# AC-LGADs for 4D reconstruction

## from ATLAS to EIC


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# AC-LGADs — 4D detection goals

Brookhaven National Laboratory

- **Space resolution**
  *Driven by:* **EIC,FCCee/hh**

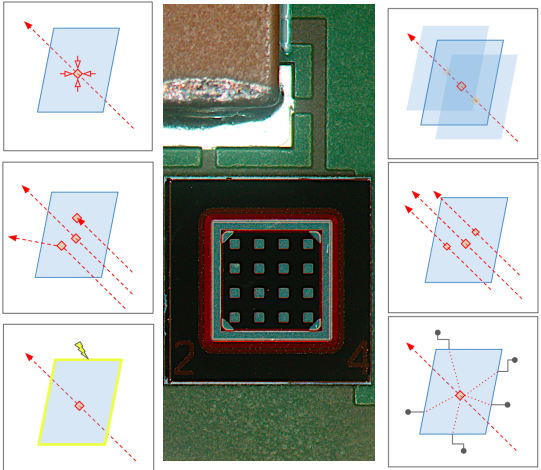
  Hit position res <5 $\mu$m for pile-up reduction and $\pi$/K/p separation

- **Material budget**
  *Driven by:* **EIC,FCCee**

  Equivalent thickness (per layer) <100 $\mu$m to minimize multiple scattering

- **Power consumption**
  *Driven by:* **EIC,(FCCee/hh)**

  < 1mW/channel in EIC RP due to location, beam proximity, ...



(info here)

- **Time resolution**
  *Driven by:* **FCChh**

  Time res/track < 5 ps for pile-up reduction/vertex disentanglement

- **Radiation tolerance**
  *Driven by:* **FCChh**

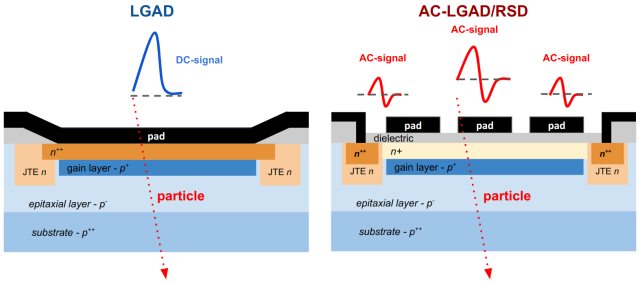
  Fluence increasing by $\times$20 compared to HL-LHC

- **DAQ bandwith**
  *Driven by:* **EIC,FCCee/hh**

  Number of channels to be readout increasing by a factor $\sim$5-10 compared to HL-LHC

# AC-LGADs — 4D detection





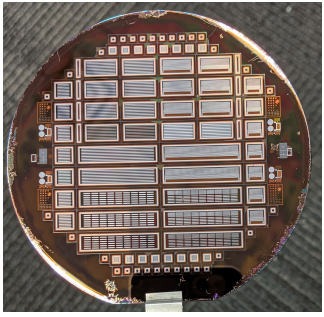

AC-LGAD/RSD

- Combines **internal gain** with internal **signal sharing**
- Keep 100% fill factor on thin substrate (30-50 $\mu$m)
- LGAD-level time resolution (< 30 ps) already proven
- Particle position reconstructed from signal shared on multiple pads
- Can achieve $\sigma_x < \frac{pitch}{\sqrt{12}}$ with ToT/analog info!
- Allows for high spatial resolution with smaller number of channels

# AC-LGADs — BNL production

Brookhaven National Laboratory

Silicon Fabrication Facility and wire-bonding @ *BNL Instrumentation Div.*
Class-100 Clean Room, full characterization, design and simulation of silicon sensors @ *Si-Lab*



New 2022 Production includes:

- **Long Strip AC-LGAD** (ETA next week, great spatial resolution vs number of channels; available before January 2023 testbeam season) (A.Apresyan@CPAD2022)
- **EICROC AC-LGAD** (ETA December 2022, focused on studies for EIC)

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

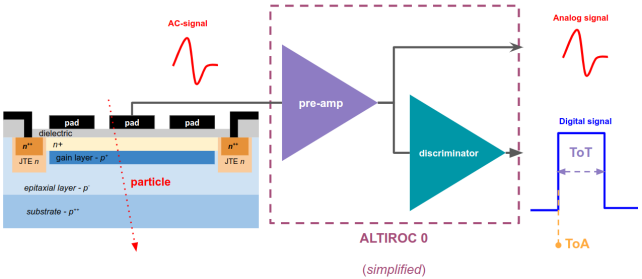

Laser dicing

# ALTIROC 0 — Overview

Brookhaven National Laboratory

G.D'Amen et al., Signal formation and sharing in AC-LGADs using the ALTIROC 0 front-end chip, JINST 17 2022

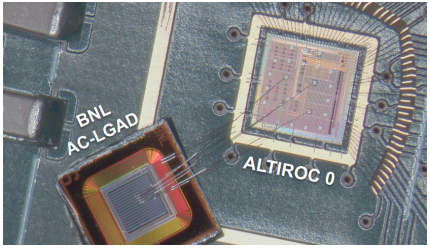
In large-scale, multi-channel systems targeting 4D tracking, we need to evaluate AC-LGAD performances when coupled to higher-complexity readout systems.




## ATLAS LGAD Timing ROC

- ALTIROC designed for LGAD (unipolar/DC-) signals for ATLAS High-Granularity Timing Detector (HGTD).
- Compatibility to AC-LGAD bipolar signals not ensured!
- **ALTIROC 0 ASIC** first prototype of ALTIROC chip (CMOS 130 nm); includes Pre-amplifier (Analog VPA signals) + Discriminator (Digital signals) for ToT measurement

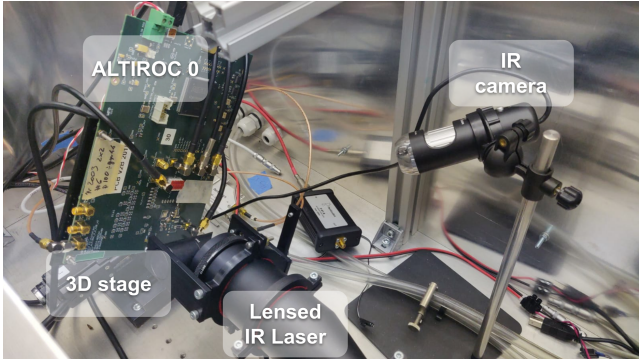
# ALTIROC 0 — Coupling to AC-LGAD



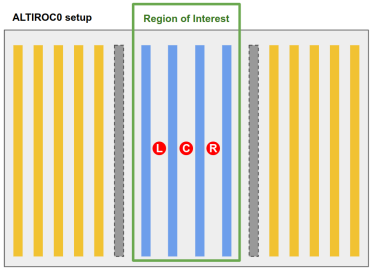

## BNL AC-LGAD characteristics

- Area: 2×2 mm$^2$
- 16 strips
- strip pitch 100 $\mu$m, gap 44 $\mu$m
- $V_{bias}$ = -170 V

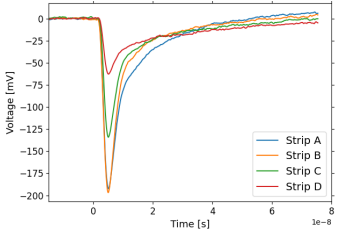
Betas from $^{90}$Sr and IR Laser from TCT used to characterize ALTIROC response to AC-coupled signals



# ALTIROC 0 — VPA characterization




- Signals acquired at the ALTIROC 0 VPA stage on four strips when the laser is focused at the left, center, or right of the sensor
- The laser injects 32 mips onto the sensor
- Signal amplitude decreases linearly with distance due to the resistivity of the n++ layer

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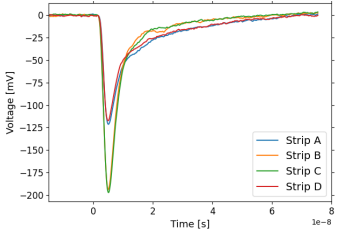


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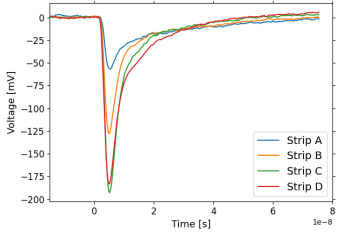


Point R

# ALTIROC 0 — Signal sharing profile

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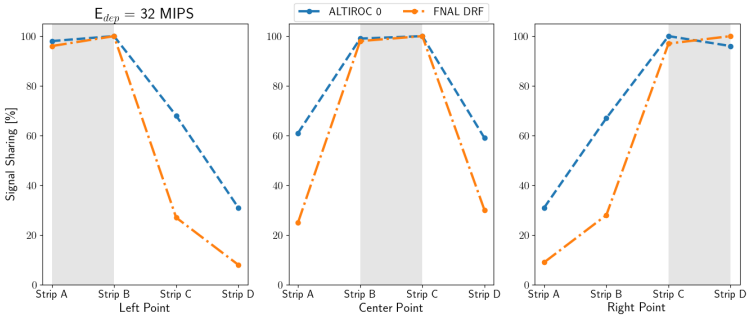
Signal sharing profile on AC-LGAD strips read out by ALTIROC 0 or a discrete RF amplifier (FNAL DRF)

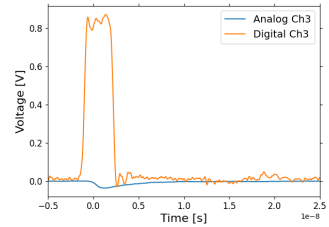


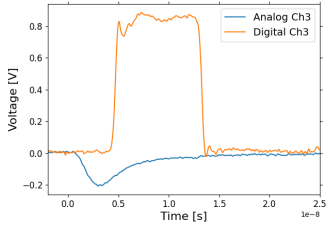

$$\text{Signal Sharing}_i\ [\%] = \frac{\text{A}_i}{\text{A}_{highest}}$$

- $A_i$: Signal amplitude measured by *i*-th strip
- $A_{highest}$: Signal amplitude measured by the strip closest to the focus-point (gray area)

Measured difference in signal sharing profile can be explained, on first order, due to different input impedance of ALTIROC 0 and the RF amplifier

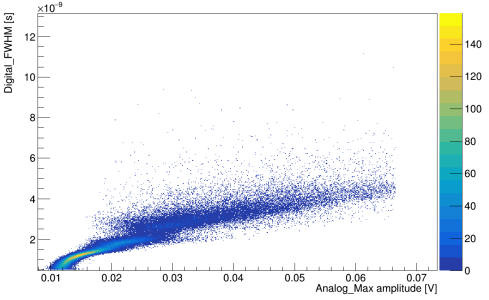
# ALTIROC 0 — Digital response




Analog and digital output of ALTIROC extracted from Strip C generated by the interactions of **betas** (top) and **IR laser** (bottom)

Width of the digital signal (ToT) proportional to the amplitude of the analog signal




- FWHM of discriminator output as function of the amplitude of the analog signal
- Interaction with beta particles leaves a long tail of deposited energies
- Univocal dependence on the analog signal amplitude/deposited energy

# ALTIROC 0 — Energy sensitivity

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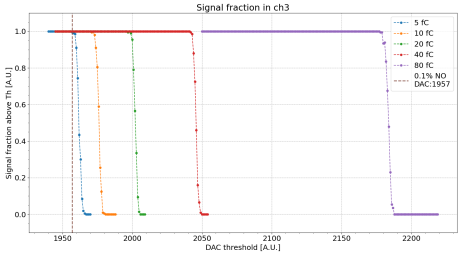
- Fast signal injected from pulse generator
- **S-curve of digital signal fraction** computed for multiple (200) DAC points in wide range

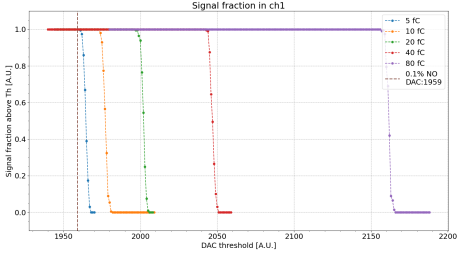
$$\text{SIGNAL}\% = \frac{\text{SIGNALS ABOVE} > 500\ \text{mV}}{\text{TOTAL SIGNALS}}$$

S-curves scan repeated with **multiple input charges** ( **5 fC**, **10 fC**, **20 fC**, **40 fC** and **80 fC**) obtained by modulating input signal amplitude (50 - 800 mV)[1]

Can discriminate signals with charge as low as 5 fC

[1] ALTIROC0 input capacitance: 100 fF and Q = C * V



EIC

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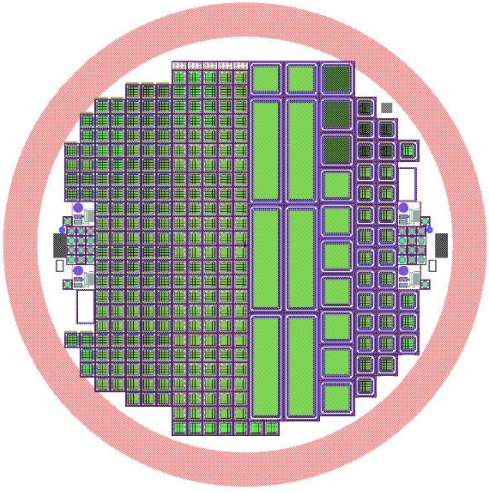
## AC-LGADs for EIC

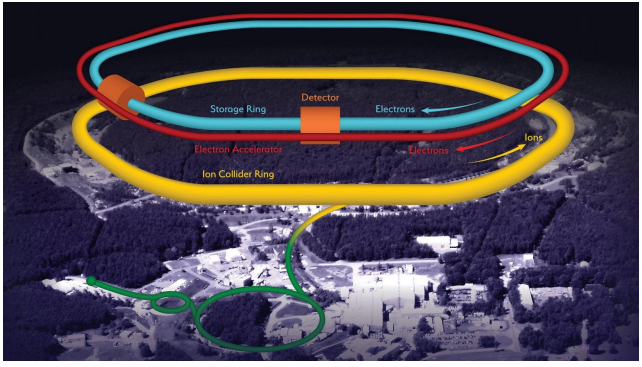


# EIC — The Electron Ion Collider @ BNL

Brookhaven National Laboratory

## EIC parameters

- High Luminosity: $\mathcal{L} = 10^{33}$–$10^{34}$ $cm^{-2}s^{-1}$, 10–100 $fb^{-1}$/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: $E_{cm}$ = 20 – 140 GeV
- Electron Beam: 5-18 GeV Ion (protons - Uranium): 40, 100-275 GeV
- Large Detector Acceptance and Good Background Conditions
- Accommodate two Interaction Regions (IR)



# EICROC — Fundamentals

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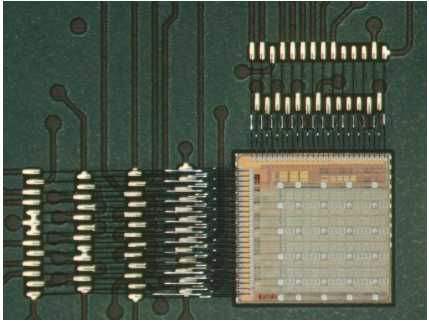
EIC Roman Pots (RP): aim for 500 x 500 $\mu m^2$ pixels with $\sim$30 ps time resolution (O.Hartbrich@CPAD 2022)

- 1,310 $cm^2$ silicon, 128 modules, 512 ASICs (32$\times$32 channels), $\sim$500k channels
- Signal sharing between pixels to improve time and space resolution
- Low occupancy
- Low radiation environment
- Triggerless system

1st ASIC prototype (EICROC 0) for EIC Roman Pots, based on ALTIROC experience

- TDC for ToA and ADC for amplitude measurements exploit Signal Sharing

Similar design may be used in EIC ToF detector



# EICROC — Main differences with ALTIROC

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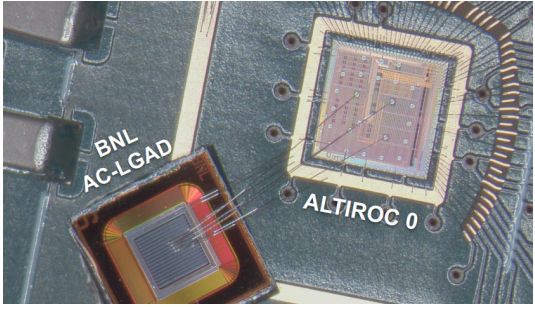


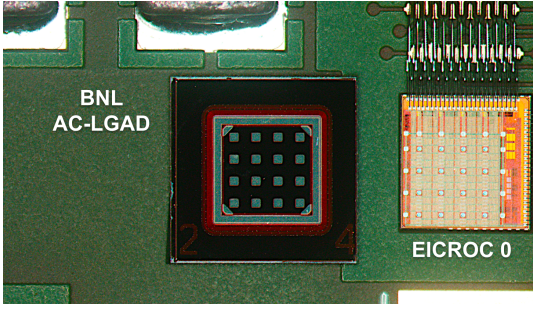


| ALTIROC 0 | |
|---|---|
| Target sensor | DC-LGAD |
| Pixel size | $1.3 \times 1.3$ mm$^2$ |
| Channels | 4 |
| Pixel capacitance | 4 pF |
| TDC (TOT) | 8bit/10bit |

| EICROC 0 | |
|---|---|
| Target sensor | AC-LGAD |
| Pixel size | $0.5 \times 0.5$ mm$^2$ |
| Channels | 16 |
| Pixel capacitance | 0.5 pF |
| ADC (Amplitude) | 8bit@40MHz |

# EICROC — Testing strategy

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## Already available

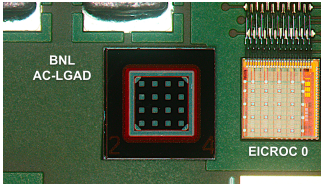
- EICROC 0 bonded to custom designed mezzanine board and readout via Xilinx Zynq-7000 ZC706 evaluation board
- BNL AC-LGAD wire-bonded to EICROC 0

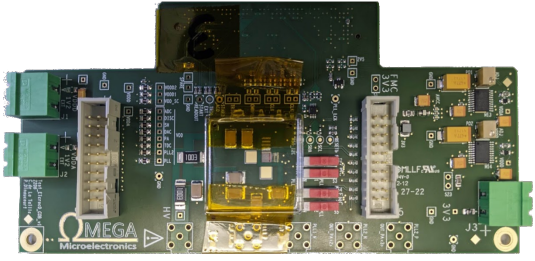
## Under construction

- Firmware & C/C++ Embedded Software under development by IJCLAB team
- Dedicated AC-LGAD design coming soon

## Next steps...

- Characterization of ADC linearity for signal sharing
- Study of detector response to TCT (IR laser) and particle sources/test beams




FMC MEZZANINE BOARD, design by OMEGA Team

# Recap & Conclusions

- The next generation of accelerators will pose several experimental challenges; this requires **a new generation 4D detector**
- The AC-LGAD paradigm proved to be a prime candidate for 4D reconstruction thanks to its fast timing and signal sharing capabilities, among others
- A new detector requires a **dedicated readout system**: we have successfully read out a BNL-made AC-LGAD using the ALTIROC 0 chip, designed for DC-LGADs
- AC-LGAD dedicated readout system for EIC application, **EICROC** (based on the ALTIROC design) is being developed by OMEGA and IJCLAB
- A first chip prototype, EICROC 0, is now available and has been coupled to a BNL AC-LGAD
- The readout system is currently under development and will be tested following the procedures developed during the AC-LGAD + ALTIROC 0 testing campaign

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# BACKUP

# ALTIROC 0 — 11 MIPS vs 32 MIPS

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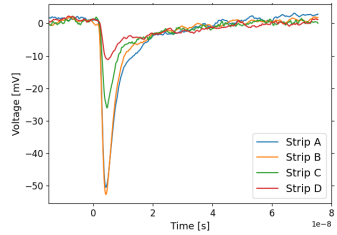
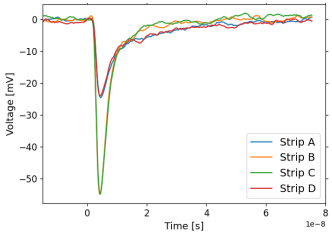



Point L

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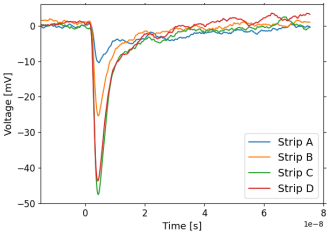


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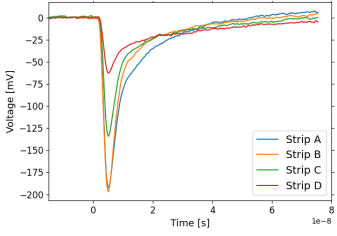


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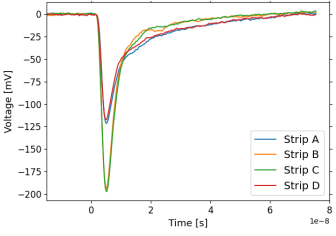


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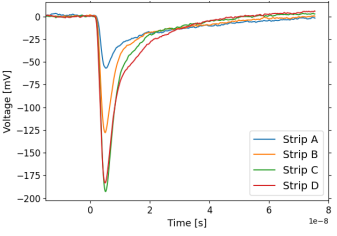


Point R

# IR laser — ALTIROC vs FNAL

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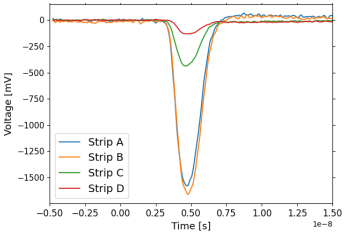


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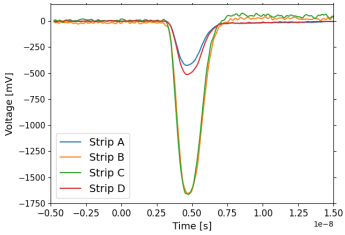


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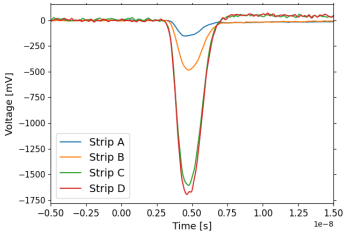


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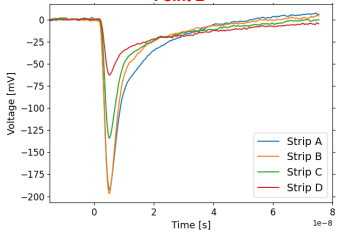


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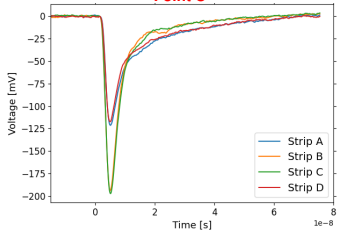


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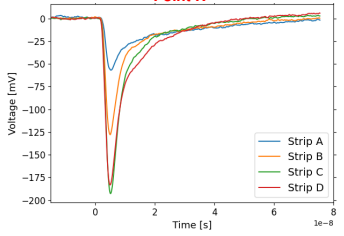


Point R

# DIGITAL CHARACTERIZATION - TRIMMING