Characterization of AC-LGAD performances for 4D detectors

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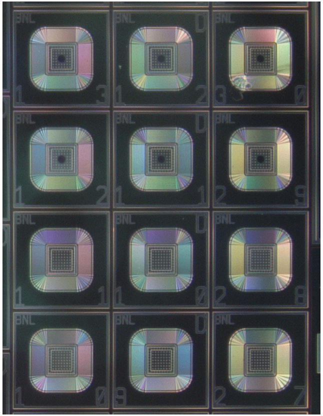
Low-Gain Avalanche Diodes

Low-Gain Avalanche Diodes (LGAD) have gathered interest in the Physics community thanks to fast-timing and radiation-hardness:

- **HEP:** ATLAS (HGTD) and CMS (MTD) timing detectors at the HL-LHC
- **Imaging**, soft X-rays and low-energy electron detection etc.
- **Quantum information, Nuclear and forward physics**, etc...

LGAD: highly doped layer of p-implant (**Gain layer**) near p-n junction creates a high electric field that accelerates electrons enough to start multiplication

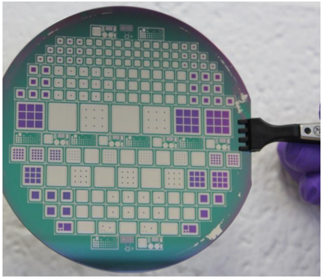


Wafer of LGADs produced at BNL

LGAD fabrication @ BNL

Silicon Fabrication Facility and wire- and bump- bonding @ *BNL Instrumentation Div.*, full characterization, design and simulation of silicon sensors @ *Si-Lab*

- Leakage current (measured on diodes) for 1x1 mm^2 of $\sim$ 10 pA (1 nA/cm^2)
- Consistency from batch to batch
- Clear current and V$_{breakdown}$ dependence on gain layer dose
- layout with pads of 1x1 mm^2, 2x2 mm^2, 3x3 mm^2 and arrays

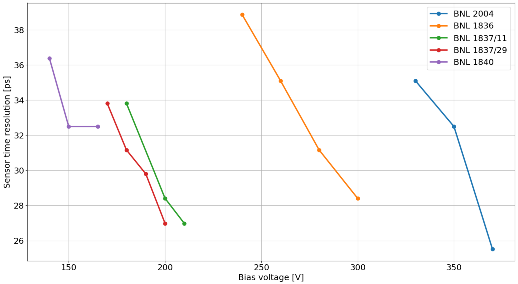


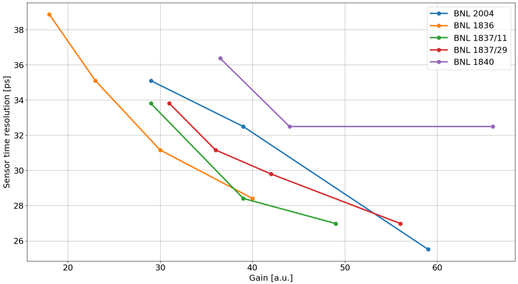
All silicon process done in BNL Instrumentation Division Class-100 Clean Room

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

Performance Goals

Time resolution





- **Time resolution of BNL produced LGAD** sensors (50 μm thick) measured in β coincidences from ^{90}Sr using HPK 1.2 LGAD as reference ($\sigma_t = 28$ ps)
- Pre-irradiation sensors with high gain can reach $\sigma_t \simeq$ **26 ps**

Characterization of **BNL AC-LGAD sensors**[1]

[1] In collaboration with A.Apresyan (FNAL, US), K.F.Di Petrillo (FNAL, US), R.E.Heller (FNAL, US), H.Lee (Kyungpook National University, KR), C.S.Moon (Kyungpook National University, KR)

AC-LGAD characterization

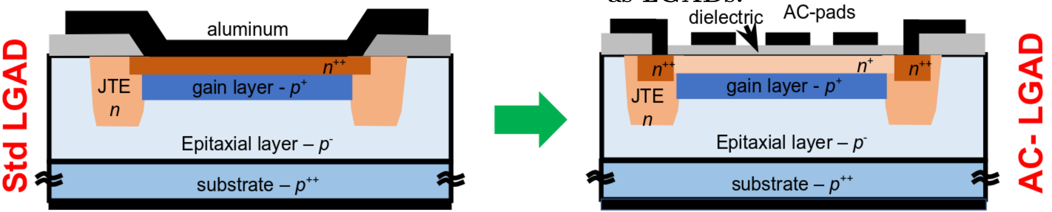
AC-LGAD for 4D detectors

Limits of LGADs

- **Dead volume** (gain 1) extends outside the JTE and inside the implanted gain layer
- Small pixels/strips with gain layer below implant have Fill Factor «100%. Large pads ($\sim$ 1 mm) are preferred
- High-granularity 4D detector not possible...

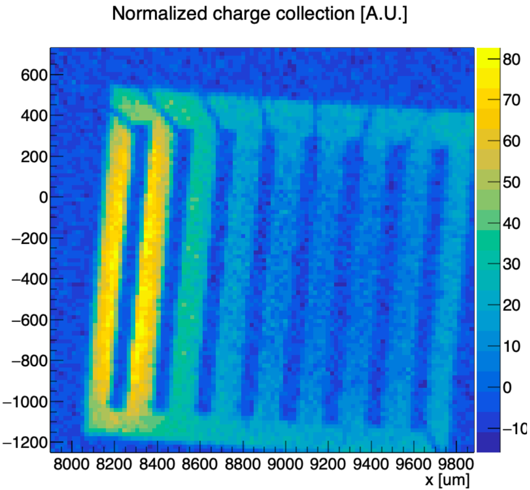
The AC-LGAD

- Signal **AC-coupled** through dielectric to metal pads
- Both **100% Fill Factor and fast timing** information can be achieved
- **Signal shared** on neighbouring pads helps in achieving spatial resolution $\mathcal{O}(10\ \mu\mathrm{m})$
- **Our goal: smaller pixels, but same σ_t as LGADs!**

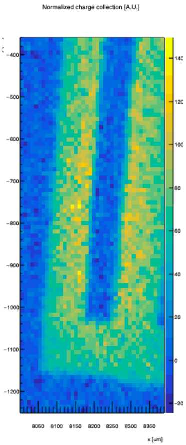


AC-LGAD characterization

TCT scan



- Response of a strip as a function of shining position of IR or red laser (*Transient Current Technique scan*)
- **Sensitive to charge** collected by the sensor
- Signal sharing visible when laser is far from readout strip (leftmost)
- TCT can be used to **characterize signal sharing** between neighbouring strips

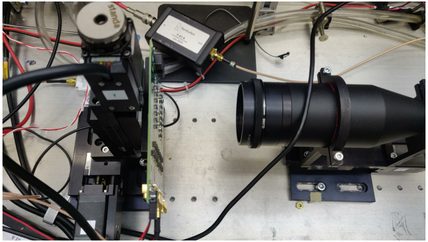


AC-LGAD characterization

Signal sharing with TCT scan

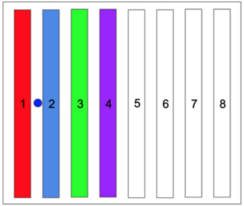
Signal sharing characterized as **ratio between signal observed by different strips** at different distances from the IR laser.

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



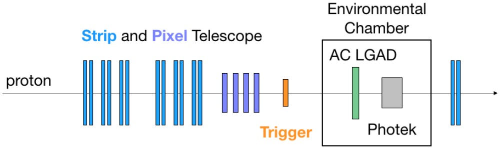
Laser focused in between Strip 1 and Strip 2

	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%

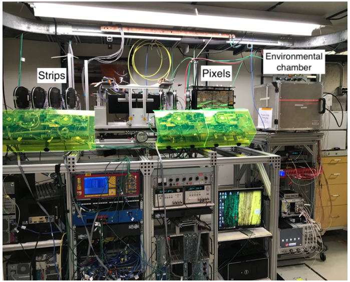


AC-LGAD characterization

Proton Test-Beam @ FNAL(US)[2]



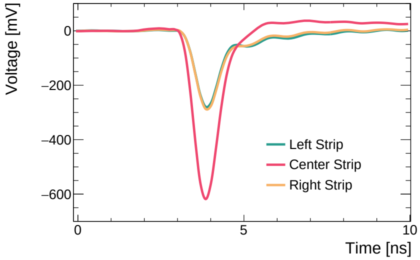
- Results cross-checked at protons test beam, using the FNAL Silicon Telescope
- Beam of 120 GeV protons (beam spot width: few mm) with ~100k protons per 4 seconds spill per minute
- **Trigger:** scintillator
- **Track position:** Strip/Pixel Telescope
- **Photek MCP:** time reference ($\sigma_t = 10$ ps)

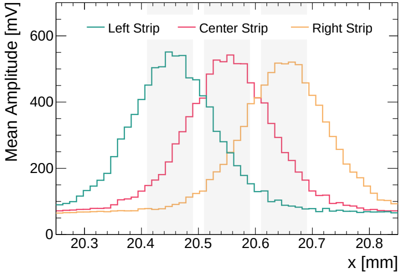


[2] A. Apresyan et al., *Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam*, JINST 15 (2020) 09

AC-LGAD characterization

Signal sharing and time resolution





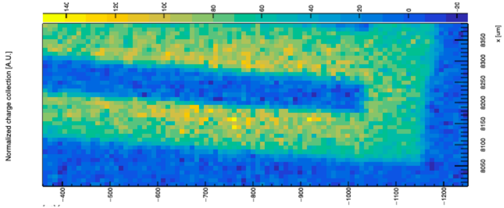
- AC-LGAD strip gain ~ 17
- Signal amplitude induced on strip decreases with distance to proton hit position
- Adjacent strip sees lower amplitude signal
- Detection efficiency ~ 100 %

- **Time resolution** $\sim$ 30-35 ps for single AC-LGAD strip (previous talk by *A.Apresyan*)
- **Measured time resolution consistent with standard (DC-) LGADs!**
- **Space resolution** < 15 μm!

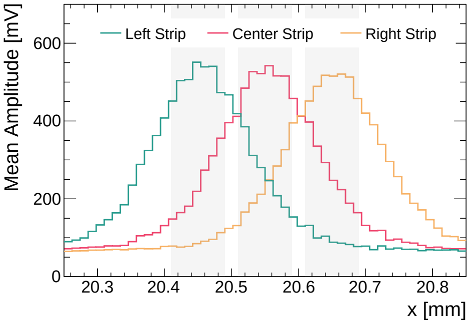
AC-LGAD characterization

Signal sharing between strips

TCT (IR photons)



120 GeV **protons**



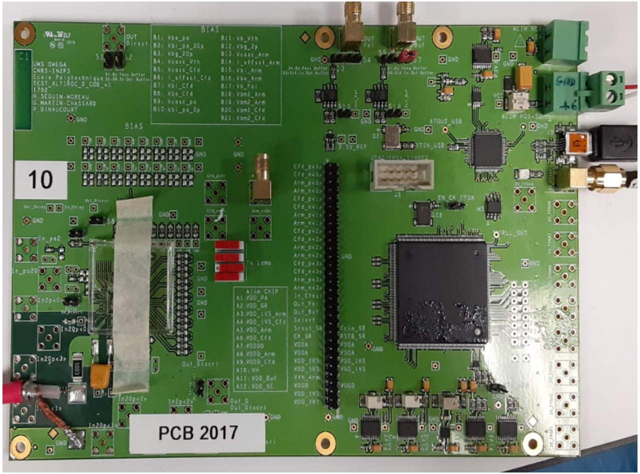
- **Consistent signal profile** as a function of protons and IR position
- Protons allow to probe the region under the sensor electrode (laser blocked by metal)
- Next AC-LGAD batch will have "naked" back (no metallization) to shine from back

AC-LGAD Readout using an **ALTIROC ASIC**[3]

[3] In collaboration with R. Dupré (IJCLAb, Orsay, FR), D. Marchand (IJCLAb, Orsay, FR), C. Munoz Camacho (IJCLAb, Orsay, FR), L. Serin (IJCLAb, Orsay, FR), C. de La Taille (Omega, Palaiseau, FR), M. Morenas (Omega, Palaiseau, FR)

Readout with Altiroc ASIC

Altiroc Setup



- **A**TLAS **L**GAD **Ti**ming **ROC** = Designed to readout **DC-coupled LGAD** for ATLAS High-Granularity Timing Detector(HGTD) at HL-LHC
- **ALTIROC0 ASIC** is the first prototype of the ALTIROC chip
- ALTIROC0 includes *Pre-amplifier* + *Discriminator* for **Time Over fixed Threshold measurement** over 2x2 channels
- σ_t strongly linked to front-end analog performance; time jitter smaller than 20 ps for input charge larger than 5 fC

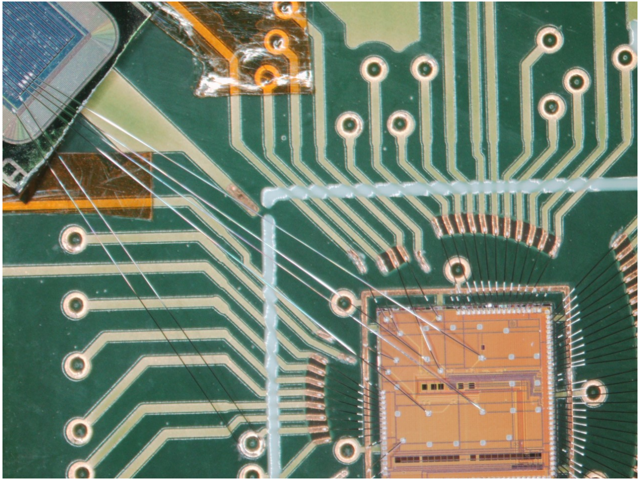
Readout with Altiroc ASIC

Device Under Test

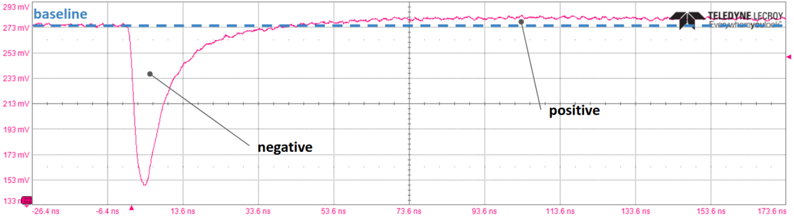
Linear strip BNL AC-LGAD 1x16

- Area: 2×2 mm^2
- Strip pitch 100 μm, gap 20 μm
- Devices from this wafer already characterized with betas, IR laser (BNL) and protons (FNAL)
- 4 strips bonded to 4 input channels of ALTIROC0 FE ASIC

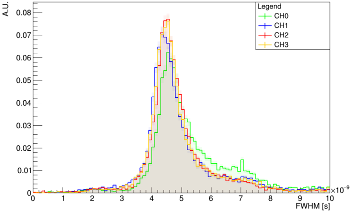
Betas from ^{90}Sr used to characterize the ALTIROC response to AC-coupled signals



Readout with Altiroc ASIC



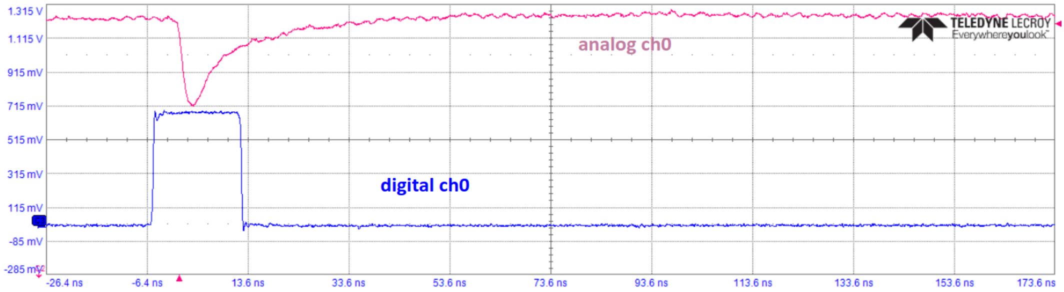
- Signals from interactions with betas from ^{90}Sr
- **Analog output** of the ALTIROC shaper
- **Bipolarity** typical of AC-LGAD signals
- Fast (∼5 ns) signal **compatible with published results for (DC-)LGAD sensors** read-out via ALTIROC0 [4]



[4] C. Agapopoulou et al., *Performance of a Front End prototype ASIC for picosecond precision time measurements with LGAD sensors*, JINST 15 (2020)

Readout with Altiroc ASIC

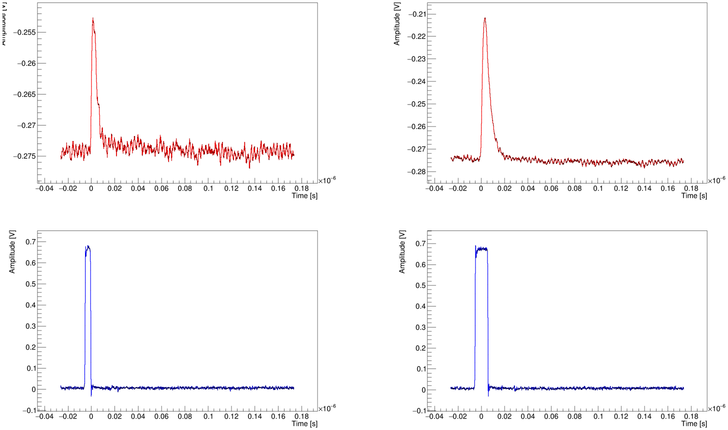
Observed digital signal



- ALTIROC0 also mounts a **fixed threshold discriminator** for TOT calculation
- Output of the **digital channel** provides a measure of the Time-over-Threshold of the **analog channel**

Readout with Altiroc ASIC

TOT measurement

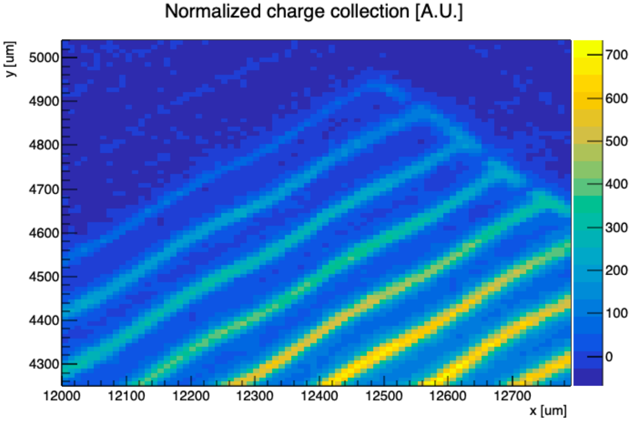


- **ToT measurement** compared to the respective outputs of the **analog channel**
- For a complete study of the correlation between observed ToT and shape of the analog signal, currently working on a new setup using the **ALTIROC 1 ASIC**
- ALTIROC 1 is a newer and more complete version of the ALTIROC chip

Readout with Altiroc ASIC

TCT characterization

- Characterization of the signal sharing and space resolution is ongoing using ALTIROC0
- **ALTIROC setup adapted to TCT station**; characterization performed by using an IR laser with 10 kHz frequency
- Colour indicates **integral charge of the signal peak** from the ALTIROC analog output
- Results are (very) preliminary, but **consistent with those** obtained with ^{90}Sr β [5]

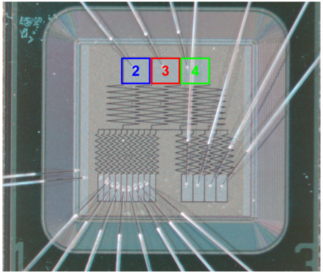


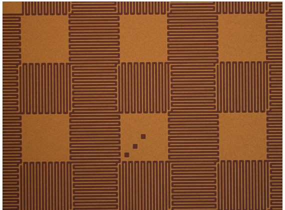
[5] "Wafe" effect is due to mechanical vibration in the board support. Will be addressed with a new support in the near future

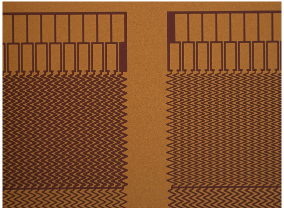
Study and optimization of **New Topologies**

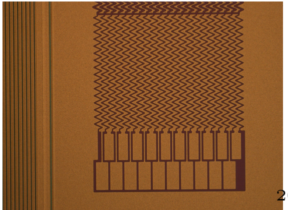
New Topologies

- Currently experimenting with **different configurations** in wafer to improve spatial resolution and adapt to different physics
- In AC-LGAD, signal is sensed by multiple strips; **zig-zag** configuration profits from this, **maximizing signal sharing information and improving centroiding** (design by *A.Kiselev, BNL*)
- Study of **Signal Sharing** by applying off-line software selection in interactions with ^{90}Sr β; results compared with **TCT** and at **proton test-beams**







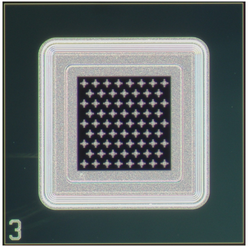


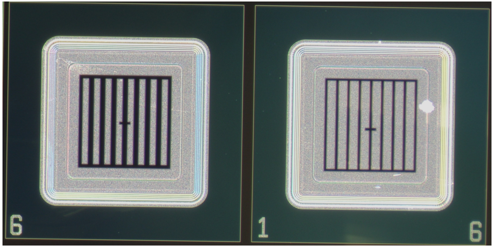
New Topologies

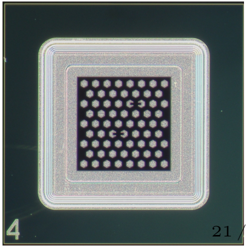
Geometry optimization

Study of different **pixel and strip shape, pitch, gap, doping, and gain layer depth** to optimize spatial resolution using TCT and proton test-beam.

1. **Reference AC-LGAD strip** with variable pitches and gap sizes
2. *Regular* and *Deep* (higher tolerance to radiation) gain layer **AC-LGAD strips** with same pitches and gap sizes as reference
3. *Regular* and *Deep* gain-layer AC-LGAD sensors with same pitches and gap sizes but different pad shapes (**squares, hexagons, crosses**)







Summary

- Fabrication of LGAD and AC-LGAD sensors fully in-house @ BNL with consistent characteristics from batch to batch
- **Time resolution of $\sim$ 26 ps** achieved using LGADs fabricated at BNL
- Use of **TCT scans** using red and IR lasers allows signal sharing and space resolution characterization
- Results obtained in collaboration with FNAL using 120 GeV proton beam show **excellent 4D performances for AC-LGADs** (σ_t = 30 - 35 ps, $\sigma < 15\ \mu$m) and ~100% detection efficiency
- Additional **two test-beams @ FNAL** allowed a first study of LGAD and AC-LGAD prototypes fabricated at BNL, with different resistivity, pitch, gap size, configuration (pixel, strip, zig-zag)
- **First readout of an AC-LGAD via an ASIC**. Demonstration of compatibility between AC-LGAD signal and ALTIROC input. Performance results compatible with those of standard LGADs + ALTIROC0 assemblies

Useful Links

- Layout and Performance of HPK Prototype LGAD Sensors for the High-Granularity Timing Detector
- Fabrication and performance of AC-coupled LGADs
- Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam

Backup

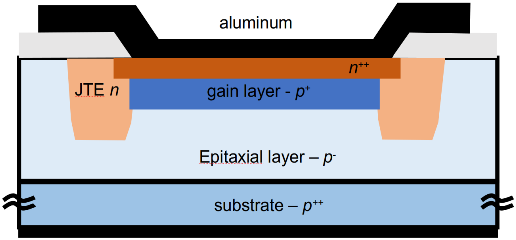
Introduction
LGAD structure

LGADs

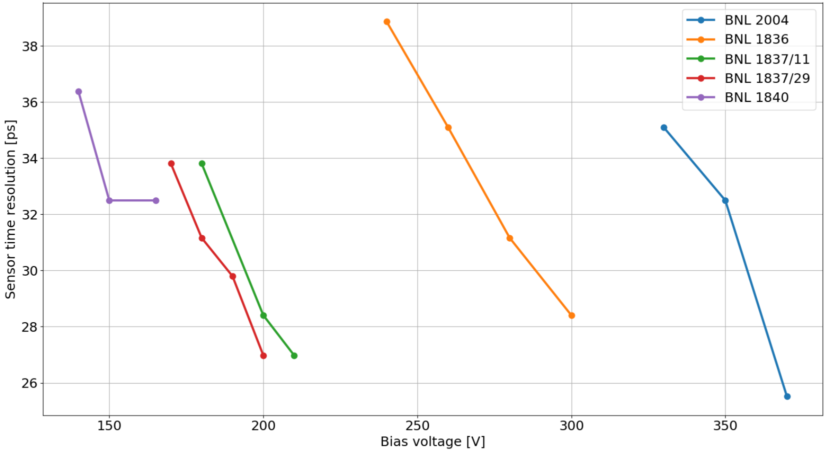
- $1{\times}1$ mm^2 sensor size
- 50 μm ^{28}Si p epitaxial layer, ^{10}B and ^{11}B doped ($7{\times}10^{13} cm^{-3}$)
- different doping concentrations (3, 3.25 and 2.7 $\times 10^{13} cm^{-3}$) and gain layer thickness
- 500 μm substrate

Wafer structure

- 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, thickness 0.5 μm



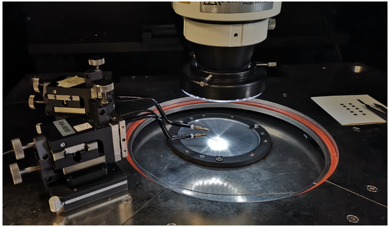
Sensors characterization

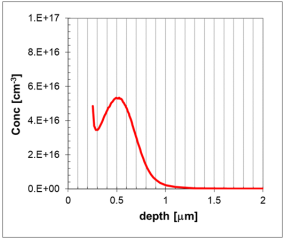


LGAD characterization

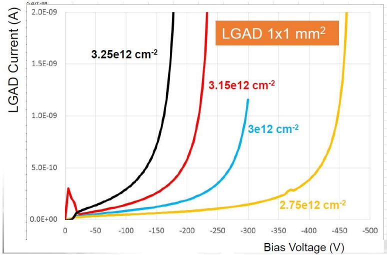
IV/CV curves

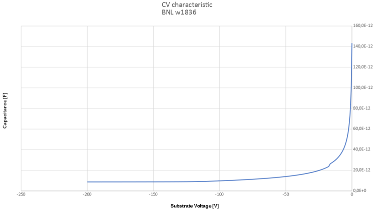
- Probe station to measure I_{GR}, I_{Pad}, I_{Tot}...
- Extraction of the gain layer depth from **Doping Profile**





- Wafer pre-selection using **current/capacitance characteristics** at different V_{bias}
- Estimation of $V_{breakdown}$





LGAD characterization

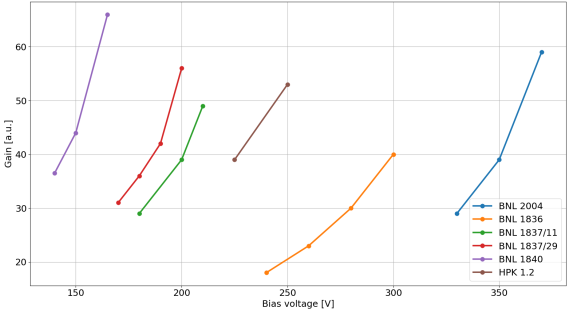
Gain vs Bias Voltage

BNL sensors:

- $1{\times}1$ mm^2 sensor size
- 50 μm active layer
- W1836 (dose: 3e12 cm^{-2}), W1837/W1837 (3.25e12 cm^{-2}) $E_{implant}$ = 300 keV
- W1840 (2.75e12 cm^{-2}), W2004 (2.5e12 cm^{-2}) $E_{implant}$ = 380 keV
- 1840 not fully depleted at $V_{breakdown}$

Hamamatsu (HPK) sensors:

- $1.3{\times}1.3$ mm^2 sensor size
- 35 μm active layer
- HKP 1.2 LG1-SE5

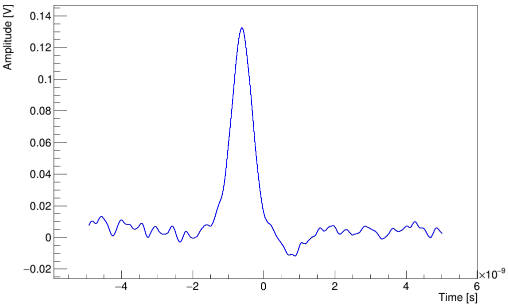


Gain in HPK and BNL-produced LGADs measured with beta interactions from ^{90}Sr

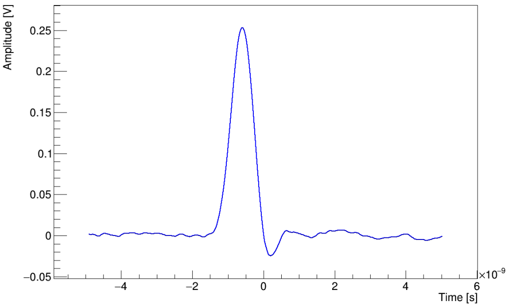
LGAD characterization

Waveforms

HPK 1.2 interaction with β



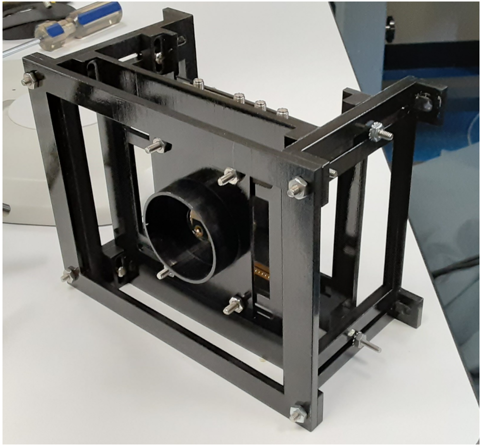
BNL W2004 interaction with β

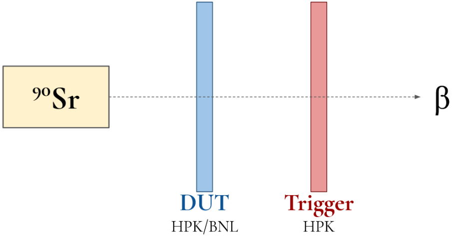


Short and narrow pulses ($\sim$1 ns)

LGAD characterization

Time resolution



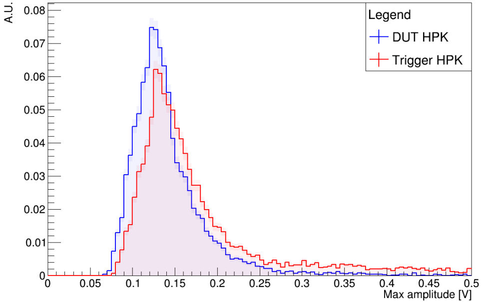


- Two identical HPK 1.2 used (DUT, trigger) to measure σ_t^{HPK} in coincidences with β generated by a 7.5 MBq ^{90}Sr source
- σ_t of BNL LGADs measured using HPK sensor as trigger
- Output signals amplified with **Mini-Circuits ZX60-3018G-S+ amplifiers** (Gain=10) on board output

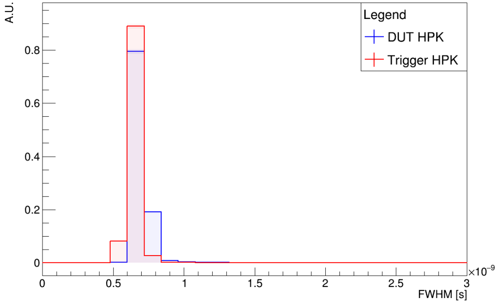
LGAD characterization

Time resolution of HPK 1.2 sensors

Signal **Amplitude**



Signal **FWHM**

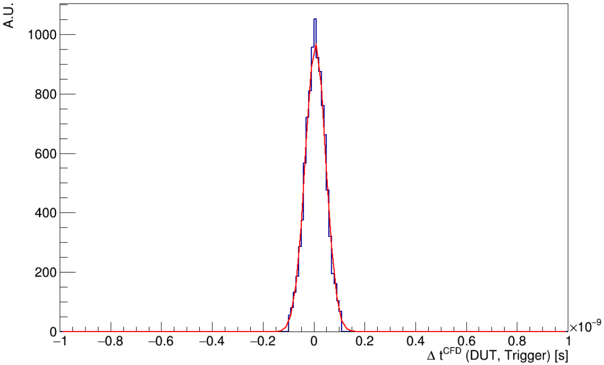


Trigger level of 50 mV allows us to keep entire Landau distribution of beta signals and not bias our σ_t measurement

LGAD characterization

Time resolution of HPK 1.2 sensors

- Trigger level of 50mV
- V^{bias} = -250 V
- Gaussian fit of time difference between DUT and Trigger
- Distribution width of ∼40 ps, corresponding to a **time resolution per sensor of ∼28 ps**, compatible with results in literature for HPK LGADs
- **Next step:** measure time resolution of BNL LGADs as DUTs using HPK 1.2 as trigger



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

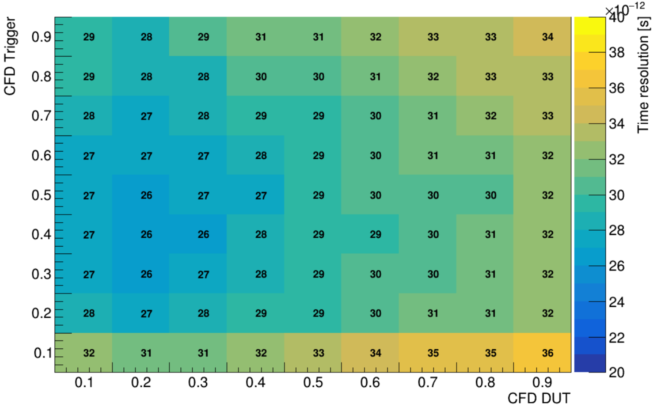
LGAD characterization
Time resolution

HPK 1.2 used as Trigger for characterization of BNL-produced LGADs

- Time of arrival of beta on sensors 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 Discrimination** for both DUT and Trigger sensors (for time-walk minimization)

DUT time resolution

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



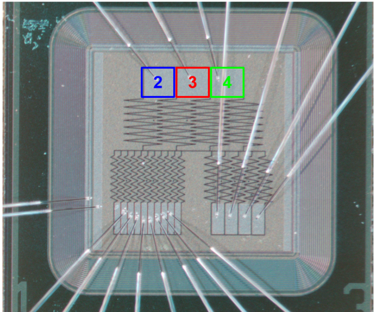
New Topologies

Offline Signal Sharing analysis

Two types of Veto studied: **Single Veto** and **Hierarchical Veto**

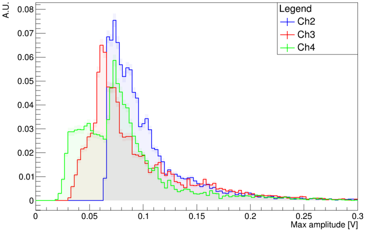
- When **Single Veto** is active, signals are kept of the amplitude on the trigger channel $A^{trigger}$ is the highest amplitude (*ex.* Trigger on Ch2, Ch2 > Ch3 and Ch2 > Ch4)

- When **Hierarchical Veto** is active, signals are kept if the amplitudes A^{i} gets smaller increasing the distance from trigger strip (*ex.* Trigger on Ch2, Ch2 > Ch3 and Ch3 > Ch4)

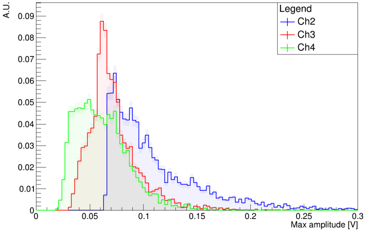


Trigger on Ch2

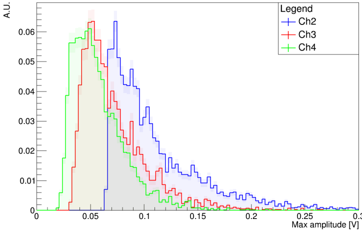
No Veto



Single Veto

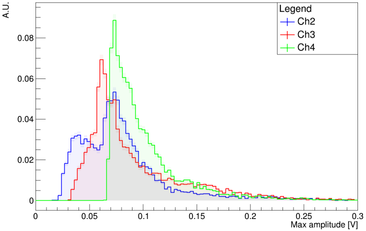


Hierarchical Veto

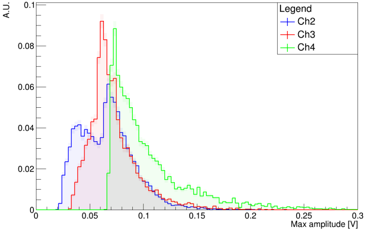


Trigger on Ch4

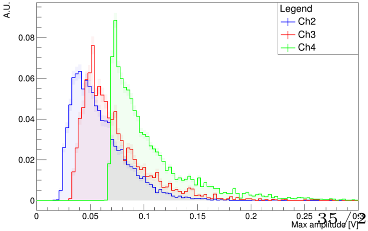
No Veto



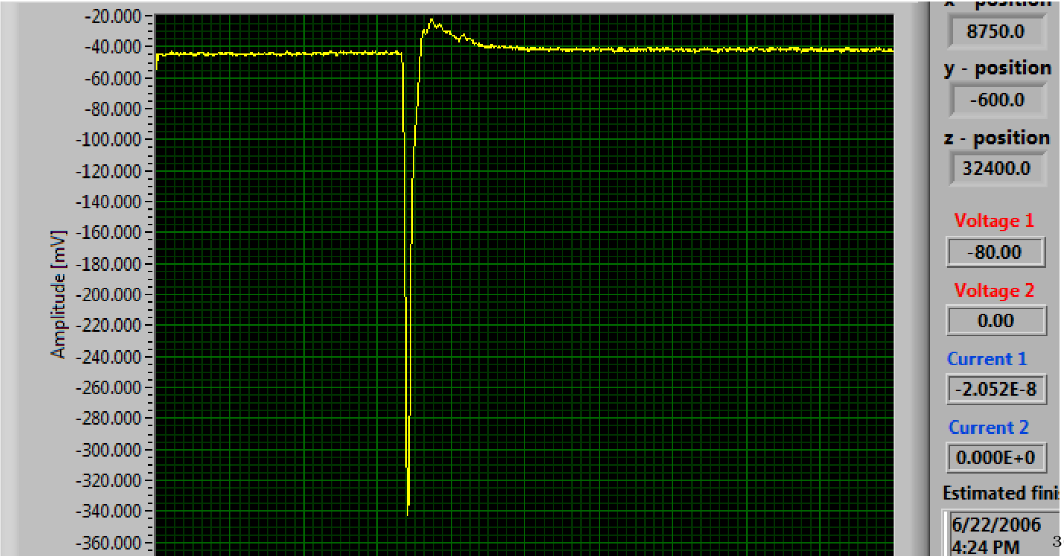
Single Veto



Hierarchical Veto

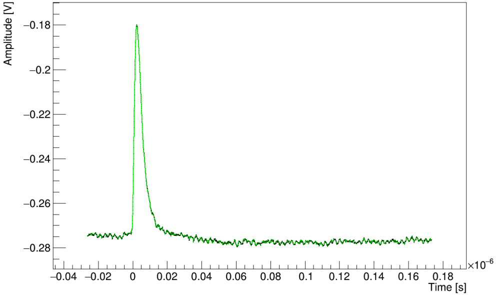


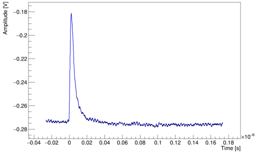
AC-LGAD PULSE (TCT)

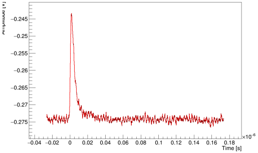


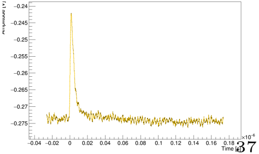
Readout with Altiroc ASIC

Cherry-picked Altiroc outputs that make us look good









- **Consistent signals from all four strips** connected to ALTIROC
- Absolute value of width and amplitude mostly given by the ALTIROC ASIC