THE 16TH VIENNA CONFERENCE ON INSTRUMENTATION

21 – 25 FEBRUARY 2022

ONLINE

# Studies of LGAD performance limitations, Single Event Burnout and Gain Suppression, with Fs-Laser and Ion Beams


Gordana Lastovicka-Medin[1], Mateusz Rebarz[2], Gregor Kramberger3, Tomas Lastovicka[4], Jakob Andreasson[2], Jiri Kroll[4], Kamil Kropielnicki[2], Milko Jaksic[5], Mauricio Rodriguez Ramos[5], Andreo Crnjac[5] , Milos Manojlovic[1]

[1]University of Montenegro (ME)

[2]Extreme Light Infrastructure (CZ)

[3]Jozef Stefan Institute (SI)

[4]Czech Academy of Sciences (CZ)

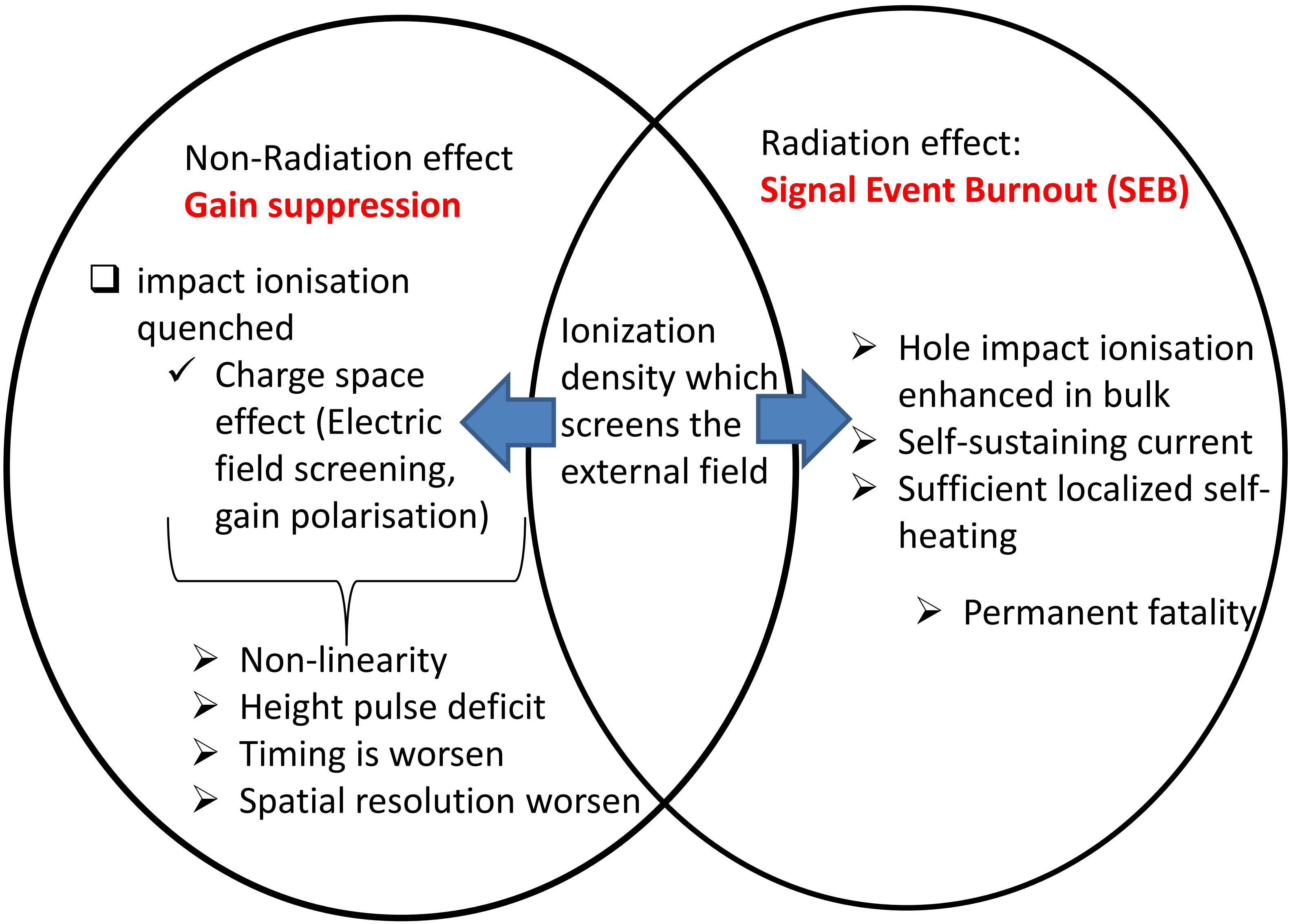
[5]Rudjer Boskovic Institute (HR)

# LGAD – open questions/problems

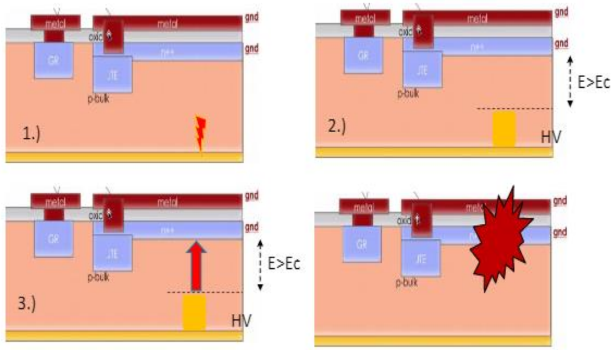
| Problem | Consequence | Mitigation technique | Future Prospect |
|---|---|---|---|
| radiation hardness (removal of active acceptors in the gain layer) | limited to 3e15 $n_{eq}/cm^2$ or less for charged hadrons | ✓ Increase of bias voltage up to the point of SEB<br>✓ Critical el field (threshold mapping)<br>✓ Introduction of carbon as an impurity in the gain layer | With C implantation and thickness optimization the lifetime of the sensors can be extended. Other gain layer dopants are investigated. |
| active area/fill factor (space occupied by pad isolation) | limited to large pads for present production-ready design | high rate environments:<br>DC coupled (pixels):<br>✓ Trench-Isolated LGADs<br>✓ iLGADs (inverse LGADs)<br>Low rate environments:<br>AC-LGADs | For small pixel LGADs TI-LGADs , iLGADs can provide the solution, but not yet proven<br>Limitations of AC LGADs are yet to be investigated |
| response dependence of ionization density which screens the external field | Gain depends on the particle type | inclination of detectors for reduction of carrier density in the gain layer | |

Subjects of this presentation

# LGAD response to ionisation density

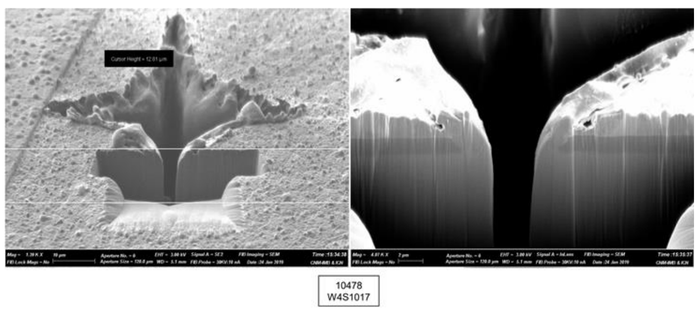


# Radiation Hardness of LGADs: SEB in Test Beams with protons

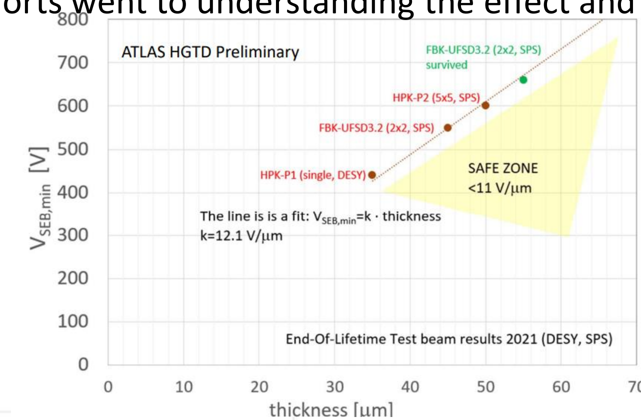


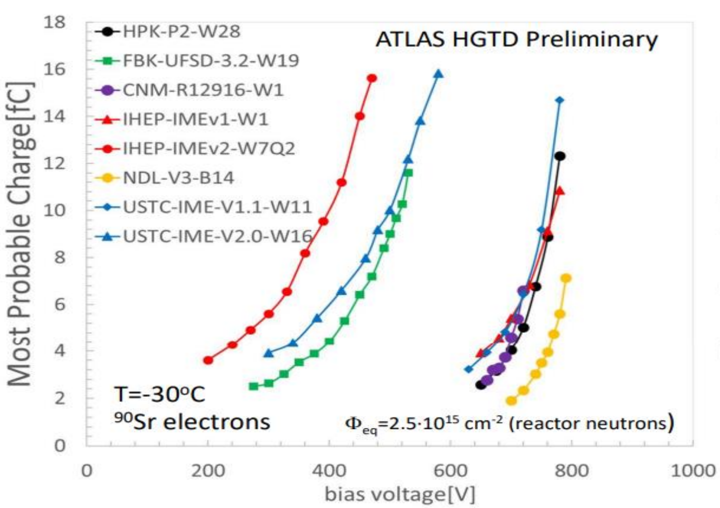

Initial acceptor removal and reduction of electric field can be compensated by increase of bias, but only up to certain level limited by the breakdown; recovery of the gain and high velocity completely recovers the time resolution

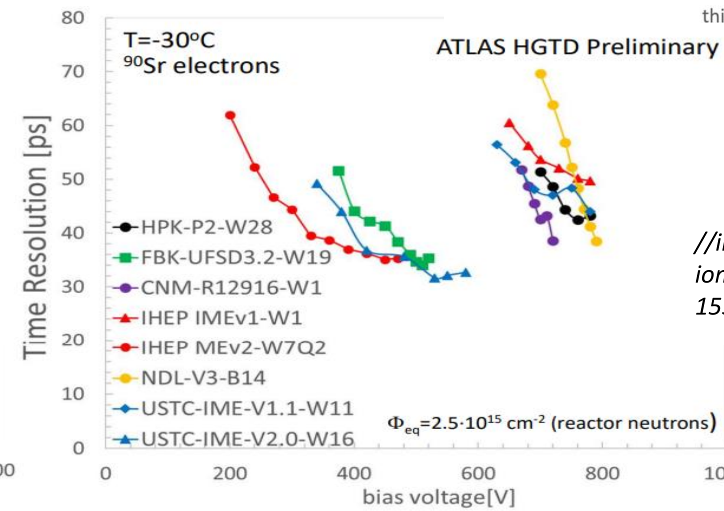
➢The problem recently discovered is so called SEB, where a highly energetic particle in the test beam leads to the permanent damage of the device – lots of efforts went to understanding the effect and safe limits of operation.




SEB results from TB with proton



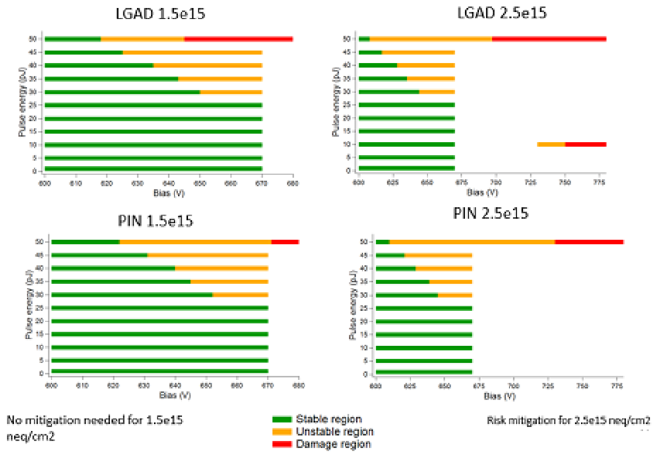




*//indico.cern.ch/event/1096427/contributions/4671384/attachments/2372216/4051559/HK2022-4D-Tracking.pdf*

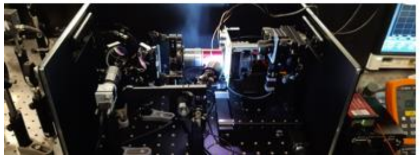
# SEB in Femtosecond Laser studies at ELI Beamline

Alternatively, as result of the collaborative effort of a few institutions within the RD50 Collaboration and the laser ELIBIO team from the laser facility ELI Beamlines, set of experiments have been conducted at ELI Beamlines exploiting the fs-laser "state-of-the-art" technology and the optical parametric amplification (OPA) system.

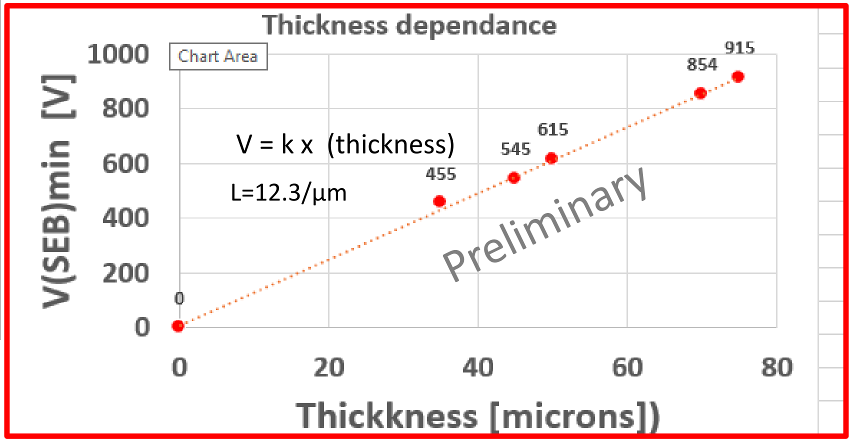
Study of three phases: stable, instable and irreversible breakdown (only HPK-3.2)




*Gordana Laštovička-Medin et al., Femtosecond laser studies of the Single Event Effects in Low Gain Avalanche Detectors and PINs at ELI Beamlines, submitted to NIM A, December 2021.*

Study on LGADs from different vendors (FBK, HPK, CNM)



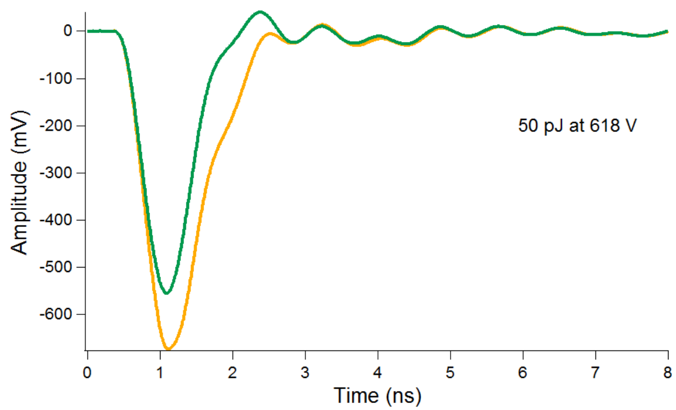
# Sable, unstable & irreversible phases: examples of waveforms

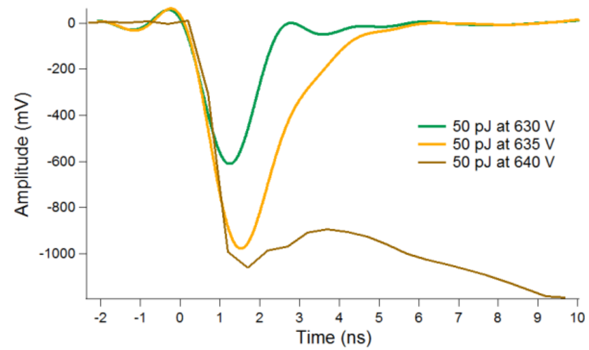
- HPK-3.2 samples

Stable regime

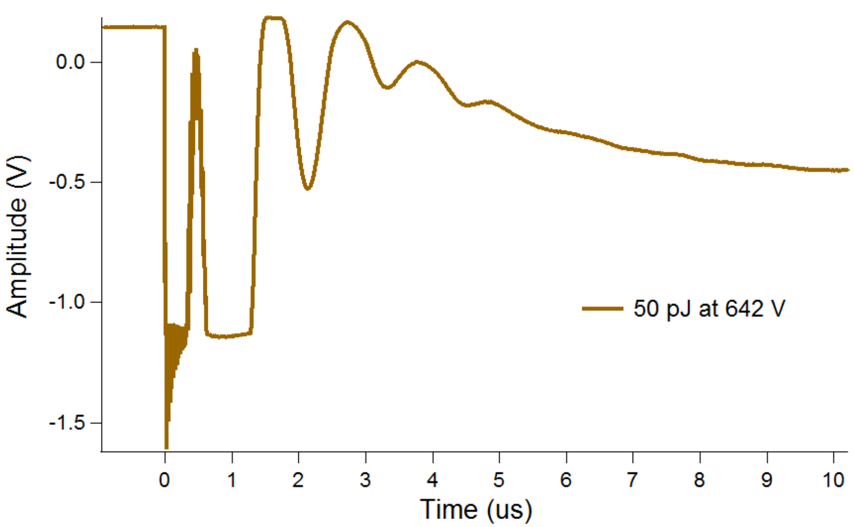
LGAD 1.5e15$n_{eq}$/cm$^2$

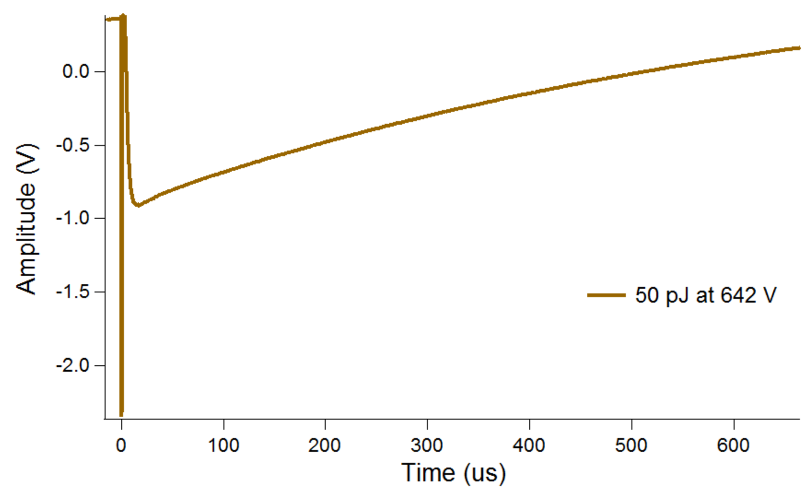
Unstable regime




Just before LGAD is permanently broken

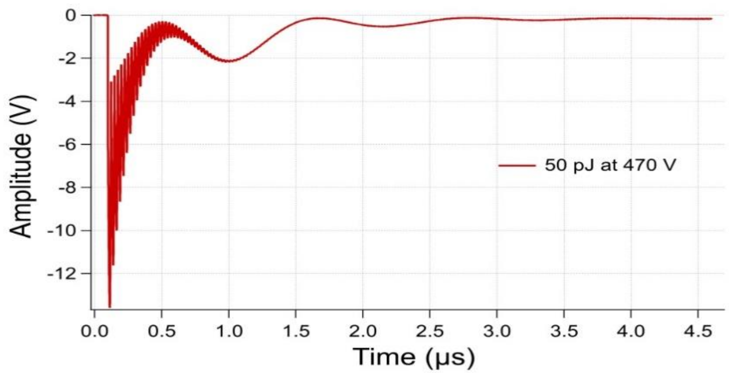


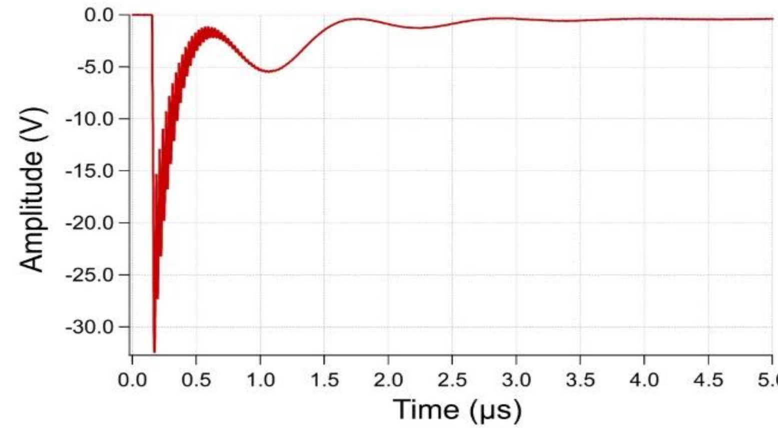
# Sable, unstable & irreversible phases using samples: examples of waveforms

- Sample from different vendors (HPK, BFK, CNM) different thickness

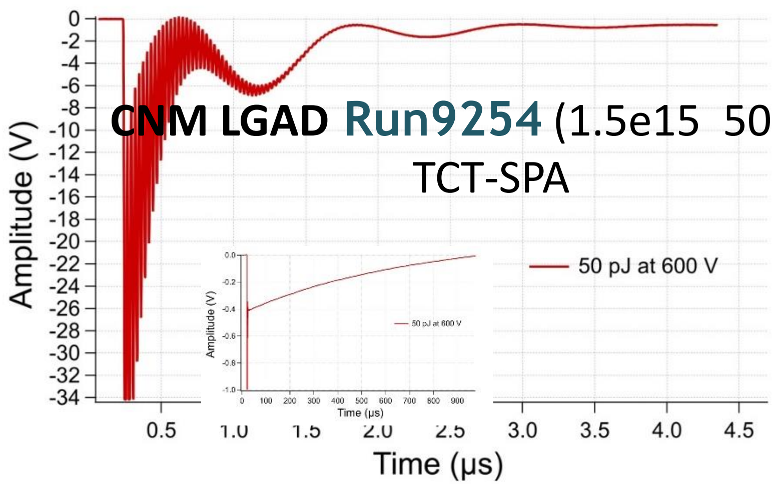
**HPK-P1 LGAD** (2.5e15 35 µm )
TCT-SPA



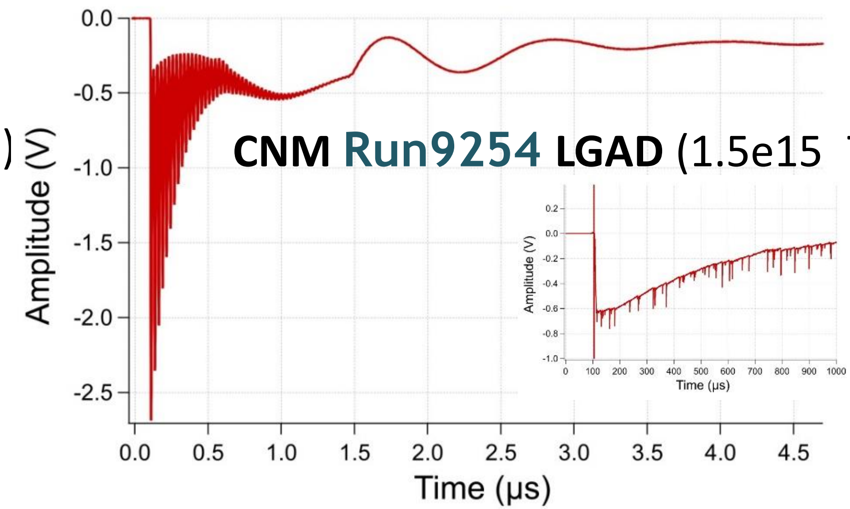

**HPK-P1 LGAD** (2.5e15 35 µm)
**TCT-TPA**




**CNM LGAD Run9254** (1.5e15 50 µm)
TCT-SPA



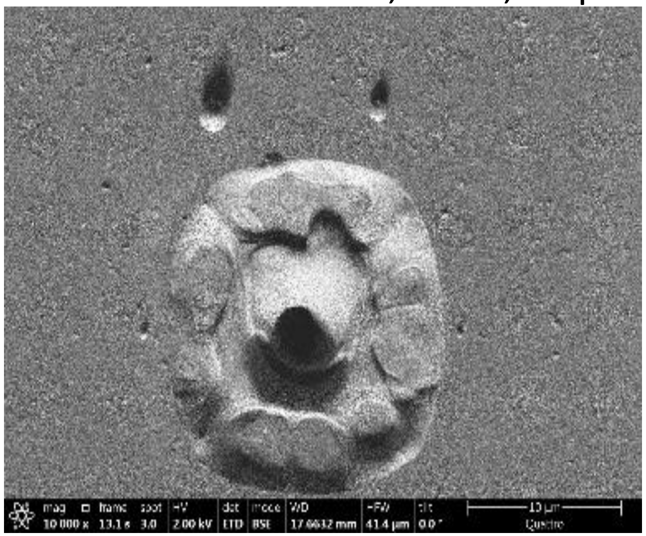

**CNM Run9254 LGAD** (1.5e15 70



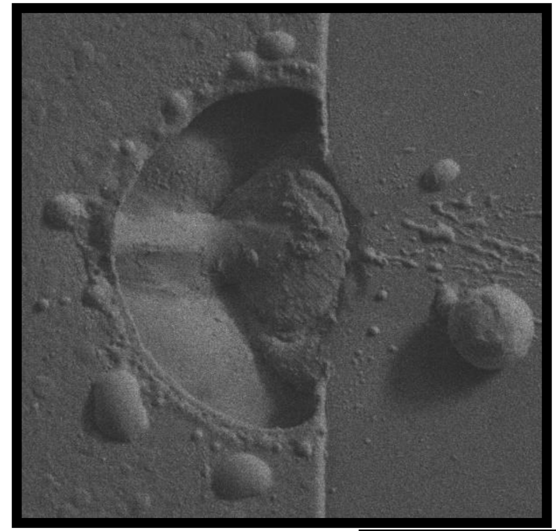
# Permanent fatalities: Damage signature in tests with fs-laser

**CNM, PIN** 2.5e15,
75 um, 910 V, 50 pJ

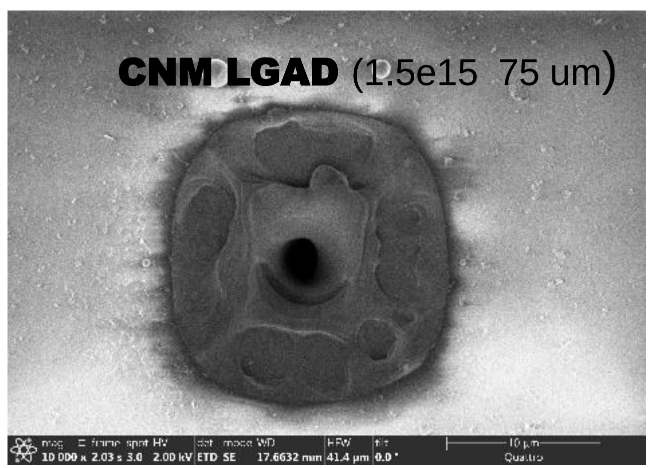
Fatality signature at the same place where illumination was performed (seen in our study as **characteristic feature for CNM sensors)**

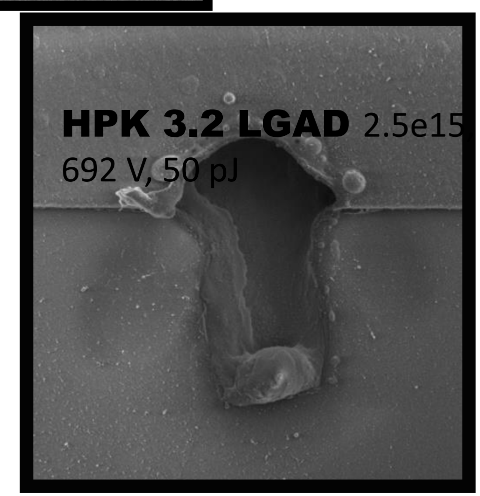


**HPK-3.2, PIN,** 2.5e15 $n_{eq}/cm^2$,
50 pJ, 730 V



**Edge effect**: Fatality signature at the border between metal and semiconductor **HPK features**)

# Main Findings (combining with TB results with protons)

Different tests have been produced and answer given:

- different fluences LGAD –does irradiation matter? – the way it facilitate high bias
- irradiated PINs – does intrinsic gain matter? - NO
- 0.1 MGy g irradiated PINs – does bulk damage matter? - NO
- 35,45,50, 70, 75 mm thick LGADs – effect of thickness? - YES
- different producers (HPK, FBK, CNM)– does process matter? - NO

Finding in the recent test beam campaigns: (https://indico.cern.ch/event/1029124/contributions/4411270/)

- around 10-30 k 120 GeV p are required for SEB at voltages at >12 V/mm
- around 1M 3-6 GeV electrons are required for SEB at voltages at >12 V/mm (tested 3 thicknesses)

Combining ELI thresholds with TB results with protons: ➡

Average electric field in the device is the critical driver:

- safe region - < 11 V/mm
- danger region - ~11-12 V/mm
- SEB region - >12 V/mm

To avoid SEB is keeping the voltage low enough wrt thickness – possible thickness optimization.
➢ possible solutions the use of carbon enriched GL where required performance is reached at lower bias voltages.

Due to smaller fluence the CMS is less affected even if “standard” sensors are used.

ATLAS would be more affected at the end of lifetime (in the last 1000 fb-1)

# Gain suppression (GS)

- Space charge screening effects (SCSE) depend highly on the spatial distribution of injected charge.
- MeV heavy ions of different masses and energies will result in a wide distribution of track structures, some of which may or may not lead to anomalous gain and possible breakdown.
- Investigating the role of screening in determining the charge collection dynamics is best performed by altering the density of electron-hole pairs along the ion track in a quantifiable manner.
- As we show there is critical charge density for gain suppression but how and where ithis charge density is created inside LGAD is of crucial importance (type of paticle,depth of deposited charge, drift path, diffusion, depletion /overdepletion voltage – all play roles)

.

## Comparing to SEB

- SEB to sustain needs a minimum current for a minimum time, to create sufficient localized self-heating, such that the current becomes locally self-sustaining (conditions only reached with high energetic particles with energy deposit of 30-40 MeV)
- Unlike the case of Singe Event Breakdown (SEB) event, here higher injection levels lead to significant quenching of impact ionization in the high field of the gain layer in LGAD.
- THe catastrophic failure that is not related to displacement damage (induced by radiation) is very unlikely to occur .
- Field is not high enough in bulk to seed avalanche to overtake "gain dumping . Critical value for electric field has to be reached for SEB, as well as deposited energy has to be - 30-40 MeV." .

.

- Sustaining avalanche in bulk is needed for SEB; but gain in gain layer not required (SEB seen in both – LGAD and PIN). Gain suppression even if happened will not suppressed SEB if other conditions are met.

.

- Temperature is known to be an important factor for single event burnout. Some critical values has to be reached.

.

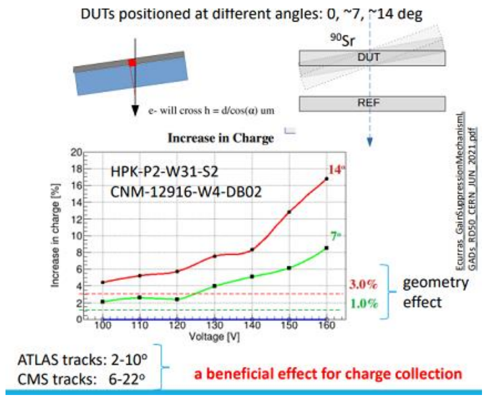
# Published studies

- Gain suppression in LGADs can be induced by formation of micro plasmas in the bulk due to the generation of a high ionization density, i.e., a high carrier density along the particle's track. Not expected without formation of micro plasmas.

  **Miller, G.L; Brown, W.L.; Donovan, P.F.; Mackintosh, I.M. Silicon p-n junction radiation detectors. IRE Trans. Nucl. Sci. 1960, 7, 185–189. Laird, J.S.; Onoda, S.; Hirao, T.; Edmonds, L. Quenching of impact ionization in heavy-ion induced electron-hole pair plasma tracks in wide bandwidth avalanche photodetectors. J. Appl. Phys. 2010, 107**

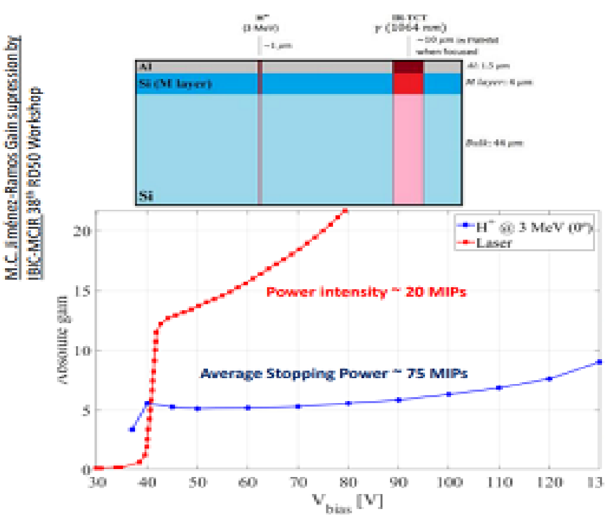
- . Contrary, a recent study (within RD50 Coll) has shown that even the ionization density produced by a MIP when passing through an LGAD generates gain suppression; there is a local drop in the electric field which causes the impact ionization parameter to decrease, resulting in a lower gain. Here the tests with IR laser have been compared to tests with Sr-90. Angle dependence studded too,

  **Currás, E.; Fernández, M.; Moll, M. Gain suppression mechanism observed in Low Gain Avalanche Detectors. arXiv 2021, arXiv:2107.10022**




- Beside tests with laser and Sr-90, another set of experiments with ion beams have been performed within RD50 collaboration using 3 MeV protons in a nuclear microprobe; the rotation angle has been increased to get the Bragg Peak inside the bulk of the LGAD detector, since at that point the injected carrier density generate a micro-volume of ionization similar to the use of TPA.

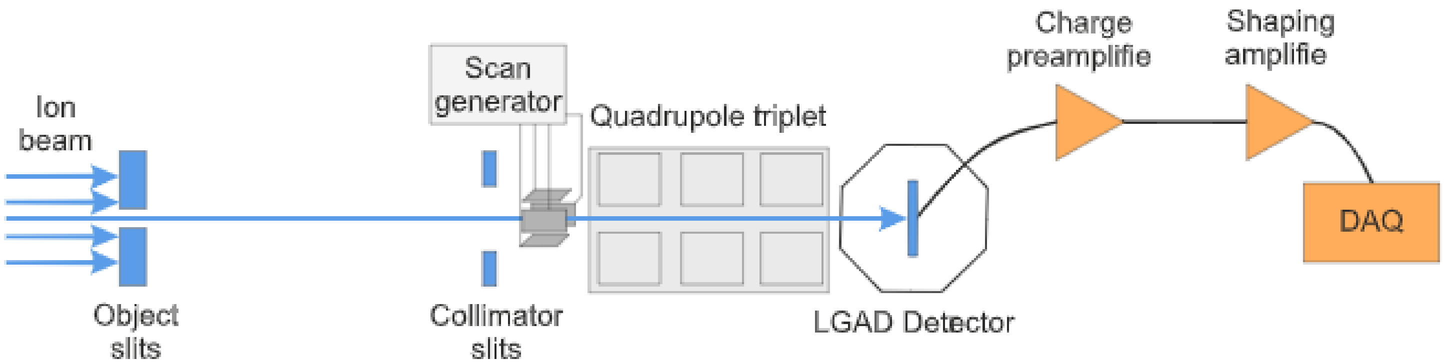
  **Jiménez-Ramos, M.C.; García López, J.; García Osuna, A.; Vila, I.; Currás, E.; Jaramillo, R.; Hidalgo, S.; Pellegrini, G. Study of Ionization Charge Density-Induced Gain Suppression in LGADs. Sensors 2022, 22, 1080. https://doi.org/10.3390/s22031080**



# Further verification with IBIC and Ion-TCT at RBI

Methods:

- Ion Beam Induced Charge (IBIC)
- Ton-Transient Current Technique  (Ion-TCT)




RBI: Rudjer Boskovic Institute

*Schematic presentation of the ion microprobe focussing and scanning system with IBIC pulse processing electronic chain. Charge sensitive preamplifier used was Ortec 142A, while the amplifier was Ortec 570. Data acquisition was based on Canberra ADC 8701 and in house made SPECTOR software.Ex*

## Samples

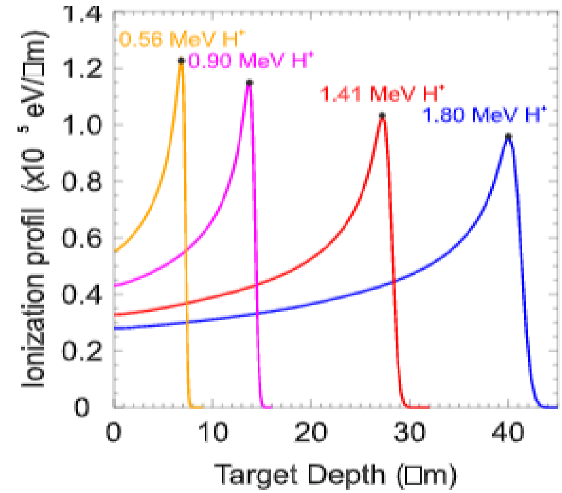
Hamamatsu (HPK) with an equally thick 50 µm sensitive depth

- HPK W28 IP5-SE3, (2x2 or single pad)
- HPK W36  IP7-SE3, (2x2 or single pad)

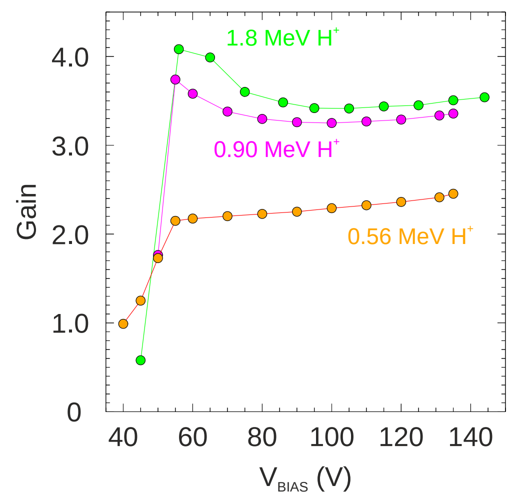
# Results: Gain to voltage dependences (Part I)

Probing LGAD's depths with **proton and carbon ions**:

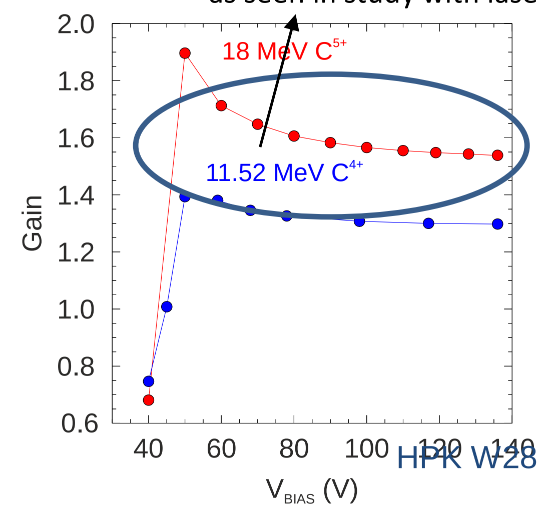
- ❑ different energy
- ➢ different Bragg position (**all in bulk**)




a) 2x2 pixel structure HPK-P2 IP5-SE3




b) Not observed monotonous behaviour as seen in study with lasers




HPK W28 IP5-SE3

## Observations:

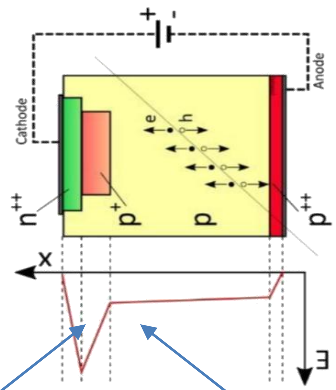
- ➢ Steeper and more pronounce "gain" peak for more penetrating ions (fully absorbed by LGAD), for low bias observed.
- ➢ **Suggested hypotheses**: **Influence of diffusion on the charge carrier density**; widening the charge cloud entering the gain layer due to diffusion of the charge carriers reduces the electric field screening.

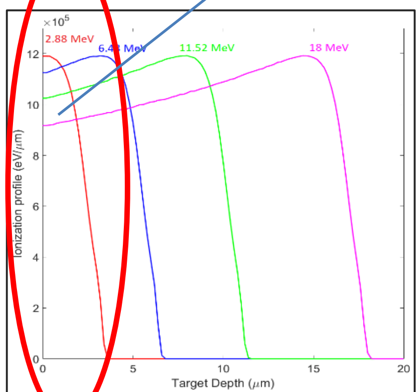
# Results: Gain to voltage dependences (Part II)

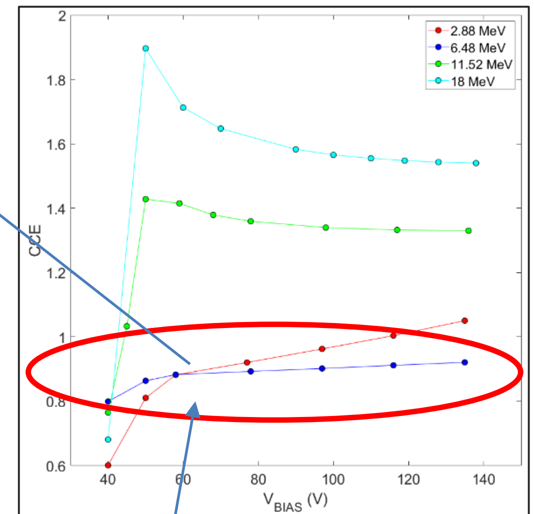
Probing LGAD's depths with **Carbon ions**:

- ❑ different energy
- ➢ different Bragg position (**all in bulk**)

- Probing Ion Beams (**PIBs**): **18 MeV $C^{5+}$**, **11.52 MeV $C^{4+}$**, **6.48 MeV $C^{3+}$** and **2.88 MeV $C^{2+}$**

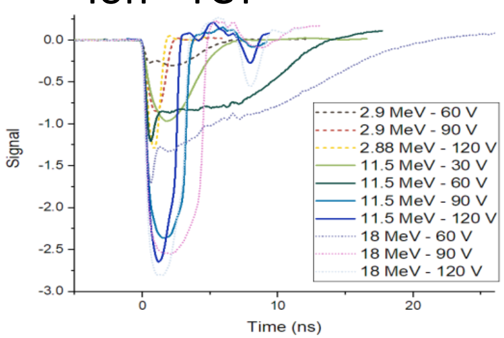


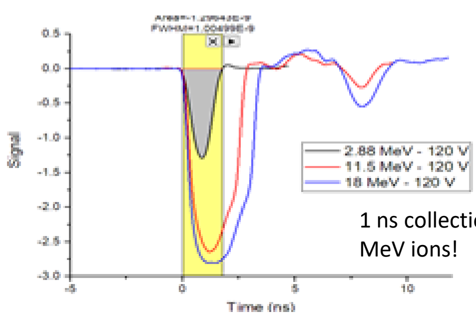




- ➢ Steeper and more pronounce "gain" peak for more penetrating Carbon
  - ➢ **Influence of diffusion on the charge carrier density!**

Ion - TCT




1 ns collection time for 2.88 MeV ions!

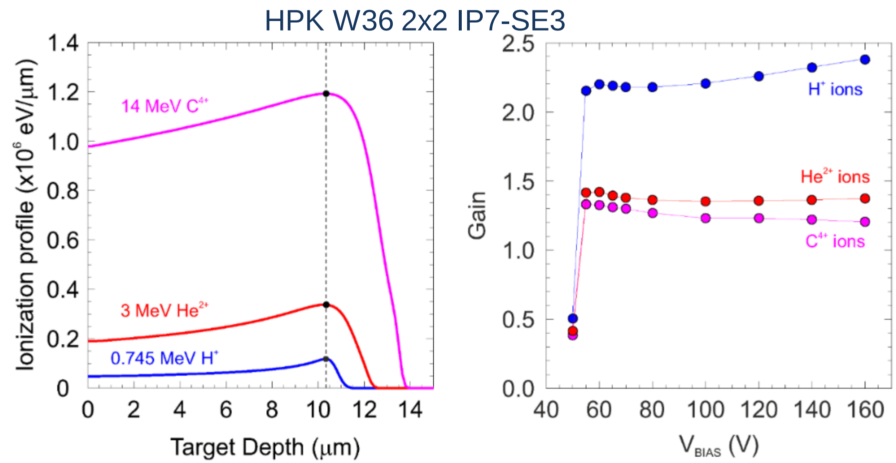
- ➢ Impact ionisation does not happen at all for carbon induced carriers, if their track length ends very close to the gain layer! Screening of el field is so strong that carriers do not gain energy needed to undergo impact ionisation.

Area (C-18 MeV) / Area (C-2.88 MeV) = **5.62**
Area (18) / Area (11.5) = 1.40
Area (11.5) / Area (2.88) = 4.04; at V=120 V

# Results: Gain to voltage dependences (Part III)

Probing LGAD's response to charge density using **different ions**:
different energy

- **Bragg position at the same LGAD's depth (10 μm)**




- Observation: Due to higher ionisation, gain is more supressed in the case of heavier ions

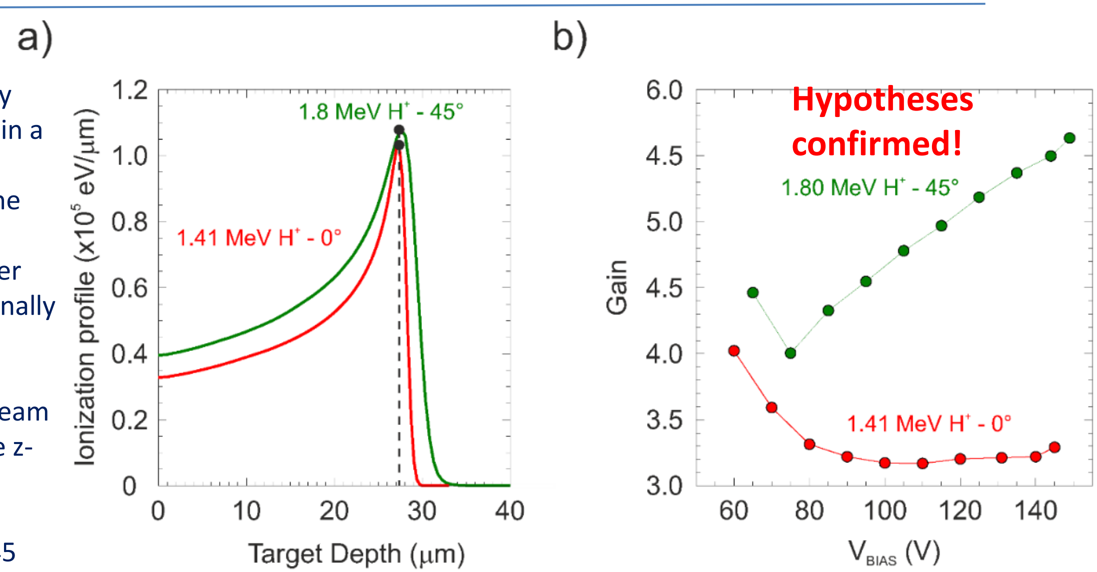
---

**Verification of hypotheses**:

Widening the charge cloud entering the gain layer reduces the electric field screening

Idea: Inclining the ion beam

- ❑ does not modify the charge density along the ionizing path in the bulk in a significant way
- ❑ it modifies the charge density of the charges arriving to the gain layer;
- ❑ The projected charge density under the gain layer decreases proportionally a factor d/sin (alpha) ('d' is the thickness of active LGAD)
- ❑ We compared gain from proton beam entering LGAD vertically (along the z-axis) towards the detector surface (1.41 Mev) to gain from proton entering LGAD under an angle of 45 degrees.

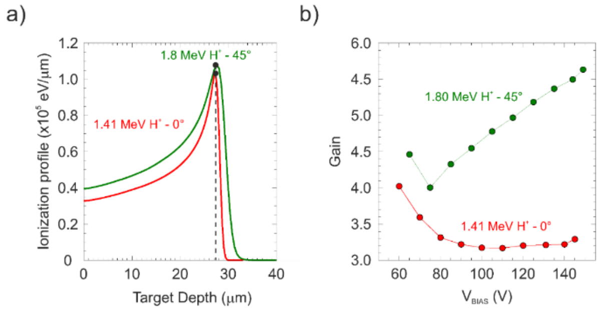



We

# Main Findings

- Gain suppression has been confirmed and explanation. large density of carriers, primary and multiplied, polarize the gain layer and effectively screen the external field that leads to the reduction of the field
- **Influence of <u>diffusion</u> on the charge carrier density experimentally verified**
- Prominent 'gain peak" in gain curves is observed in studies with ions at RBI; not seen in other published papers. It is observed at HV < $V_{FD}$ where diffusion of the charge carriers (electrons) overtake the role of drift.
- This Gain 'peak' is more pronounced for more penetrated ions and it is qualitatively similar for proton and carbon ions (effect of diffusion).
- For smaller penetration ranges, the diffusion contribution is less pronounced since the drift time of charge carriers is shorter. By increasing the voltage, the charge carriers drift faster, and the spatial density of charge carriers increases, resulting in a higher electric field screening effect. Therefore, the gain 'peak', which is visible for deep penetration ions, is less pronounced for the low-range ions.
- As result of diffusion-facilitated expansion of charge cloud at low bias, the volume of the charge cloud arriving at the gain layer is much larger than it is for higher bias. This means that the charge density in the gain layer and the screening effect of electric field decrease, and eventually the gain becomes higher.
- Two different ion incidence angles have been further proposed to confirm the earlier assumption that widening the charge cloud entering the gain layer (due to diffusion of the charge carriers) reduces the electric field screening.

❖ *See talk of Milko Jaksic on Friday.*




❖ Milko Jakšić, Andreo Crnjac, Gregor Kramberger, Miloš Manojlović, Gordana Lastovicka-Medin, Mauricio Rodriguez Ramos, *Ion microbeam studies of charge transport in semiconductor radiation detectors with three-dimensional structures: An example of LGAD, submitted to Frontiers in Physics, section Radiation Detectors and Imaging.*

# ACKNOWLEDGMENT

Fundings:

- This project received funding from the European Union’s Horizon 2020 Research and Innovation programme under grant agreement No 101004761.
- The European Regional Development Fund for the ‘Center of Excellence for Advanced Materials and Sensing Devices’ (Grant No. KK.01.1.1.01.0001).
- Support provided by the IAEA within the framework of Coordinated Research Projects G42008 andF11020.
- the Ministry of Science in Montenegro within the project “Improving research infrastructure and measuring techniques for testing of fast ”state-of-the-art” LHC-HL time detectors,” Contract 340 No. 03/1- 062/20-500/3.
- Slovenian Research Agency (ARRS J1-6199).
- ELI Beamlines in Czech Republic, for providing beamtime.
- LM2018141, MEYS –344 Large research infrastructure project ELI Beamlines Advanced research using high-intensity laser-produced photons and particles (ADONIS)(CZ.02.1.01/0.0/0.0/16 019/0000789), Structural dynamics of biomolecular systems (ELIBIO)(CZ.02.1.01/0.0/0.0/15 003/0000447) (both from the European Regional Development Fund and the Ministry of Education, Youth and Sports).

Thank you to all involved