Characterization and Simulation of Timing and Spatial Resolution Within AC-LGAD Sensors

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ABSTRACT

The Electron-Ion Collider (EIC) at Brookhaven National Laboratory is equipped with a suite of detectors optimized for precision measurements. Among these, silicon detectors are traditionally used for tracking, but their application has been extended to time-of-flight measurements. In this project, we characterized the spatial and temporal resolution of Alternating Current Low-Gain Avalanche Diodes (AC-LGADs) through a combination of experimental data analysis and simulation. Our work focuses on the trade-off between spatial and timing resolution, demonstrating that with appropriate fine-tuning, these sensors can be optimized for specific measurement priorities in a realistic detector environment. Thus far, we have improved analog timing measurements and initiated simulations to replicate AC-LGAD behavior within the EIC framework.

INTRODUCTION

The vast majority of the research we have been focused on has been a newly developed instrument in detecting charged particles, colloquially named the Alternating Current Low-Gain Avalanche Diode (AC-LGAD). Similar to its previous generation of detectors, LGADs collect charge from incoming particles by ejecting electrons from the conduction band in the p-Si layer, causing them to drift towards the doped n+ layer. When this excess charge is picked up in the n+ layer, they induce displacement currents in the conducting pads, allowing for detection of interaction with charged particles as well as ionizing radiation.

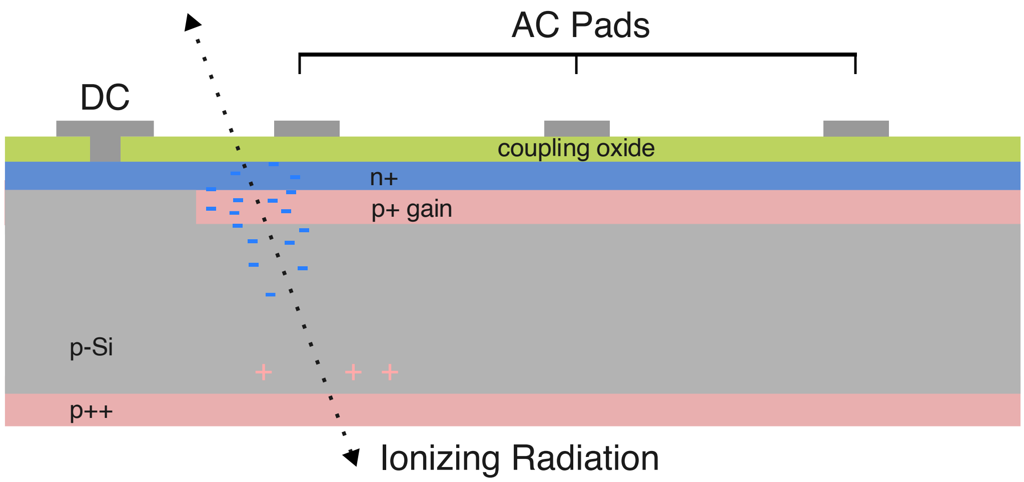


Figure 1. Ionizing particle displacing electrons in the p-Si layer inside an AC-LGAD, note that the direction of the incoming radiation from a Minimum Ionizing Particle (MIP), from the direction of the p++ layer or the conducting pads has no effect on the signal.

In principle this makes AC-LGAD sensors both more precise and versatile compared to LGAD sensors. But not without the drawbacks of being more fragile with higher energy particles and being harder to discriminate true particle hits against background noise. Thus, requiring an experimental approach to determine the sensitivity of this new generation of sensors and accurately characterize particle hits both in experiment and simulaton.

METHODS

Our goals in this project are multifaceted, get sensor data from various AC pads in controlled experiments, characterize the sensor output, and recreate the distribution of sensor outputs in simulation for the Electron Ion Collider. In this section, we will cover all of the steps taken along this pipeline in detail:

Experimental Data Collection

In general, we have a few ways of obtaining sensor data: Charge Injection, Laser Pulses, and Radiation sources, each of which gives us some method of being able to obtain sensor pulses, we will cover the first two in detail, as that is what follows from most of our results, and work on radiation sources will be left to the discussions section of this report, provided that we had still yet to finish work with getting data from laser pulses to arrive at doing experiments with radiation sources.

Charge Injection

This method employs a secondary component to the sensor itself, which is responsible for the readout of the signal in both analog and a secondary digital format commonly referred to as the Application-Specific Integrated Circuit or ASIC for short. We use this largely to 'clean' the signal as well as get readout information about how much current and thus total charge was collected from each pad and at what time this current was being read.

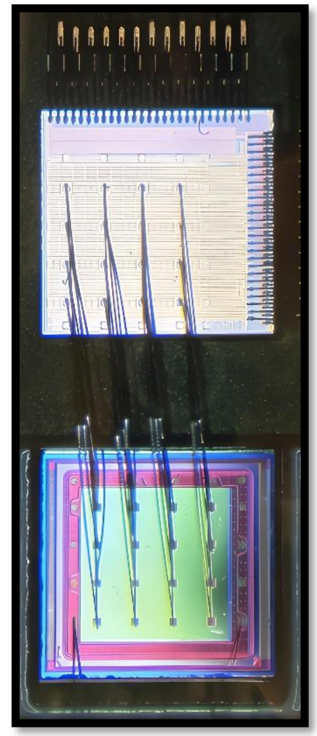


Figure 2. ASIC readout chip (top) wire-bonded to AC-LGAD sensor (bottom)

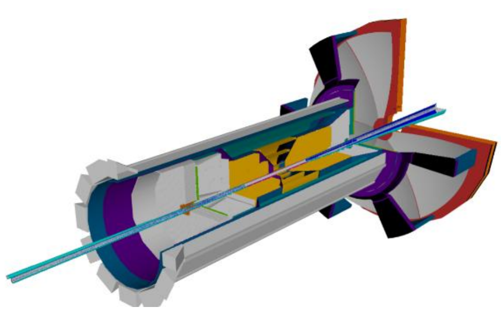
The ASIC is a subsystem of a larger system that BNL has been testing known as the Electron-Ion Collider Read Out Chip (EICROC). This system is directly responsible for formatting and saving the data, which can output information in one of two ways: either through raw analog output, or through a compressible binary framework developed for this sensor for charge collection known as Analog to Digital Conversion (ADC), as well as when this charge was collected in a format known as Time to Digital Conversion (TDC).

This allows us to verify the ASIC analog and digital readout. As well as be able to fine tune potential errors in timing within the readout. As will be discussed in later sections. We will be able to use these jitter measurements to better characterize peaks and be able to make the most of our timing and accuracy when taking measurements from collisions. Thus, allowing better readout.

Laser Pulses

Another method we have of being able to take data is by sending a laser pulse into the sensor, ionizing the atoms in the p-Si layer and inducing currents in the AC Pads. Despite not using charged particles, the light is high enough energy such that we may still cause an avalanche within the sensor. This allows us to interact with the sensor directly and emulate the results we can expect from Minimum Ionizing Particle. In the scope of the project d development in the time of my internship, we concerned ourselves mainly with the characterization of these pulses, and being able to determine more deeply the properties of this sensor output with respect to a laser input of varying initial conditions.

Simulation of Data



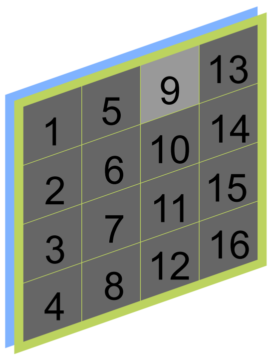
Once this data had been processed, the next steps were to implement these sensor response characteristics into a simulation framework for the Electron Ion Collider known as EICrecon, this repository was built on top of GEANT4 as well as a few applications specific dependencies that would allow us to view and modify the attributes of responses from different detector subsystems, in our case this had applied firstly to the barrel time of flight detector.

Figure 3. 3D Rendering of the Inner Tracker subsystems within the EIC. The Barrel Time-of-Flight tracker (BTOF) is denoted in cyan.

RESULTS

Experimental Data Collection

Charge Injection



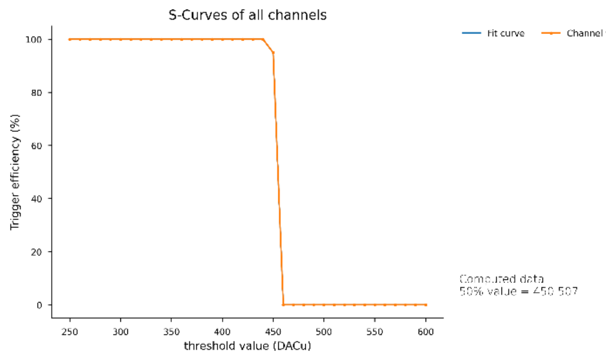


Figure 4 & 5. Diagram of the AC-LGAD prototype, with active testing pixel 9 highlighted in a brighter grey, AC-Pad sizes in are exaggerated for demonstration (left). And S-Curve for Pixel 9 on the AC-LGAD sensor. The average between all sensors was about ~450 DAC units (right).

Much of the data collected via. Method of charge injection consisted mainly of sanity checks. This sensor was a four-by-four AC Pad prototype, bump-bonded to the ASIC, we will note why this currently may be the issue for further testing in the laser pulses section. Generally, we checked to make sure that the avalanche threshold in Digital-to-Analog Converter (DAC) units, the most responsive cell is depicted in Figure 4. This allowed for a method to verify that the sensors had a similar avalanche value in DAC units. While we found little variation in threshold value, unfortunately two particular cells, cell 7 and cell 11 were problematic, as they had boasted threshold values of about 250 DAC units.

Laser Pulses

A vast majority of the analysis of the laser scan data came from determining a quantity known as jitter. One of the defining characteristics of AC-LGADs are their precise timing measurements, we are specifically interested in quantitatively determining the timing for our use within Time-of-Flight detectors. However, there are a few different points of error that could occur to increase the jitter:

$$\sigma_{sensor}^2 = \sigma_{laser}^2 + \sigma_{ASIC}^2$$

the largest considerations in determining the jitter with respect to the waveform of the sensor itself, however calculations were also done to determine the jitter of the laser to also get an accurate determination of the jitter of the ASIC as well.

For our analysis, these waveforms were collected from a high time-resolution oscilloscope where we took repeated measurements of the response in the sensor output, these response times were distributed normally and could be fit to determine a jitter. The main analysis done here was to minimize this jitter by varying the threshold value by which a response would be classified as a 'hit'. We would vary this threshold both from the hardware, as denoted by each unique plot in Figure 6. As well as the threshold as computed by each readout.

The results for the timing in the data, while seemingly consistient proved to be at a minimum at around 0.4V-0.8V. While due to errors in analysis, the exact jitter timing was not determined, we suspect the entire sensor's jitter to be on the order of ~20ps.

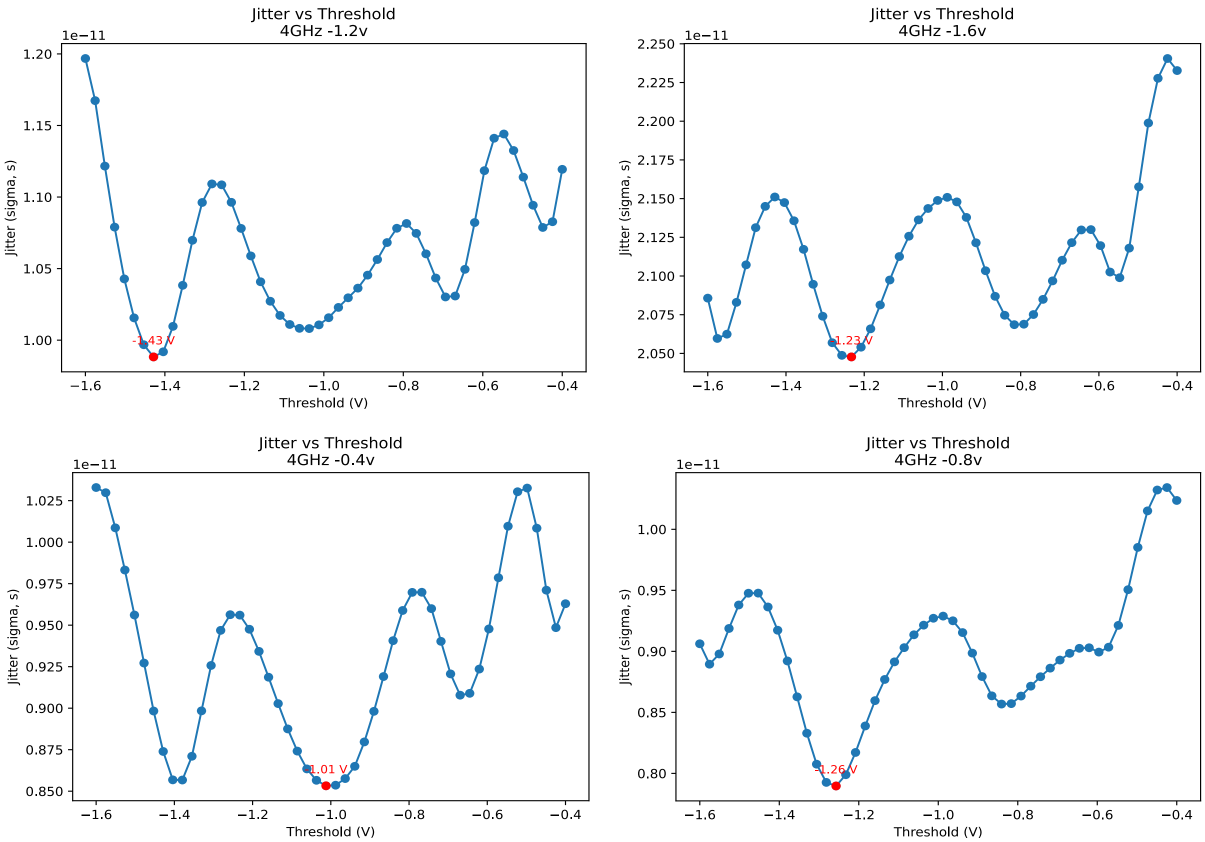


Figure 6. Plots for the hardware threshold value (given by the voltage in the plot title), as minimizing curves for the numerically computed jitter timings as a function of the threshold value computed in analysis.

Simulation of Data

The processing pipeline envisioned for translating experimental charge-sharing measurements into the framework relies on a stepwise procedure: once the full characterization of charge-sharing events is available, the pipeline can process these data through digitization, clustering, and reconstruction modules. This framework is designed to systematically transform raw charge distribution measurements into structured inputs compatible with EICrecon, enabling straightforward incorporation of these results into downstream reconstruction workflows. With the acquisition of additional charge-sharing data, the pipeline should facilitate a relatively streamlined and reproducible process for integrating these measurements, minimizing the development overhead and ensuring consistency with existing reconstruction protocols. During my tenure at Brookhaven, I was unable to make direct contributions to the integration of charge-sharing data into the EICrecon codebase due to the current limitations in the available datasets.

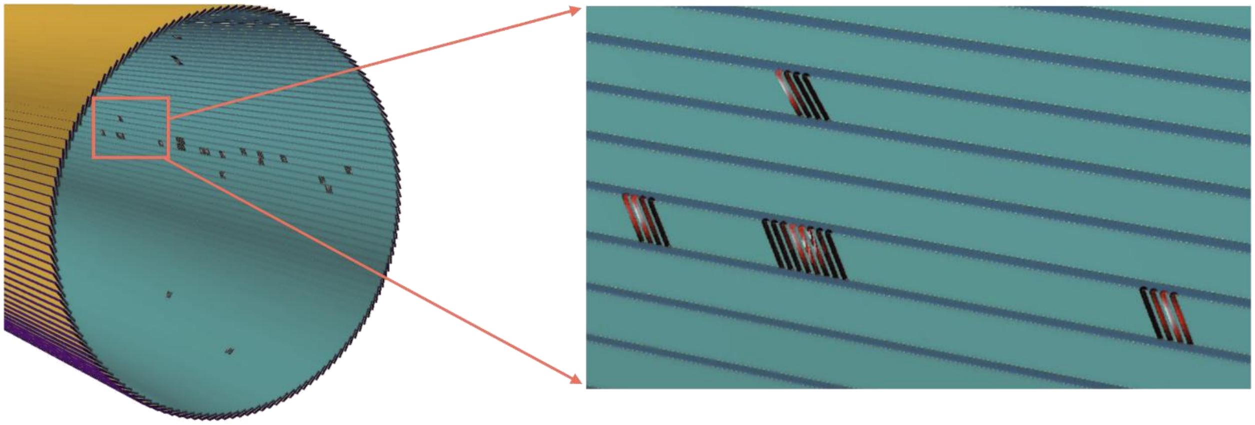


Figure 7. Schematic of the Barrel Time-of-Flight (TOF) detector illustrating charge-sharing behavior across sensor rows in AC-LGADs. The alternating current LGAD sensors enable precise timing measurements while distributing charge across neighboring channels, enhancing spatial resolution and enabling accurate hit reconstruction across the detector plane

CONCLUSION

In this project, we characterized the spatial and temporal performance of AC-LGAD sensors for application in the Electron-Ion Collider's Barrel Time-of-Flight detector. Through charge injection and laser pulse measurements, we were able to probe the sensor response, quantify timing jitter, and evaluate the uniformity of avalanche thresholds across prototype AC pads. While exact timing resolution could not be fully determined due to hardware limitations and incomplete datasets, preliminary analysis suggests that these sensors are capable of sub-50 ps timing precision, consistent with the expected performance of AC-LGAD technology.

The work further established a framework for incorporating experimental sensor characteristics into the EICrecon simulation environment. Although direct integration of charge-sharing data into the codebase was not realized during this internship, the stepwise processing pipeline encompassing digitization, clustering, and reconstruction provides a clear and reproducible pathway for future implementation. With additional charge-sharing data, this pipeline should allow for efficient translation of raw sensor outputs into formats compatible with downstream reconstruction modules, enabling high-fidelity simulations of detector response.

Overall, this project demonstrates both the potential of AC-LGAD sensors for high-precision timing applications and the feasibility of integrating experimental measurements into the EIC reconstruction framework. These results lay the groundwork for continued optimization of sensor performance and the eventual deployment of AC-LGAD-based systems within the EIC detector suite.