FAST3 asic: front-end electronic with ps resolution, designed for thin LGADs read-out

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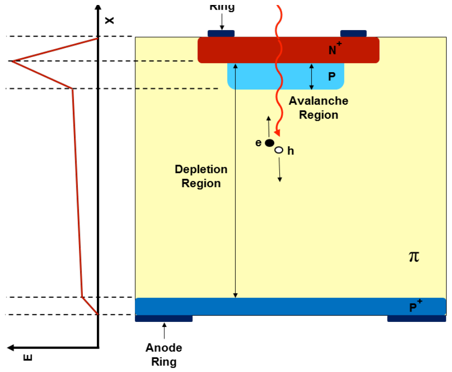
In collaboration with the Microelectronic group and electronic Laboratory of INFN Turin

TWEPP 2024 – Topical Workshop on Electronics for Particle Physics

Motivation

LGAD: planar silicon sensor with internal gain



Requirements of read-out electronics to match LGAD performance:

- Wide input charge range: **3-50fC**
- Capability to reach temporal resolution of **30-35ps**:
  - Temporal jitter **(<20ps**), lower than landau noise
  - wide bandwidth **(> 500 MHz**) to preserve the slew rate of the LGAD signal
  - High signal-to-noise ratio (**SNR > 60**)

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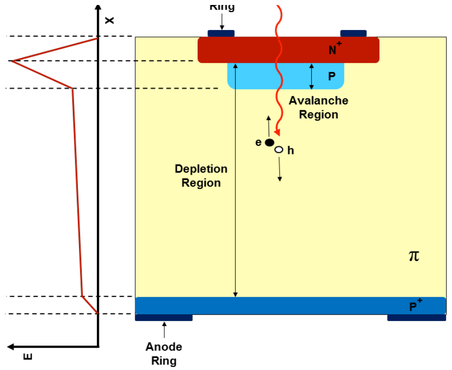

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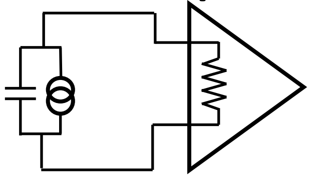
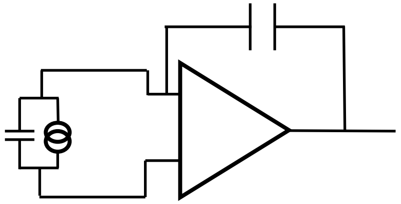
Two architecture approaches of front-end

Current amplifier



- Fast slew rate
- Higher noise
- Sensitive to landau fluctuation
- **High power**

Integrator amplifier



- Slower slew rate
- Lower noise
- **Lower power**

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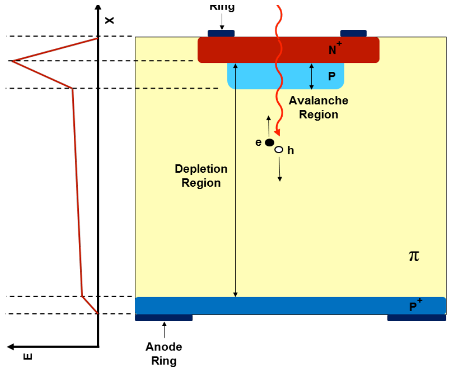

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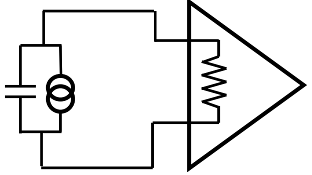

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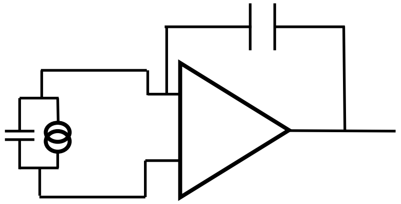

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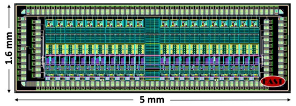
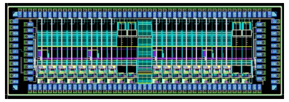
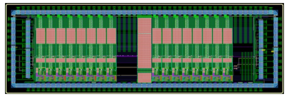
The Family of FAST ASICs belong to charge sensitive amplifier



FAST1



FAST2



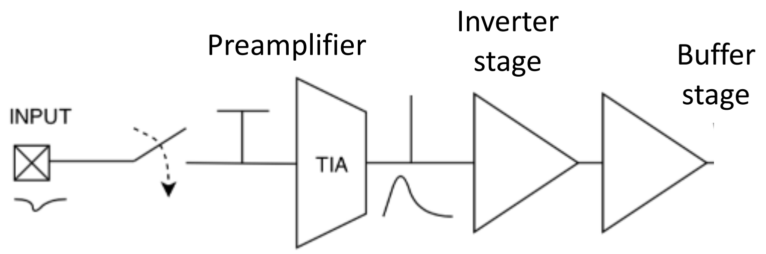
FAST3

FAST ASICs have been developed to explore low power front-end architecture, aiming to achieve ps-timing resolution when coupled to Low Gain Avalanche Diodes (LGADs)

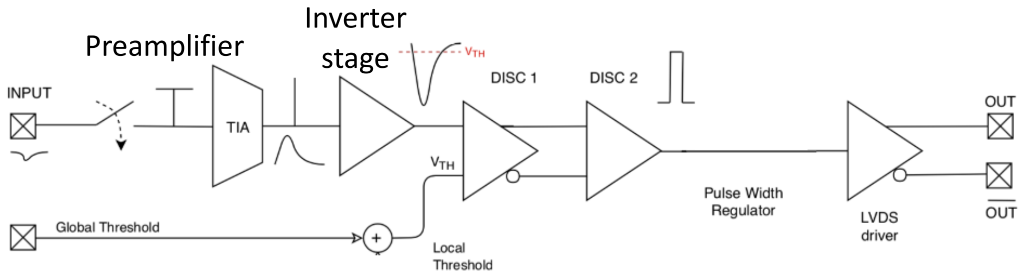
FAST3 ASIC versions

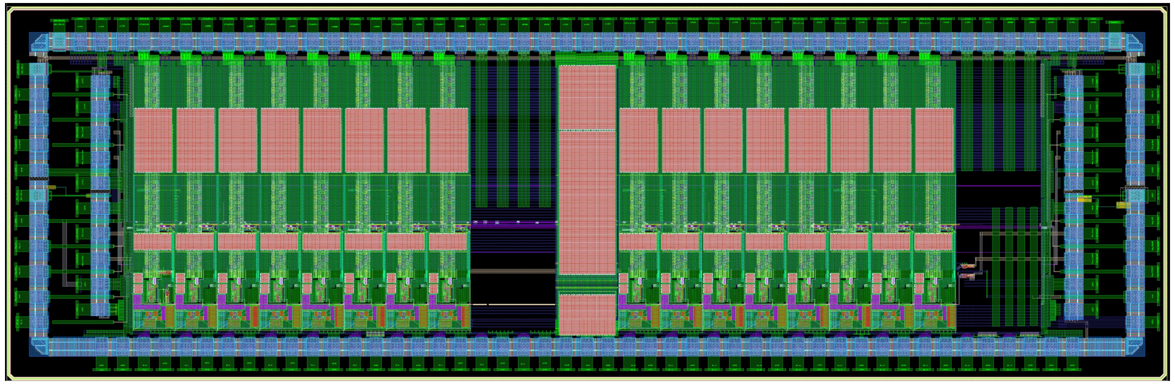
FAST3s were designed in UMC 110 nm CMOS technology by Microelectronic group of INFN Torino

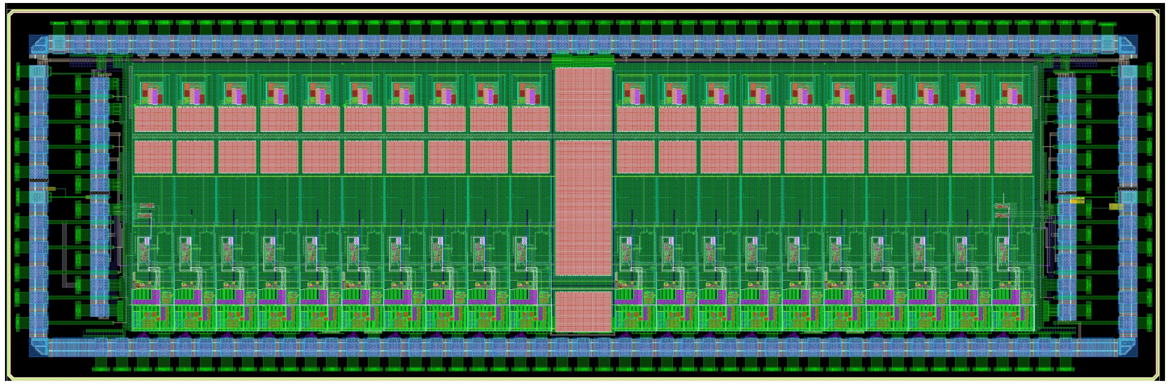
FAST3 Amplifier-only architecture (Analog version)



FAST3 amplifier-discriminator architecture







FAST3: Front-End Electronics to Read Out Thin Ultra-Fast Silicon Detectors for ps Resolution, AM. Rojas, et al., *J. 2022 IEEE Latin American Electron Devices Conference (LAEDC)*, 2022, 10.1109/LAEDC54796.2022.9908192

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Topic of the talk

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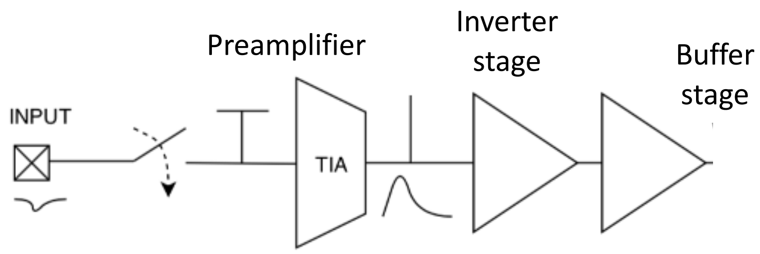

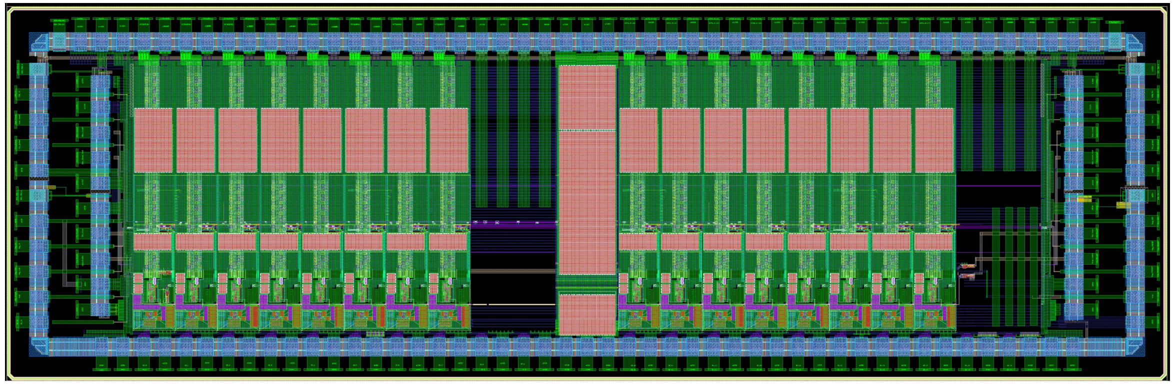

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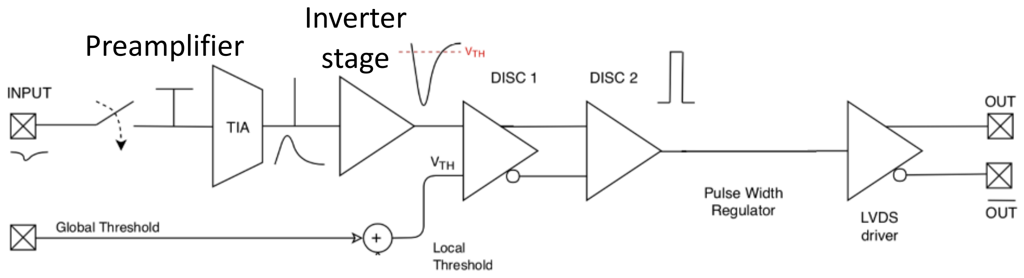

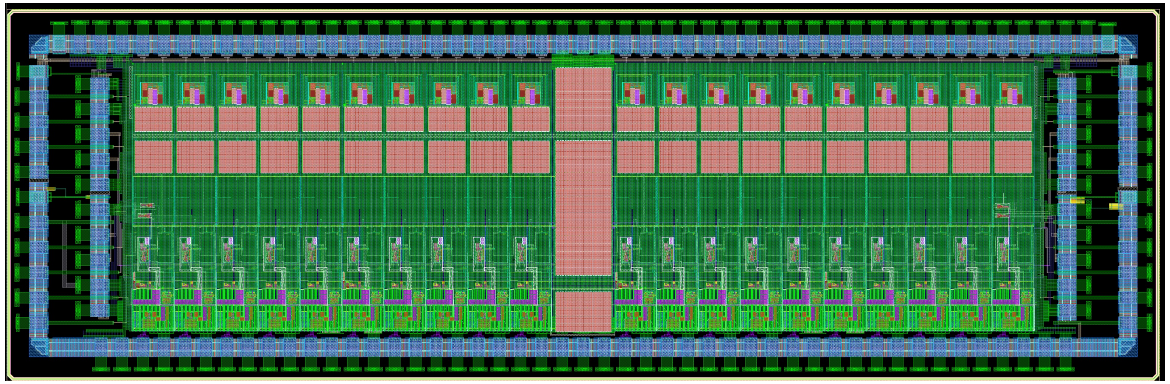

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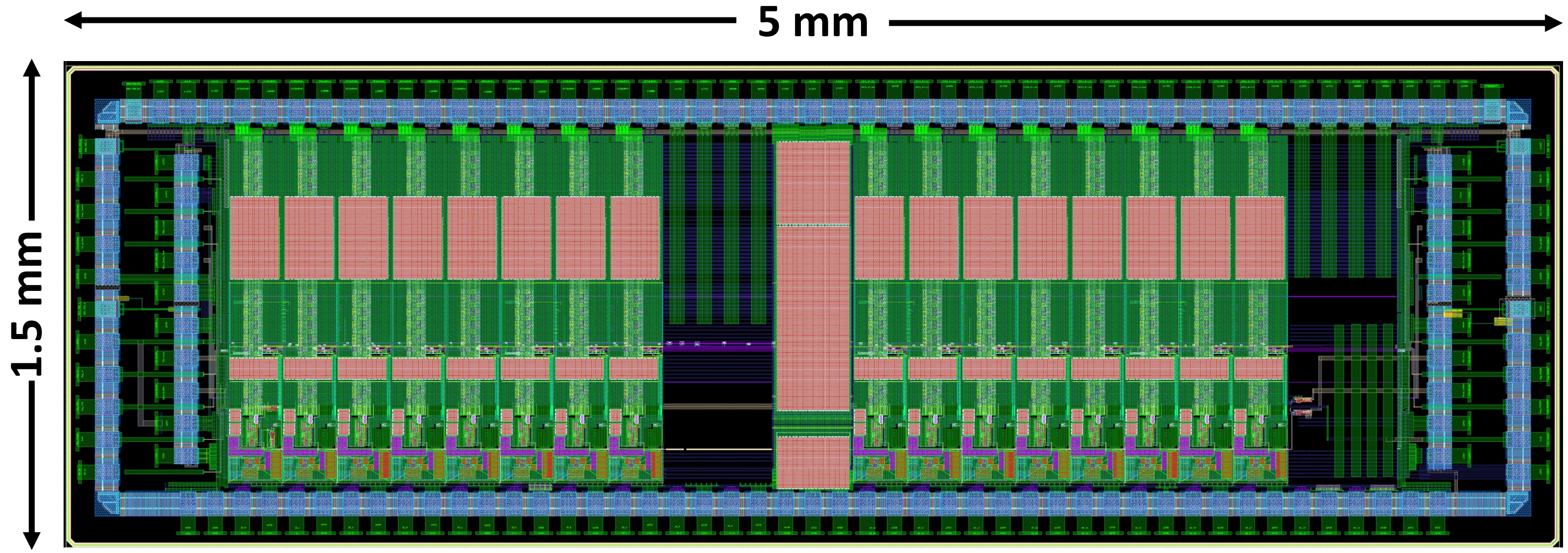
Outline

- Main characteristics of FAST3-Analog and its architecture

- **Study of the signal shape:** comparison between measured signal shape and post-layout simulated signal

- **Performance characterization of FAST3:** conducted with pulser, β-source and during beam test activity. The results are compared with post-layout simulation outputs:
  - **Channel gain** and **output dynamic range** (sensor not connected to FAST3)
  - **Temporal jitter** (sensor not connected to FAST3)
  - Interplay between channel gain and sensor capacitance (sensor with different capacitances connected to FAST3)
  - **Noise, slew rate, SNR and temporal resolution:** characterized using two LGAD sensors (50μm-thick, C=3.8pF and 80μm-thick, C=1.8pF)

FAST3 prototype: Layout and specification (Amplifier-only version)



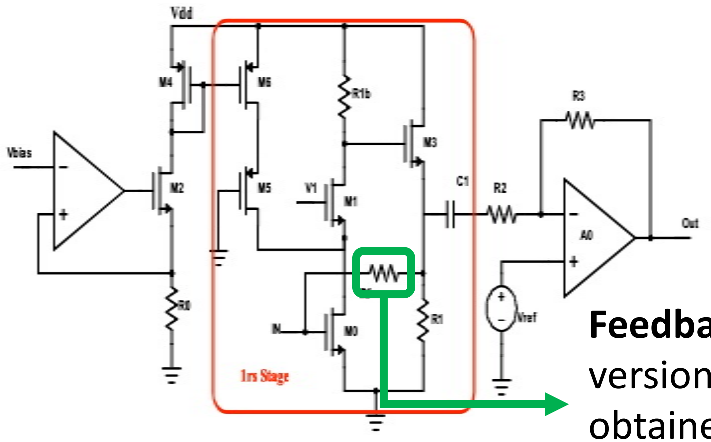
- Bottom side: Input pad
- Top side: Output pad
- Lateral sides: Bias and Power input

Table of specifications	
Power rail	1.2 V
Number of Ch	16
Power consumption	2.3 + 7.7 mW/ch
Input dynamic range	3-40 fC
RMS Noise	1.1 mV
Output signal (@ 8 fC)	102 mV
SNR (@ 8 fC)	93
Voltage output range	~ 800 mV
Bandwidth	~ 1 GHz
Temporal Jitter (@ 8 fC)	20 ps

Channel architecture

Pre-amplifier stage (2.3 mW/ch)

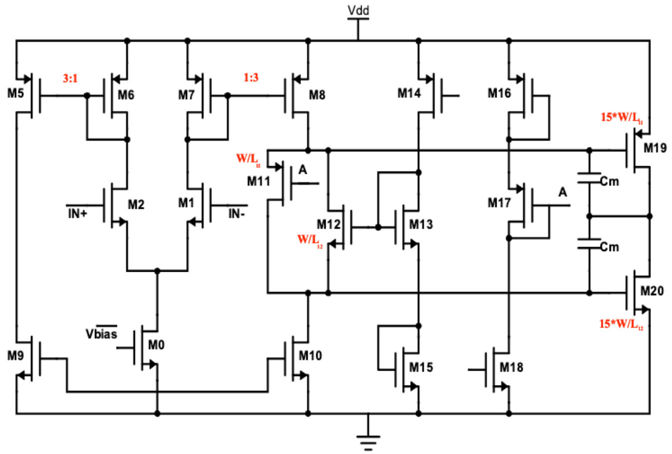
- Transimpedance Amplifier
- Common source topology implemented with RF input transistor
- 2 channel version:
  - Programmable DC gain: 3-bit adjustable gain
  - Fixed DC gain



Feedback resistor: in programmable version 8 different DC gain are obtained by combining three resistances: 5kΩ, 15kΩ and 30kΩ

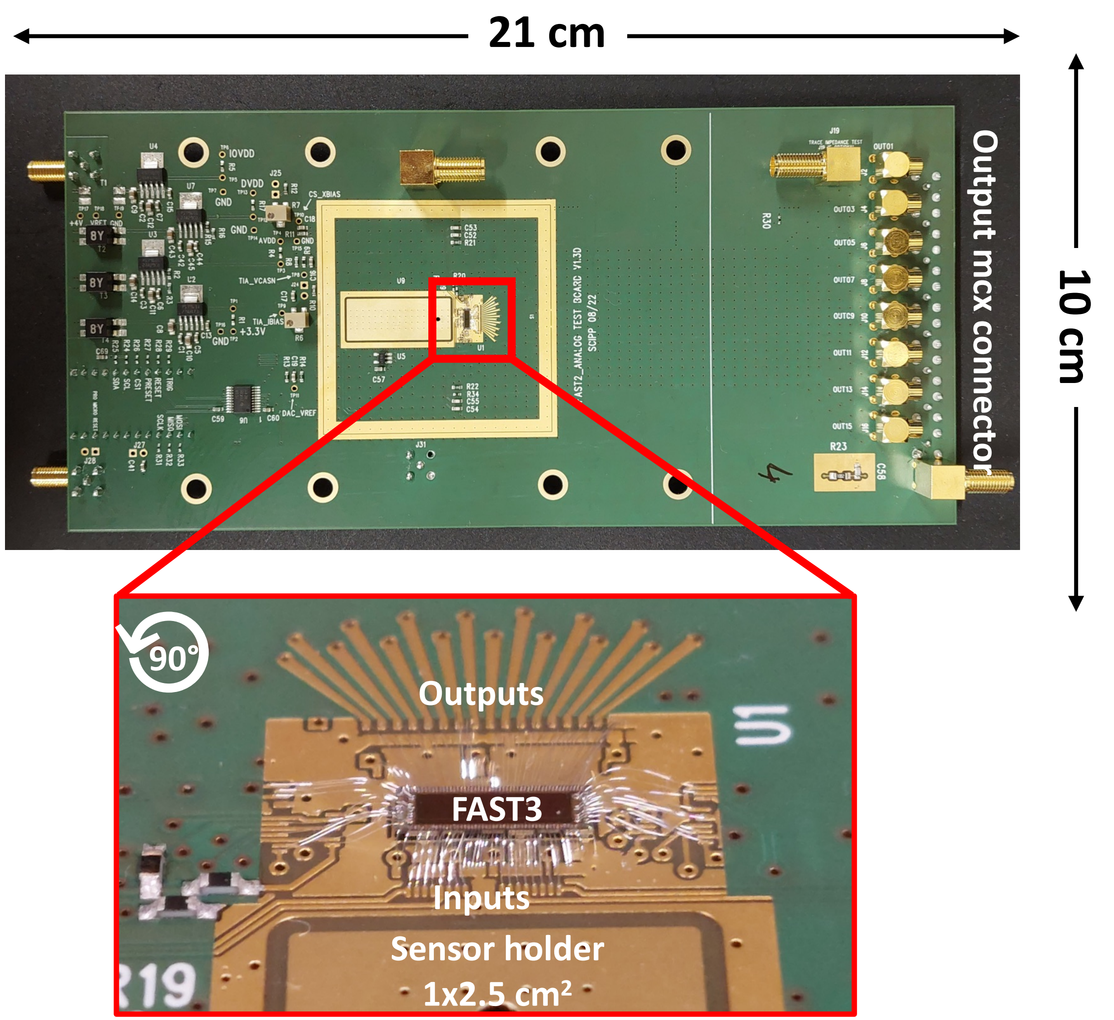
Buffer stage (7.7 mW/ch)

- Operational amplifier (Class AB stage)
- DC gain = 6
- Guaranteed signal rise time of 1.5 ns
- Bandwidth = 1 GHz

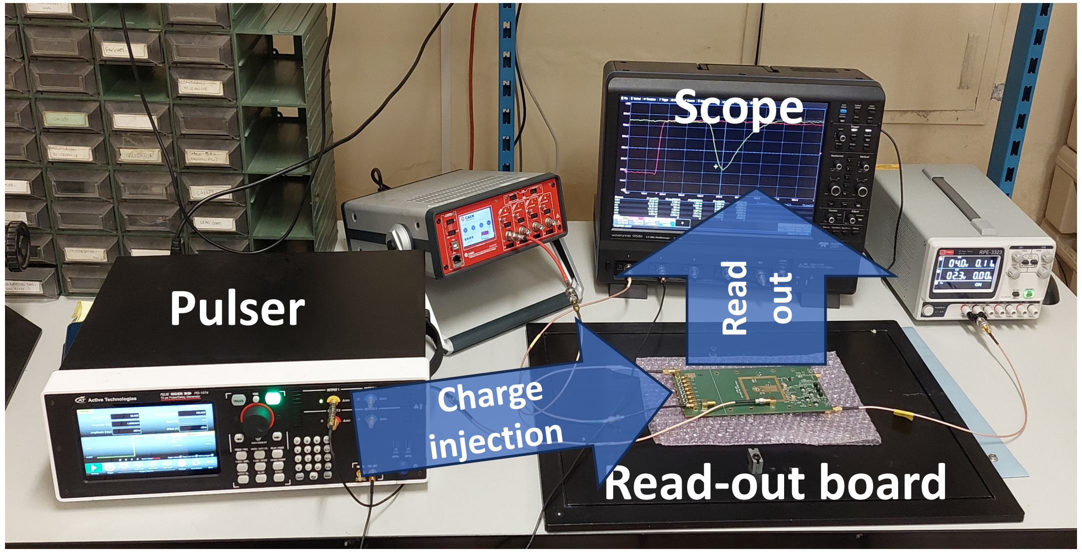


Pulser setup

Read-out board



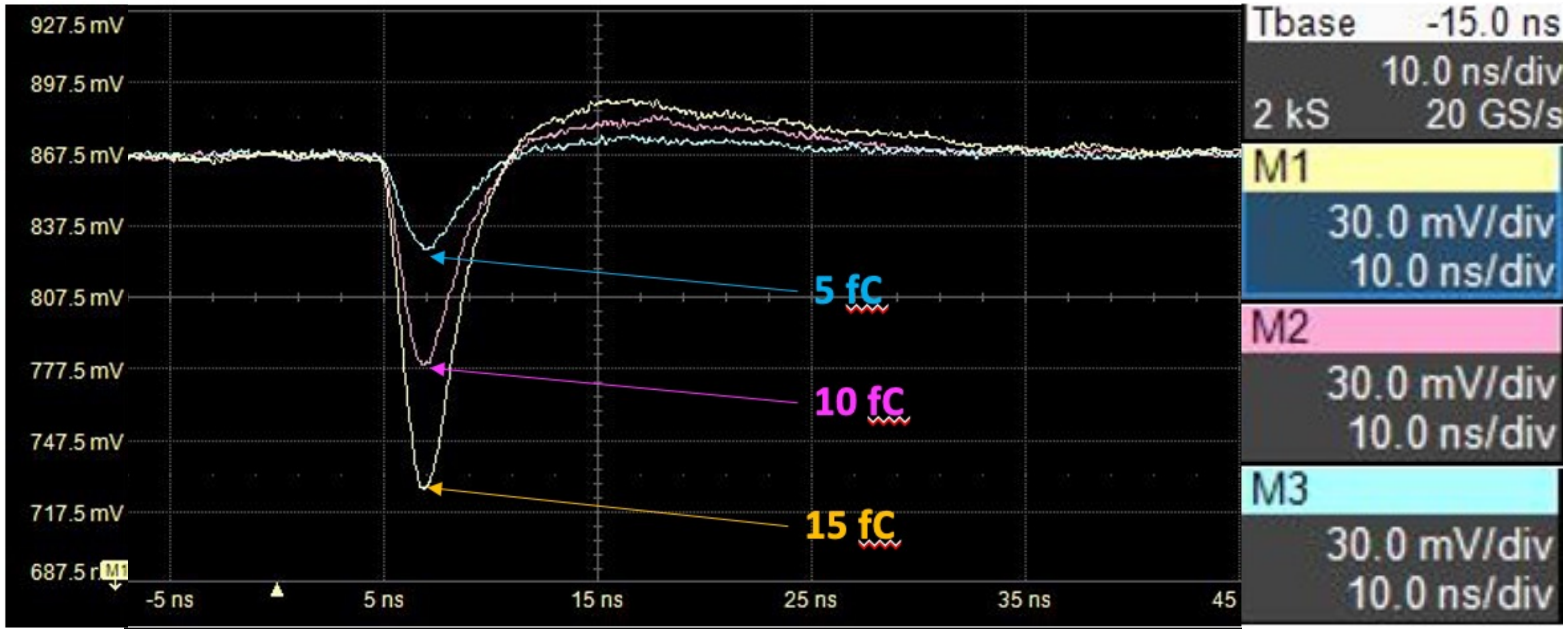
Laboratory setup for charge injection



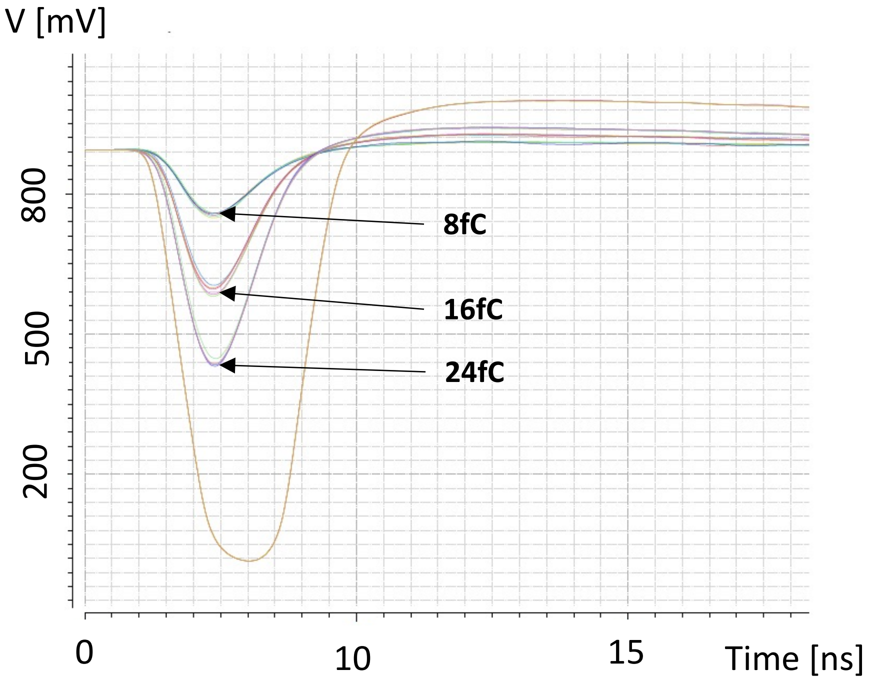
- Active Technology PG-1074 pulser **(temporal jitter of 10ps for input charge $\geq$ 10fC)**
- 4 Ch Lecroy-WaveRunner 9254M oscilloscope
  - Sampling: 20 or 40 GSa/s
  - Bandwidth: 2.5 GHz

FAST3 Output Signal

FAST3 signals from charge injection:
generated with a 0.5pF capacitance at input of FAST3 channel

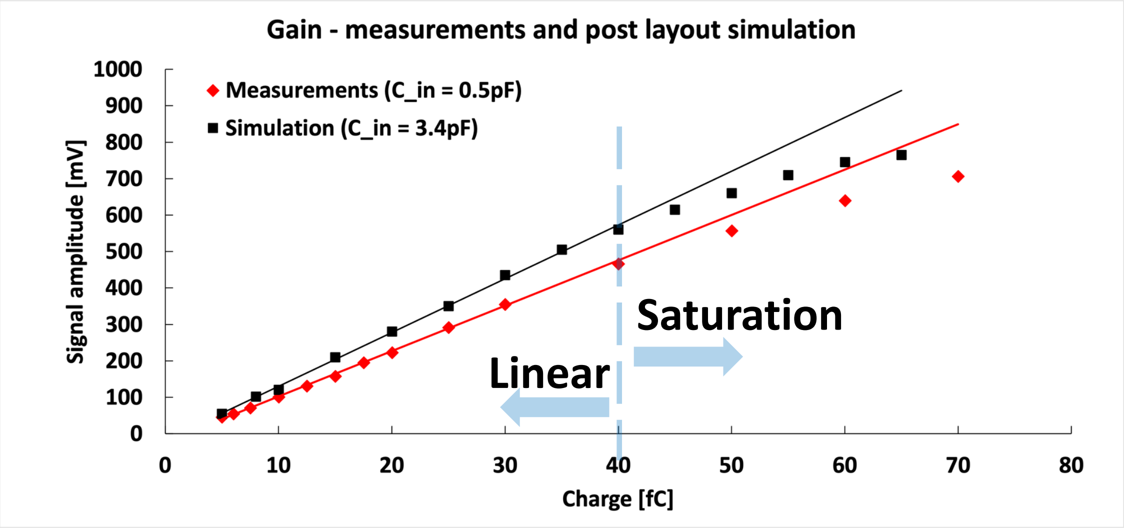


Post layout simulation



- Signal Duration: **5 ns**
- Signal rise time: ~ **1.5 ns**
- Amplitude scaling: Linear relationship between signal amplitude and injected charge
- Good agreement in term of signal shape between laboratory measurements and with post-layout simulations

Gain measurements



- **Linearity**: maintained up to 40 fC with a signal amplitude ~ 500mV
- Gain: ~ **10-11 mV/fC**
- Output range consistent with post-layout simulation results
- **No crosstalk** between channel was observed up to 40fC

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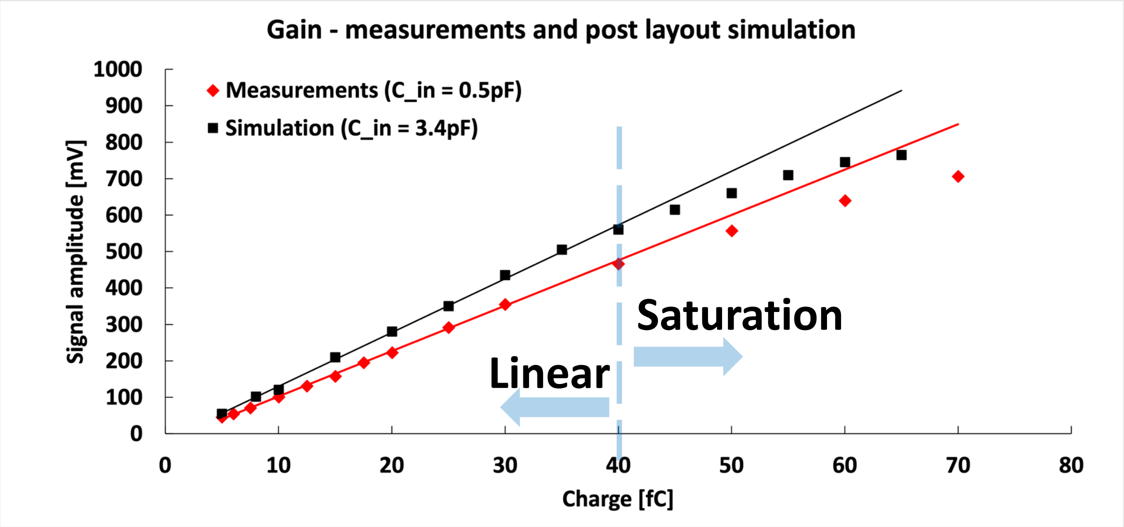

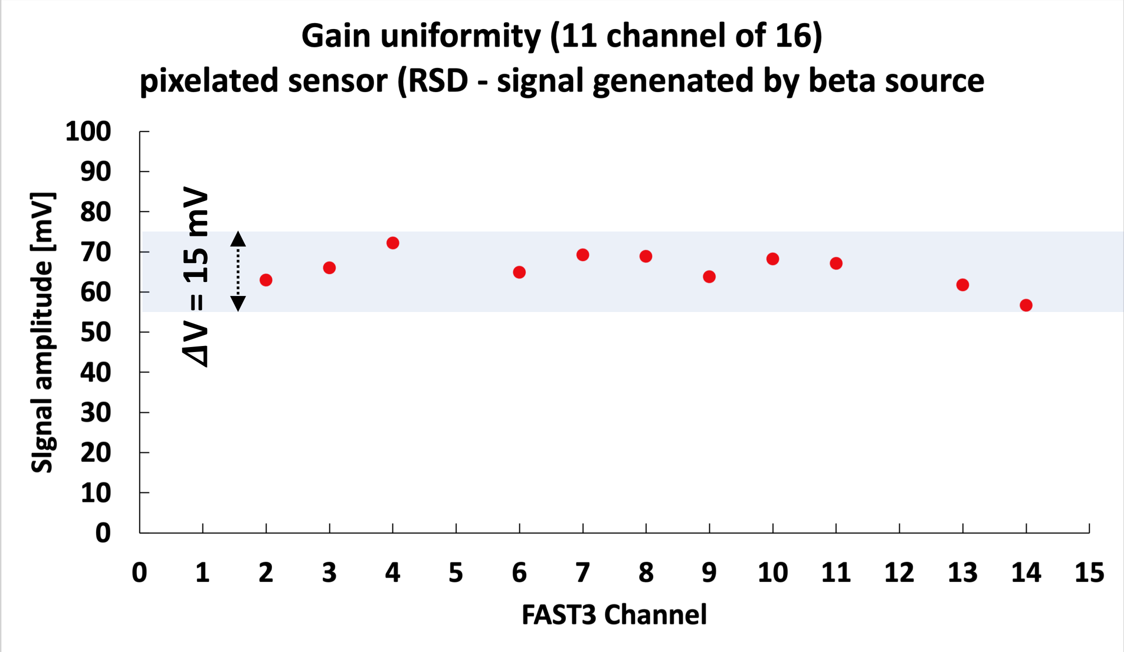

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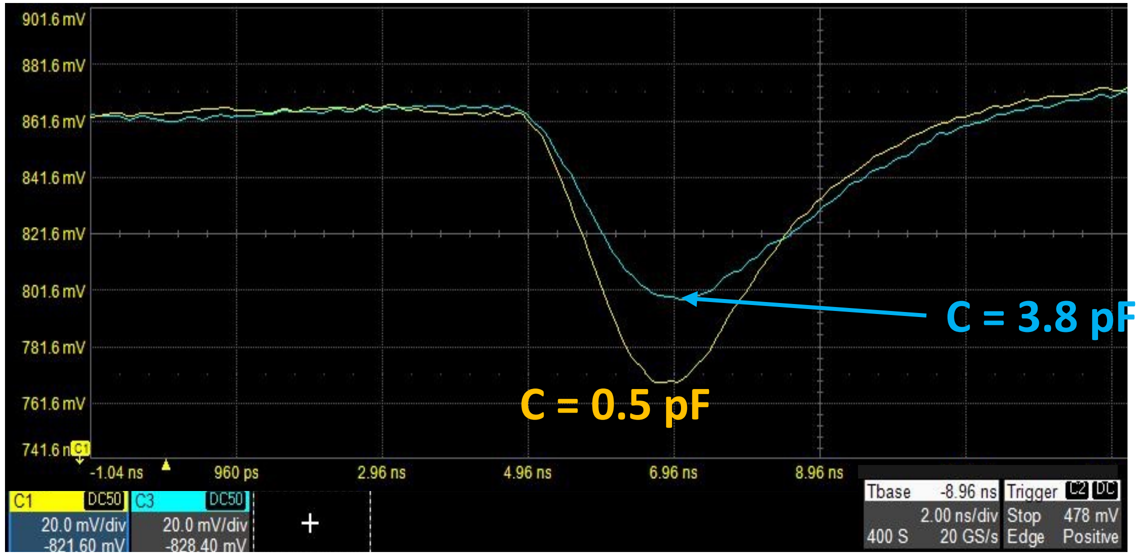
Signal variation of ~ **15mV** at a signal amplitude of 60-70mV

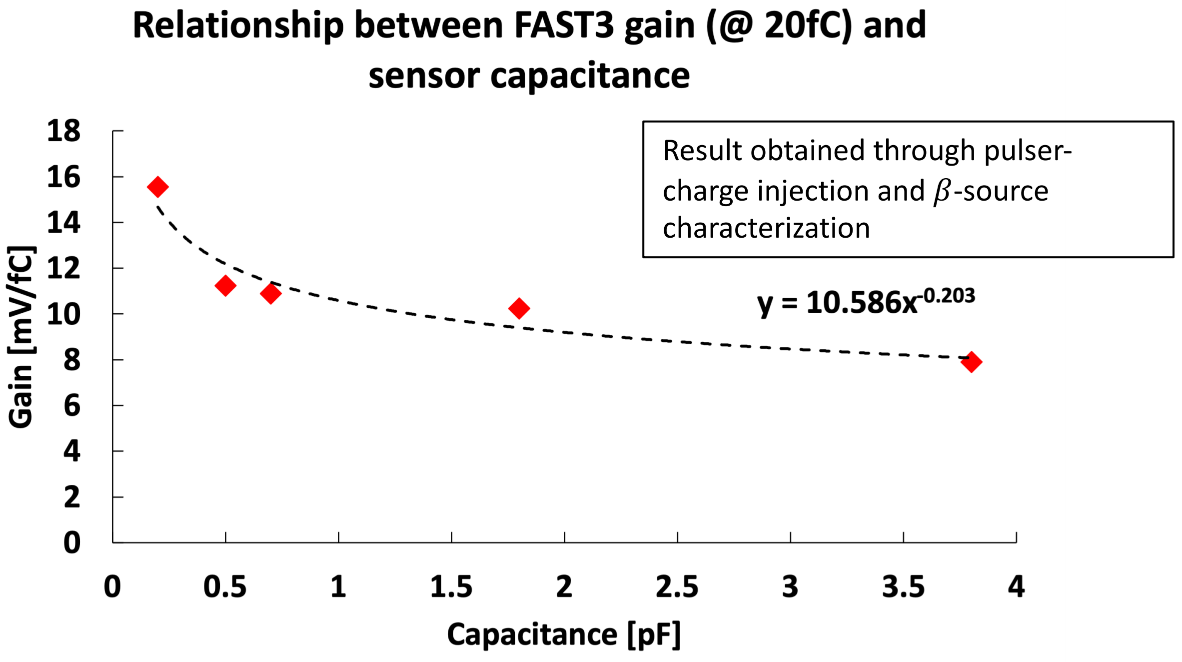
Interplay between preamplifier gain and sensor capacitance

The sensor capacitance significantly affect the output signal for a fixed amount of charge

- Larger capacitance reduces the channel gain in term of mV/fC
- Larger capacitance increase the rise time of the signal

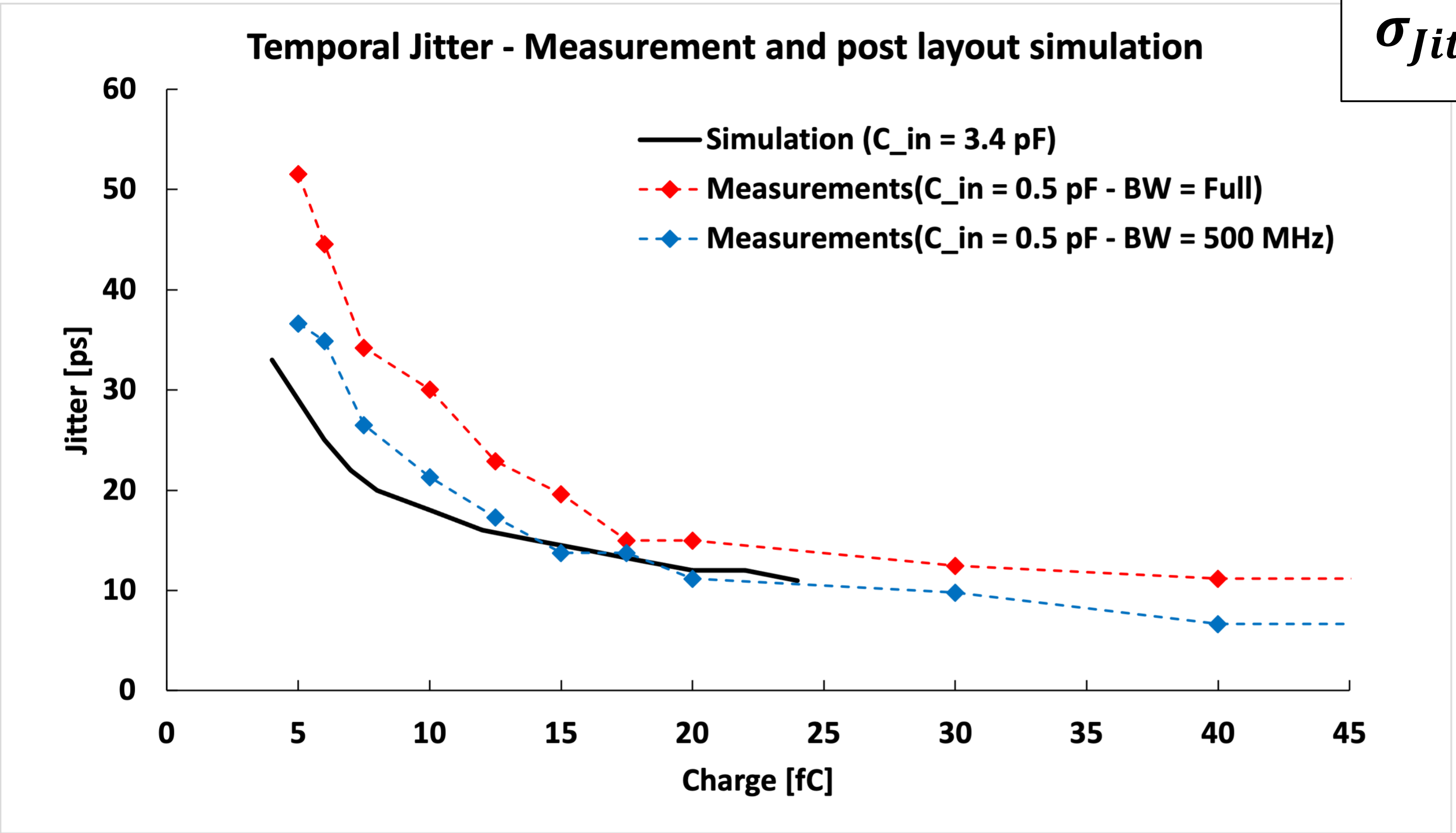
Signals corresponding to input capacitances of 0.5pF and 3.8 pF, generated by injecting 10 fC





FAST3 is expected to perform better with smaller pixel, at a fixed sensor thickness

Temporal Jitter



$$\sigma_{Jitter} = \frac{Noise}{dV/dt}$$

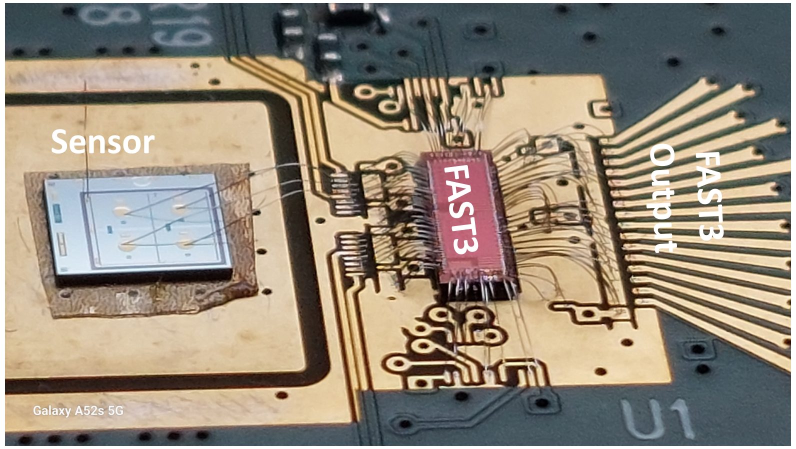
The jitter was measured with **CFD method** at 50% for experimental data and at 40% in simulation

- Jitter is below 25 ps at 10 fC
- Minimum jitter below 10 ps
- Jitter is lower at BW = 500 MHz
- Measurements (BW = 500MHz) in good agreement with post layout simulations

β-source and beam test characterization– DUTs and setups

The temporal resolution of FAST3 wire-bonded to LGADs have been evaluated with **β-Source** and at **beam test**

DUTs geometry	**Pixel capacitance [pF]**	**Active thickness [μm]**
2x2 matrix	3.8	50
Singe pixel	1.8	80



LGAD - 2x2 matrix wire-bonded to the input of the ASIC

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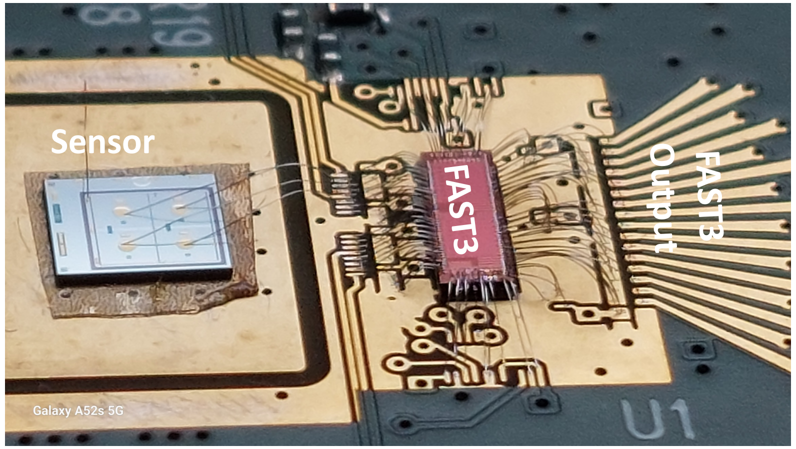

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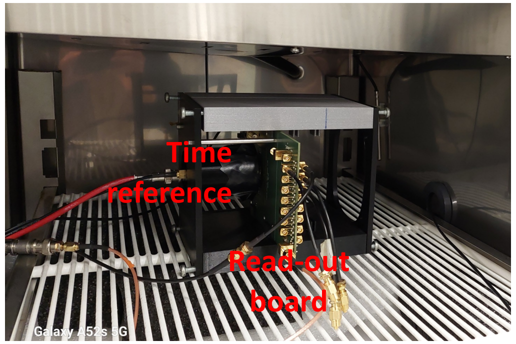
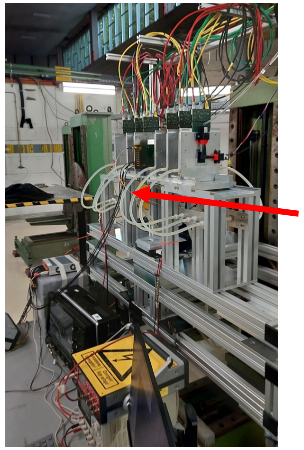
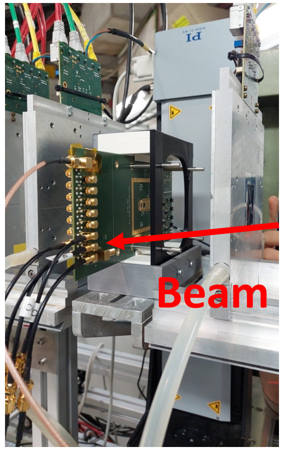


β-Source setup:

- **Sr^{90}** source
- Temperature control
- DAQ based on Lecroy oscilloscope (**20 GSa/s, BW limited to 500 MHz**)
- Time reference: Photonis MCP whit **t_{res} ~10-20 ps**





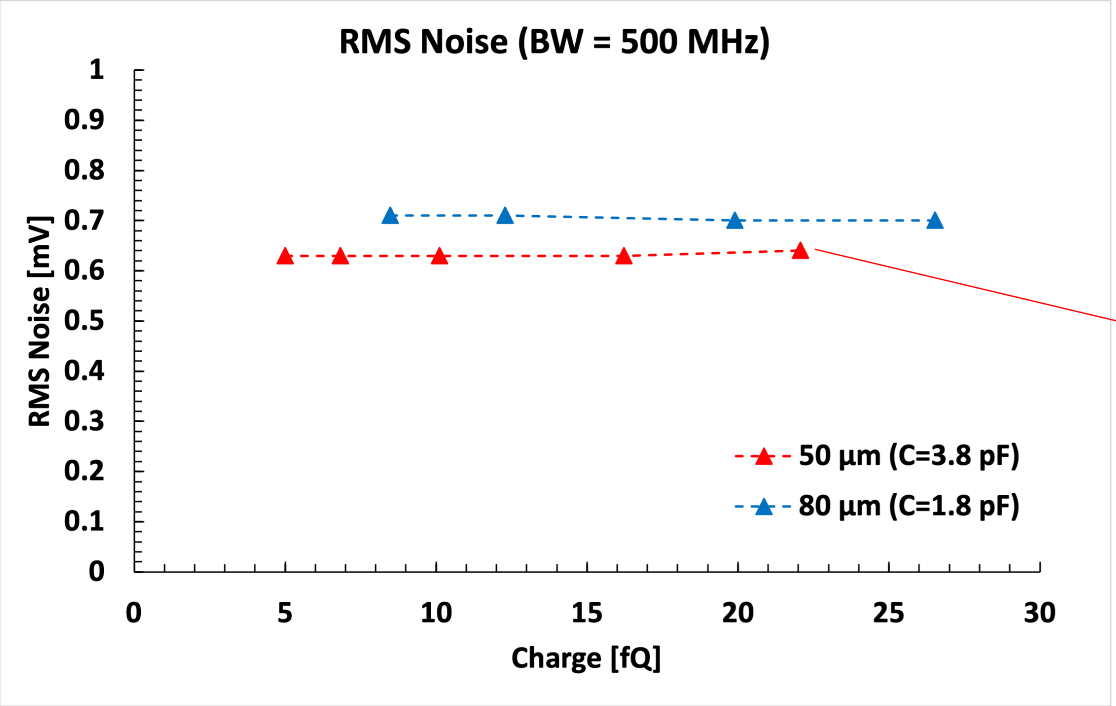
Zoom on read-out board

DESY beam test setup:

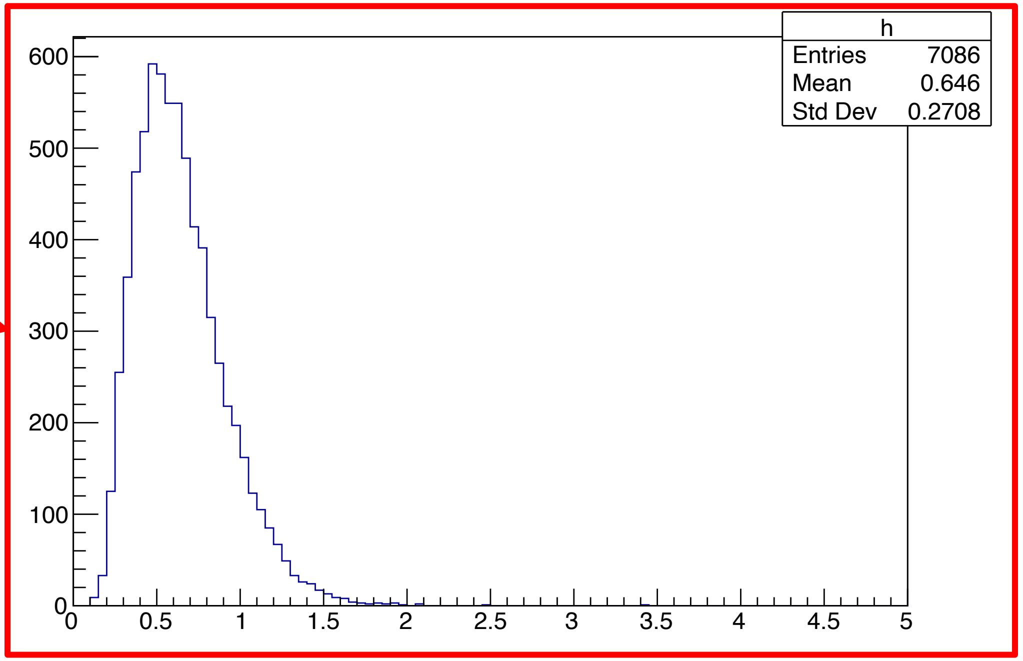
- Electron beam: **E = 5GeV**
- No temperature control
- DAQ based on Lecroy oscilloscope (**20 GSa/s, BW limited to 500 MHz**)
- Time reference: Photonis MCP whit **t_{res} ~10-20 ps**

Beta and beam test characterization provided fully equivalent performance

RMS Noise

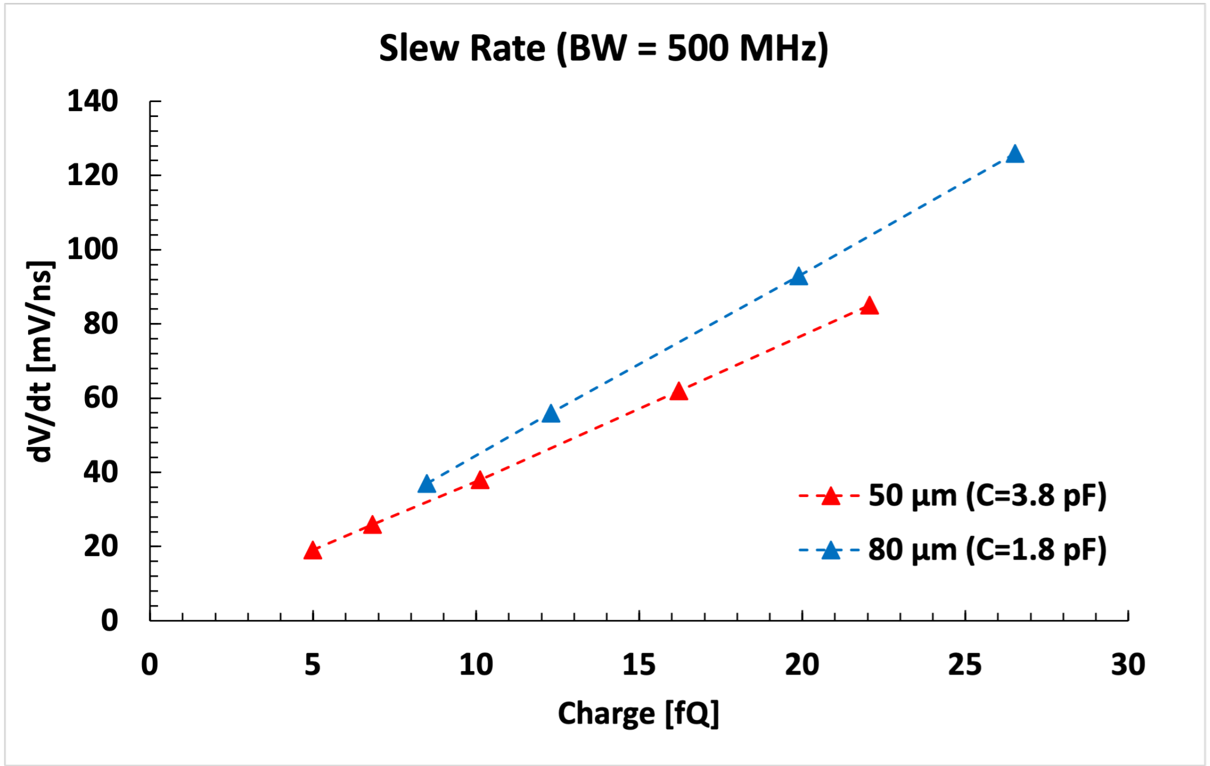


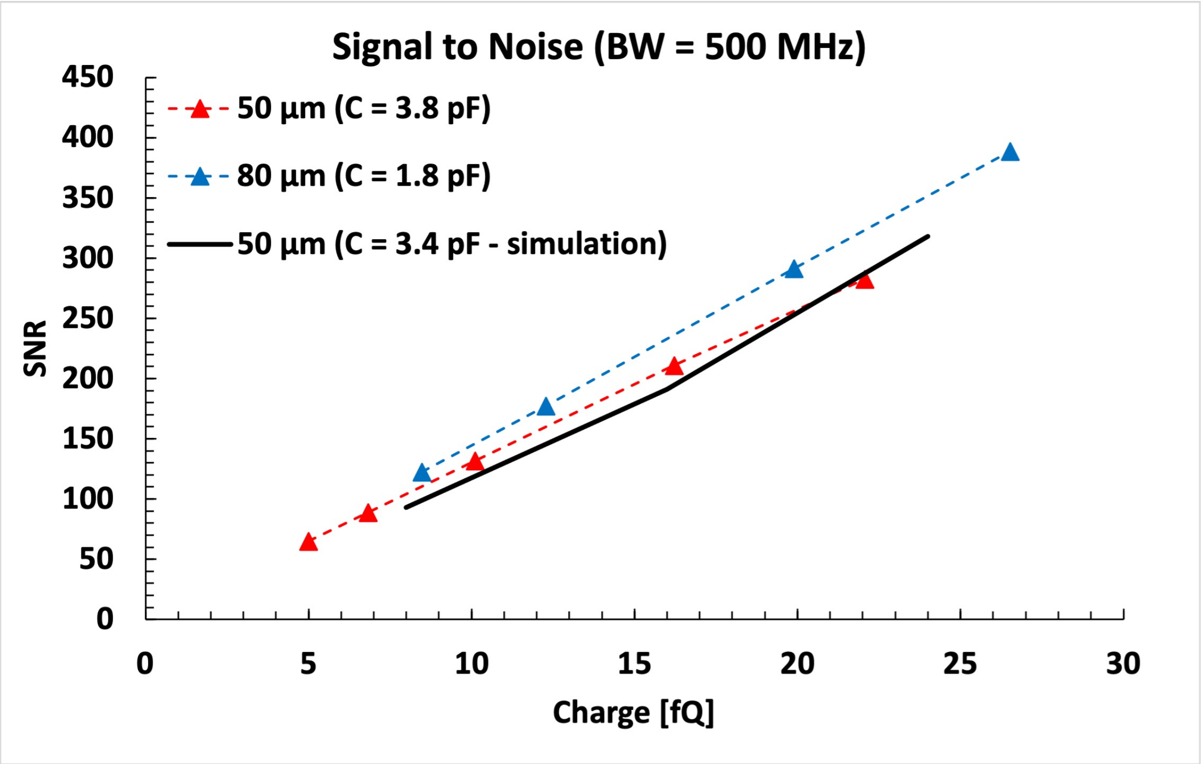
RMS Noise distribution (Sensor 50µm-thick – C = 3.8 pF)



- RMS Noise of **0.6 – 0.7 mV** with a BW = 500 MHz
- Clear effect of the pixel capacitance on RMS noise value (**lower sensor capacitance → higher noise**)
- Asymmetric distribution of the noise, attributed to 500 MHz filter

Characteristics of the signal: Slew Rate and SNR



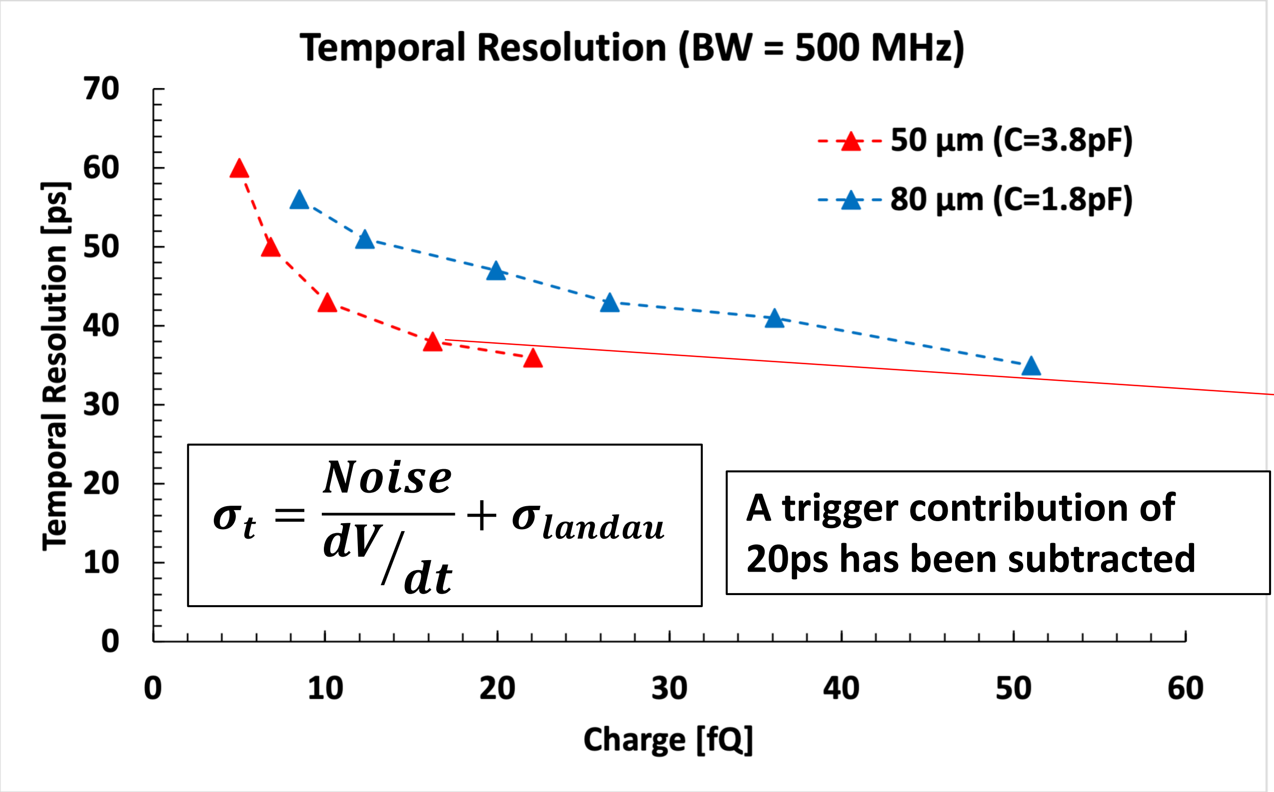


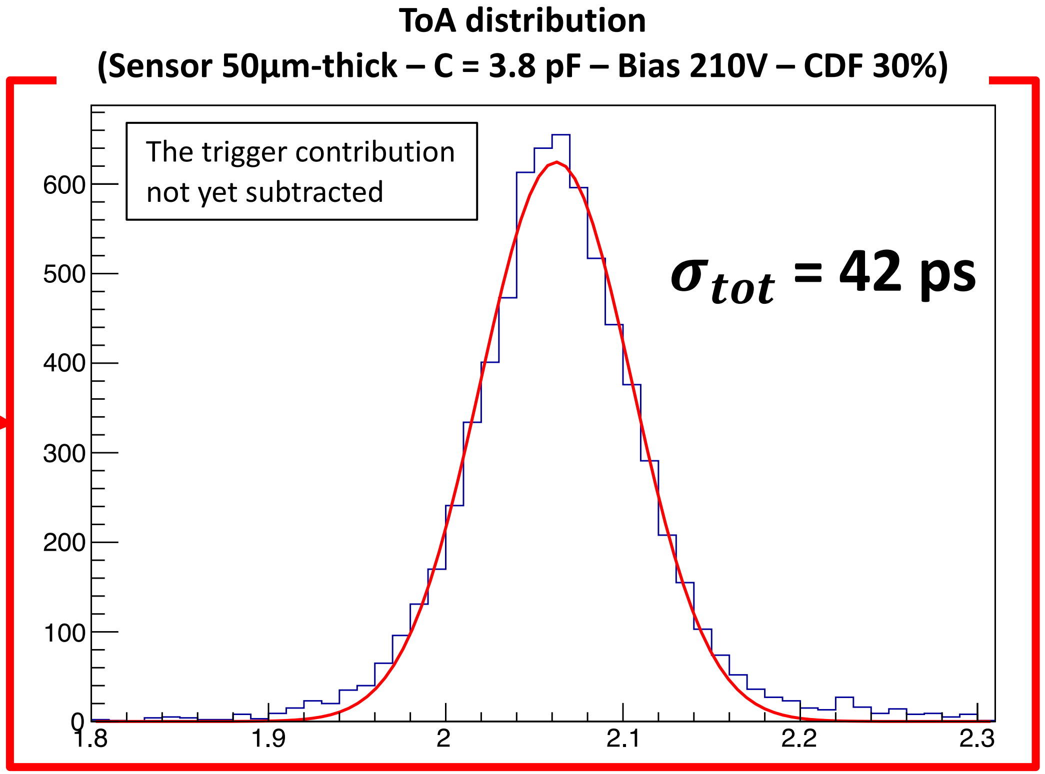
Slew rate and **SNR** are affected by sensor capacitance:

- Smaller pixel capacitance results in a steeper slew rate and higher SNR
- SNR in good agreement with post-layout simulation results

Temporal resolution

Temporal resolution estimated using the CFD method at 30% of the signal amplitude





- FAST3 is able of achieving **35 ps** of resolution for both investigated senso thickness
- Differences between 50 and 80µm-thick sensors are attributable landau noise, not to FAST3.
- The Time of Arrival distribution exhibits good gaussian shape, with no extra tail are present

Conclusions

- FAST3 (Analog-version) is a 16-channel, low power and low noise ASIC design to readout thin-LGAD sensors

- Laboratory characterizations have been performed with low temporal jitter pulser. Key results include:
  - **Linearity of the gain** as a function of the injected charge up to 40fC, consistent with post-layout simulations.
  - A measured relationship between pixel capacitance and FAST3 channel gain: the ASIC gain decreases as C_{pixe} increases (Gain∼10mV/fC for C_{pixel} ∼1pF).
  - **The temporal jitter** is below **25 ps** for injected charge above 10 fC.

- FAST3, wire-bonded to 50µm- and 80µm-thick LGADs, has been characterized with particles (Sr^{90}-source and 5GeV electrons at beam test). Key observations include:
  - Pixel capacitance affects Noise, Slew Rate and SNR (**lower C_{pixe}= higher SNR**)
  - SNR measurements are in good agreement with post-layout simulation
  - FAST3 achieves a temporal resolution of **35 ps**

FAST3 is an excellent read-out front-end for R&D activities on LGADs and experiments with a moderate number of readout channels

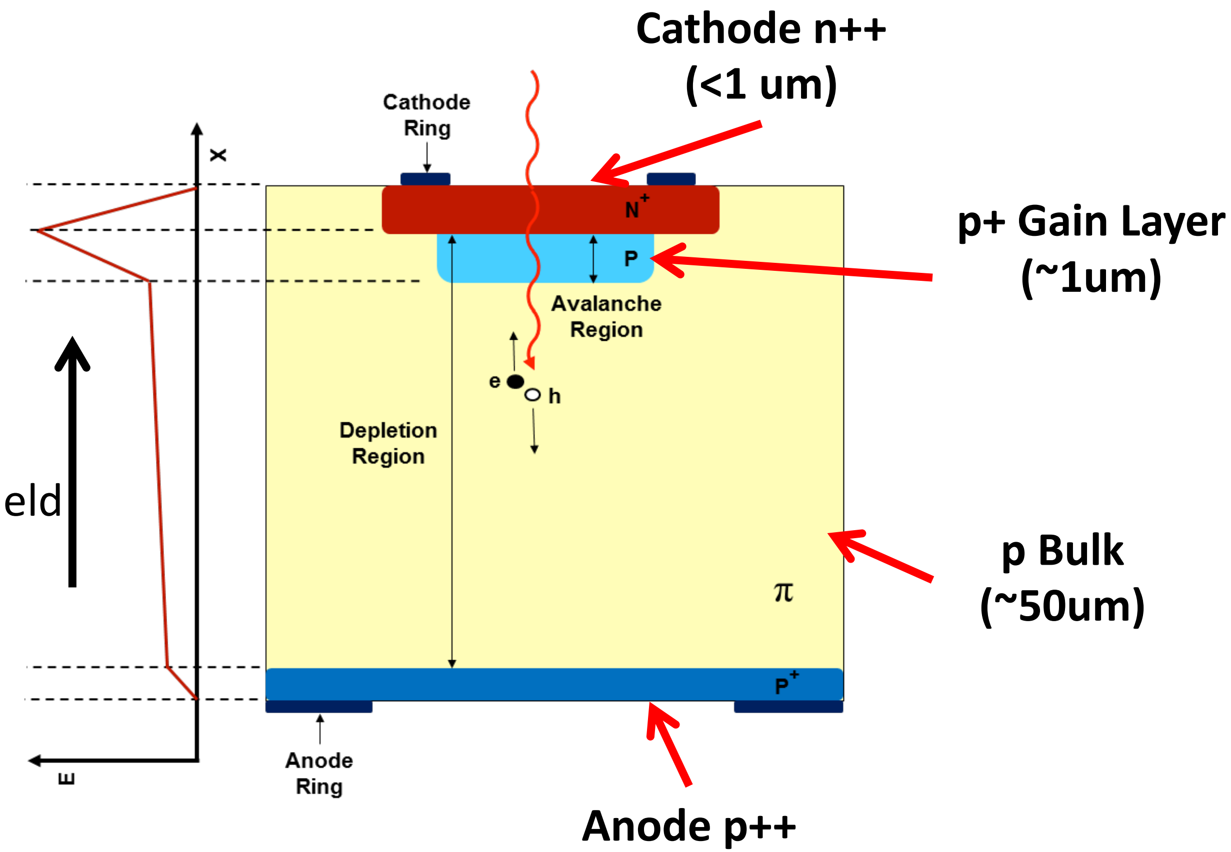
Acknowledgment

- Microelectronic group and electronic Laboratory of INFN Turin
- DESY staff for the support during the beam campaigns

Backup

LGAD - thecnology

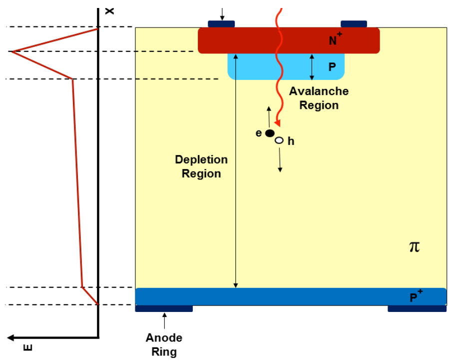
The Gain Layer (~10^16/cm^3) generate a region with an high electric field (300kV/cm), enough to activate the multiplication of electrons and holes.



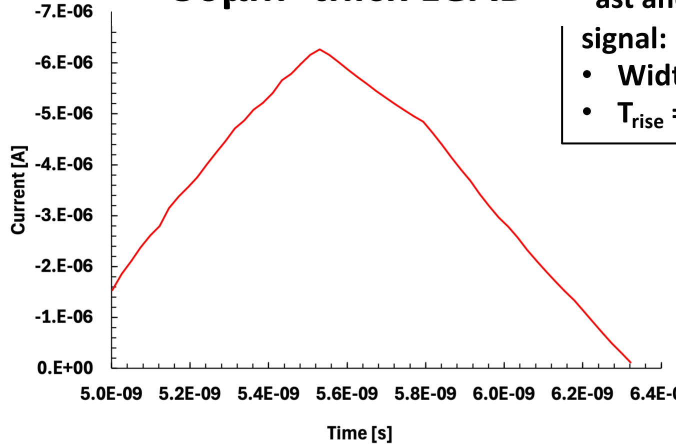
LGAD is a cross breed between APD and standard detector

LGAD performance

LGAD: planar silicon sensor with internal gain



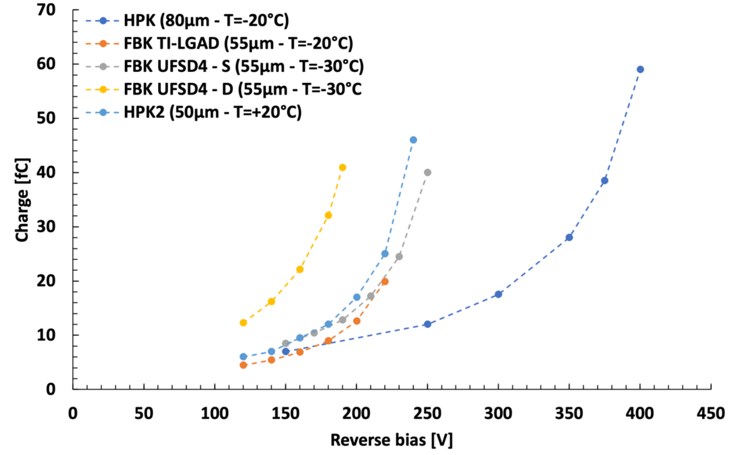
Typical signal from 50µm–thick LGAD



Fast and steep signal:

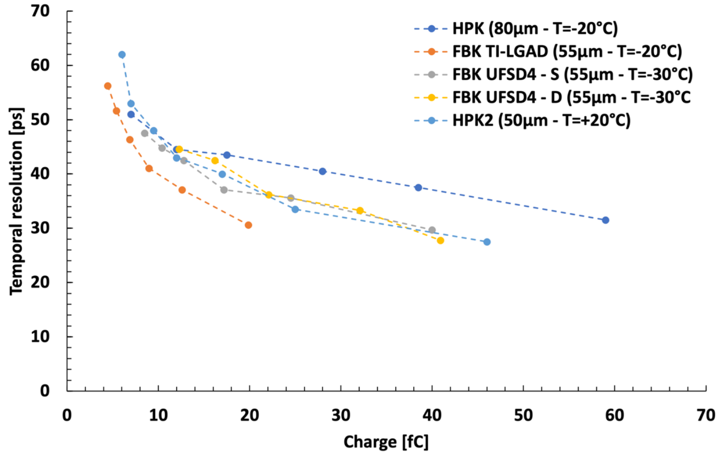
- Width = 1.3 ns
- T_{rise} = 500 ps

Typical LGAD delivered charge



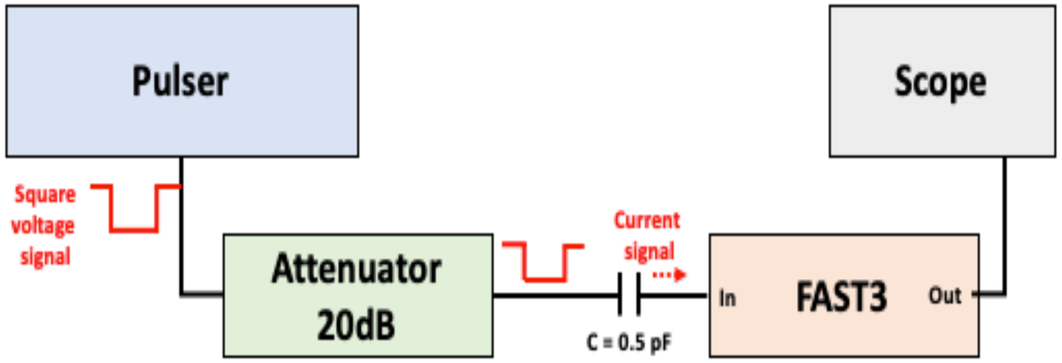
Range of delivered charge: 3-50 fC

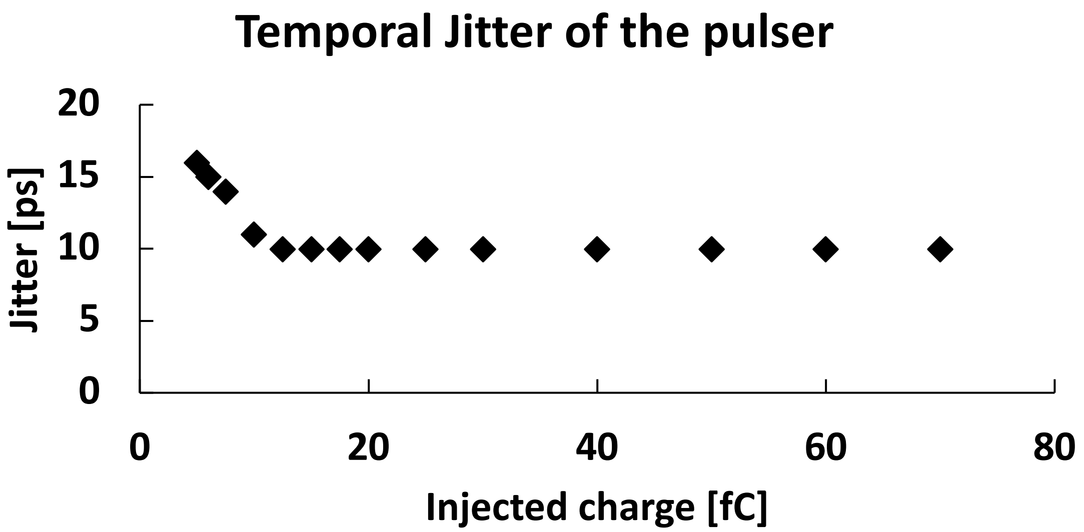
Typical LGAD temporal resolution



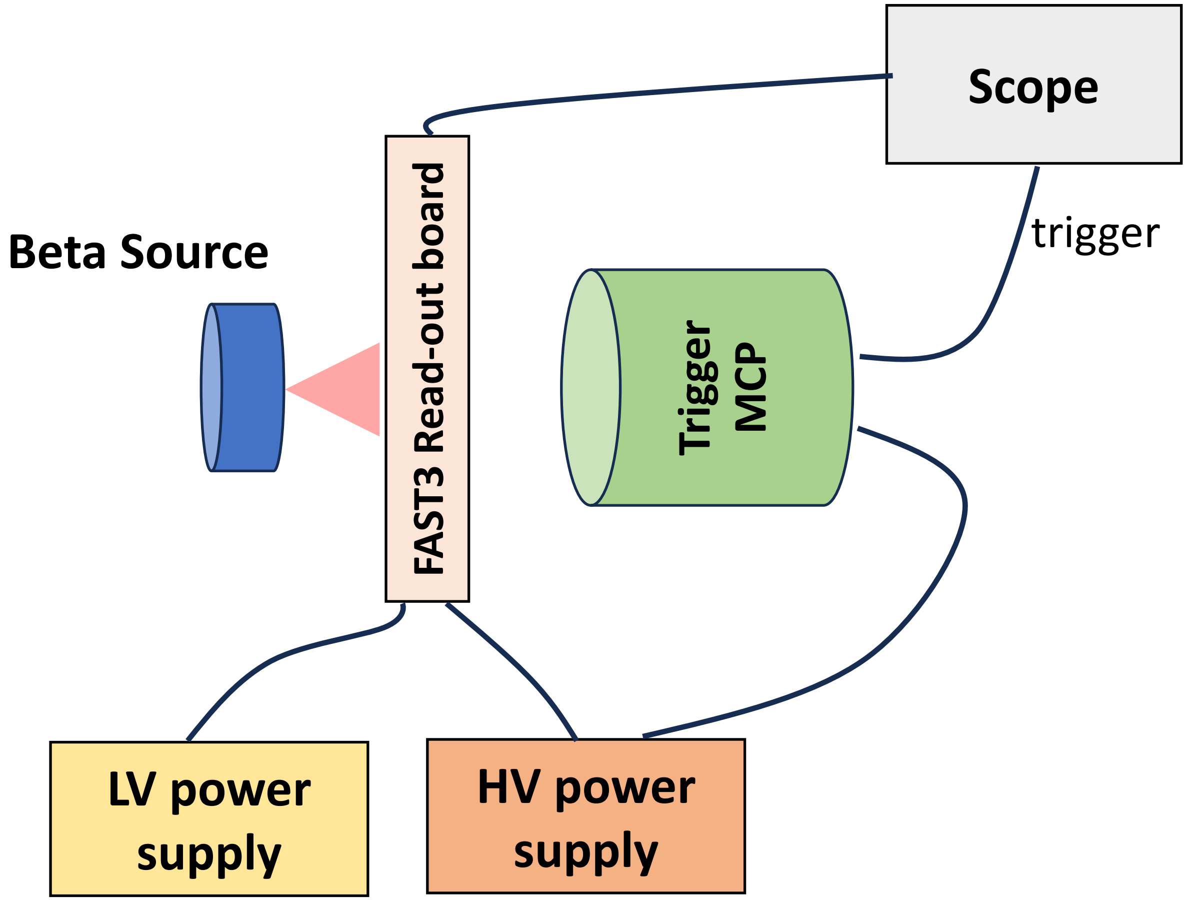
Temporal resolution of 30-35 ps

Pulser setup



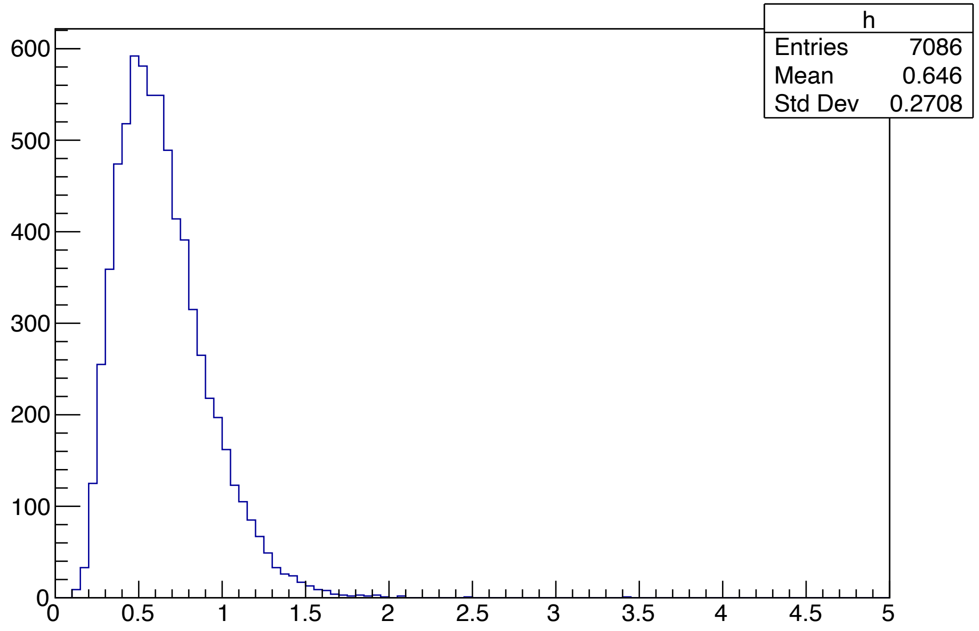


β and beam test setup



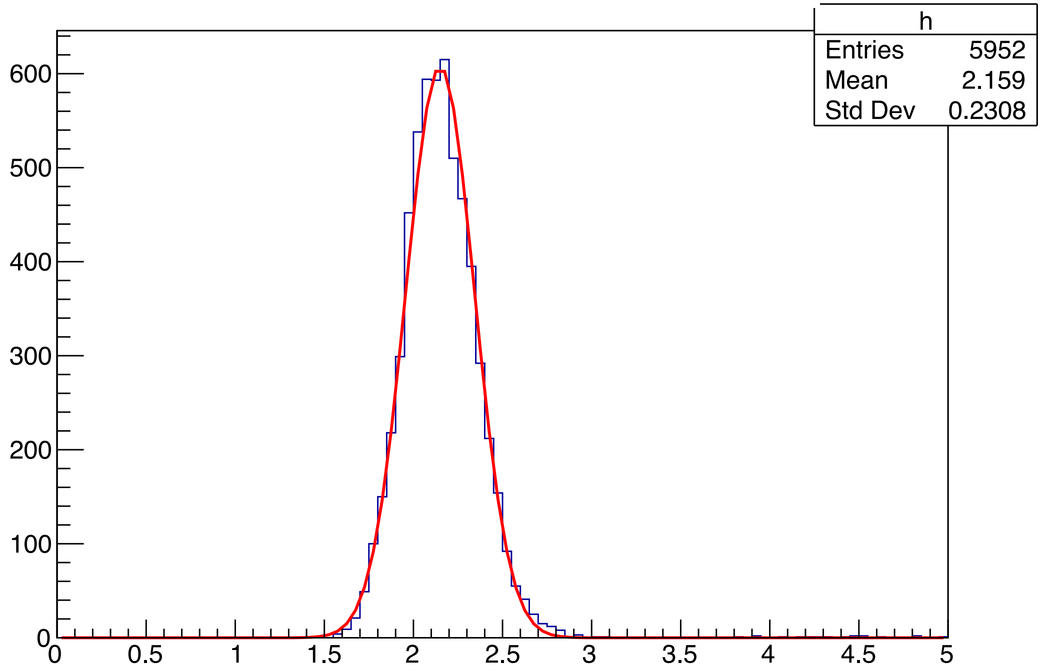
RMS noise – comparison with 2 GHz and 500MHz bandwidth

RMS Noise (BW = 500 MHz)
50 µm-thick LGAD (C = 3.8 pF)



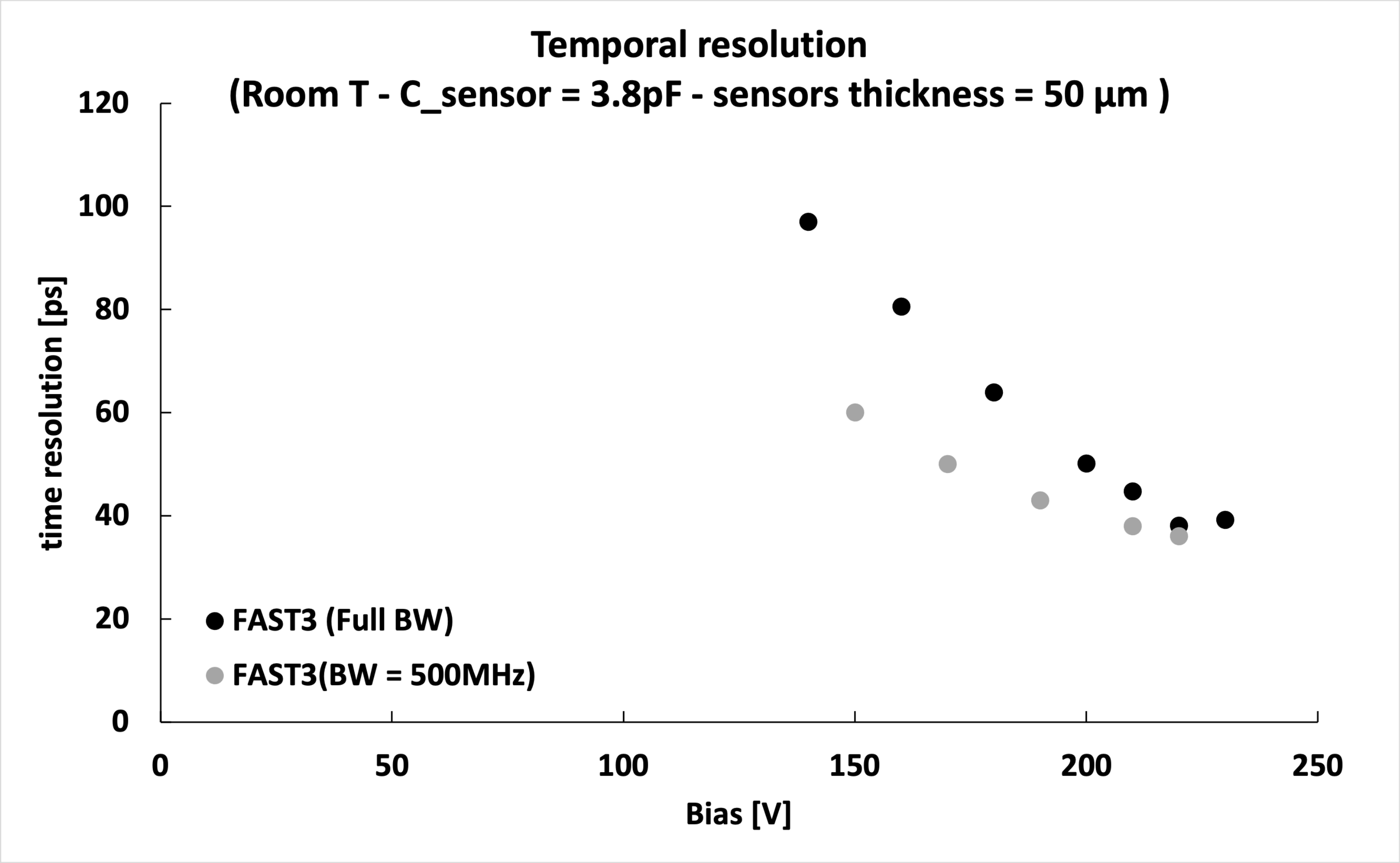
- Not gaussian distribution
- Peak distribution at ~ 0.6 mV

RMS Noise (Full bandwidth)
50 µm-thick LGAD (C = 3.8 pF)



- Gaussian distribution
- Peak distribution at ~ 2.1 mV

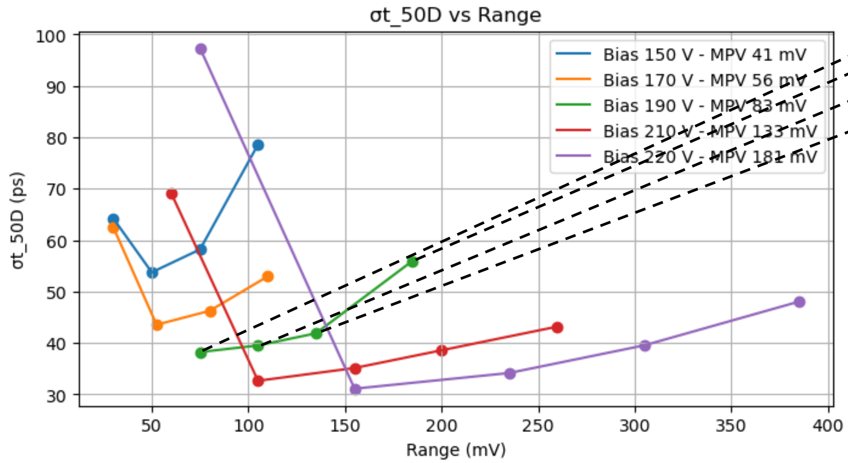
Temporal resolution– comparison with 2 GHz and 500MHz bandwidth

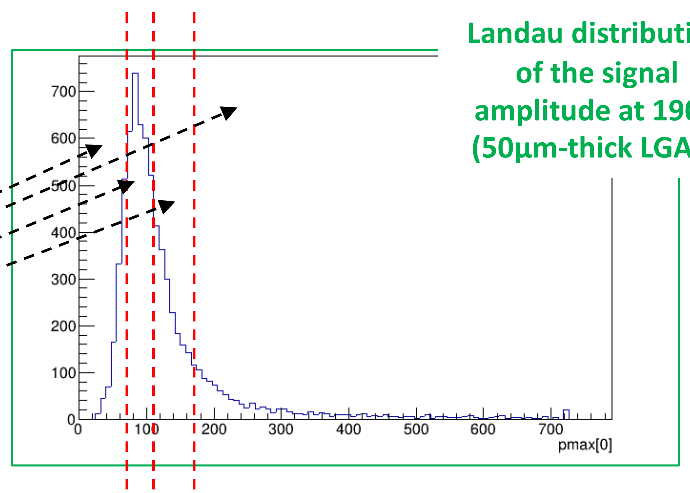


Clear effect of the DAQ bandwidth on FAST3 temporal performance

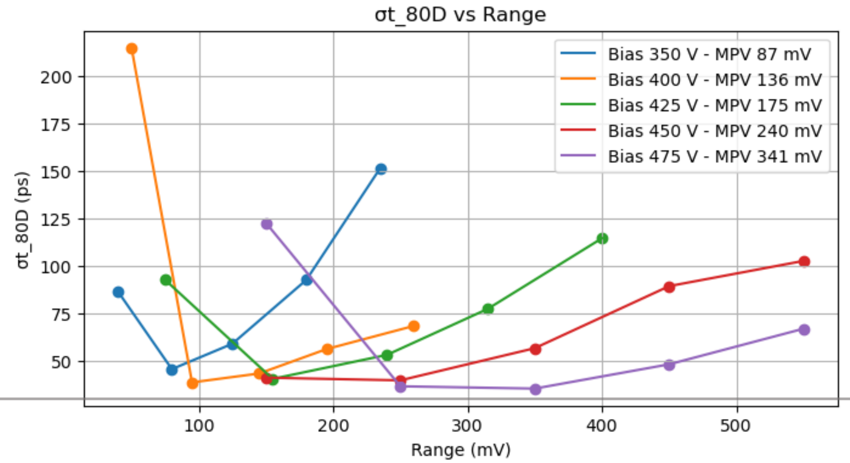
Comparison between β-source and beam test measurements on 80µm-thick LGAD

Time resolution by selecting different signal amplitude ranges in the landau distribution



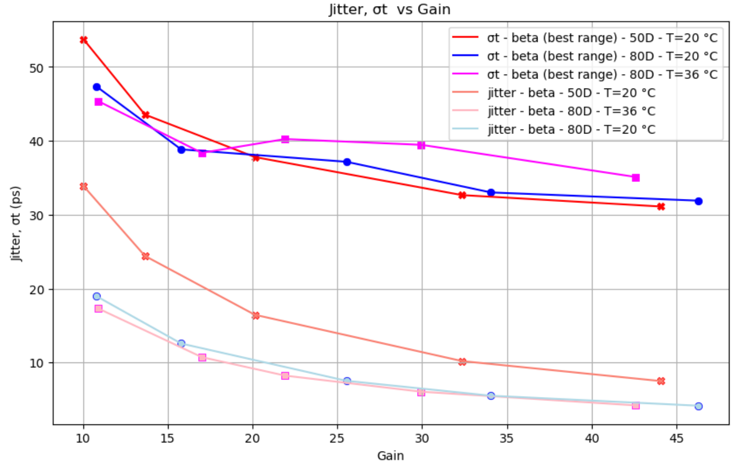


Landau distribution of the signal amplitude at 190V (50µm-thick LGAD)



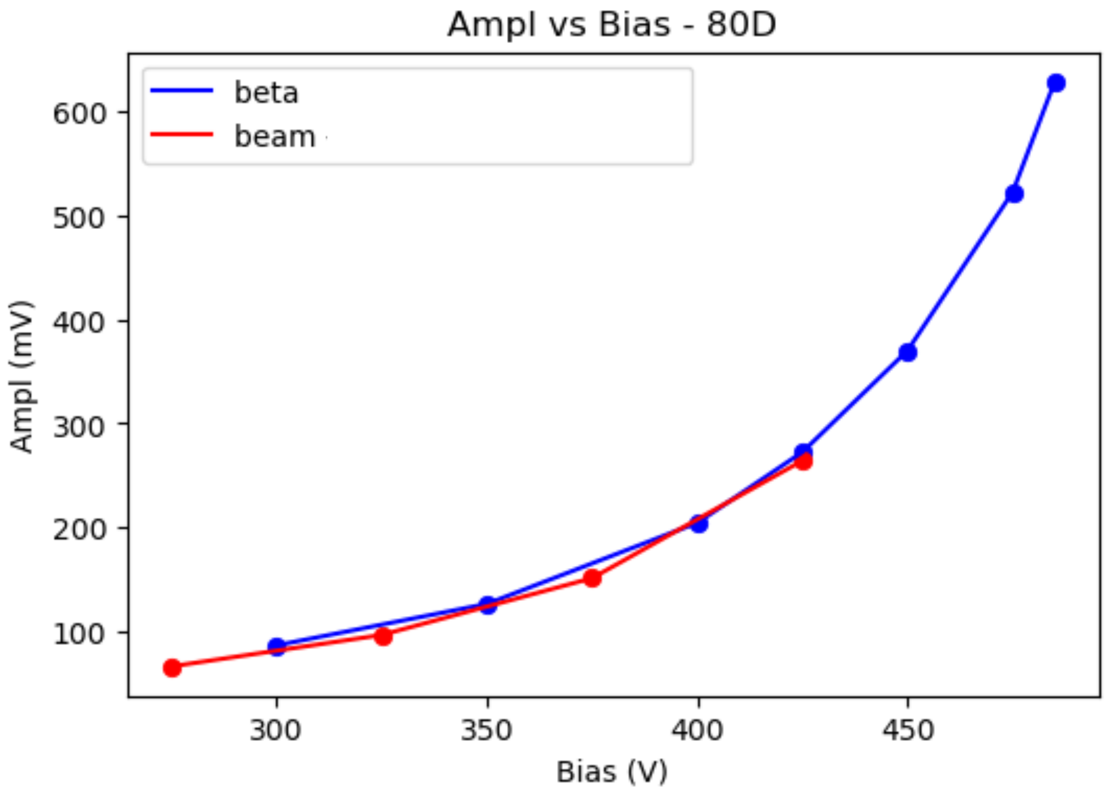
the minimum temporal resolution value is obtained selecting events in the peak of the landau

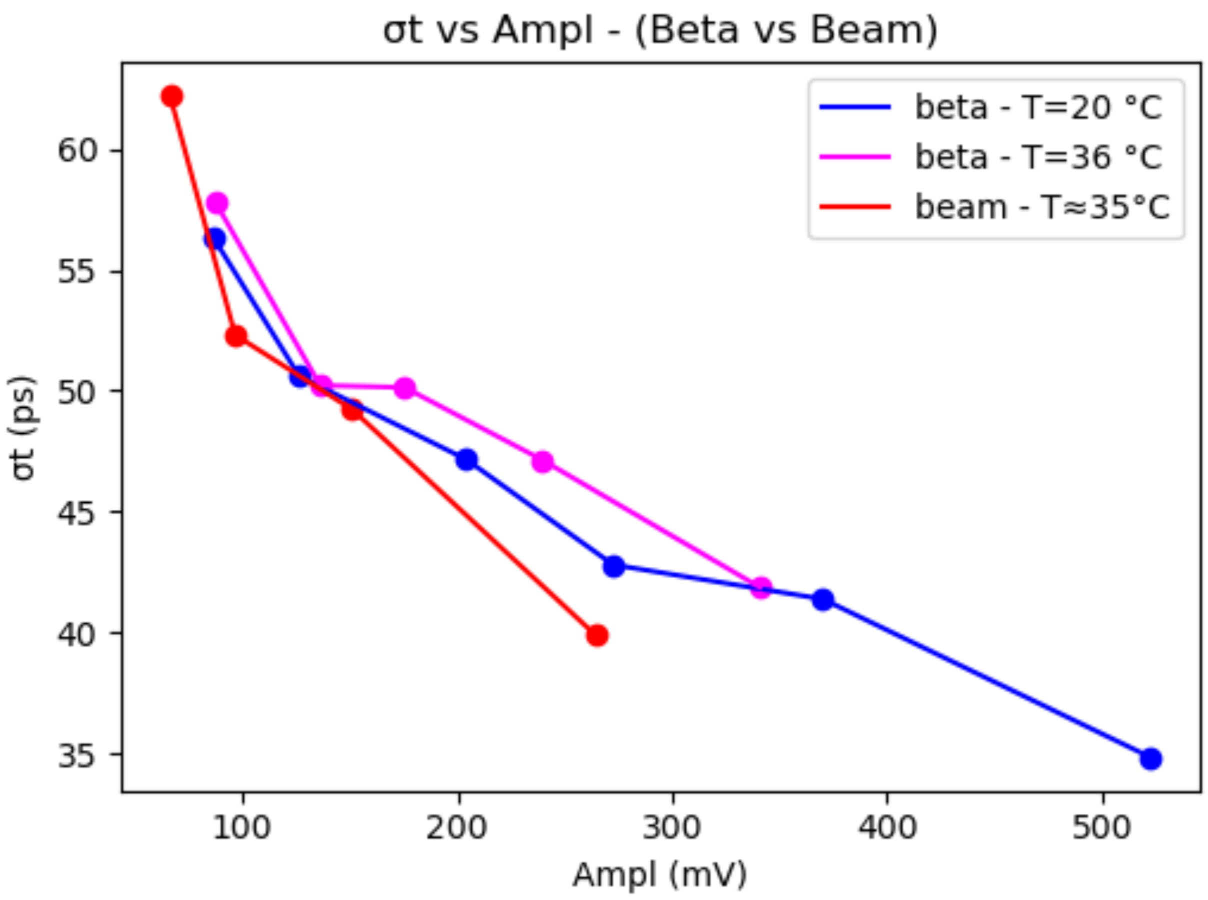
Temporal resolution of 50 and 80 µm-thick LGAD obtained by signal from the peak of the landau distribution



50 and 80 µm-thick LGAD achieve the same temporal resolution by selecting event from the peak of landau distribution

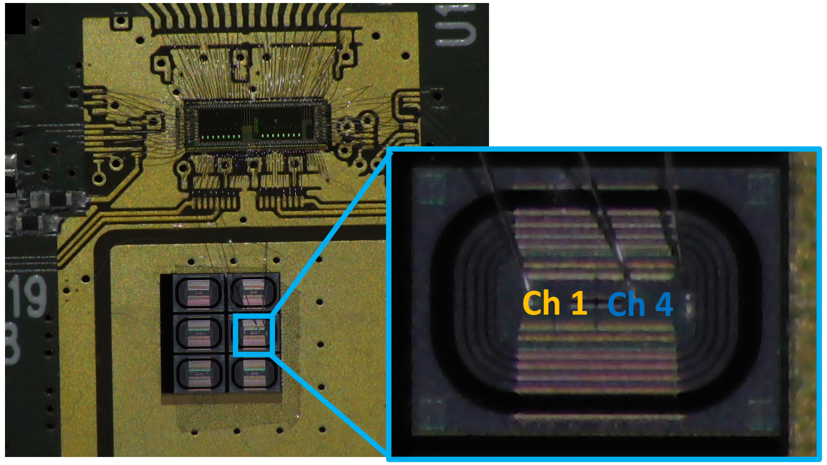
Comparison between β-source and beam test measurements on 80μm-thick LGAD



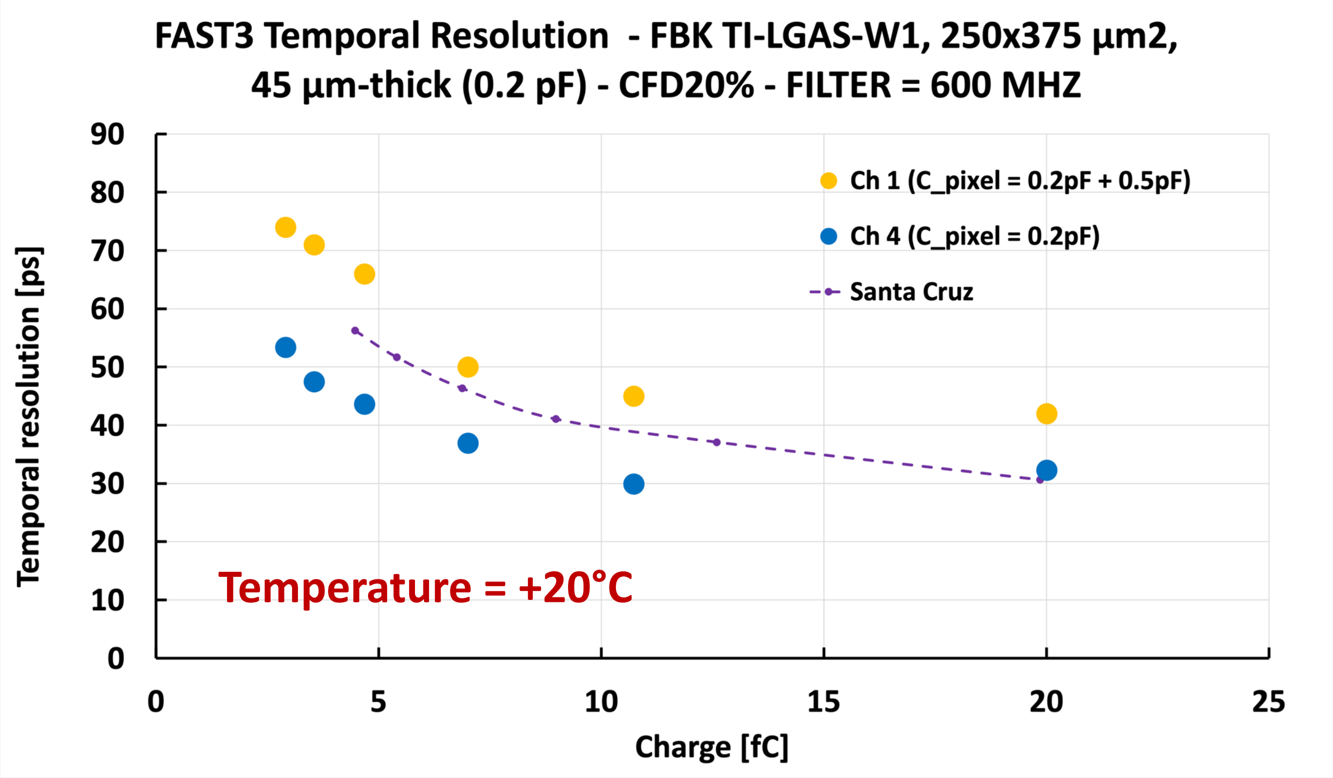


Comparison of FAST3-performance with pixels wit different capacitances

ASIC2 + FBK-TI-LGAD1 2x1 array (45µm-thick)
Sensor pixel size: 250 x 375 µm^2 (C_{pixel} = 0.2 pf)

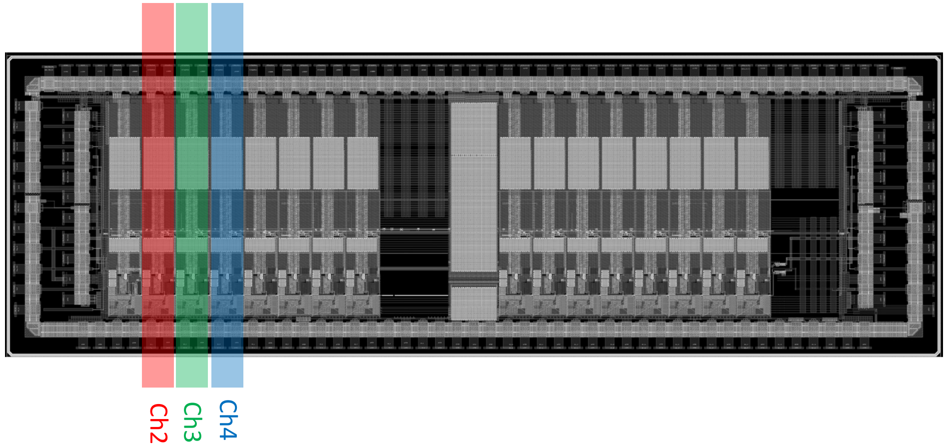


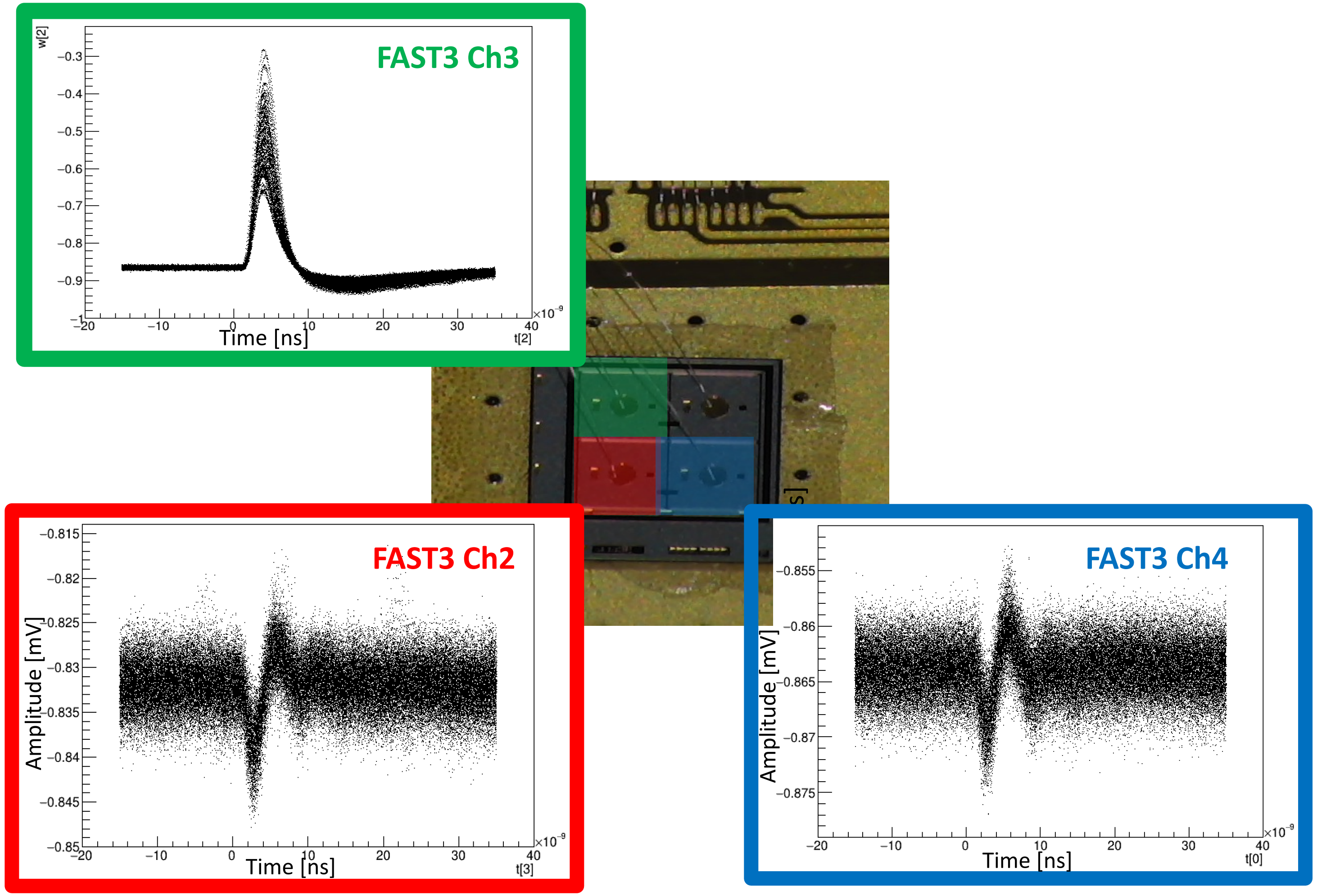
- Ch 1 → C = 0.5pF + 0.2pF (C_{pixel})
- Ch 4 → C = 0.2pF (C_{pixel})



- The difference in performance between Ch1 and Ch4 is solely due to the different capacitance in input to FAST3-channels
- FAST3 performance are for smaller pixels (C_{pixel} < 0.5pF)

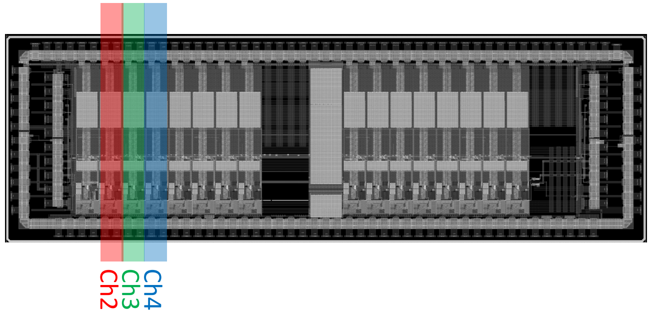
Inter-channel cross talk – signal shape

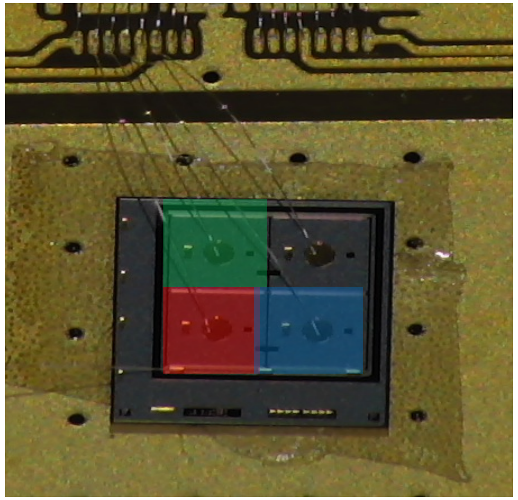




Investigation of Inter-channel crosstalk

Read out channels





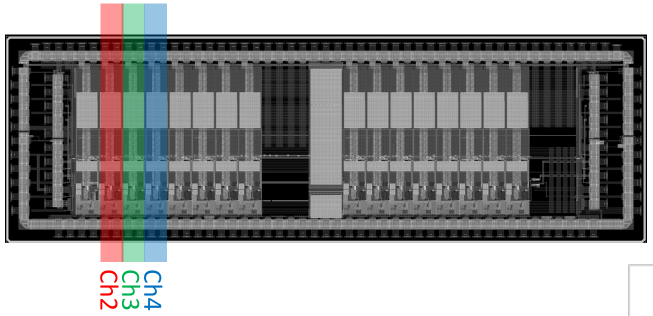
Read out pixel

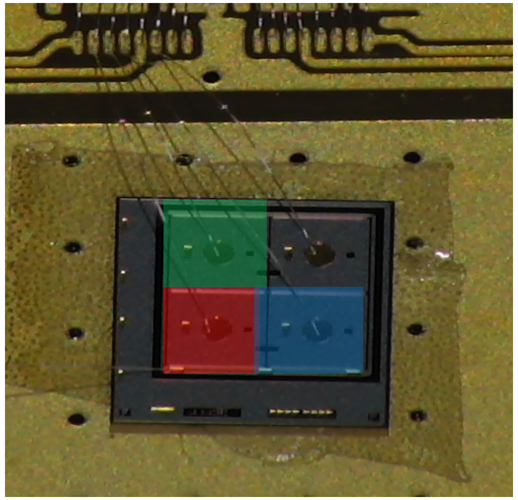
Crosstalk analysis

- FAST3 channel involved in the analysis: Ch2, Ch3 and Ch4
- Analysis of data acquired using β-setup with the 50µm-thick LGAD
- Isolation of signals generated by the passage of an e^- in the pixel readout by ch3
- Exclusion of all signals generated by the passage of an e^- in pixels readout by ch2 and 4

Investigation of Inter-channel crosstalk

Read out channels





Read out pixel

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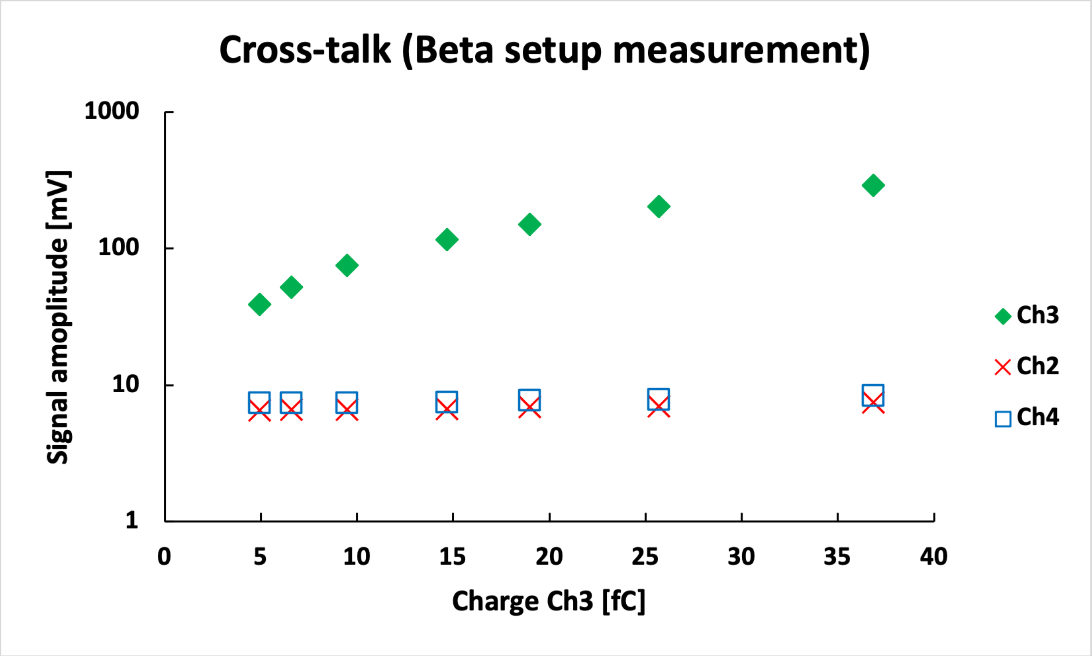

No cross-talk was observed

Increasing the charge injected into a FAST3 channel the adjacent ones do not show an increase in signal