AC-LGAD strip sensor measurements with 120 GeV protons

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Motivation for 4D Trackers

Future colliders present tremendous challenges for trackers

- Eg: at FCC-hh we expect 1000 pile-up interactions per bunch crossing
  - LHC: PU ~ 50
  - HL-LHC: PU ~ 200
- Future trackers need $O(10 \text{ ps})$ and $O(10 \text{ µm})$ resolution per-hit
  - simplify pattern recognition
  - correctly associate tracks to pile-up vertices
- Need a sensor with both precise time resolution and fine segmentation!

At HL-LHC already need ~50 ps time resolution per track to resolve pile-up vertices
Why AC-LGADs

- Low Gain Avalanche Detectors (LGADs) achieve 30 ps time resolution
  - ATLAS and CMS plan to use 1.3 x 1.3 mm² pads at HL-LHC
  - cannot easily shrink pitch: 50-80 µm inactive region between pads

- AC-coupled LGADs solve the fill factor problem
  - uninterrupted gain layer, read out with AC-coupled electrodes
  - → smaller pitch and signal sharing between pads
  - can easily achieve O(10 µm) and 30 ps time resolution with same sensor
The AC-LGAD sensor

- Fabricated at BNL
  - 50 µm thick p- substrate
  - Depletion voltage -150 V
  - Breakdown -225 V at 22°C
  - Bias Voltage -210 V

- 17 Strips
  - 100 µm pitch
  - 80 µm width

- DC contact surrounds pads
  - behaves as a standard LGAD when directly traversed by a proton
  - used to measure gain

- Readout with Fermilab 16-channel board
  - 15 strips (additional stage of amplification)
  - DC pad

Guard Ring
DC-contact
strips: 0-17
Simulation

- AC-LGAD simulations with a similar geometry
  - 100 µm pitch, 80 µm width, similar doping/gain, but shorter strip length
  - simulations performed with SILVACO

Current-sharing between adjacent strips

DC-contact signals for different proton positions
Fermilab Test Beam setup

- Main injector provides 120 GeV protons
  - Beam width: few mm to few cm
  - ~100k protons per 4 seconds spill, every minute

- Independent scintillator provides trigger
- Telescope provides proton track position
- Photek MCP serves as time reference (10 ps resolution)
- Oscilloscope saves waveforms from Photek and three channels
- Study $\Delta t(\text{AC-LGAD,Photek})$
Analysis strategy

- Basic requirements
  - Well measured proton track
  - Photek signal
  - Proton x and y consistent with sensor

- Can only study 3 strips + Photek at a time with oscilloscope
  - Three adjacent strips
  - Or stitch separate events together

- Hit amplitude thresholds
  - Strips: 110 mV
  - DC contact: 11 mV

- Clusters formed from adjacent strips with hits

*Following slides include amplifier gain*
Signal Properties

- **Center strip**
  - initial negative pulse
  - 1 ns FWHM
  - followed by overshoot
  - S/N~27

- **Adjacent strips**
  - lower amplitude signals
  - longer tails
Signal sharing between strips

- Confirms predictions from simulation
  - strip amplitude decreases with distance to proton
  - adjacent strip sees lower amplitude signal, usually above threshold
  - 2nd adjacent rarely sees signal above threshold (few percent)
Estimating cluster size

• Since we can only read out 3 channels at once, we use amplitude distributions to estimate cluster size
  • ~70% of events have a 3 hit cluster
  • ~25% have 2 hits
  • few% will have a 4th or 5th hit
  • <1% of clusters have 1 hit or less

• Majority of signal contained within three strips
  • sum of amplitudes well described by landau convolved with a gaussian
DC-contact

- DC-pad signal amplitude decreases with distance to incident proton
  - direct hits in DC pad (>30 mV), induced hits near DC pad (11-30 mV)
- DC-pad behaves like a standard LGAD when struck directly by proton
  - measure collected charge to be 11 fC, 30% systematic uncertainty
  - corresponds to gain of 17

![Graph showing collected charge and events distribution](image)
Efficiency measurement

- Study the efficiency as a function of proton x and y position
- Efficiency definition: amplitude > 100 mV, $t_{peak}$ ~ consistent with MIP
- Measure efficiency = 99.4 ± 0.1
- Observe no loss of efficiency between strips!
Efficiency measurement cont.

- Can also study efficiency of individual strips
  - consistent across the device
  - indicative of good uniformity!
Spatial Resolution

- **AC-LGAD feature** - signal sharing between strips can improve position measurement beyond \((\text{strip size})/\sqrt{12}\)

- **Our measurement**
  - \(\sigma(\ x_{\text{sensor}} - x_{\text{tracker}})\)
  - dominated by tracker resolution \(\sim 50\ \mu\text{m}\)*

- **Looking into ways to improve tracker resolution for future**

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*50 \(\mu\text{m}\) res due to extrapolation to DUT, not intrinsic to telescope*
Time resolution

- Measurement:
  - time difference with respect to photek ($t_0 - t_{ref}$)
  - $t_0$ and $t_{ref}$ defined at 20% of pulse maximum amplitude
  - resolution: sigma of gaussian fit

- Within a 2 or 3 hit cluster
  - leading strip: 45-47 ps
  - subleading: 70-90 ps
  - no significant improvement from combining hits within clusters - at most few ps expected

- Future improvements
  - investigate lower noise electronics
  - systematic study of how gain/geometry/charge sharing impacts time resolution
Conclusions

• AC-LGADs make excellent candidates for future 4D trackers

• We present numerical simulations & first measurements of an AC-LGAD strip sensor with 120 GeV pp-collisions
  • characterization of signal properties, including signal sharing
  • efficiency demonstrated to be >99%
  • steps towards spatial & time resolution measurements

• Read more in arXiv:2006.01999