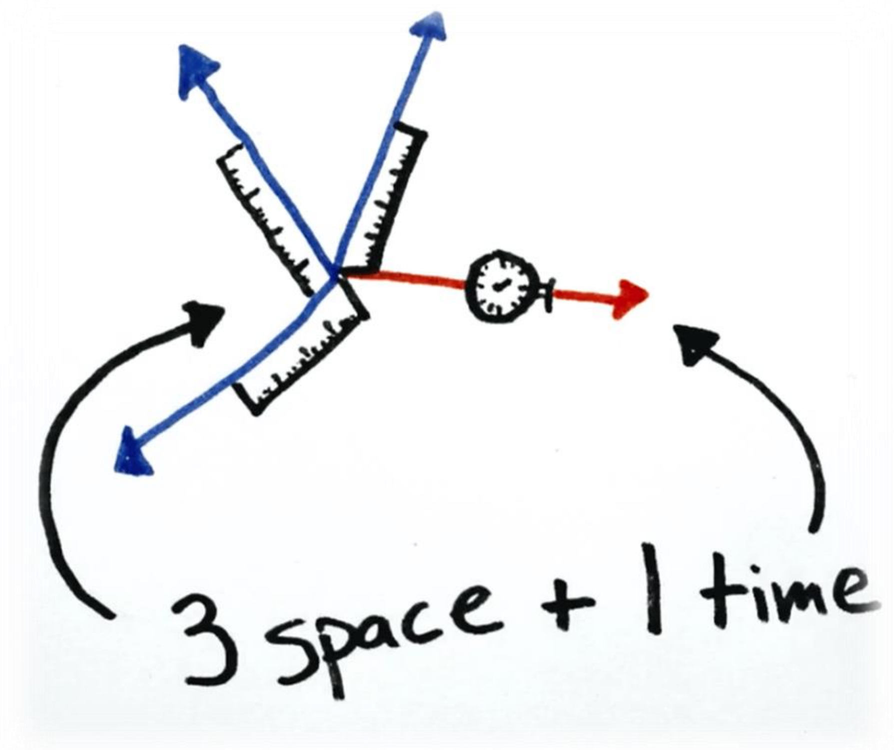
Challenges and new trends in LGAD technologies

32nd International Workshop on Vertex Detectors

October 17th, 2023



Iván Vila Álvarez

Instituto de Física de Cantabria (CSIC-UC)

Outline

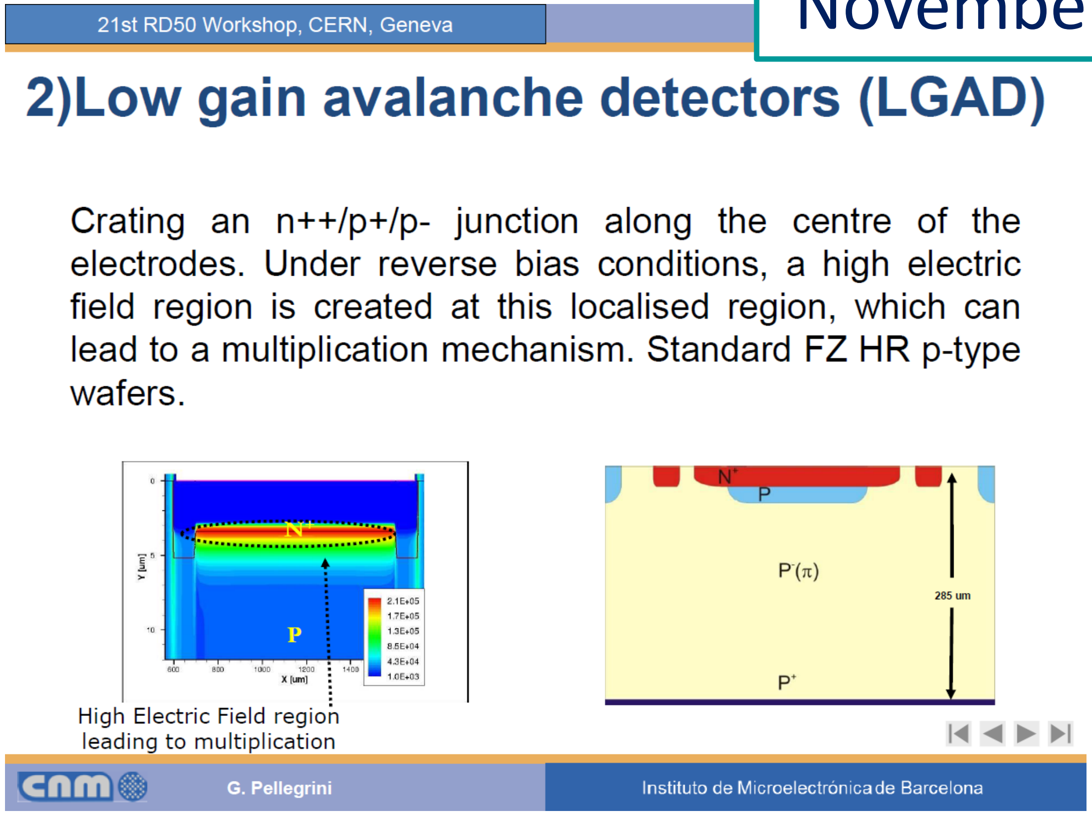
- The reasons behind the widespread interest in LGADs or why I not going to talk about the main hidden R&D challenge.
- Solutions for the HL-LHC R&D challenges
- Strategies to address forthcoming challenges in High-Energy Physics (HEP):
  - High-precision 4D tracking
  - Extreme radiation tolerance.
- Outlook

Early Historical developments :The first appearance on scene of the LGAD

Why LGADs became such a hot topic in the last decade? My recall of how the whole thing started

Status of the RD50 funding request for "detectors with enhanced multiplication"

November 2012



21st RD50 Workshop, CERN, Geneva

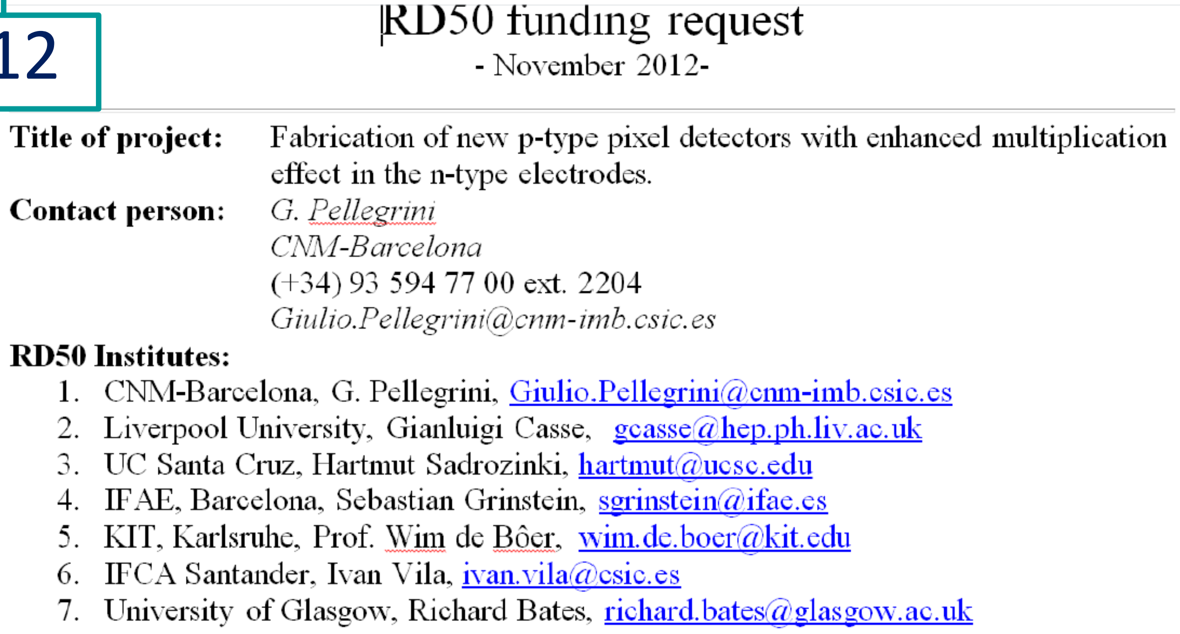
2)Low gain avalanche detectors (LGAD)

Crating an n++/p+/p- junction along the centre of the electrodes. Under reverse bias conditions, a high electric field region is created at this localised region, which can lead to a multiplication mechanism. Standard FZ HR p-type wafers.

High Electric Field region leading to multiplication

G. Pellegrini

Instituto de Microelectrónica de Barcelona



RD50 funding request

- November 2012-

Title of project: Fabrication of new p-type pixel detectors with enhanced multiplication effect in the n-type electrodes.

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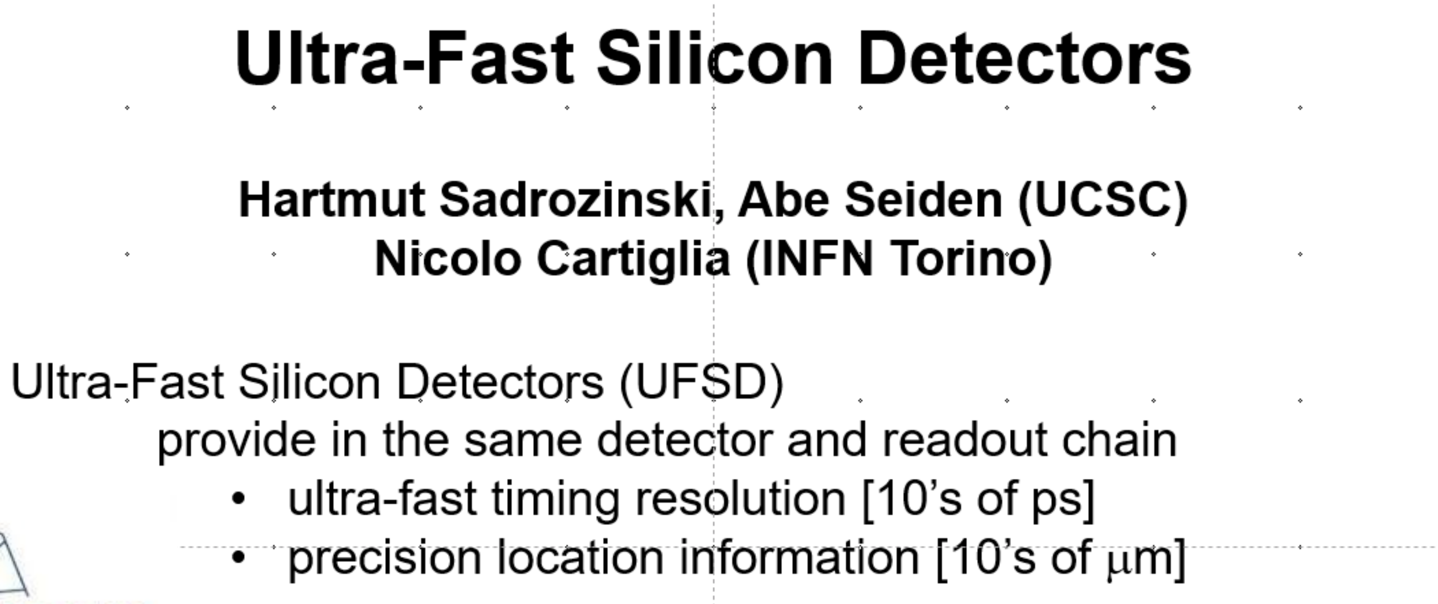
Who requested the LGAD? A few months before in Bari…



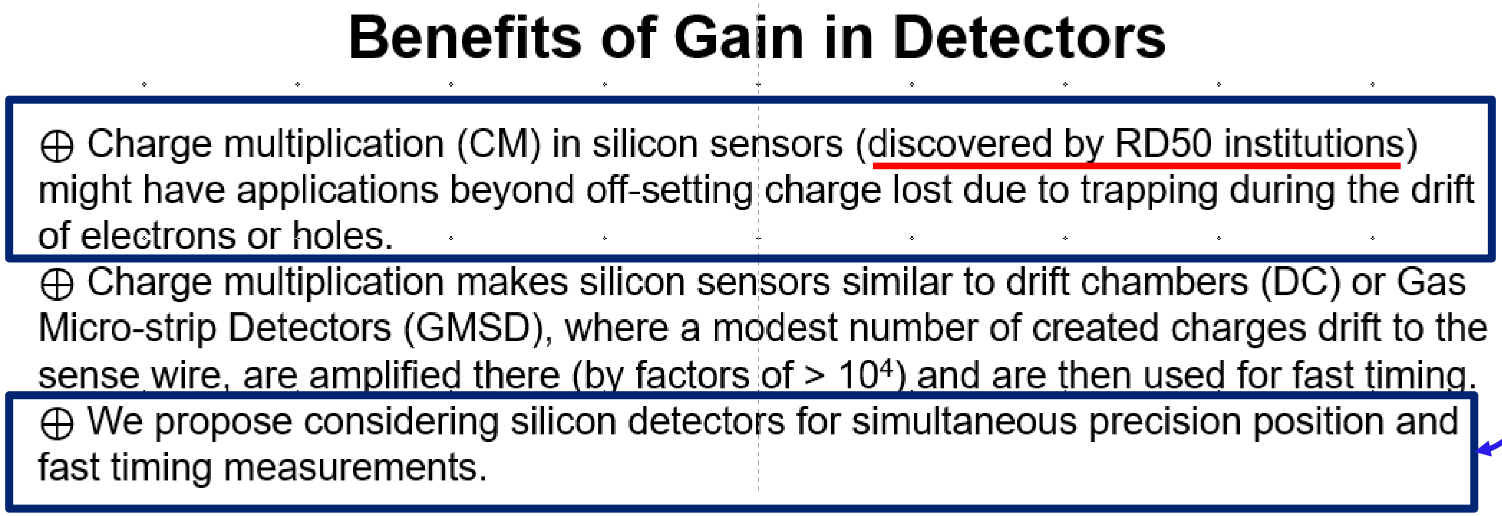
Ultra-Fast Silicon Detectors

Hartmut Sadrozinski, Abe Seiden (UCSC)
Nicolo Cartiglia (INFN Torino)

Ultra-Fast Silicon Detectors (UFSD)
provide in the same detector and readout chain
- ultra-fast timing resolution [10's of ps]
- precision location information [10's of μm]

June 2012

Great vision!



Benefits of Gain in Detectors

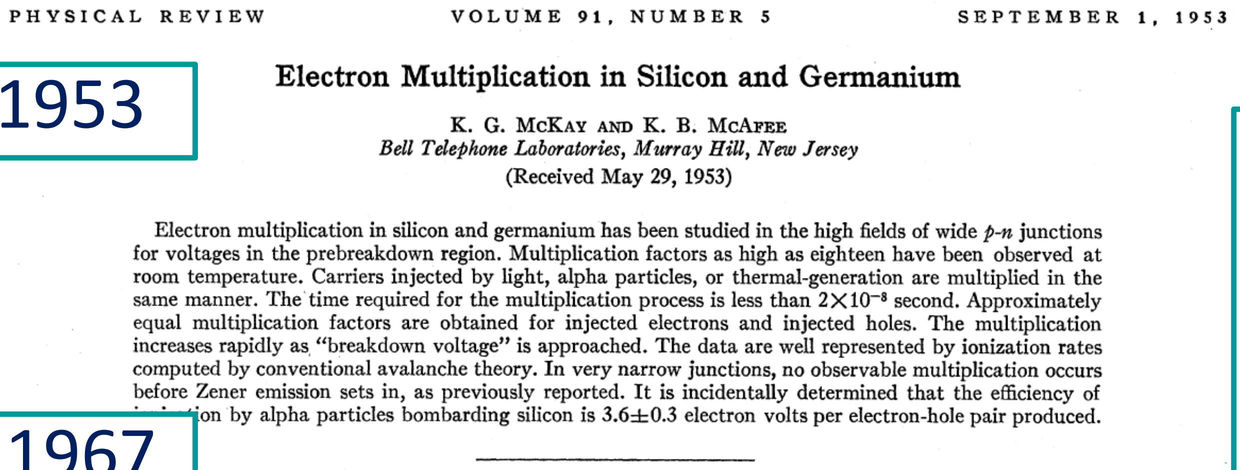
⊕ Charge multiplication (CM) in silicon sensors (discovered by RD50 institutions) might have applications beyond off-setting charge lost due to trapping during the drift of electrons or holes.

⊕ Charge multiplication makes silicon sensors similar to drift chambers (DC) or Gas Micro-strip Detectors (GMSD), where a modest number of created charges drift to the sense wire, are amplified there (by factors of > 10^4) and are then used for fast timing.

⊕ We propose considering silicon detectors for simultaneous precision position and fast timing measurements.

Sensor-wise, no such a novelty…

Sep 1953



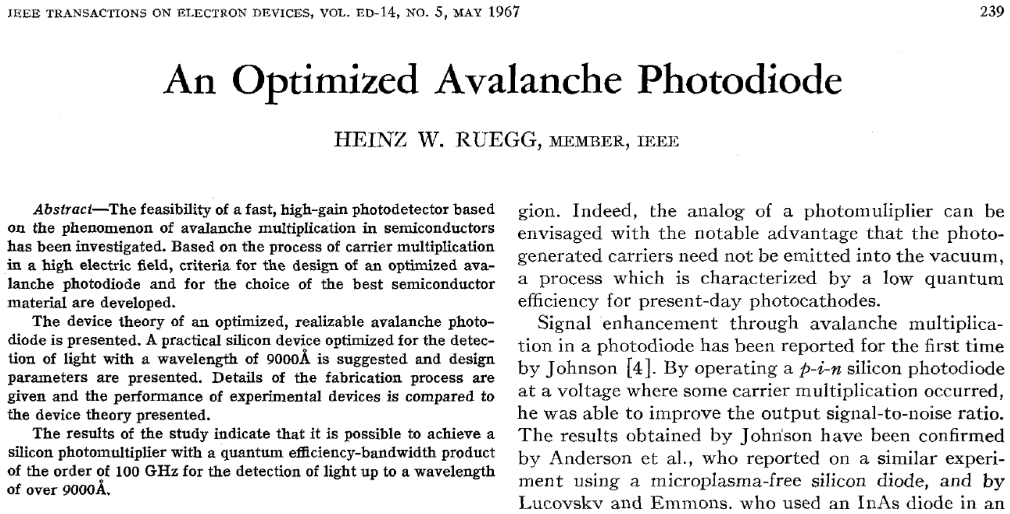
PHYSICAL REVIEW VOLUME 91, NUMBER 5 SEPTEMBER 1, 1953

Electron Multiplication in Silicon and Germanium

K. G. McKay and K. B. McAfee
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received May 29, 1953)

Electron multiplication in silicon and germanium has been studied in the high fields of wide p-n junctions for voltages in the prebreakdown region. Multiplication factors as high as eighteen have been observed at room temperature. Carriers injected by light, alpha particles, or thermal-generation are multiplied in the same manner. The time required for the multiplication process is less than 2×10^{-8} second. Approximately equal multiplication factors are obtained for injected electrons and injected holes. The multiplication increases rapidly as "breakdown voltage" is approached. The data are well represented by ionization rates computed by conventional avalanche theory. In very narrow junctions, no observable multiplication occurs before Zener emission sets in, as previously reported. It is incidentally determined that the efficiency of ionization by alpha particles bombarding silicon is 3.6±0.3 electron volts per electron-hole pair produced.

May 1967



IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. ED-14, NO. 5, MAY 1967 239

An Optimized Avalanche Photodiode

HEINZ W. RUEGG, MEMBER, IEEE

Abstract—The feasibility of a fast, high-gain photodetector based on the phenomenon of avalanche multiplication in semiconductors has been investigated. Based on the process of carrier multiplication in a high electric field, criteria for the design of an optimized avalanche photodiode and for the choice of the best semiconductor material are developed.

The device theory of an optimized, realizable avalanche photodiode is presented. A practical silicon device optimized for the detection of light with a wavelength of 9000Å is suggested and design parameters are presented. Details of the fabrication process are given and the performance of experimental devices is compared to the device theory presented.

The results of the study indicate that it is possible to achieve a silicon photomultiplier with a quantum efficiency-bandwidth product of the order of 100 GHz for the detection of light up to a wavelength of over 9000Å.

gion. Indeed, the analog of a photomuliplier can be envisaged with the notable advantage that the photogenerated carriers need not be emitted into the vacuum, a process which is characterized by a low quantum efficiency for present-day photocathodes.

Signal enhancement through avalanche multiplication in a photodiode has been reported for the first time by Johnson [4]. By operating a p-i-n silicon photodiode at a voltage where some carrier multiplication occurred, he was able to improve the output signal-to-noise ratio. The results obtained by Johnson have been confirmed by Anderson et al., who reported on a similar experiment using a microplasma-free silicon diode, and by Lucovskv and Emmons. who used an InAs diode in an

Low Gain Avalanche Detectors
are
Reach-through Avalanche Diodes
proposed by W. Heinz in 1967

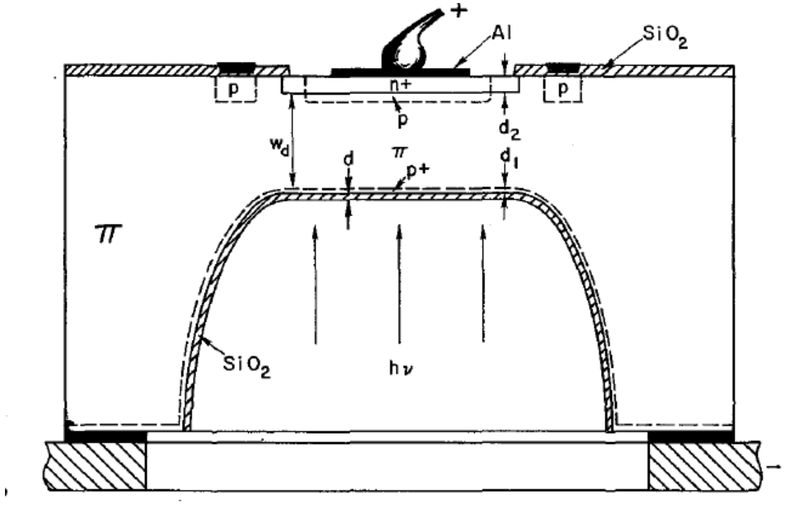
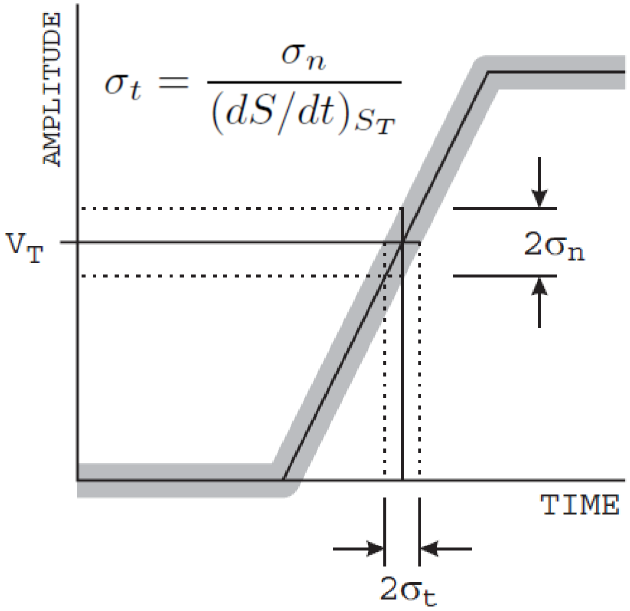


Fig. 11. Cross section through an experimental RAPD. $d=0.5\ \mu$; $d_1=1\ \mu$; $d_2=5\ \mu$.

… then, what is the reason behind the recent coolness of RAPDs (aka LGADs)?

- A precise **Position Sensitive Detector** (PSD) requires small signal collecting electrodes with a high **Signal-to-Noise ratio.**
- A precise **Time Stamping** detector requires a high **Slope-to-Noise ratio.**



The ultimate time resolution (negligible jitter) depends on:

- **Signal amplitude** (dominated by **sensor)**
- **Noise** (dominated by the **front-end electronics** noise)
- **Rise time** (dominated by **front-end electronics** risetime)

Conclusion: Of the three requirements for effective time-stamping detectors, two are related to the front-end electronics.

The *double-Low* answer

- **A favorably fact and two inconvenient truths:**
  - A low in-sensor amplified MIP signal, when read out with a low-noise, fast rise-time amplifier, achieves tens of picoseconds time stamping resolution.
  - Low noise amplifiers demand higher power consumption.
  - Amplifiers with fast rise-times also require more power.
- **The catalytic idea behind the LGAD concept is that a LOW SENSOR GAIN enables the use of *relatively* LOW POWER FRONT-END electronics.**
  - A low gain results in a narrower signal dynamic range, which can be managed by **low-power** amplifiers.
  - A low gain enables preamplifiers with smaller electronic gain, reducing again the power consumptions.
  - One may say that low-gain in the sensor is environmentally friendly and efficient energetically compared with having the gain in the front-end.

Corollary and *the main past and future RD challenge*

- Precise time stamping is a matter of two: sensor and front-end electronics
- During this decade the front-end design evolved towards low-power.
- The elephant in the room: **the primary optimization** factor for a practical **4D tracking** system (millions of readout channels) is **power consumption (scales with # of channels not with the detector area).**
- The **main challenge for the future of LGAD-based** 4D trackers remains **the front-end power consumption**.

"I suppose I'll be the one to mention the elephant in the room."

LGAD for HL-LHC timing layers (status report in nutshell)

- Provide about 30ps MIP time stamping for disentangling between the different interaction vertices.
- LGAD is the baseline technology of the endcap MIP timing detector for the HL upgrade of Atlas and CMS experiments
- Main challenges (and solutions)
  - **Radiation tolerance to (mostly) neutrons and protons:**

    Damage Mechanisms: primary carriers trapping, acceptor deactivation, mean-free-path reduced, electric field modification,

    Solutions: Thin bulk (higher electric field), co-doping with Carbon (suppression of the acceptor removal mechanism), deep multiplication layer.

    Current status: radiation tolerance up to 1.5 e15 n/cm2 achieved (conservative bound).
  - **Long-term reliability:**

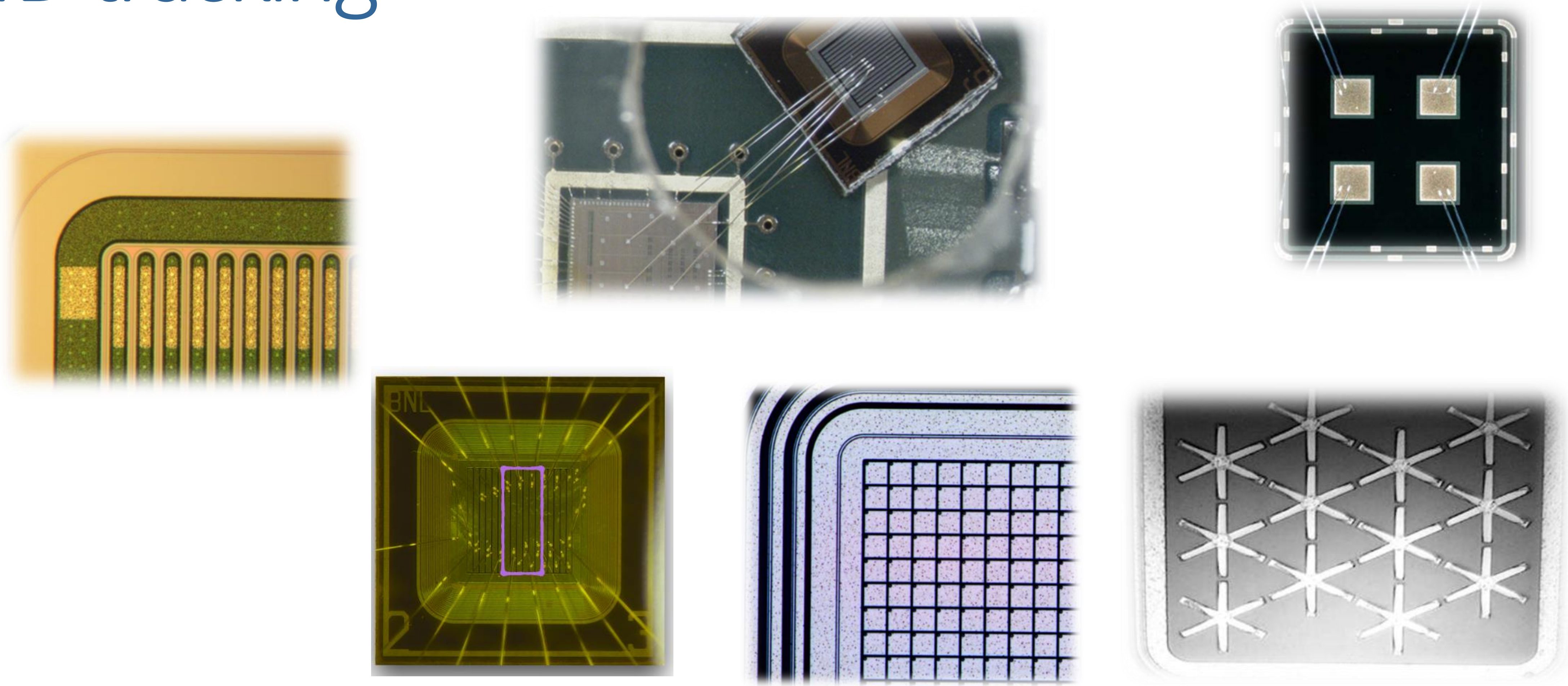
    Damage mechanism: very rare highly ionizing events induce fatal diode breakdown (also in PINs @ very high HV)

    Solution: limited average E field (< 11V/um).

    Current status: fatal damage mechanism understood and implementation of maximum voltage bias.
  - Large scale **manufacturing yield (99.8% of good pad achieved by HPK in recent manufacturing runs).**
  - Increase **fill-factor and increase the granularity**
  - **Extreme radiation tolerance**

Rest of the talk

Panorama of LGAD technologies for 4D tracking



Towards a LGAD-based 4D tracking enabling sensor

- Several technologies for improving the spatial resolution and increased fill factor:
  - Resistive AC-Coupled LGADs (**AC-LGADs**), more recently Resistive DC-Coupled

    (Initially from FBK; new foundries joining IHEP, BNL, HPK, etc.)
  - Trench-isolated LGADs (**TI-LGAD**)

    (first manufacturing run from FBK)
  - Deep Junction Low Gain Avalanche detectors (**DJ-LGAD**)

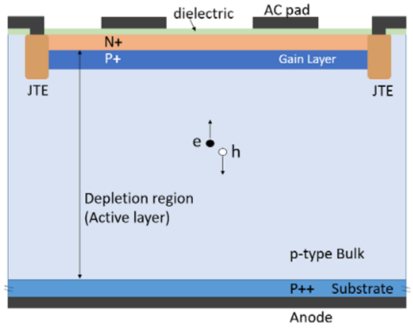
    (first manufacturing from BNL)
  - Thin Inverse Low Gain Avalanche detectors (**iLGAD**)

    (first production just completed at IMB-CNM)

AC-LGAD – RSD AC

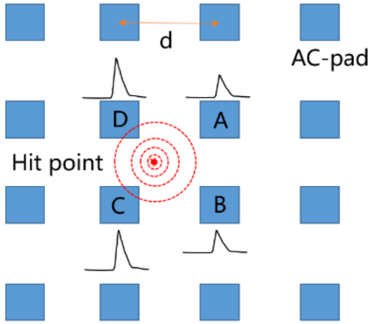
See talk from
T. Mamura and L. Menzio
in this session

Non-segmented LGAD gain layer; segmented electrode on top of a dielectric layer

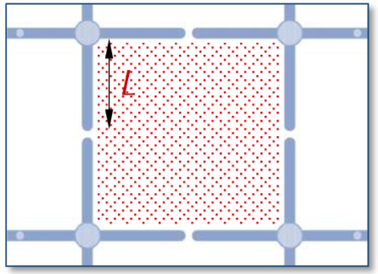


AC-LGAD (AC-coupled LGAD)

Hit position reconstruction algorithm based on charge sharing among the electrodes (Smarter ML algorithms possible) achieve sub-pitch hit resolution figures.



AC-pad layout scheme

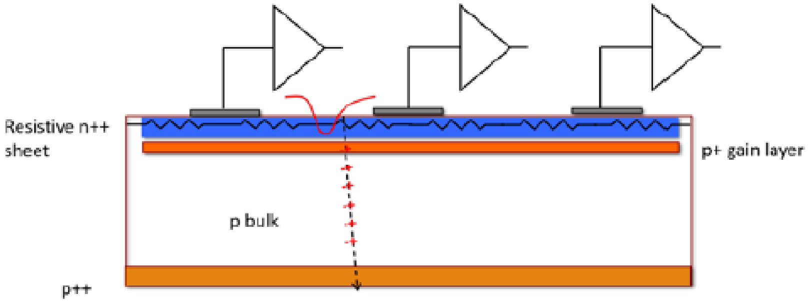


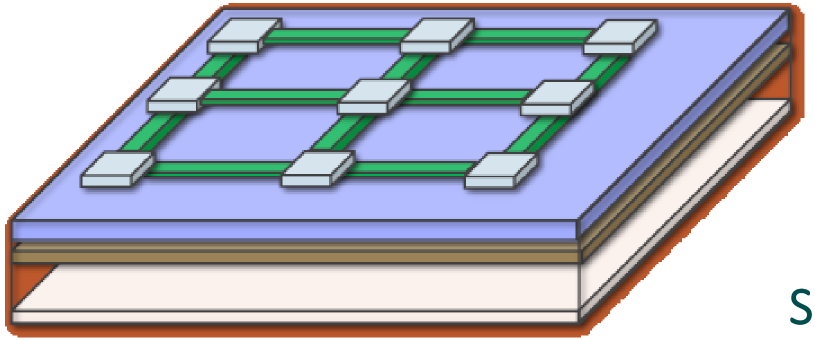
Alternative improved electron lay out

- Advantages:
  - 100% fill factor
  - high spatial resolution (few % of the pitch) ⇐ This is the strongest point (decoupling # of channels, i.e., power, with high spatial resolution)
  - Timing resolution similar to LGAD.
- Limitations:
  - Highly non-linear response, hits on top of the electrode (or very close to it) collect all the charge (resolution degraded due to the lack of charge sharing), non confinement of the signal to closest electrodes
  - Realistic Readout ASICs just provide signal amplitude (ToT), time of arrival (ToA), optimal reconstruction algorithms require full bipolar waveform.
  - Maximum hit occupancy one hit / electrode pitch.

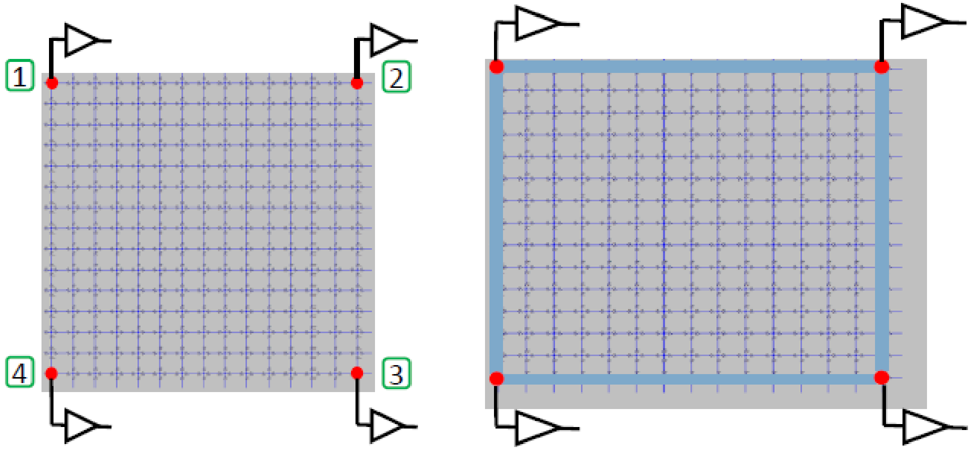
Resistive DC-Coupled Silicon Detectors

To overcome the AC-LGAD concept limitations (baseline fluctuations, bipolar pulses, reconstruction limitations…)

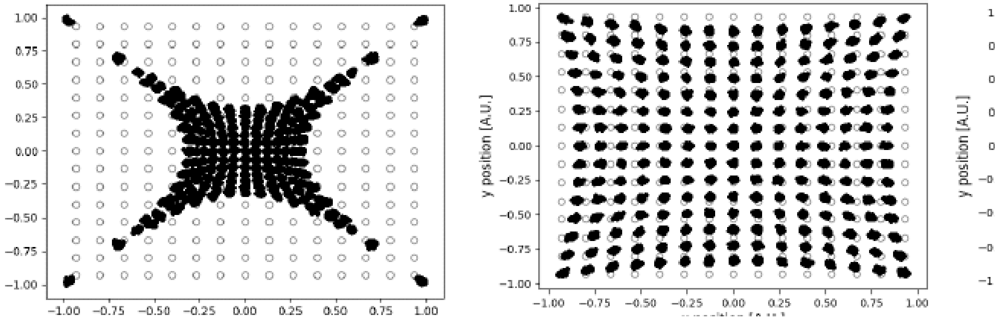




See talk from Luca Menzio in this session



L Menzio
16th VCI

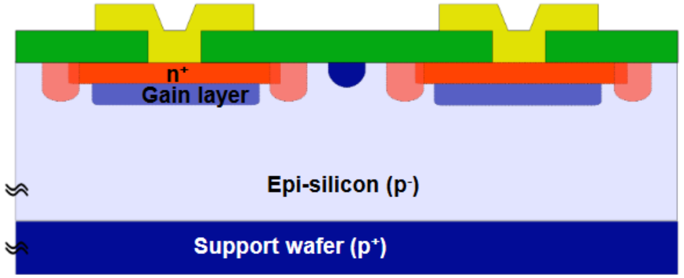


$$x_i = \frac{Q_2 + Q_3 - Q_1 - Q_4}{Q_{tot}}$$

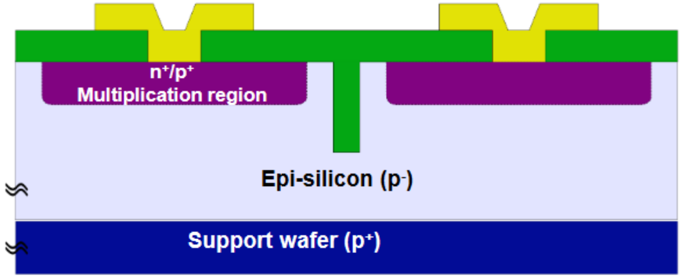
$$y_i = \frac{Q_1 + Q_2 - Q_3 - Q_4}{Q_{tot}}$$

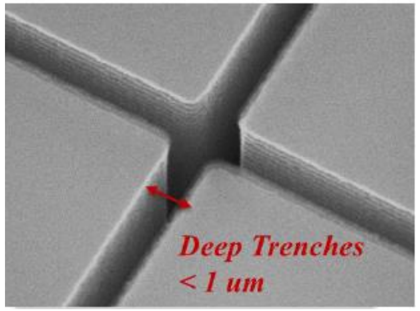
Trench-isolated Low Gain Avalanche detectors (**TI-LGAD**)

Segmented Standard LGAD



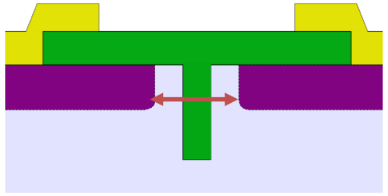
Trench-Isolated LGAD





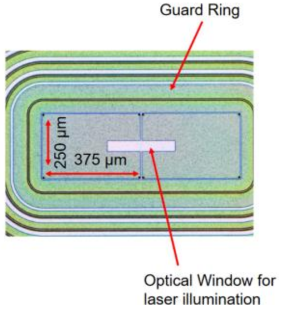
- Pixel border region hosts structures to control E field (JTE, p-stop, etc..)
- Trench isolation could drastically reduce inter-pixel border region down to few µm
  - Typical trench width < 1 µm (max aspect ratio: 1:20)
  - Trench filling with: SiO2, Si3N4, Polysilicon

Gain to Gain distance

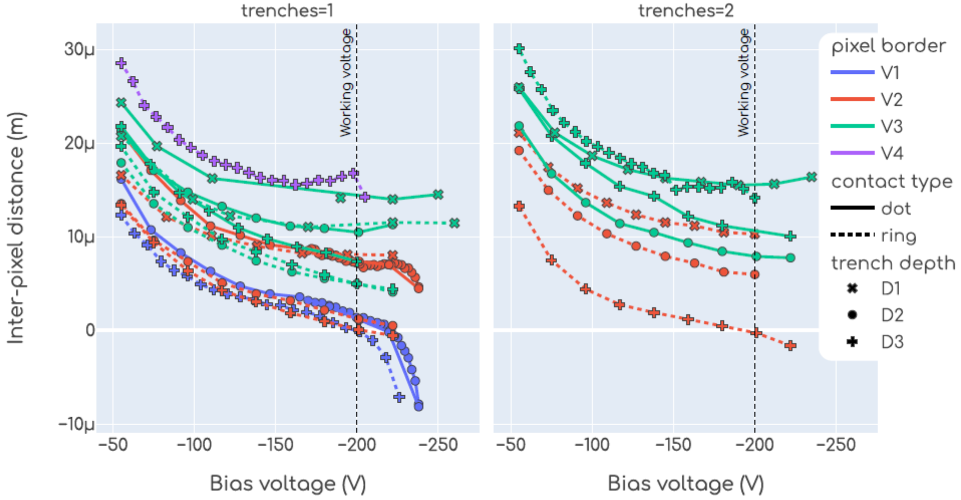


Nominal no-gain width

- V1 < 1um
- V2 < 3um
- V3 < 4um
- V4 < 5 um



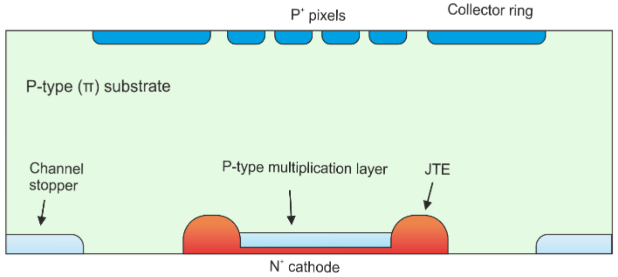
Laser measurement

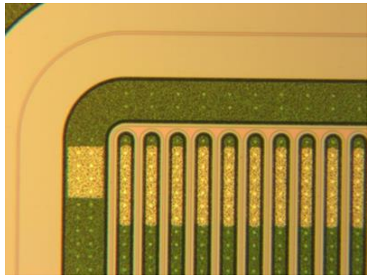


M. Senger et al.
https://doi.org/10.3390/s23136225

(Thin) Inverse LGAD (iLGAD)

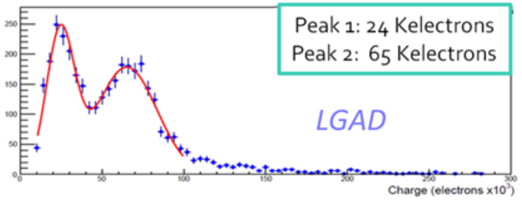
- Continuous multiplication layer, segmented hole readout.

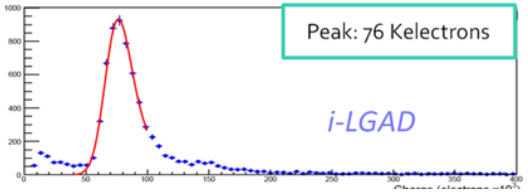




Strip iLGADs from CNM
$80\mu m$ pitch
SPS test beam

I. Vila,
13th Trento Workshop,

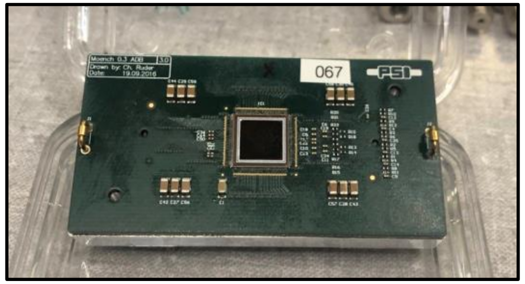


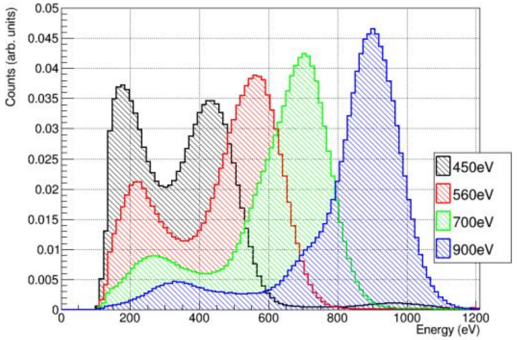


Large area 100% pixelated ILGAD manufactured by FBK for soft X-ray detection $E_{ph} \in [200eV, 1keV]$.)

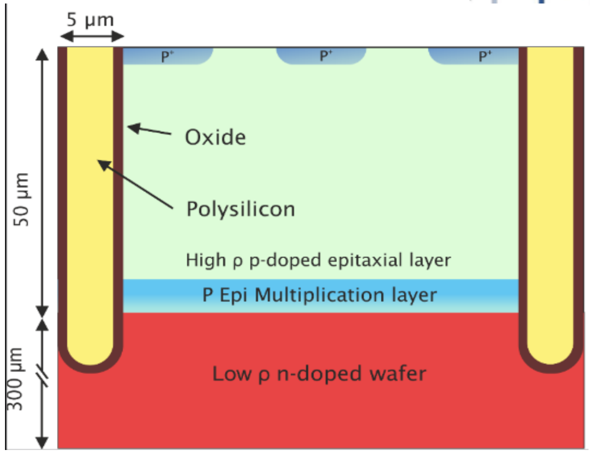
275 μm thick with **different entrance window and gain layer (GL)** designs.

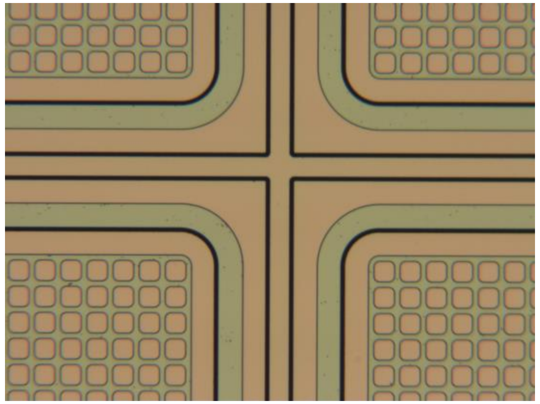
Pixelated iLGADs ($25\mu m$ pitch) charge integrating Mönch readout





A Liguori
18th Trento Workshop

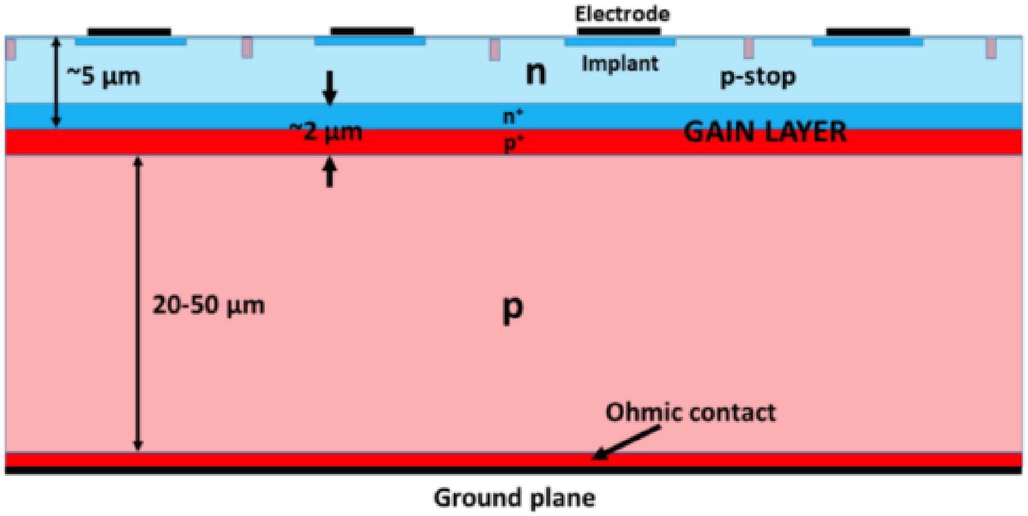




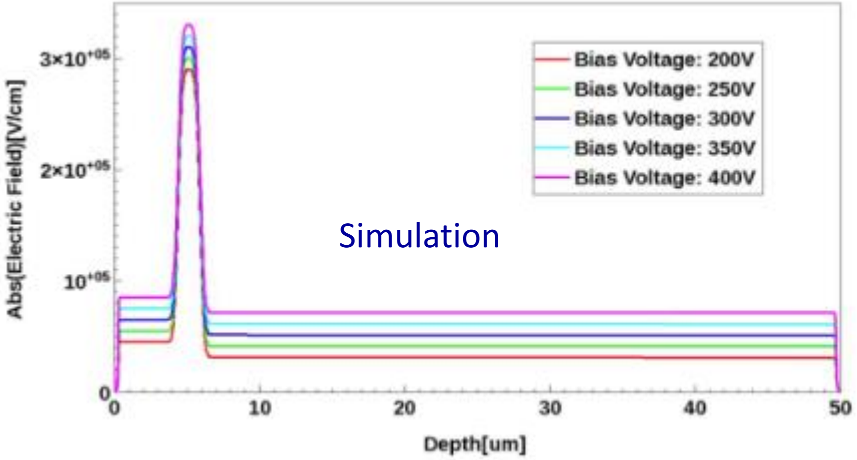
Thin Single-sided design for 4D tracking (just) manufactured at IMB-CNM

Deep Junction - LGAD

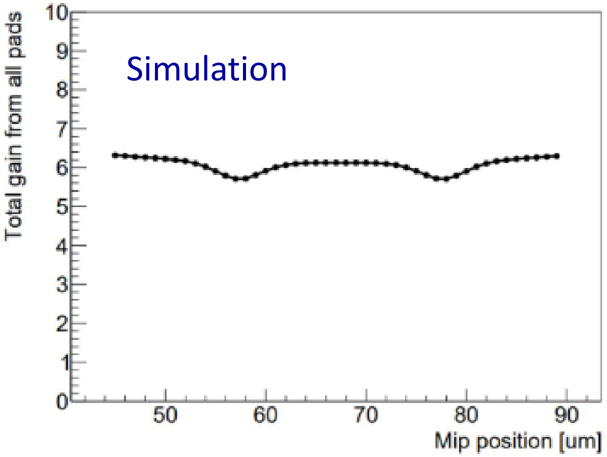
C. Gee, 39th RD50 Workshop, Nov 2021



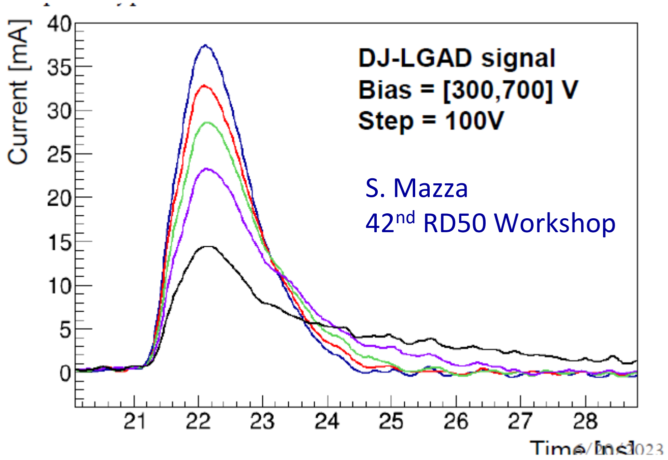
- Advantageous to bury high p-n junction several um below the surface of the sensor so fields low at surface, allowing conventional granularization
- Electric field in p-n junction is high enough to maintain drift-velocity saturation
- Maintains fine granularity on order of tens of microns
- Preserves direct coupling of signal charge to readout electrodes
- Initial prototype manufacturing at BNL



Simulation



Simulation

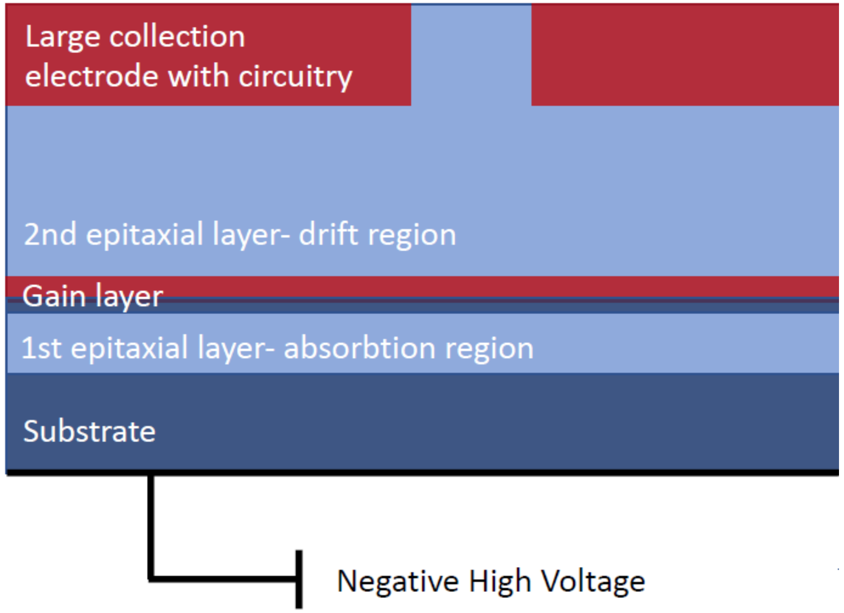


S. Mazza
42^{nd} RD50 Workshop

Picosecond Avalanche Detector - PicoAD sensor concept

- Monolithic silicon sensor (SiGe HBT front-end)
- Placement of gain layer deep inside sensor:
  - De-correlation from pixel implant size/geometry
  - High pixel granularity possible (spatial precision)
- Only small fraction of charge gets amplified
  - Reduced charge fluctuations (timing precision)

Schematic view of PicoAD sensor concept:



Large collection electrode with circuitry

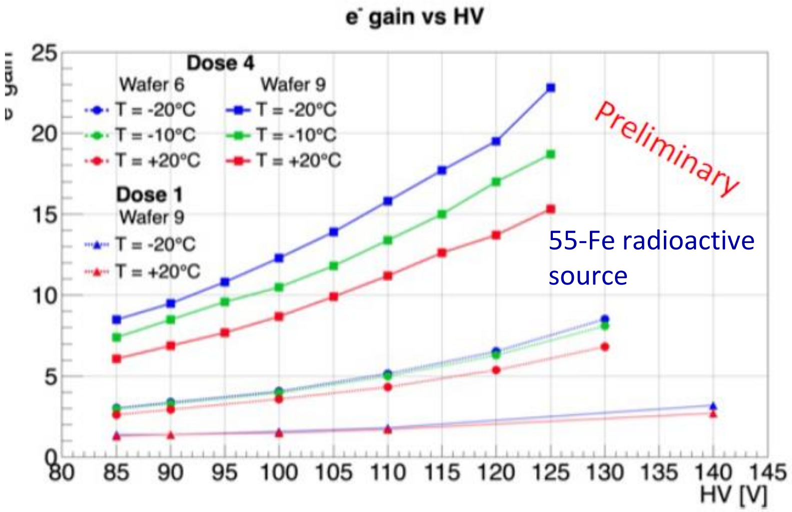
2nd epitaxial layer- drift region

Gain layer

1st epitaxial layer- absorbtion region

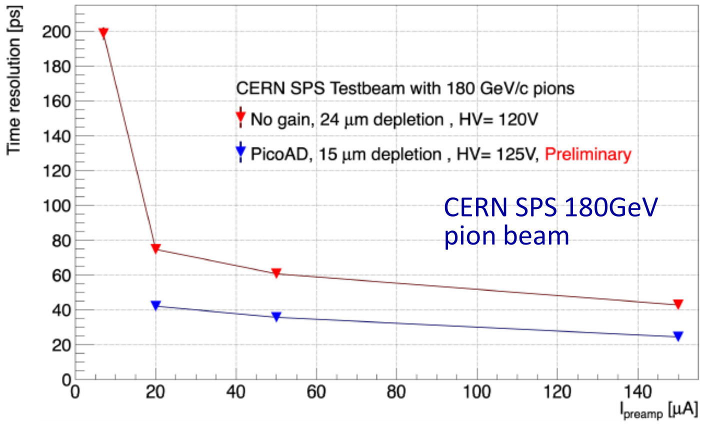
Substrate

Negative High Voltage



55-Fe radioactive source

Time resolution as a function of preamplifier current:



CERN SPS 180GeV pion beam

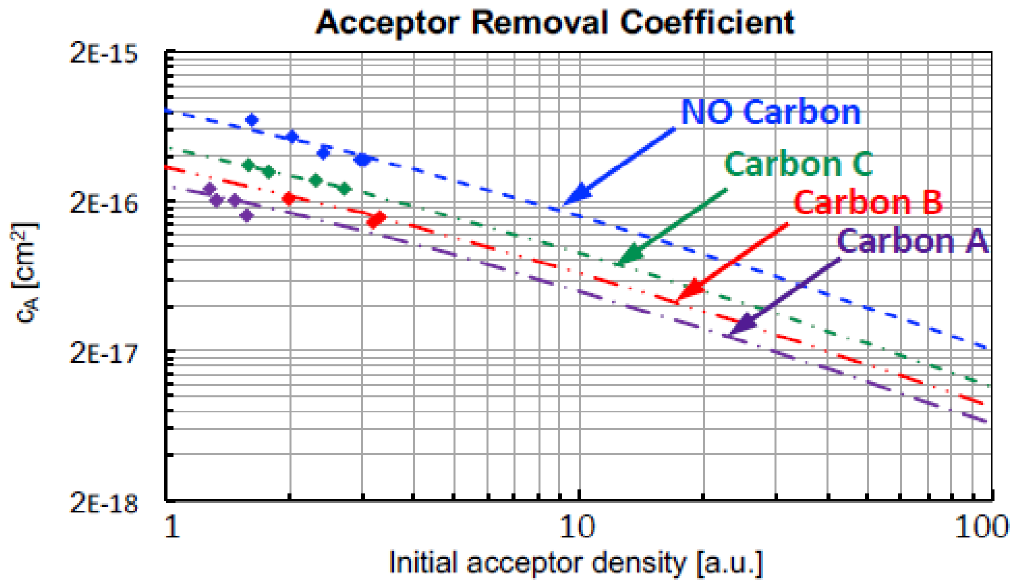
$$\sigma_{PicoADp_0} = (24.2 \pm 0.7)ps$$

M. Munker
42th Trento Workshop

Radiation tolerance: Current status

- Recipes for Acceptor removal mitigation:
  - Thin bulk (higher electric field), co-doping with Carbon, deep multiplication layer.
- SEB damage mechanism, very rare highly ionizing events induce fatal diode breakdown
  - Solution: limited average E field (< 11V/um)

$$p^{+}(\Phi) = p^{+}(0)\cdot e^{-c_A\Phi}$$



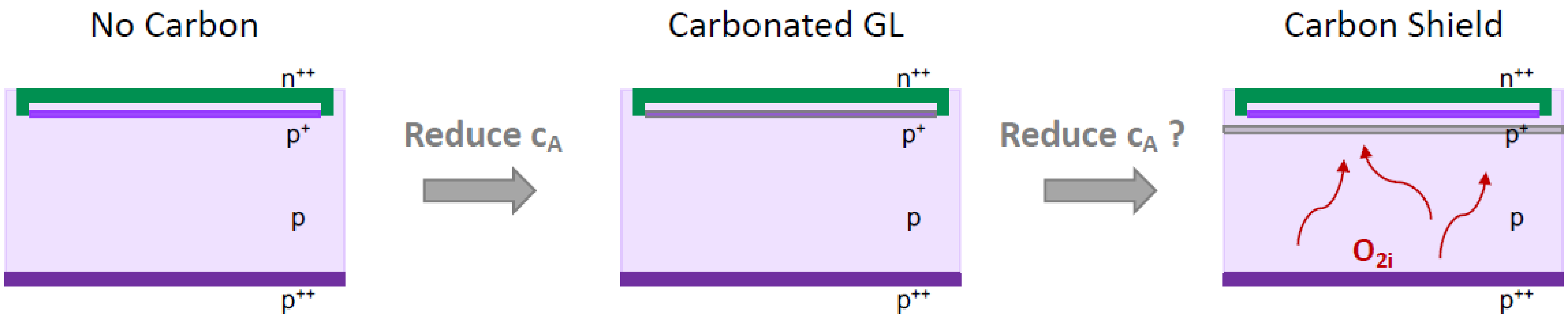
C enrichment mastered to the level that sensors can survive 2.5e15 cm^{-2} (HL-LHC)

Radiation tolerance: New R&D Challenges

- Difficult to operate silicon sensors above 10^{16} n_{eq}/cm2 due to:
  - defects in the silicon lattice structure → increase of the dark current
  - trapping of the charge carriers → decrease of the signal induction
  - change in the bulk space charge → impossible/difficult to fully deplete the sensors
- The current approach is going thin:
  - Shorter drift distances between carrier and electrode (plarnar, 3D) → less change of getting the carrier trapped.
  - Increase the E_{field} in the sensor by increasing the Vbias BUT SEB fatal breakdown and power supplies will limit this strategy
- Can LGAD sensors be the solution by providing an additional in-sensor gain?
  - BUT we need to suppress the acceptor deactivation mechanism first.

Radiation tolerance: New approaches – Carbon Shielding

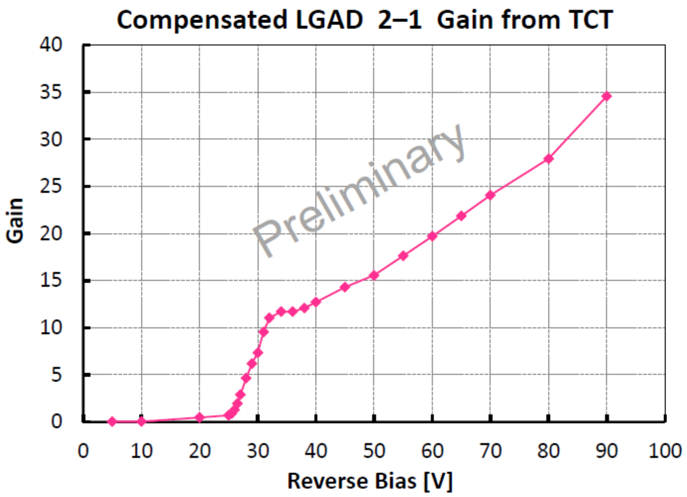
- A spray of Carbon will be introduced below the gain layer region to protect the gain layer
- Atoms from defects moving towards the n++ electrode during process thermal loads or exposure to particle radiation
    - Oxygen dimers can be captured by the Carbon atoms, preventing the removal of acceptors (combination with Bi created by irradiation)

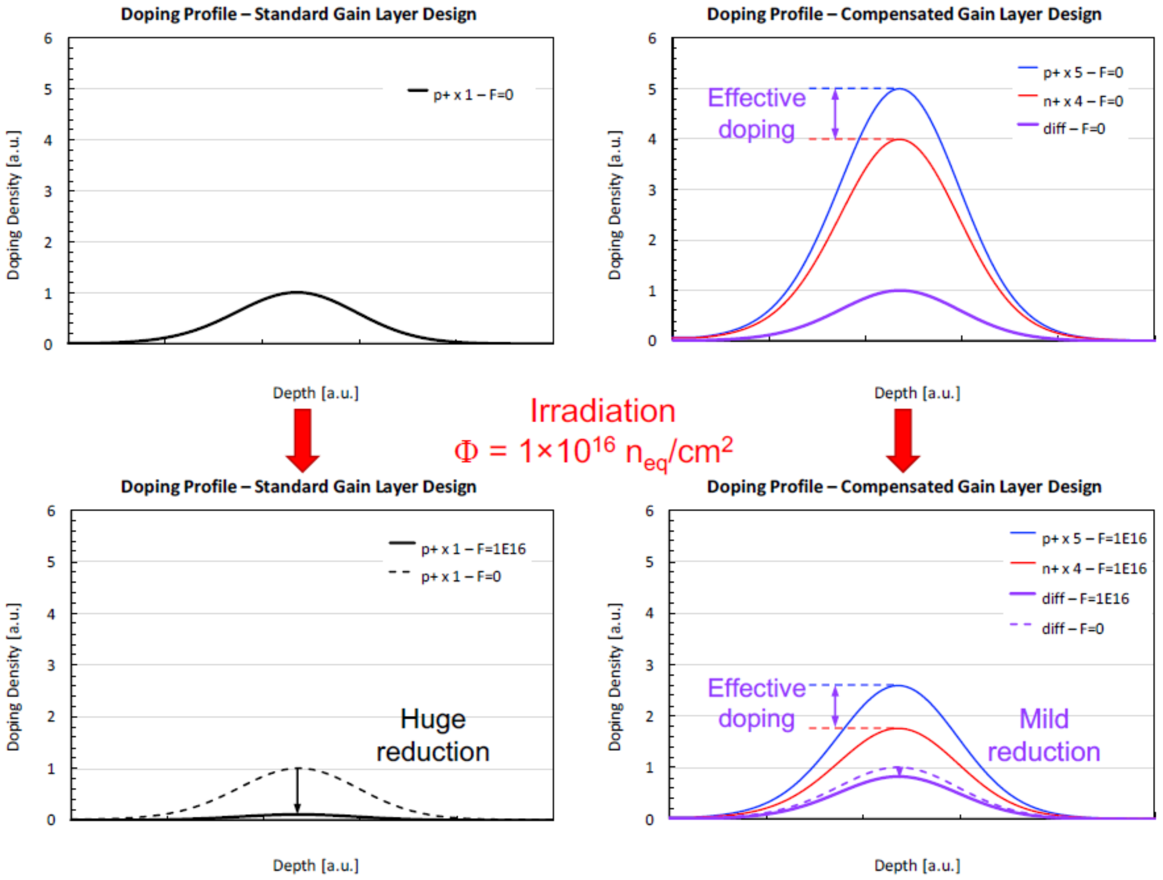


V. Sola
IEE NSS 2022

Radiation tolerance: New approaches – doping by compensation

- Use the interplay between acceptor and donor removal to keep a constant gain layer active doping density
- Many unknown:
  - Donor removal coefficient
  - Interplay between donor and acceptor removal (c_D vs c_A)
  - super fine tune of doping levels ?
- Initial experimental validation in progress.

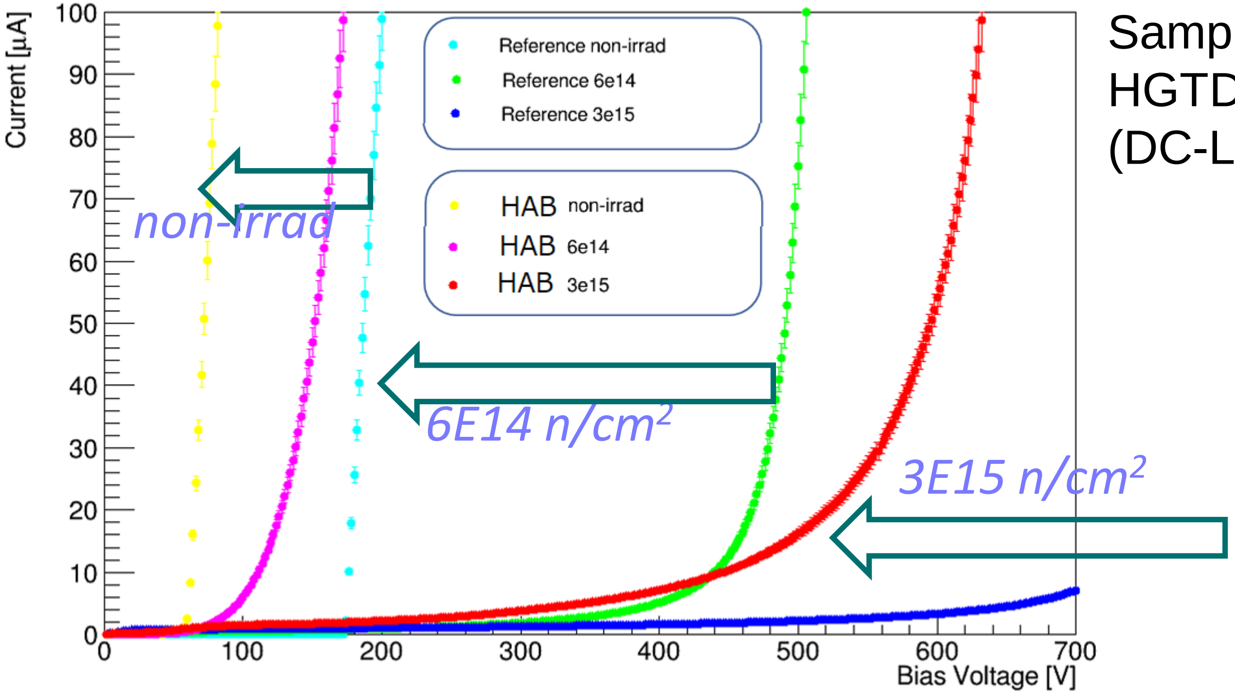




V. Sola
42th RD workshop

Radiation tolerance: half activated gain layer

- Dope Boron more than required -> insufficient annealing process
- Boron atom not in Si lattice suppresses “acceptor removal”:
  - Capture of Oxygen impurities, preventing the creation of BiOi dimer.
- Promising initial results



Samples from HPK HGTD prototype (DC-LGAD)

Kazuhiko Hara
18th Trento workshop

Take home messages

- LGAD (HEP jargon for an RAPD with moderate gain) is the solution towards:
  - larger SNR (decoupled from the material) for O(10ps) hit resolution
  - O(10um) spatial resolution with fine electrode segmentation and AC coupling
- Many 4D LGAD architectures are under intense R&D.
- Can be LGAD also the solution for extreme radiation tolerance: promising strategies are starting now.
- The technology is maturing and attracting the interest of major manufacturing companies BUT still a long way to go:
  - Complete proof-of-concept studies.
  - Reliability (long term stability, noise and destructive breakdown)
  - Manufacturing yield?
  - Scalability (larger area sensors) ?
  - Uniformity ?
  - Radiation tolerance and fine pitch devices?
- Disclaimer: Other strategies for the implementation of a 4D tracking based on PID diodes should not be forgoted: PIN diodes with special junction geometries (TimeSPOT project) or monolithic CMOS based.

Final (personal) remark: The elephant in the room

- I do not see any technical showstopper for the LGAD sensors as true 4D sensing technology.
- Quite confident that LGAD sensor can become the baseline technology for the next generation of large 4D tracker systems.
- But LGAD are (mostly) hybrid sensors interconnected to a dedicated readout ASIC:

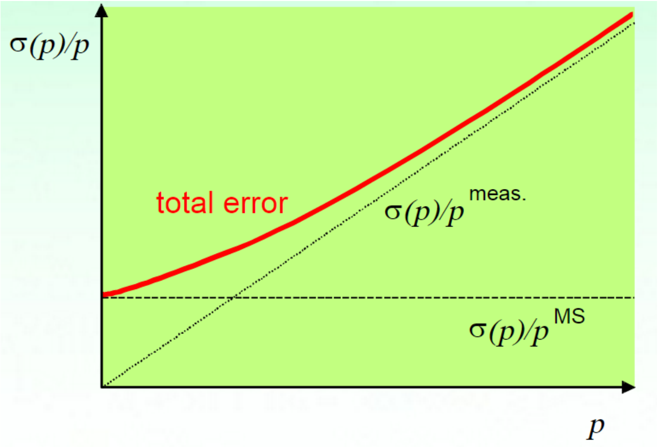
The feasibilty of a front-end readout electronics with a relatively high density of readout channels is still to be proven; the power consumption and the corresponding heat disipation could become the showstopper.

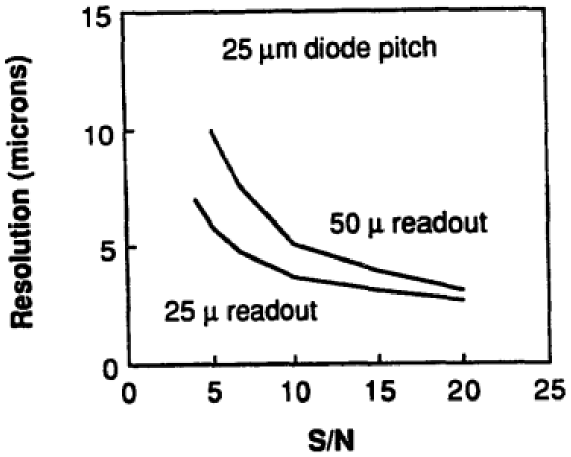
THANK YOU FOR YOUR ATTENTION

BACK - UP

Motivation… not just timing

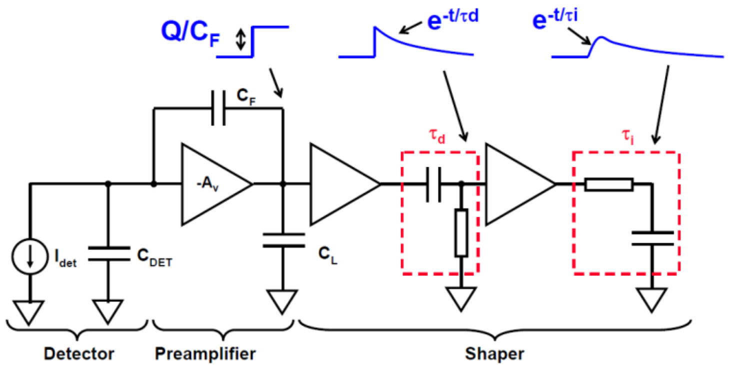
- Sensors with large SNR and small material budget to enable few tens of picoseconds time stamping of MIP particles (high precision ToF).
- Integrated signal amplification increases the Signal-to-Noise ratio increasing the tracking resolution:
  - Thinner detectors (reduction of the **multiple scattering**)
  - Improved **intrinsic hit resolution**.



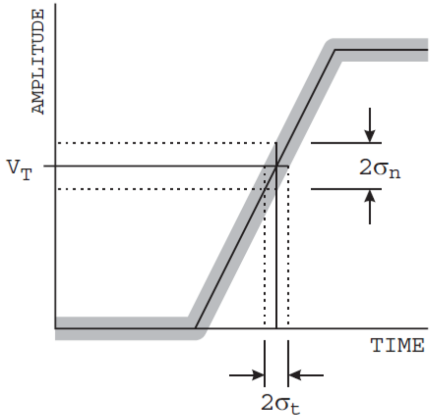


Precision timing: basics

Timing 101: Timing resolution contributions - Jitter



Leading Edge Timing



Ideally, for a constant amplitude pulse, the time resolution is given by the jitter which depends on:

- **Noise** (dominated by the **amplifier** noise)
- **Signal amplitude** $v_n \propto \sqrt{f_u} \propto \sqrt{\frac{1}{t_{ra}}}$ ed by **sensor's** response)
- **Rise time** (dominated by **amplifier** risetime)

$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} \qquad \frac{dV}{dt} \approx \frac{V}{t_r} \rightarrow \sigma_t = \frac{t_r}{SNR}$$

$$\boxed{\sigma_t \propto \frac{1}{V_0}\frac{1}{\sqrt{t_{ra}}}\sqrt{t_{rs}^2 + t_{ra}^2}}$$

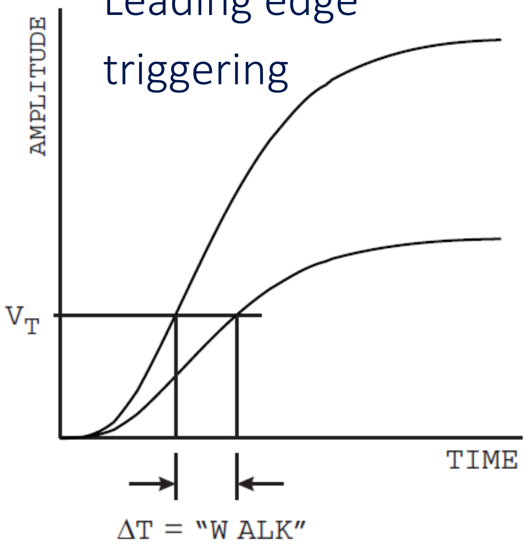
$$t_r = \sqrt{t_{rs}^2 + t_{ra}^2}$$

Typical bandwidth of HL-LHC timing layer preamplifier of around 400 MHz →$t_r \sim t_{ra} \sim$ 1ns then a (modest) SNR of about 30 should provide a timing resolution of about 30 ps

Timing 101: Time resolution contributions – Time walk

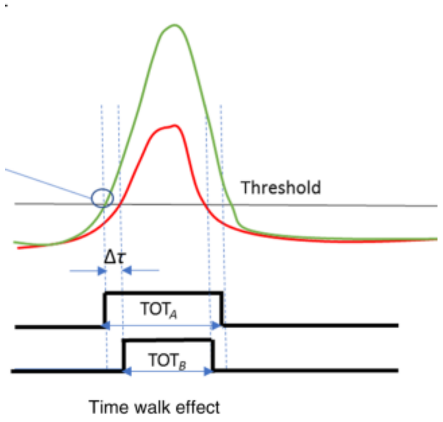
In real conditions, the pulse amplitude is not always constant.

Leading edge triggering

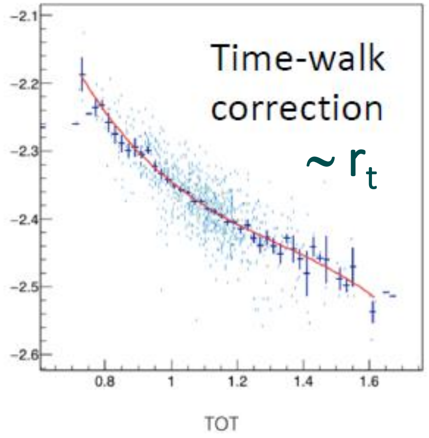


Option 1

Correct the time shift using the pulse amplitude



Time walk effect



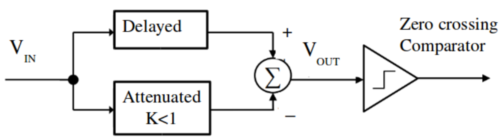
Time-walk correction

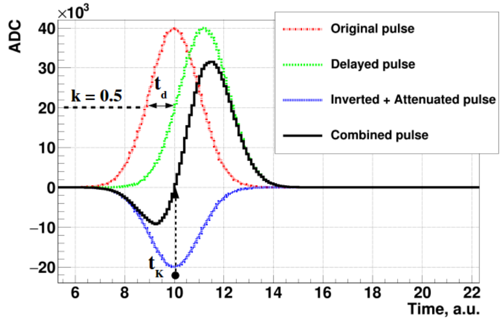
$\sim r_t$

Option 2

Constant Fraction Triggering

CFD principles of operation





Both methods: Amplitude-corrected LET and CFT have a similar performance as long as THE SHAPE OF THE PULSE'S LEADING EDGE IS CONSTANT.

Caveat: ToT correction is a off-line method while CDF is a real-time correction.

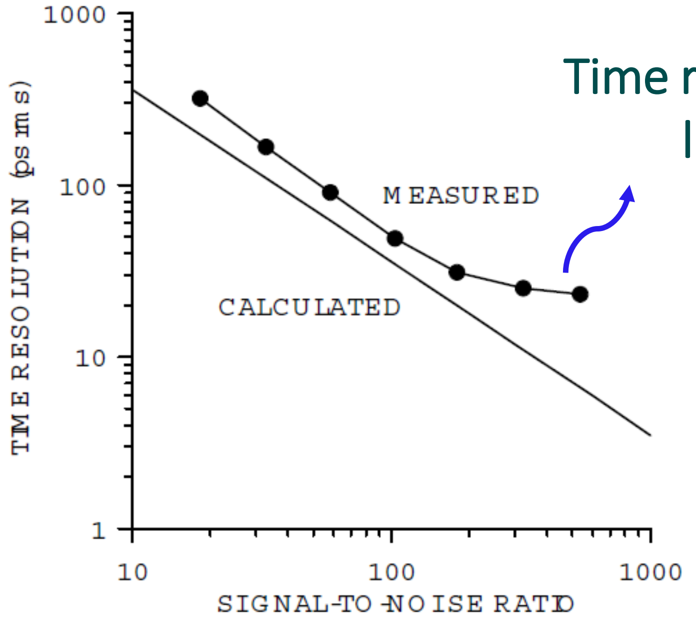
Timing 101: Time resolution contributions – limiting systematics

Jitter induced by pulse shape changes

- Changes on the leading edge shape (i.e., different rise times or its distortions) translate into additional jitter

System aspects:

- TDC resolution.
- ADC (ToT) resolution limits time-walk correction.
- Clock distribution (jitter, slew and thermal drifts).



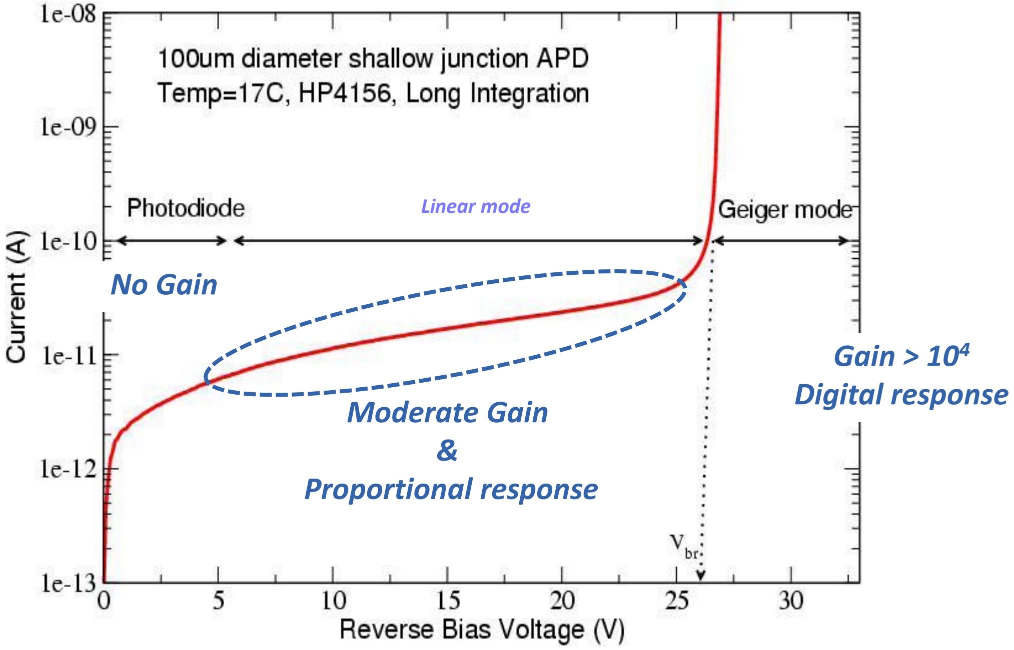
Time resolution limit

These are the limiting factors and off-line data-based corrections are needed.

Enabling Technology: Low Gain Avalanche Sensor

Silicon sensors as enabling sensing technology for 4D tracking ?

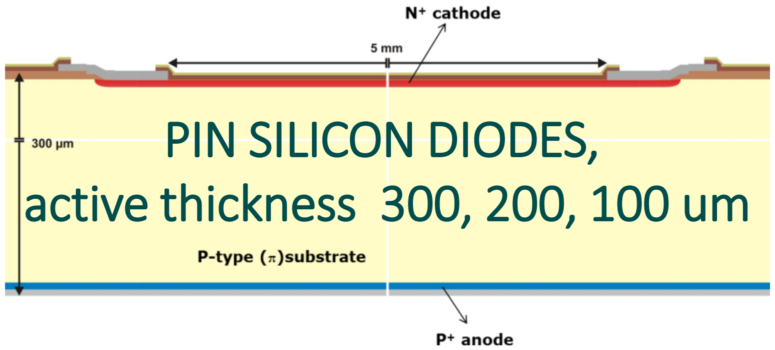
- Silicon-based diodes provide both **fast rise time and relatively large signal/noise ratio**.
- Well **stablished high-precision tracking technology** (electrode patterning)
- Three operating modes: no signal gain (**PIN**), proportional (**APD**) and Geiger mode (**SiPMT**).



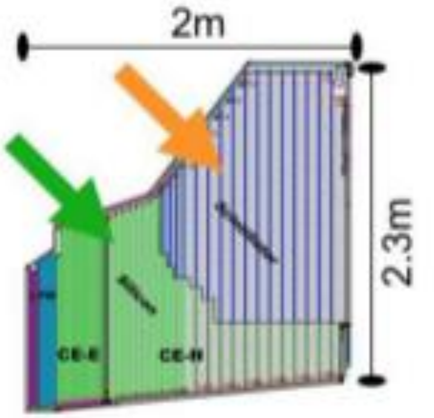
[1] A.G. Stewart et al. in Proc. of SPIE, Vol. 6119, 2006

Timing with PIN diodes : CMS HGCAL as case of use

- Very reliable and mature mass production technology
- Main limitation: low SNR

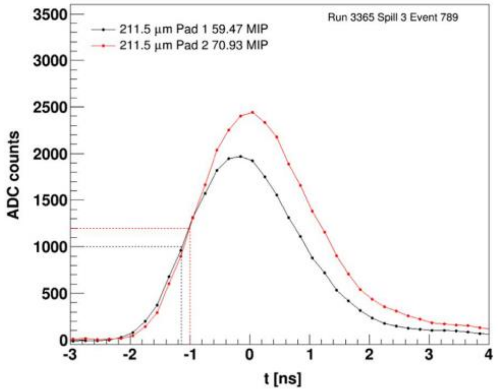


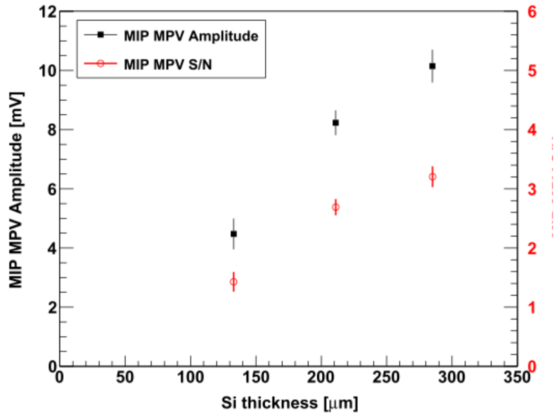
PIN SILICON DIODES,
active thickness 300, 200, 100 um

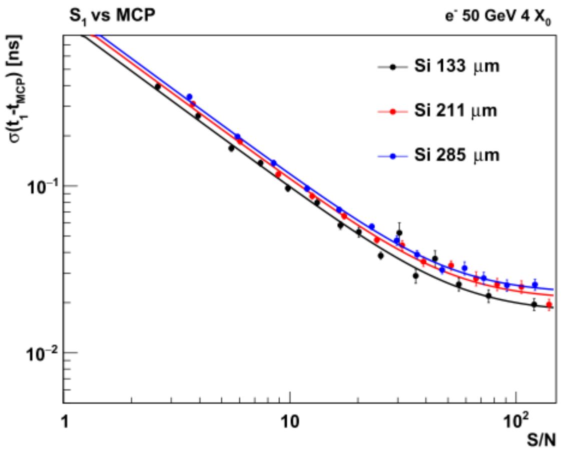


Scintillator + SiPM

Pin diode



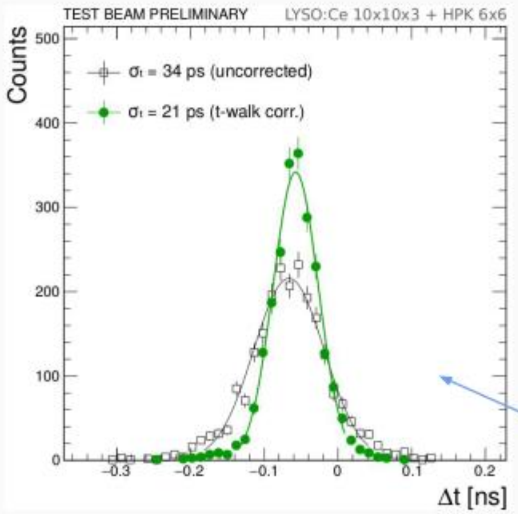


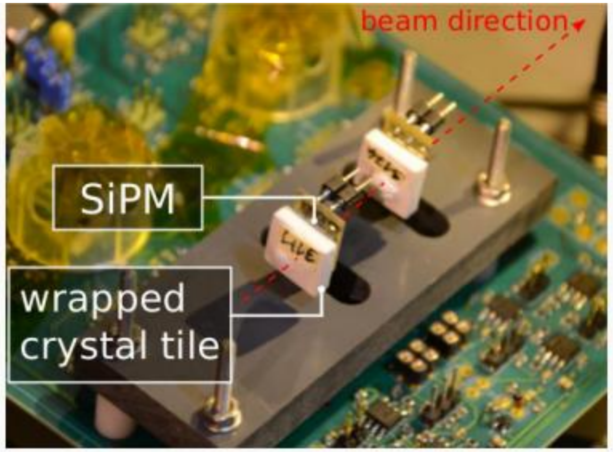


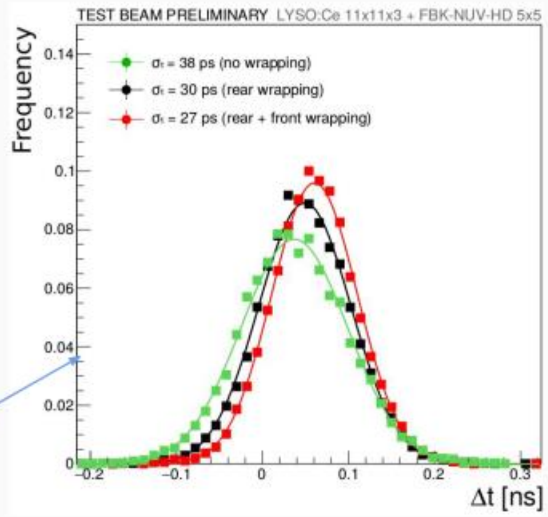
E. Currás, Nucl.Instrum.Meth. A859 (2017) 31-36

Silicon Photomultipliers: (Geiger-mode APD)
Case of use BTL detector at CMS

- Mature technology, mass produced and cheap sensing element.
- Main limitations: moderate radiation tolerance < $2\text{x}10^{14}$ n_{eq}/cm2 and concept with intrinsic poor spatial resolution, high fake pulse rate



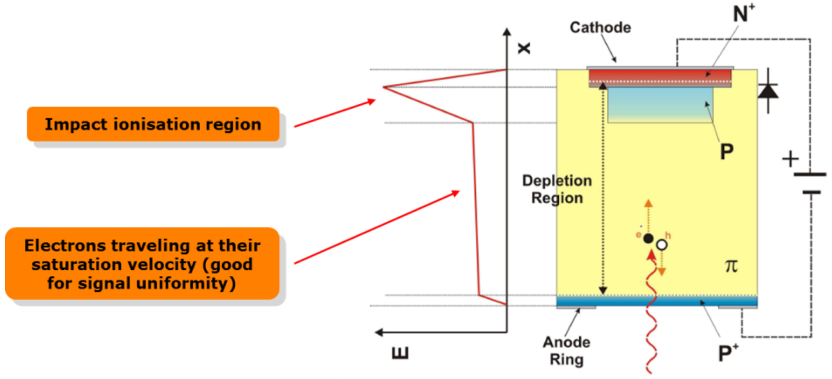




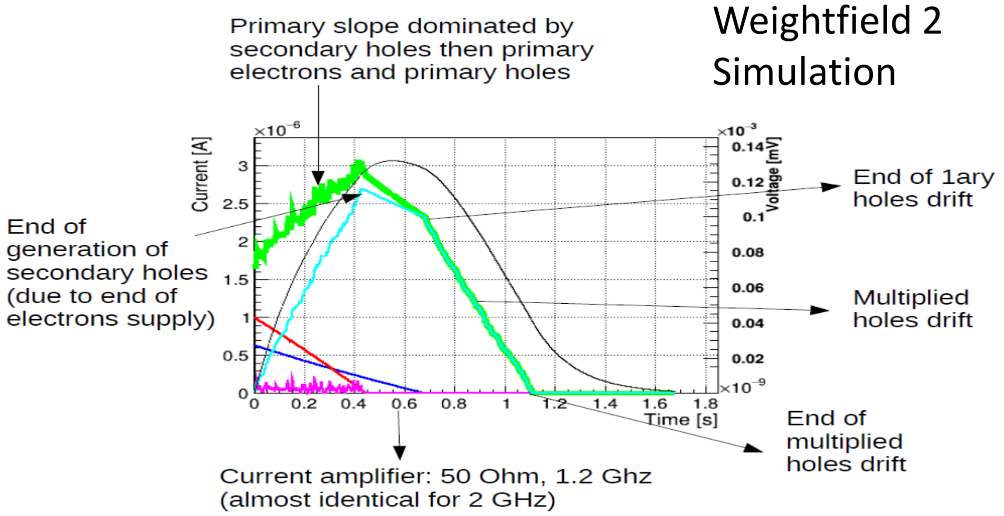
30 ps resolution demonstrated

Avalanche mode diode (Low Gain Avalanche Detector LGAD) :

- Proportional multiplication mode (impact ionization of primary carriers)
- Main advantage: custom SNR for optimal for timing and tracking (introduced by IMB-CNM)


Impact ionisation region

Electrons traveling at their saturation velocity (good for signal uniformity)


Weightfield 2 Simulation

Primary slope dominated by secondary holes then primary electrons and primary holes

End of generation of secondary holes (due to end of electrons supply)

End of 1ary holes drift

Multiplied holes drift

End of multiplied holes drift

Current amplifier: 50 Ohm, 1.2 Ghz (almost identical for 2 GHz)

LGAD have a much larger **rise-time** (collecting time of primary electrons) than PIN (all carriers ballistic movement).

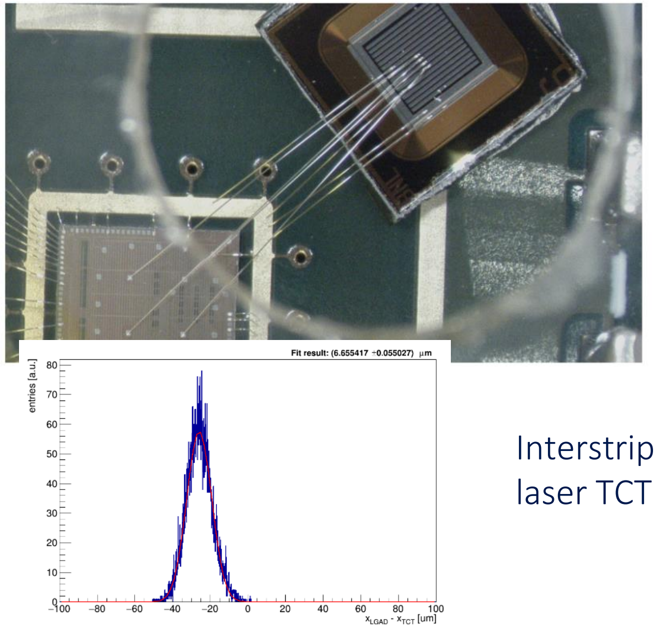
Go thinner to reduce the collecting time of the primary electrons and make $t_{rs} << t_{ra}$

LGAD **SNR** better than PIN due to gain

Taylor the gain for optimal jitter wrt limit time resolution

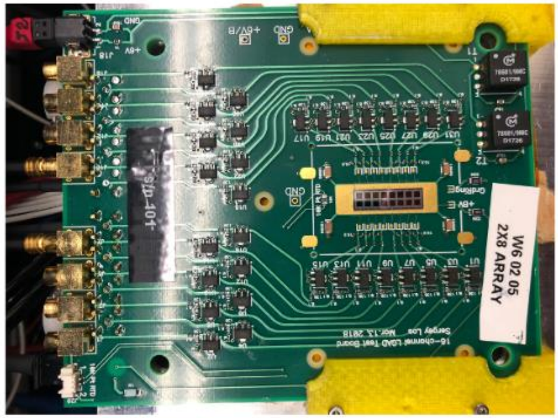
Resistive AC-Coupled Silicon Detectors (2)

- Beyond the proof-of-concept limitations.
- 16 strips, pitch 100 µm, gap 44 µm
- Central and neighbouring strips wire bonded to the four input channels on the ALTIROC ASIC (Atlas HGTD ROC)
- Strips chosen to be far from the device guard-ring to minimize border effects Lateral strips on their left and right are wire-bonded to the same ground as the ASIC
- Second prototype bonded to dedicated discrete front-end amplifier board from Fermilab + fast digitizer.
- **Test beam studies** of second prototype

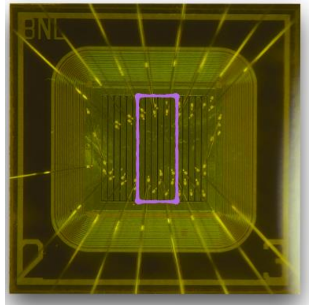


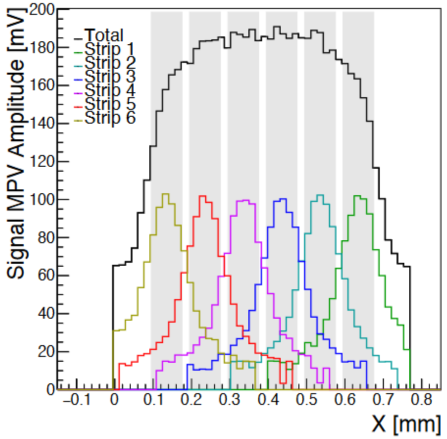
G. D’Amen, C. Madrid, 39th RD50 Workshop, Nov 2021

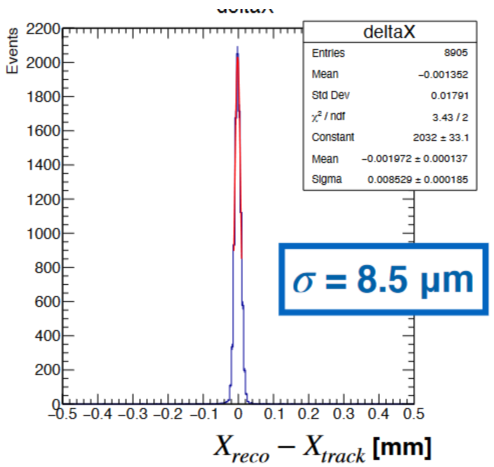
Interstrip spatial resolution estimated with laser TCT setup. Estimated resolution of 6 um.



16-ch sensor LGAD on Fermilab readout board







Timing resolution between 30 and 40 ps

Discontinuities are observed where the relative fraction is large or when we get direct hits to the strip

Name	Sensor	Node [nm]	Pixel size [μm^2]	Temporal precision [ps]	Power [W/cm^2]
ETROC	LGAD	65	1300x1300	~ 40	0.3
ALTIROC	LGAD	130	1300x1300	~ 40	0.4
TDCpix	PIN	130	300x300	~ 120	0.32 matrix + 4.8 periphery
TIMEPIX4	PIN, 3D	65	55x55	~ 200	0.4 analog + 0.3 digital
TimeSpot1	3D	28	55x55	~ 30 ps	3-5
FASTPIX	MAPS	180	20x20	~ 130	5-10
miniCACTUS	MAPS	150	500x1000	~ 90	0.15 – 0.3
MonPicoAD	MAPS	130 SiGe	100x100	~ 36	1.8
Monolith	Multi Junct. MAPS	130 SiGe	100x100	~ 25	0.9