First survey of centimeter-scale AC-LGAD strip sensors with a 120 GeV proton beam

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Future trackers need timing

- 4D-trackers will play a key role at future machines
  - For bkg reduction and triggering
  - Enhance PID and LLP reco capability
  - Unique opportunity for detector design

- HL-LHC timing detectors is major first step
  - LGADs with 1.3x1.3 mm$^2$ pixels
  - Resolutions of ~375 μm and 30 ps

| Measurement                  | Technical requirement       |
|------------------------------|----------------------------|
| Tracking for e$^+$e$^-$      | Granularity: 25x50 μm$^2$ pixels |
|                              | Resolutions of 5 μm and <10 ps |
| Tracking for μ$^+$μ$^-$      | Granularity: 25x25 μm$^2$ pixels |
|                              | Resolutions of 5 μm and <30 ps |
| Tracking for 100 TeV pp     | Radiation tolerant up to 8x10$^{17}$ n/cm$^2$ |
|                              | Resolutions of 5 μm and <10 ps |

Technical requirements for future trackers:
from DOE’s HEP BRN and Snowmass 4D tracker whitepaper

HL-LHC: pileup ~ 200, 14 TeV

Future collider: >1000 pileup, 100 TeV
AC-coupled LGADs

- Conventional LGAD suffers from poor fill factor
  - Gain layer termination requires ~50 μm interchannel gap size

- AC-LGADs solve this issue
  - Electrons collect at the resistive n+ and then slowly flow to an ohmic contact at the edge

- Signal sharing allows for improved position resolution
High resolution AC-LGAD strips

- Excellent performance from several BNL 100 to 200 μm strip prototypes
  - Well-tuned signal sharing → uniform 2-strip efficiency

• Promising 4D sensors: 26-30 ps timing and 5-10 μm resolution
Large-area AC-LGAD strips

- To cover large areas, need to demonstrate performance with longer (larger) strip

- First test of cm-length sensors
  - A promising approach for TOF layer of ePIC detector @ EIC to achieve PID
Measurements

- **Conducted at Fermilab Test Beam Facility (FTBF)**
  - Results based on two separate test beam campaigns
  - Used 120 GeV proton beam from main injector

- **First beam test in March 2022** focusing on first batch of long strip BNL sensors
  - Paper detailing 2022 beam test results ([2023 JINST 17 P06013](#))

- **Second beam test concluded in January 2023** on second batch of long strip BNL sensors and HPK pixels with thickness variation
FTBF 4D-tracking Infrastructure

- Permanent setup in FNAL test beam facility (FTBF)
  - Movable: slide in and out of beamline as needed
  - Tracking with ~5 μm resolution
  - Time reference detector with ~10 ps resolution (MCP)
  - Specialized readout boards for LGAD characterization
  - DAQ: high bandwidth, high ADC resolution 8-channel scope
  - Environmental control and monitoring: Temp (-25 C to 20 C) & Humidity

8-channel oscilloscope, 2 GHz, 10 GSa/s
Long (cm) strip sensors

- Survey conducted on ~30 sensors
  - Strips with 500 μm pitch and 0.5, 1.0, and 2.5 cm long channels
  - Pixels with 500x500 μm² channel size

- Focused on geometry optimization and tradeoffs with larger channels
Checking gain uniformity

• **Initial sensors** had localized gain featured
  - BNL adapted their gain implantation procedure
• Greatly improved gain uniformity with **second batch**
Propagation delays across surface

- Signal arrival depends on location of hit with $O(100 \text{ ps})$ delays
- Can be corrected with dual-end readout

\[ \Delta t_{L-R} \rightarrow \text{reconstruct longitudinal position with mm precision} \]
4D tracking performance: BNL 1cm strips

- Sensor provides 100% efficiency with ~80% having signals in two or more strips
- Measure mostly uniform 20 μm position resolution
- Quantified different time resolutions based on how the time delay is accounted
  - Using perfect time delay (eg. using full tracking) can achieve ~40 ps time resolution
4D tracking performance: HPK strips

- Better quality sensor fabrication from HPK results in improved signal to noise
- Best prototype achieves 12 μm position resolution and 34 ps time resolution
Sensor Thickness Study

- Competing effects from Landau fluctuations vs S/N
  - Thinner sensors decrease Landau contribution but have smaller signals
  - Thinner sensors also have faster rise time
- We study this effect using HPK sensors of thickness 20, 30, 50 μm

HPK 2x2, each 500x500 μm²
Sensor Thickness Study

- Achieve excellent timing performance for 20 μm sensors
  - 20 ps resolution for 20 μm sensors
  - 25 ps resolution for 30 μm sensors
- Uniformity is maintained
Summary

• AC-LGADs provide excellent 4D performance while achieving:
  - 100% fill factor
  - few micron level spatial resolution
• Progress made towards large area sensors with promising performance
  - Achieved 12 μm spatial resolution and 34 ps time resolution simultaneously
  - Close to meeting design goals of EIC’s ePIC TOF detector
• Demonstrated path towards sub-30 ps time resolution using 20 and 30 μm thick sensors from HPK
• Great progress in 4D tracking in past year and more to follow!
Backup
| Name | Wafer | Pitch (μm) | Strip length (mm) | Metal width (μm) | Active thickness (μm) | Resistivity (Ω/□) | Capacitance (pF/mm²) | Optimal bias voltage (V) |
|------|-------|------------|------------------|------------------|----------------------|-------------------|----------------------|-------------------------|
| SHW1 | W9    | 500        | 5                | 50               | 20                   | 1600              | 600                  | 110                     |
| SHW2 | W9    |            | 5                | 50               | 20                   | 1600              | 600                  | 114                     |
| SHW3 | W4    |            | 5                | 50               | 50                   | 400               | 240                  | 204                     |
| SHW4 | W8    |            | 5                | 50               | 50                   | 1600              | 600                  | 200                     |
| SHW5 | W2    |            |                  | 100              | 20                   | 1600              | 240                  | 180                     |
| SHW6 | W5    |            |                  | 100              | 50                   | 1600              | 600                  | 190                     |
| SHW7 | W9    |            |                  | 100              | 50                   | 400               | 600                  | 208                     |
| SHW8 | W8    |            |                  | 100              | 50                   | 400               | 600                  | 112                     |
| SHN1 | WN1   | 80         | 10               | 60               | 20                   | 1600              | 240                  | 112                     |
| SHN2 | WN2   |            | 80               | 60               | 50                   | 1600              | 240                  | 190                     |
| BNL  |       |            |                  |                  |                      |                   |                      |                         |
| SB1  | WB2   | 500        | 10               | 50               | 20                   | 1600              | 240                  | 95                      |
| SB2  | WB3   |            |                  | 50               | 20                   | 1600              | 240                  | 80                      |
| SB3  | WB1   |            |                  | 50               | 20                   | 1600              | 240                  | 170                     |
| SB4  | WB4   |            |                  | 50               | 20                   | 1600              | 240                  | 185                     |
| SB5  | WB3   |            |                  | 50               | 20                   | 1600              | 240                  | 95                      |
| SB6  | WB2   |            |                  | 100              | 20                   | 1600              | 240                  | 80                      |
| SB7  | WB1   |            |                  | 100              | 20                   | 1600              | 240                  | 160                     |
Pulse shapes

- Longer strips associated with slower rising edge
  - Likely due to extra capacitance, and transmission line reflection effects

- 1 cm strips: already work well!
- > 2 cm: trying few ideas to improve in next beam test.