Radiation tolerance of thin (50 & 35 μm) LGAD sensors… …and epilogue (maybe) on I-LGAD timing

14th Workshop on Advanced Silicon Radiation Detectors

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Developed inside the RD50 collaboration & AIDA -2020 WP7 on Advanced Hybrid Detectors.

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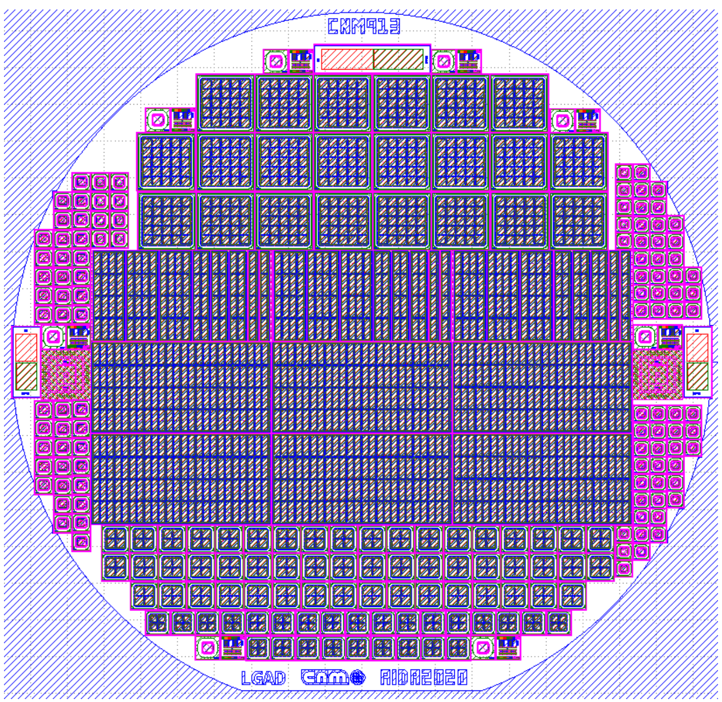
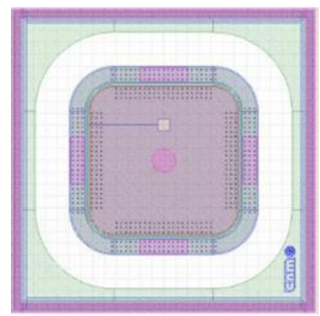
Outline

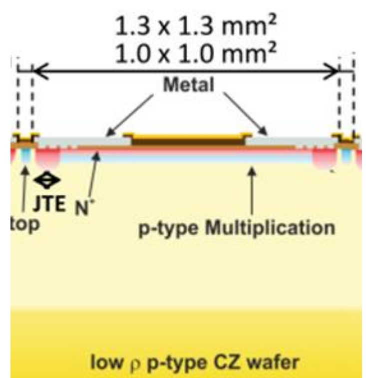
- Radiation tolerance of thin LGADs
  - Motivation & sample description
  - Electrical characterization: IV & CV
  - Charge collection vs fluence.
  - On the radiation damage mechanism(s)
  - Slewing rate vs fluence.
- Detailed timing study of Inverse-Low Gain Avalanche Detectors (ILGAD)
  - Technology description.
  - Performance of proof-of-concept prototype

Motivation , Samples & Irradiation points

- Compare the radiation tolerance (protons) of LGAD with **two different active thickness: 50 and 35 μm**.
- Samples form CNM Run#11748 (AIDA-2020 WP7)





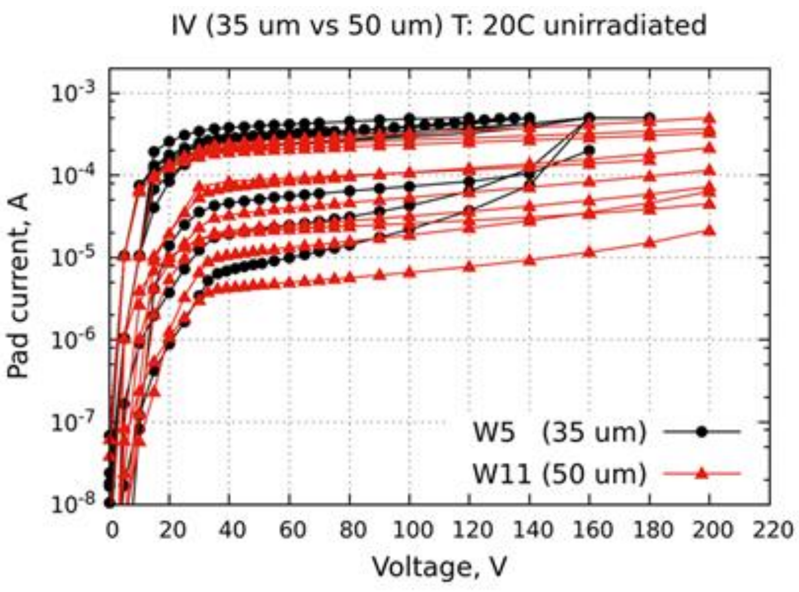


Total area of 2.6x2.6 mm^2
Active area of 1.3x1.3 mm^2
Intermediate gain

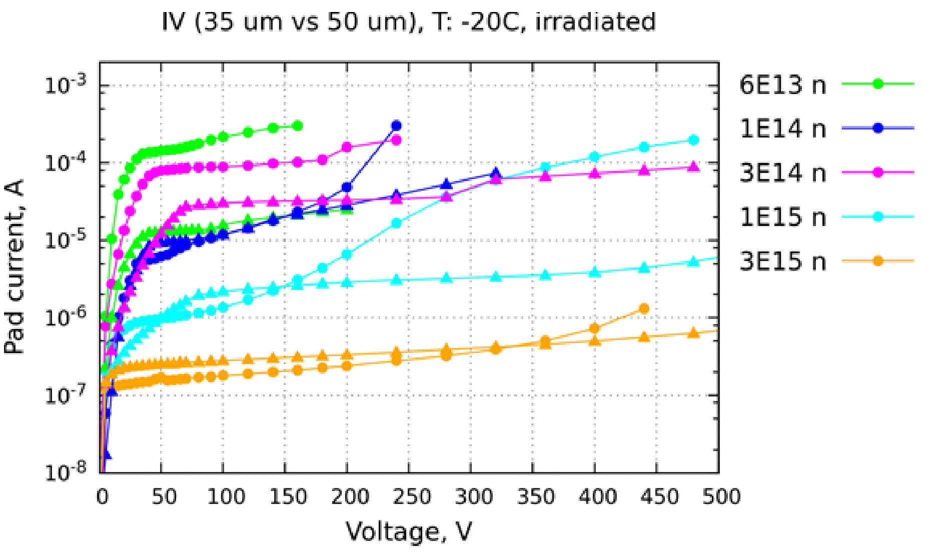
- Irradiated at CERN PS with 24 GeV protons at **5 different fluences.**
  - 6E13 n_{eq}/cm2
  - 1E14 n_{eq}/cm2
  - 3E14 n_{eq}/cm2
  - 1E15 n_{eq}/cm2
  - 3E15 n_{eq}/cm2

Electrical Characterization: IV Curves

- Large reverse current (unexpected).
- The reverse current is suppressed by irradiation.
- Originated (most likely) at the at diode perifery (JTE structure).



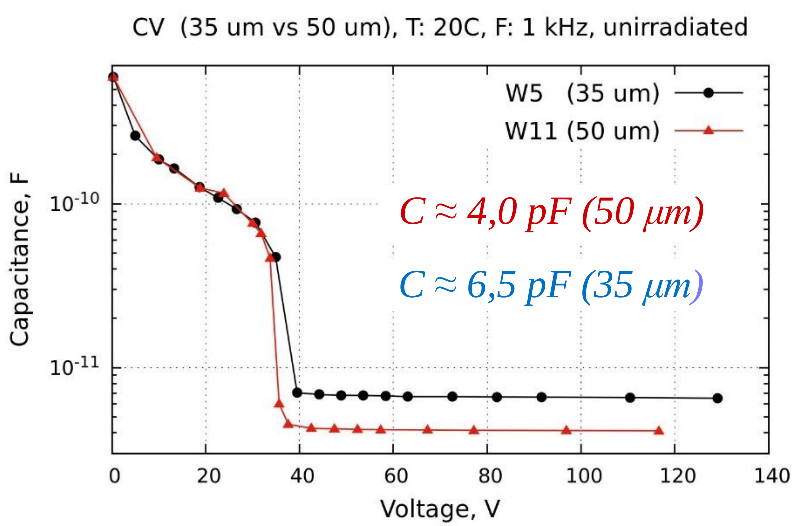
BEFORE IRRADIATION



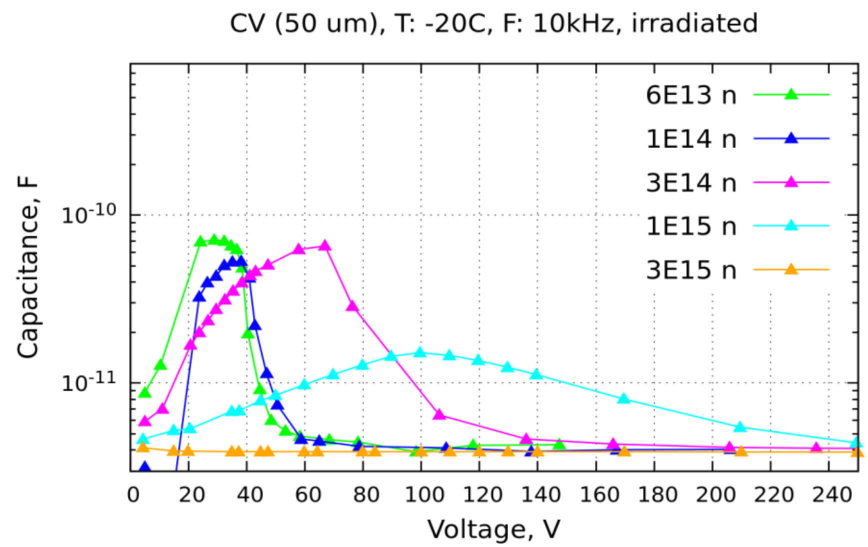
AFTER IRRADIATION

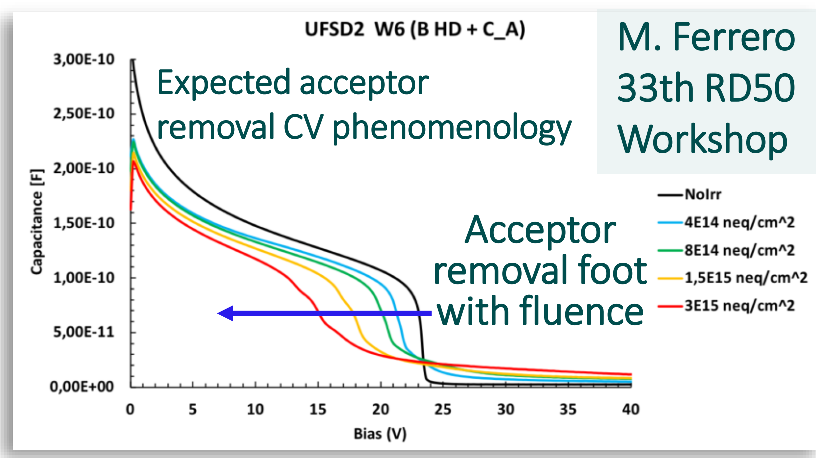
Electrical characterization: CV curves

BEFORE IRRADIATION



AFTER IRRADIATION



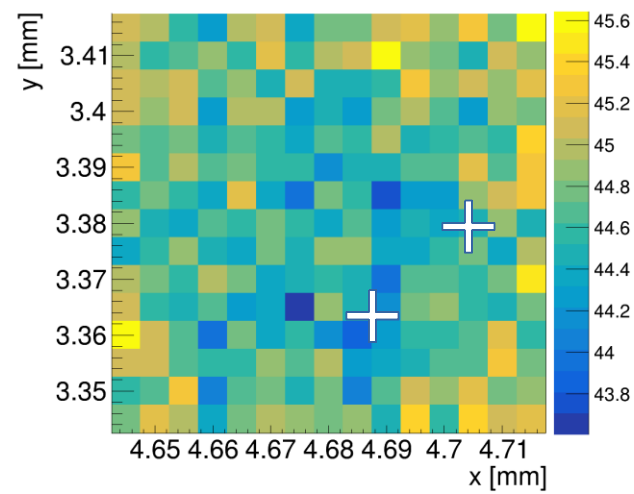


CV characteristics does not follow simple acceptor removal model after irradiation (to be discussed)

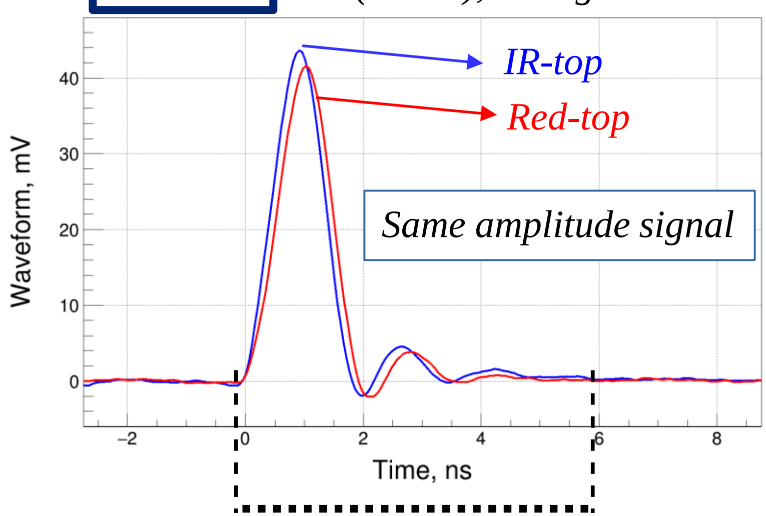
TCT Characterization: Charge Collection Uniformity

- IR laser and red laser
- Top illumination
- Same laser intensity in both cases
- Temperature: -20 C
- Amplifier: CIVIDEC C2, 2 GHz, 40 dB
- Oscilloscope: Agilent DSO 9254, 2.5 GHz, 20 GSa/s
- Averaging of 256.

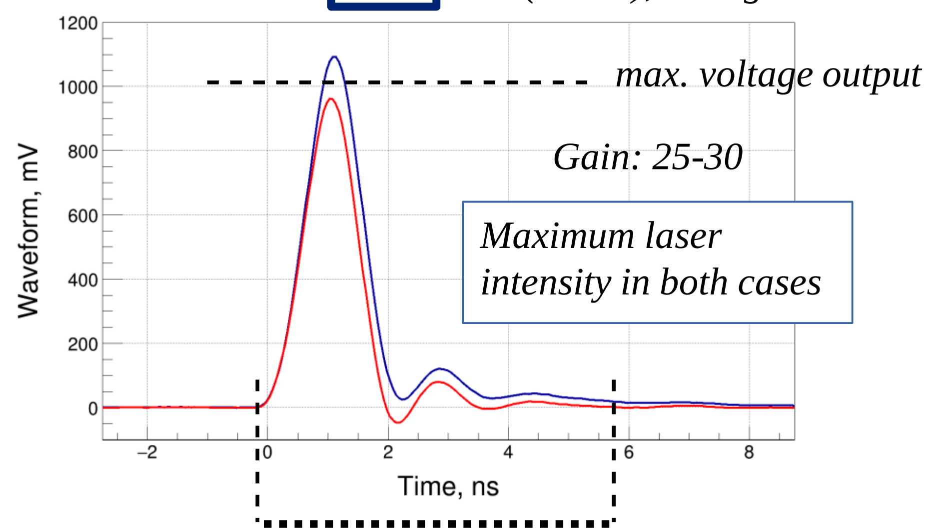
2D amplitude map, mV



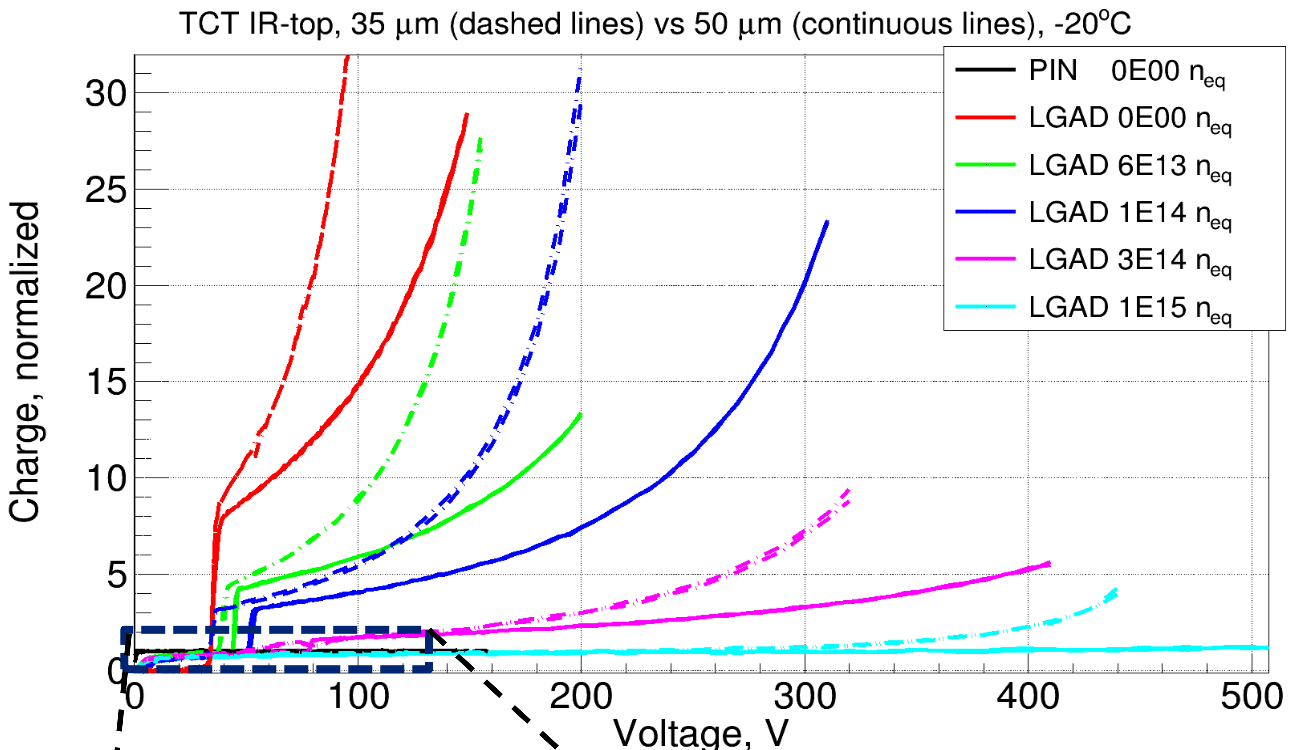
PIN diode W11 (50 um), Voltage: 100 V

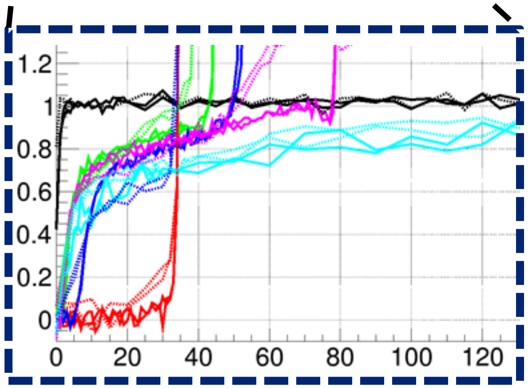


Unirradiated LGAD W11 (50 um), Voltage: 150 V

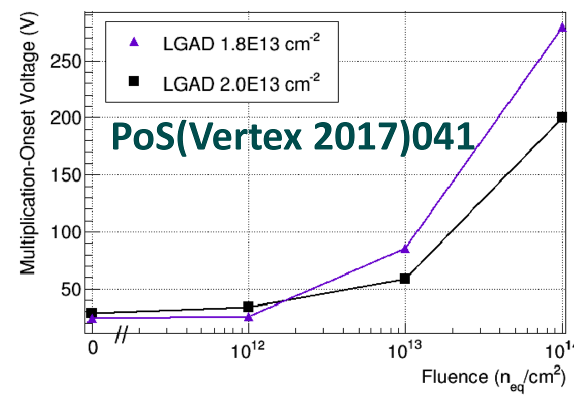


TCT Characterization: Charge vs. Bias Voltage





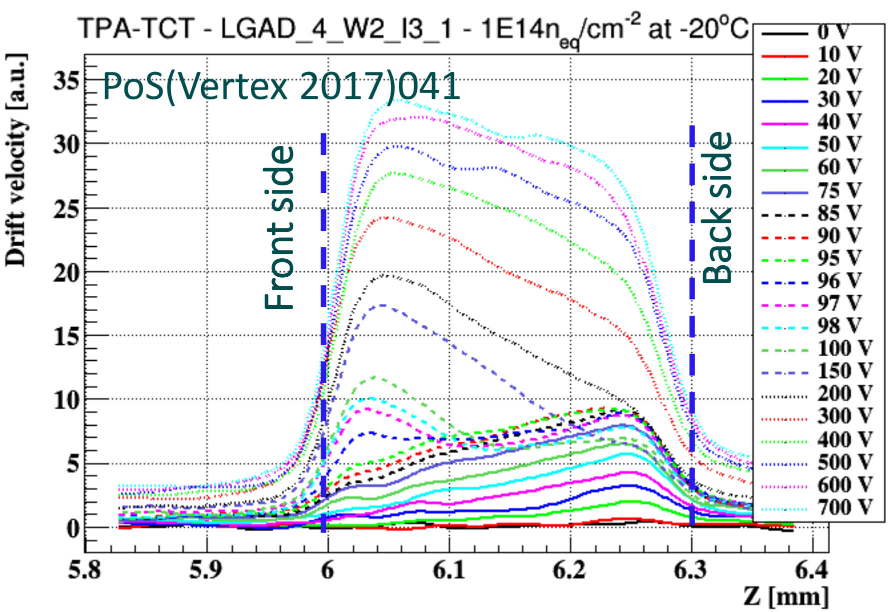
Positive shift of gain offset observed in [S. Otero et al., PoS(Vertex 2017)041] on 300µm thick sensors.

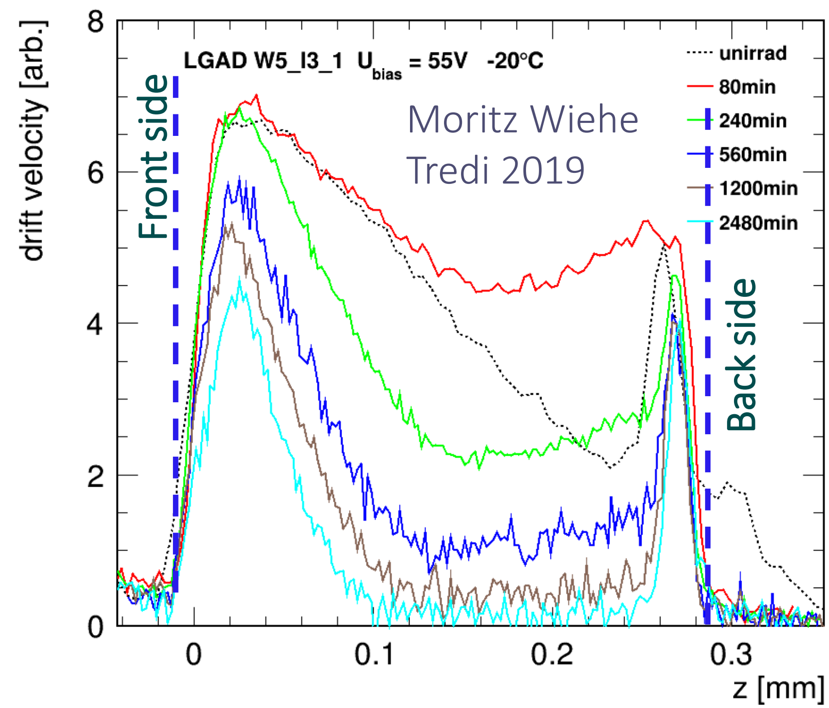


Fluence (n_{eq}/cm^2)	On-set Voltage (Volts)	CV Voltage@maximum
0	30-35	35(CV foot)
6e13	40-45	35
1e14	45-50	40
3e14	75-80	70

TCT Characterization: Charge vs. Bias Voltage (2)

- Positive shift of charge collection on-set observed previously in 300mm thick pad diodes with low reverse currents (few hundrend of nA on irrad).
- Caused by the Bulk Space Charge Inversion (BSCI) (trapped carriers)
- Double peaked E-field (velocity) with TPA-TCT and E-TCT profiles demostrated BSCI.



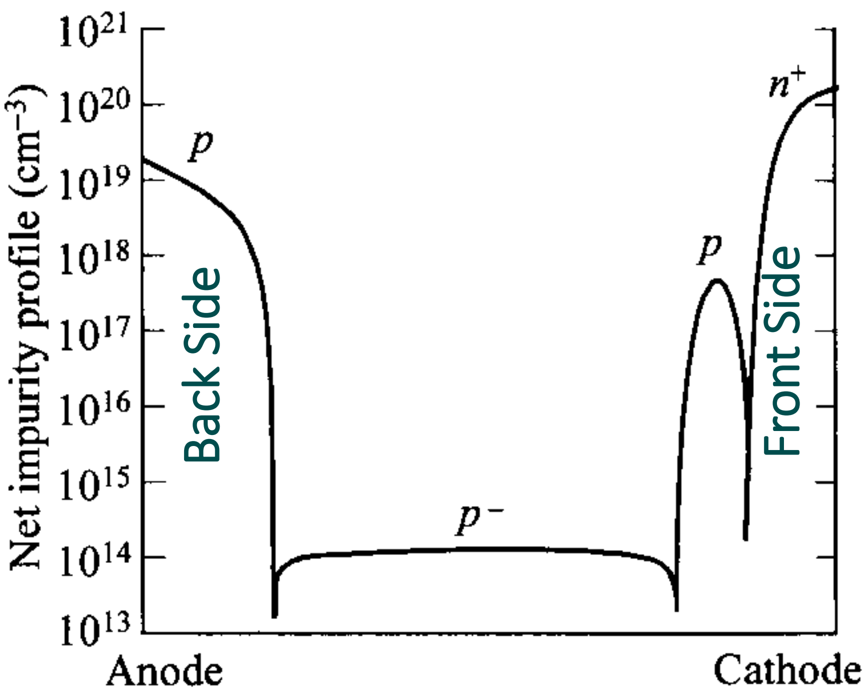


Does the BSCI induce the shift on the gain on-set?

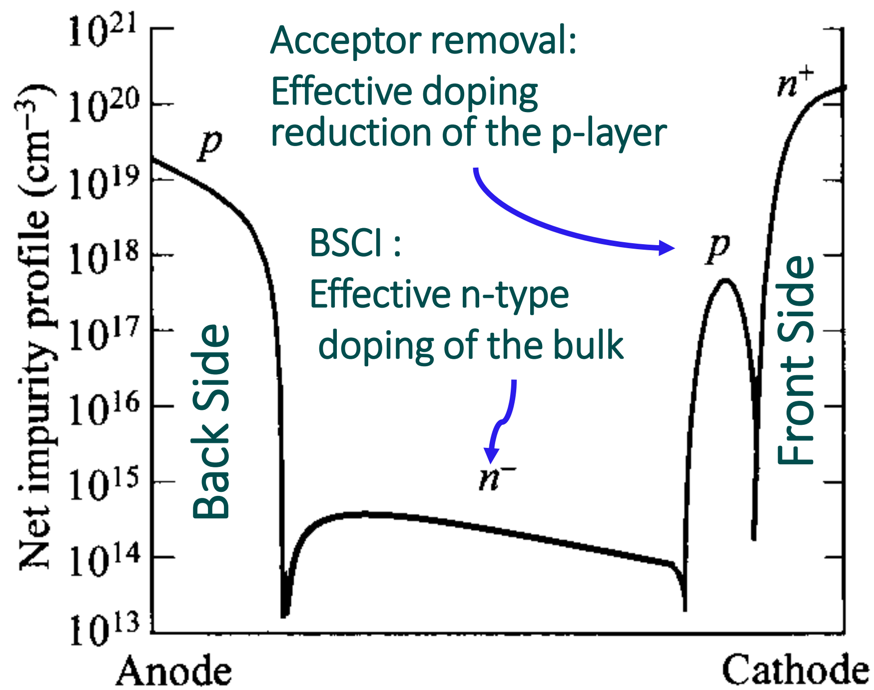
CV characteristic (revisited) - I

- Due to the BSCI of the p bulk, the LGAD becomes effectively a **Shockley four-layer diode** (aka Thyristor with floating gate).
- Can we explain the CV characteristic based on a Shockley four-layer diode?

Before irradiation,

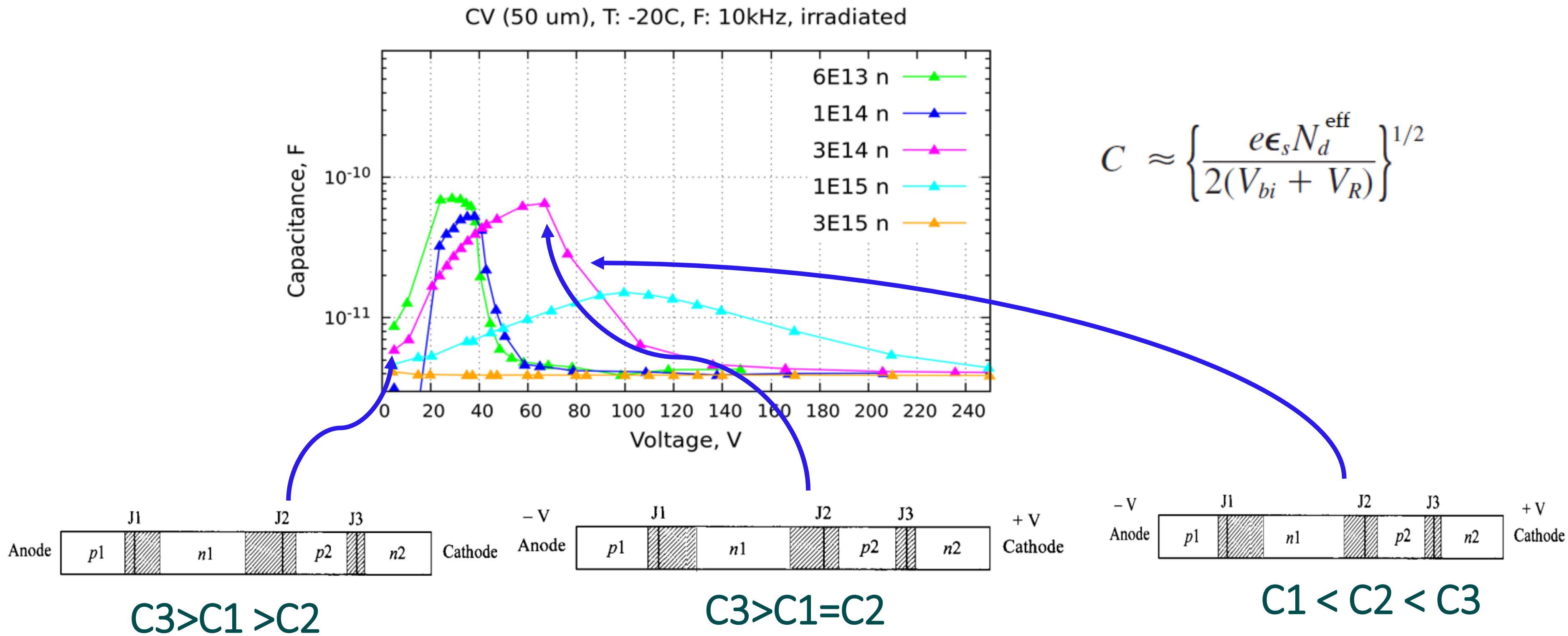


After irradiation,



CV characteristic (revisited) - II

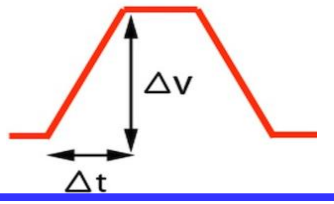
- The multijunction total capacitance is small than the smallest single junction capacitance.
- No biased:
  - J1 & J3 built-in field with same direction, J2 oposite
- Under bias(VR):
  - J1 & J3 reverse biased but **J2 is forward biased**.
  - J2 capacitance increases with VR while J1 & J3 decrease with VR.
  - Eventually J2 is not longer the smallest capacitance, J1 dominates (back side depletion and then J3 depletion)



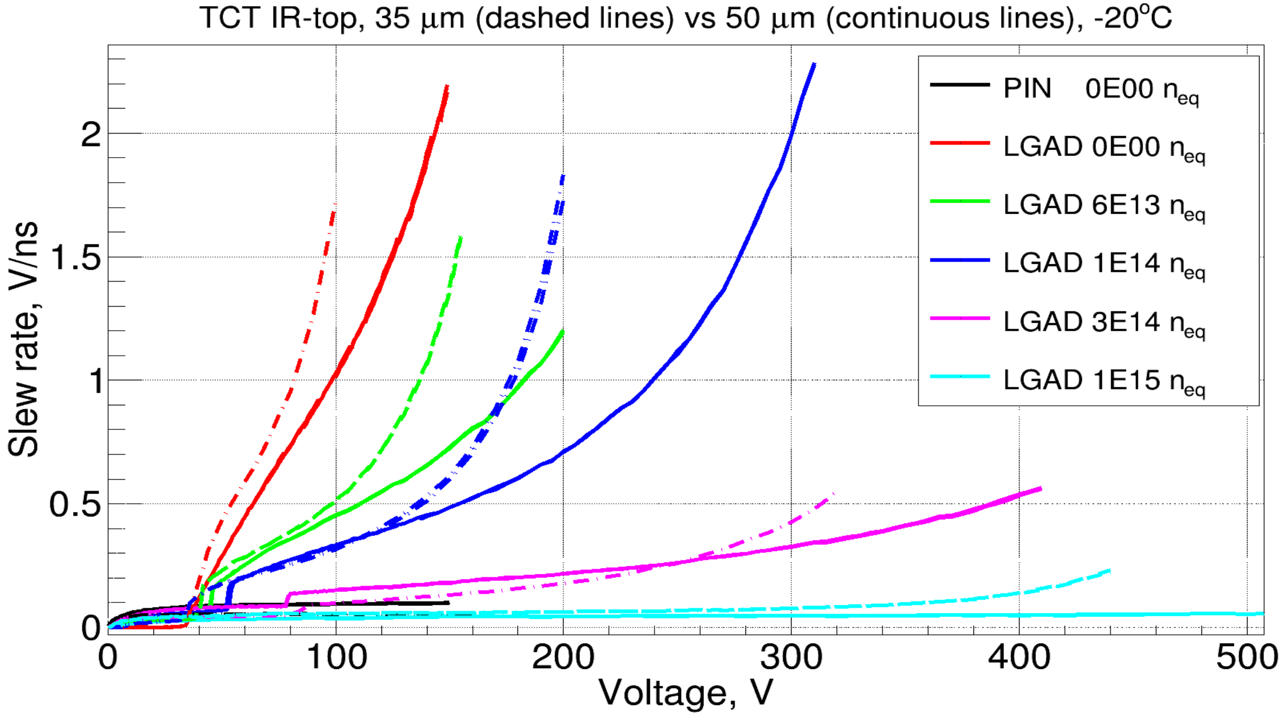
$$C \approx \left\{ \frac{e \epsilon_s N_d^{\mathrm{eff}}}{2(V_{bi} + V_R)} \right\}^{1/2}$$

First estimation of timing performance: slew rate.

$$\delta_{time} \propto \frac{\delta_{noise}}{\left|\frac{dV}{dt}\right|} \propto \frac{\Delta t}{\Delta V} * \delta_{noise} = \frac{\delta_{noise}}{SR}$$



$$SR = \frac{\Delta V}{\Delta t}$$



– Slew rate significantly better for the case of thiner LGADs.

Summary and Outlook

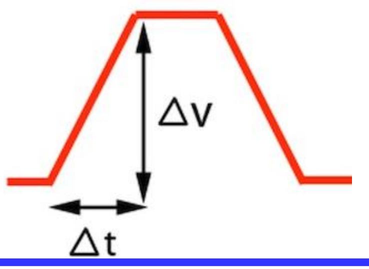
– On the radiation damage mechanism
  - CV characteristics and IR-TCT voltage on-set point to radiation-induced Bulk's Space Charge Inversion (BSCI) (first time in a thin LGAD)
  - BSCI shifts the gain on-set voltage towards higher values.

– On radiation-tolerance:
  - Better behavior of 35mm thick LGAD compared with 50 mm thick LGAD (**gain** and **leading slew-rate** wise)
  - Timing resolution assessment still in progress.

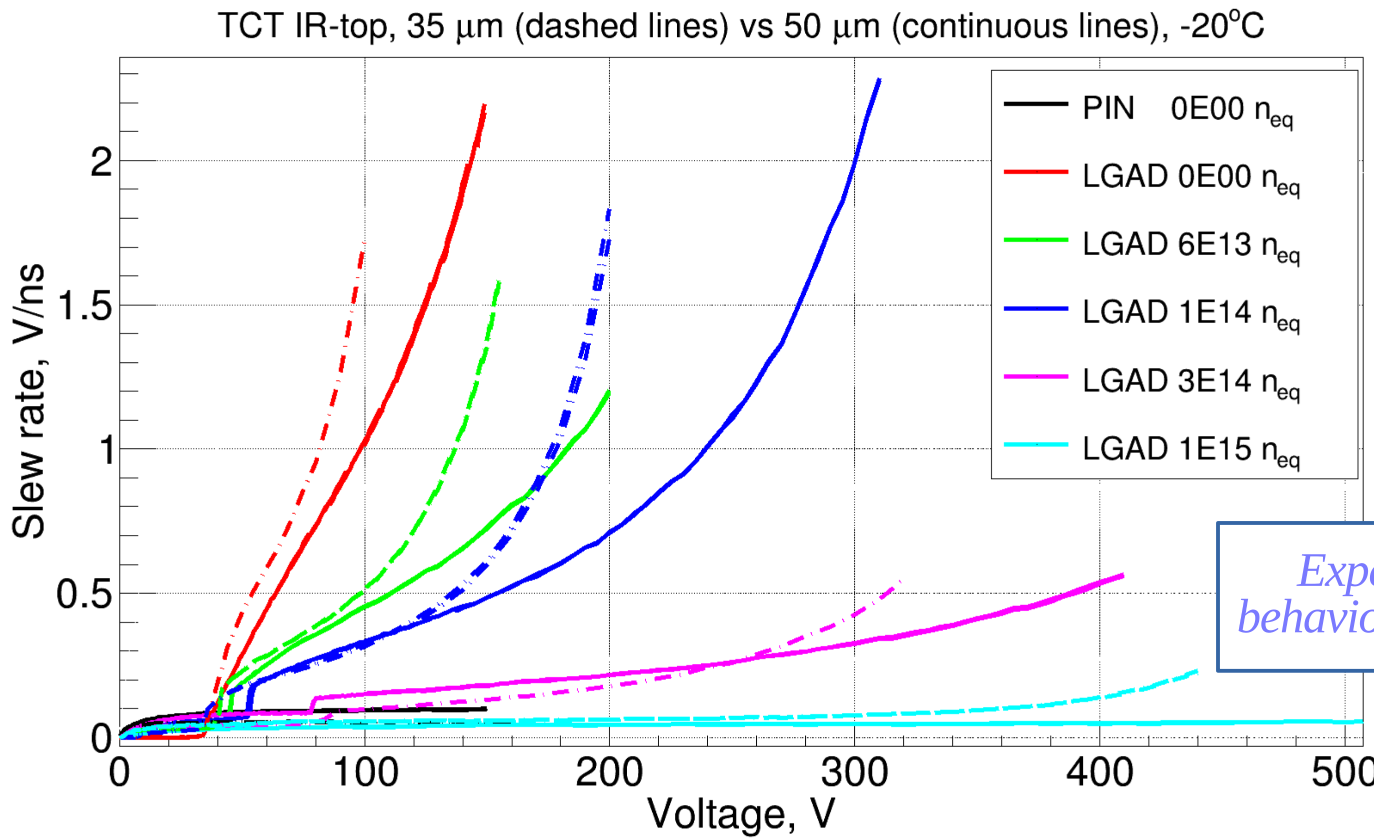
Laser measurements: Slew rate (SR)

IR laser measurements 35 um vs 50 um

$$\delta_{time} \propto \frac{\delta_{noise}}{\left|\frac{dV}{dt}\right|} \propto \frac{\Delta t}{\Delta V} * \delta_{noise} = \frac{\delta_{noise}}{SR}$$



$$SR = \frac{\Delta V}{\Delta t}$$

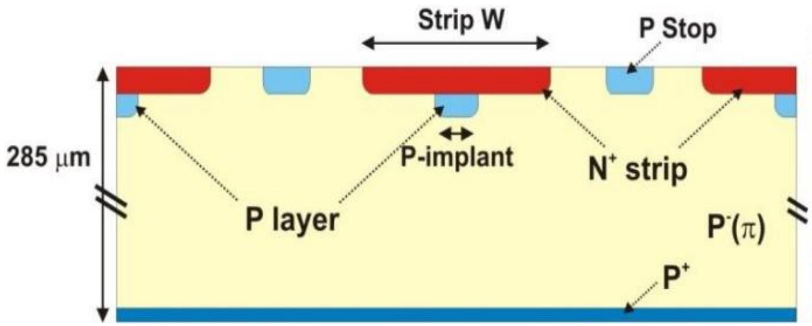


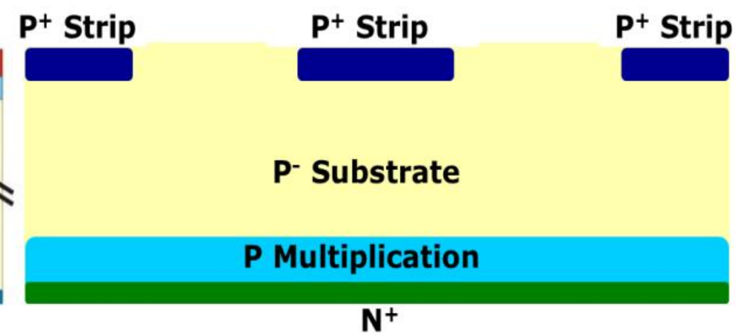
Expected good timing behavior up to 3E14 n_{eq}/cm^2

I-LGAD description

Multiplication layer divided into strip
Collects negative carriers (e)
Simple single side process

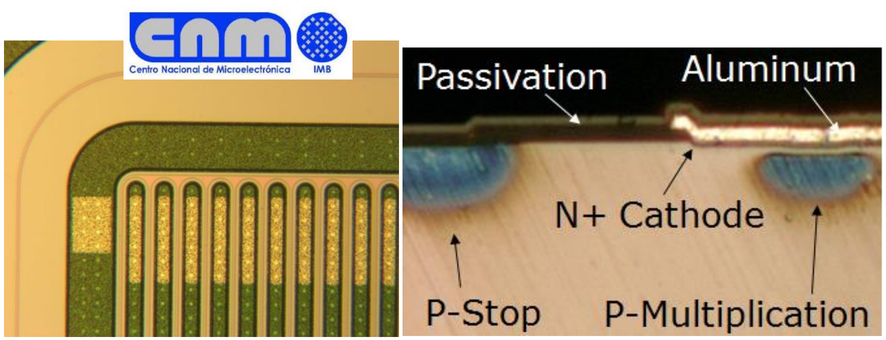
Multiplication layer extended over the electrode
Collects positive carriers (h)
Complex double side process





LGAD N on P microStrip

P on P microStrip **iLGAD**



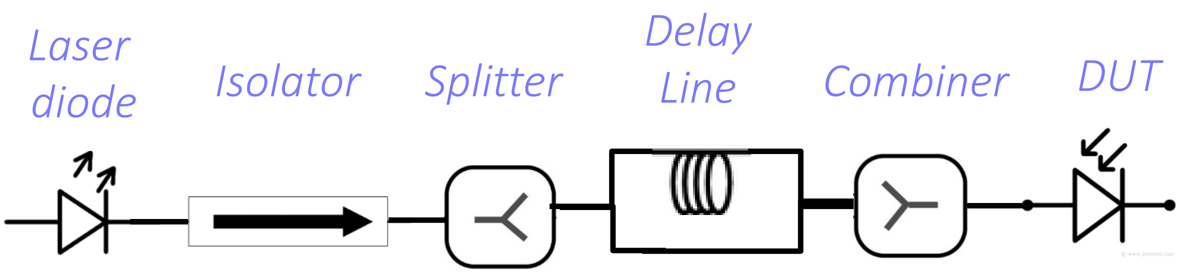
***The fill factor issue**: gain spatial uniformity*

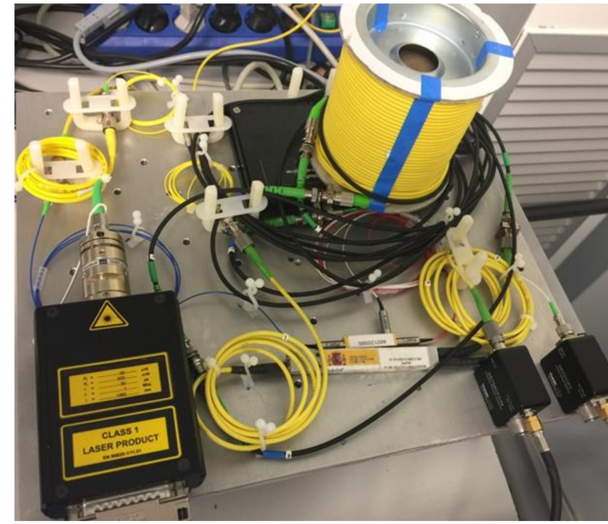
- *LGAD: multiplication layer inter-space presents reduced/suppressed gain.*
- *I-LGAD: non-segmented multiplication layer should present uniform gain.*

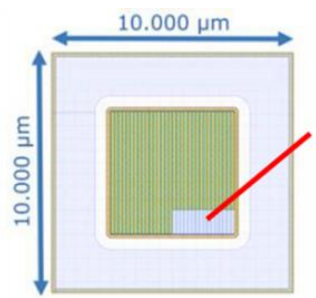
- ** Fill factor studies were presented at Trento workshop 2017→ [Link to the talk]*

https://indico.cern.ch/event/666427/contributions/2881813/attachments/1603622/2544525/20180219_I-LGAD_IvanVila.pdf

Set- up and Samples





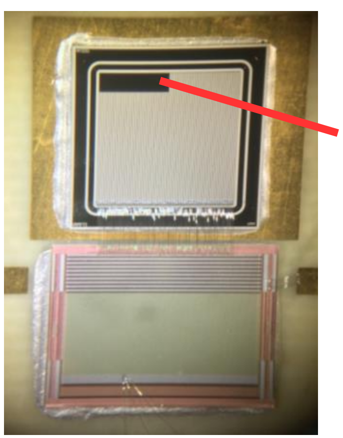


I-LGAD strip

45 strips

Thickness 285 um

Pitch 160 um



PIN strip

90 strips

Thickness 285 um

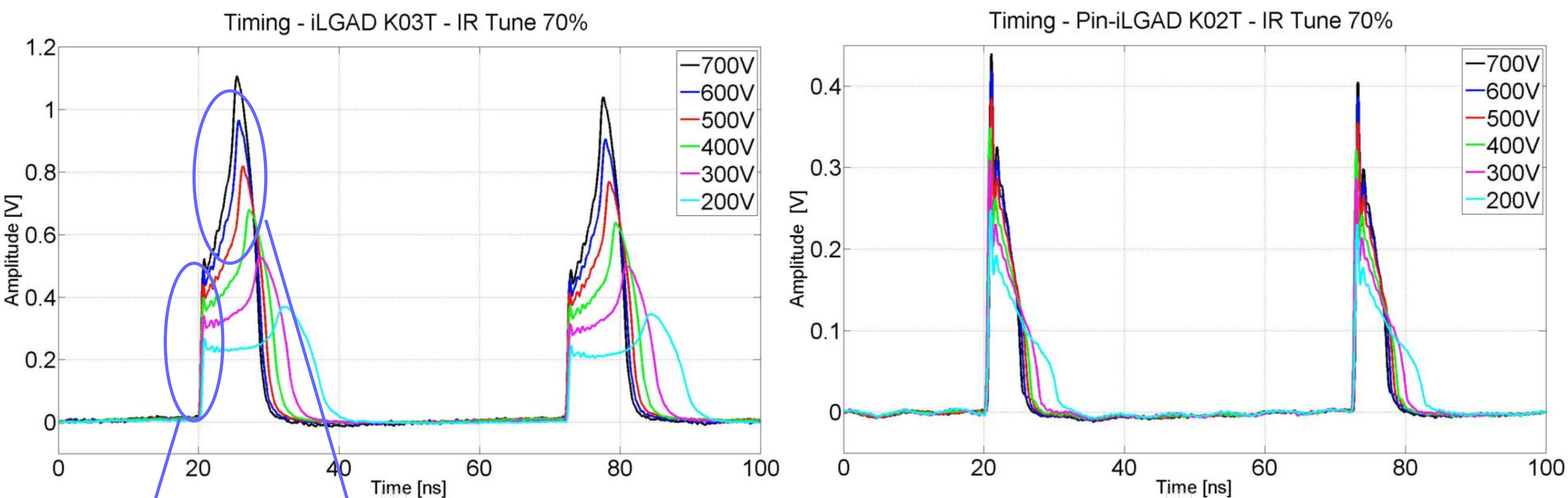
Pitch 80 um

- ***Time standard:*** *constant time interval between two picosecond IR laser pulses (1060 nm)*
- *Fixed time interval between laser pulses generated by optical splitting and delayed recombination of a single laser pulse.*
- ***External time reference is not needed.***

** Strips → small electrode capacitance → good for timing studies*

Set-up for timing characterization and DUT (2)

- Signal amplified (60db, miteq 1660) & digitized (25GSa/s)
- Acquired averaged waveform from I-LGAD and PIN sensors with a time interval of 52.23 ns between pulses

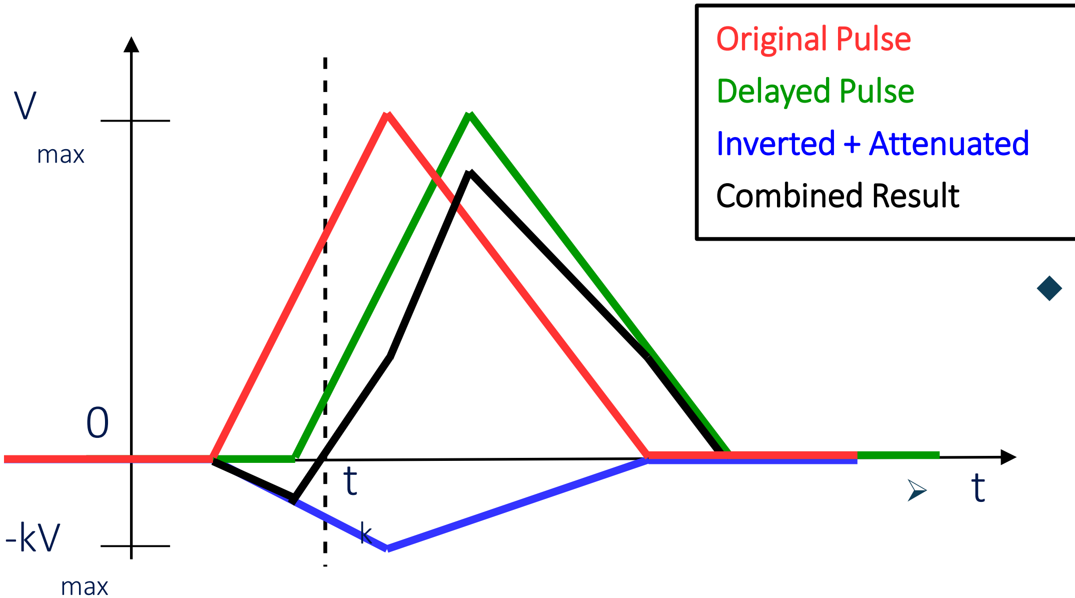


Primary electrons contribution

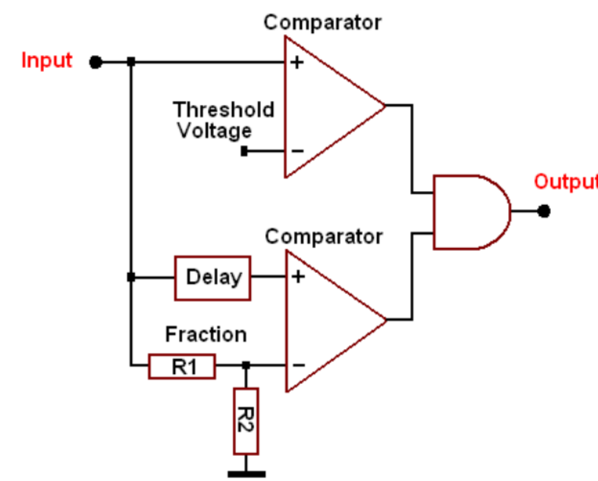
Secondary holes contribution

Timing computation:
Constant Fraction Discrimination method (CFD)

- **CFD principles of operation**

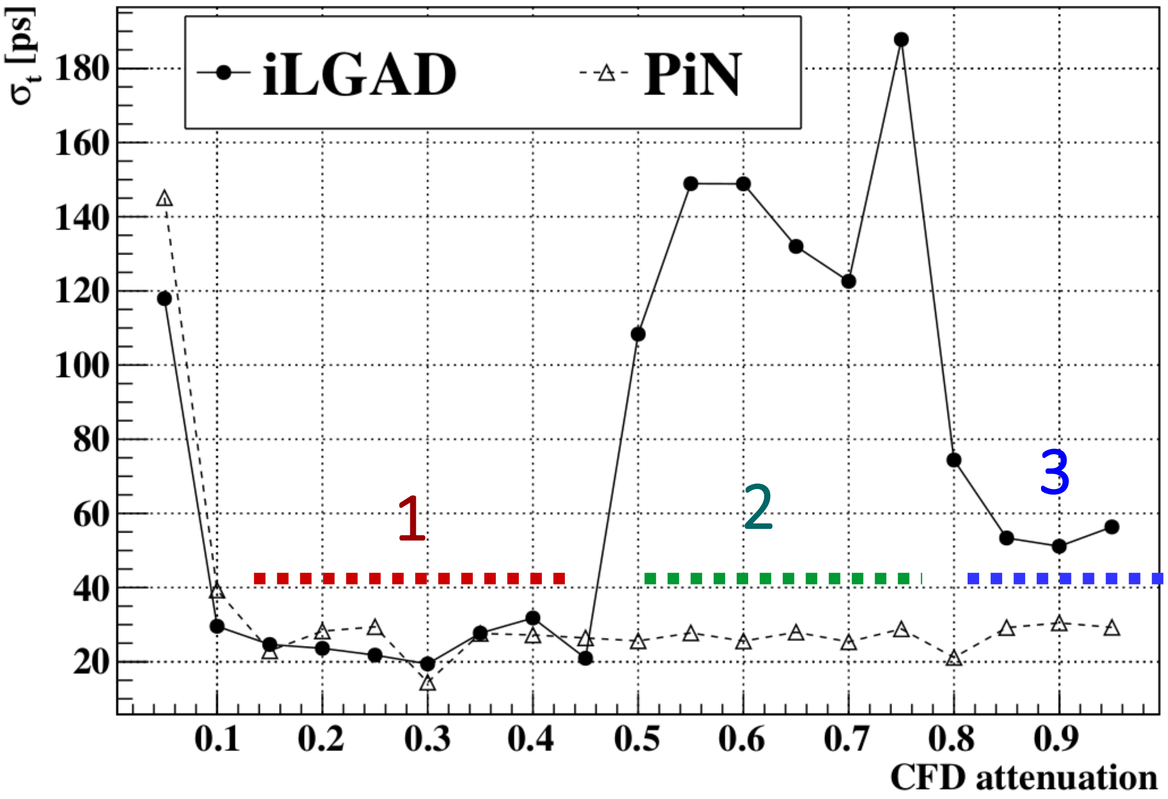


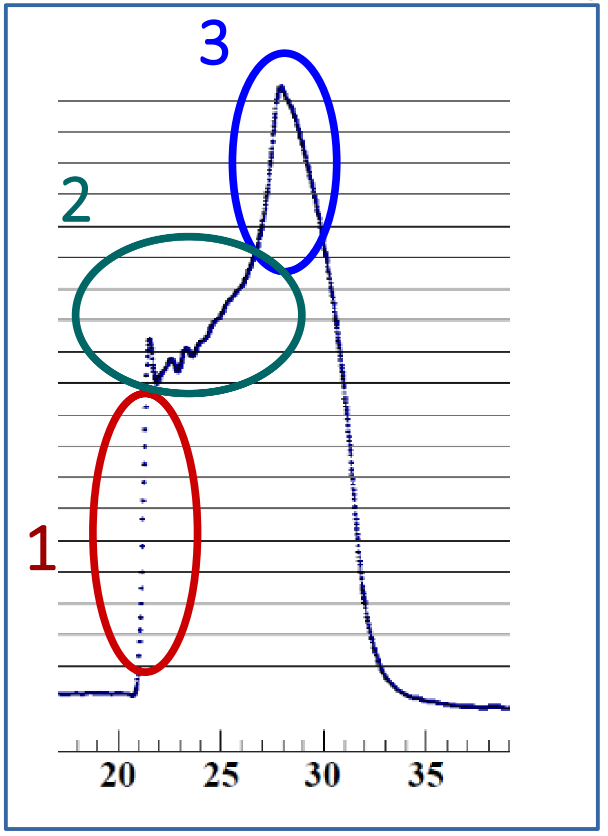
- Emulate by software a real CFD electronic circuit



  - Split the input signal in two parts
  - Delay on part
  - Attenuate ($-kV_{max}$) and invert the other
  - Add the two signals together
  - The zero crossing point of the bipolar signal (t_k) will always be constant

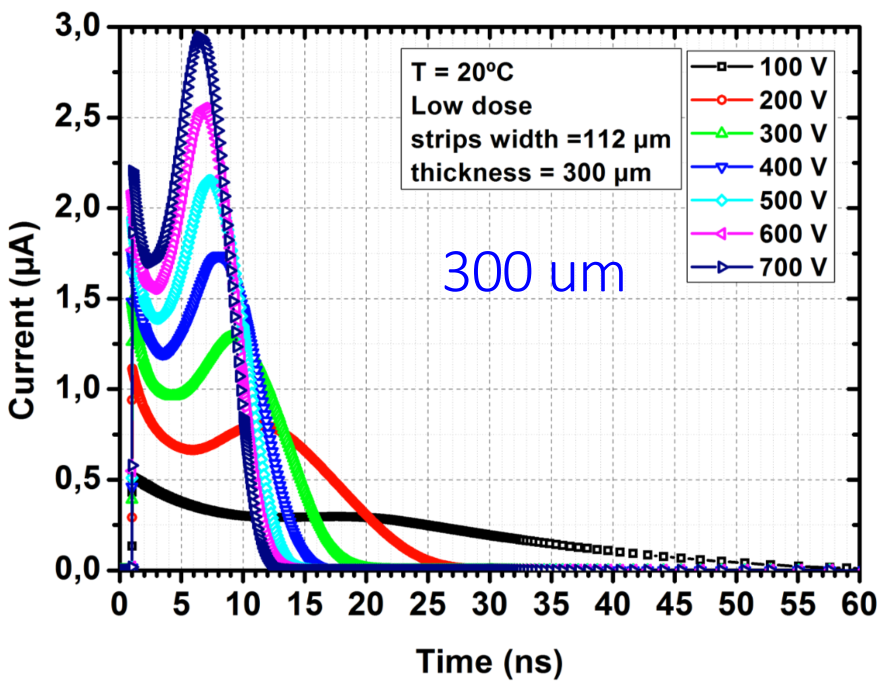
Constant Fraction Discrimination method (CFD):

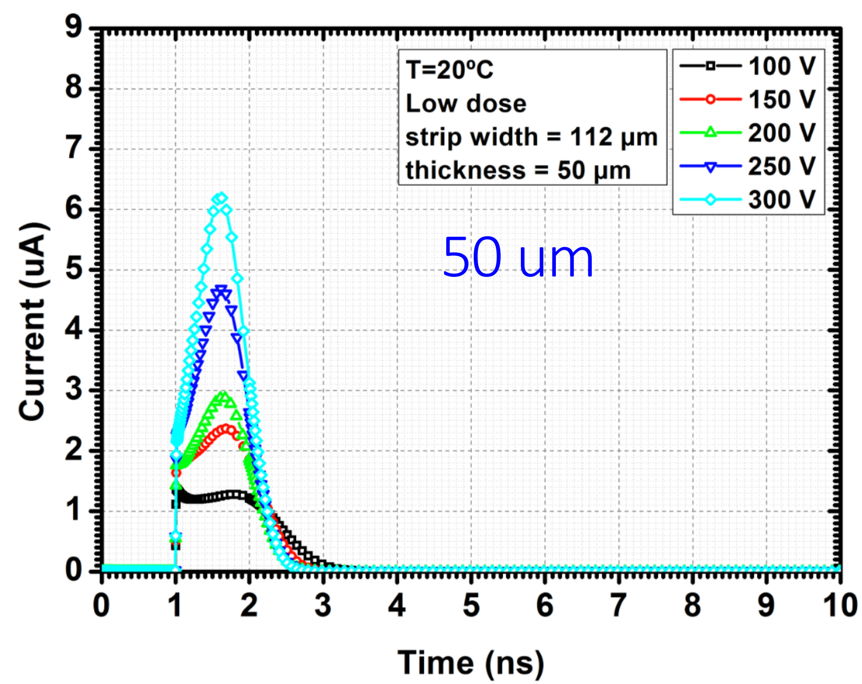




- Optimum value of the k parameter for the I-LGAD in zone 1.
- For the PIN k parameter is optimum in almost the full range.

Constant Fraction Discrimination method (CFD):
Simulation 300 um vs 50 um.





- First part of the signal very fast and good for timing but not as good in SNR terms.
- Second part still good with better SNR but worse rise time.
- If we go to 50 um we can have both benefits: Good SNR and low rise time.

Summary

- We compared the timing performance of one I-LGAD strip sensor with a similar PIN strip sensor.
- Time resolution was estimated using a more realistic CFD method.
- Better time resolution with the I-LGAD sensor for a lower SNR.
- Simulations show a promising time performance of 50 um I-LGADs strip devices.

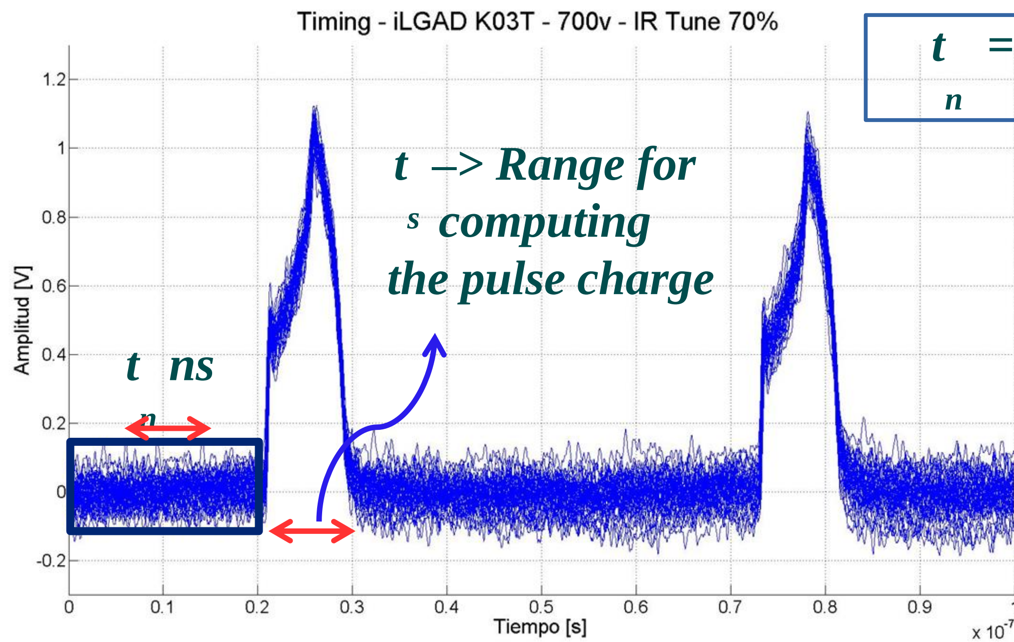
THANK YOU FOR YOUR ATTENTION

Parameter extraction of the waveform.

- *Single-shot (non-averaged) superposition of signals.*
- *For each shot measured: Rise time, Signal amplitude and noise.*
- ***Signal estimation** as the charge under the transient waveform.*
- ***Noise estimation** as the RMS of charge (from the first nanoseconds of the waveform).*

$$\sigma \equiv RMS\ (Charge\ baseline)$$

$$SNR \equiv \frac{Signal\ Charge}{\sigma}$$



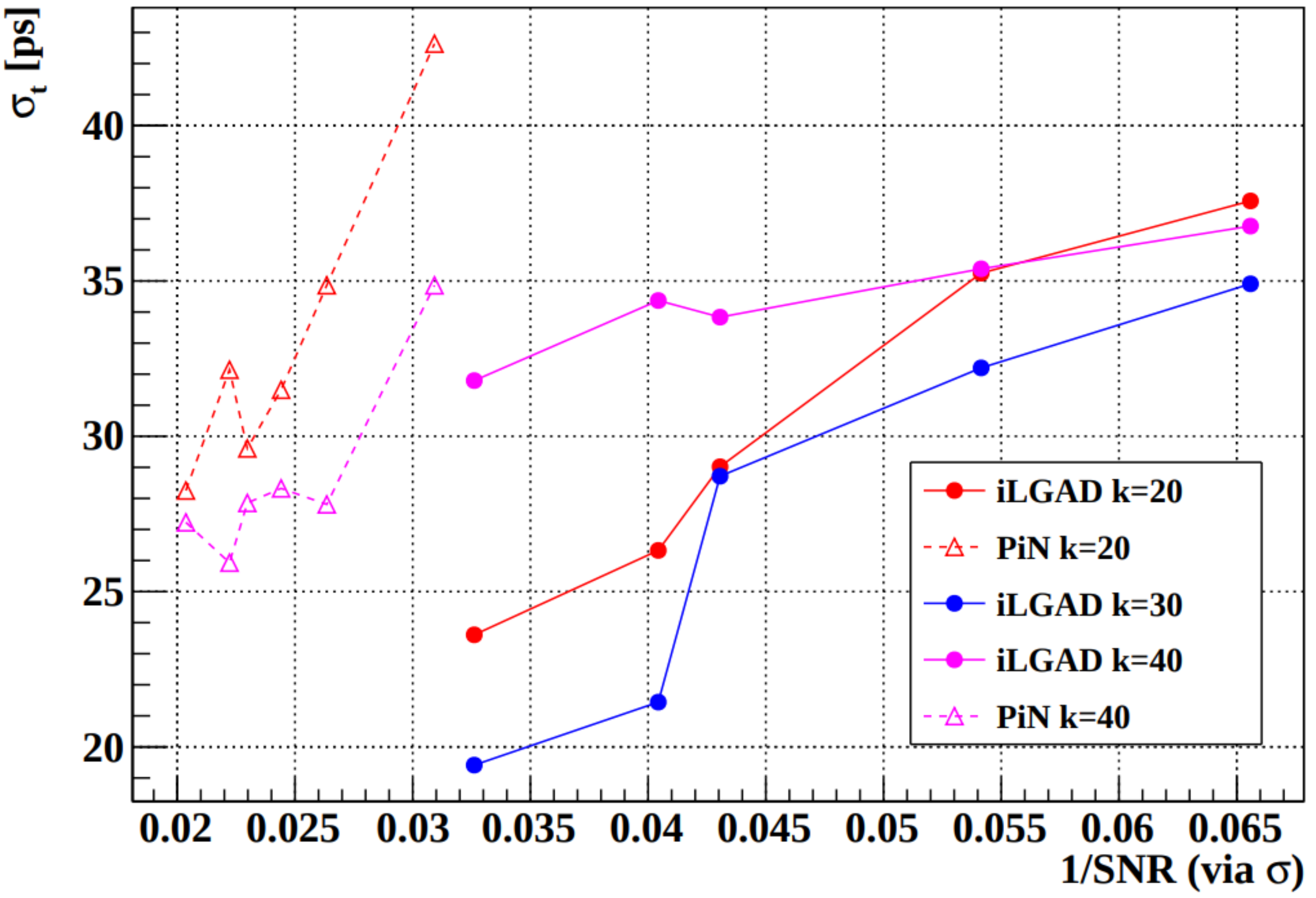
$t_n = t_s$

t_n ns

t_s –> Range for computing the pulse charge

Waveform section from where the baseline noise is estimated

Constant Fraction Discrimination method (CFD):



- *Better time resolution for the I-LGAD even with lower SNR.*

… a particular case concerning radiation tolerance.

- The layout of the proposed LHC timing detectors: a mosaic of mini-pads (elements with area of few mm^2)
- **A pad-like LGAD is also a pad-like I-LGAD therefore they exhibit the same radiation tolerance**