Electrical and Timing Performance of AC-LGADs

Gabriele D'Amen (BNL),
Giacomini Gabriele (BNL Instrum. Div.),
Wei Chen(BNL Instrum. Div.),
Alessandro Tricoli (BNL)

BROOKHAVEN NATIONAL LABORATORY

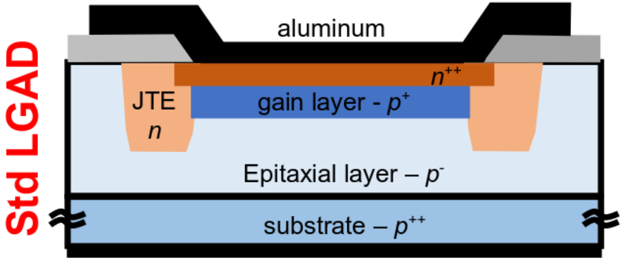
The 37th RD50 Workshop (Zagreb, online)
18th – 20th November 2020

Overview

- Presentation of BNL LGADs, and AC-LGADs towards a 4D detector
  - Reference studies of BNL's and HPK's LGAD performance
  - Focus on electrical and time performance
- Measurements of current, capacitance, charge collection, signal sharing and timing in AC-LGADs
  - Comparison of timing measurements with 120 GeV protons and with beta-scope (beta's from ^{90}Sr source)
- Simulation studies to give insight on signal sharing between AC-LGAD pixels
- Alternative designs to exploit signal sharing to improve space resolution

(AC-)LGAD Fabrication and Testing at BNL

- Silicon fabrication and testing facilities
- Wire- and bump-bonding
- Full characterization, design and simulation of silicon sensors
- Several productions of LGADs and AC-LGADs with different designs, e. g. geometries, doping concentrations, gain depth etc.



All silicon process done in BNL Instrumentation Division Class-100 Clean Room

Furnaces for dry oxidations and annealings

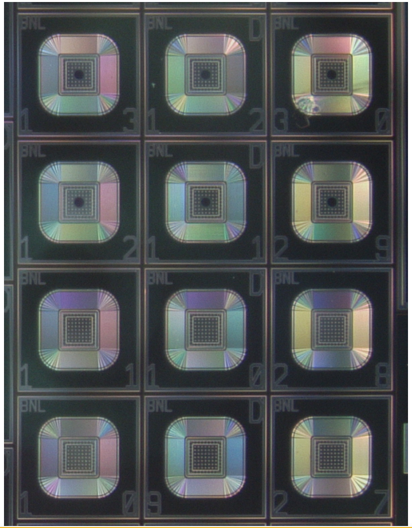
Double-sided mask aligner

Wet bench (HF, RCA I & II, piranha, polyetch, ...)

Sputtering (Al, Al1%Si, Ti)

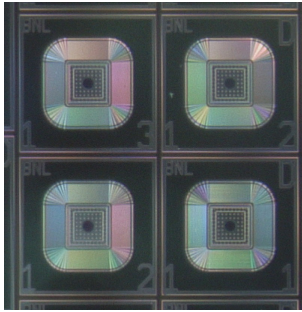
RTA for sintering

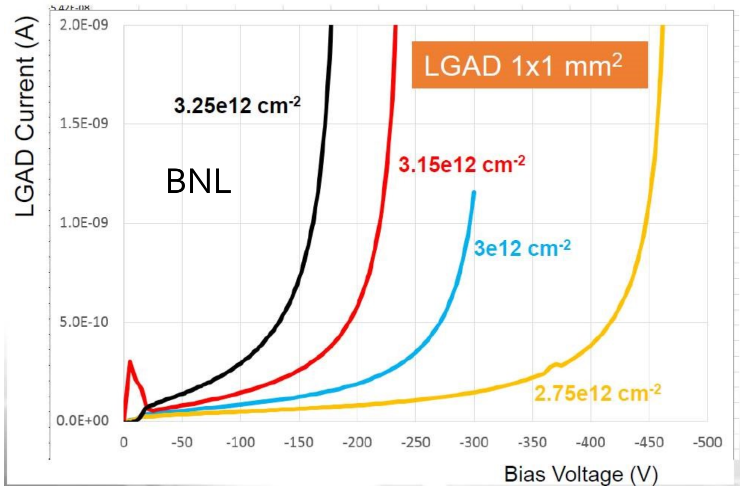
Laser dicing

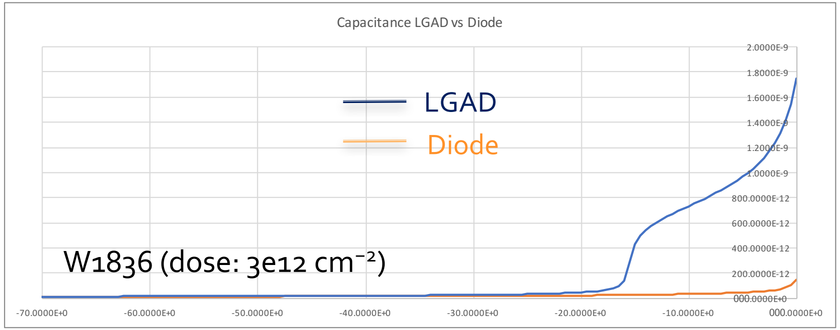


LGAD Characterization (IV, CV scans)

- Probe station to measure I_{GR}, I_{Pad}, I_{tot} as a function of V_{bias}
  - Clear current and $V_{breakdown}$ dependence on gain layer dose
  - Leakage current for 1x1 mm² of ~10 pA (1 nA/cm²)
- Capacitance at full depletion 8 pF for 2x2 mm² pad, compatible with 50 um thickness

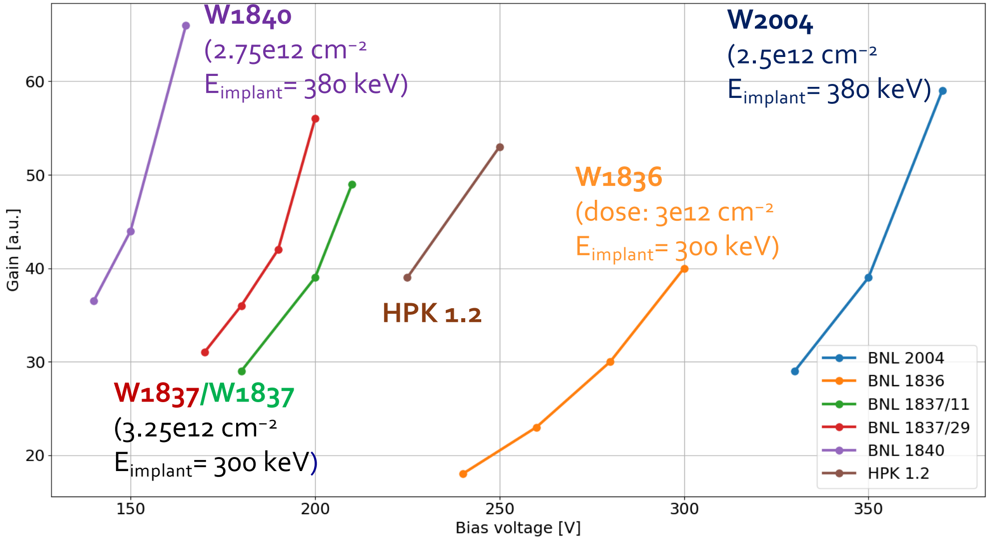






LGAD Characterization (Gain)

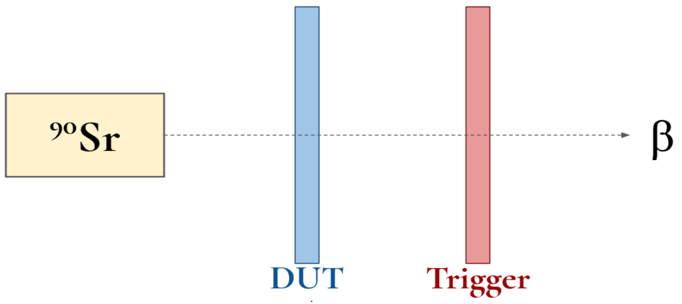
- **BNL sensors:**
  - 1×1 mm² sensor size
  - 50 µm active layer
  - Different implantation energies for gain layer: $E_{implant}$= 300-380 keV
    - **W1840** only initially depleted at $V_{breakdown}$
- **Hamamatsu (HPK) sensors:**
  - 1.3×1.3 mm² sensor size
  - 35 µm active layer
  - HKP 1.2 LG1-SE

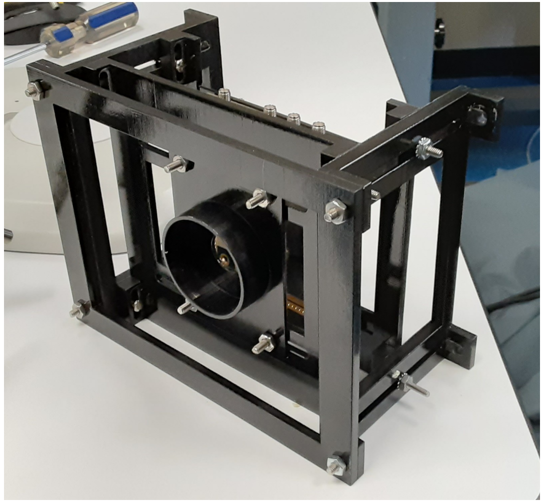


Gain in HPK and BNL-produced LGADs measured with beta's from ^{90}Sr

LGAD Characterization (Time Resolution)

- Time resolution measured using a 3D-printed beta-scope with a 7.5 MBq ^{90}Sr source
  - Santa Cruz's **single channel test-board** for readout
  - Oscilloscope, Le Croy WaveRunner 9404M-MS (4 GHz, 40 GS/s)
  - Output signals amplified with Mini-Circuits ZX60-3018G-S+ amplifiers (Gain=12-13)

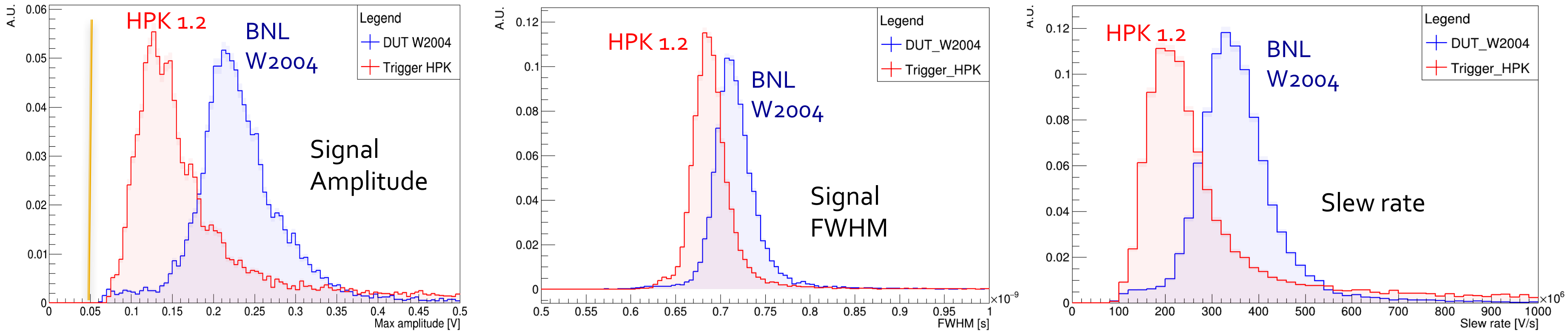




- **Trigger sensor: HPK 1.2 LGAD (σ_t ~28 ps, gain ~55, 35 µm thickness)**
- **DUT: BNL sensors**

LGAD Characterization (Time Resolution)

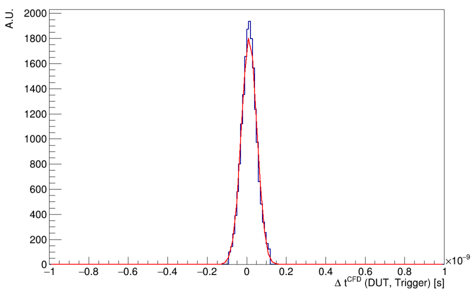
- Trigger sensor: HPK 1.2 (σ_t ~28 ps, gain ~55, 35 μm thickness)
- DUT: BNL LGAD (W2004) sensor (50 μm thick, V_{bias} = -370 V)

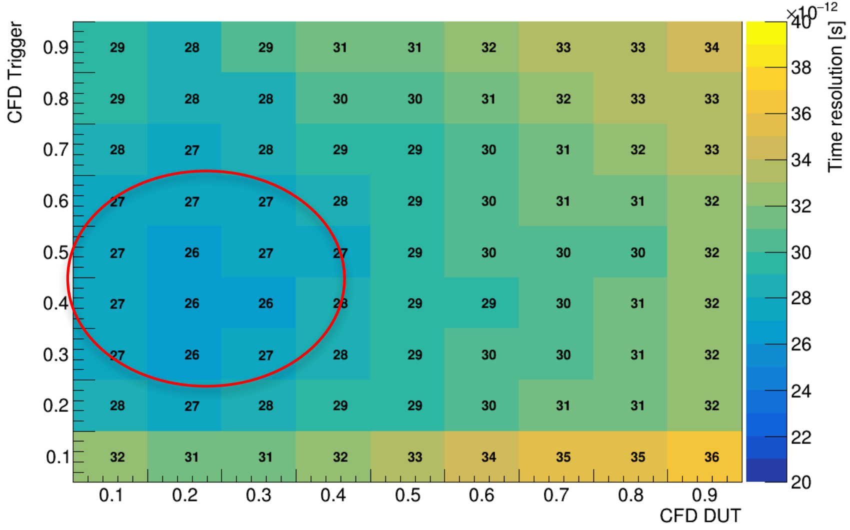


- Oscilloscope trigger level of 50 mV allows us to keep entire Landau distribution of beta signals and not bias σ_t measurements

LGAD Characterization (Time Resolution)

- Trigger sensor: HPK 1.2 (σ_t ~28 ps, gain ~55, 35 µm thickness)
- DUT: BNL LGAD (W2004) sensor (50 µm thick, gain ~ 60, V_{bias} = -370 V)





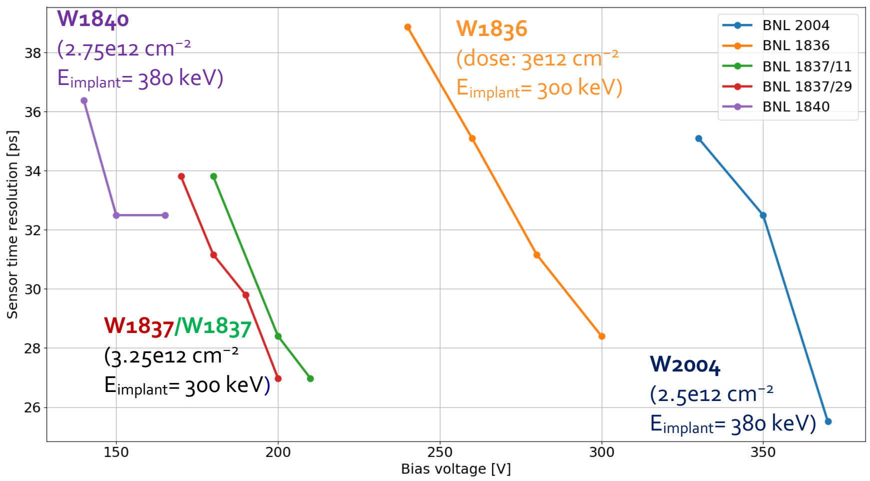
- **Time of arrival of beta's** on sensors is defined as the time at which the signal crosses a certain fraction of the total signal amplitude
- Scan of σ_t as a function of **Constant Fraction Discriminator (CFD)** for both DUT and Trigger sensors

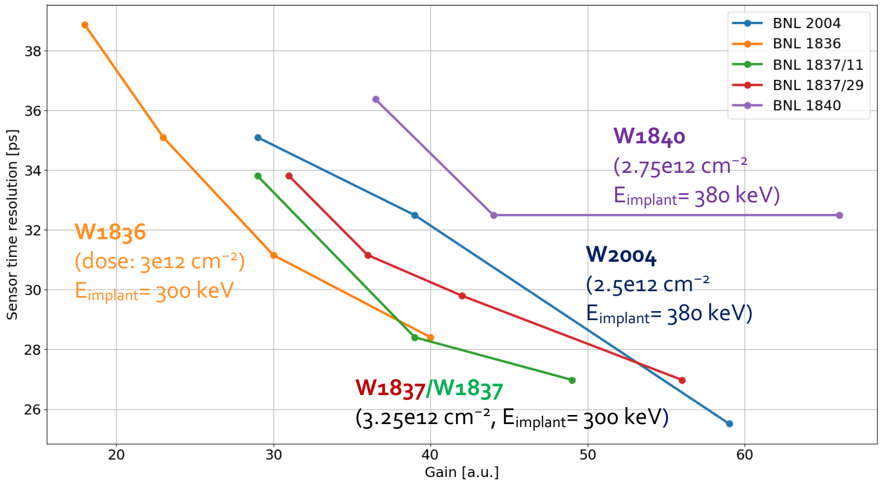
$$\sigma_t^{DUT} = \sqrt{(\sigma_t^{TOT})^2 - (28\ ps)^2}$$

➔ BNL LGAD's time resolution of 26 ps

LGAD Characterization (Time Resolution)

- Time resolution of several BNL LGADs as a function of V_{bias} and Gain



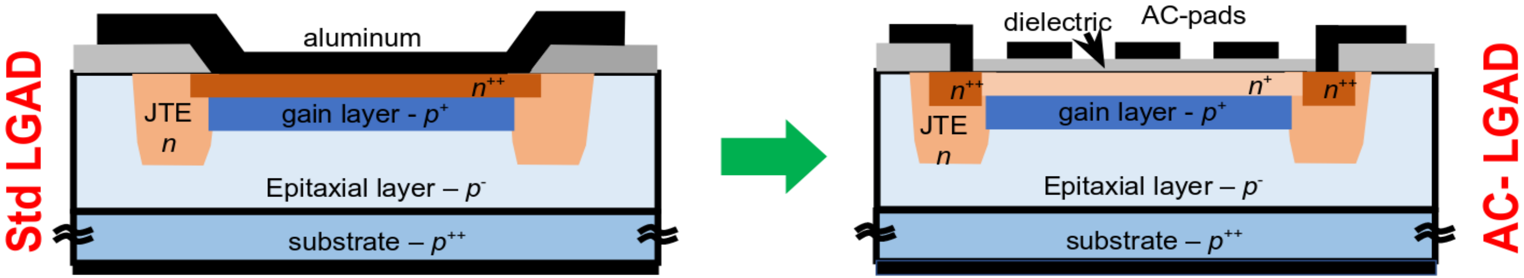


- Time DUT time resolution measured with σ^{HPK}_t = 28 ps
- BNL LGADs thicker than HPK (**50 µm vs 35 µm**)

➔ Time resolution of 26 ps is achieved with BNL LGADs with 50 µm sensor thickness and gain~60

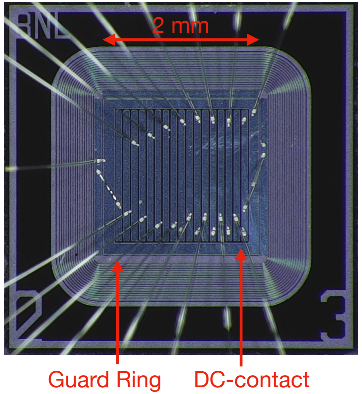
AC-LGAD Concept (a 4D detector)

- Limits of LGADs
  - Lateral size of Gain Layer must be larger than thickness of substrate, for a uniform multiplication
    - large pads are preferred (~ 1 mm), e.g. HGTD and MTD
  - Dead volume (gain 1) extends outside the JTE and also slightly inside the implanted gain layer region
    - pixels/strips with gain layer below the implant have a Fill Factor <<100% (Voltage dependent)
  - 4D detector not possible…
- The AC-LGAD
  - Signal AC-coupled through dielectric to metal pads
  - 100% Fill Factor
  - Fast timing information at a per-pixel level
  - Signal is shared with neighboring pads
  - **…4D detector is possible!**

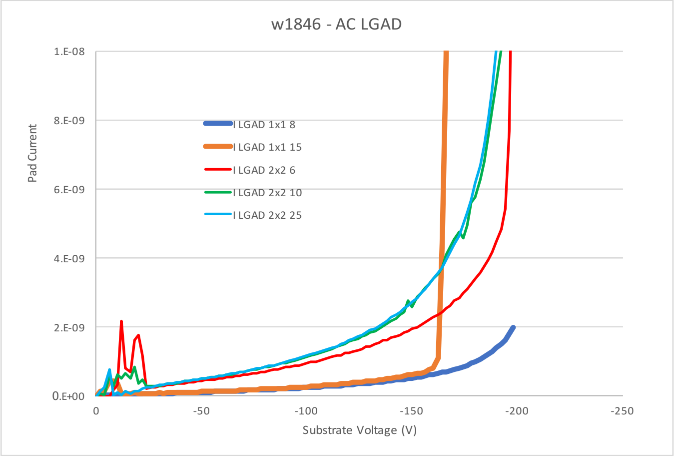


AC-LGAD Characterization (IV, CV scans)

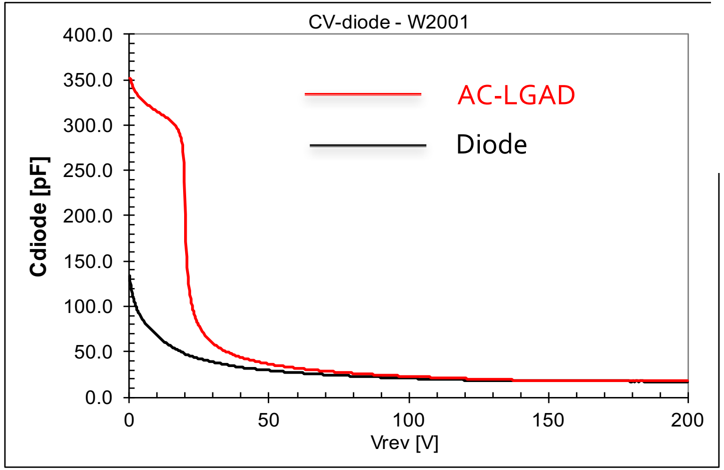
- IV scan for a few 1x1 mm² and 2x2 mm² AC-LGAD (W1846) sensors (DC-connected pad)
- CV scan of the whole AC-LGAD (W2001) sensor area
  - at full depletion 17 pF for a 3x3 mm² device, compatible with 50 μm thickness



Current of the DC-connected pad surrounding pixel area

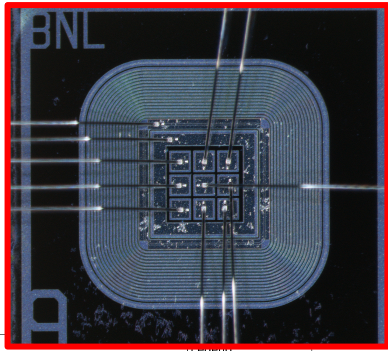


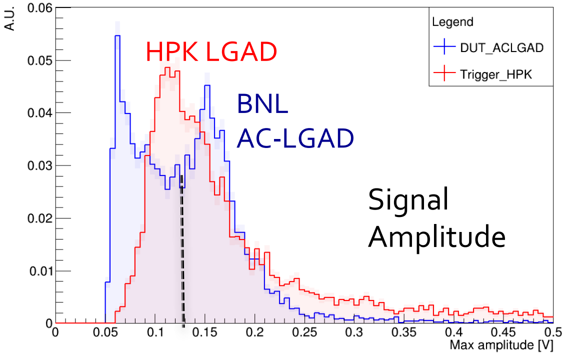
CV scan for the whole sensor area (3x3 mm²)

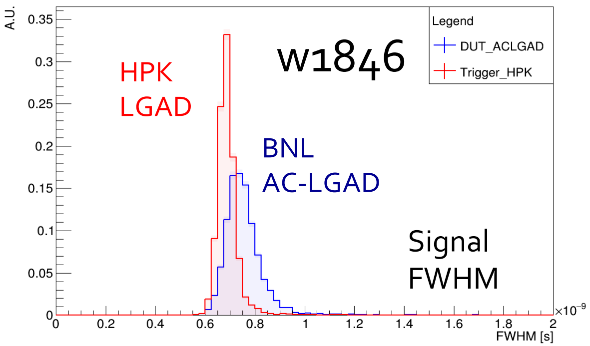


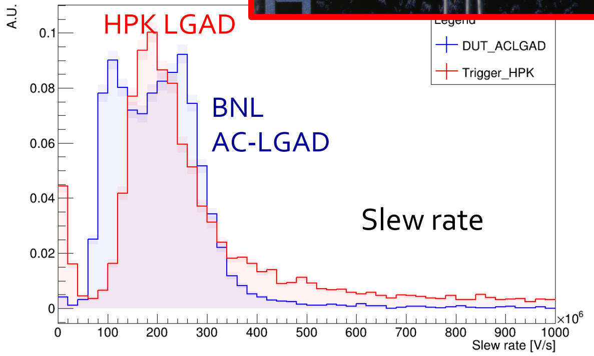
AC-LGAD Characterization (Time Resolution)

- Standards (DC) LGAD HPK 1.2 as Trigger sensor for characterization of BNL AC-LGAD
- BNL AC-LGAD (W1846) **pixel sensor, 220 µm pitch, 20 µm gap** (V_{bias} = -210 V)
  - Santa Cruz's **single channel** test-board for readout
  - Beta's from ^{90}Sr





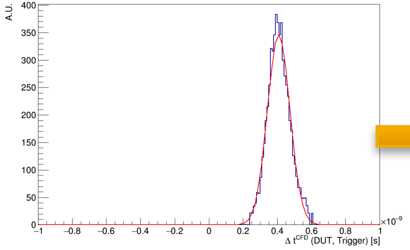




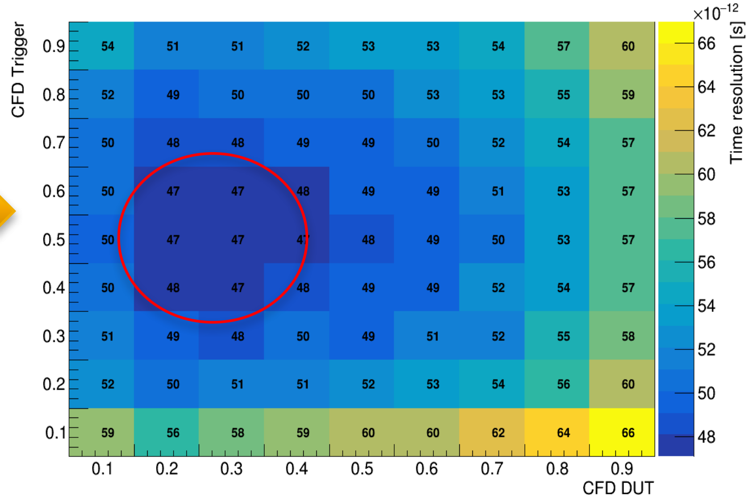
➔ Two populations of events in Amplitude and Slew Rate distributions:
- signal is "primary" – readout strip is hit directly by particle
- signal is "secondary" – particle hits an adjacent strip and signal is shared

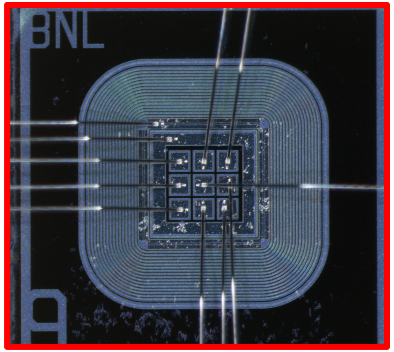
AC-LGAD Characterization (Time Resolution)

- Standard (DC) LGAD HPK 1.2 as Trigger sensor for characterization of BNL AC-LGAD
- BNL AC-LGAD (W1846) **pixel sensor, 220 µm pitch, 20 µm gap** (V_{bias} = -210 V)



$$\sigma_t^{DUT} = \sqrt{(\sigma_t^{TOT})^2 - (28\ ps)^2}$$



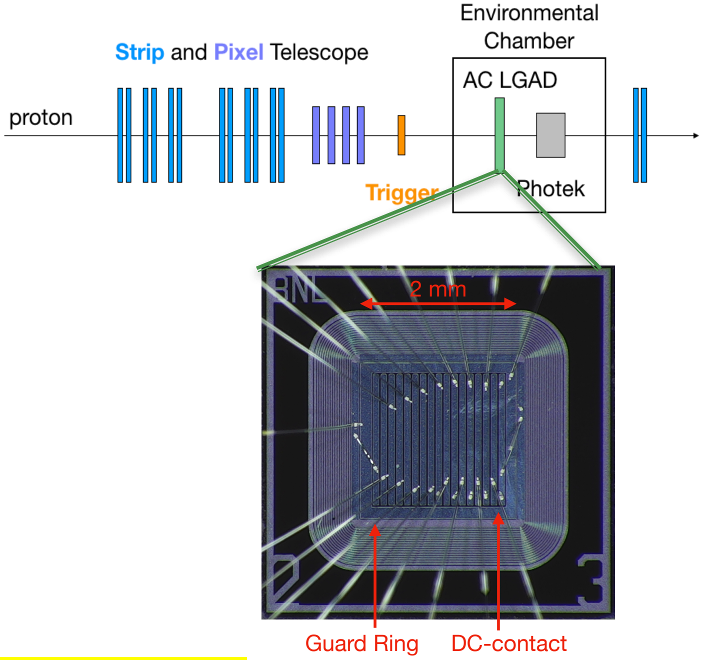


- Keeping all amplitudes ➔ time resolution 59 ps
- Cutting on amplitudes >0.13 V to enhance contribution from primary signals

➔ time resolution reaches 47 ps (see plot) – for more accurate measurements will use multi-ch. board

AC-LGAD Characterization (test-beam)

- Study of BNL's **AC-LGAD strip sensor** at FNAL test-beam, **with 120 GeV protons**
  - Wafer W1846
  - 50 µm thick p-substrate
  - $V_{Depletion}$ = -150 V , $V_{Breakdown}$ = -225 V at 22C , V_{Bias} = -210 V
  - **17 strips**
    - **100 µm pitch**
    - **80 µm width**
    - **strip gain ~17**
- **Read-out: FNAL 16 ch. board**

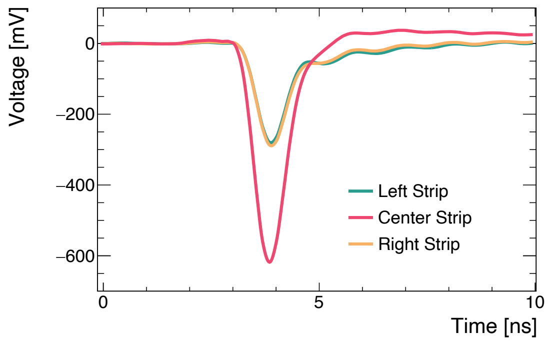


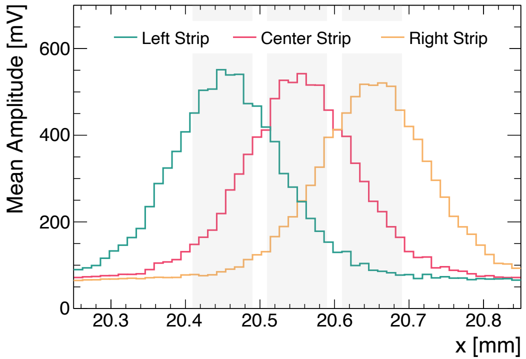
➔ For more details and results, see presentation by **Karri Di Petrillo** (FNAL) at last June RD50 workshop (https://indico.cern.ch/event/918298)

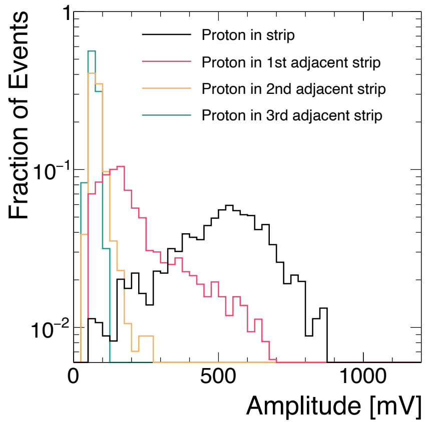
In collaboration with Artur Apresyan, Ryan Heller, Hakseong Lee, Sergey Los, Chang-Seong Moon

A. Apresyan et al., "Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam", JINST 15 (2020) 09

AC-LGAD Characterization (test-beam)







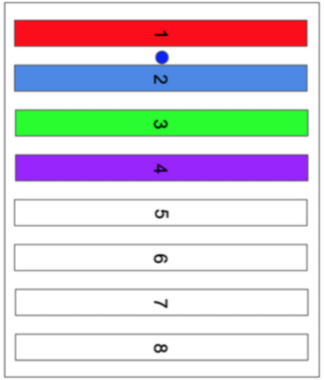
- **Measured time resolution of leading strip 45-47 ps in test-beam**

➔ AC-LGAD's time resolution measured with beta's (47 ps) is consistent with results from test-beam
➔ Time resolution close to standard (DC) LGADs with similar gain (σ_t~40 ps at gain ~20)

- Signal amplitude induced on strip decreases with distance to proton hit position
- Distinct distributions of amplitudes for hit and adjacent strips

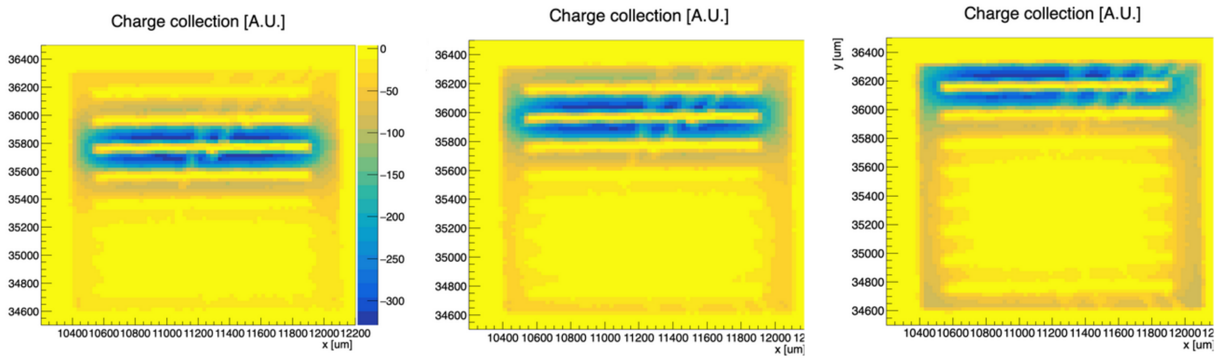
AC-LGAD Characterization (TCT scans)

- TCT scans for BNL's AC-LGADs
  - Response of each strip as a function of shining position of IR or red laser
  - Studies of charge collection and signal sharing between neighboring strips



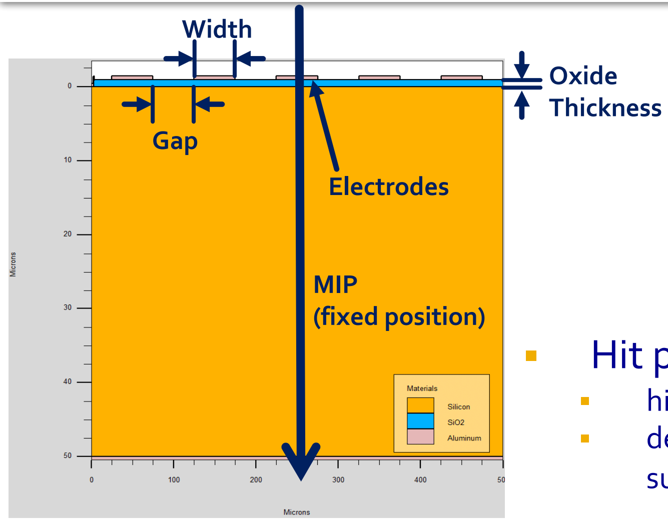
BNL AC-LGAD Strip array
(lateral strip pitch 100 µm)

Laser focused in non-metalized area between Strip 1 and Strip 2



	Shared Signal
ratio Amp 2/Amp 1	100%
ratio Amp 3/Amp 1	13%
ratio Amp 4/Amp 1	6%
ratio Amp 6/Amp 1	4%

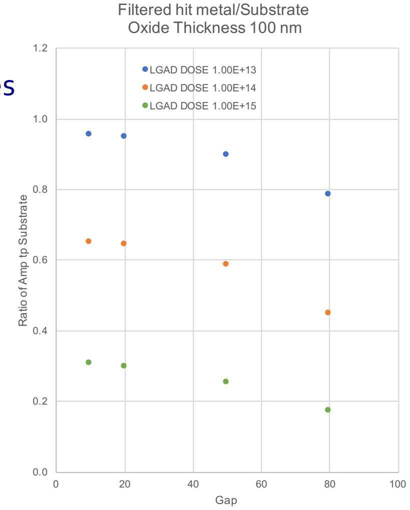
AC-LGAD Simulation

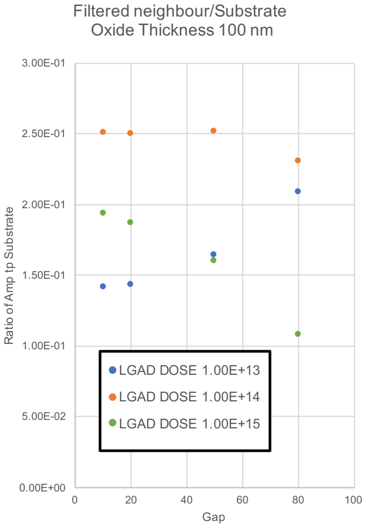


- TCAD simulation to study signal dependence on pixel geometry
  - Fixed pixel width (100 μm), oxide thickness (100 nm), and MIP position
- **Study of amplitudes vs inter-pixel gap for hit and adjacent pixels, for several implantation doses of resistive (n+) sheet**

R~1/dose

- Hit pixel:
  - higher signal fraction as R increases
  - decreasing signal fraction to substrate as pixel gap increases

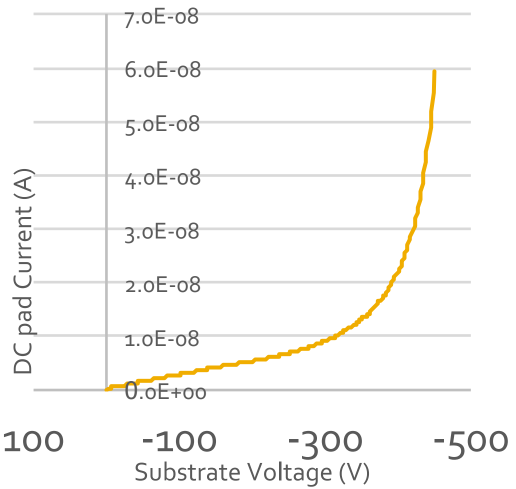


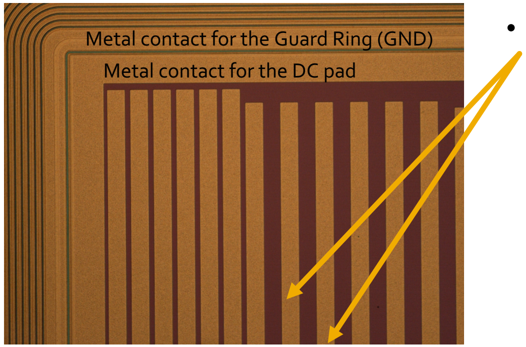


- Adjacent pixel:
  - higher signal fraction as R decreases
  - at higher R (blue), amplitude ratio to substrate increases for wider gaps (signal sharing is between hit and adjacent pixel only)
  - at lower R (green/orange), amplitude ratio to substrate decreases for wider gaps (sharing among several neighboring pixels)

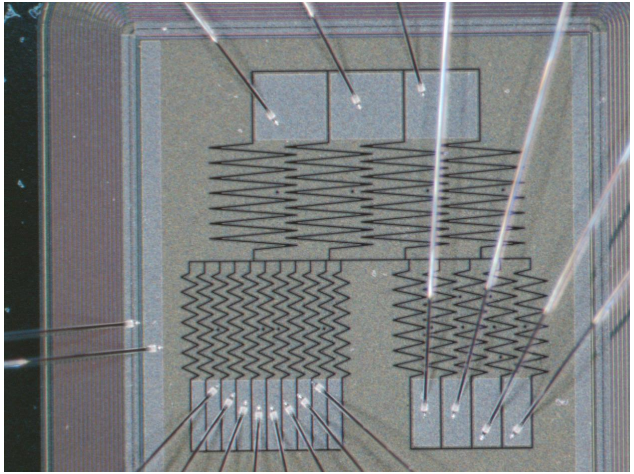
New AC-LGAD metal patterns (Space Resolution)

- **New production of alternative metal patterns to study and improve spatial resolution**
  - Different pixel/strip sizes, and inter-pixel/strip gaps
  - Zig-zag geometries to enhance information on cluster centroid, exploiting signal sharing between pixels/strips





- AC strips connected to the read-out.
- Different gaps/width to test signal sharing between strips.



In collaboration with A. Kiselev (BNL)

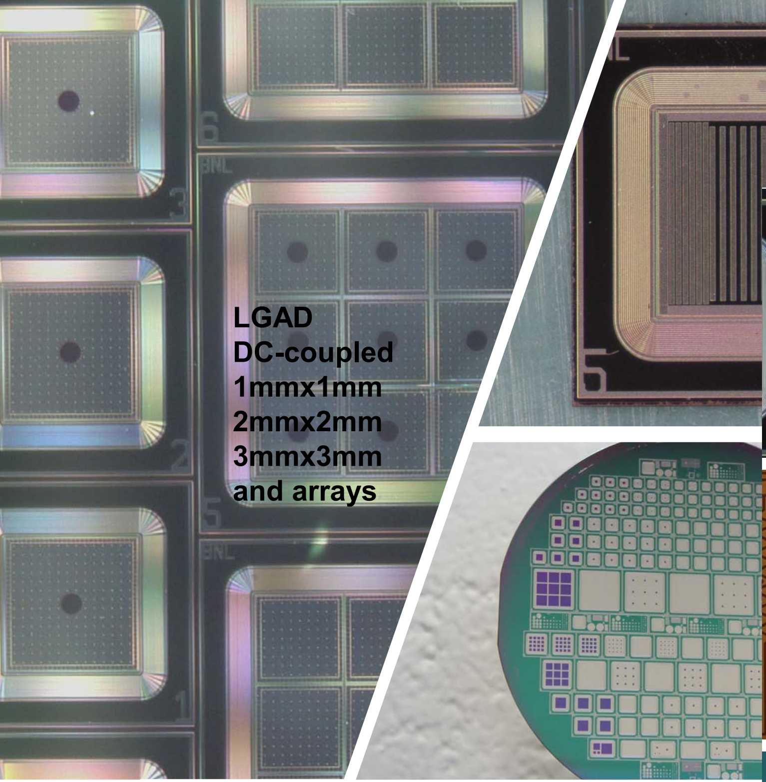
Summary

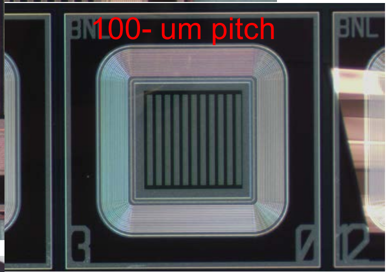
- Design, fabrication and testing of LGAD and AC-LGAD sensors at BNL
- Characterization by IV/CV scans, TCT scans, beta-scope and in test-beam
  - LGADs by HPK and BNL are used as references for AC-LGAD characterization
  - **Time resolution of ~26 ps is achieved with LGADs with gain~60 fabricated at BNL**
- **AC-LGAD characterization of a strip and pixel sensors**
  - Gain ~20 for sensors tested so far
  - **Time resolution ~ 45-47 ps measured consistently at test-beam and with beta's, and close to that LGADs with same gain**
- Ongoing studies of signal induced on strips/pixels as a function of distance of hit position
  - Signal induced on hit and adjacent strips/pixels can be exploited to improve spatial resolution
  - Alternative designs with different geometrical metal patterns
  - Comparison between simulations and lab measurements is ongoing

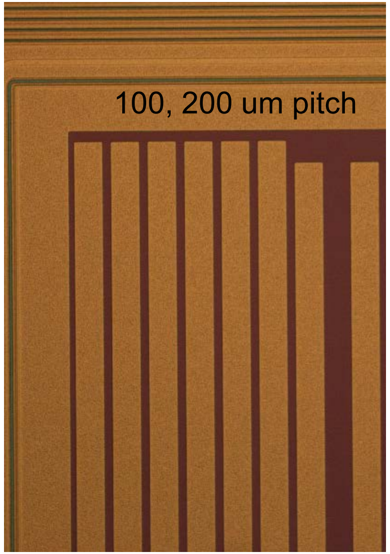
Back-up

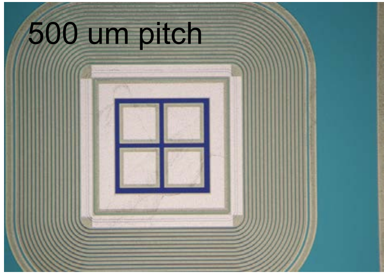
Back-up

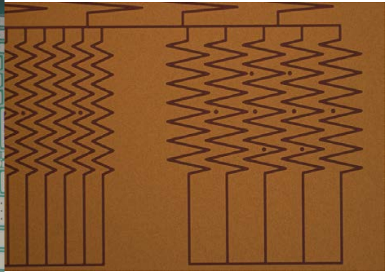
LGADs and AC-LGADs

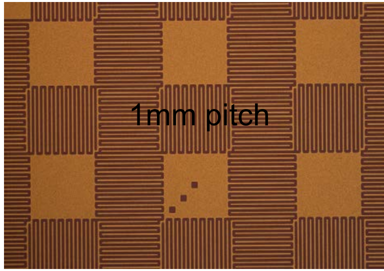


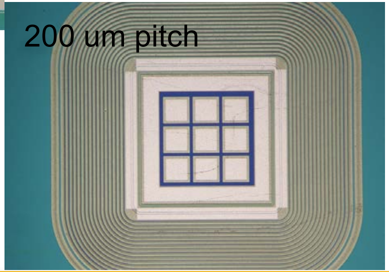










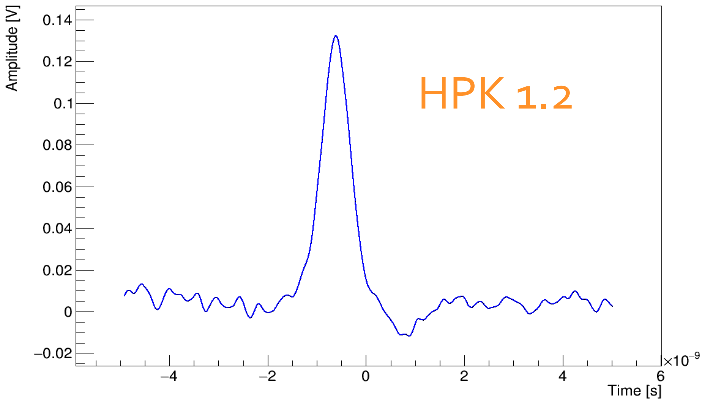


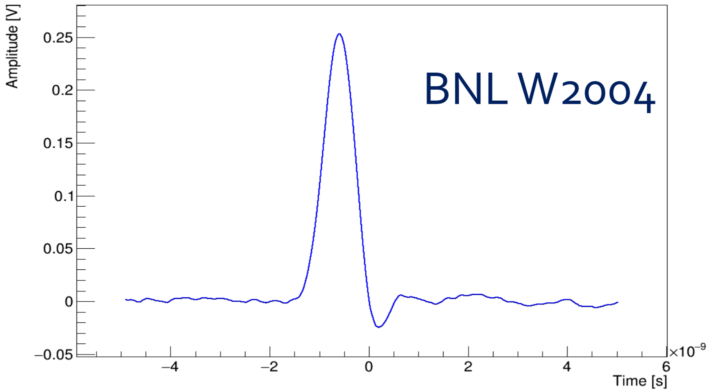
Next slides will present results with several of these LGAD and AC-LGAD designs

Some AC-LGAD designs

LGAD Characterization (Waveforms)

- Waveforms generated by beta's from ^{90}Sr
- Santa Cruz's single channel test-board for readout
- Oscilloscope, Le Croy WaveRunner 9404M-MS (4 GHz, 40 GS/s)

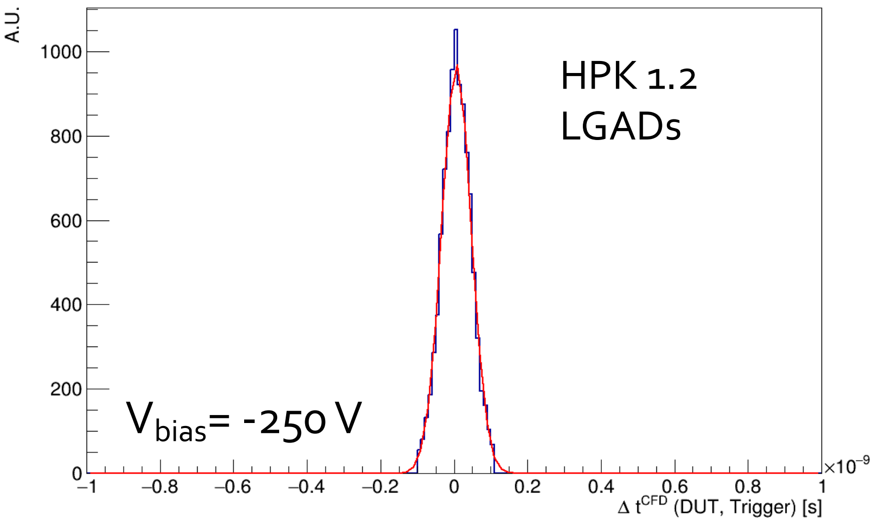




➔ Short and narrow pulses (~1 ns)

LGAD Characterization (Time Resolution -HPK)

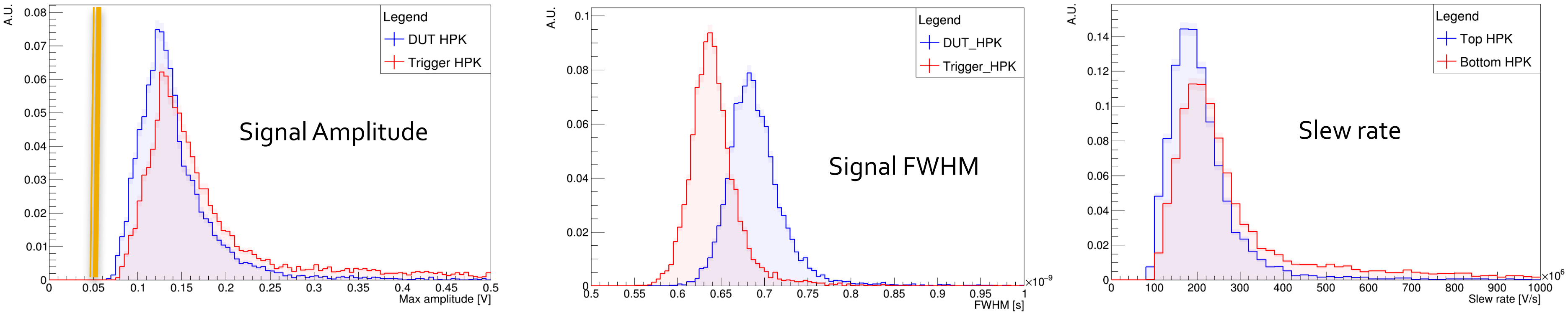
- **Time of arrival of beta's** on sensors is defined as the time at which the signal crosses a certain fraction of the total signal amplitude
- Gaussian fit of time difference between DUT and Trigger sensors
- Distribution width of~40 ps, corresponding to a **time resolution per sensor of ~28ps**, compatible with results in literature for HPK LGADs



$$Width = \sigma_t^{TOT} = \sqrt{(\sigma_t^{DUT})^2 + (\sigma_t^{trig})^2} \simeq \sqrt{2}\sigma_t^{DUT}$$

LGAD Characterization (Time Resolution -HPK)

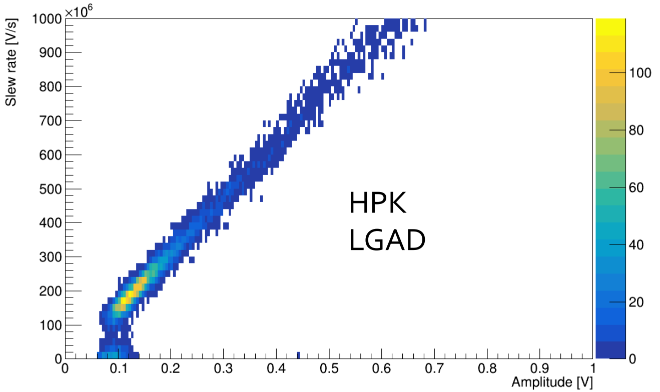
- HPK 1.2 sensors, V_{bias}= -250 V

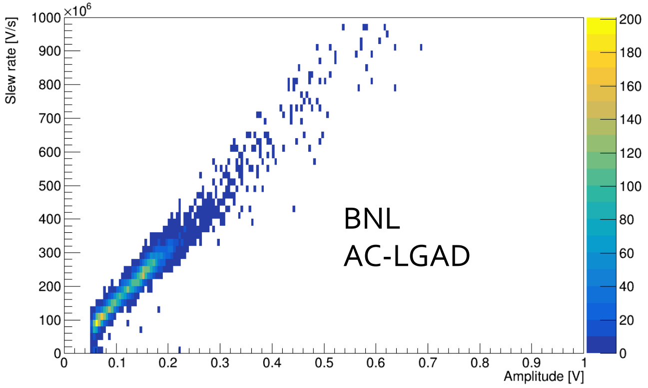


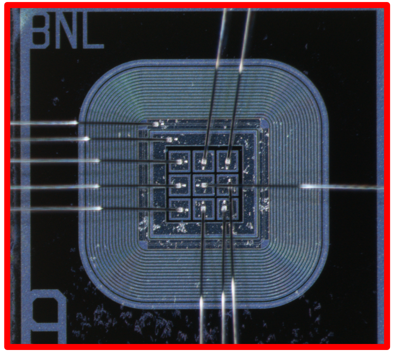
- Oscilloscope trigger level of 50 mV allows to keep entire Landau distribution of beta signals and not bias σ_t measurements

AC-LGAD Characterization (Time Resolution)

- Comparison of Slew Rates and Amplitudes in Standards (DC) LGAD HPK and in BNL AC-LGAD
- BNL AC-LGAD (W1846) **pixel sensor, 220 µm pitch, 20 µm gap** (V_{bias} = -210 V)
  - Santa Cruz's **single channel** test-board for readout





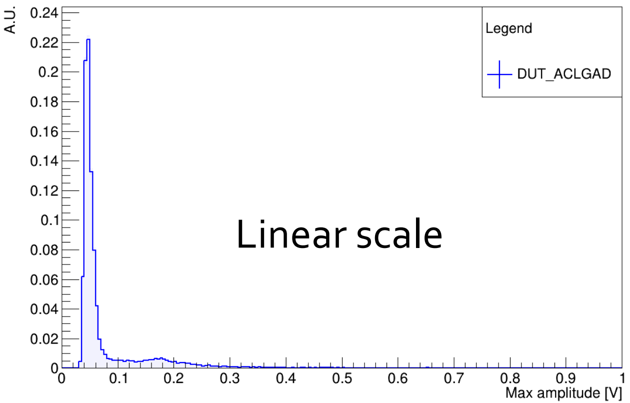


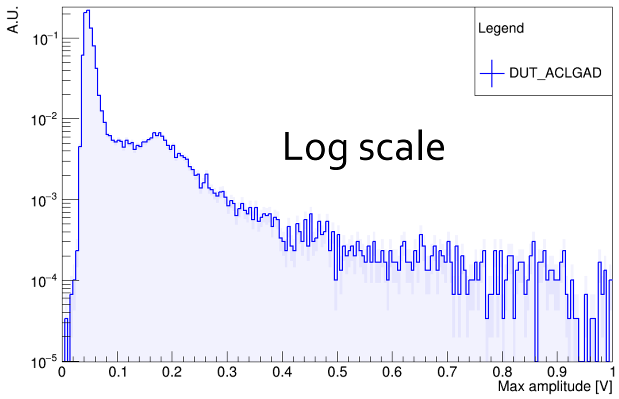
➔ Two populations of events in AC-LGADs in Amplitude and Slew Rate distributions – fully correlated:

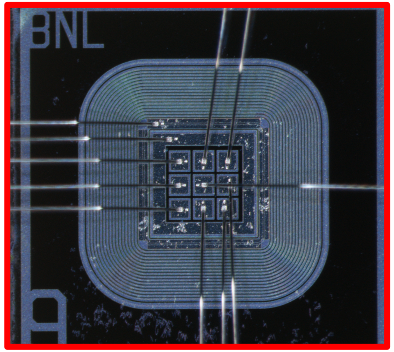
- signal is "primary" – readout strip is hit directly by particle
- signal is "secondary" – particle hits an adjacent strip and signal is shared

AC-LGAD Characterization (Amplitudes)

- BNL AC-LGAD (W1846) **pixel sensor, 220 µm pitch, 20 µm gap** (V_{bias} = -210 V)
  - Santa Cruz's **single channel** test-board for readout
  - Very low trigger threshold on oscilloscope to see full amplitude spectrum







→ Two (and only two) populations of events in AC-LGADs in Amplitude distributions:
- signal is "primary" – readout strip is hit directly by particle
- signal is "secondary" – particle hits an adjacent strip and signal is shared

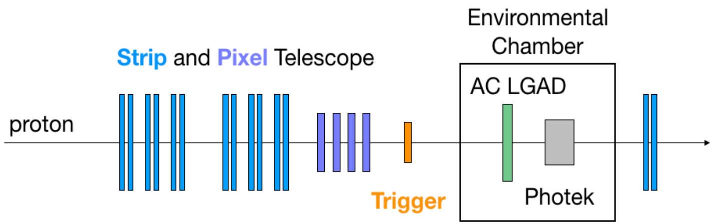
BNL's LGAD & AC-LGAD Design

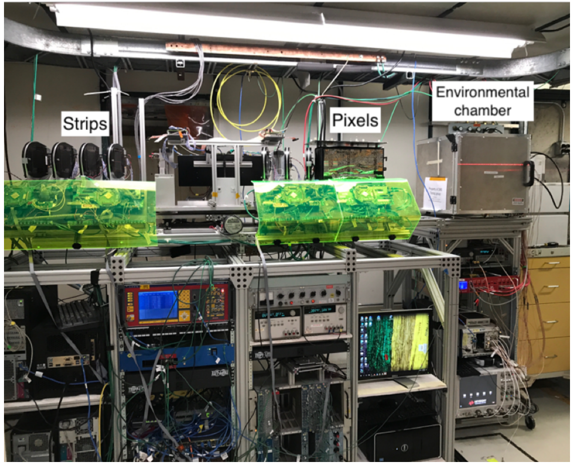
- LGADs & AC-LGAD
  - 50 µm ^{28}Si p epitaxial layer, ^{10}B and ^{11}B doped ($7\times10^{13}cm^{-3}$)
  - 500 µm substrate
  - Aluminum thin layer, thickness 0.5 µm
  - Silicon Oxide SiO_2, thickness 0.3 - 0.5 µm
  - n++ layer, ^{31}P doped, thickness 0.5 µm
  - Gain p+ layer, ^{11}B doped, depth (from n+) 0.5 µm, different doping concentrations (3, 3.25 and $2.7\times10^{13}cm^{-3}$)
  - Dielectric in AC-LGAD is ~80-100 nm SiN

AC-LGAD Characterization (test-beam)

In collaboration with Artur Apresyan, Ryan Heller, Hakseong Lee, Sergey Los, Chang-Seong Moon

- FNAL Test Beam Facility (FTBF)
  - Beam of 120 GeV protons
    - Beam width: few mm to few cm
    - ~100k protons per 4 seconds spill, every minute
  - Trigger: scintillator
  - Track position: Strip/Pixel Telescope
  - Photek MCP: time reference (σ_t= 10 ps)

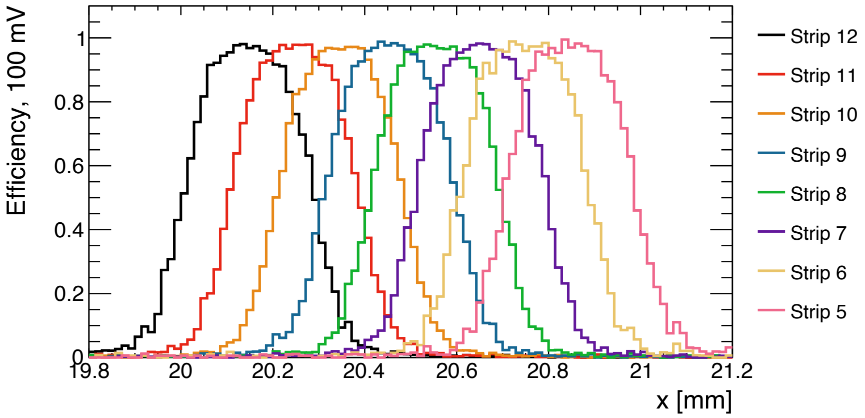




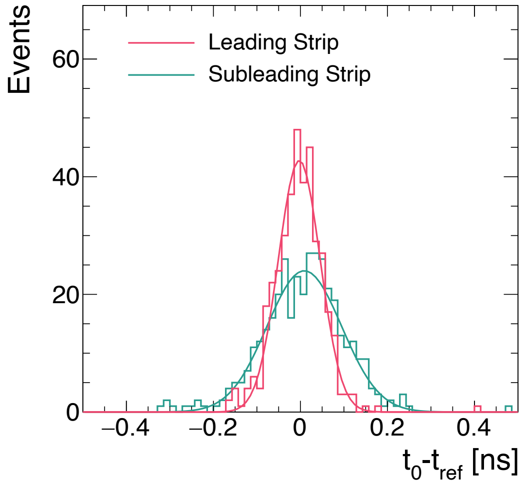
➔ For more details and results, see presentation by **Karri Di Petrillo** (FNAL) at last June RD50 workshop (https://indico.cern.ch/event/918298)

A. Apresyan et al., "Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam", JINST 15 (2020) 09

AC-LGAD Characterization (test-beam)



Efficiencies of individual strips as functions of incident proton x position

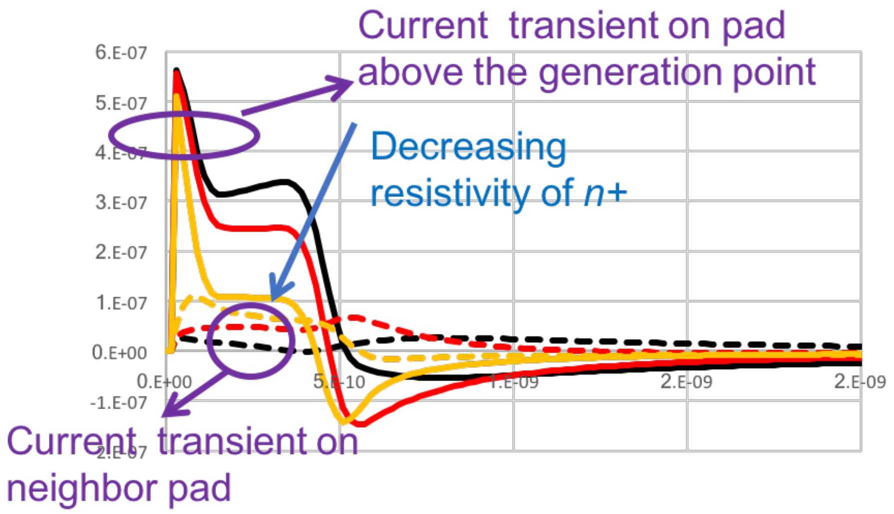


Time resolution measurement in events with a three-strip cluster

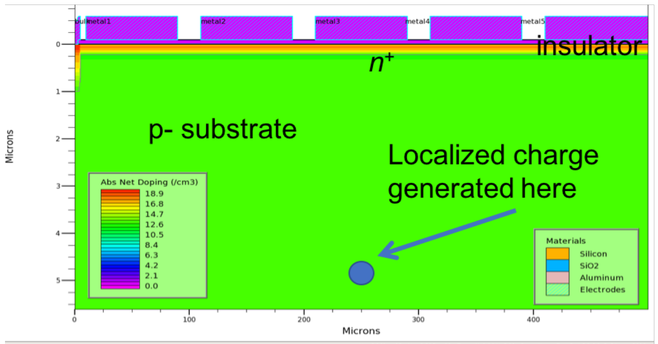
A. Apresyan et al., "Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam", JINST 15 (2020) 09

AC-LGAD Simulations

- Fabrication details (doping, oxide thickness) impact macroscopic quantities e.g. RC
- TCAD simulation to explore large parameter space



Simulation of AC-LGAD



- Signal fed to the read-out electronics strongly depends on R(C):
  - Higher signal share if RC is SMALL
  - Higher signal on hit pad if RC is HIGH
- The RC value can be tuned during fabrication to have an acceptable compromise