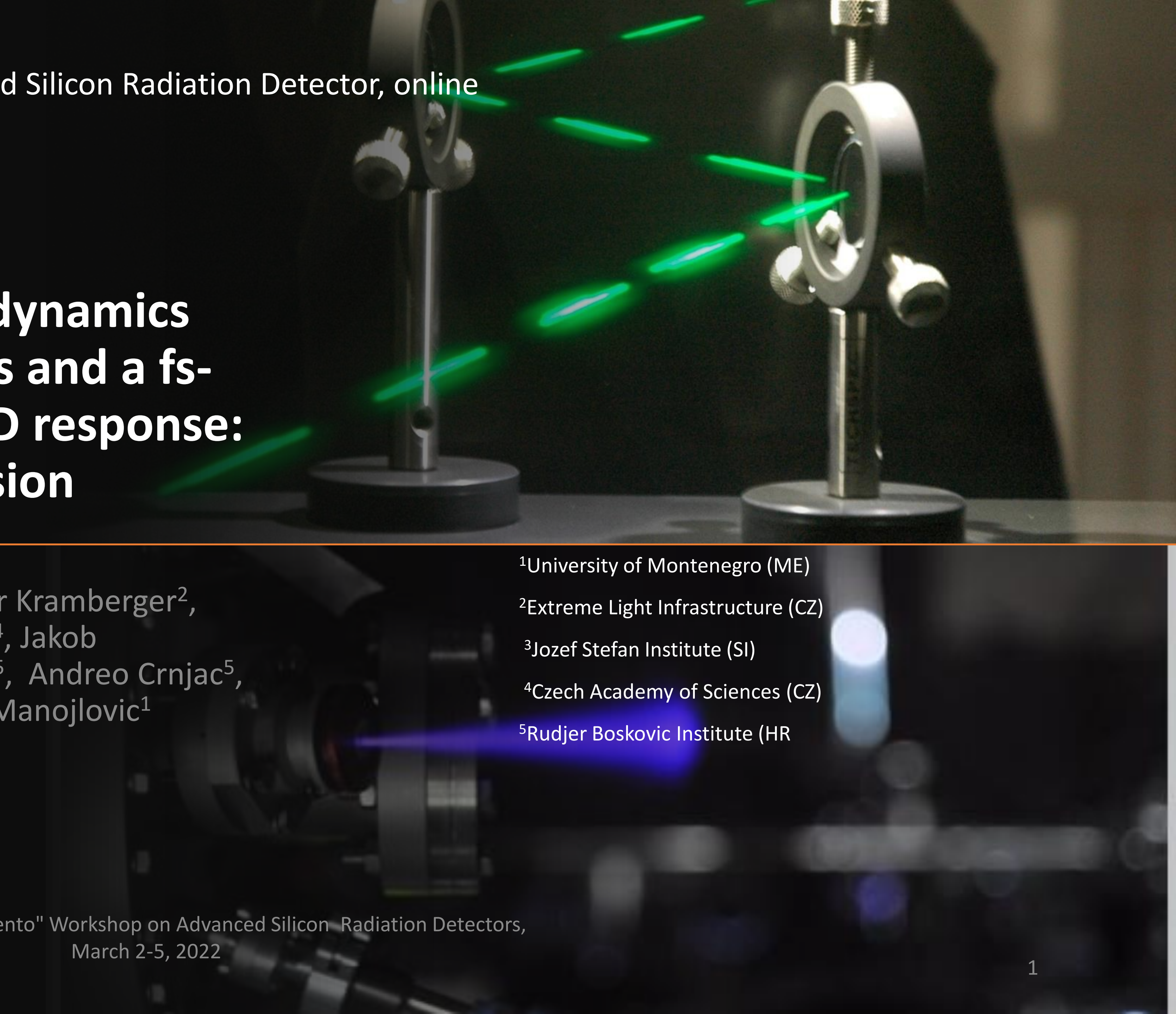
17th “Trento” Workshop on Advanced Silicon Radiation Detector, online
March 2-5, 2022, Freiburg



High-injection carrier dynamics generated by MeV ions and a fs-laser, limiting the LGAD response: SEB and Gain Suppression

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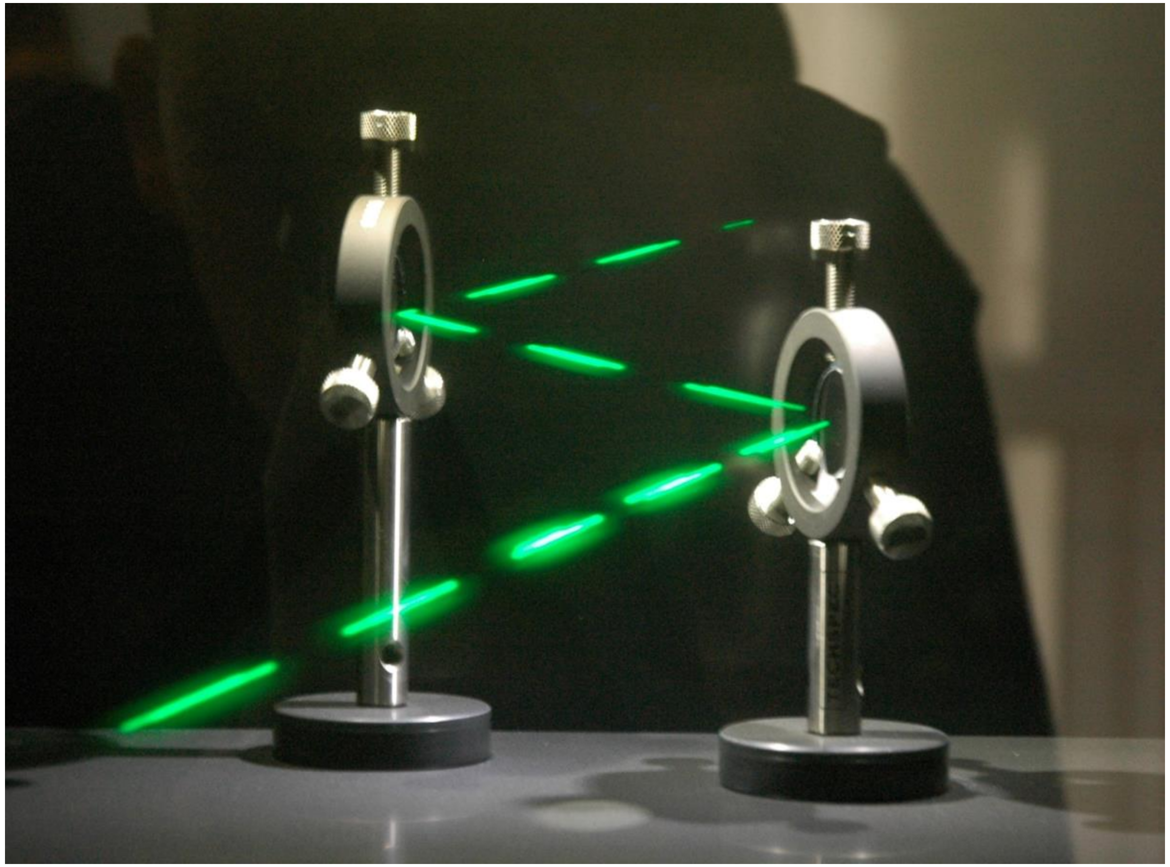
[2]Extreme Light Infrastructure (CZ)
[3]Jozef Stefan Institute (SI)
[4]Czech Academy of Sciences (CZ)
[5]Rudjer Boskovic Institute (HR



Outline

- ☐ Motivation : LGAD limits
- ☐ SEB
  - ☐ Fs-laser (ELI Beamlines)
- ☐ Gain Suppression
  - MeV Ion Beams (Rudjer Boskovic Institute)
- ☐ Conclusions

Note:

- ☐ **SEB study: based on irradiated samples**
- ☐ **Gain Suppression: non-irradiated samples**

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 electric 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

G. Kramberger, AS Program on High Energy Physics (HEP , 13-19 Jan 2022

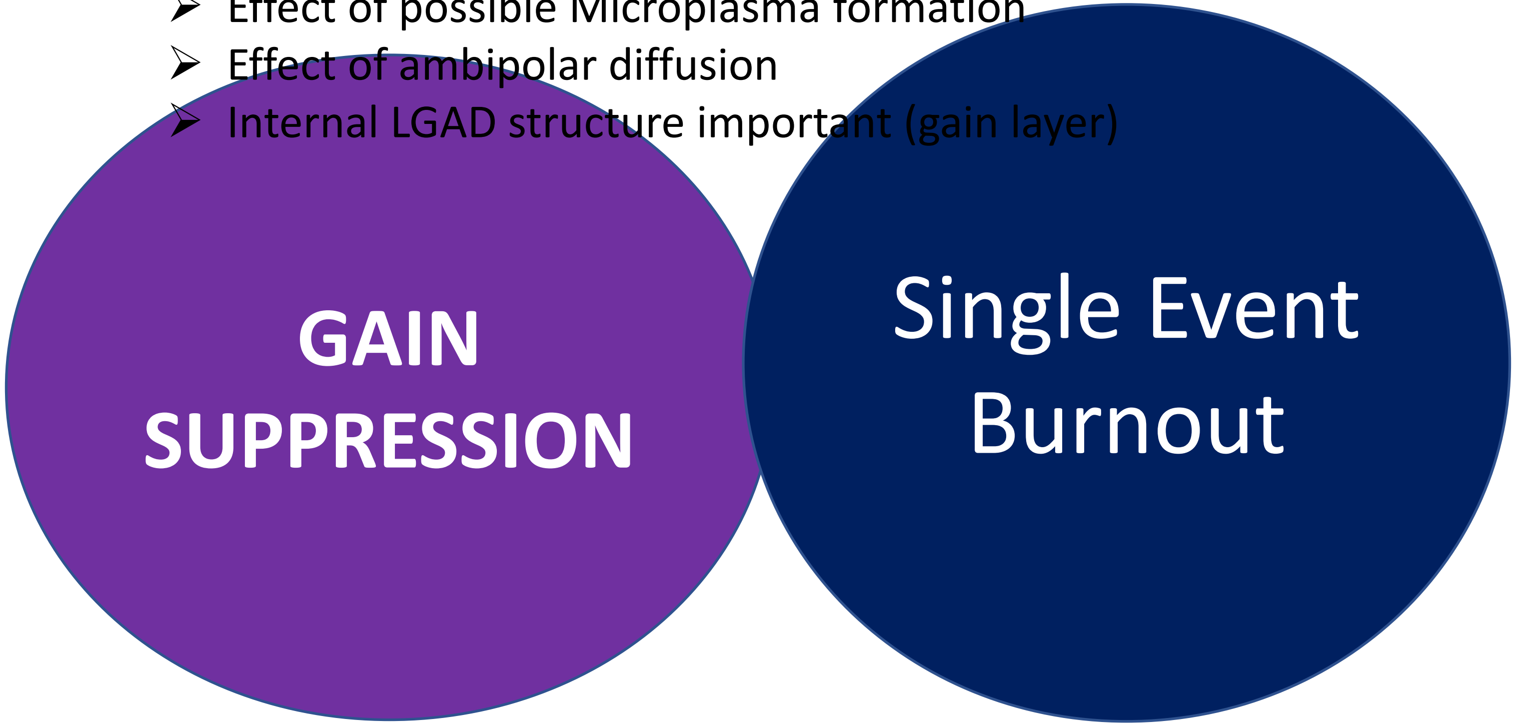
Single Event Burnout (SEB) & Gain Suppression What made them so different

Low MeV

- ➢ **High Injected charge**
  - ➢ Large charge density
  - ➢ Charge space screening effect
  - ➢ External electric field reduced
  - ➢ Effect of possible Microplasma formation
  - ➢ Effect of ambipolar diffusion
  - ➢ Internal LGAD structure important (gain layer)

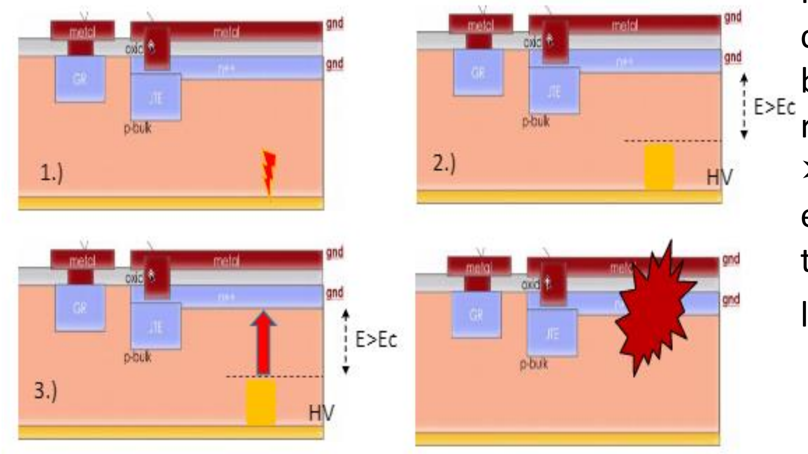
High MeV

- ➢ **High injected/deposited energy (>20 MeV)**
  - ➢ Rare, high ionization event “Highly Ionizing Particle”
  - ➢ Highly localized conductive path by excess charge
  - ➢ Large current in narrow path→ “SEB”
  - ➢ Thermal runaway
  - ➢ Estimation: >20 MeV deposit needed to induce SEB



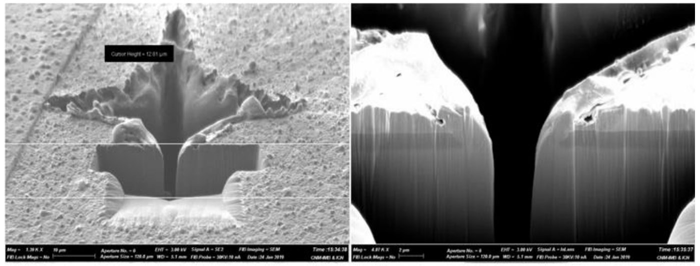
Radiation Hardness of LGADs: SEB

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

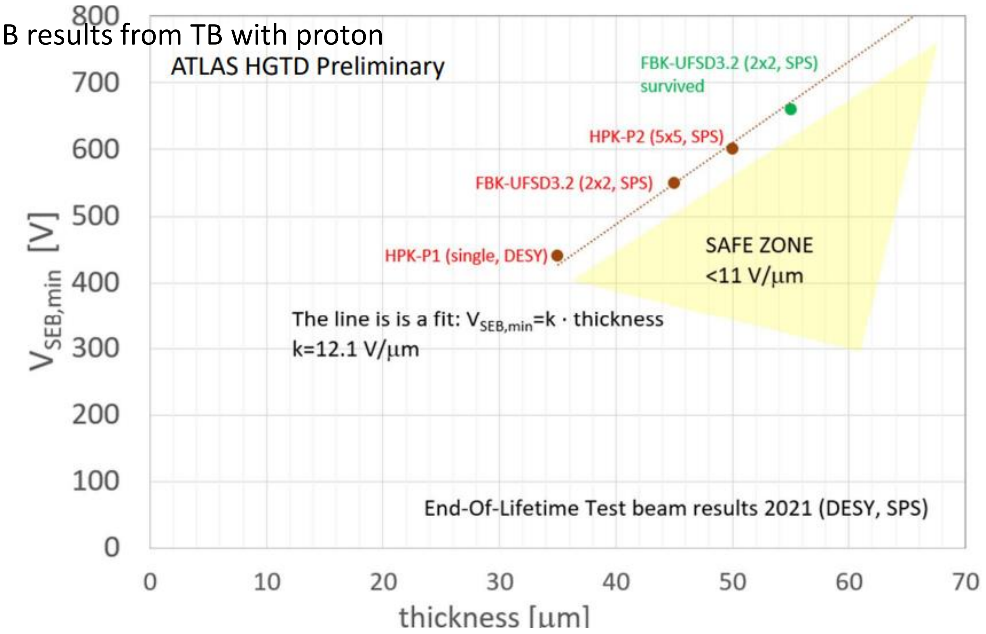
➢The problem recently discovered is so called SEB, where a highly energetic particle in the test beam leads to the permanent damage of the device – lots of efforts went to understanding the effect and safe limits of operation.



10478
W4S1017

LGAD fatality feature observed in proton beam tests at the Fermilab (courtesy of CNM, ATLAS TB sensor) [ref: S. Hidalgo, M. Carulla, A. Doblas, D. Flores, M. Manna, A. Merlos, G. Pellegrini, D. Quirion, LGAD for ATLAS:358 IBM-CNM activities (2019).]

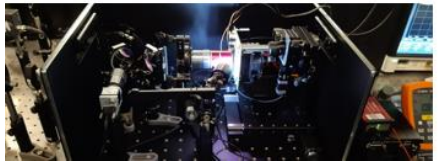
SEB results from TB with proton



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

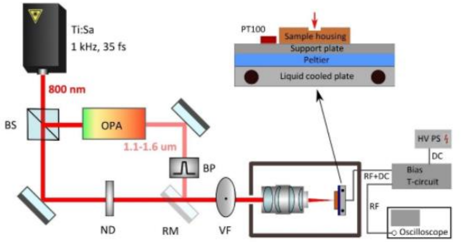
SEB in Femtosecond Laser studies at ELI Beamline

Alternatively, as a result of the collaborative effort of a few institutions within the RD50 Collaboration and the Department of Structural Dynamics from the laser facility ELI Beamlines, a 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.



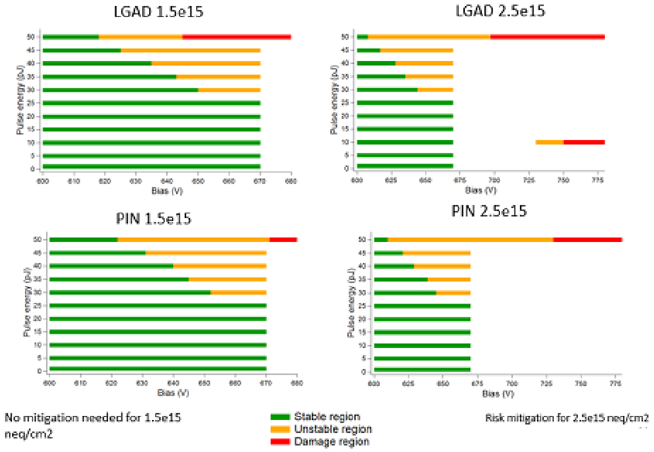
G.Lastovicka-Medin et al, 16th 17th "Trento" Workshop, Feb 2021
G.Lastovicka-.Medin et al., 39th RD50 Workshop, Seville, Jun, 2021
G.L.astovicka-Medin et al., 38th RD50 Workshop, CERN (online) Nov, 2021

*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.*



Schematic view of the setup for TCT-SPA and TCT-TPA measurements at ELI Beamlines (BS – beamsplitter OPA – optical parametric amplifier, BP – bandpass filter, ND – neutral density filter, RM – removable mirror, VF – variable filter).

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

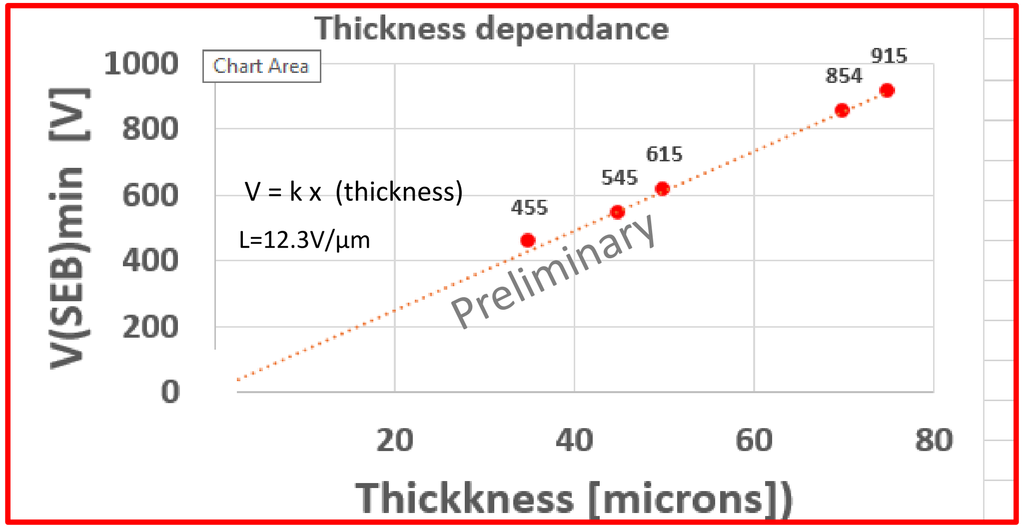


No mitigation needed for 1.5e15 neq/cm2

🟩 Stable region
🟧 Unstable region
🟥 Damage region

Risk mitigation for 2.5e15 neq/cm2

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



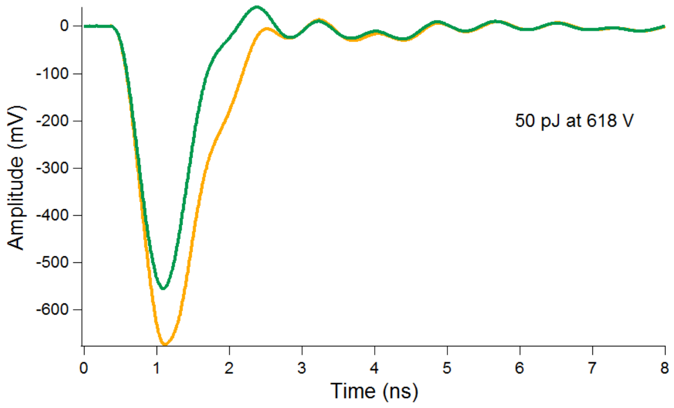
Thank you to Salvador Hidalgo, Giulio Pellegrini & Jairo Villegas for supplying us with CNM sensors and supporting the study.

Sable, unstable & irreversible phases: examples of waveforms

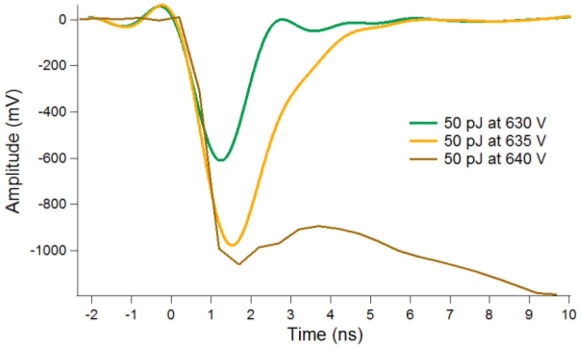
- HPK-3.2 samples

LGAD 1.5e15n_{eq}/cm^2

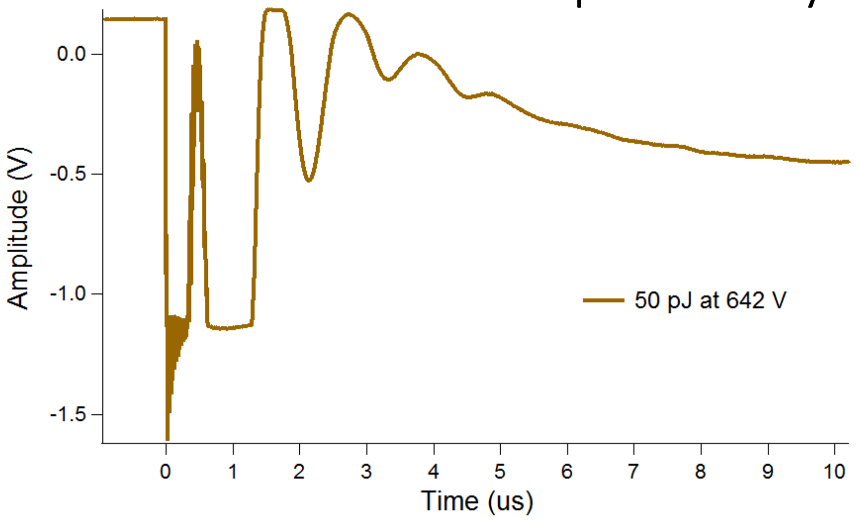
Stable regime

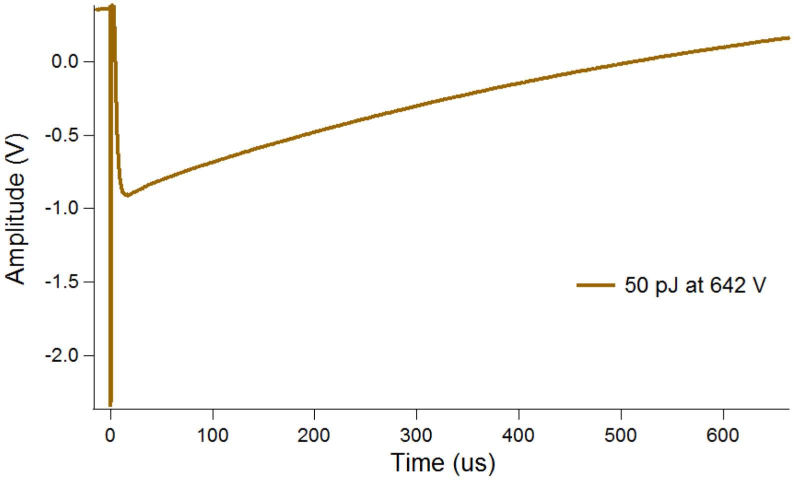


Unstable regime



Just before LGAD is permanently broken

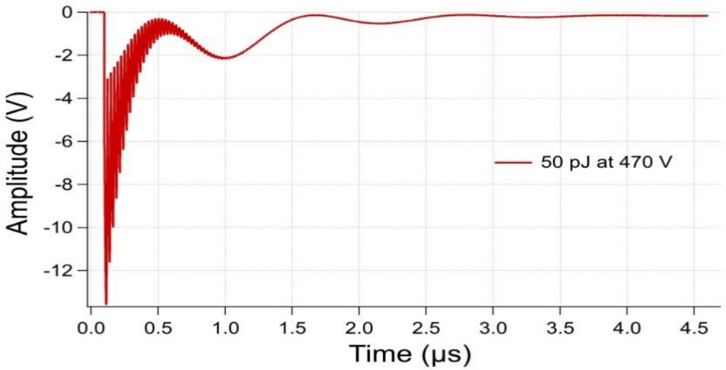




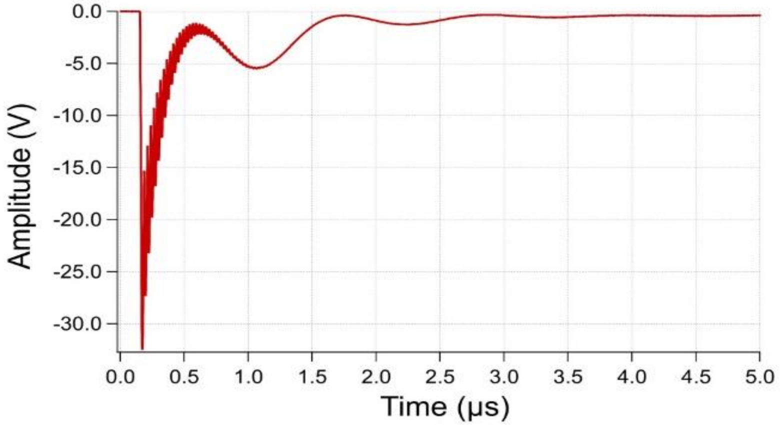
Waveform just before LGAD was irreversibly broken

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

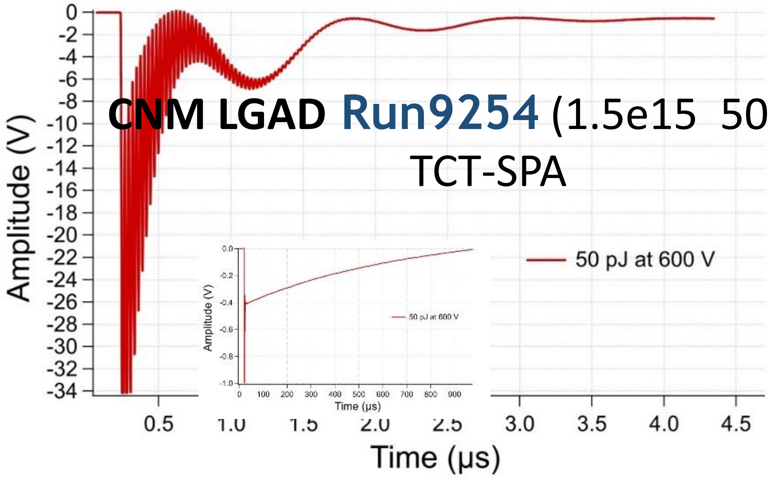
HPK-P1 LGAD (2.5e15 35 µm)
TCT-SPA



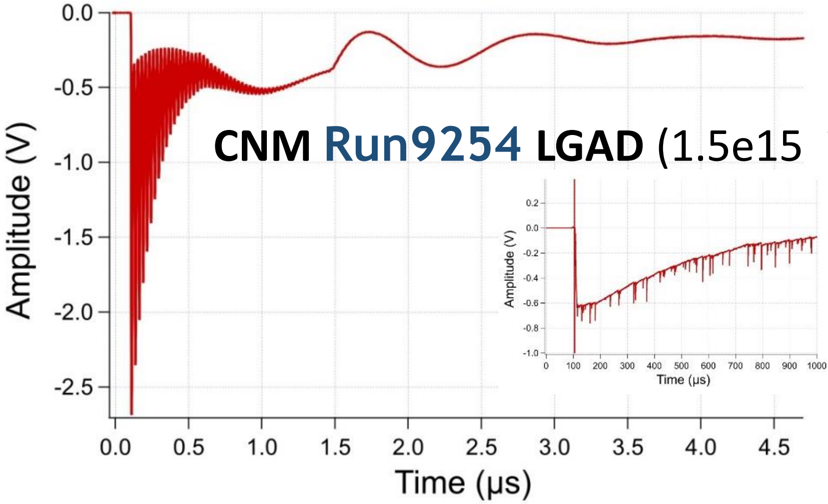
HPK-P1 LGAD (2.5e15 35 µm)
TCT-TPA



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



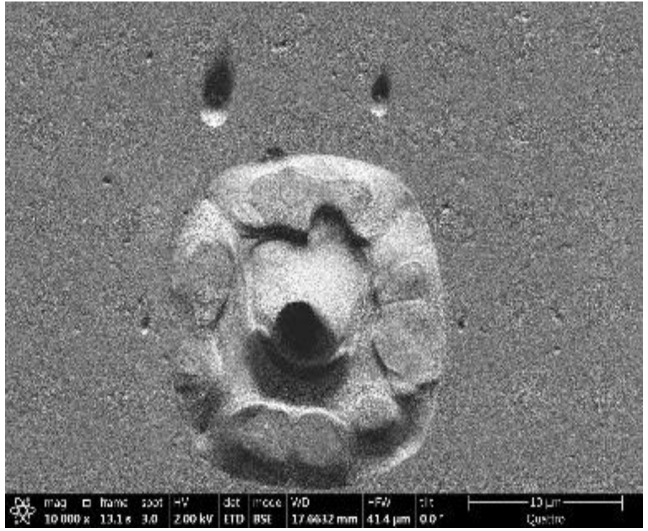
CNM Run9254 LGAD (1.5e15 70



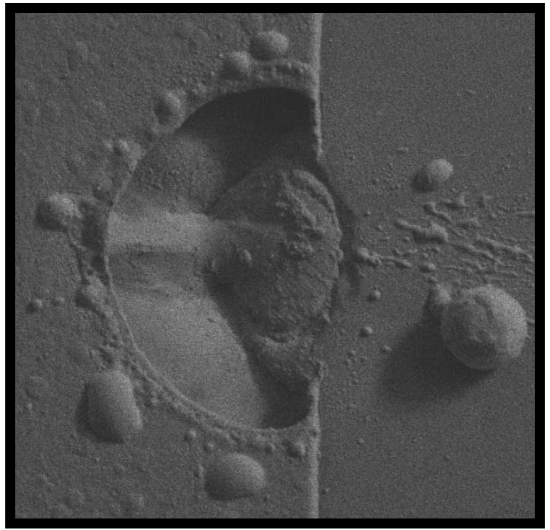
Permanent fatalities: Damage signature in tests with fs-laser

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 a **characteristic feature for CNM sensors)**

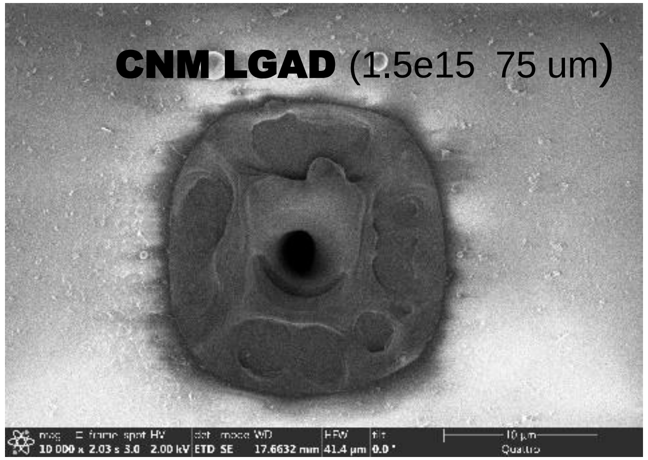


HPK-3.2, PIN, 2.5e15 n_{eq}/cm^2,
50 pJ, 730 V

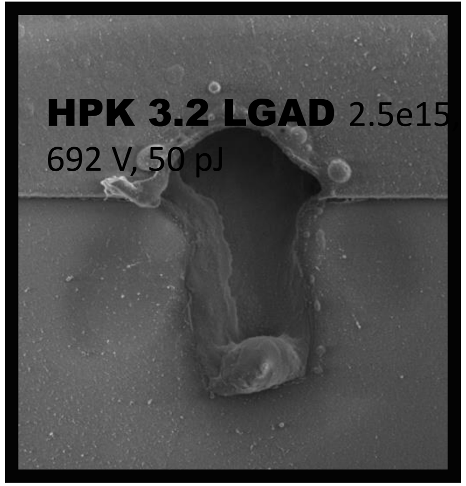


Edge effect: Fatality signature at the border between the metal and semiconductor **HPK features**)

CNM LGAD (1.5e15 70 um)



CNM LGAD (1.5e15 75 um)



HPK 3.2 LGAD 2.5e15
692 V, 50 pJ

Damaged sensors have been inspected by Martin Precek from ELI under a scanning electron microscope (Thermo Sci-310 entific / FEI Quattro S ESEM).

Main findings from laser study at ELI

Different tests have been produced and answers given:

- different fluences LGAD –does irradiation matter? – only in the sense that it facilitates high bias
- irradiated PINs – does intrinsic gain 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)

Electric field thresholds: →

Average electric field in the device is the critical driver:

- safe region - < 11.4 V/µm
- danger region - ~11.4-12.3 V/µm
- SEB region - >12.3 V/µm

This is in line with CMS and ATLAS results

R. Heller; https://indico.cern.ch/event/1029124/contributions/4411270/

To avoid SEB is keeping the voltage low enough vs thickness – possible thickness optimization.

- possible solutions include 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)

LGAD. Run12916. AIDA2020v2

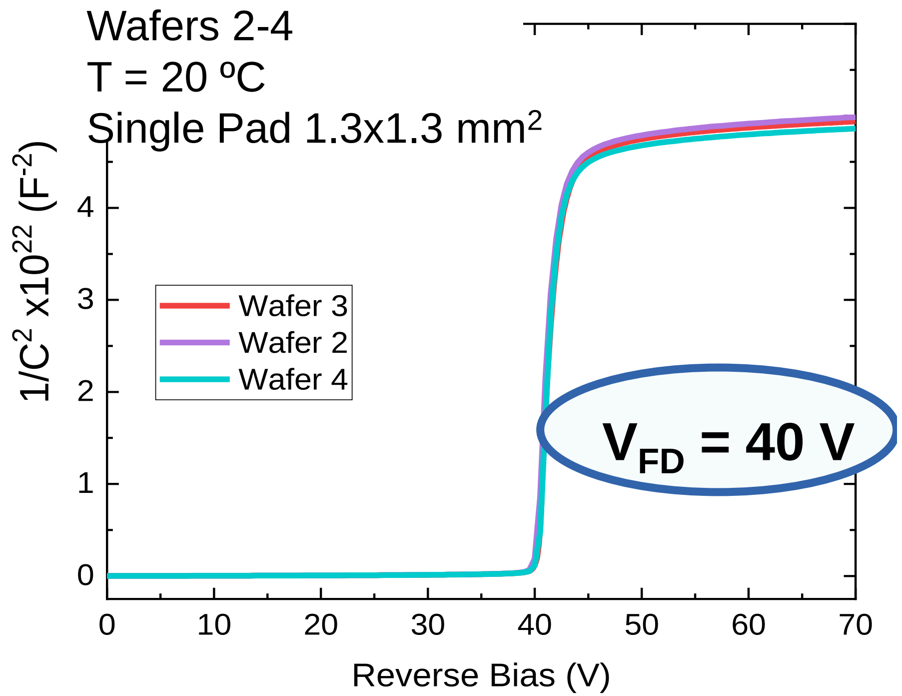
Prepared by Jairo Villegas, CNM

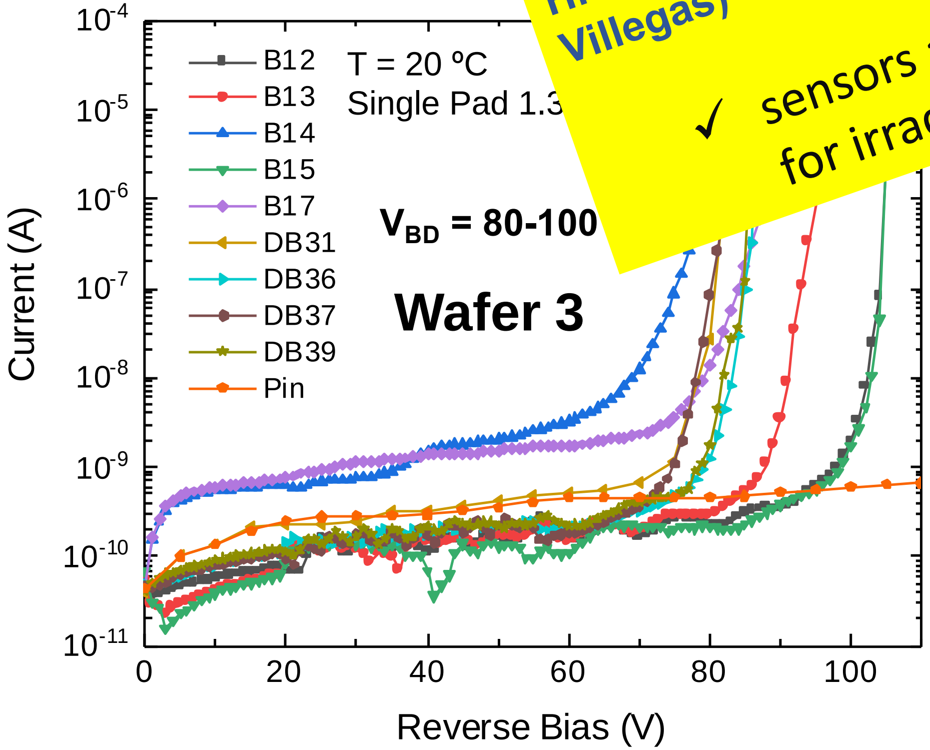
- LGADs for ATLAS & CMS Timing Layers
  - 4 inch, 50+300 µm thick Si-Si. 4 Wafers
  - N$^+$-Layer overhang Multiplication Layer until the JTE end
  - use only one implantation dose and energy value for the multiplication area (m ow energy)
  - Leakage current values are the expected (0.1-1 nA)
  - IV/CV measurements
  - Voltage breakdown and full depletion close to high dose valu
  - Gain estimation shows a value around 15

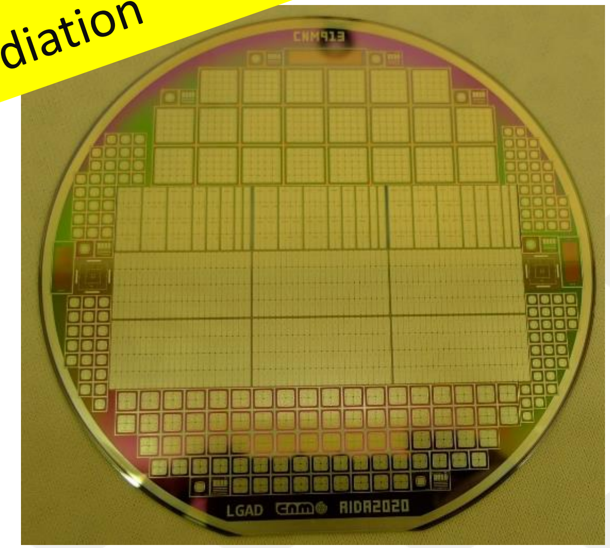
OUR future plan

(in collaboration with Salvador Hidalgo, Giulio Pellegrini & Jairo Villegas)

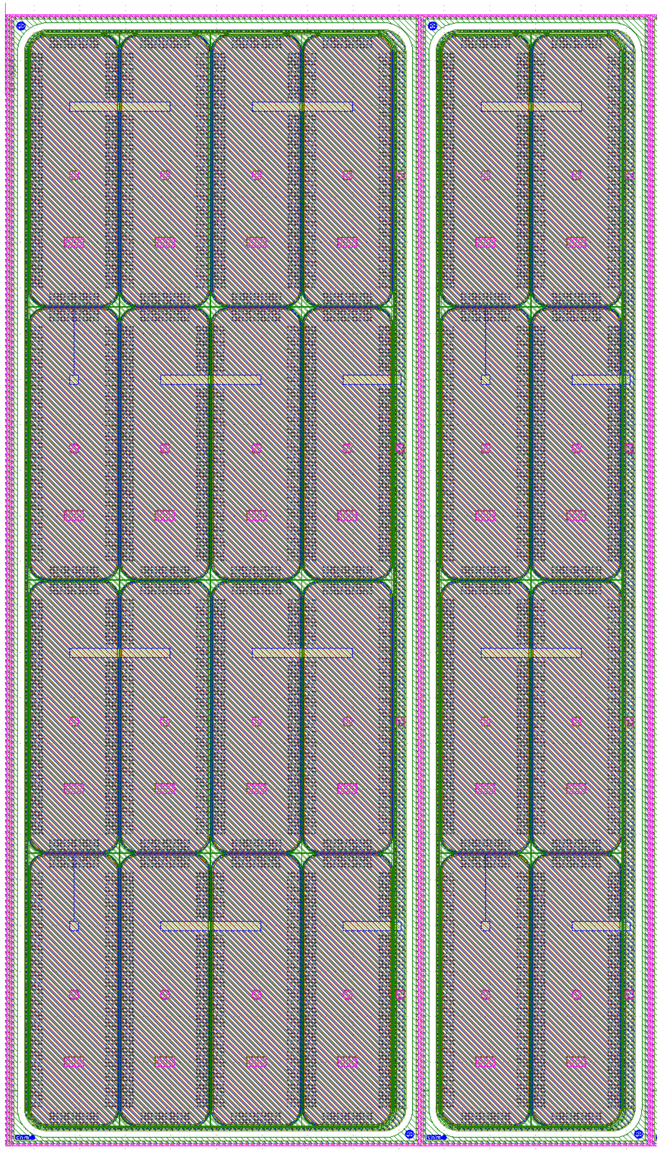
✓ sensors are sent to JSI for irradiation







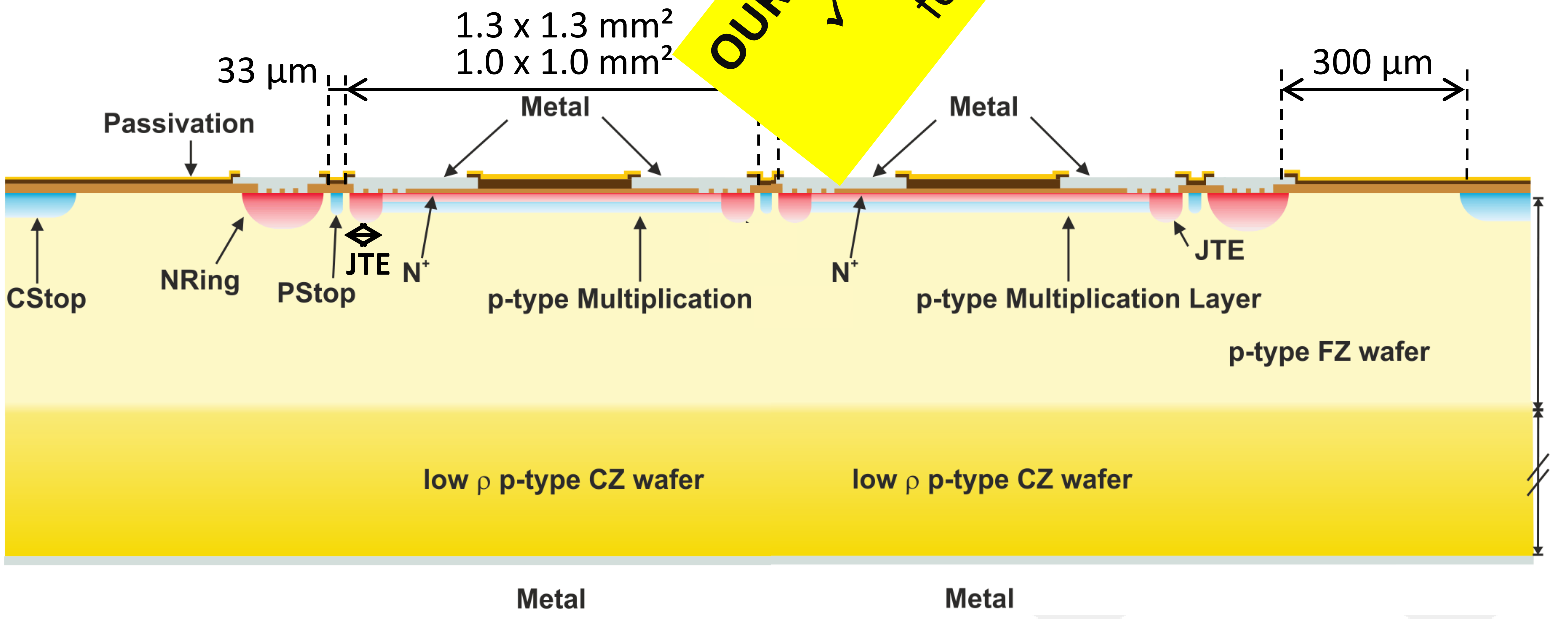
LGAD. AIDA2020v2. Device Geometry



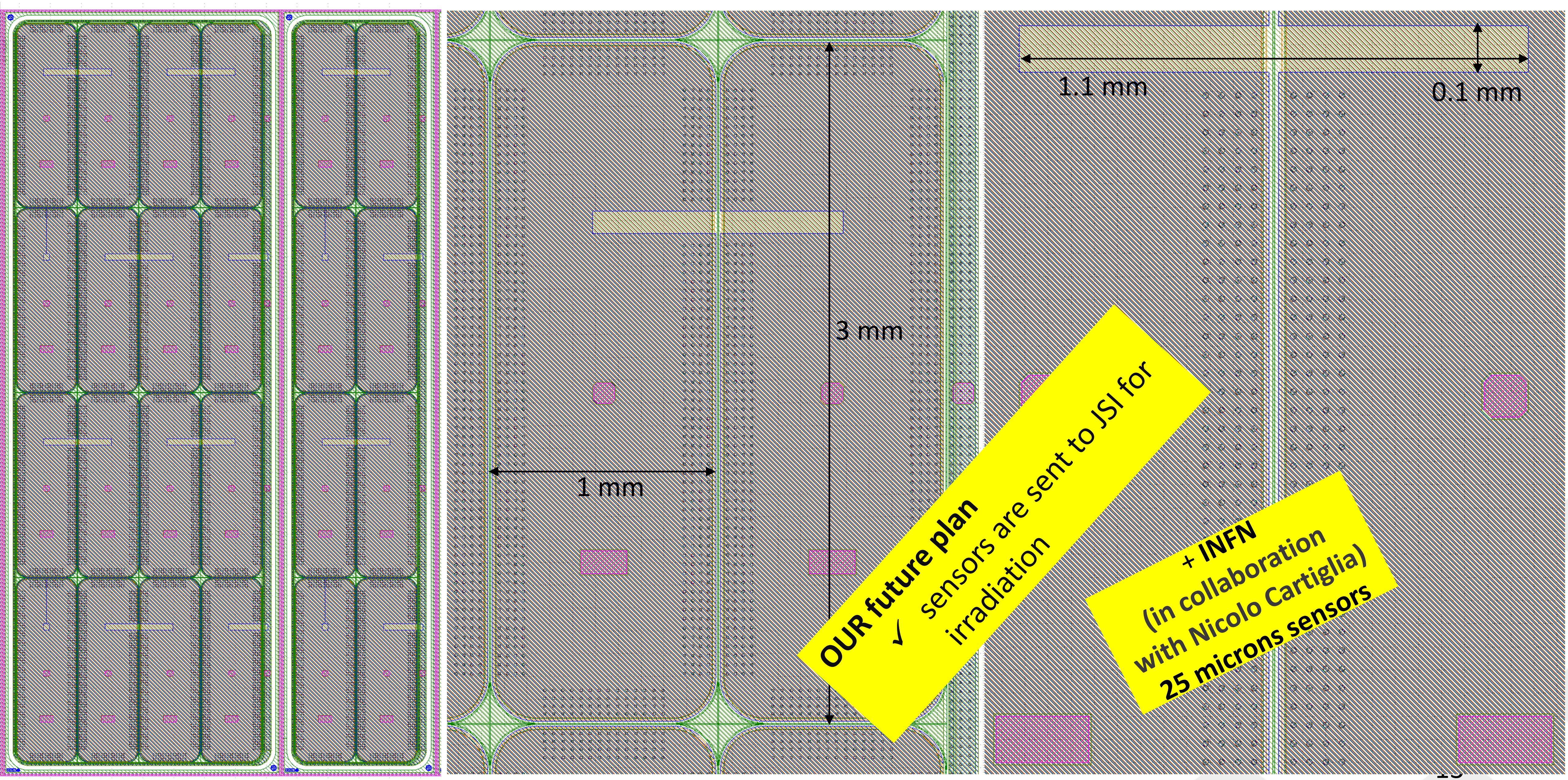
- LGADs for ATLAS & CMS Timing Layers
  - 4x4 and 4x2 Pixels
  - Active Area: 1 x 3 mm^2
  - Metal window for Laser measurements
    - Inter-pixel area
    - Periphery
  - Full Depletion Voltage: 40 V
  - Breakdown Voltage: 80-100 V
  - 50 µm thick high resistivity lay

OUR future plan

✓ sensors are sent to JSI for irradiation



LGAD. AIDA2020v2. Device Geometry

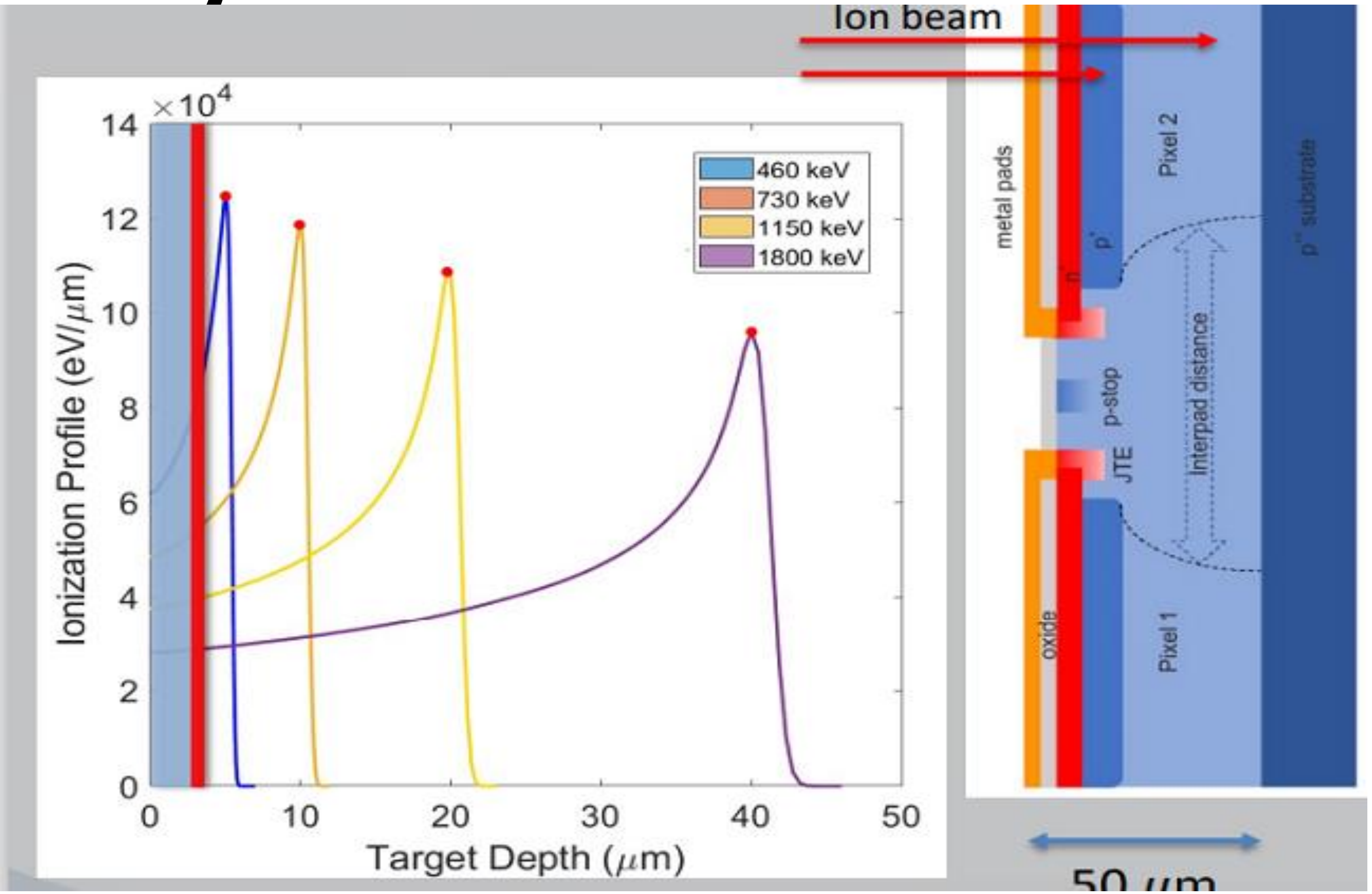


OUR future plan
- ✓ sensors are sent to JSI for irradiation

+ INFN
(in collaboration with Nicolo Cartiglia)
25 microns sensors

Gain Suppression Study

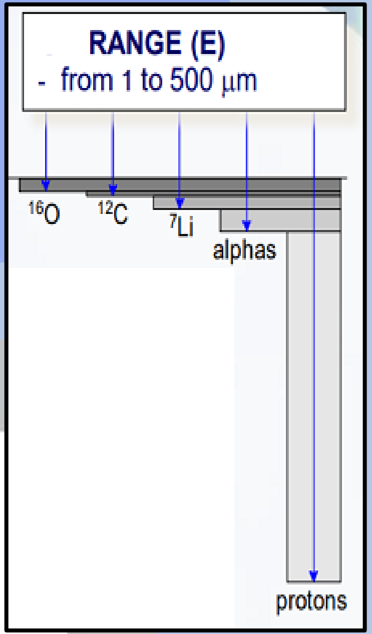
Why IBIC ?

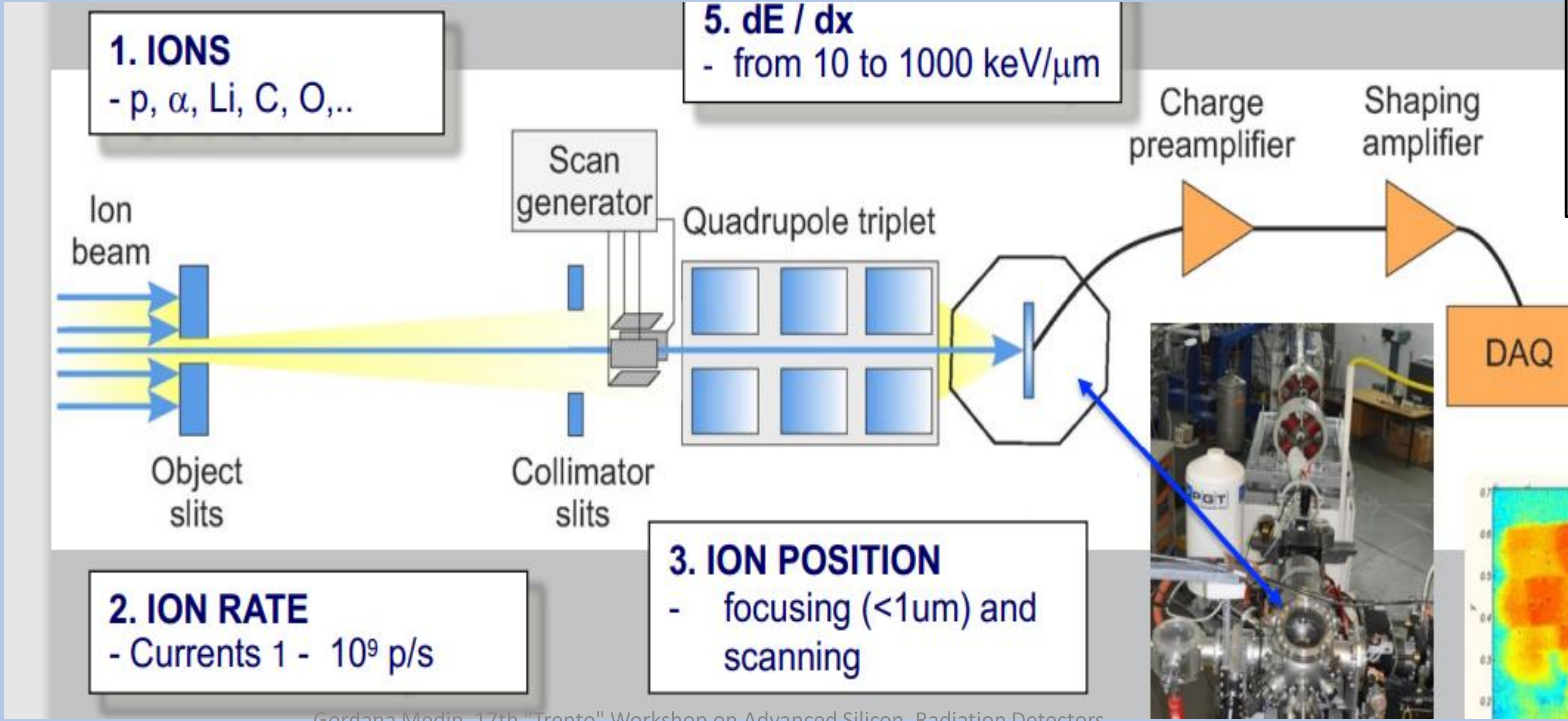


- ❑ Different ion ranges
  - ➢ IBIC probes different detector depths
- ❑ Low penetration Surface layers
- ❑ Deep penetration
  - ➢ interpad distance

Microbeam probe station at RB

4. RANGE (E)
- from 1 to 500 μm


RANGE (E)
- from 1 to 500 μm


5. dE / dx
- from 10 to 1000 keV/μm

1. IONS
- p, α, Li, C, O,..

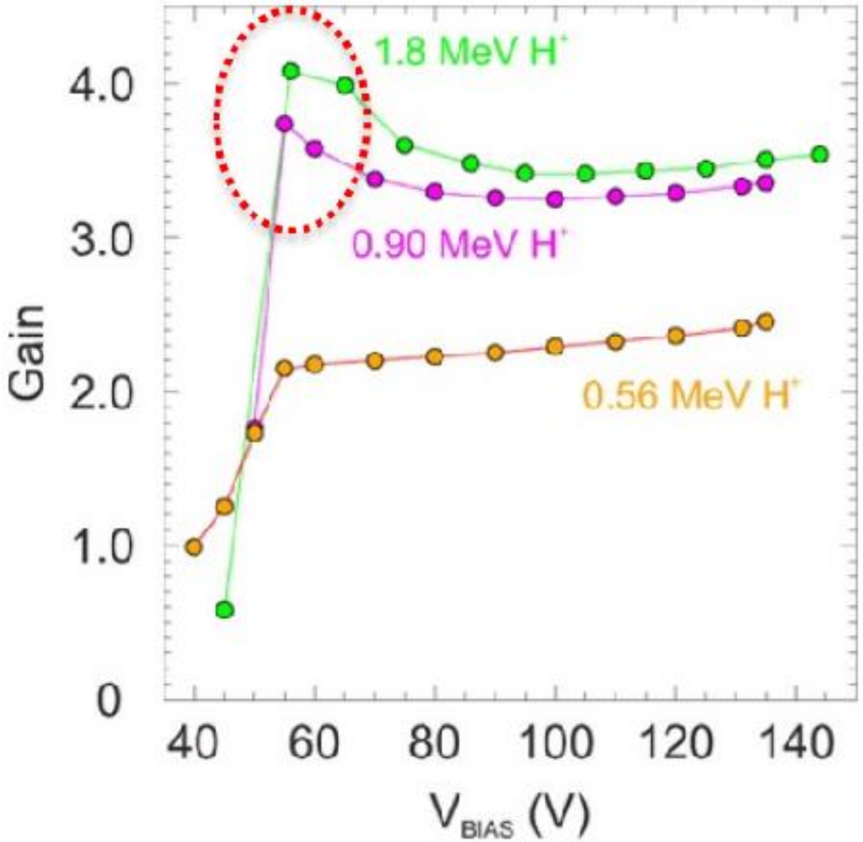
2. ION RATE
- Currents 1 - 10^9 p/s

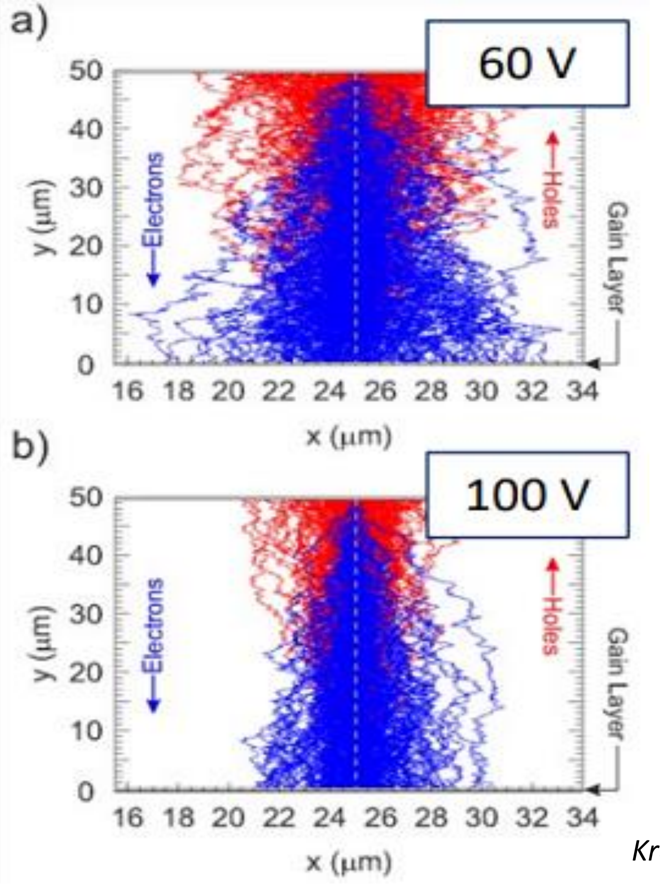
3. ION POSITION
- focusing (<1um) and scanning

Gain vs bias:

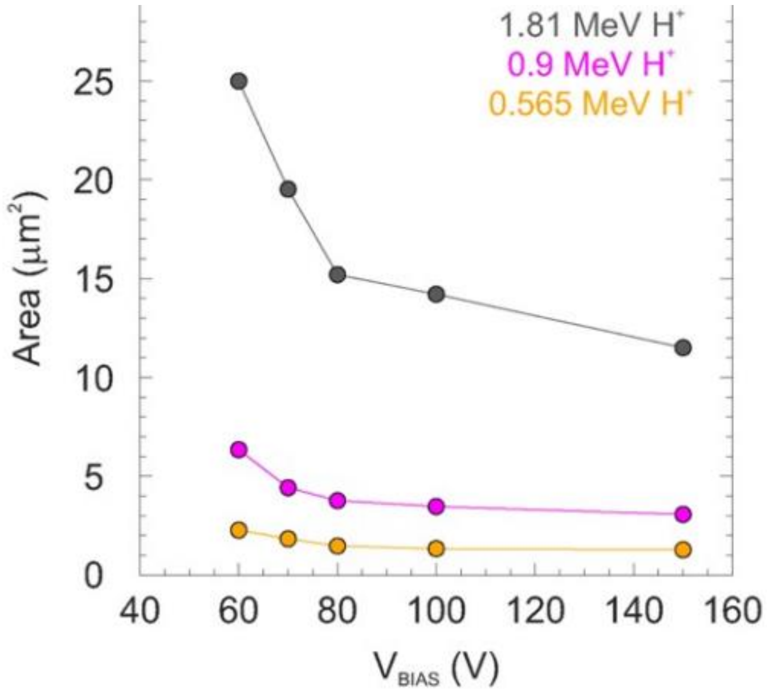
Signs of suppression & Diffusion role

proton ion





Area of emerging charge cloud arriving to the gain layer



Kramberger, G. "KDetSim—a simple way to simulate detectors." (2016).

In the conditions of low electric field & for deep probing ions is the gain higher ?

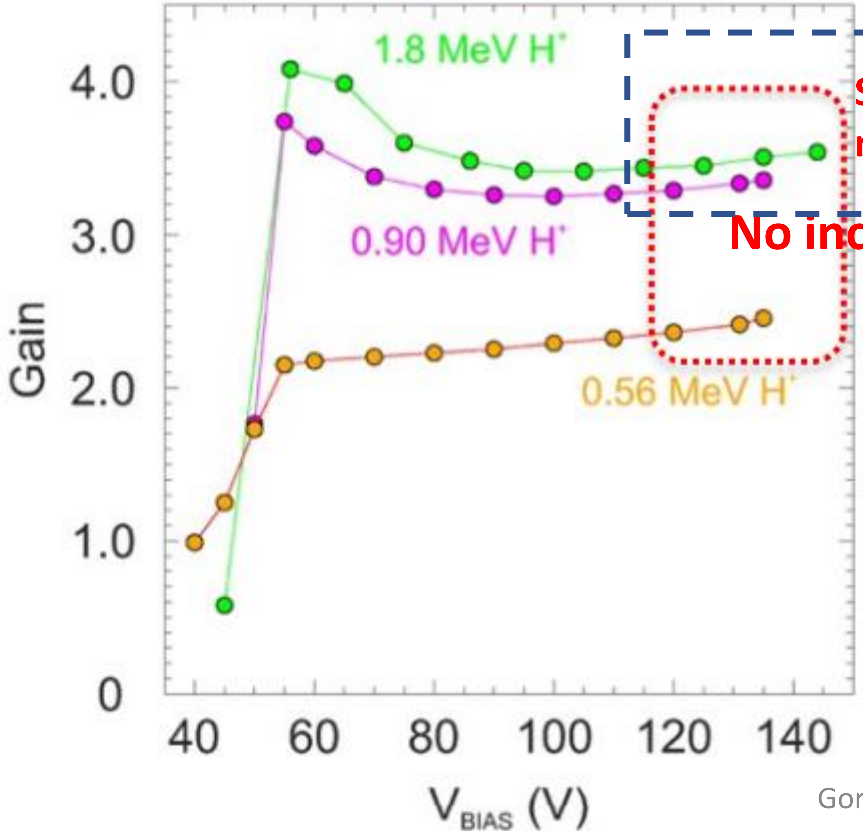
- Diffusion of charge carriers becomes important !!
- Charge cloud is extending
- Electric field screening is reduced
- Gain increases !

Gain vs bias

proton ions

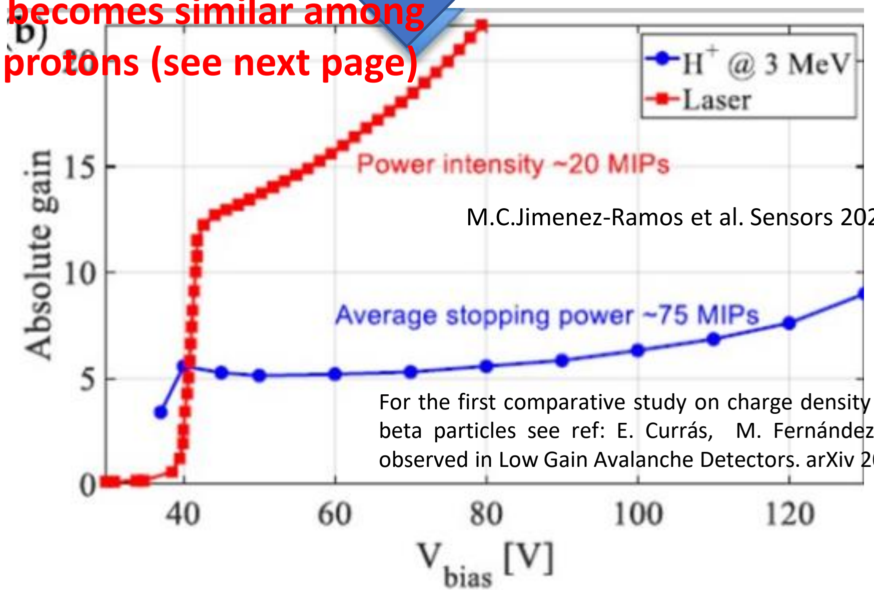
Protons (<2 MeV) have significantly larger deposition then MIPs

Ion Specie	Energy (MeV)	Range (μm)	E_{dep} (MeV)	N_{MIP}
H	0.745	10.8	0.745	51.7
He	3	12	3	208.3
C	14	13.4	14	972.2
C	2.88	3.18	2.88	200.0
C	6.48	6.27	6.48	450.0



Saturation of gain becomes similar among more penetrating protons (see next page)

No increase!



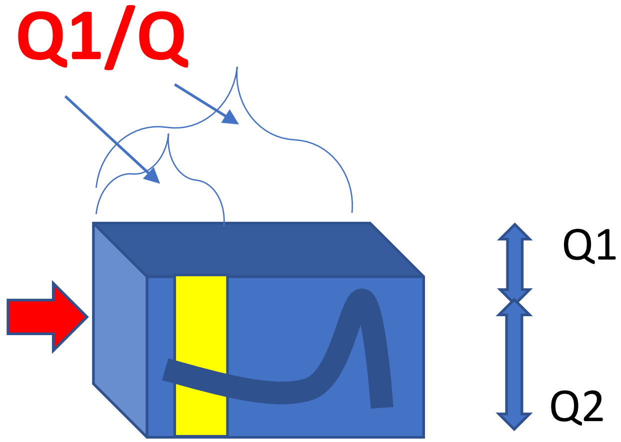
M.C.Jimenez-Ramos et al. Sensors 2022, 22(3)

For the first comparative study on charge density induced gain suppression using laser and beta particles see ref: E. Currás, M. Fernández, M. Moll, Gain suppression mechanism observed in Low Gain Avalanche Detectors. arXiv 2021, arXiv:2107.10022

For the first time alpha particle induced gain suppression was reported too:
See M. Manojlovic, G. Lastovicka-Medin, M, Jaksic, A. Crnjac ,G. Kramberger, M. Rodriguez Ramos, A comprehensive feasibility study on the utilisation of the Ion Beam Induced Charge (IBIC) Nuclear Microprobe Technique at the RBI for the LGAD's Characterization including the Interpad-Gap Measurements.38th RD50 Workshop, CERN (online)

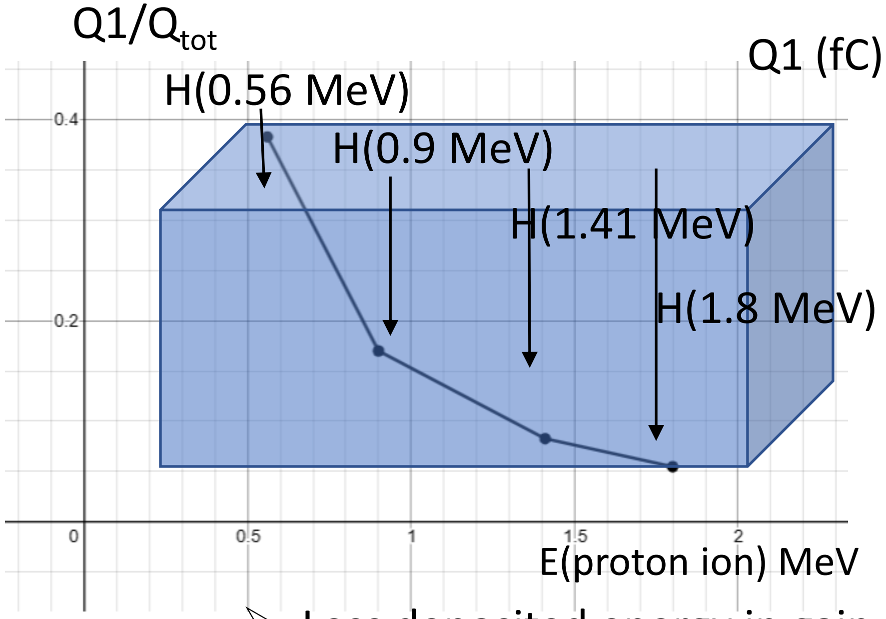
Gain vs bias: proton ions

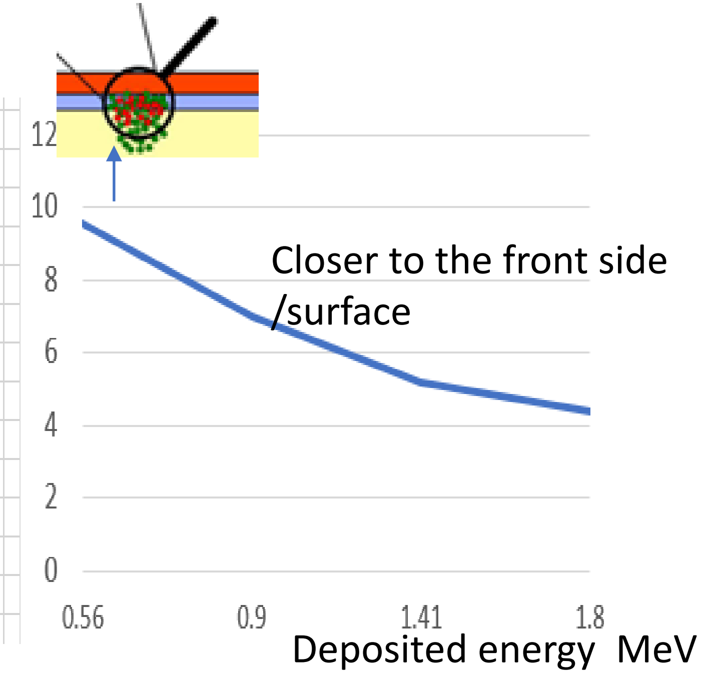
Non-uniform charge generation



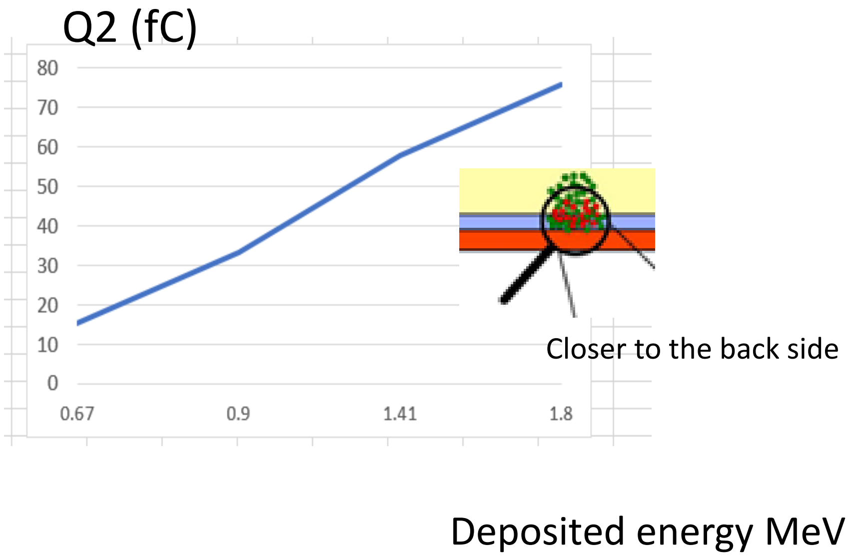
SRIM calculation

Ion	Energy (MeV)	Deposited energy (MeV)	Total charge Q (fC)	Total charge Q1 (fC)
H	1.8	1.805	80.322	4.405
H	1.41	1.414	62.922	5.207
H	0,9	0.902	40.139	6.986
H	0.56	0.561	24.965	9.567





Closer to the front side /surface

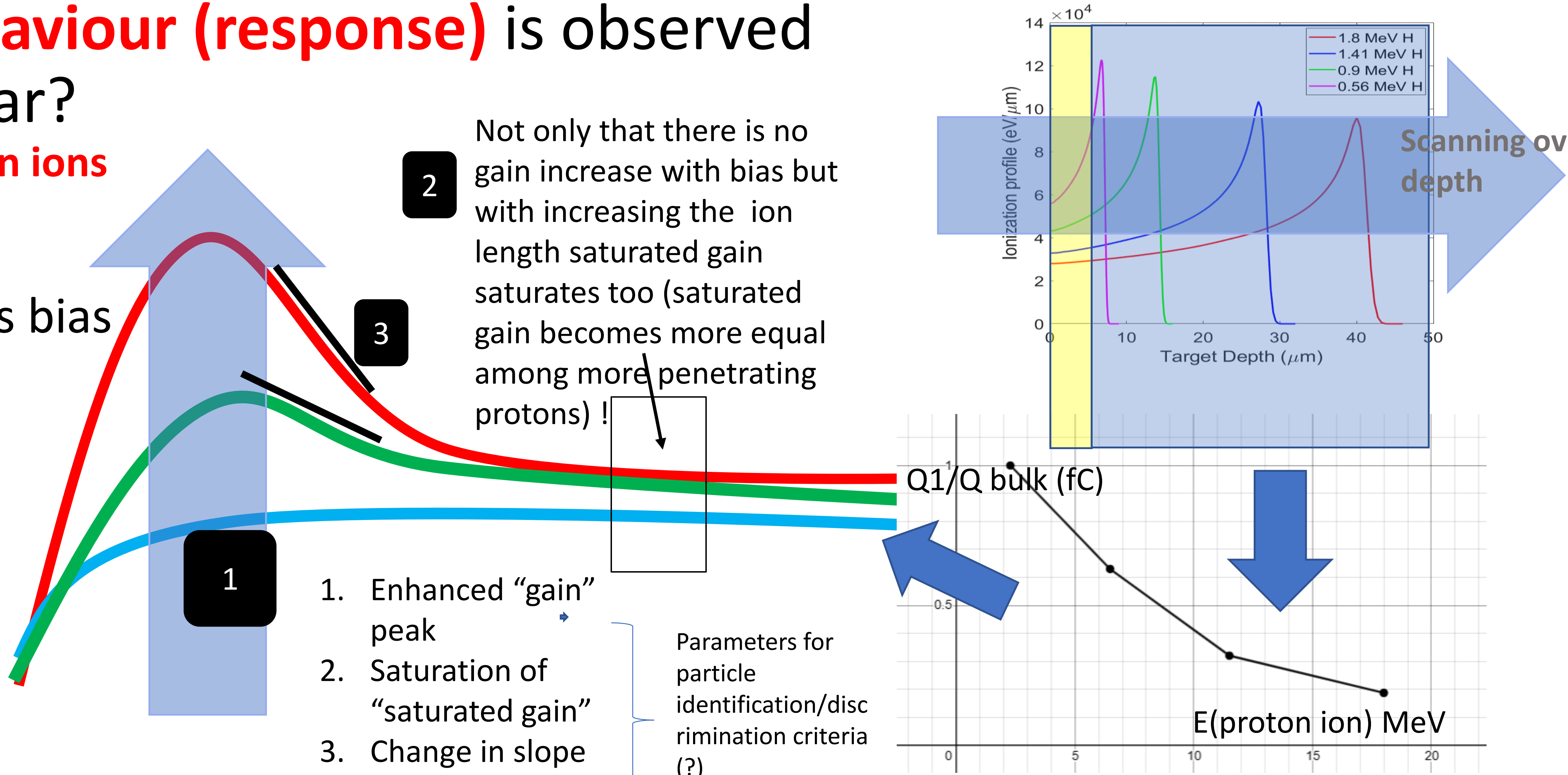


Closer to the back side

- Less deposited energy in gain layer with more penetrating particles
- Q1/Q slope becomes less steep

So, what **tendency in LGAD's behaviour (response)** is observed so far?

proton ions



Not only that there is no gain increase with bias but with increasing the ion length saturated gain saturates too (saturated gain becomes more equal among more penetrating protons) !

1. Enhanced "gain" peak
2. Saturation of "saturated gain"
3. Change in slope

Parameters for particle identification/discrimination criteria (?)

When LGAD is screened by hydrogen ions over its depth (scanning over depth deposition of Braggs peak) clear increase in "gain" peak and change in gain slope is recorded.

Gain vs Bias

Carbon ions

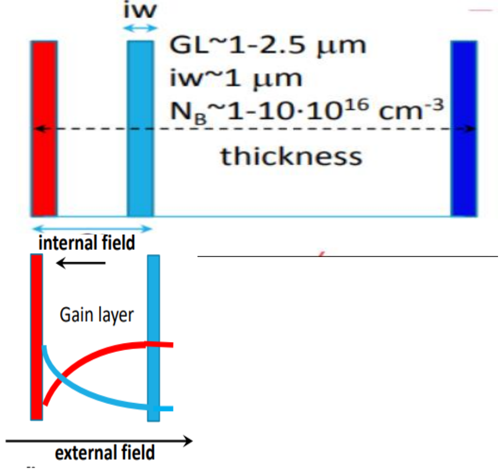
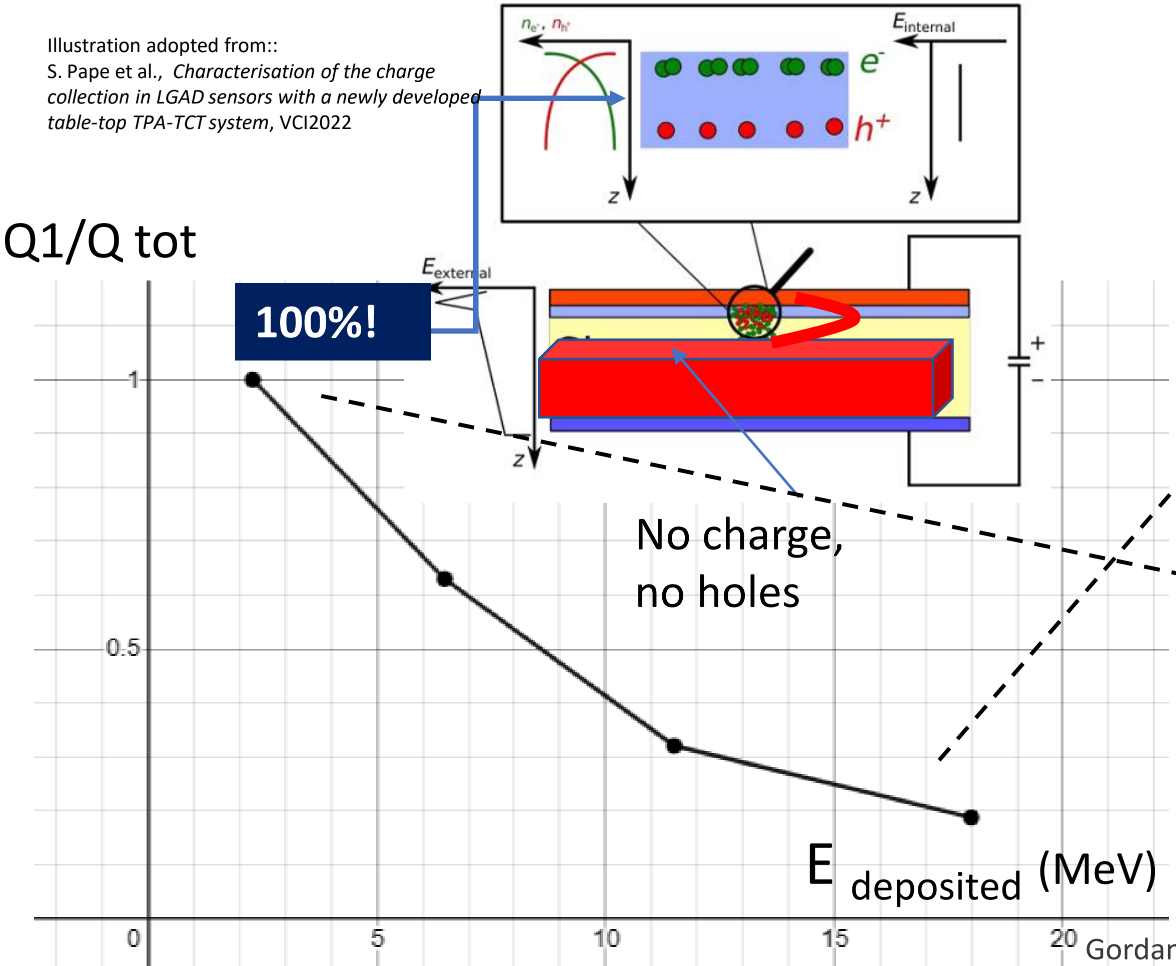


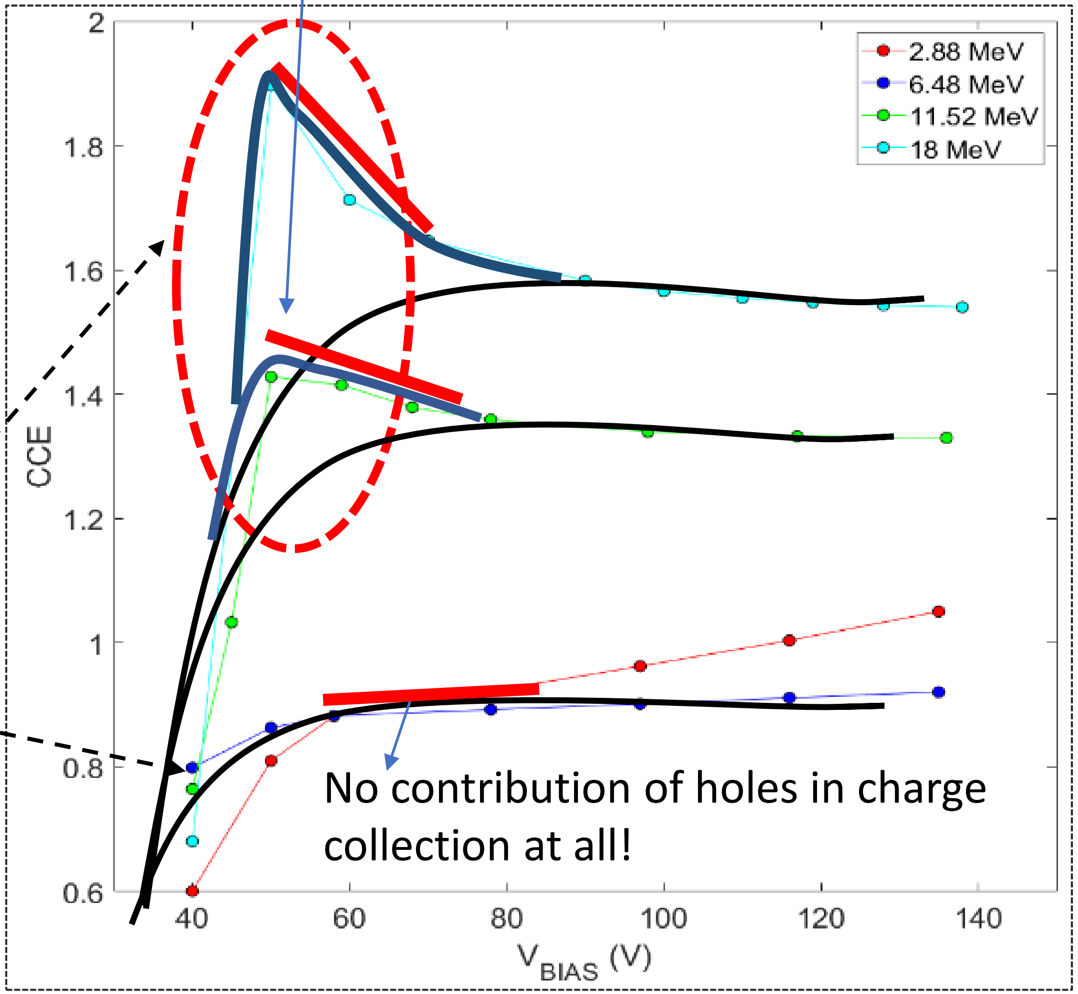
Illustration adopted from::
S. Pape et al., *Characterisation of the charge collection in LGAD sensors with a newly developed table-top TPA-TCT system*, VCI2022



100%!

No charge, no holes

For smaller penetration ranges, the diffusion contribution is less pronounced since the drift time of charge carriers is shorter.

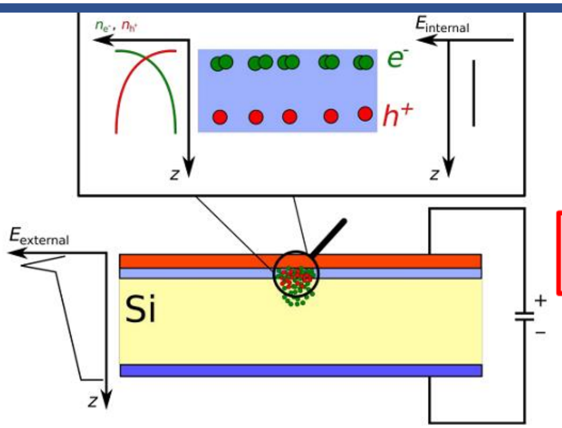


No contribution of holes in charge collection at all!

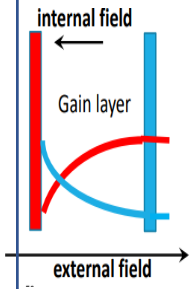
Gain suppression model

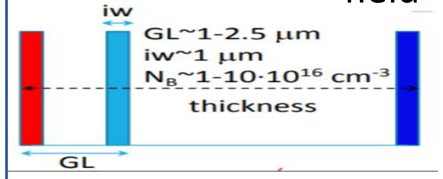
Gain Polarization

G .Kramberger, 39th RD50 Workshop



$$E_{int} = \frac{n_{e-h} G(V_{bias}) x_{gl}}{\varepsilon\varepsilon_0}$$

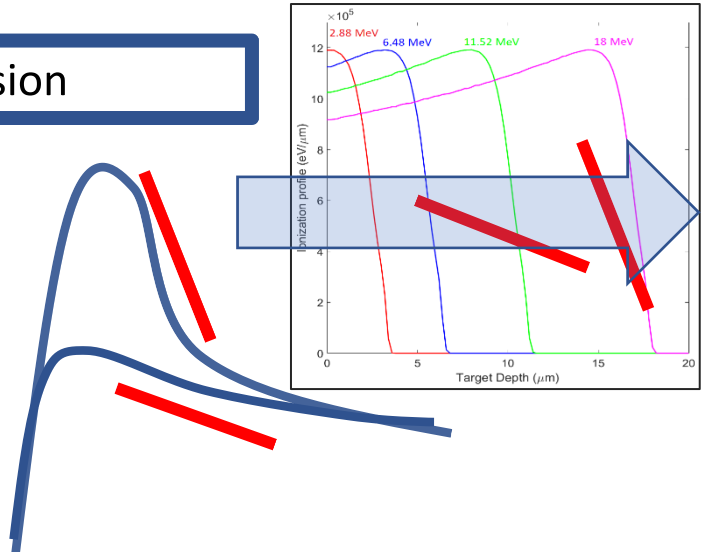




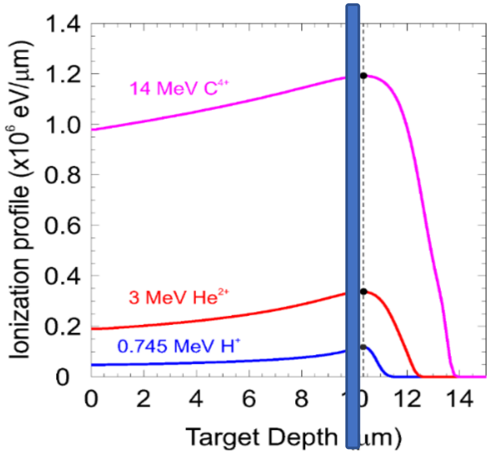
- all the electrons are concentrated at the n++ implant
- all the holes are the end of the gain layer x_{gl}
- the polarization opposes to the external field

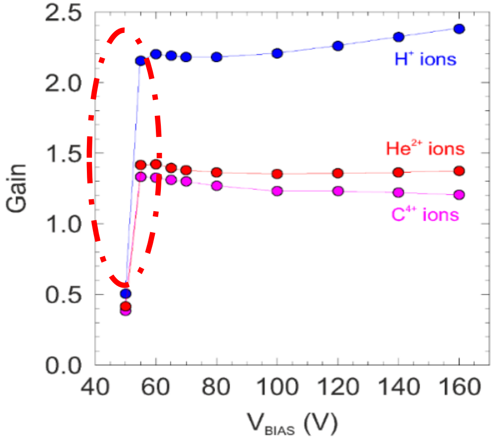
hypothesis: **multiplied carriers are present during the gain process screen the external field**

Diffusion



- Position of the Bragg peak is shifted deeper (along z-axes),
  - **the slope of Gain curve is steeper – diffusion effect**





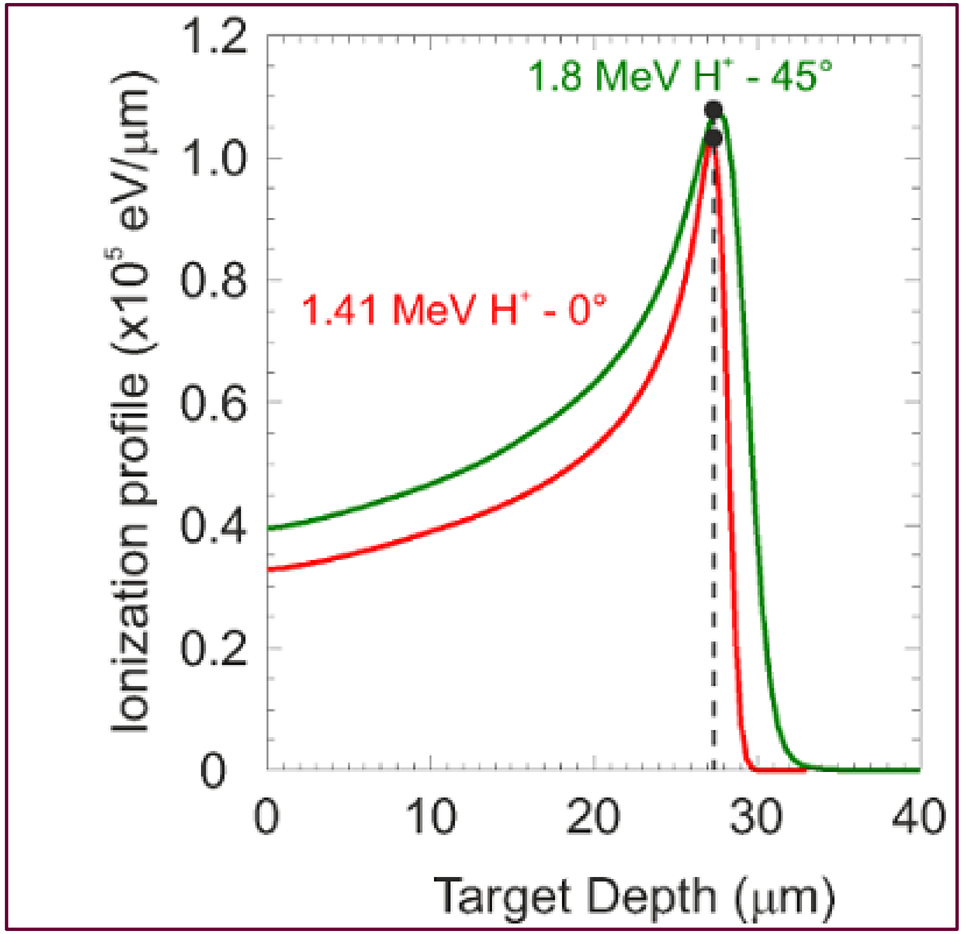
- Bragg peak at the same depth in LGAD;
- **No change in slope**

Experiment design to verify the ionization charge density-gain suppression induced hypotheses

Hypotheses: widening the charge cloud entering the gain layer (due to diffusion of the charge carriers) reduces the electric field screening

How did we do it:

- We selected a proton beam that enters
  - vertically (along the z-axis) towards the detector surface
  - under an angle of 45 degrees.
- Ions of different ranges in LGAD respond in a different way, so
  - we adjusted the energy of inclined irradiation in a way to have the same range as those done vertically.
- This has been achieved for 1.41 MeV protons (vertical irradiation) and 1.8 MeV protons (irradiation under 45º).



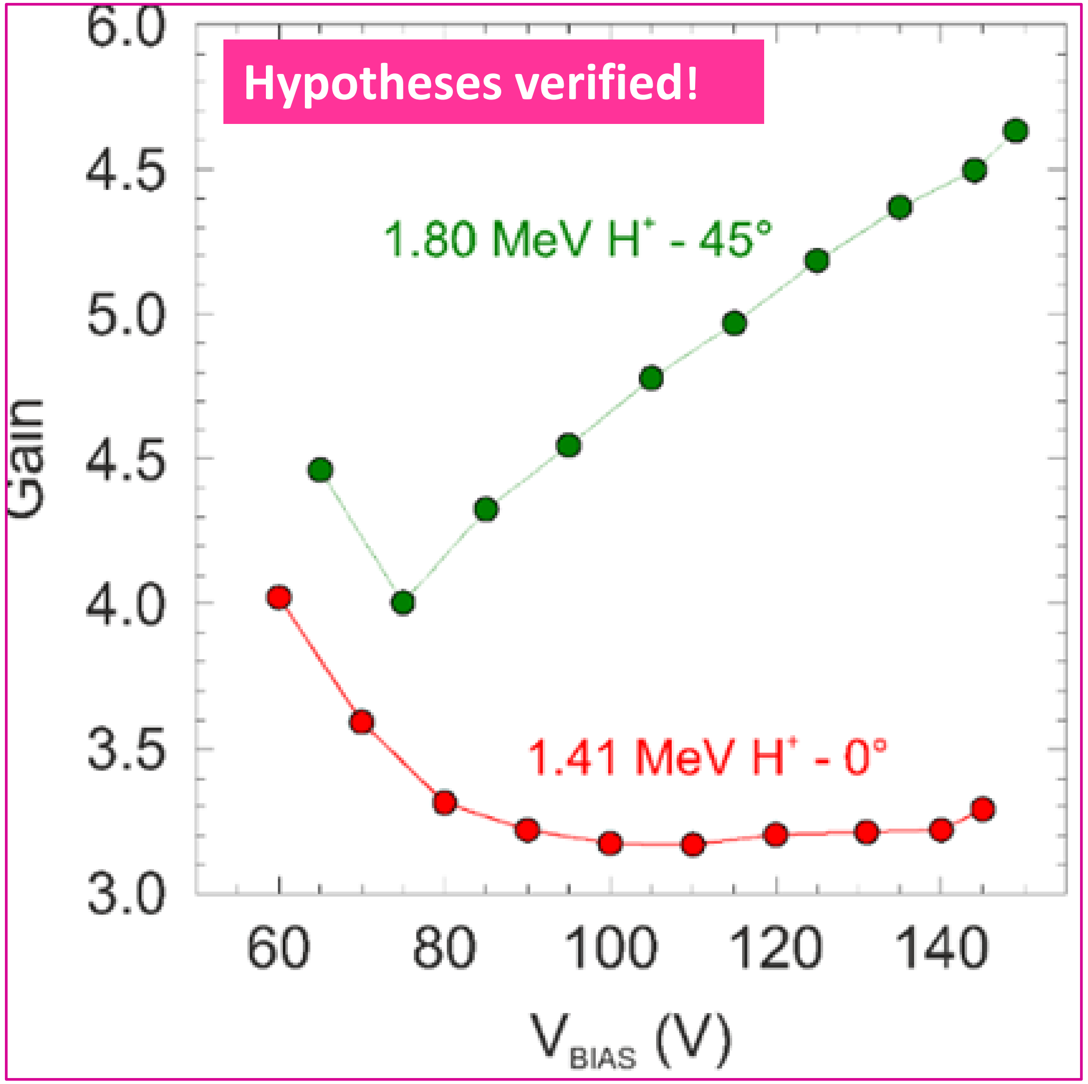
- The ionisation depth profile (along the z-axis) is similar.
- **But,** For 45º irradiation, the (x,y) projection of the charge cloud arriving at the gain layer will be spread in one dimension (x) to more than 15 micrometres
- its density and subsequently the electric field screening will be much smaller.

RESULT

- a reduction in the size/density of the charge cloud minimized the electric field screening and reduced the gain suppression.

- Nevertheless, at the lowest bias value measured, just **above the V_{FD} value, the increase in efficiency for inclined irradiation is also noticed**, as is the case for the vertical irradiation direction.

- Thus, the final shape of the gain-to- voltage dependence for inclined irradiation is a superposition of
  - the characteristic shape obtained for MIPs (at high voltages)
  - and the strongly screened shape obtained for vertical irradiation (at lower voltages).



Hypotheses verified!

Main Findings

- Gain suppression has been confirmed and explained. Large density 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 gain suppression has ben experimentally verified**
- Prominent 'gain peak" in gain curves is observed in studies with ions at RBI;.
- 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 the higher bias; the screening effect of electric field decreases, and eventually the gain becomes higher.
- **Exp with tiled detector or inclined tracks: reduced charge density reduces charge screening effect, and consequently gain increases**
    - **Observation important for**
        - **INFLUENCE OF THE TILT PARAMETER DURING SEE CHARACTERIZATION WITH HEAVY ION BEAMS**
        - **Using cluster shape to improve reconstruction of hit position estimation**

Taking about the gain makes sense only for given particle type (and angle)

- 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.*

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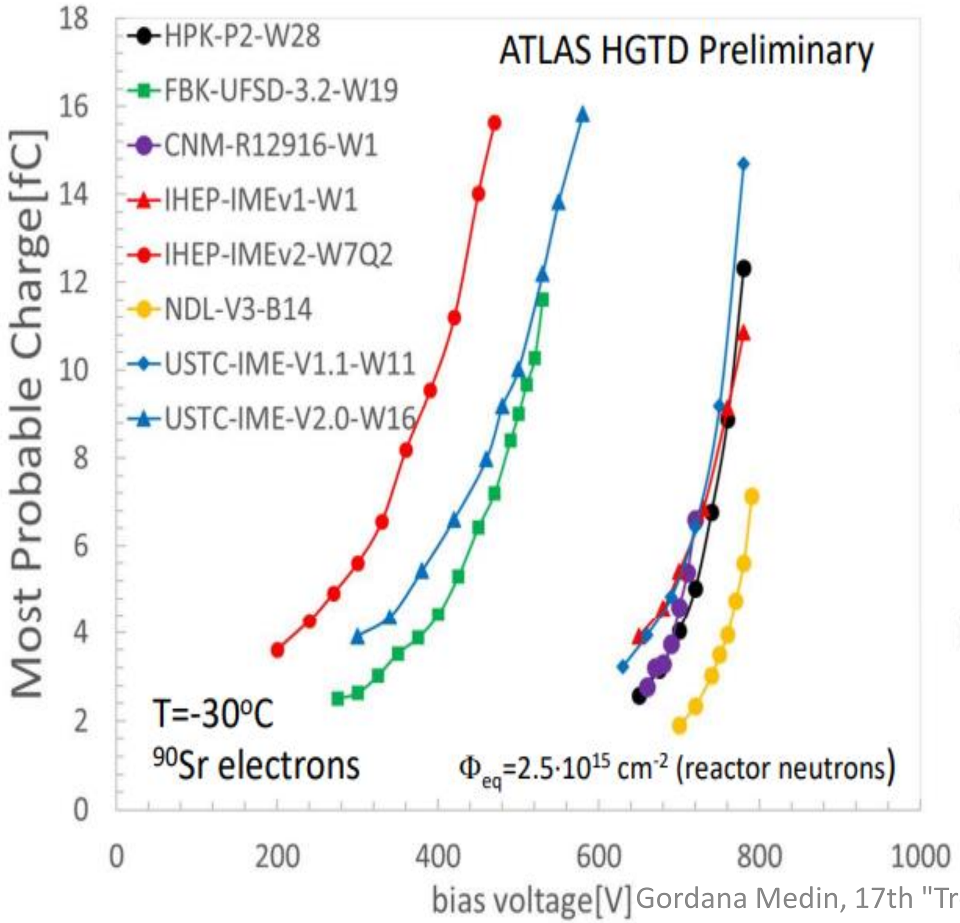
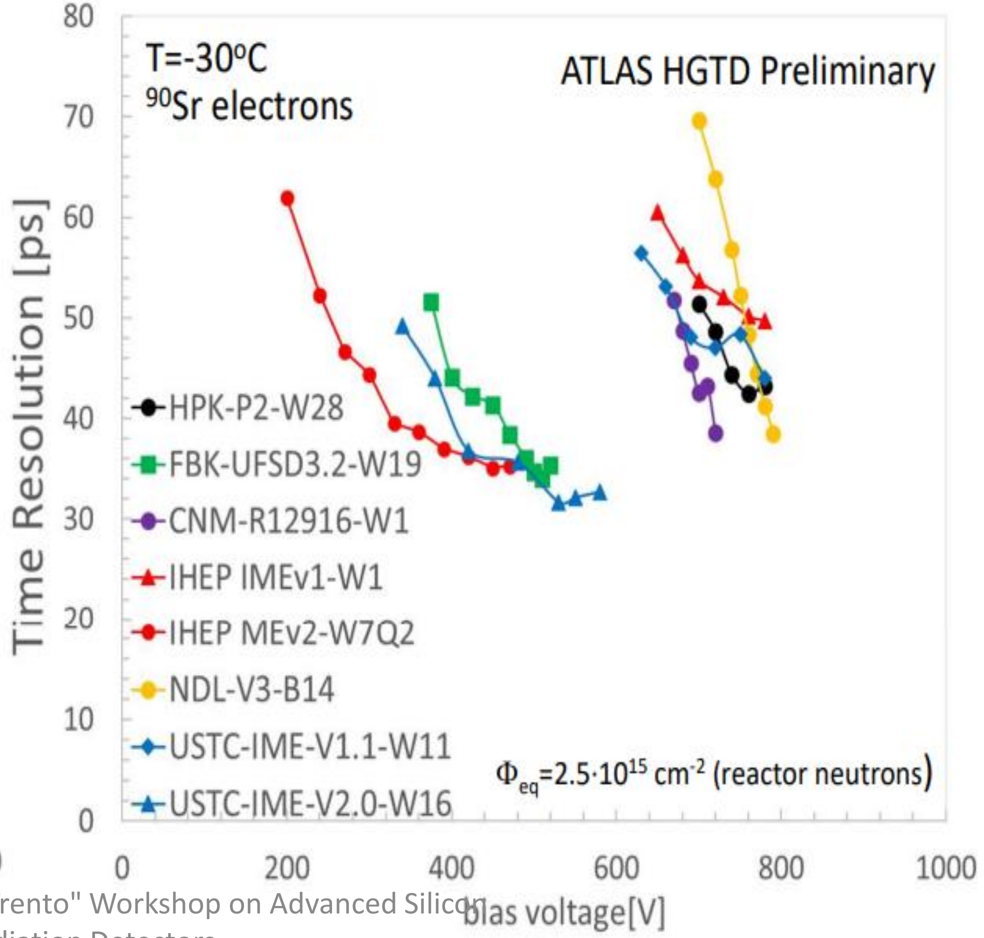

ATLAS HGTD Preliminary
Most Probable Charge[fC]
bias voltage[V]
0
2
4
6
8
10
12
14
16
18
0
200
400
600
800
1000
HPK-P2-W28
FBK-UFSD-3.2-W19
CNM-R12916-W1
IHEP-IMEv1-W1
IHEP-IMEv2-W7Q2
NDL-V3-B14
USTC-IME-V1.1-W11
USTC-IME-V2.0-W16
T=-30°C
⁹⁰Sr electrons
Φeq=2.5·10¹⁵ cm⁻² (reactor neutrons)


ATLAS HGTD Preliminary
T=-30°C
⁹⁰Sr electrons
Time Resolution [ps]
bias voltage[V]
0
10
20
30
40
50
60
70
80
0
200
400
600
800
1000
HPK-P2-W28
FBK-UFSD3.2-W19
CNM-R12916-W1
IHEP IMEv1-W1
IHEP MEv2-W7Q2
NDL-V3-B14
USTC-IME-V1.1-W11
USTC-IME-V2.0-W16
Φeq=2.5·10¹⁵ cm⁻² (reactor neutrons)