# Precise timing and position needs for AC-LGAD and readout testing

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On behalf of SCIPP and ePIC TOF

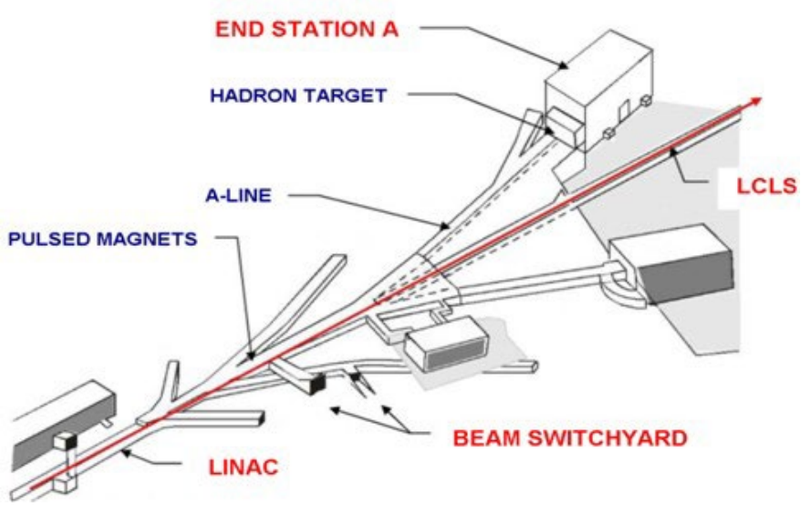
SLAC LESA workshop 2025, Sept. 2025, SLAC

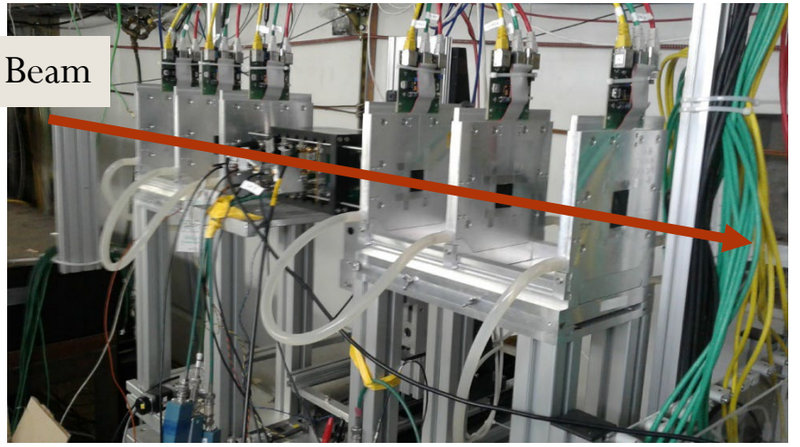
# Previous LGAD tests at SLAC ESA

Slides presented at BTTB workshop in 2019

# SLAC Beam setup

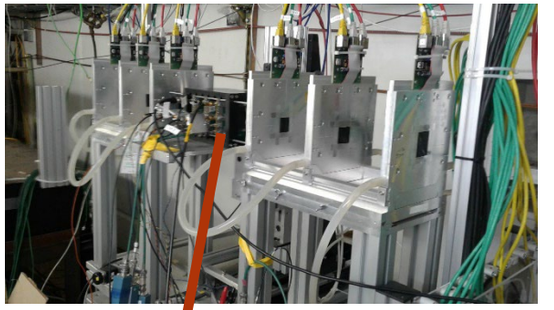
- Rate of the beam is constant 5Hz, it is usually stable
  - Electron bunches are really short (~ns)
- Beam intensity and shape can be adjusted in ESA beam line through the phone with the operator
- Beam will change energy 9am/9pm
  - Every time it needs to be retuned
- CALADIUM telescope is on the beam line in the center of End Station A
  - The entire setup is moveable
  - Precision ~10-20 um?

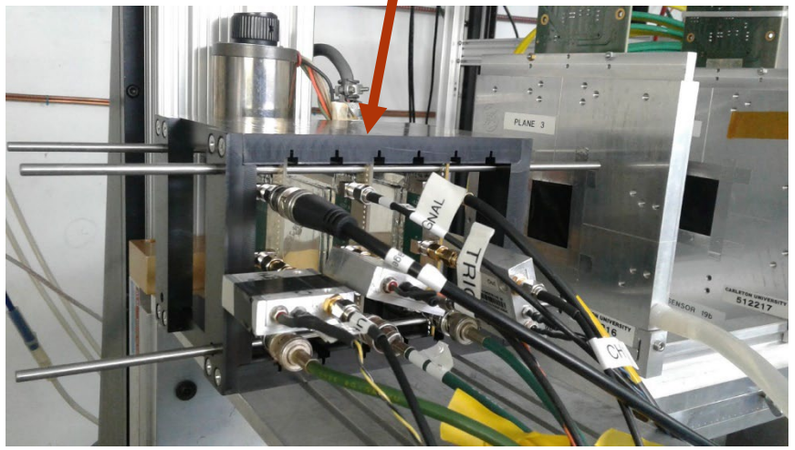


# Test beam setup

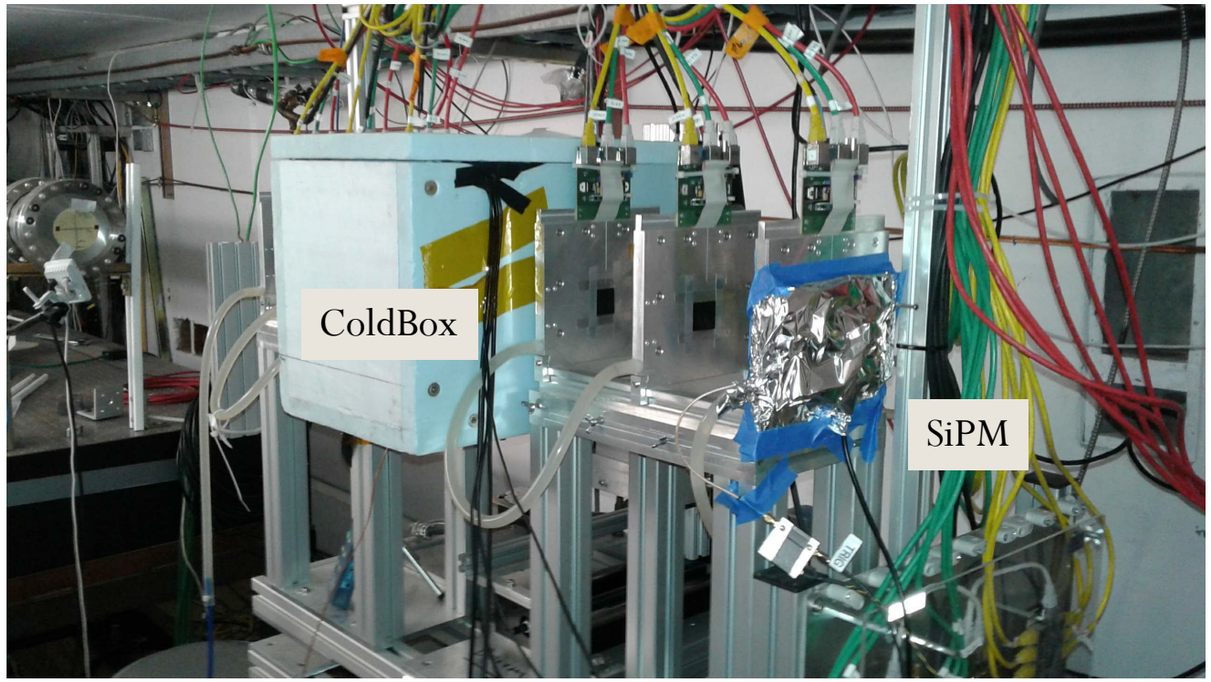
- Sensors are mounted on amplifier boards
  - 6 slot alignment mounter with alignment rods
  - Stage sits on the telescope frame and it is moveable independently (x, y, rotation)
- Cold box half filled with dry ice for cold measurements
  - Dry air pumped inside the box
  - Temperature/humidity is monitored by a sensor read remotely
  - Can reach -30C but dry ice needs to be replenished often

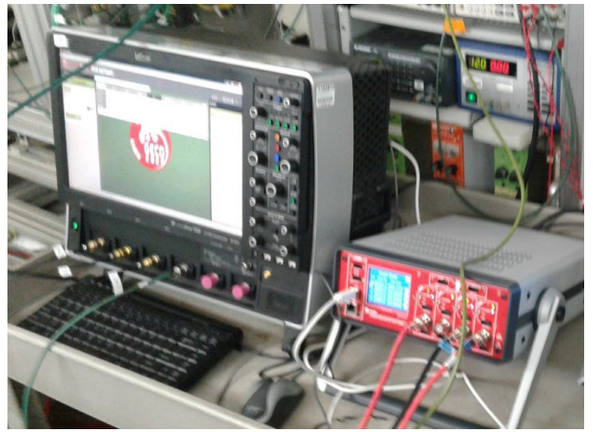




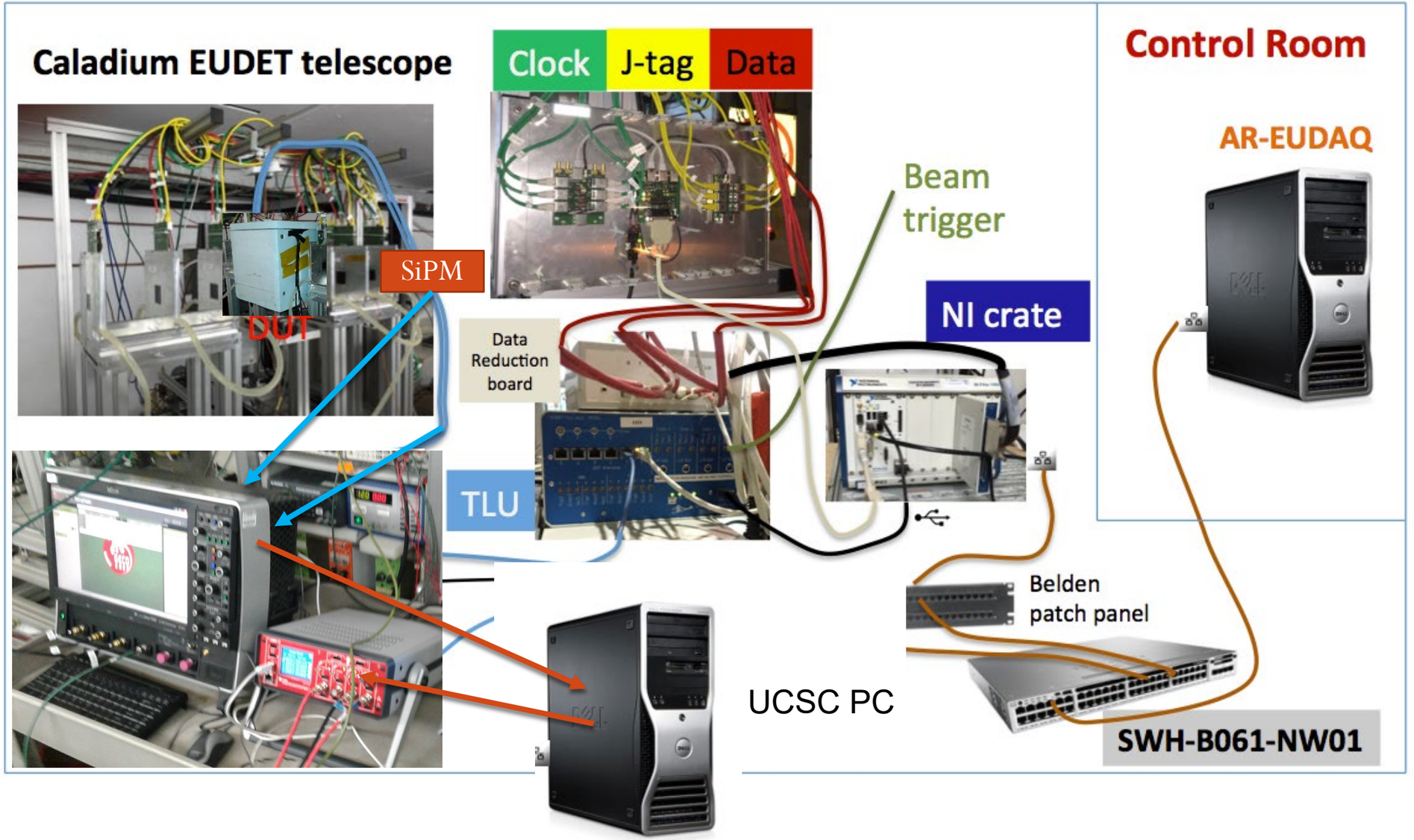
# Test beam setup

- Time reference is given by a SiPM mounted on one of the planes of the Caladium
  - Centered on the Caladium plane
- Sensors and SiPM are read out by a GHz LeCroy scope
  - Scope is read out by a PC in the counting house with custom DAQ software
- Caladium and LeCroy Scope are triggered by a 5Hz beam trigger
- HV is supplied by a CAEN remote controlled HV supply



# SLAC setup overview

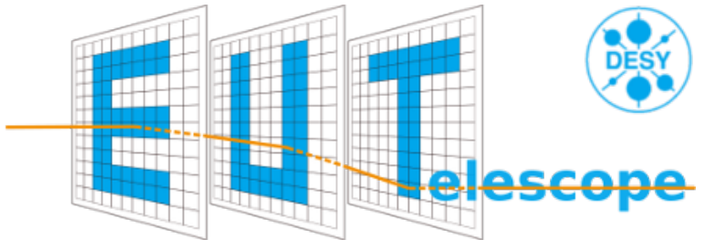


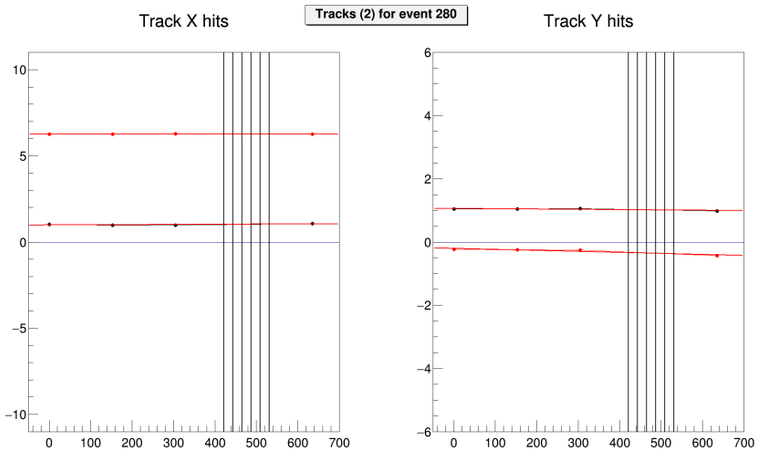


Twiki: https://confluence.slac.stanford.edu/display/Atlas/TestBeam

# Data reconstruction and matching

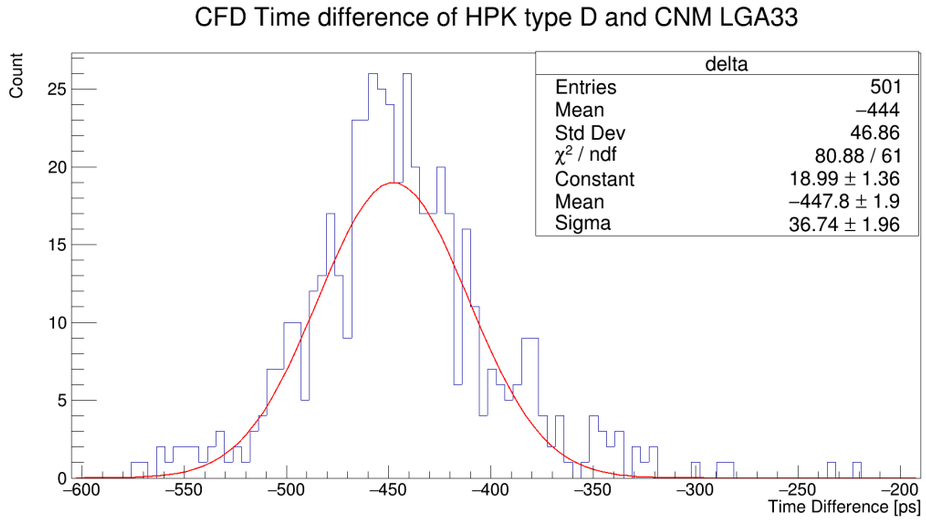
- Reconstruction and tracking of Caladium data done with EUTelescope (v01-19-02)
  - Clustering, aligning and fitting
  - Hot pixels are masked in the process
- LeCroy scope data analyzed with custom software
  - Starting from analog pulse coming from the amplifier
- Synchronization between Caladium tracking data and scope data is done with time matching
  - Precise enough since the rate is low (5Hz)
- Example tracking of an event with 2 electrons using 4 Caladium planes



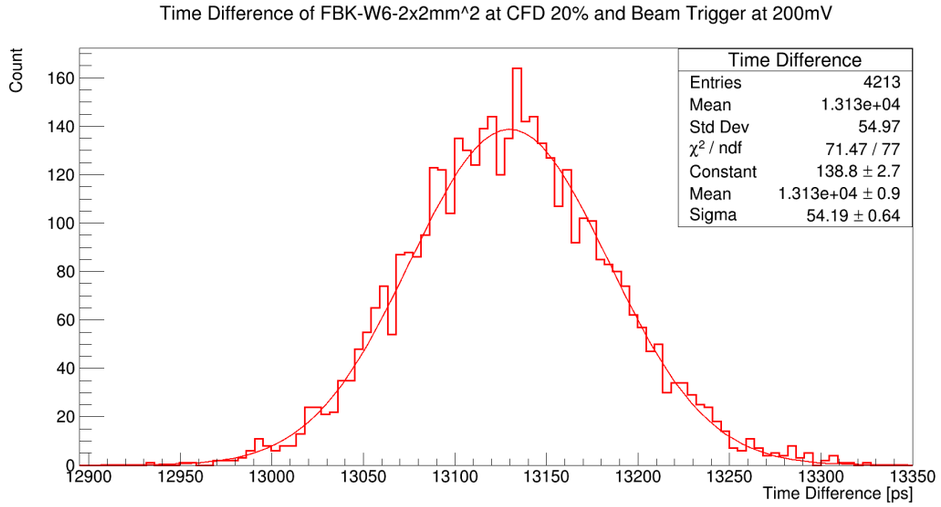



# Time resolution

- Time resolution measured is the same seen with b-scope measurements
- Looking at the coincidence hit of two detectors with time resolution of CNM LG (~35ps) and HPK II type D (~15ps)
  - Total time resolution (squared sum) ~36ps

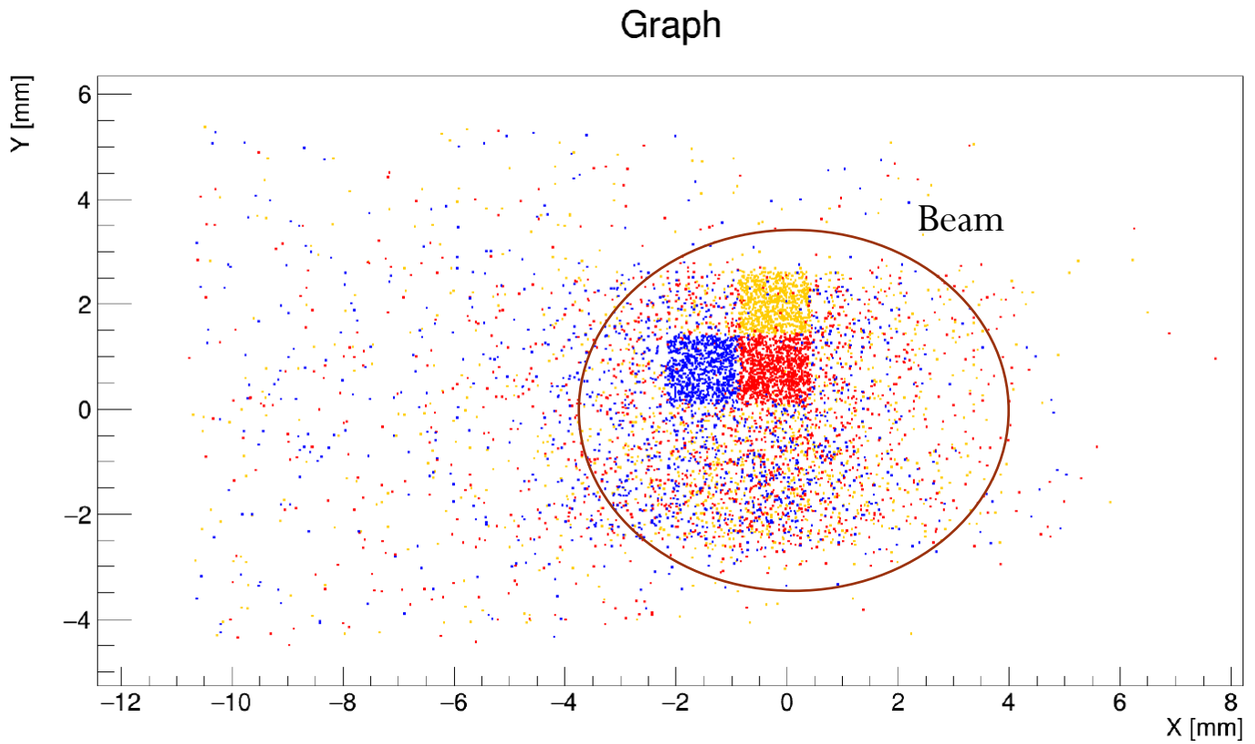



- Time resolution of beam trigger
  - ~40-50 ps
  - Sub-optimal for precision studies on LGADs
  - Probed with a sensors with precise timing
  - Looking at ToA 200 mV on beam trigger
- the SiPM was used For timing reference



# Hits vs position

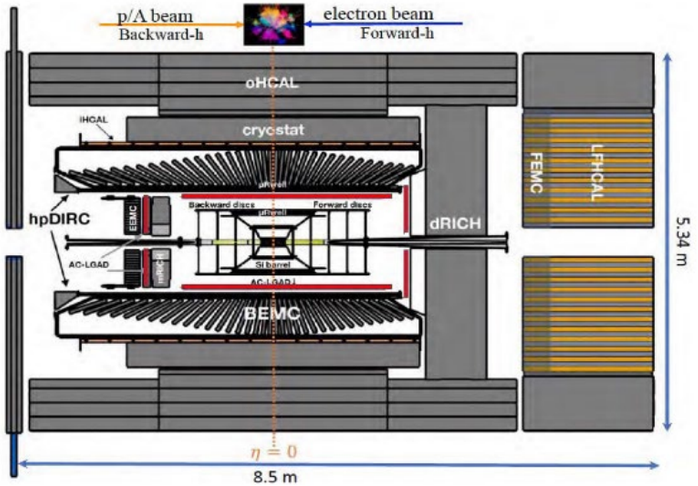
- Beam is the halo of events
- Entirely in the Caladium plane, covering all of the sensors
- 3 pads of the array are clearly seen
- Rate ~2000 good hits per pad for a 1h run

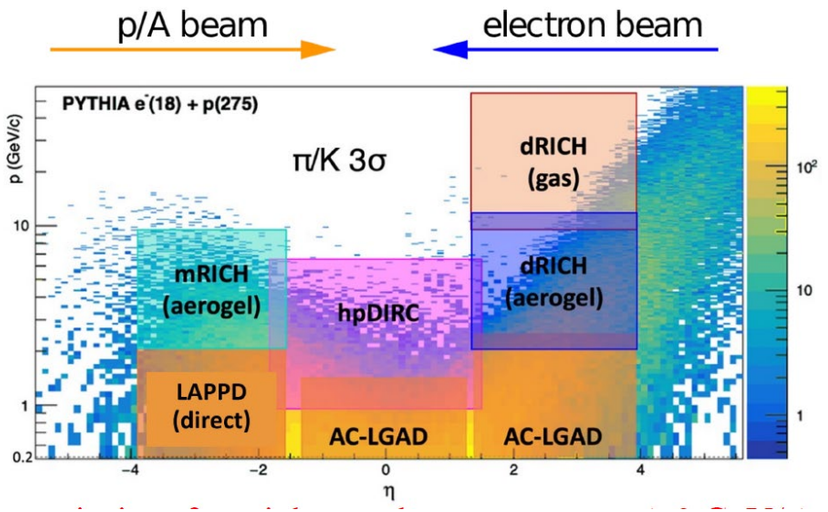


# Testing plans and schedule for ePIC

# The ePIC detector

- **4D tracking** is a necessity to reach ePIC's physics goals
- **Particle identification with time of flight (TOF)**
  - For e/π/K/p at low/intermediate momentum
  - Require good time resolution and meaningful flight distance
- **A TOF layer** is foreseen for both barrel and end-cap in EPIC
  - Barrel (BTOF) with 500um x 1cm-long strip
  - End-cap (FTOF) with 500 x 500 um pixels
  - Off-momentum detector (OMD) with same design as FTOF
- **TOF layers based on AC-LGAD technology**

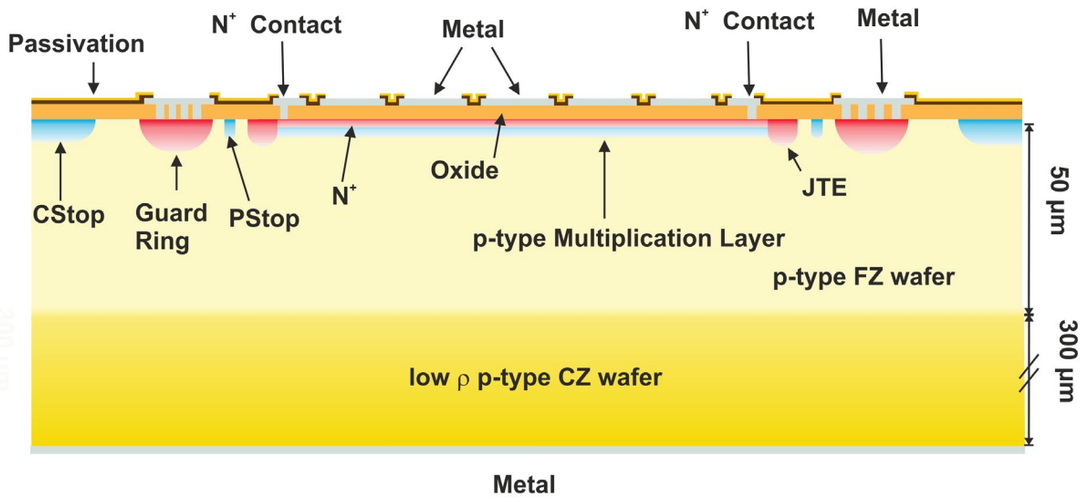


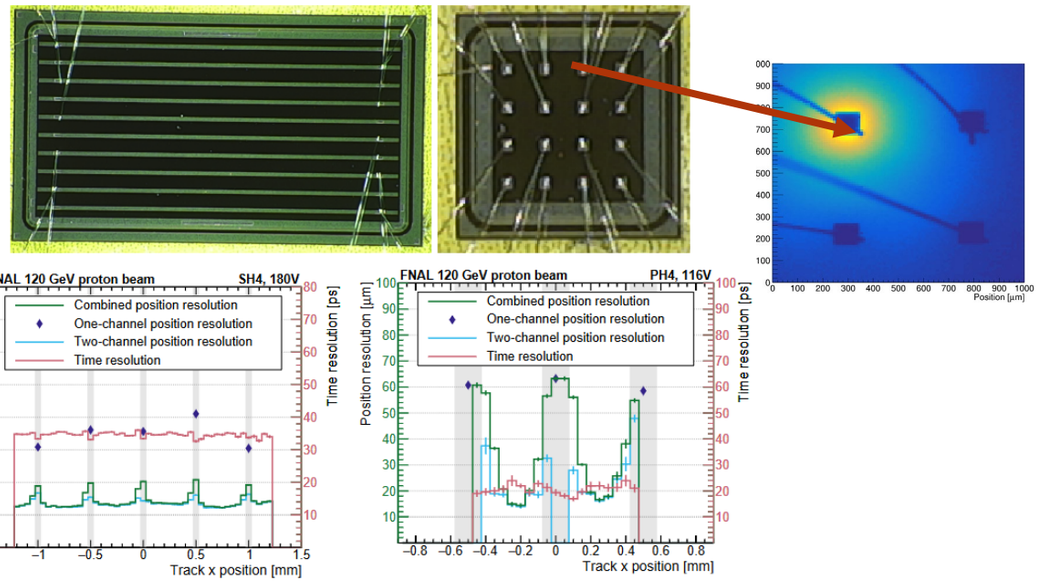




| Subsystem | Area ($m^2$) | dimension ($mm^2$) | channel count | timing $\sigma_t$ (ps) | spatial $\sigma_x$ ($\mu$m) | material budget ($X/X_0$) |
|---|---|---|---|---|---|---|
| Barrel TOF | 12 | 0.5*10 | 2.4M | 35 | 30 ($r \cdot \phi$) | 3% |
| Forward TOF | 1.1 | 0.5*0.5 | 3.2M | 25 | 30 ($x, y$) | 5% |

# AC-LGADs

- **LGAD**: Si detector with a thin gain layer
  - Time resolution 30ps or less
- High-granularity prototype: **AC-coupled LGAD**
  - Continuous multiplication layer coupled with resistive (low doping) N+ layer after the gain layer
  - Readout pads are AC-coupled with insulator (oxide) layer
- **AC-LGAD has intrinsic charge sharing**
  - Using information from multiple pixels/strips for hit reconstruction
  - Reduce channel density and power dissipation while maintaining good resolution
- Position resolution ~20um (for ePIC geometry)
- Time resolution ~20ps (for ePIC geometry)

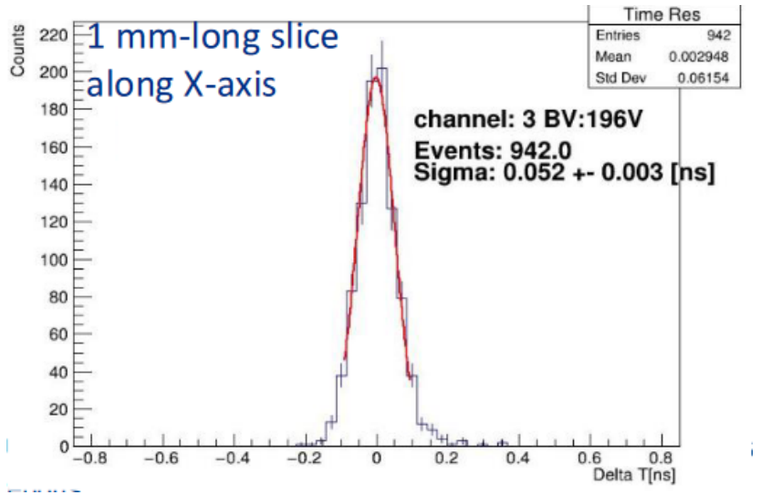


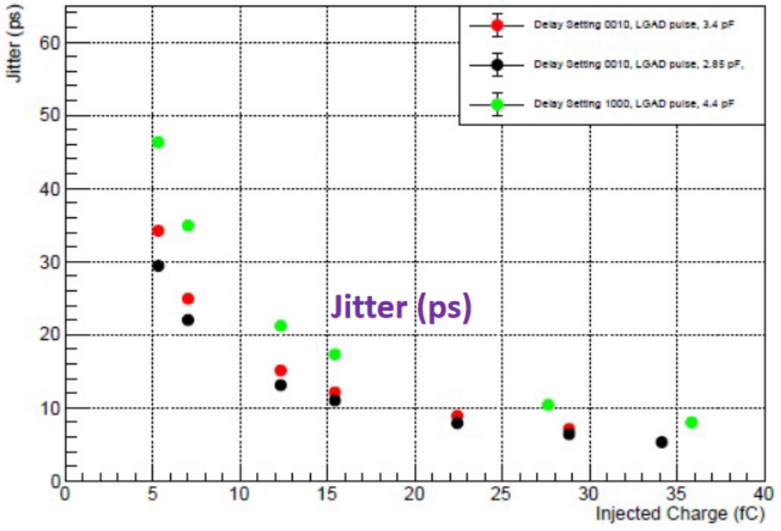



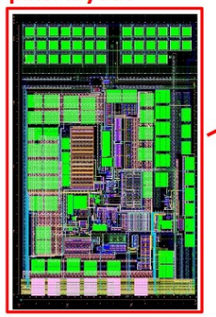

https://arxiv.org/abs/2407.09928

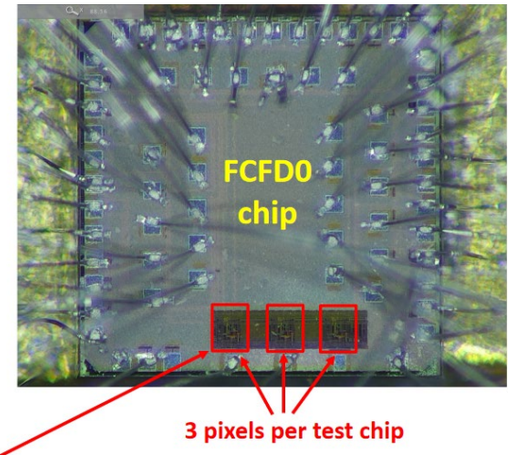
# AC-LGAD readout – EICROC (iomega) - FCFD (FNAL)

- **Initially, testing of bare AC-LGADs on analog electronic boards**
- Eventually test of AC-LGADs assembled on readout chips
- AC-LGAD readout chip depends on detector geometry
- **EICROC being developed for pixels at Iomega**: target capacitance few hundred fF
  - Time resolution target 20ps
- **FCFD strip readout developed at Fermilab**: can accept higher input capacitance o(10pF)
  - Time resolution target 35ps



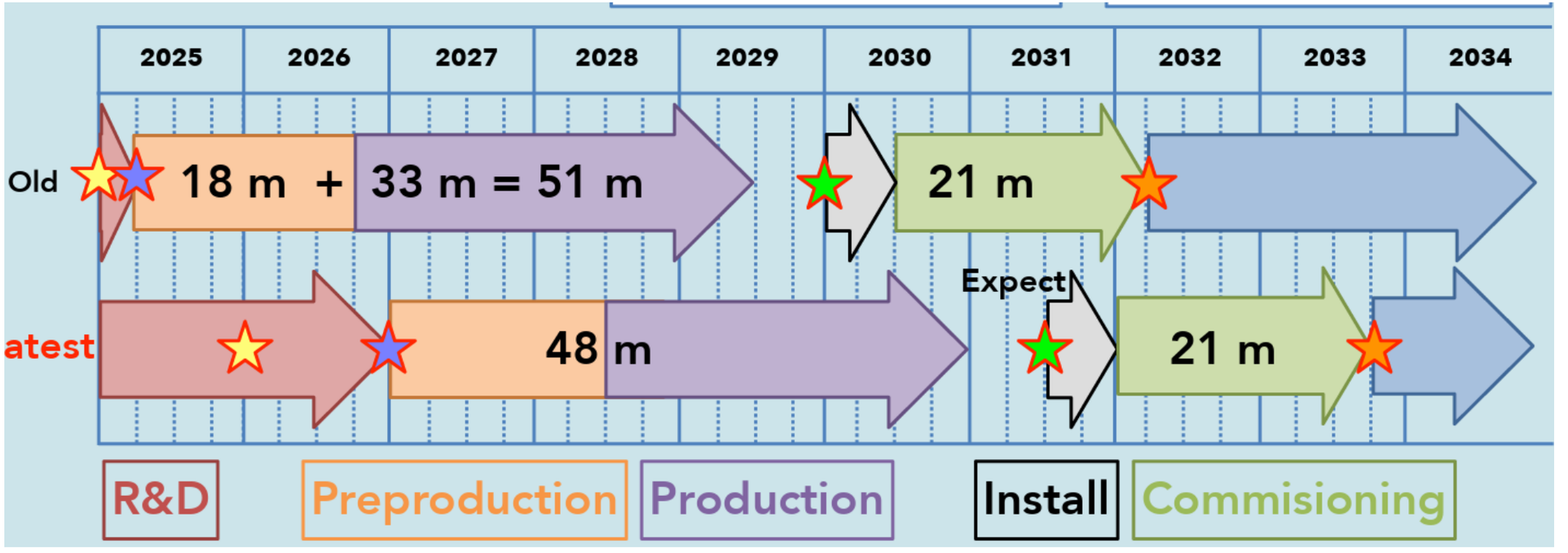



# Previous/current/future test beams

- AC-LGAD from the first production for ePIC have been tested at FNAL with results in e.g. https://arxiv.org/abs/2407.09928
- Recently we received two new HPK productions
  - ePIC full-size production of HPK strip AC-LGADs with devices up to 3.2x4.2 cm
  - ePIC full-size production of pixel AC-LGADs from HPK with devices up to 1.6x1.6 cm
  - Can't be tested at FNAL for now
- Recent test beam at Jlab with a few strip sensors
- Recent test beam at DESY with FCFD, plan for another DESY TB in December

- Test beam needs in the coming years
  - An additional HPK production is ongoing, will receive devices soon. Additional production incoming.
  - Another FBK production is ongoing, will receive early next year
  - Plans to start another HPK production next year
  - Tests of chip + sensor with EICROC and FCFD
  - Tests of instrumented modules and sub-staves

# TOF schedule




Demonstrator assembly

Develop tooling

Pre-production: assembly N stavelets

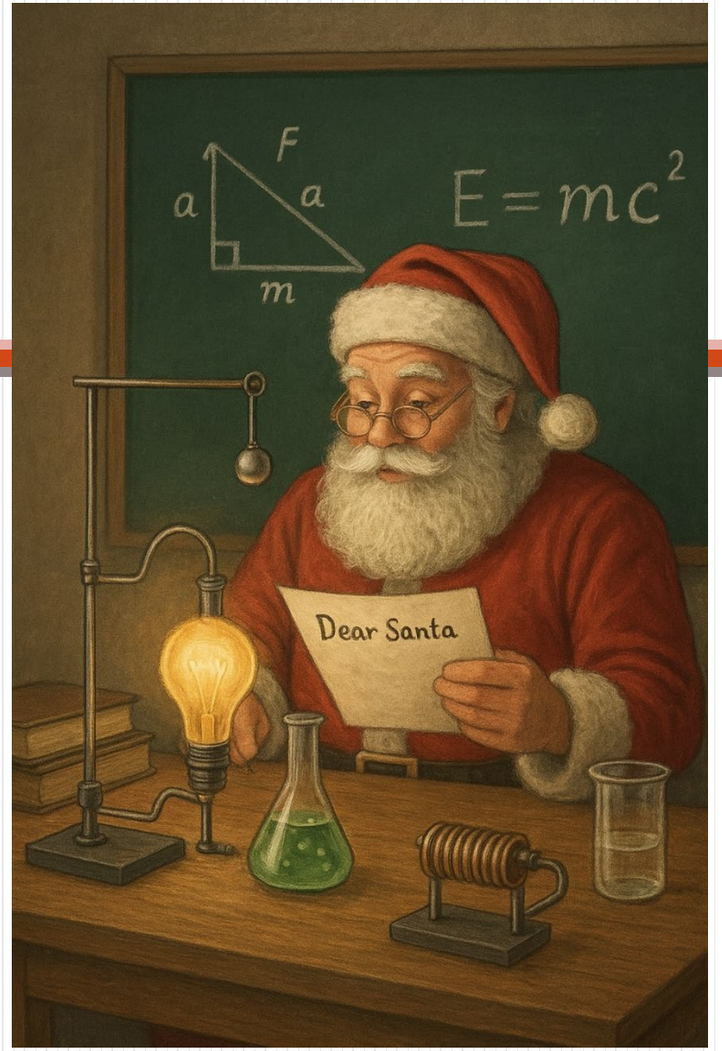
Full assembly

Test beams on ePIC AC-LGAD (w/without chip)

**Test beams on sensors/chips for EIC det. 2**

**Blue sky R&D on LGADs**

# Requirements and wishes



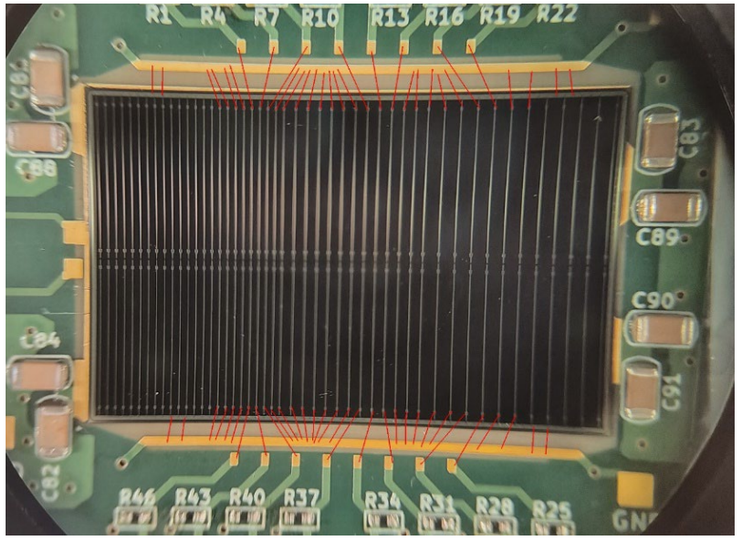
# TB requirements

- Timing reference trigger
  - <10 ps Jitter for trigger would be useful to avoid using extra timing references
  - Need line with low jitter over long distances to make it work
- <5um tracking for AC-LGAD testing
  - How can it be achieved with current Caladium telescope? Need additional planes?
- AC-LGADs can't separate events if within 1ns and a 1mm (depends on pitch)
  - Run with 1e per bunch to avoid overlap in the AC-LGAD
- Repetition rate of 5 Hz is quite slow for efficient data taking, is higher rate (with no overlap) possible?
  - Need, tentatively, a thousand event per 10x10um box, so ~100k events per 1x1 mm area
  - Area of interest is ~2x2mm (pixels) or 2x10mm (strips), so need a few million events per region in a reasonable time. 5 Hz is <0.5 million events in a full 24h day. A factor 10 would help a lot.

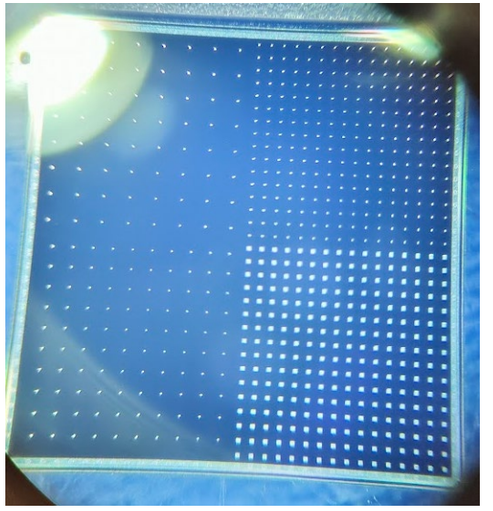
# TB wishes

- X-Y table decoupled with telescope to move DUT around
- Enough space for custom telescope
- Support for extra detectors (other X-Y table?)
- Trigger sensor to select region of interest (ROI) dynamically
  - This helps in efficient data taking with a wide beam
  - Devices can be either few mm scale to few cm scale
- Cooling available for temperature control
  - Chillers that could be used either with the distilled water or with propylene glycol, option to go cold

ePIC full size strip detector: 3x2cm




ePIC full size pixel detector: 1.6x1.6cm

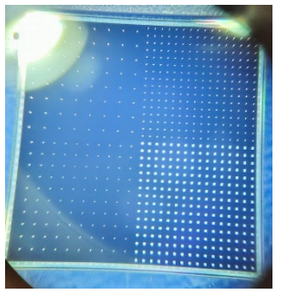


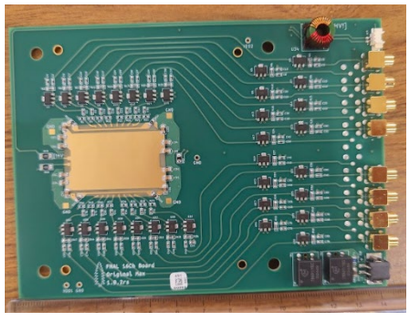
# Other hardware wishes

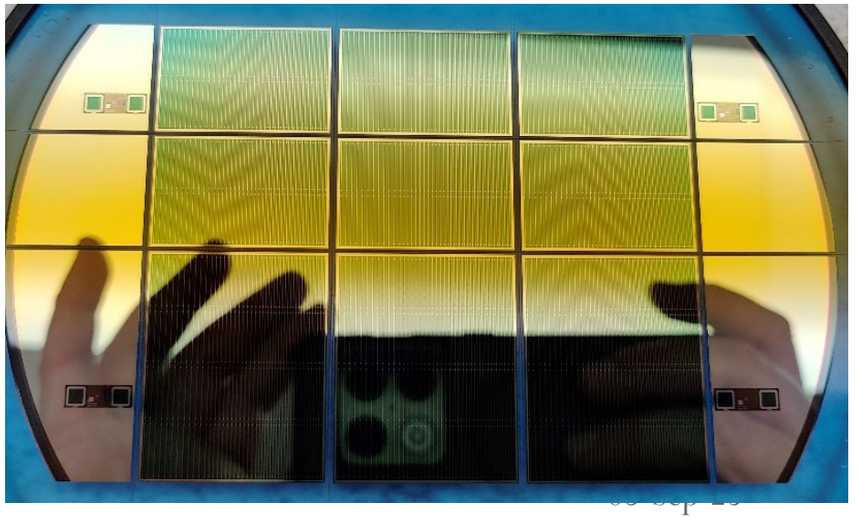
- Fancy, low jitter delay module
- LV and HV power supplies (probably with a few spare cables and connectors).
- Chillers that could be used either with the distilled water or with propylene glycol
- Parasitic possibilities for extended run time
- Cameras and laser pointing for alignment
- Control room not up the stairs?

# Conclusions

- Sensors for the ePIC TOF layers are reaching maturity
  - Received first large-scale AC-LGAD production from HPK, first results are good, see https://indico.phy.ornl.gov/event/677/contributions/2683/
  - → **still a lot to test!**
- Few test beams in the past but need reliable facility to test assembled prototypes all the way to the construction of the TOF
- There's still time for R&D for EIC detector 2, plan to test new types of device for it
- And of course, it's always time for blue sky timing detector R&D…







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# Thanks for the attention

**Many thanks to the SCIPP group students and technicians!**
**In particular to students:**
**J. Ding, G. Stage, A. Borjigin, C. Altafulla, M. Davis, S. Beringer**

Thanks to HPK for providing sensors for this study

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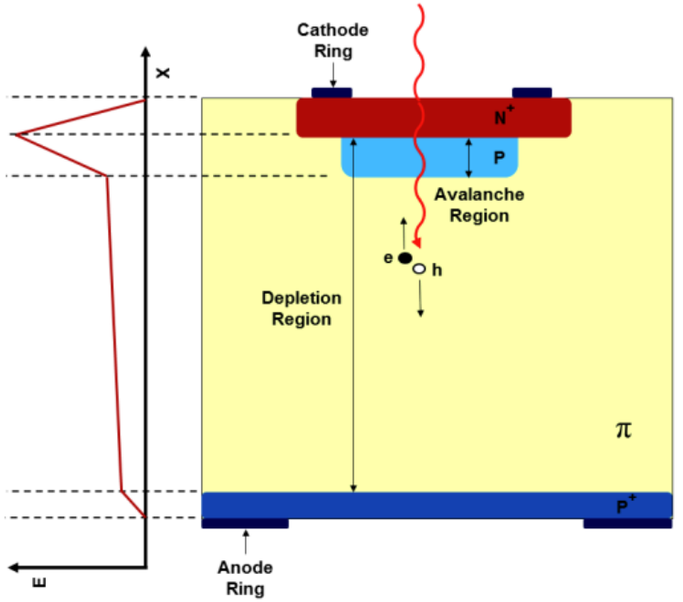
# Backup

# Low Gain Avalanche Detectors for 4D tracking

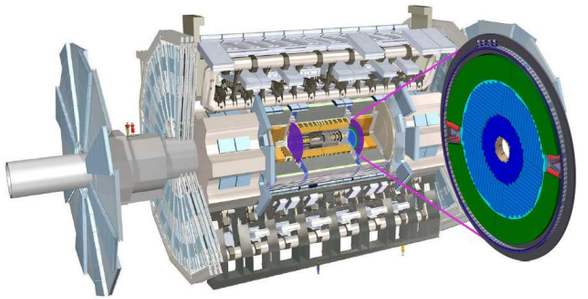
- LGAD: silicon detector with a thin (<5 μm) and highly doped (~$10^{16}$) multiplication layer
  - High electric field in the multiplication layer
  - Field is high enough for electron multiplication but not hole multiplication
- LGADs have intrinsic modest internal gain (10-50)
  - Gain = $\frac{Q_{LGAD}}{Q_{PiN}}$ (collected charge of LGAD vs same size PiN)
  - Not in avalanche mode → controlled tunable gain with applied bias voltage
  - Thanks to gain LGADs can be thin (20um, 50um)
- **Great hit time resolution: <20 ps!**
- LGADs are a great device to allow 4D tracking (x,y,z,t)
- Issues with 'standard' LGADs: granularity, limited at ~mm scale




Nucl. Instrum. Meth. A765 (2014) 12 – 16.
Nucl. Instrum. Meth. A831 (2016) 18–23.

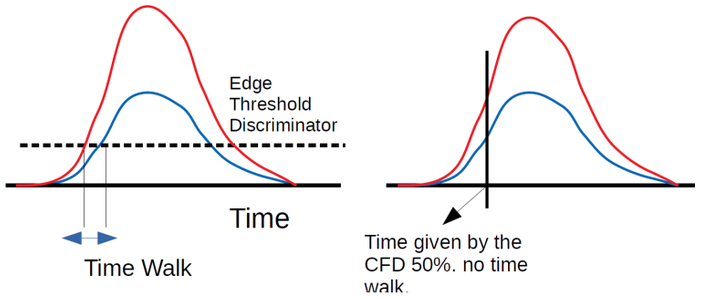
**First application HL-LHC timing layers for ATLAS and CMS**

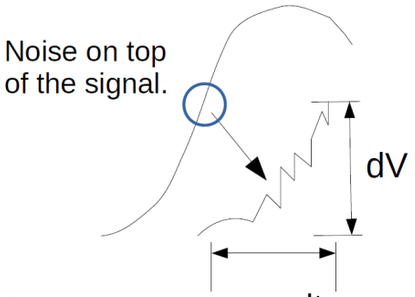
- Several producers of experimental LGADs around the world
  - CNM (Spain), HPK (Japan), FBK (Italy), BNL (USA), NDL (China)



https://cds.cern.ch/record/2719855
https://cds.cern.ch/record/2667167

# LGADs timing resolution




$$\sigma_{Jitter} = \frac{Noise}{dV/dt[CFD\%]} \approx \frac{T_{rise}}{SNR}$$

**Sensor time resolution main terms**

$$\sigma^2_{timing} = \sigma^2_{time\ walk} + \sigma^2_{Landau\ noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

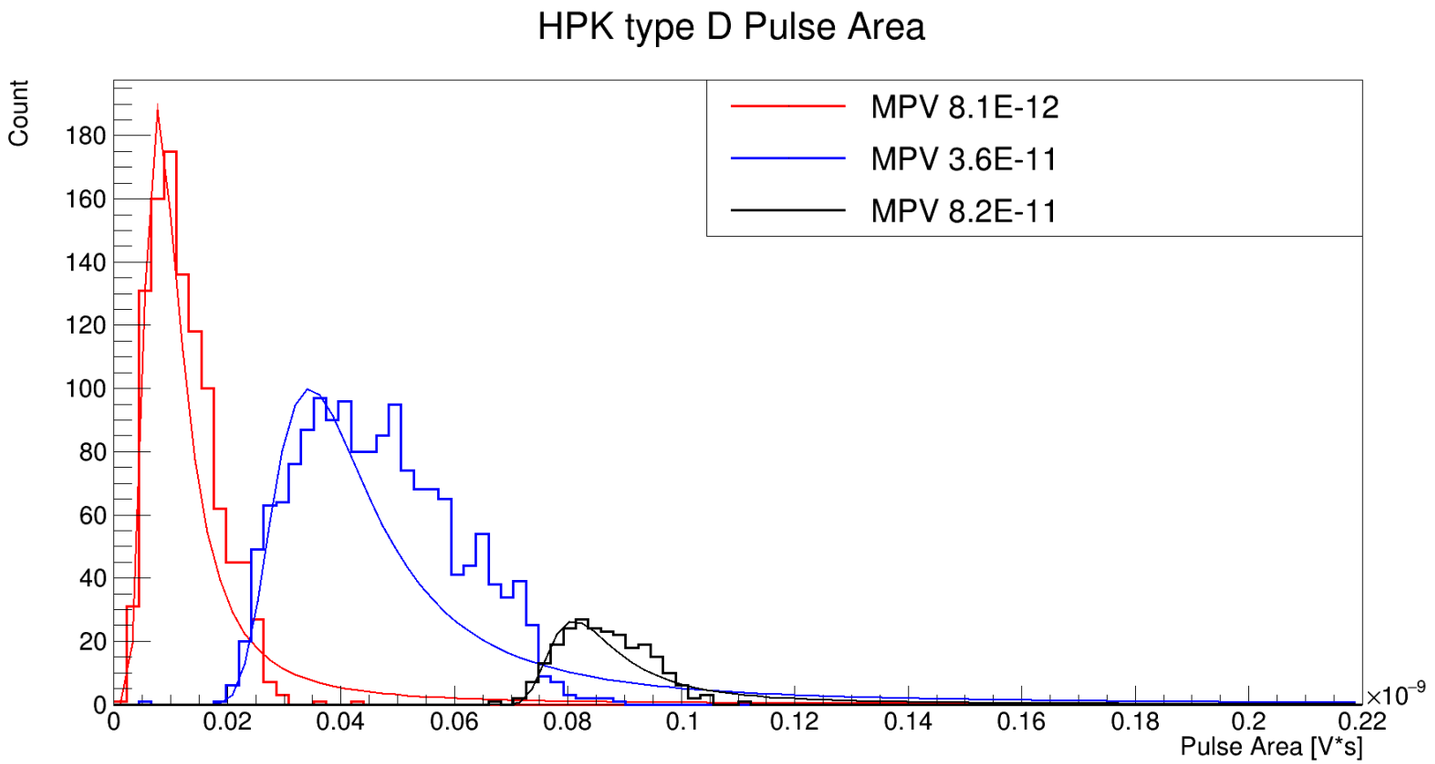
- Time walk:
  - Minimized by using for time reference the % CFD (constant fraction discriminator) instead of time over threshold
- Landau term:
  - Reduced for **thinner sensors** (50,35 μm)
- Jitter:
  - Proportional to $1/\frac{dV}{dt}$
  - Reduced by increasing S/N ratio with gain

# SLAC End station A


- **SLAC end station A left its mark on particle physics history**
- Researchers at SLAC observed for the first time electrons scattering at wide angles much more frequently than expected.
- By the early 1970s, detailed analyses of the distribution of the scattered electrons measured in the giant magnetic spectrometers in End Station A revealed three scattering centers within the nucleon.
- **First experimental evidence that quarks were in fact real.**
- Physicists Jerome Friedman, Henry Kendall, and Richard Taylor received the Nobel Prize for this discovery in 1990

# Pulse area for multiple hits

- Pulse area of sensor for: 1 e-, 2 e-, 3e-
  - At 4e- the amplifier saturates



# First look at inter pad distance (with low statistic)