BERKELEY LAB

AC-LGAD Sensor Beam Test @ JLab Hall-D

- *parasitic experiment on Jul.17 to Aug. 13, 2025*

Yu Hu @ Lawrence Berkeley National Lab

Provakar Datta[1], Xuan Li[2], Simone Mazza[3], Adam Molnar[3],
Grigory Nigmatkulov[4], Zhengwei Xue[1], Zhenyu Ye[1]

1. 2. Las Alamos National Lab, 3. Univ of California, Santa Cruz, 4. Univ of Illinois Chicago

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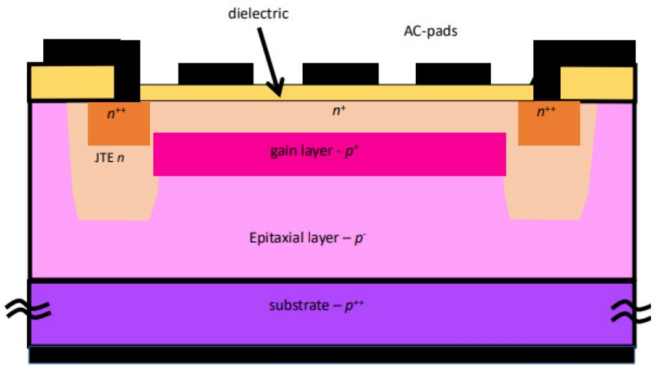
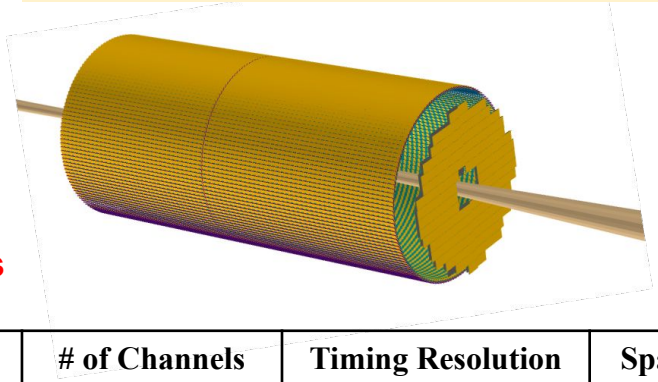
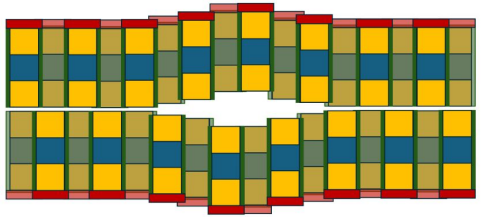
AC-LGAD Detectors for ePIC



AC-coupled Low Gain Avalanche Diodes

Multiple ePIC detector subsystems will use AC-LGAD:
Barrel and Forward TOFs, Roman Pots, B0 Tracker, Off-Momentum Detector @ Far-Forward, Luminosity monitor @ Far-Backward





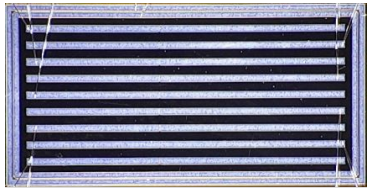
	Area (m^2)	Channel size (mm^2)	# of Channels	Timing Resolution	Spatial resolution	Material budget
Barrel TOF	10	0.5*10	2.4 M	35 ps	30 μm in r·φ	0.03 X_0
Forward TOF	1.1	0.5*0.5	3.2 M	25 ps	30 μm in x and y	0.05 X_0
B0 tracker	0.07	0.5*0.5	0.28 M	30 ps	20 μm in x and y	0.05 X_0
RPs/OMD	0.14/0.08	0.5*0.5	0.56/0.32 M	30 ps	140 μm in x and y	no strict req.

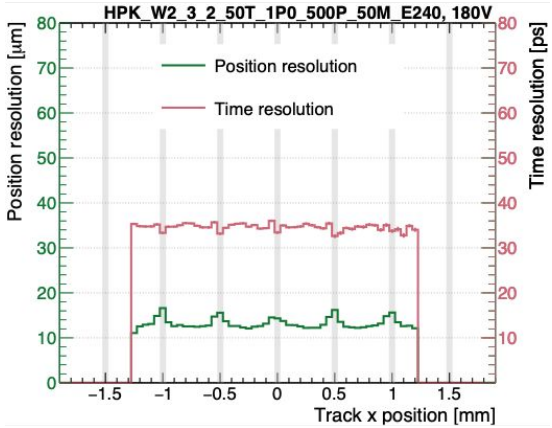
Small Size AC-LGAD Sensors (1st HPK Production)

Small size prototype sensors with different design parameters were tested at FTBF with 120 GeV protons

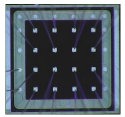
- Best performing 1 cm long, 500 um pitch strip sensors: ~35 ps time resolution and <15 um spatial resolution.
- Best performing 500 um pitch pixel sensors: ~20 ps time, ~20 um spatial resolution* (~50-60 um under metal). NIMA 1072 (2025) 170224

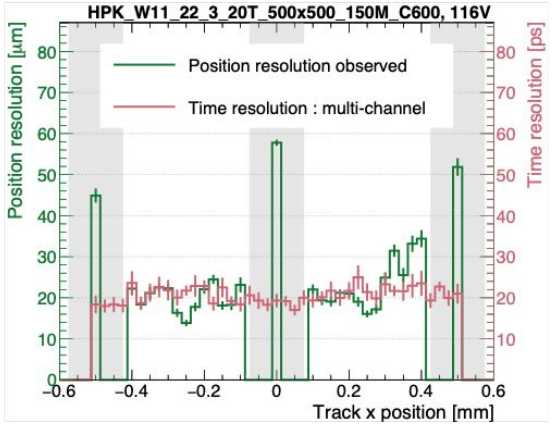
HPK Strip Sensor (1 cm x 4.5 mm)



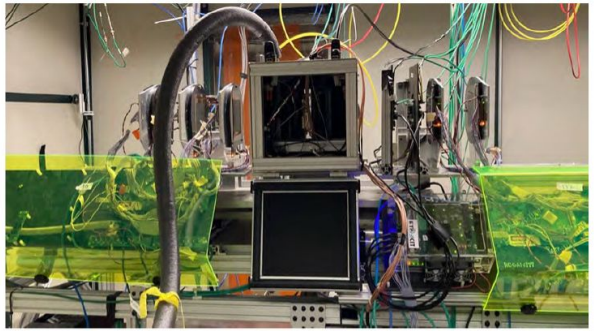


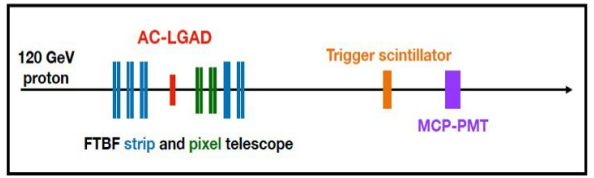
HPK Pixel Sensor (2mm x 2 mm)



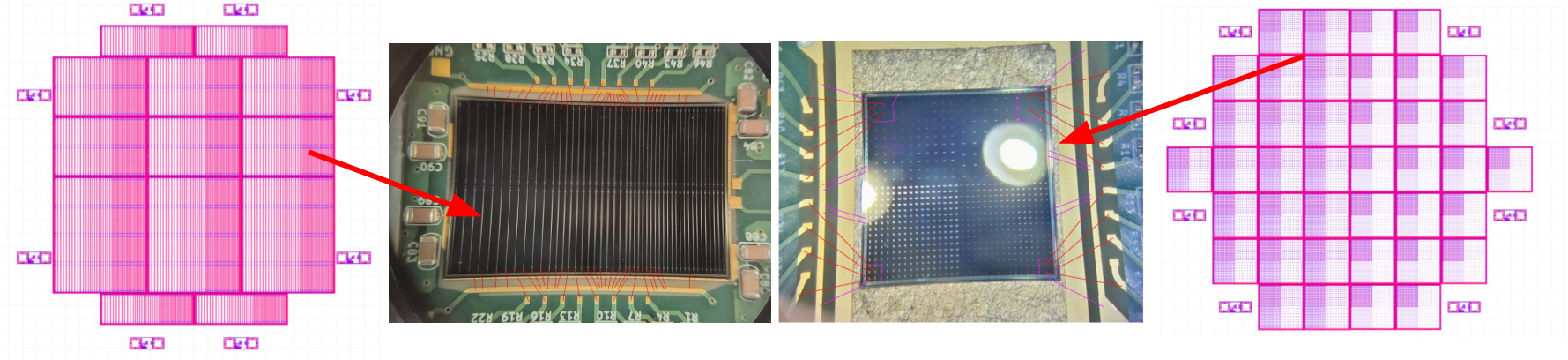


Fermilab Test Beam





New Module-Size AC-LGAD Sensors (2nd HPK Production)



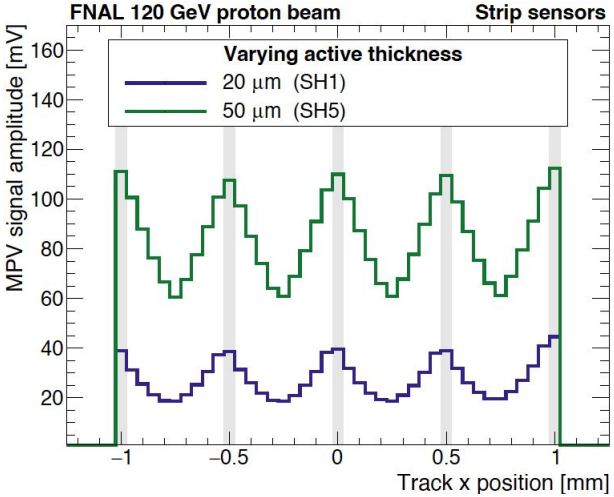
- **Strip sensors**: 3.2 cm x [1, 2, 4] cm
  - E-type, 600 pF/cm^2, 30/50 um thickness, 1 cm strip length, 500/750/1000 um pitch, 40/50 um electrode width
- **Pixel sensors**: 1.6 cm x 1.6 cm
  - C-type, 600 pF/cm^2, 20/30 um thickness, 500/750/1000 um pitch, 100/150 um electrode width

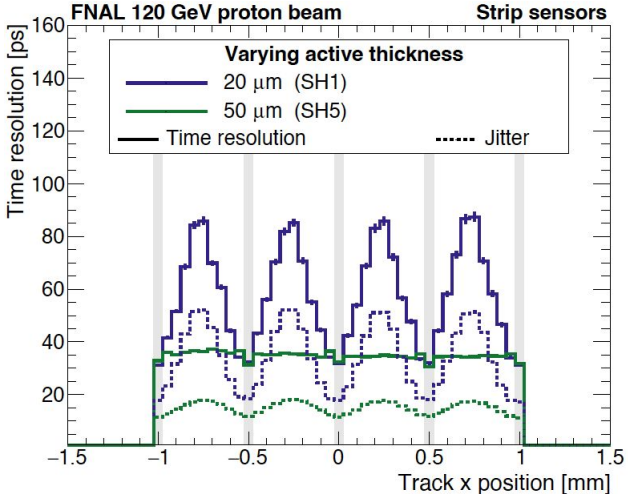
Main interests:
- Efficiency
- Time resolution
- Position resolution

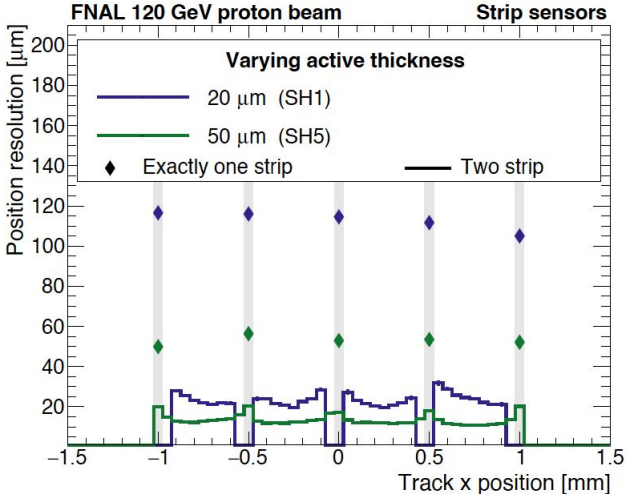
Green: tested in previous production

Red: new configurations in this production

Performance of Small Size AC-LGAD Sensors







NIMA 1072 (2025) 170224

Module-Size AC-LGAD Sensors

- **Strip sensors**: 3.2 cm x 2 cm
  - E-type, 600 pF/cm^2, 30 um thickness, 1 cm strip length, 500 um pitch, 50 um electrode width

Green: tested in previous production

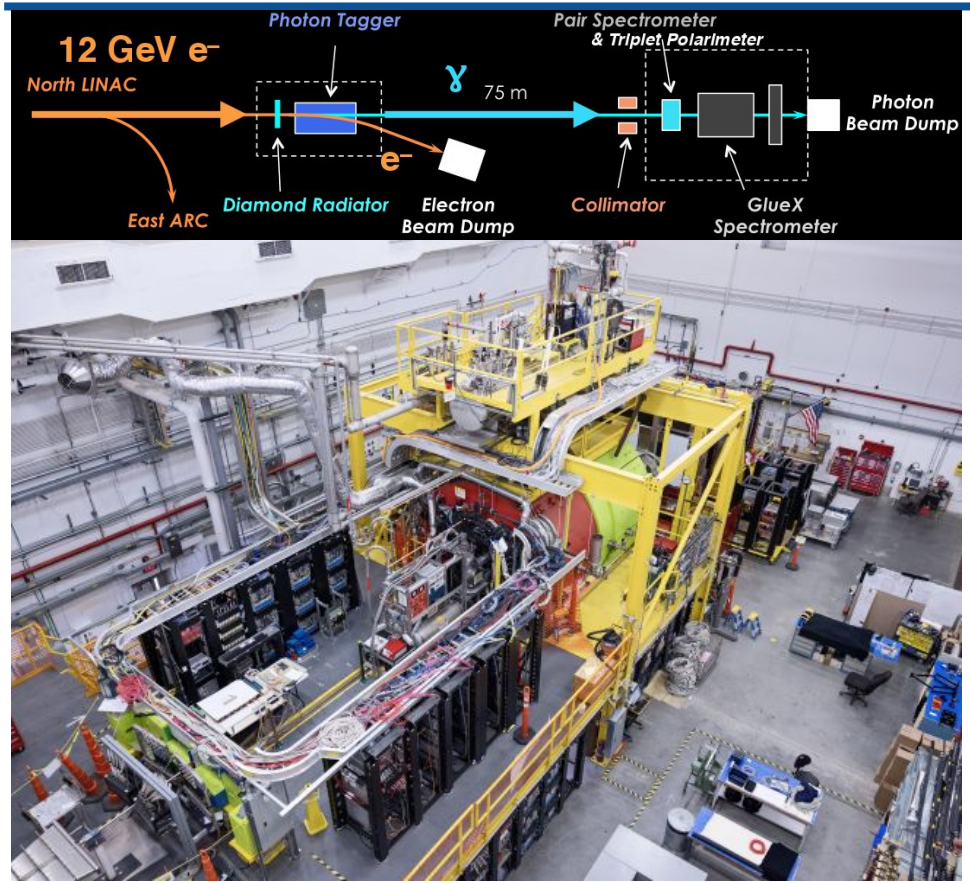
Red: new configurations in this production

$$\sigma_t^2 = \sigma_{sensor}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2 + \sigma_{time\ walk}^2$$

σ_{sensor}: increase with sensor thickness

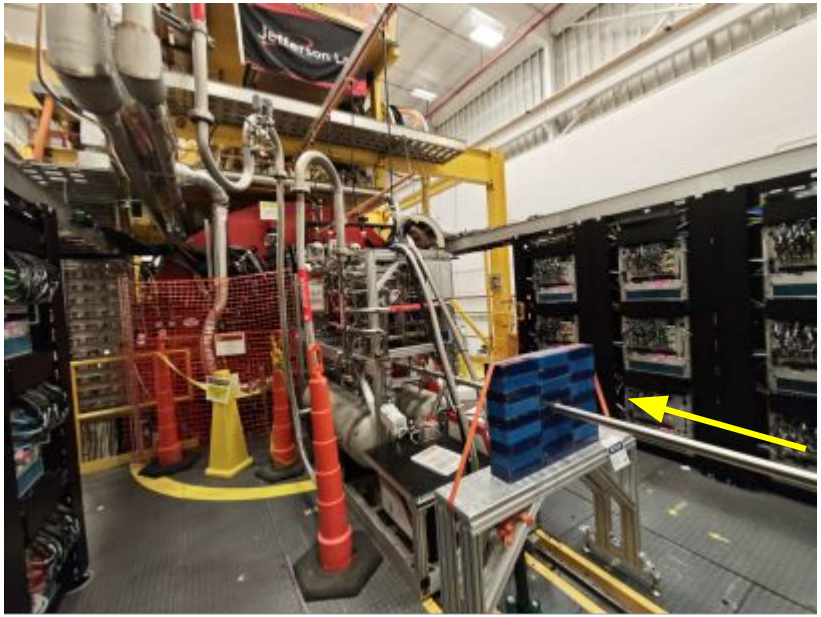
$\sigma_{jitter} \propto risetime \cdot N/S$: decrease with sensor thickness

Parasitic Beam Test Opportunities at JLab Hall-D

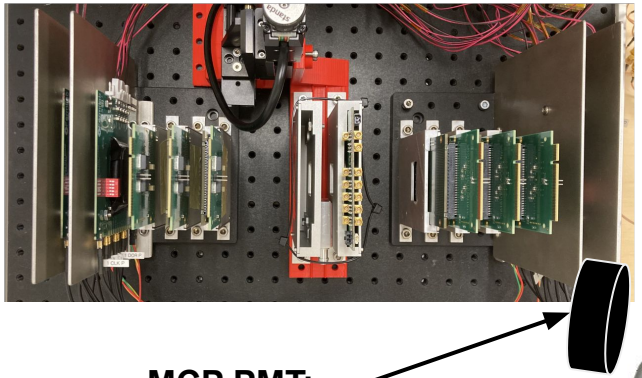


- Beam: 3-6 GeV/c electrons
- Vertical beam size: 0.5 cm
- Beam intensity: ~1 kHz/cm2
- Running mode: parasitic
- Schedule: July 17 to Aug 13, 2025

Beam Test @ JLab Hall-D



AC-LGAD Beam Test System



MCP PMT:
As timing reference
MCP PMT (Microchannel Plate Photomultipler Tubes)

DC-LGAD:
4 layers (2+2) as another timing reference

MAPS:
6 layers (3+3) as position reference
MOSS (MOnolithic Stiched Sensors)

Steppers:
Move AC-LGAD on X-Y

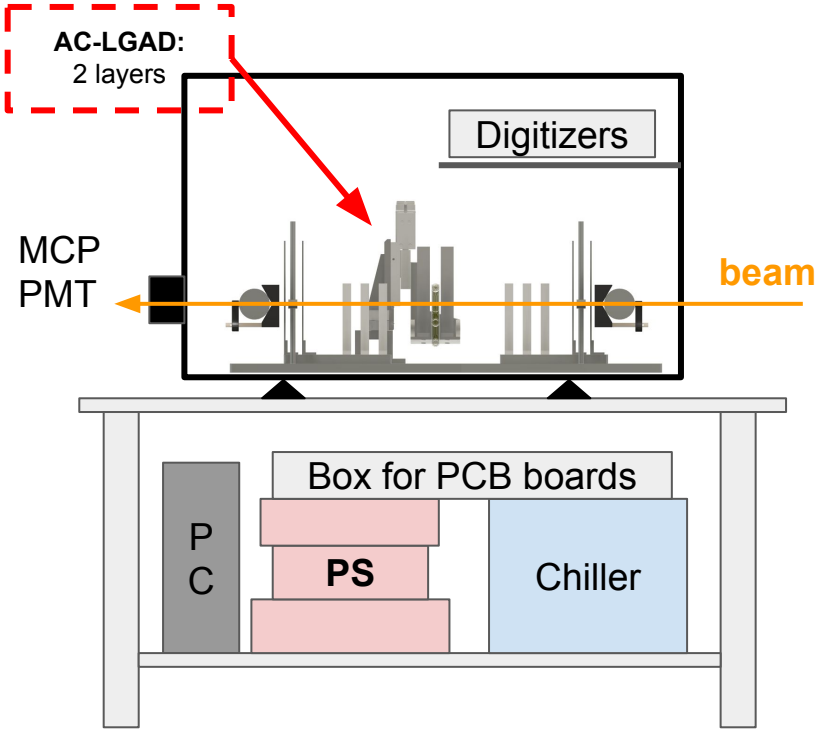
AC-LGAD:
2 layers

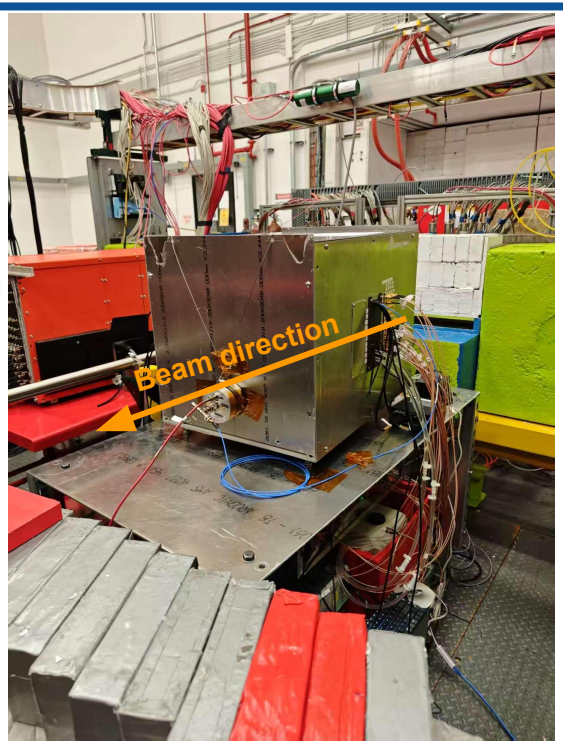
Scintillator+PMTs:
Provide trigger to the system

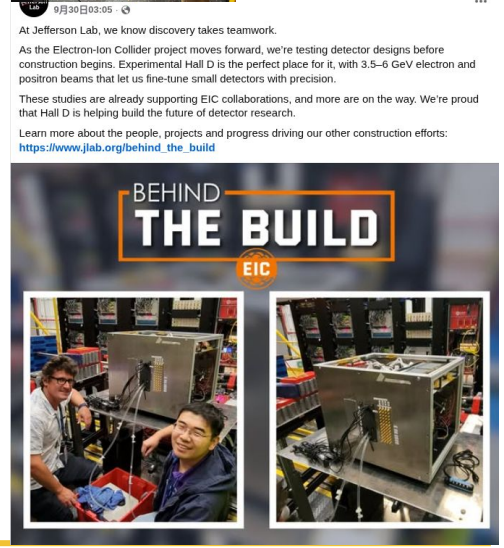
Electrons Direction (Compton+Pair)

Cooling plate:
Maintain the stable T for AC-LGADs

Installation & Setups

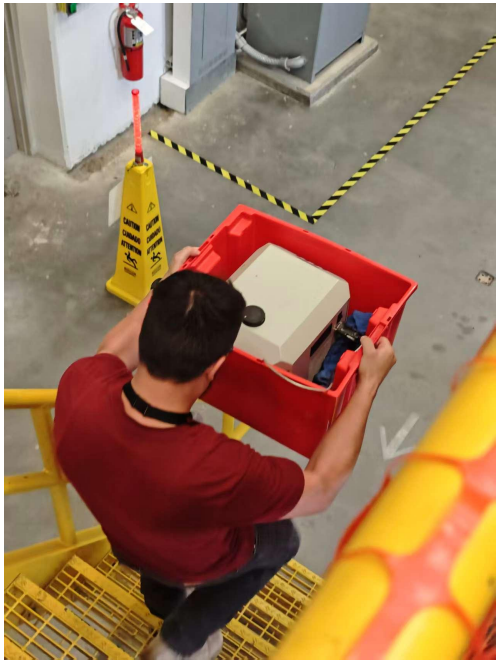


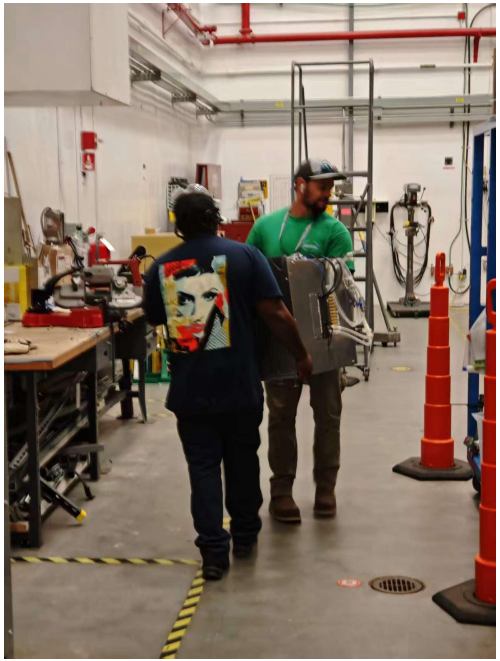




- DUT temperature controlled at 20 C by a water chiller
- Telescope installed on July 17, MCP PMT added on Aug 6th
- Lots of help from EIC and Hall-D members

Uninstallation

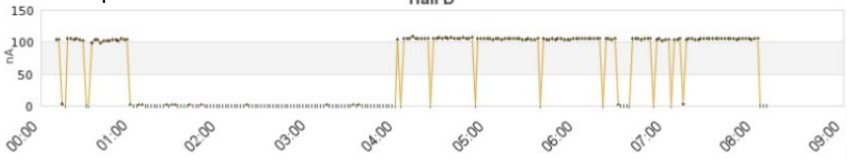


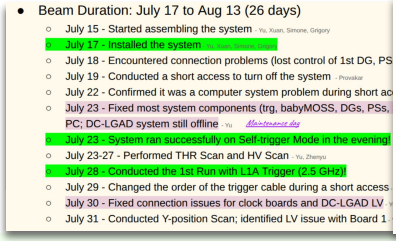


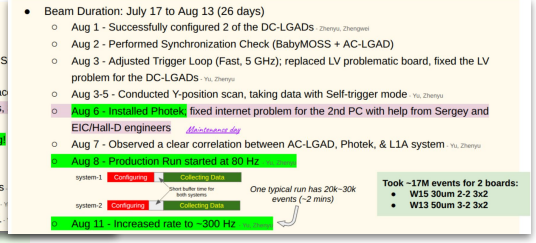
- Removed on Aug 13, with help from JLab EIC and Hall-D members

Short Summary of Data Taking

An example beam current monitor



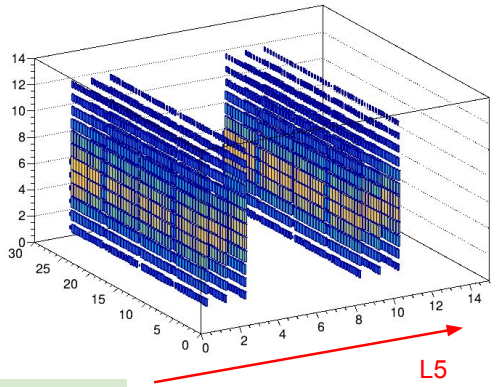


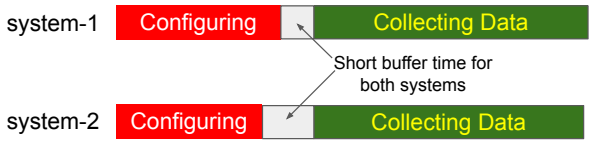


- Beam from July 17 to August 13 (26 days) with various beam configurations during this time; stable beam for most of the duration.
- Five long access periods for maintenance and beam studies, plus over 10 rapid accesses

- Many challenges with new systems and limited access time, but we successfully commissioned the system and collected approximately 17 million events for two strip sensors

Hit-Map w. MAPS





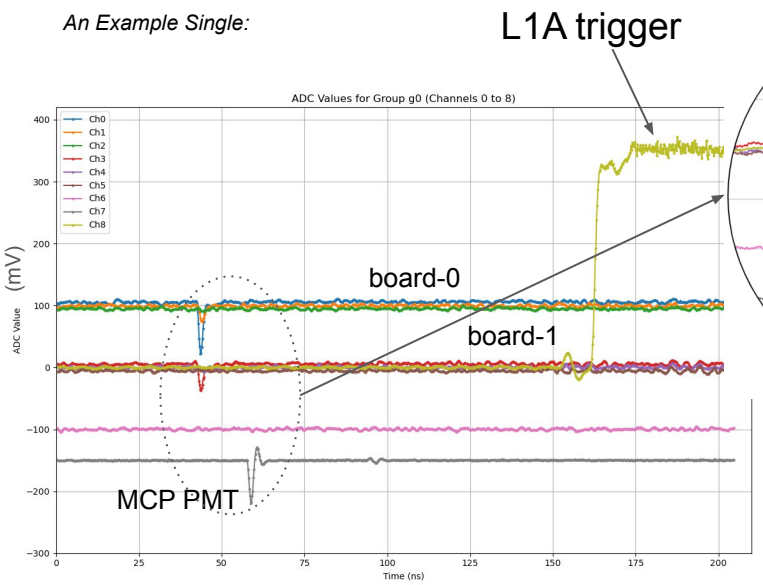
One typical run has 20k~30k events (~2 mins)

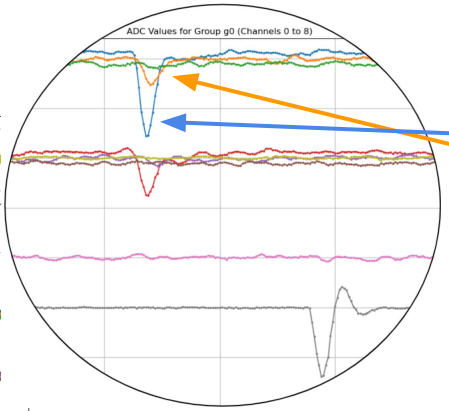
~17M events for 2 strip sensors:
- **W15 30um, 3 cm x 2 cm**
- **W13 30um, 3 cm x 2 cm**

AC-LGAD Signal & HV scan

Signal amplitude might be the limitation

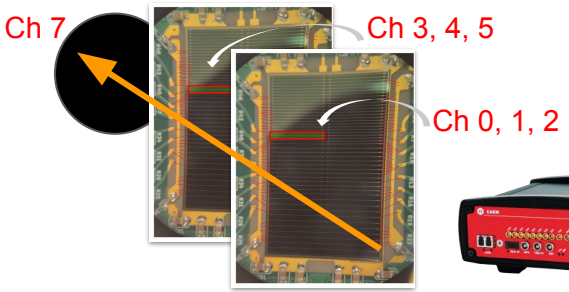
An Example Single:

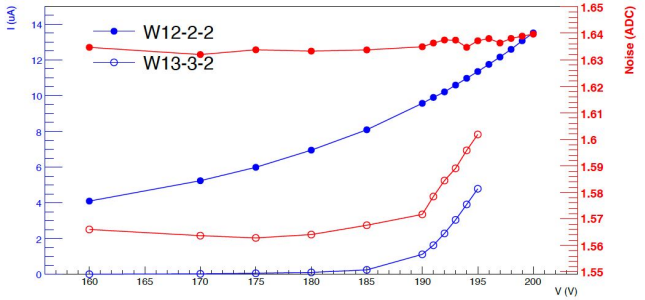




Charge sharing

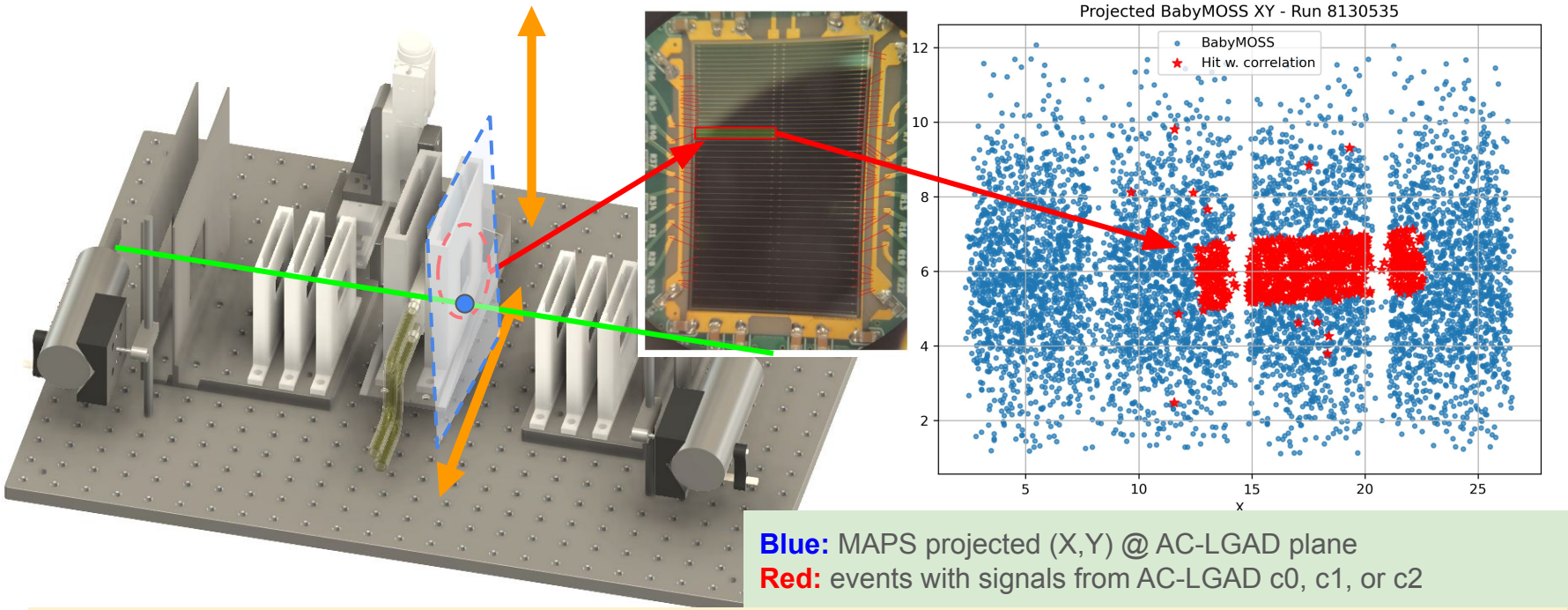
- Trigger from Scintillator for MCP PMT and AC-LGAD DAQ
- HV Scan to Optimize Voltage - based on current & noise





Measurements done for one HV setting only; HV scans are needed in future beam tests to find optimal setting

AC-LGAD - Y Position Study

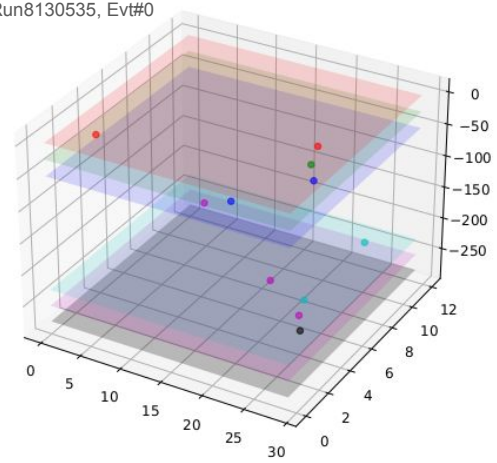


Blue: MAPS projected (X,Y) @ AC-LGAD plane
Red: events with signals from AC-LGAD c0, c1, or c2

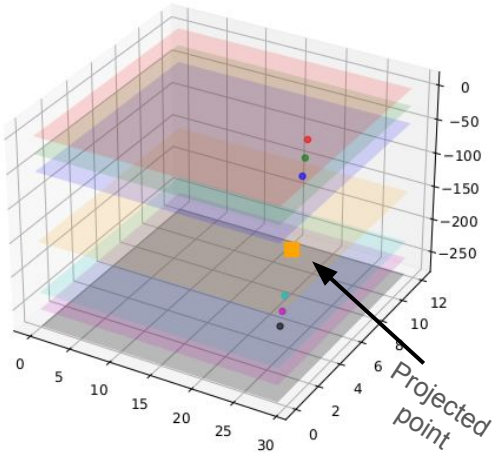
- Correlation between AC-LGAD and MAPS signals; the DAQ is well synchronized
- Current measurements focus on the 500 μm pitch region; further studies are needed for other areas of interest in future beam tests

Telescope Alignment

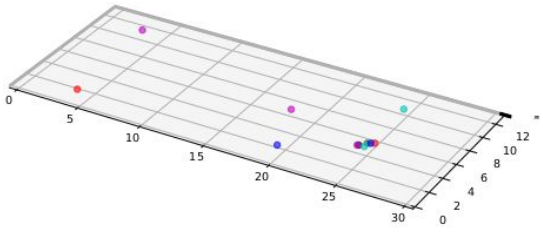
Run8130535, Evt#0

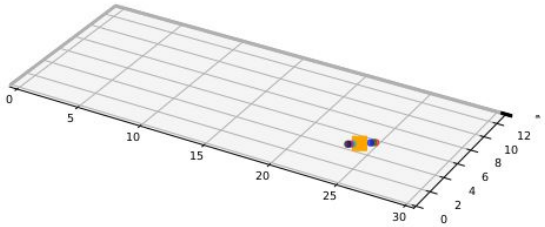


Before alignment & hot-pixel masking

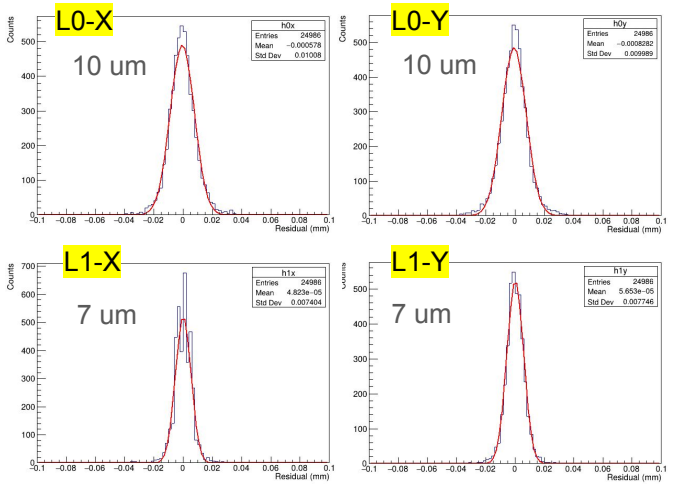


After alignment & hot-pixel masking



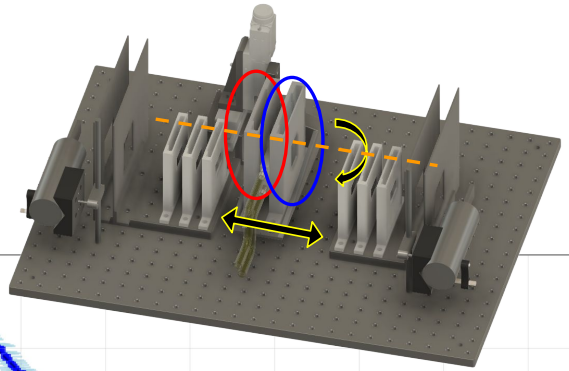


Example of residual distributions

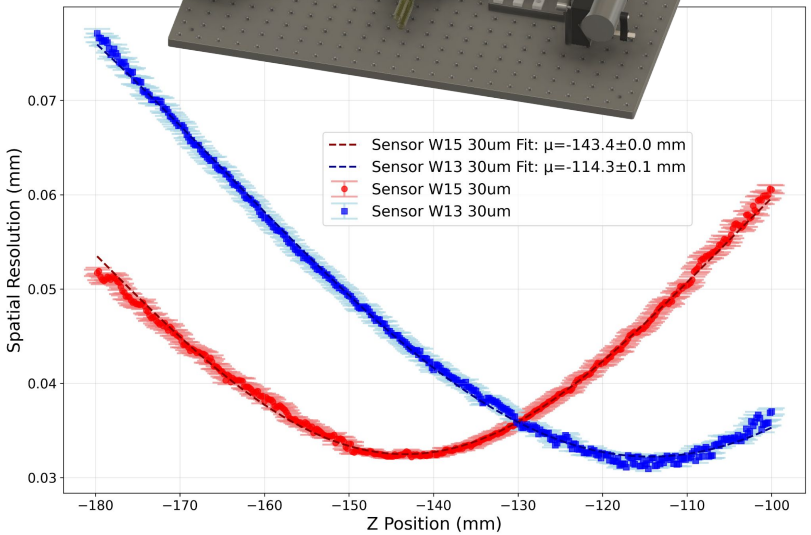


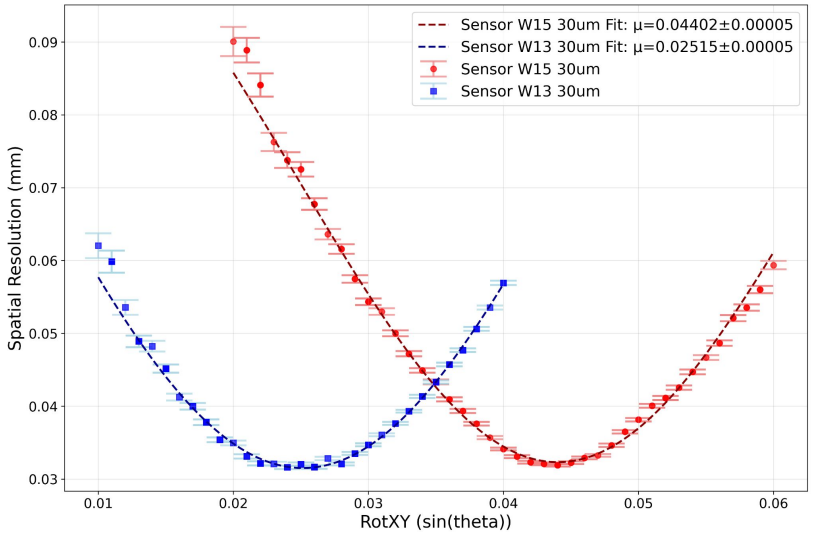
- Clear improvement after applying preliminary alignment correction
- Residuals are 7-10 μm

AC-LGAD Alignment

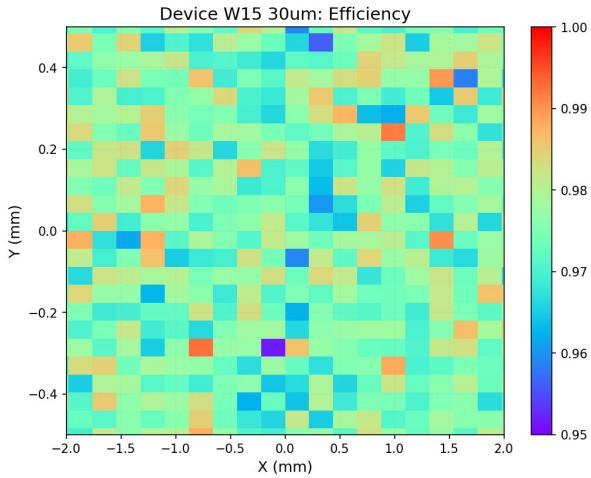


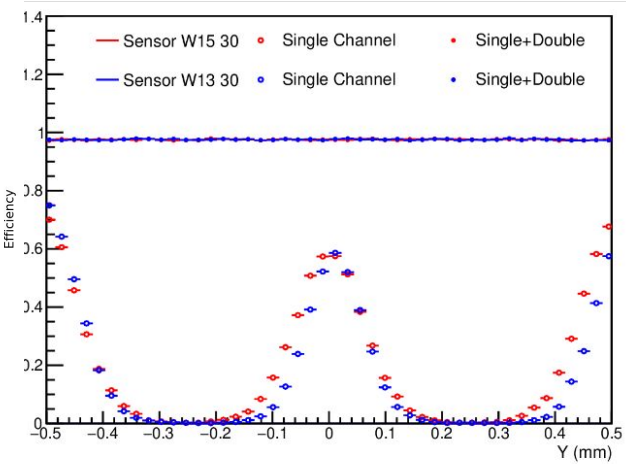
- AC-LGAD are aligned to the tracking systems
- Distance between two modules are ~29 mm — consistent with the testing setup

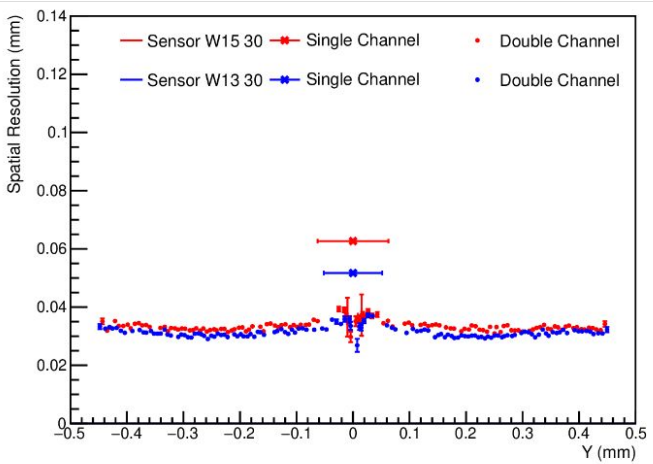




Efficiency & Spatial Resolution

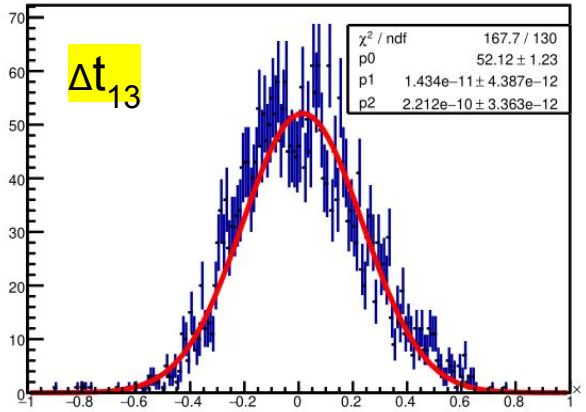


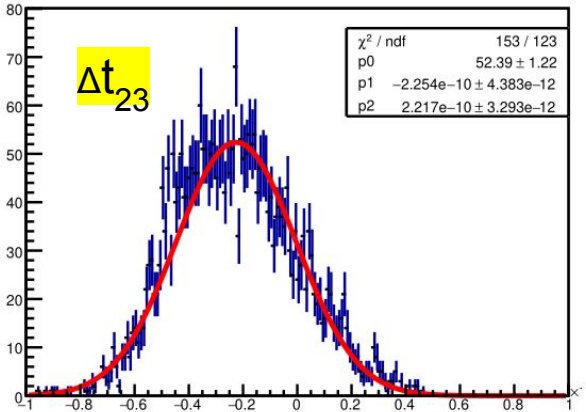


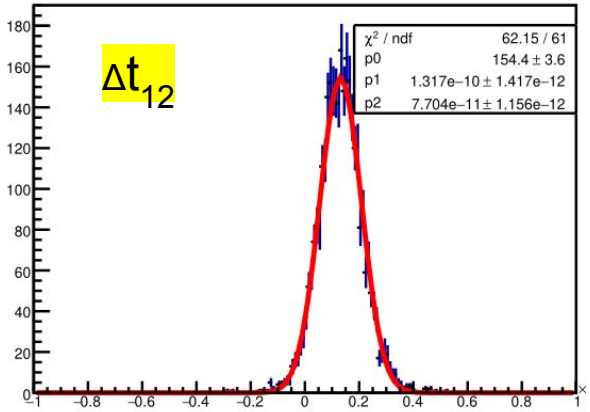


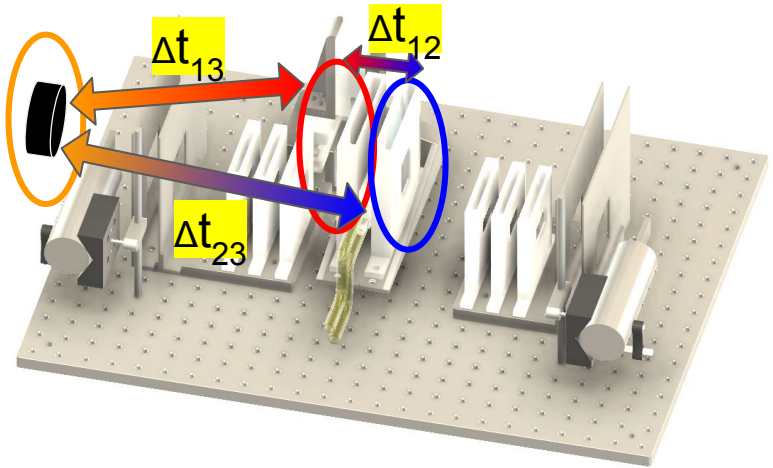
- AC-LGAD average single+double channel efficiency exceed 98%.
- Average spatial resolutions of ~30 μm achieved
  - W15 (30um): 33.42 ± 0.10 um
  - W13 (30um): 31.32 ± 0.06 um

Time Resolution



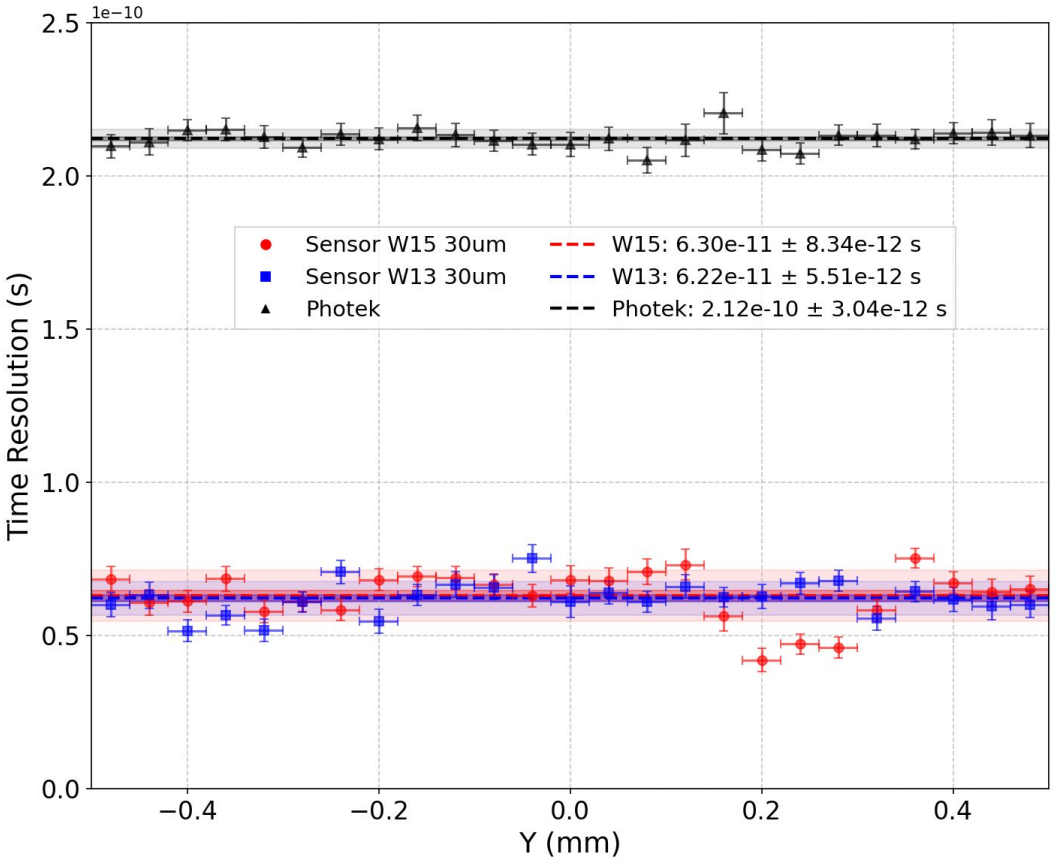






- Time resolution is extracted from Δt's between each two devices
- Single- & Double- channel clusters are analyzed separately and merged by weight to get the total resolution

Time Resolution



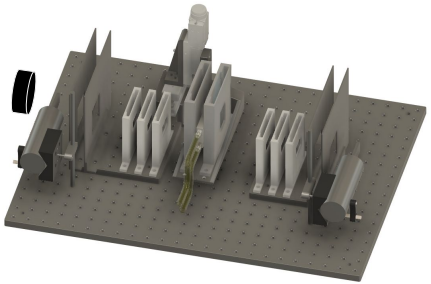
Time resolution:

- W15 (30um): 63 ± 8 ps
- W13 (30um): 62 ± 5 ps

Summary & Outlook

Summary: parasitic beam test at JLab Hall-D on in July-August, 2025

- Successfully commissioned and collected ~ 17M good events on 30um (new) module-size AC-LGAD strip sensors
- Results consistent with the trend observed with 20um and 50um small size sensors.



Efficiency	Spatial resolutions	Time resolutions
>98%	W15 (30um): 33.42 ± 0.10 um W13 (30um): 31.32 ± 0.06 um	W15 (30um): 63 ± 8 ps W13 (30um): 62 ± 5 ps

Outlook - future beam tests

- **50um module-size strip sensors** w. different pitch
- **20 and 30um module-size pixel sensors** w. different pitch

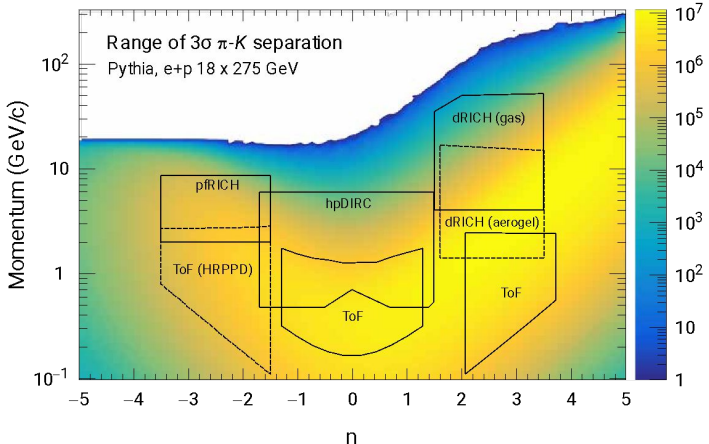
Thank you!

BERKELEY LAB

Jefferson Lab

Backups

ePIC PID Detectors



Time-of-Flight: AC-LGAD

- Backward: HRPPD with 10-20 ps resolution
- Barrel: AC-LGAD strip sensors with 35 ps resolution
- Forward: AC-LGAD pixel sensors with 25 ps resolution

dRICH: dual radiator RICH

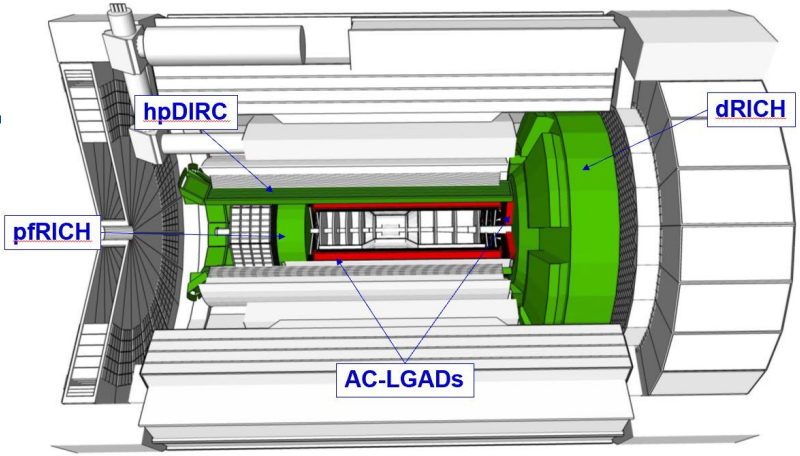
- Aerogel and C_2F_6 gas with SiPM for light detection

pfRICH: proximity focusing RICH

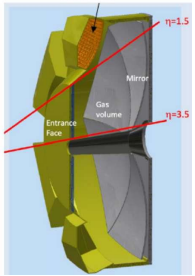
- Single volume with long proximity gap (~30 cm), using Aerogel as radiator and HRPPD as photon sensors

hPDIRC: high performance DIRC

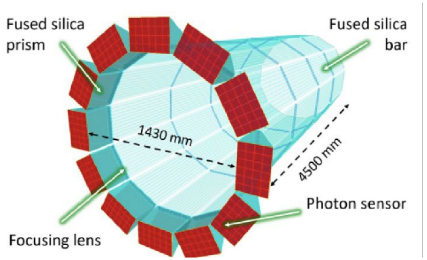
- Quartz bar radiator (BABAR bars reuse) with MCP-PMT



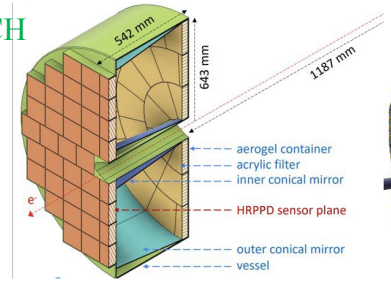
dRICH



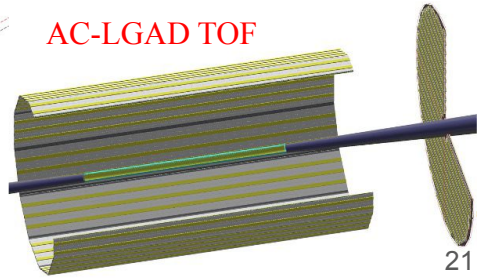
hpDIRC



pfRICH



AC-LGAD TOF



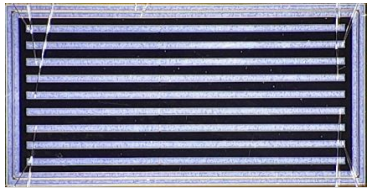
Small Size AC-LGAD Sensors (1st HPK Production)

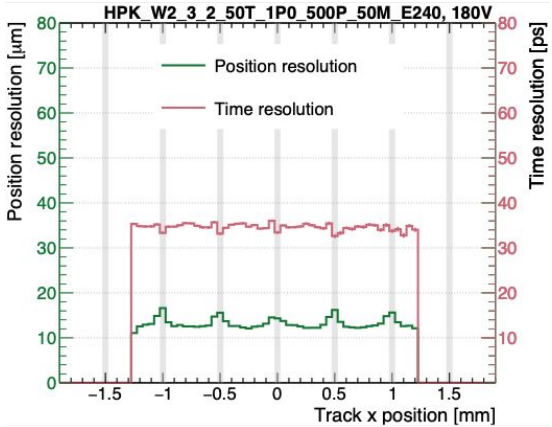
Two papers from Shirsendu, Zhenyu, etc..
C. Madrid et al 2023 *JINST* 18 P06013
Nucl.Instrum.Meth.A 1072 (2025) 170224

Small size prototype sensors from HPK were tested at FTBF with 120 GeV protons

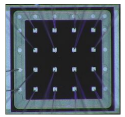
- Best performing 1 cm long, 500 um pitch strip sensors: ~35 ps time resolution and <15 um spatial resolution.
- Best performing 500 um pitch pixel sensors: ~20 ps time, ~20 um spatial resolution* (~50-60 um under metal).

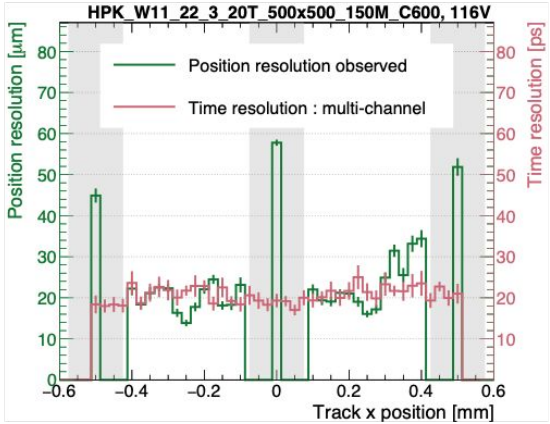
HPK Strip Sensor (1 cm x 4.5 mm)



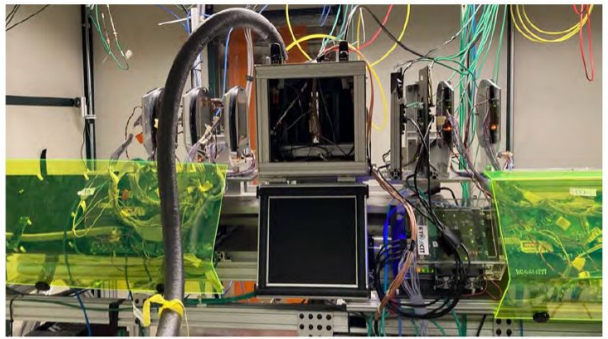


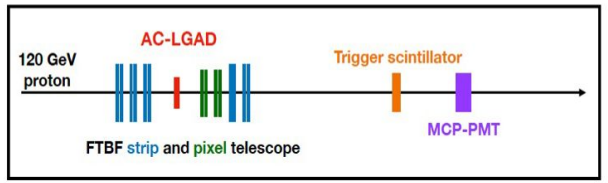
HPK Pixel Sensor (2mm x 2 mm)



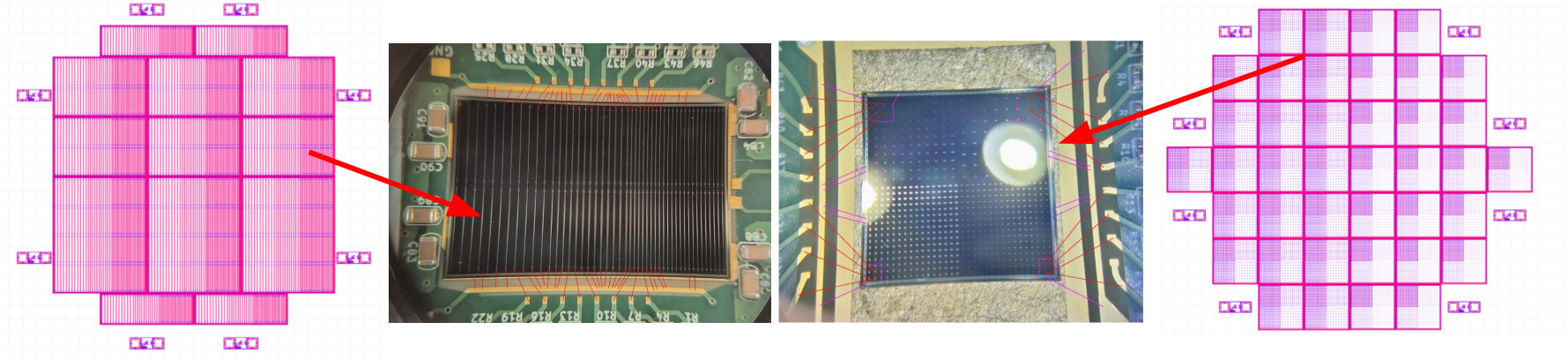


Fermilab Test Beam





Real Size AC-LGAD Sensors (2nd HPK Production)



- **Strip sensors**: 3.2 cm x [1, 2, 4] cm
  - E-type, 600 pF/cm^2, 30/50 um thickness, 1 cm strip length, 500/750/1000 um pitch, 40/50 um electrode width
- **Pixel sensors**: 1.6 cm x 1.6 cm
  - C-type, 600 pF/cm^2, 20/30 um thickness, 500/750/1000 um pitch, 100/150 um electrode width

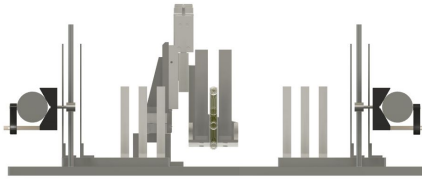
Green: tested in previous production

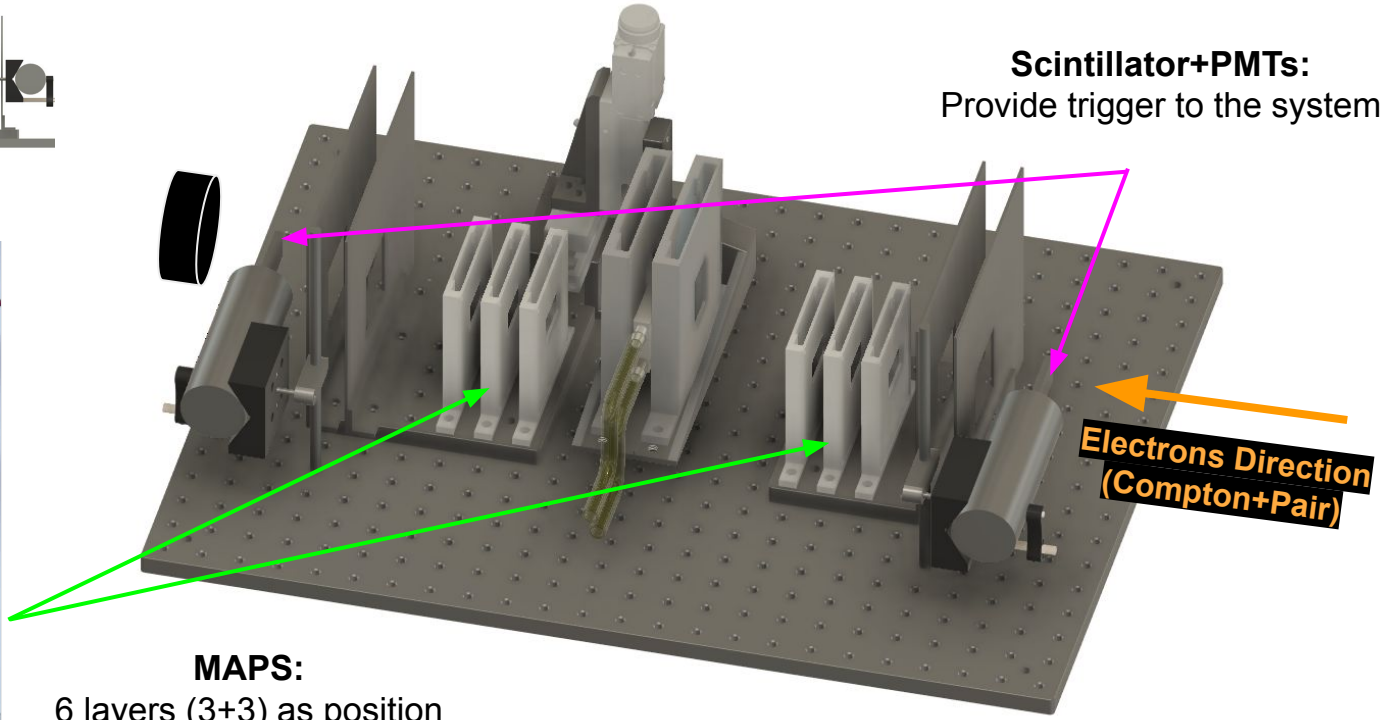
Red: new configurations in this production

Our main interests:

- Efficiency
- Time resolution
- Position resolution

AC-LGAD Beam Test System

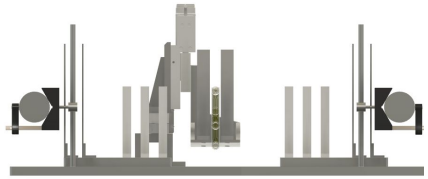


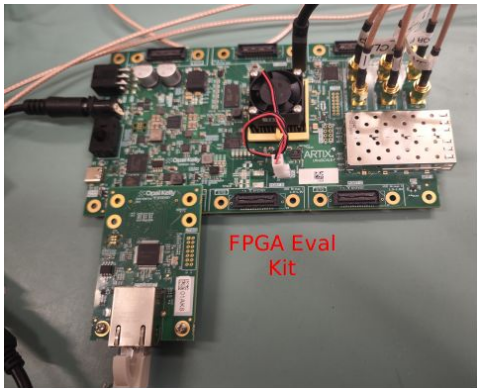


Scintillator+PMTs:
Provide trigger to the system

MAPS:
6 layers (3+3) as position reference
MOSS (MOnolithic Stiched Sensors)

AC-LGAD Beam Test System

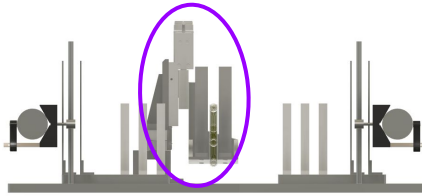


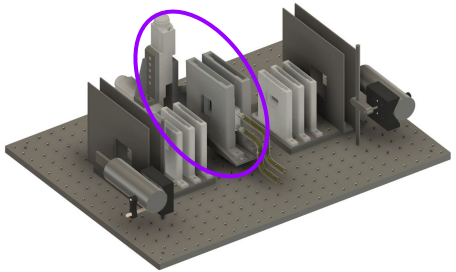


MCP PMT:
As timing reference
MCP PMT (Microchannel Plate Photomultipler Tubes)

DC-LGAD:
4 layers (2+2) as another timing reference

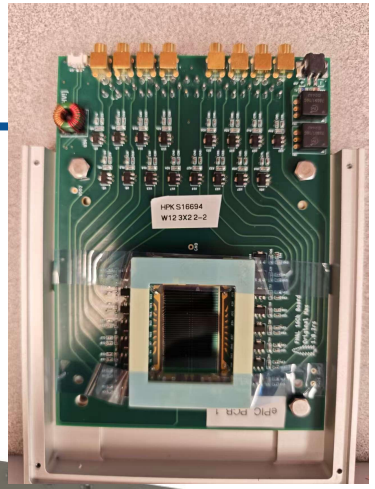
AC-LGAD Beam Test System





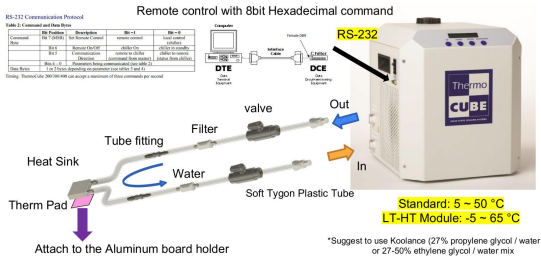
Steppers:
Move AC-LGAD on X-Y

AC-LGAD:
2 layers

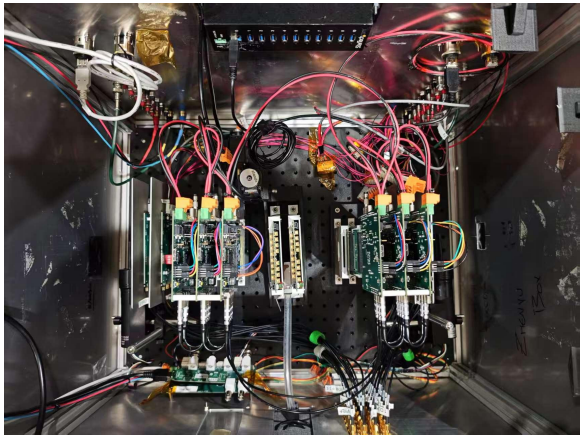


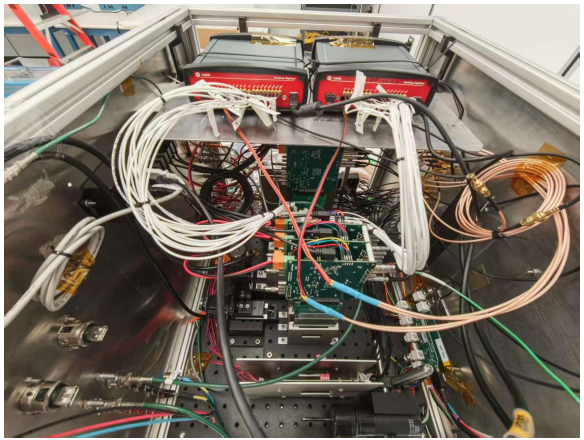
DT5742: 16+1
Channel 12 bit 5 GS/s
Switched Capacitor
Digitizer based on the
DRS4 chip

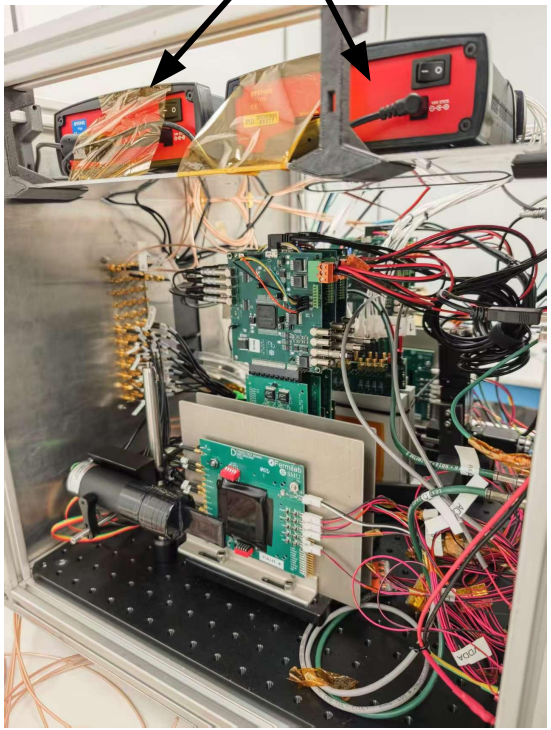
Cooling plate:
Maintain the stable T for
AC-LGADs

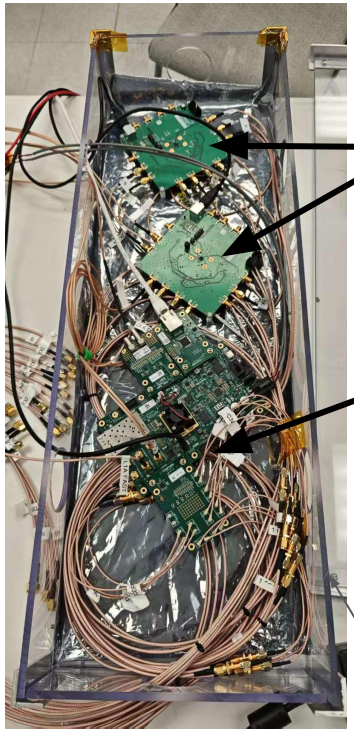


AC-LGAD Beam Test System



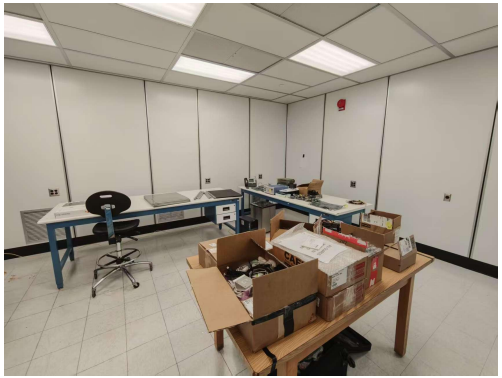


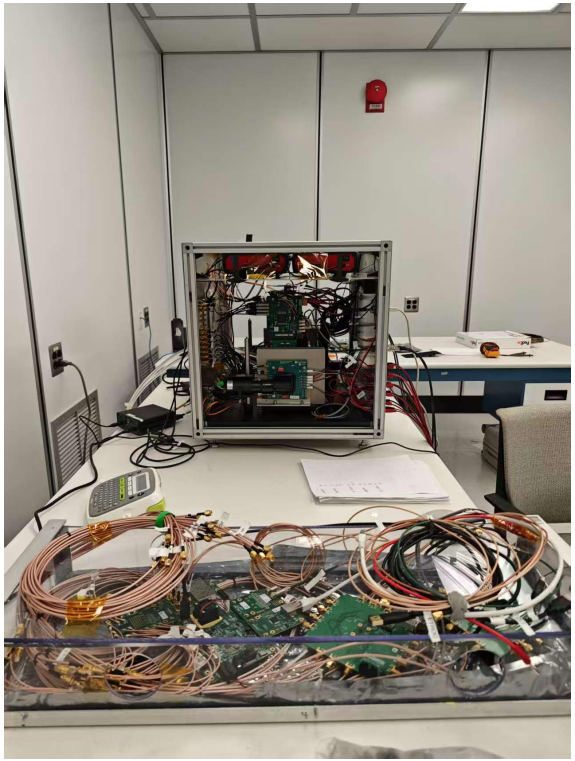


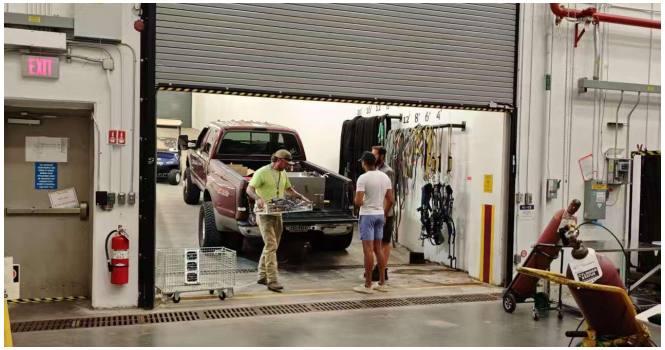


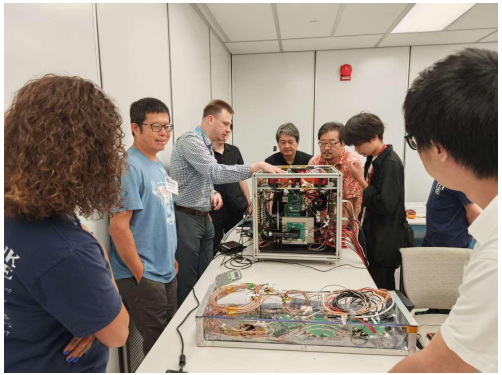
Thanks to Andrew and Caleb for making this nice box

Assembly & Installation



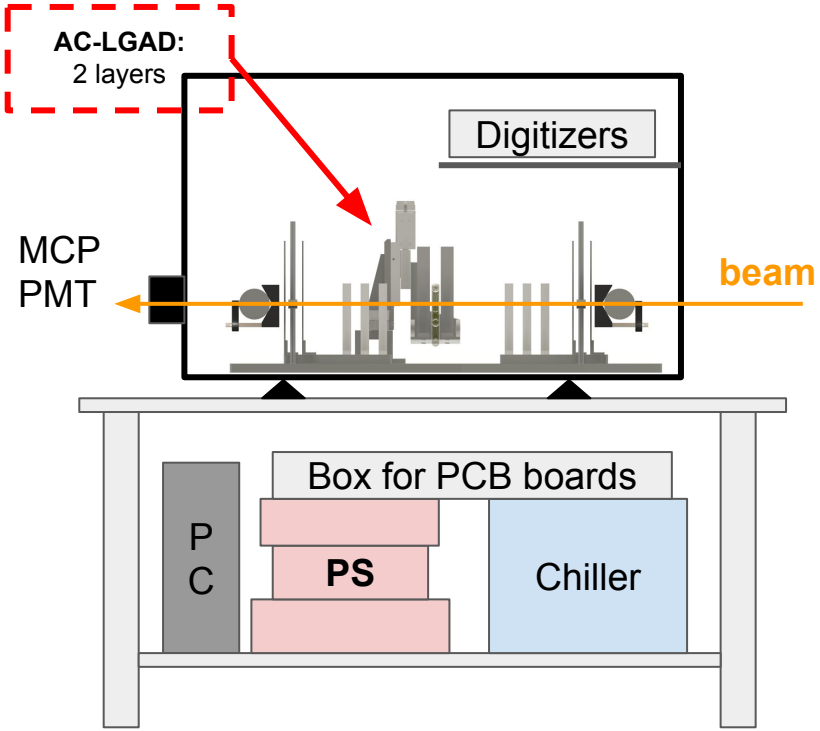


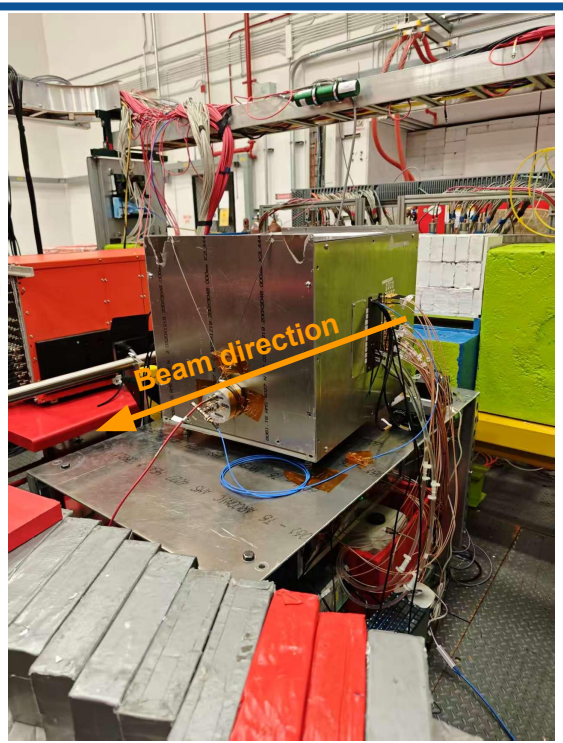


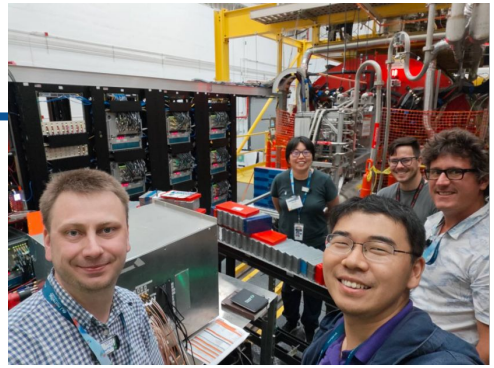


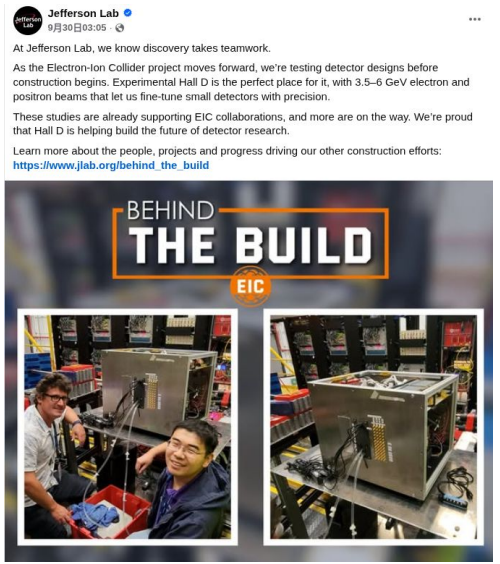
- Installed on July 17, with help from JLab EIC and Hall-D members

Installation & Setups



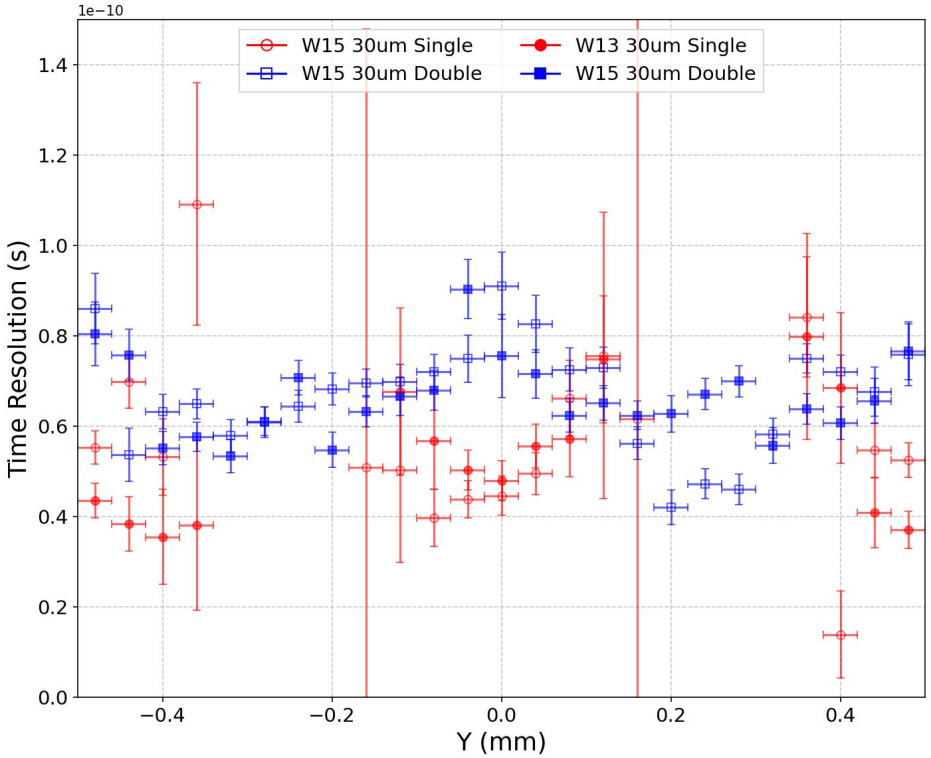


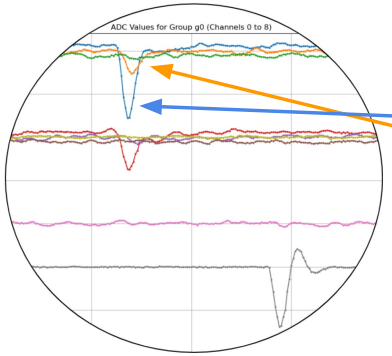




- DUT temperature controlled at 20 C by a water chiller
- Telescope installed on July 17, MCP PMT added on Aug 6th
- Lots of help from EIC and Hall-D members

Time Resolution from Single & Double channels

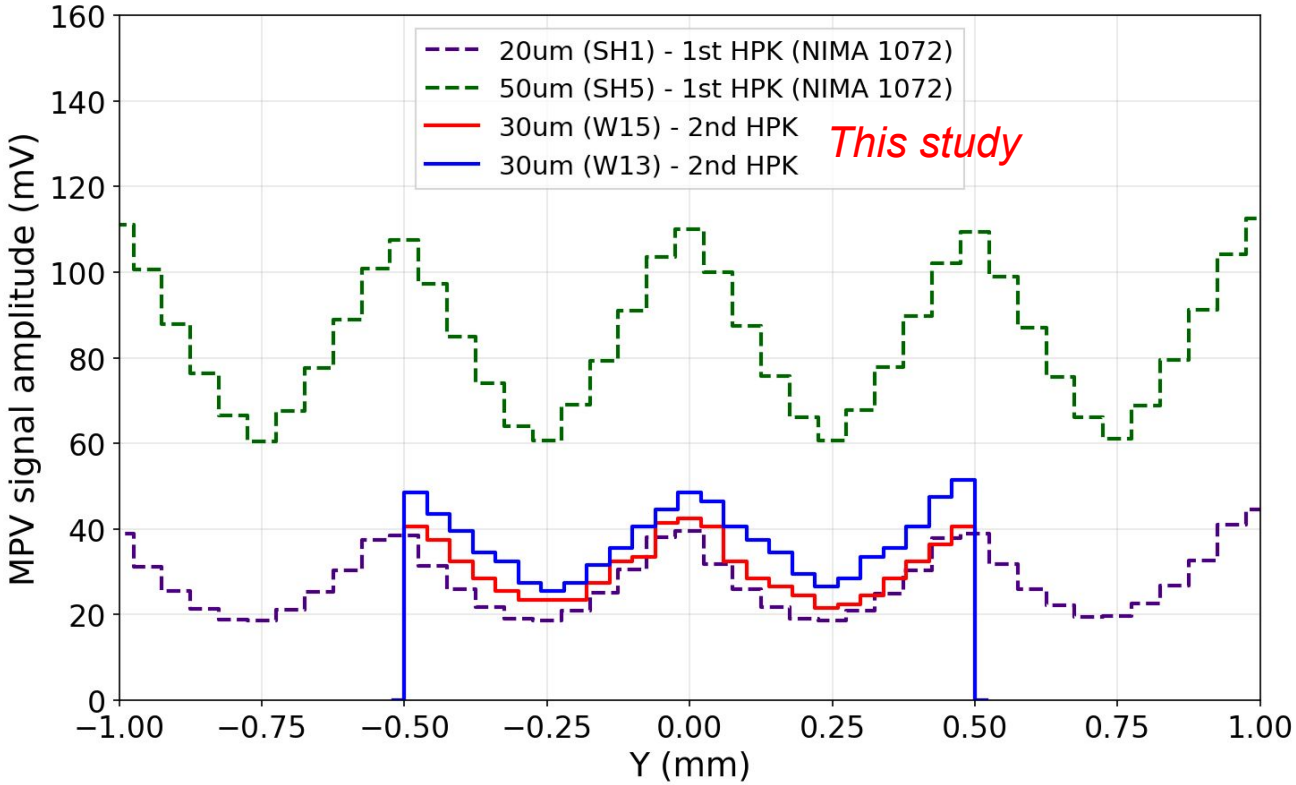




An example of double-channel signal

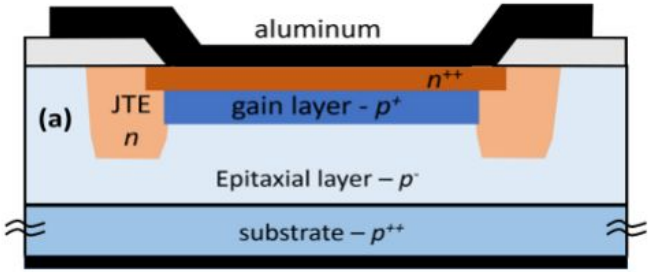
- Distance between two strips is 0.5 mm
- Counts from single & double channels are used as weight

MPV Signal Amplitude

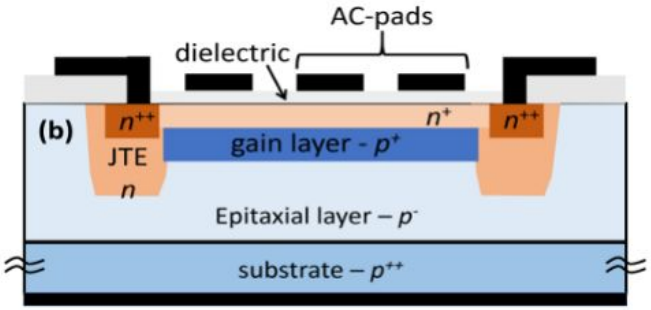


MPV amplitude of leading strip

DC-LGAD & AC-LGAD



DC-LGAD



AC-LGAD

- The read-out electrode is placed and connected to the N++ layer.
- Large pixel size and dead zone between pixels(JTE, Pstop)

Timing performance:<35ps
Position resolution: pixel size/√12
1.3mm/ √12
Dead area: JTE, P-stop

- metal AC readout electrode and a thin dielectric layer (Si_3N_4, SiO_2) above the N+ layer
- Less dead area and better position resolution

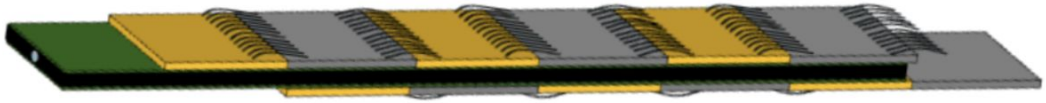
AC-coupled LGADs, n++ implant well is replaced by a more resistive n+ layer, with electrodes that are AC coupled to it via a thin dielectric layer

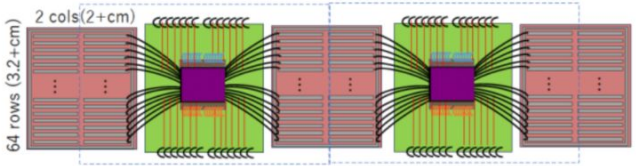
- Research institute: FBK, HPK,INFN, BNL, CNM, USTC, IHEP…

https://indico.ihep.ac.cn/event/24862/contributions/178750/attachments/87361/112469/LGAD%20development%20and%20its%20application%20for%20X-ray%20detection_Mei.pdf

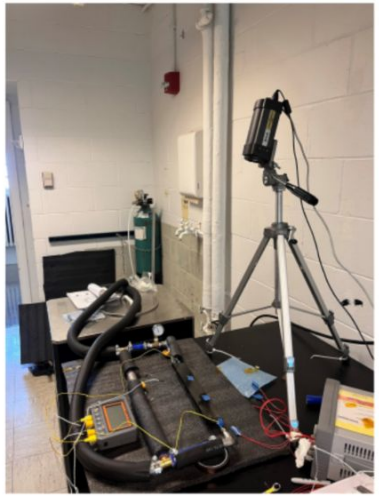
BTOF Module Prototyping

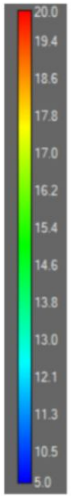
UCSC: prototype assembly of 33 sensors/ASICs on each side of 135 cm double-sided long stave

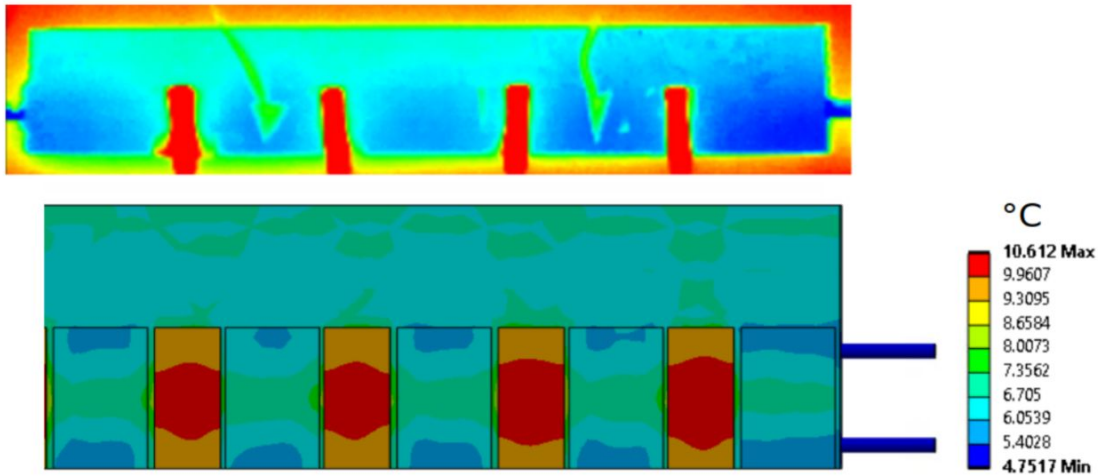




Purdue: produce 135 cm long staves with embedded cooling tubes embedded in low-mass CF

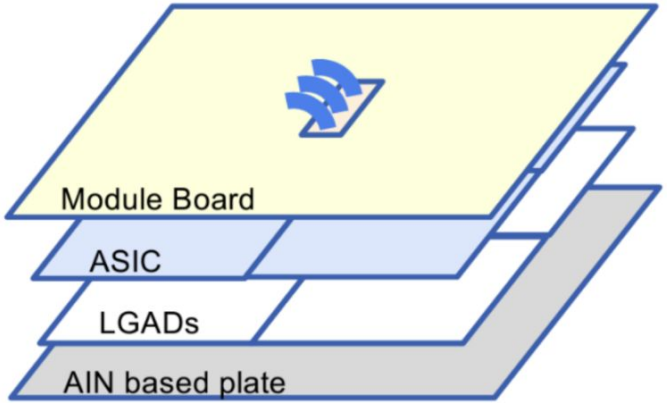


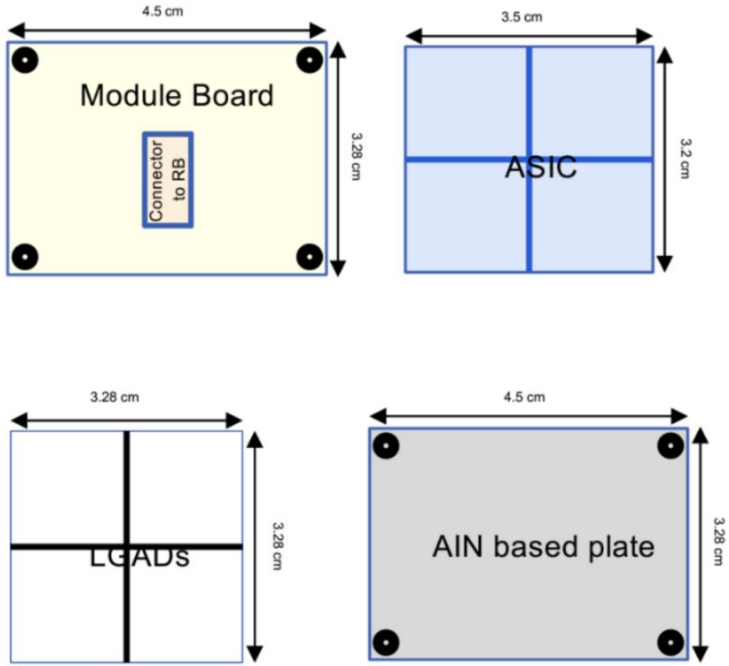




FTOF Module Prototyping

- 4 AC-LGADs sensor per module
- Each sensor: 32x32 pixels and 1.6x1.6 cm^2





More realistic dimensions considering guard rings, mounting holes etc.

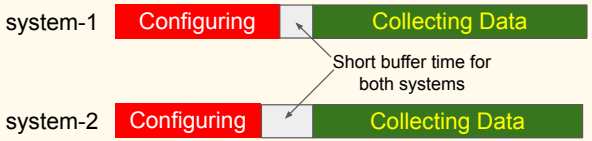
Long Story of Data Taking

- **Beam Duration: July 17 to Aug 13 (26 days)**
  - July 15 - Started assembling the system - Yu, Xuan, Simone, Grigory
  - July 17 - Installed the test setup - Yu, Xuan, Simone, Grigory ½ Maintenance day
  - July 18 - Encountered connection problems (lost control of 1st DG, PSs, I2C, Clock boards…)
  - July 19 - Conducted a short access to turn off the system - Provakar
  - July 22 - Confirmed it was a computer system problem during short access - Yu
  - July 23 - Added a 2nd PC to control the LV power supplies and steppers - Yu Maintenance day
  - July 23 - System ran successfully on Self-trigger Mode
  - July 23-27 - Performed THR Scan and HV Scan - Yu, Zhenyu
  - July 28 - Conducted the 1st Run with L1A Trigger from scintillators
  - July 29 - Changed the order of the trigger cable during a short access - Yu
  - July 30 - Fixed connection issues for clock boards and DC-LGAD LV - Yu, Zhenyu Maintenance day
  - July 31 - Conducted Y-position Scan; identified LV issue with Board 1 - Yu, Zhenyu
  - Aug 1 - Successfully configured 2 of the DC-LGADs - Zhenyu, Zhengwei

Long Story of Data Taking

- **Beam Duration: July 17 to Aug 13 (26 days)**
  - Aug 2 - Performed Synchronization Check (MAPS + AC-LGAD) - Yu, Zhenyu
  - Aug 3 - Adjusted Trigger Loop (Fast, 5 GHz); replaced problematic AC-LGAD sensor, fixed the LV problem for the DC-LGADs - Yu, Zhenyu
  - Aug 3-5 - Conducted Y-position scan, taking data with Self-trigger mode - Yu, Zhenyu
  - Aug 6 - Installed MCP-PMT (on-loan); fixed internet problem for the 2nd PC with help from Sergey and Hall-D members

    Maintenance day
  - Aug 7 - Observed a clear correlation between AC-LGAD, Photek, & L1A system - Yu, Zhenyu
  - Aug 8 - Production data taking started at 80 Hz - Yu, Zhenyu



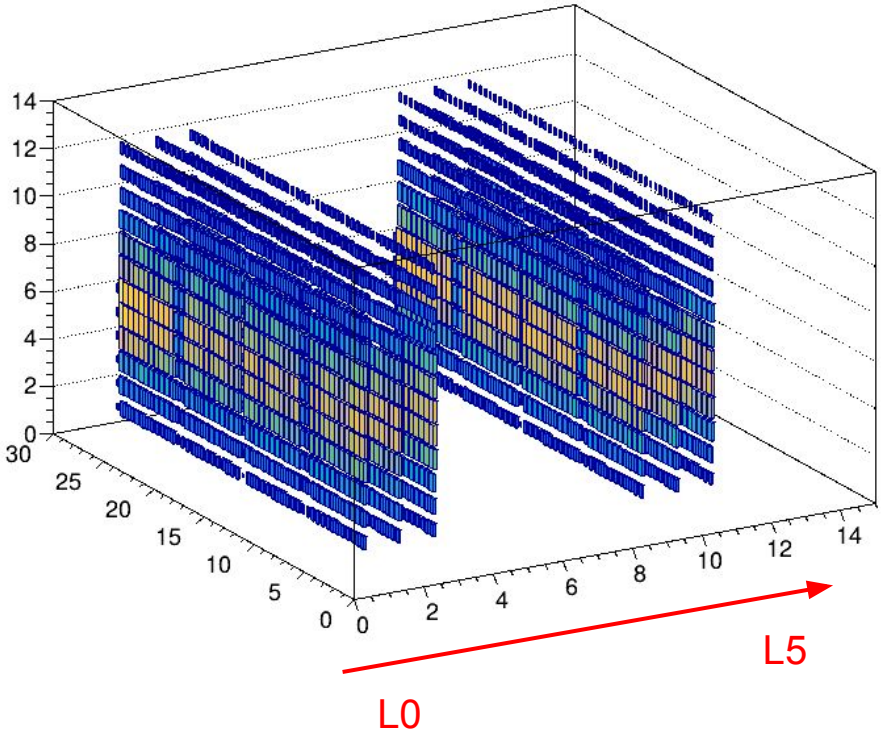
One typical run has 20k~30k events (~2 mins)

~17M events for 2 strip sensors:
- **W15 30um, 3 cm x 2 cm**
- **W13 50um, 3 cm x 2 cm**

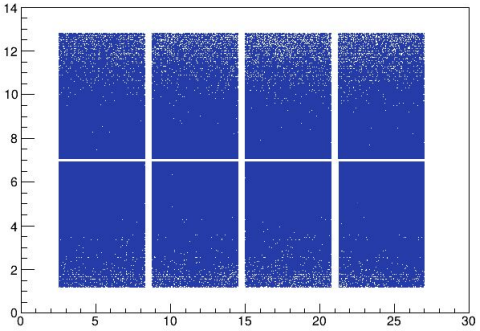
  - Aug 11 - Increased rate to ~300 Hz - Yu, Zhenyu
  - Aug 13 - Testing setup removed from Hall-D - Yu, Andrew, Cable, David, Sourav

Maintenance day

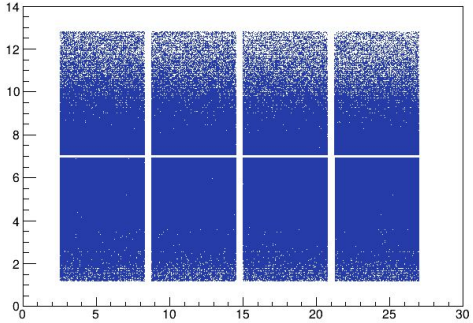
Tracking system - Hits-Maps of the Telescope



L0



L5



- Most of the beam are within ~5 mm

CMS DC-LGAD+ETROC2 HV Scan