The 40th RD50 Workshop
21–24 June 2022
CERN

Observation & characterisation of the charge screening effect in LGAD

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Motivation

A lot of interest in the study of the charge screening effects raised within the RD50 Community

Representative examples

- E. Curras Rivera el al., Gain suppression mechanism observed in Low Gain Avalanche Detectors, TREDI 2021 Virtual
- G. Kramberger et al., Effects of charge screening in LGADs, 39th RD50 Workshop (2021) Valencia

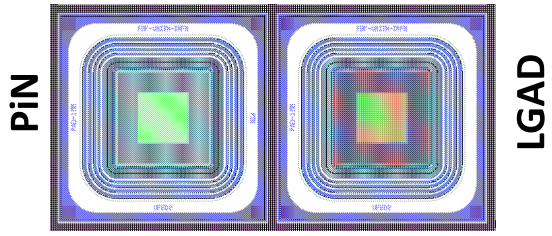
We want to further investigate the gain suppression mechanism via

→ **TCT measurements**

→ **Low energy protons**

→ **TCAD simulation**

An LGAD-PiN sensor from the FBK UFSD2 production has been used for tests
[doi:10.1016/j.nima.2018.07.060]

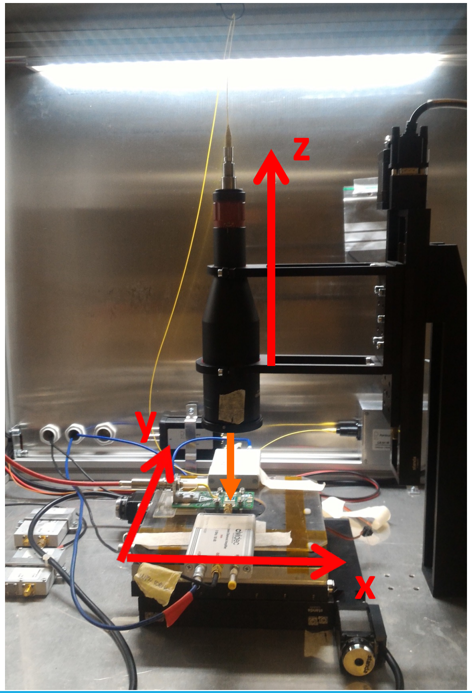


W10 – FBK UFSD2

G(V) from TCT – Laser Intensity

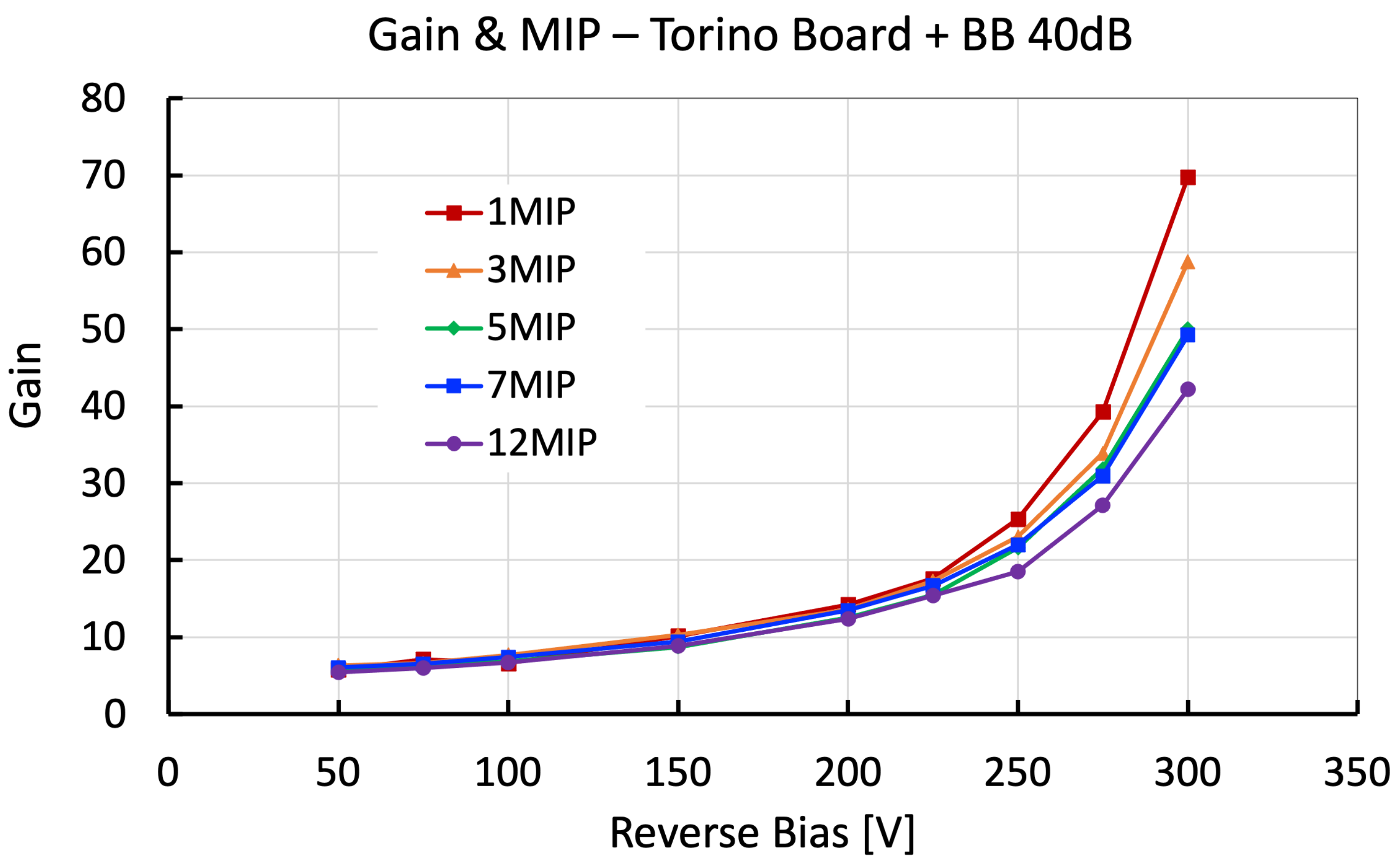
TCT Setup from Particulars

Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Room temperature



$$\mathbf{Gain} = \frac{\mathbf{Q_{LGAD}}}{\mathbf{Q_{PiN}}}$$

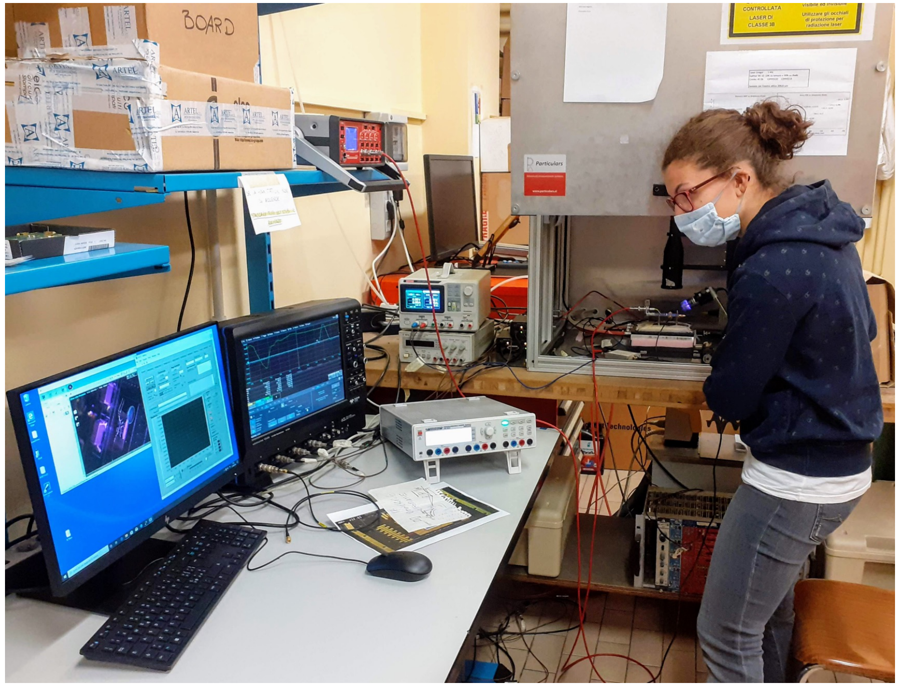
The gain distributions have been normalised at $V_{bias} \leq 100$ V to concentrate on the relative evolution of the gain

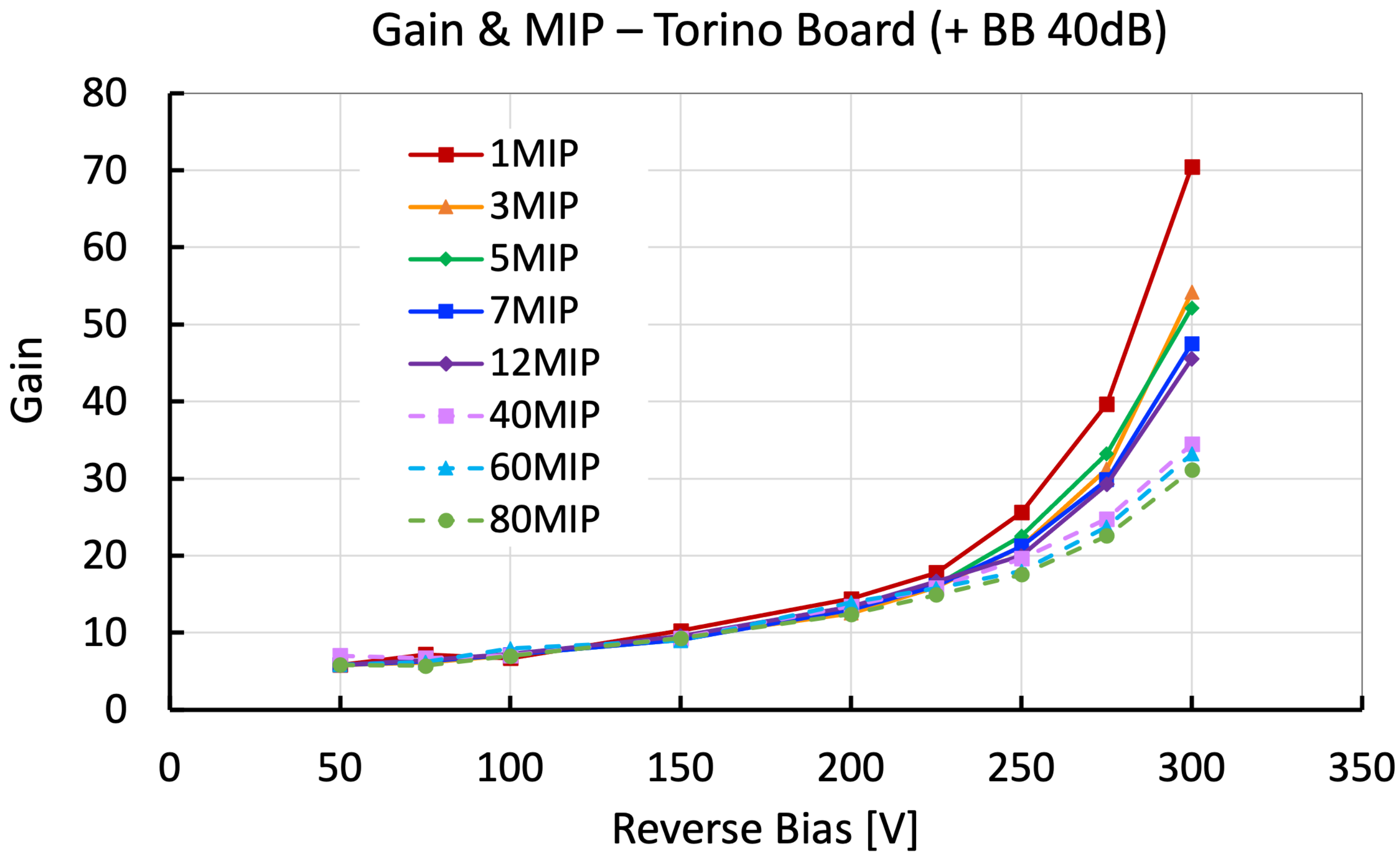


→ Gain suppression mechanism observed above 200 V

G(V) from TCT – High Laser Intensity

TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Without external amplification
Oscilloscope LeCroy 640Zi
Room temperature





→ Suppression of gain enhanced for laser intensity ≥ 40 MIPs

G(V) from TCT – ZOOM

TCT Setup from Particulars

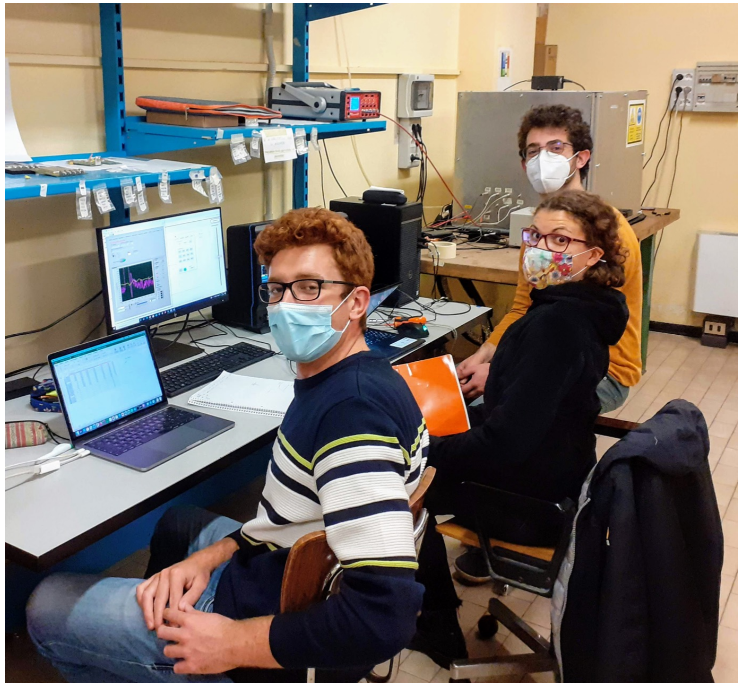
Pico-second IR laser at 1064 nm

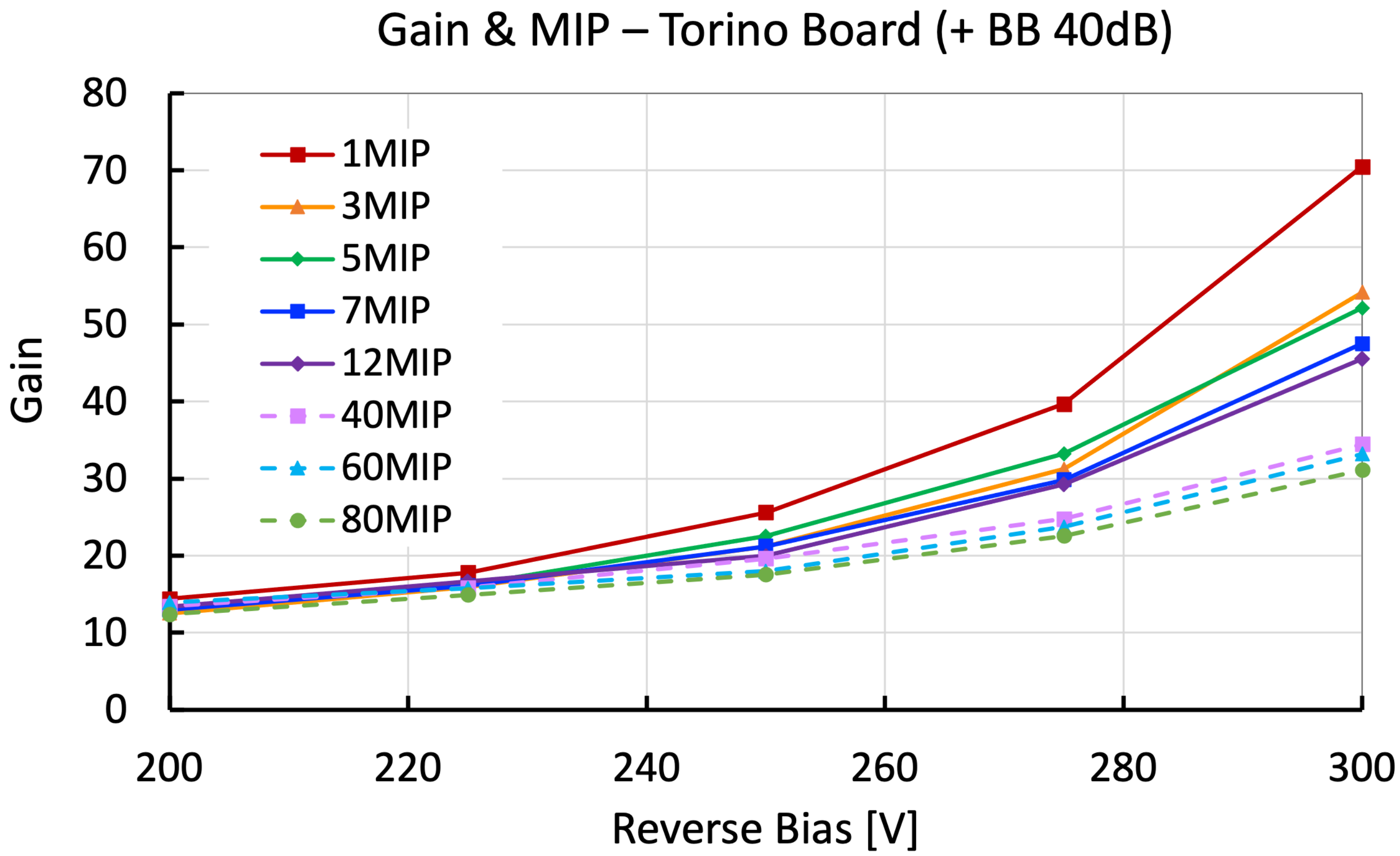
Laser spot diameter ~ 10 µm

Without external amplification

Oscilloscope LeCroy 640Zi

Room temperature



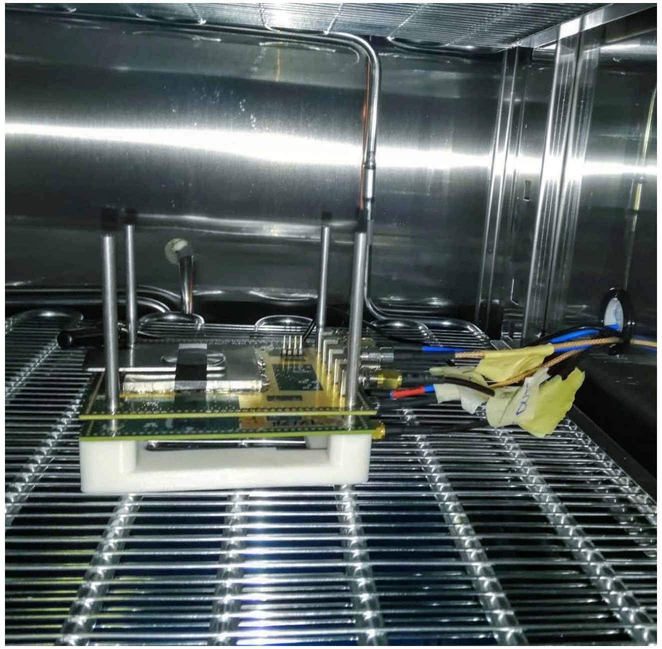


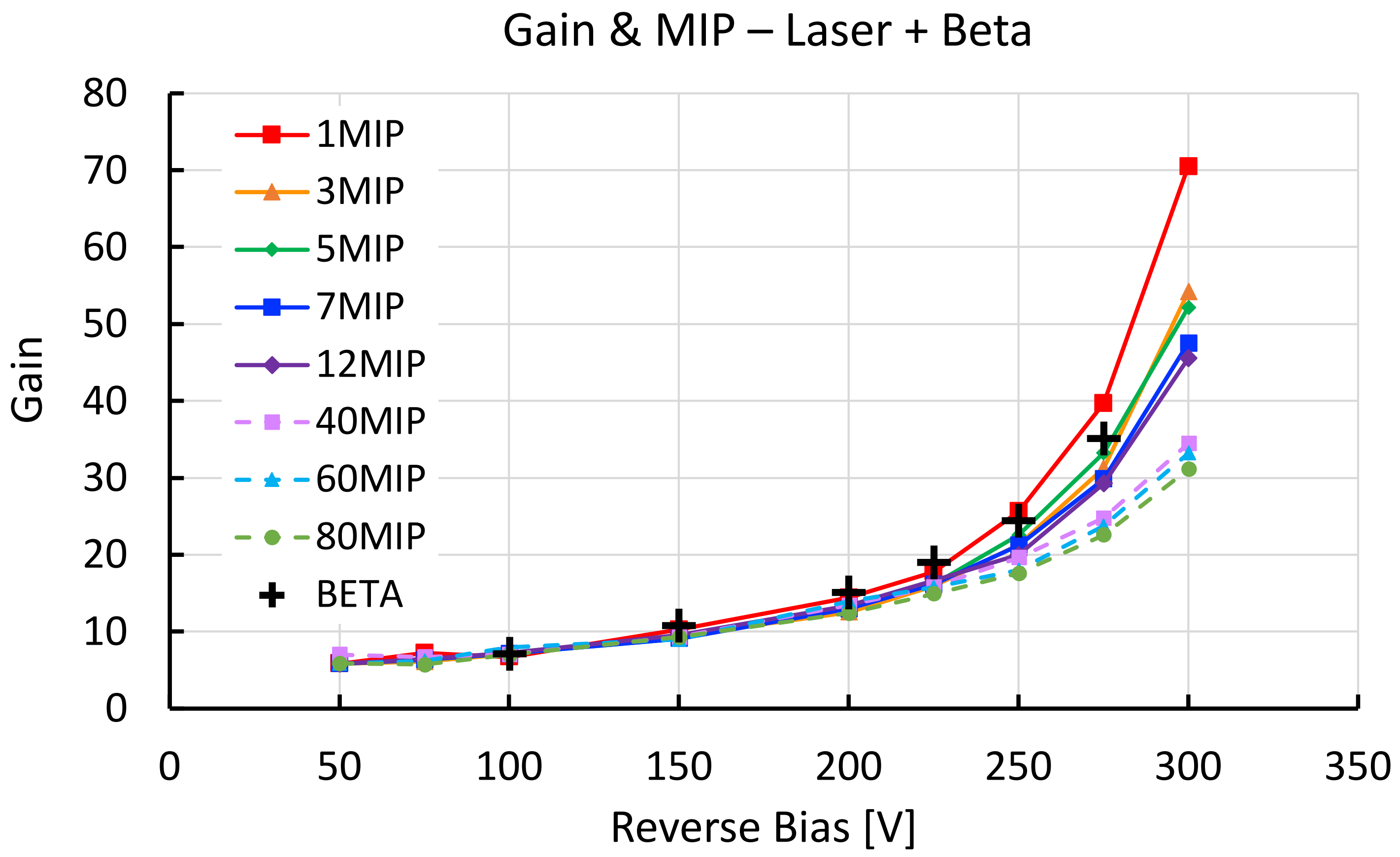
→ More than 50% of gain suppressed going from 1 to 80 MIPs

G(V) from β Particles – Comparison with TCT

β Particles Setup

Sensor on UCSC Board
Civídec Broadband Amplifier (20dB)
System transimpedance ~ 4700 Ω
Oscilloscope LeCroy 640Zi
Room temperature
Trigger below the DUT





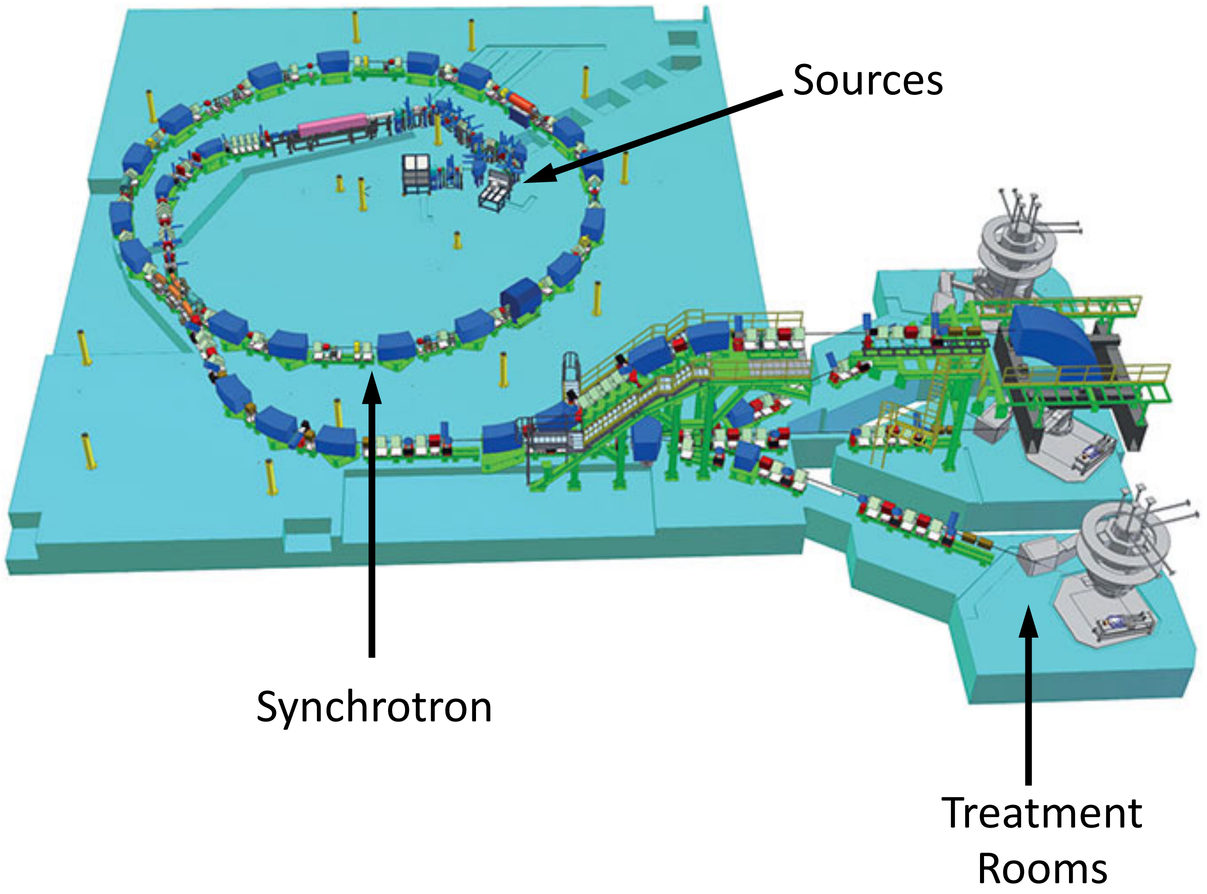
→ Gain evolution from β particles between 1 and 3 MIPs

G(V) from Low-Energy Protons

fondazione CNAO
Centro Nazionale di Adroterapia Oncologica

Goal: use a medical facility for particle therapy to investigate the gain suppression mechanism with low energetic proton beams

Proton Energy [MeV]	Equivalent MIPs
62	5.0
110	3.3
170	2.4
226	2.0

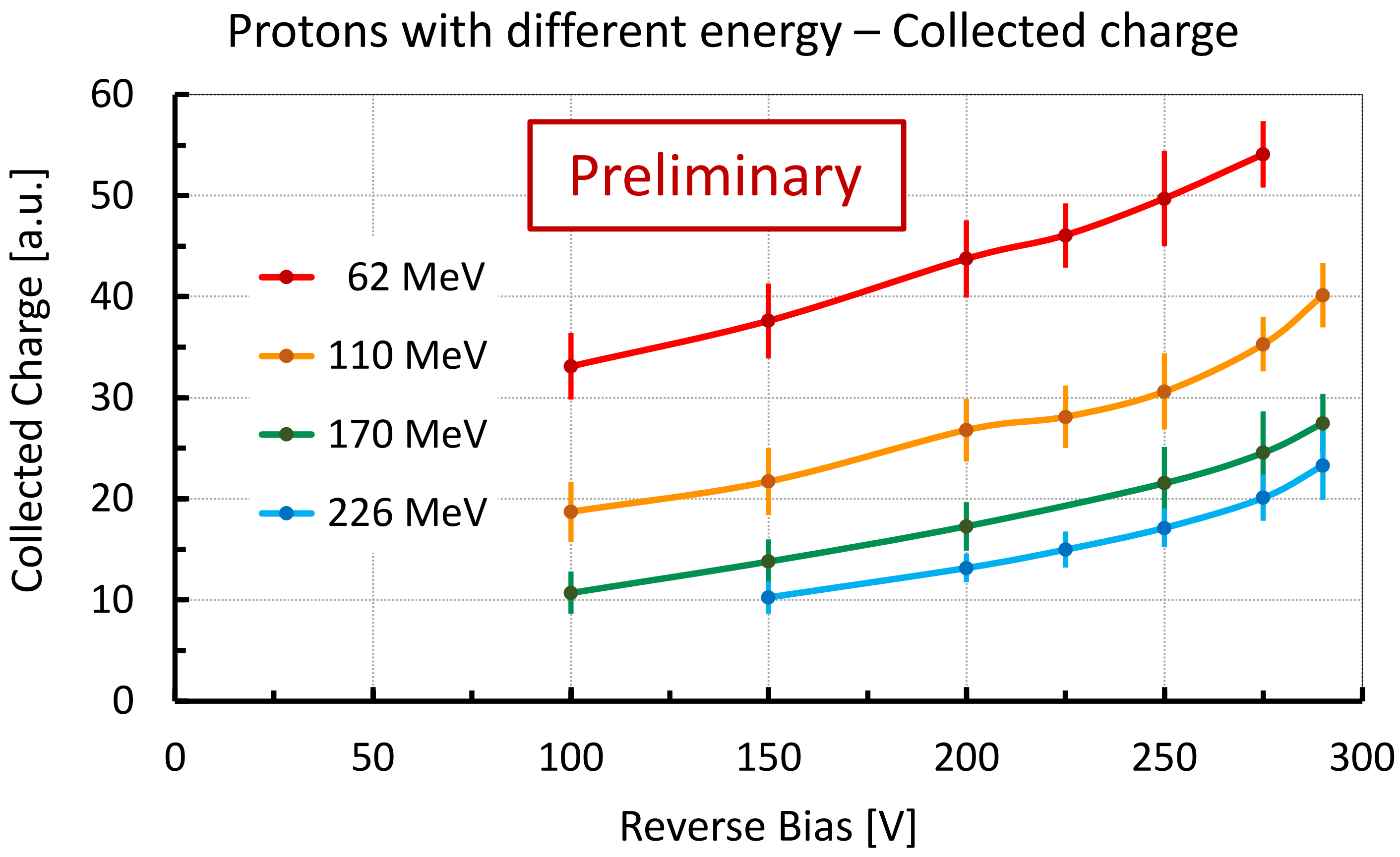


Q(V) from Low-Energy Protons

fondazione CNAO
Centro Nazionale
di Adroterapia Oncologica

CNAO Beam Test Setup

Same FBK UFSD2 LGAD-PiN under test
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Room temperature
Trigger behind the DUT



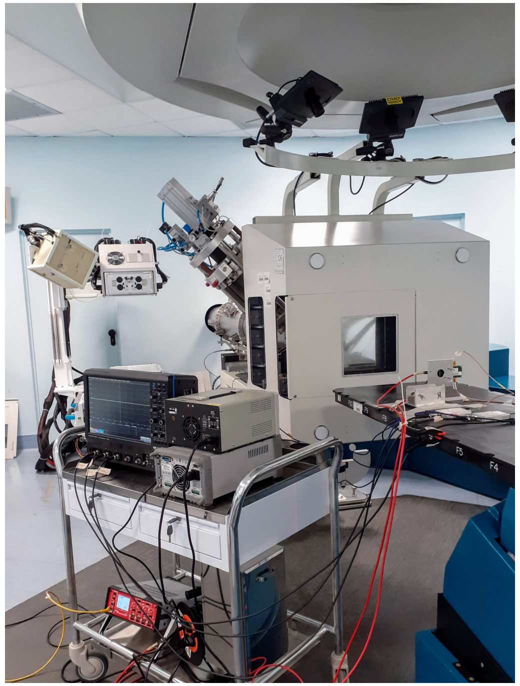
→ Collected charge scales with the impinging proton energy

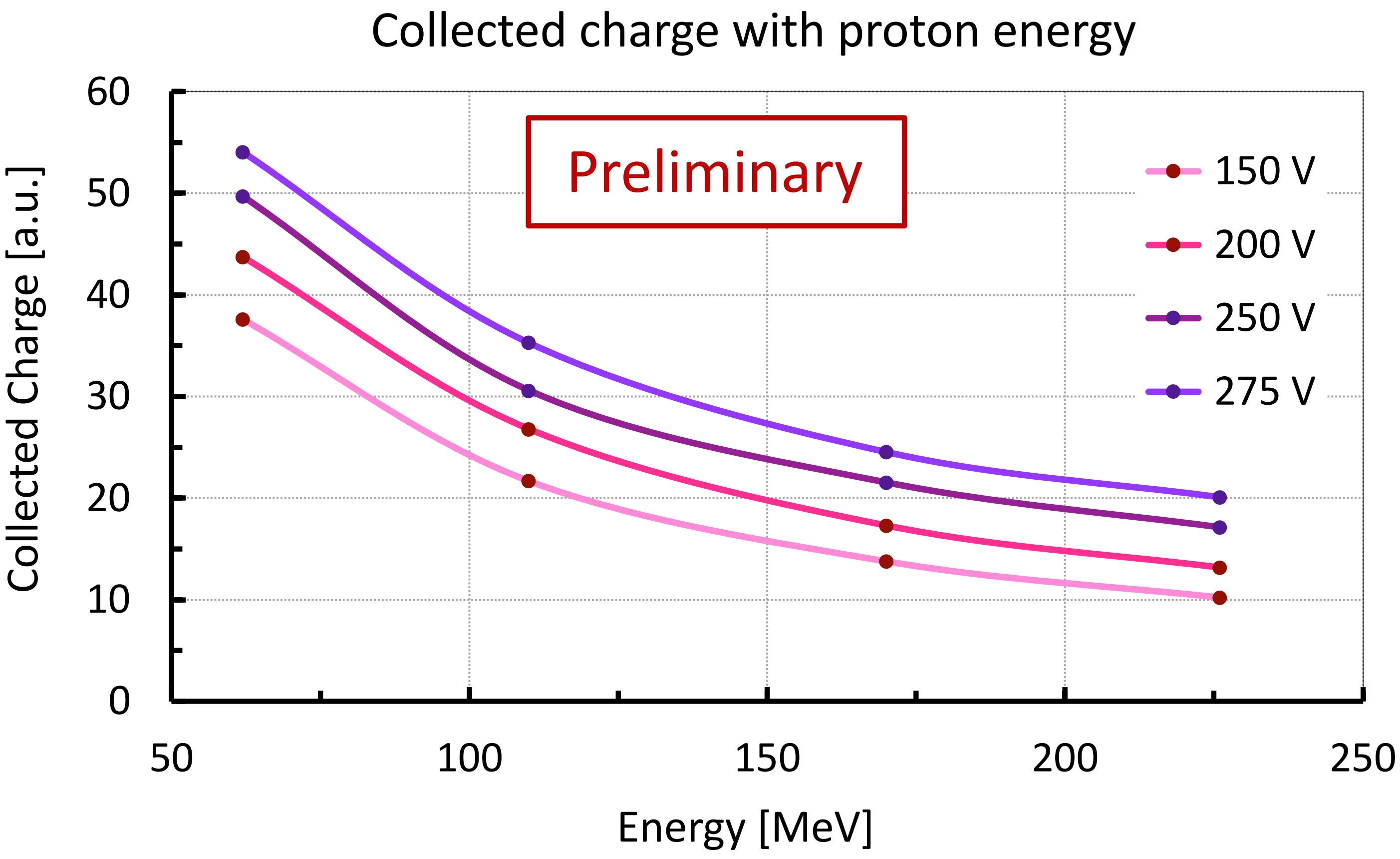
Q(E) from Low-Energy Protons

fondazione CNAO
Centro Nazionale di Adroterapia Oncologica

CNAO Beam Test Setup

Same FBK UFSD2 LGAD-PiN under test
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Room temperature
Trigger behind the DUT

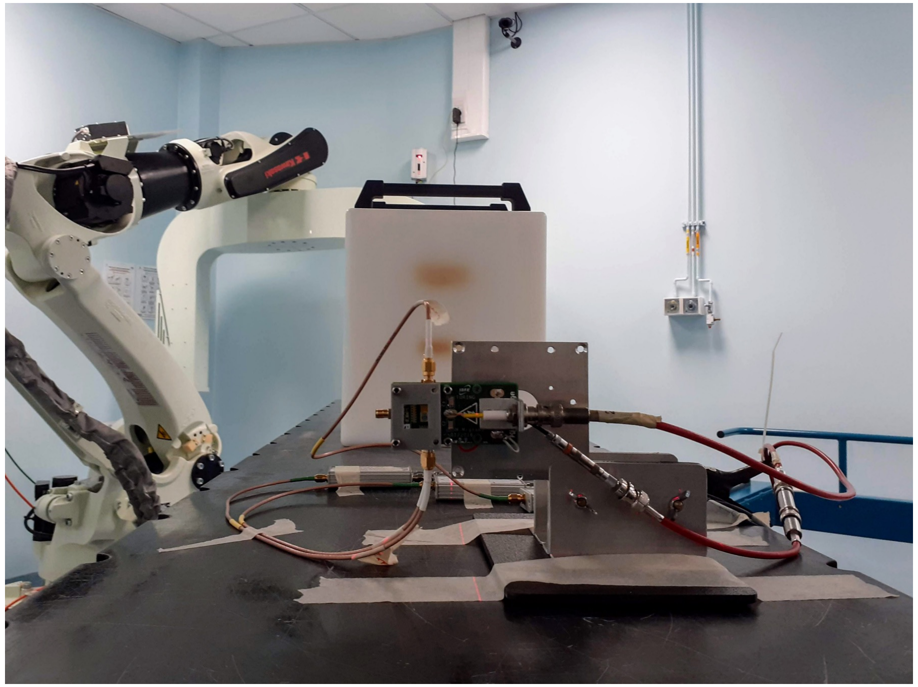


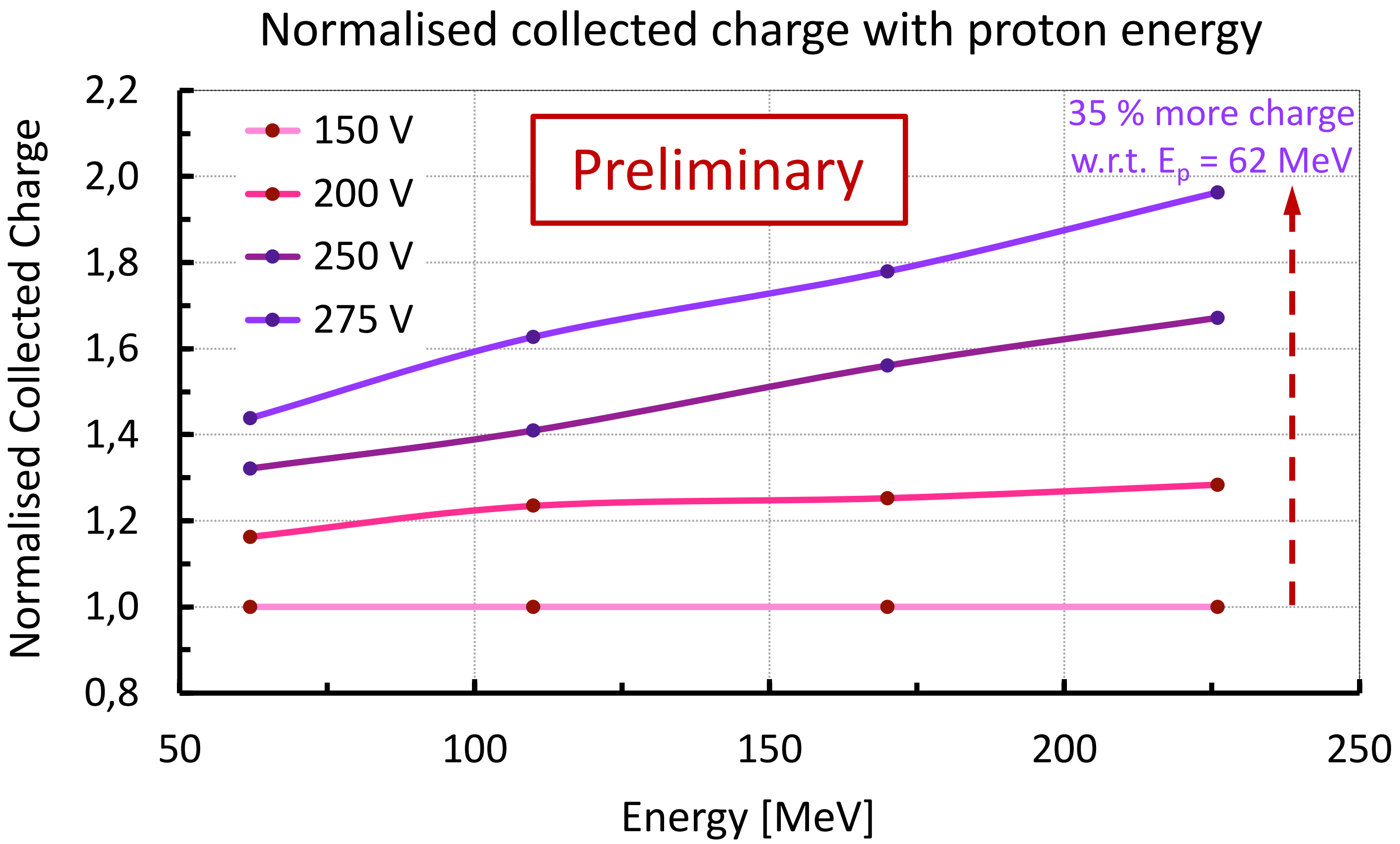


→ At fixed V_{bias}, the collected charge scales with the energy

Q(E) from Low-Energy Protons

The collected charge distributions have been normalised to the one at V_{bias} = 150 V, to observe the relative evolution of the collected charge with the proton energy





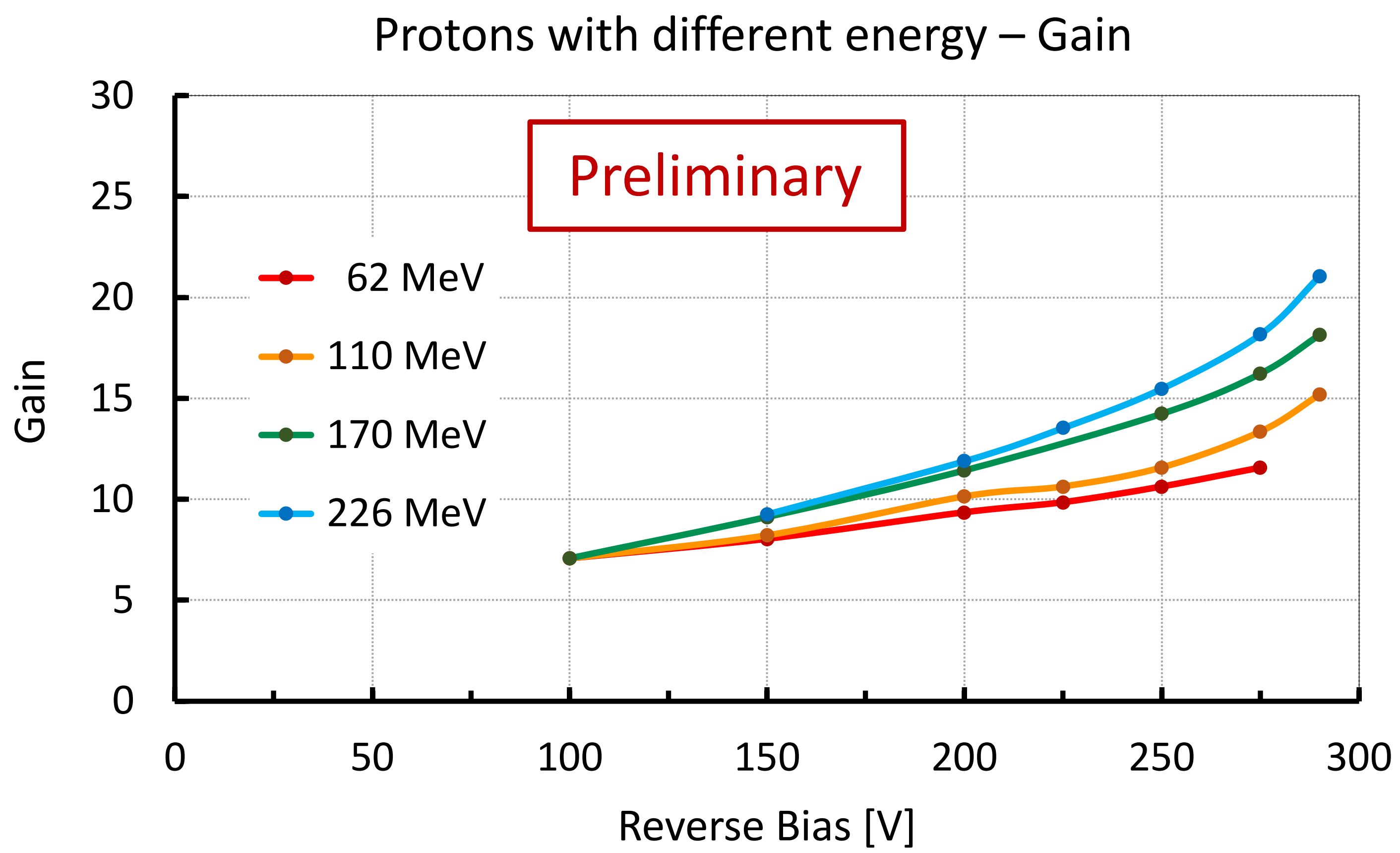
→ **Higher energies show a steeper increase of the collected charge**

G(V) from Low-Energy Protons

fondazione CNAO
Centro Nazionale
di Adroterapia Oncologica

$$\text{Gain} = \frac{Q_{LGAD}}{Q_{PiN}}$$

To make the gain measurement independent of the resolution on the Q_{PiN}, all the curves have been normalised at low $V_{bias} \leq 150$ V



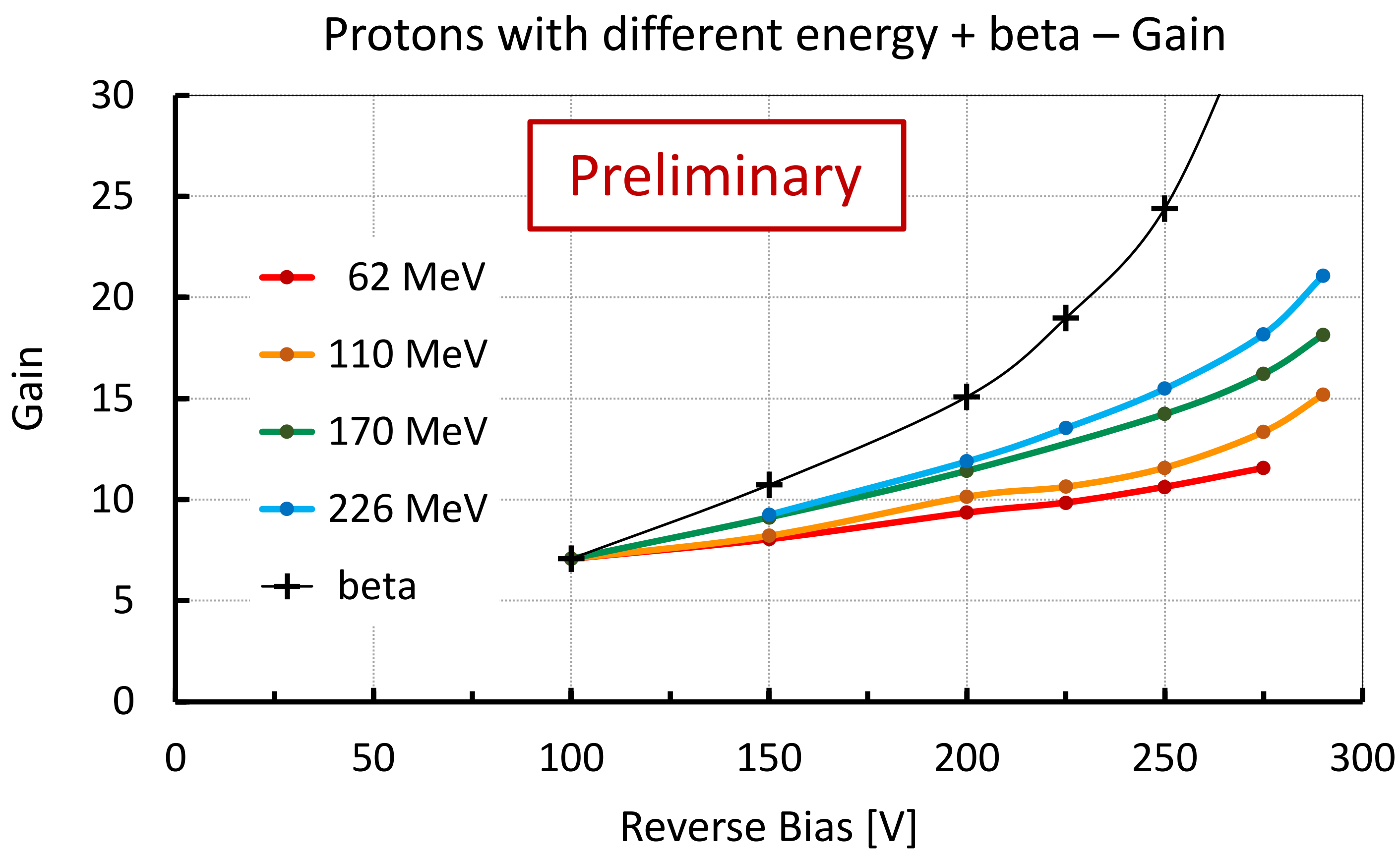
→ **A gain reduction is observed with decreasing proton energy**

G(V) from Low-Energy Protons +β

fondazione CNAO Centro Nazionale di Adroterapia Oncologica

$$\text{Gain} = \frac{Q_{LGAD}}{Q_{PiN}}$$

To make the gain measurement independent of the resolution on the Q_{PiN}, all the curves have been normalised at low $V_{bias} \leq 150$ V

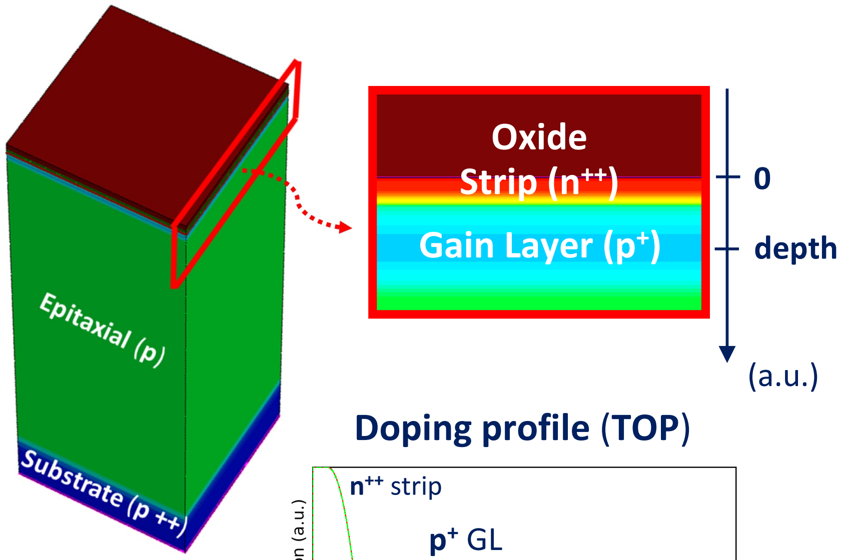


→ **Gain reduction is more pronounced if compared to β particles**

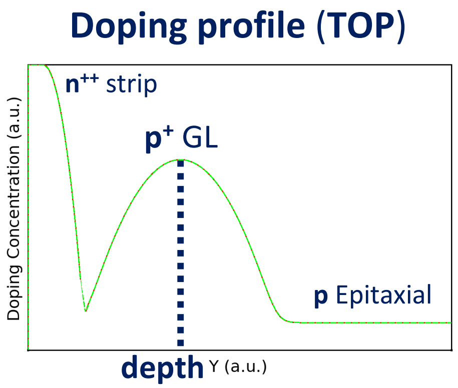
TCAD Simulation of the Impact Ionisation

A **TCAD device-level simulation** has been performed in **2D and 3D domain**

⟶ Qualitative study of **saturation** of the **gain mechanism**



Gaussian Gain Layer (GL) **profile**



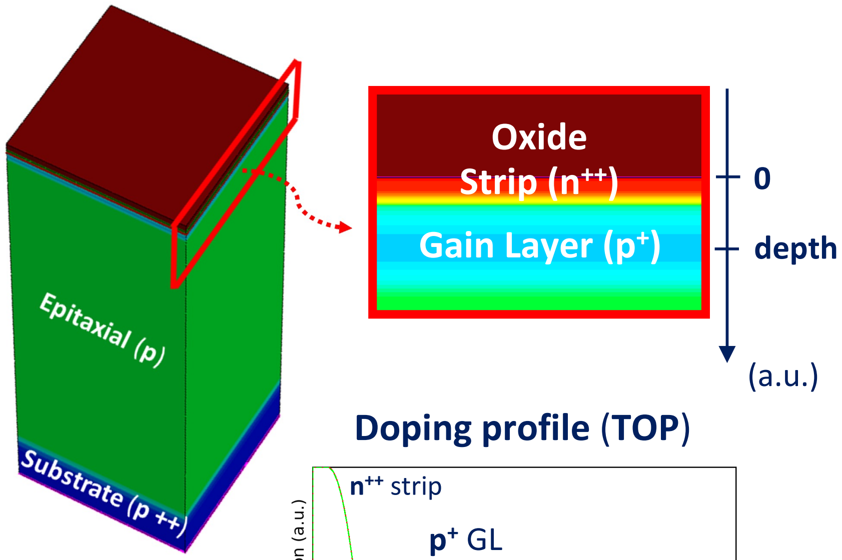
The *HeavyIon* function is activated in Sentaurus to emulate an ion travelling through the detector to study charge multiplication with the passage of a charged particle

The *HeavyIon* function allows the user to control the amount of ionisation energy released by the impinging ion

TCAD Simulation of the Impact Ionisation

A **TCAD device-level simulation** has been performed in **2D and 3D domain**

→ Qualitative study of **saturation** of the **gain mechanism**



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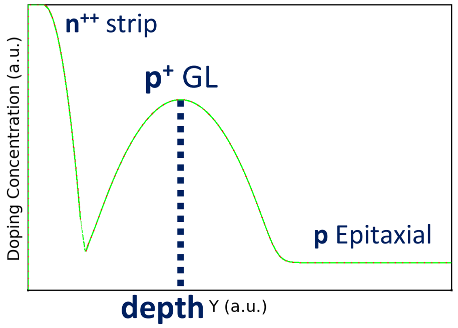
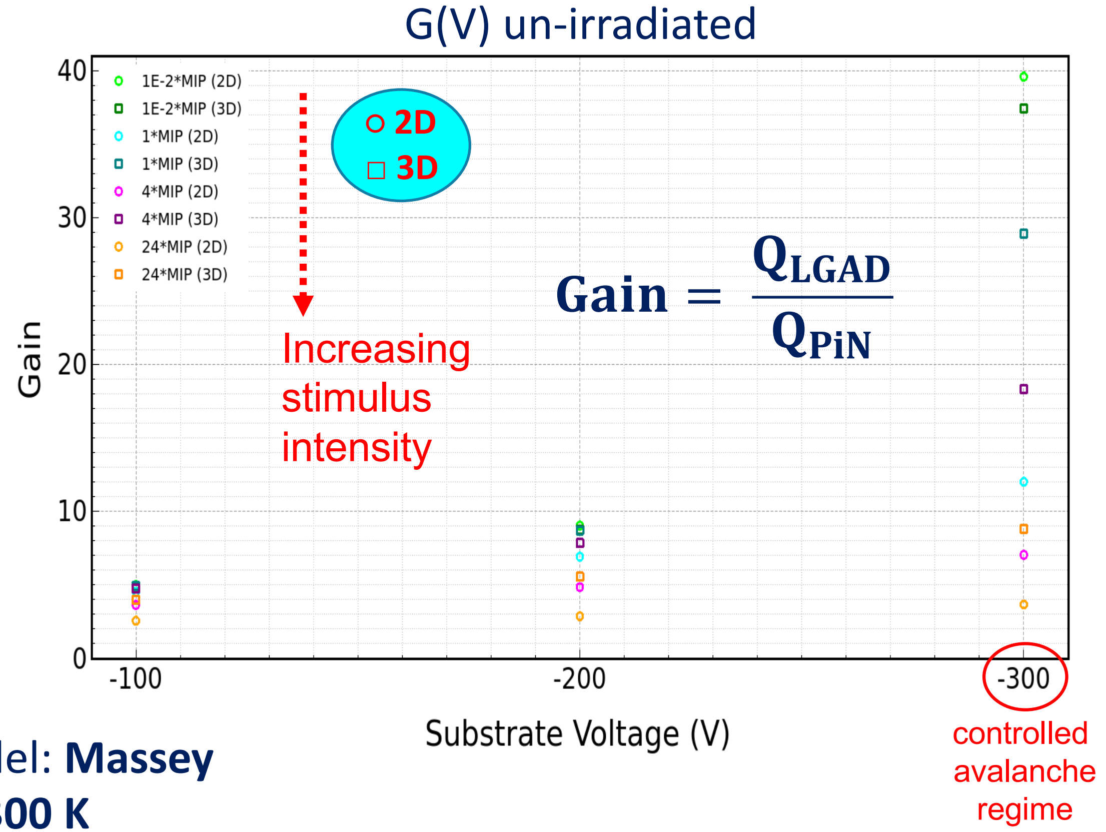




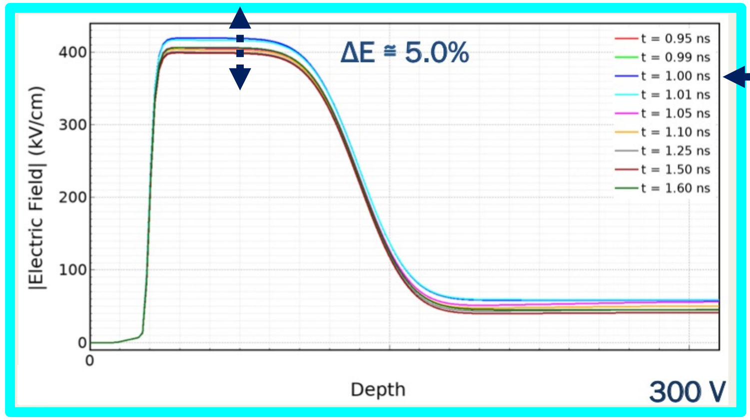
Avalanche model: **Massey**

Temperature: **300 K**

TCAD Simulation – 2D vs 3D Domain

→ **Impact** of the **high electic field** region – e.g. **1 MIP**

2D



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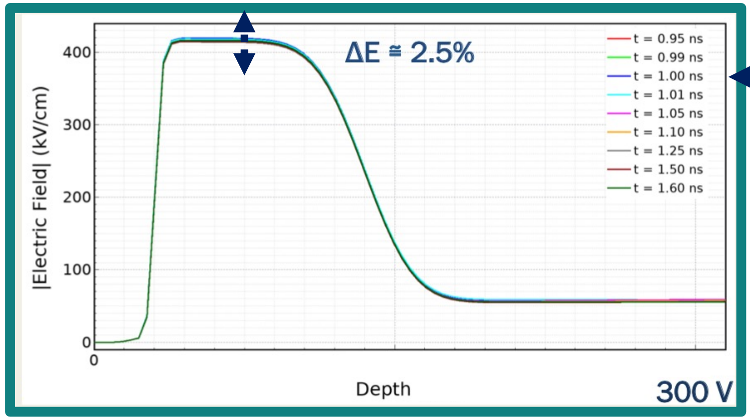
3D



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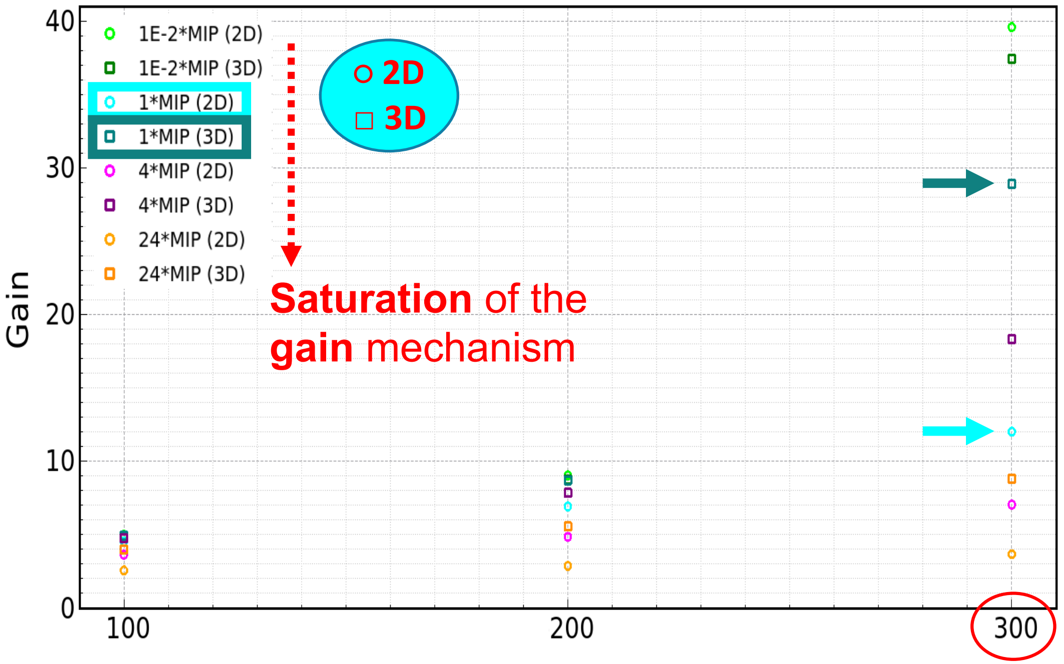
G(V) un-irradiated



controlled avalanche regime

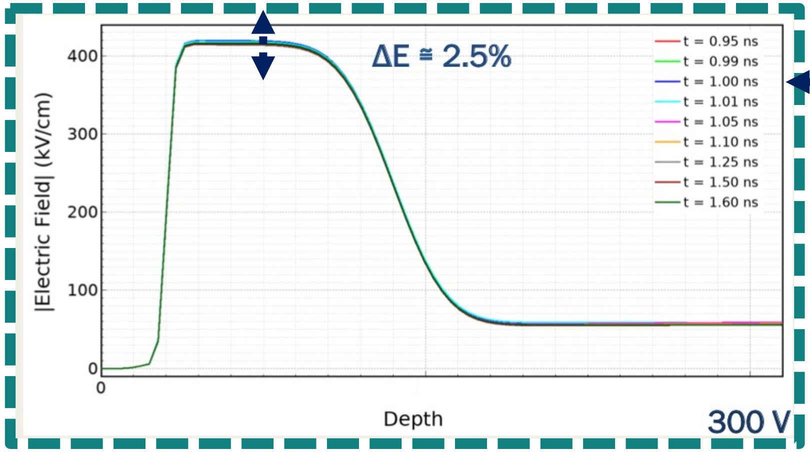
Avalanche model: **Massey**

Temperature: **300 K**

TCAD Simulation – 3D Domain

→ **Impact** of the **high electic field** region – e.g. **0.01 MIP**

3D
1 MIP



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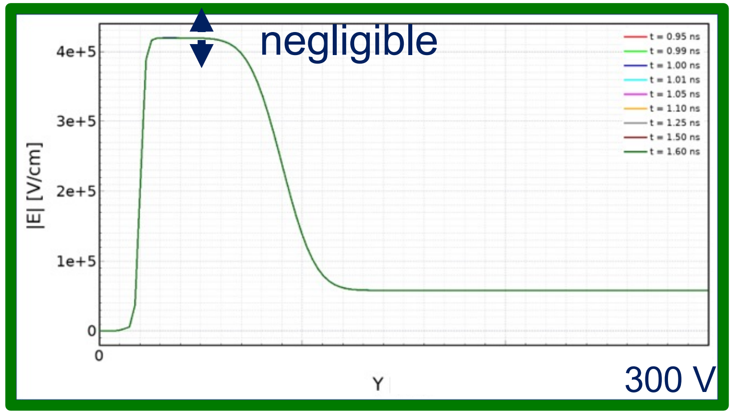
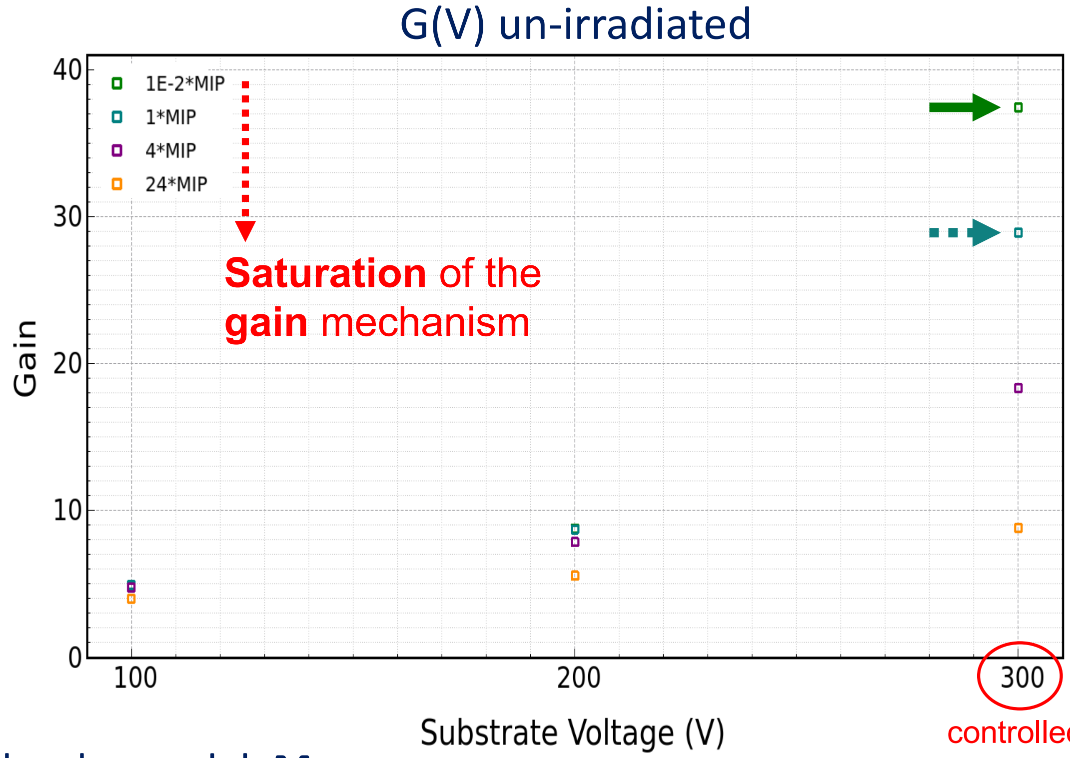




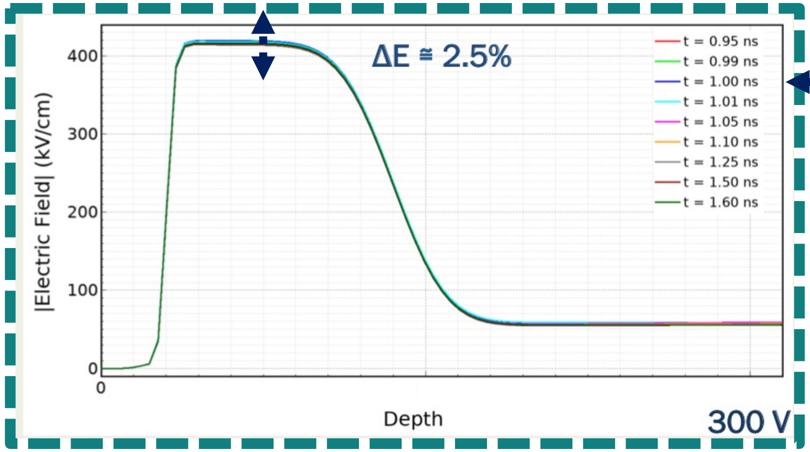
controlled avalanche regime

Avalanche model: **Massey**
Temperature: **300 K**

TCAD Simulation – 3D Domain

→ **Impact** of the **high electic field** region – e.g. **4 MIP**

3D
1 MIP



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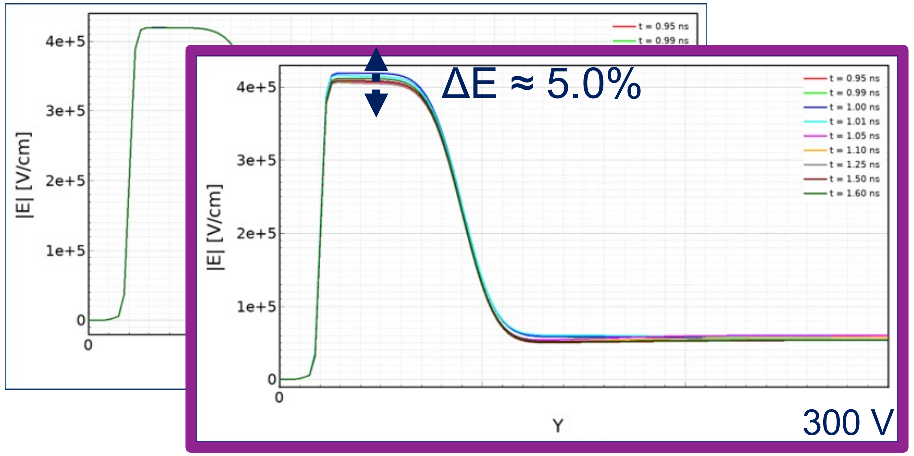
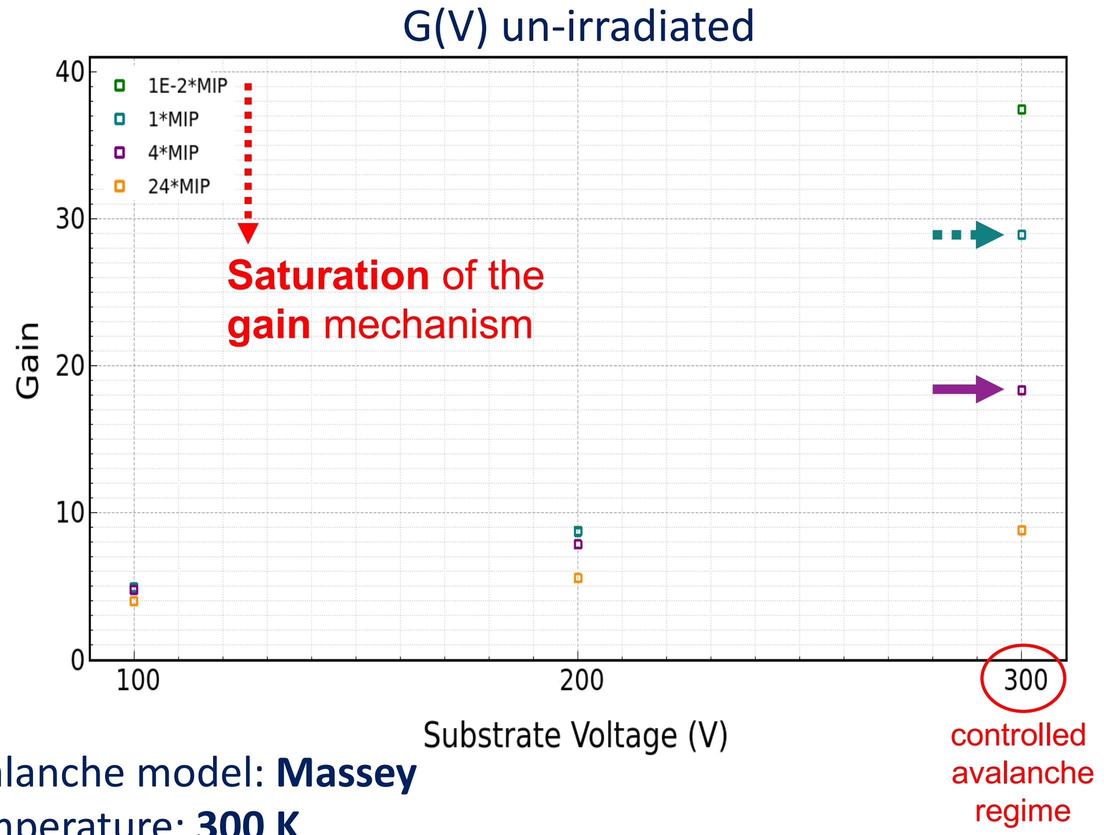


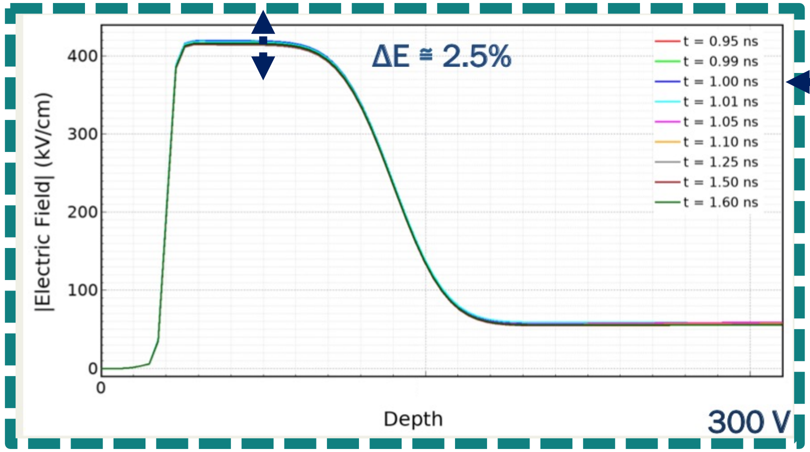


Avalanche model: **Massey**
Temperature: **300 K**

TCAD Simulation – 3D Domain

→ **Impact** of the **high electic field** region – e.g. **24 MIP**

3D
1 MIP



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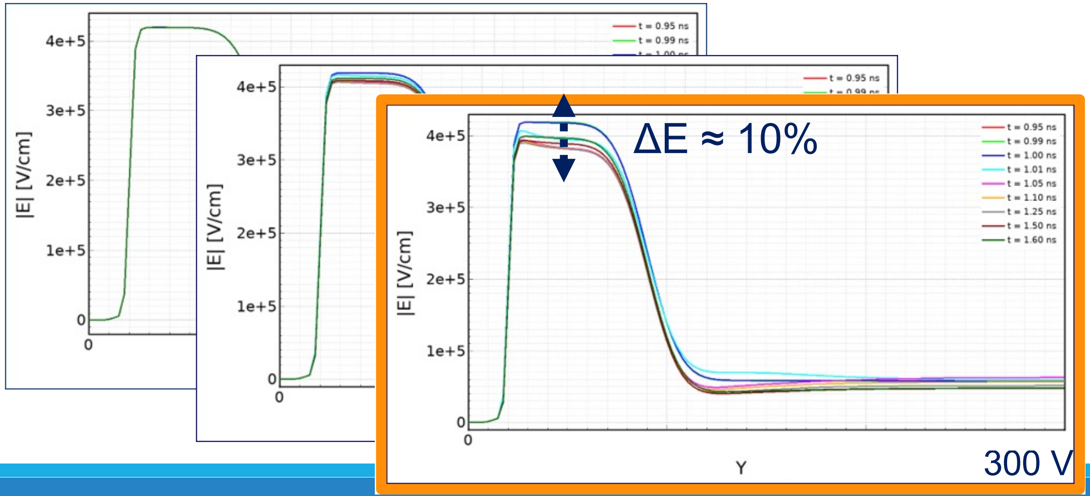

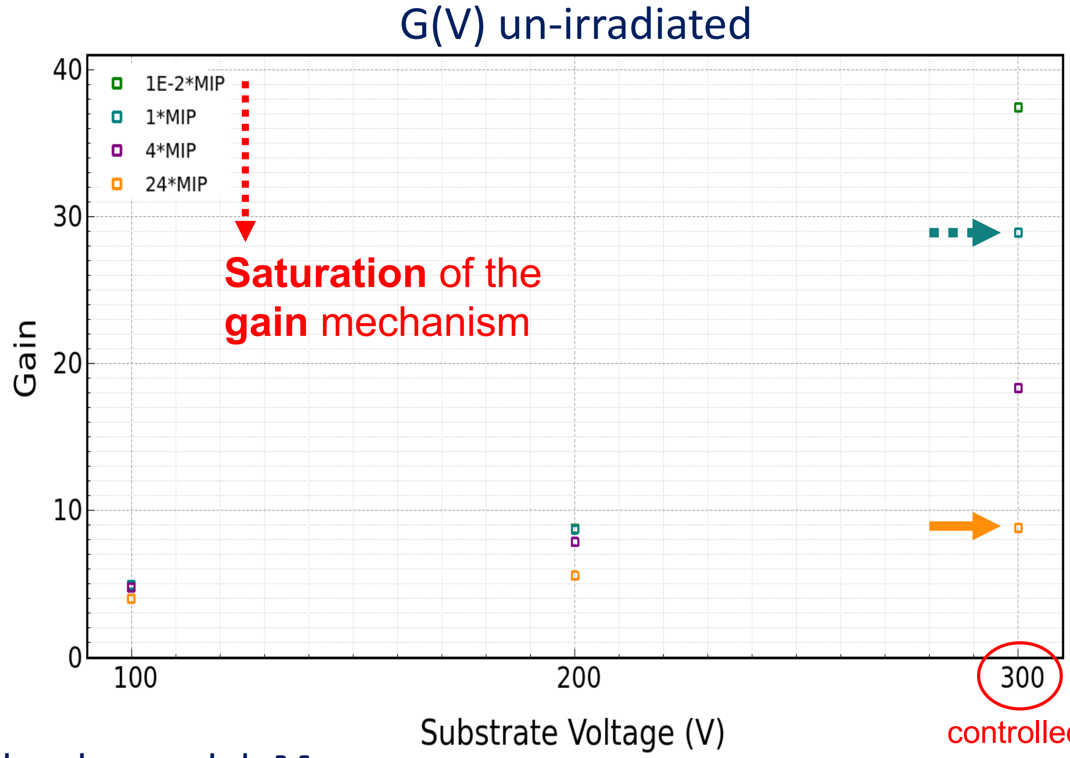

Avalanche model: **Massey**

Temperature: **300 K**

Summary

- ▻ Gain suppression mechanism observed in TCT measurement while increasing the intensity of the laser stimulus
  - → Results in agreement with previous observations from other groups
- ▻ Gain suppression mechanism observed for low-energy protons used in particle therapy
  - → Preliminary results need further scrutiny
- ▻ To simulate the gain suppression mechanism at the device level, the 3D domain is necessary
  - → The gain suppression observed using the *HeavyIon* function tends to overestimate the suppression observed in TCT data
  - → The suppression behaviour is similar to the one observed for the low-energy protons

Summary

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  - → The suppression behaviour is similar to the one observed for

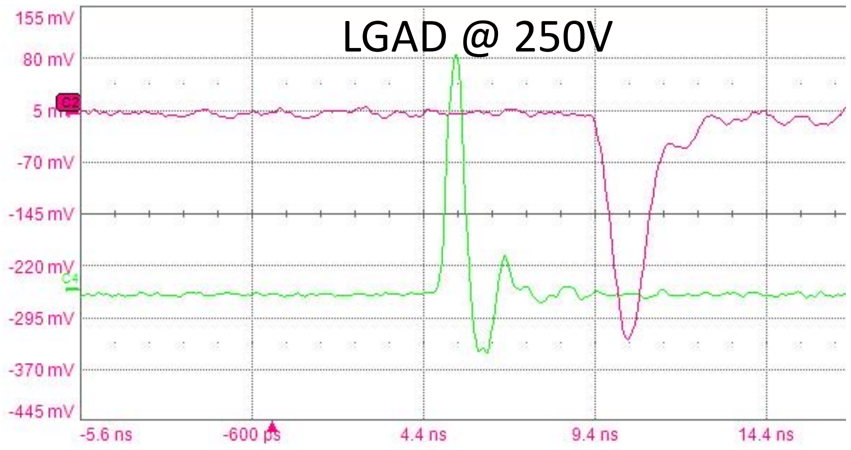
Acknowledgements

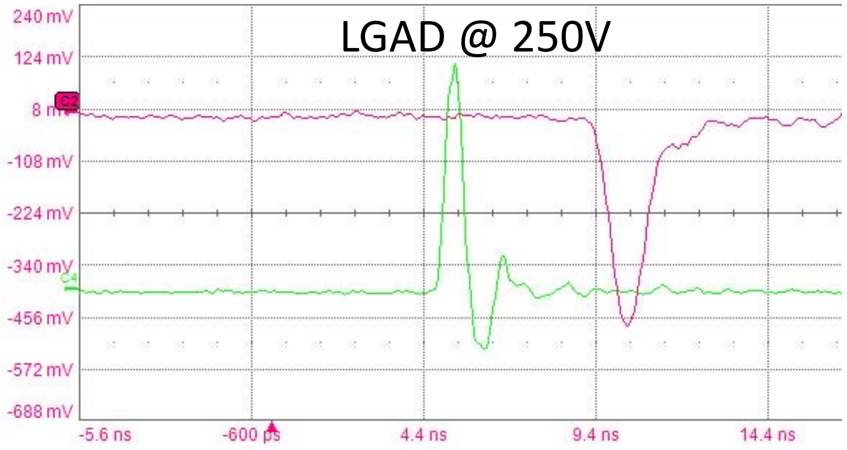
We kindly acknowledge the following funding agencies and collaborations:

- INFN CSN5
- Ministero della Ricerca, Italia, FARE, R165xr8frt_fare
- Ministero della Ricerca, Italia, PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- MIUR, Dipartimenti di Eccellenza (ex L. 232/2016, art. 1, cc. 314, 337)
- European Union's Horizon 2020 Research and Innovation programme, Grant Agreement No. 101004761
- Fondazione CNAO
- RD50, CERN

Bonus Slides

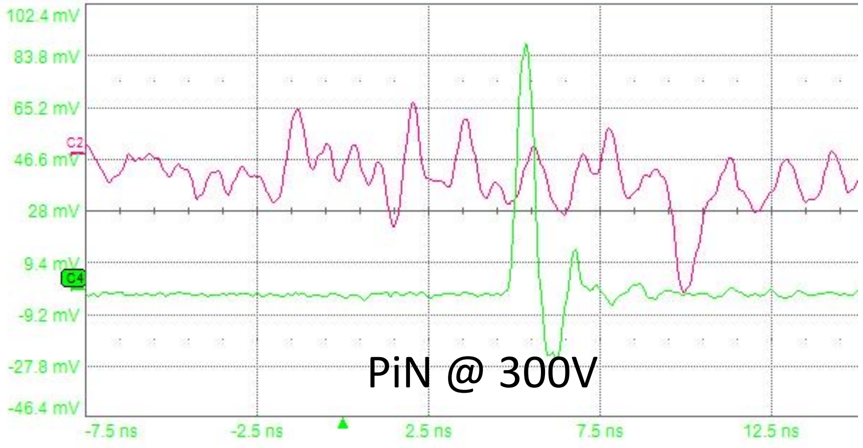
TCT Setup – Signal Shapes from the Scope

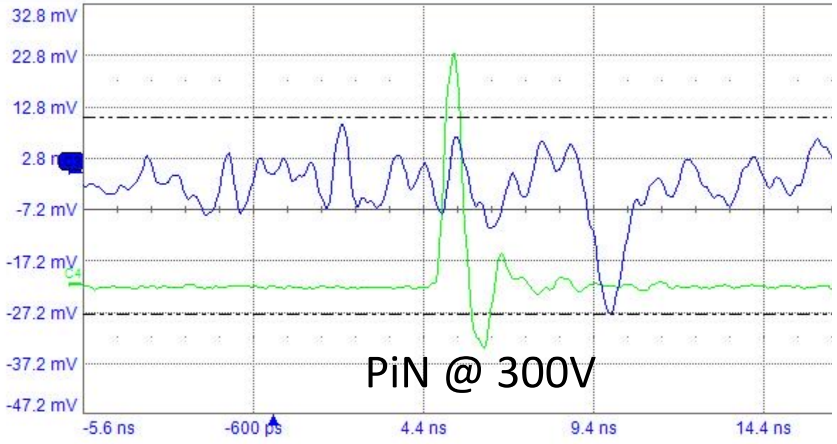




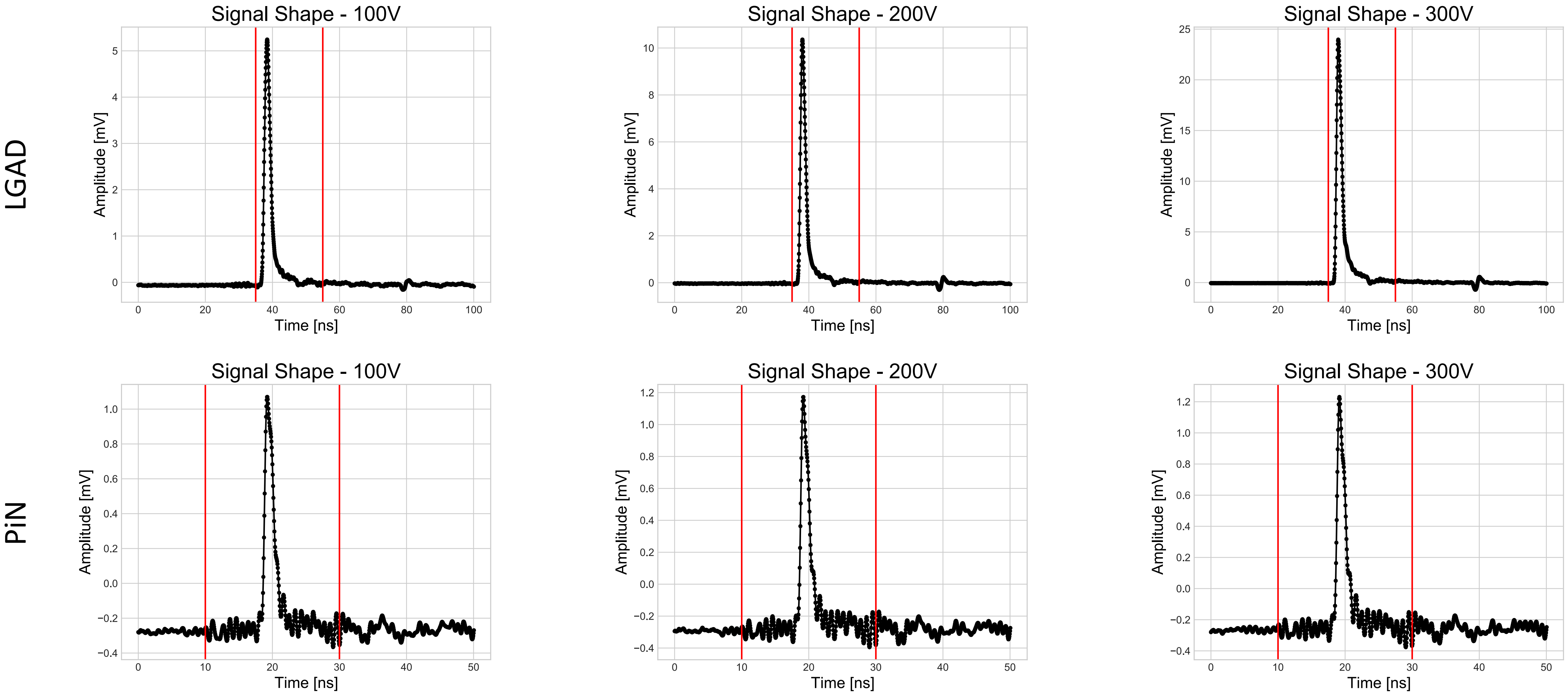
10 MIP

12 MIP



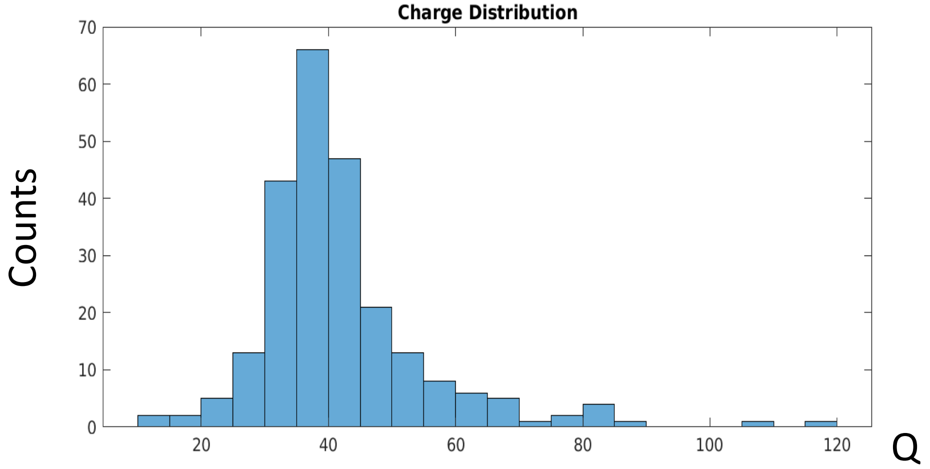


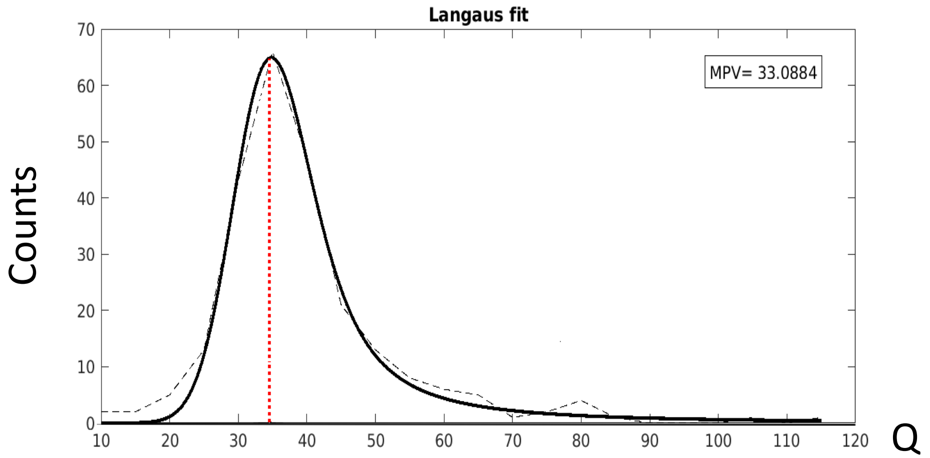
TCT Setup – Signal Shapes @ 40 MIPs



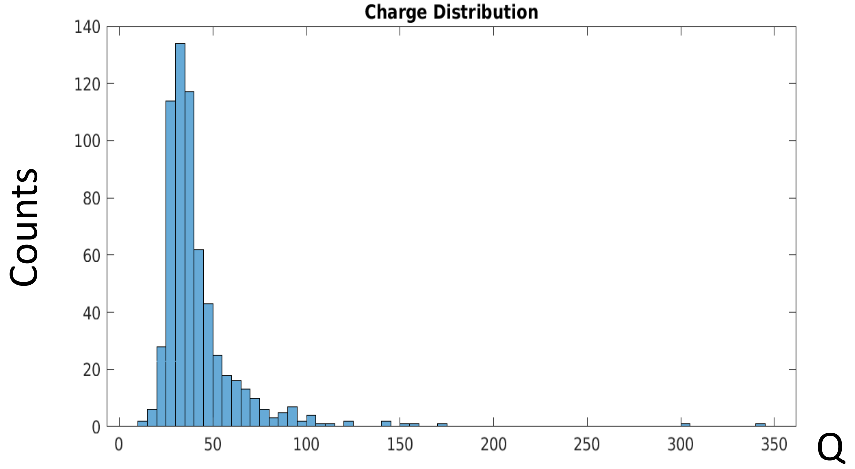
CNAO Beam Test – Collected Charge

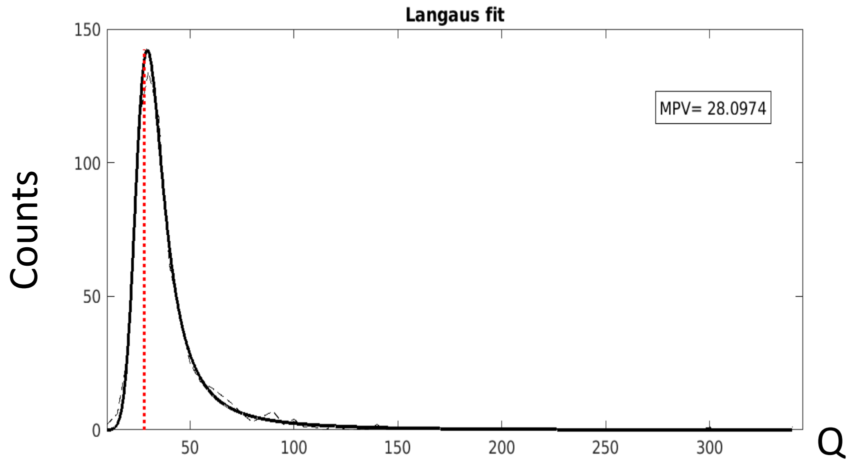
E_p = 62 MeV – V_{bias} = 100 V





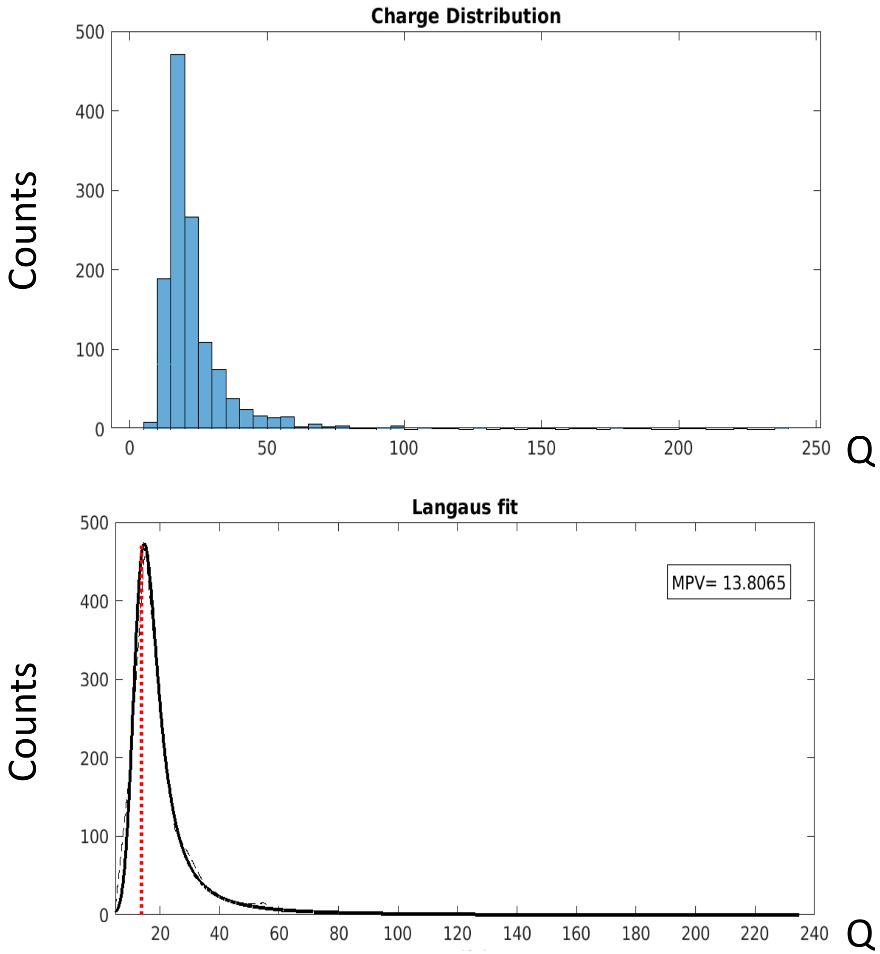
E_p = 110 MeV – V_{bias} = 225 V



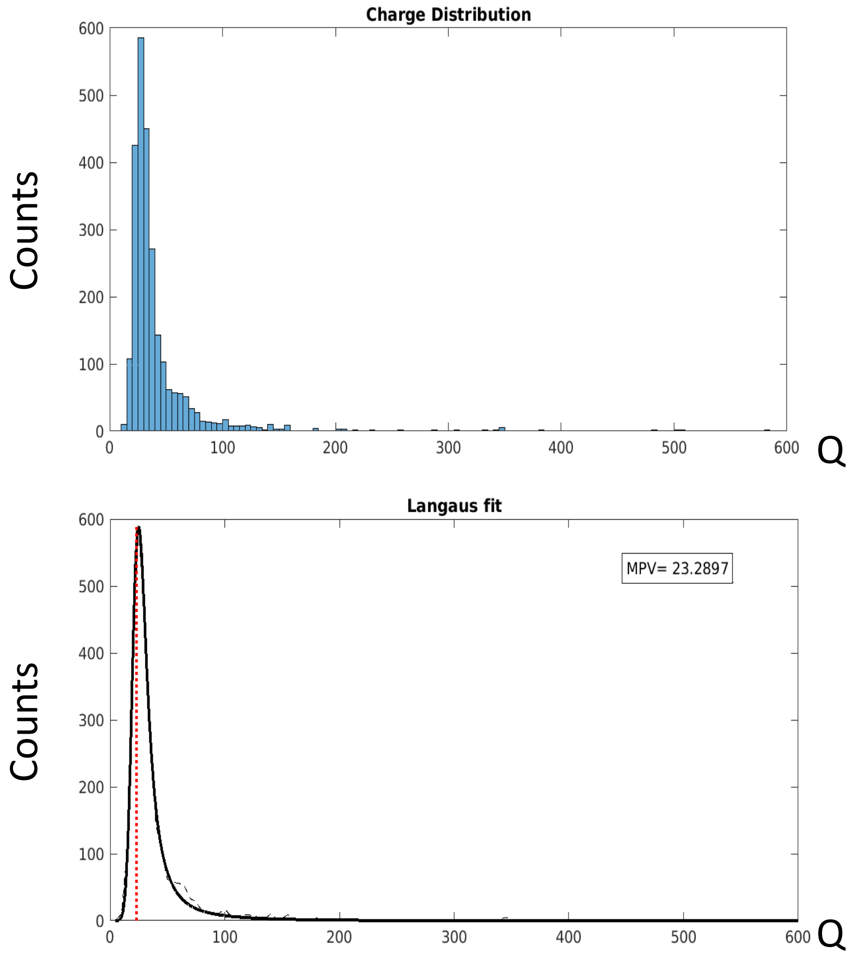


CNAO Beam Test – Collected Charge

E_p = 170 MeV – V_{bias} = 150 V

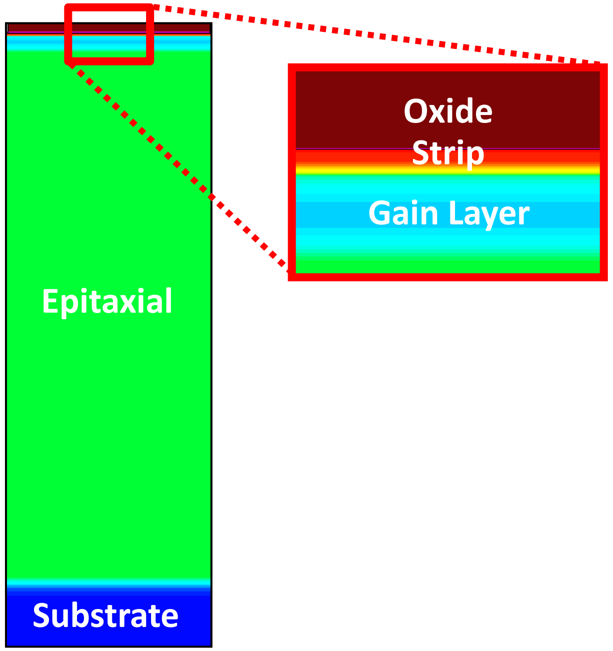


E_p = 226 MeV – V_{bias} = 290 V



Simulated Layout – Quasi 1D

✓ **Quasi-1D** structure



✓ **Silicon**

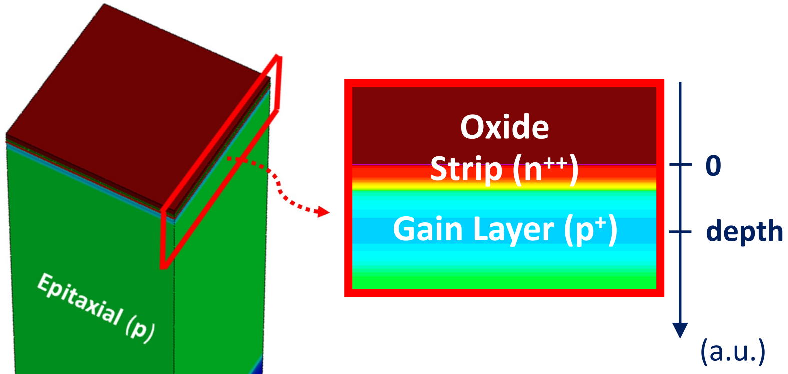
- width **20 µm**
- thickness **55 µm**
  - Epitaxial layer 50 µm
  - Substrate 5 µm

✓ **Silicon Oxide**

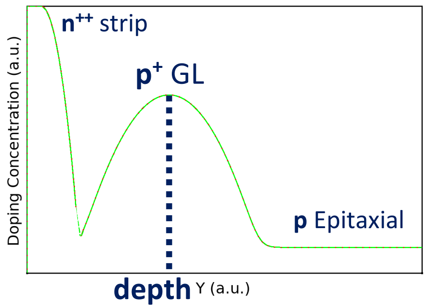
- width 18 µm
- thickness 1 µm

Simulated Layout – Fully 3D

✓ **Fully-3D** structure



Doping profile (**TOP**)



Gaussian
Gain Layer
(GL) **profile**

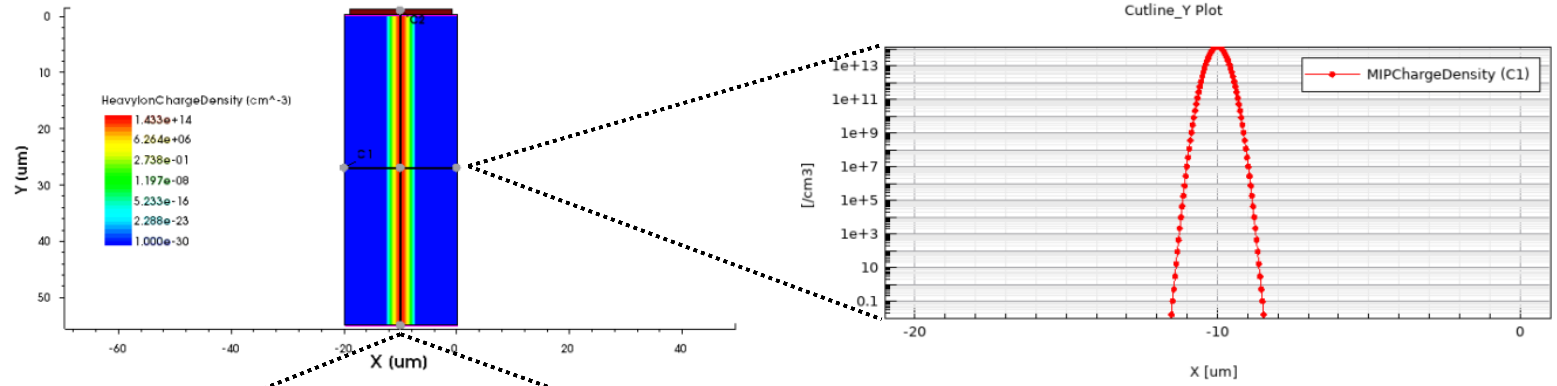
✓ **Silicon**

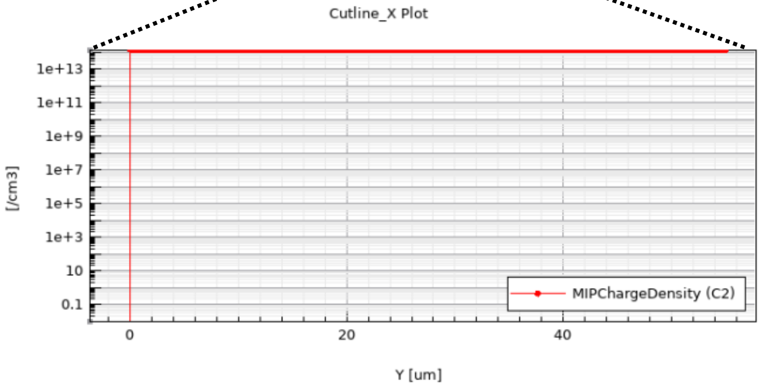
- Width and Length
  20 x 20 μm
- thickness
  55 μm
  - Epitaxial layer 50 μm
  - Substrate 5 μm

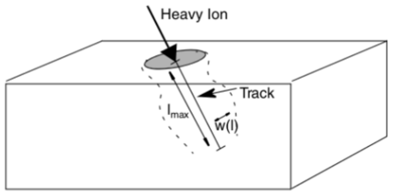
✓ **Silicon Oxide**

- width **20 μm**
- thickness 1 μm

Transient Response – *HeavyIon* model





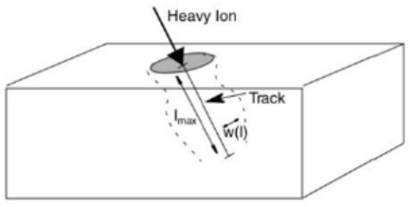


$$G(l, w, t) = G_{LET}(l)\, R(w, l)\, T(t)$$ → **Gaussian**

$$G_{LET}(l) = a_1 + a_2 l + a_3 e^{a_4 l} + k' [c_1 (c_2 + c_3 l)^{c_4} + LET\_f(l)]$$

TCAD Simulation – Stimulus Width

✓ **Charge density** generated by the **MIP equivalent stimulus** for different $\mathbf{w_t}$

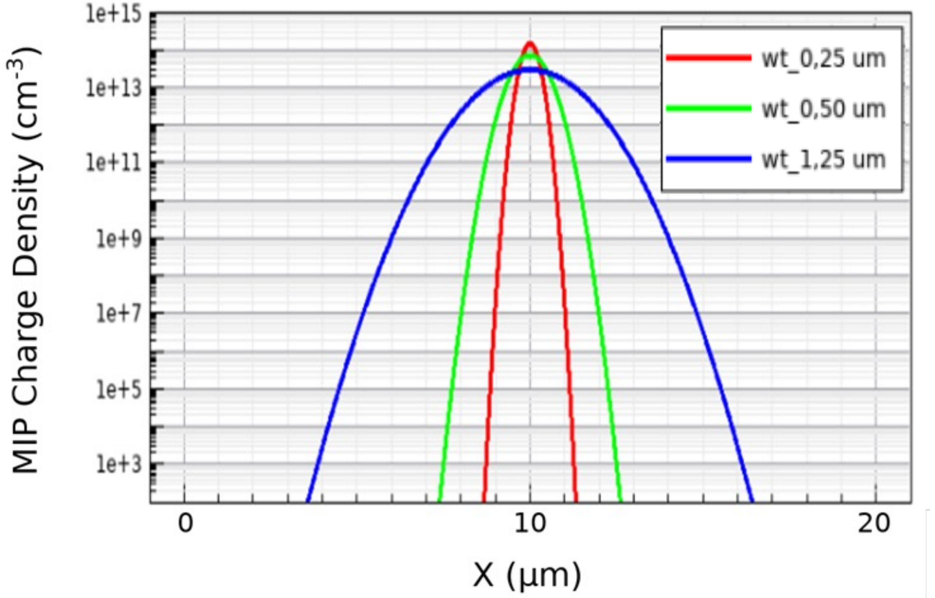


$$G(l,w,t) = G_{LET}(l)\,\mathbf{R}(\mathbf{w},\mathbf{l})\,T(t)$$

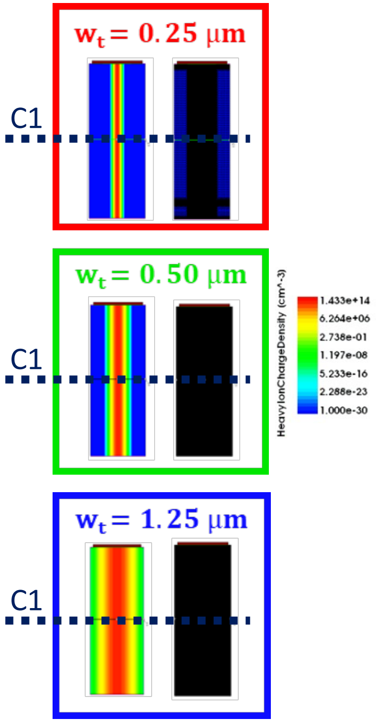
$$R(w,l) = \exp\left(-\left(\frac{w}{w_t(l)}\right)^2\right)$$

Gaussian

Cutline, C1

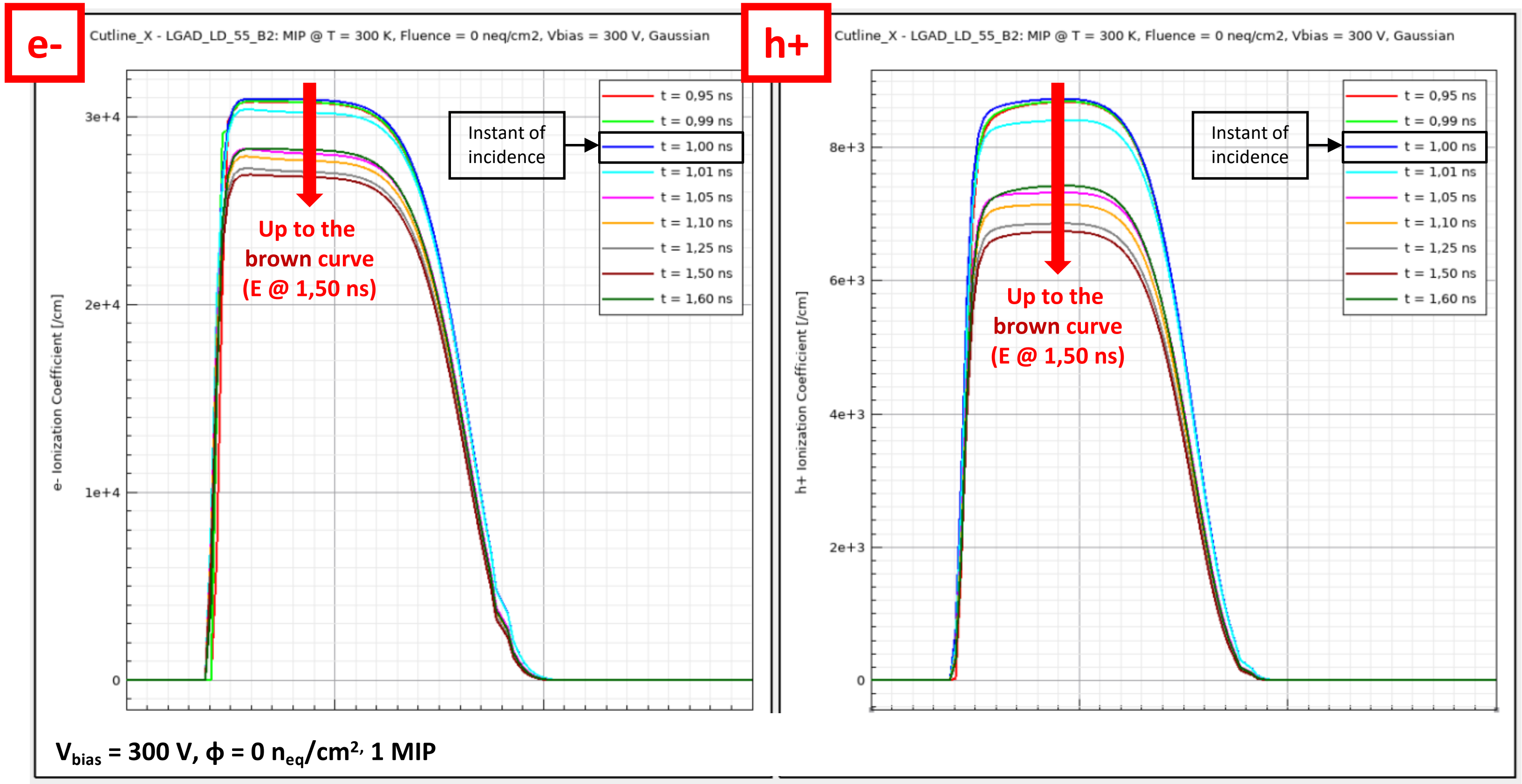


1 MIP => GC = 0,56 fC (3502 e-) **Fixed!**



→ w_t has very limited impact on the gain value, as it affects similarly the PiN and the LGAD

Time Evolution of the Ionisation Coefficients



V_{bias} = 300 V, ϕ = 0 n_{eq}/cm^2, 1 MIP