Donor removal and Global Gain Quenching (GGQ) in n-type LGAD detector

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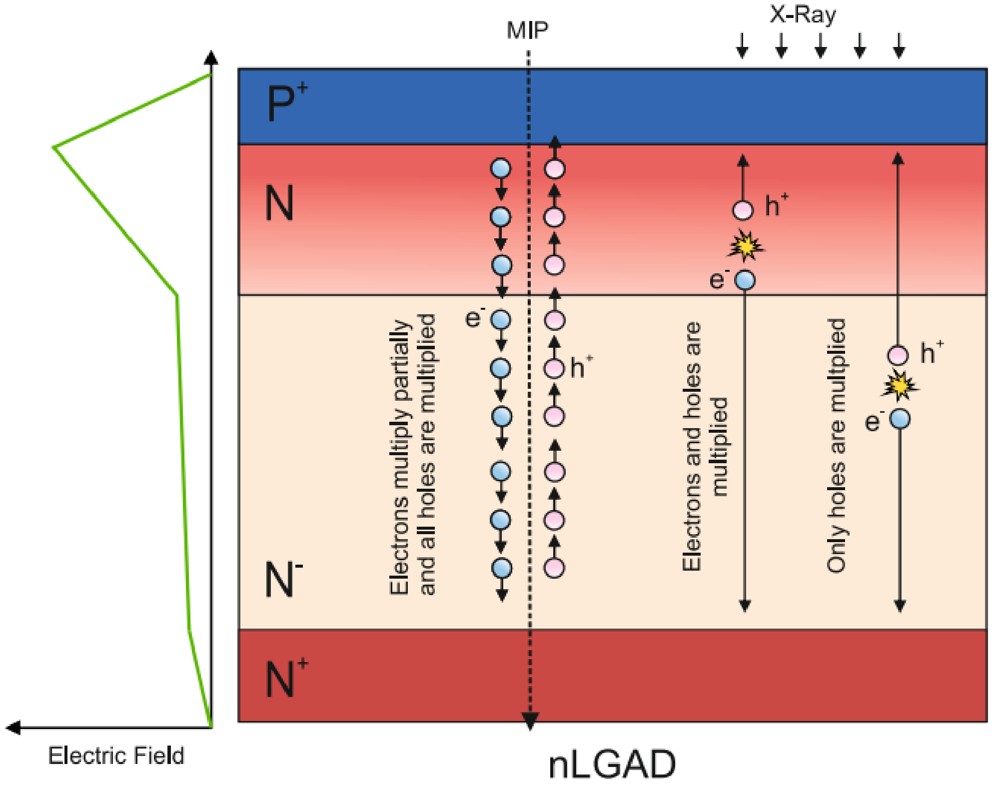
Outline

- n-type LGAD
- Gain measurements (UV-TCT)
- IBIC measurement
  - Gain measurement with shallow-penetrating ion (1.2 MeV Ga)
  - Donor removal mechanism
  - Global Gain Quenching
- TSC analysis (search for VP defect)
- Conclusions & future work

Pellegrini, G., Salvador, H. V., David, F. G., Waleed, K., & Manfred, V. (2023). *Low-Penetrating Particles Low-Gain Avalanche Detector*. European Patent EP 3 971 997 B1.

nLGAD concept

- Inverted doping polarity: n-substrate with phosphorus gain layer (p++/n+/n/n++ structure)
- Shallow-penetrating radiation (electron-driven multiplication)



Already established → UV/DUV light

(run in progress... Ultra-shallow junction (USJ-nLGAD) → Soft X-ray detection (run soon to finish)

Motivation for this talk... → Low-energy ion?

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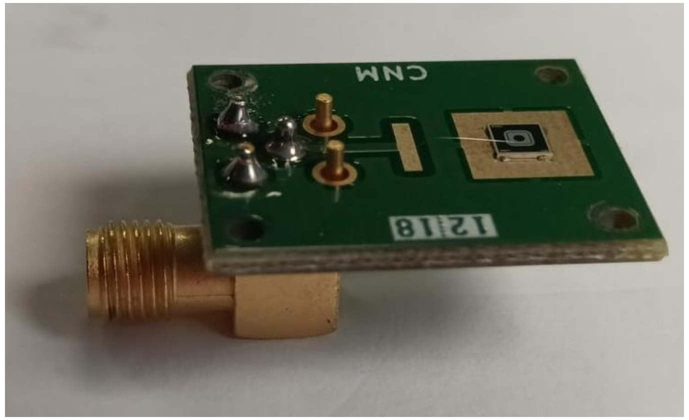
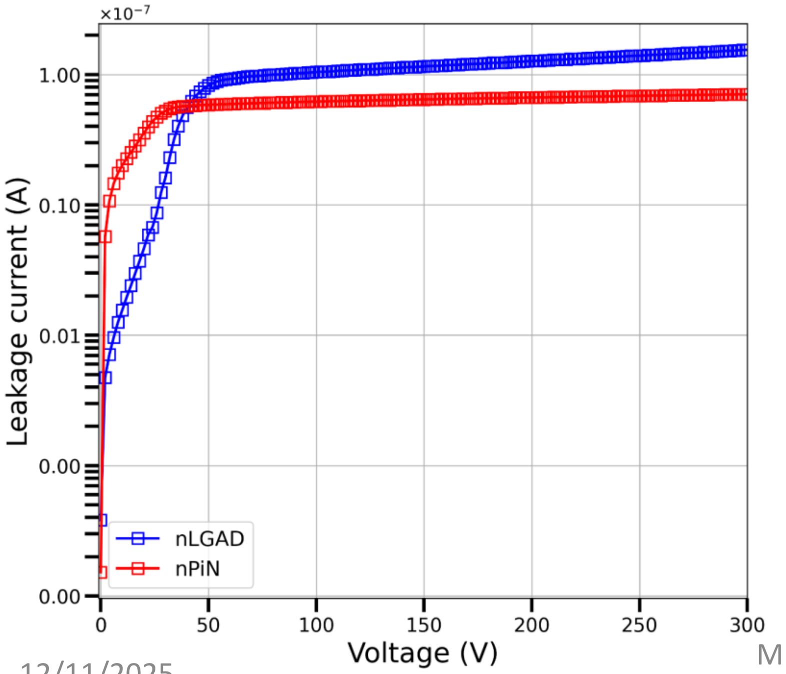
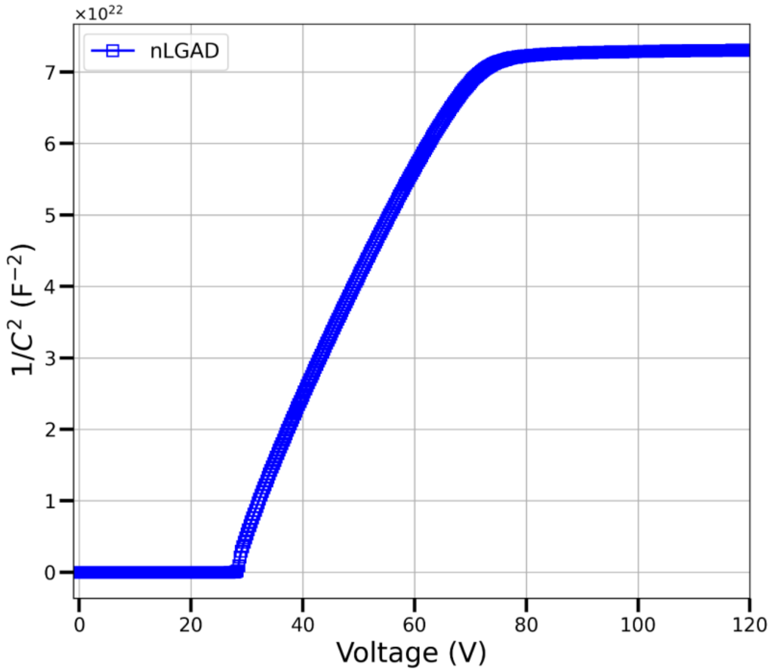
nLGAD for ion detection

Samples & precharacterization



- Single pad nLGAD detector (nPiN & nLGAD)
- 300 µm thick, 3.3 mm x 3.3 mm active area
- Opening stripped of SiO_2 (adapted mask for X-ray testing)

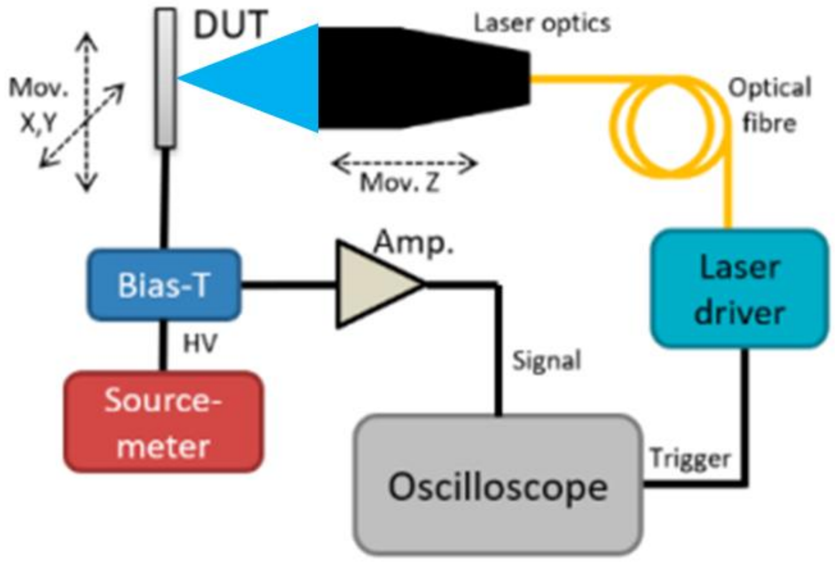




TCT Pre-characterization

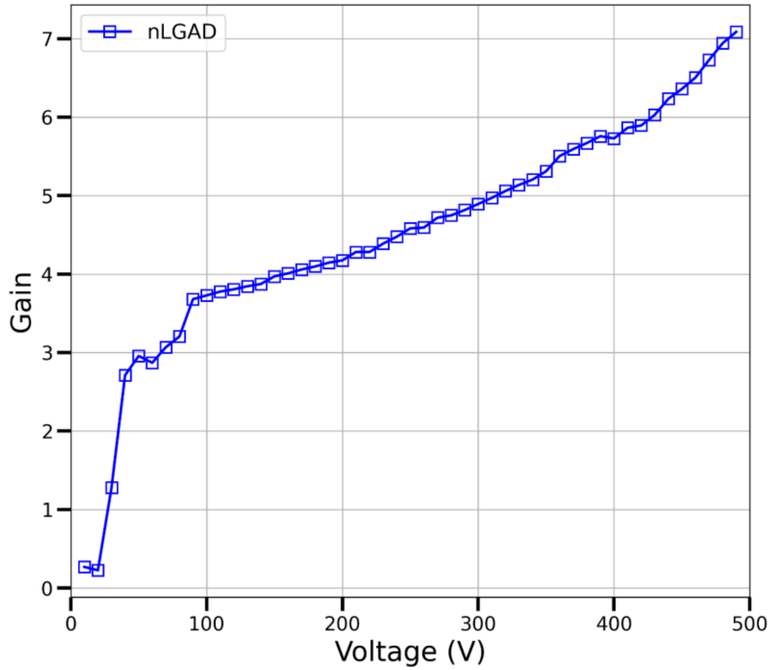
TCT pre-characterization

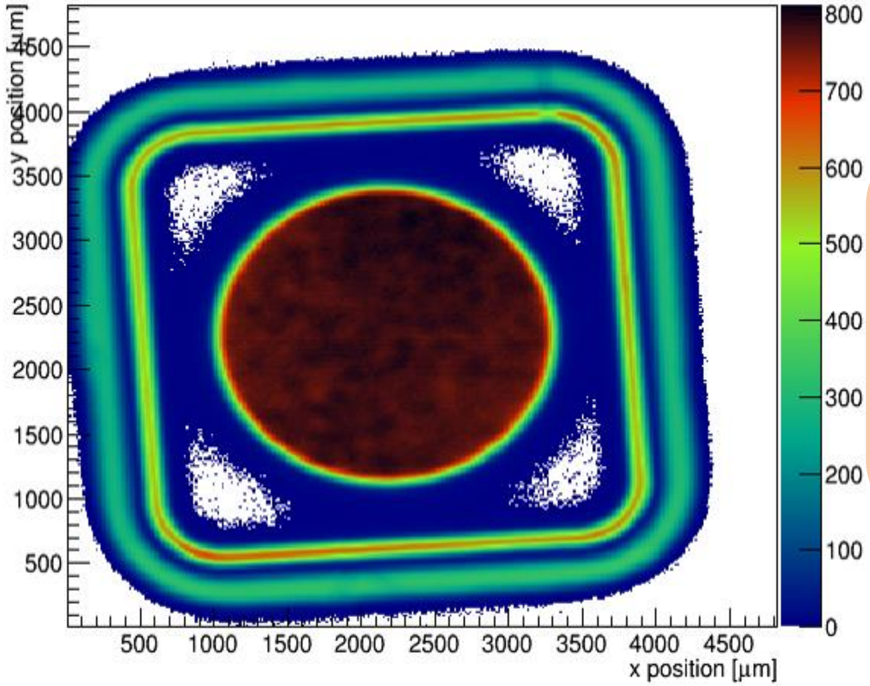
- **Standard TCT setup**
- **Parameters: 404 nm laser, 200 V, Max intensity (2%)* (suppression expected)**



[3] I. L. Paz et al. "Position-resolved charge collection of silicon carbide detectors with an epitaxially-grown graphene layer." Scientific Reports 14.1 (2024): 10376.

*Optics is not optimized for transmission of wavelenghts of 369 nm, so max power results in low output power (insufficient S/N ratio in nPIN)





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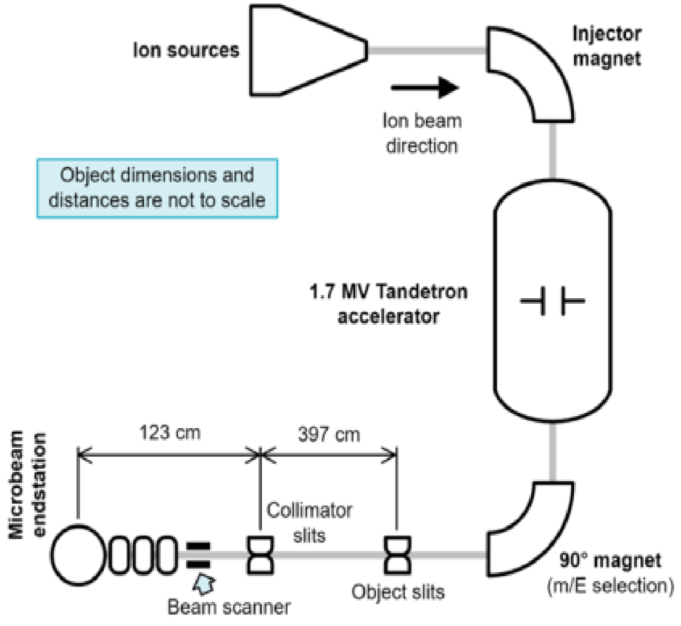
IBIC experiment

Ion irradiation (IBIC)

Tandem accelerator (ETH Zurich)
- Laboratory of Ion Beam Physics (part of DRD3)



- Ion Beam Induced Charge Technique (IBIC)
  - 2D charge maps
  - Ideal for structure investigation

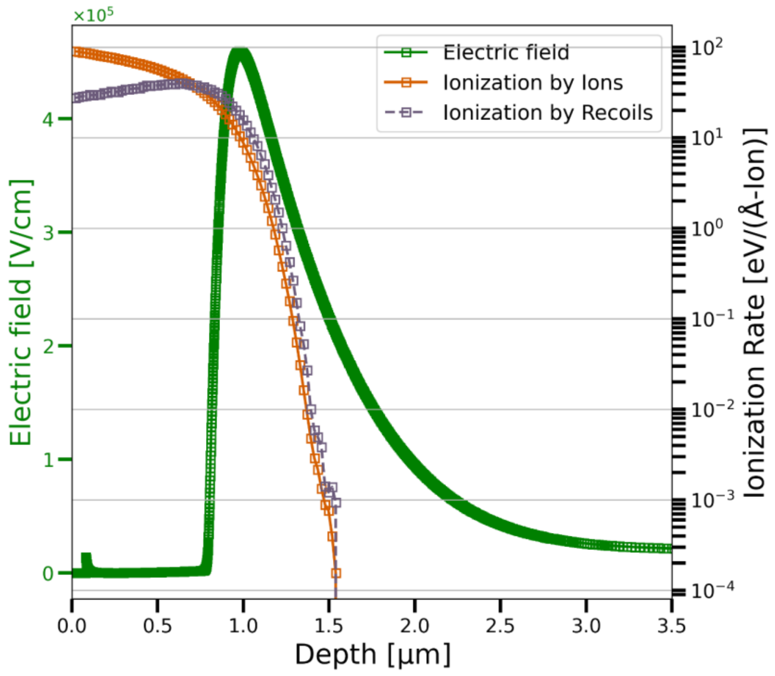
- Electronic chain:
  - low-noise charge sensitive preamplifier (ORTEC 142A)
  - Shaping amplifier (ORTEC 570)
  - Canberra 8701analog-to-digital converter and a multichannel analyzer

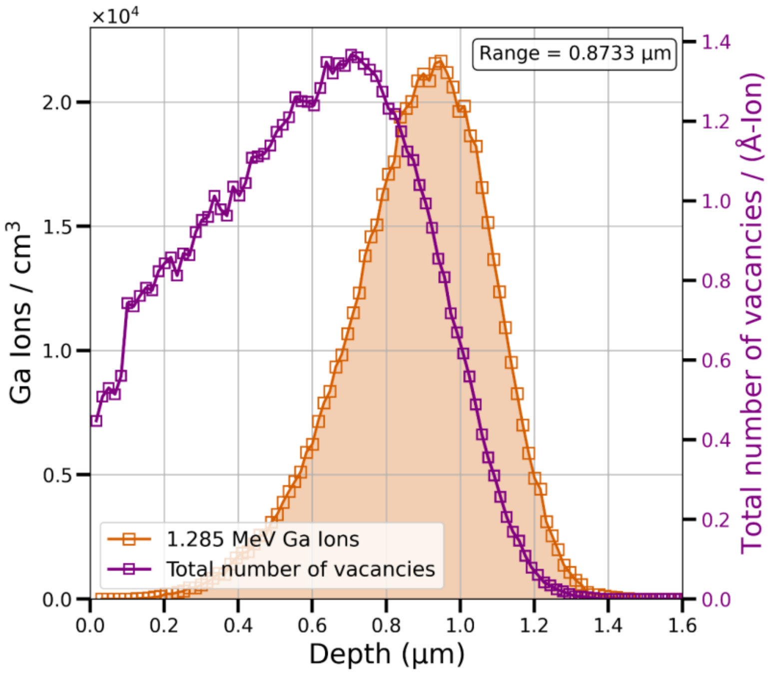
- Microprobe is capable of irradiation in high current regime & “online” measurements

$$Gain = \frac{CENTROID_{nLGAD}}{CENTROID_{nPIN}}$$

Ion-irradiation (SRIM simulation)

- **Shallow penetrating radiation?**
  - **Gallium ion of 1.285 MeV**
  - **Ionization peek at the electric field peak**





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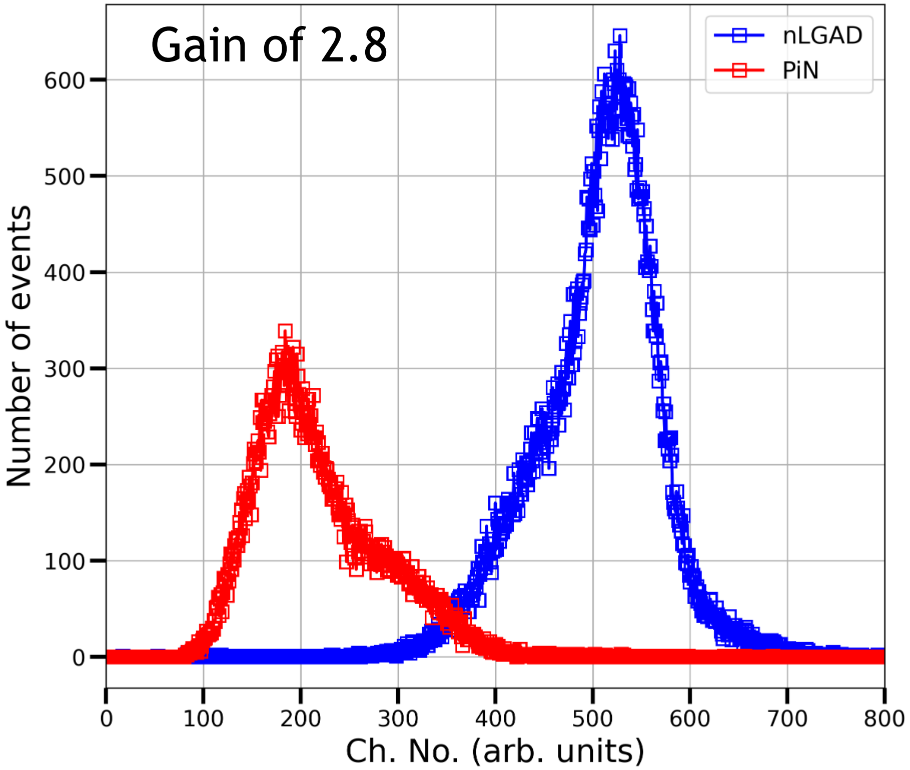
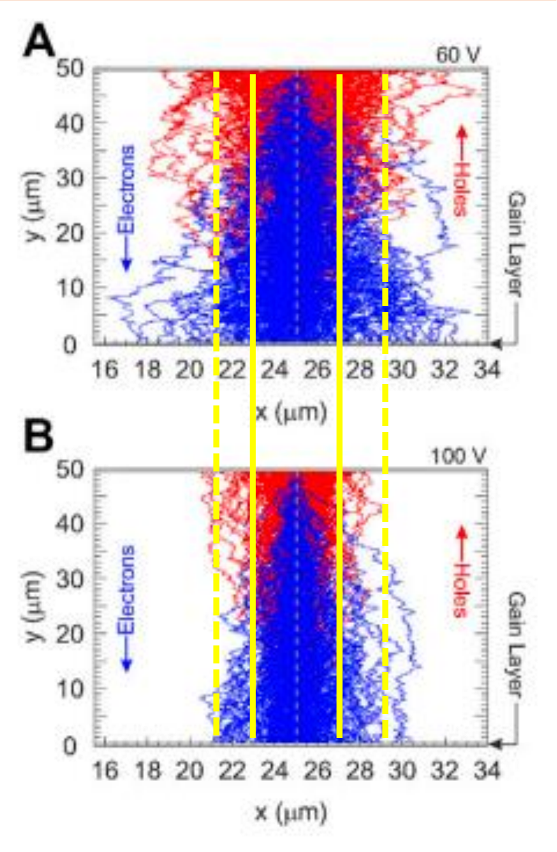
Ion-irradiation - Gain measurements

$$Gain = \frac{CENTROID_{nLGAD}}{CENTROID_{nPIN}}$$



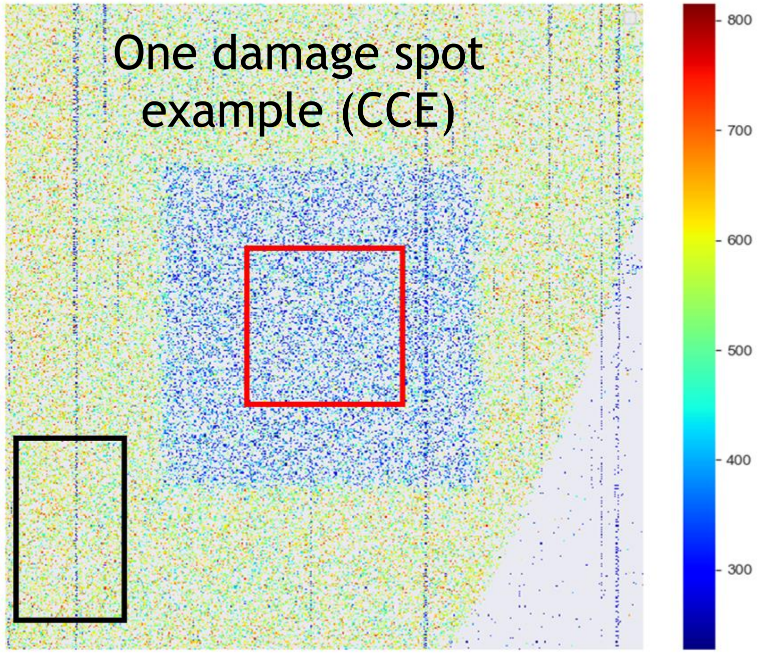
- Gain measured for 130 V
- Lowest voltage yields highest gain due to biggest lateral diffusion – low suppression
- Angle-resolved IBIC was impossible due to setup limitations
- Gain (laser) > Gain (Ion)
- Bumps in the spectrum caused by ion struggling

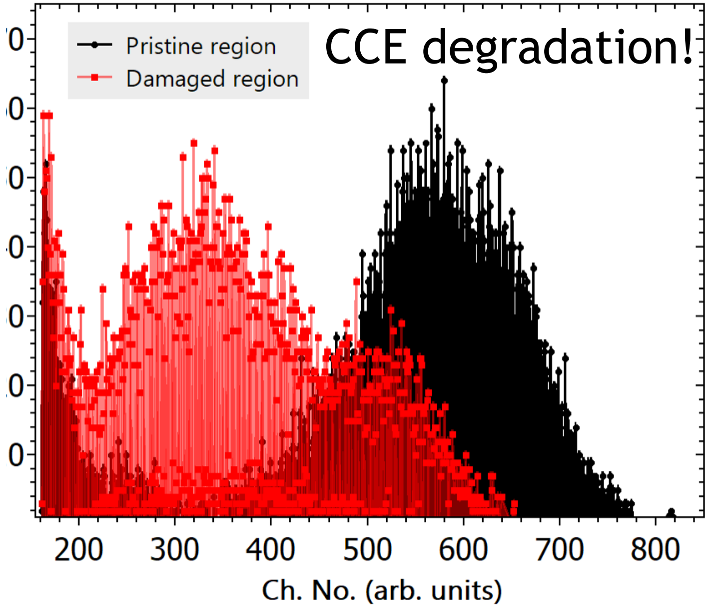


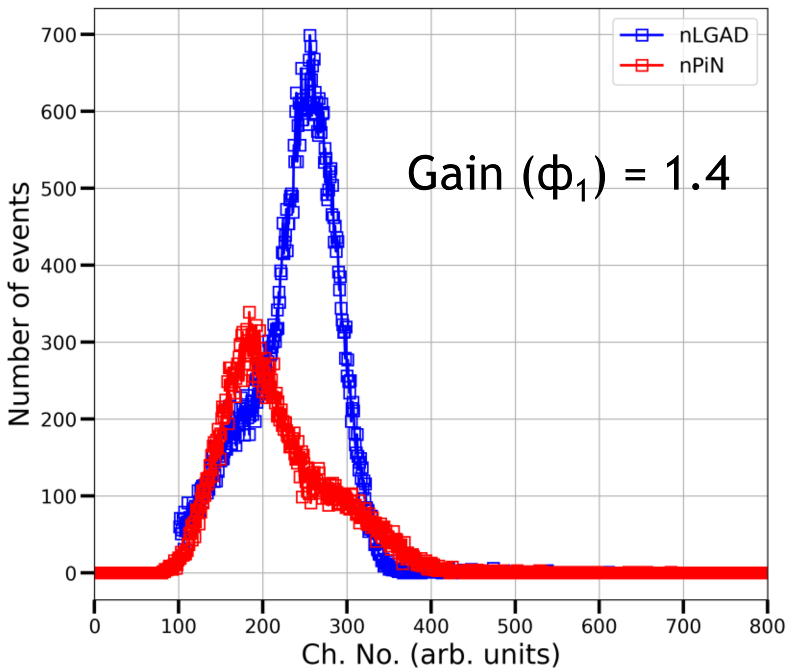
KDetSim (Gregor Kramberger)

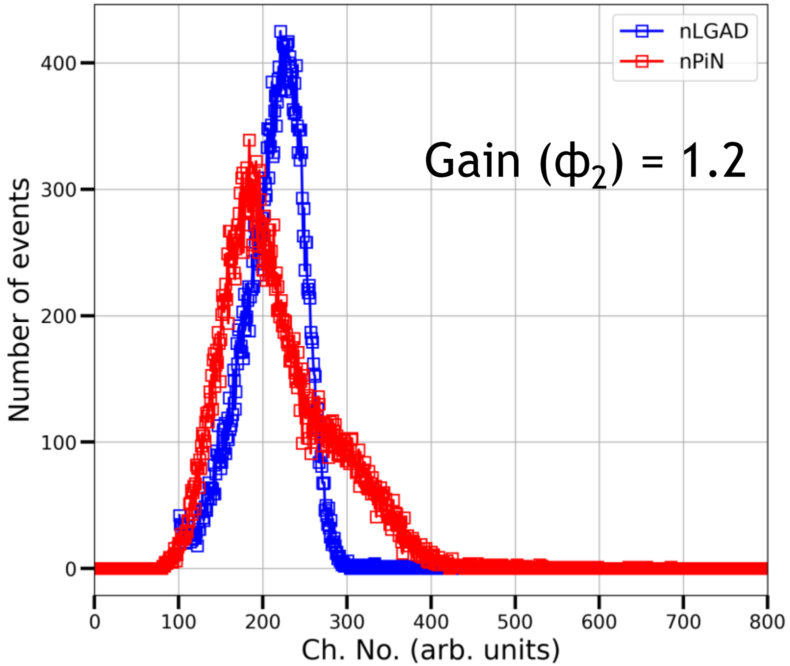
Ion damage studies (donor removal)

- **Local damage application (250 x 280 μm^2)**
- **Two fluences:**
  - **ϕ_1 = 4.3e9 ion/cm^2 and ϕ_2 = 6.4e9 ion/cm^2**









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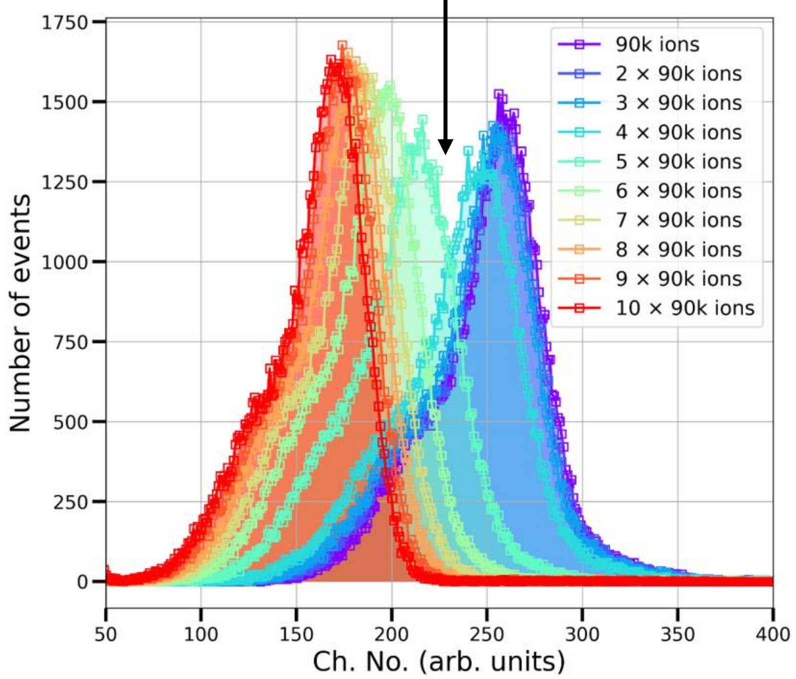
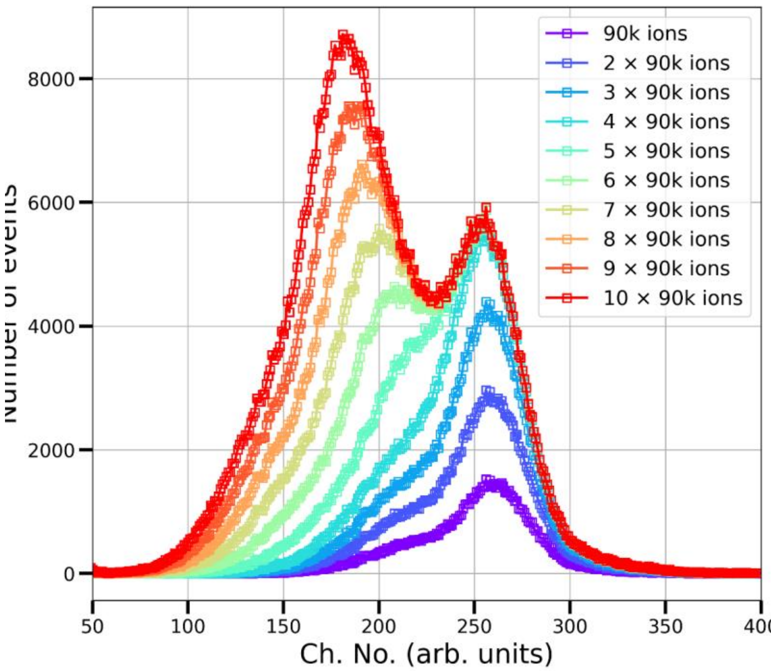
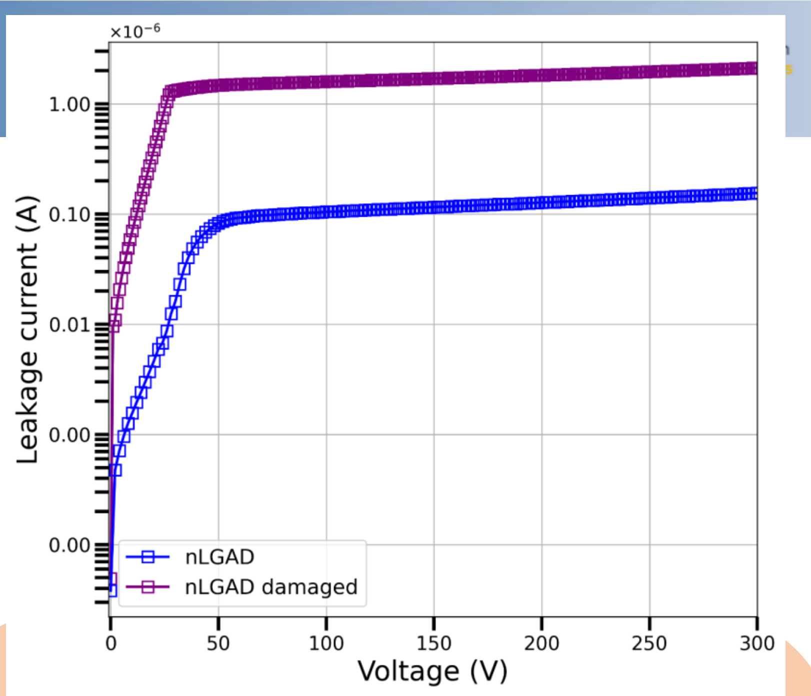
Donor removal - speed of degradation

4 x 90k ion step



Cumulative spectrum





- nLGAD is radiation resistent up to aprox first four iterations, which transaltes to 3.5e15 vac/cm3
- In the next two irradiations, abrupt CCE happens (0.5e16 vac/cm3),
  - Number of vacancies on the order of gain layer doping
- Once donor has been removed, satured effect is observed…

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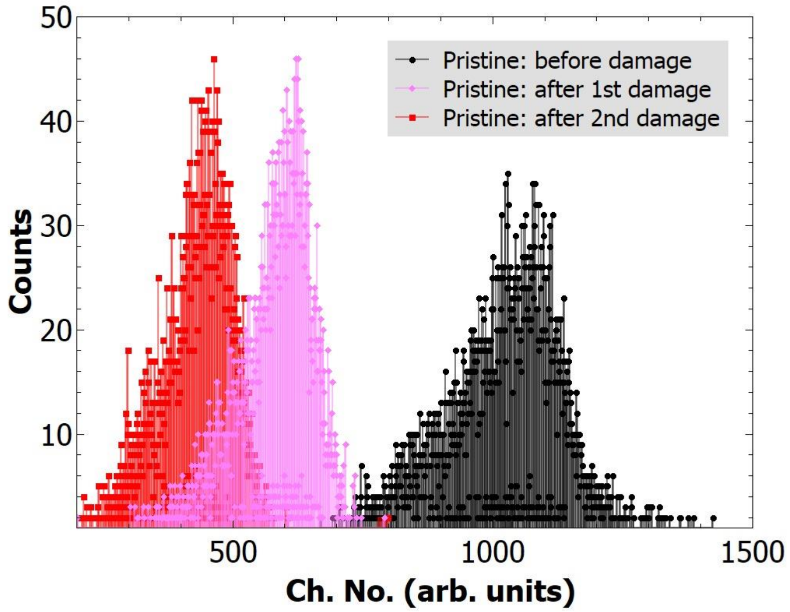
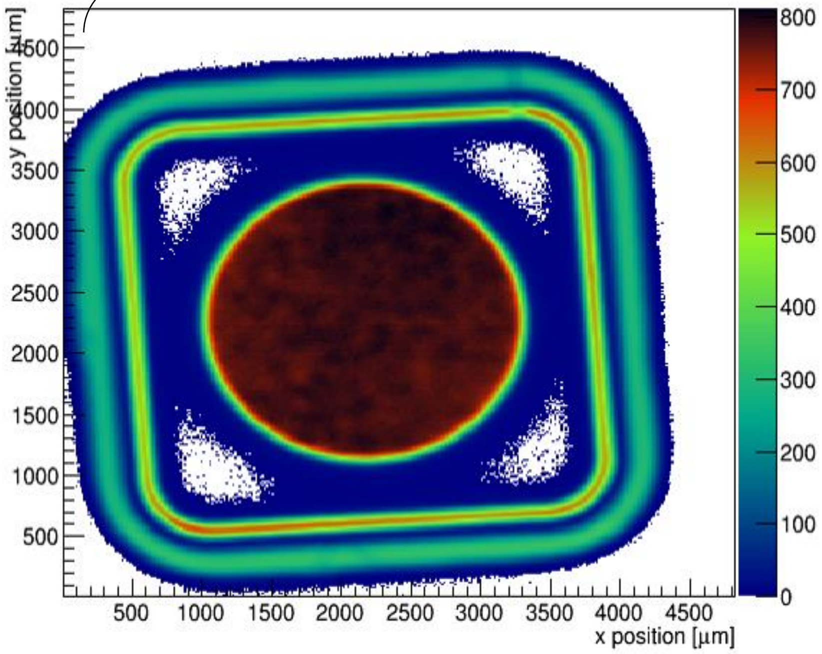
Global Gain Quenching (GGQ effect)

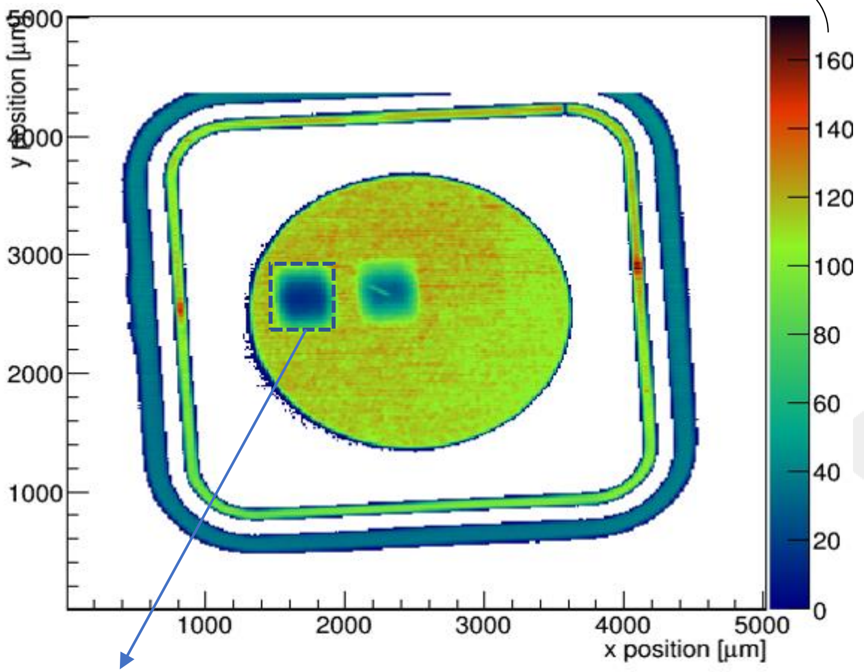
- **Local donor removal causes global gain drop!**

Ion experiment



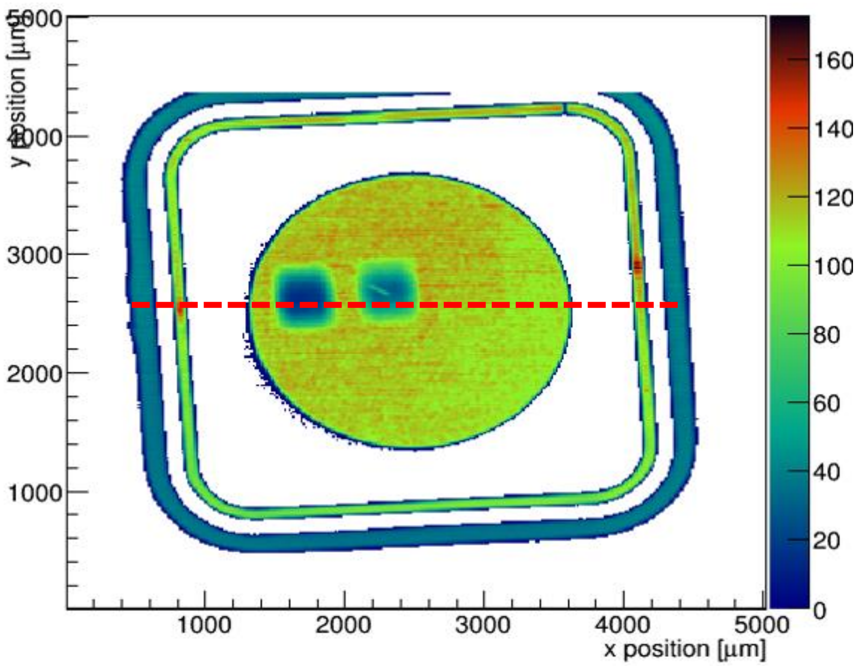
404 nm blue laser

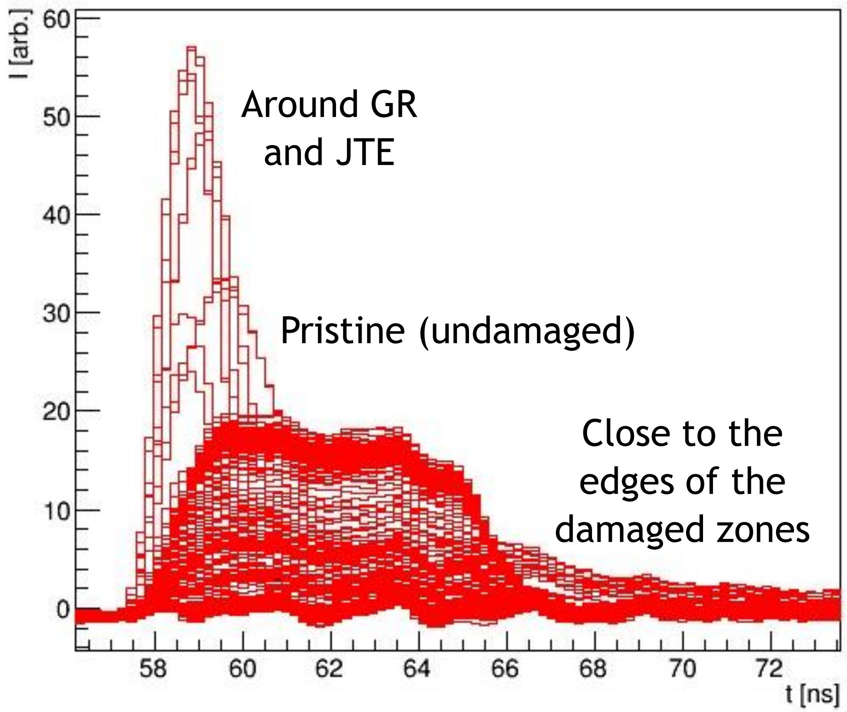


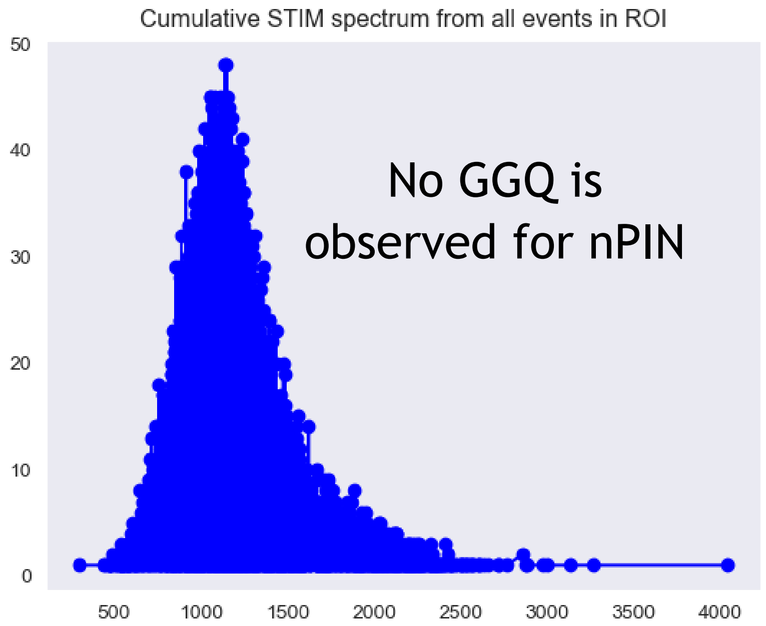


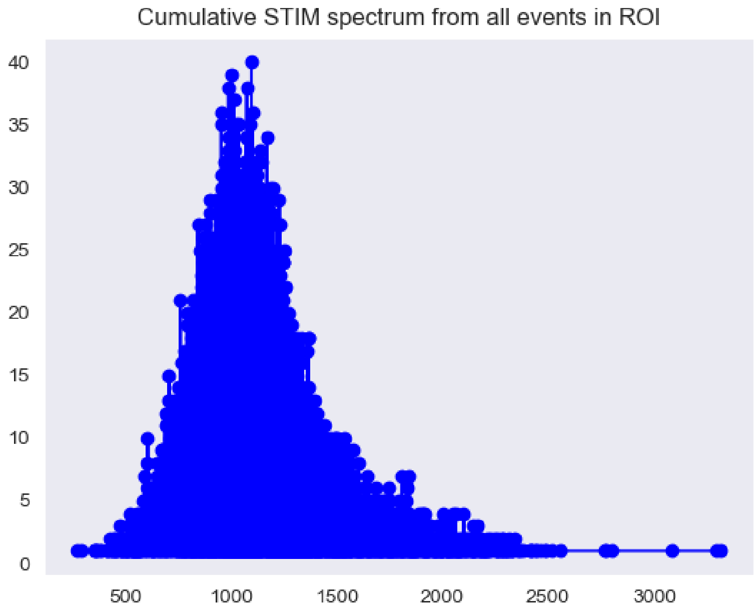
No signals generated in the damage zones!

Global Gain Quenching (GGQ effect)









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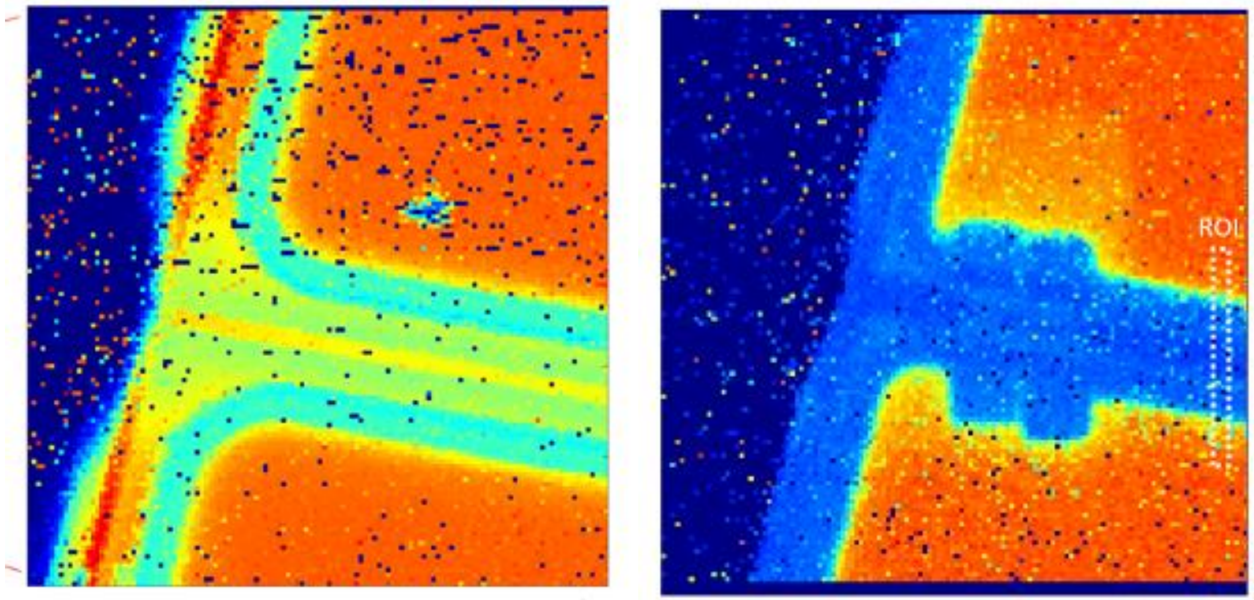
Comparison with p-substrate LGADs (back to 2022)

- 6 MeV C^{+++} used in some previous experiment
- Local damage induced only local CCE drop!



Can the GGQ happen in p-substate LGADs if junction line is raptured?

- 6 MeV carbon causes most damage in the bulk, not in the junction line
- 1.285 MeV Ga ions cause more ionization, more vacancies
- Gain drop observed on 3e11 ion/cm^2 acceptors get in activated slower

Different mechanism behind donor removal compared to acceptor removal?

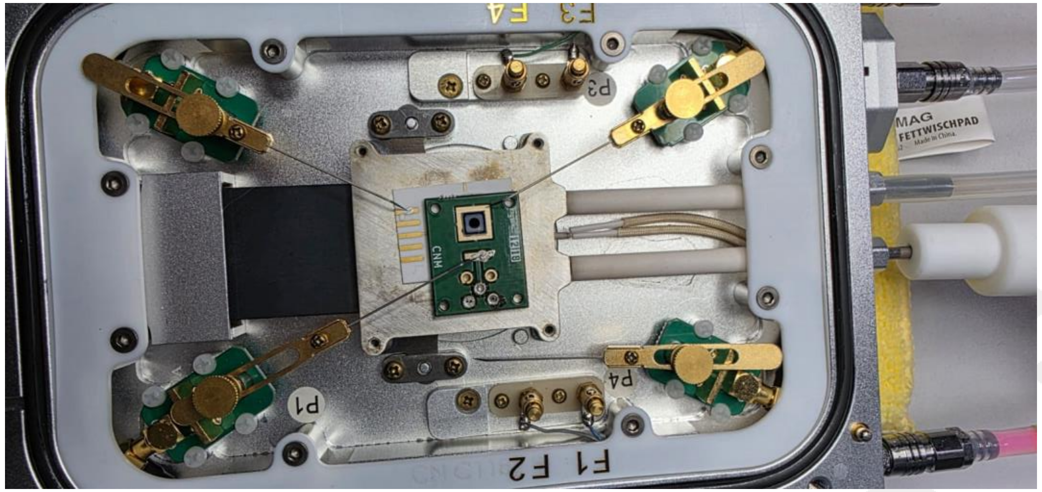
Defect studies

Thermaly stimulated current (TSC spectroscopy)

NIMP

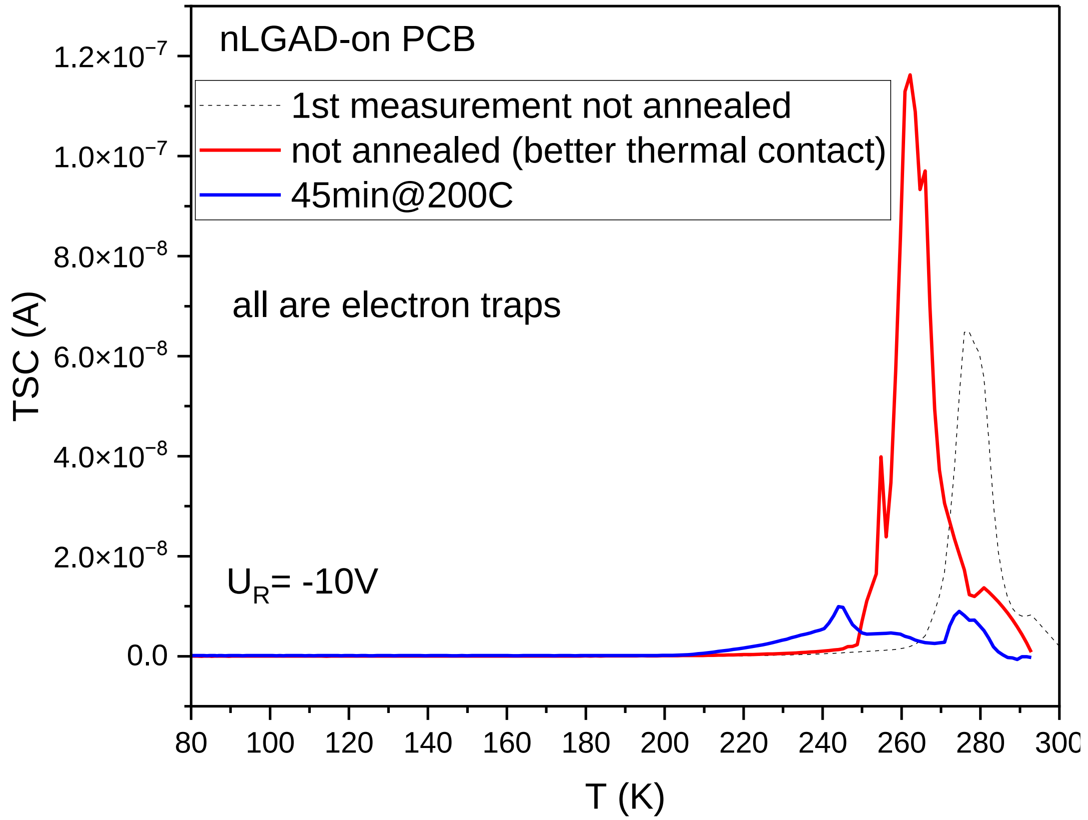
National Institute of Materials Physics - Romania

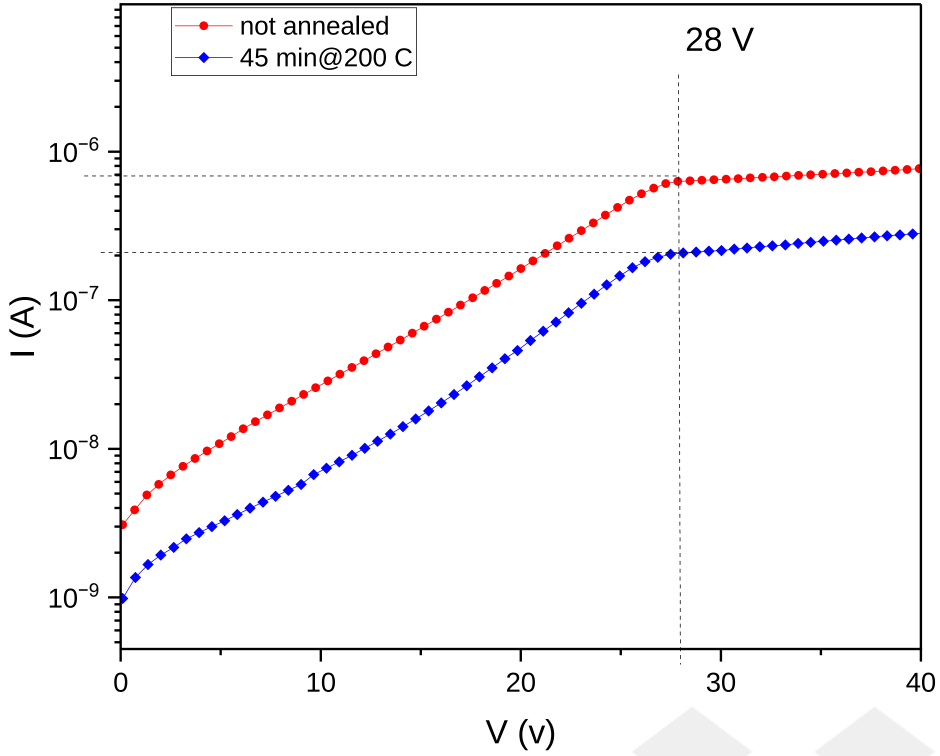
- Cool sample to low temperature.
- Fill traps (forward bias or illumination).
- Apply reverse bias and heat at constant rate.
- Released carriers create a current peak → TSC spectrum



Work done by Ioana Pintilie, Cristina Besleaga, Andrei Nitescu…

Preliminary result…





- 10 V reverse bias allows to detect some TSC signal coming from electron traps but the shape of the signal is affected by the variation of the depletion depth and temperature of the sample – so, no accurate evaluation can be done!
- The annealing at 200 C significantly reduces the amount of defects as well as the leakage current.
- These effects can be attributed to the electron trap with TSC peak recorded at ~260 K which almost vanishes after 45 min@200C. Such a behavior is expected for VP center in n-type Silicon

Conclusion

- nLGAD can be used shallow-penetrating ion radiation
- nLGAD are more vulnerable to damage - donor removal appears faster than acceptor removal
  - Particullary relevant for compensated design of LGAD
- Damage mechanism seems to be vacancy-driven

Future

- nLGAD for single-ion detection?
- More ion irradiation
  - Spreading Resistance Profiling (SRP)
  - More TSC/DLTS studies

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Thanks for your attention

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Acknowledgements

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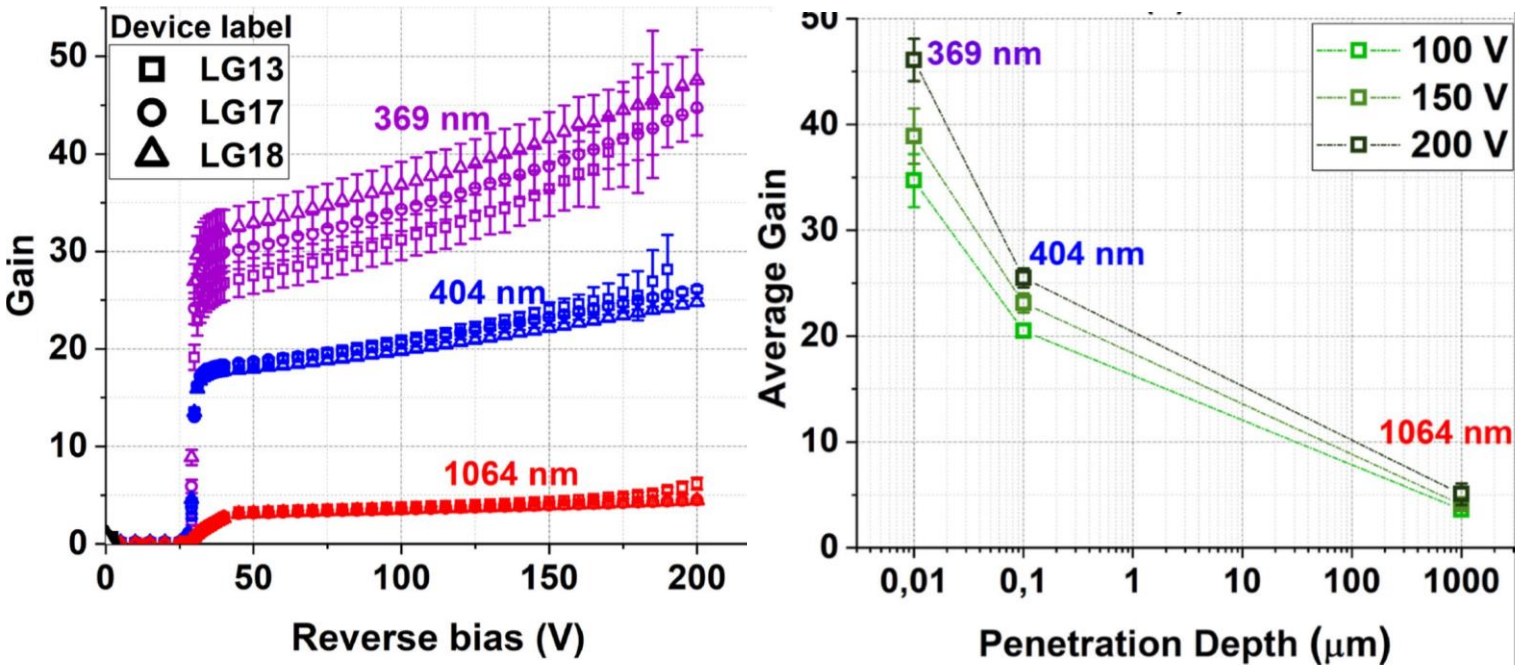
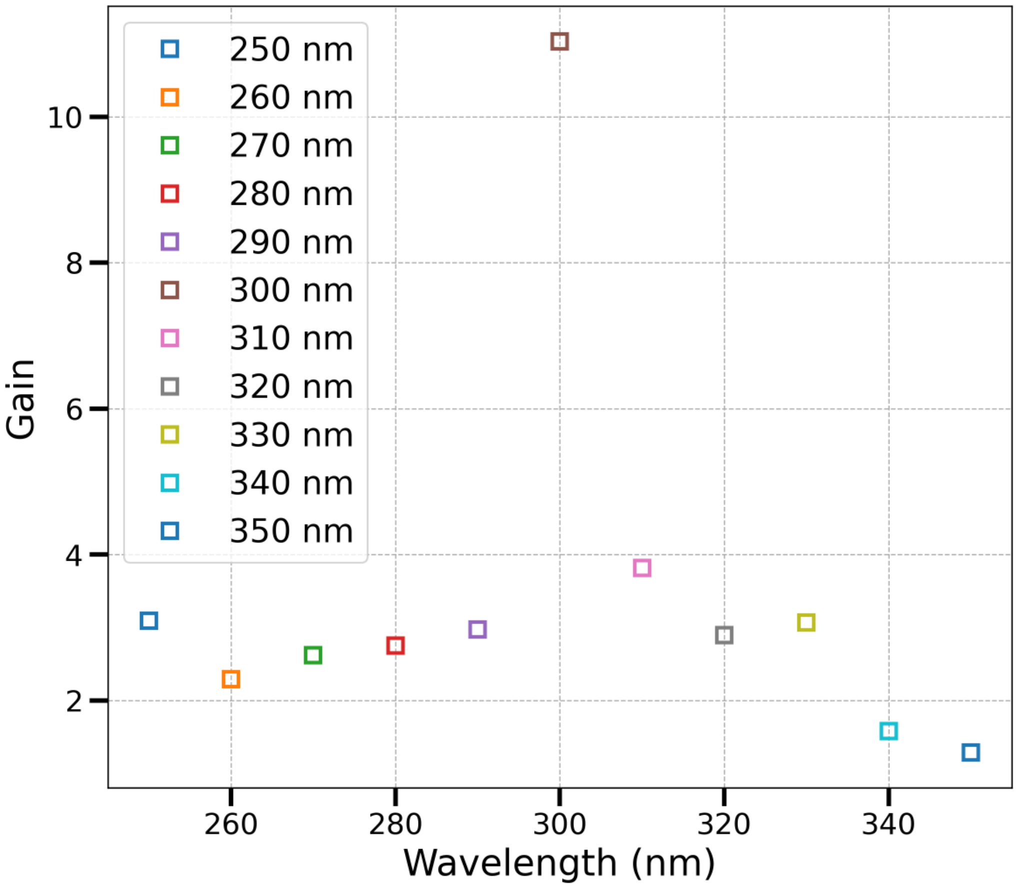
Backup

Photon detection (some results)

UV, blue and IR (in-house testing)



down to D-UV (at ELI Beamlines)

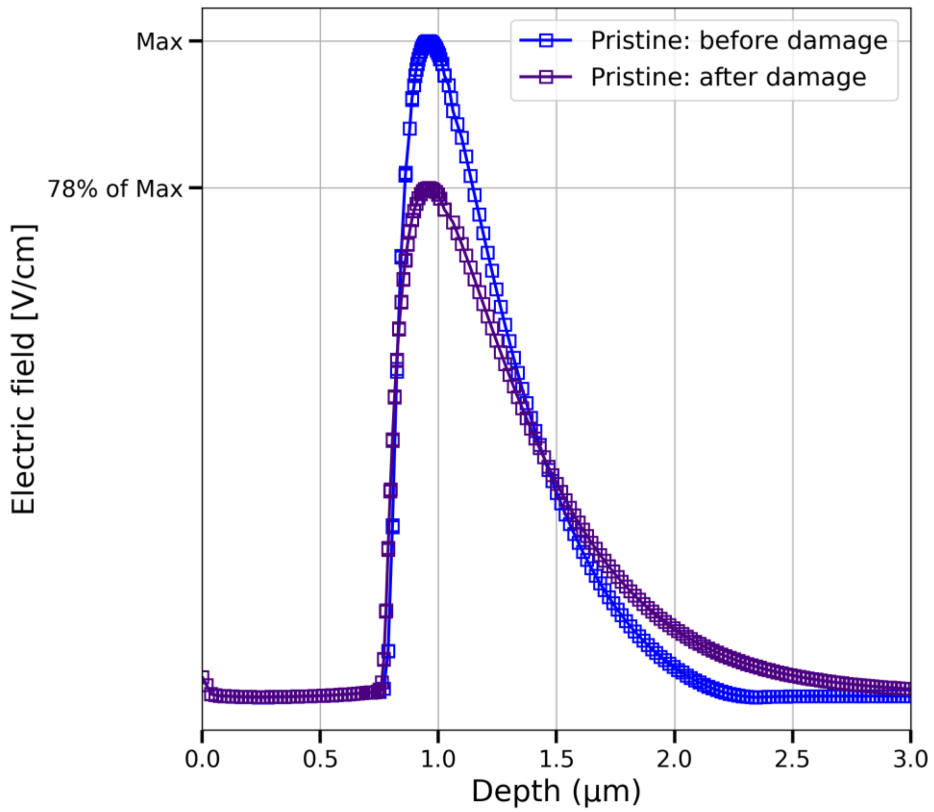


[1] Villegas, J., Torres, C., Manojlovic, M., Jimenez-Ramos, M. C., Moffat, N., Lopez, J. G., & Hidalgo, S. (2025). ***NLGAD gain response to low-penetrating particles***. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *1072*, 170208. https://doi.org/10.1016/j.nima.2025.170208

[2] Milos Manojlovic, Neil Moffat, Pablo Fernandez, Jairo Villegas, Ma-teusz Rebarz, Enric Cabruja, Giulio Pellegrini, and Salvador Hidalgo.nlgad detector gain response to deep and near-ultraviolet (uv) light.SSRN Electronic Journal, 2025. doi:10.2139/ssrn.5498200. Availableat SSRN: https://ssrn.com/abstract=5498200

TCAD Simulation of GGQ

- **More back-and-forth SRP-TCAD iterations are necessary**



CV after applied damage

- No obvious change in the V_{gl}
- Influenced by frequency?