Investigating the Impact of Isolation Structures Configurations on the Charge Carrier Excess in the Interpad Region in segmented LGAD within high charge intensity injection using fs-laser

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IJS
eli beamlines
FZU Institute of Physics of the Czech Academy of Sciences

Outline

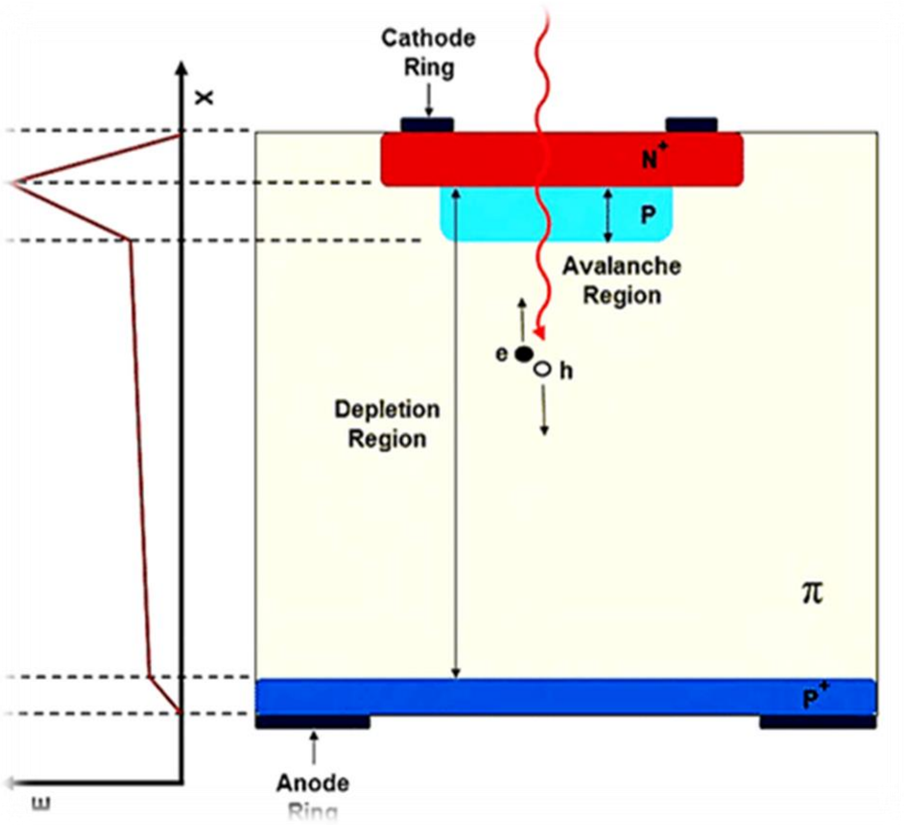
- LGAD (brief introduction)
- Research question and research methodology explained
  - Exploring the Interpad (IP) Gap Region in Ultra Fast Silicon Detectors: Insights into Isolation Structure and Electric Field Effects on Charge Multiplication
  - Focus on LGAD’s IP response on the high intensity charge injection
- Experiments conducted on different LGAD prototypes
  - 2p-stops + bias ring in IP region as isolation stricture
    - 2 samples: from Ti-LGAD and UFSD 4.0 (latest CMS and ATLAS) batch production
  - Ti-LGAD with 2 trenches in IP region
    - Non-irradiated
    - Irradiated sample
  - Ti-LGAD with 1 trench in IP region
- Conclusions

LGAD

- LGAD – mature technology for timing detectors;
  - it has excellent timing resolution (30 ps),

- Radiation hardness – sufficiently good for fluencies up to $2.5x10^{15}$ n_{eq}/cm^2, but above the gain is lost; LGASD behaves as PIN diode
  - ✓ Gain is not lost, but decreases below the required level (acceptor removal mechanism)

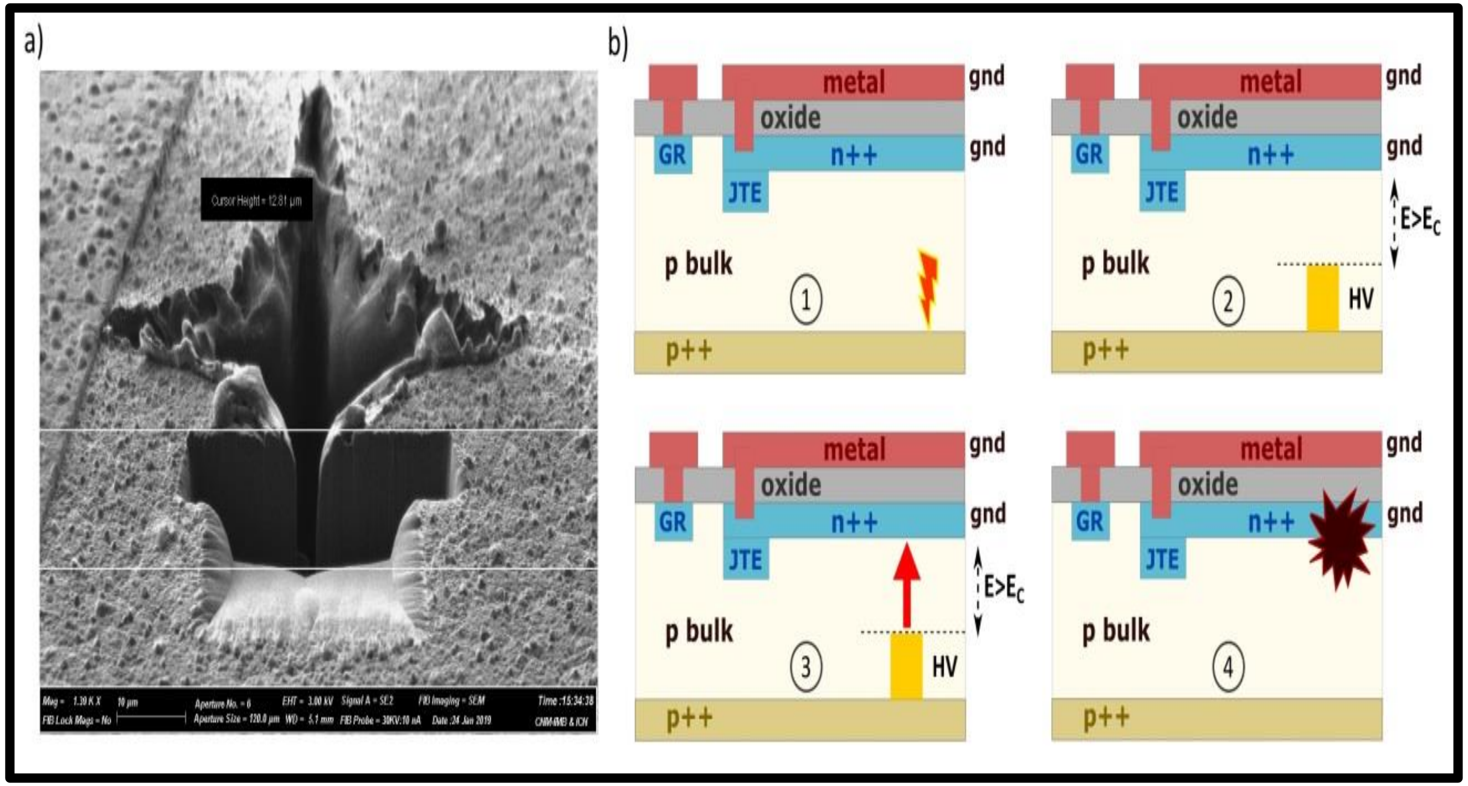
- 4D tracking – a new paradigm in HEP and medical applications (pCT)
  - ✓ segmentation problem
  - ✓ Fill factor (total area /gain area) problem



LGAD & Single Event Burnout SEB

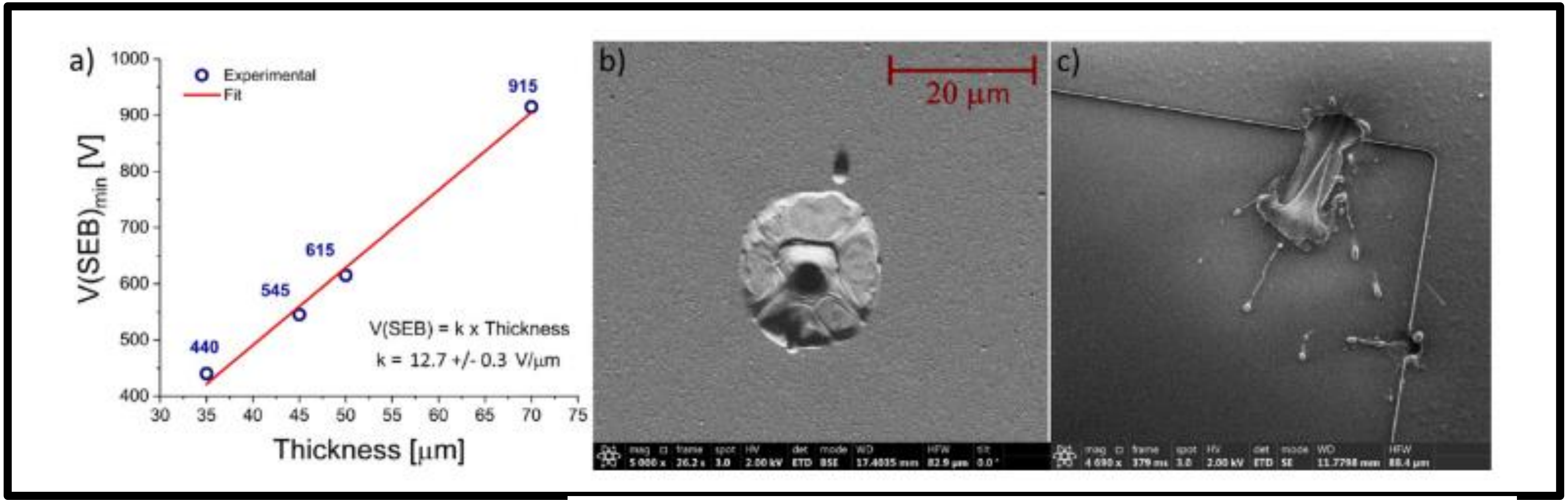
LGAD fatality feature observed in proton beam tests at the Fermilab (courtesy of CNM, ATLAS TB sensor) Ref: S. Hidalgo at al., CMSRUN2B. IMB-411 CNM Activities. FPA2017-85155-C4-2-R Coordination Meeting. (2019).

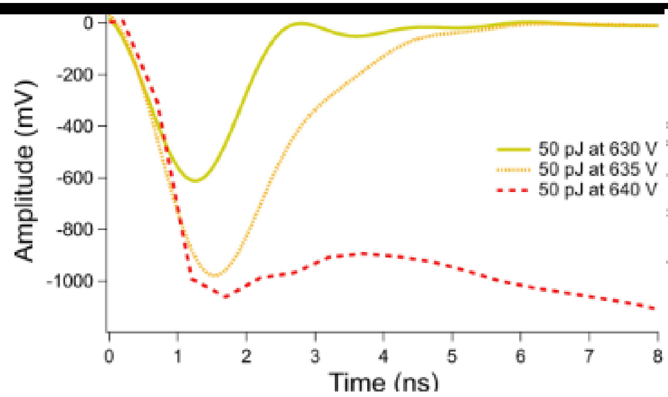
Stages of SEB that lead to irreversible damage

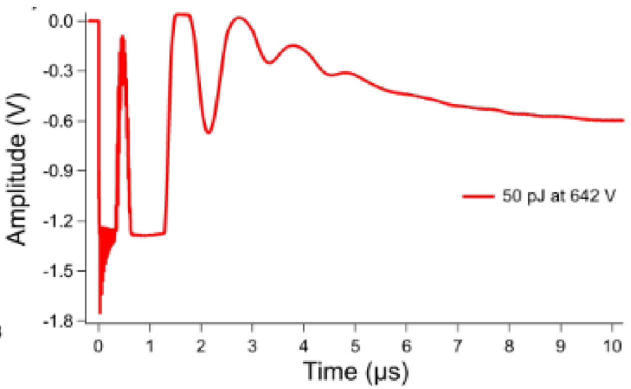


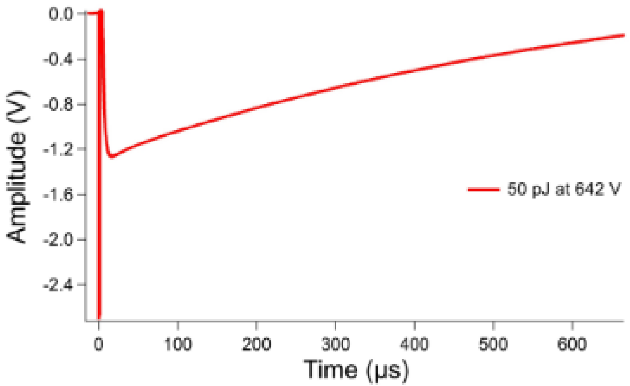
1) for fatality to happen a larger deposition of the charge (fragments producing deposition in few mm as large as 1000 mips are possible) in a few mm is needed;
2) a larger carrier density leads to a collapse of the field (screening prevents the carriers from being swept away);
3) once the field collapses the HV is brought closer to the pad which leads to a very high field strength and to the avalanche breakdown causing a full
discharge of the sensors and the bias capacitor;
4) the discharge leaves a crater behind if enough energy is stored to melt the silicon (~10 nF).

Study at laser facility, ELI Beamlines, ELI ERIC in Prague





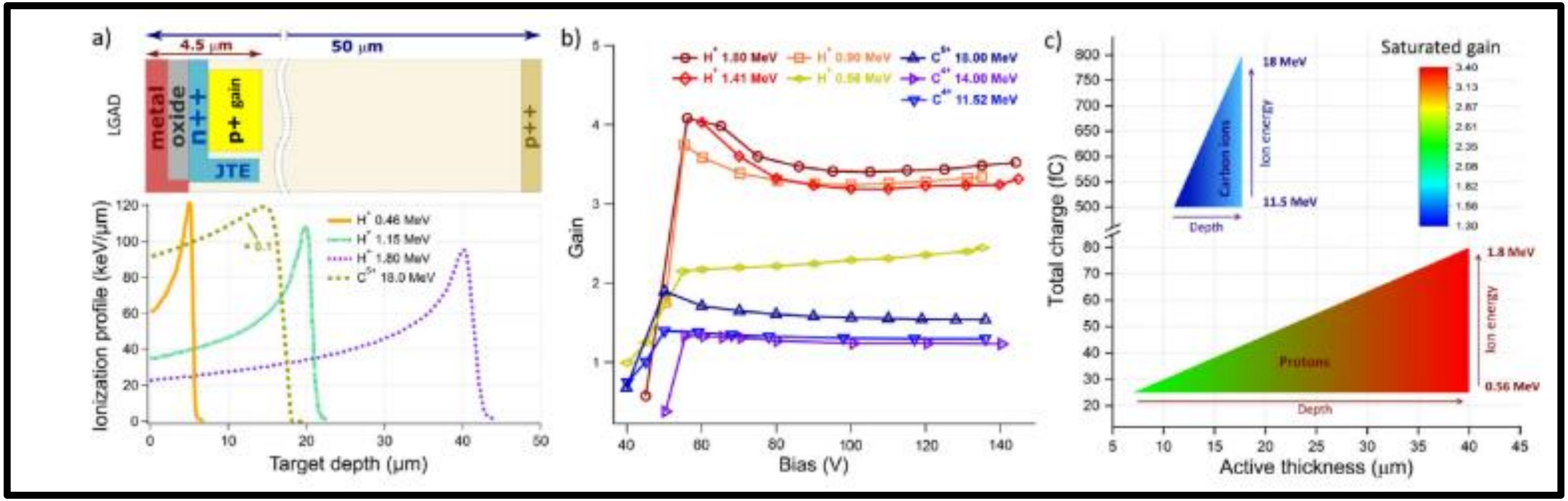




Ref: Gordana Laštovička-Medin, et al., *Femtosecond laser studies of the Single Event Effects in Low Gain Avalanche Detectors and PINs at ELI Beamlines*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1041 (2022): 167321.

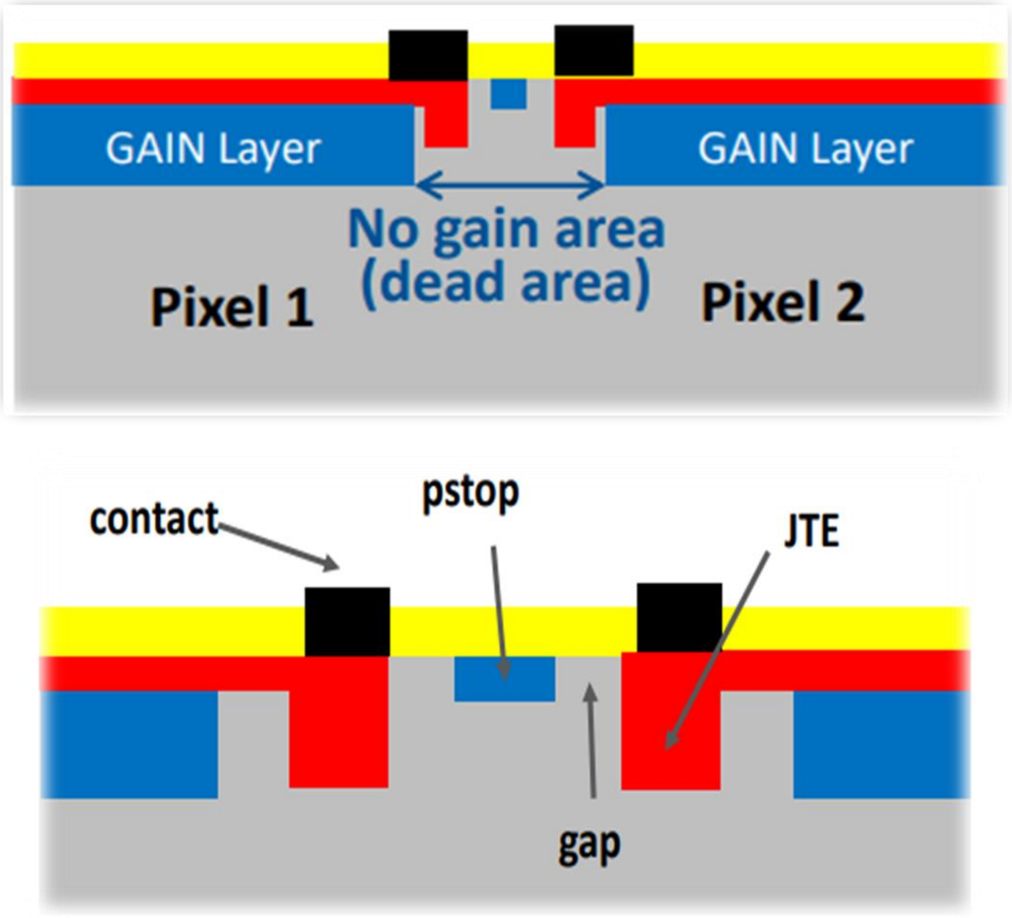
LGAD & Gain Suppression (GS)

- ❑ From experiment with ions
- ❑ Experiment conducted at the Rudjer Boskovic Institute using IBIC method



1. Ref: Gordana Laštovička-Medin, et al., *Studies of LGAD performance limitations, Single Event Burnout and Gain Suppression, with Femtosecond-Laser and Ion Beams*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1041 (2022): 167388.

LGAD & Segmentation problem



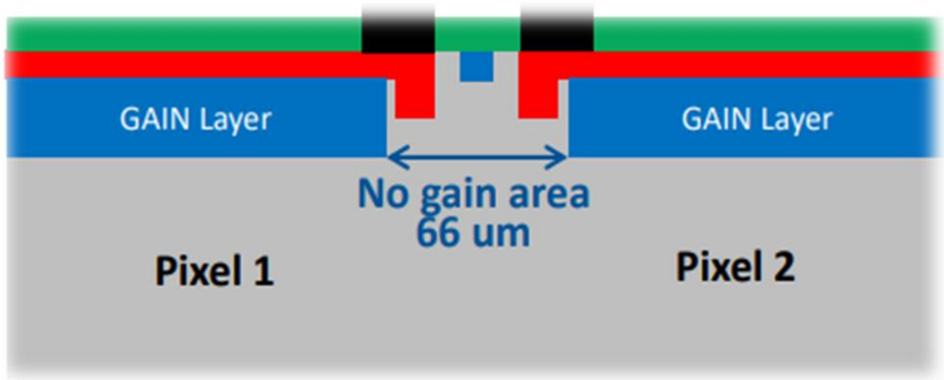
- Detectors with internal gain are typically affected by Fill Factor reduction.

- Two regions are present:
  - GAIN region (pixel core)
  - NO-GAIN region (pixel border)

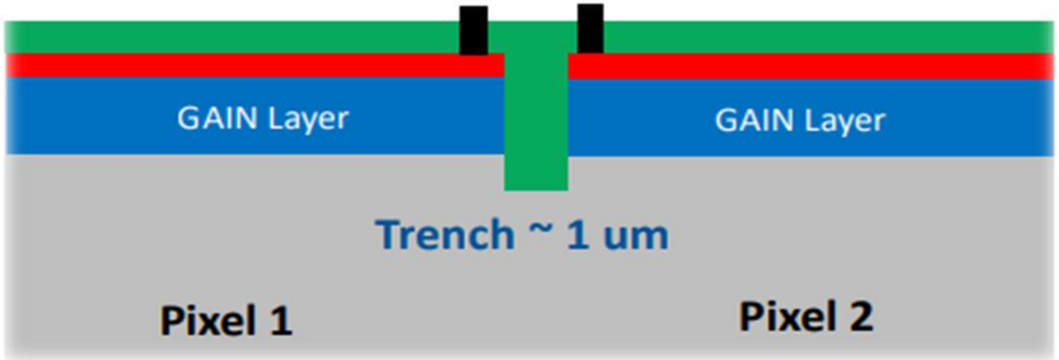
- The pixel border is a dead-region.
- The carriers generated in this area are not multiplied.
- The periphery and inter-pad region hosts the structures needed to control the E field (JTE, p-stop, etc..)
- Its dimensions are due to design and technology constraints.

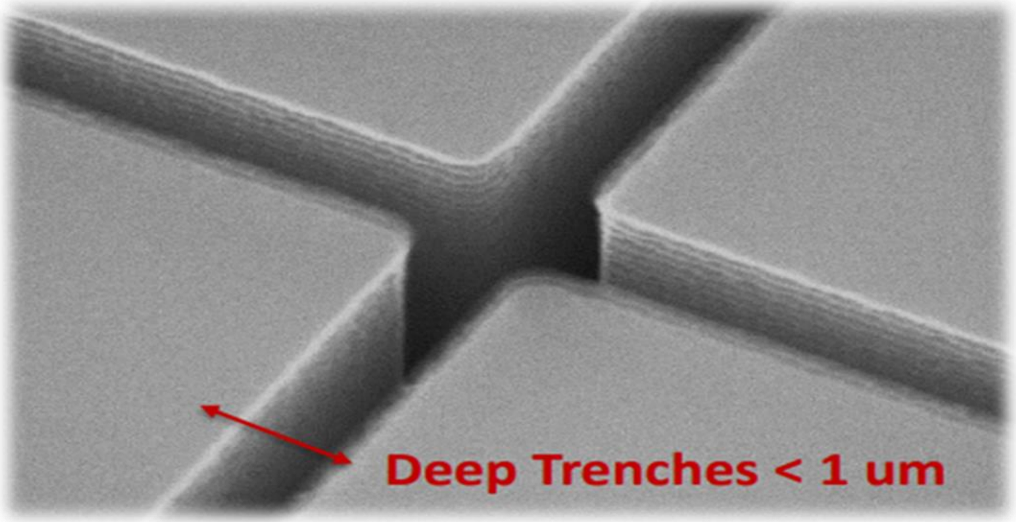
New strategies to improve Fill Factor

Standard JTE + p-stop isolation



Trench Isolation LGAD





- Trench isolation drastically reduces the inter-pixel border region down to few microns
- Typical trench width < 1 um

Research question and research methodology

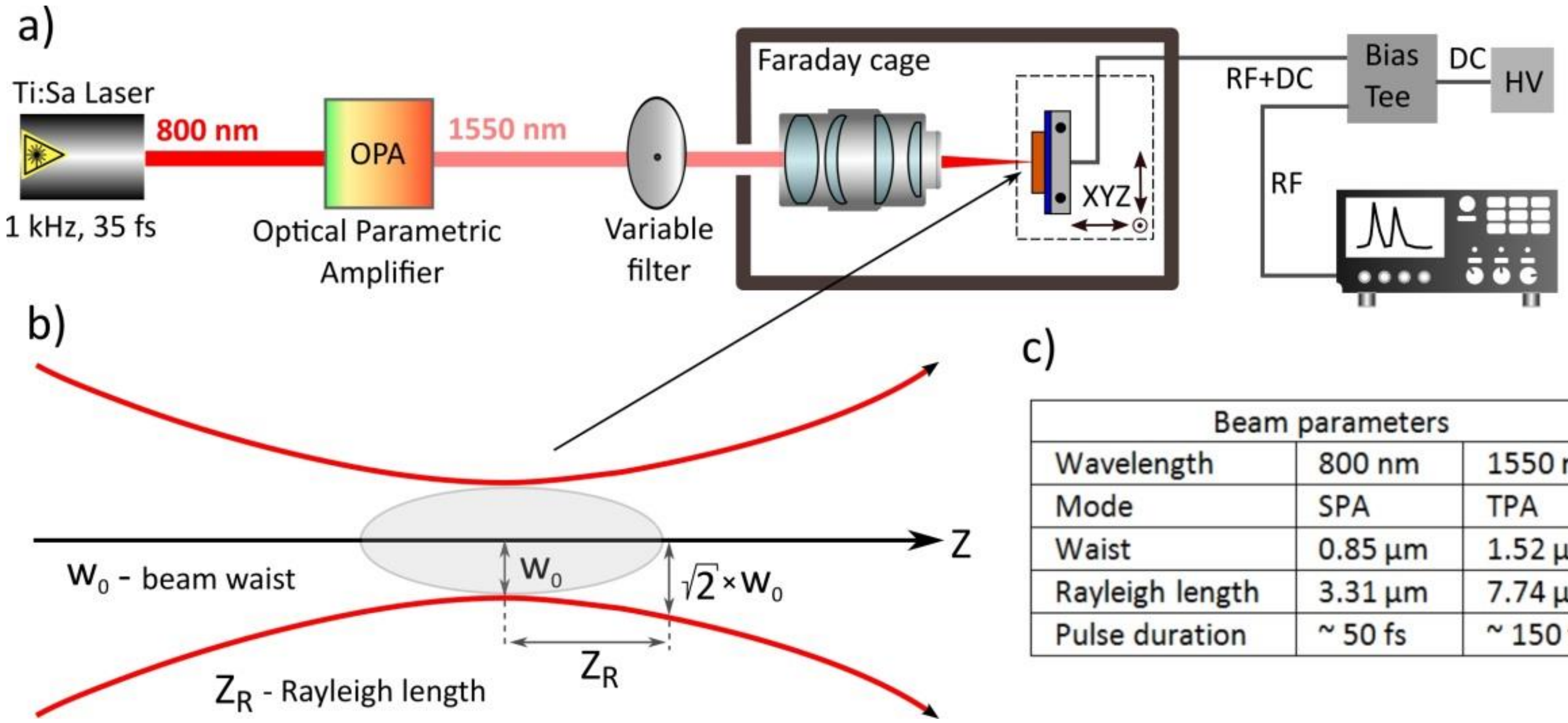
<u>Research question:</u> Investigating the Impact of Isolation Structures Configurations on the Charge Carrier Excess in the Inter-Pad Region in segmented LGAD within high charge intensity injection using fs-laser

<u>Experimental technique:</u> TCT technique
Designed and developed at the laser facility ELI Beamlines, ELI ERIC in Prague

- ➢SPA & TPA
- ➢Fs-laser, 1KHz
- ➢OPA system (for TPA)
- ➢XYZ tables
- ➢IR laser (800 nm basic wavelength) with beam focusing
- ➢HV on backplane

Operating conditions
- ➢**Cooling @ -25°C**
- ➢Insulation cap
- ➢Closed environment

<u>Research methodology:</u> Study of waveforms and X-profiles (Integrated charge versus shooting points)



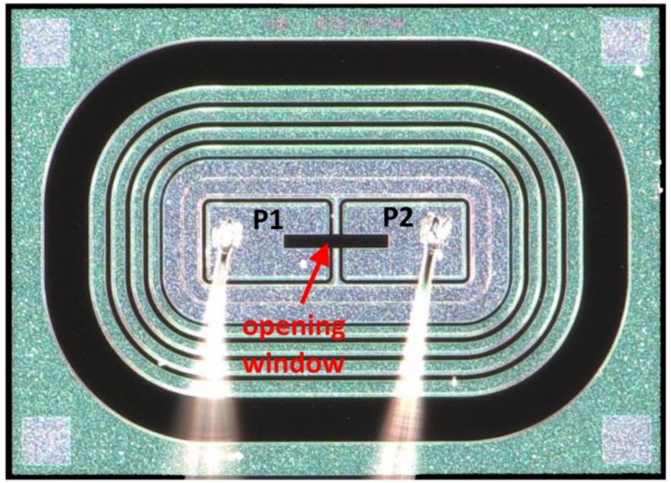
c)

Beam parameters		
Wavelength	800 nm	1550 nm
Mode	SPA	TPA
Waist	0.85 µm	1.52 µm
Rayleigh length	3.31 µm	7.74 µm
Pulse duration	~ 50 fs	~ 150 fs

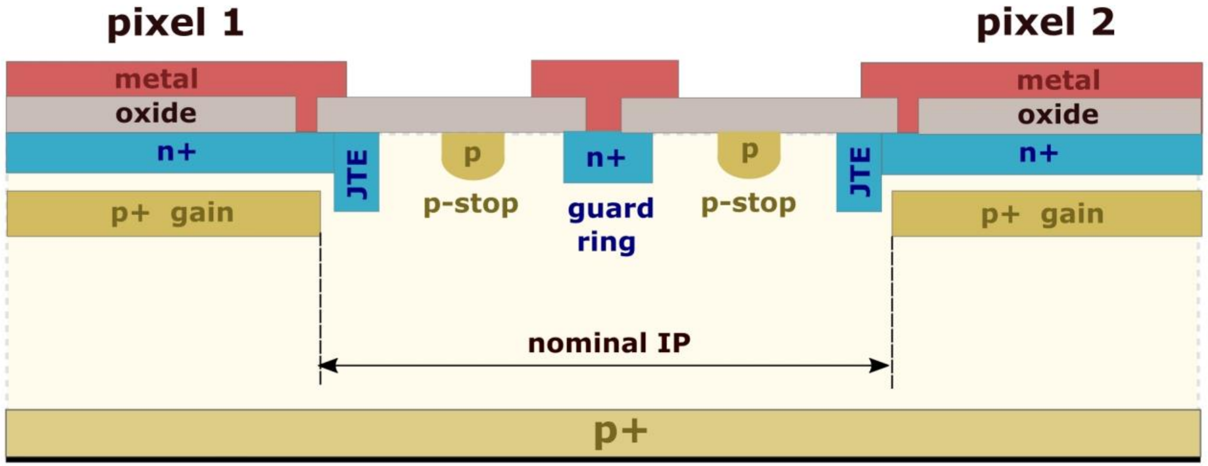
Study on Segmented LGAD with 2 p-stops + bias ring from TI-LGAD production

2x1 area, 250x375 μm²

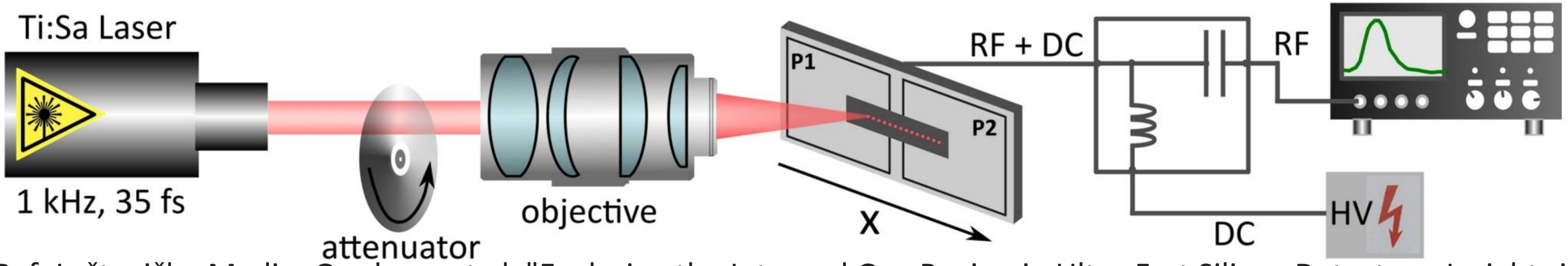
a)



b)



c)



Ref: Laštovička-Medin, Gordana, et al. "Exploring the Interpad Gap Region in Ultra-Fast Silicon Detectors: Insights into Isolation Structure and Electric Field Effects on Charge Multiplication." *Sensors* 23.15 (2023): 6746.

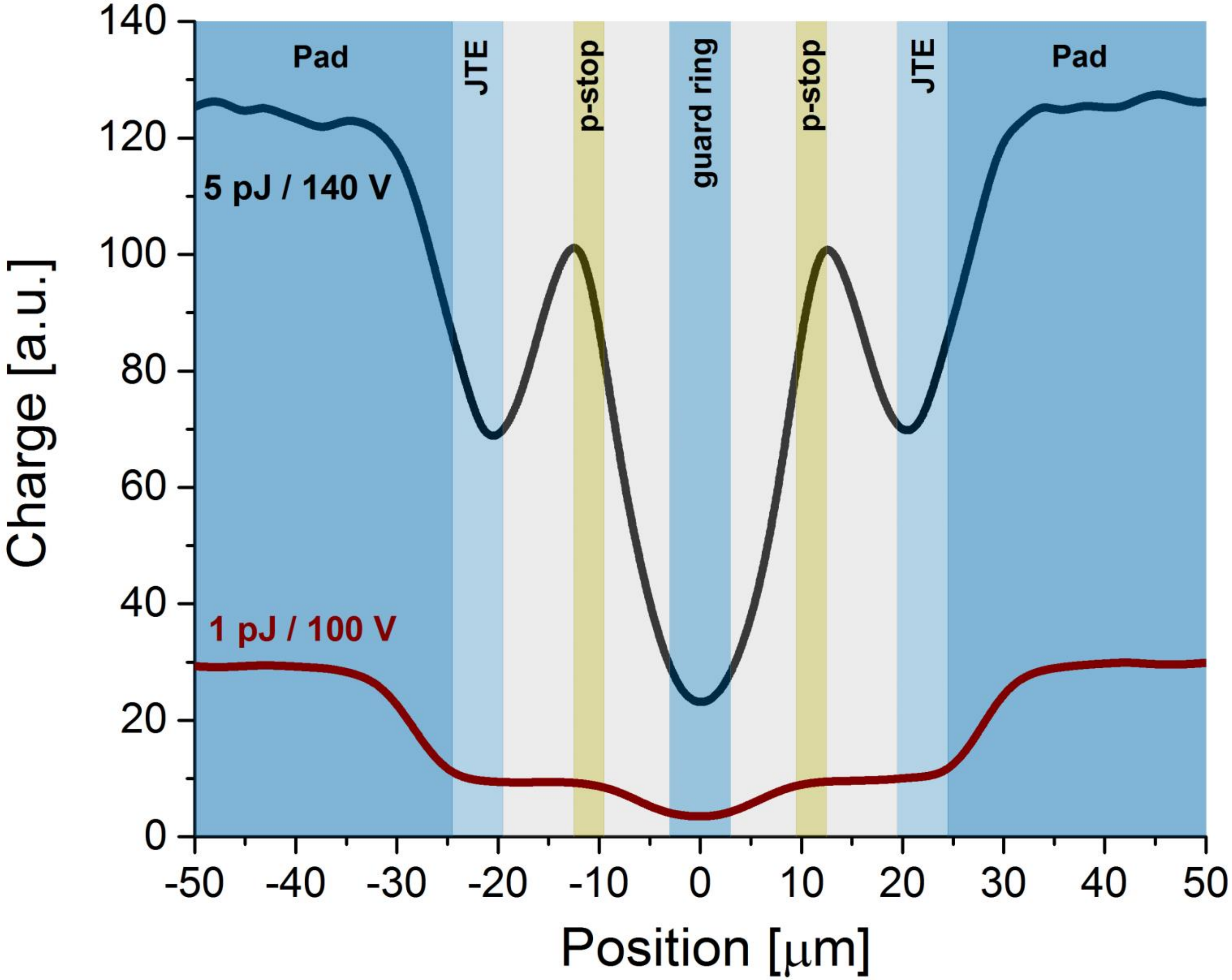
Interpad isolation structures resolved

Space-charge profiles of the interpad region of the Type 10 LGAD sensor were recorded for low (1 pJ/100 V) and high (5 pJ/140 V) charge injection conditions.

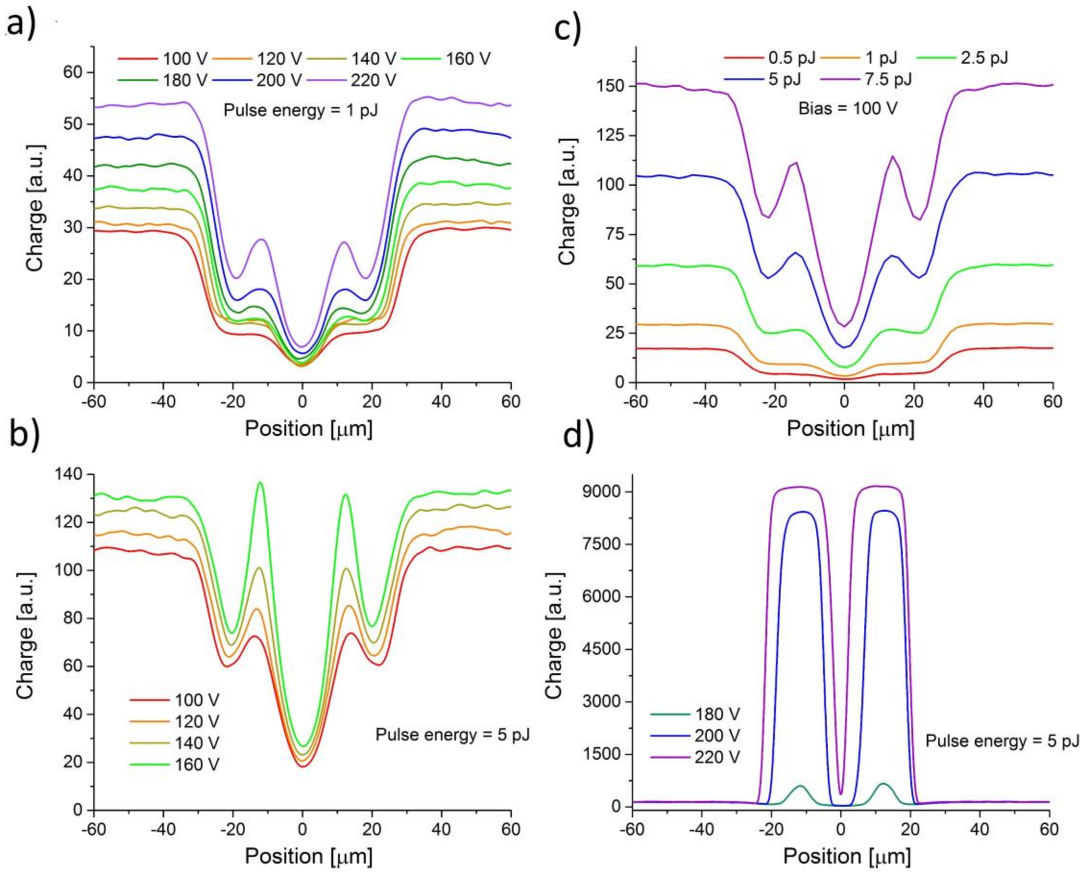
The background of the graph represents the estimated position and size of the corresponding elements of the interpad area

Comment guard ring is bias ring (set on GND)

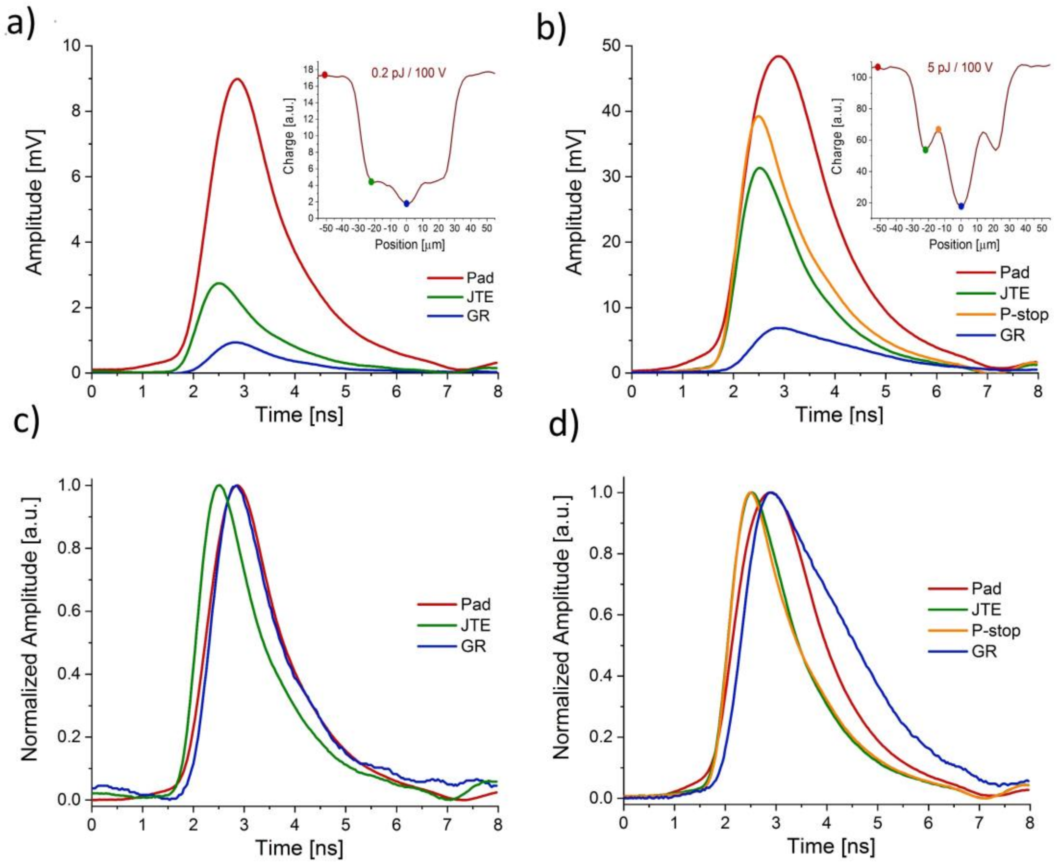
W11: shalow trenches was studied



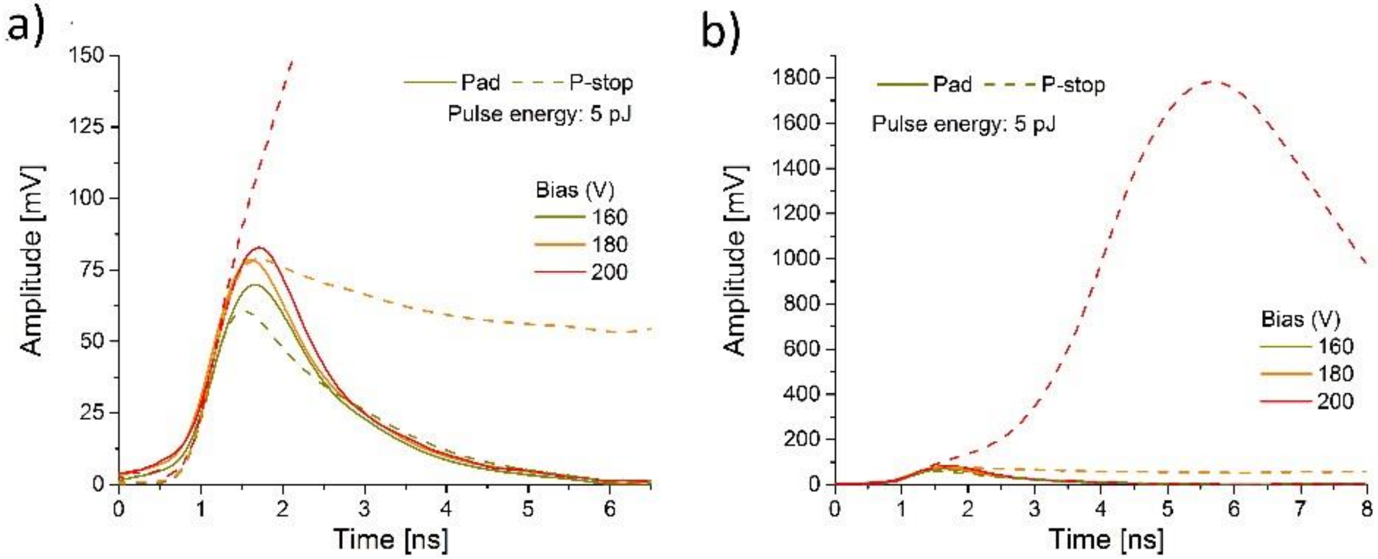
X-profile



Waveforms

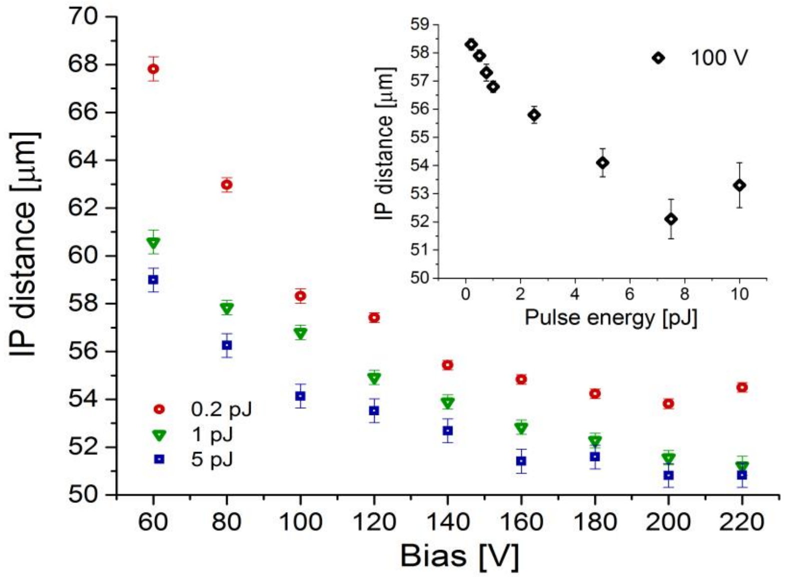


Waveforms (extreme cases)



b) Is the same as a) - not scaled

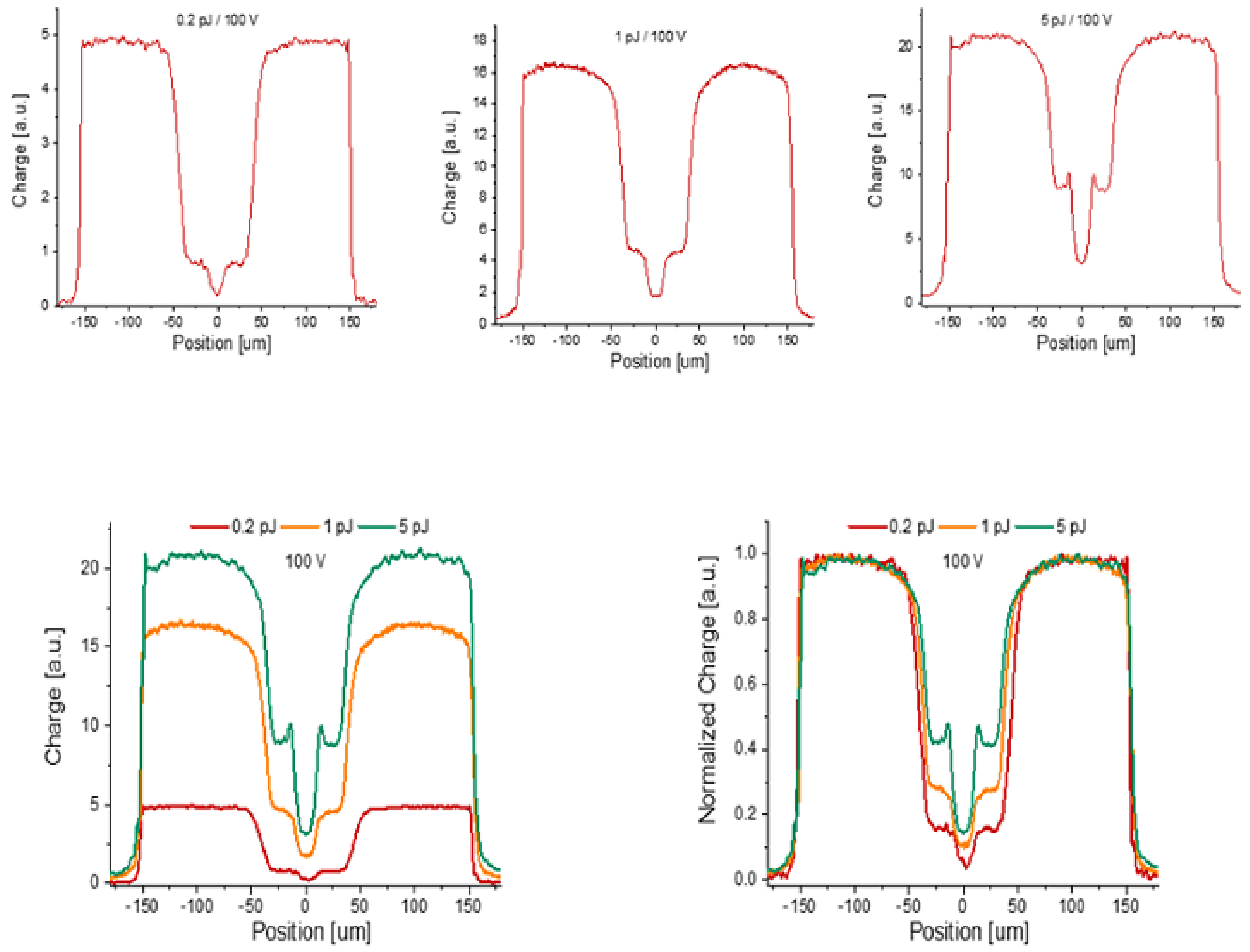
IP distance vs bias and laser power



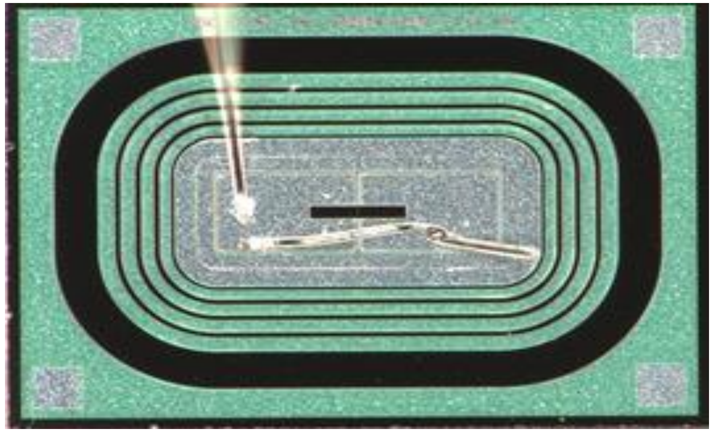
Study on Segmented LGAD from UFSD 4.0 production

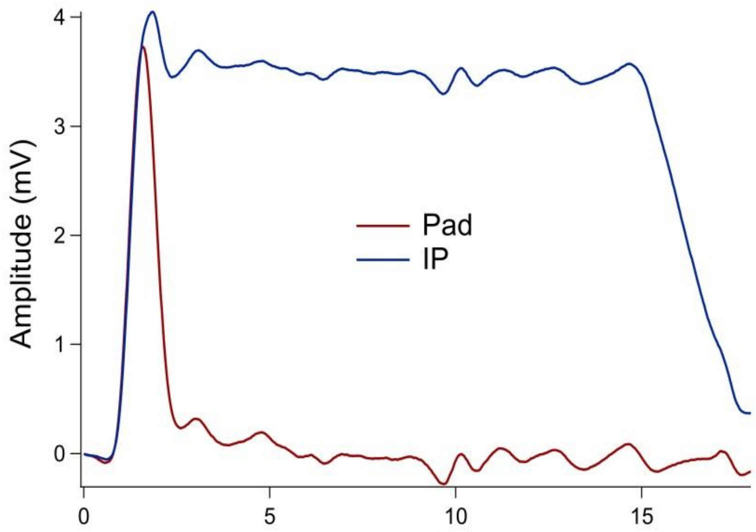
- As in the previous analysis a signal drop originating from the n-guard ring located precisely at the centre of the interpad is observed.
- This signal drop becomes more enhanced as the laser power increases (with increased charge density).
- Notably, no spikes in the IP region are observed at laser power of 0.2pJ and 1 pJ.
- Only at very high laser power (at 5 pJ and above) some sign for charge multiplication can be seen (as little spikes near the edge of p-stops).
- Gain is still present in the pad but becomes reduced with increased laser power (this becomes obvious by comparing an increase in the gain in the pad and ratio of applied laser intensity; the applied bias for those shown measurements was kept at the constant value: 100 V).

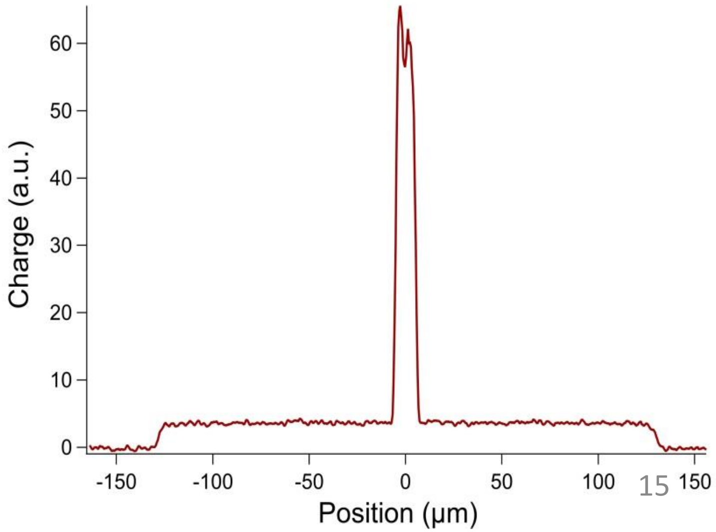
X-profile; IPD = 61 μm



Study on Segmented LGAD with 2 trenches in IP region







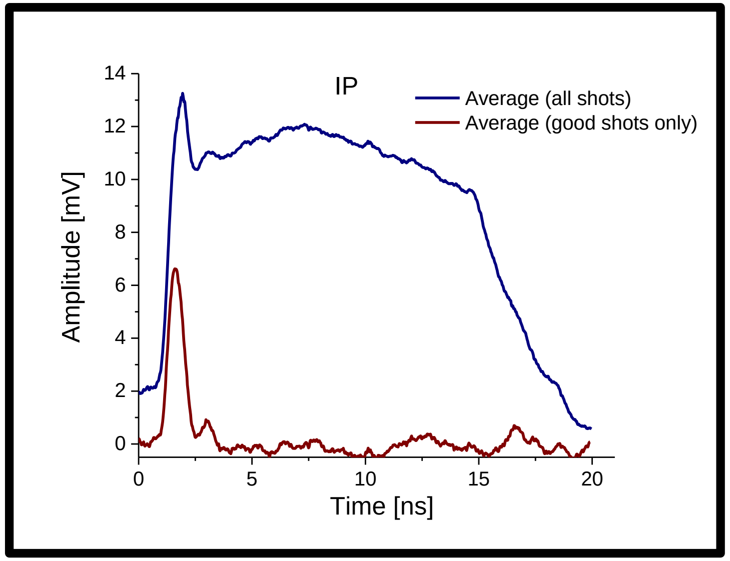
- ✓ Unexpectedly high collected charge in IP region, with long duration of waveform

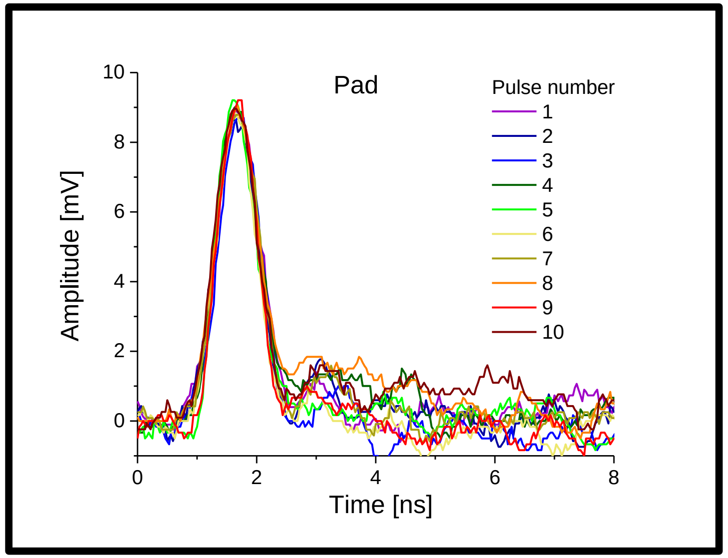
- ✓ Hypotheses: Some strange state is created in connection to local field; it sems like a local charge is created which is changed through the pulse and then large amount of electric charge is drifting towards the electrodes

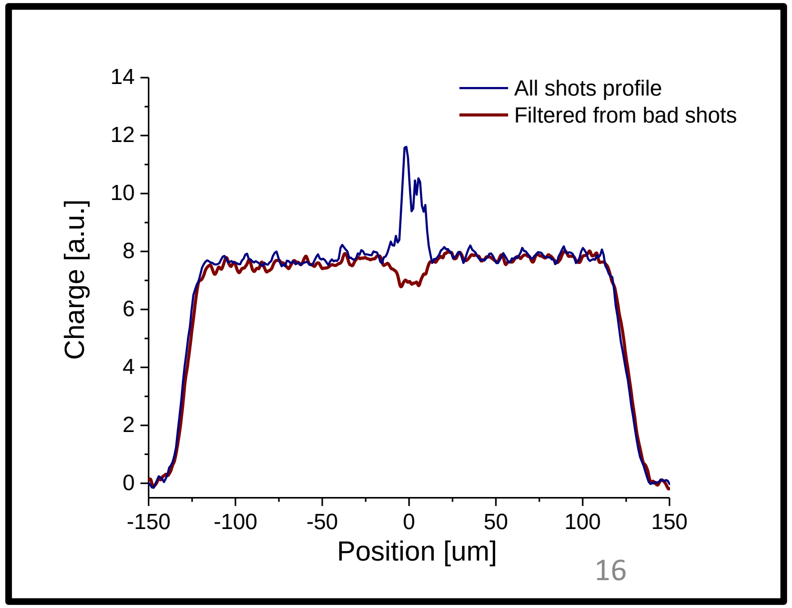
➢ Further inspection by analyzing single shot waveforms

(0.2 pJ / 100 V / -20 C)

- Single shot waveforms in IP region are very unstable (even at -20 C)
- Leak current is stable at the same time
- We have completely random occurrence of very deformed waveforms (“bad shots”) with different shapes and amplitudes
- Some of the waveforms are so strong that amplitude is higher than oscilloscope window
- Averaging several waveforms where some of them are too strong (cut) results in “artificial” plateau
- Averaging “good shots” only gives waveform similar to pad region with slightly lower amplitude

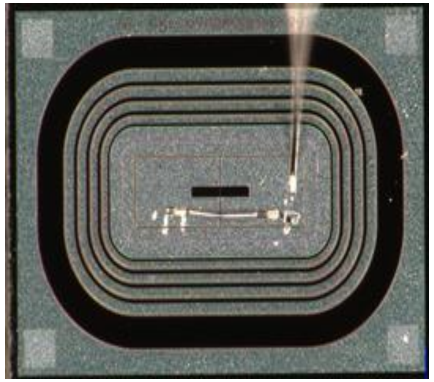


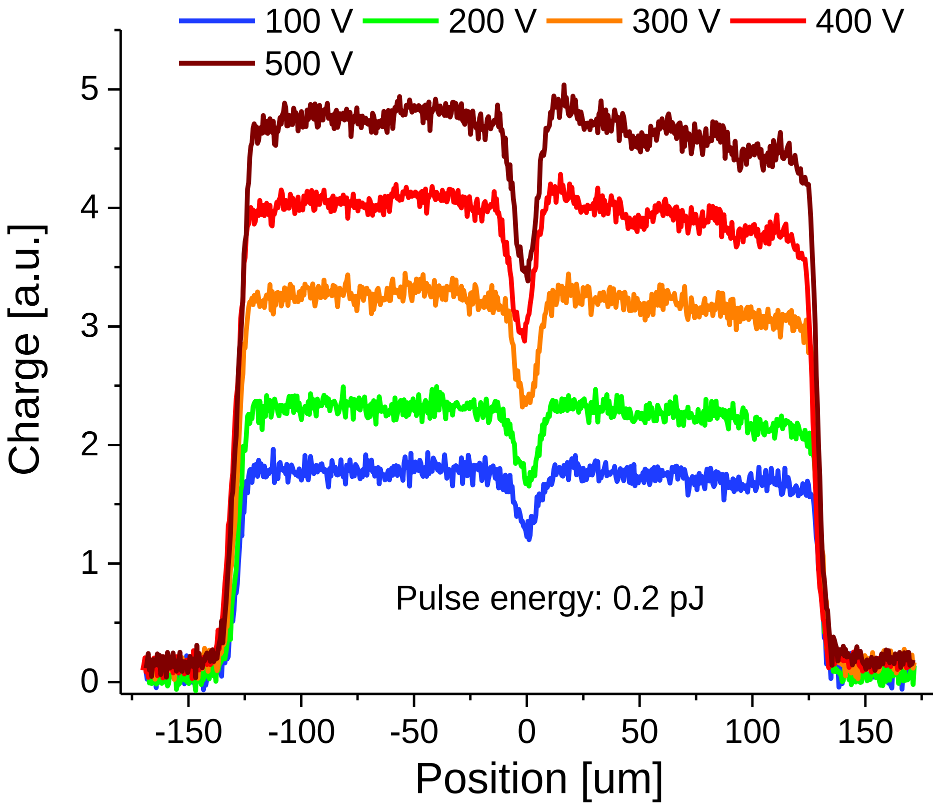


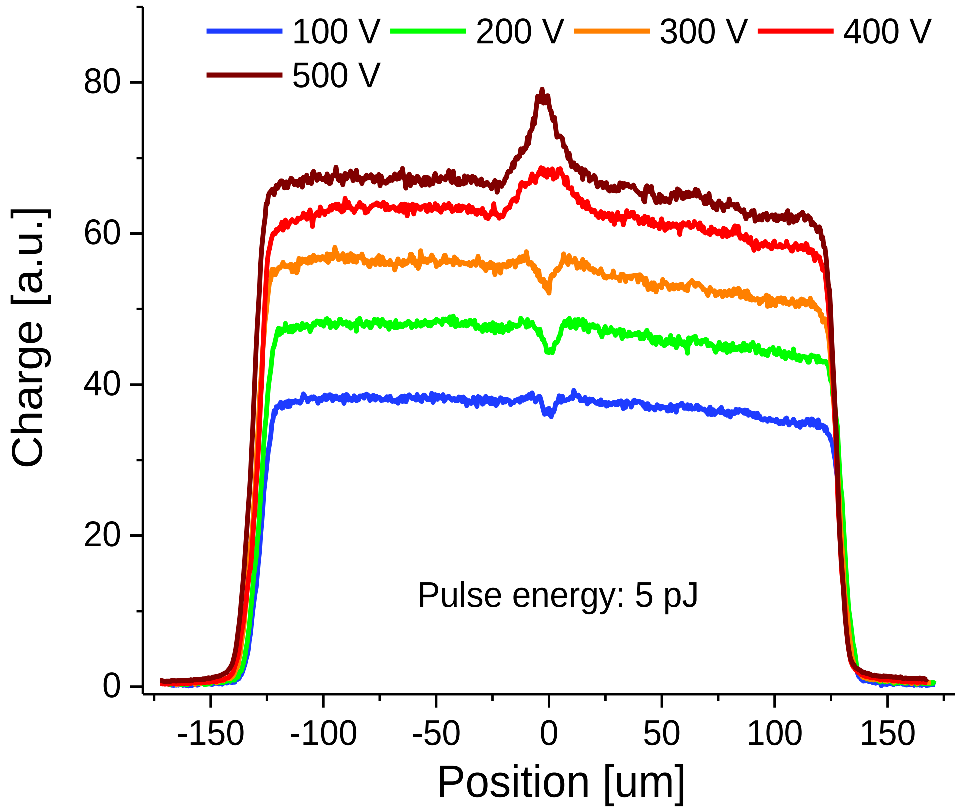


➢ A few campaigns are expected to be conducted at ELI in near future, so we hope to have soon more conclusive statement based on larger pool of tested 2Tr Ti-LGADs.

Study on Irradiated LGAD with 2 trenches

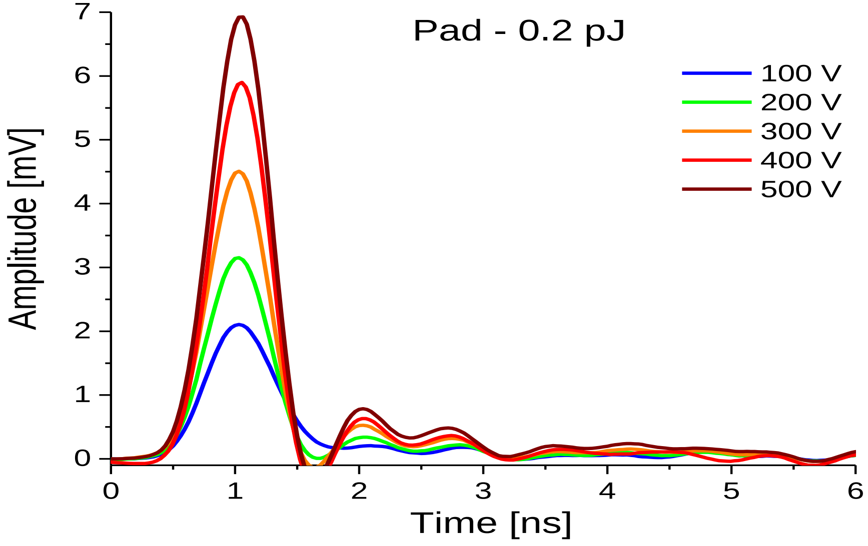


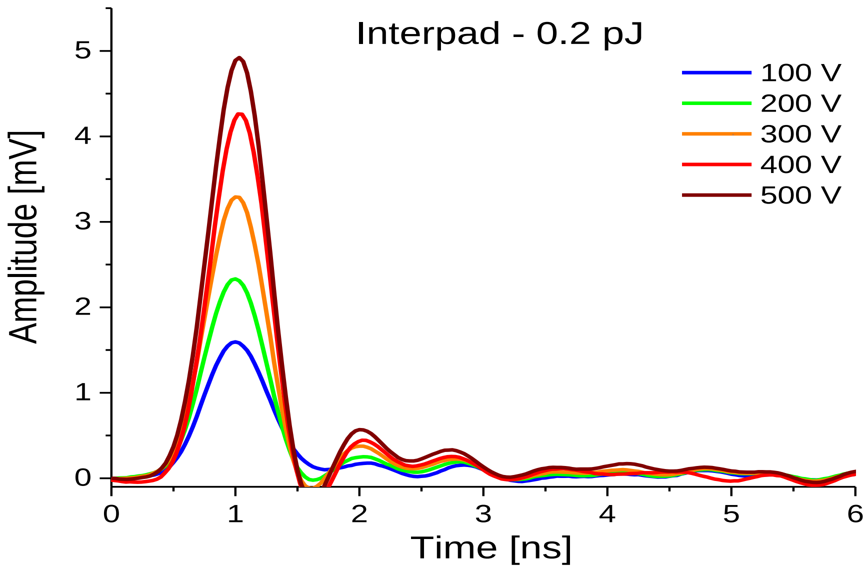


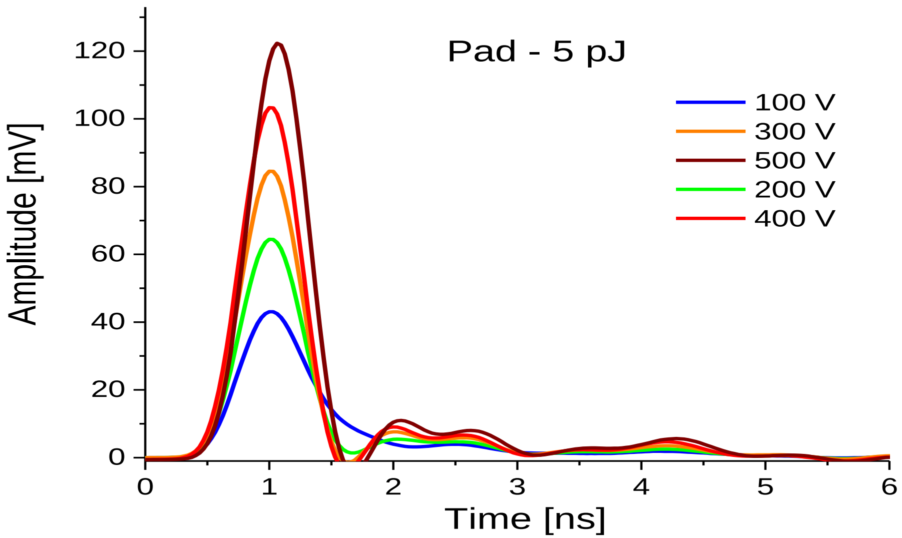


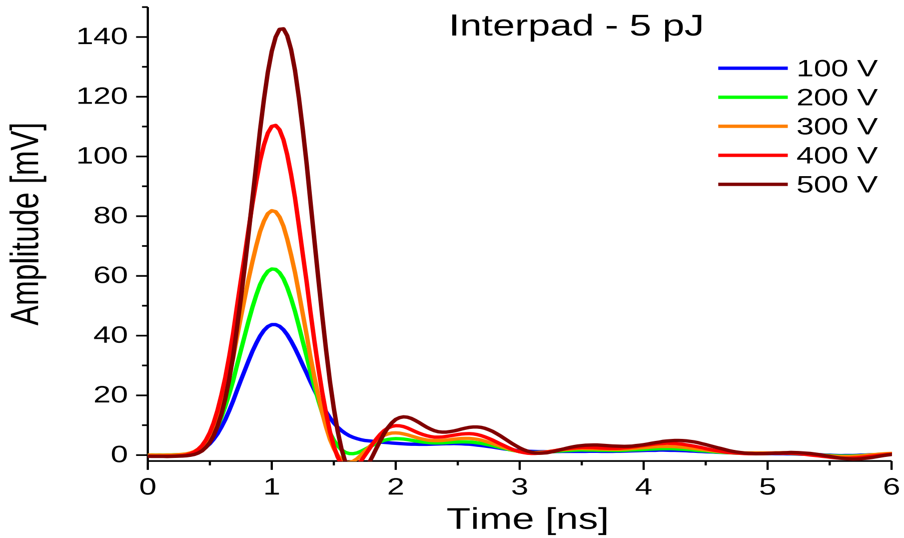
- ✓ Large spikes in proximity of p-stops are not observed; some indications for charge multiplication at much higher laser power

Examples of waveforms at 0.2 pJ and 5 pJ vs bias



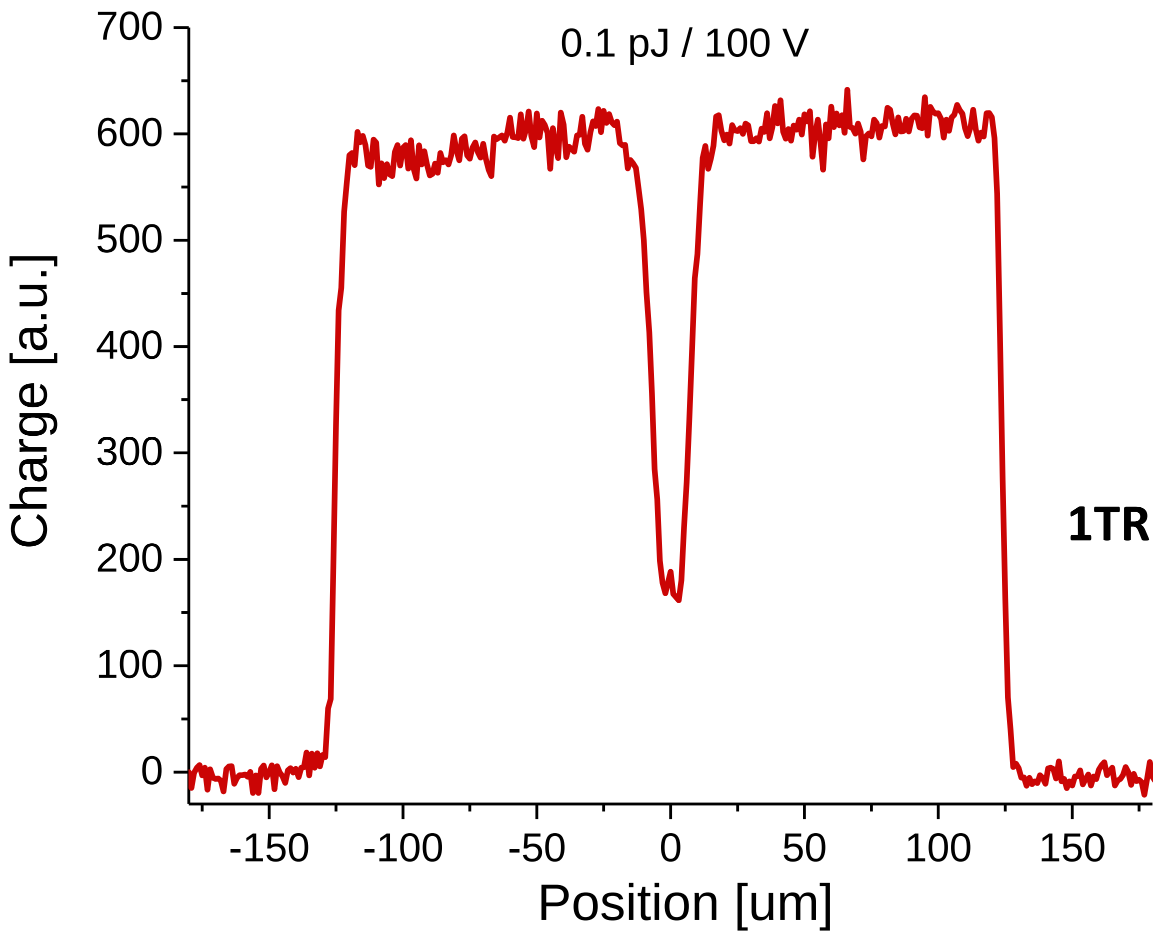






Non-irradiated LGAD with single trench

Full X-profile at 0.1 pJ and 100 V



1TR W11 A1 54 C1V4

- ✓ Charge multiplication was not observed, even at higher bias and higher laser power

Conclusion

- Interpad Gap Region in Ultra Fast Silicon Detectors has been studied on different UFSD samples with aim to investigate the Isolation Structure and Electric Field Effects on Charge Multiplication in IP region.
- High charge intensity injection was studied using fs-laser at ELI Beamlines, Eli ERIC.
- Experiments have been conducted at the ELI Beamlines, ELI ERIC in Prague where TCT setup with SPA and TPA mode is developed (originally for SEB study on LGAD).
- Extremely high spikes of collected charge in proximity of p-stop[s are observed in UFSD with 2 p-stops and bias ring.
- Those spikes are drastically reduced in prototypes from UFSD 4.0 production (with the same type of isolation structure).
- Ti-LGAD with 2 trenches exhibit enormously large charge excess in IP region; detailed study of single shots indicated the random fluctuations of occasionally extreme signals in IP region (not clear the reason).
- When LGAD is irradiated, those spikes are drastically reduced.
- LGAD with single trench does not show spikes in interpad region as it is observed in LGAD with 2 trenches.

Conclusions

- At high energy deposit, namely at high level of charge injection, IP region is very sensitive to the fluctuations of electric field; high excess of charge (charge multiplication) is recorded in IP region when Ip distance becomes significantly shorten..
- Charge multiplication in IP region depends strongly on the length of the distance between the pixels, and on the isolation layout design.
- LGAD prototypes with shorter and multiple trenches are more susceptible to fluctuations of electric field and to the multiplication of intrinsic carriers then single trenched LGADs.
- We plan to test large pool of sensors with different processing and fabrication parameters in order to provide more conclusive statements on conditions for CM in interpad region within conditions of larger charge injection.
- Only 2 Tr Ti-LGAD with shallow trenches are studied. In future we will look at Ti-LGADs with deep trenches, and results will be compared.
- Once study is completed on large pool of different samples with different processing parameters and isolation structure layouts, we believe that we can offer valuable data for further R&D on LGADs within larger charge injection (made by passage of HIP particles).