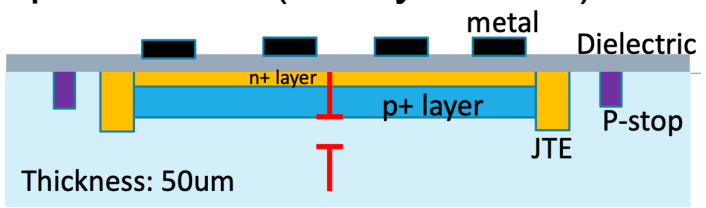
[Development of LGAD for ATLAS HGTD and CEPC TOF out-tracker 赵梅，第十四届全国粒子物理学术会议(2024)]

Latest Progress on AC-LGAD Sensor R&D

From Mei Zhao

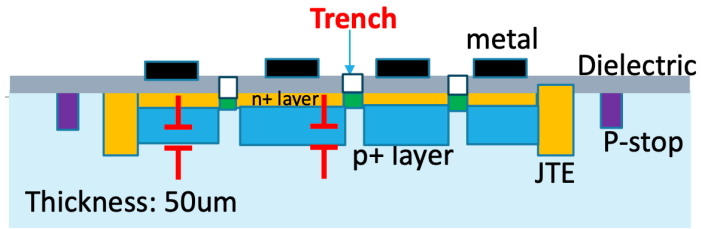
- New IHEP AC-LGAD strip sensor prototype: summitted for tap-out in March 2025. The new layout and design include:
  - Strip lengths: 1 cm, 2 cm, and 4 cm
  - Strip pitch sizes: 100 μm, 200 μm, and 500 μm
  - Electrode widths: 25 μm, 50 μm, and 100 μm
  - Optimized isolated structure design and EPI thickness to reduce sensor capacitance (correlated with power consumption)
  - Process design optimization (n+ layer dose) for better spatial resolution



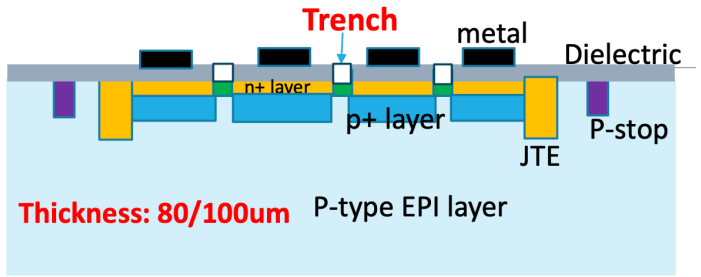


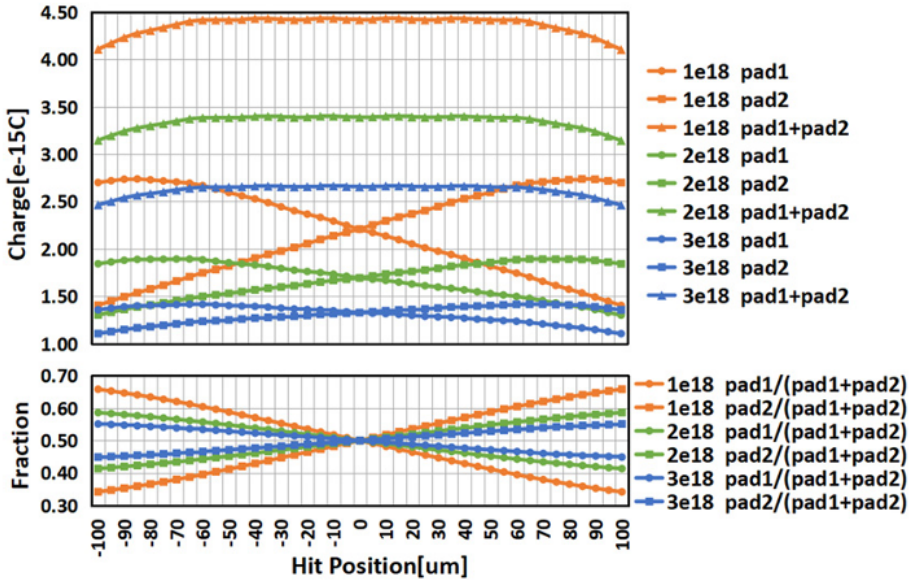
Introducing isolated structure:

$C = \varepsilon_0 * \varepsilon_r * A \downarrow / d$



Increasing EPI thickness: $C = \varepsilon_0 * \varepsilon_r * A / \mathbf{d} \uparrow$

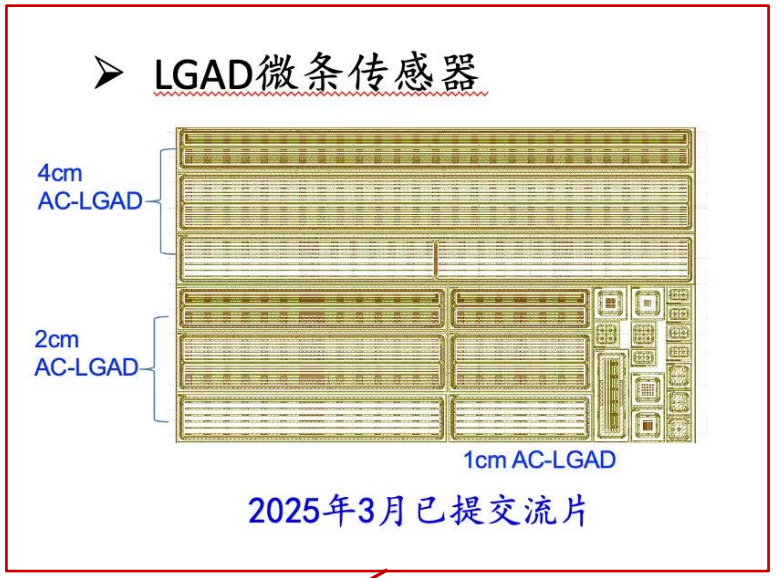




The sensor test will be launched once we received the latest tap-out.

LGAD tests

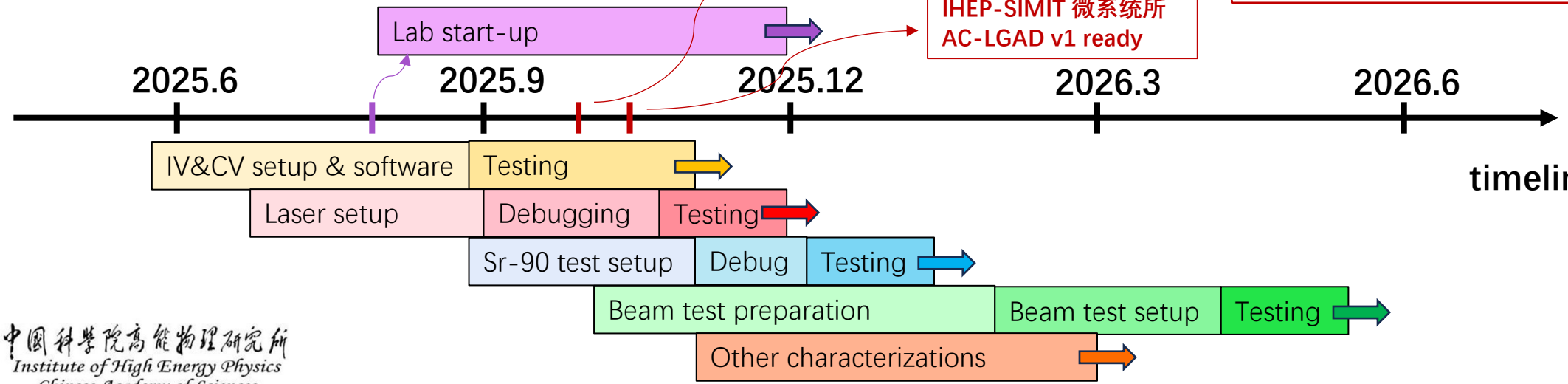
- I-V test & C-V test
- NIR TCT for spatial resolution
- ^{90}Sr test for time resolution
- Beam test



IHEP-IME
AC-LGAD v3 ready

IHEP-SIMIT 微系统所
AC-LGAD v1 ready

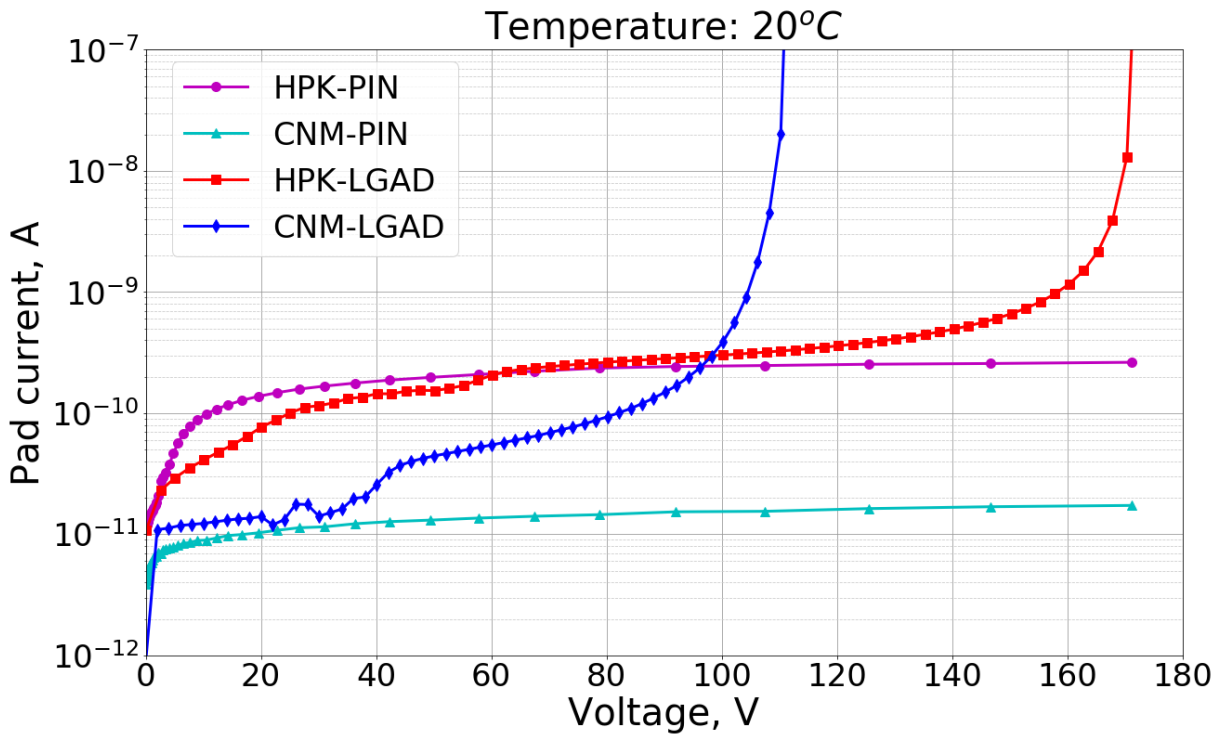
本人将实地参与微系统所AC-LGAD 的全流程工艺，包括离子注入、热处理、光刻等等环节。



I-V & C-V tests

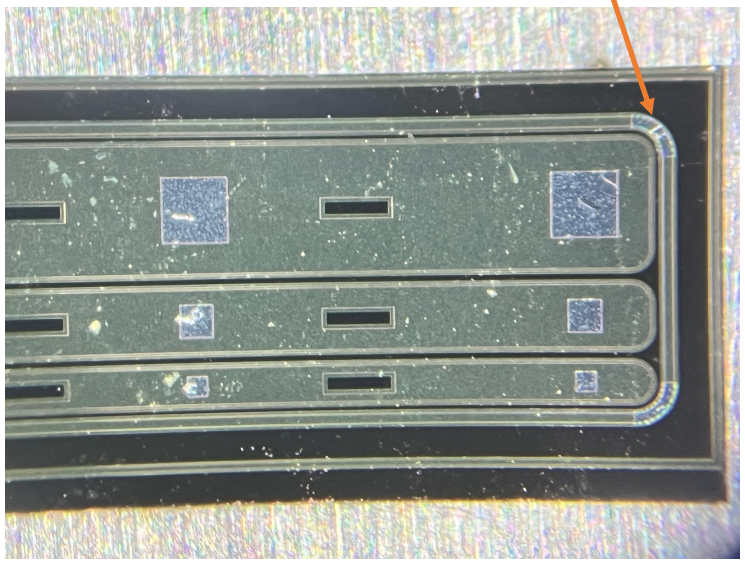
I-V test

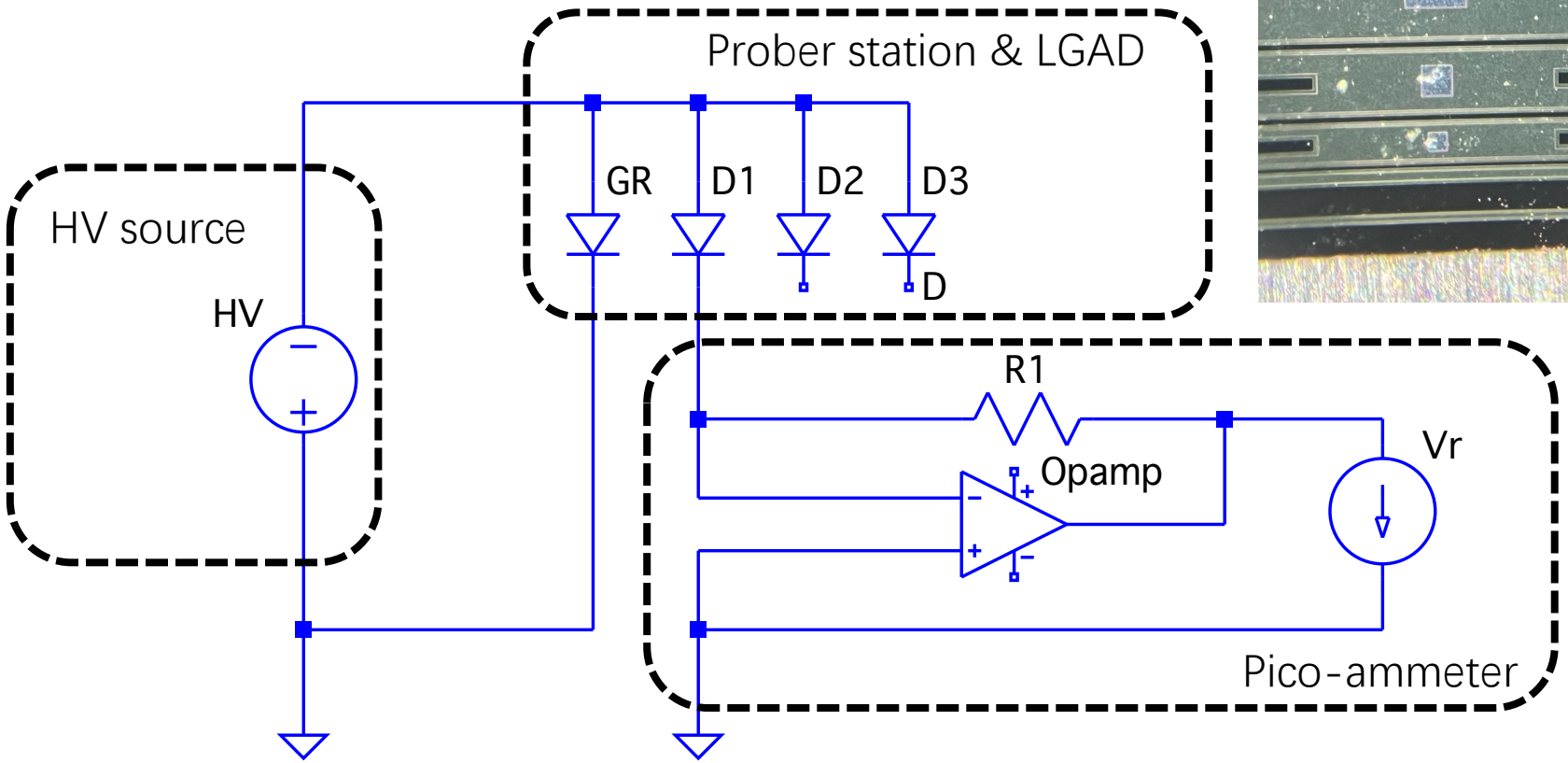
- Standard method to evaluate semiconductor electrical performance
- Result: I-V curve (voltage vs. current)
- Reveals key parameters: **breakdown voltage**, **leakage current**, **on-resistance**



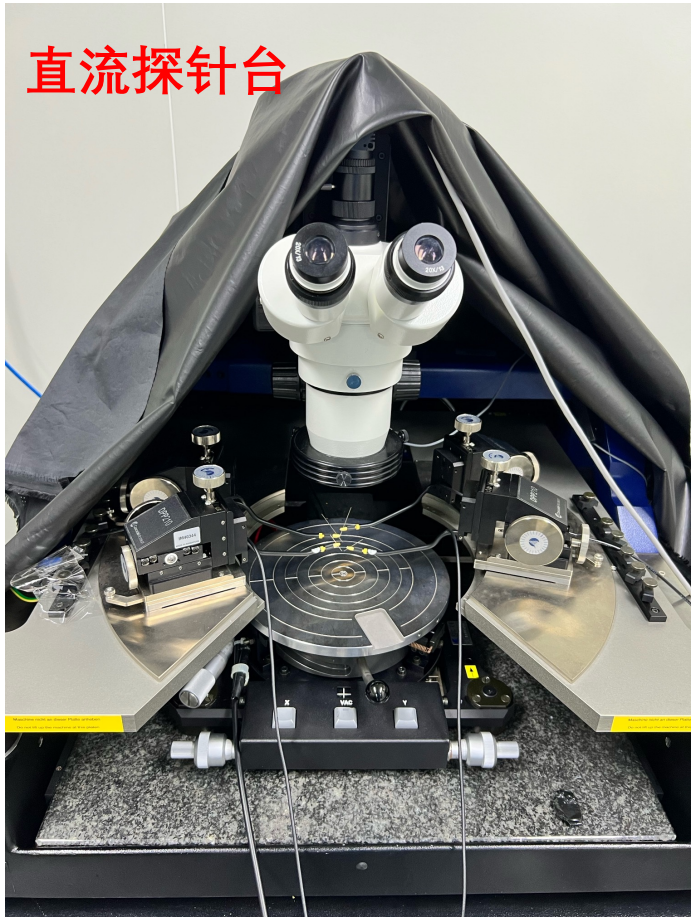
https://cds.cern.ch/record/2776521/plots

I-V test schematic





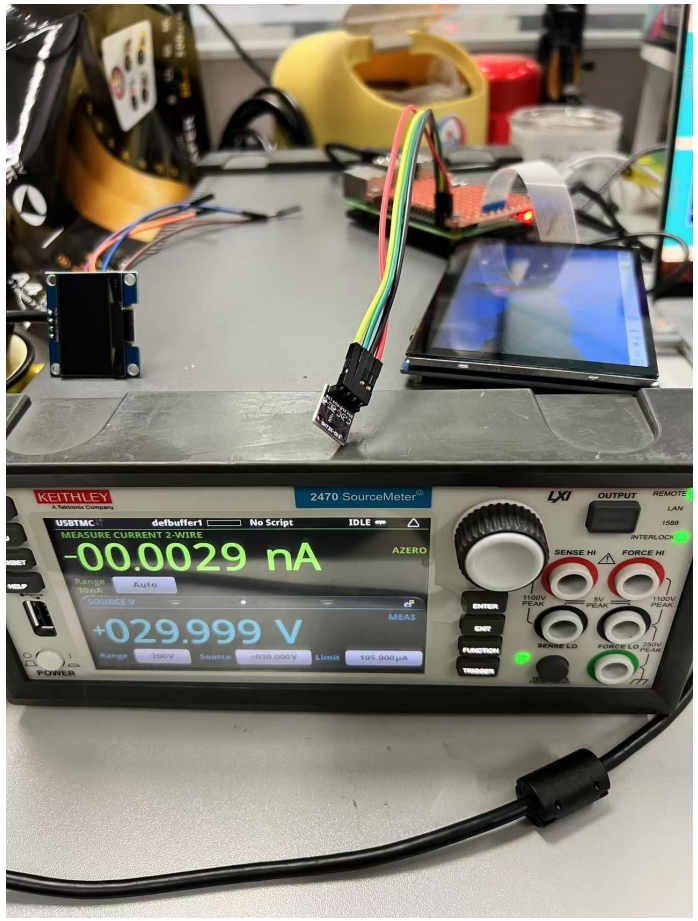
I-V test equipment

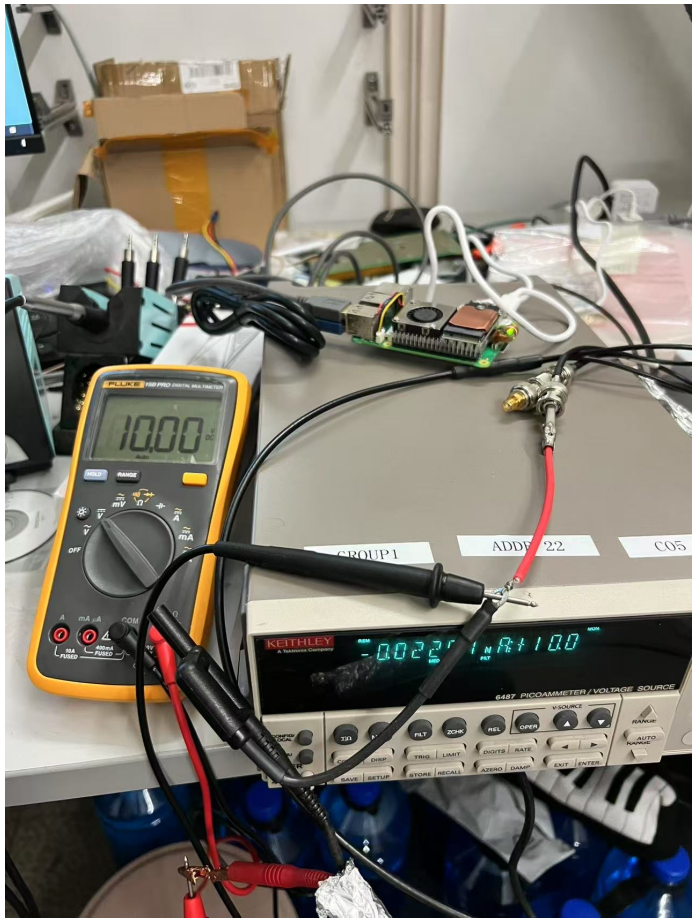


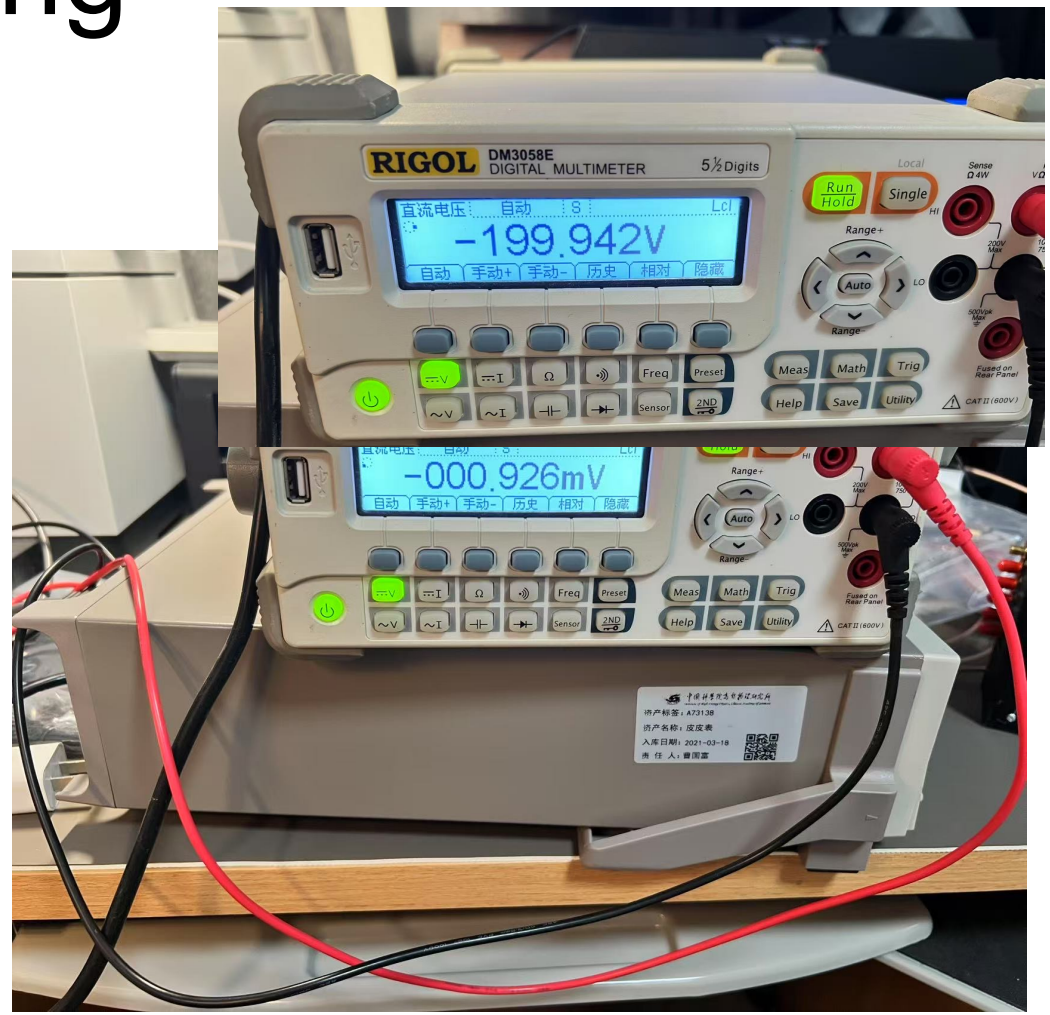
高压源（临时）
Keithley 2470 (± 1000V)，
Keithley 6487 (± 500V)

皮安表
keithley 6487，
keithley 6485

Script control & debugging







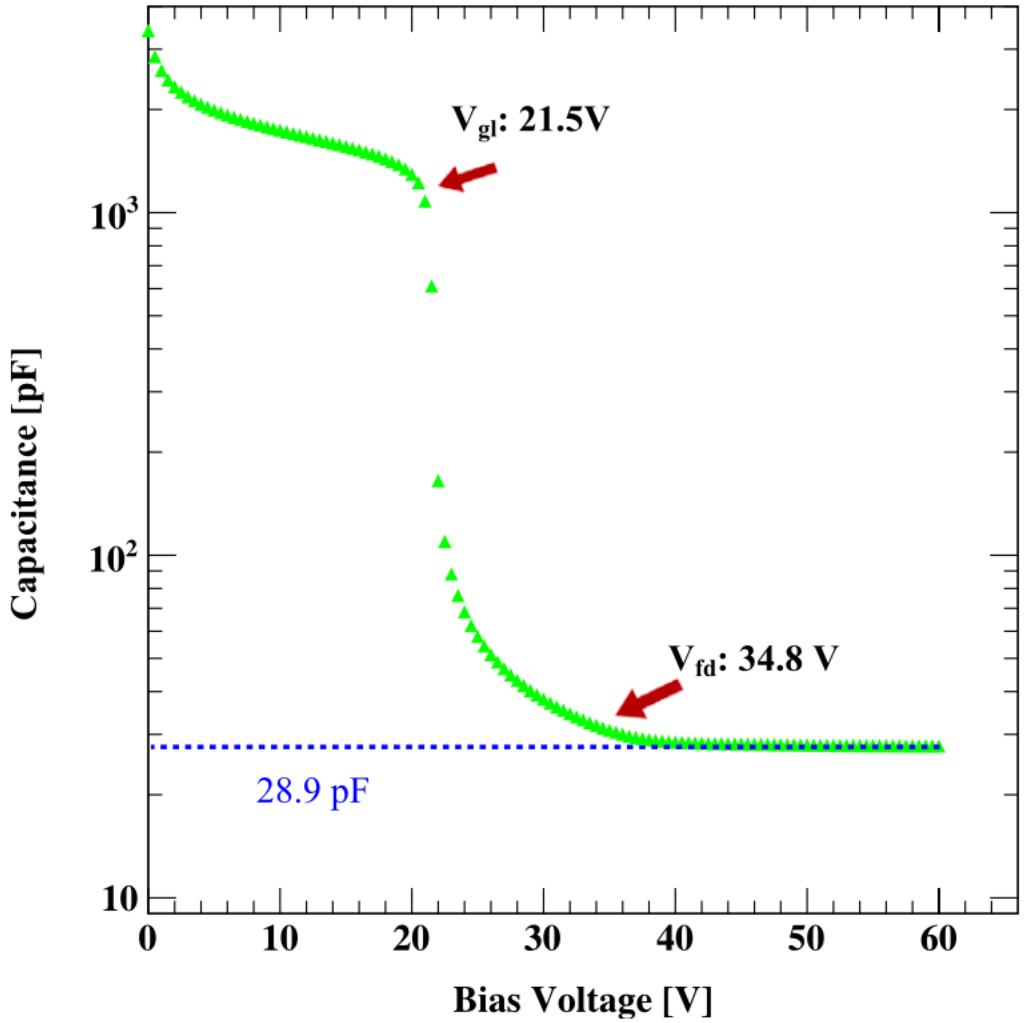
Keithley 2470 HV output test

Keithley 6487 HV output test

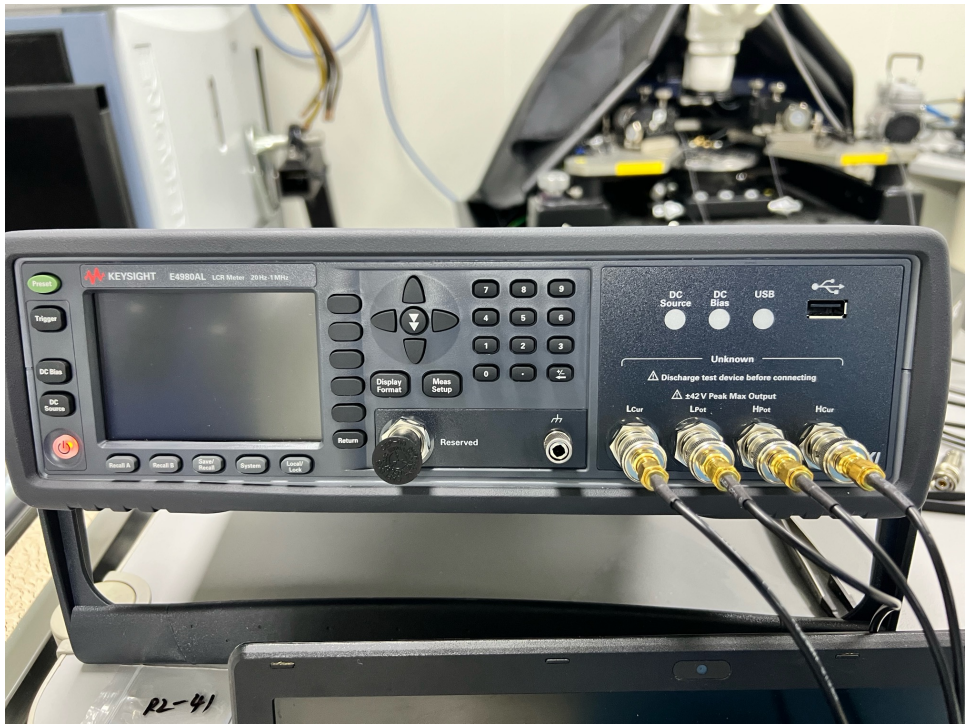
C-V test

NIM A.2024.169203

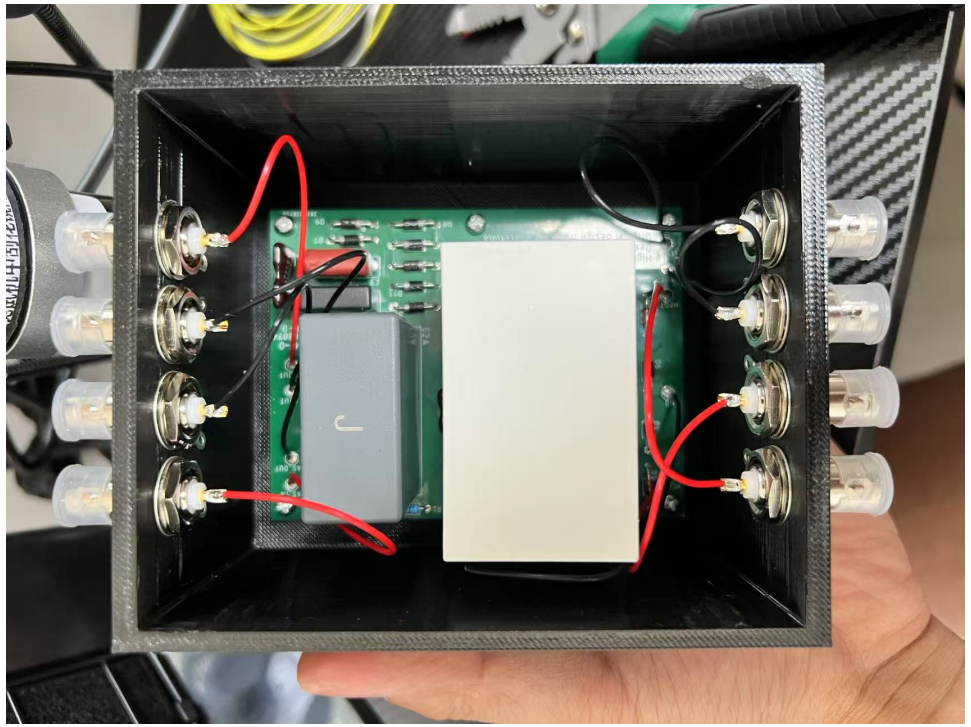
- Also a standard semiconductor test
- **C-V curve** reveals key parameters:
  - **V_{gl}= 21.5 V** Gain Layer Depletion: onset of gain layer depletion; capacitance drops rapidly
  - **V_{fd}= 34.8 V** Full Depletion Voltage
  - Plateau capacitance ≈ **28.9 pF**: minimum junction capacitance
  - Further extraction: **depletion depth**, etc.



C-V test equipment



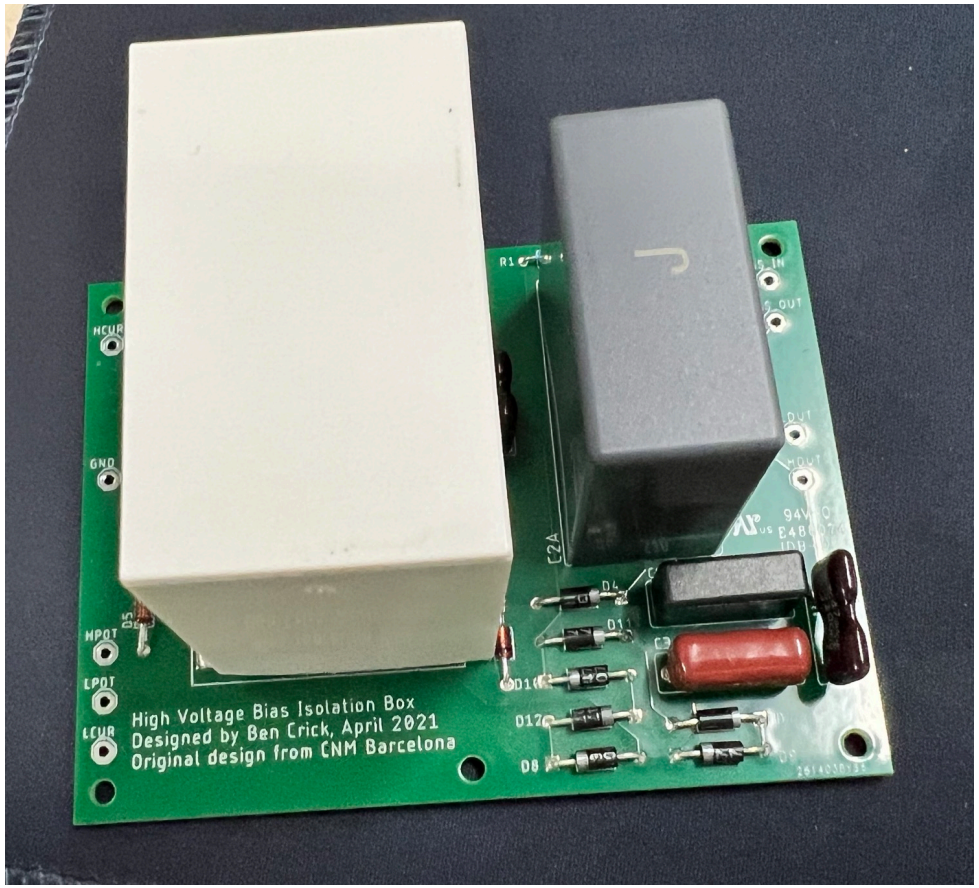
LCR meter



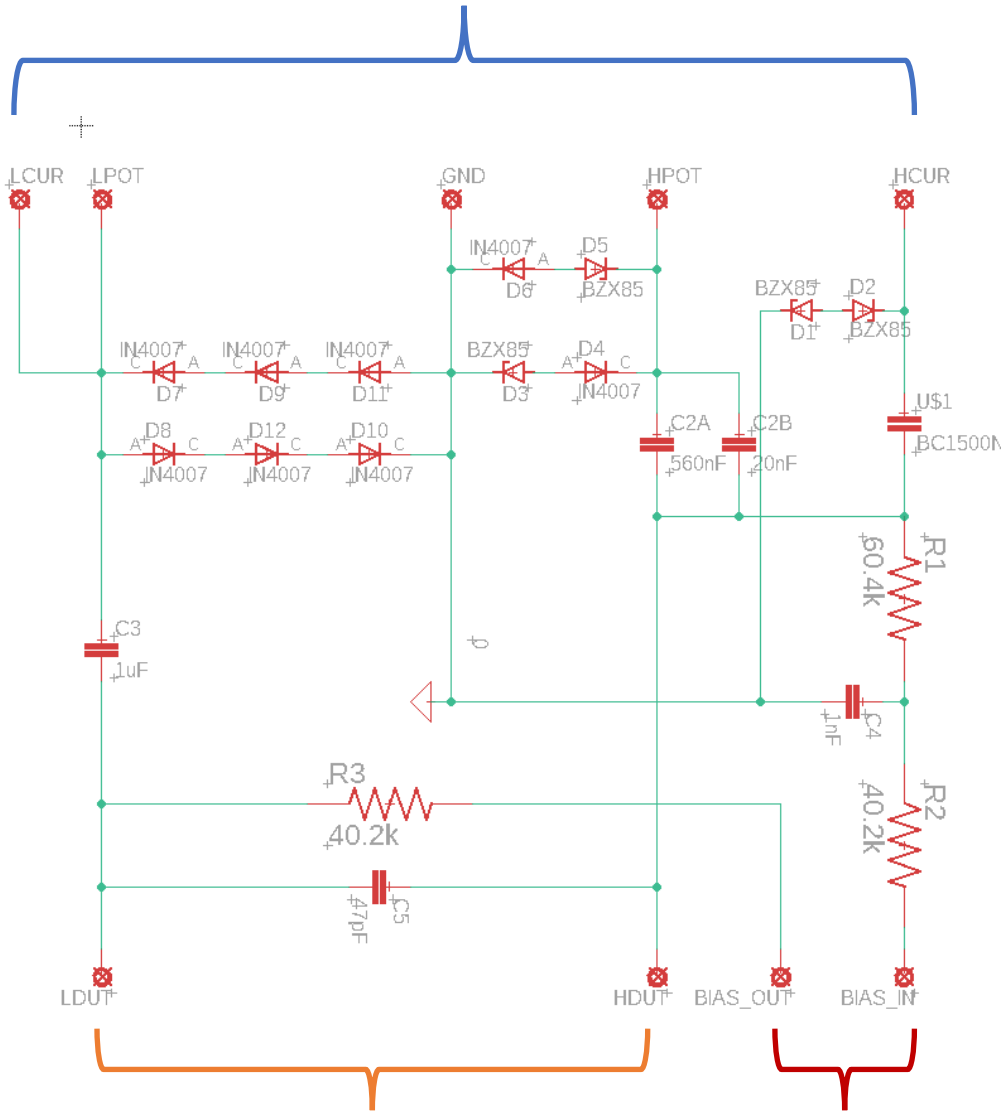
Bias-tee box

叠加直流偏压（Bias）与交流小信号（AC）

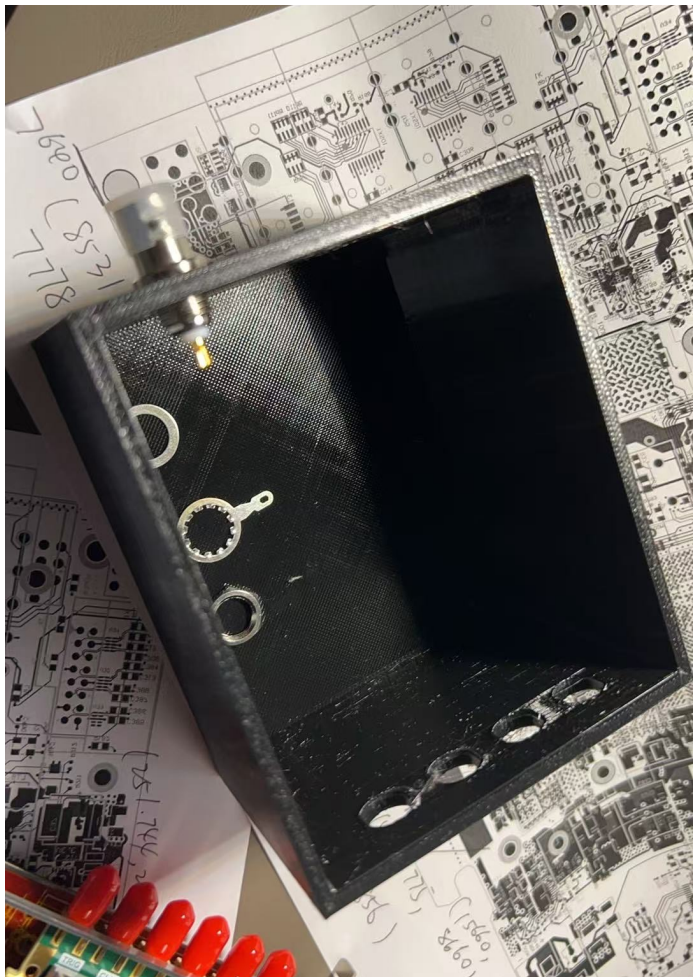
Bias-tee schematic



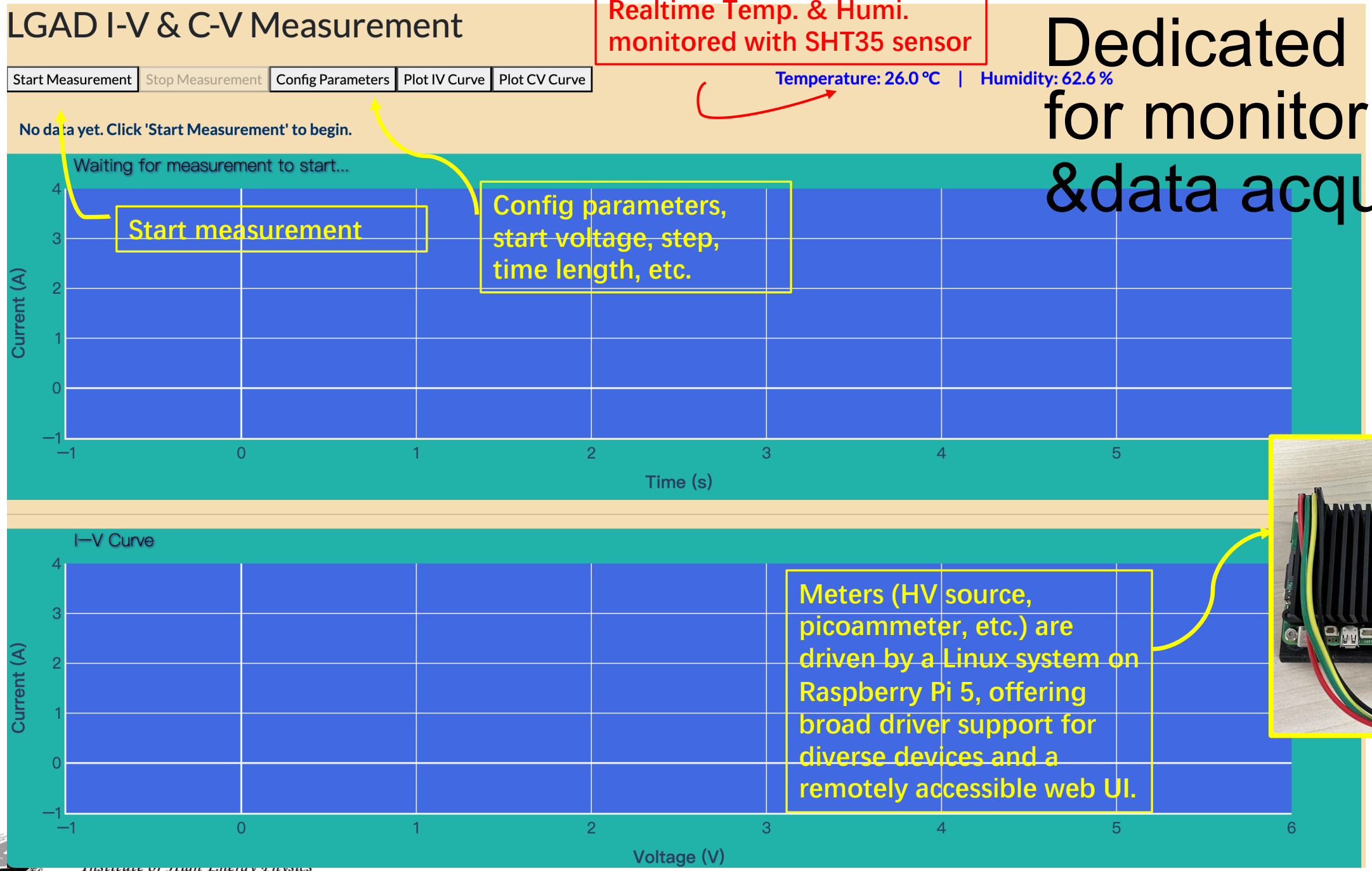
4 terminal 接LCR表

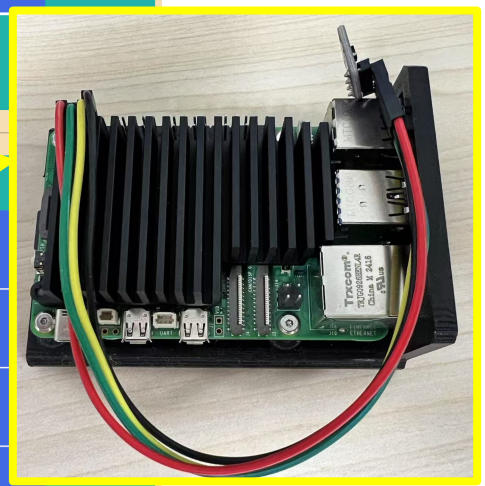


3D printed box & Soldering



Dedicated UI for monitoring &data acquisition





LGAD I-V & C-V Measurement

Start Measurement | Stop Measurement | Config Parameters | Plot IV Curve | Plot CV Curve

Measurement Configuration

Start Voltage: -332
Stop Voltage: -355
Step Voltage: 2
Measurement Duration (s): 20
Sample Interval (s): 0.5
Stabilization Time (s): 12
Maximum Current (μA): 50
AC Voltage (mV): 100
AC Frequency (kHz): 10

For I-V

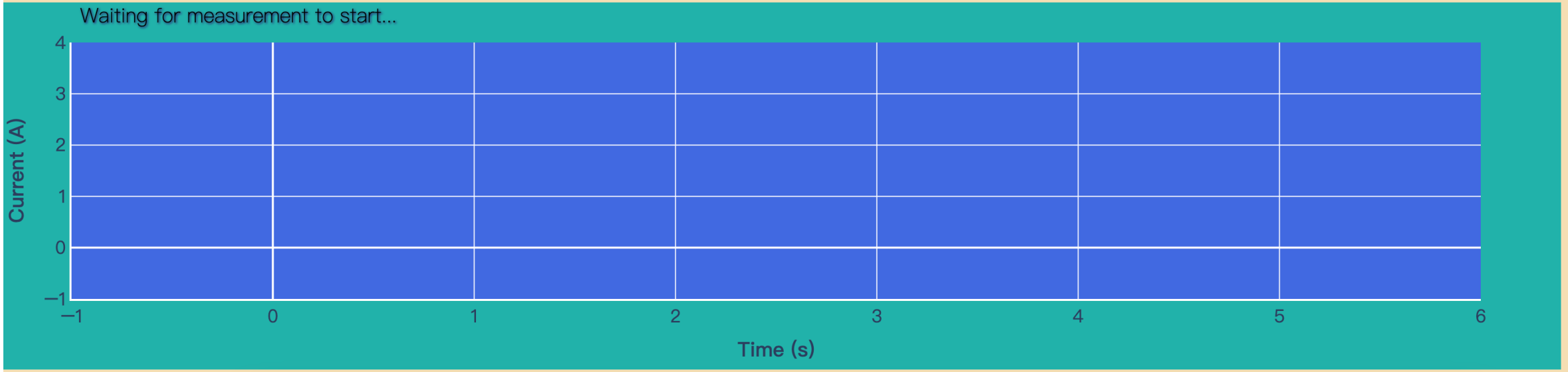
Preserved for C-V test

Confirm | Cancel

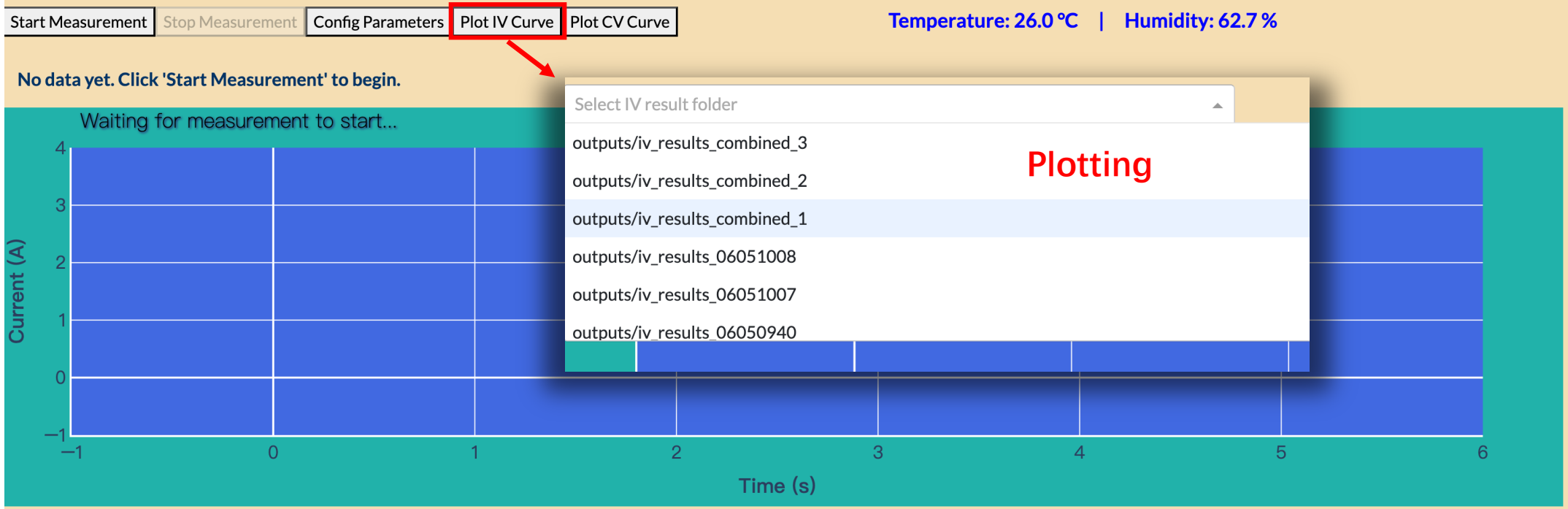
Config parameters, start voltage, step, time length, etc.

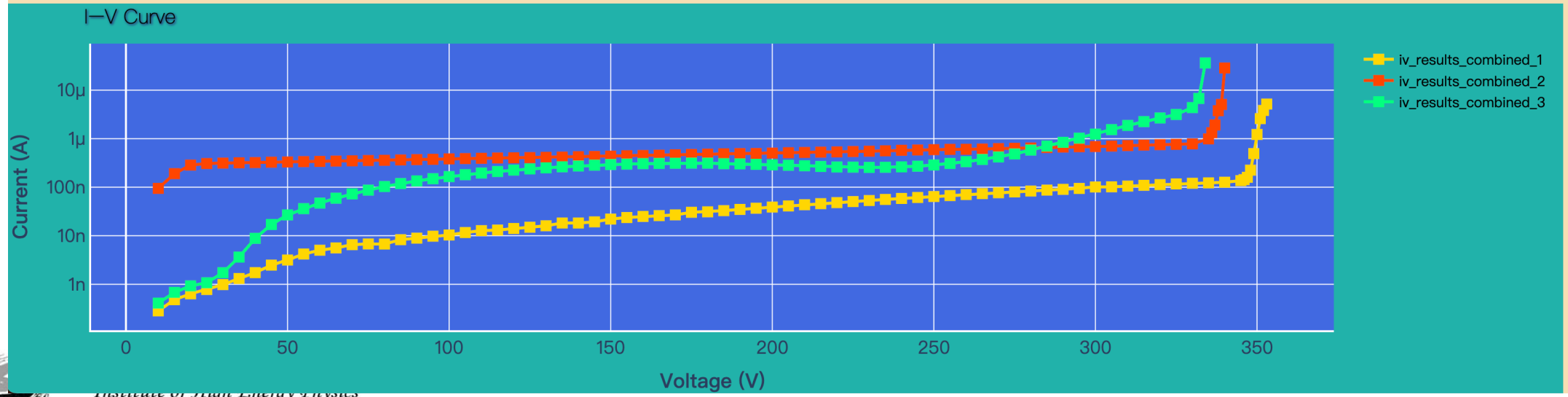
Temperature: 26.4 °C | Humidity: 62.0 %

No data yet. Click 'Start Measurement' to begin.



LGAD I-V & C-V Measurement

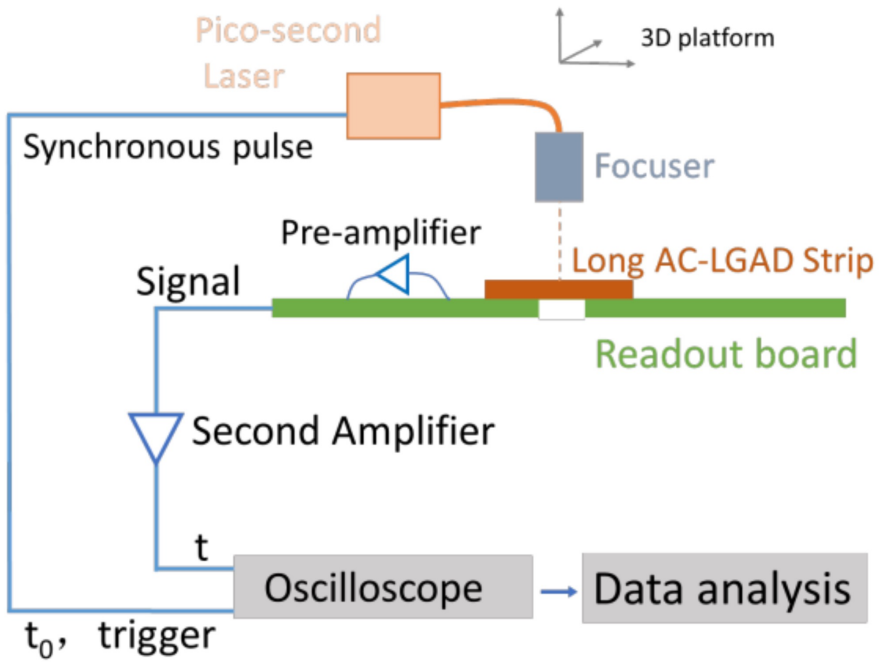


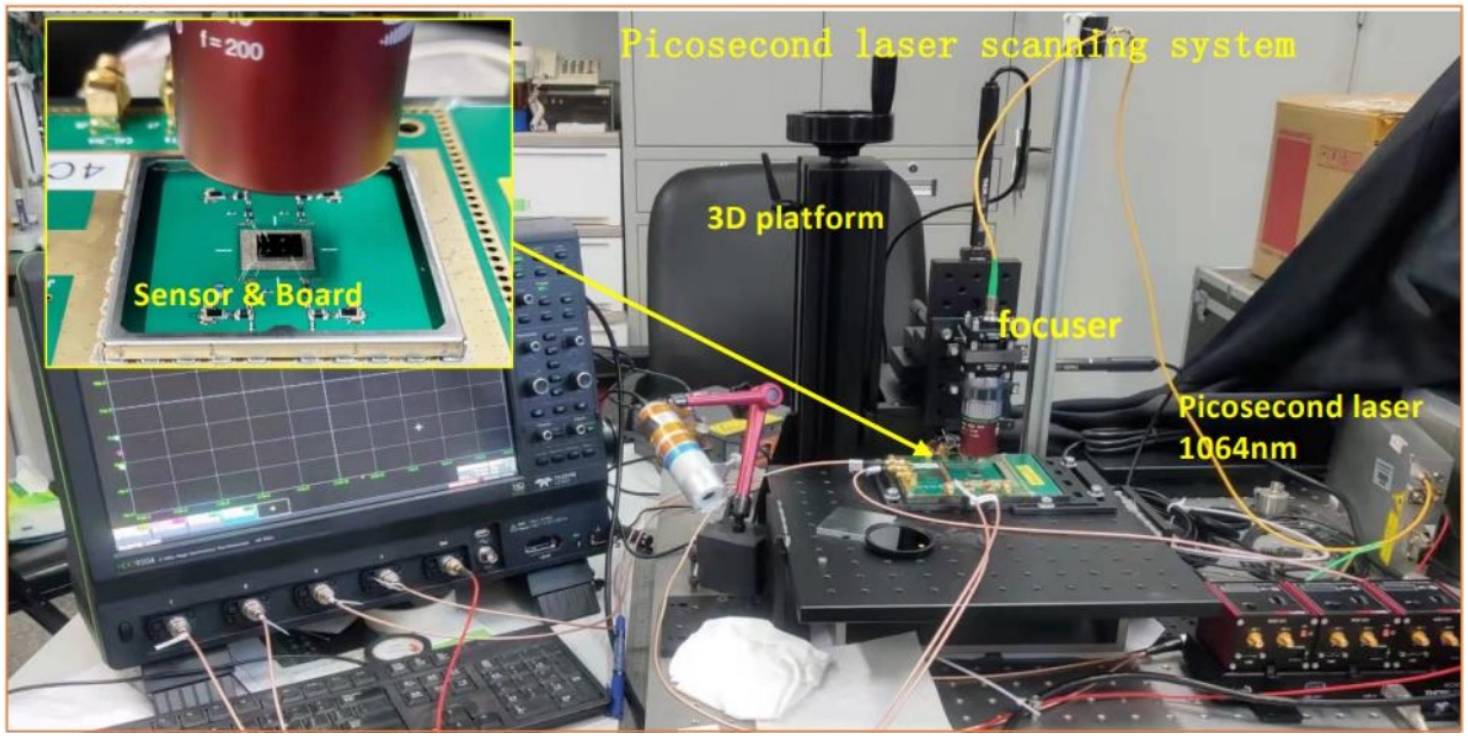


Laser test

NIR TCT for spatial resolution study

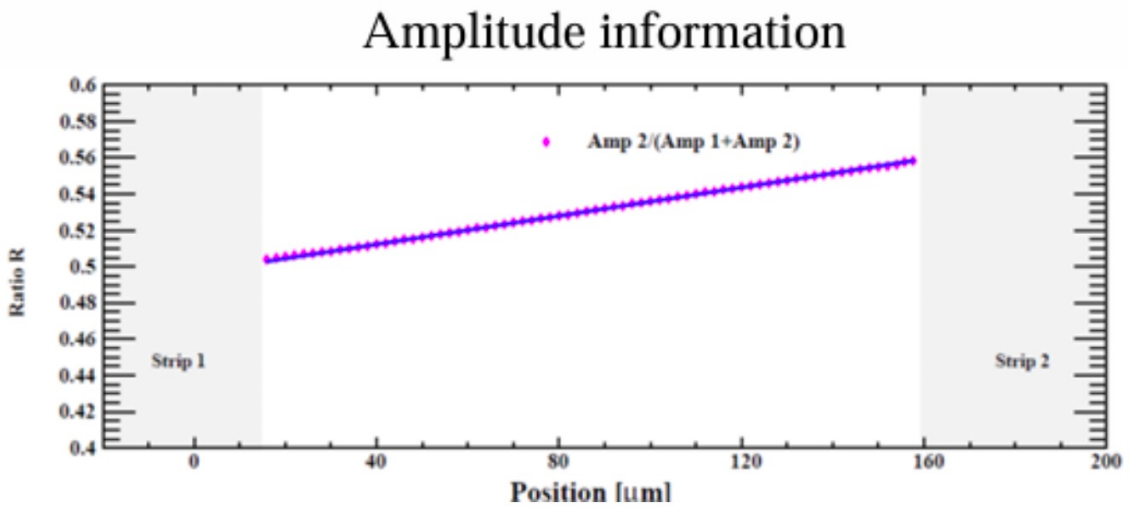
Laser test & spatial resolution

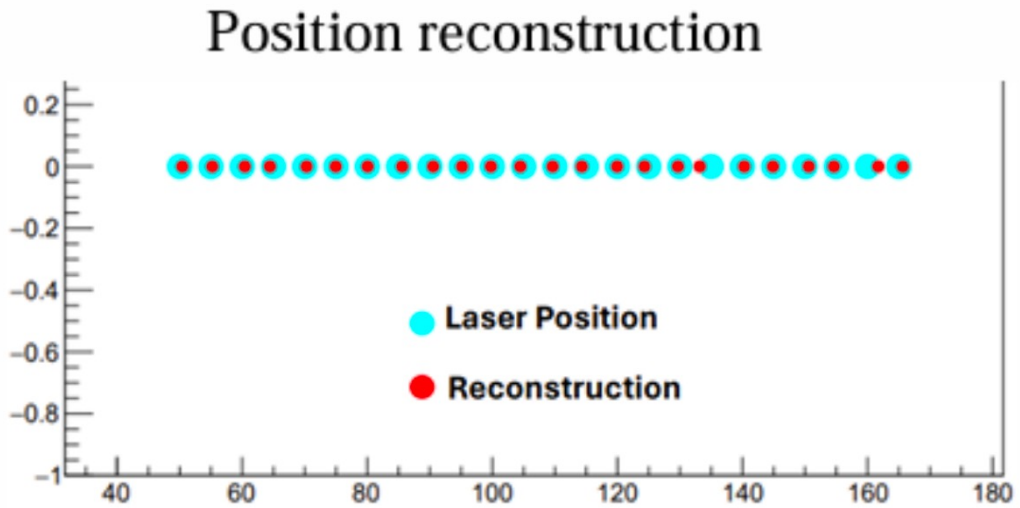


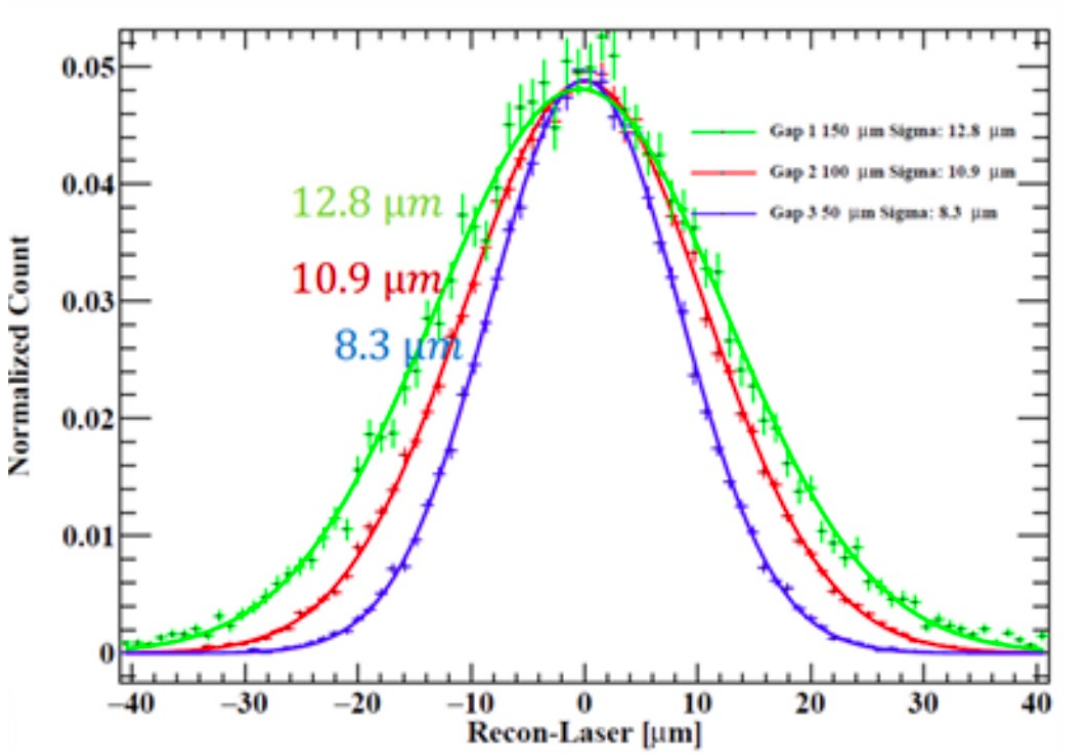


Picosecond laser (1064 nm) & x-y scanning system with step accuracy < 1μm

Laser test & spatial resolution



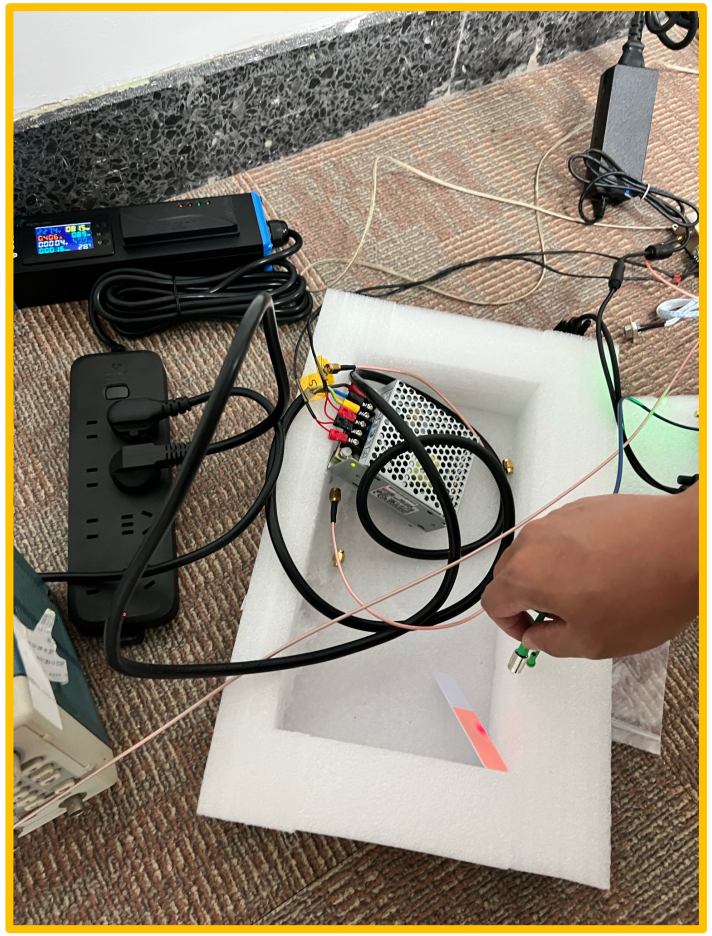




Position reconstructed by amplitude ratio among different channels.
Spatial resolution of a certain laser point is derived with statistical methods (1D / 2D gaussian distribution).

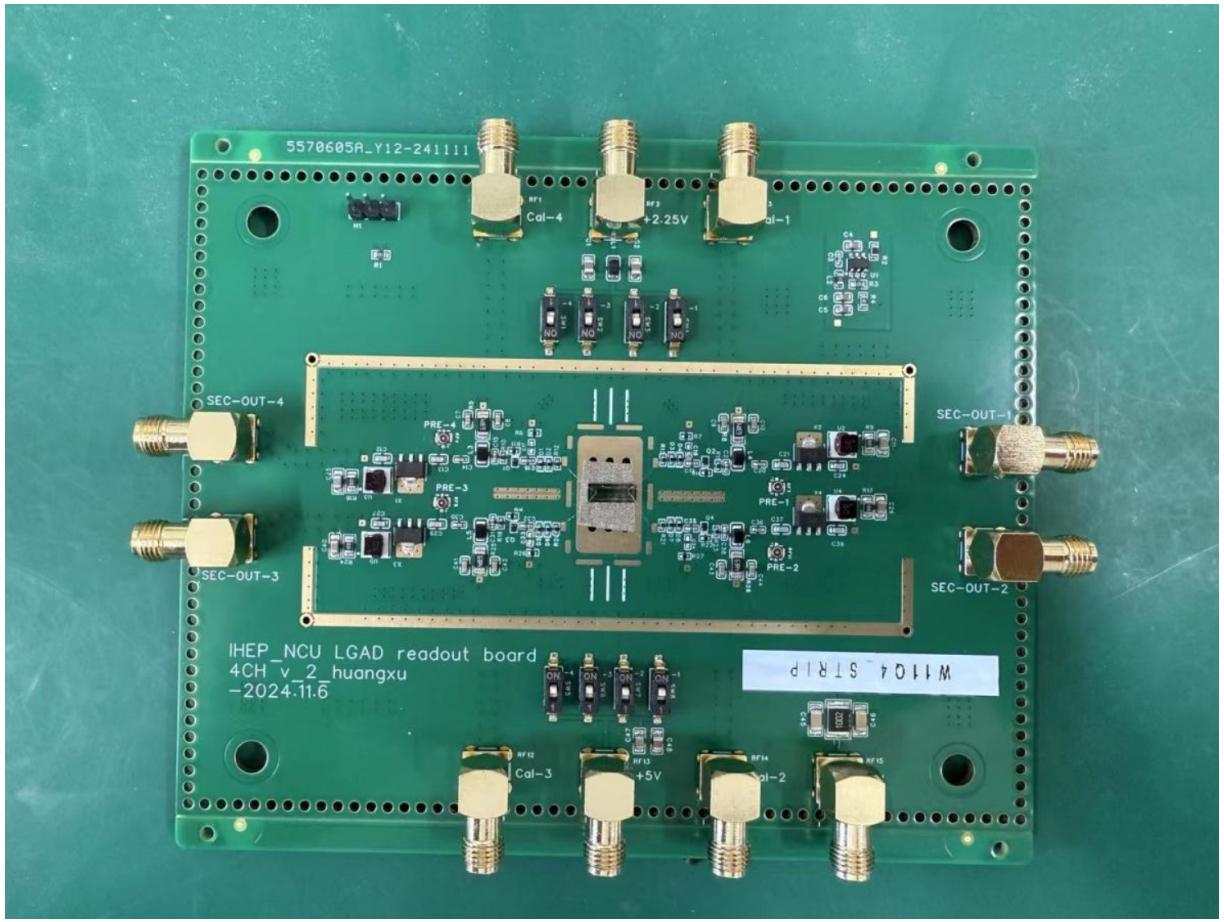
NIR Picosecond Laser

Center wavelength: 1064 nm
Pulse width: < 8 ps
Pulse energy: 0.5 – 3 nJ
Average power: 6 – 200 mW
Peak power consumption: > 350 W
Spectral width: < 0.5 nm
Repetition rate: 20 MHz
Polarization extinction ratio: > 100 : 1
Power stability: < 1 % RMS @ 3 h
Beam quality: TEM_{00}, M^2 < 1.1
Output: Polarization-maintaining fiber
Cooling: Air cooling



4-ch Readout board

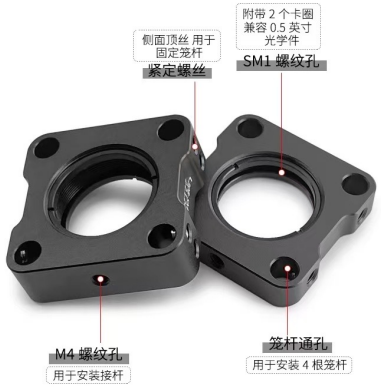
- 2-stage fast amplification (Gain~70)
- Chip mounted through electrically conductive glue (substrate) & wire bonding (top pad)
- Single channel gain can be calibrated



Optical Setup

卓立汉光双频阻尼隔振光学平台
DRN24-12 2400 × 1200 × 800

GBE15-B - 15X
消色差伽利略扩束器



同轴系统

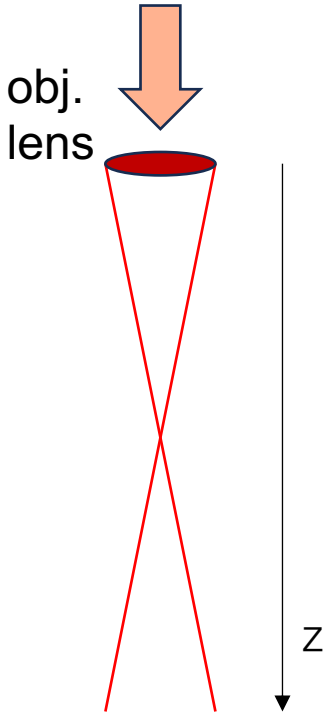
三丰M PLAN APO
NIR 20X 红外物镜

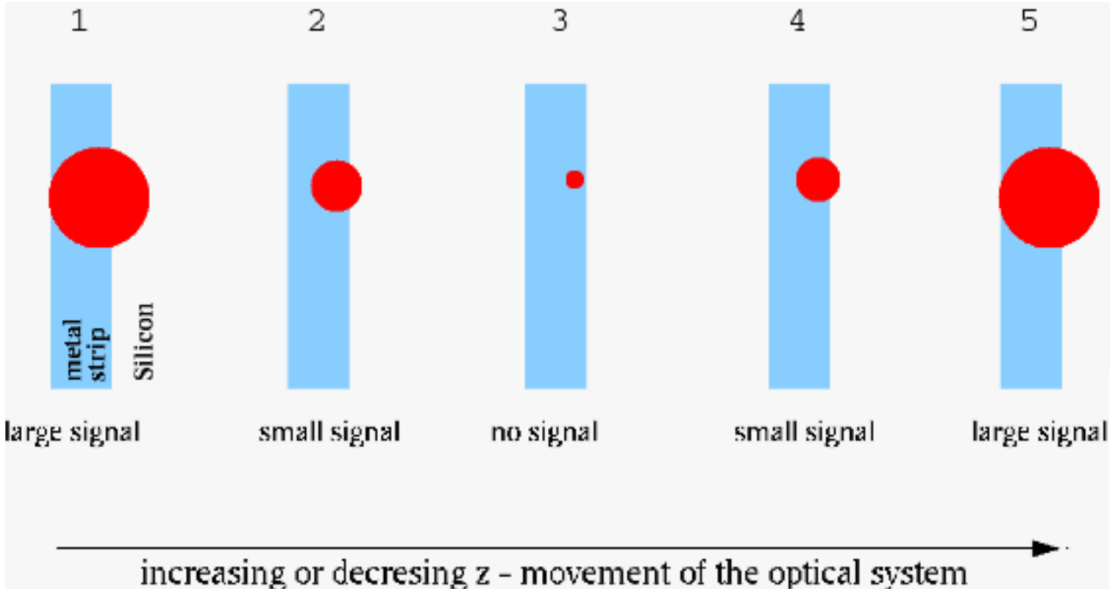
固定式非球面
光纤准直器

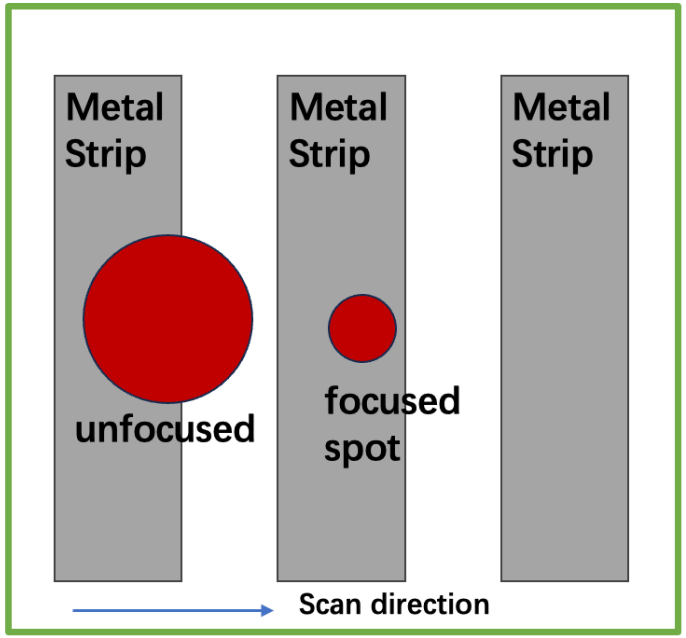
步进电机位移滑台

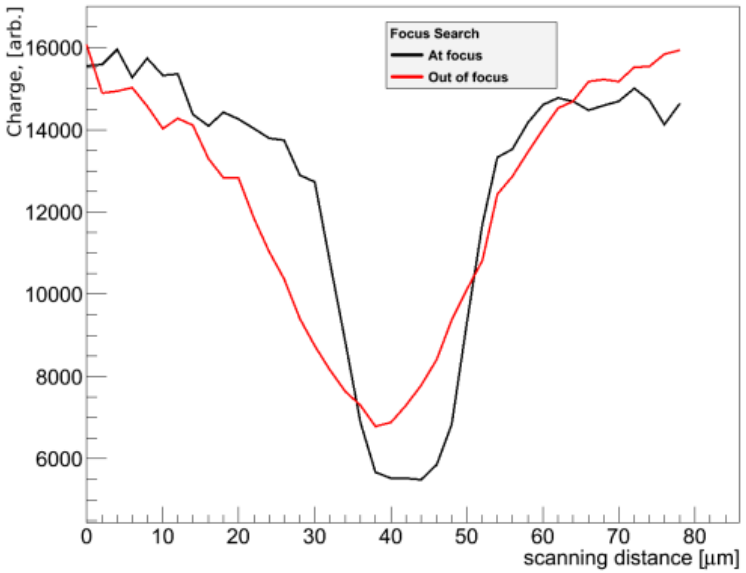
压电位移滑台

Focusing & Alignment





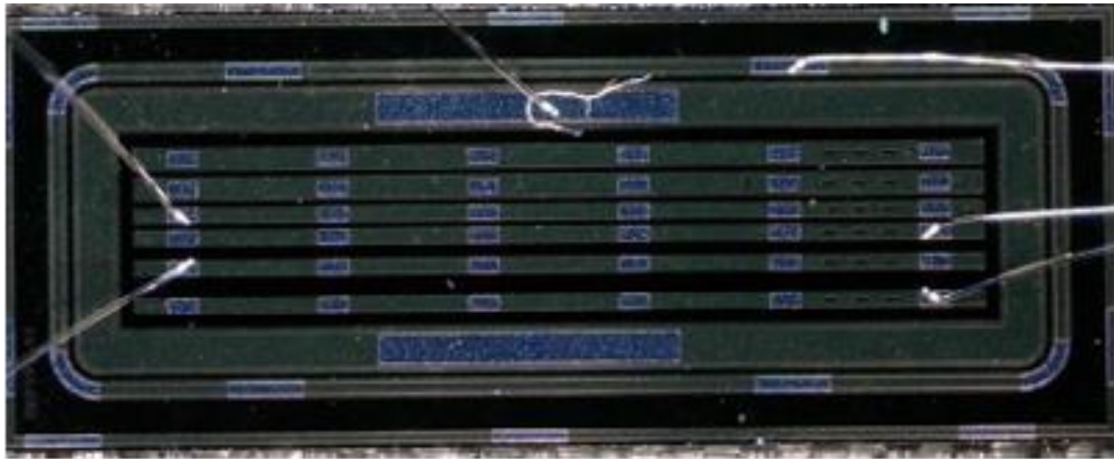




Two different methods for focusing adjustment

Focusing & Alignment

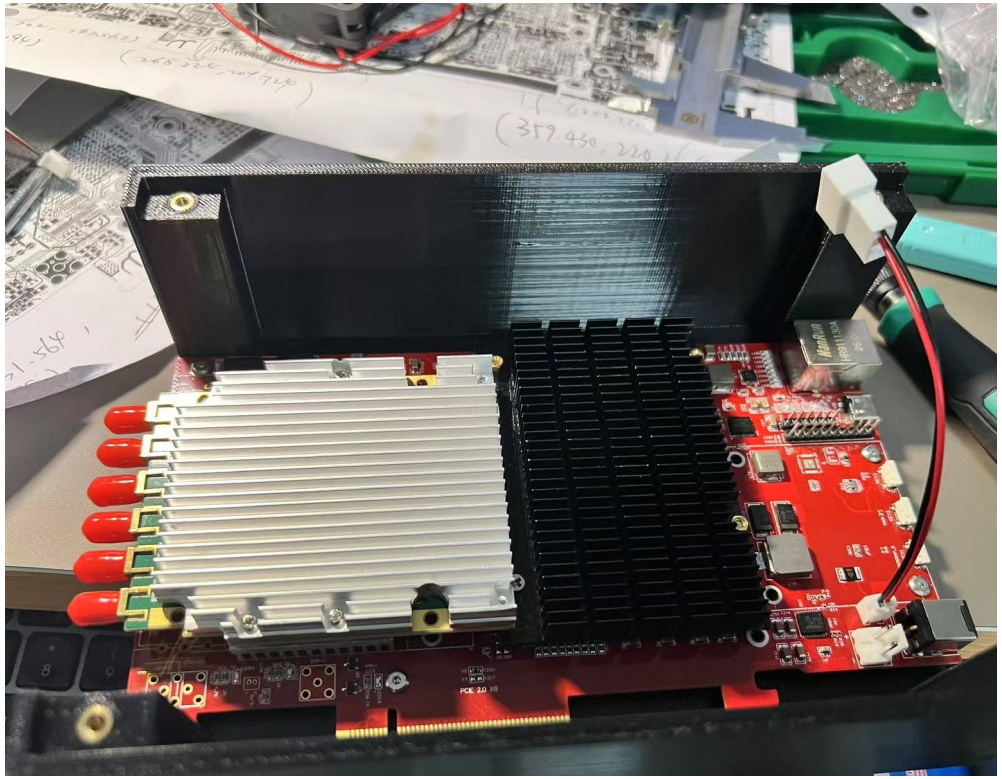
- The chip mounted on the board is prone to rotation in the x–y plane.
- Matching of the original point (or absolute position) is also required.
- Reconstruction & calibration methods are needed for such purposes

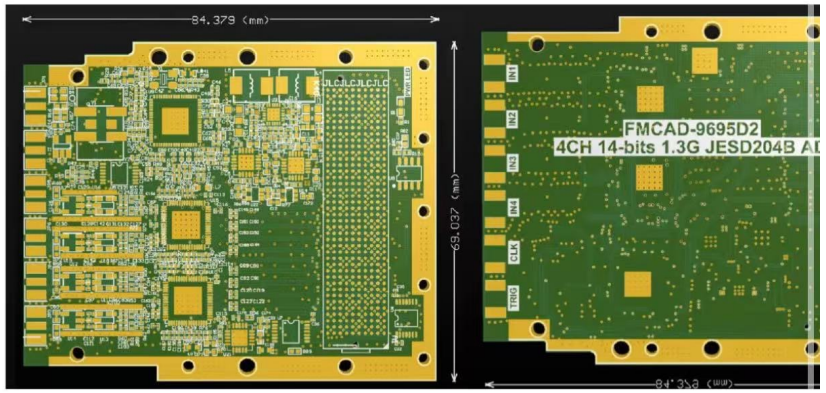


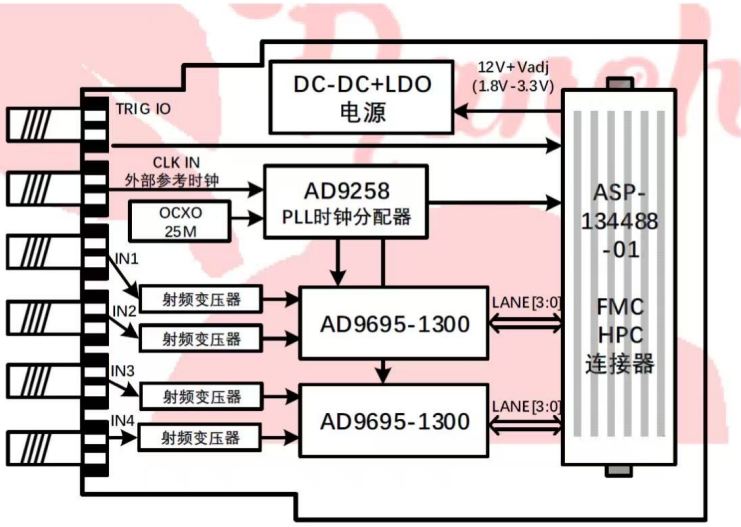
DAQ

- Baseline: Oscilloscope
  - 5~10Gsps sampling rate,
  - >1.5GHz bandwidth
- Option: FPGA + ADC
  - ADC12DJ3200 6.4Gsps FMC AD子卡 (1-ch 6.4 / 2-ch 3.2)
  - AD9695 1.25Gsps FMC AD子卡 (4-ch 1.25)
  - AD6688 / AD9208 3.0Gsps FMC AD子卡 (2-ch 3.0)
  - DC couple up to 900MHz bandwidth
  - AC couple 50M ~ 1GHz to 6GHz (Balun transformer)
  - Further study is also performed for **bandwidth & sampling rate** requirement
- Option: FPGA + customized TDC

4-ch ADC for waveform recording



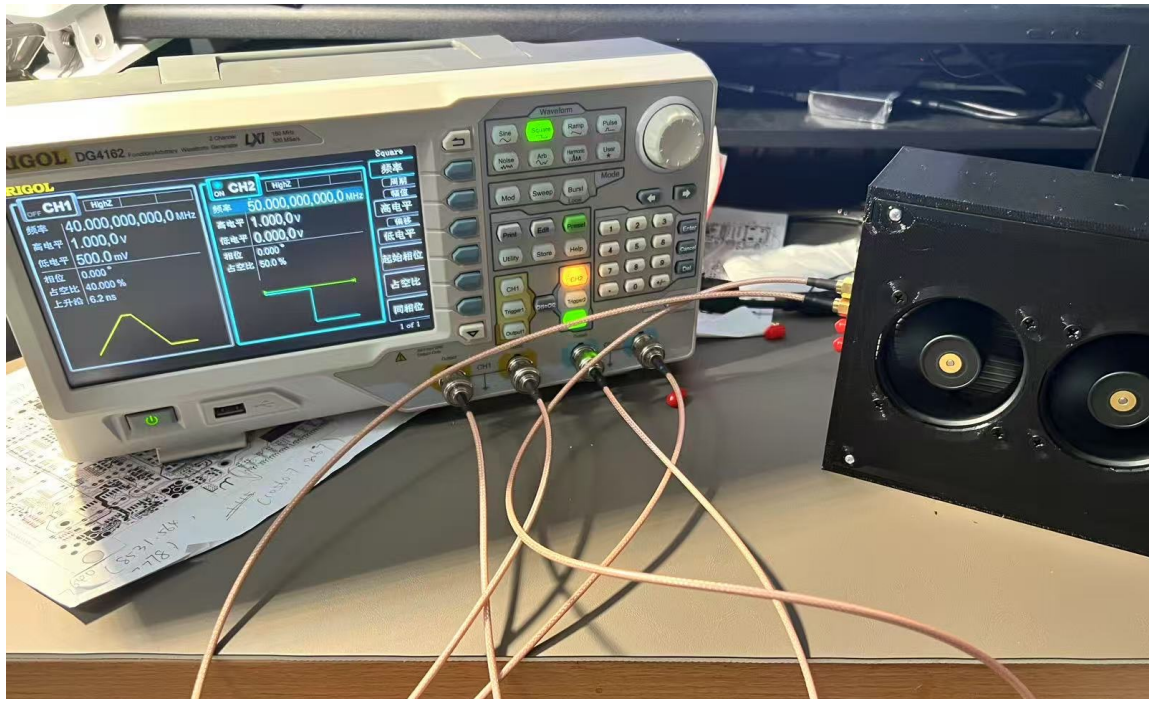


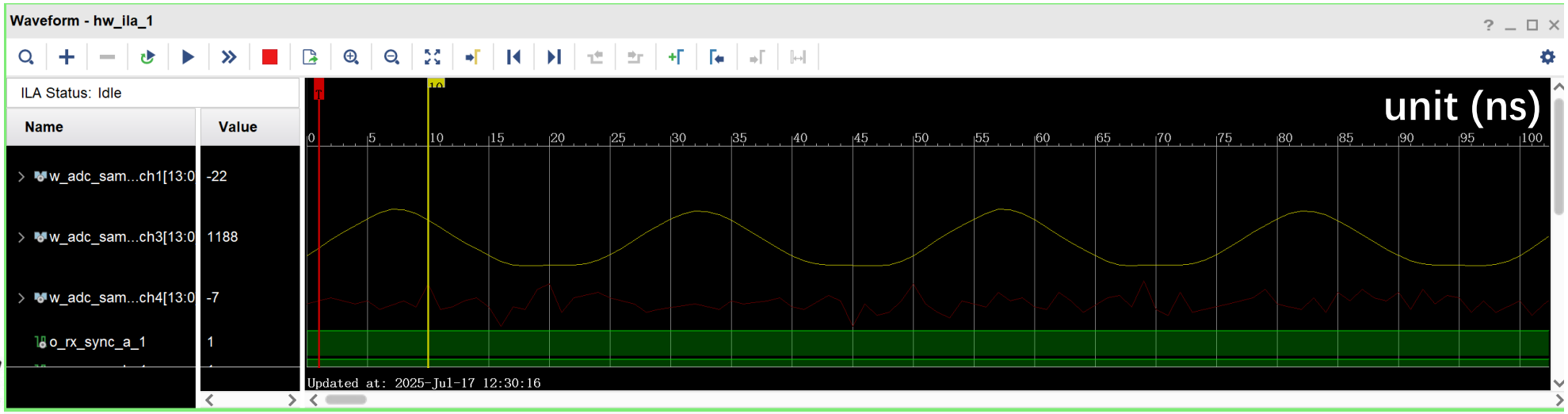


- 4ch ADC based on two AD9695 chips and AD9528 (1250 Msps), bandwidth 400k~500MHz (AC-coupled)

ADC test

- Signal injection with Rigol DG4162
- **Sine** 160MHz, **Pulse** 40MHz (6.2 ns rising edge), **Ramp**, **Square**, user-defined, etc.
- ILA triggered & monitored





Signal Shape Analysis for ADC requirement study

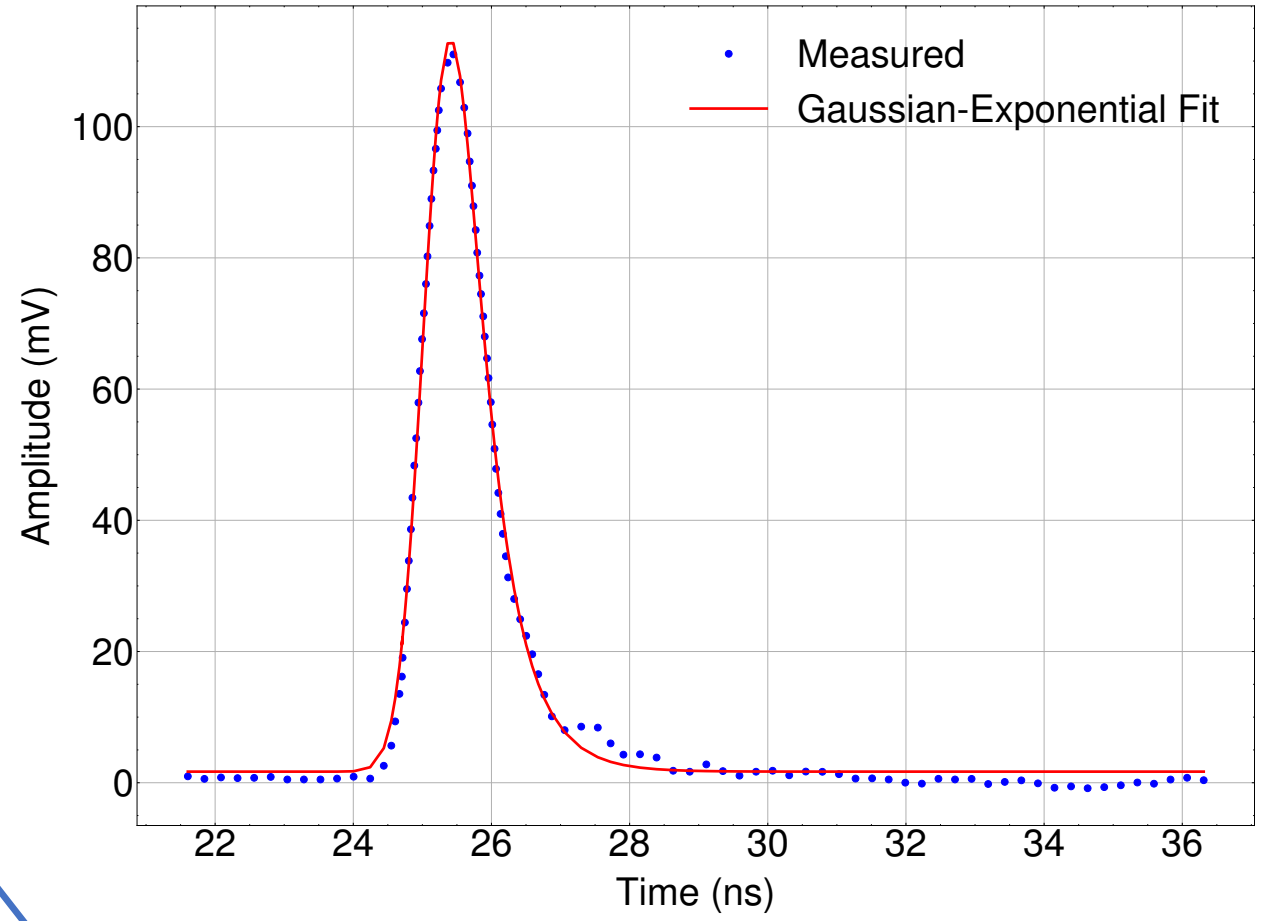
A typical pulse shape of LGAD signal
Rise time ~ 700 ps
Pulse width ~ 2.5 ns

Fit function:
Gaussian-Exponential Convolution

Parameters:

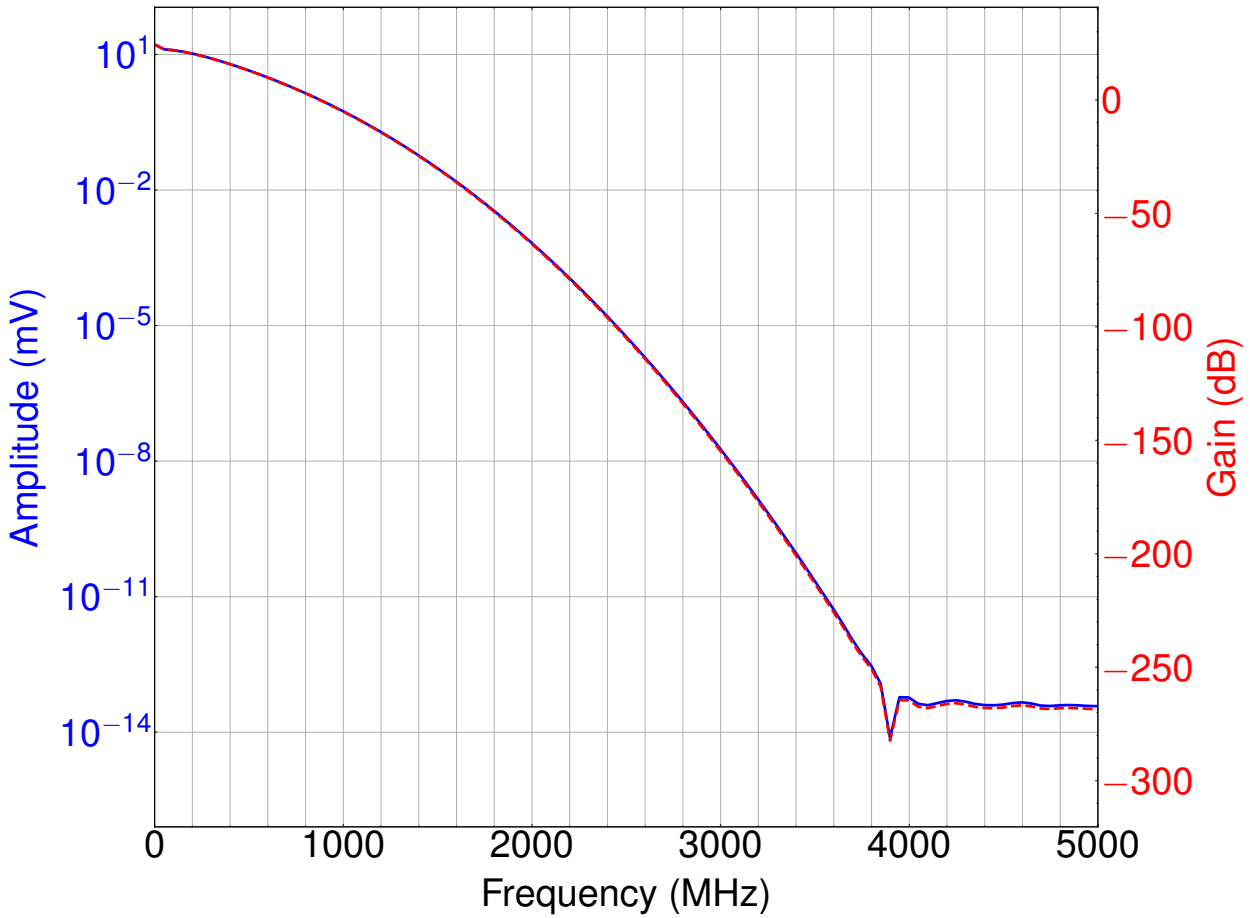
- A = 137.97 mV
- B = 1.69 mV
- t_0 = 25.13 ns
- σ = 0.320 ns
- τ = 0.48 ns (max to 1/e)

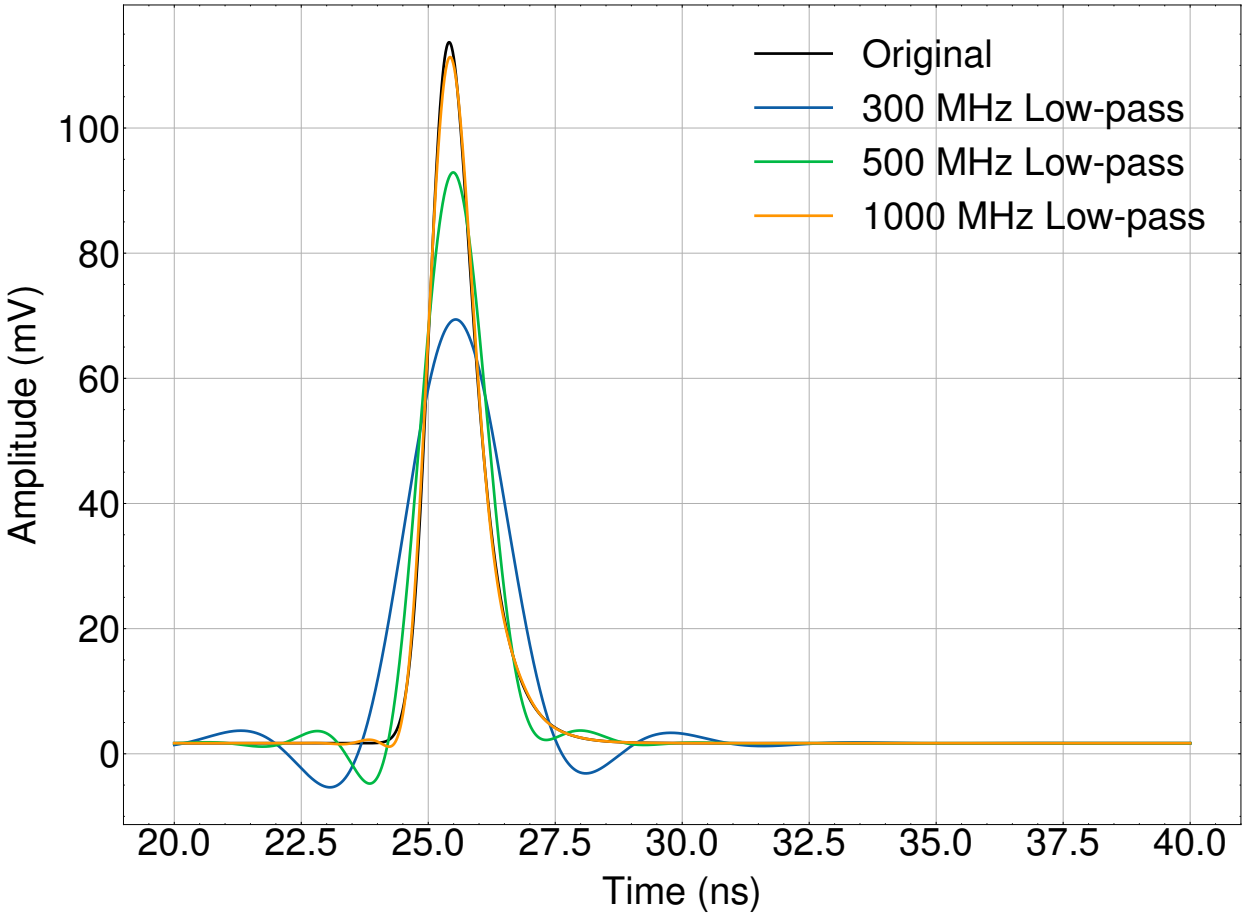
rise time （10% to 90%) $t_{rise} \approx 2.355\,\sigma \approx 0.75$ ns



$$V(t) = A \cdot \exp\left(\frac{\sigma^2 - 2\tau(t-t_0)}{2\tau^2}\right) \cdot \left[1 + \mathrm{erf}\left(\frac{t - t_0 - \sigma^2/\tau}{\sqrt{2}\sigma}\right)\right] + B$$

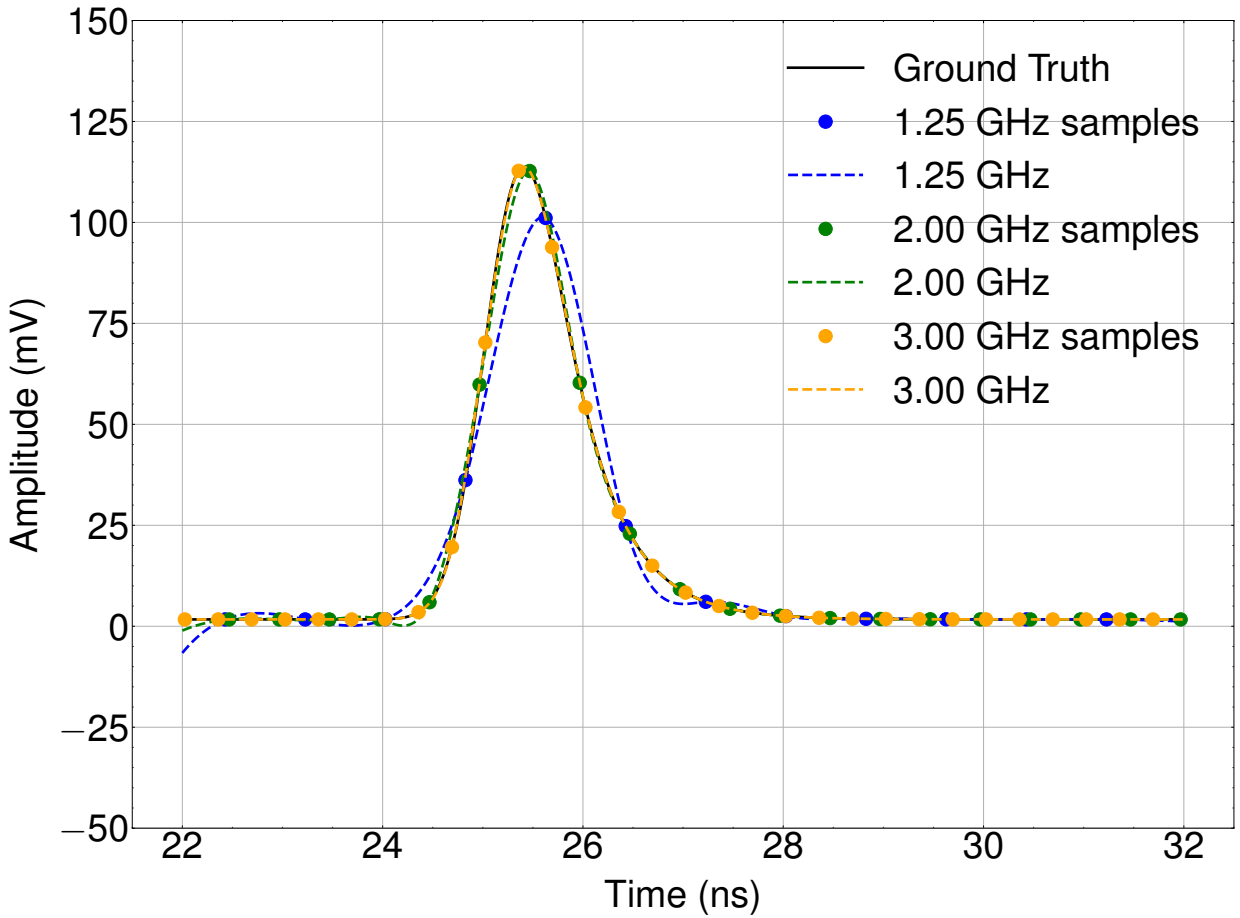
Distortion from insufficient bandwidth

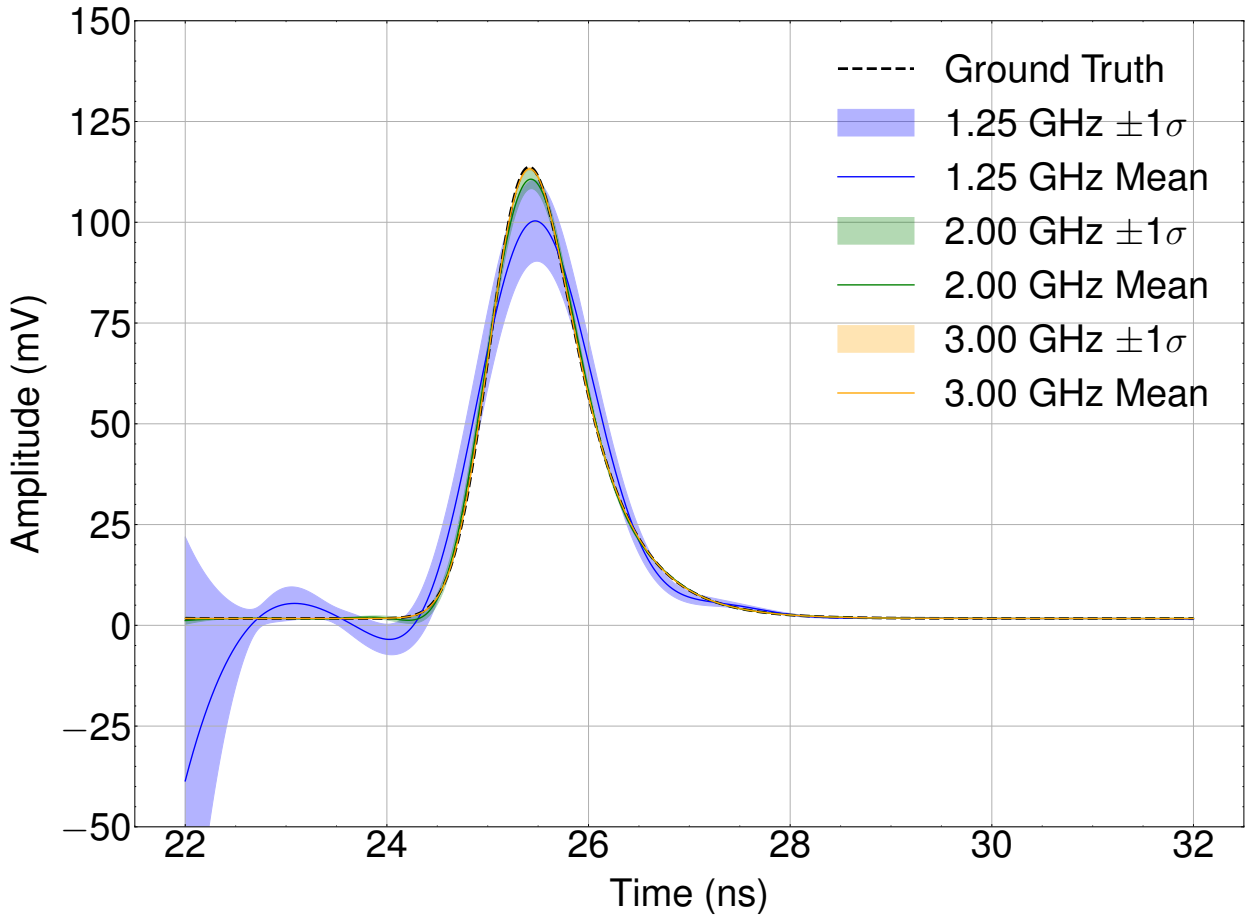




Bandwidth >= 1 GHz is preferable!

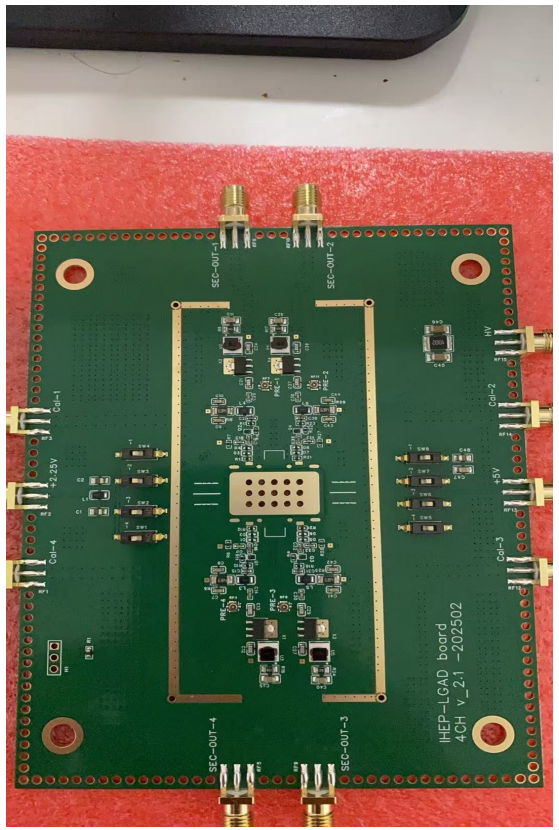
Uncertainty from insufficient sampling rate



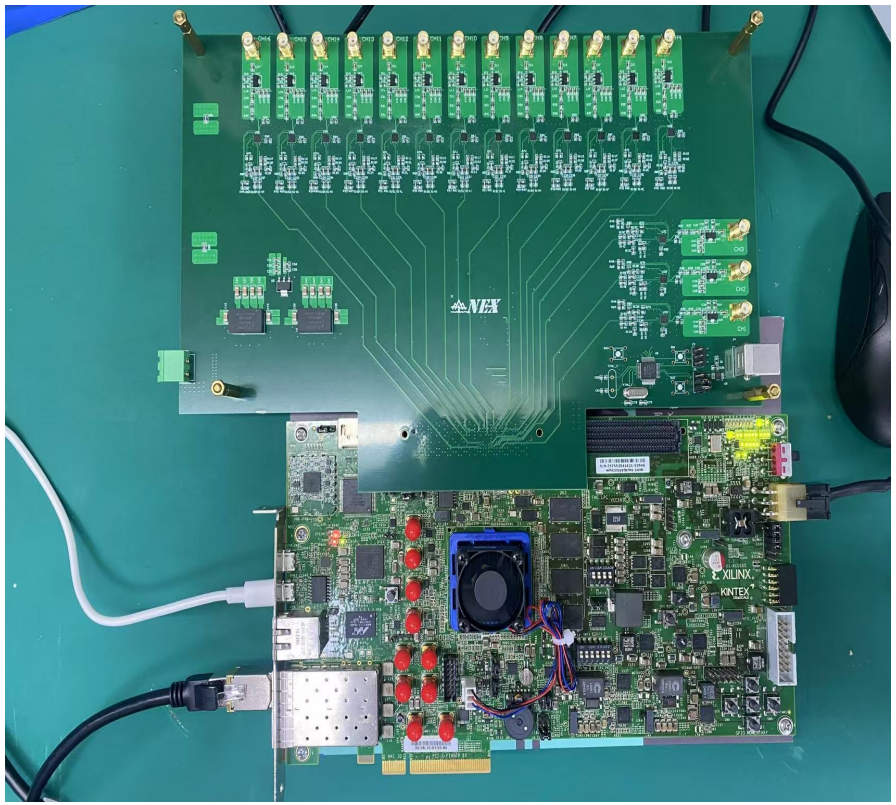


Sampling rate >= 3 Gsps is preferable!

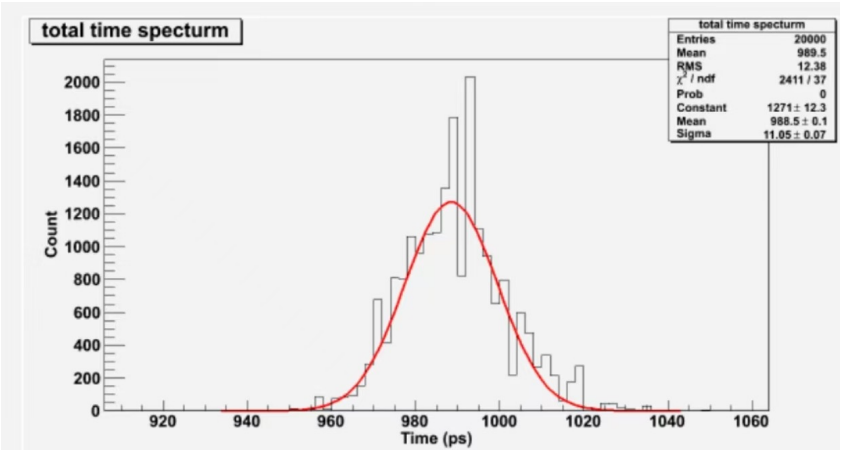
TDC scheme & test



前端版
- 4通道 SMA输出



读出板
- 16通道 FMC接口
- Xilinx K7开发板搭载TDC模块

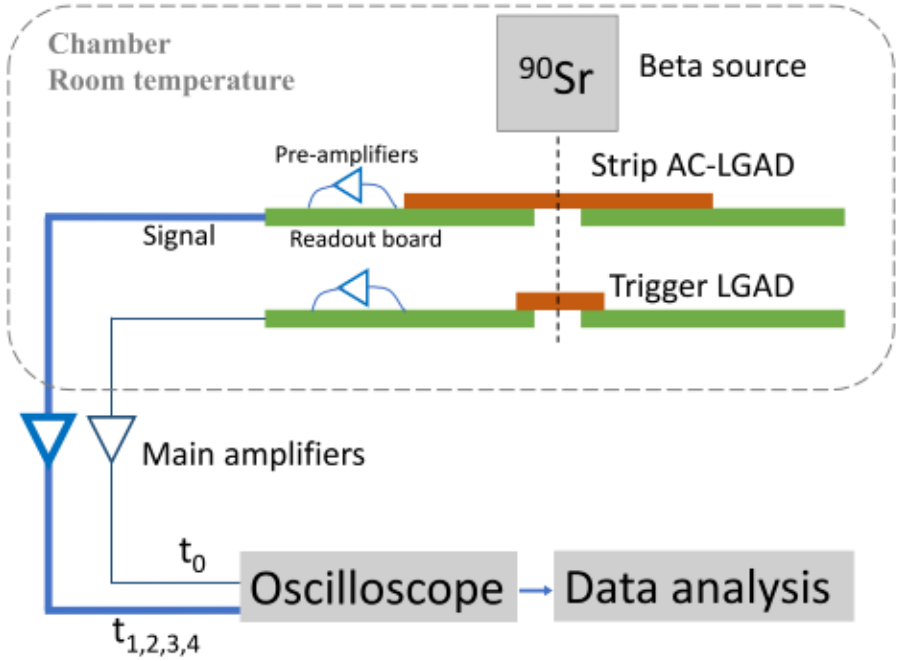


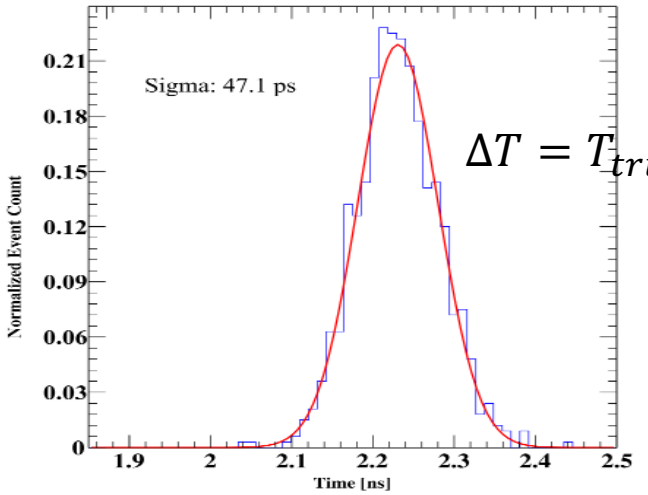
TDC初步测试结果，TOA精度~11 ps

Beta source & Beam test

Principals, methods & designs

^{90}Sr test & time resolution





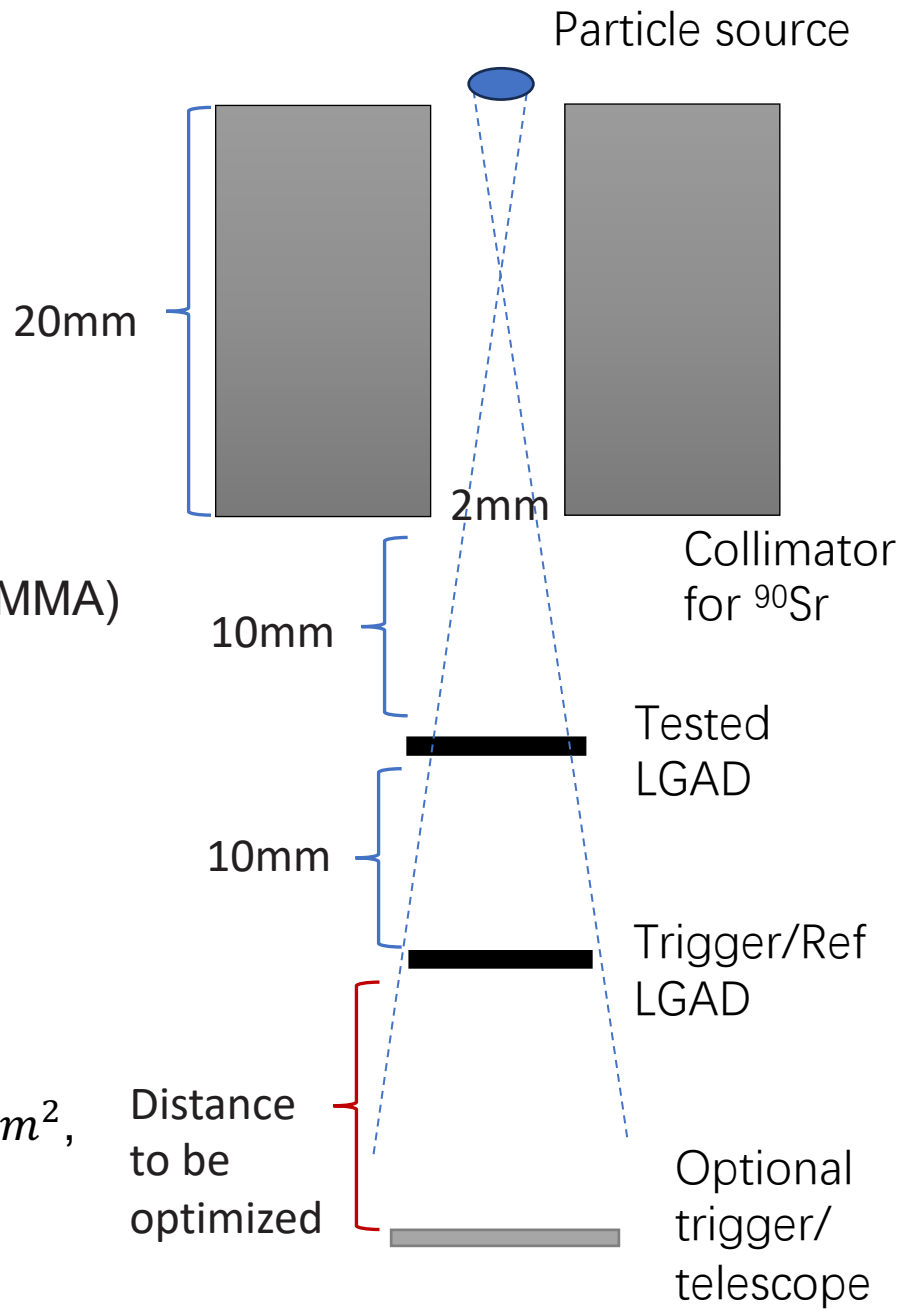
$$\Delta T = T_{trigger} - \frac{\Sigma a_i^2 T_i}{\Sigma a_i^2}$$

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

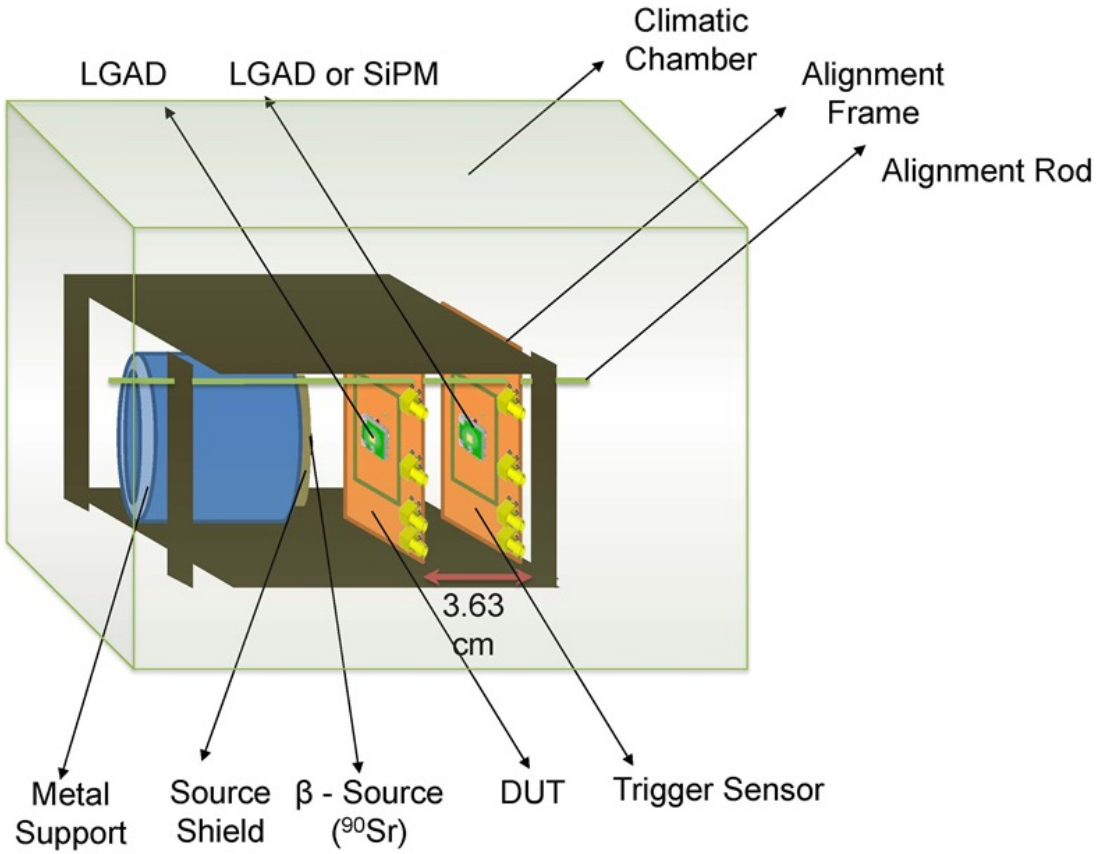
- Time walk effect $\sigma_{TimeWlak}$，与信号幅值分布、放大器响应速度有关
- Landau effect σ_{Landau} 由能量沉积（空间、时间）不均匀性引起
- Jitter effect $\sigma_{Jitter} = \frac{N}{dV/dt} \propto t_{rise}/\frac{S}{N}$，由噪声与上升沿速度共同决定
- σ_{TDC} = Δt / $\sqrt{12}$ （Δt : TDC bin 宽，即时间分辨单元）
- Distortion 信号在读出链路（电缆、放大器、ADC）中形状被展宽、反射、非线性失真

^{90}Sr / beam test setup

- β源^{90}Sr
  a) 面源，假设活性区域d=1mm
  b) 豁免源(V类)活度 1e4 Bq
- 准直（PMMA + Al + Cu + PMMA）减少β轫致辐射、同时吸收γ和软X
  a) 内直径2mm，长20mm (1mm PMMA, 3mm Al, 15mm Cu, 1mm PMMA)
  b) 距离LGAD 10mm，距离trigger LGAD 20mm
- e^-角度带来的 $\Delta t \sim 0.1ps$
- 穿过准直器的粒子 $R_{out} \sim 10个/s$
- LGAD（7.4mm×2.85mm）
- 穿过trigger LGAD的粒子 $R_{\text{trigger LGAD}} \sim 5个/s$
- Optional trigger: 塑料闪烁体/石英（切伦科夫）+ fast SiPM（$1.3\times1.3mm^2$, $3\times3mm^2$), can also be used as telescope for the beam test



^{90}Sr / beam test setup



Stack of LGAD planes and the trigger plane

Convenient laboratory tool to measure the gain and the timing resolution.
No position resolution.

Summary & Plan

- I-V & C-V test ✅ (almost), schematic & software are ready, waiting for HV source & LCR meter
- Currently preparing for the laser test & lab building🔄
  - Optical setup
  - Power sources & meters & other infrastructures
- Design of Sr-90 & beam test setup for time resolution study is also on-going🔄, preparing for beam reservation⏳
- Participate in the AC-LGAD fabrication run and process flow at SIMIT.📝
- More results & news will be updated later