Low Gain Avalanche Detectors for 4-dimensional tracking applications in severe radiation environments

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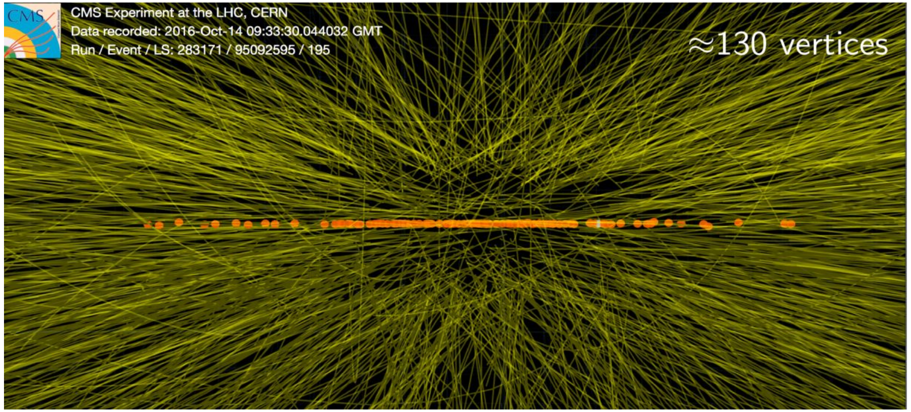
Outlook

- Challenges and motivation
- Time resolution & LGAD technology
- Fill factor and 4D-tracking performance
- LGAD performance after irradiation:
  - Gain layer degradation
  - Timing resolution
  - Collected charge
  - Annealing
- Summary and conclusions

HL-LHC and future colliders

HL-LHC



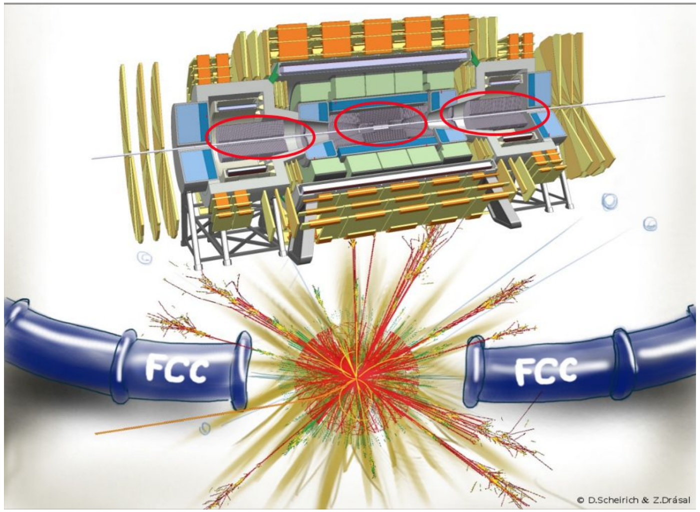
LGADs will be used at ATLAS-HGTD and CMS-ETL as timing detectors

Radiation tolerance: up to ~ $2.5 \times 10^{15}\ n_{eq}/cm^2$.

LGADs performance **after irradiation**:

- Time resolution < 70 ps per-hit in a MIP.
- Charge collected > 4 fC per MIP.
- Leakage current per pad < 5 uA.

FCC-hh



Pile-up mitigation (up to 1000) → time resolution needed of ~10 ps per MIP.

Also → spacial resolution per-hit of ~10 um

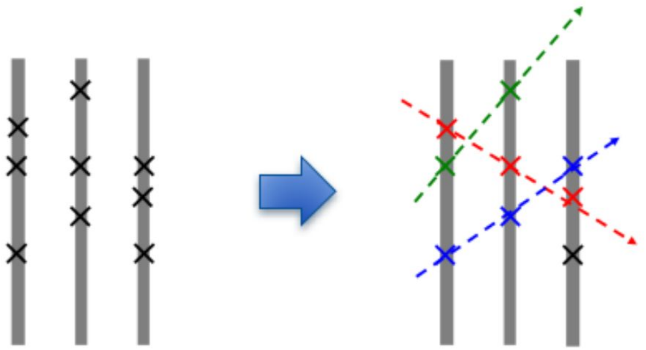
Much higher radiation tolerance (~$10^{17}\ n_{eq}/cm^2$) !!

4D Tracking at HL-LHC

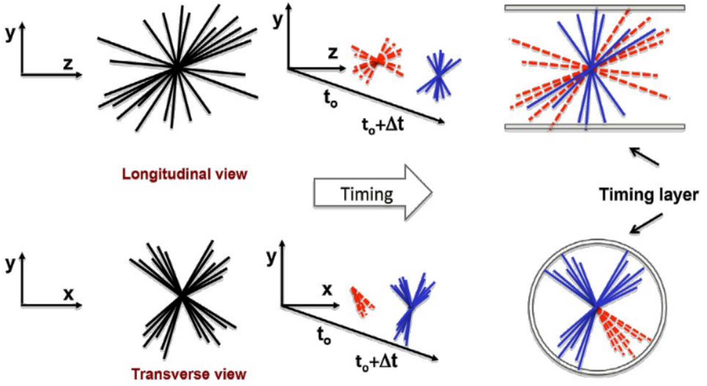
Why is timing important?

- Timing information is needed to avoid the loss of primary vertices.
- The time spread of the beam spot is between 180 and 200 ps.
- Overlapping of around 10 to 15% of the interactions vertices.

- Time tagging at each point
  - LHCb Upgrade II (Run 5 ~2030)



- Timing in the event reconstruction
  - HL-LHC: ATLAS and CMS

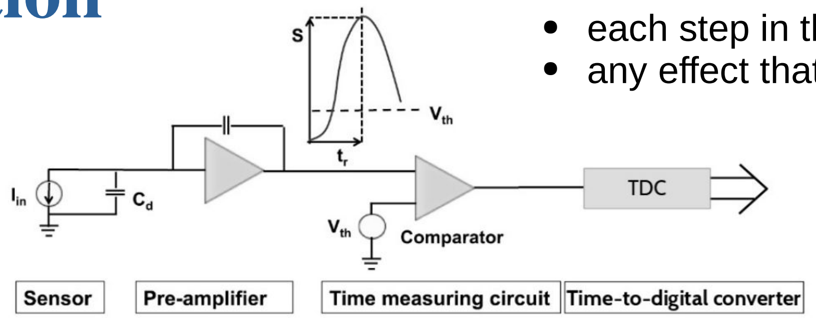


[V. Sola et al., ICHEP, Jul. 2018]

Time resolution

Time resolution is affected by:

- each step in the read-out process
- any effect that changes the shape of the signal



$$\sigma_t^2 = \sigma^2_{\text{Time walk}} + \sigma^2_{\text{Landau noise}} + \sigma^2_{\text{Jitter}} + \sigma^2_{\text{Distortion}} + \sigma^2_{\text{TDC}}$$

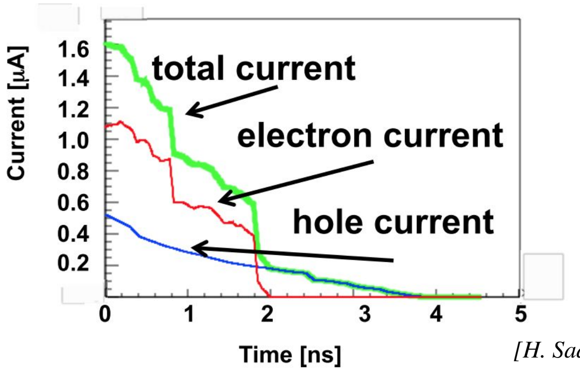
^{90}Sr & TB

IR laser

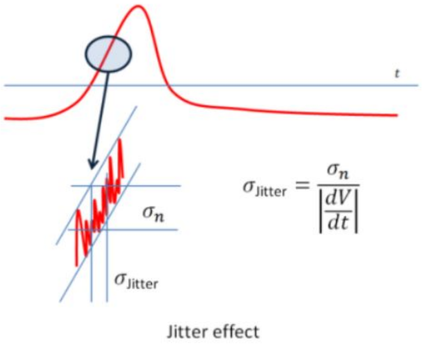
In-homogeneous drift velocity and weighting field.
Work with saturated drift velocity and optimized geometry.

Signal shape variations for MIPs.
One way to minimize this is going thinner.

Variations in the time of arrival because of the noise.
The way to reduce it is with low noise sensors, low electronics noise and fast slew rates.

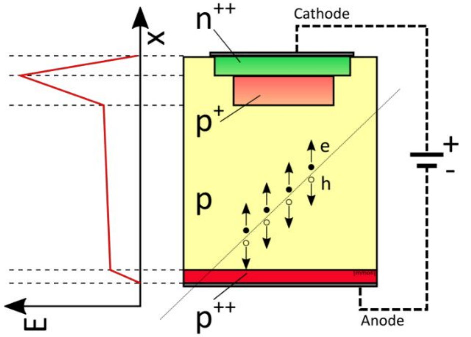


[H. Sadrozinski. et al., "4D tracking with ultra-fast silicon detectors", 2017 IOP]

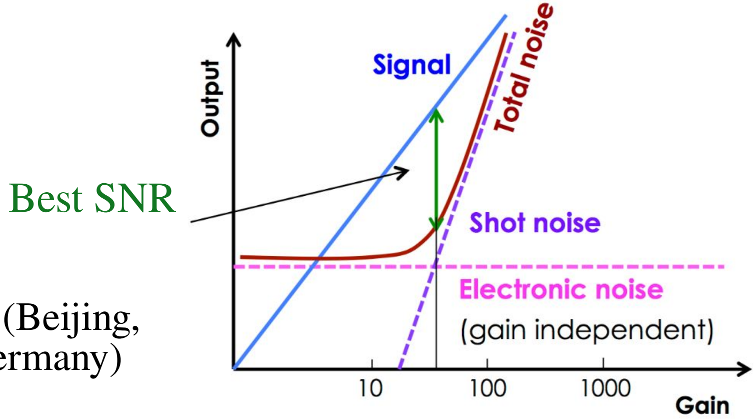


Low Gain Avalanche Detector (LGAD)

- Internal multiplication of charge → Highly doped p+ gain layer that increases the signal:
  - Improve the signal-to-noise ratio (SNR)
  - Improve the timing capabilities
- High electric field region in the multiplication layer
  - Amplification of the charge by impact ionization
  - Gain highly depends on:
    - Doping profile of the gain layer (GL)
    - Bias voltage
    - Temperature
- Foundries:
  - CNM (Barcelona, ES), FBK (Trento,IT), HPK (Japan), IHEP-NDL (Beijing, China), Micron(UK),BNL(USA) and in preparation: CIS(Erfurt, Germany)



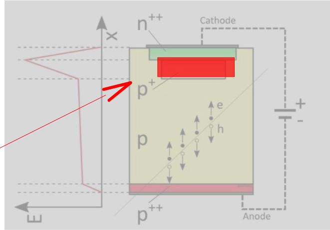
$$\sigma_{jitter} = \frac{Noise}{dV/dt} \approx \frac{t_{rise}}{S/N}$$

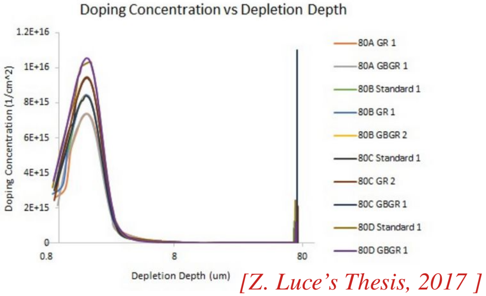


V. Sola et al., JINST (2017) 12 C02072

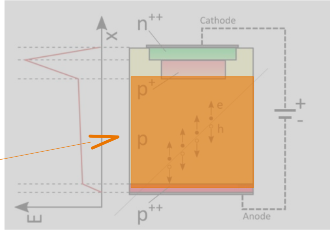
Low Gain Avalanche Detector (LGAD)

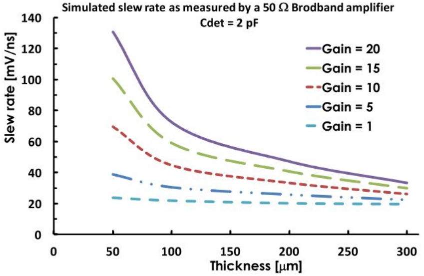
- LGAD performance can be optimized by:
  - Co-implantation of the GL with different dopants: C and Ga.
  - The position and doping profile of the GL: shape, concentration, and thickness.
  - Bulk thickness: going thinner will increase radiation hardness and improve the timing performance.
  - Geometry: standard LGAD technology in segmented detectors is affected by the fill factor issue. To solve this problem a different approach is needed:
    - Trench Isolation LGAD, AC-LGAD, Deep Junction LGAD or Inverse LGAD.





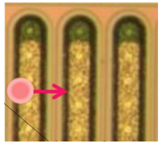
[Z. Luce's Thesis, 2017]

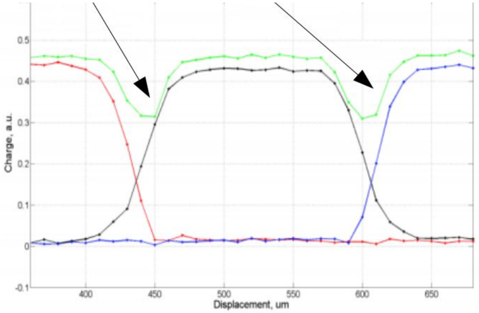




[H. Sadrozinski. et al., 2017 IOP]

Signal collected not passing through the multiplication layer

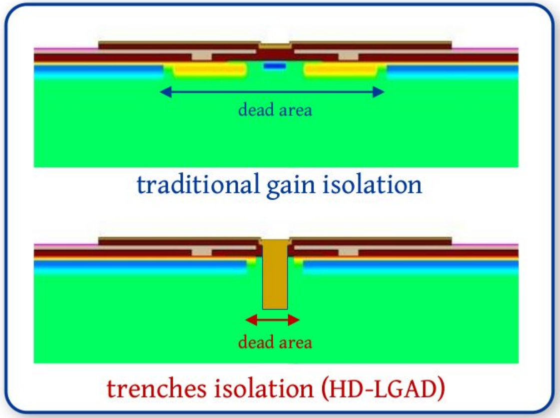




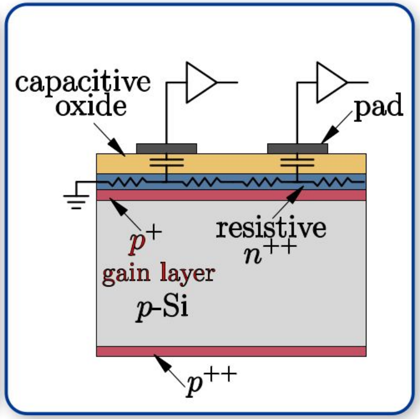
Fill factor and 4-D tracking performance

- Two opposing requirements to fulfill:
  - Good events **timing reconstruction**:
    - homogeneous signal with no dead areas
    - homogeneous weighting filed
  - But a pixel-border termination is needed to host all structures **controlling the Electric field**
- Several new approaches are being studied:

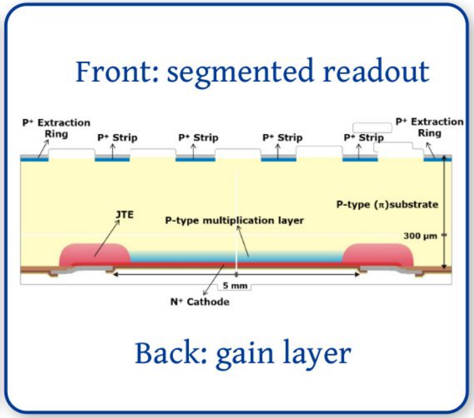
Trench Isolation LGAD



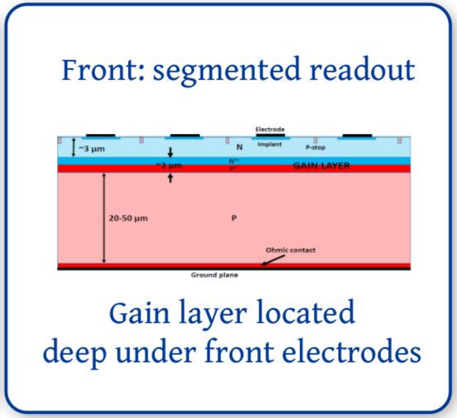
AC-LGAD



Inverse LGAD



Deep Junction LGAD



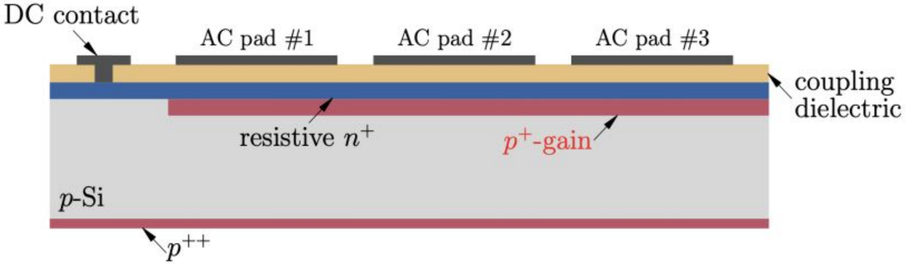
Concepts simulated, designed, produced and tested in 2015/19

..new concept 2020

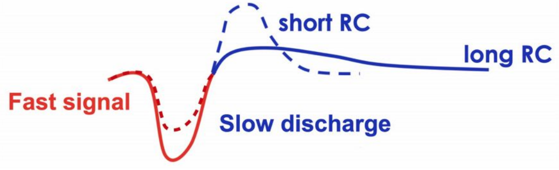
AC-LGAD (FBK): Resistive AC-coupled Silicon Detectors (RSD)

M. Tornago et al., RD50 Workshop (2020)

Cross-section of RSDs internal structure



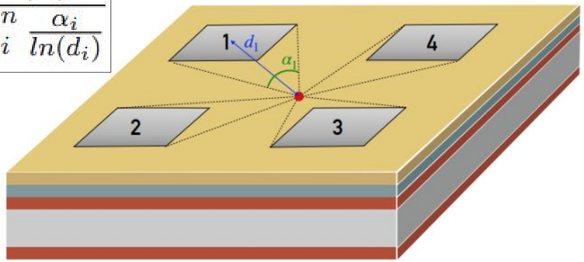
A typical signal generated by an RSD device



- Resistive AC-coupled Silicon Detectors (RSD) fabricated at FBK:
  - Designed as detectors with 100% fill factor for high precision 4D-tracking.
  - AC coupling occurs through the oxide layer, allowed by n^+ resistive electrode.
  - One continuous gain layer.
  - Segmentation obtained with read-out pads.
  - Spatial resolution improved by charge sharing
  - Benefit from excellent LGAD timing performances

Analytical model for hit reconstruction:

$$F_i(\alpha_i, d_i) = \frac{\frac{\alpha_i}{ln(d_i)}}{\sum_i^n \frac{\alpha_i}{ln(d_i)}}$$



F_i: fraction of the total signal amplitude seen on the pad i

d_i: distance from the hit point to the pad i metal edge

α_i: pad i angle of view

Signals time of arrival is also delayed as function of distance d:

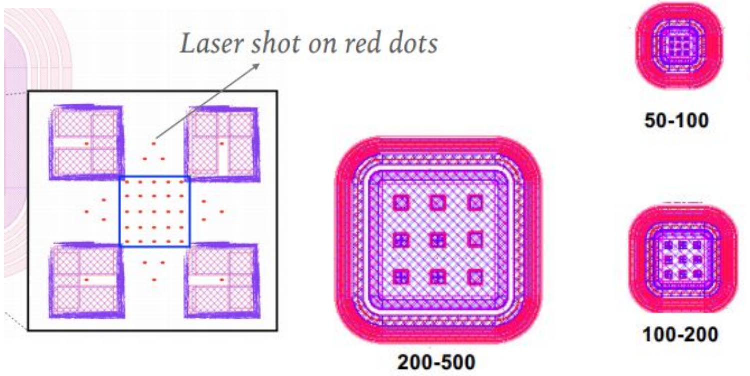
$$t(d) = t_0 + \textbf{delay} * d$$

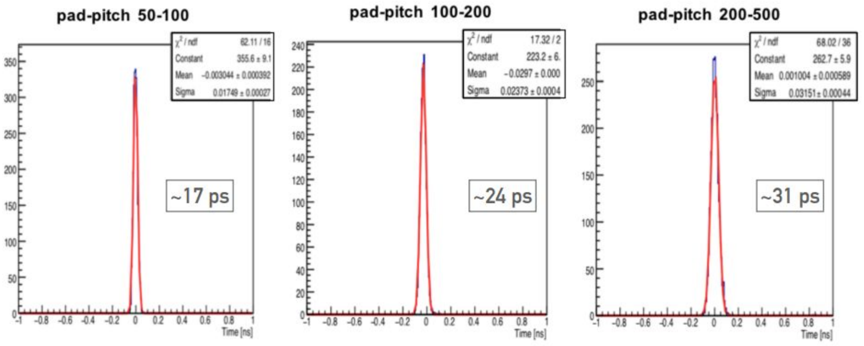
t_0 → *time in the pad centre*

AC-LGAD (FBK): Resistive AC-coupled Silicon Detectors (RSD)

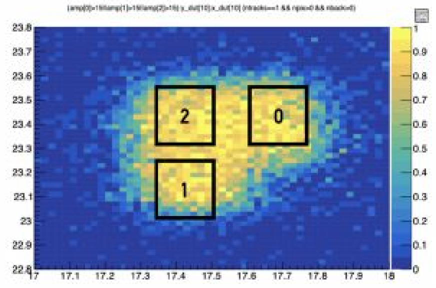
M. Tornago et al., RD50 Workshop (2020)

IR laser: timing performance

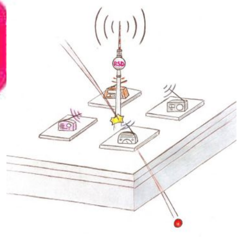


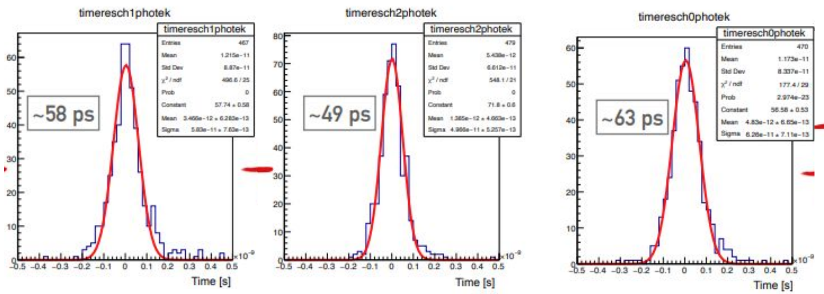


Test beam: timing performance

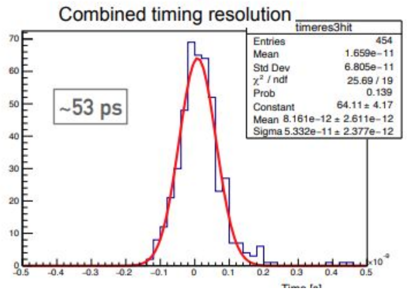


3 AC pads + Photek for timing studies





Expected resolution from 3 uncorrelated pads ~33ps

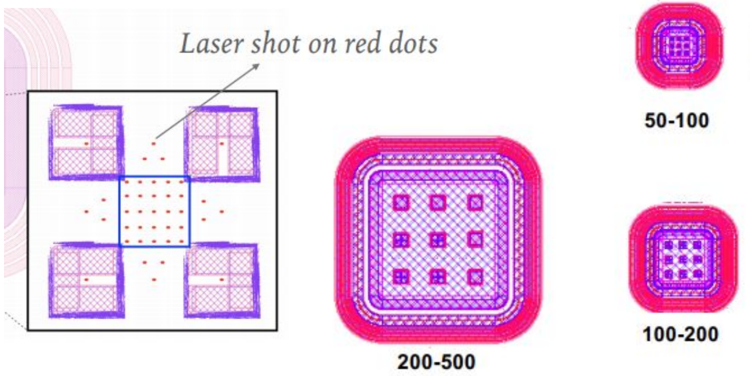


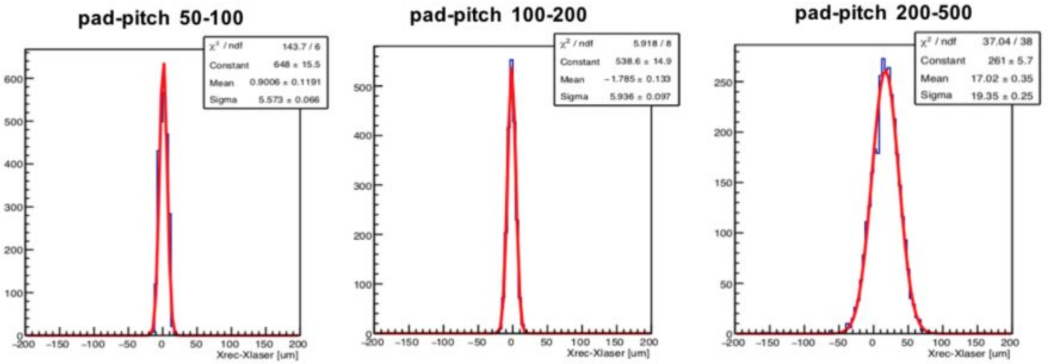
→ *combining signals from multiple pads, jitter term improves as it is uncorrelated, while **Landau term doesn't improve** since its fluctuation is correlated in the read-out pads*

AC-LGAD (FBK): Resistive AC-coupled Silicon Detectors (RSD)

M. Tornago et al., RD50 Workshop (2020)

IR laser: spatial resolution

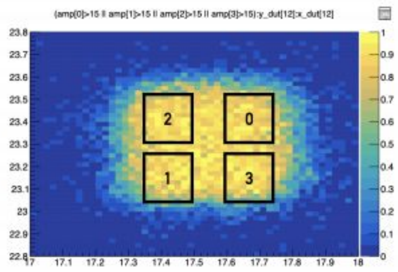




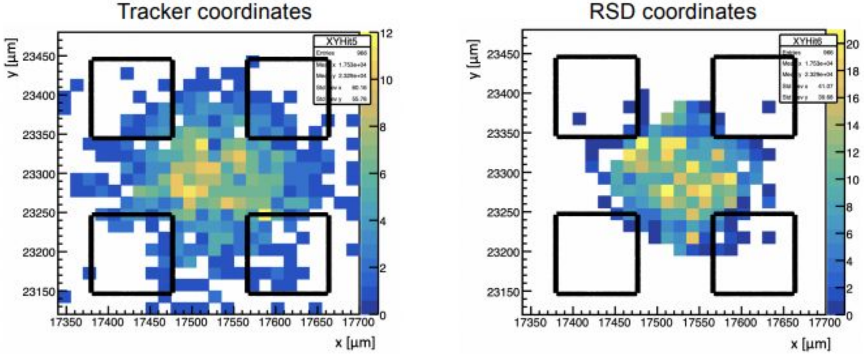
~6 µm binary ~28 µm	~6 µm binary ~58 µm	~20 µm binary ~140 µm

Test beam: spatial resolution

4 AC pads for position studies



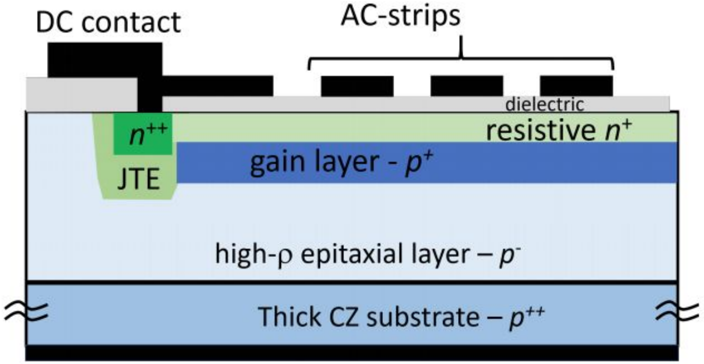
Reconstruction of events in which all the 4 pads see a signal



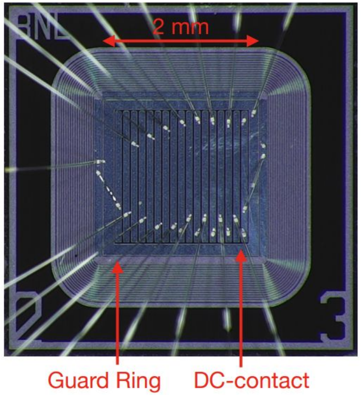
- *Evaluation of the system spatial resolution as $x_{tracker} - x_{reco}$, completely dominated by the tracker resolution (~45 µm)*

AC-LGAD (BNL)

K. Folan et al., RD50 Workshop (2020)

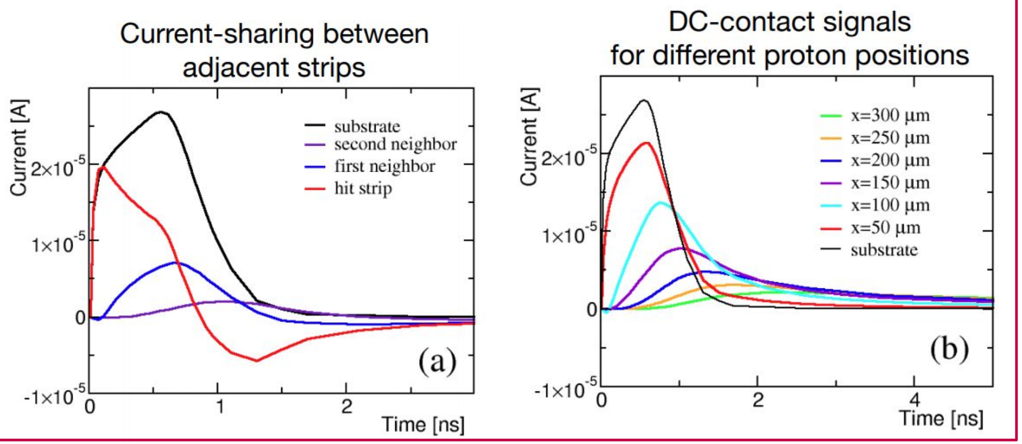


- AC-coupled LGADs solve the fill factor problem
  - Uninterrupted gain layer, read-out with AC-coupled electrodes
  - Smaller pitch and signal sharing between pads
  - Can easily achieve O(10 um) and 30 ps time resolution with the same sensor



- Fabricated at BNL
  - 50 um thick p-substrate
  - Depletion voltage: 150V
  - Breakdown voltage: 225 V at 20ºC
  - Operational bias voltage: 210 V

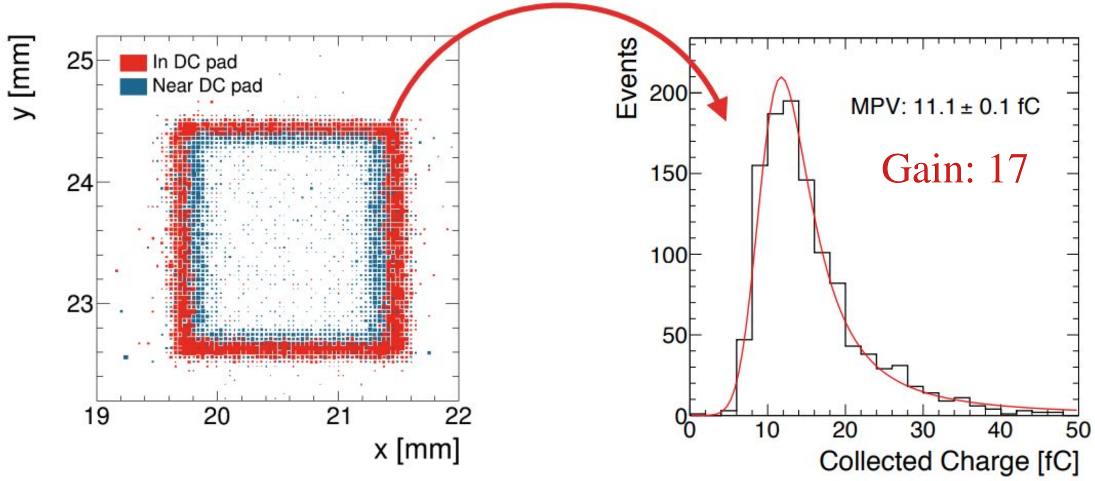
AC-LGAD simulation (SILVACO)



AC-LGAD (BNL)

K. Folan et al., RD50 Workshop (2020)

- Tested at Fermilab Test Beam
  - DC-pad behaves like a standard LGAD



- Within a 2 or 3 hit cluster
  - leading strip: 45-47 ps
  - subleading: 70-90 ps
  - no significant improvement from combining hits within clusters - at most few ps expected

Improve: lower electronics noise.

Study the impact of the gain and geometry in the charge sharing.

- Our measurement
  - $\sigma(x_{sensor} - x_{tracker})$
  - dominated by tracker resolution ~50 μm*

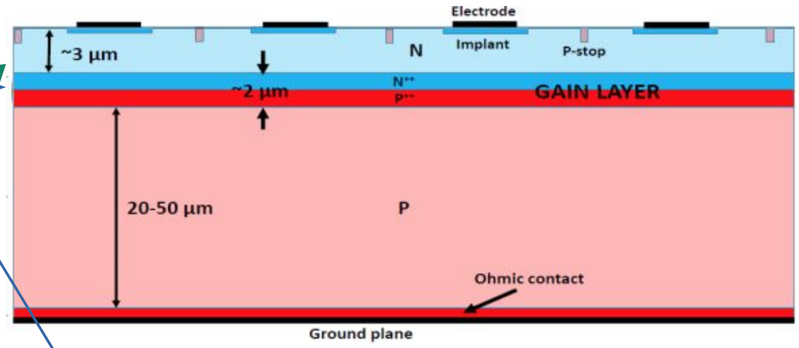
Improve tracker resolution for the next test beams.

- Study the efficiency as a function of proton x and y position
  - Efficiency definition: amplitude > 100 mV, t_{peak} ~ consistent with MIP
  - Measured efficiency = 99.4±0.1
  - Observed no loss of efficiency between strips!

Deep Junction LGAD

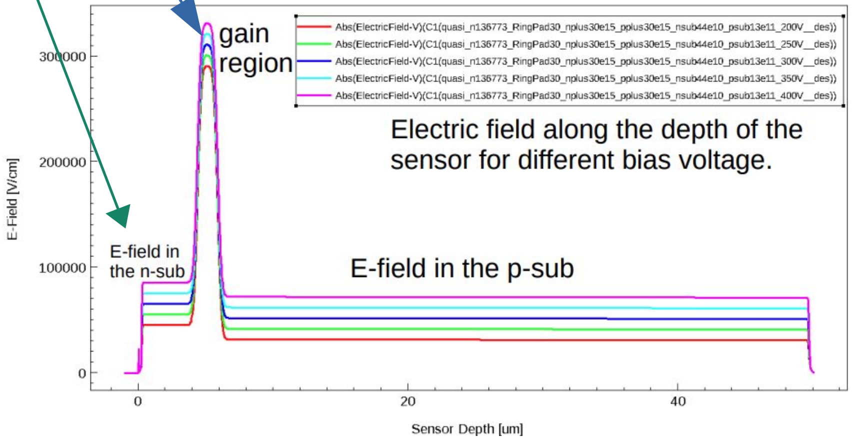
Y. Zhao et al., RD50 Workshop (2020)

- Working principle and ideas of DJ-LGAD:
  - High electric field region is localized within the sensors. Junction region burying ~5 um below the surface.
  - A low doped n-type substrate lowers the electric field near the surface.
  - Standard (pixel) segmentation techniques can be used to increase granularity. JTE structure is not needed!
  - The n-type substrate is DC coupling to the electrode.

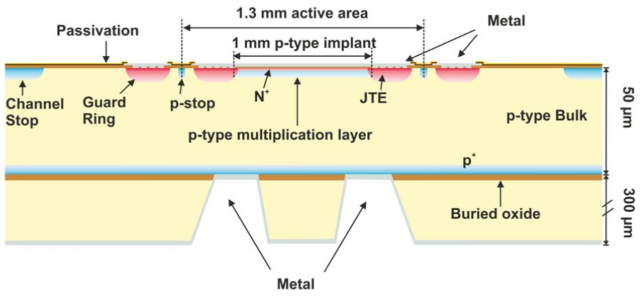


First prototype is expected by the end of the year !

Vbias from 200V to 400 V



Standard LGAD layout for comparison



Inverse LGAD (I-LGAD)

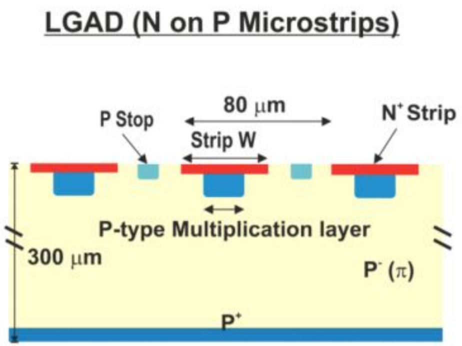
Centro Nacional de Microelectrónica IMB

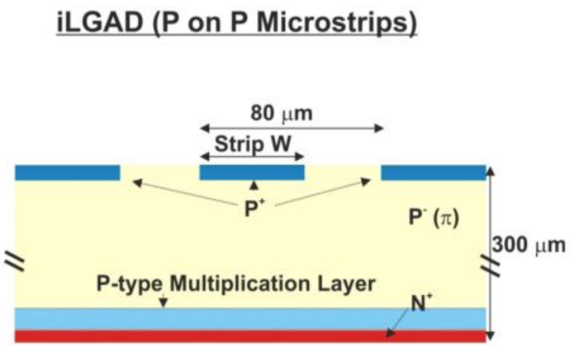
RD50

E. Curras et al., VCI (2019)

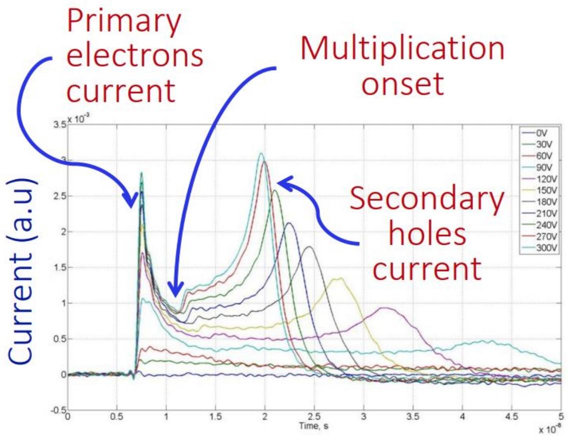
Multiplication layer divided into strip
Collects negative carriers (e^-)
Simple single side process

Multiplication layer extended over the electrode
Collects positive carriers (h)
Complex double side process





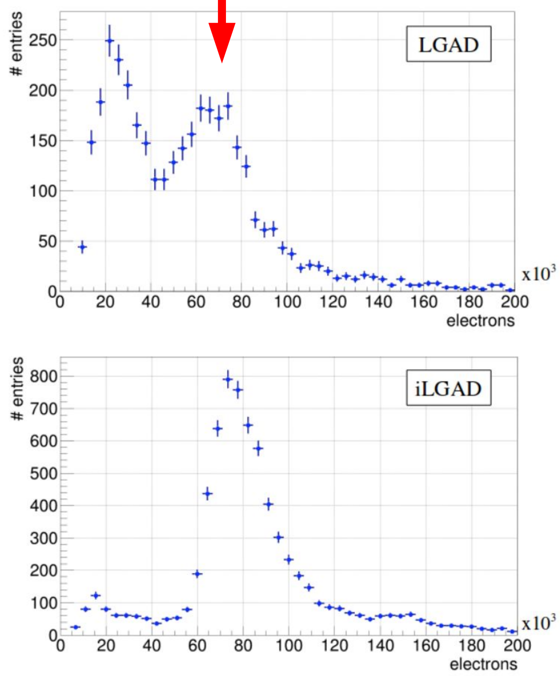
300um I-LGAD signal shape



>> Better performance expected for **thin sensors** as the rise time will improve significantly.

Not amplified signals

Amplified signals



100% Fill factor proven with TB data

Starting this year: "Proof-of-concept and radiation tolerance assessment of thin pixelated ILGAD"

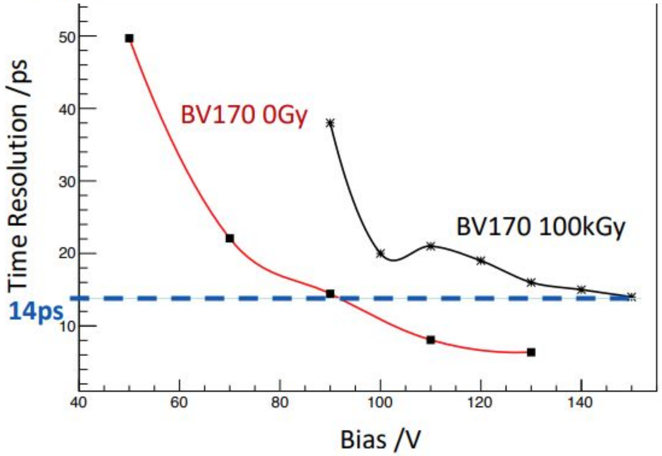
LGAD performance after irradiation

Y. Fan et al., RD50 Workshop (2020)

- LGAD developed by **IHEP-NDL in China**
  - Epitaxial layer: 33 um thick
  - Resistivity: 100 and 300 ohm·cm
  - Different doping profiles

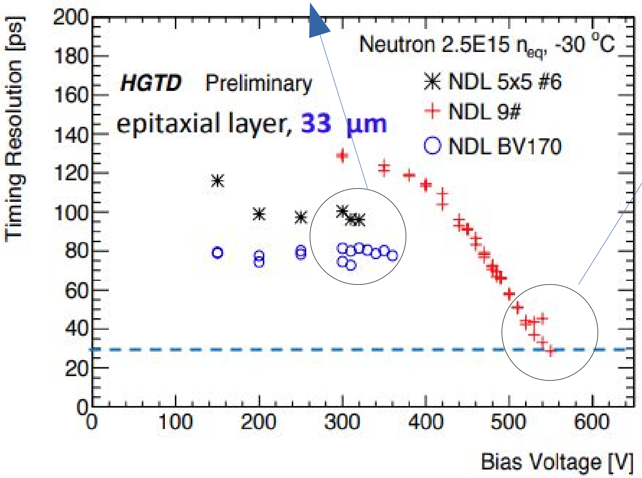
X-ray irradiation and Laser measurements

- The timing resolution contributed from jitter is about 14 ps
- The time resolution have a potential to satisfy the request 70 ps



Neutron irradiation and beta measurements

96 ps > 70 ps (worse because the wafer lower resistivity)



30 ps << 70 ps

LGAD performance after irradiation

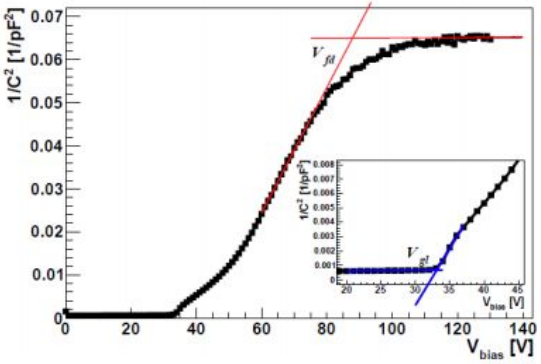
A. Howard et al., RD50 Workshop (2020)

- LGAD performance dependence on **neutron fluxes**
  - HL-LHC fluxes will be around 10^7-10^8cm^{-2}s^{-1} … but irradiation studies are done at much higher fluxes
  - Irradiation with neutrons at three different fluxes: 1.6e10, 1.6e12 and 7e12 cm^{-2}s^{-1}
  - Same irradiation fluence: 4E14 n_{eq}/cm^2
  - Same annealing time: 80 min at 60^{O}C
  - Effects in the bulk? No effect in the N_{eff} or I_{leak} … effects to removal of initial dopants?

➢LGADs from ATLAS-HGTD prototype run with HPK were used – they're different in implant dose and also in depth profile of the implant

Sample name	Thickness	Vgl [V]	Vfd [V]
HPK-3.1-50	50 µm	42	49
HPK-3.2-50	50 µm	56	64

Samples

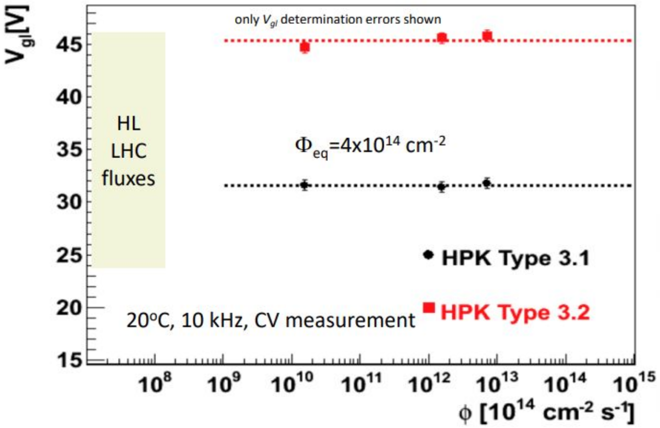


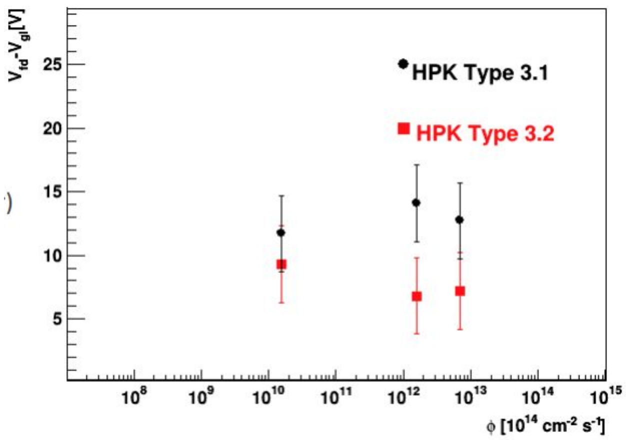
LGAD performance after irradiation

A. Howard et al., RD50 Workshop (2020)

Data from the CV curves

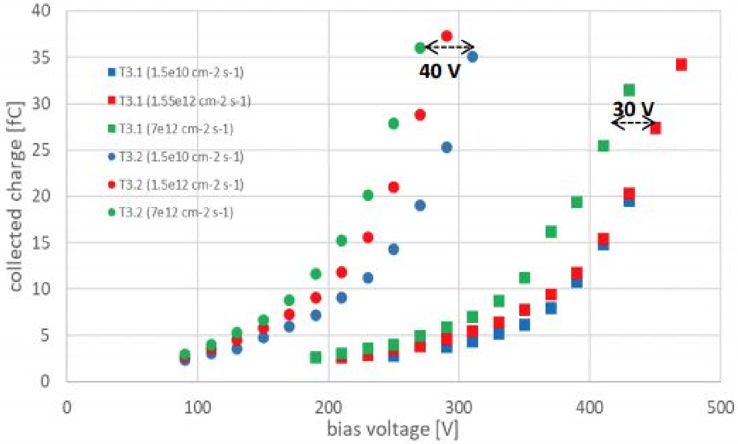
No flux impact on the V_{GL} and V_{FD}

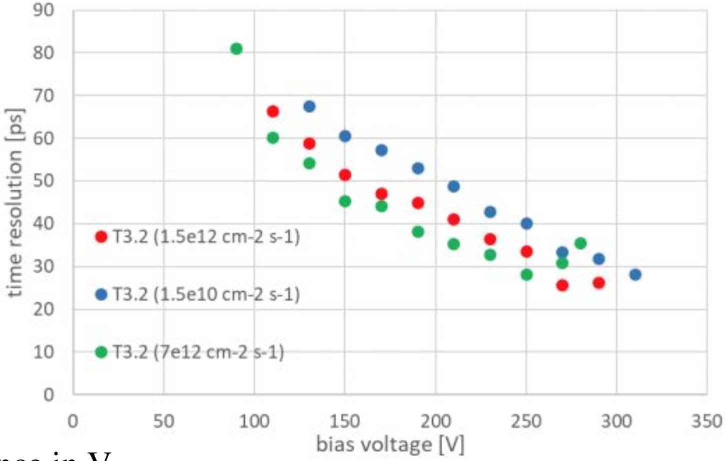




Beta source

No effects of different flux observed in the gain and timing performance





* Small difference between the samples can be to large extent explained by the small difference in V_{GL}

LGAD performance after irradiation

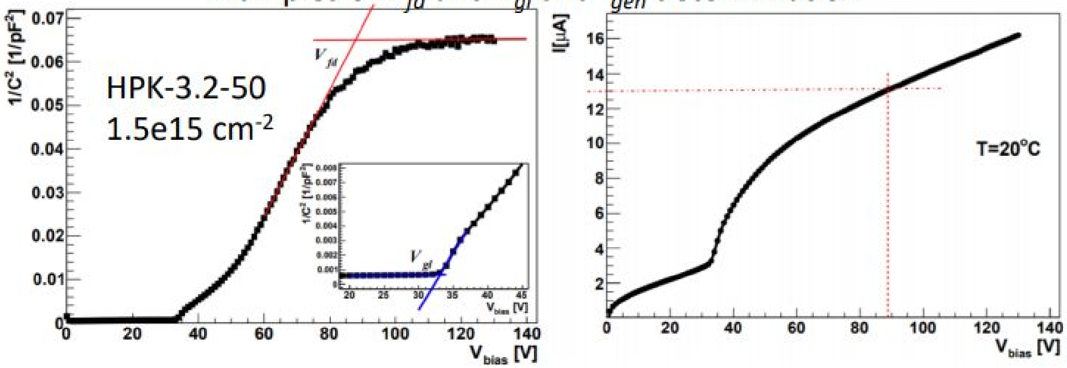
G. Kramberger et al., 2020 JINST 15 P08017

- **Annealing effect** on the LGAD performance
  - Many annealing studies on LGAD but almost all of them at 80 min at 60^{O}C
  - Annealing is important in the detector operation.
  - Detector bulk properties change with annealing. Is annealing also influencing initial acceptor removal?

Samples

Sample	Thickness	V_{gl}	V_{fd}	Φ_{eq} $[10^{14}$ cm$^{-2}]$
HPK-1.1-35	35 μm	31 V	195 V	8, 15, 30
HPK-1.2-35	35 μm	33 V	36 V	8, 15, 30
HPK-3.1-50	50 μm	42 V	49 V	8, 15, 30
HPK-3.2-50	50 μm	56 V	64 V	4, 6, 8, 15, 22.5, 30

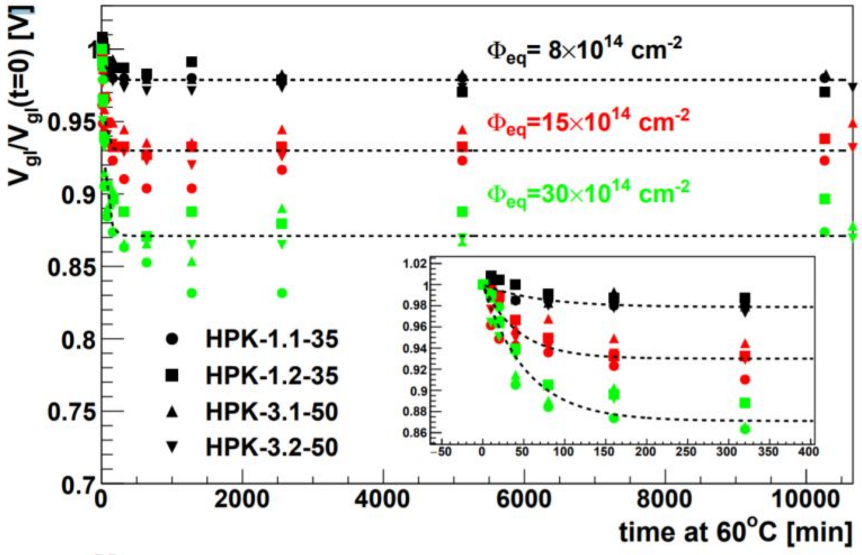
Examples of V_{fd} and V_{gl} and I_{gen} determination



LGAD performance after irradiation

G. Kramberger et al., 2020 JINST 15 P08017

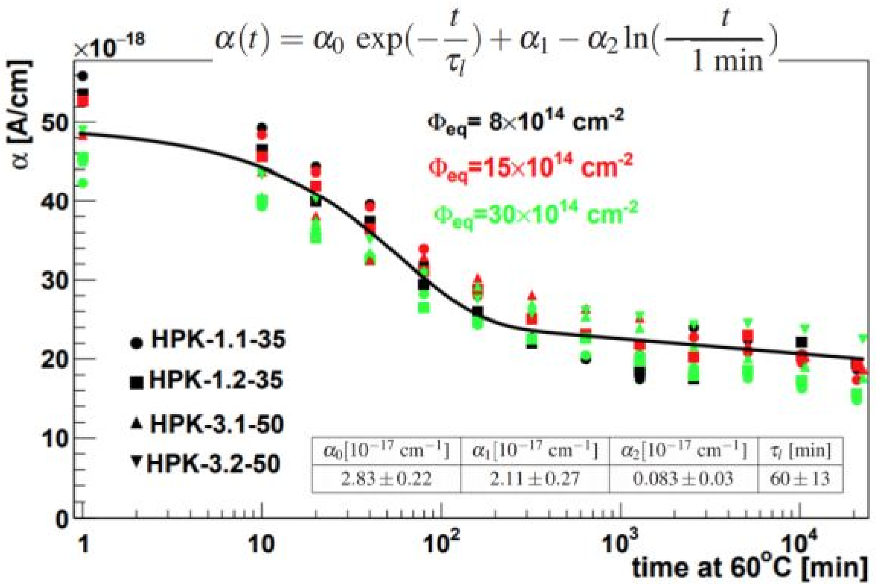
Annealing of V_{gl}



$$\frac{V_{gl}}{V_{gl}(t=0)} = F \cdot \exp(-t/\tau_{gl}) + (1-F)$$

average $\tau_{gl} = 50 \pm 5$ min

Annealing of the space charge in the bulk and generation current



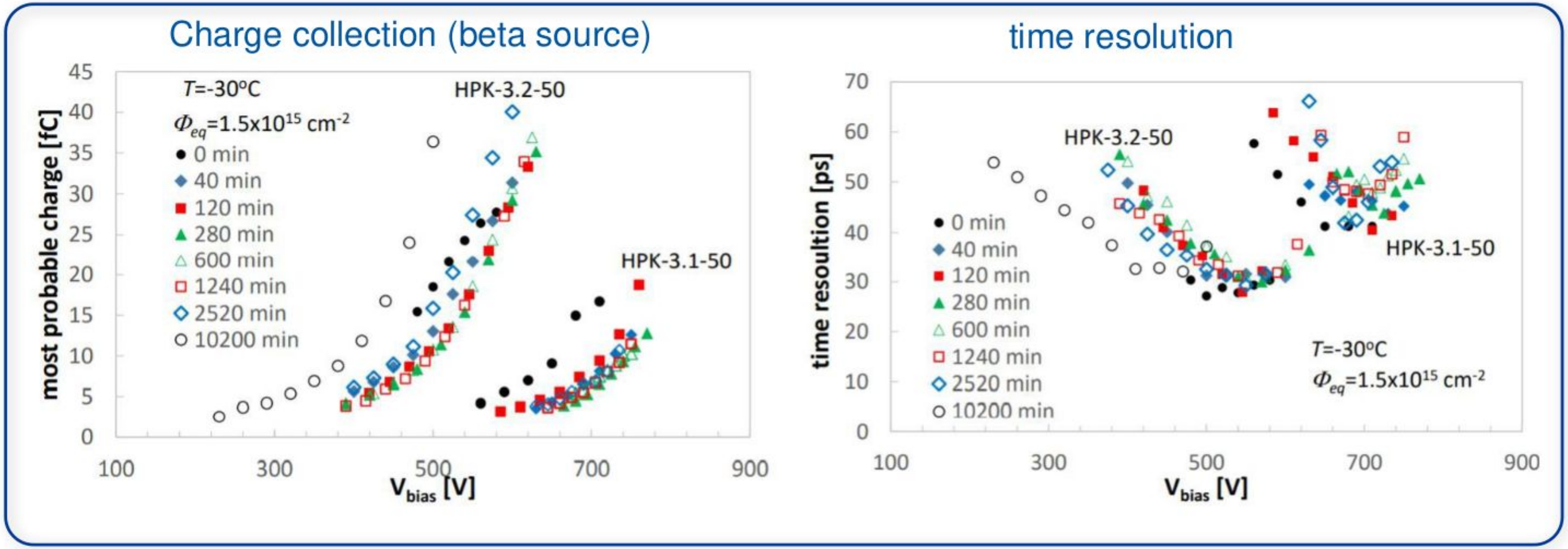
$I_{leak} = G \cdot I_{gen}$

- At the standard annealing point of 80min @ 60°C we get a conservative estimation of the required operation voltage.
- Generation current shows universal behavior and in agreement with previous measurements

LGAD performance after irradiation

G. Kramberger et al., 2020 JINST 15 P08017

- Annealing changes N_{eff} with time after irradiation: check for influence on timing response.
- Important for temperature scenario in experiments!

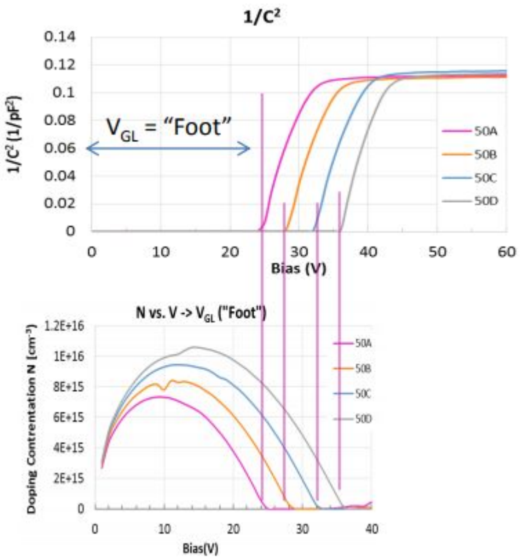


Better charge collection and time resolution for 0 min annealing;
after that no strong change (with exception of very long annealing > 10.000 min)

LGAD performance after irradiation

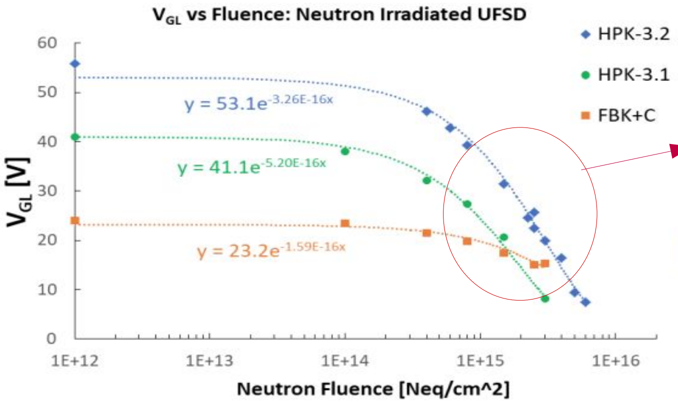
H. Sadrozinski et al., RD50 Workshop (2020)

- **Acceptor removal** dependence with protons of different energies vs neutrons
  - Irradiation with protons at CYRIC in Japan, LANL Los Alamos in USA and IRRAD at CERN
  - Proton energies of 70 MeV, 800 MeV and 23 GeV respectively.



Samples

Manufacturer	Type	Active Thickness	Physical Thickness	V_{FD}	V_{BD}	Carbon
HPK	HPK-3.1	50 µm	300 µm	50 V	250 V	no
HPK	HPK-3.2	50 µm	300 µm	70 V	120 V	no
FBK	FBK3+C	55 µm	500 µm	25 V	400 V	yes
FBK	FBK3noC	55 µm	500 µm	25 V	400 V	no



Neutrons!!

Strong sensor dependence but at high fluence all kind of merge

Preliminary

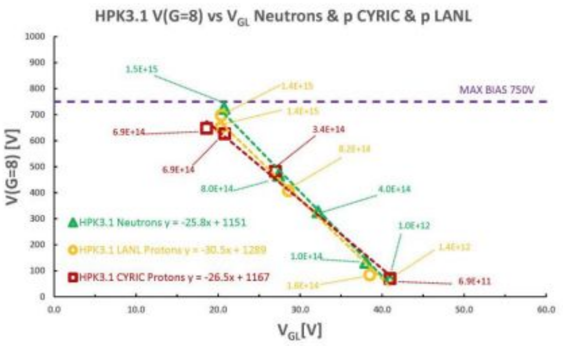
V_{GL} vs Fluence Φ exhibits Acceptor Removal

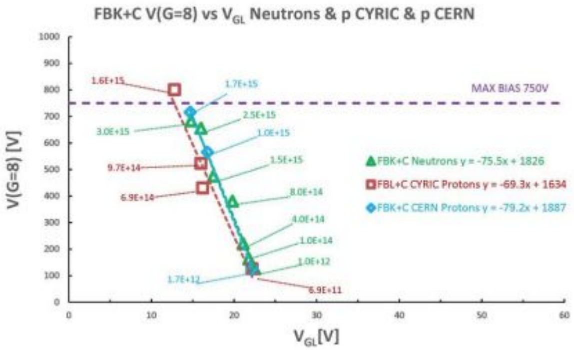
Neutrons: $V_{GL}(\Phi) = V_{GL}(0) * e^{-cn*\Phi n}$

cn = acceptor removal constant for neutrons

LGAD performance after irradiation

H. Sadrozinski et al., RD50 Workshop (2020)





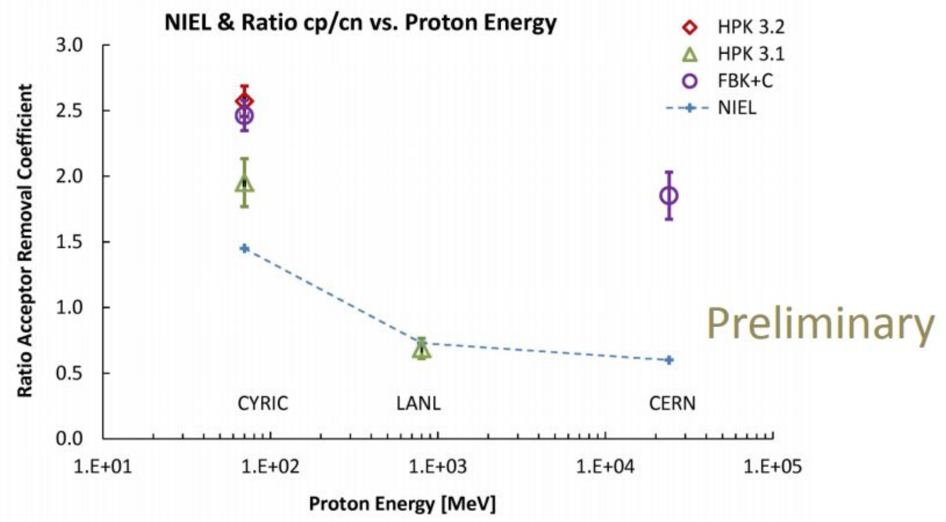
- **On the same sensor, neutrons and all protons have the same slope**

Gain depends on doping density and bias In the same way, regardless how the acceptors have been removed

- **Different sensors have different slopes**

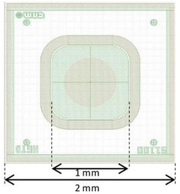
Gain dependence on doping profile and bias are different for different sensors

- No clear general trend (besides cp/cn > NIEL):
  - Is cp/cn on "FBK+C" independent of the proton energy
  - Does cp/cn on "HPK3.1" continue to decline with energy beyond 800 MeV?
  - Further studies are needed ...



LGAD performance after irradiation

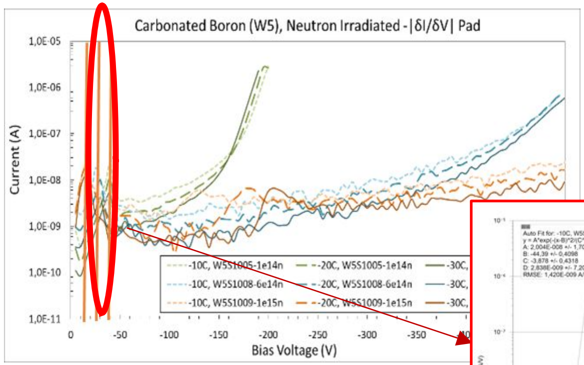
- CNM single diodes from run 10478 and 10924
  - 50 um active thickness on 250 um SoI wafers
  - **Boron, Boron+Carbon diffused and Gallium implanted gain layer**
  - Irradiations:
    - Protons at CERN-PS: 23 GeV
    - Reactor neutrons at JSI
  - 5 fluences: 1e14, 6e14, 1e15, 3e15, 6e15 n_{eq}/cm^2



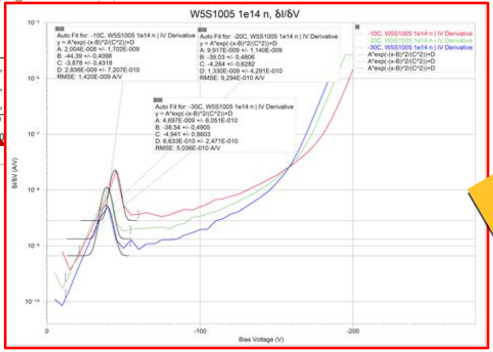
E. Gkougkousis et al., RD50 Workshop (2020)

30 sensors x 3
90 Series of measurements

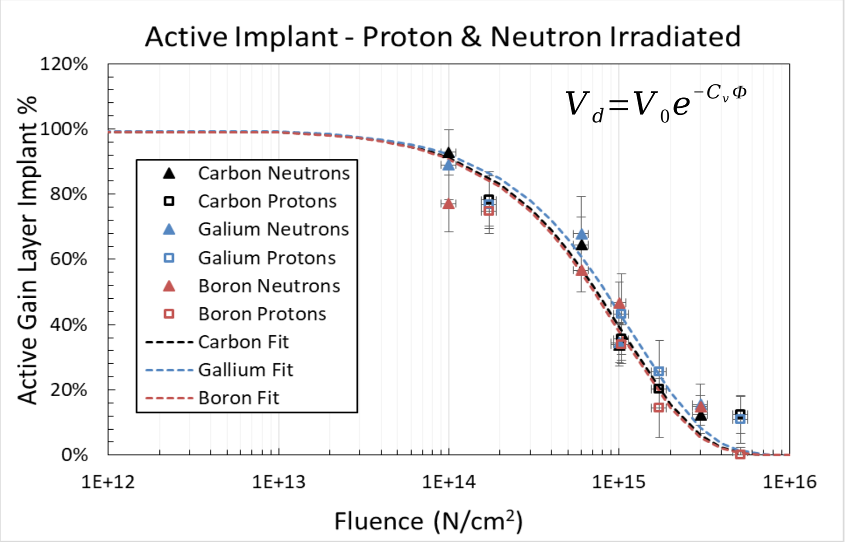
- Depletion voltage by Gaussian fit on IV derivative
- Repeated for -10, -20 & -30°C
- Active dopant extrapolated



Gain Layer depletion voltage



$$f(V)=\left|\frac{\partial I}{\partial V}\right|$$

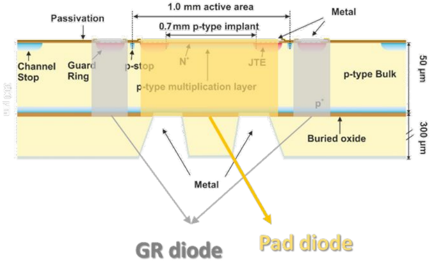


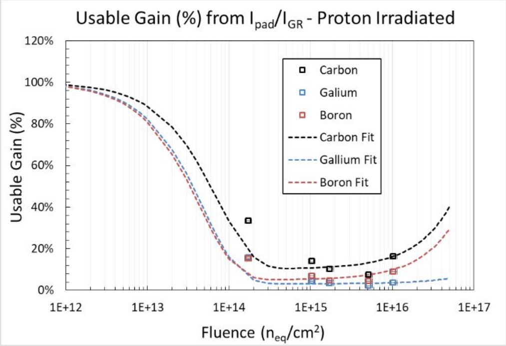
No active dopant difference between different implantation types – neutron/proton

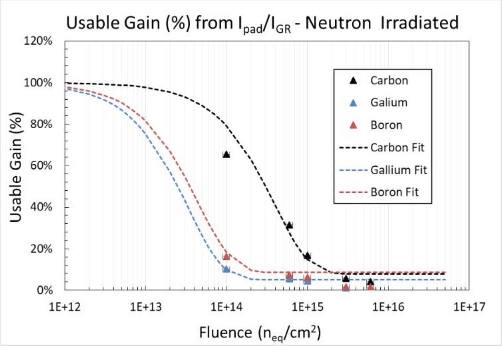
LGAD performance after irradiation

E. Gkougkousis et al., RD50 Workshop (2020)

- Usable gain estimated by comparing GR-pad leakage current
  - GR – gain region share shame cathode
  - Separate removal factors for Protons/ neutrons
  - Exponential behavior in depleted region



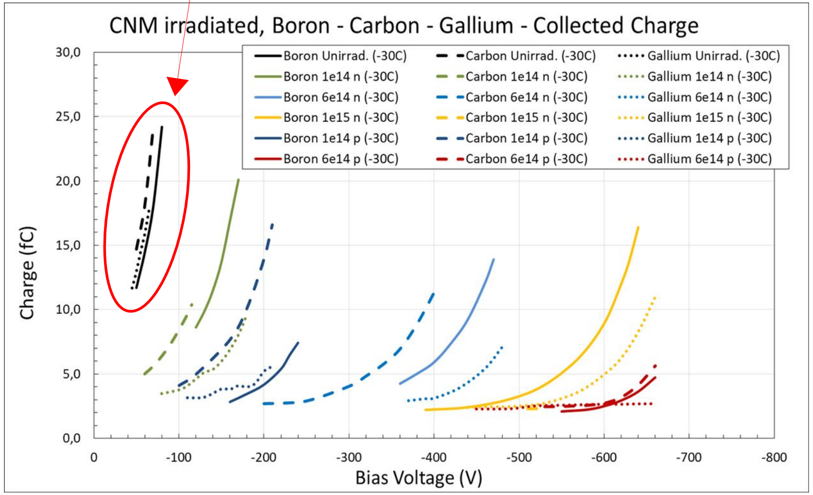




Sensor Gain

- Collected charge measured with MIPs
  - 5k events, beta measurements with Sr90
  - Repeated in -10°C, -20°C -30°C with concurrent results

Very similar performance before irradiation !

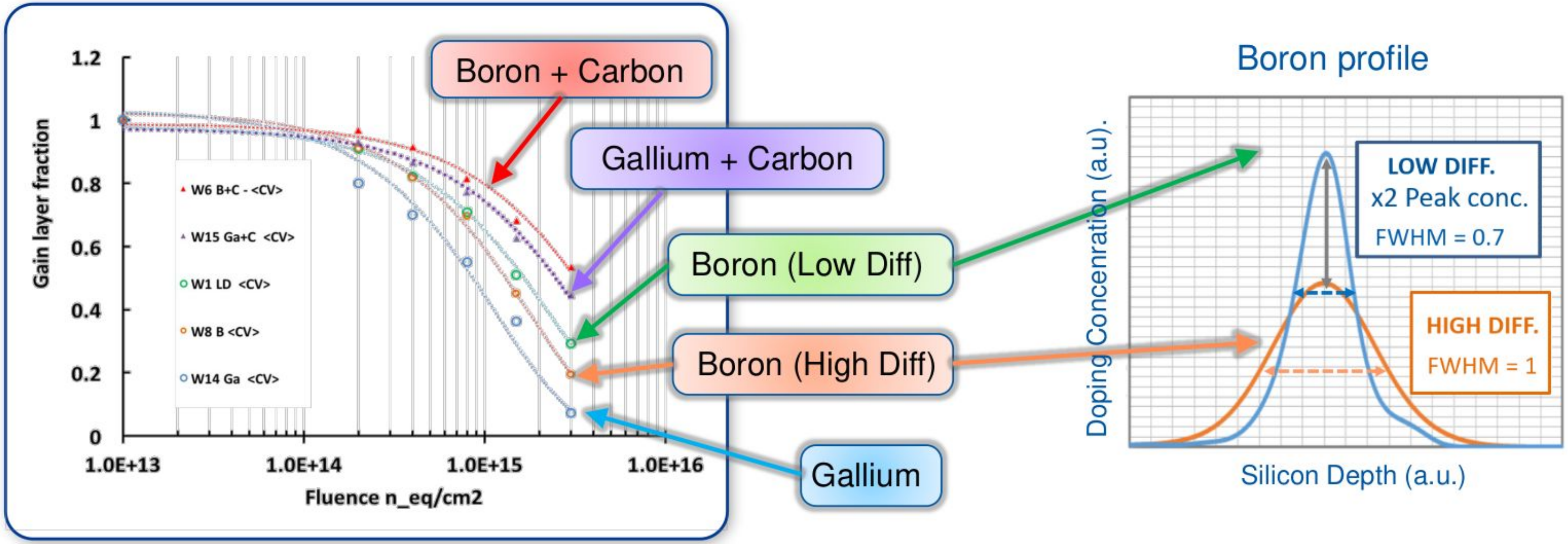


Both methods agree: Gallium ~20% worse and carbon ~ 20% better

LGAD performance after irradiation

Summary

- Defect Engineering of the gain layer
  - Carbon co-implantation mitigates the gain loss after irradiation
  - Replacing Boron by Gallium did not improve the radiation hardness
- Modification of the gain layer profile
  - Narrower Boron doping profiles with high concentration peak (Low Thermal Diffusion) are less prone to be inactivated



[G.Paternoster, FBK, Trento, Feb.2019]

Summary and conclusions

- Studies very focused at this moment toward the **ATLAS and CMS timing detectors**.
  - Requirements seemingly achieve up to fluences of 1e15 n_{eq}/cm^2.
  - Important to study mix irradiations: protons + neutrons.
- Studying the influence of the possible mitigation of the radiation effect on thin LGADs using **Gallium and Carbon as a GL dopants**.
  - Carbon helps to mitigate radiation effect. Gallium does not seems to help.
- Detailed **annealing studies** were done. It is an important effect to keep under control, but not important effects observed in timing resolution and collected charge.
- **Increasing the fill factor** of the LGAD technology. Several promising new approaches are being studied.
- Going forward on radiation tolerance: studies ongoing on radiation effects **up to fluences of 1e17 n_{eq}/cm^2**.

Thank you for your attention