Gain suppression mechanism observed in Low Gain Avalanche Detectors

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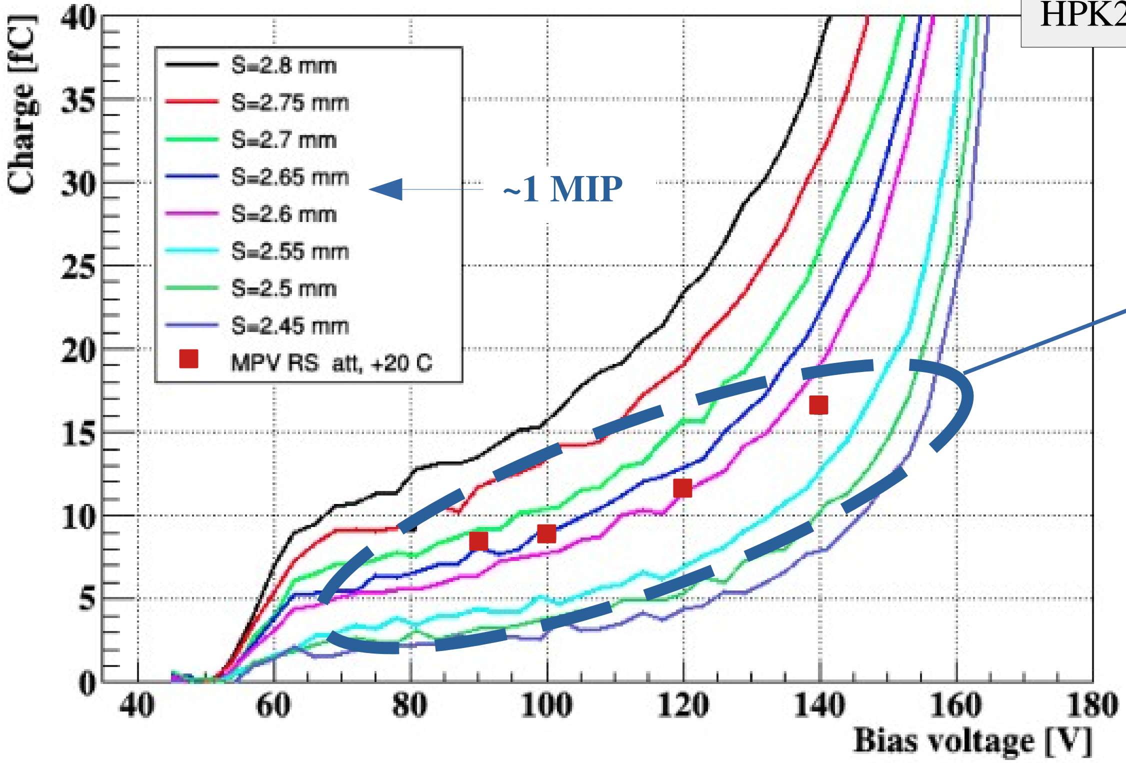
Outlook

- Motivation: better understanding of gain and timing studies performed with TCT IR-laser and Sr-90 source.
- Comparison between IR-laser and Sr-90 measurements.
- Gain suppression mechanism with IR-laser:
  - ▹ Gain suppression in LGADs with different type of gain layers.
  - ▹ Gain suppression in irradiated LGADs.
- Gain suppression mechanism with Sr-90 source.
- Summary.

For more details see also:
“E.Curras et al, 16th (Virtual) "Trento" Workshop on Advanced Silicon Radiation Detectors”

Motivation: understand the differences between Sr-90 and IR-laser measurements

IR-laser at different power intensities vs Sr-90 source



HPK2-W31-LGAD (1.3x1.3 mm^2 x 50 um)

LGADs:

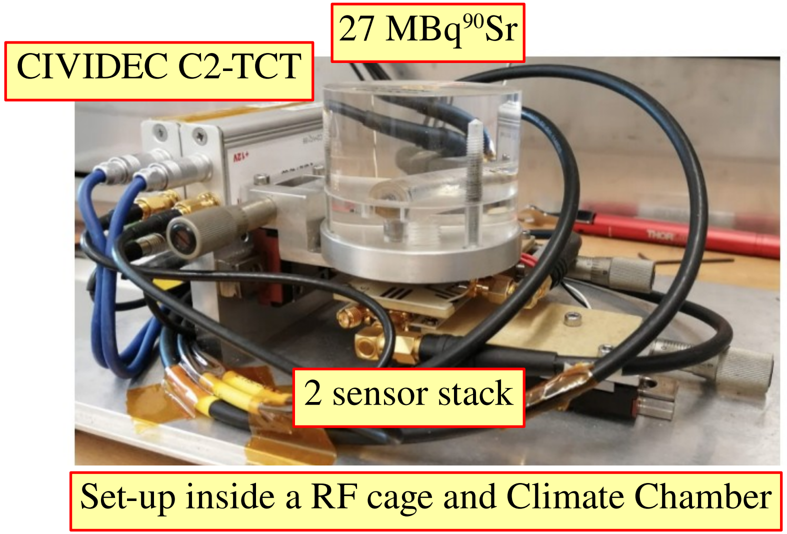
- **Can we compare IR-laser measurements with Sr-90 ones: charge, gain, timing ...?**
- **Is there any IR-laser setting that will induce the same charge than the Sr-90 source ?**

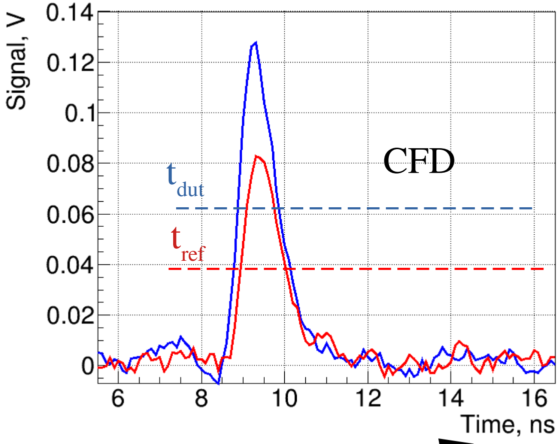
Value of shutter "S" is proportional to the laser power.

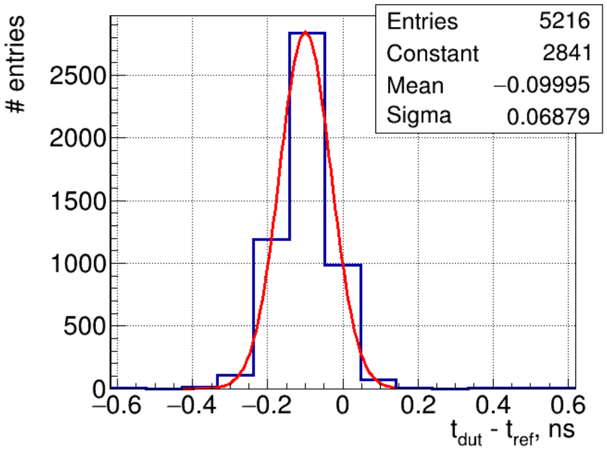
LGADs used:

HPK2 and CNM-12916 (1.3x1.3 mm^2 x 50 um).

Gain and timing measurements with Sr-90





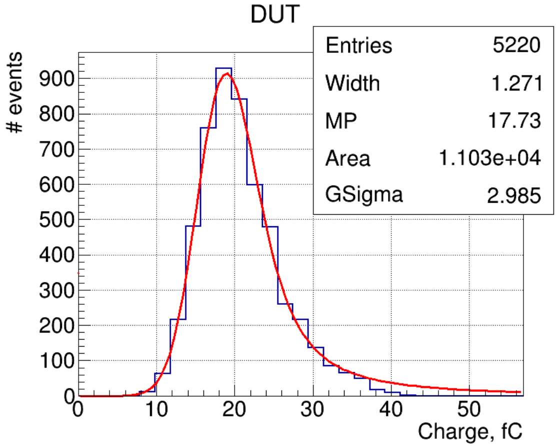


System time resolution: $\sigma^2_{sys} = \sigma^2_{dut} + \sigma^2_{ref}$

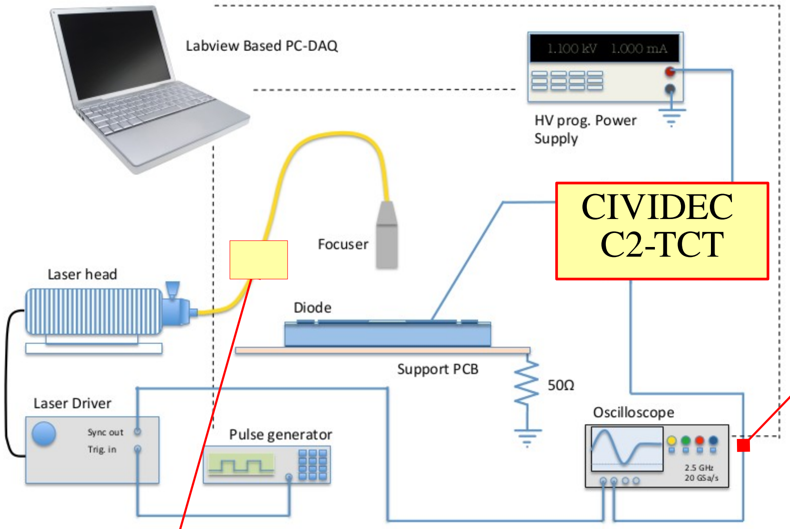
Gain definition: $G(V) = Q\,(V)_{LGAD}/Q_{PIN}$

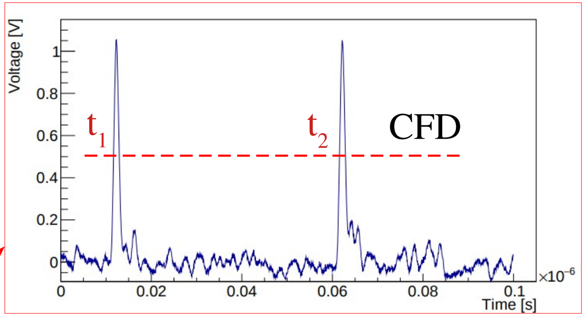
Q_{PIN} measured: ~ 0.5 fC for a 50 um thick PIN.

$Q(V)_{LGAD}$ is the MPV of the charge distribution.



Gain and timing measurements with IR-laser



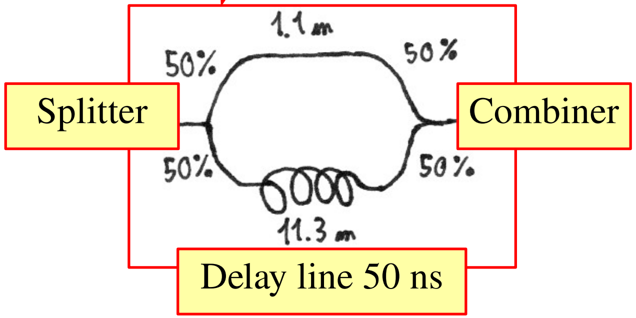


System time resolution:

$$\sigma^2_{sys} = \sigma^2_{t1} + \sigma^2_{t2}$$

$$\sigma^2_{dut} = \frac{1}{2}\sigma^2_{sys}$$

- **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.**

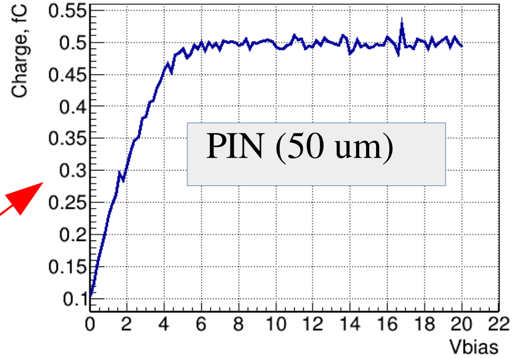


Gain definition: $G(V) = Q(V)_{LGAD}/Q_{PIN}$

* Q_{PIN} and Q_{LGADs} are measured in the same conditions.

* IR-laser intensity calibrated to have 1 MIP equivalent:

$Q_{PIN}(V>V_d) \approx 0.5$ fC for a 50 um thick PIN.



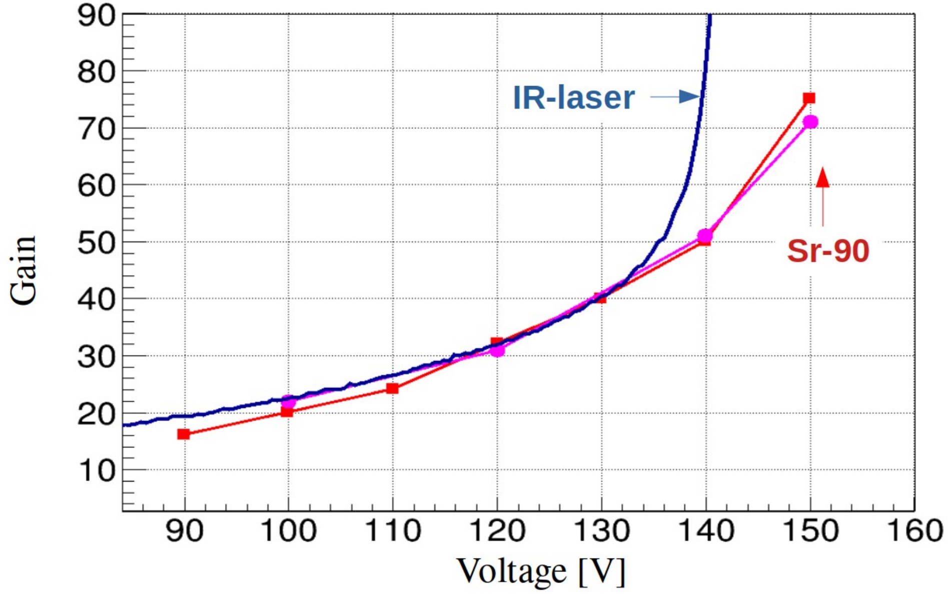
Are IR-laser and Sr-90 measurements comparable ?

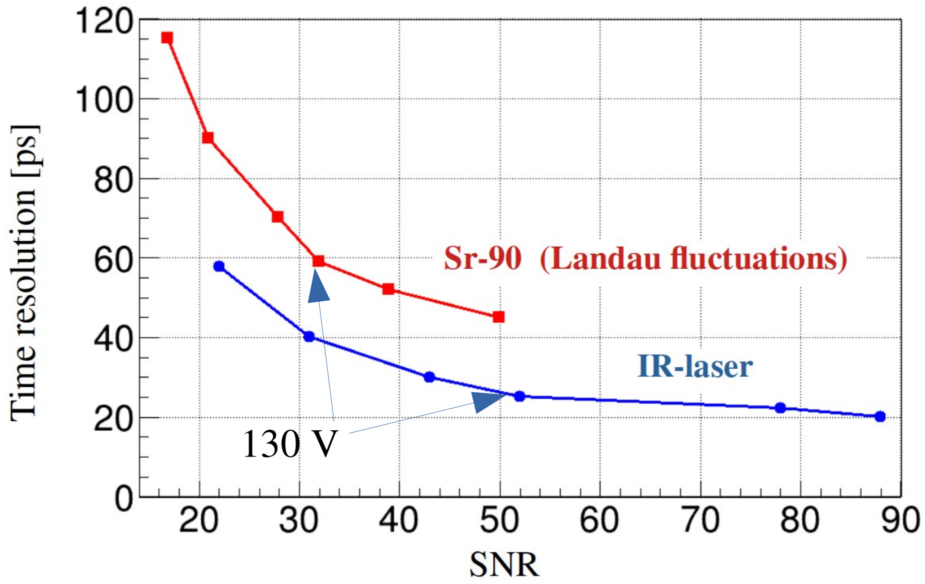
Initial idea: IR laser in TCT tuned to ~ 1 MIP to compare with Sr-90.

Samples: HPK2 and CNM 12916 (50 um thick devices of 1.3x1.3 mm^2 active area).

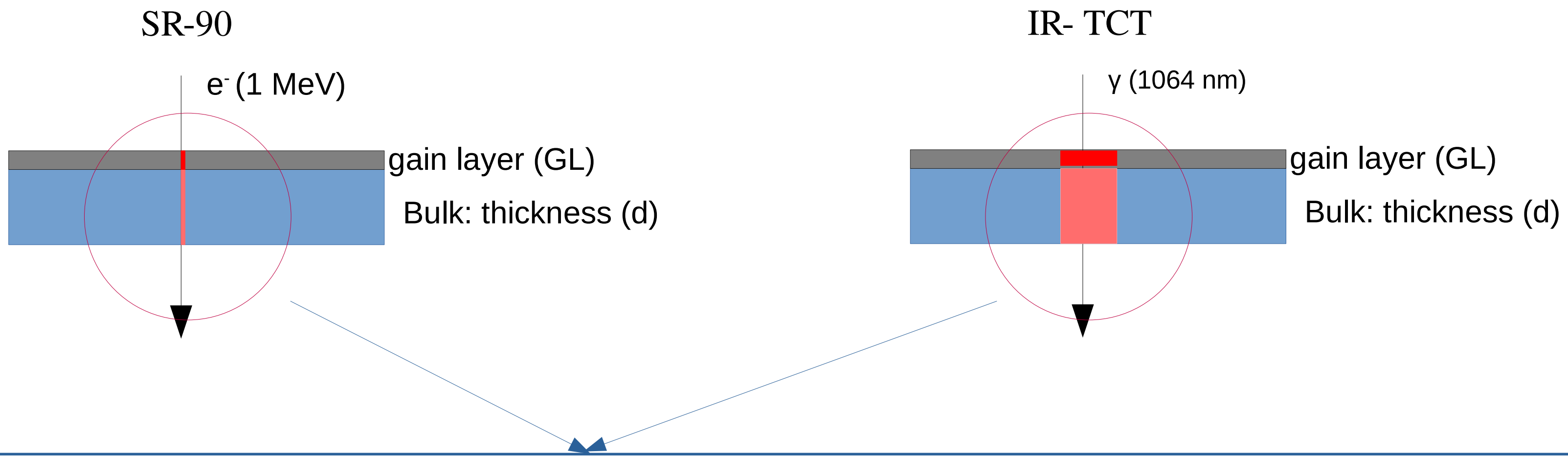
Problems found:

- Two identical sensors measured under the same conditions in TCT and RS-90 show different gain curves.
- Also the jitter measured in TCT is much lower than the time resolution measured in Sr-90.





Differences between IR-TCT (~ 1 MIP) and RS:



We generate the same amount of charge in both, but inside a different volume in the bulk:

With Sr-90 we have a much higher charge density because the ionizing path is narrower.

With the IR-laser we have less charge density, the ionizing "path" is wider: around 10 um in FWHM when focused.

Hypothesis

Low charge density in the **GL** will lead to a higher gain: there will be a negligible gain suppression.

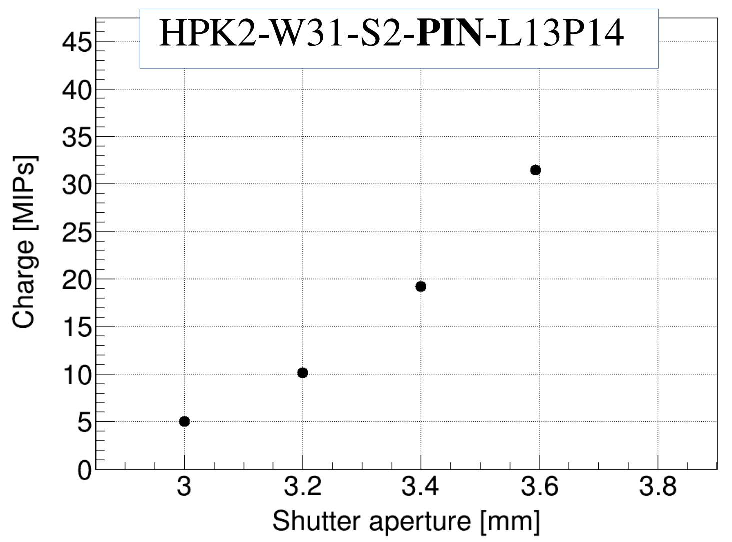
High charge density in the **GL** will lead to a reduction in the gain: drop in the GL E-field (less amplification).

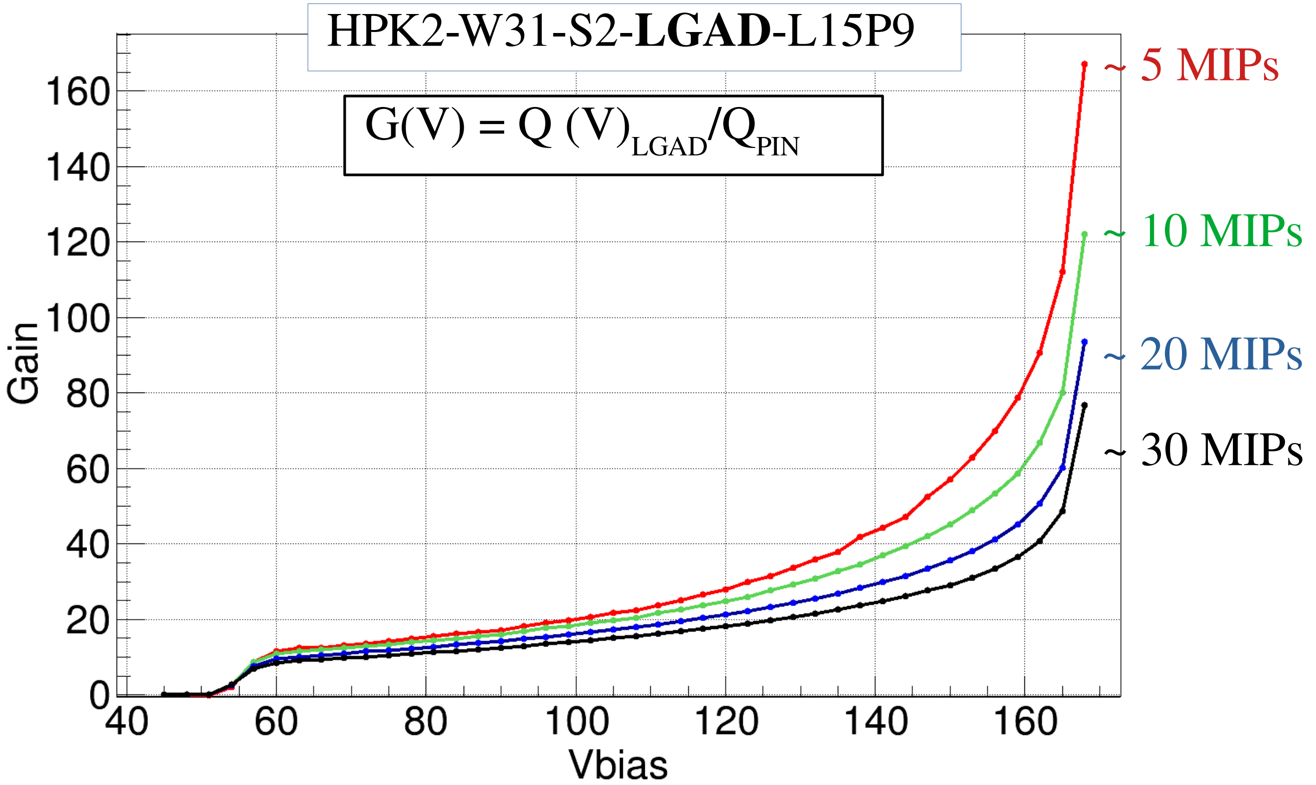
Study of the gain suppression mechanism with TCT IR-laser

Increasing laser intensity in TCT:

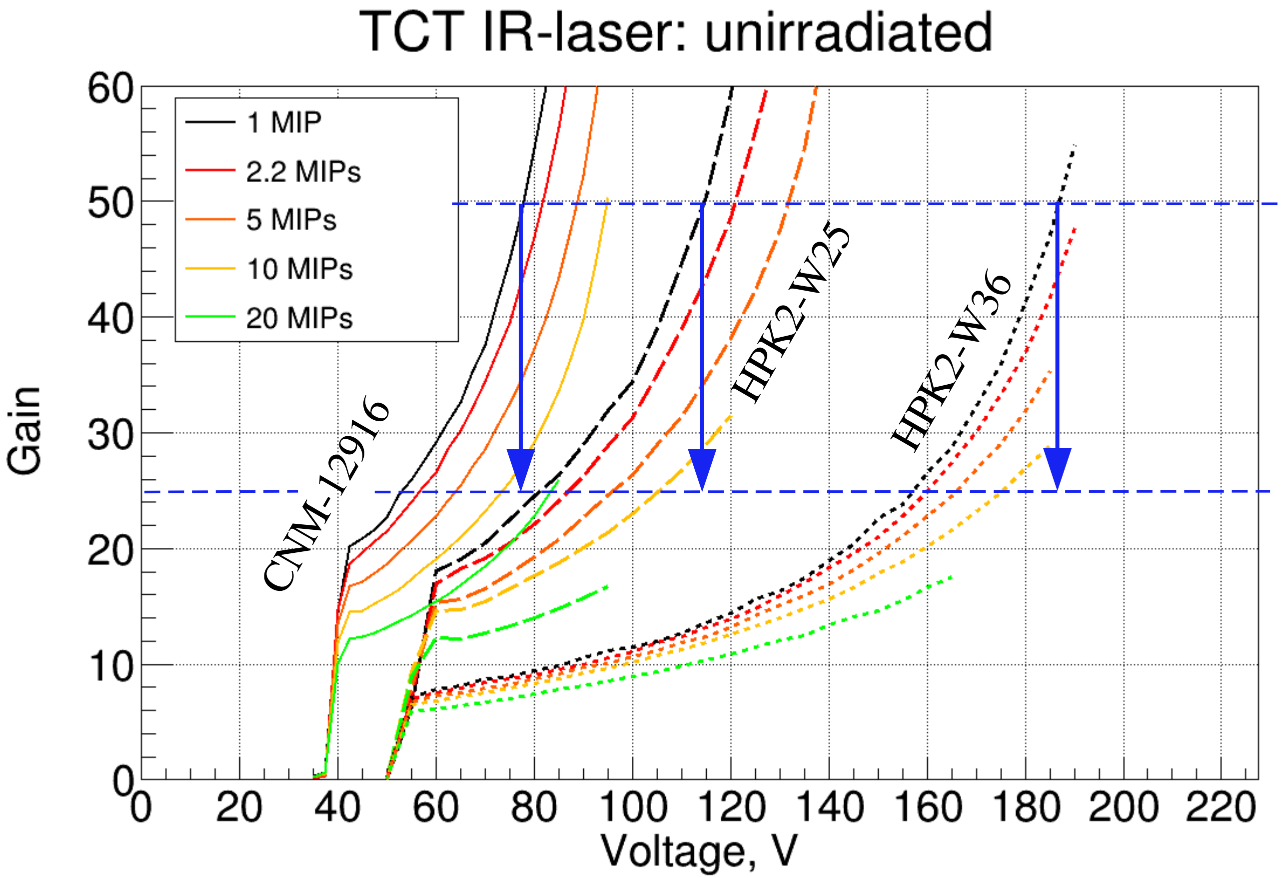
T: +20 ^{O}C
Averaging: 1024
No amplifier
IR shutter aperture:
- 3.0 (~ 5 MIPs)
- 3.2 (~10 MIPs)
- 3.4 (~20 MIPs)
- 3.6 (~30 MIPs)

IR laser intensity (Charge density) ↑ Gain ↓





Different types of unirradiated LGADs



Measurements done at +20C

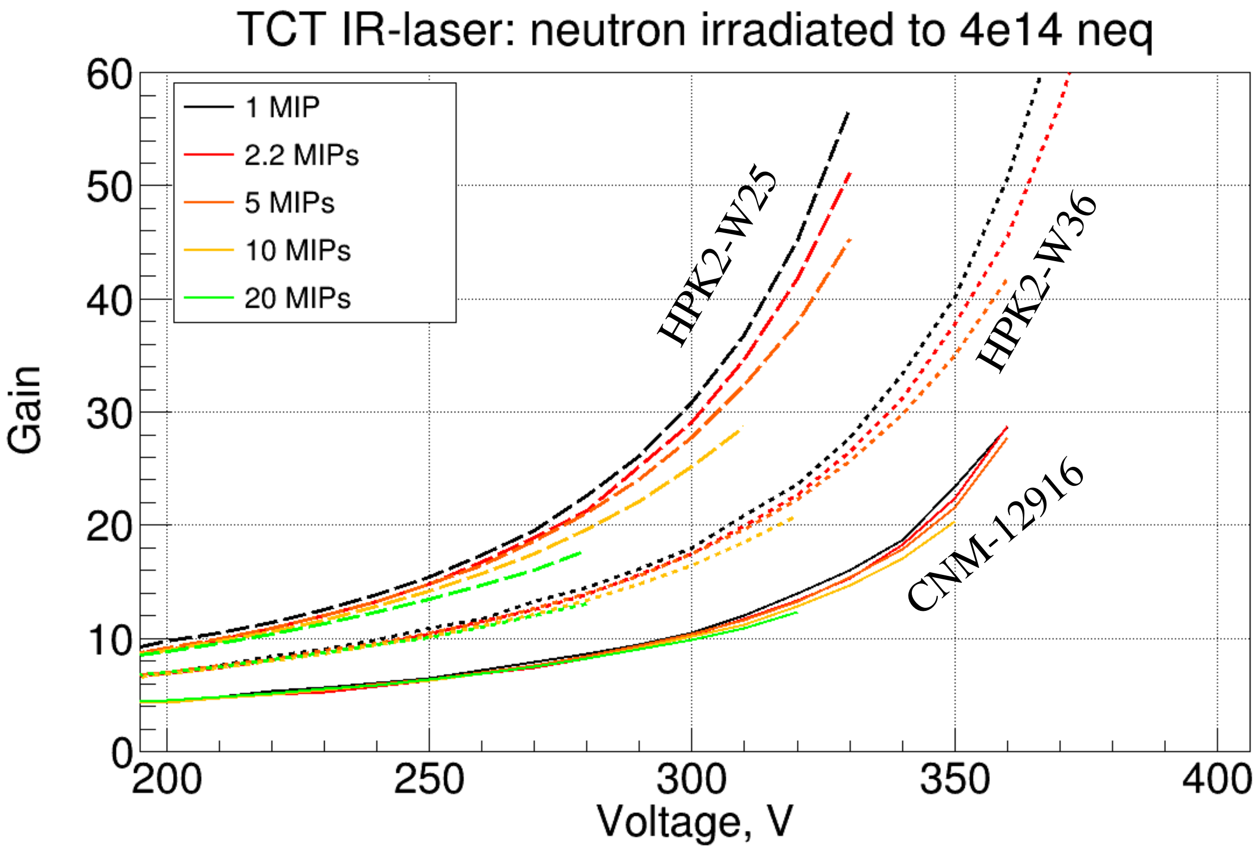
Gain suppression effect observed for all the 50 um LGADs that we studied.

We observe a higher suppression for the LGADs with a higher nominal gain.

For all the samples: the higher the gain the higher the suppression, e.g:

- For a gain of 50 at 1 MIP the gain drops more than 50% for 20 MIPs.

Different types of irradiated LGADs: $4x10^{14}$ n_{eq}/cm^2



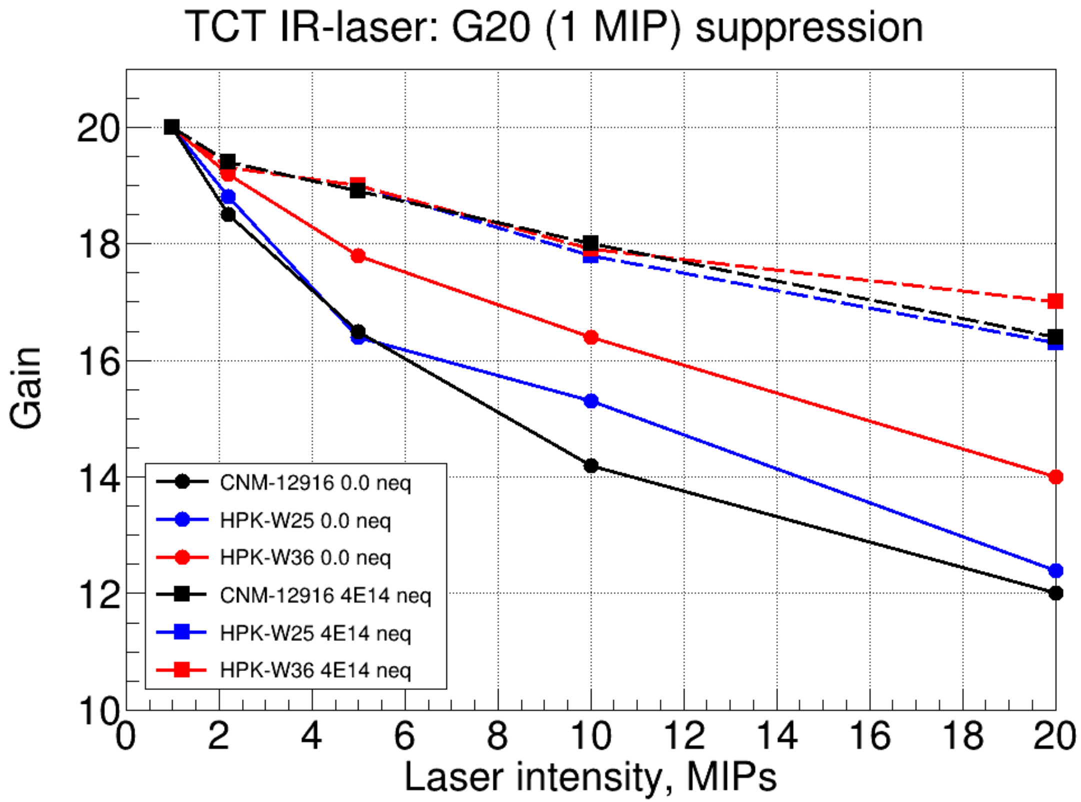
Measurements done at -20C

Gain suppression effect observed for all the 50 um irradiated LGADs to 4e14 n_{eq}.

The gain suppression is reduced with irradiation for all these devices.

For all the samples: the higher the gain the higher the suppression. But the effect is reduced w.r.t the non-irradiated ones.

Comparison: gain suppression for a gain of 20 (at 1MIP)

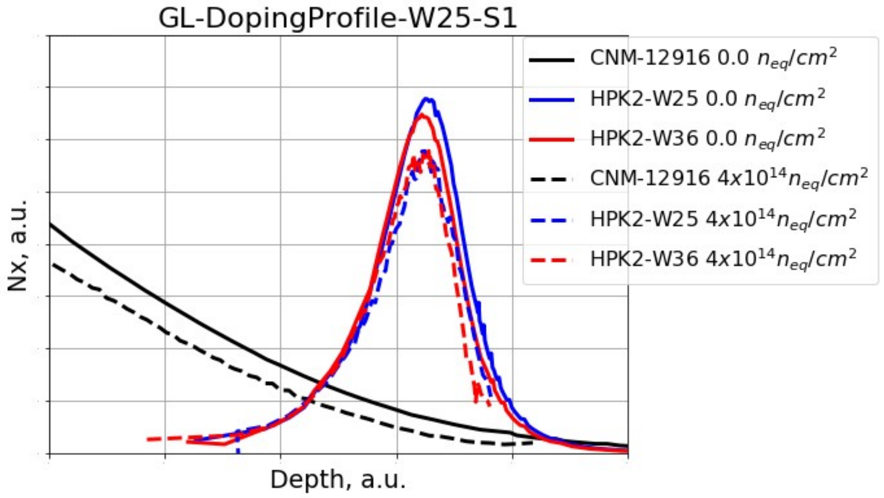


For a gain > 20, this reduction is more dramatic !

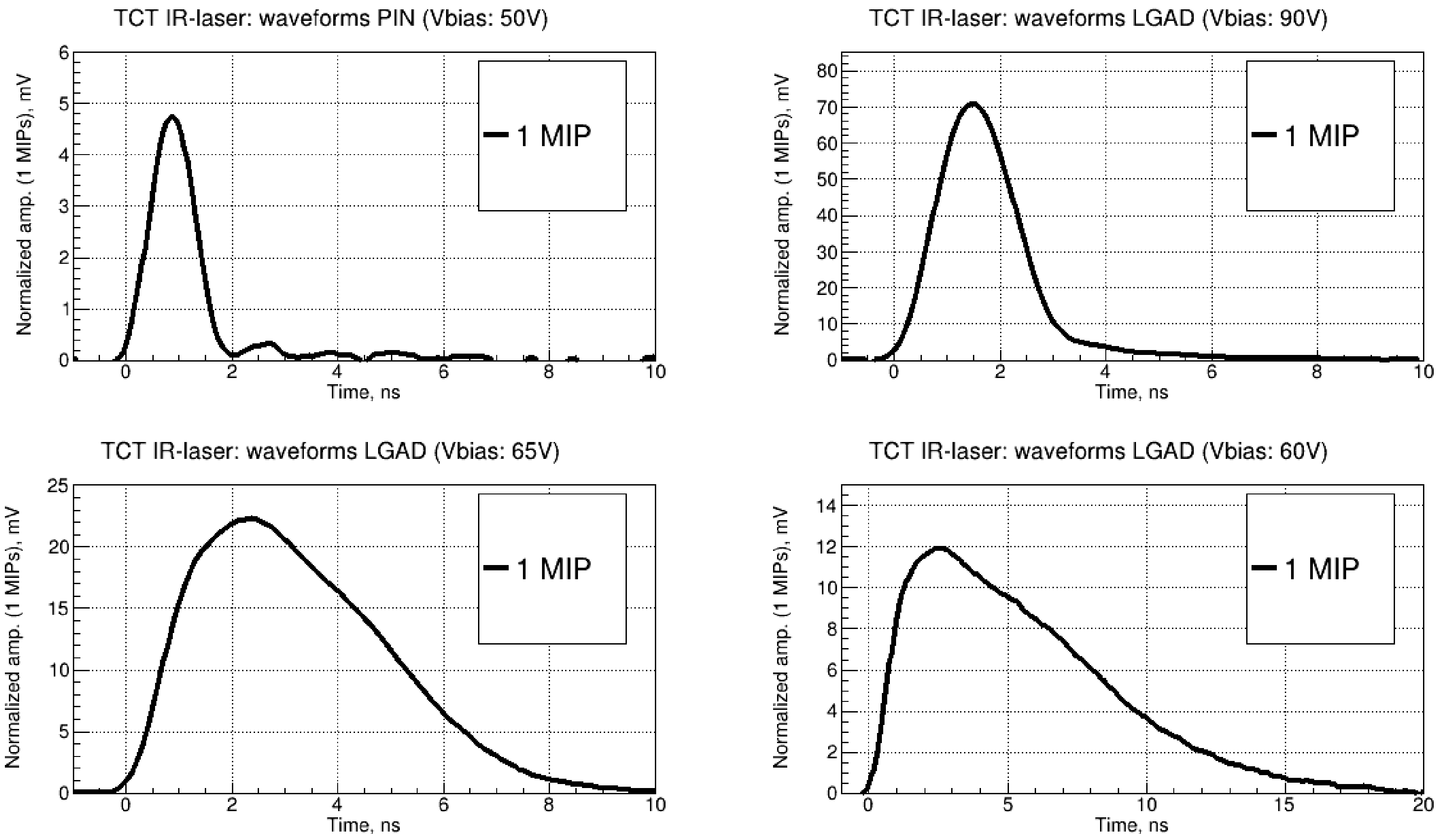
Gain suppression depends on the electric field distribution inside the detector.

Each sample gets G20 at different reverse bias.

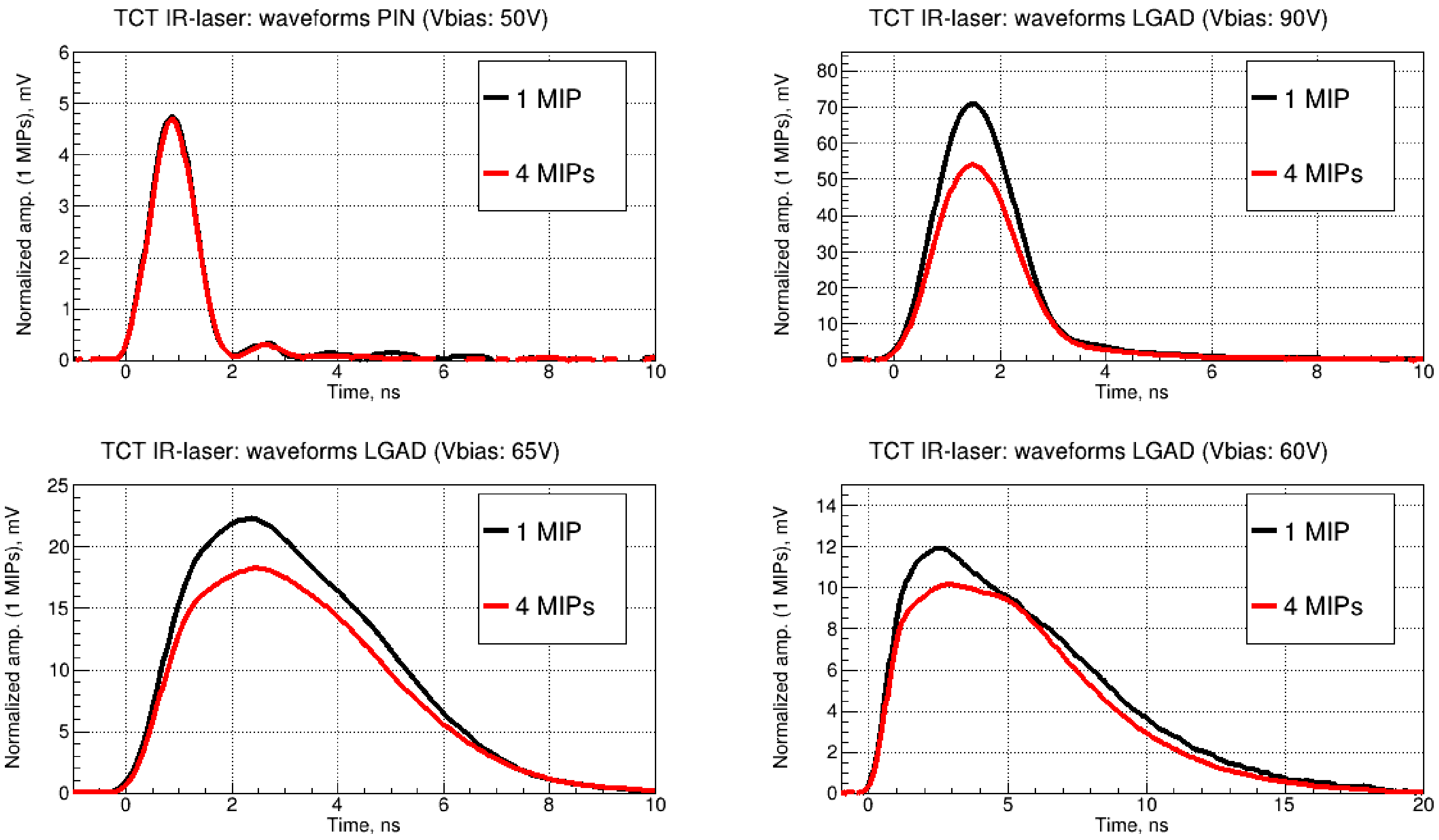
Different doping profile!



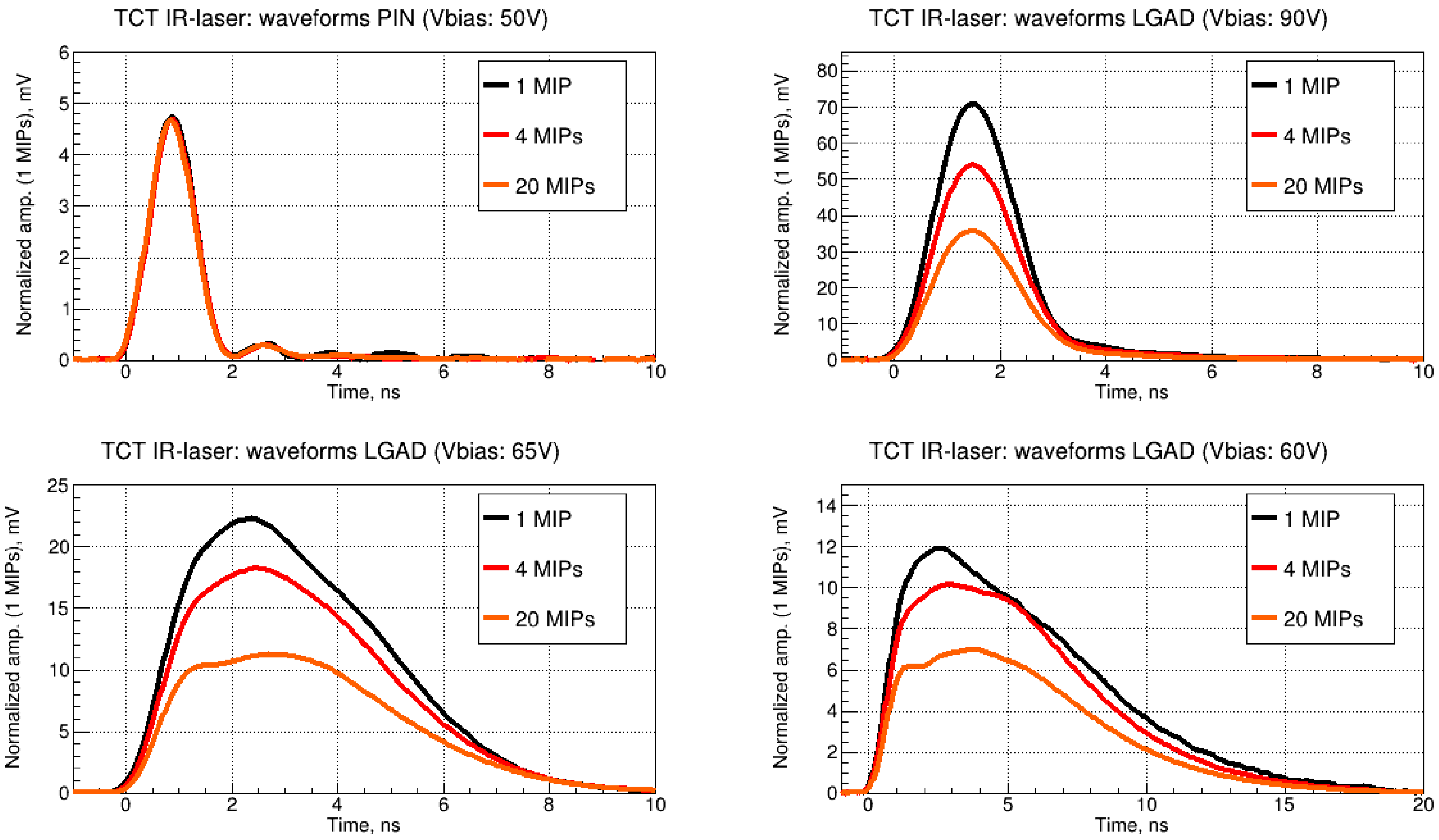
TCT waveforms: non-irradiated LGAD-HPK2-W25



TCT waveforms: non-irradiated LGAD-HPK2-W25



TCT waveforms: non-irradiated LGAD-HPK2-W25



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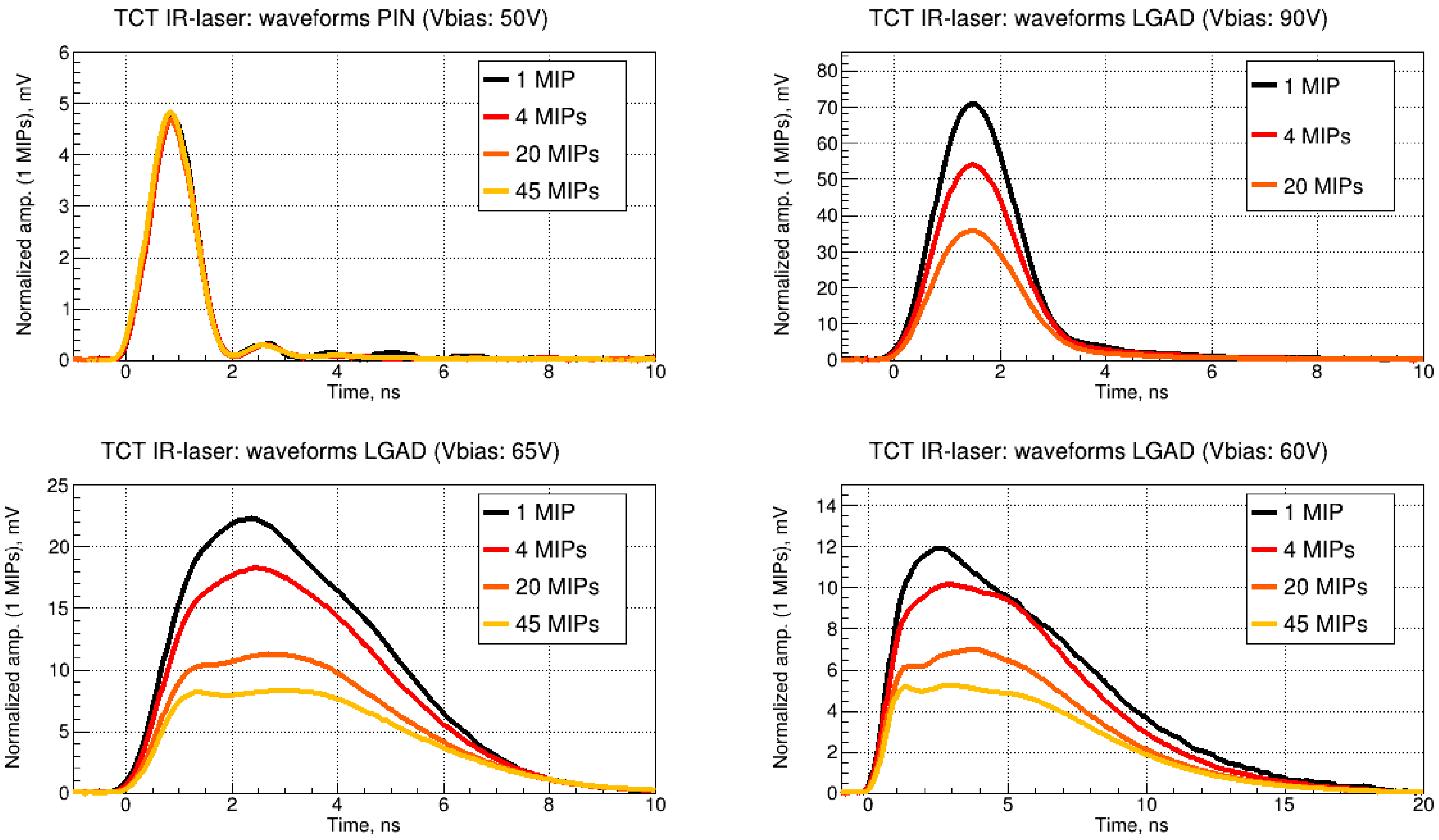

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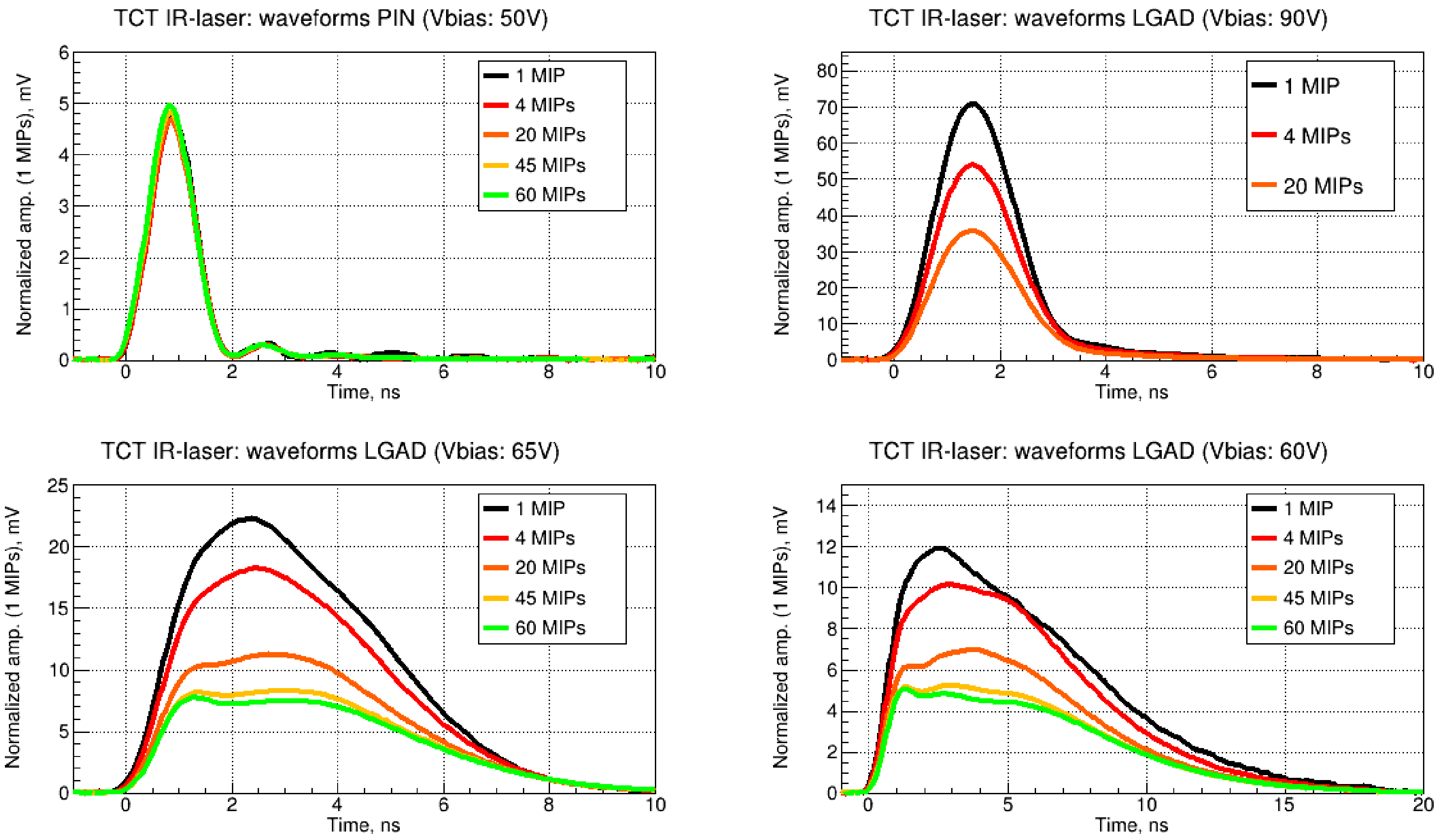
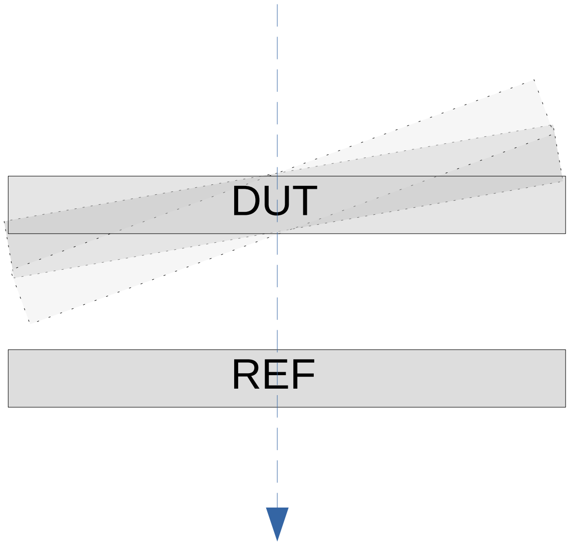
EP R&D



- Hint of saturation at 60 MIPs.
- No plasma observed.
- Gain reduction observed in the size of the pulses.
- Change in the pulse shape at low E-fields:
  - Reduction of the contribution of the secondary holes in the signal !

Study of the gain suppression mechanism with Sr-90

Sr-90 measurements: DUT tilted at different angles

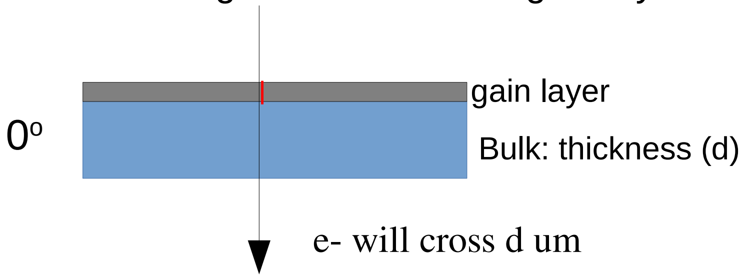


Temperature constant at 20.0 deg

DUTs positioned at different angles: 0, ~7, ~14 deg
- HPK-P2-LGAD-W31-S2
- CNM-12916-W4-DB02

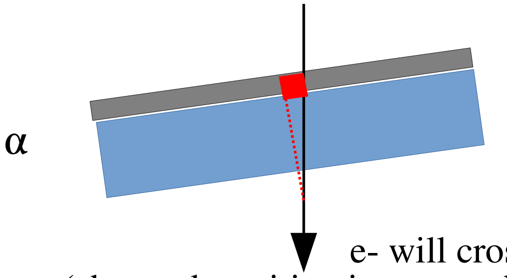
HPK-P2-LGAD-W42-S4: always the same sensor, not tilted and same Vbias = 180 V.

Narrow ionizing “area” under the gain layer.



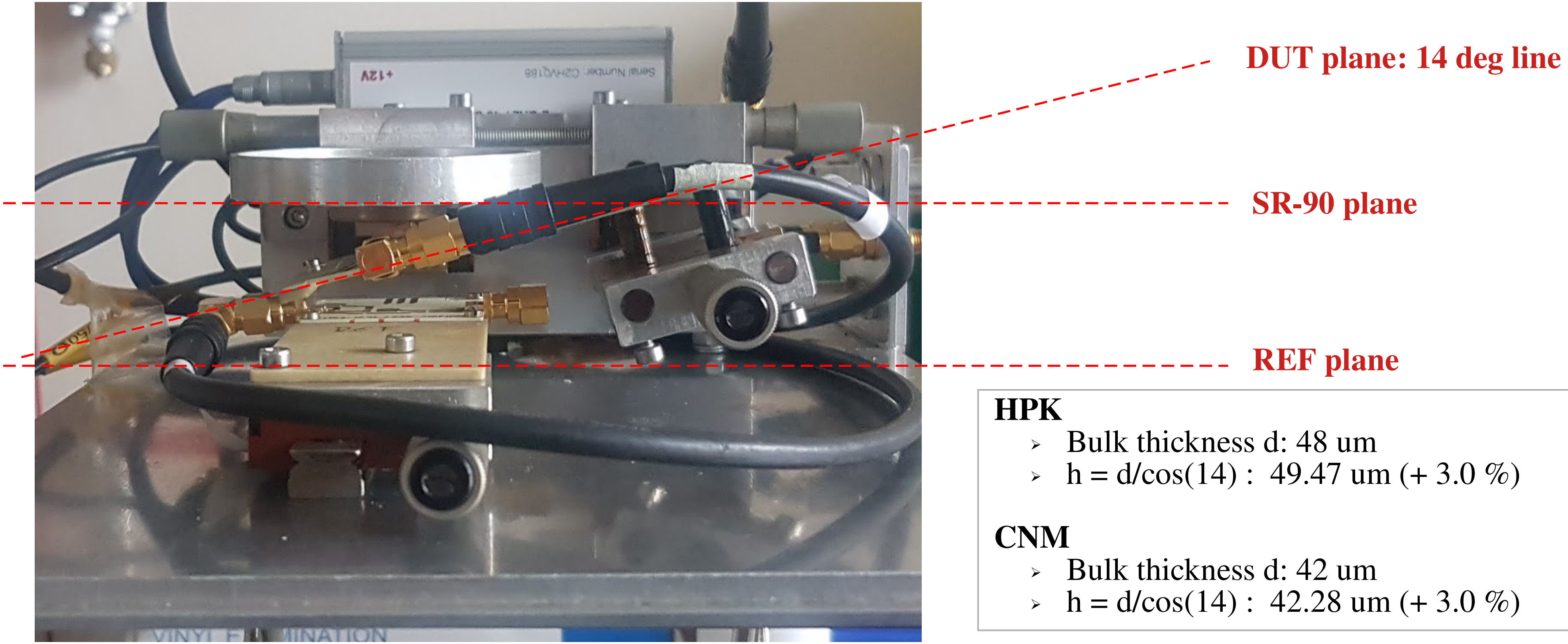
e- will cross d um

Larger Ionizing “area” projected under the gain layer → less charge density in the amplification layer).



e- will cross h = d/cos(α) um
(charge deposition increases due to a larger ionizing path)

Set-up picture at 14 deg



HPK

- Bulk thickness d: 48 um
- h = d/cos(14) : 49.47 um (+ 3.0 %)

CNM

- Bulk thickness d: 42 um
- h = d/cos(14) : 42.28 um (+ 3.0 %)

- Low Gain (low Vbias) → low E-fields: low effect and we should be close to the 3.0% increase in the signal
- High Gain (high Vbias) → high E-fields: high effect and we should see an increase in the charge higher that 3.0%

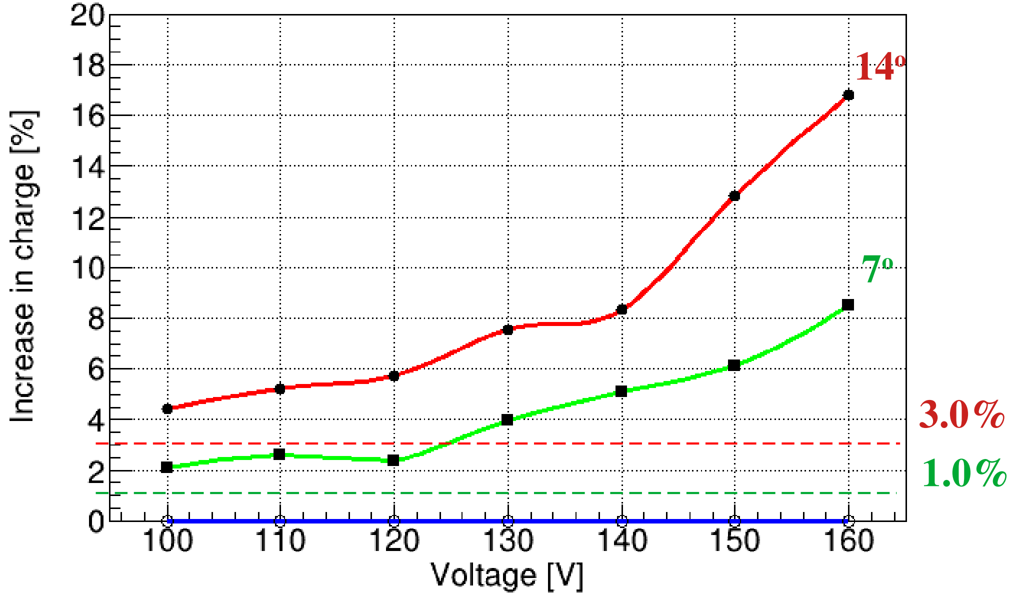
Effect in the timing performance and charge

Summarizing Sr-90 results:

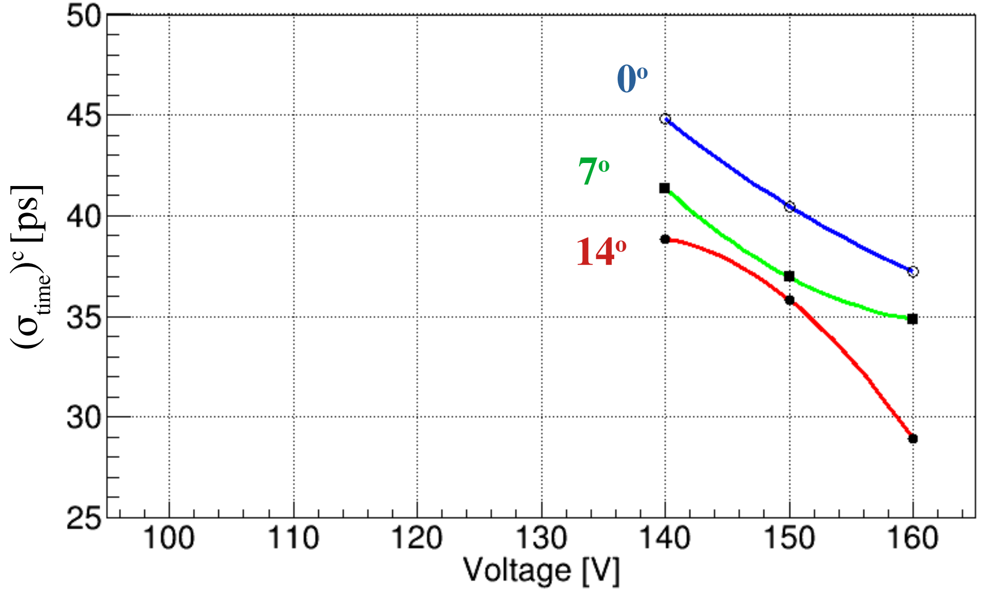
- Clear increase in the **charge collected** by tilting the sample.
- Clear improve in the **time resolution** by tilting the sample.

DUT: HPK2-W31-S2

Increase in Charge



Decrease in Time Resolution



Summary

EP R&D

- Discrepancies between IR-TCT and RS-90 were observed.

- They can be explained by the gain reduction produced for different charge densities inside the bulk under different conditions. This is affecting the impact ionization process in the gain layer:
  - RS generates a higher charge density → lower gain than IR-TCT.
  - Lower gain implies less charge collected → worse SNR and worse time resolution.

- Measurements in TCT and RS modifying the charge density were carried out to confirm it.
  - Effect observed for different types of LGADs.
  - Still present, but less accentuated, after neutron irradiation to $4x10^{14}$ n_{eq}/cm^2.

- Comparison of Gain and Charge measurements between TCT and RS set-ups is not straightforward.

- New parameter to keep under control: charge density. Especially important during the TCT measurements.

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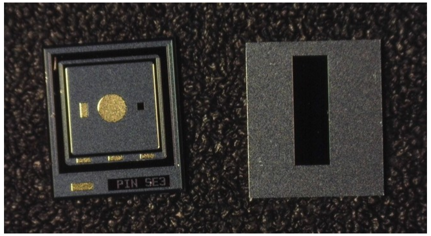
Thank you for your attention !

Backup slides

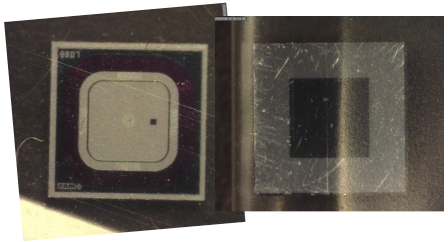
IV measurements: LGADs

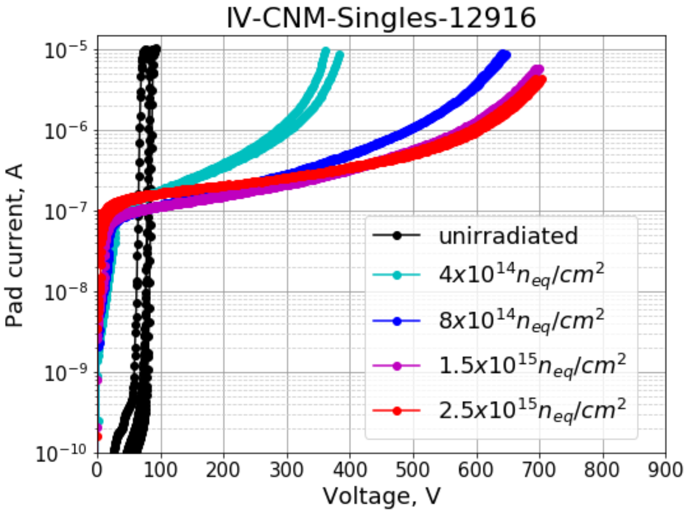
- Settings for HPK2 and CNM:
  - GR connected (except for the unirradiated HPK)
  - Temperature: -20 C (for all the irradiated)
  - Compliance: 10 uA

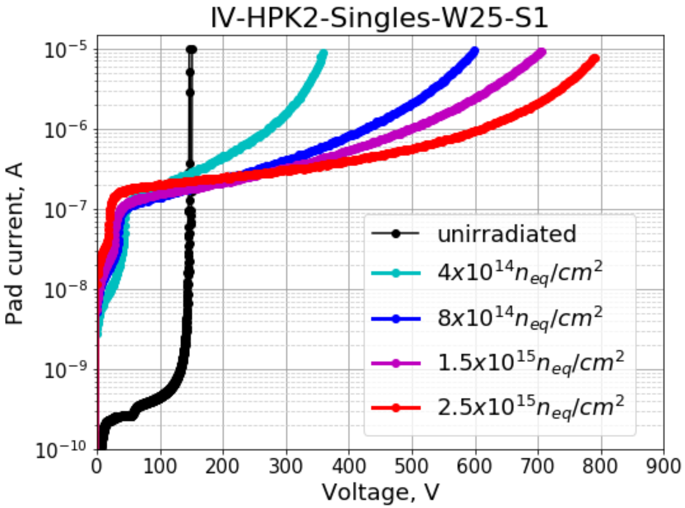
HPK2

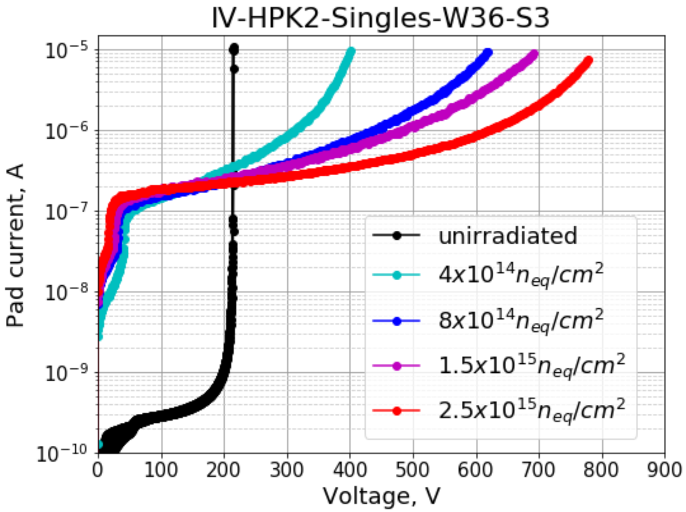


CNM



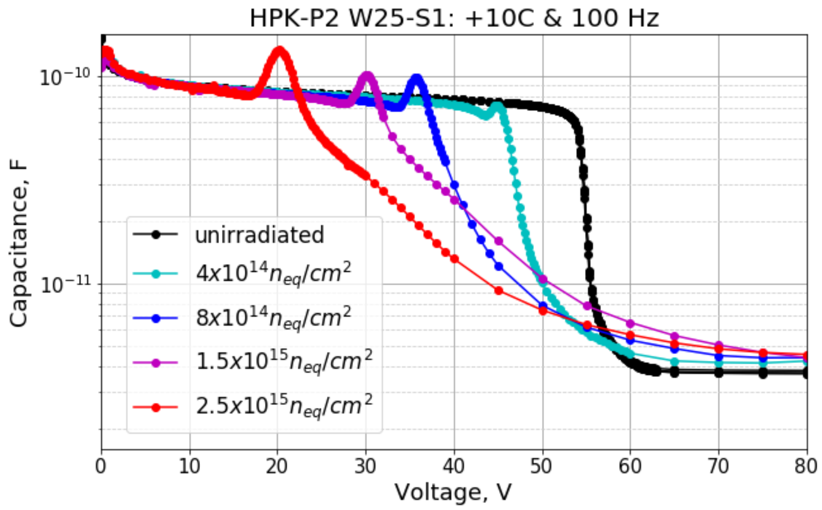


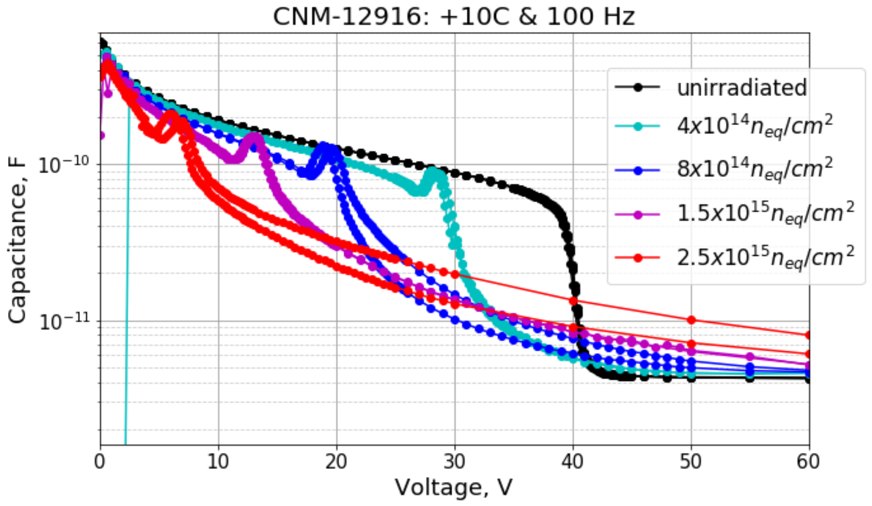


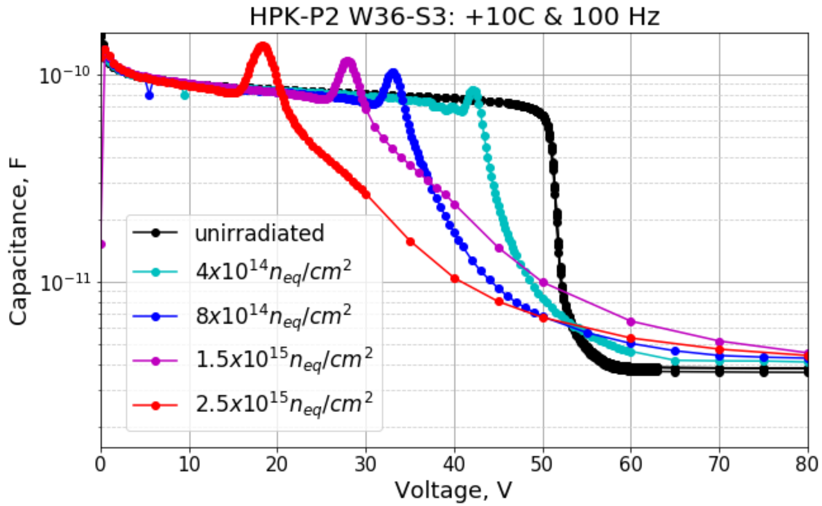


CV measurements: LGADs

- Settings for HPK and CNM irradiated LGADs:
  - GR connected
  - Temperature: 10 C
  - Frequency: 100 Hz



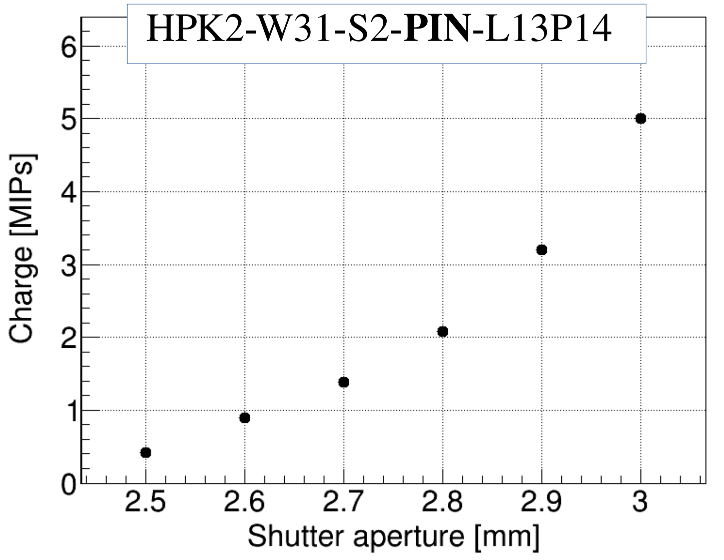


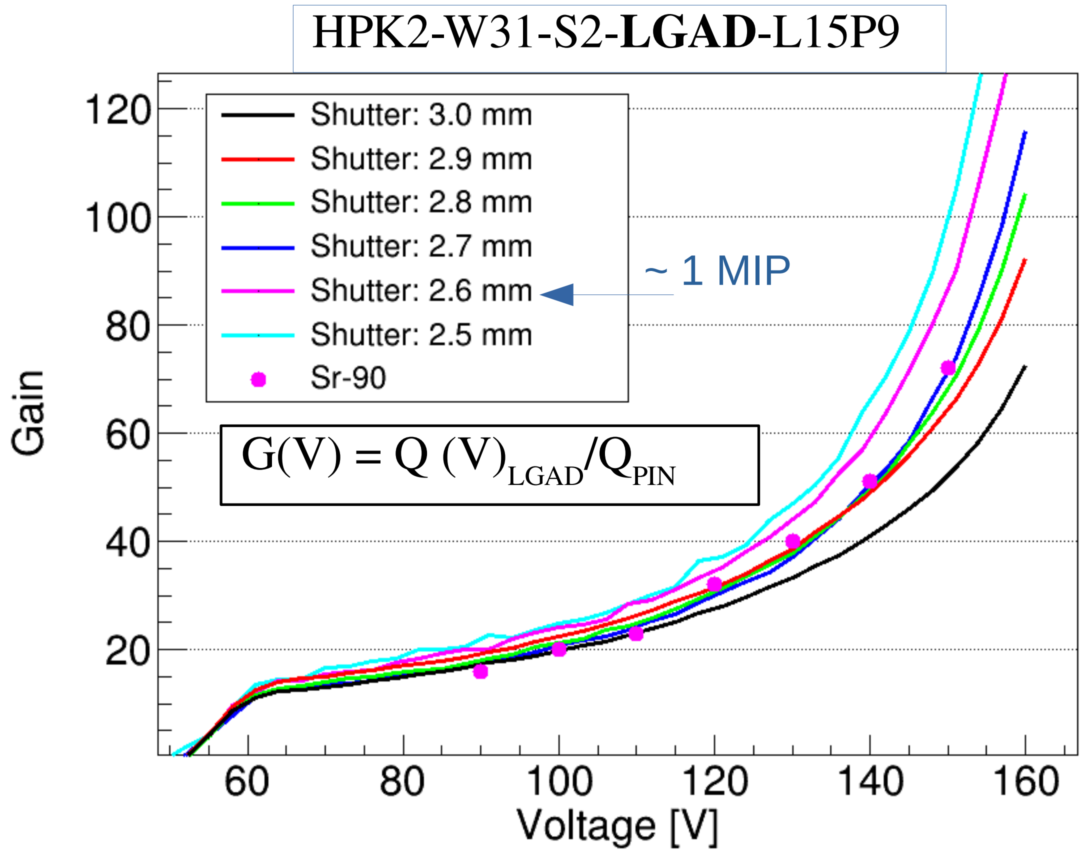


Decreasing laser intensity in TCT:

IR laser intensity ↓ Gain ↑

T: +20 ^{o}C
Averaging: 1024
Amplifier
IR shutter aperture:
- 3.0 (~ 5.0 MIPs)
- ...
- 2.5 (~ 0.4 MIPs)

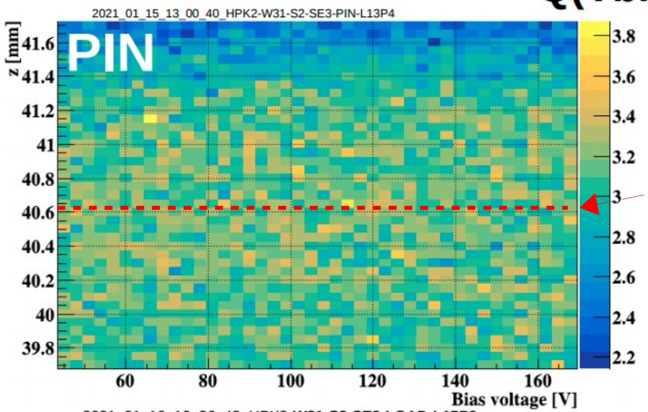




Out-of-focus measurements

Charge density inside the detector can be changed by defocusing the laser.

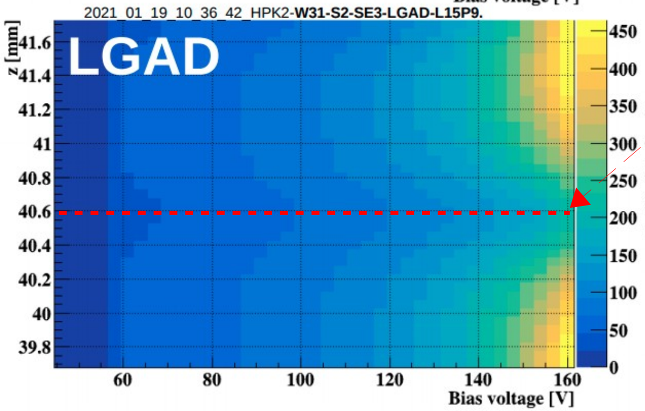
Q(Vbias,z)

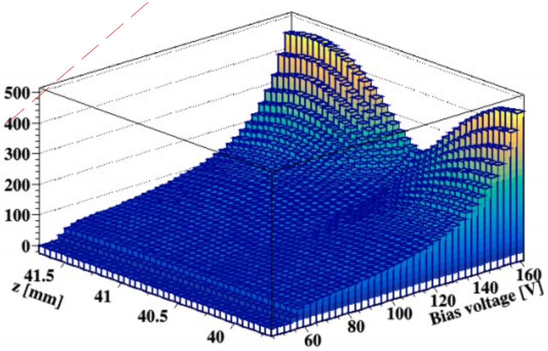


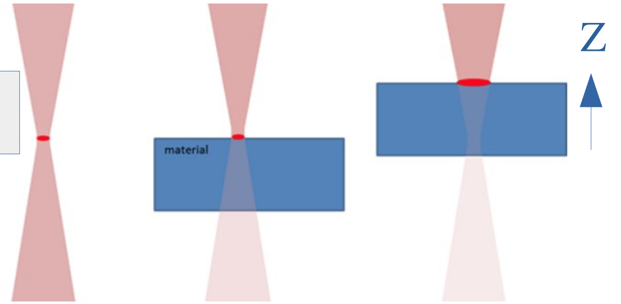
PIN: charge is z-invariant

Focus spot size (20 um)

For an **LGAD** measured in IR-TCT the collected charge depends on beam waist position (focusing)

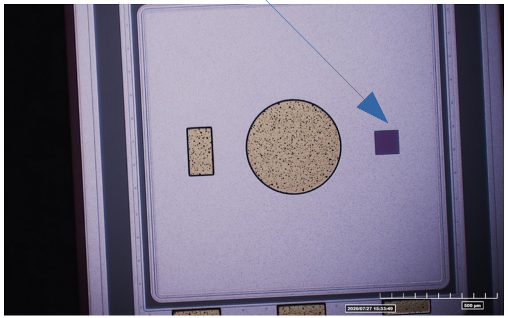






Sketch not-to-scale

The laser beam is always inside the opening window in the metallization. 100x100 um^2

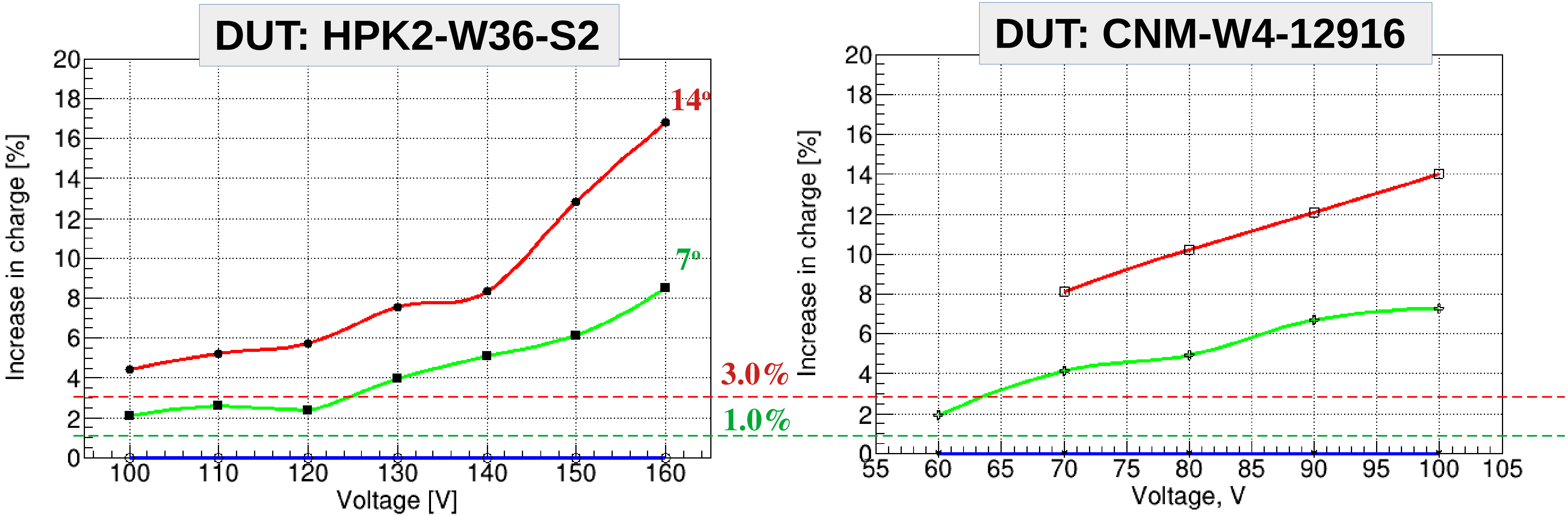


Clear effect in the gain observed

Remarkably more charge collected by tilting the sample than expected by simple geometry.

Expected increase by only geometrical aspects marked with dotted lines:

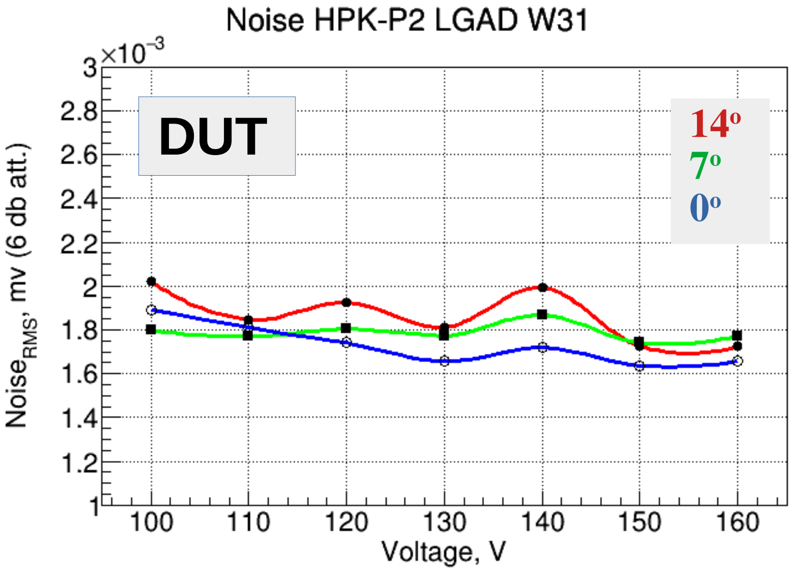
- 3.0 % for 14^{O} and 1.0% for 7^{O}.



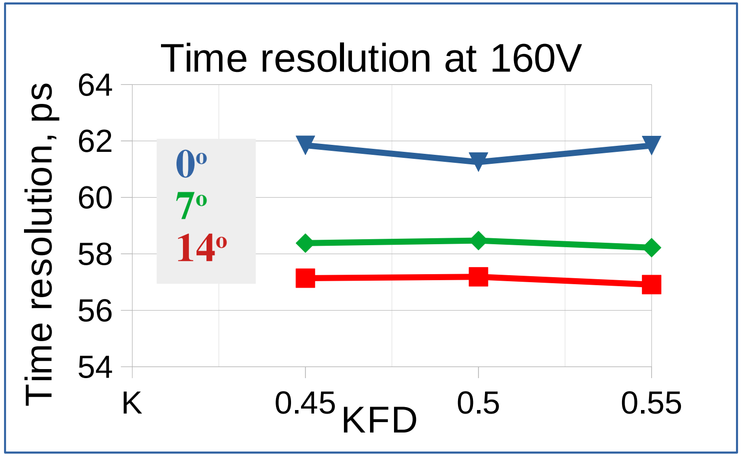
Effect in the timing performance

RS set-up still not optimized for low noise measurements. Not easy to measure because of the noise fluctuation between measurements:

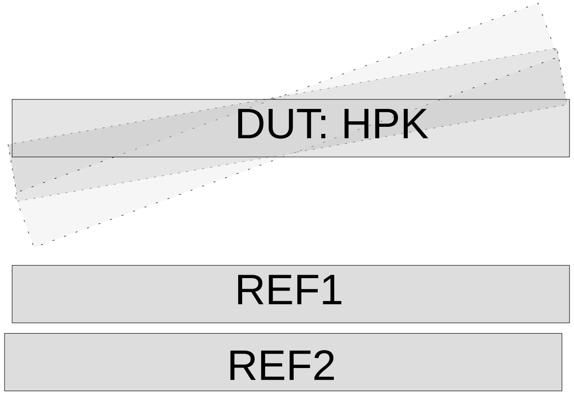
- We have noise fluctuations between different measurements of almost 10 %.
- We can only measure the time resolution of the whole system (DUT+REF) and it was dominated by REF.
  - The timing resolution of the REF has to be much lower than the DUT one.
  - Move to a three sensor configuration.



Best case scenario



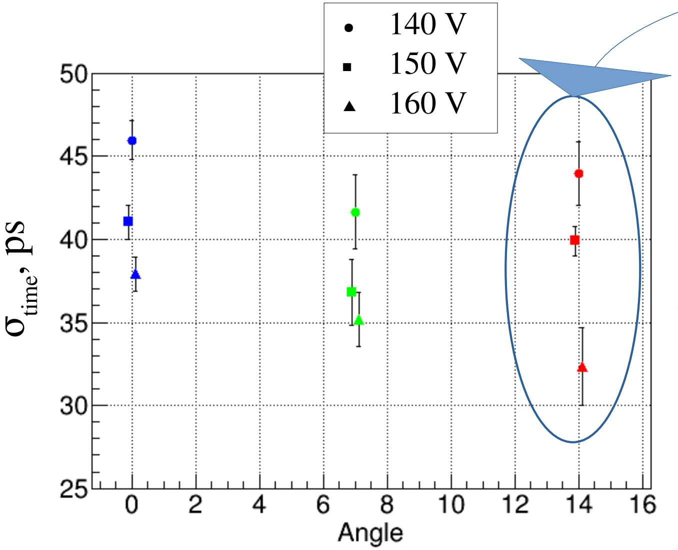
Effect in the timing performance



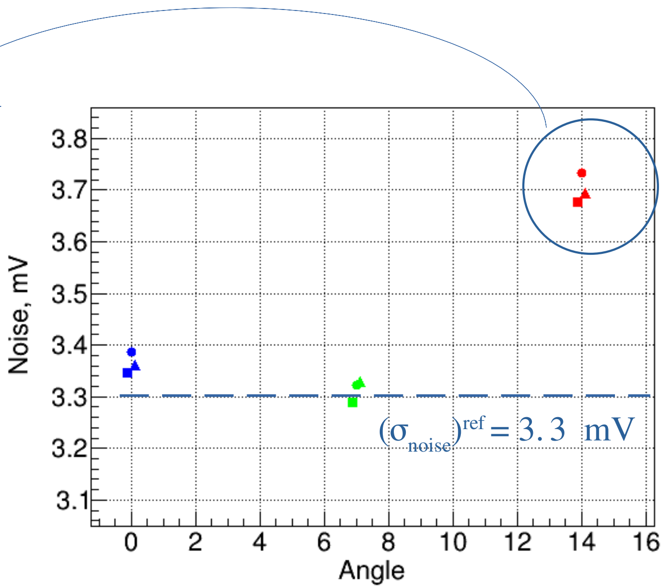
Measuring in a three sensors configuration !

It is possible to get directly the time resolution of the DUT. It is less affected by noise fluctuations in the system in a two sensors configuration (DUT + REF).

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

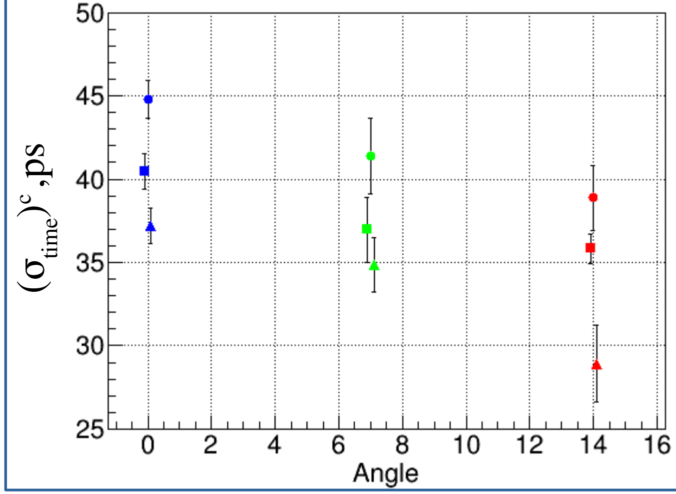


Higher noise!



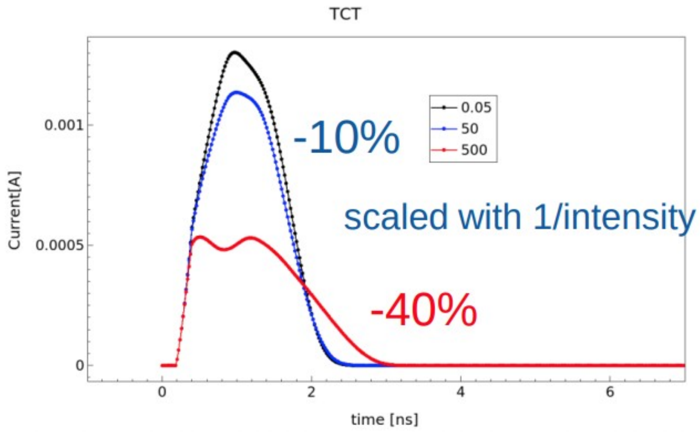
With noise correction

$$(\delta_{time})_i^c = (\delta_{time})_i \times \frac{(\delta_{noise})^{ref}}{(\delta_{noise})_i}$$

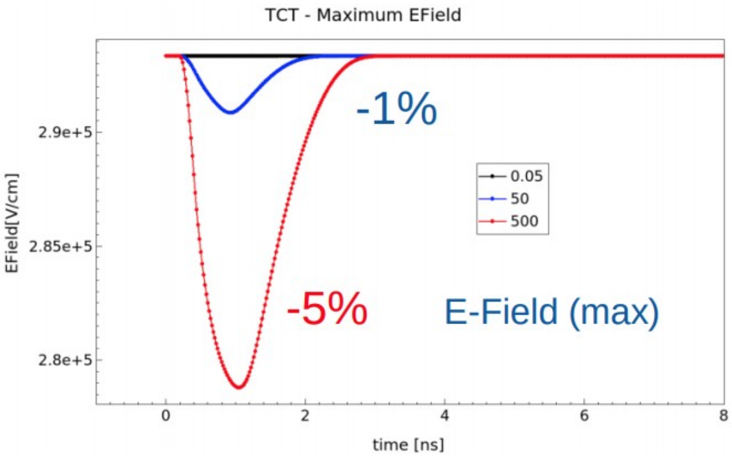


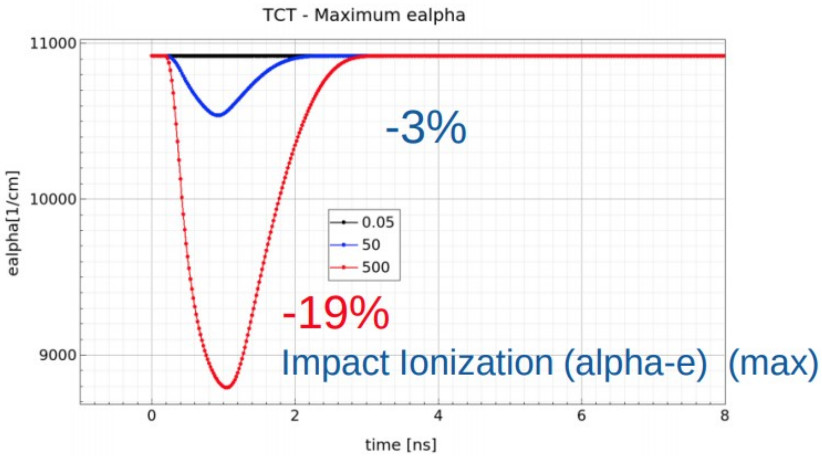
1-dim TCAD simulation: origin of the damping process?

EP R&D



- Carrier generation by impact ionization leads to reduction of Field strength
- Reduction of Field strength leads to reduction of impact ionization coefficient
- Reduction of impact ionization coefficient leads to less gain (i.e. signal reduction)





Beware: very conservative!
1-dim model for a clearly 3-dim problem!