Development of Ultrafast Silicon Sensors for Precision Timing and 4D Tracking

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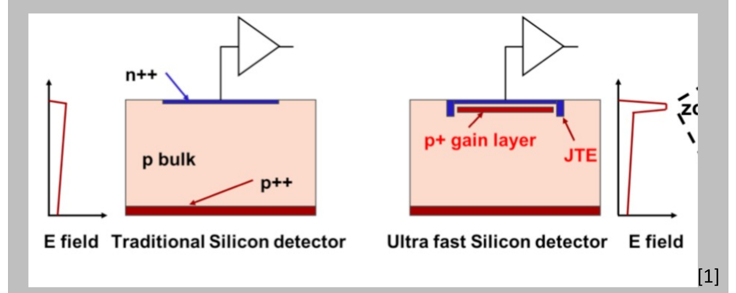
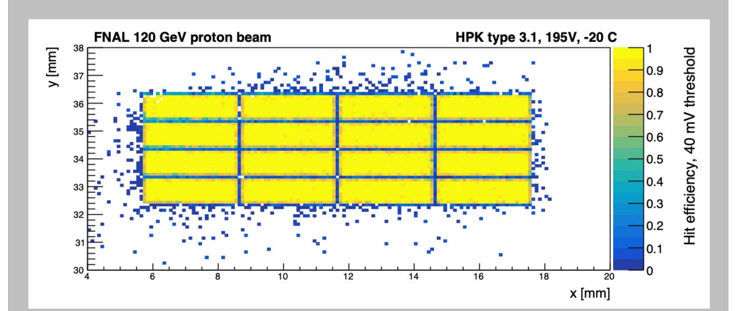
Motivation

Traditional Sensor and DC-LGAD



[1]

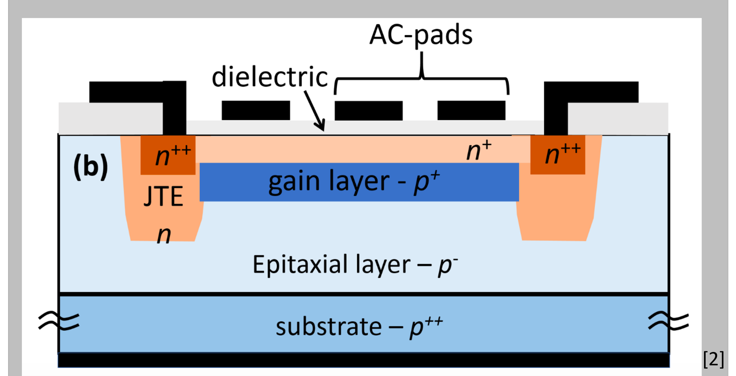
Unlike standard silicon detectors DC-LGADs have an **internal gain layer** allowing even very small signals to be read out. In fact, the HL-LHC will be read out by DC-LGADs in both the CMS and ATLAS experiments and these sensors have been found to have excellent uniformity and time resolution (~30 ps). However, DC-LGADs have a major downside which is that due to the **JTE** (Junction Terminating Extension) **gaps must exist in between the strips or pixels limiting granularity.**



Plot above shows the efficiency map of a DC-LGAD showcasing the gaps in blue.

AC-LGAD

AC-LGADs have **one continuous gain layer** which **eliminates the gaps between pixels** that were the major downfall of DC-LGADS. AC-LGADs also attain better spatial resolution due to **charge sharing** while **retaining or having an even better timing resolution.** These sensors are called AC due to the fact that the readout pads are now **AC-Coupled** to the P-N junction by a dielectric.



[2]

DOE's HEP Technical Requirements for Future Trackers

Collider experiments of the future will require technology robust to large radiation fluences and able to resolve individual events in very high density pileup environments, while simultaneously retaining granularity and position resolution requirements. In the DOE's HEP Basic Research Needs report [3] they published technical requirements necessary for future 4D particle trackers for tracking e^+e^- and 100TeV pp:

- **Granularity of 25x50 μm² pixels**
- **Per track resolution of 5-10 ps**
- **5 μm single hit resolution**
- **Radiation tolerance up to 8x10¹⁷ n/cm²**

AC-LGADs are a **promising candidate** to address the needs of future detectors!

Measurements

Hamamatsu Photonics K.K. (HPK) Pad Sensor: Position Reconstruction Using Charge Sharing

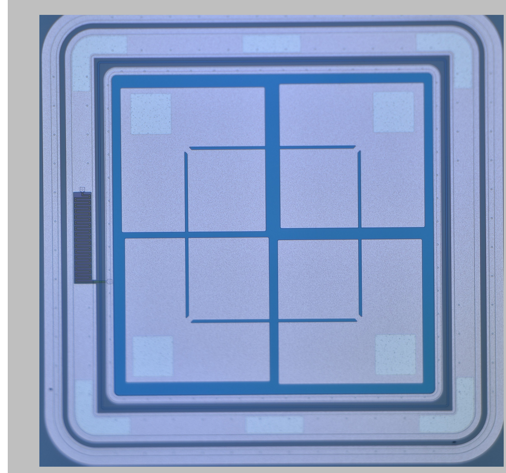
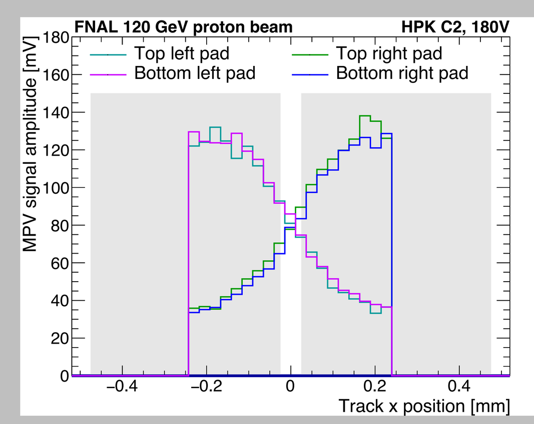
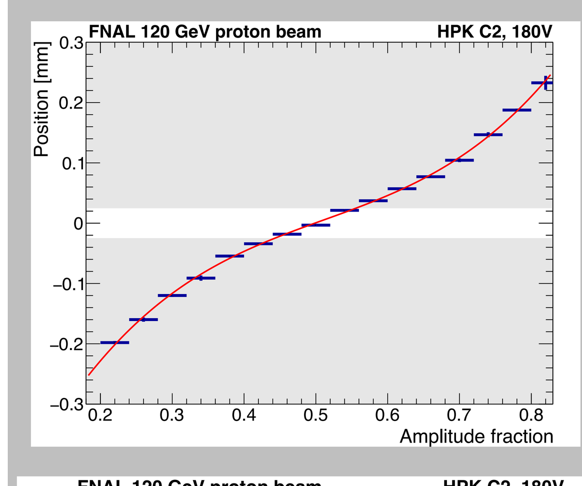


Image of a HPK pad sensor tested at FNAL. Each pad was 500x500μm² with inter pad gap size of 20, 30, 40, and 50μm.



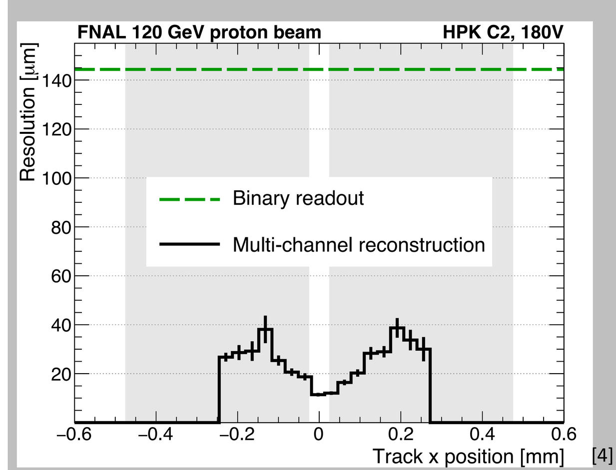
[4]

Mean peak value plot shows all four pads overlaid. Scanning in the y direction gives similar results. Grey region is the metallization of pads. Only half the pad was considered as this was a 2x2 array and charge sharing requires a readout on both adjacent sides.



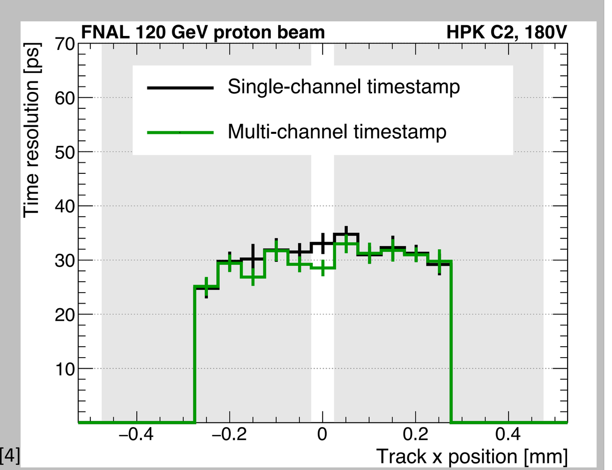
[4]

In a nominal sensor there is no differentiation in position between the top, bottom, or middle of a strip. **Due to charge sharing AC-LGADs are capable of obtaining much finer resolutions.** The figure (left) gives an example of a relatively simple algorithm for determining x position between two neighboring pads. First, the x position vs average amplitude was plotted based off of the reference tracker. **Then for each event the amplitude fraction was calculated and fitted onto a polynomial**, and from this the x position is determined.



[4]

The plot (above) shows position resolution vs position of the hit proton using the charge sharing algorithm. As expected the resolution gets worse in the middle of the pads but **significantly better than the expected binary resolution pitch/$\sqrt{12}$.** For the entire sensor the resolution was **22±1μm.**



[4]

The plot (above) shows temporal resolution vs position of the hit proton. Single channel corresponds to only using the time of arrival of one channel. The multi channel study uses **charge sharing to combine waveforms** from multiple channels to then **get the time of arrival**. For the entire sensor the resolution was **30±1ps.**

Brookhaven National Lab (BNL) 2021 AC-LGAD Sensor with Variable Pitch: Baseline Sensor

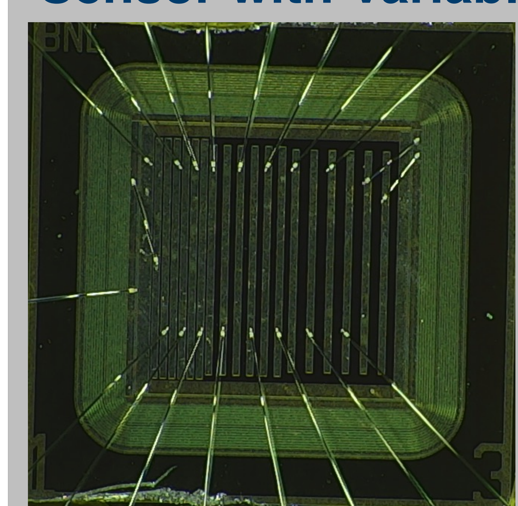
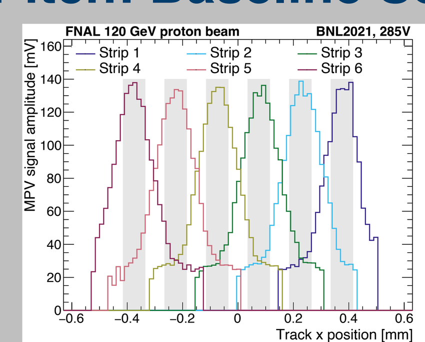
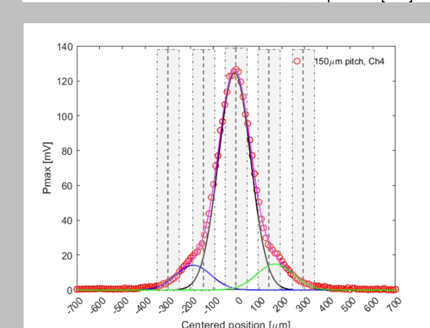


Image of the BNL 2021.Wide strips have a pitch of 200 microns, medium 150 microns, and narrow 100 microns.



Mean peak value plot shows the sensor charge sharing. Results for medium pitch. Grey region is the metallization of the strips

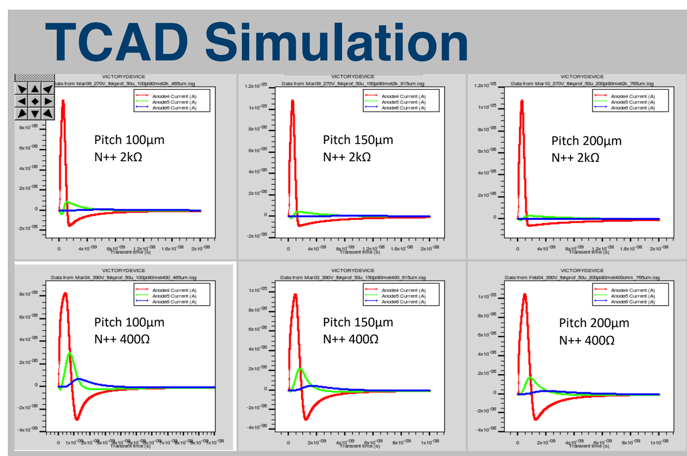


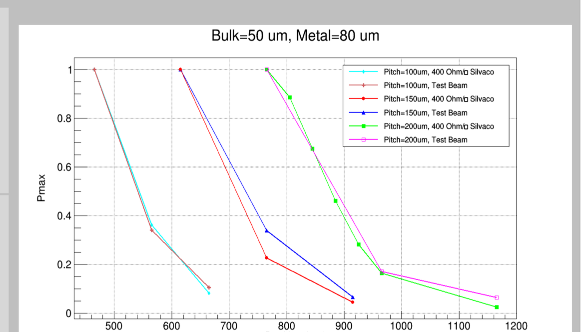
Plot shows the **charge sharing of a hit as the beam is swept in the x direction.** Pmax is the max amplitude of the signal. **Response fit as a three Gaussian function.**

Sensor	Spatial Resolution (μm)	Temporal Resolution (ps)
BNL 2021 Narrow	≤9	32±1
BNL 2021 Medium	≤11	30±1
BNL 2021 Wide	≤11	33±1

The table (above) shows the response of the BNL 2021 sensor in the different regimes. The spatial and temporal resolutions are calculated the same way as for the HPK pad sensor. Reaching these resolutions shows the **competitiveness of AC-LGADs as future 4D trackers**.

TCAD Simulation

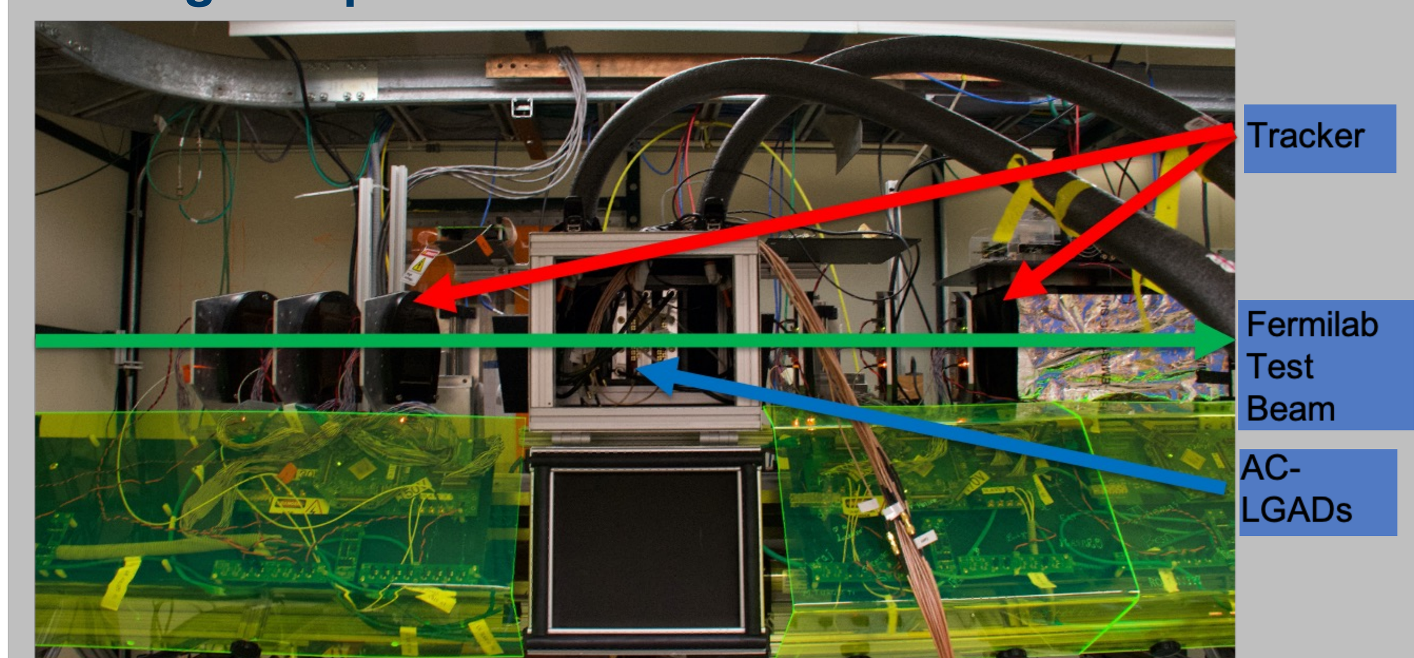




AC-LGADs have several **parameters that can be tuned to optimize the sensor response** to the specific application. The **geometry of the electrodes in terms of pitch and pad dimension** is the most important one, however also the **N+ sheet resistivity and the dielectric thickness** between N+ and electrodes influence the charge sharing mechanism. These parameters have been **studied with TCAD Silvaco** to have a good representation of the observed sensor performance. Simulations with TCAD software are important to **compare with existing prototype data and to help in optimizing the design.** Above on the left are simulated pulses and to the right is a comparison to test beam data.

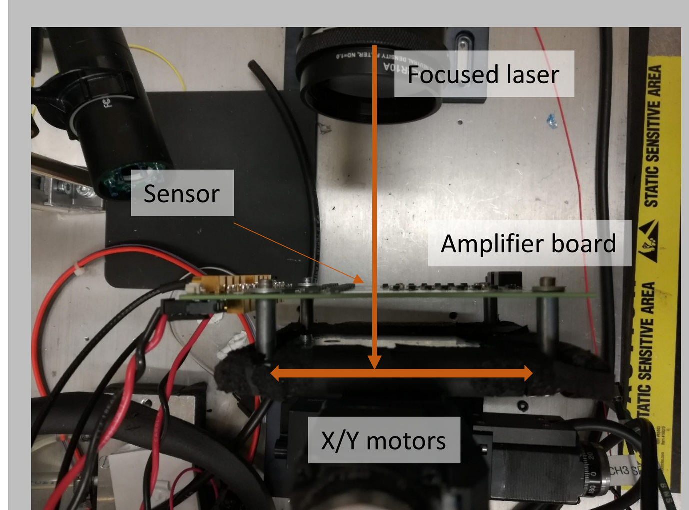
Experimental Apparatuses

Permanent FTBF (Fermilab Test Beam Facility) Sensor Testing Setup

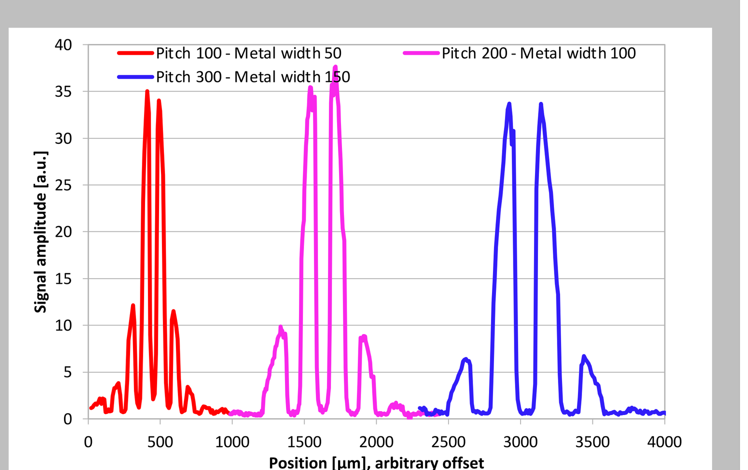


- Permanent setup lives at FTBF to test AC-LGADs designs
- **120 GeV protons** are "spilled" for 4 seconds every minute.
- **Tracker with ~10 μm resolution**
- Remote control (stages, HV, LV), logging & **reconstruction; σ_T ~ 10 ps time reference MCP** (Multi Channel Plate)

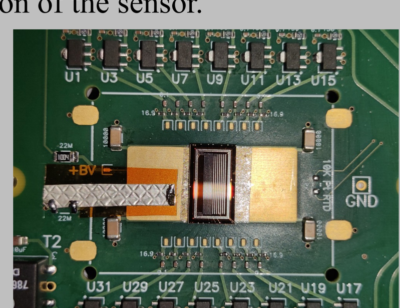
SCIPP Laser Sensor Testing Setup



- IR laser (1064 nm) **emulates the charge deposition of a minimum ionizing particle (MIP)**
- **Metal structures** of the sensors are not transparent to IR **so no response can be seen when laser is on top of metal**
- Focused beam spot width of < 20 um
- Amplifier board is mounted on X/Y moving stages
- **Charge injection as a function of position**

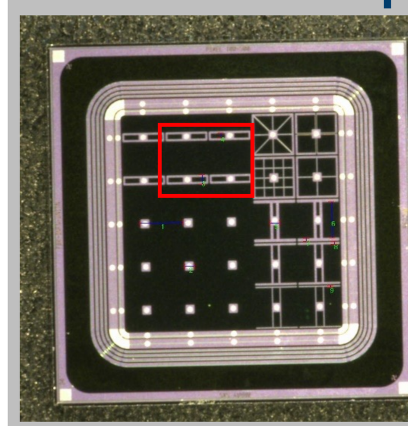


Representative scan of the laser setup showing the dips in response when the laser is striking the metallization of the sensor.

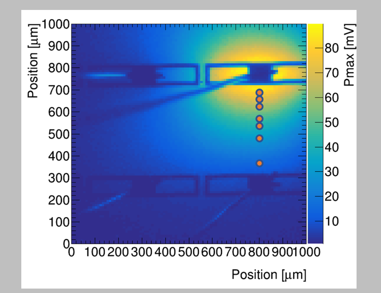


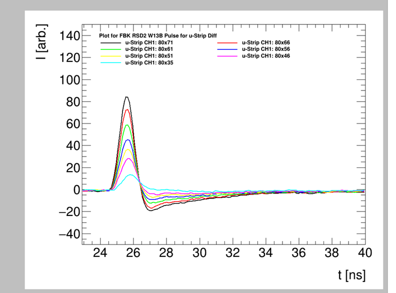
LGAD Sensor mounted on the Santa Cruz Board.

FBK Microstrips: Novel Geometries

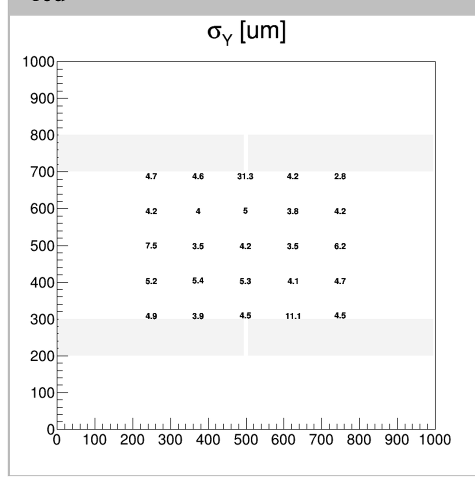


Multiple unique geometries tested with this sensor results presented on 100x500μm microstrips boxed in red

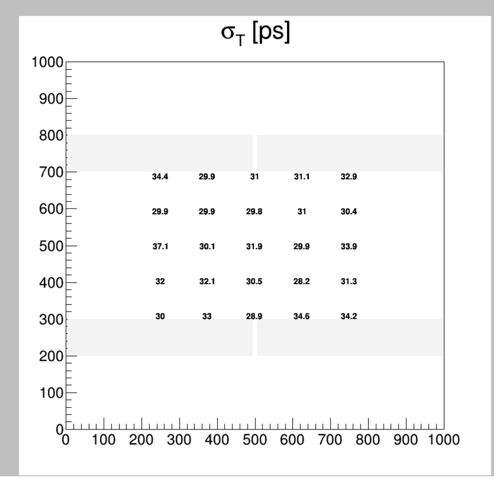




- **Position reconstruction is made by generating a reference file on the detector itself.**
- Fraction map is calculated for each of the 4 channels from a fine scan using the SCIPP laser setup shown by orange dots.
- The position of each events is calculated by doing a fit of the fractions in the event and the fraction maps from the average scan.
- **The best fit is taken as the reconstructed position.**

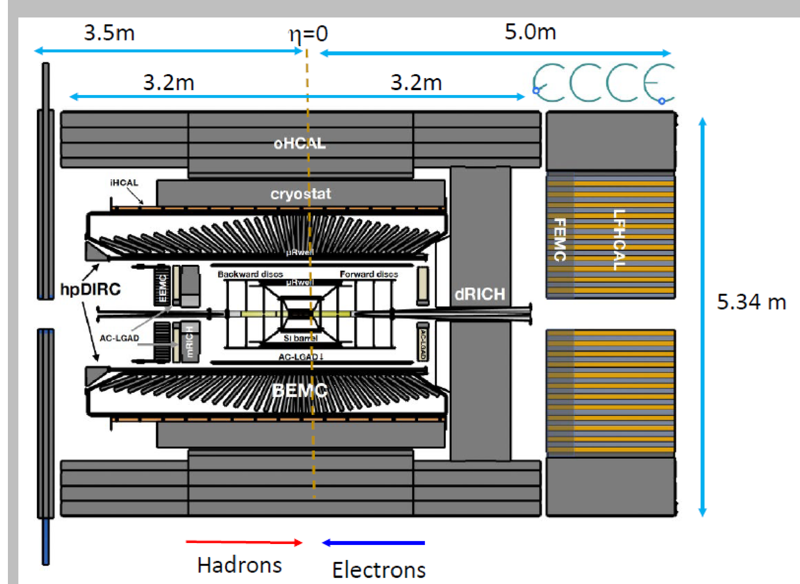


Left gives the spatial resolution in the y direction and the right gives the temporal resolution both given as a function of position using the SCIPP laser scanning setup.



Future Applications

Electron Ion Collider (EIC)



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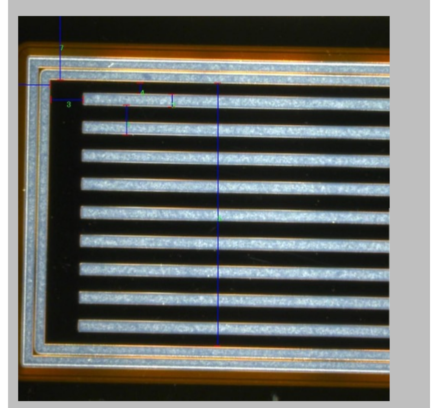


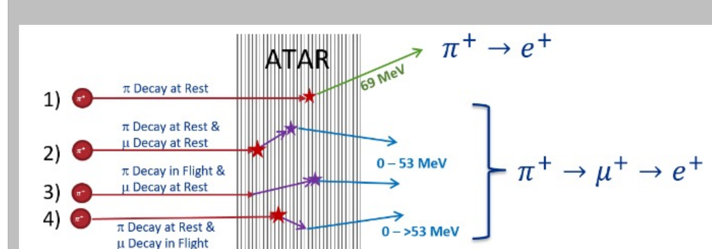
BNL 2021 2.5cm Long Strip Sensor

- The EIC is a collider being built at BNL with the **science goal of investigating the gluons** that mediate the strong nuclear force.
- Detector 1 will be the tracking layer of the EIC experiment.
- Both recently issued **designs include a time-of-flight particle ID detector layer with AC-LGADs as the baseline technology**.
- Design requirements for detector 1 include a **low material budget, radiation hard sensors, a combined temporal of 25ps, and a spatial resolution of 30μm a hit.**
- 2022 Fermilab beam test done to look at a potential iteration of AC-LGADs: long strip AC-LGADs with lengths from 0.5cm to 2.5cm.

PIONEER

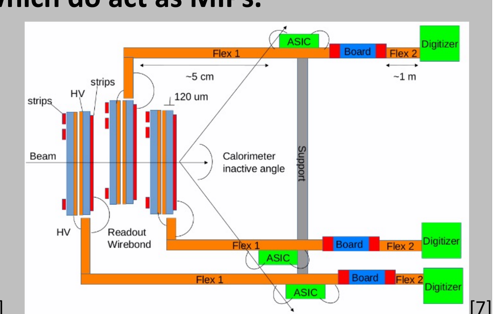

[6]

PIONEER is an upcoming rare pion decay experiment approved to be put into the Paul Scherrer Institute Beamline. PIONEER is a next generation fixed target experiment designed to **measure the charged pion decay branching ratio.** PIONEER will consist of an active **target (ATAR), likely made of AC-LGADs, surrounded by a calorimeter**. Most data gathered with AC-LGADs have been done with MIPs, however, the ATAR will have to be able to read out **pions, which can deposit approximately 4-5 times the amount of energy as a MIP, and electrons which do act as MIPs.**



[6]

The ATAR will need to be able to differentiate the **different possible decay modes** (above) of the pion and make **particle ID**. It is an active area of research and simulation to see what these "discriminating variables" could be.


[7]

ATAR initial design: 48 layers of 120μm thick AC-LGADs, compromise between granularity, total active area, timing and dead material. **LGAD signal is transmitted via a flex** to the readout ASIC and then to the digitizer stages in the back end.

Other Future Applications

In addition, to **PIONEER** and **EIC** mentioned above there is interest from several facilities in using LGADs for **X-Ray monitoring**. And far future experiments like the **Future Circular Collider**. AC-LGADs have proven their capability in reaching **a simultaneous 5 μm spatial resolution and a 30ps temporal resolution**. In addition to solving the issue of granularity present in DC-LGADs. They are a **very promising candidate for future 4D tracking**!

Acknowledgements

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