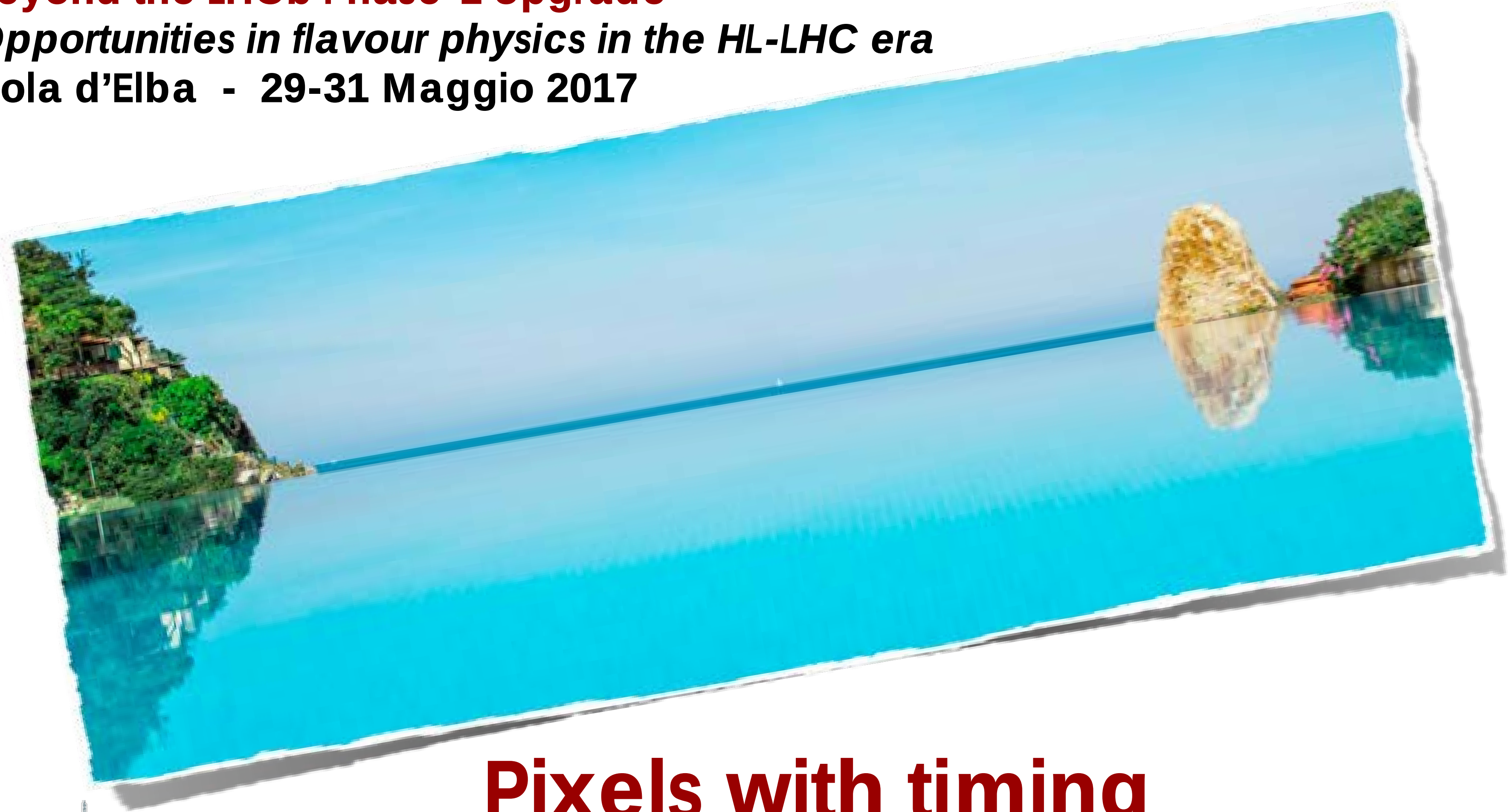
Beyond the LHCb Phase-1 Upgrade

Opportunities in flavour physics in the HL-LHC era

Isola d’Elba - 29-31 Maggio 2017



Pixels with timing

(the UFSD project)

Maria Margherita Obertino

University and INFN, Torino

on behalf of the UFSD group

UFSD

The effect of timing information

The inclusion of track-timing in the event information has the capability of changing radically how we design experiments.

Timing can be available at different stages in the event reconstruction:

1) Track timing in the event reconstruction

→ **CMS timing layer for HL-LHC (see T. Tabarelli's talk)**

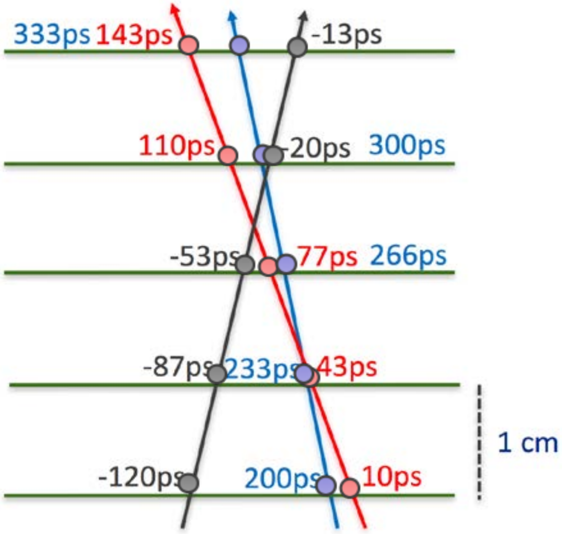
or track timing at the trigger level

→ **ATLAS timing layer for HL-LHC [ref]**

2) Timing at each point along the track:

massive simplification of patter recognition, new tracking algorithms will be faster even in very dense environments

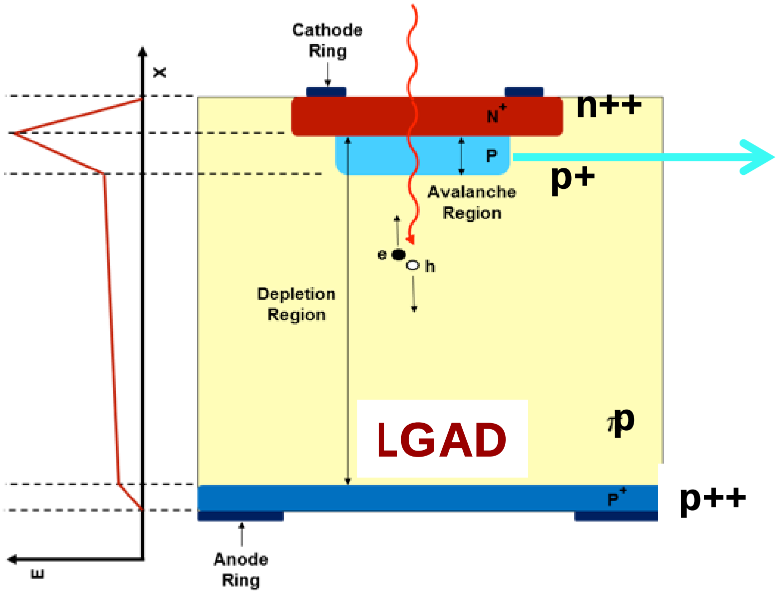
UFSD final goal
90 x 90 μm^2
d ~ 50 μm
σ_t ~ 30 ps



Use only "time compatible points"

Ultra-Fast Silicon Detectors (UFSD)

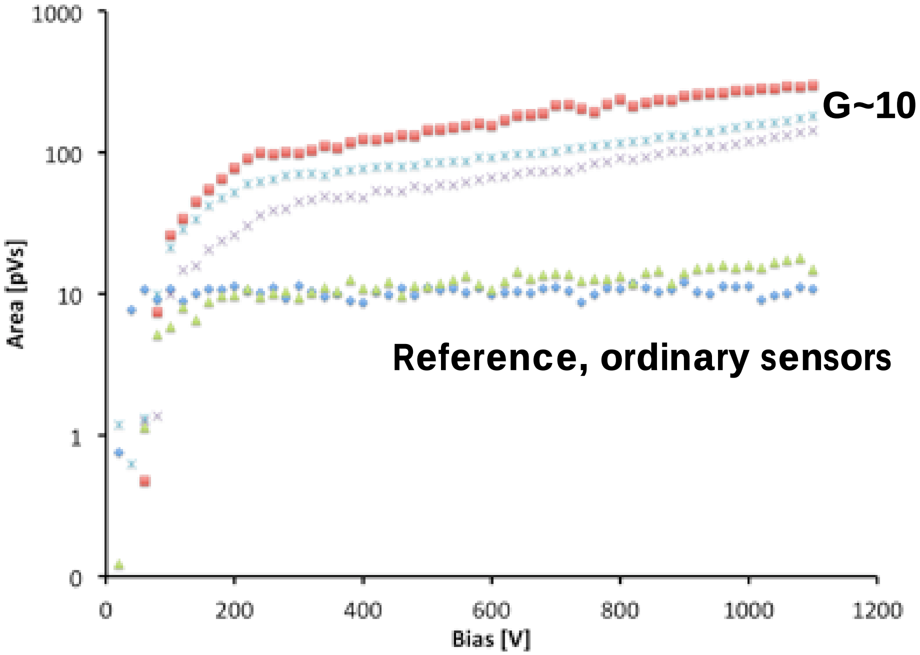
High electric field accelerates e- enough to start multiplication



Thin, highly doped, p-implant near the p-n junction ($N_d \sim 10^{16}$ Boron/cm^3)

Gain changes very smoothly with bias voltage.

→ Easy to set the value of gain requested.

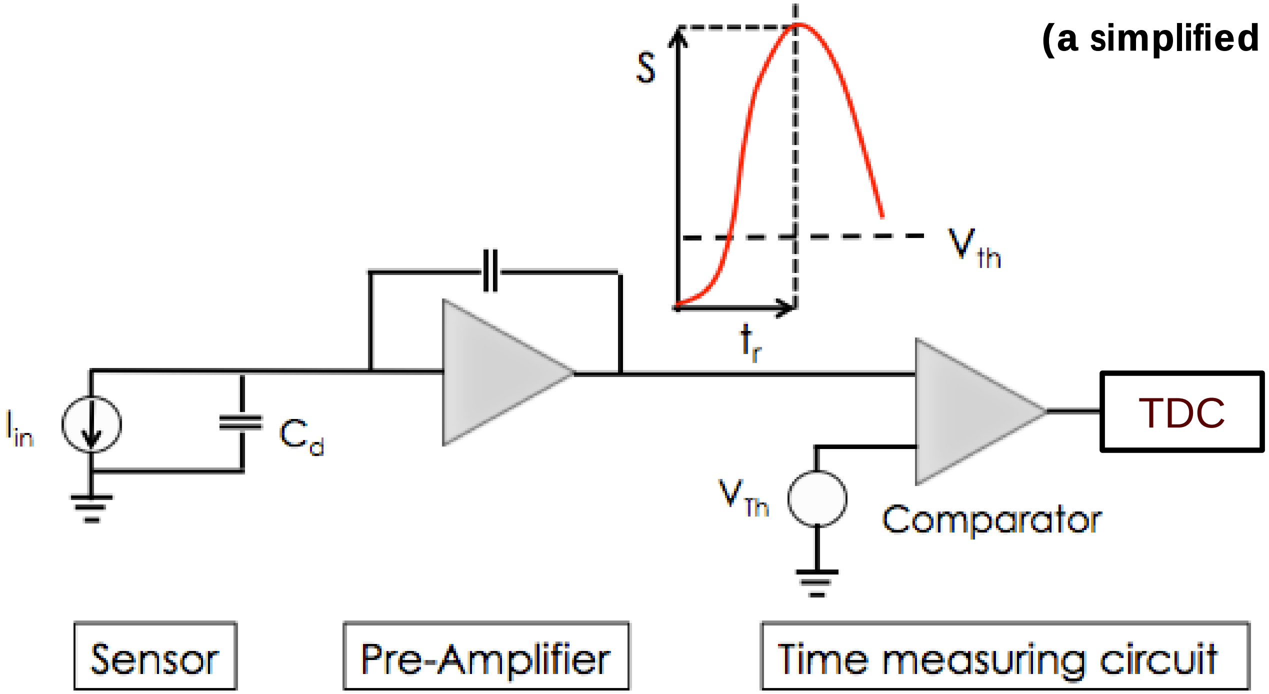


G~10

Reference, ordinary sensors

Silicon time-tagging detector

Time is set when the signal crosses the comparator threshold



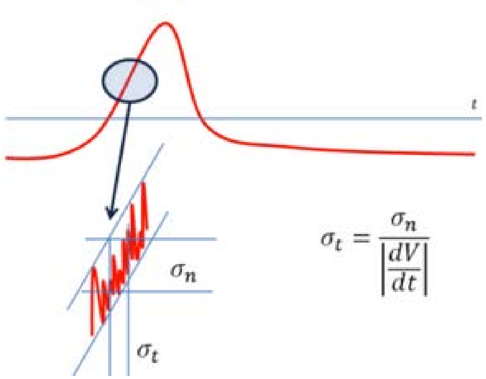
(a simplified view)

The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning.

Time resolution in silicon detectors

$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \left(\frac{TDC}{\sqrt{12}}\right)^2$$

Jitter: here enters the noise and the slope of the signal around the comparator threshold



→ reduced by optimized sensor and electronics design

Negligible

Es. HPTDC binning: 25 ps

25ps/√12 ~ 7 ps

Time walk: change in the signal amplitude due to variation in the deposited energy

→ corrected in electronics

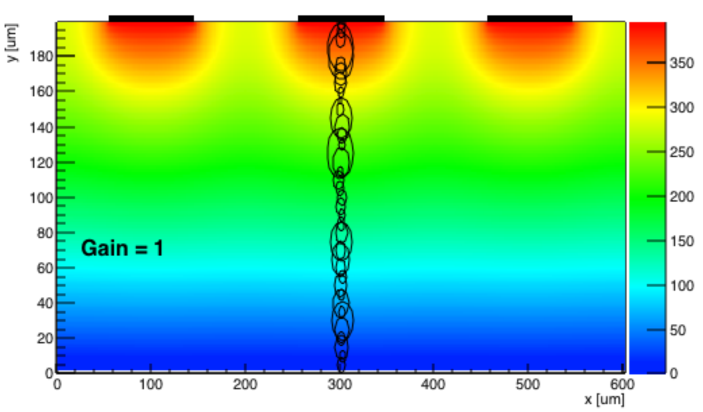
Landau Noise: shape variations due to non homogeneous energy deposition

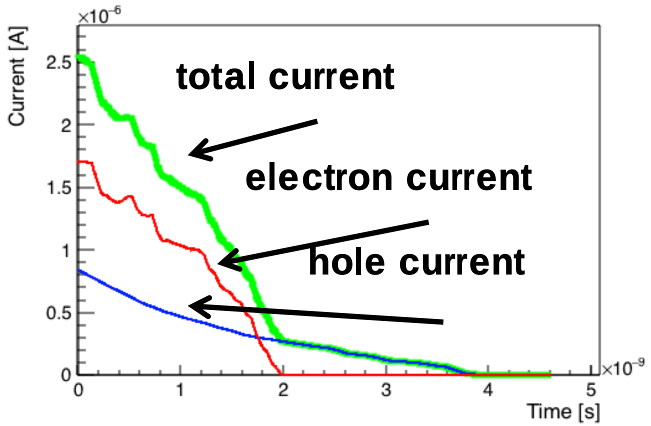
→ mitigated by optimized sensor design

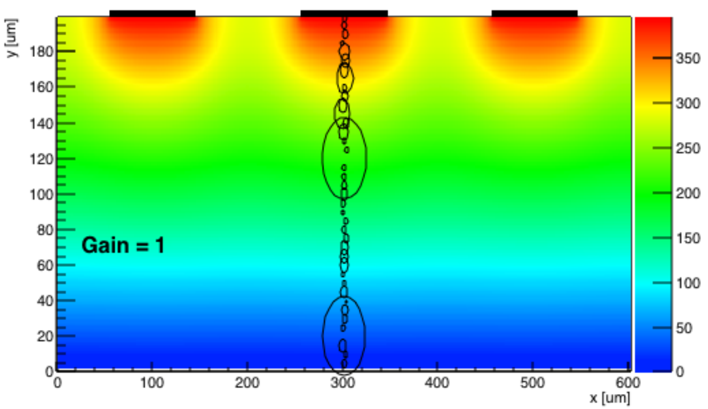
✓ **Strong interplay between sensor and electronics**

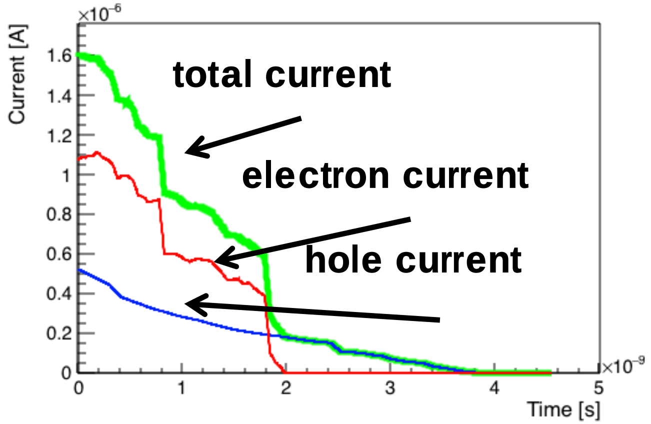
Uniformity of signals: key to good timing

Local density of electron-hole pairs created along the particle path varies on event by event → Irregular current signal









✓ **Mitigated with optimized sensor design: thin sensors minimize the effect**

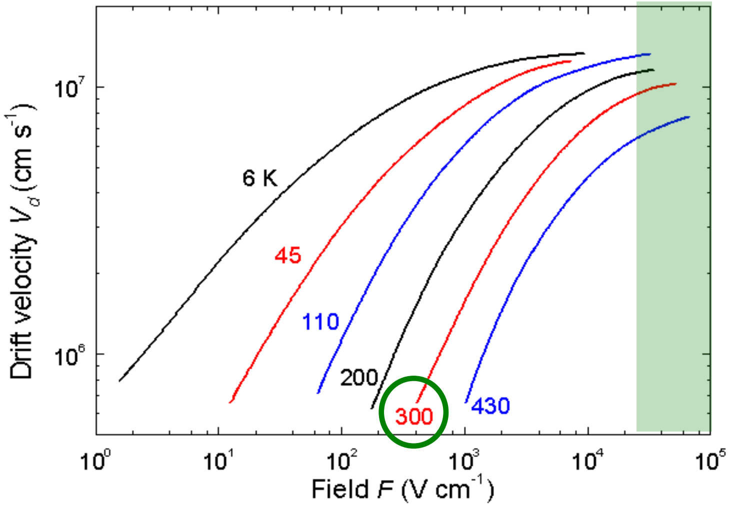
→ **Set the intrinsic limit of the sensor in measuring time**

Ingredients for uniform signals

Signal shape is determined by Ramo's Theorem:

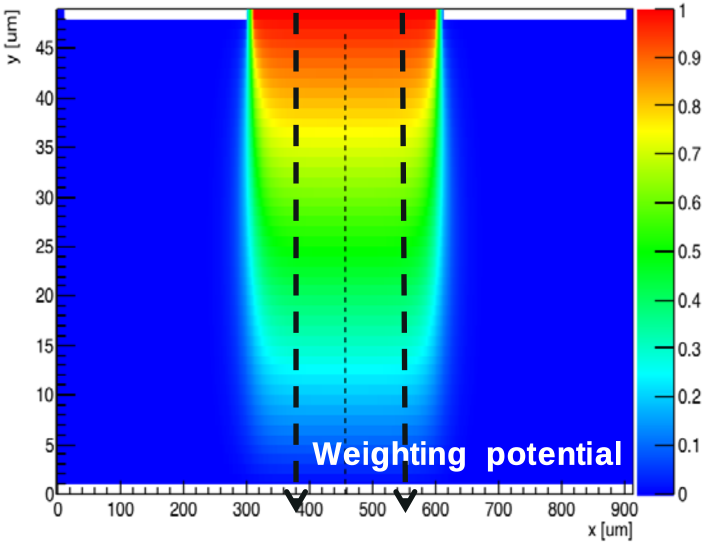
$$i \propto v_d E_w$$

Drift velocity **Weighting field**



Drift velocity and **Weighting field** need to be **as uniform as possible**

High electric field in the bulk to saturate v_d

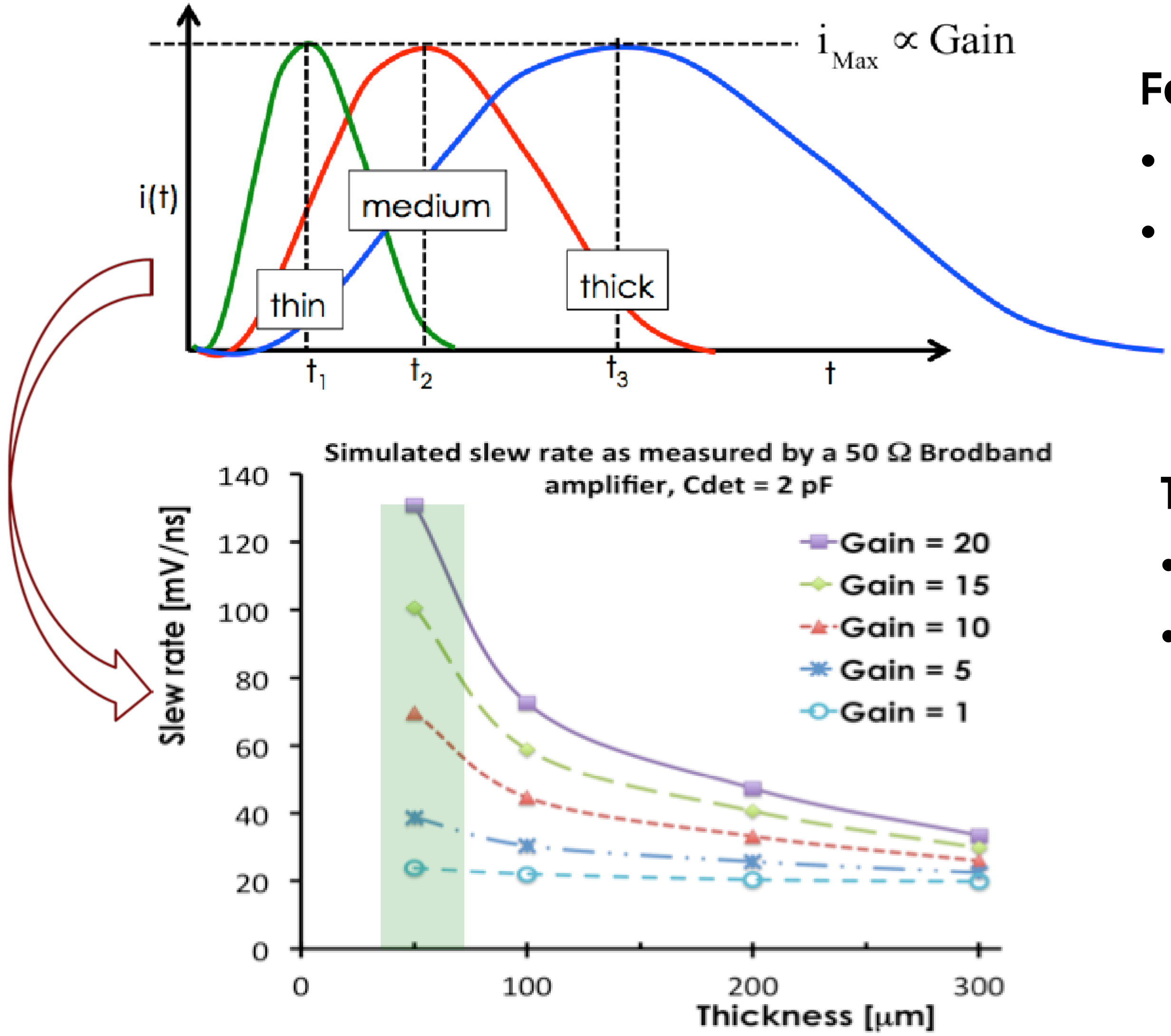


50 μm thickness
300 μm pitch
290 μm implant

✓ **Parallel plate geometry:**

strip implant ~ strip pitch >> thickness

Slew rate in silicon sensors with gain



For a fixed gain:

- amplitude = constant
- rise time increases with thickness

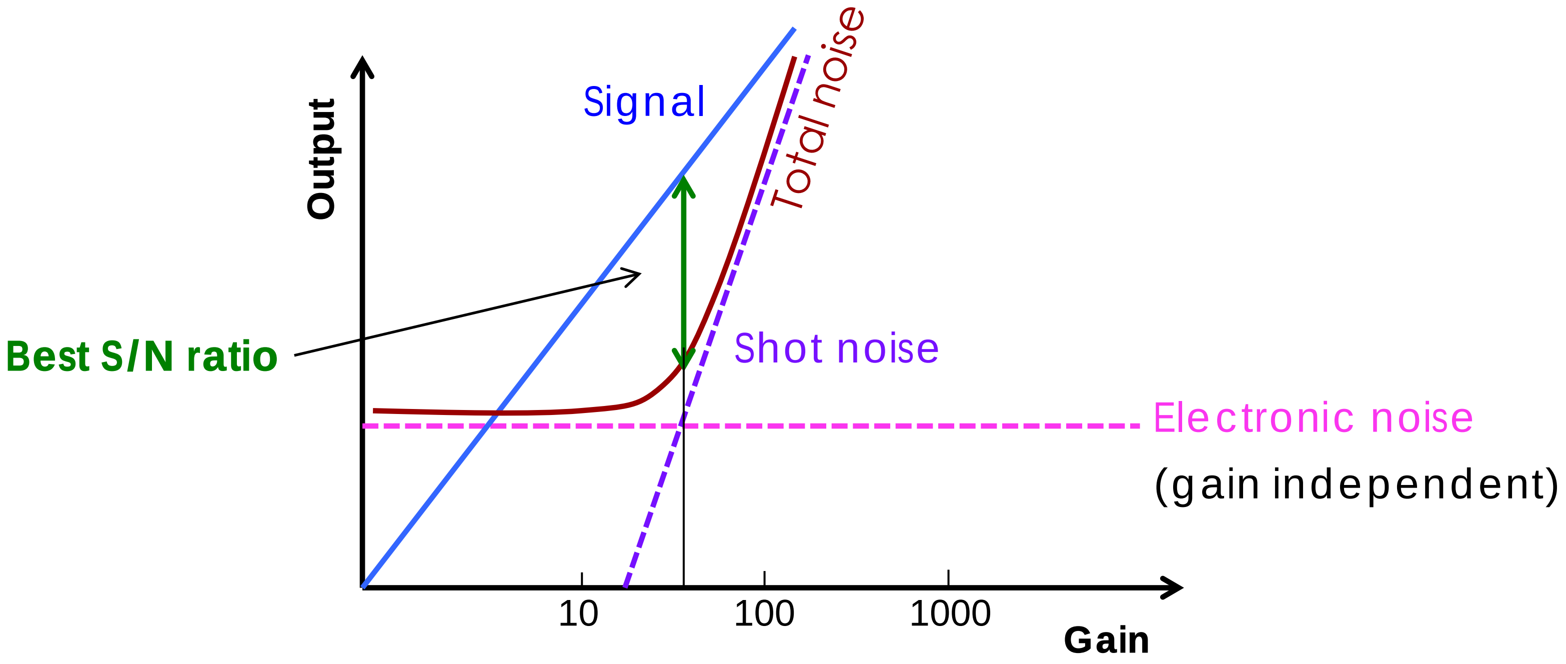
The slew rate:

- Increases with gain
- Increases ~ 1/thickness

$$\boxed{\frac{dV}{dt} \propto \frac{G}{d}}$$

✓ **Significant improvements in time resolution require gain and thin sensors but gain cannot be too high ...**

Noise in silicon sensors with gain

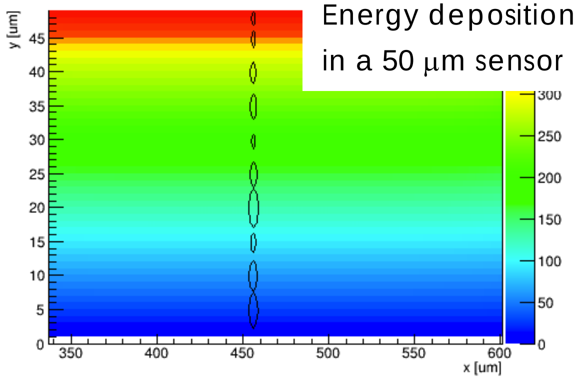


→ **Noise increases faster than then signal**

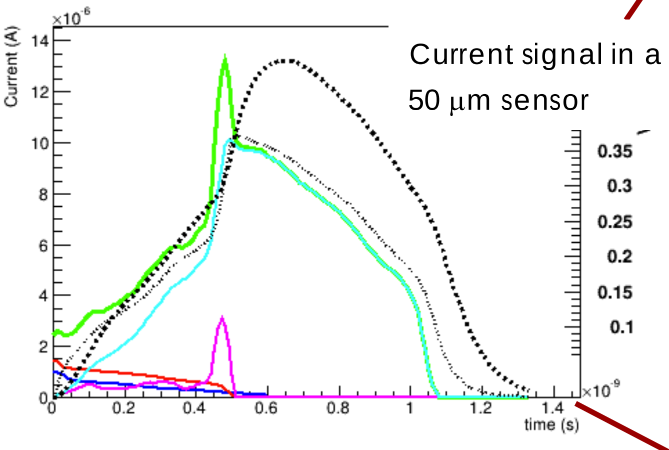
→ **the ratio S/N becomes worse at higher gain**

✓ **Set the lowest gain sufficient to perform accurate time measurements: between 10 an 20 for σ_t ~ 30 ps**

Choice of pre-amp architecture

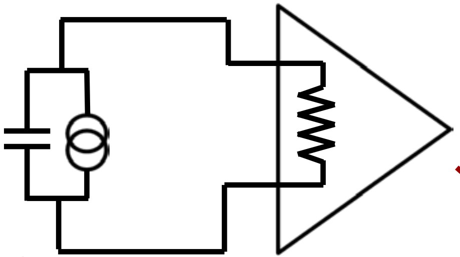


Energy deposition in a 50 µm sensor



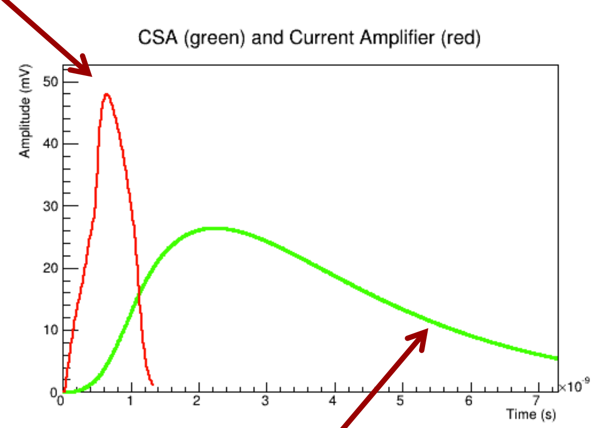
Current signal in a 50 µm sensor

Current Amplifier



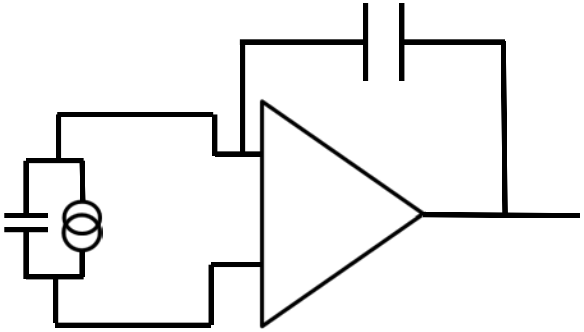
BBA

- Fast slew rate
- Higher noise
- Sensitive to Landau bumps
- More power



CSA (green) and Current Amplifier (red)

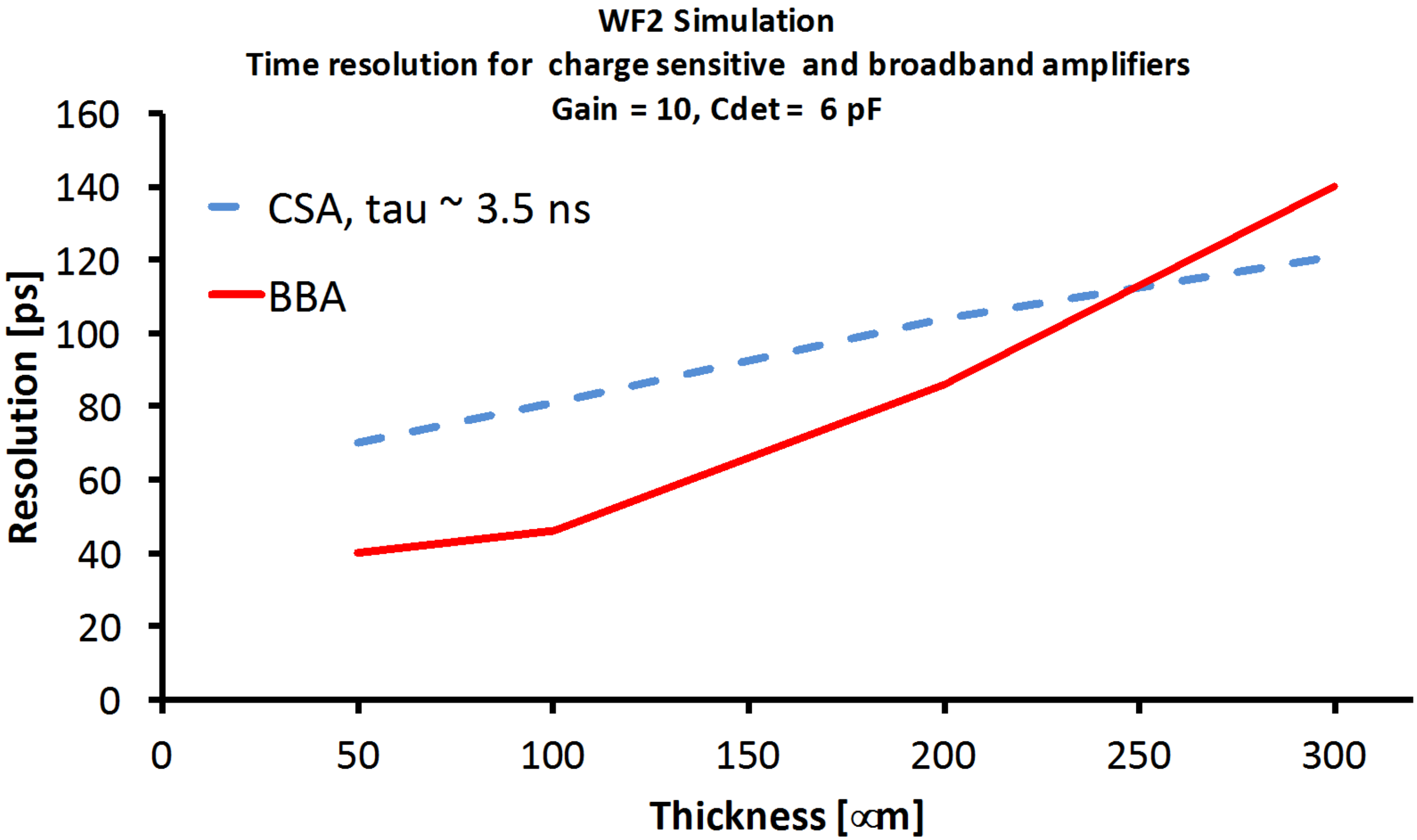
Integrating Amplifier



CSA

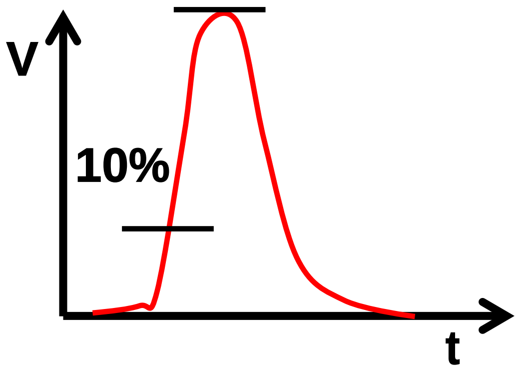
- Slower slew rate
- Lower noise
- Signal smoothing
- Less power

Integrator or current amplifier?



- Current amplifiers work best with very fast signals
- Integrators work best with signals that are longer than their integration time

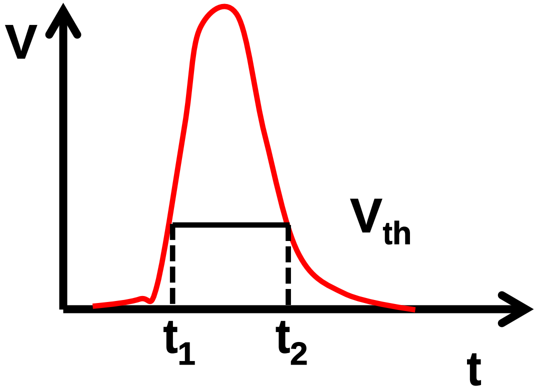
Time walk correction circuit



Constant Fraction Discriminator

The time is set when a fixed fraction of the amplitude is reached

- → **Very well suited to the UFDS sensors read out by BBA**
- → **More circuitry required**

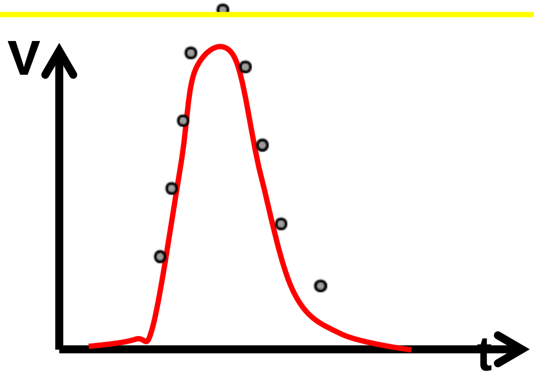


Time over Threshold

The amount of time over the threshold is used to correct for time walk

- → **Better if pixel area is small**

CAN BE IMPLEMENTED PER PIXEL WITHIN THE ROC



Multiple sampling

Most accurate method, needs a lot of computing power.

POSSIBLY TOO COMPLICATED FOR LARGE SYSTEMS

LGAD – UFSD: a bit of history

2010: LGAD proposed & developed at CNM within **RD50 collaboration**

2012: First 4 inch wafer, 300 µm thick, LGAD produced by **CNM**

2014: UFSD project founded by EC

2016: First 75 µm and 50 µm thick LGAD produced by **CNM** for Timing applications (ATLAS HGTD and CMS CT-PPS) - SOI and SOS, 4” wafer

First 300 µm thick LGAD produced **FBK**, Trento (p-side and n-side segmentation, pixel, strip, AC coupling, ...)

2017: First 50 and 80 µm thick LGAD produced **HPK**

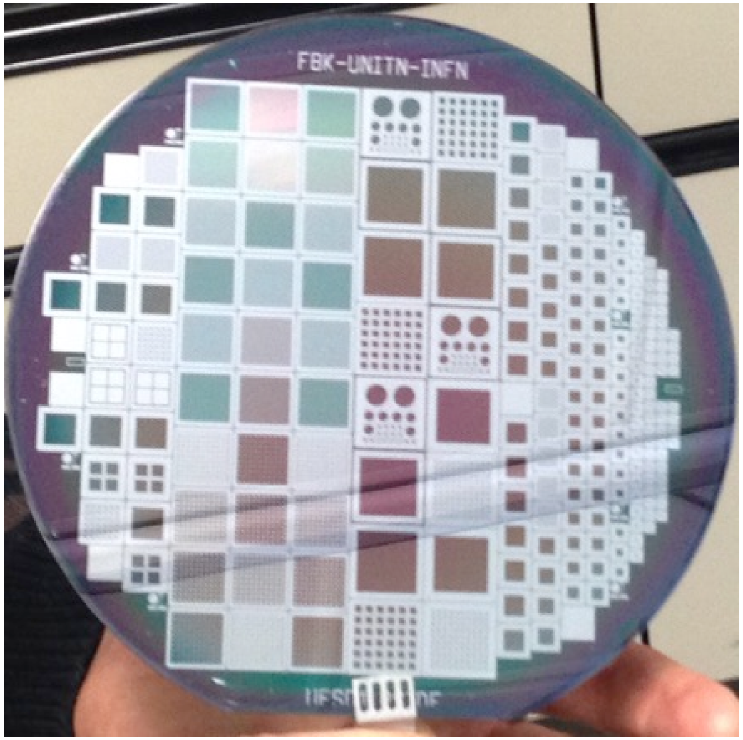
New 50 µm thick LGAD in production at **CNM**

First 50 µm thick LGAD in production at **FBK** (delivery foreseen in a month from now) -

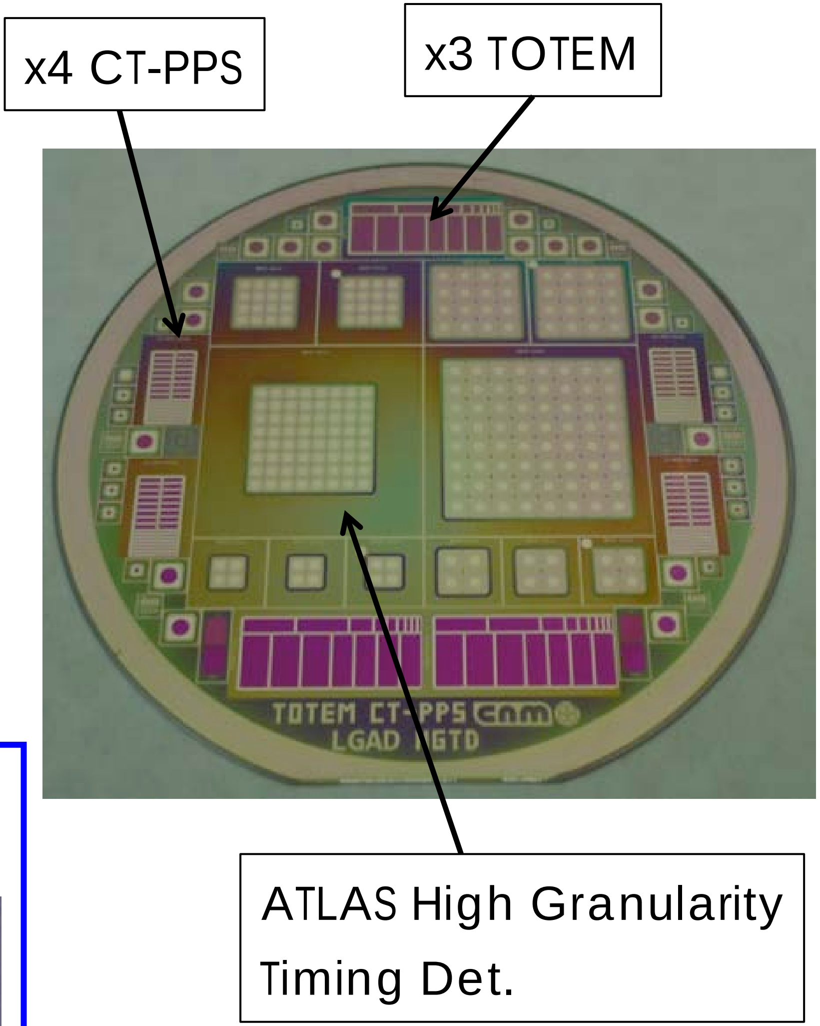
Today 3 suppliers (CNM Spain, FBK Italy and HPK Japan)

Sensors: FBK, CNM and HPK

FBK 300-micron production



CNM 75-micron
CNM 50-micron production



x4 CT-PPS

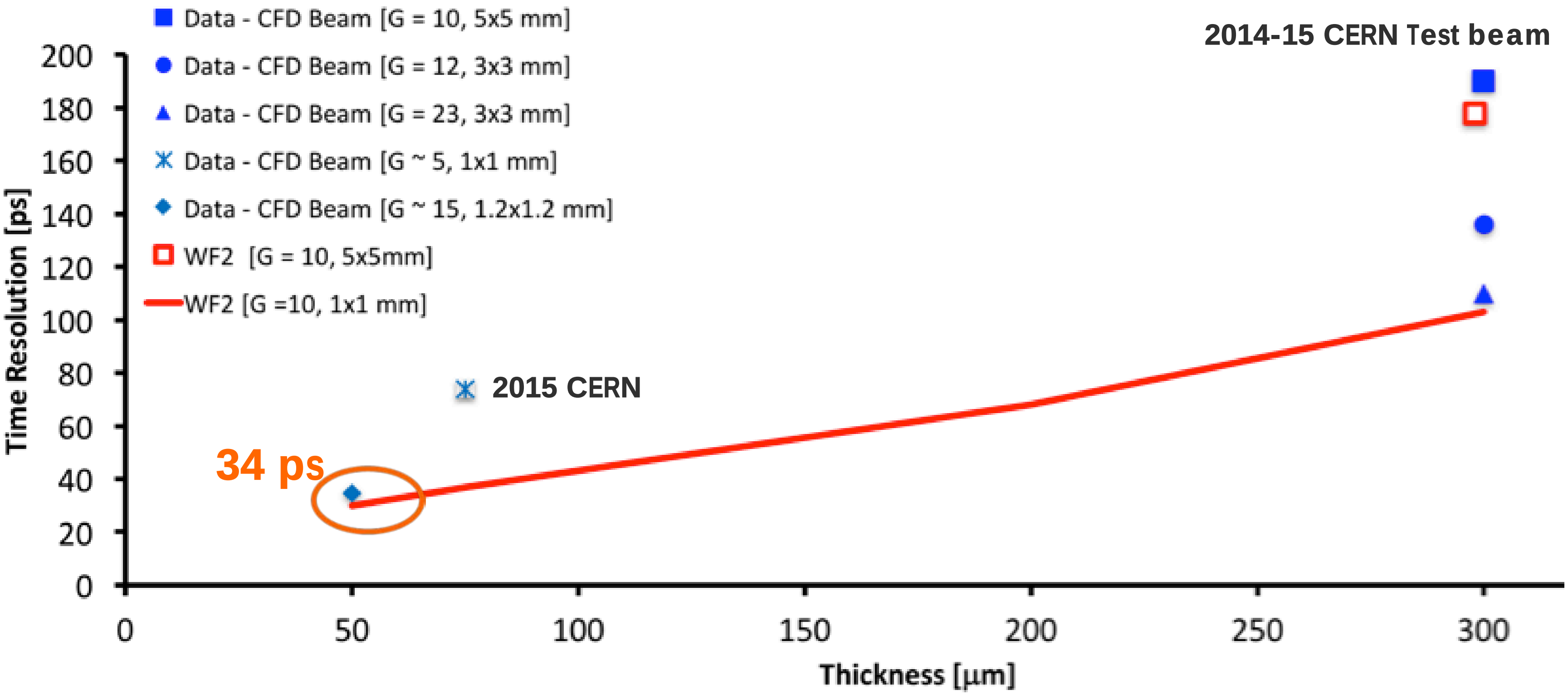
x3 TOTEM

ATLAS High Granularity Timing Det.

HPK-micron production

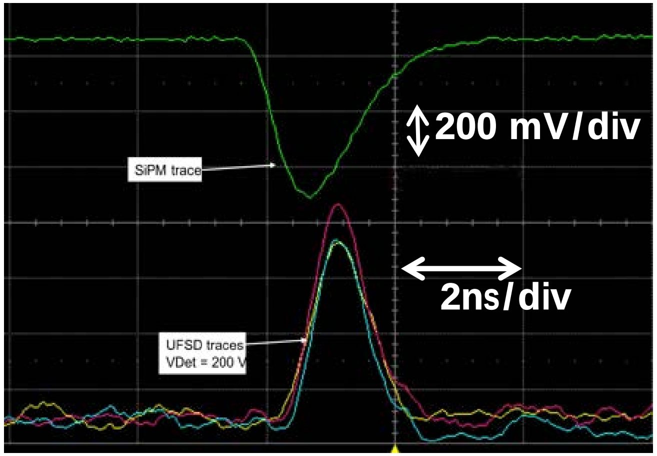
- 2 different thickness: 50 μm - 80 μm
- 4 different gains
- Circular single pad sensors
- Sensor active area: ~1 mm^2
- Different guard ring design

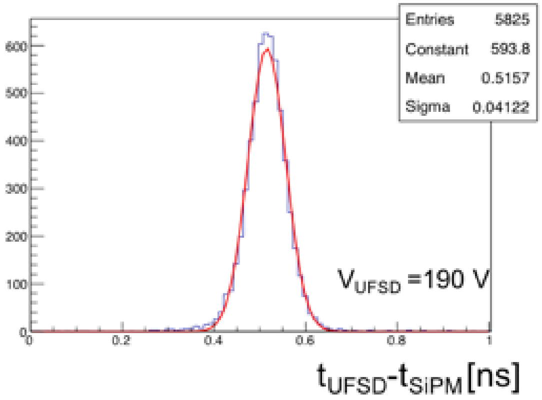
Summary of UFSD (CNM) beam test results



2016 CERN Test beam:
50 µm UFSD
$1.2\text{x}1.2\text{mm}^2$
(C = 3pF, Gain =15)

Readout: custom made BBA optimized for 50 µm LGAD



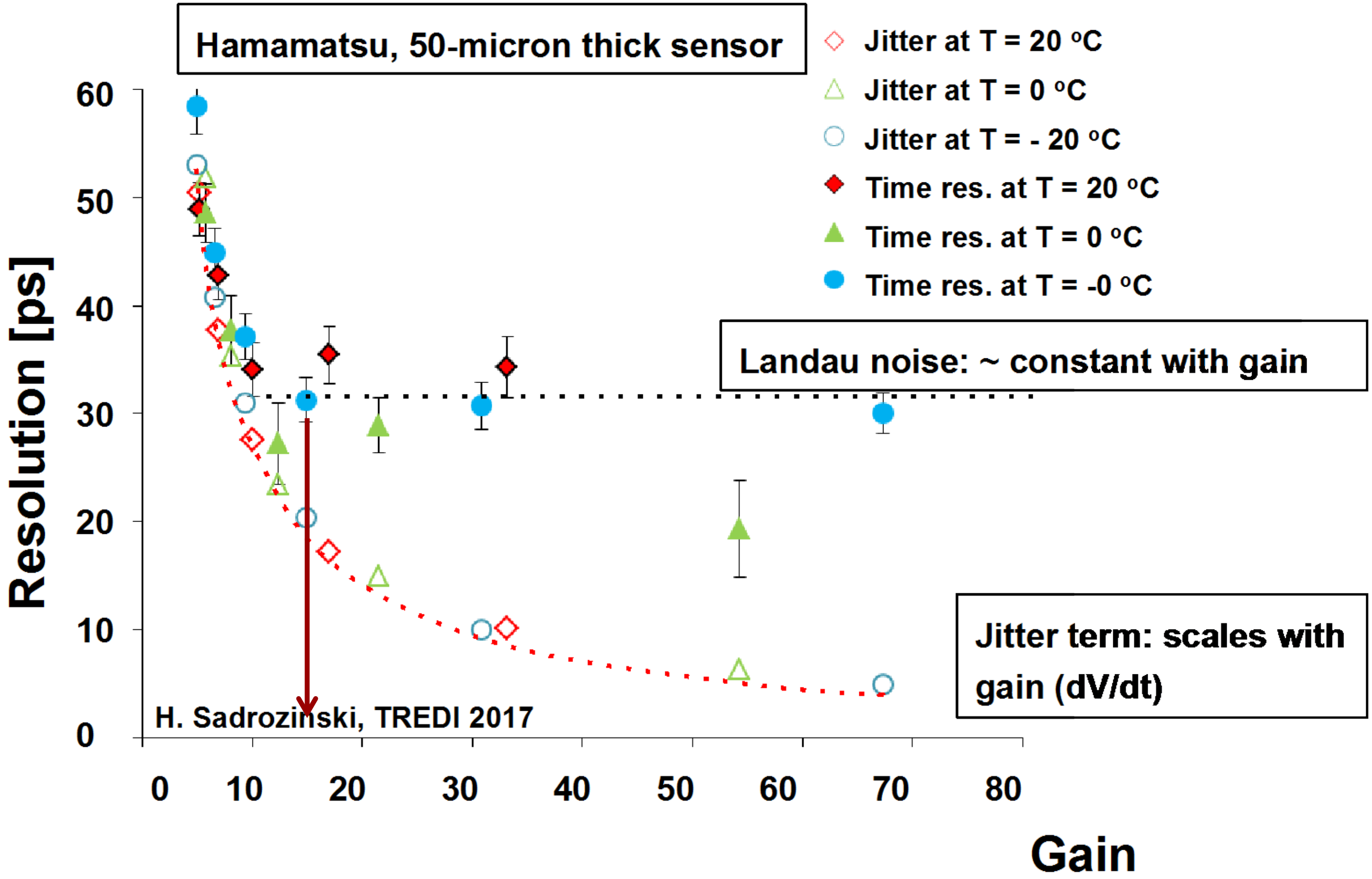


Fast, low noise signals, ideal for timing

Latest results on UFSD time resolution

1 mm², 50 μm thick UFSD pads from Hamamatsu

Readout: custom made BBA optimized for 50 μm LGAD



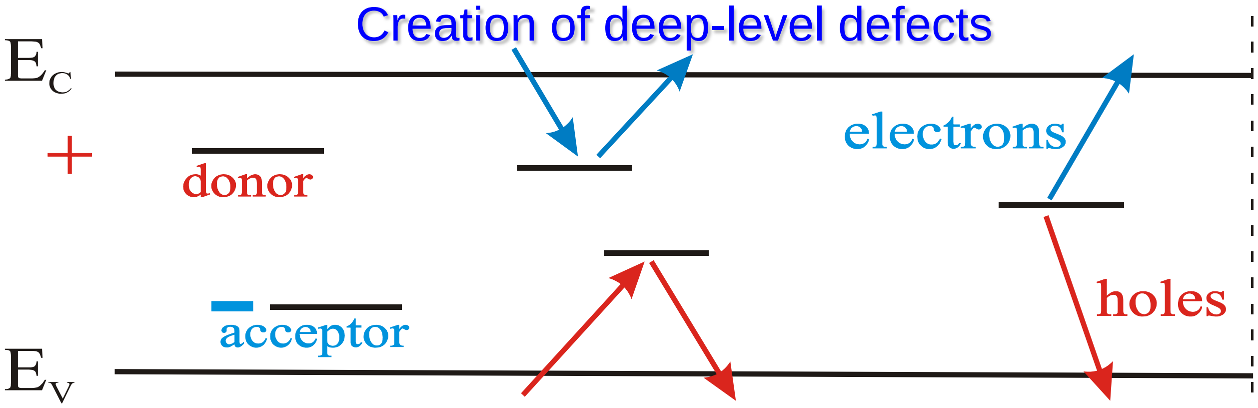
✓ **30 ps time resolution achieved with G~15 – in agreement with simulation**

Radiation damage in silicon sensors

Radiation effects on silicon sensors can be classified as:

- **surface damage**
  → modification to breakdown properties, electrode isolation and surface e-h recombination
- **bulk damage**

Michael Moll – MC-PAD Network Training, Ljubljana, 27.9.2010



Acceptor/donor like defects
⇒ **Variation in effective doping concentration and consequently V_{FD}**

($V_{FD} \propto N_D$)

Trapping (e and h)
⇒ **Charge collection efficiency (CCE) degradation**

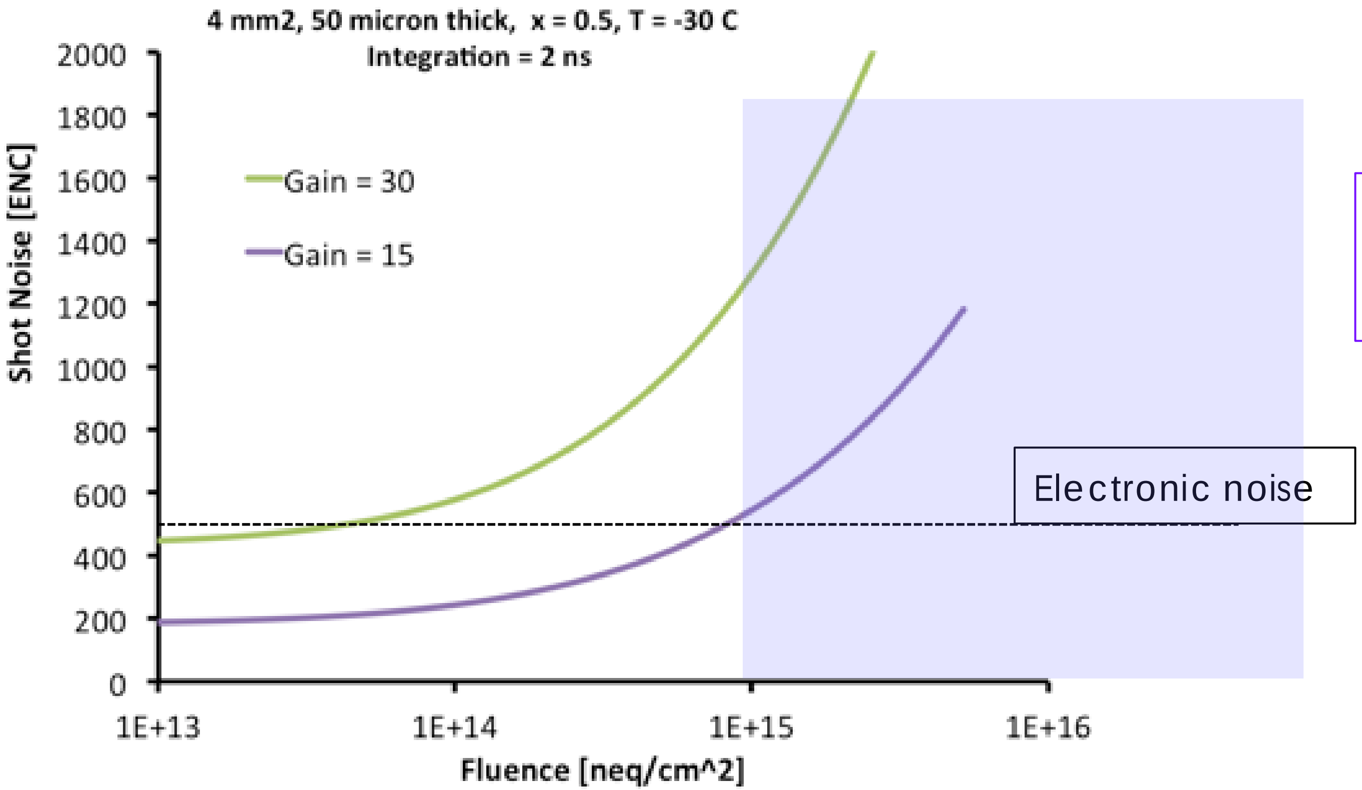
Negligible in 50 μm thick sensor

Enhanced generation-recombination rate
⇒ **higher leakage current**

Levels close to midgap most effective

Radiation effects specific of LGAD (I)

→ **Increased bulk current is multiplied by gain**



4 mm^2 pad,
50 micron thick

To minimize Shot noise:

- Low gain (below ~ 20)
- Keep the sensor cold
- Use small pads to have less leakage current

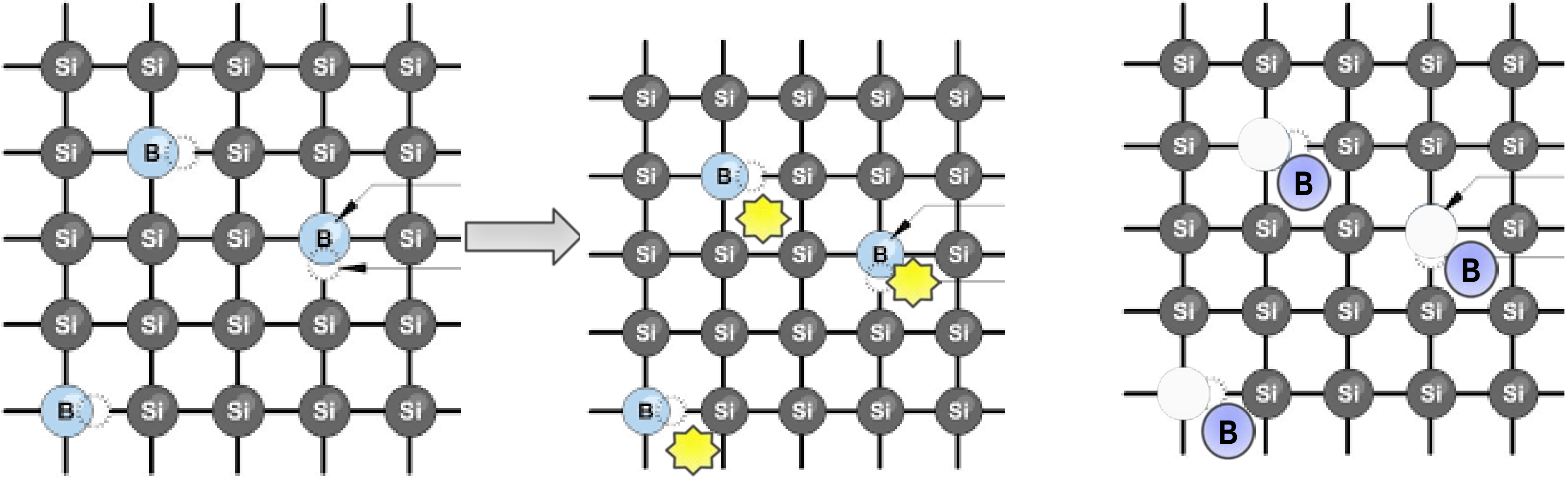
Radiation effects specific of LGAD (II)

→ Change in doping profile affect the gain value

This term indicates the “removal” of the initially present p-doping.

For UFSD this is particularly problematic as it removes the gain layer

Irradiation ➔ Interstitial defects ➔ Boron becomes interstitial



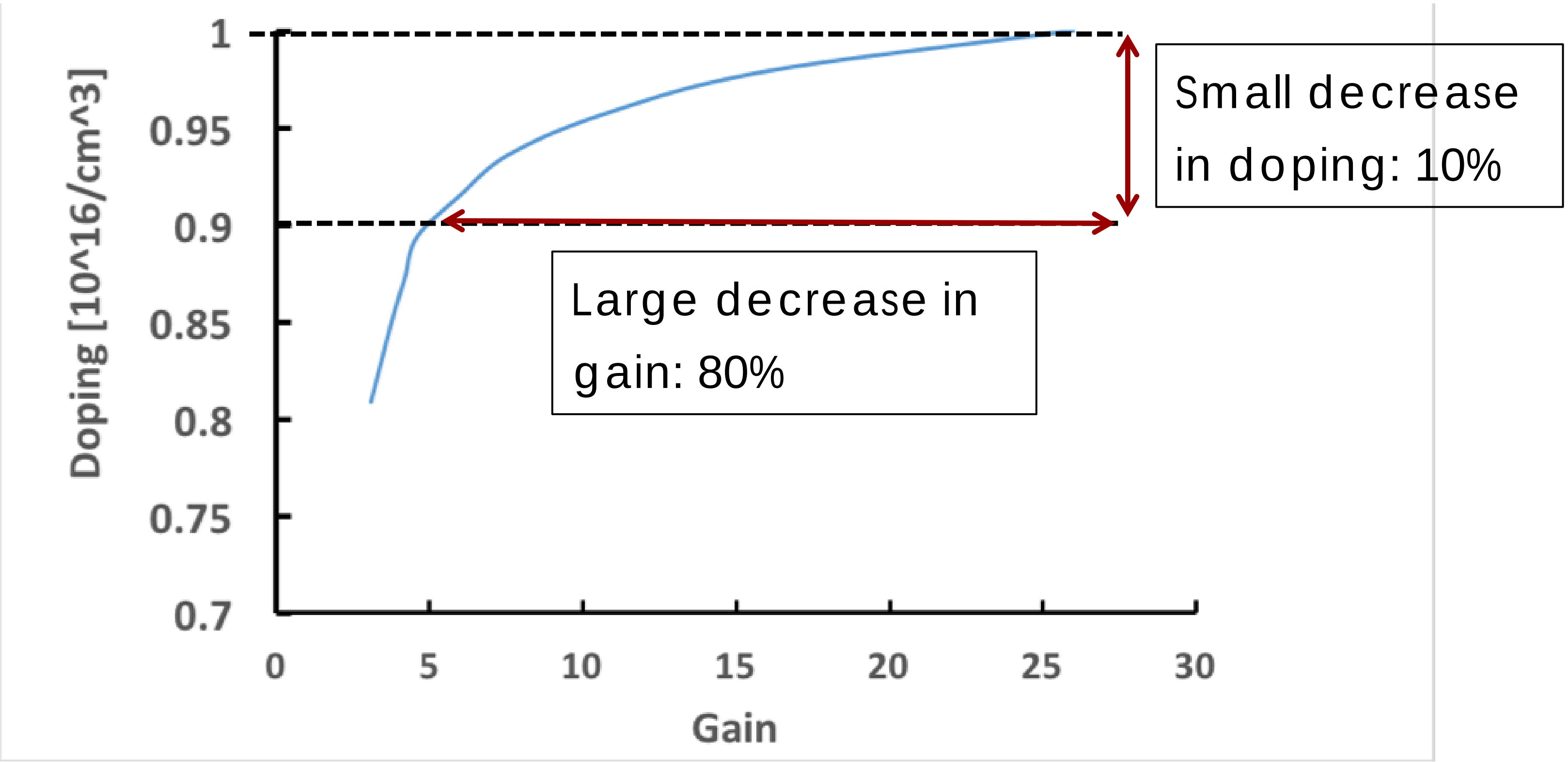
WATKIN’S REPLACEMENT MECHANISM

The **boron** doping is **still there**, only it has been moved into a different position and it does not contribute to the doping profile, it is **inactive**

Gain vs gain layer doping

The gain is very sensitive to the doping level

LGAD sensor, 50 μm thick, V_{BIAS} = 200 V



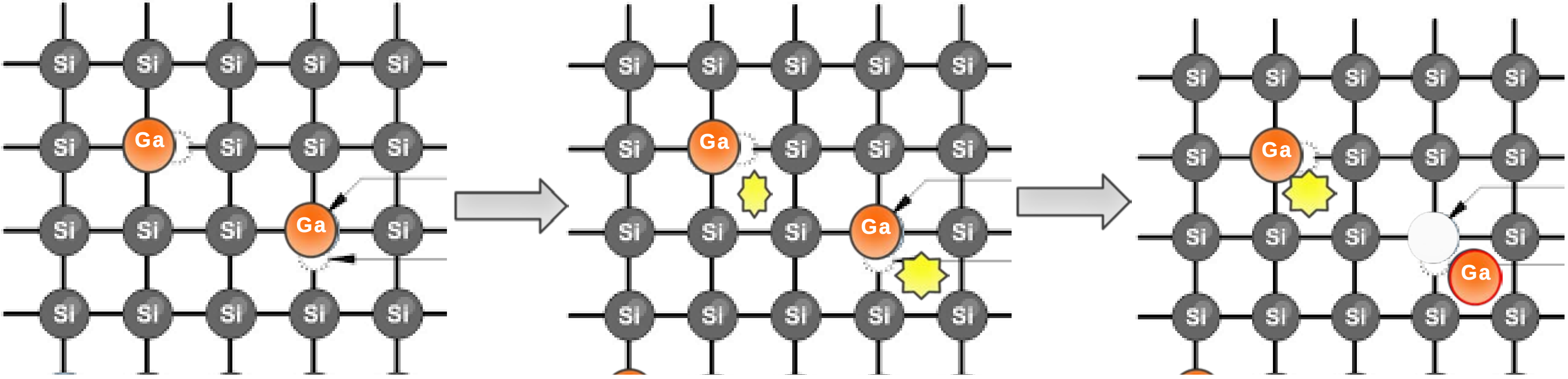
Small decrease in doping: 10%

Large decrease in gain: 80%

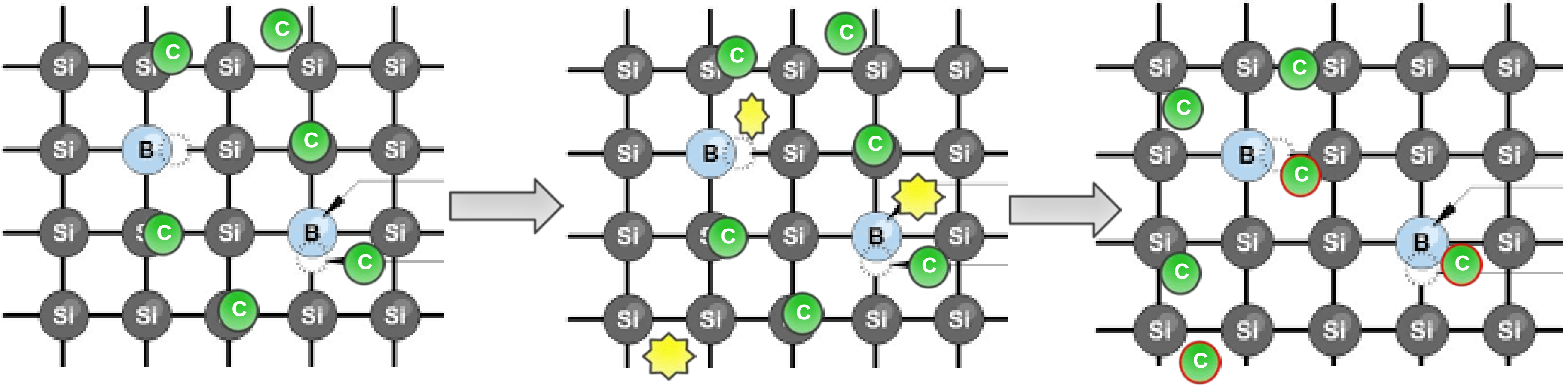
Studies of radiation damage in LGAD important part of RD50 program

Initial acceptor removal: mitigation

Gallium doping: **Gallium less prone to become interstitial**



Carbon enriched wafer: **interstitial defects filed with C instead of with B**



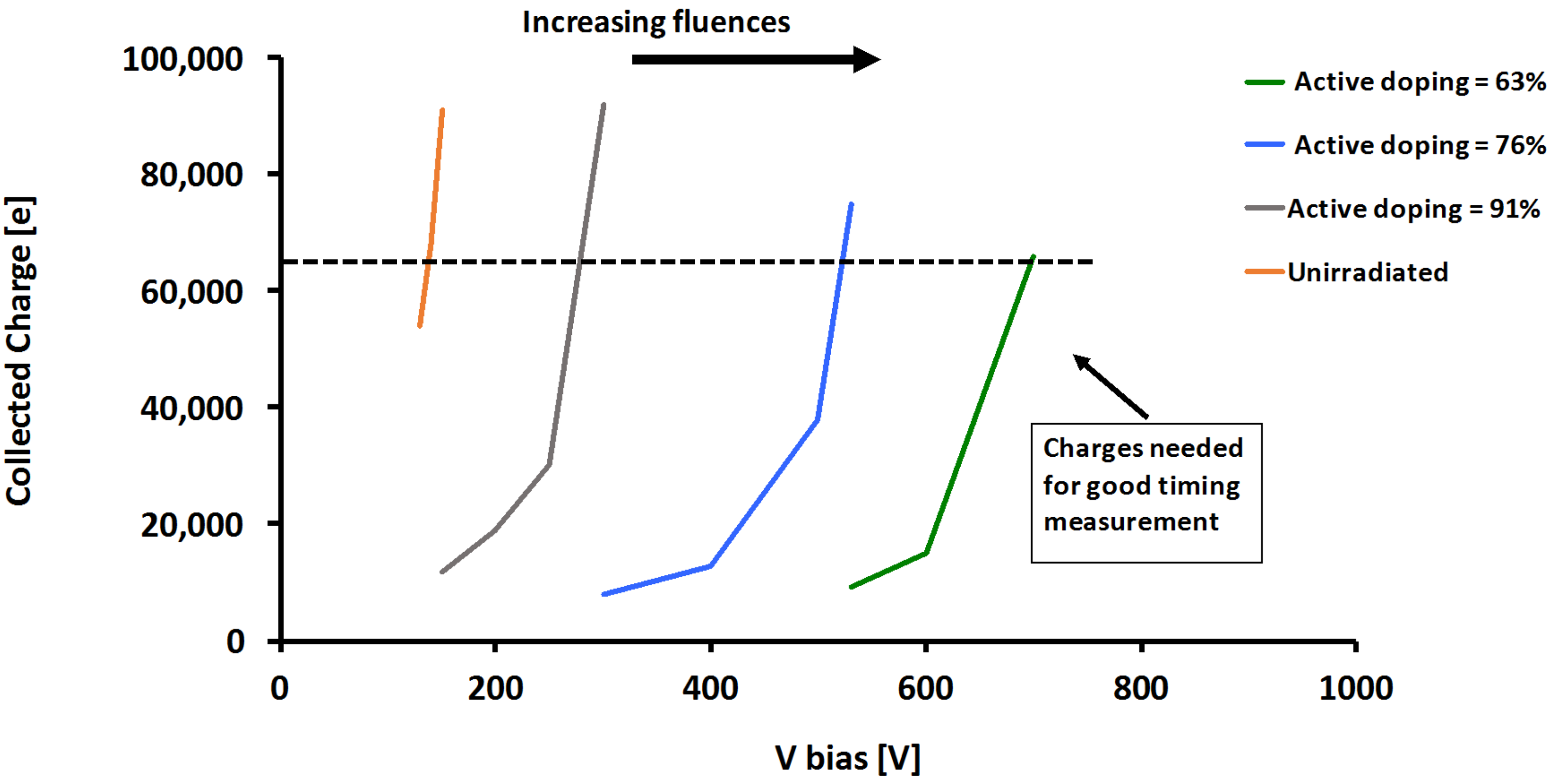
Productions with Ga, B/C, Ga/C gain layer completed at CNM and FBK

Results coming soon!

Short term solution: compensation with V_{bias}

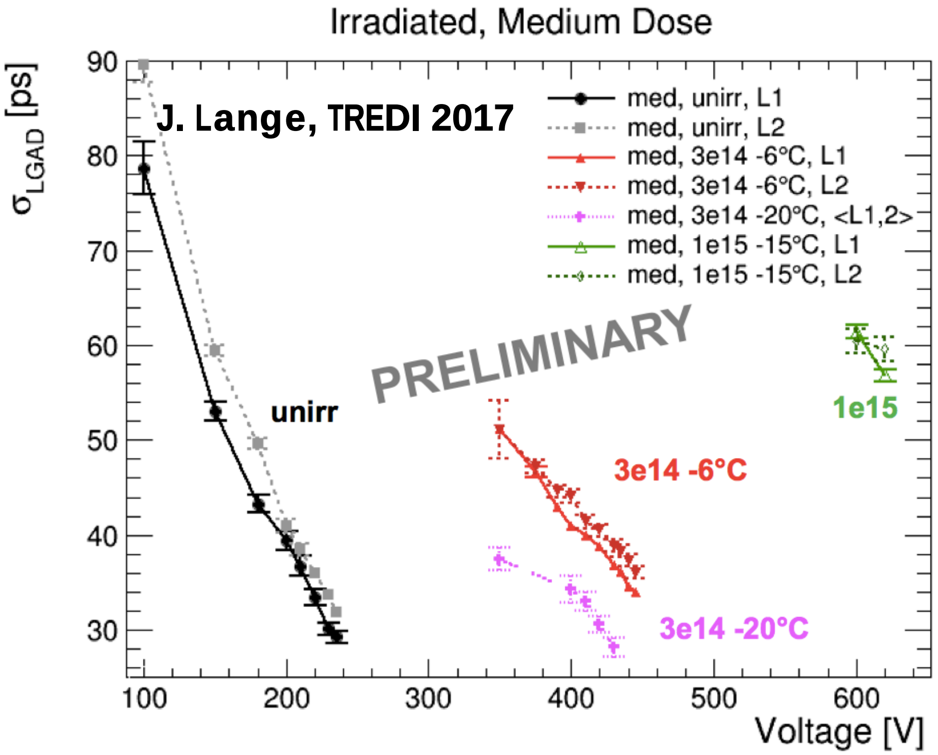
The necessary field can be recovered by increasing the external Vbias:

proven to work up to 3 10^{14} n_{eq}/cm^2



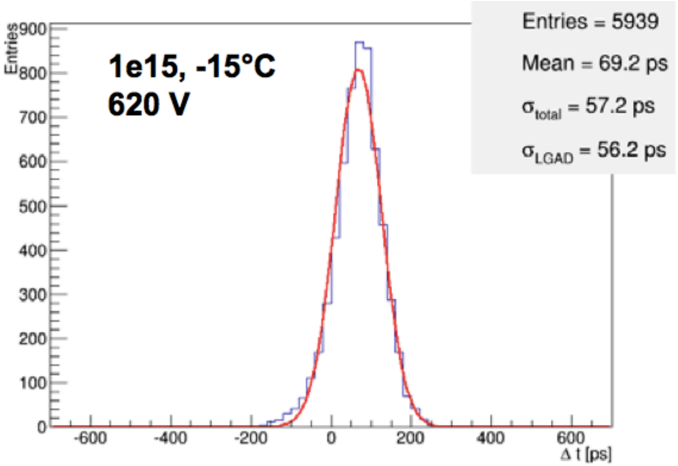
Charges needed for good timing measurement

Time resolution for irradiated sensors



50 μm CNM 1x1 mm^2 pads

Test beam results (CERN SPS, 120 GeV pions)



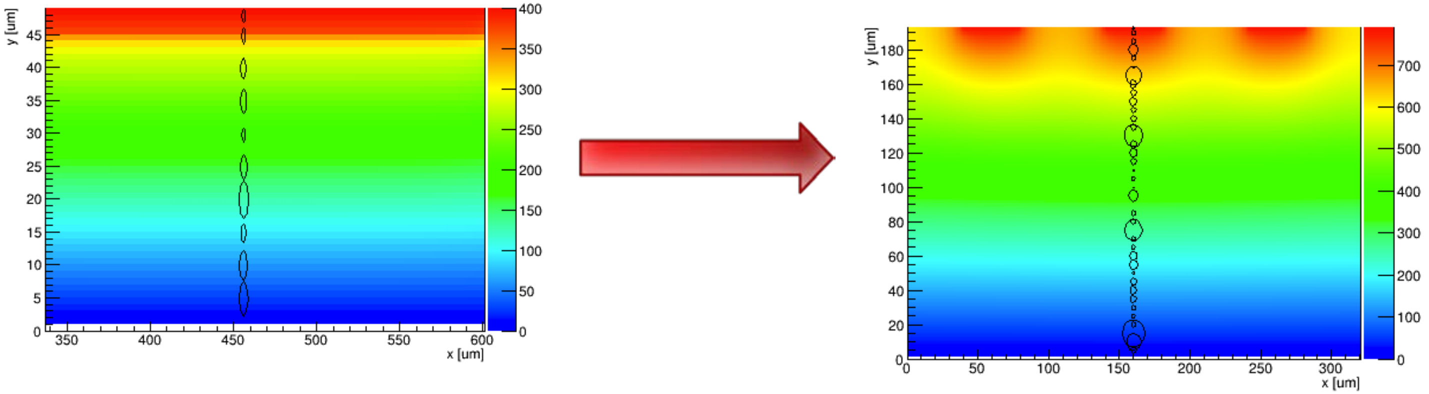
Good Gaussian behavior also after irradiation

- ✓ At **3 10^{14} n_{eq}/cm_2** similar time resolution as before irradiation (at higher V)
  σ_t ~ 33 ps at 445V and T=-6°C **σ_t ~ 28 ps at 430V and T=-20°C**

- ✓ At 10^{15} gain is highly reduced and voltage stability not high enough to compensate for it (σ_t ~ 55-60 ps at 620V)

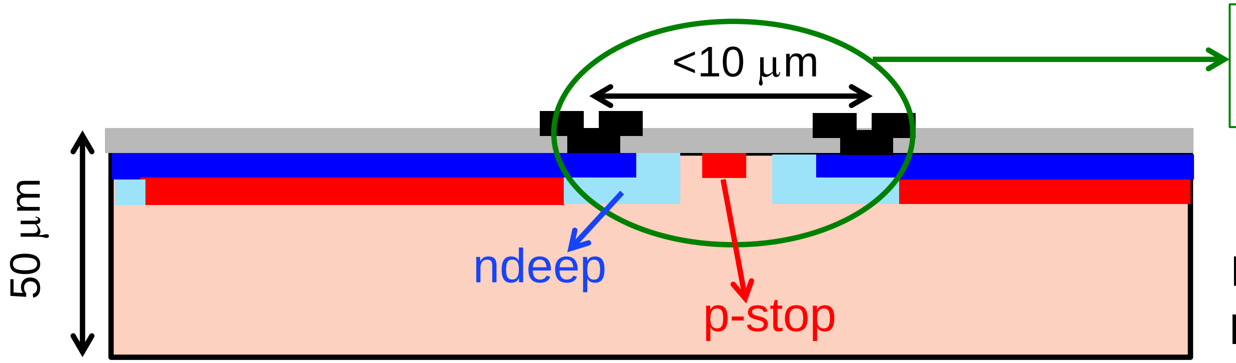
Merging timing with position resolution

Electrode segmentation makes the E field non uniform, and therefore ruins the timing properties of the sensor



We need to find the smallest pixel area which allows :

- very uniform E field and gain in the sensor pixel
- high fill factor
- enough space for the timing circuit in the ROC pixel

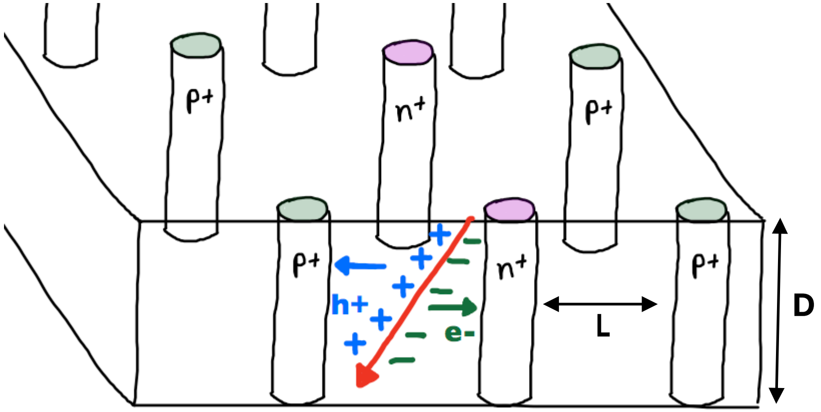


Optimization in the next FBK production (pads)

Pitch ~ 90 μm
Implant ~ 80 μm

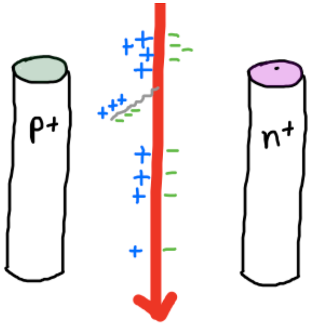
3D sensors for timing measurements

Very fast: decouple signal amplitude from collection time



- Sensor thickness (D) ~ 200 μm
  - → **amplitude ~ 15000 e-**
- Drift distance (L) ~ 50 μm
  - → **collection time ~ 500 ps**
  - → **rise time: tens of ps**

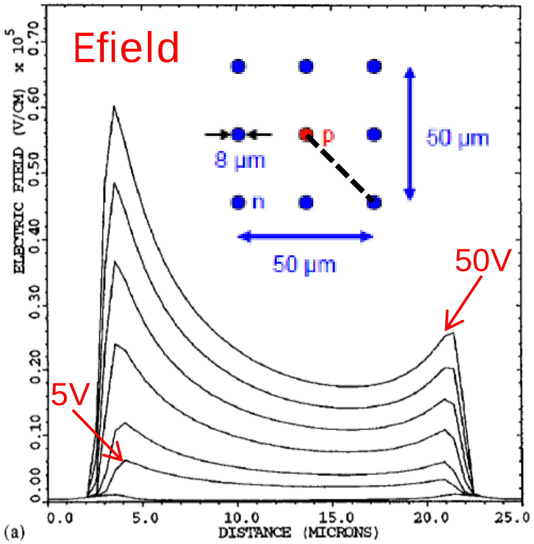
- **3D geometry minimizes time uncertainties from non-uniform ionization density**



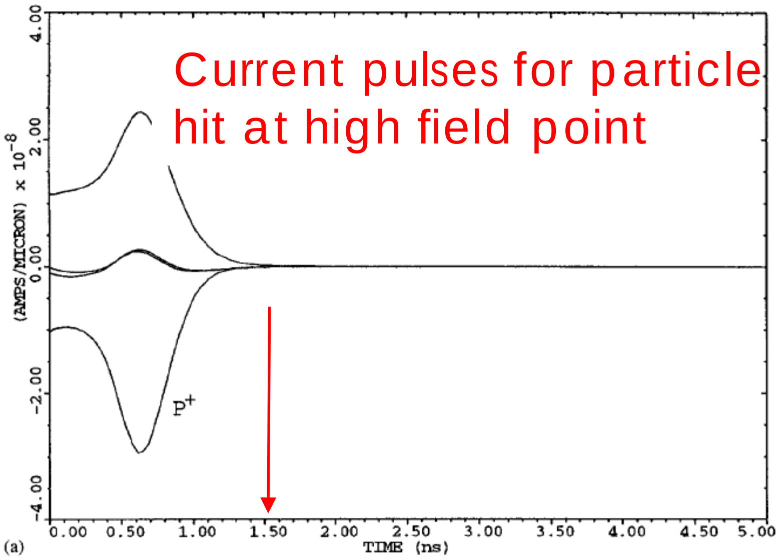
Optimized design and fabrication technology necessary to fully exploit these features

- **Excellent radiation hardness (tested up to 1.4 10^{16} n_{eq}/cm^2)**

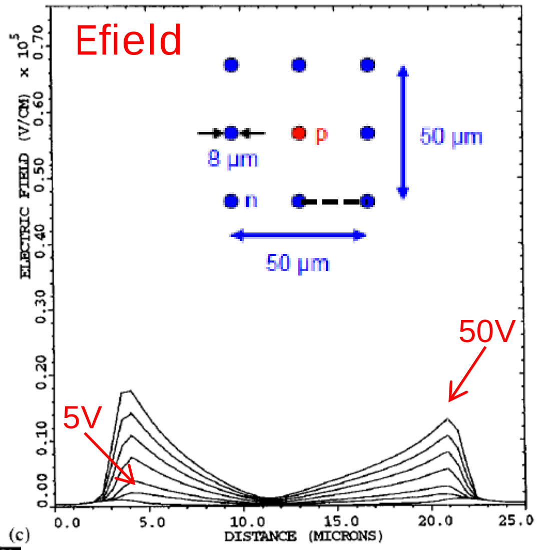
Null field points and delayed signals



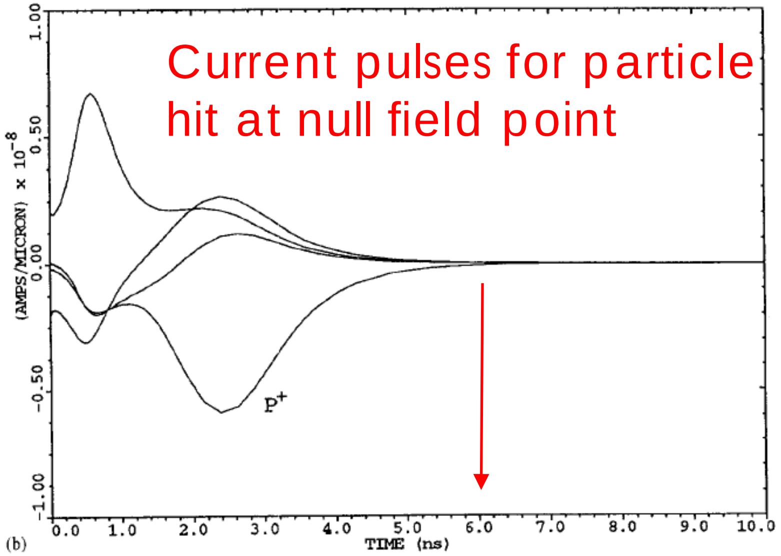
Efield



Current pulses for particle hit at high field point

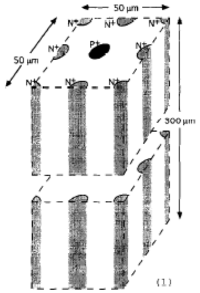


Efield



Current pulses for particle hit at null field point

S. Parker et al.
NIMA395 (1997) 328

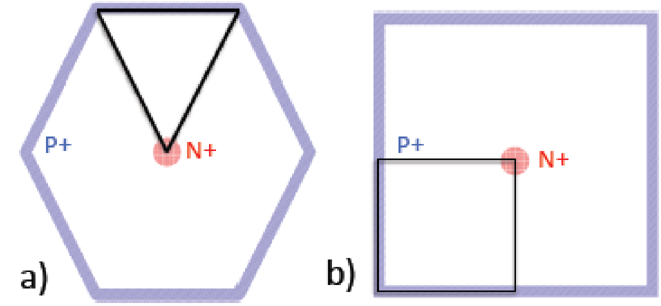


- 3D structure implies null field points in between columnar electrodes of the same doping type

  Carriers generated at null field points first have to diffuse before drifting, thus delaying signals

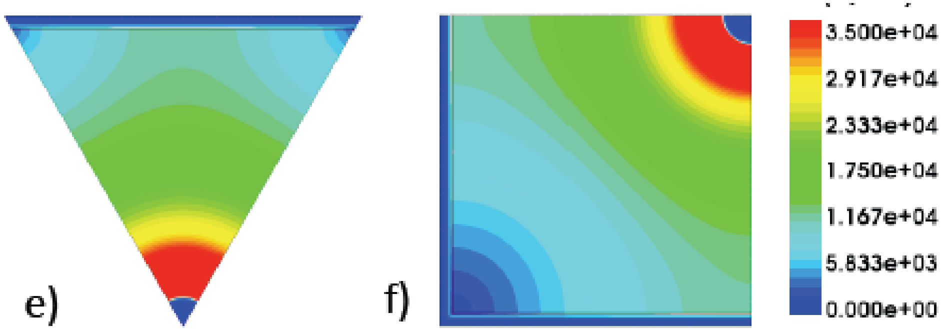
  This can be improved with trenched electrodes

“Tens of ps” timing



Signal **read-out** from the **n$^+$** electrode to exploit the higher e- speed.

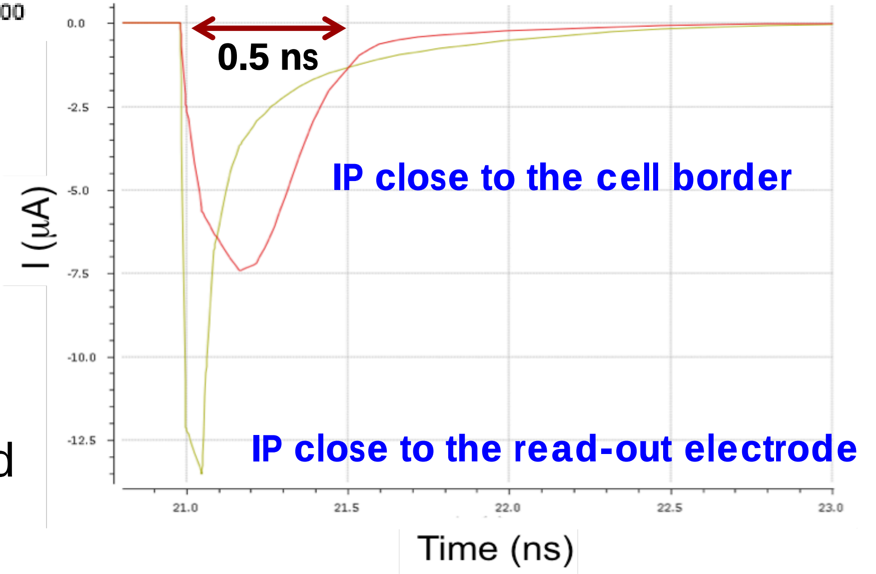
p+ trenched electrode



Electric field (V/cm)
V_{BIAS} = 100V

G.F Dalla Betta

3D sensor output signals for different impact points (hexagonal pixel cell)



IP close to the cell border

IP close to the read-out electrode

Simulations (3D sensor coupled to a “partly optimized” readout chip) show that time resolution of ~30-40 ps are achievable

Possible improvement by optimizing concurrently the sensor and the front-end electronics design.

Conclusions

These are ambitious, but realistic goals.

The VELO Phase-II upgrade is a very interesting project

It is challenging

Pixel area: 27.5 x 27.5 μm^2

Thickness ~ 100 μm

σ_t < 200 ps

but gives you the possibility to develop a new type of pixel detector (and new pattern recognition strategy!)

UFSD with low gain (~15) thin (~ 50 μm) LGAD sensors with custom ad hoc electronics might be the right solution but … there are still open issues to be studied:

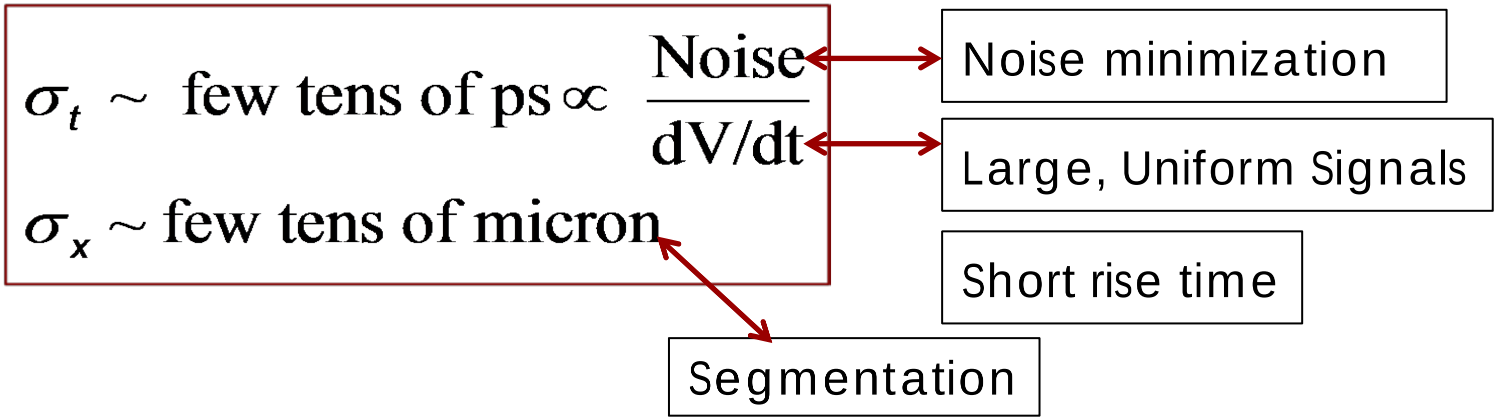
- Radiation hardness
- Small segmentation

3D sensors are another interesting solution to be exploited but more studies and dedicated productions are necessary

If you are interested in developing UFSD for the VELO, we are glad to collaborate!

The UFSD R&D program

Final goal



$$\sigma_t \sim \text{few tens of ps} \propto \frac{\text{Noise}}{dV/dt}$$

$$\sigma_x \sim \text{few tens of micron}$$

Noise minimization

Large, Uniform Signals

Short rise time

Segmentation

Sensor and electronics designs need to be optimized concurrently

Cross experiment R&D within the RD50 collaboration

- Strong collaboration between CMS and ATLAS for the development of the forward timing layer

  LHCC in November will evaluate the timing layer proposal of CMS and ATLAS

ACKNOWLEDGEMENTS

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- U.S. Department of Energy grant number DE-SC0010107
- The RD50 collaboration

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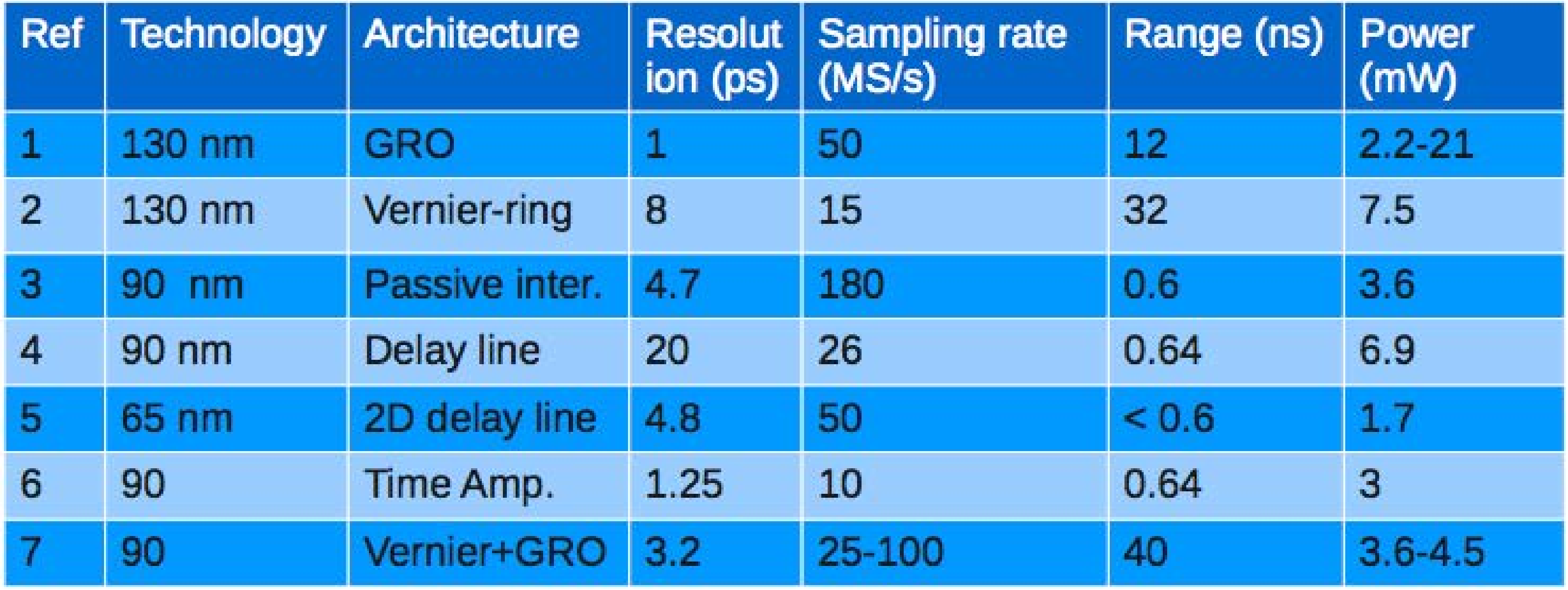
Dr. Manuel Rolo (University of Torino)
Dr. N. Cartiglia (INFN - Torino)

BACKUPS

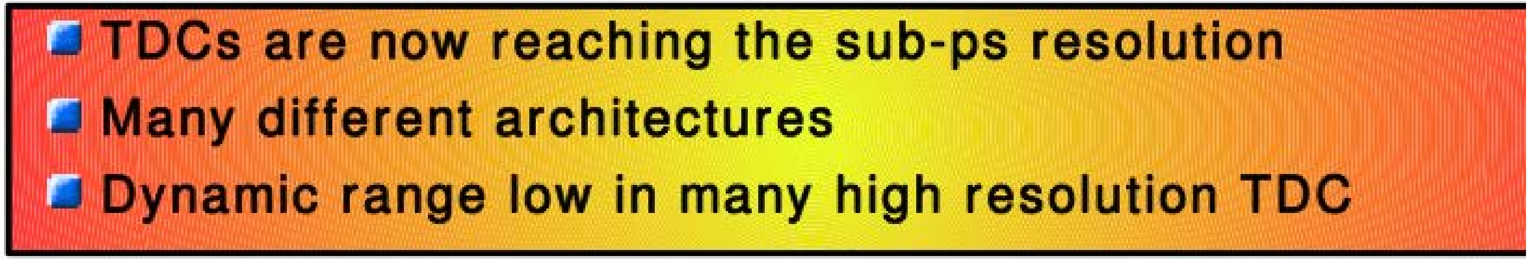
Are TDC fast enough?

Fine timing steps

Course timing steps



Ref	Technology	Architecture	Resolution (ps)	Sampling rate (MS/s)	Range (ns)	Power (mW)
1	130 nm	GRO	1	50	12	2.2-21
2	130 nm	Vernier-ring	8	15	32	7.5
3	90 nm	Passive inter.	4.7	180	0.6	3.6
4	90 nm	Delay line	20	26	0.64	6.9
5	65 nm	2D delay line	4.8	50	< 0.6	1.7
6	90	Time Amp.	1.25	10	0.64	3
7	90	Vernier+GRO	3.2	25-100	40	3.6-4.5

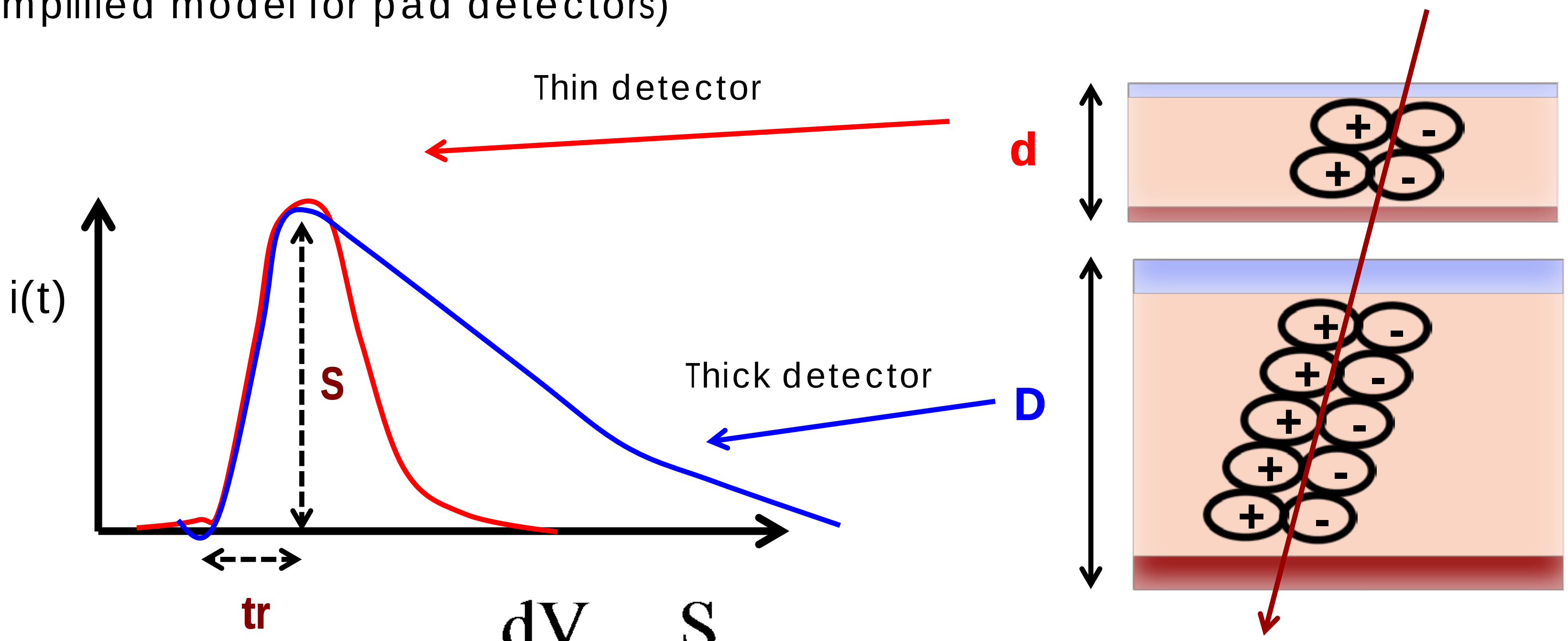


- TDCs are now reaching the sub-ps resolution
- Many different architectures
- Dynamic range low in many high resolution TDC

A. Rivetti – Hiroshima Symposium 2013

Slew rate in standard silicon sensors

(Simplified model for pad detectors)



$$\frac{dV}{dt} \sim \frac{S}{t_r} \sim \text{const}$$

Thick detectors have longer signals, not higher signals

Best result : NA62, 150 ps on a 300 x 300 micron pixels

✓ **To do better: add internal gain**

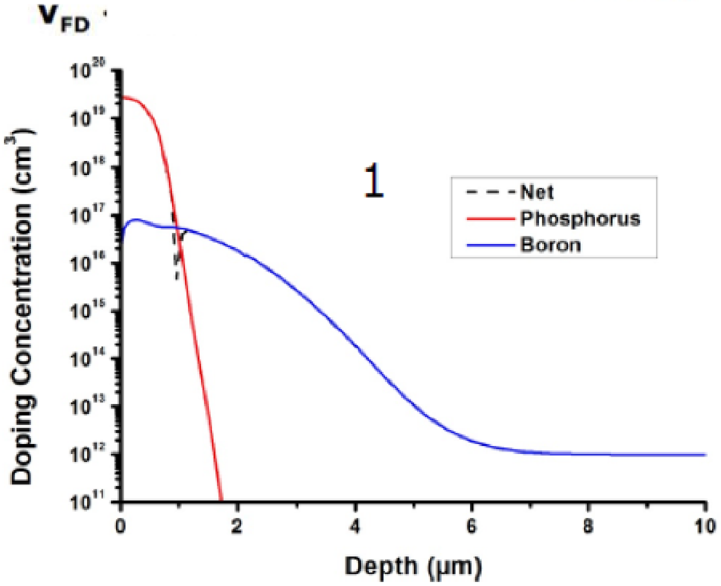
Low Gain Avalanche Detectors (LGADs)

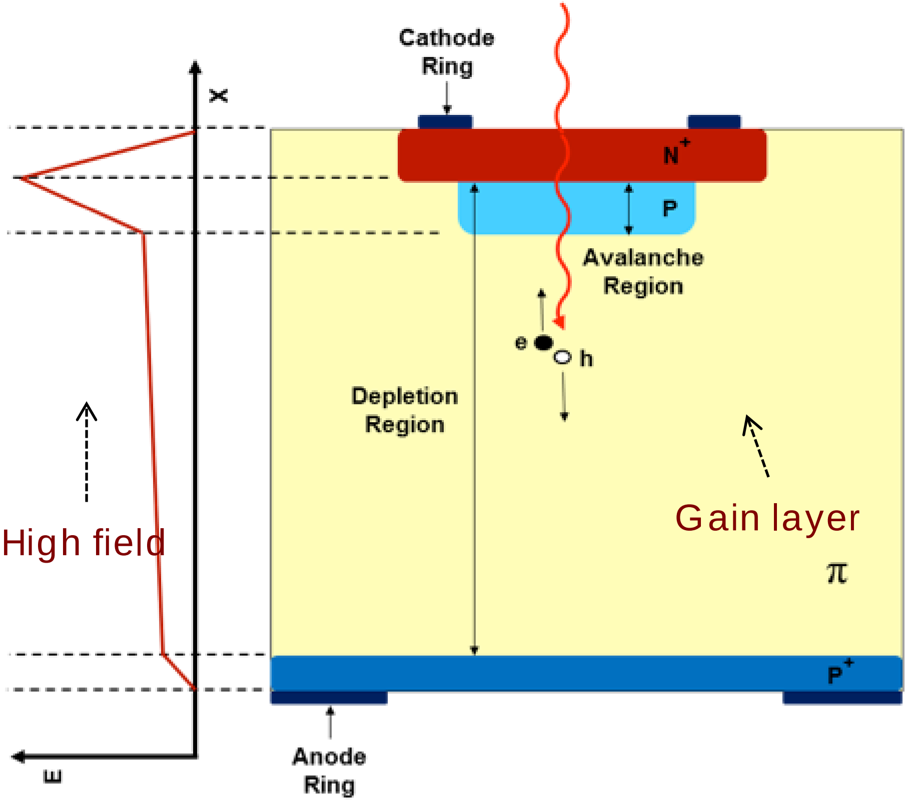
The LGAD sensors, as proposed and manufactured by CNM

(National Center for Micro-electronics, Barcelona):

High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage

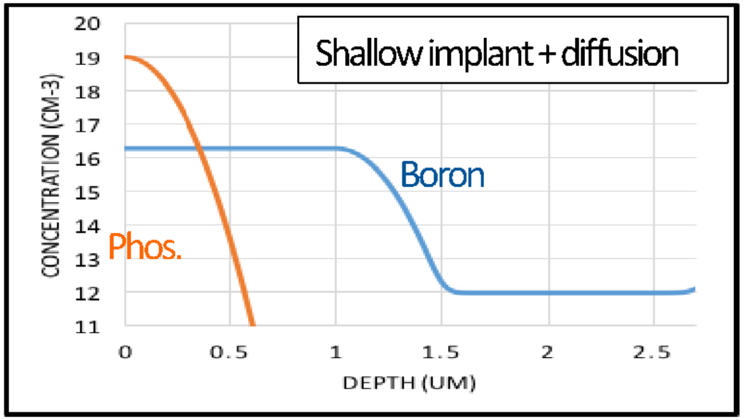


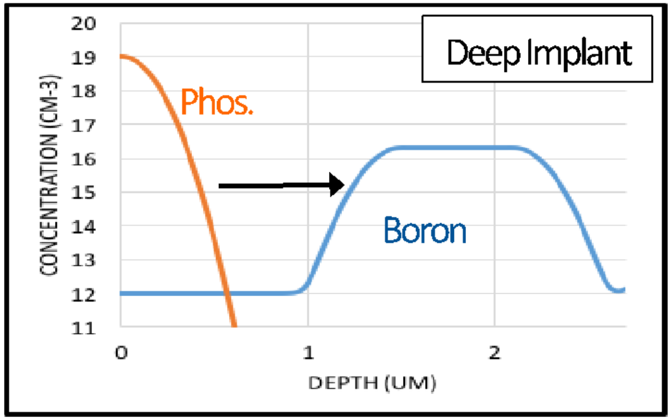


Gain layer design

The doping profile of the Gain layer controls the shape of the Electric Field

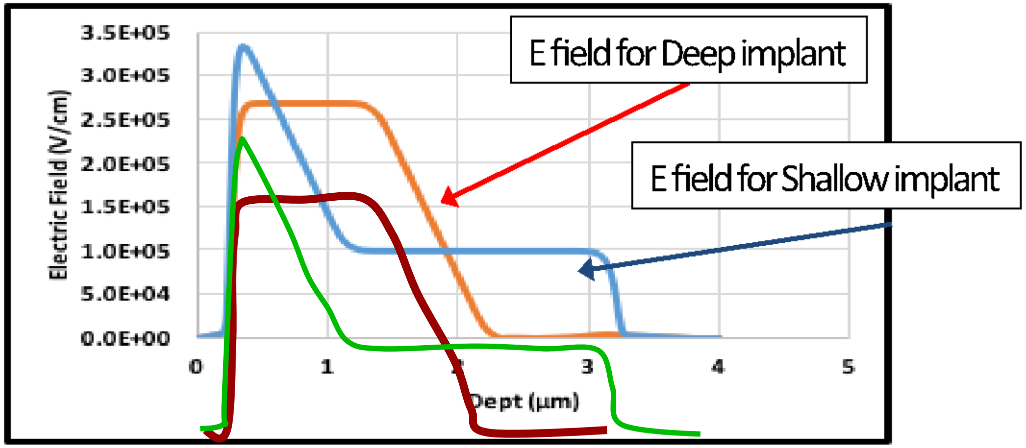
2 technological approaches are possible:





The deep implant approach has several advantages:

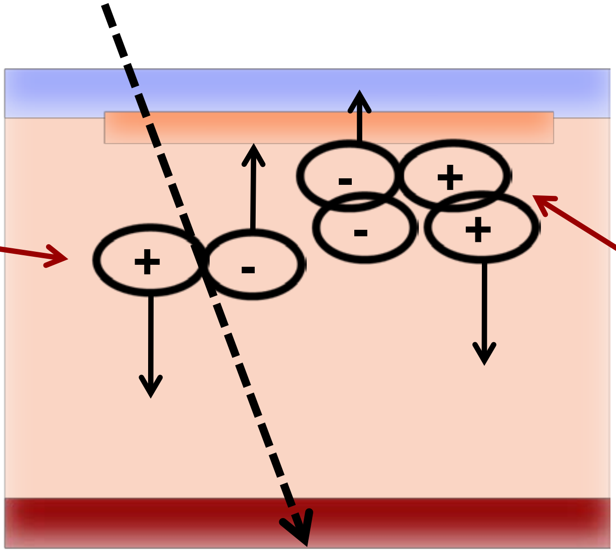
- Avoid peaked Electric Field -> less noise
- Is more reliable (independent of thermal diffusion and of doping compensation effect)



CMM
CENTRE FOR MATERIALS AND MICROSYSTEMS

M.M.Obertino – Università e INFN, Torino - Beyond the LHCb Phase-1 Upgrade

How gain shapes the signal



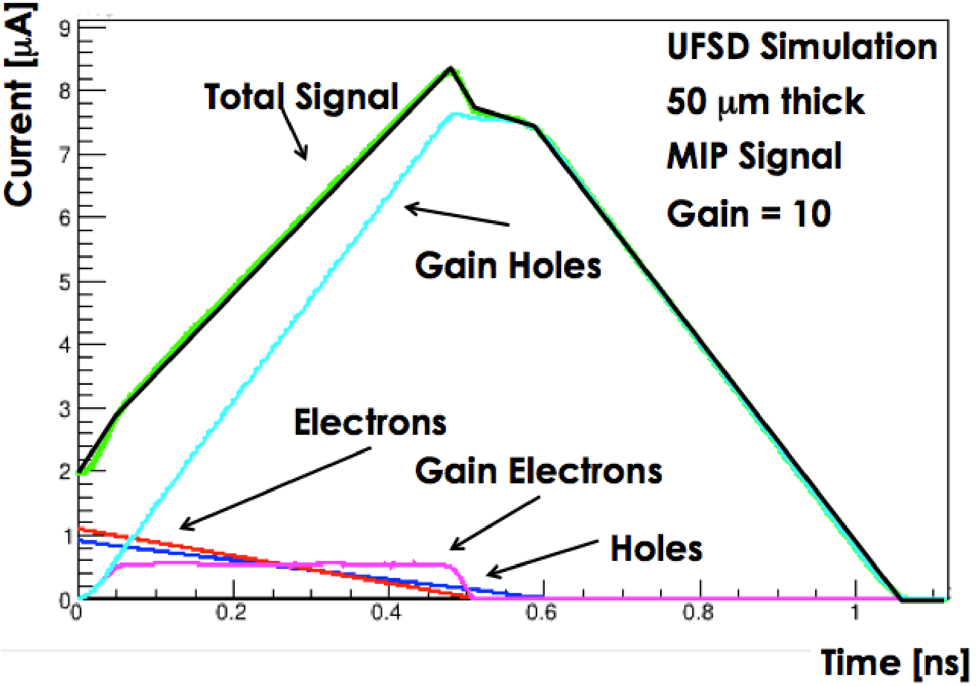
Initial electron, holes

Gain electron:

absorbed immediately

Gain holes:

long drift home

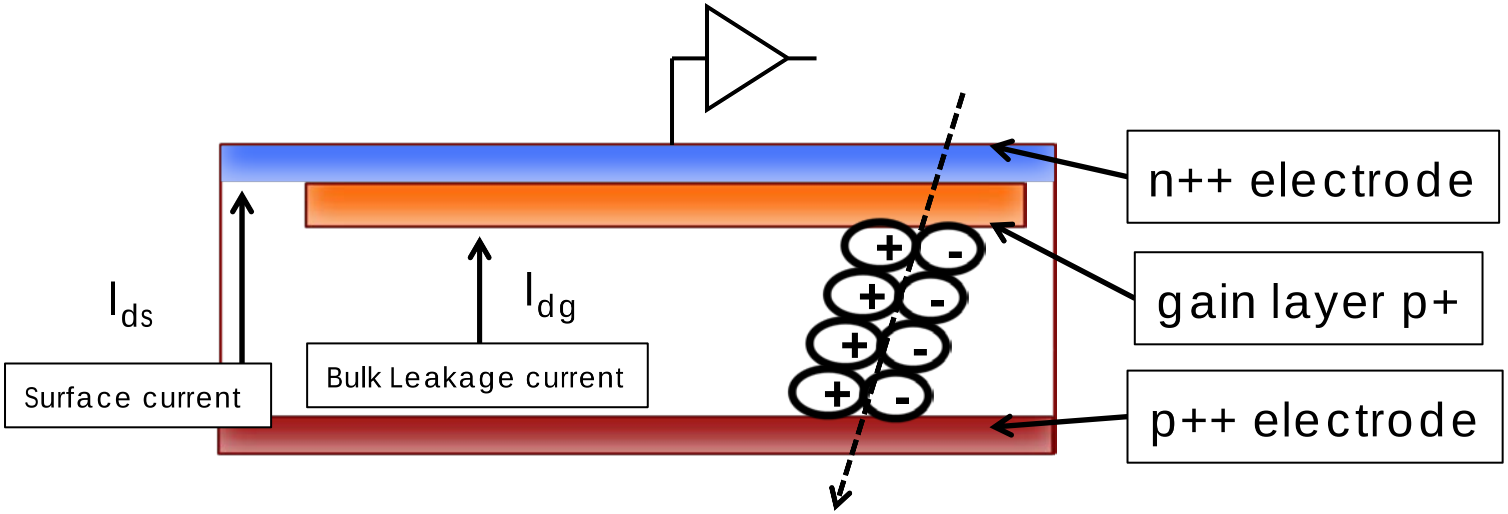


Electrons multiply and produce additional electrons and holes.

- **Gain electrons have almost no effect**
- **Gain holes dominate the signal**

➔ **No holes multiplications**

Shot noise in LGAD - APD



I_{ds}

Surface current

I_{dg}

Bulk Leakage current

n++ electrode

gain layer p+

p++ electrode

$$i^2_{Shot} = 2eI_{Det} = 2e\left[I_{Surface} + (I_{Bulk})M^2F\right]$$

Current density, nA/sqrt(f)

$$F = Mk + \left(2 - \frac{1}{M}\right)(1-k)$$

$$F \sim M^x$$

k = e/h ionization rate

x = excess noise index

M = gain

Correction factor to the standard Shot noise, due to the noise of the multiplication mechanism

$$F = \frac{\langle M^2 \rangle}{\langle M \rangle^2} \Rightarrow \langle M^2 \rangle = \langle M \rangle^2 F$$

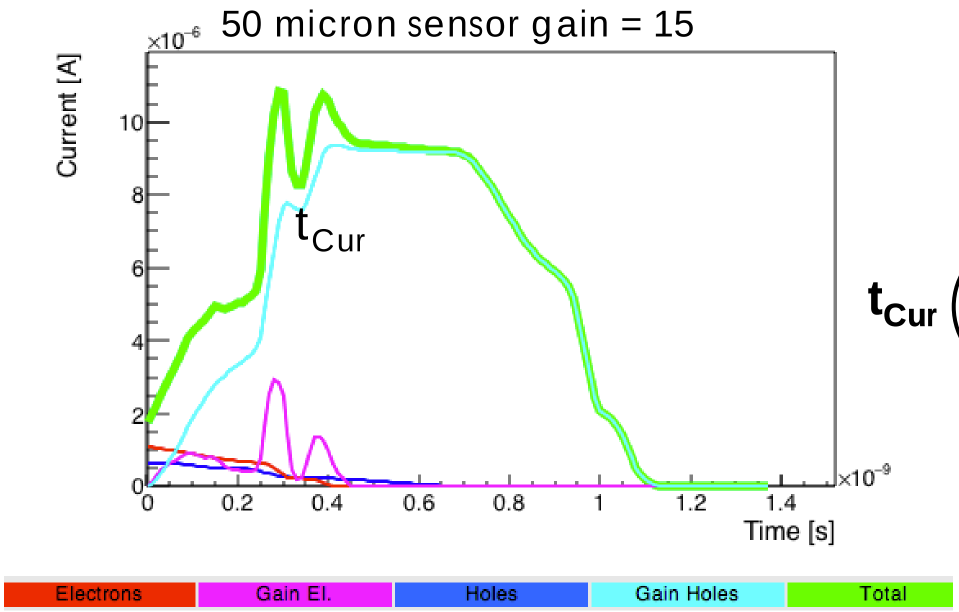
The players: signal, noise and slope

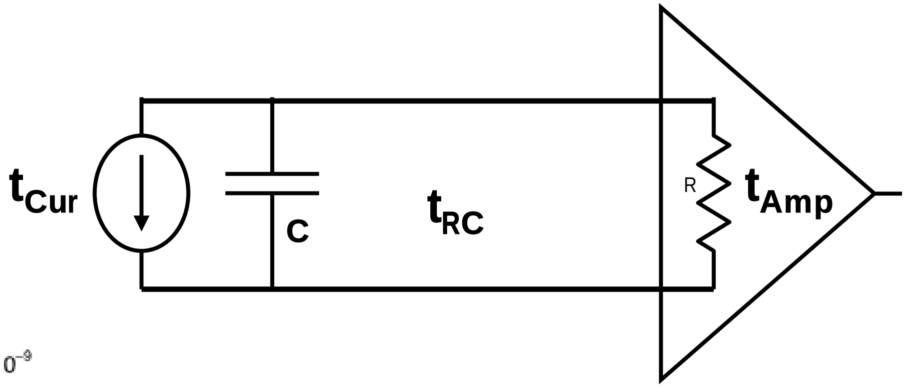
Signal dV/dt

Landau Noise

Shot Noise

Electronic Noise


50 micron sensor gain = 15



The current rise time (t_{Cur})

The RC circuit (t_{RC})

Amplifier rise time (t_{Amp})

There are 3 quantities determining the output rise time after the amplifier:

1. The signal rise time (t_{Cur})
2. The RC circuit formed by the detector capacitance and the amplifier input impedance (t_{RC})
3. The amplifier rise time (t_{Amp})

Sensor - State of the art

Silicon Sensors

- ▹ GigaTracker NA62: $\sigma_t \sim 150$ ps
- ▹ Silicon detector + SiGe HBT amplifier[1]: $\sigma_t \sim 105$ ps
- \+ Fine segmentation easy
- \+ Known technology
- \- Small signal

➼ Intrinsic resolution: **$\sigma_t \sim$ 100 ps**

Diamond Detectors

- ▹ TOTEM Diamonds for CT-PPS ToF: $\sigma_t \sim 100$ ps
- \+ No leakage current
- \+ Radiation hard
- \+ Small capacitance, high mobility
- \- Small signal

➼ Intrinsic resolution: **$\sigma_t \sim$ 100 ps**

APD (Avalanche PhotoDiodes)

- \+ Thin sensors (30-50 μm)
- \+ High signal (gain 50-500)
- \- Sensitive to shot noise
- \- Radiation resistance up to 10^{14} n_{eq}/cm^2
- \- Fine segmentation difficult

➼ Intrinsic resolution: **$\sigma_t \sim$ 30 ps**

LGAD (Low Gain Avalanche Diodes)

- \+ Thin sensors (50 μm)
- \+ Medium-high signal (gain 10-20)
- \+ Shot noise under control
- \- Radiation resistance under investigation (within RD50 Coll.)
- \- Possible fine segmentation

➼ Intrinsic resolution: **$\sigma_t \sim$ 30 ps**

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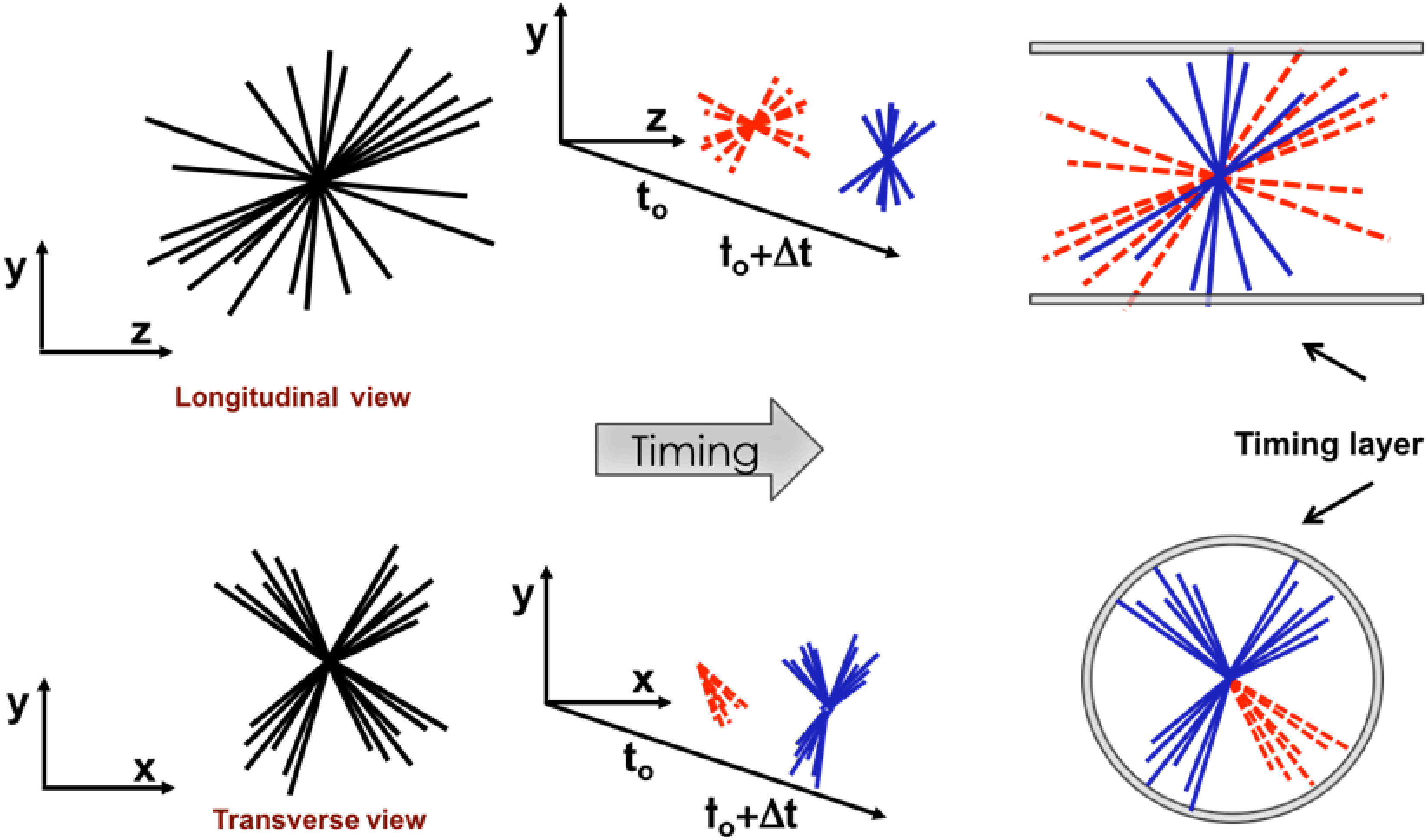
[1] M. Benoit et al., arXiv:1511.04231

Track timing in the event reconstruction

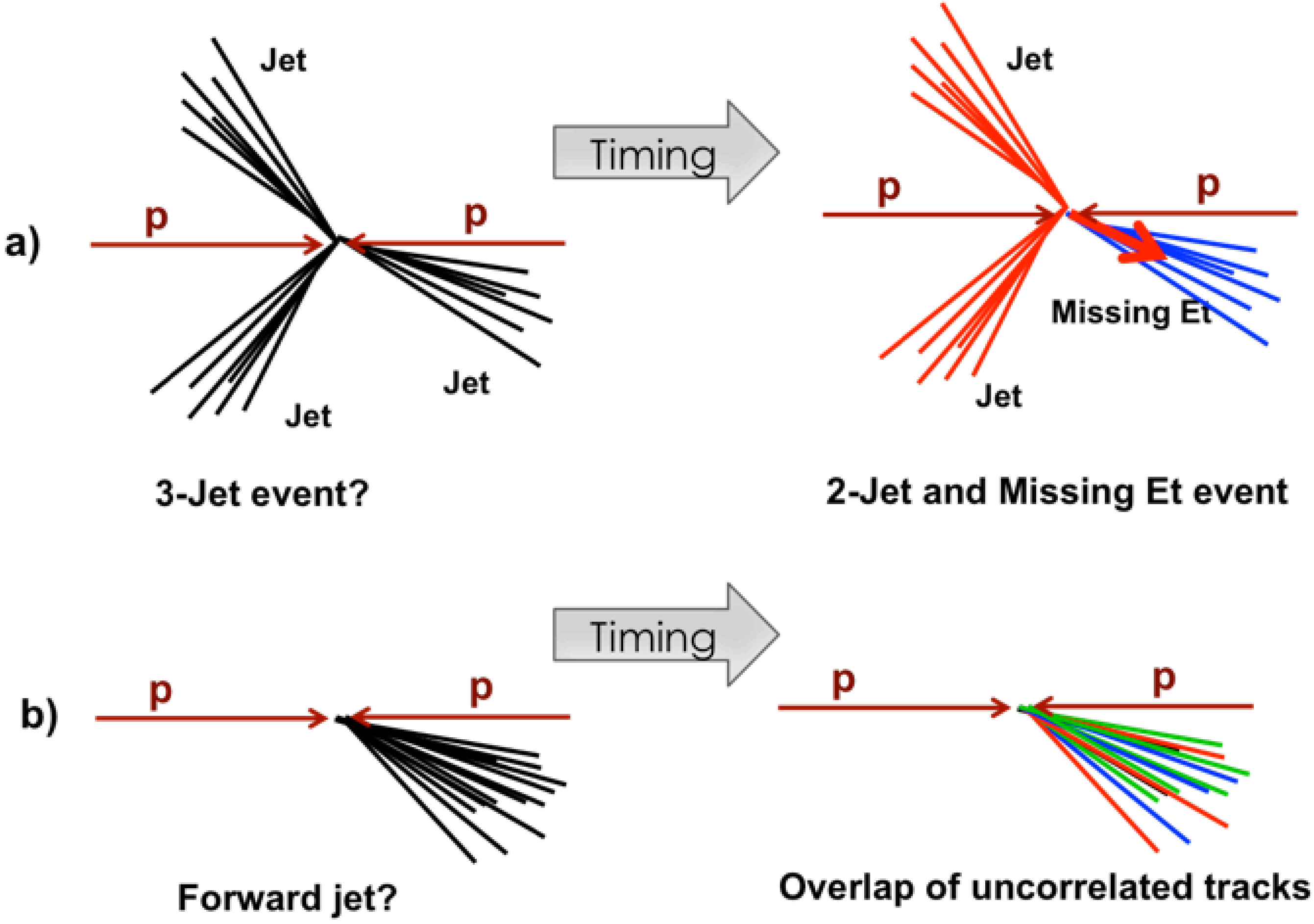
Timing allows distinguishing overlapping events by means of an extra dimension.



→ **CMS timing layer for HL-LHC**

Track timing at the trigger decision

Timing at the trigger decision: it allows reducing the trigger rate, rejecting topologies that look similar, but they are actually different.

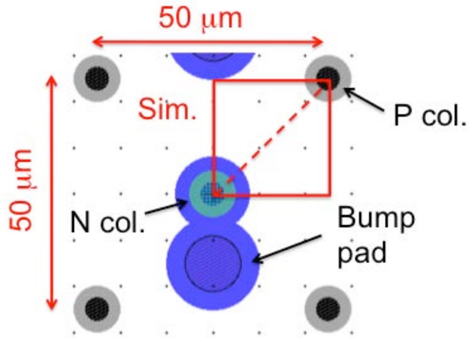


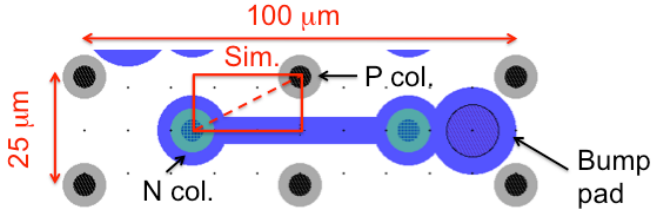
→ **ATLAS timing layer for HL-LHC [ref]**

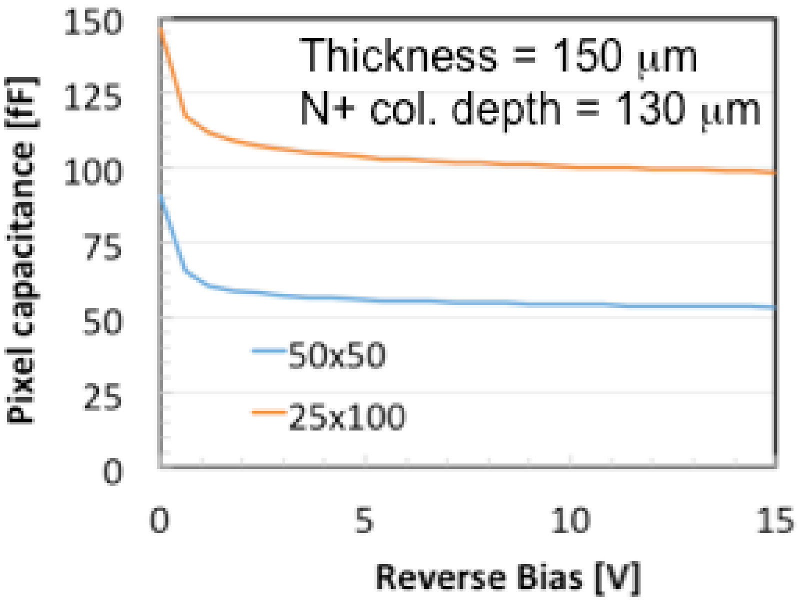
Proposed 3D Sensors

- Reduced material budget → thinner sensors: 100 to 150 μm active thickness
  → active edge
- Better geometrical efficiency → narrower electrodes: 5 μm column diameter
- Increased granularity → Two pixel layouts: 50x50 μm² and 25x100 μm²

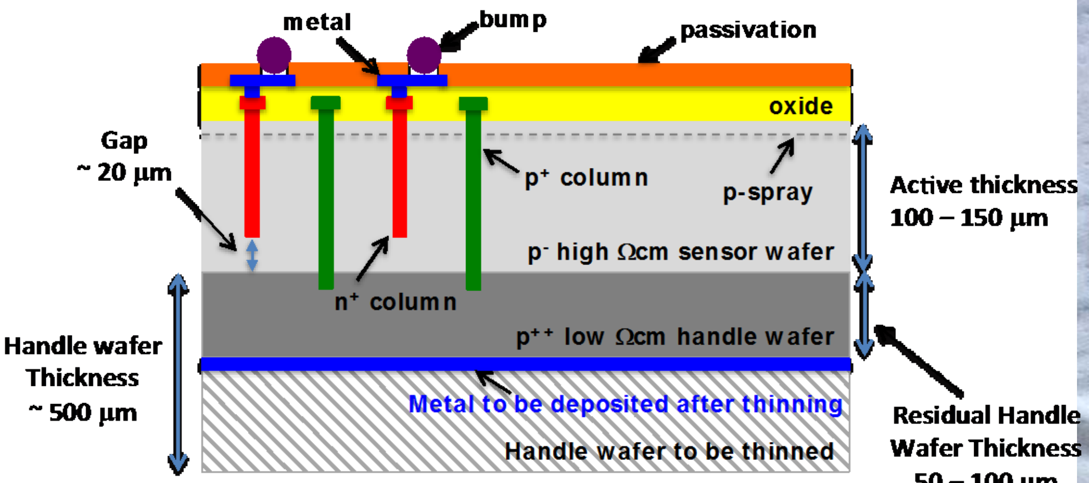
Single-sided process with support wafer

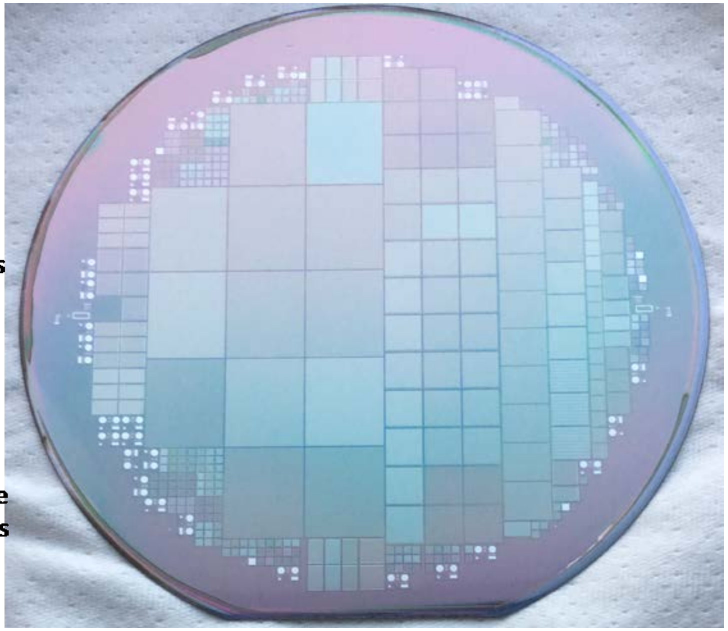


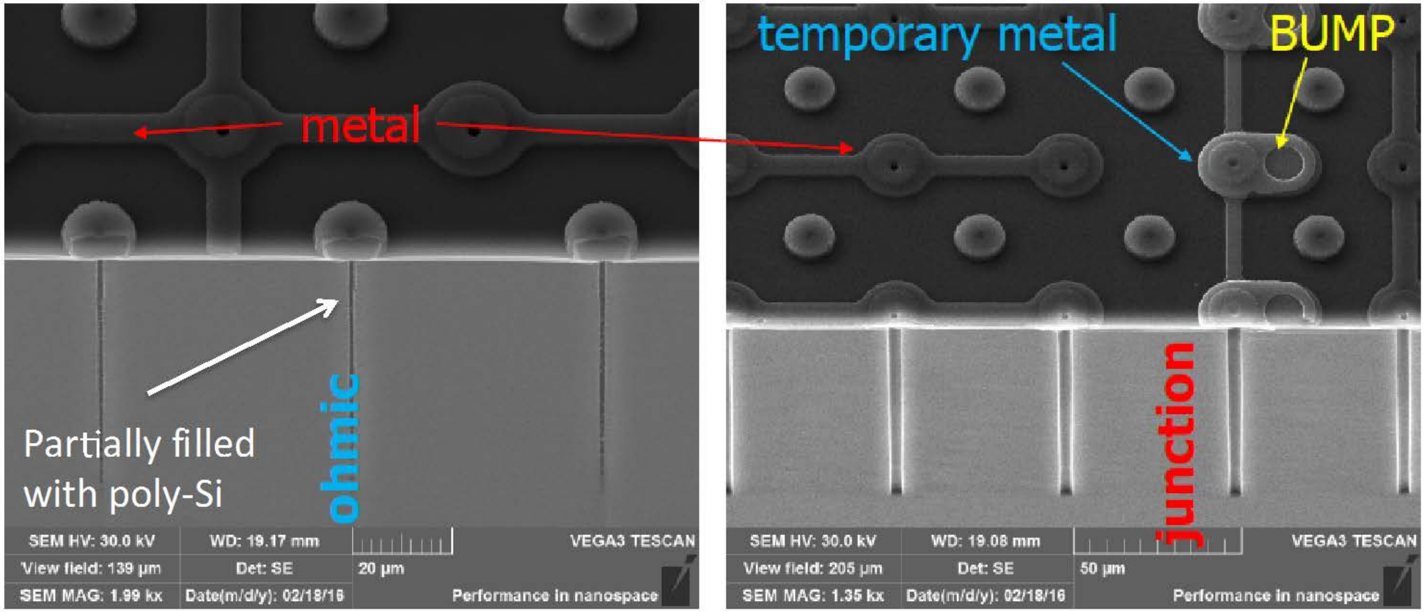




FBK 3D-SS technology: 1st batch

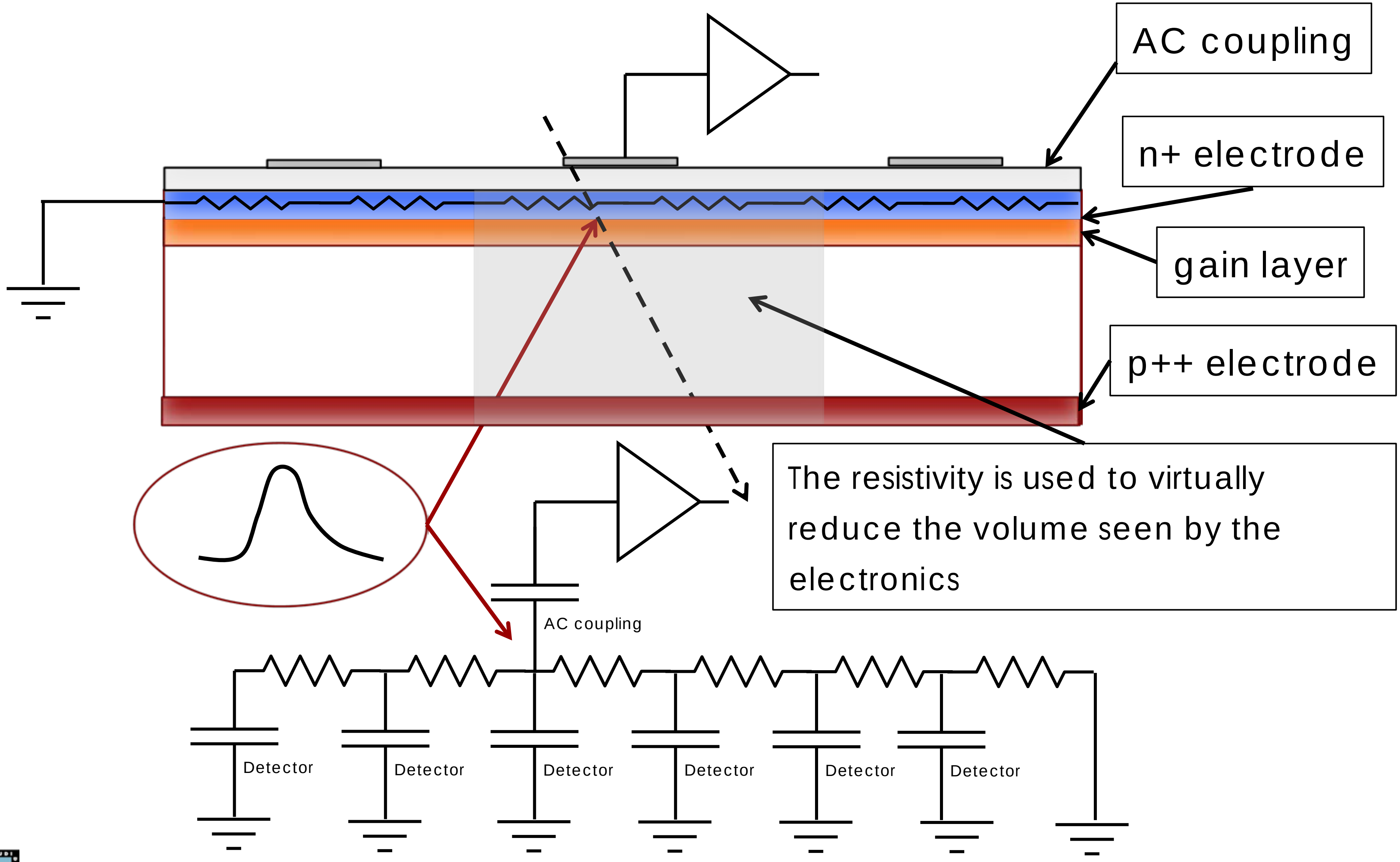






Segmentation: AC coupling

Standard n-in-p LGAD, with AC read-out



The resistivity is used to virtually reduce the volume seen by the electronics