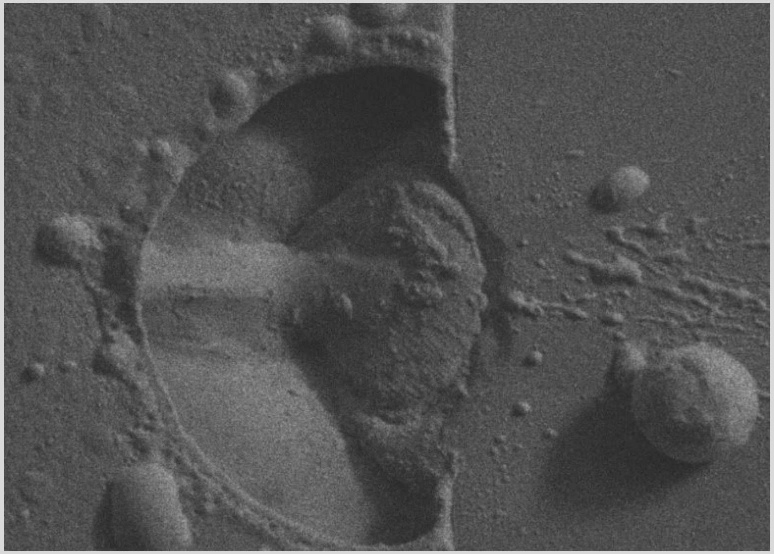
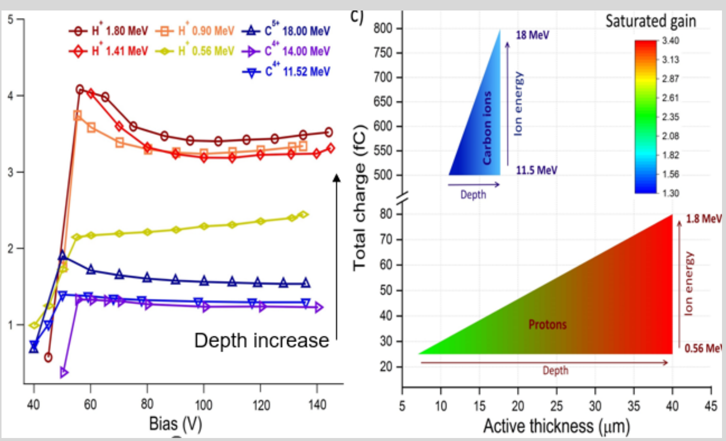
THE 40TH RD50 COLLABORATION MEETING,
JUNE 21-24 2022, CERN





Overview of our understanding on the limits of LGAD as studied by the low energy ions, low energy protons and femtosecond laser beams: Past, present and future experiments

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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 ✓ Critical el field (threshold mapping) ✓ 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: DC coupled (pixels): √ Trench-Isolated LGADs √ iLGADs (inverse LGADs) Low rate environments: AC-LGADs	For small pixel LGADs TI-LGADs , iLGADs can provide the solution, but not yet proven 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 :
SEB & Gain Suppression

LGAD response to ionisation density

Non-Radiation effect
Gain suppression

- impact ionisation quenched
  - ✓ Charge space effect (Electric field screening, polarisation effect)
  - ✓ Hole impact ionisation supressed
  - ✓ Within micro plasma regime or without)
  - ➢ **Reversable effect**

High Ionization charge density as crucial parameter

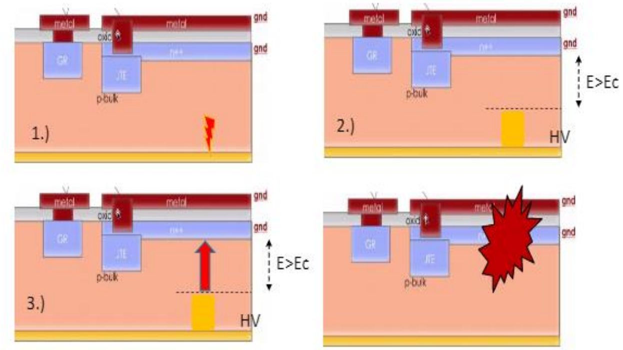
Radiation effect:
Signal Event Burnout (SEB)

- ➢ Impact ionisation enhanced
- ➢ Hole contribution enhanced
- ➢ Self-sustaining current, in narrow path
- ➢ Thermal runaway

➢ **Permanent fatality**

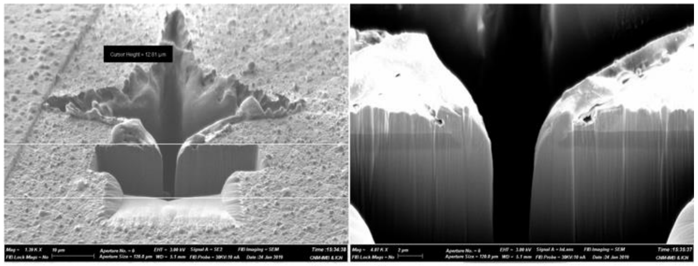
Radiation Hardness of LGADs: SEB

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.



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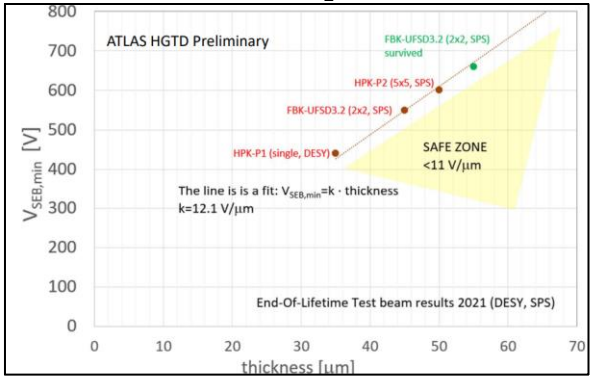
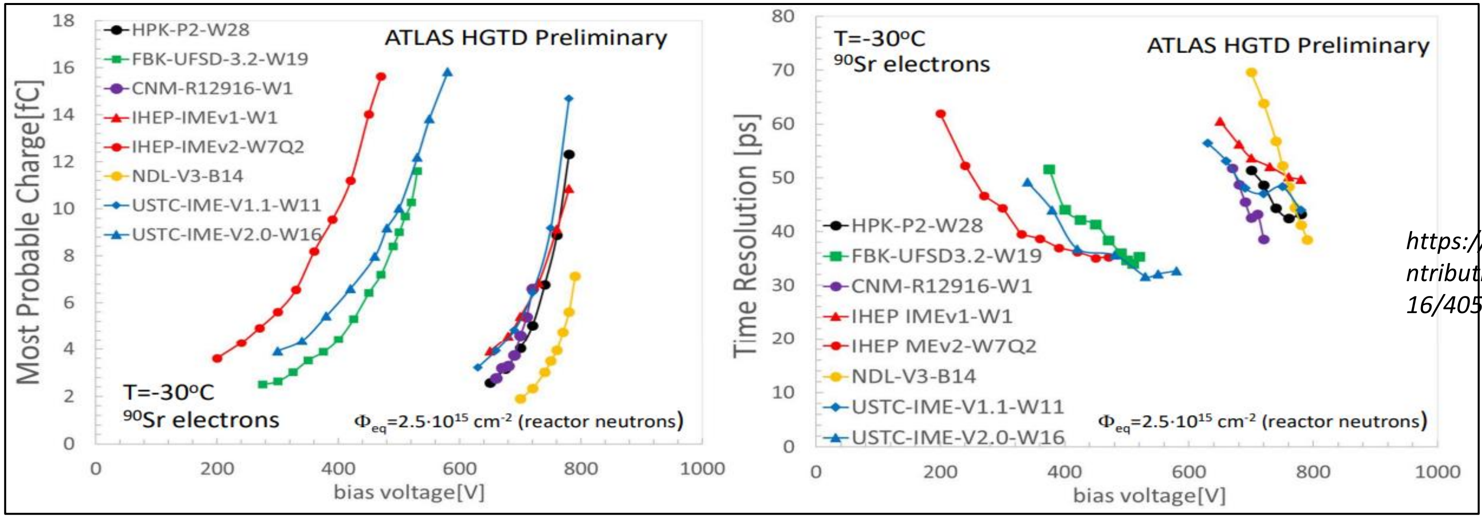
SEB results from
TB with proton

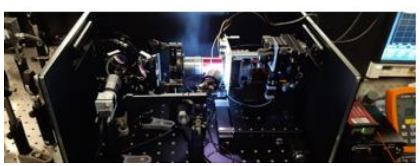


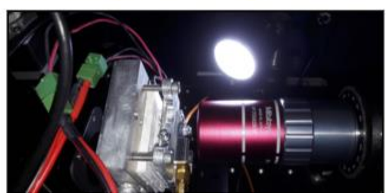


https://indico.cern.ch/event/1096427/contributions/4671384/attachments/2372216/4051559/HK2022-4D-Tracking.pdf

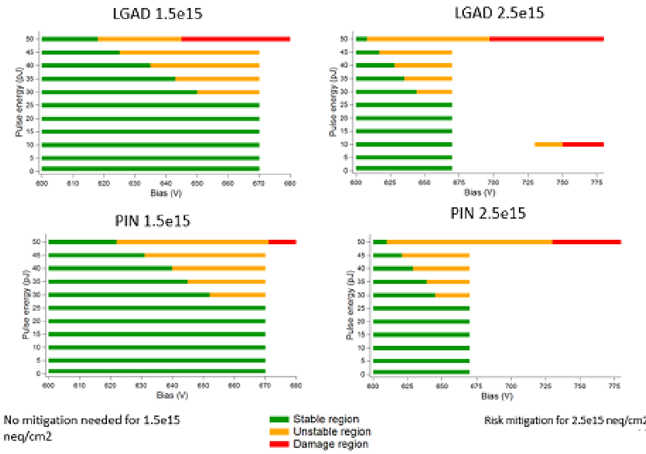
SEB in Femtosecond Laser studies at ELI Beamline

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.



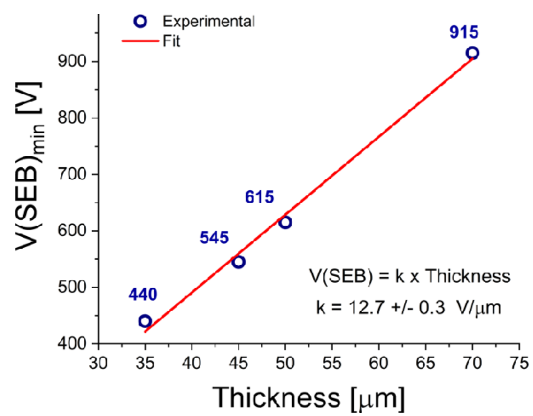


Study of three phases: stable, instable and irreversible breakdown (HPK-3.2)



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)



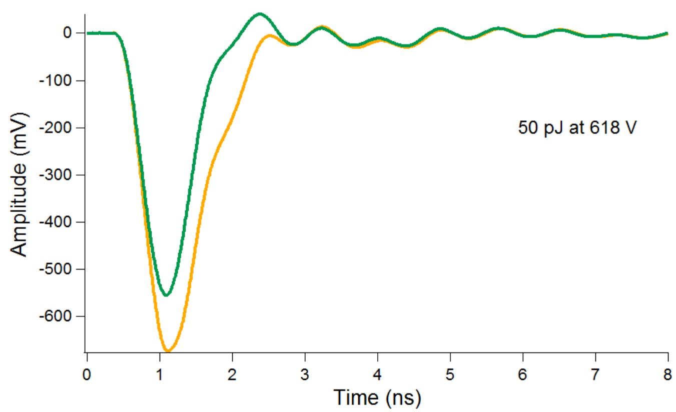
Sable, unstable & irreversible phases: examples of waveforms

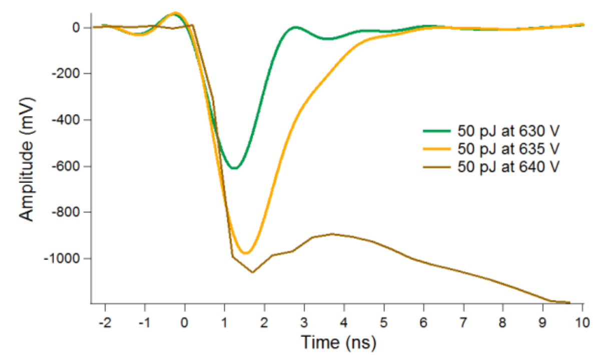
- HPK-3.2 samples

Stable regime

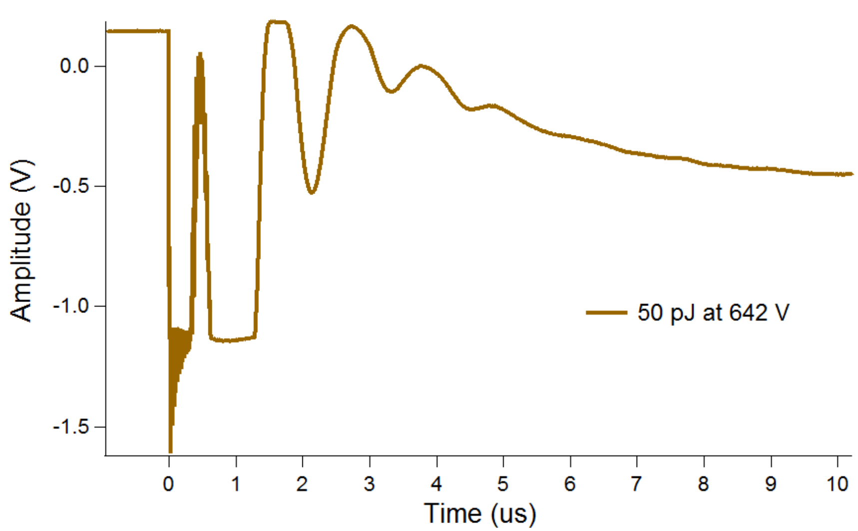
LGAD 1.5e15n_{eq}/cm^2

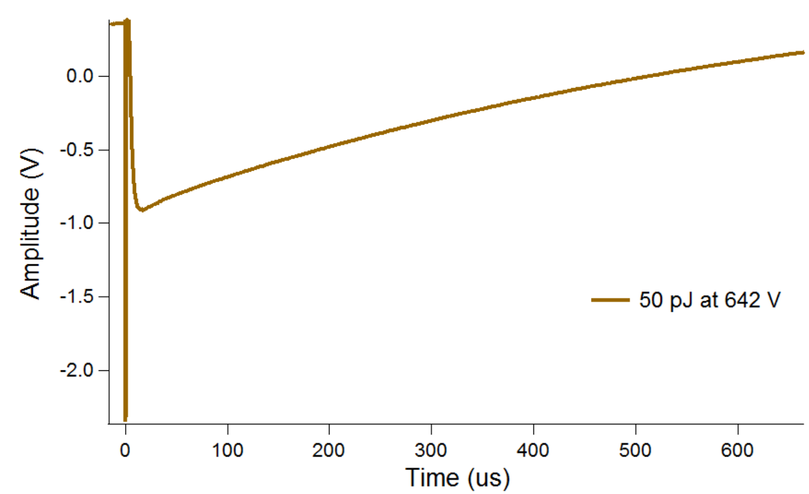
Unstable regime





Just before LGAD is permanently broken

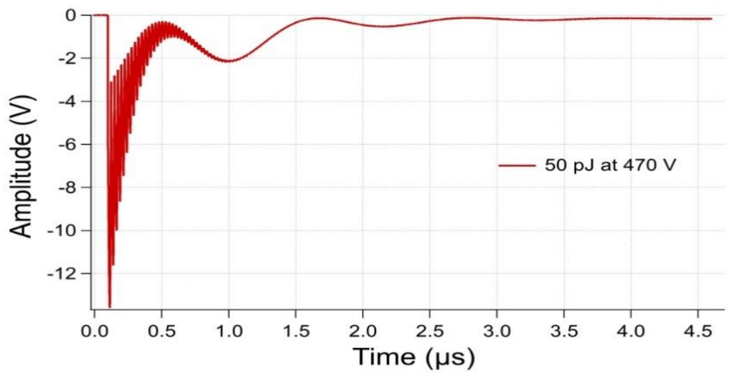




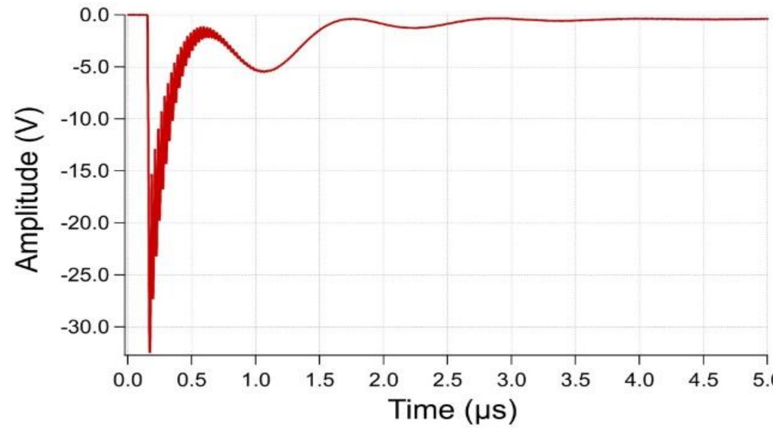
Sable, unstable & irreversible phases using samples: examples of waveforms

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

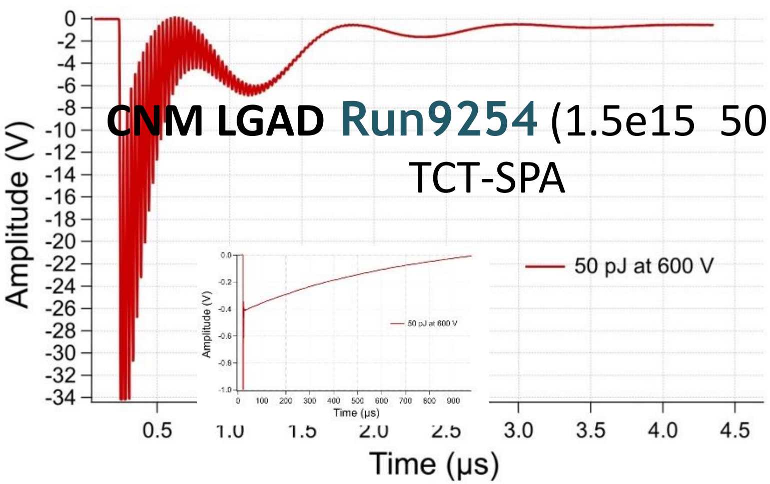
HPK-P1 LGAD (2.5e15 35 µm)
TCT-SPA



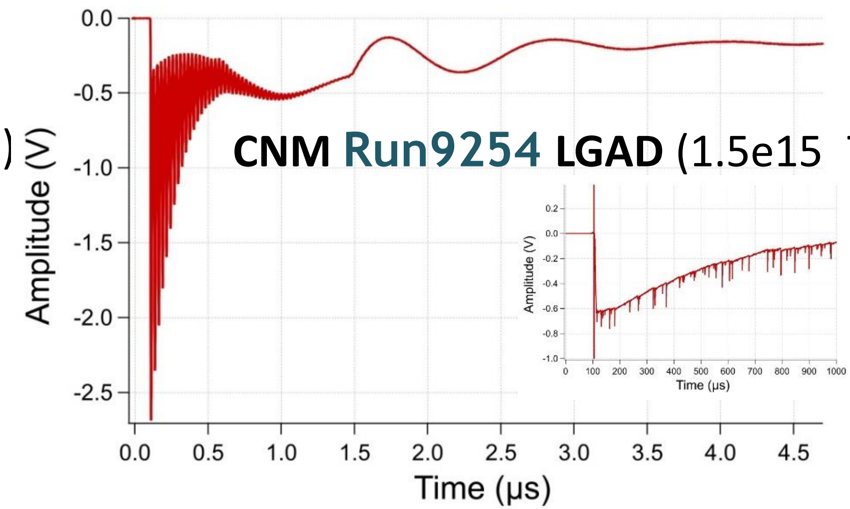
HPK-P1 LGAD (2.5e15 35 µm)
TCT-TPA



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

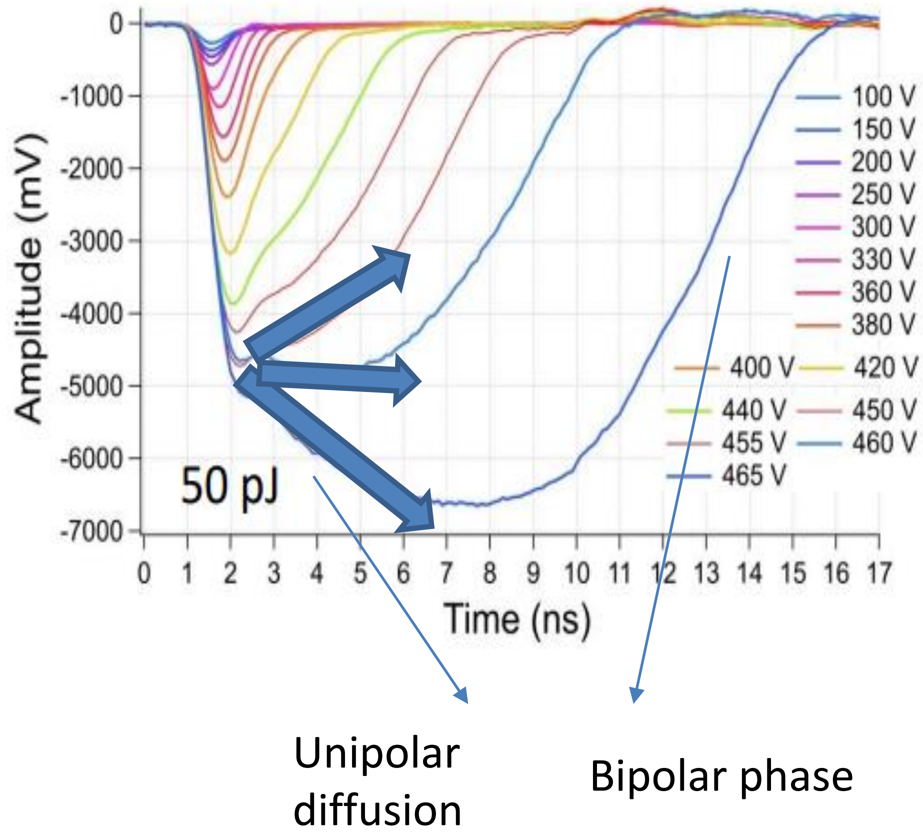


CNM Run9254 **LGAD** (1.5e15 70



Plasma effect, modified space charge & change of gain : 3 in 1 plot!

- Here we see the gain rise and the increase of the rise time.
- If the high density of carriers affects the shape of the signal the tails of normalized curves to the highest point should increase with gain.
- The tails should be longer for higher gain and shorter if there is no plasma effect screening of the field in the bulk (plasma).
- These are irradiated samples and an effect of modified space charge due to trapped holes can be seen.
- This seems to be case since the slope of the hole drift are not similar.
- Pulses are very energetic and gain layer screening plays a role as well.

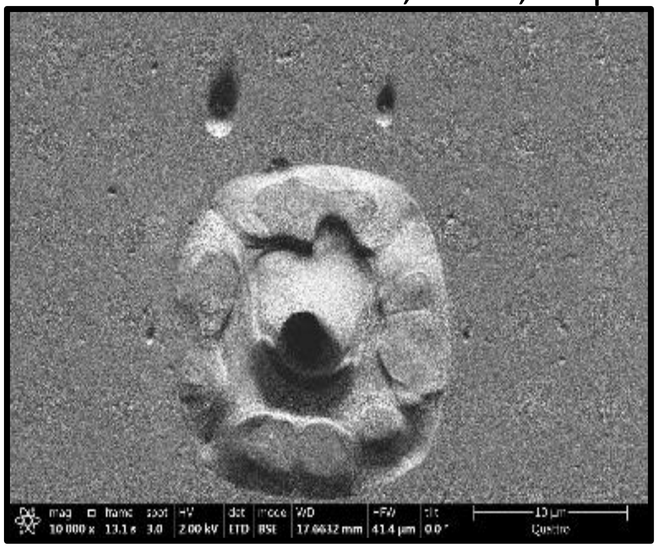


- **All above mentioned phenomena: Change of gain, plasma effect and modified space charge seen during the increase of HV, close to irreversible breakdown.**

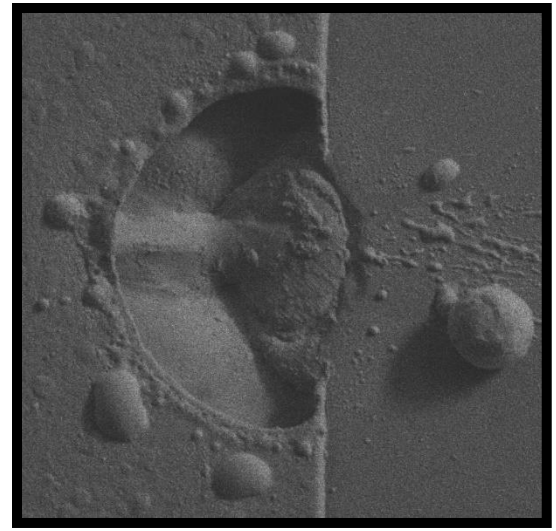
Permanent fatalities: Damage signature in tests with fs-laser

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)**

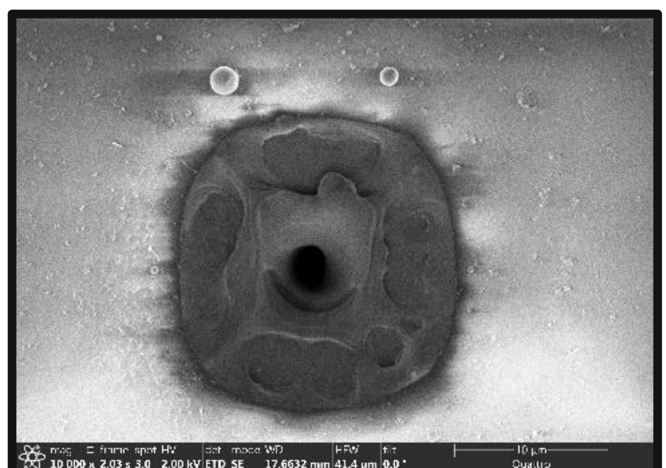


HPK-3.2, PIN, 2.5e15 n_{eq}/cm^2,
50 pJ, 730 V

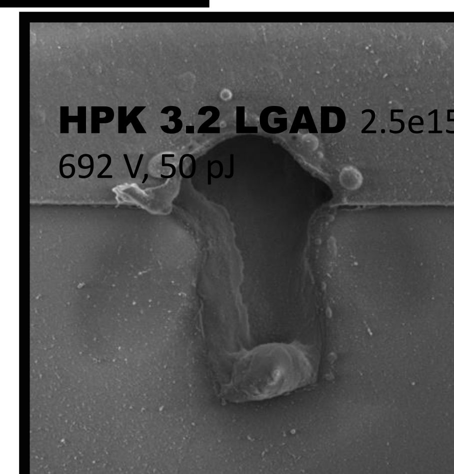


Edge effect: Fatality signature at the border between metal and semiconductor **HPK features**)

CNM LGAD (1.5e15 70 um)



HPK 3.2 LGAD 2.5e15
692 V, 50 pJ



Can we compare burning mark from the beam test to what is seen in laser tests?

- THE MECHANISM OF DAMAGE TO THE CRYSTAL IS LINKED TO THE CONDUCTIVE PATH FORMED AFTER LASER OR PARTICLE DEPOSITION AND THE CONSEQUENT HEAT RELEASE IN THE DISCHARGE.

- LASER DEPOSITION IS POSSIBLE ONLY IN THE OPTICAL WINDOW WHILE PARTICLES HIT THE DETECTORS UNIFORMLY ACROSS THE SENSOR SURFACE, MOSTLY IN THE METALIZED PART.

- HENCE A DIRECT COMPARISON BETWEEN THE DAMAGES INDUCED BY THE DIFFERENT METHODS IS NOT STRAIGHTFORWARD.

WHAT WE KNOW?

WE KNOW HOW TO AVOID SEB
AND WE KNOW HOW LGAD IS RESPONDING TO THE PERPENDICULARLY EXPOSED BEAMS ($E_{CRITICAL}$, V/DEPTH)

WHAT WE STILL DO NOT KNOW?

THE FULL CHARGE TRANSPORT DYNAMIC MECHANISM UNDER HIGH INJECTION LEVEL & DYNAMICS OF CHARGE COLLECTION EVOLUTION (FROM SEB SEEDING TO LGAD'S MELTING)

Effect of Drift propagation (only perpendicular illumination was studied)
Effect of diffusion

Trapping
Plasma effect
Space charge modification
Double junction
Increase of gai in bulk
Thermal excitation

All those phenomena may
-compete or
-collaborate

- A comprehensive explanation has not yet been found due to the complexity of the various phenomena at play.
- Very complex to build the model

Gain Suppression (GS)

A new limit imposed on LGAD's applications!

- ❑ Space charge screening effects (SCSE) depend highly on the spatial distribution of injected charge and temporal and spatial evolution of charge transport!.
- ❑ 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.
- ❑ Gain reduction is defined by electro impact ionisation but its transport, collection etc is heavily affected by hole population, hole concentration and dynamic of hole propagation

.

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)
- ❑ High charge density injections that lead to the significant quenching of impact ionization in the high field of the gain layer does not interfere with SEB (gain suppression in GL does not permit SEB event)

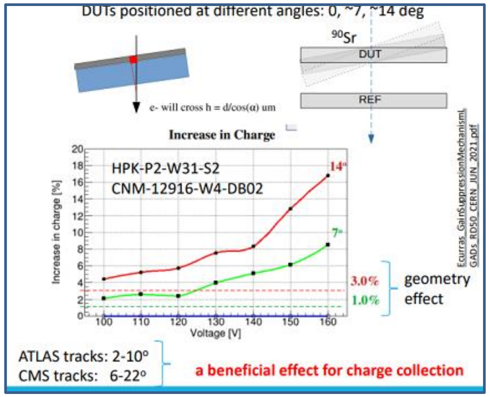
Published studies

- 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

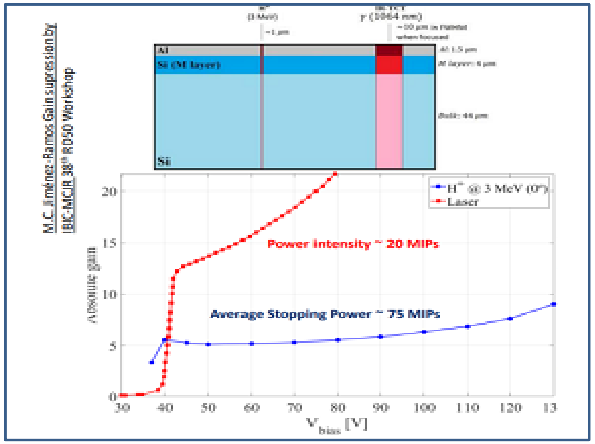
- Contrary, a recent study (within RD50 Coll) has shown that even the ionization density produced by a MIP when passing through an LGAD generates gain suppression; there is a local drop in the electric field which causes the impact ionization parameter to decrease, resulting in a lower gain. Here the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

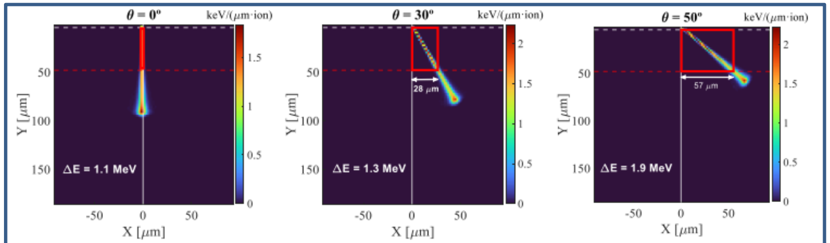
  Currás, E.; Fernández, M.; Moll, M. Gain suppression mechanism observed in Low Gain Avalanche Detectors. arXiv 2021, arXiv:2107.10022



- 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

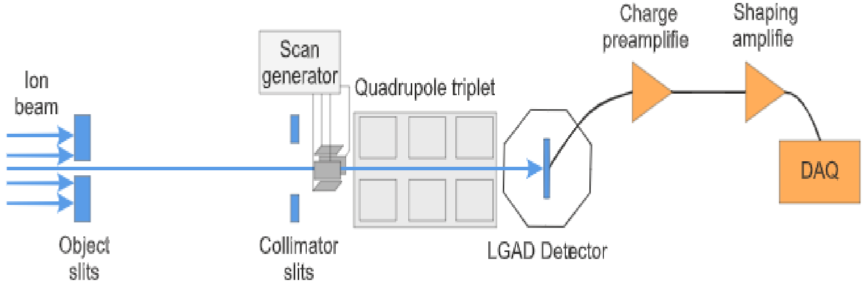


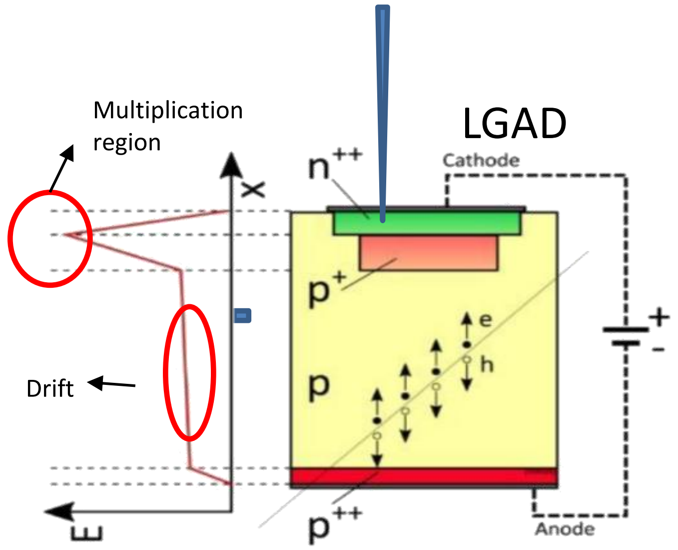


Further verification with IBIC and Ion-TCT at RBI

Methods:

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





RBI: Rudjer Boskovic Institute

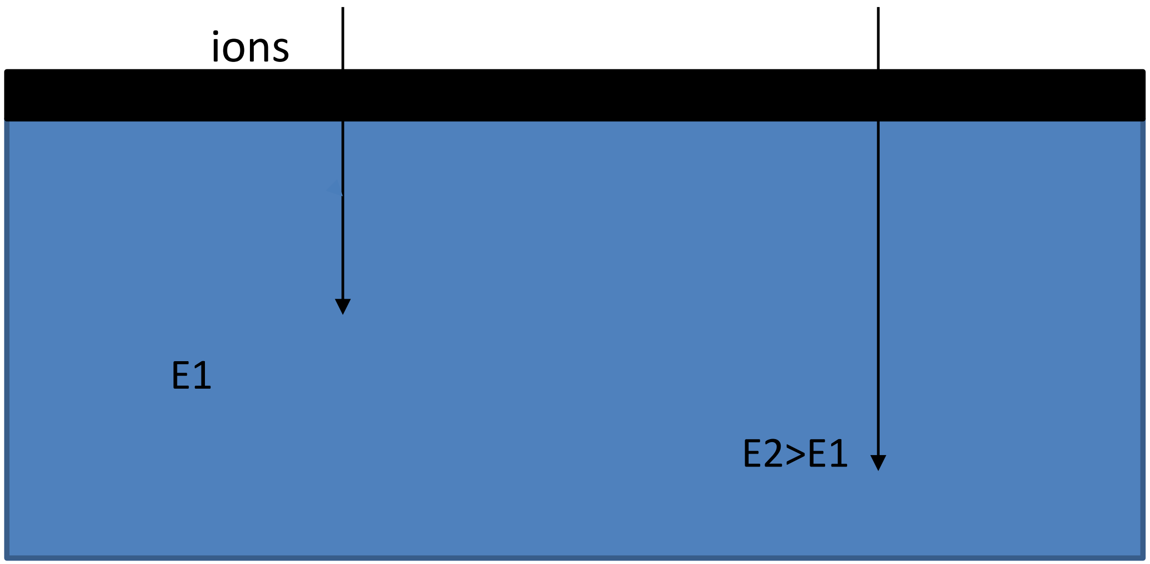
Schematic presentation of the ion microprobe focussing and scanning system with IBIC pulse processing electronic chain. Charge sensitive preamplifier used was Ortec 142A, while the amplifier was Ortec 570. Data acquisition was based on Canberra ADC 8701 and in house made SPECTOR software.Ex

Samples

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

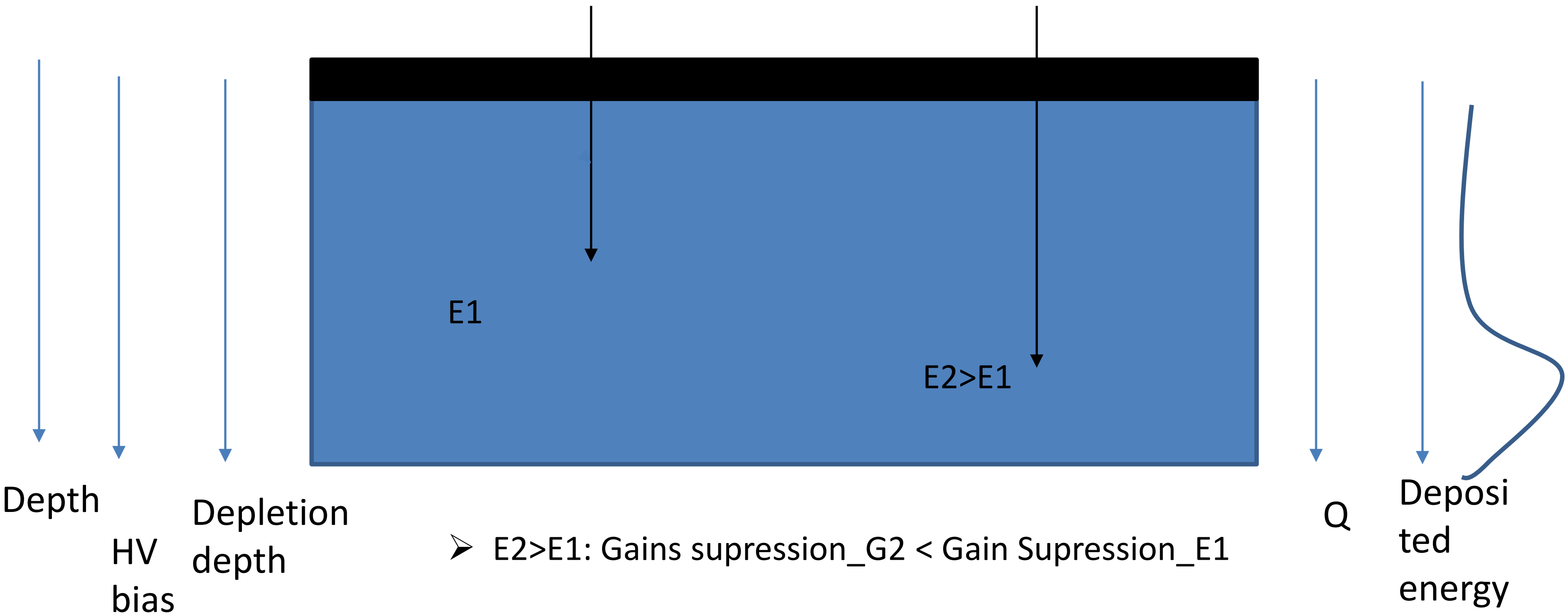
- HPK W28 IP5-SE3, (2x2 or single pad)
- HPK W36 IP7-SE3, (2x2 or single pad)

Gain suppression: Light ions



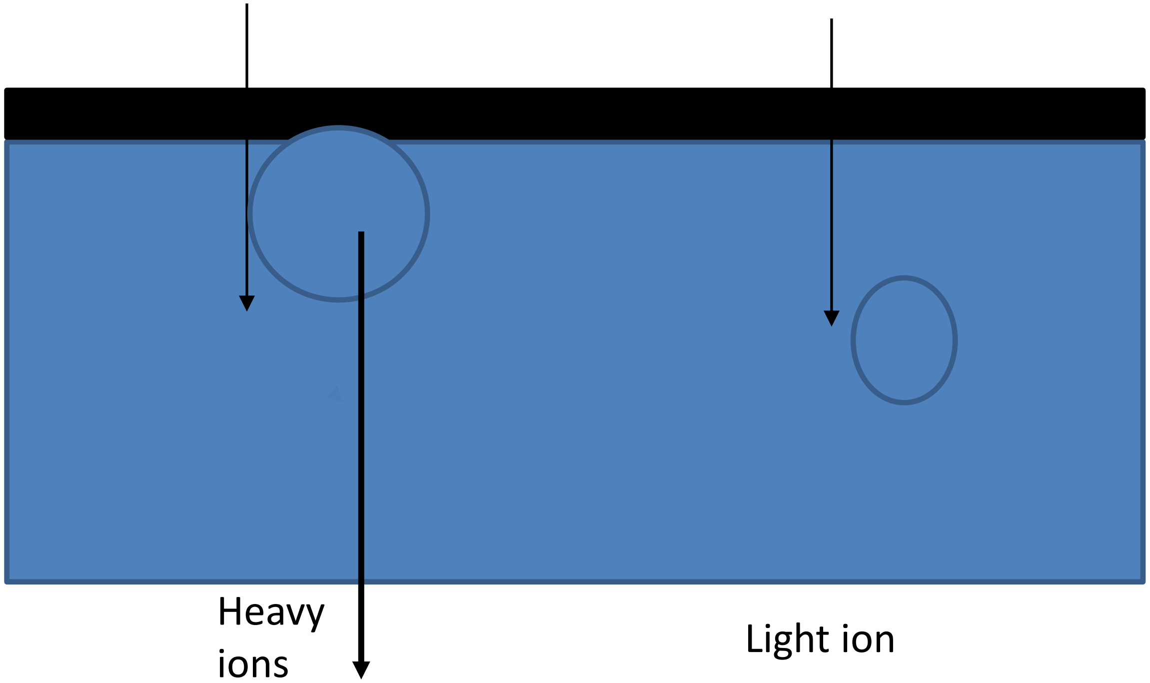
- E2>E1: Gains supression$_{E2}$ < Gain Supression$_{E1}$

Gain suppression: Light ions



- E2>E1: Gains supression_G2 < Gain Supression_E1

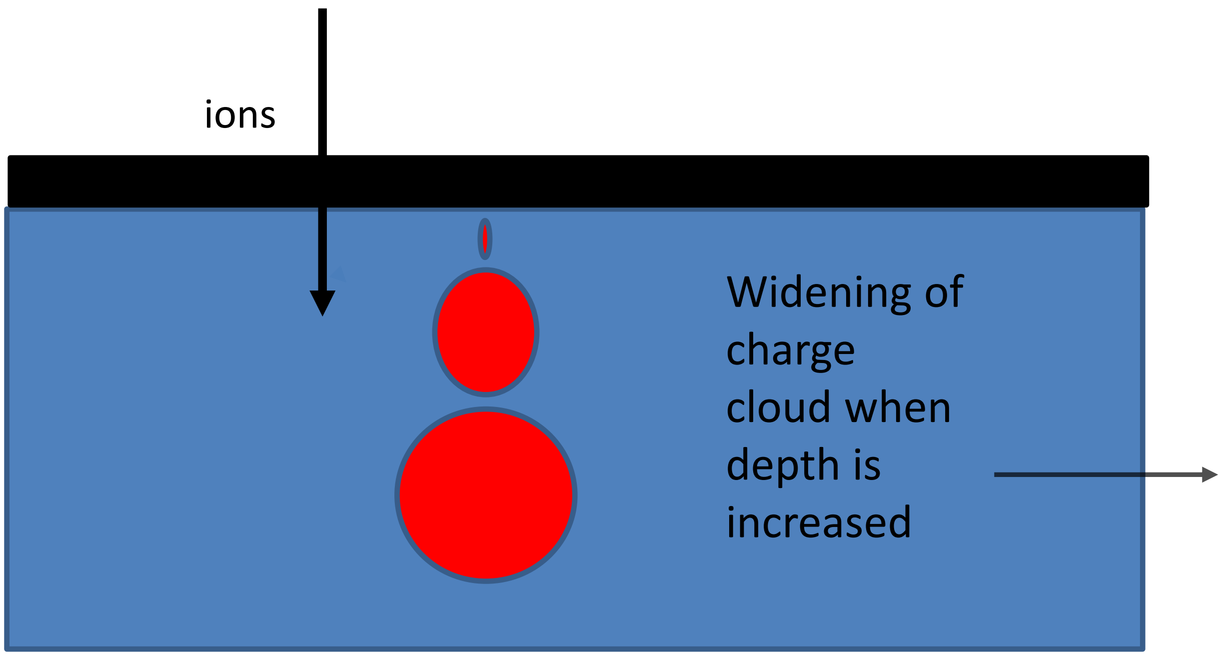
Gain suppression: Light ions vs Heavy ions



Slower movement of holes, electrons are for more prolonged period immobilized;
Unipolar phase (when holes and electros are moving together) last longer

Gains suppression from heavy ions more pronounced

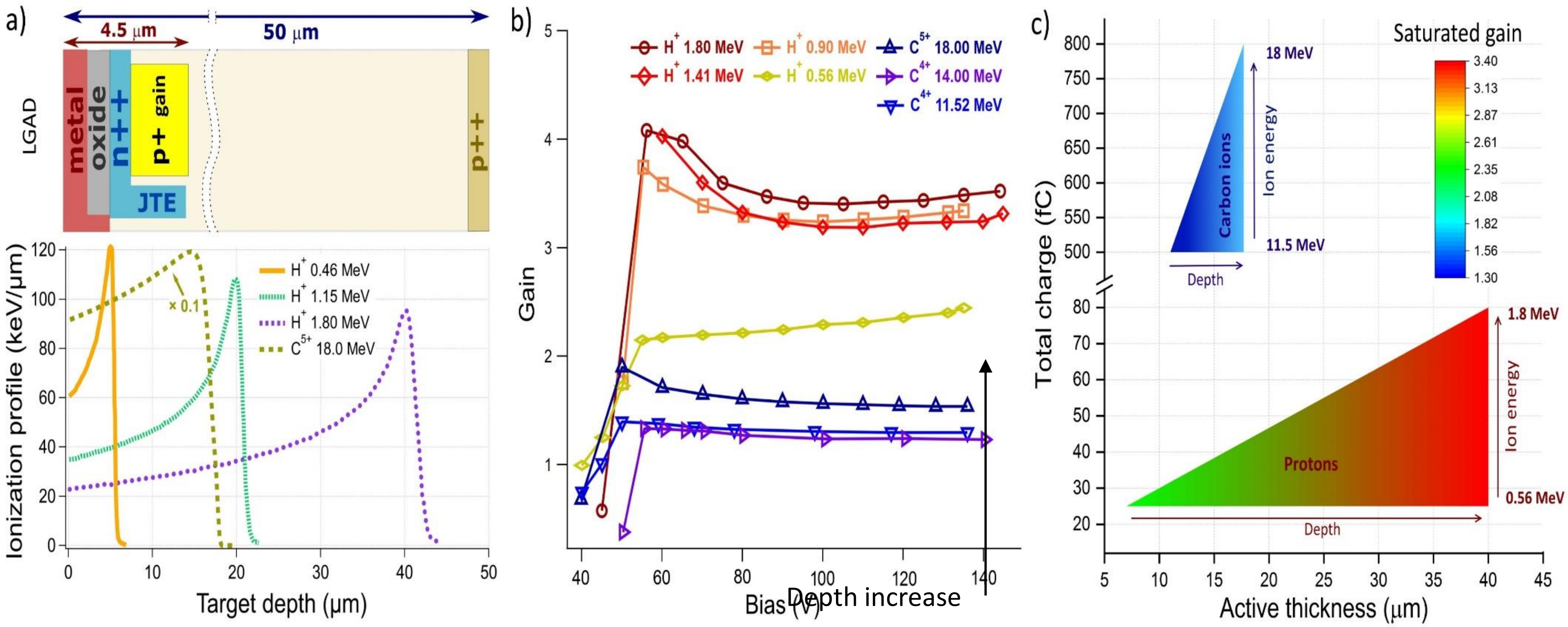
Gain suppression vs Depth



Less screening as depth in LGAD increases

(diffusion play role as well)

Ion-study:
Gain suspension vs heavy and light ion for all studied ions
:



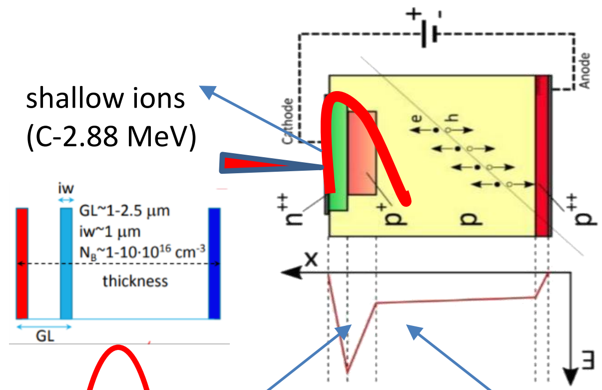
- Gain suppression changes with depth
- Gain suppression depends on ion mass and ion energy
- When LGAD is overdepleted, drop in gain becomes more pronounced; then further increase in HV very little affects the further gain suppression (hole’s velocity is reaching an “limit”)

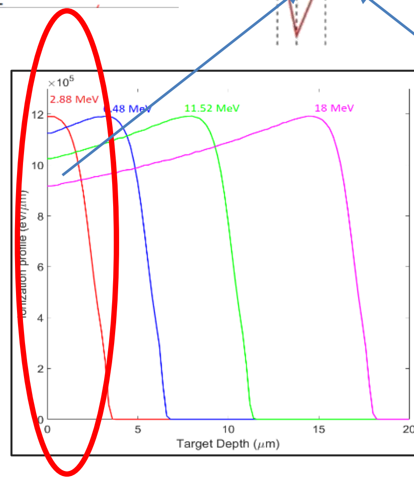
Results: Some discussion

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

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

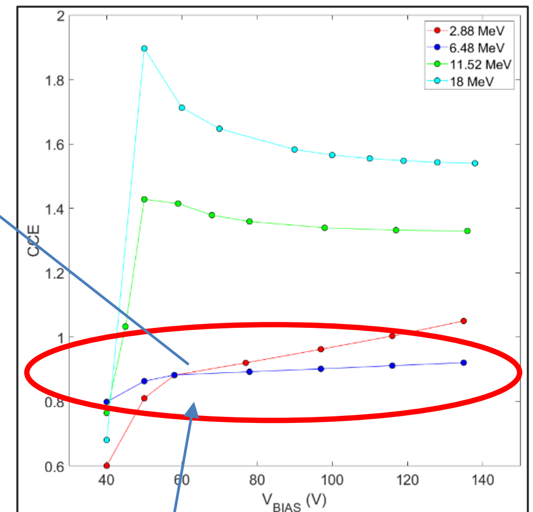
• Probing Ion Beams (**PIBs**): **18 MeV C^{5+} ,11.52 MeV C^{4+},6.48 MeV C^{3+}** and **2.88 MeV C^{2+}**



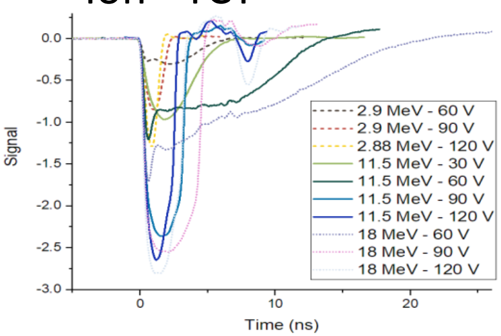


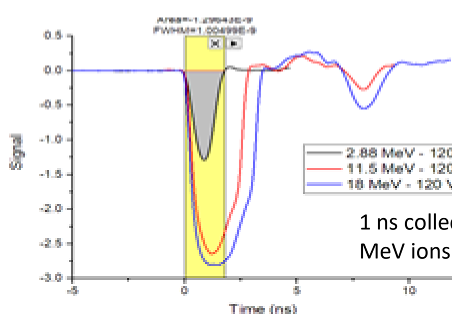
➢ Steeper and more pronounce "gain" peak for more penetrating Carbon

➢ **Influence of diffusion on the charge carrier density!**



Ion - TCT





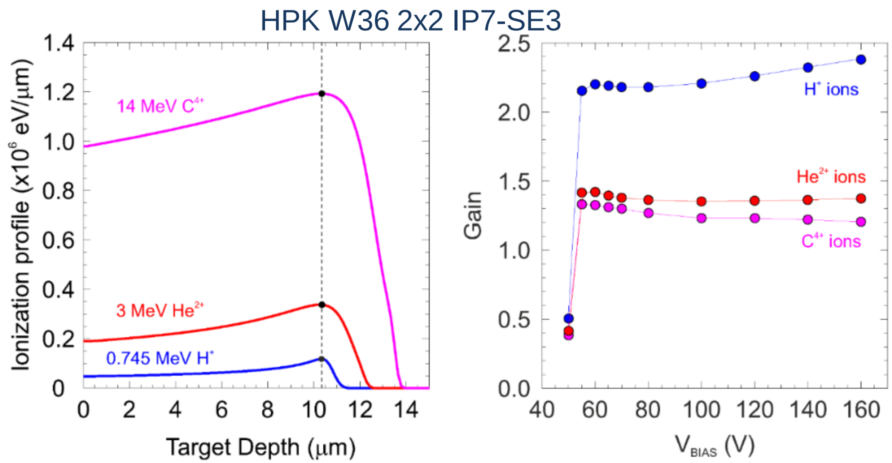
1 ns collection time for 2.88 MeV ions!

➢ 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

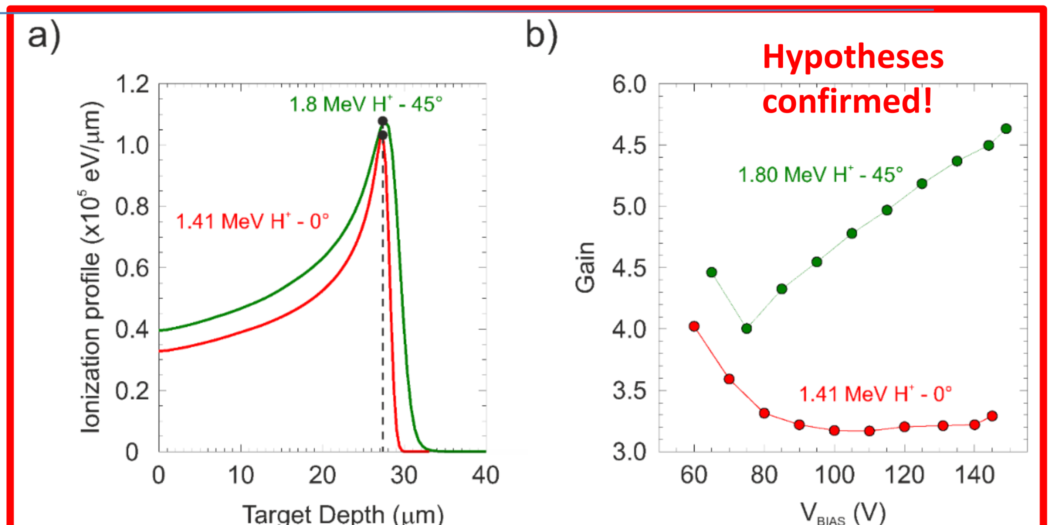
Hypotheses:

Widening the charge cloud entering the gain layer reduces the electric field screening
- ➢ **gain increase**

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)

Verification:

This has been achieved for 1.41 MeV protons (normal incidence) and 1.8 MeV protons (45º incidence angle),



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 diffusion 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 (at low bias), the volume of the charge cloud arriving at the gain layer is much larger than it is at 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.
- **Experiments with tiled detector or inclined tracks: reducing charge density reduces charge screening effect, and consequently gain increases**
    - **Observation important for**
        - **INFLUENCE OF THE TILT PARAMETER DURING SEE (including SEB) CHARACTERIZATION WITH HEAVY ION BEAMS**
        - **Using cluster shape to improve reconstruction of hit position estimates**

- 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, published in Frontiers in Physics, section Radiation Detectors and Imaging.*

NEW EXPERIMENT IN PREPARATION/PLANNING

Future experiment at thee Cyclotron in Prague with help of Filip Krizek

Motivation: LGAD response to 30 MeV; flux 1e9 p cm-2 s-1 with a beam of 2 cm spot

- The flux 1e9 p cm-2 s-1 with a beam of 2 cm spot would require too much time to do the irradiations with purpose of damaging the sensor to see its behaviour. For that we aim at ~1e14-1e15 cm-2 which means unrealistically large irradiation times.
- What would be of interest with 30 MeV p is simply: the measurement of the signal and related effects.
- Protons of 30 MeV are not minimum ionizing particles and effects of charge screening in LGADs would be nice to measure in particular for the angled tracks as well. That will give a unique opportunity to compare the measurements to our present understanding of the device operation. An interesting thing would be to test the operation of sensor at very high rates of particles of 1e7-1e8 cm-2 s-1 which are the rates seen at Large hadron collider.
- From the application point such studies would be welcome as 30 MeV are close to the protons energies encountered in proton-CT for example and energies for tumour irradiations using p beams.

- Exp is expected to run in Sep/Oct

Additional info about Cyclotron U-120M

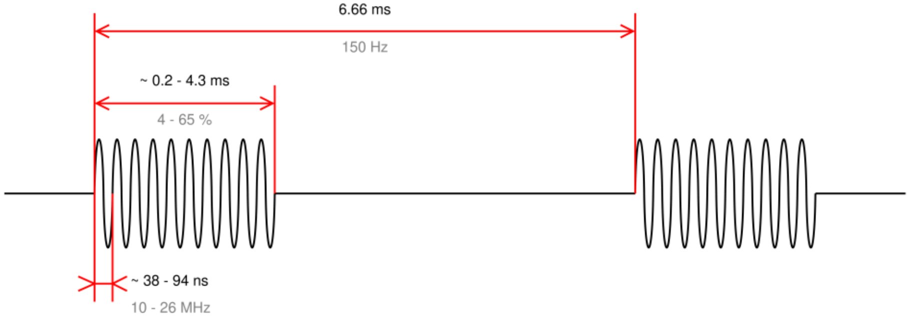
Protons ~ 30 MeV

Flux measured with ionization chamber TN30010 PTW
linear response upto 10^9 protons cm^{-2} s^{-1}

Beam profile 2D symmetric gaussian
$\sigma_{vertical} = \sigma_{horizontal}$ 11 mm or 20 mm

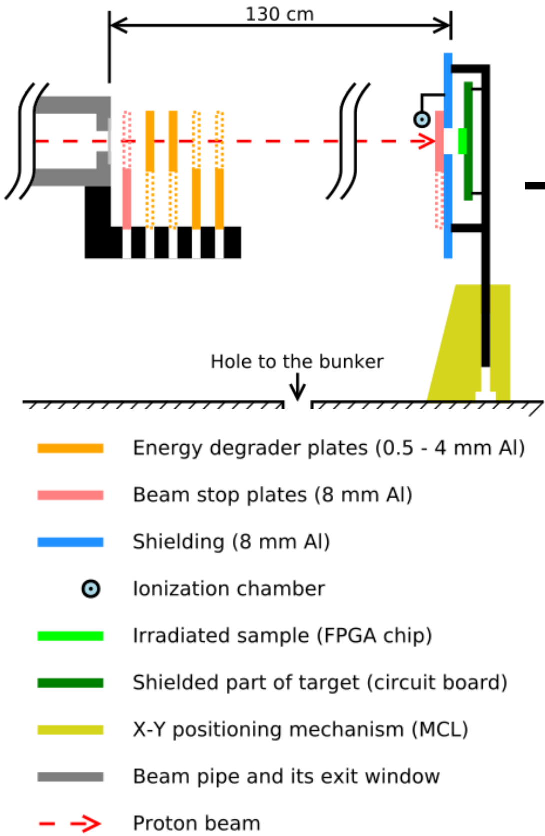
Beamline equipped with energy degrader unit
allows insertion of aluminum plates to beam
- 8 mm Al beam stop plate
- 0.5 mm Al makes beam wider

Time structure of the beam:
Frequency 25 MHz
shaped with 150 Hz macropulse
typical duty cycle 5 - 10%

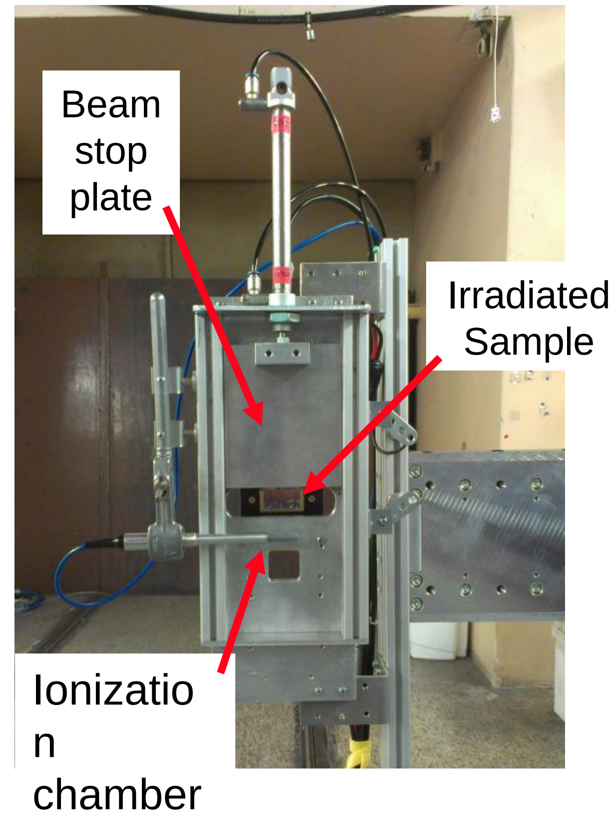


Slide prepared by Filip Krizek

Setup for irradiaiton



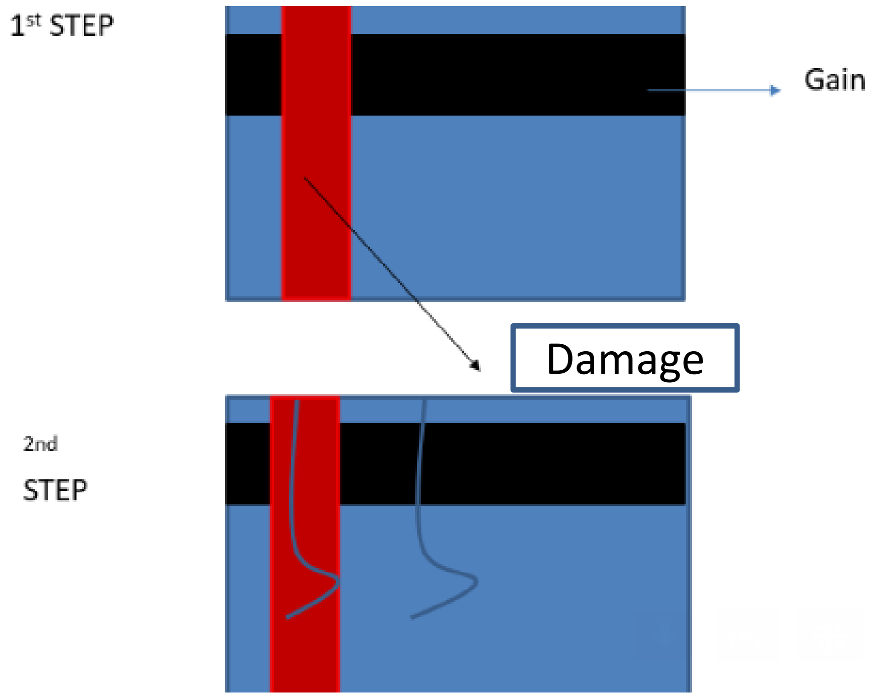
Movable XY stage



Possible Experiment with Ions at RB

<u>Study of non—homogenously damaged LGAD</u>

1) To damage one(x,y) slice but along the full depth (50 microns)
2) Study of the gain in damaged/not damaged area
3) It is important not to damage LGAD too much so we can study **transition region between damaged and not damaged region.**
4) The most important is to study the **region where effect of damage is changing quickly**



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