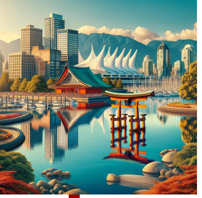
The Impact of Avalanche-based Detectors in Particle Tracking:

from 3D to 4D tracking

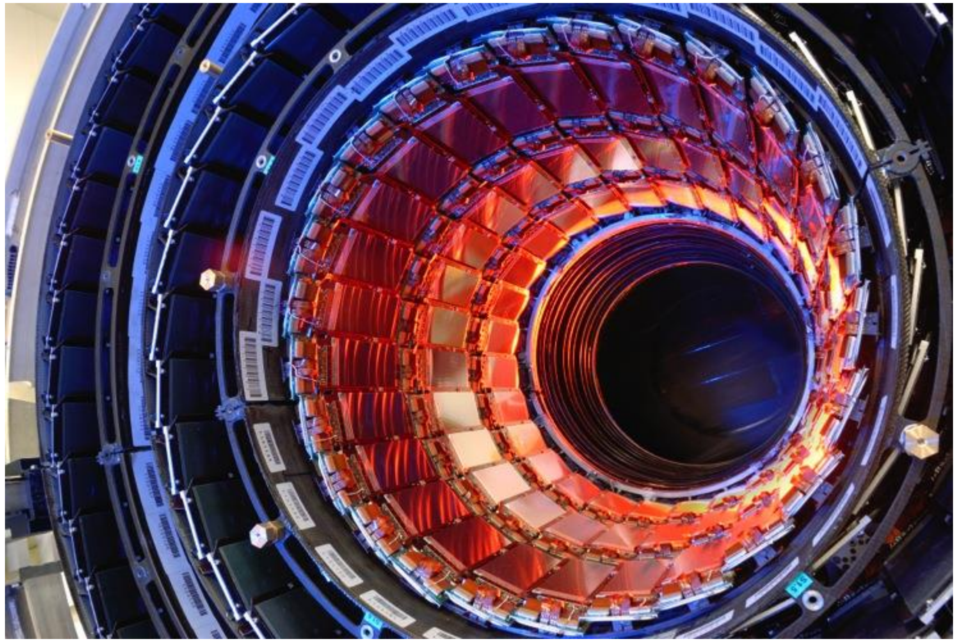
Hiroshima @ Vancouver



Silicon life in 2010

Very mature silicon systems, very large silicon trackers

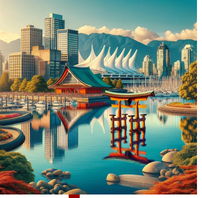
Millions of channels, very reliable, very radiation hard



Two simple facts in 2010:

1. Silicon sensors are not suitable timing detectors
2. Silicon sensors were not considered good detectors for 1-5 keV x-rays

One nagging problem: radiation damage causes charge trapping, reducing the signal in heavily irradiated sensors.



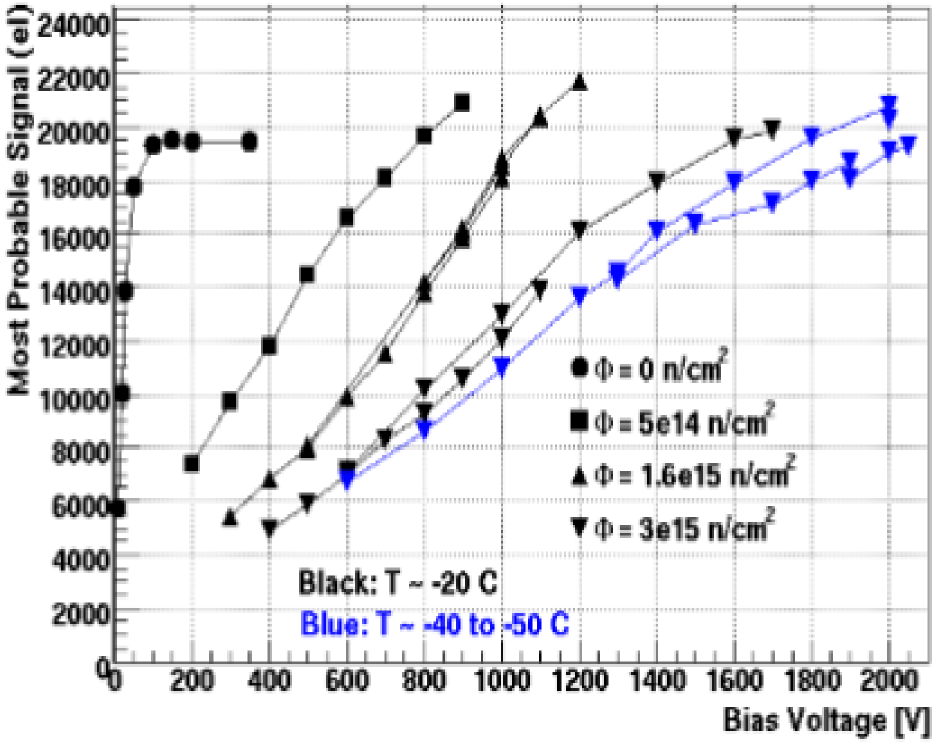
“Spontaneous” charge multiplication

By 2010, there was clear evidence of charge multiplication in highly irradiated planar strip sensors

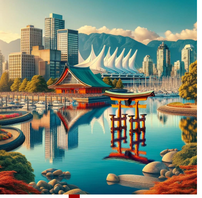
This effect was considered a possible key to design sensors able to overcome charge trapping at high radiation levels:

- **Trapping reduces the signal**
- **The internal gain will re-establish the original signal amplitude**

microstrip detectors



Note: this type of charge multiplication was not a planned feature of the sensor, it was unexpectedly measured in irradiated sensors

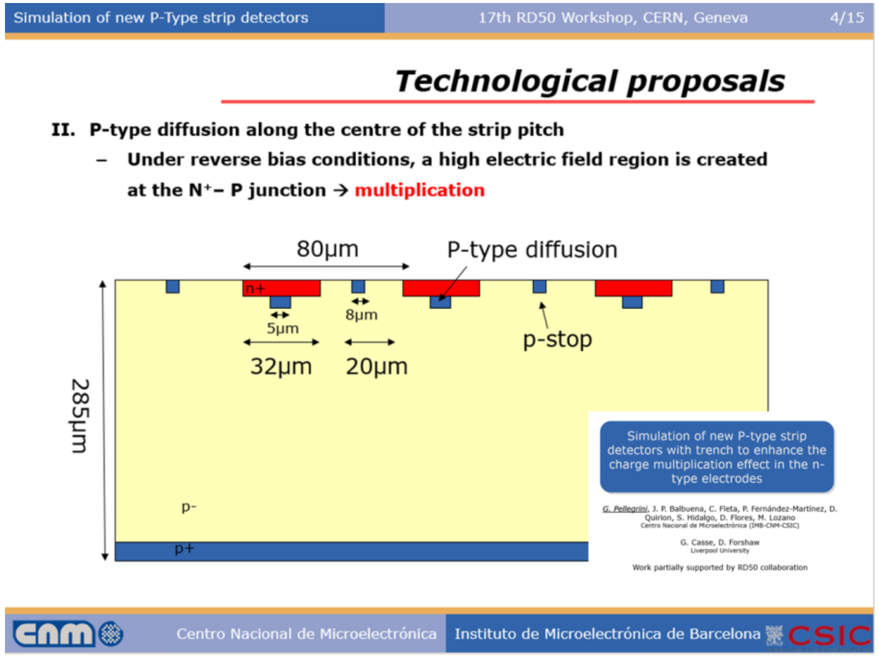


“Designed” charge multiplication

Add moderate gain, just enough to compensate for charge trapping

“to control and optimize the charge multiplication effect, **in order to fully recover the collection efficiency of heavily irradiated silicon detectors**” [1]

[1] G.Pellegrini,et al., **Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications**, Nucl. Inst. Meth. A 765 (2014) 12.


Simulation of new P-Type strip detectors 17th RD50 Workshop, CERN, Geneva 4/15

Technological proposals

II. P-type diffusion along the centre of the strip pitch
  - **Under reverse bias conditions, a high electric field region is created at the N⁺– P junction → multiplication**

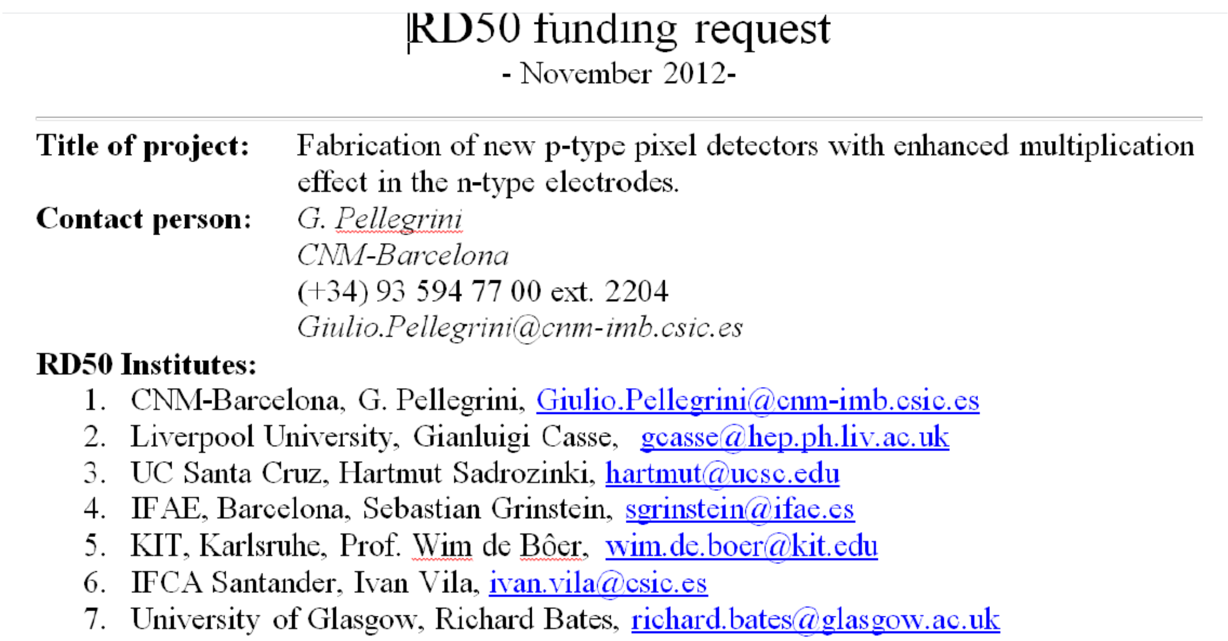
Simulation of new P-type strip detectors with trench to enhance the charge multiplication effect in the n-type electrodes

G. Pellegrini, J. P. Balbuena, C. Fleta, P. Fernández-Martínez, D. Quirion, S. Hidalgo, D. Flores, M. Lozano
Centro Nacional de Microelectrónica (IMB-CNM-CSIC)

G. Casse, D. Forshaw
Liverpool University

Work partially supported by RD50 collaboration

Centro Nacional de Microelectrónica Instituto de Microelectrónica de Barcelona CSIC


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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4. IFAE, Barcelona, Sebastian Grinstein, sgrinstein@ifae.es
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6. IFCA Santander, Ivan Vila, ivan.vila@csic.es
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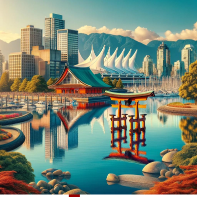
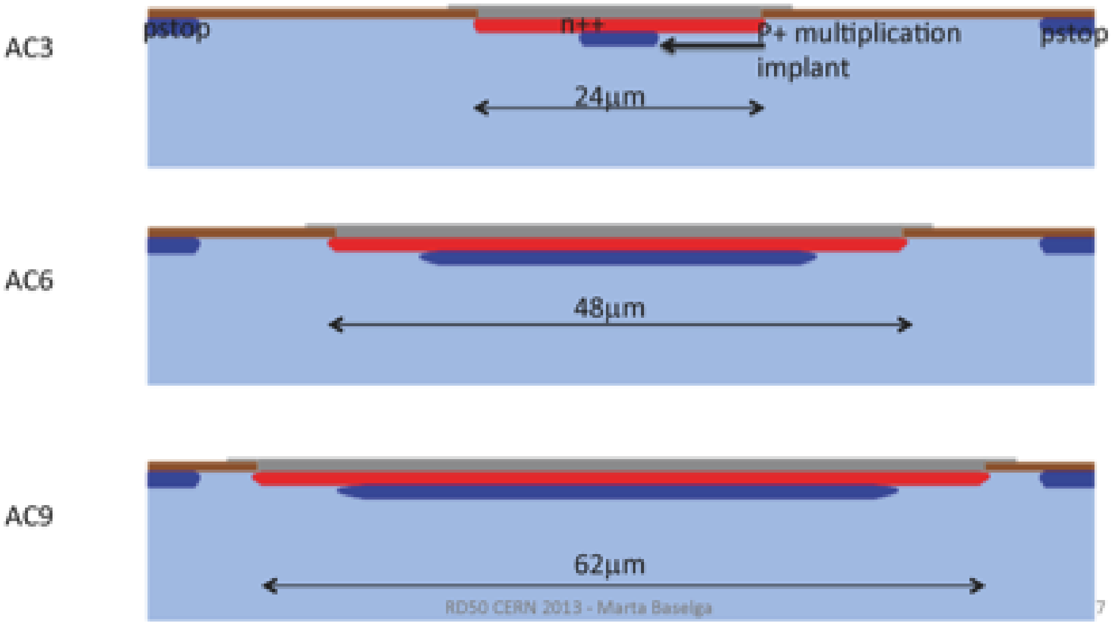
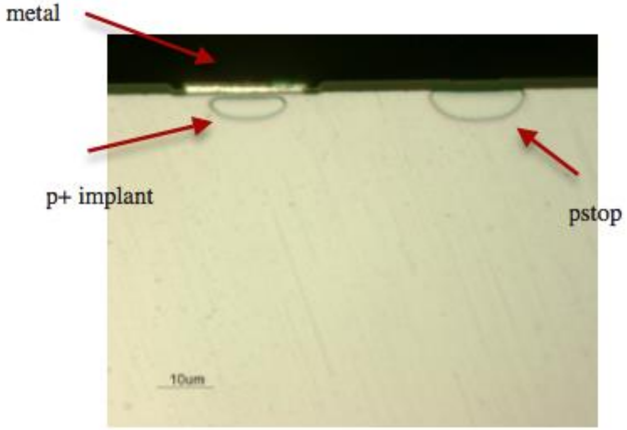


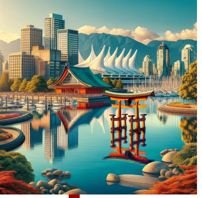
LGADs Pads, Pixels and Strips

The LGAD approach can be used in any silicon structure,

This is an example of LGAD strips

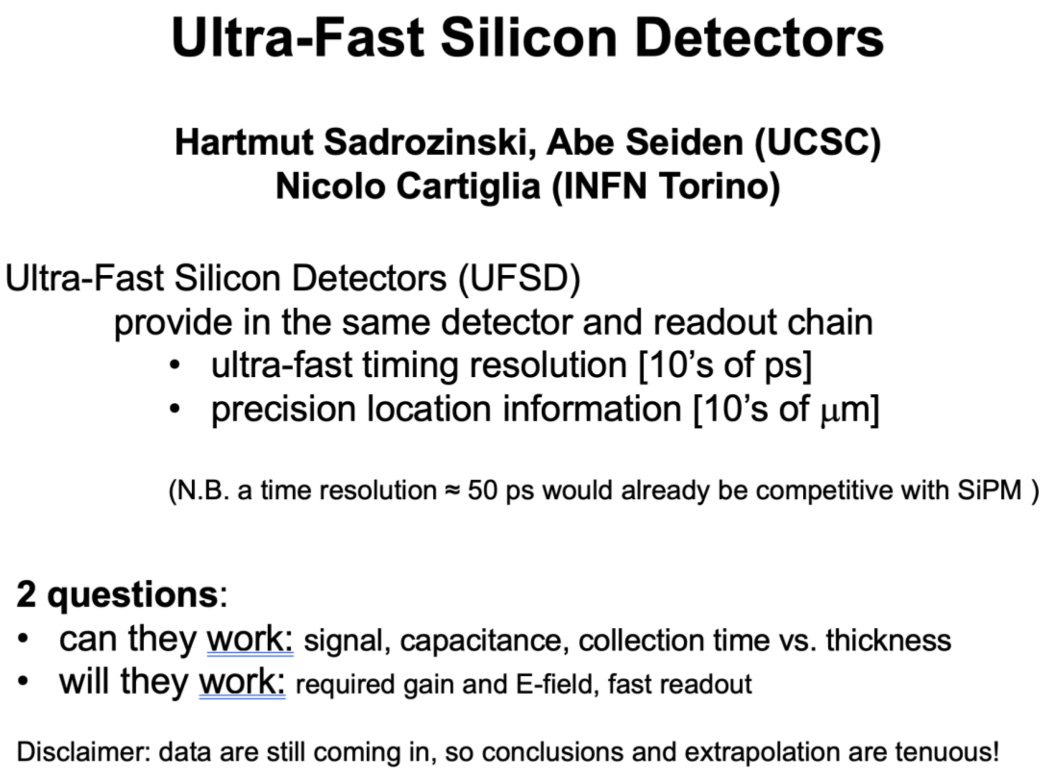






Another R&D needed internal gain: fast timing

RD50 June 2012, Bari



Ultra-Fast Silicon Detectors

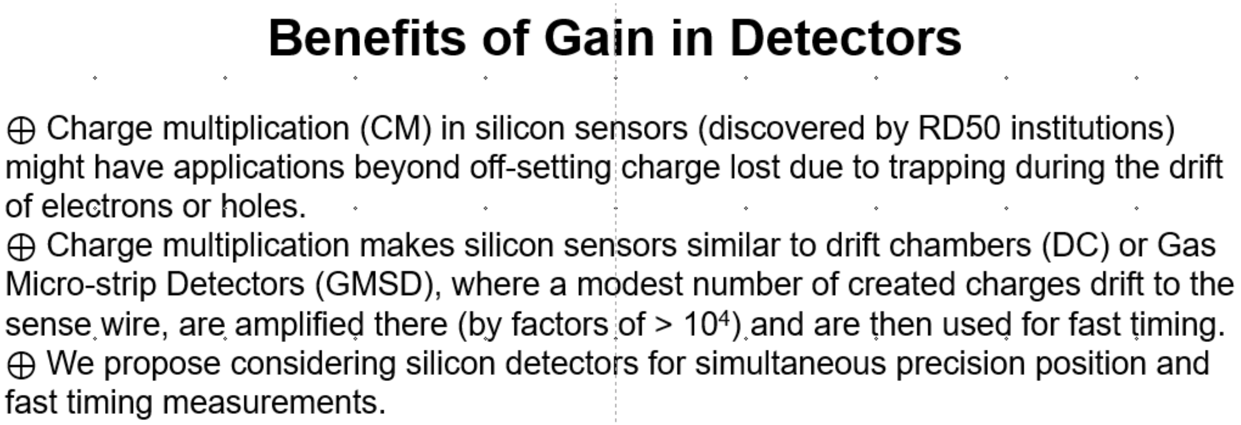
Hartmut Sadrozinski, Abe Seiden (UCSC)
Nicolo Cartiglia (INFN Torino)

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]

(N.B. a time resolution ≈ 50 ps would already be competitive with SiPM)

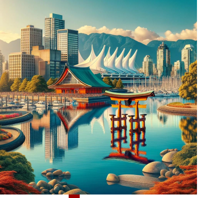
2 questions:
- can they work: signal, capacitance, collection time vs. thickness
- will they work: required gain and E-field, fast readout

Disclaimer: data are still coming in, so conclusions and extrapolation are tenuous!

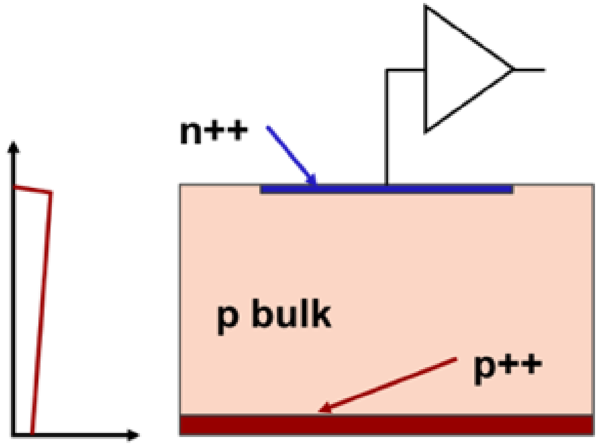


Benefits of Gain in Detectors

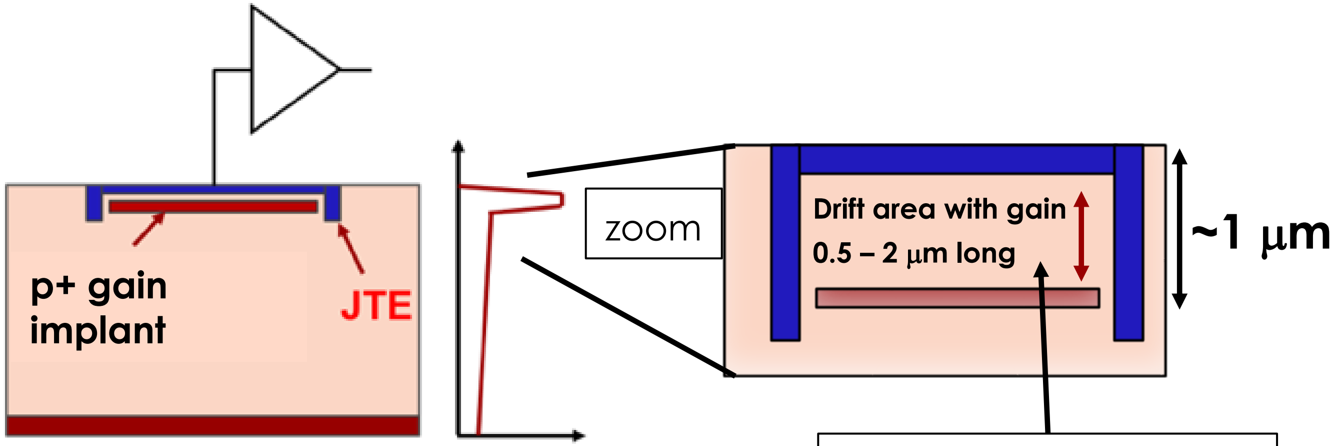
⊕ Charge multiplication (CM) in silicon sensors (discovered by RD50 institutions) might have applications beyond off-setting charge lost due to trapping during the drift of electrons or holes.
⊕ Charge multiplication makes silicon sensors similar to drift chambers (DC) or Gas Micro-strip Detectors (GMSD), 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.



Design innovation: low gain avalanche diode (LGAD)



Traditional Silicon Detector

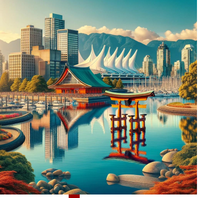


Low-gain avalanche diode

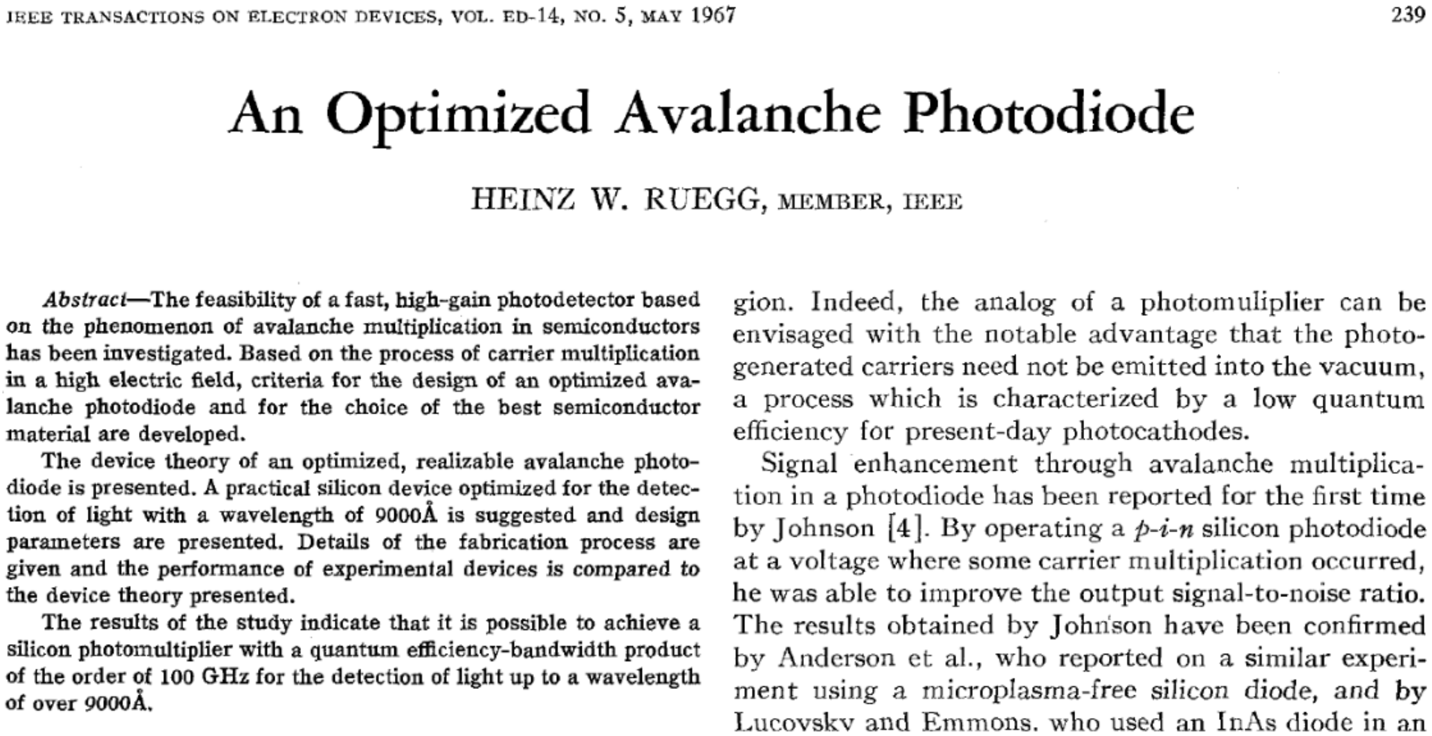
The gain layer:
a parallel plate capacitor with high field

- In LGAD, a moderately p-doped implant creates a volume of high field, where charge multiplication happens.
- It turned out that the LGAD design **does not solve the charge-trapping problem as the LGAD mechanism does not work well in high radiation environments (above 1E15 n_{eq}/cm^2)**

However, the LGAD design **did help solving a few other problems.**



Was it actually an innovation?



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 Lucovsky and Emmons, who used an InAs diode in an

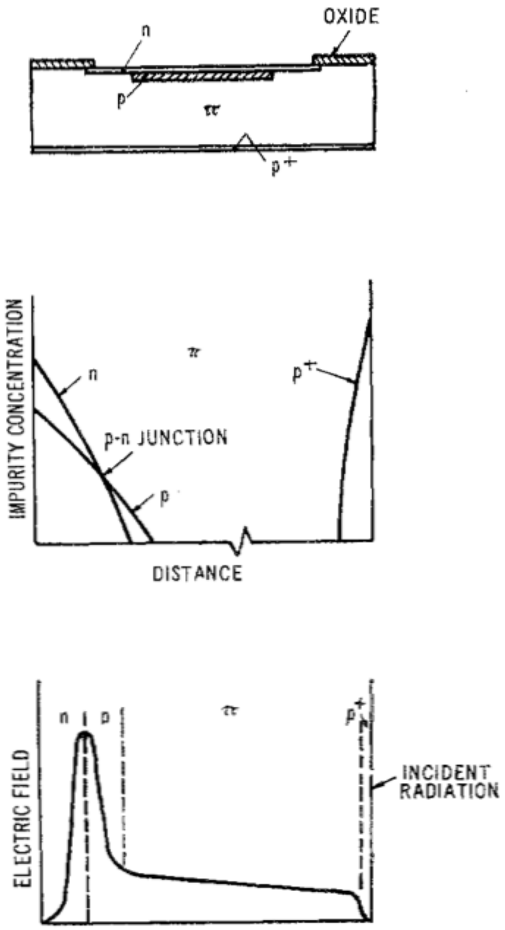
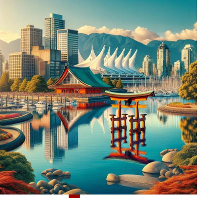


Fig. 1. Sketeches of reach-through avalanche-diode structure, impurity-concentration profile, and electric-field distribution.

Probably not…



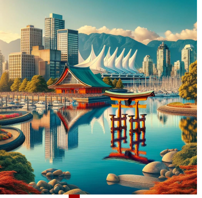
Why the idea of LGAD has been so successful?

- **There is a real need for 4D tracking** in future experiments.
  - 4D tracking is not simply "better", it is an enabling technology

- **It is technologically easy**.
  - Large knowledge base in silicon sensors, SiPM.
  - Fully compatible with standard testing tools
  - Availability of high resistivity thin p-bulk to use electron-initiated avalanche (much easier to control than hole-initiated avalanche)

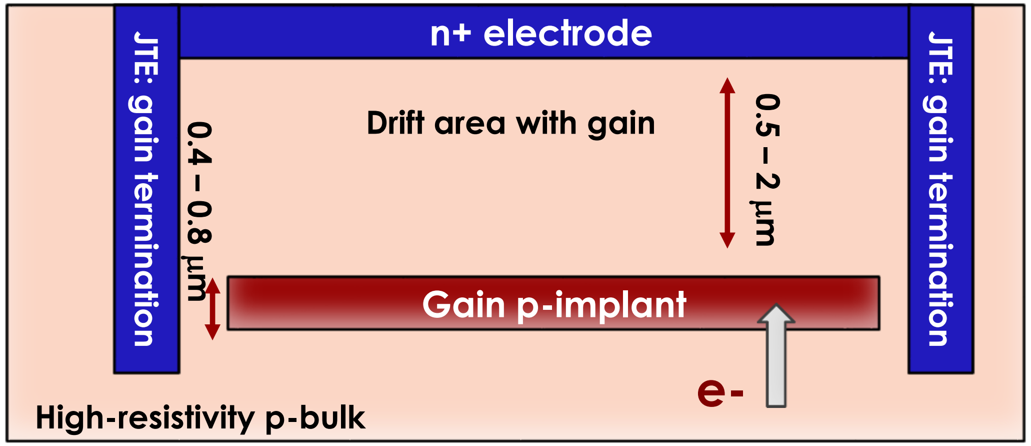
- **Complementary to non-HEP needs.**
  - LGADs are used in medicine, space application, x-rays.

- **Modularity: no need for a full 4D tracker**
  - one layer is enough to have an impact



The LGAD core: the position and design of the gain implant

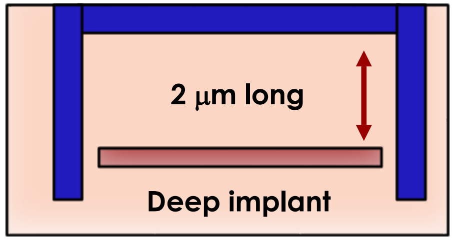
In the past 10 years, **a lot of different gain layer designs** have been developed, either because they are technically easy, or because they have interesting properties.

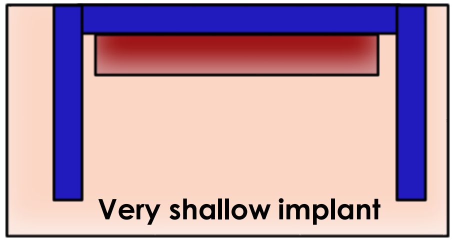


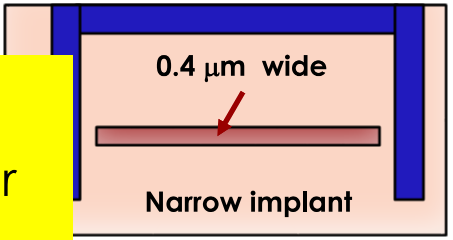
Two main parameters to play with:

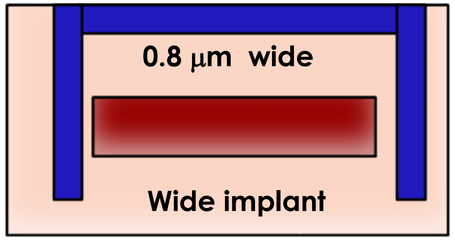
The width and position of the gain implant

- The wider the gain implant, the lower the doping level
- The deeper the gain implant, the lower the doping level





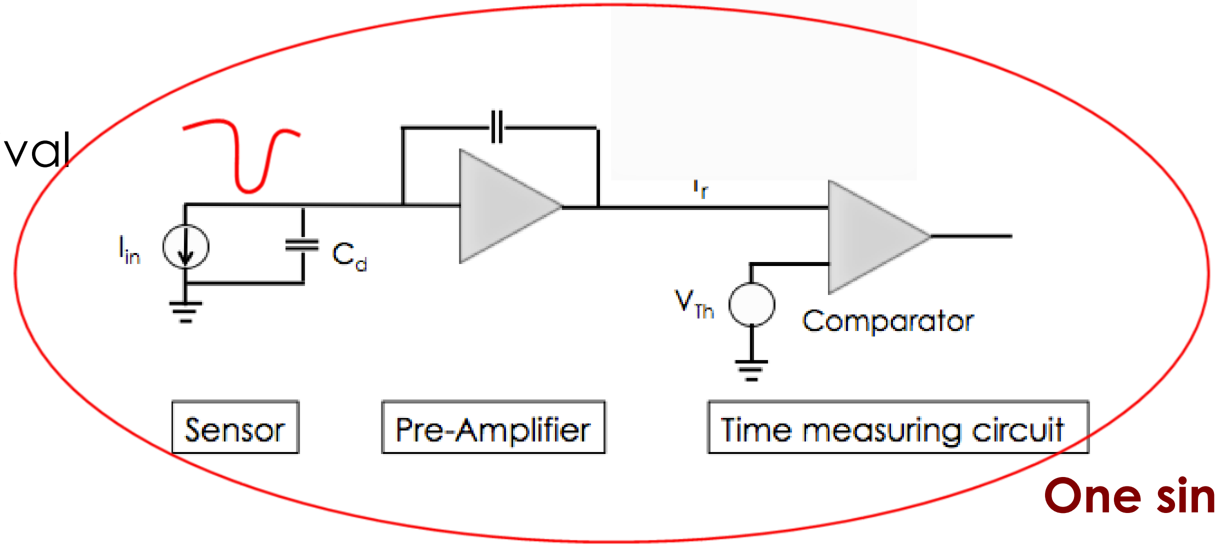




Different designs lead to different properties, such as more or less radiation resistance, easier fabrication, more uniformity, etc…

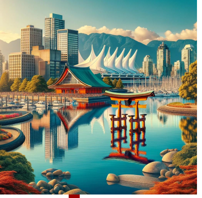
Why do LGADs allow developing 4D tracking?

- Sensors produce a current pulse
- The read-out measures the time of arrival



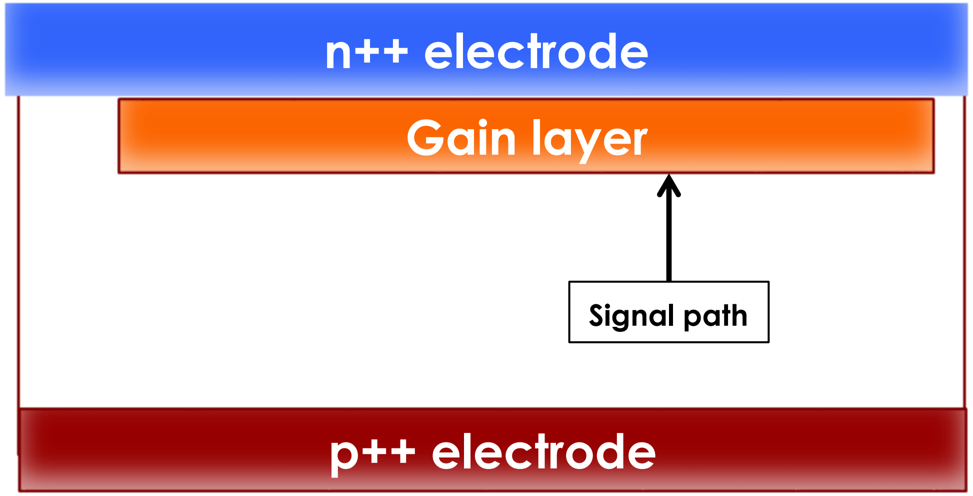
One single system

The “secret” is the signal-to-noise ratio



Signal, noise in LGAD

Caveat: noise is a boring subject, but you have to endure this slide to reach a brighter future.



First concept: gain (G) increases the signal (I):

$$Signal \; = G * I_{signal}$$

Second concept: gain increases noise more than increases the signal

$$\sigma_{Signal} = G * I_{signal}\sqrt{F}$$

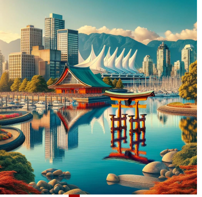
Excess noise factor: noise of the multiplication process

$$F = Gk + \left(2 - \frac{1}{G}\right) * (1 - k)$$

k = e/h ionization rate
G = gain

Use 'electron-initiated avalanche' ==> lower noise than holes-initiated avalanche

Conclusion:
internal gain decreases the signal-to-noise ratio of the signal
(not good so far..)



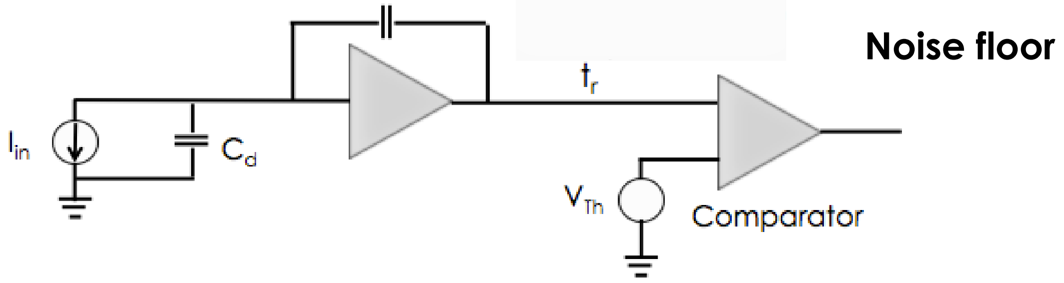
Signal, noise in LGAD + Electronics

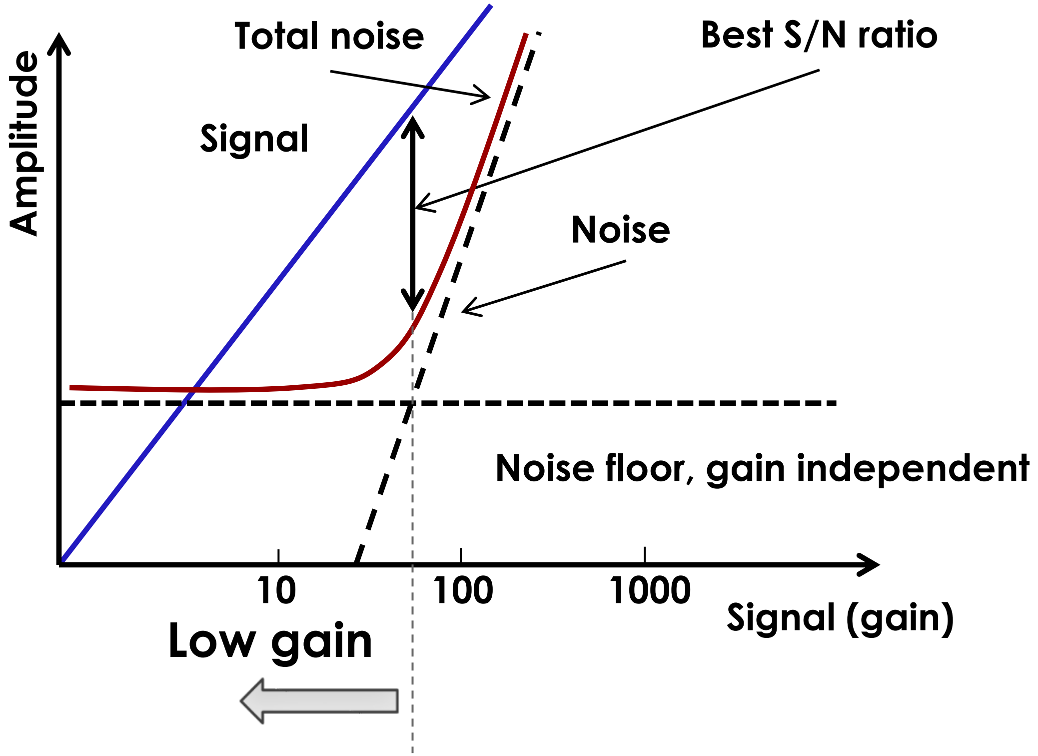
Why do LGADs work then?

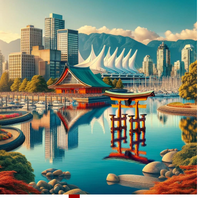
1) The electronics has a noise floor
2) The signal increases with gain
3) The noise increases with gain with steeper characteristics
4) **The total noise is flat at low gain, and then it increases fast**

"Low gain" needs to be understood in connection with the noise of the electronics: it is the range of gain with an improved signal-to-noise ratio.

The success of LGADs rests on the fact that the sensor noise is hidden by the electronic noise

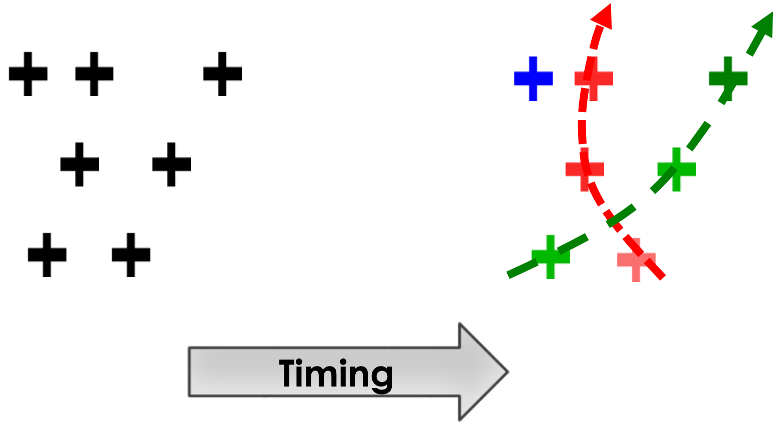






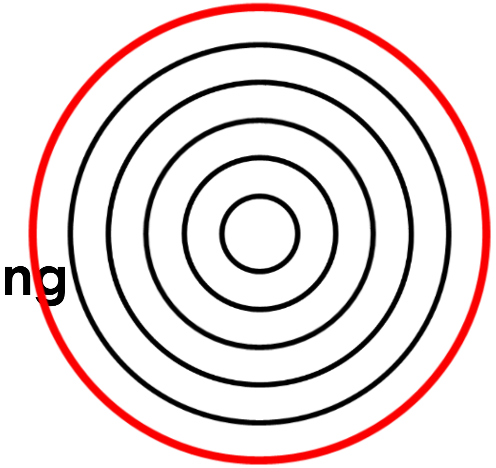
Timing layers and 4D tracking

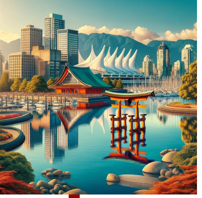
By “**4D tracking**” we mean the process of assigning a spatial and a temporal coordinate to a hit.



Timing can be available at different levels of the event reconstruction:

1) Timing in a single point (timing layer ATLAS,CMS): **3+1 tracking**





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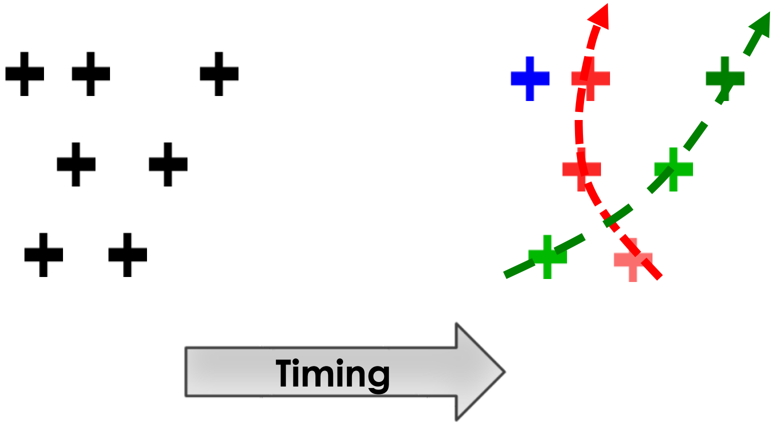
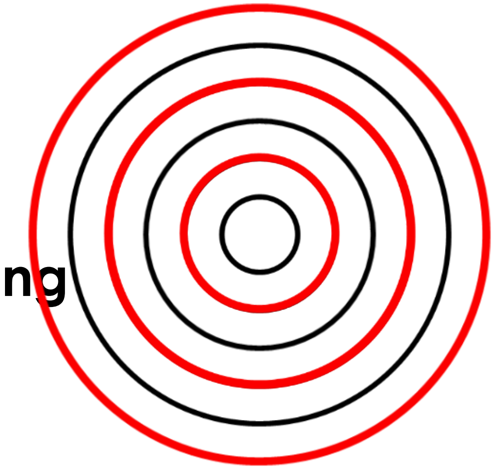
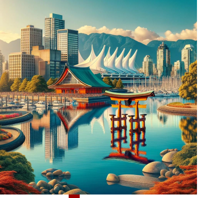


Timing can be available at different levels of the event reconstruction:

1) Timing in a single point (timing layer ATLAS,CMS): **3+1 tracking**
2) Timing at some points along the track





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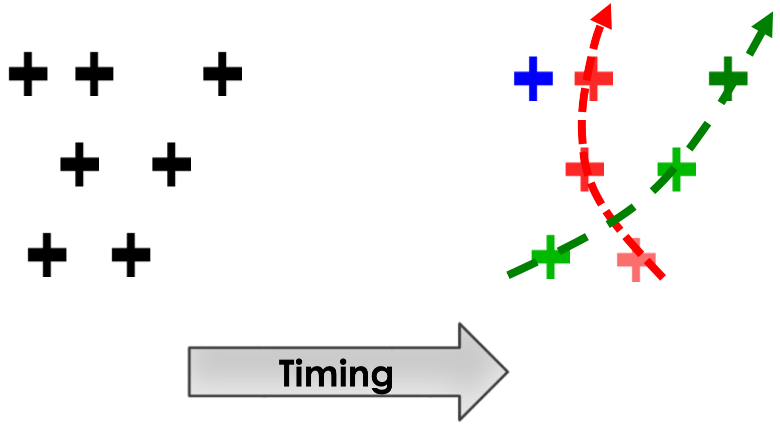
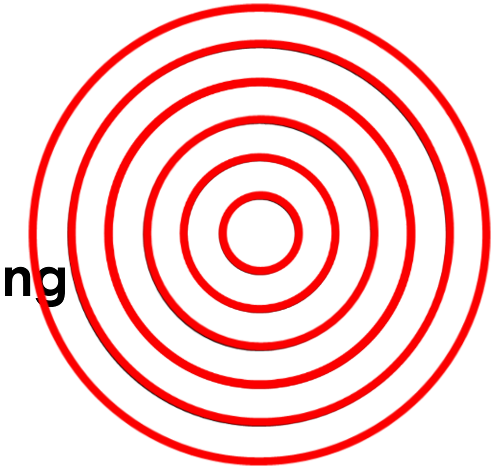
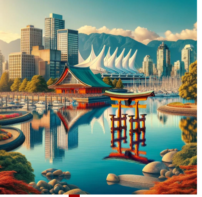


Timing can be available at different levels of the event reconstruction:

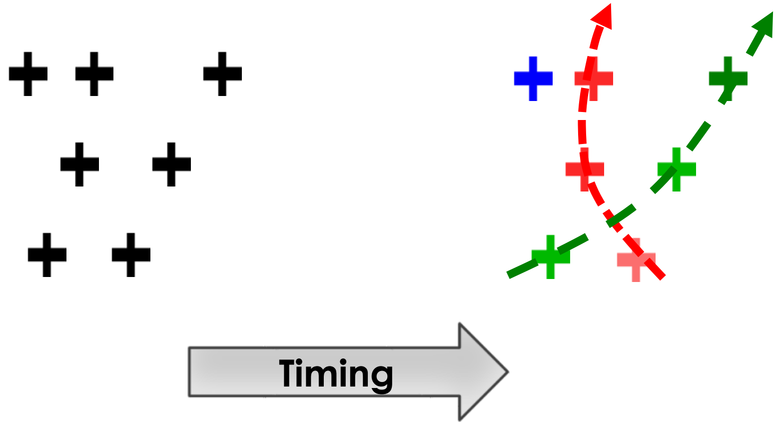


1) Timing in a single point (timing layer ATLAS,CMS): **3+1 tracking**
2) Timing at some points along the track
3) Timing at each point along the track: **4D tracking**



Timing layers and 4D tracking

By “**4D tracking**” we mean the process of assigning a spatial and a temporal coordinate to a hit.

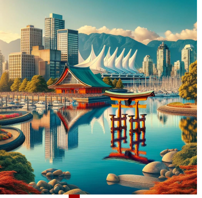


Timing can be available at different levels of the event reconstruction:

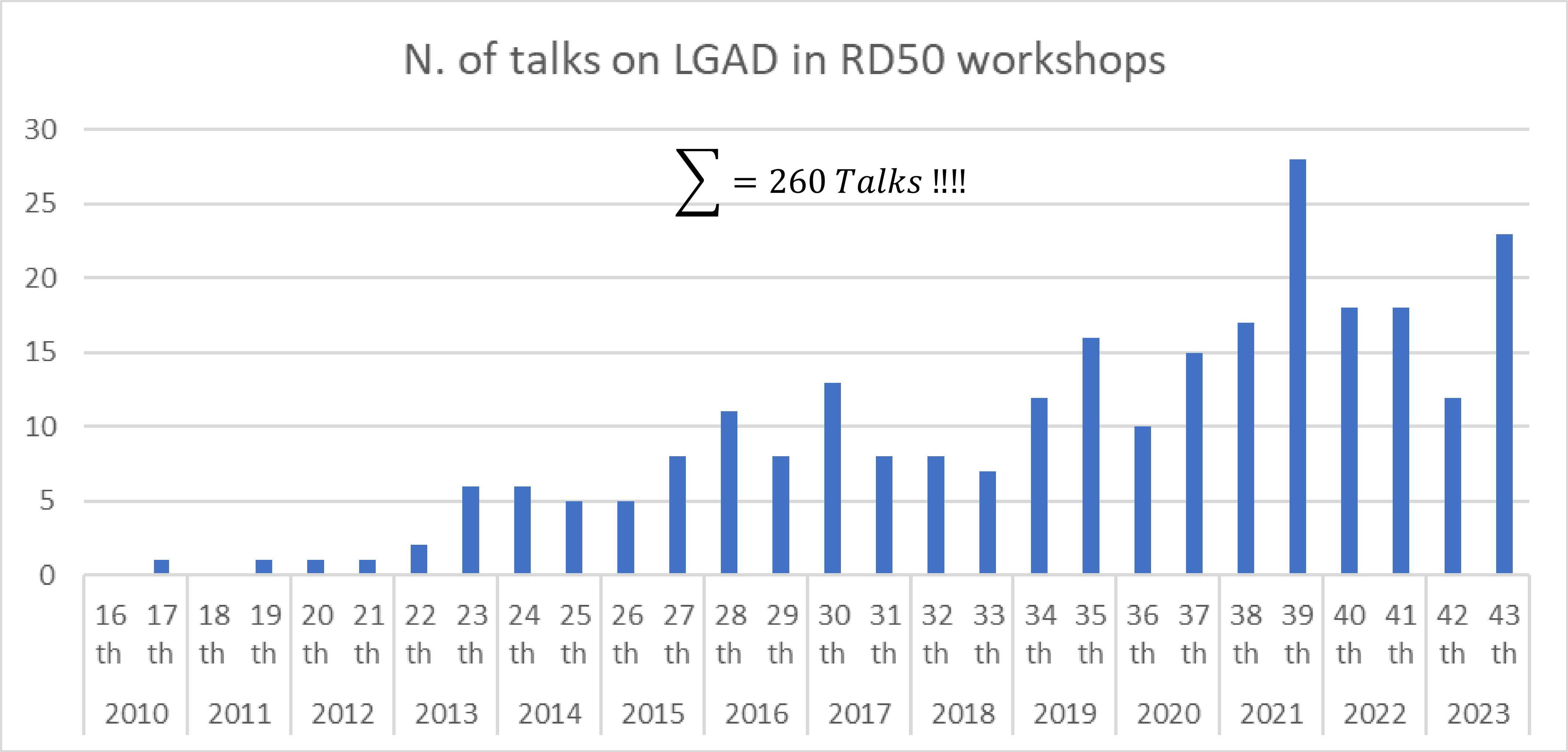
1) Timing in a single point (timing layer ATLAS,CMS)
2) Timing at some points along the track
3) Timing at each point along the track

Many timing coordinates per track yield better-performing detectors but require more complex read-out systems.

Some projects will be perfectly fine with having a limited set of timing points



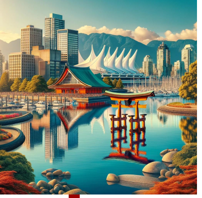
LGAD popularity @ RD50



N. of talks on LGAD in RD50 workshops

$\sum = 260\ Talks$!!!!

G. Pellegrini



Clean Rooms developing LGAD technology

2013
- CNM Centro Nacional de Microelectrónica CSIC

2016
- CNM Centro Nacional de Microelectrónica CSIC
- FBK Fondazione Bruno Kessler

2017
- CNM Centro Nacional de Microelectrónica CSIC
- FBK Fondazione Bruno Kessler
- HAMAMATSU

2018
- CNM Centro Nacional de Microelectrónica CSIC
- FBK Fondazione Bruno Kessler
- HAMAMATSU
- Institute of Microelectronics of the Chinese Academy of Sciences
- Micron Semiconductor Limited
- Brookhaven National Laboratory

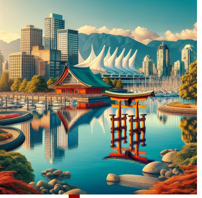
2021
- CNM Centro Nacional de Microelectrónica CSIC
- FBK Fondazione Bruno Kessler
- HAMAMATSU
- Micron Semiconductor Limited
- Brookhaven National Laboratory
- Institute of Microelectronics of the Chinese Academy of Sciences
- CiS Forschungsinstitut für Mikrosensorik GmbH
- Teledyne Technologies Everywhereyoulook™

Market size in 2024-25:

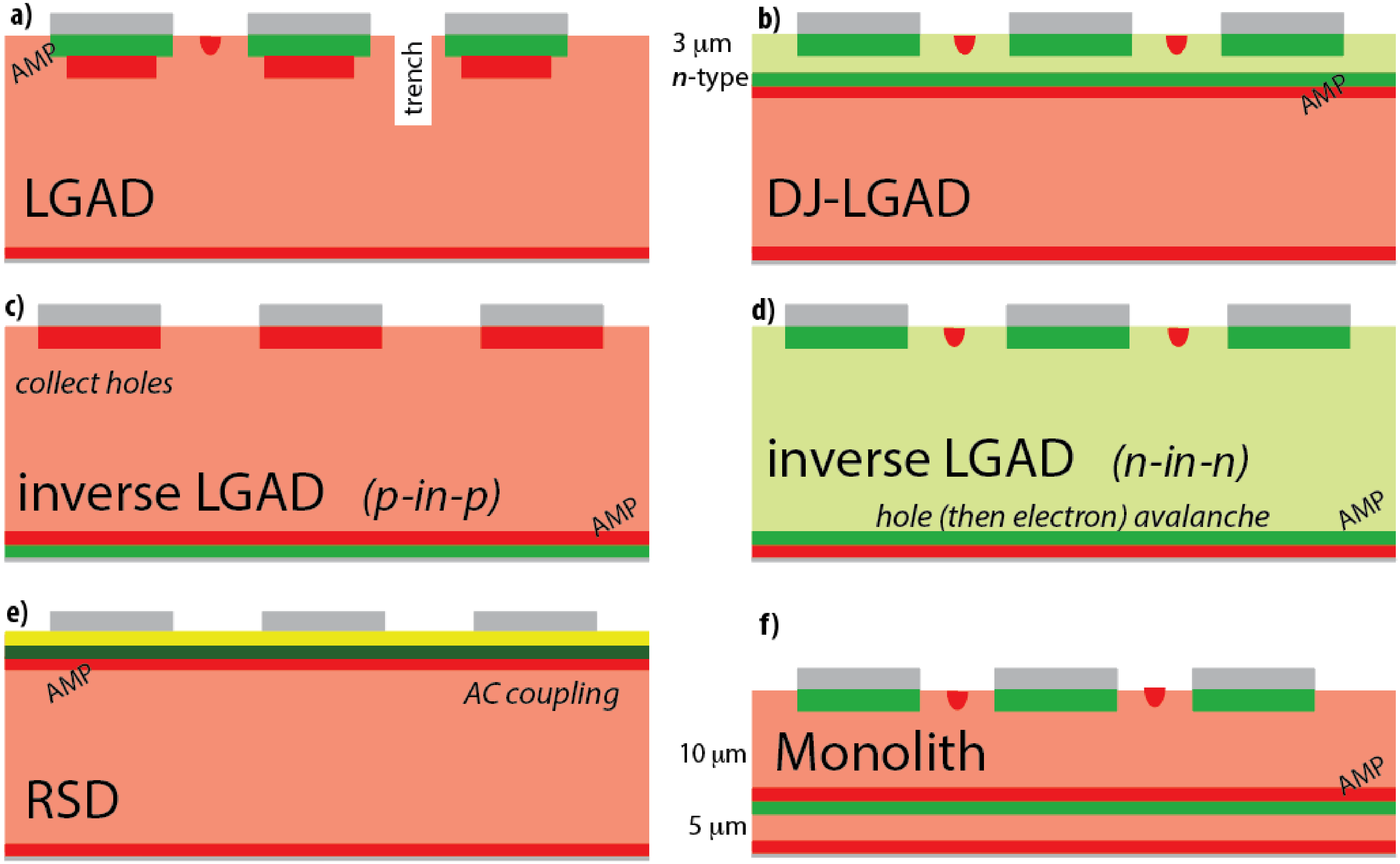
ATLAS, CMS purchase: 25 – 30 m^2

(5-6 million CHF)

G. Pellegrini

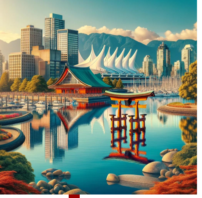


Large variety of LGAD designs



or the new DC-RSD

F. Hartmann

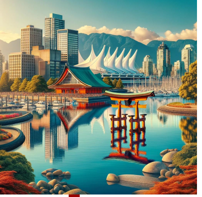


4D tracking with LGADs: kept, broken, and future promises

Mostly yes: LGADs deliver large signals so that the electronic jitter is 10 – 20 ps However: LGADs have an "intrinsic time resolution due to the ionization process.

The grand plan:

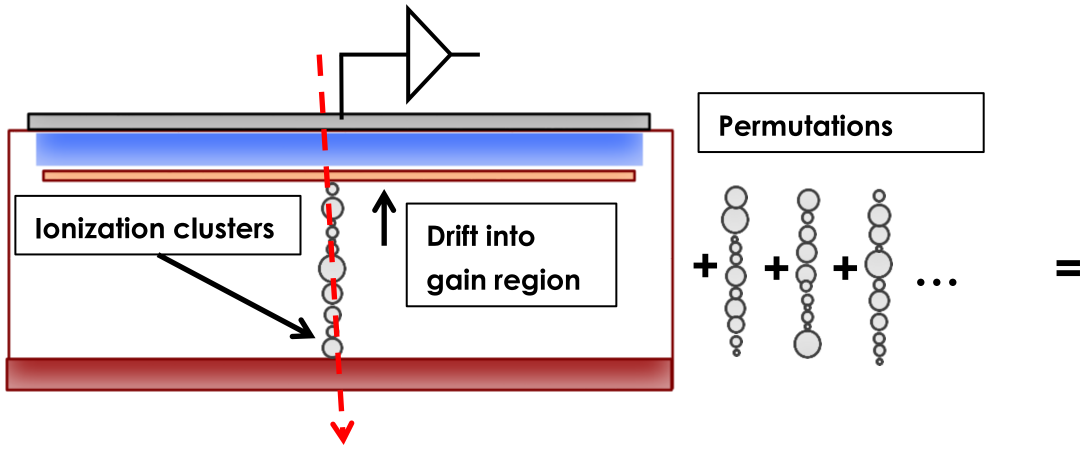
- Temporal resolution: ~10 ps
- Spatial resolution: ~ 10 micron
- Radiation hard

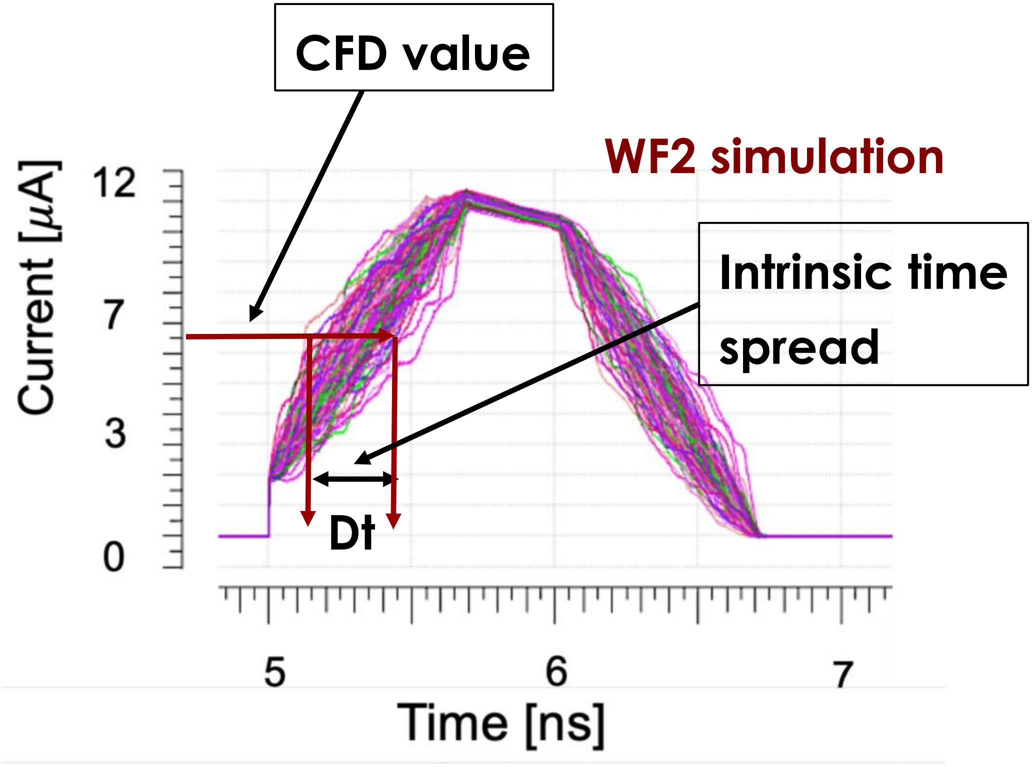


Intrinsic LGAD time resolution

Why LGAD have an “intrinsic” time resolution?

It is a combinatorial problem: how many different ways are there **to produce a given amplitude** summing up individual ionization clusters (imagine there is 1 cluster every 1 micron)?



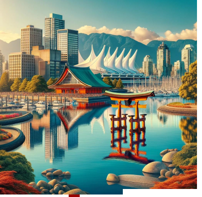


50 microns thick ==> 50! Permutations…

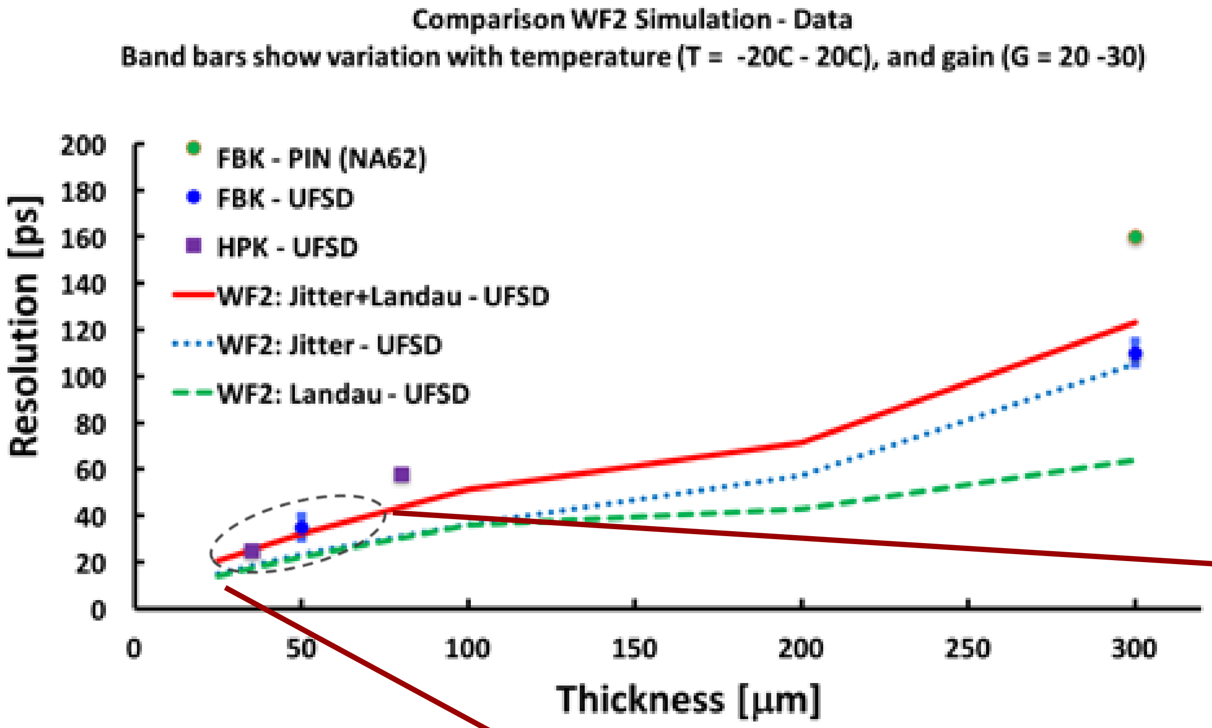
10 microns thick ==> 10! Permutation

The thinner the sensor, the smaller the intrinsic time resolution

(This effect is a consequence of non-uniform ionization due to local Landau fluctuations)

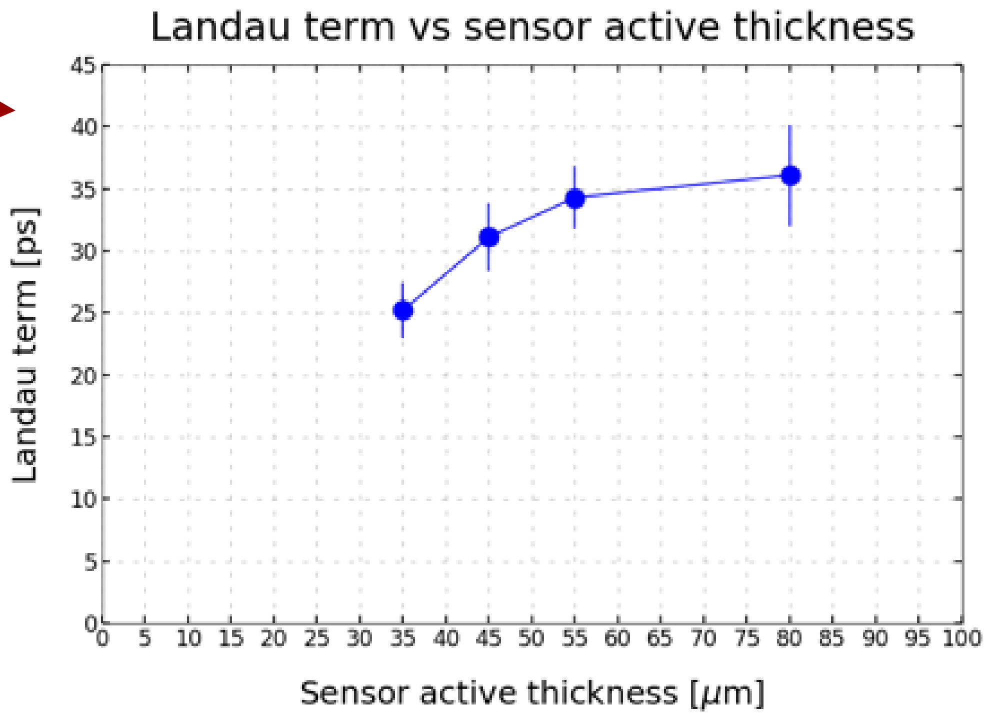


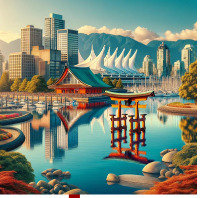
UFSD temporal resolution in thinner sensors


Comparison WF2 Simulation - Data
Band bars show variation with temperature (T = -20C - 20C), and gain (G = 20 -30)

UFSD temporal resolution improves in thinner sensors:
==> reasonable to expect 10-20 ps for 10-20 µm thick sensors.

Be aware: very difficult to do timing with small signals… power consumption increases


Landau term vs sensor active thickness

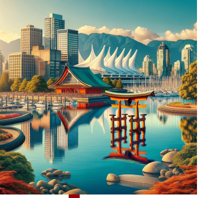


4D tracking with LGADs: kept, broken, and future promises

The grand plan:

- Temporal resolution: ~10 ps
- Spatial resolution: ~ 10 micron
- Radiation hard

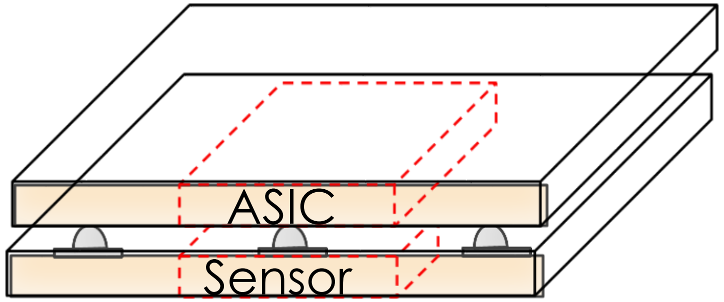
Mostly no: there is not an LGAD-based demonstrator achieving such combined spatial and temporal resolutions



Spatial resolutions

In standard applications with hybrid design, **the position resolution determines:**

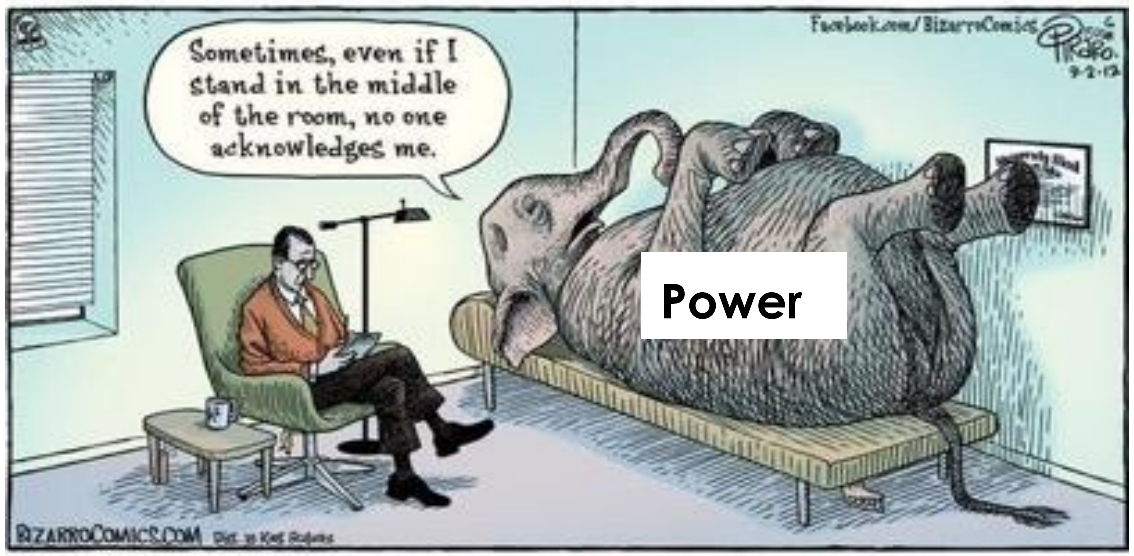
- **The pixel size**
- **The space available for the electronics.**

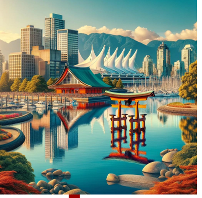


Good position resolutions implies the use of small pixels

Power will determine:

- The architecture of 4D tracking detectors
  - how many layers will be 4D and how many will be 3D
- The pixel size and the temporal precisions.



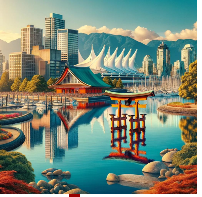


4D tracking with LGADs: kept, broken, and future promises

The grand plan:

- Temporal resolution: ~10 ps
- Spatial resolution: ~ 10 micron
- Radiation hard

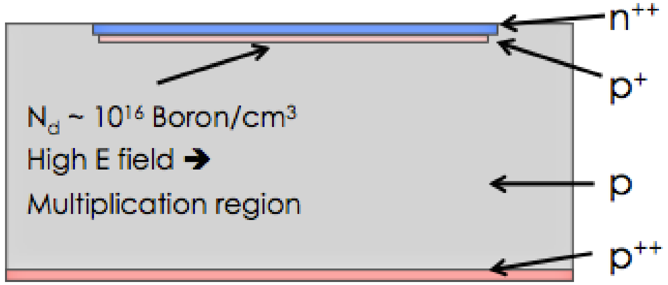
Yes and no: thanks to a very strong R&D program, LGADs survive to about 2E15 n_{eq}/cm^2

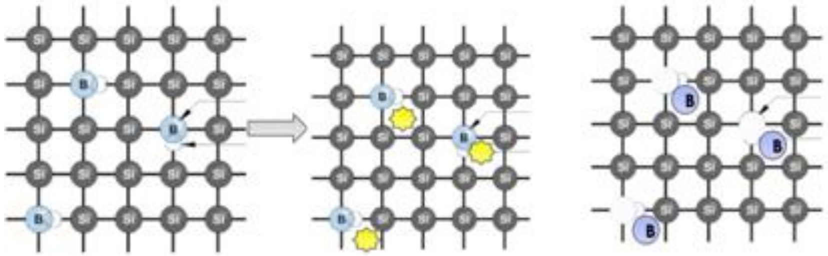


Acceptor removal in LGADs

Unfortunate fact: irradiation de-activate p-doping removing boron from the reticle

$$N(\emptyset) = N(0) * e^{-c\emptyset}$$



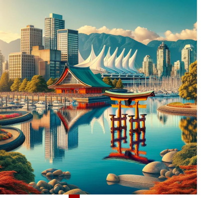


Boron
Radiation creates Si interstitial that inactivate the Boron:
Si_i + B_s ➔ Si_s + B_i

Defect engineering (Carbon addition) and **process tuning** (low-temperature dopants activation) improved the initial LGAD resistance by a factor of 2-3.

This path seems to have exhausted its potential, new approaches are needed

Several new venues are presently explored
(V. Sola in the afternoon proposing "compensation")



4D tracking with LGADs: future promises

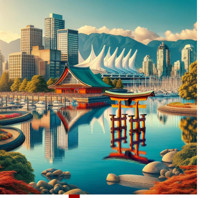
The large variety of LGAD designs addresses the needs of spatial and temporal resolutions at various degrees of resolutions.

Several possible paths:

- **Traditional approach:** design LGADs with a small pitch.
- 55 x 55 micron^2 (TimePix compatible) Trench Isolated LGADs have been manufactured and work well.
- **Resistive read-out** (RSD – AC-LGAD): design LGADs with large pixels and excellent position resolution.
- **Monolithic LGADs** are being studied, and first prototypes exist

The fulfillment of the 4D promise is mostly a "front-end design" problem.

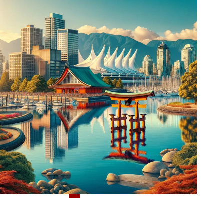
LGADs are a mature technology, the difficult part is the design of the ASIC.



LGAD legacy: a few examples

The development of LGAD has stirred the R&D in several other fields

- **Better understanding of how to control low gain in silicon.**
  - Charge screening
  - Gain dependence upon the gain implant shape and position
  - Effects of manufacturing parameters such as heat, initial wafer type, and doping
  - Simulation in 2D and 3D
- **Radiation damage in devices with gain**
  - Improved understanding of acceptor (donor) removal
  - Defect engineering to control acceptor removal (Carbon is fashionable again)
  - Dependance upon the initial doping density
- **Low power electronics for timing**
  - There has been a strong interest in designing the appropriate circuits. A wide range of technologies have been used (CMOS, BiCMOS, 110, 64, 28 nm)



Conclusions and outlook

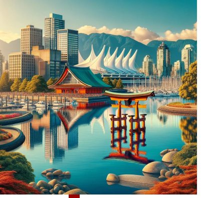
In the past 10 years, the LGAD concept has been the center of a strong R&D phase that has **established basic design parameters**.

Many variations are being explored to progress **from the present 3+1 tracking to the full 4D tracking.**

The main issue is the development of low-power front-end electronics for 4D tracking. In this moment, sensors are the easy part.

The future trackers will be a combination of 3+1 and 4D designs

I hope that in the next 10 years, we will have as much fun as we had in the past 10 years.



Materials and ideas

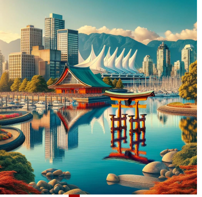
Vertex 2023 conference,

Ivan Vila, Challenges and new trends in LGAD technologies

RD50

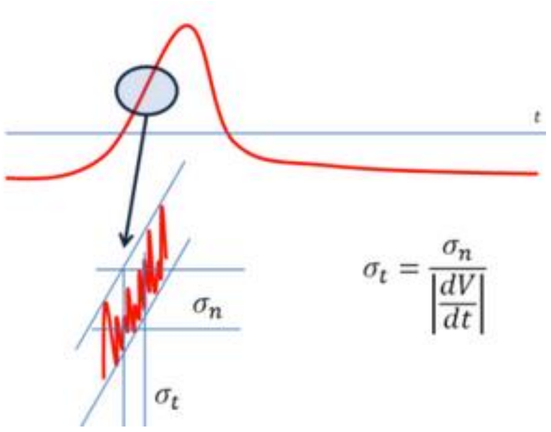
Giulio Pellegrini: LGAD: a Little bit of the early history

Frank Hartman: RD50 from Experiment perspective



Sensor and ASIC Temporal resolution

$$\sigma_t^2 = \left(\frac{Noise}{dV/dt}\right)^2 + (\Delta ionization)^2 + (\Delta shape)^2$$

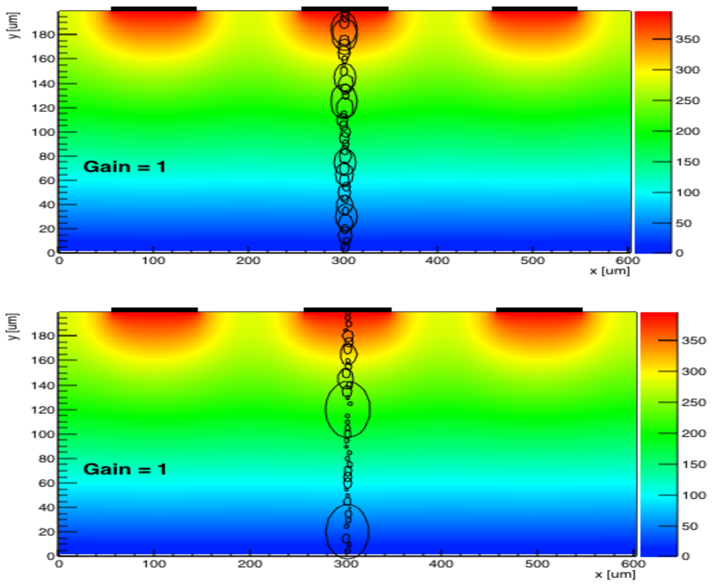


$$\sigma_t = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|}$$

"Jitter" term

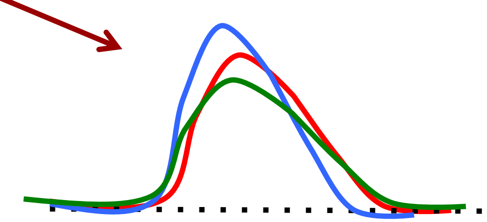
Small noise ==> choice of electronic technology

LGADs, having a larger signal, decrease the jitter component



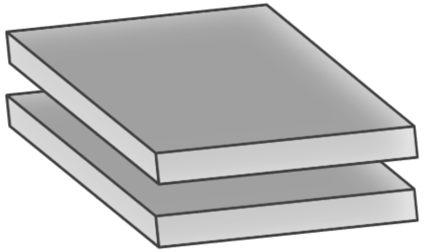
Amplitude variation ==> corrected offline (time walk)

Non-homogeneous energy deposition ==> signal change variation. Cannot be corrected, =minimized by design



Signal shape is determined by Ramo's Theorem

$i\,\mu\,qvE_w$



Saturated drift velocity v everywhere in the sensor volume

Well-designed LGAD sensors (sometimes called UFSD) optimize the temporal resolution