AIDA-2020-SLIDE-2020-019

4D tracking systems at future hadron colliders

Cartiglia, N. (INFN Torino) *et al*

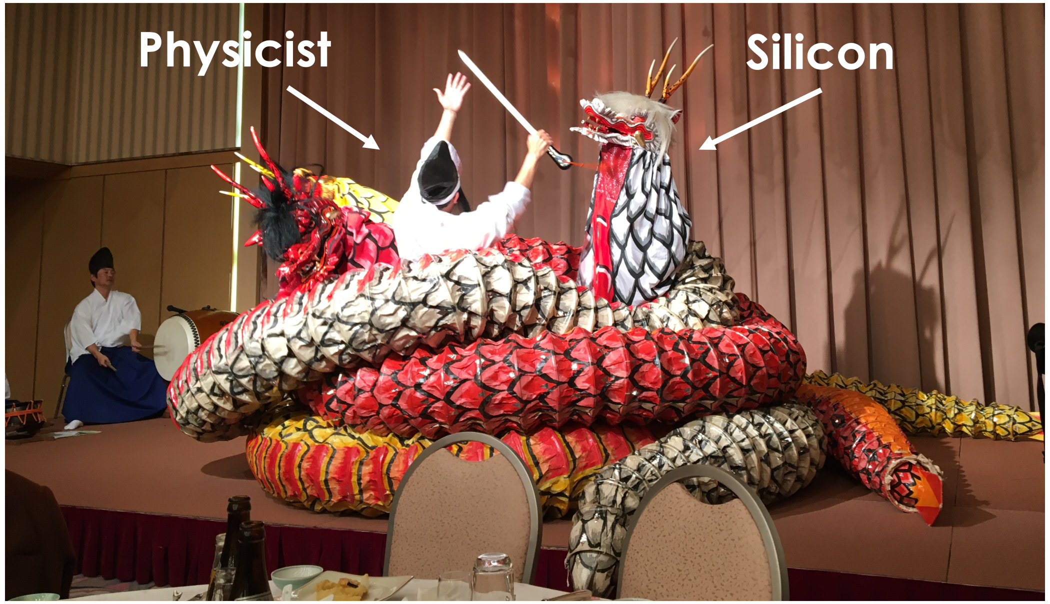
18 December 2019

The AIDA-2020 Advanced European Infrastructures for Detectors at Accelerators project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

This work is part of AIDA-2020 Work Package **7: Advanced hybrid pixel detectors**.

Future silicon trackers

4D tracking, very high fluences, very good position resolution



Nicolò Cartiglia

INFN - Italy

R. Arcidiacono[ab] , F. Fausti[ac], M. Ferrero[ab], M. Mandurrino[a], J. Olave[a], F. Siviero[a],
V. Sola[a], M. Tornago[ac], H. Sadrozinski[d], A. Seiden[d]

[a] INFN Torino, [b] Universita' del Piemonte Orientale, [c] Univerità di Torino,
[d] University of California, Santa Cruz

Future trackers

There are many futures in Silicon trackers: let me pick 3 examples:

Future Circular Collider tracker

- Position resolution: 7.5 - 9.5 µm
- Time resolution = 5 ps
- Radiation levels: up to ~1E17 n/cm^2

CLIC

- Position resolution: 3µm in vertex and 7µm in tracker

LHCb

- Position resolution: 5µm
- Time resolution = 5 ps
- Radiation levels: up to ~1E16 n/cm^2

In this talk I will cover our R&D projects addressing:

1. Extension of good time resolution to higher fluences
2. Use of silicon sensors in the range 1E16 – 1E17 n/cm^2
3. Capability of obtaining very good position resolution (<10 um) using large-pitch geometry

1. Extension of UFSD timing performances to higher fluences

Silicon as precise timing detector

Silicon sensors were never considered accurate timing devices

However, in the last 10 years there has been a very intense R&D

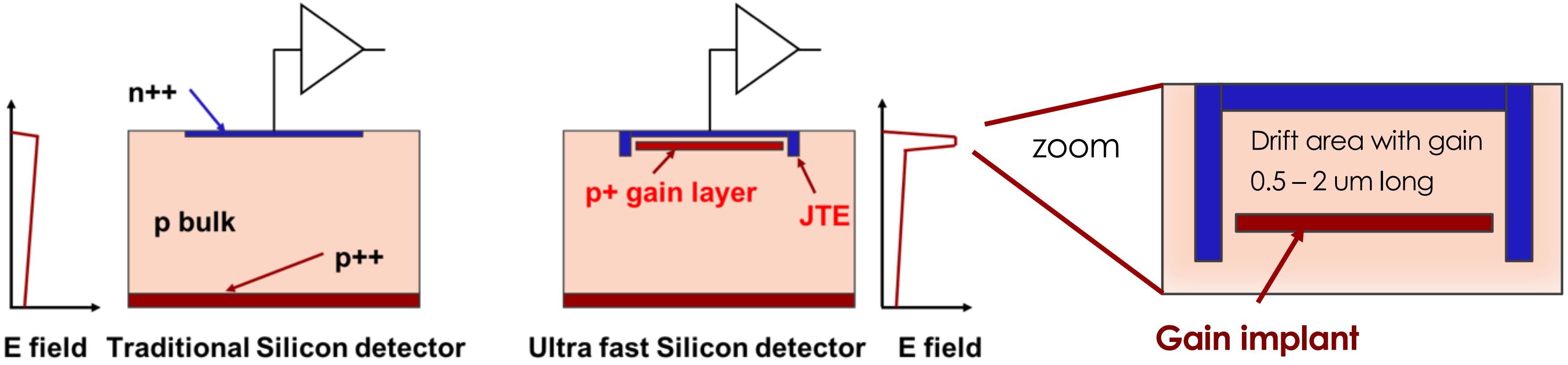
At present, silicon sensors are the ONLY detector able to provide excellent timing capability (~ 30 ps) , good radiation hardness, good pixilation, and large area coverage

Important:

Sensors provide the current signals, read-out chips use them

Timing is the to combination of these two parts,
that succeed and fail together

UFSD Time resolution

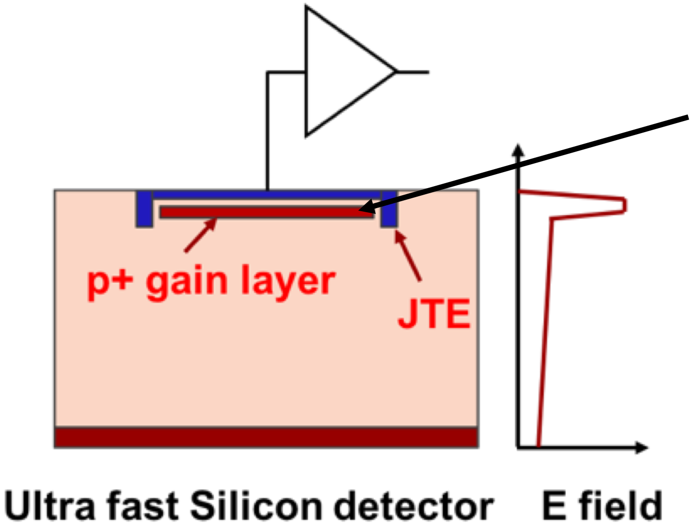


Low Gain Avalanche Diodes (LGAD), as first proposed and manufactured by CNM employ a thin layer of doping to generate the extra field needed for multiplication.

LGAD optimized for timing, the so called Ultra Fast Silicon Detectors,
obtain 30-35 ps resolution up to 1-2E15 n/cm^2

Can we extend the performances to higher fluences?

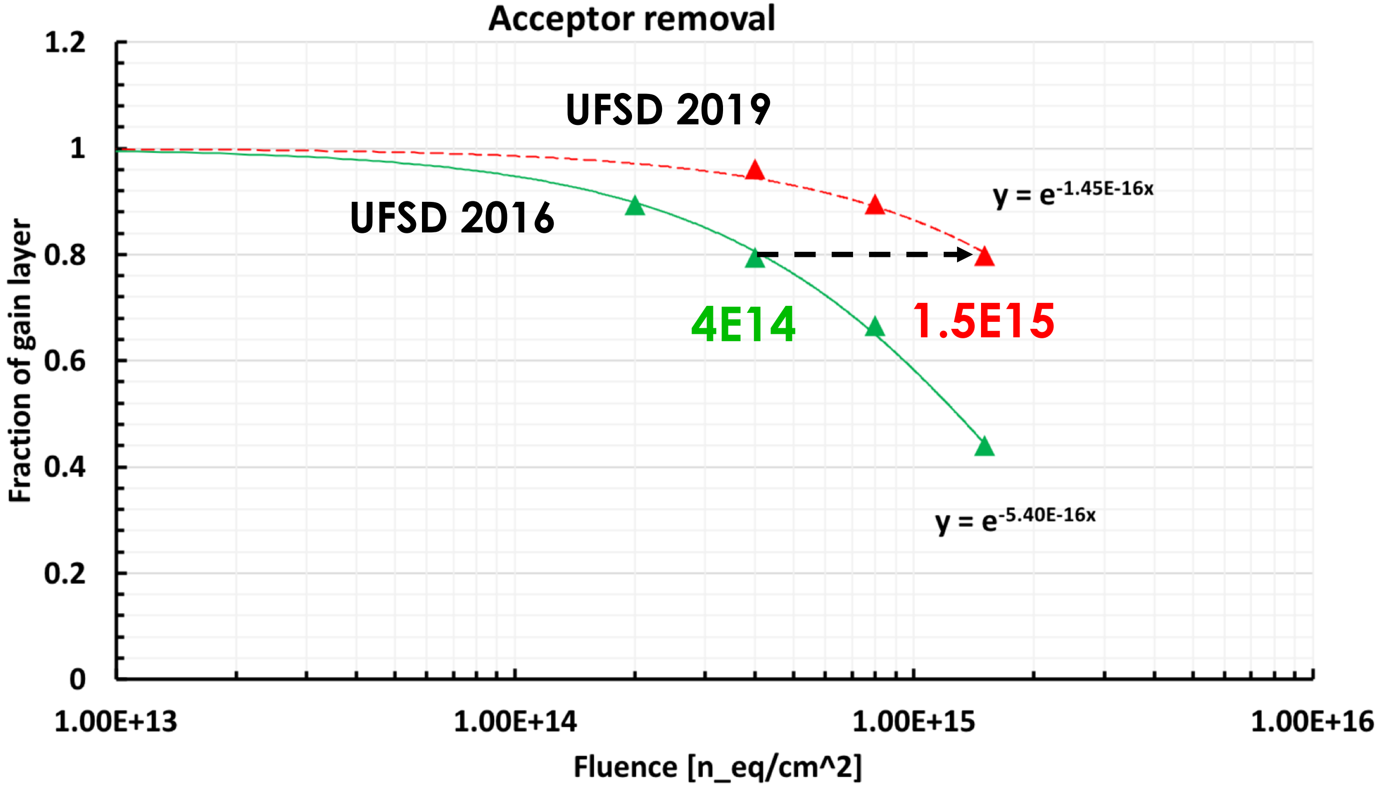
Progresses in UFSD radiation hardness



Irradiation decreases the gain layer doping (acceptor removal)

Strong R&D in finding the solution to this problem

- New gain implant design
- Defect engineering



Fluence at which 80% of the gain layer is still active:

- **2016: 4E14 n/cm^2**
- **2019: 1.5E15 n/cm^2**

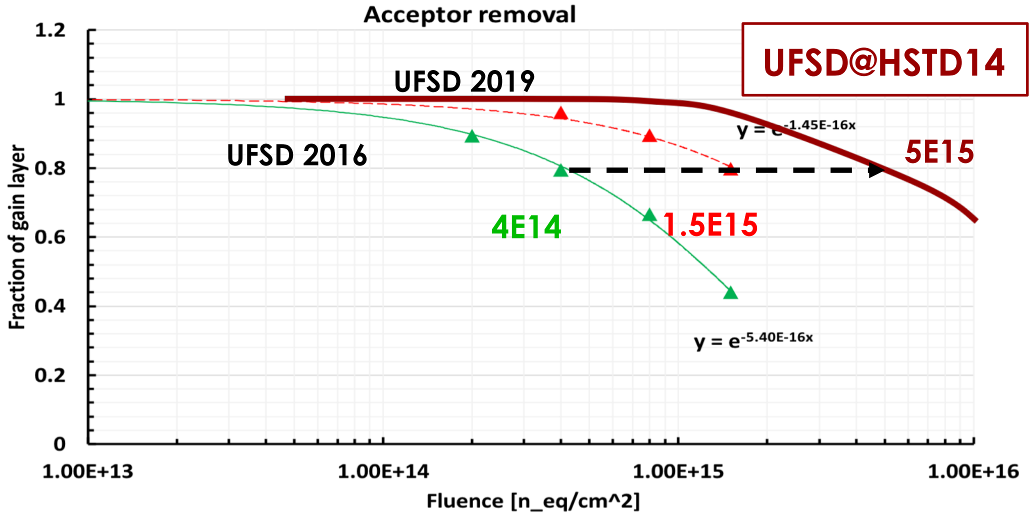
Almost a factor of 4 improvement

What can we expect in the next 5 years?

Progresses in UFSD radiation hardness

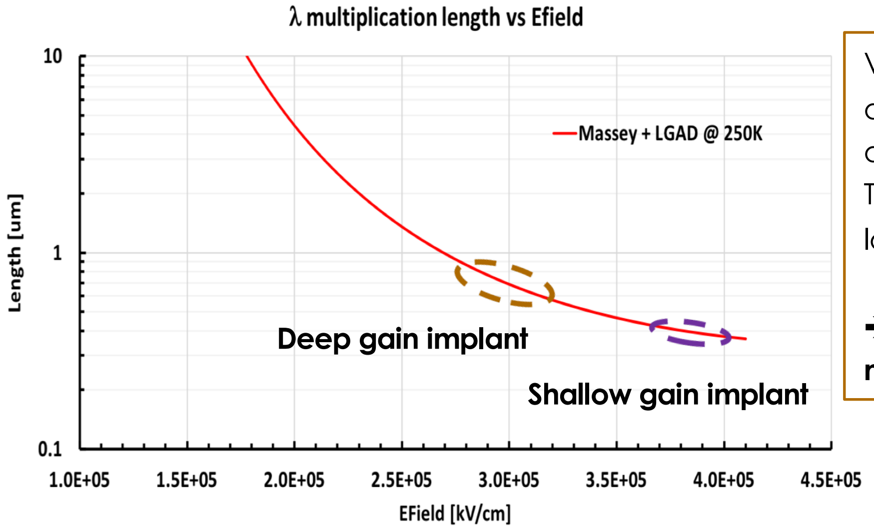
Two main drivers:

1. **Optimization of defect engineering**, to extend the gain implant radiation hardness



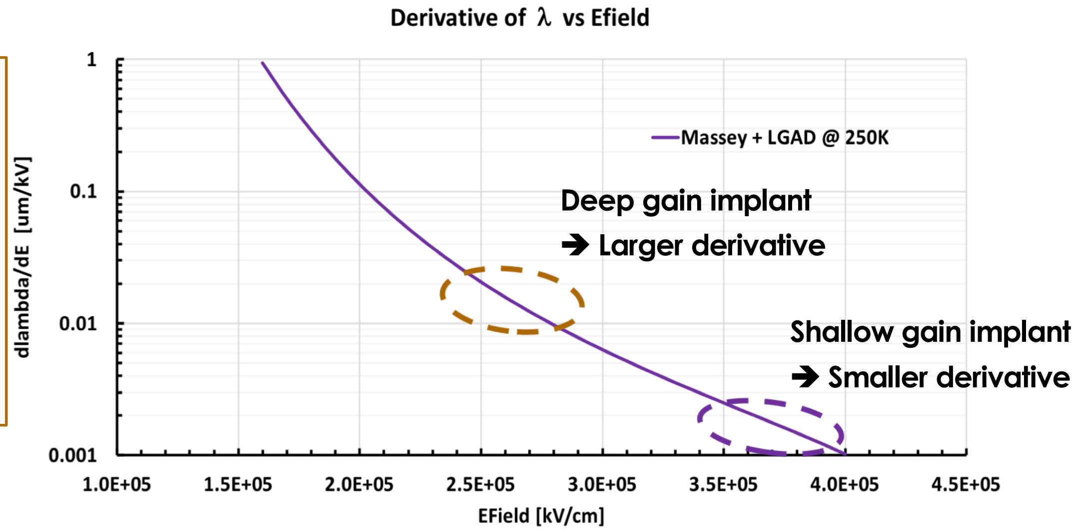
2. **Improvement in the capability of Vbias to recover the field that has been lost due to acceptor removal**

$$G \propto e^{\alpha * d}, \alpha = \frac{1}{\lambda}$$



Vbias compensates the loss of Efield due to the gain implant doping decrease.
The compensation works better at lower Efield (higher λ derivative)

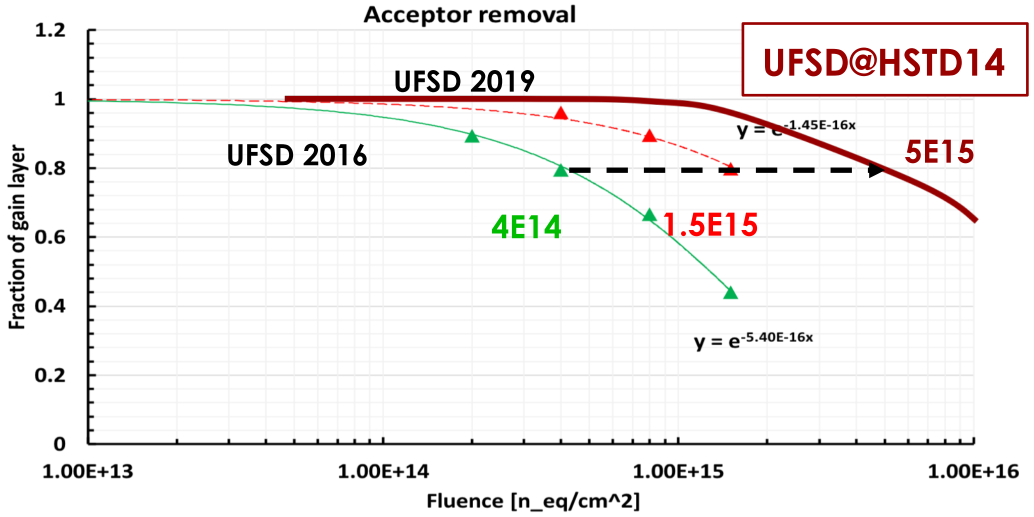
➔ In deeper gain layer, Vbias has a much stronger recovery capability



Progresses in UFSD radiation hardness

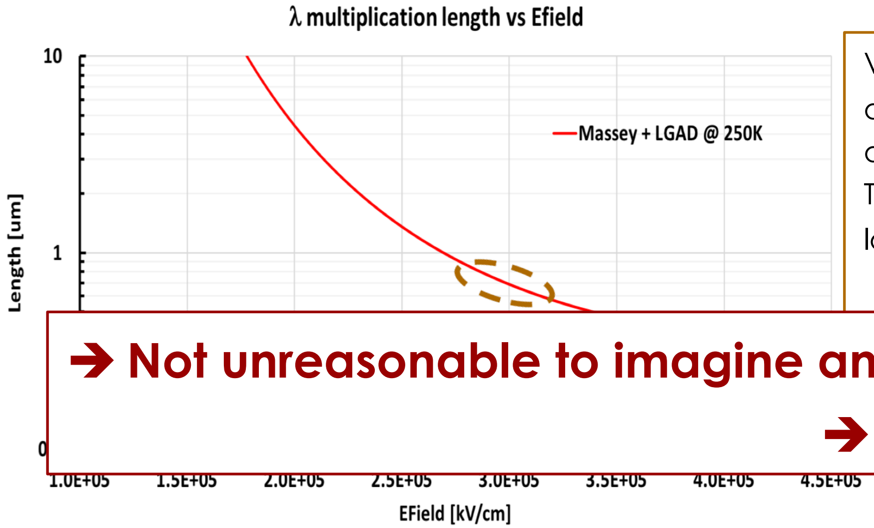
Two main drivers:

1. **Optimization of defect engineering**, to extend the gain implant radiation hardness

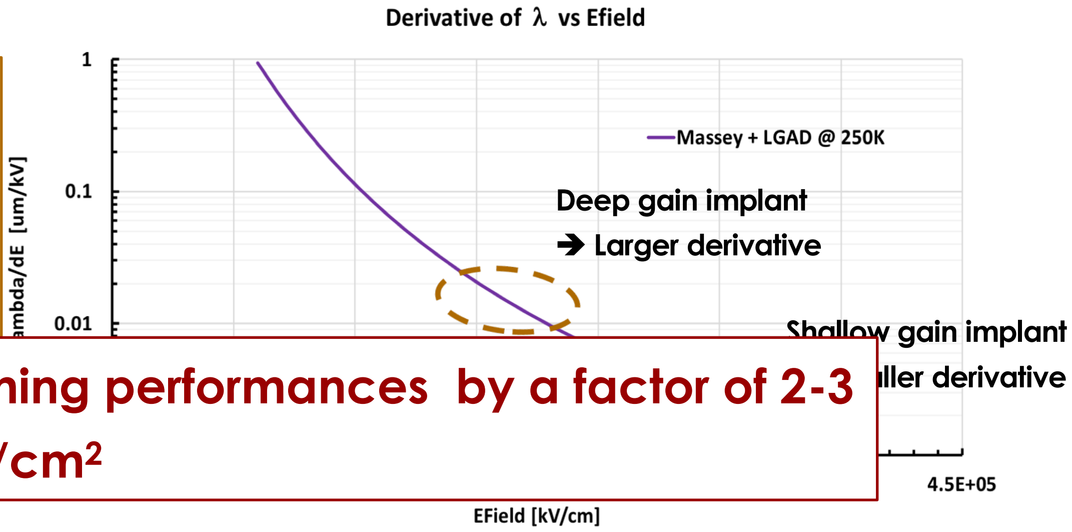


2. **Improvement in the capability of Vbias to recover the field that has been lost due to acceptor removal**

$$G \propto e^{\alpha * d}, \alpha = \frac{1}{\lambda}$$



Vbias compensates the loss of Efield due to the gain implant doping decrease.
The compensation works better at lower Efield (higher λ derivative)



➔ Not unreasonable to imagine an extension of good timing performances by a factor of 2-3

➔ Goal: 30 ps at 5E15 n/cm²

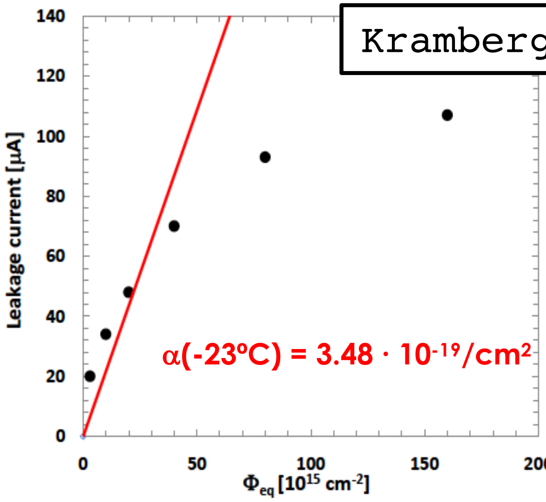
2. Use of silicon sensors in the range 1E16 – 1E17 n/cm^2

Gregor K.:

Extrapolation from low fluence data to higher fluence suggests that using silicon detector above 1E16 n/cm^2 is mission impossible

A new hope: saturation of displacement damage

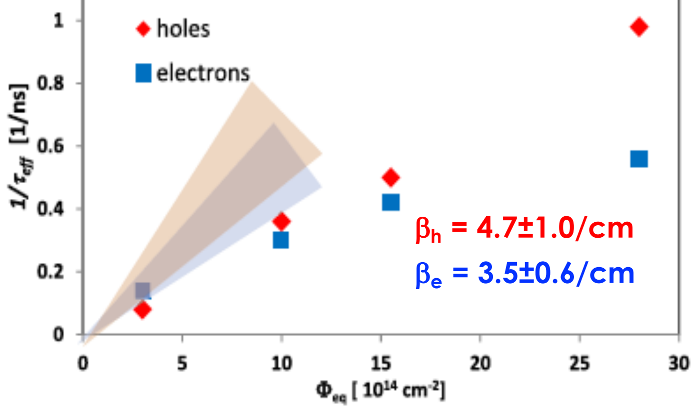
Kramberger, Ljubljana



Dark current saturation

$I = \alpha V \Phi$

α from linear to logarithmic

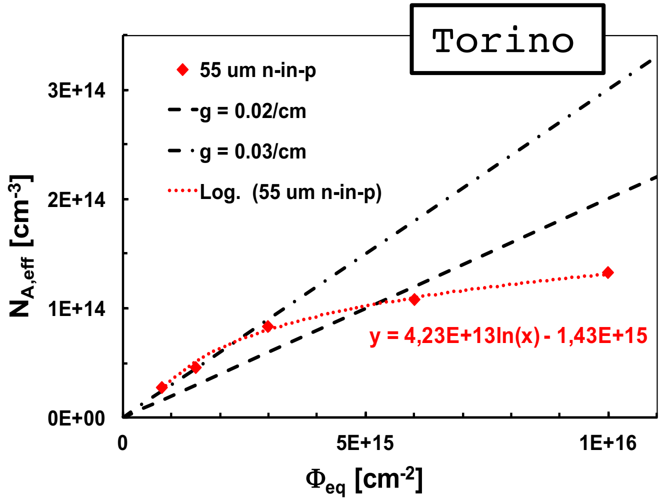


Trapping probability saturation

$1/\tau_{eff} = \beta\Phi$

β from linear to logarithmic

Torino



Acceptor creation saturation

$N_{A,eff} = g_c\Phi$

g_c from linear to logarithmic

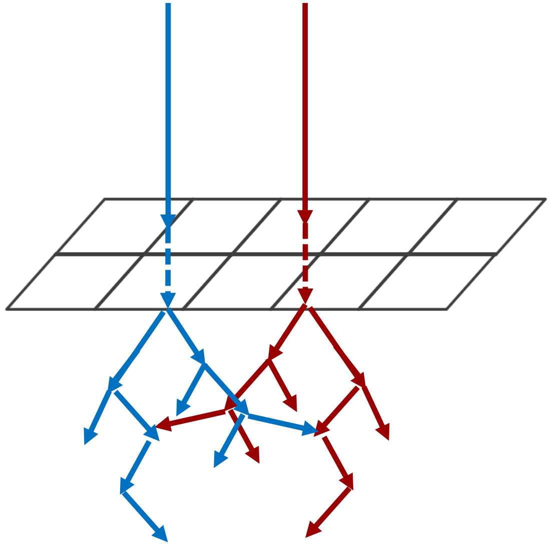
Saturation is a key aspect of the R&D in the next few years, we should learn how to take advantage of this effect

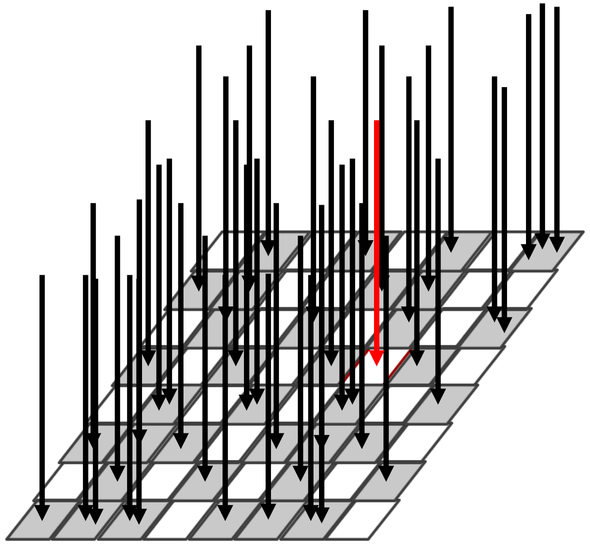
The bottom line is: Silicon detectors irradiated at fluences 1E16 – 1E17 n/cm² do not behave as expected, **they behave better**

Why saturation?

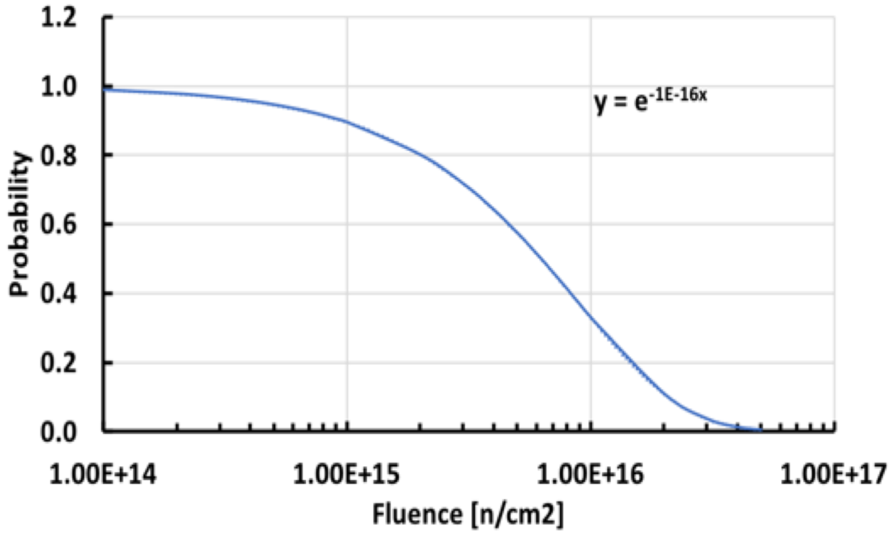
What is the probability for a particle to hit a square of 1 Å^2 that has not been hit before?

Overlapping clusters





Probability of hitting a square of area 1 Å^2 that has not been hit before



At 1E16 n/cm2 only 30% of particles will hit an “1 Å empty square”

Note: Silicon lattice has a cube of 5 Å; every cell has already been hit at 1E15.

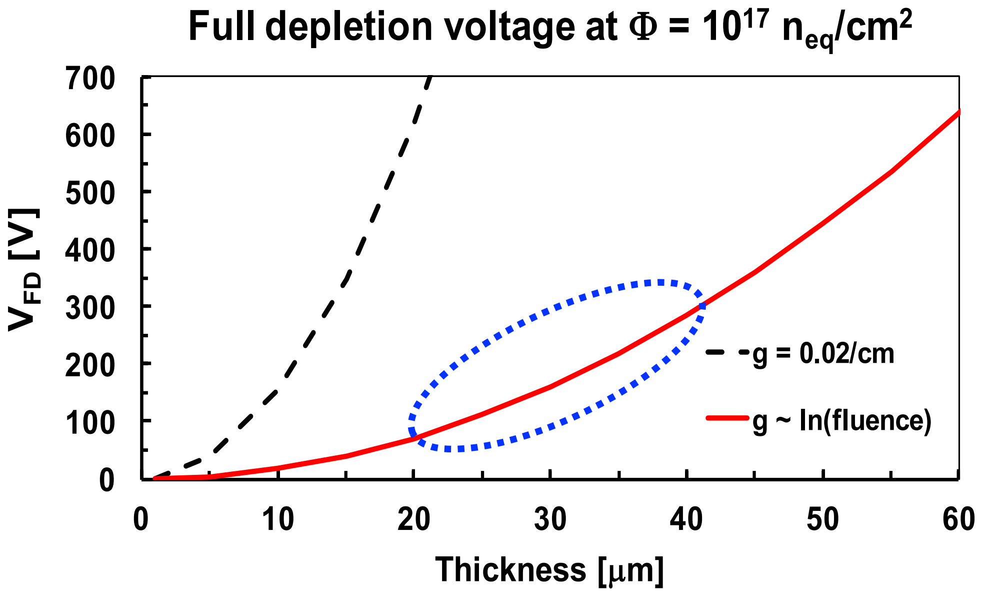
Damage on damaged Silicon probably has different consequences.

Use thin sensors

$$V_{FD} = e\,|\,N_{eff}\,|\,d^2/2\varepsilon$$

Saturation **Reduce thickness**

Thanks to saturation effects, thin sensors can still be depleted and operated at $V_{bias} \leq 500$ V



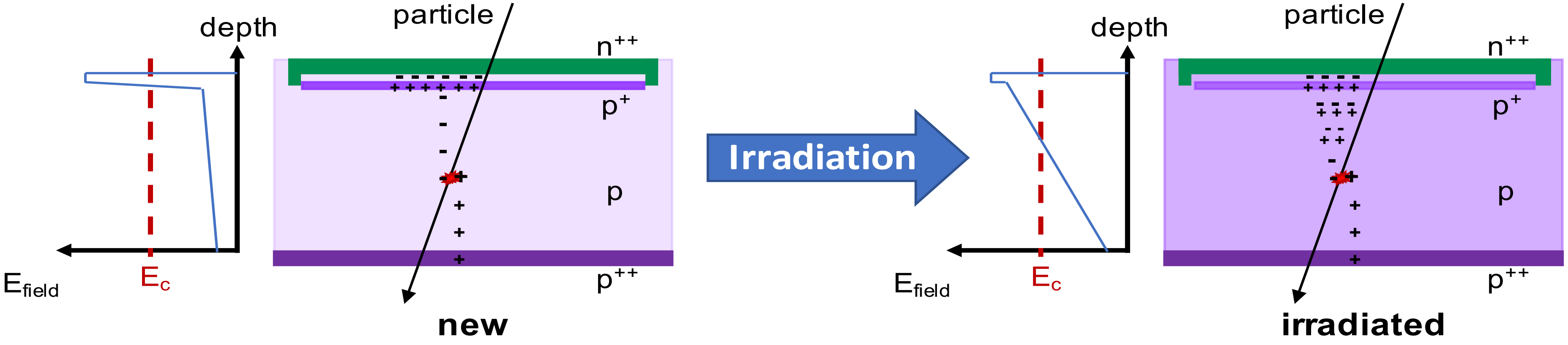
What does it happen to a 25-micron sensor after a fluence = 5E16 n/cm²?

- Trapping is almost absent
- It can still be depleted
- Leakage current is low (small volume)

However: Charge deposited ~ 0.25 fC

➔ Need a gain of at least ~ 5 in order to provide enough charge

Evolution with irradiation



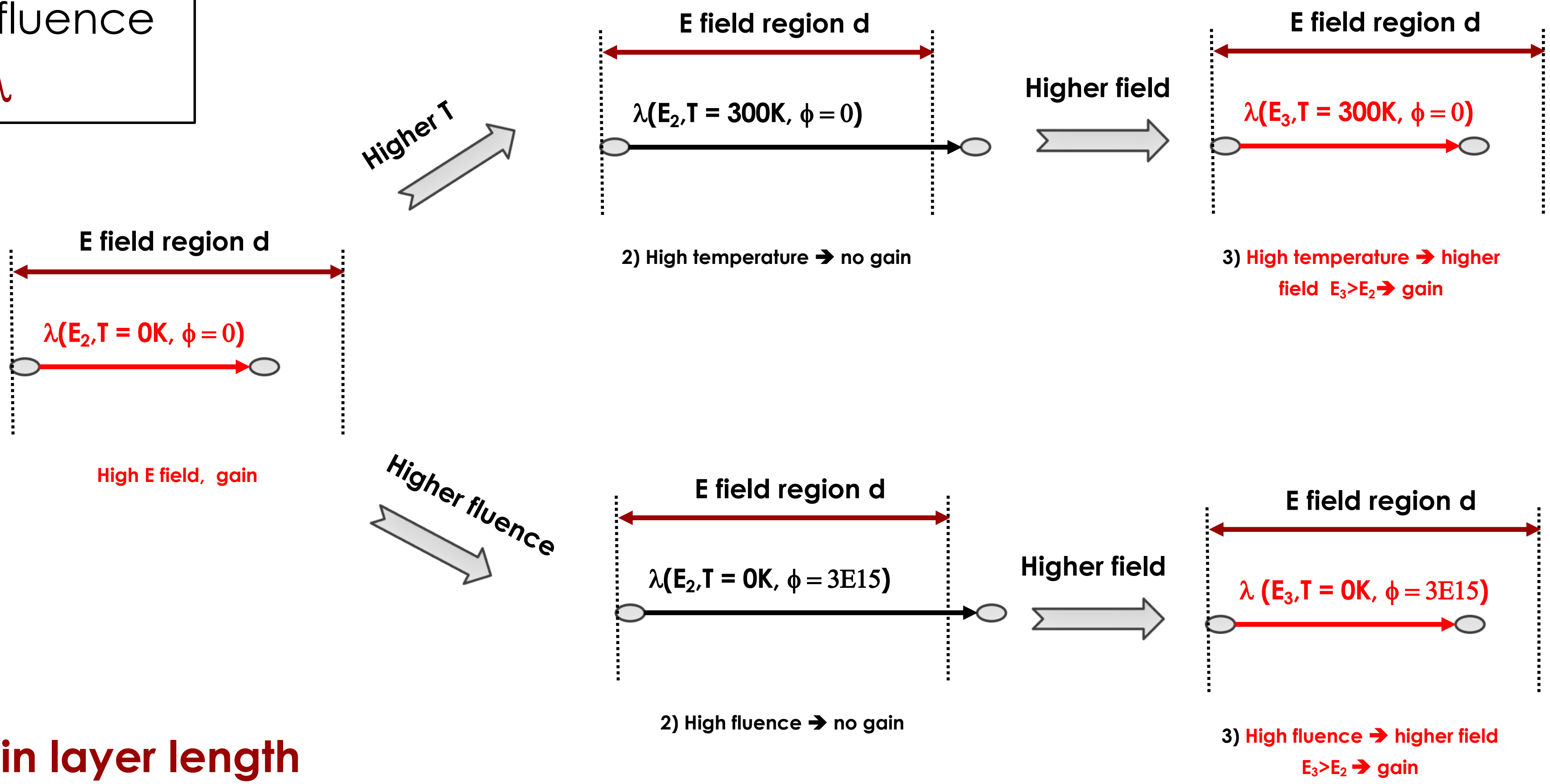
- **Start with a thin LGAD**, 20 – 35 μm thick
- **$2 \cdot 10^{15}$ – $5 \cdot 10^{15}$ n_{eq}/cm^2**: with increasing fluence, the gain layer is deactivated
- **$5 \cdot 10^{15}$ – 10^{16} n_{eq}/cm^2**: compensate the decrease power of the gain layer by shifting the multiplication region to the bulk
- **10^{16} – 10^{17} n_{eq}/cm^2**: **rely solely on bulk multiplication**

→ **Does bulk multiplication exist at these fluences?**

Effect of irradiation (and temperature) on gain

$G(E,T,\emptyset,d) \propto e^{\alpha(E,T,\emptyset)*d}$ $\lambda(E,T,\phi) = \alpha^{-1}(E,T,\phi)$

Key point: Bias compensates the effect of temperature and fluence by changing the length of λ



E field region d

$\lambda(E_2, T = 0K, \phi = 0)$

High E field, gain

Higher T

E field region d

$\lambda(E_2, T = 300K, \phi = 0)$

2) High temperature ➔ no gain

Higher field

E field region d

$\lambda(E_3, T = 300K, \phi = 0)$

3) High temperature ➔ higher field $E_3 > E_2$ ➔ gain

Higher fluence

E field region d

$\lambda(E_2, T = 0K, \phi = 3E15)$

2) High fluence ➔ no gain

Higher field

E field region d

$\lambda(E_3, T = 0K, \phi = 3E15)$

3) High fluence ➔ higher field $E_3 > E_2$ ➔ gain

Gain if : $\lambda(E, T, \lambda_{defect}(\phi)) <$ **gain layer length**

In new sensors, λ (E,T, φ) is governed by **phonons: high temperature decreases the gain.**

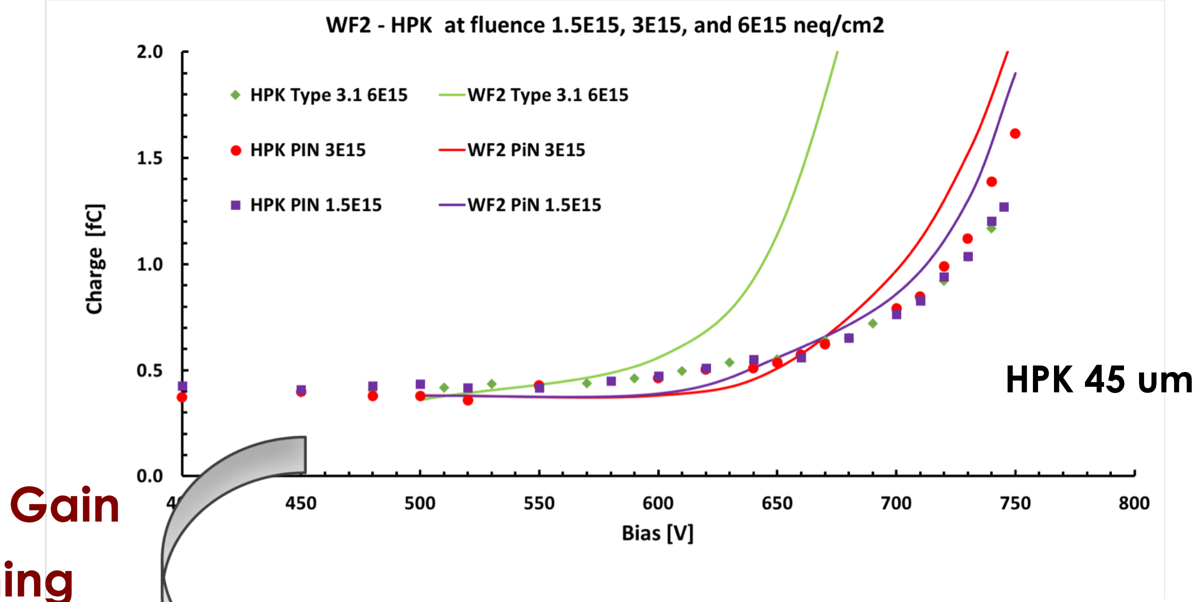
Gain in the bulk: HPK 45 um sensors

Using data on multiplication in PiN and the measured bulk doping, a value of **c** can be determined

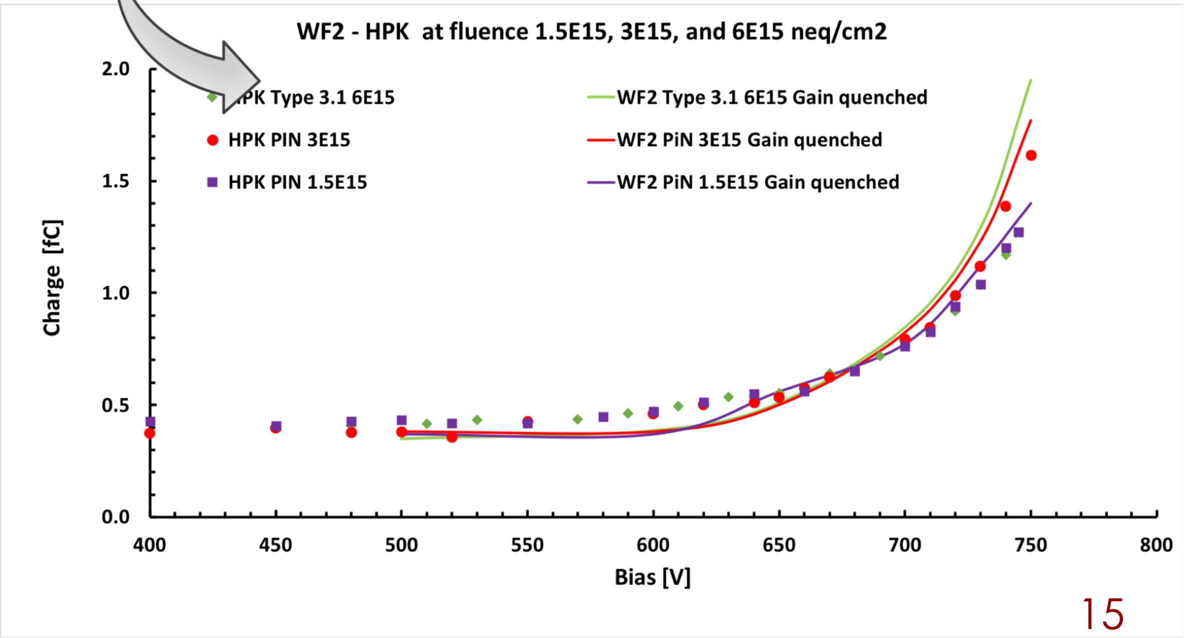
$$G \propto e^{\alpha(E,T)*d}$$

$$\alpha \propto e^{-(a+b*T+c*\emptyset)/E}$$

$$c = 2*10^{-11}\ \mathrm{V}/\emptyset$$



Adding Gain quenching



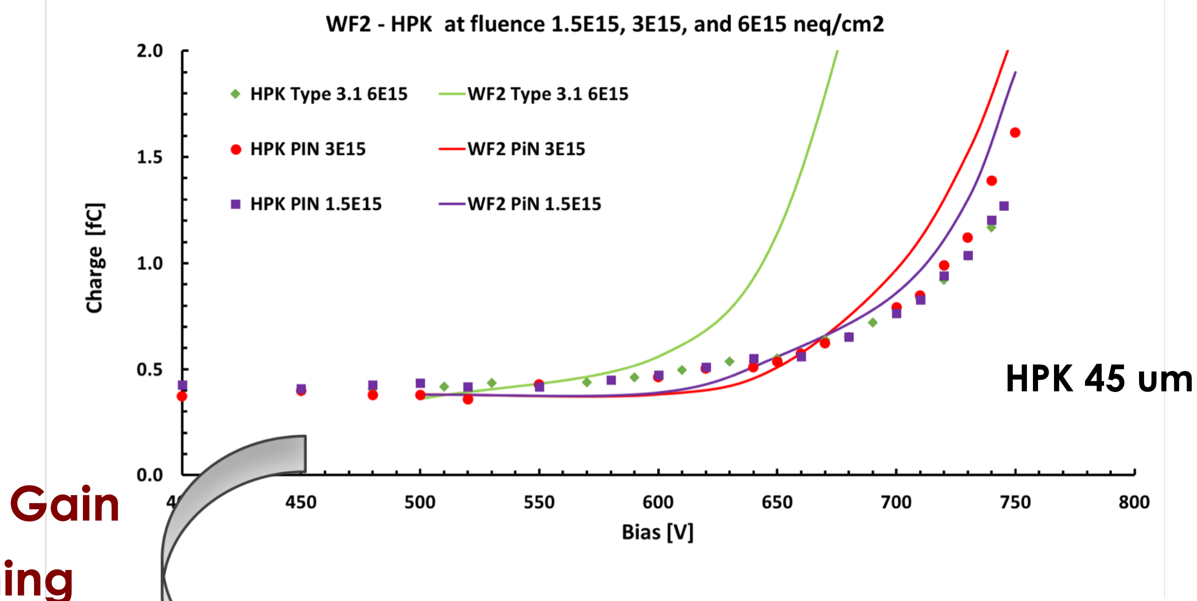
Gain in the bulk: HPK 45 um sensors

Using data on multiplication in PiN and the measured bulk doping, a value of **c** can be determined

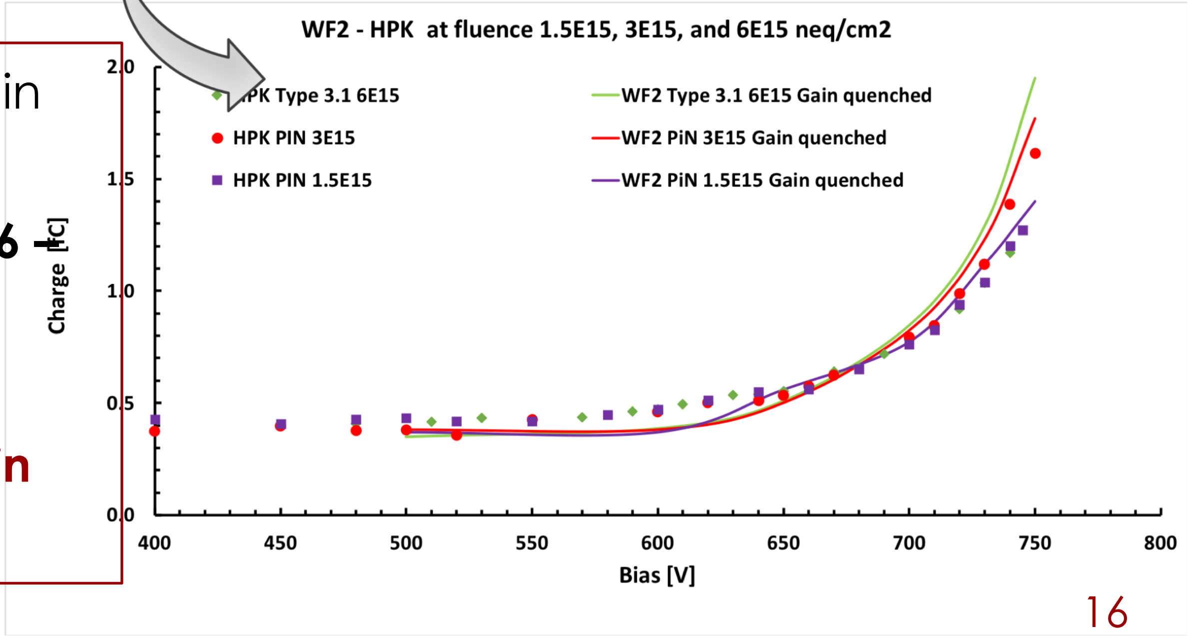
$$G \propto e^{\alpha(E,T)*d}$$

$$\alpha \propto e^{-(a+b*T+c*\emptyset)/E}$$

$$c = 2*10^{-11}\ \mathrm{V}/\emptyset$$



Adding Gain quenching



- ➔ At 1E16 n/cm2 there is evidence of moderate gain quenching.
- ➔ **We are studying thinner sensors, irradiated to 1E16 – 1E17 n/cm^2 to map the gain mechanism**
- ➔ **These studies will shed light on the possibilities of using very thin sensors with moderate internal gain as position detector at 1E16 -1E17 n/cm^2**

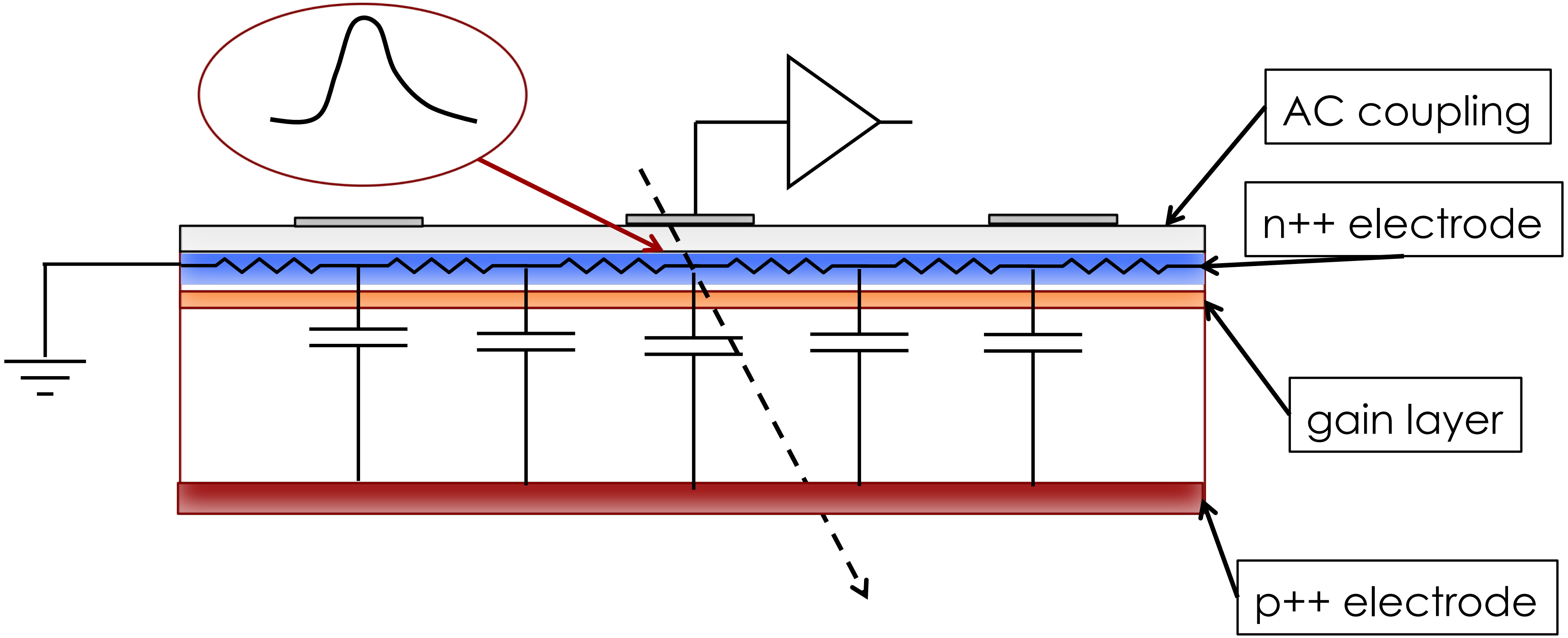
3. Very good spatial resolution (<10 um)

Very good position resolution is achieved either via very small pixels or exploiting charge sharing

Here I present a novel method that exploits charge sharing between pixels to achieve excellent position resolutions

AC – LGAD: Resistive Silicon Detectors (RSD)

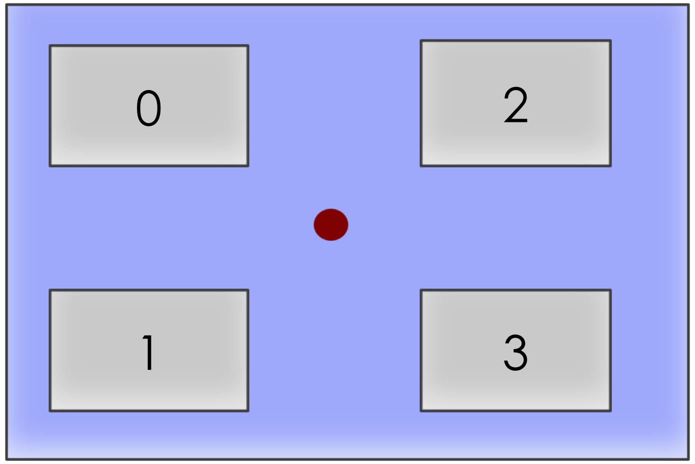
- ➔ 100% fill factor
- ➔Segmentation is achieved via AC coupling

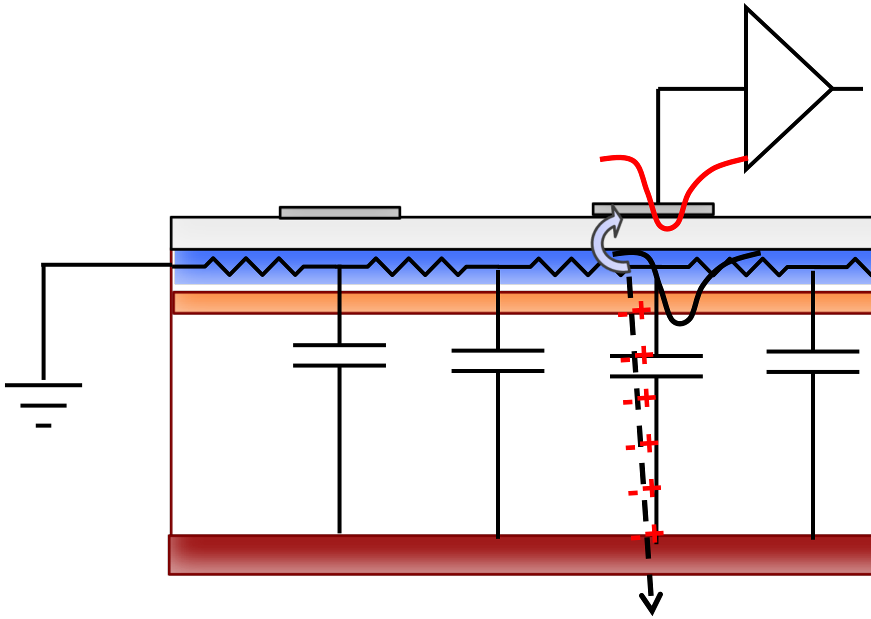


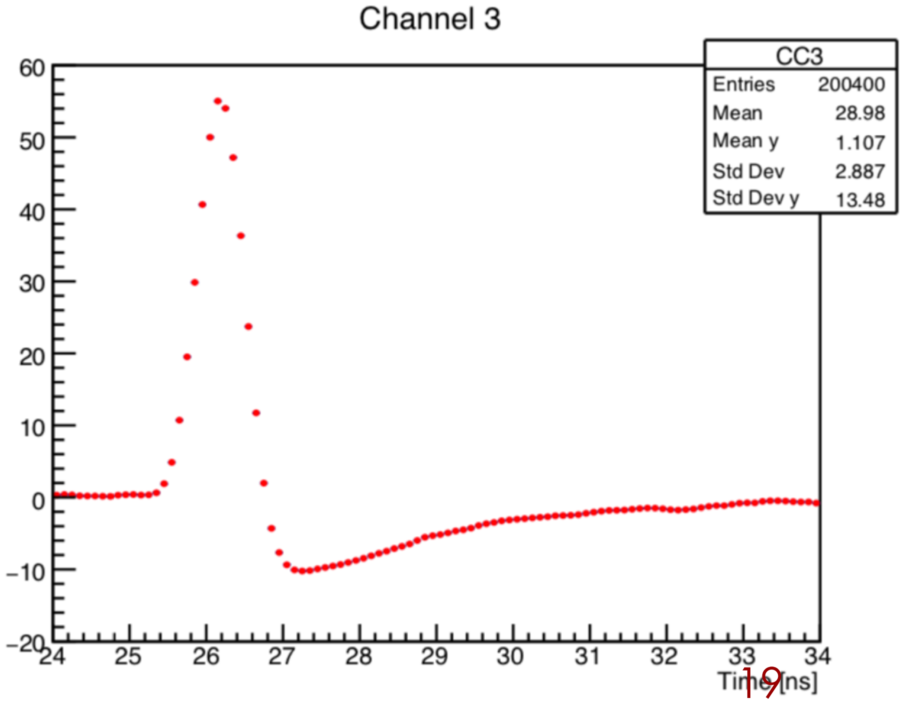
RSD Signal formation: initial charge drift toward the n++ electrode

Act 1: the e/h are drifting and they produce a direct charge induction n++

1. The signal is immediately AC-coupled to the metal pad above (if there is one), with a shape identical to a equivalent DC LGAD
2. Large signal (gain 10-20): 5 - 10 fC
3. Very fast collection (1 ns)
4. No later spread, very vertical E field and drift



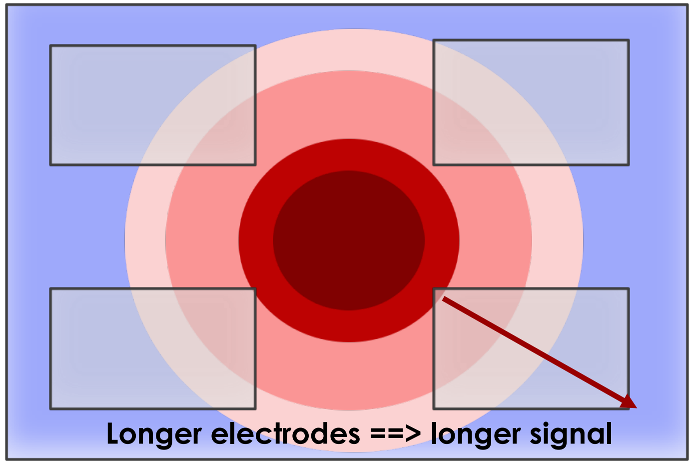


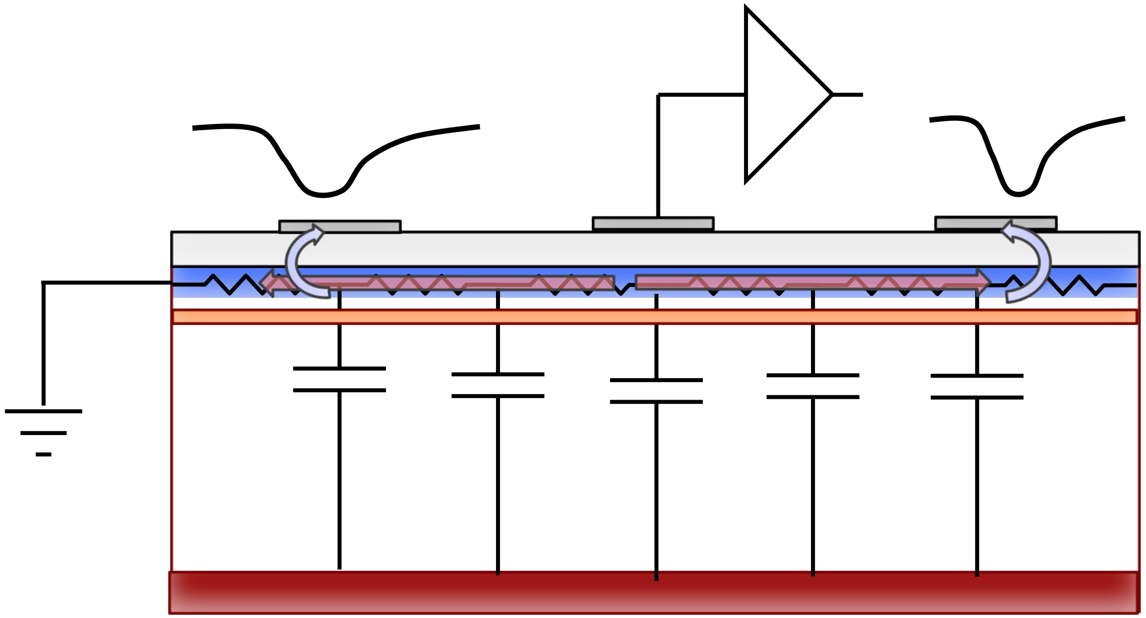


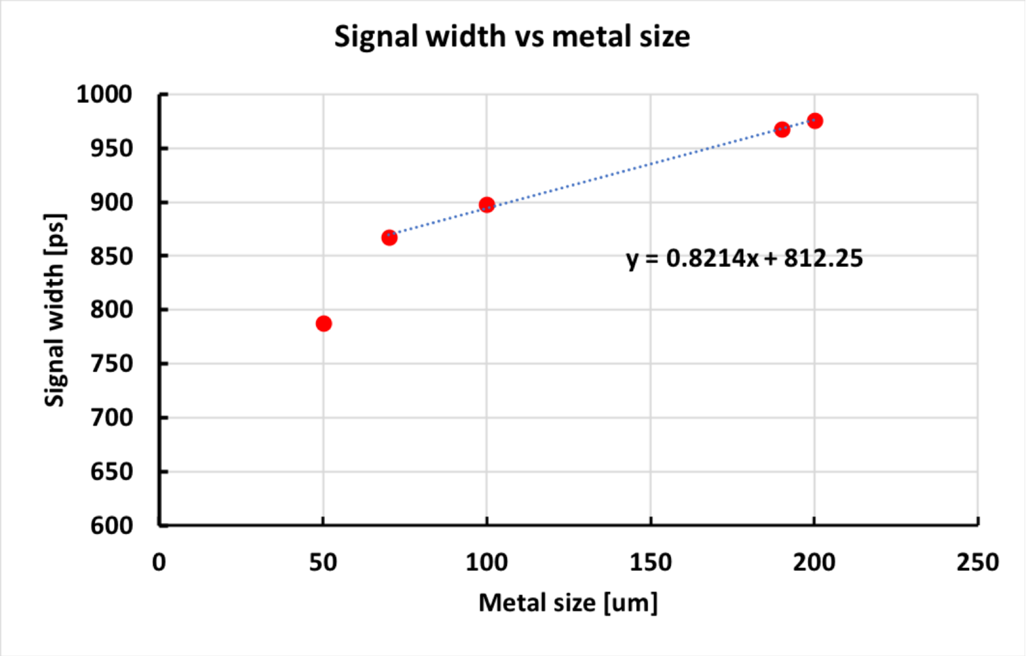
RSD Signal formation: the signal spread along the n++ electrode

Act 2: the signal propagates on the n++, firing the near-by pads

1. The n++ is an almost ideal resistive divider
2. Lateral spread controlled by geometry: n++ resistivity and metal pad capacitance
3. The metal AC pads act as "pick-up" electrodes
4. Signal gets smaller and delayed with distance



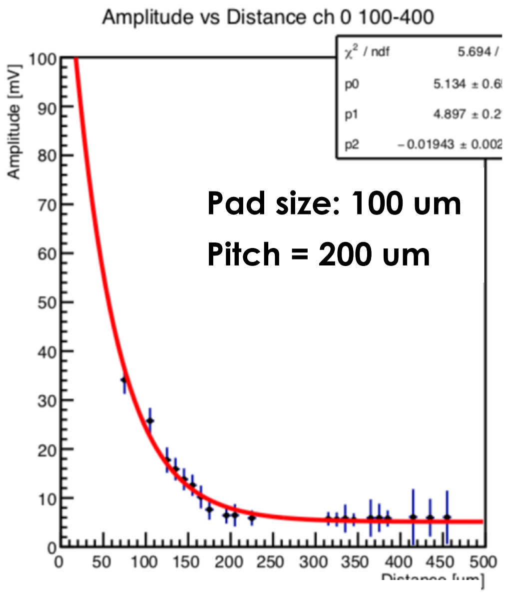




Larger pads have longer signals

RSD Signal formation: the signal spread along the n++ electrode

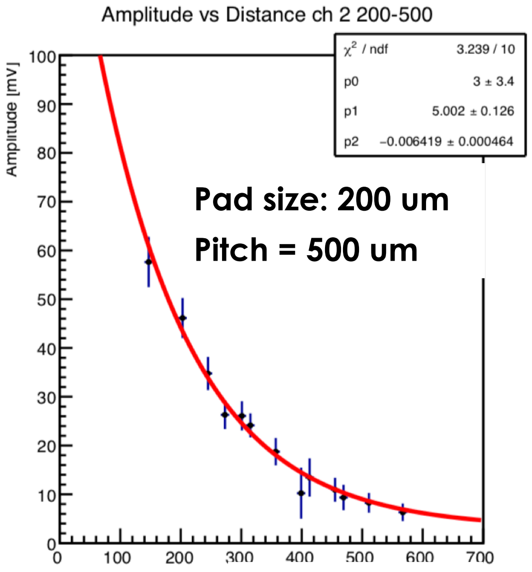
Act 2: The amplitude seen by each pad decreases as a function of the hit distance



Pad size: 100 um

Pitch = 200 um

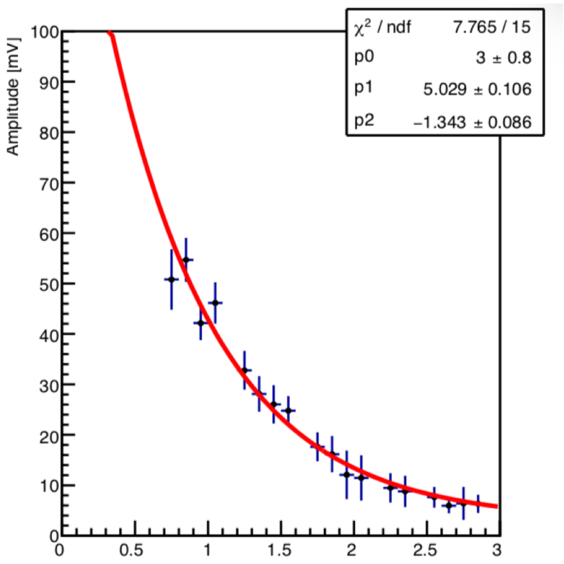
Distance [um]



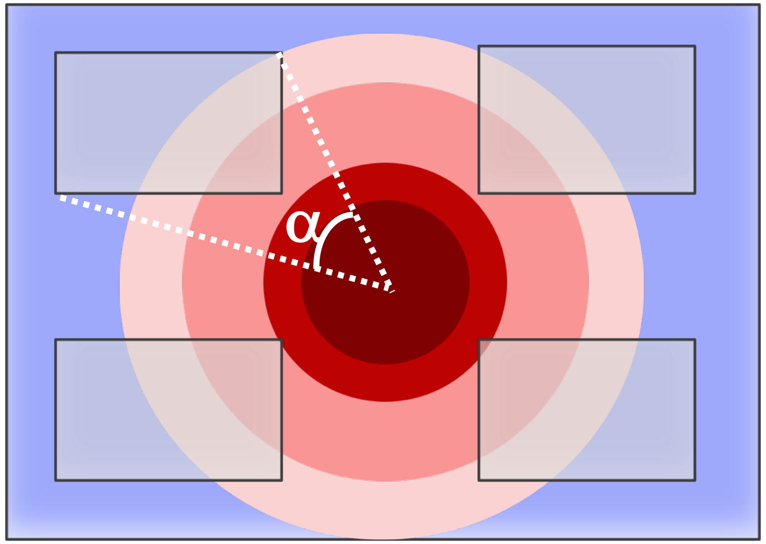
Pad size: 200 um

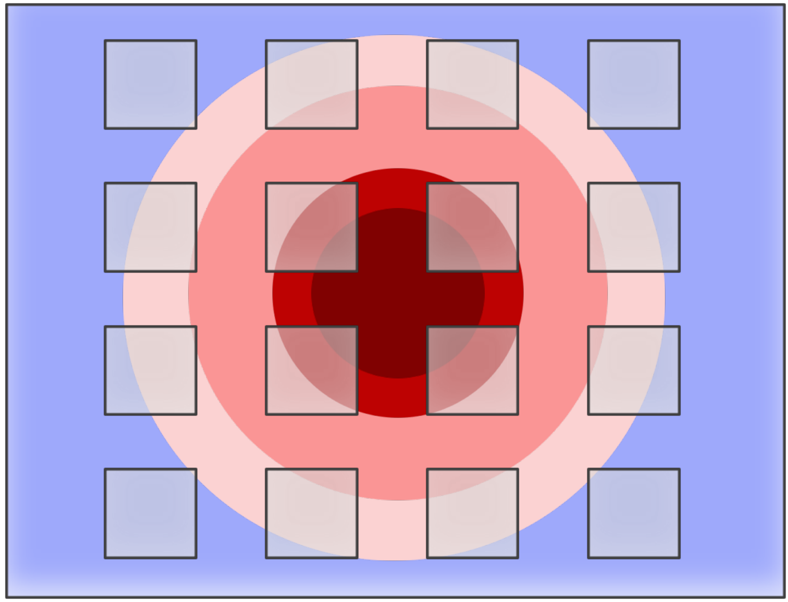
Pitch = 500 um

Distance [um]



Distance/Pad size



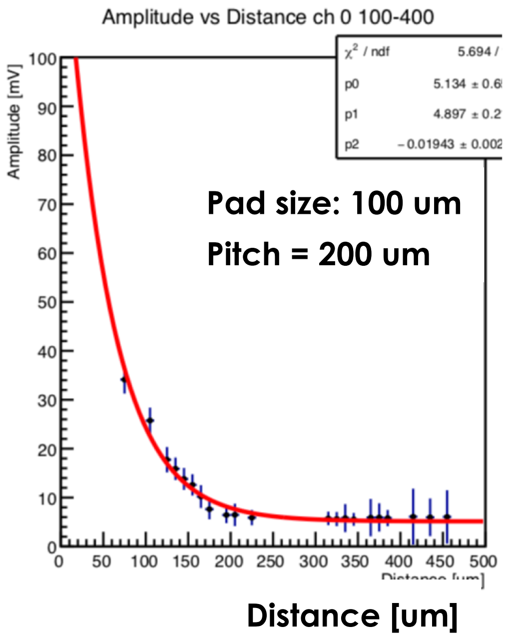


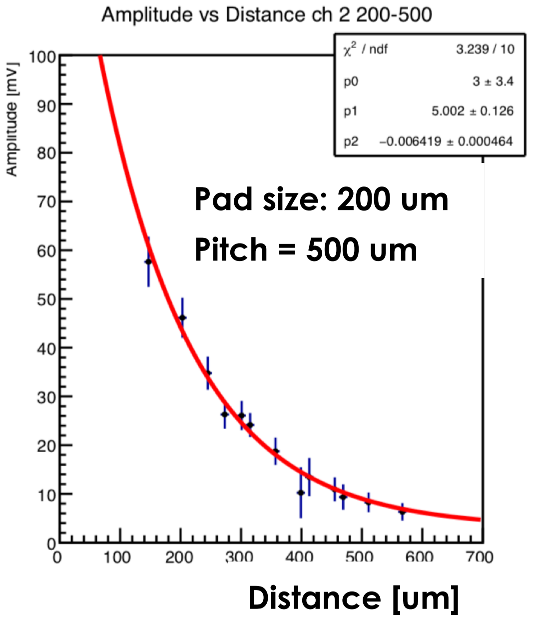
The amplitude goes to zero when the distance is about twice the metal, **scaling variable: Distance/Pad size**

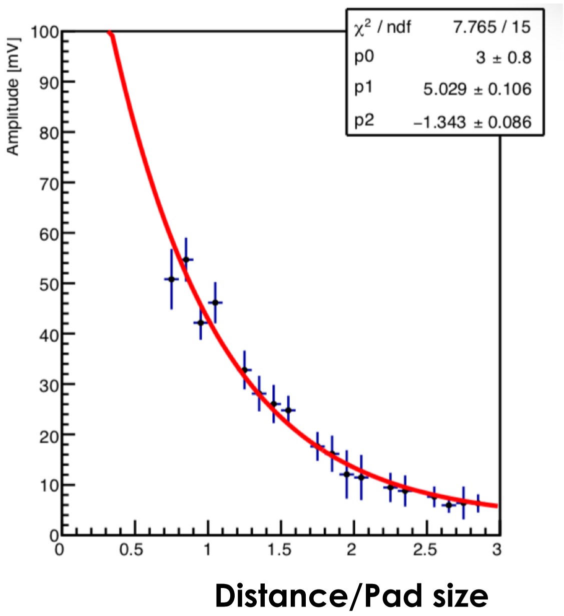
A single hit, therefore, is visible in an area that is about 4x4 pad size

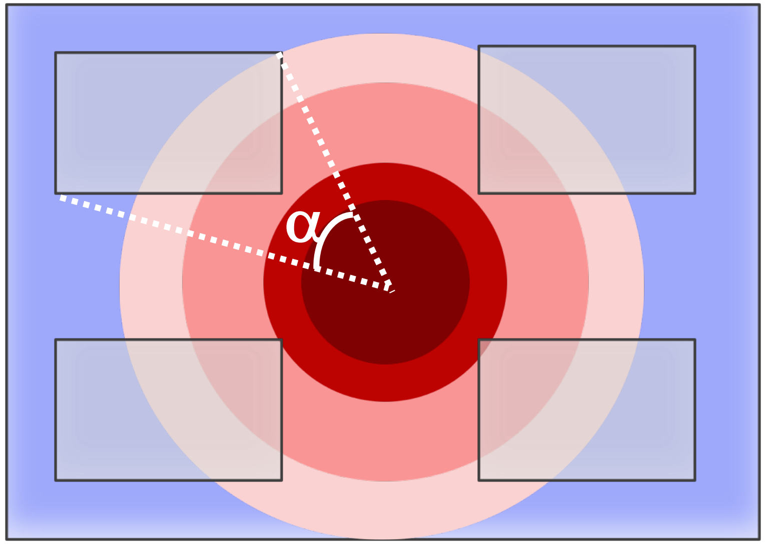
RSD Signal formation: the signal spread along the n++ electrode

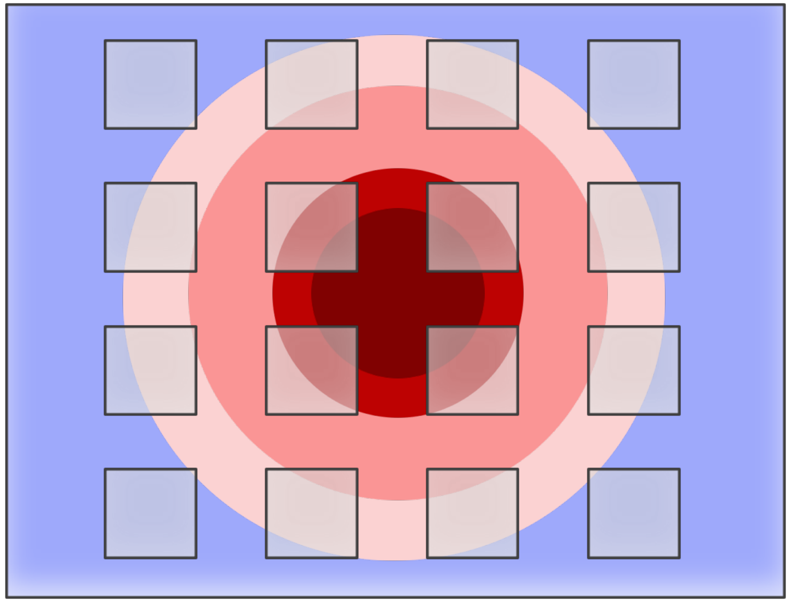
Act 2: The amplitude seen by each pad decreases as a function of the hit distance











The amplitude goes to zero when the distance is about twice the metal,

scaling variable: Distance/Pad size

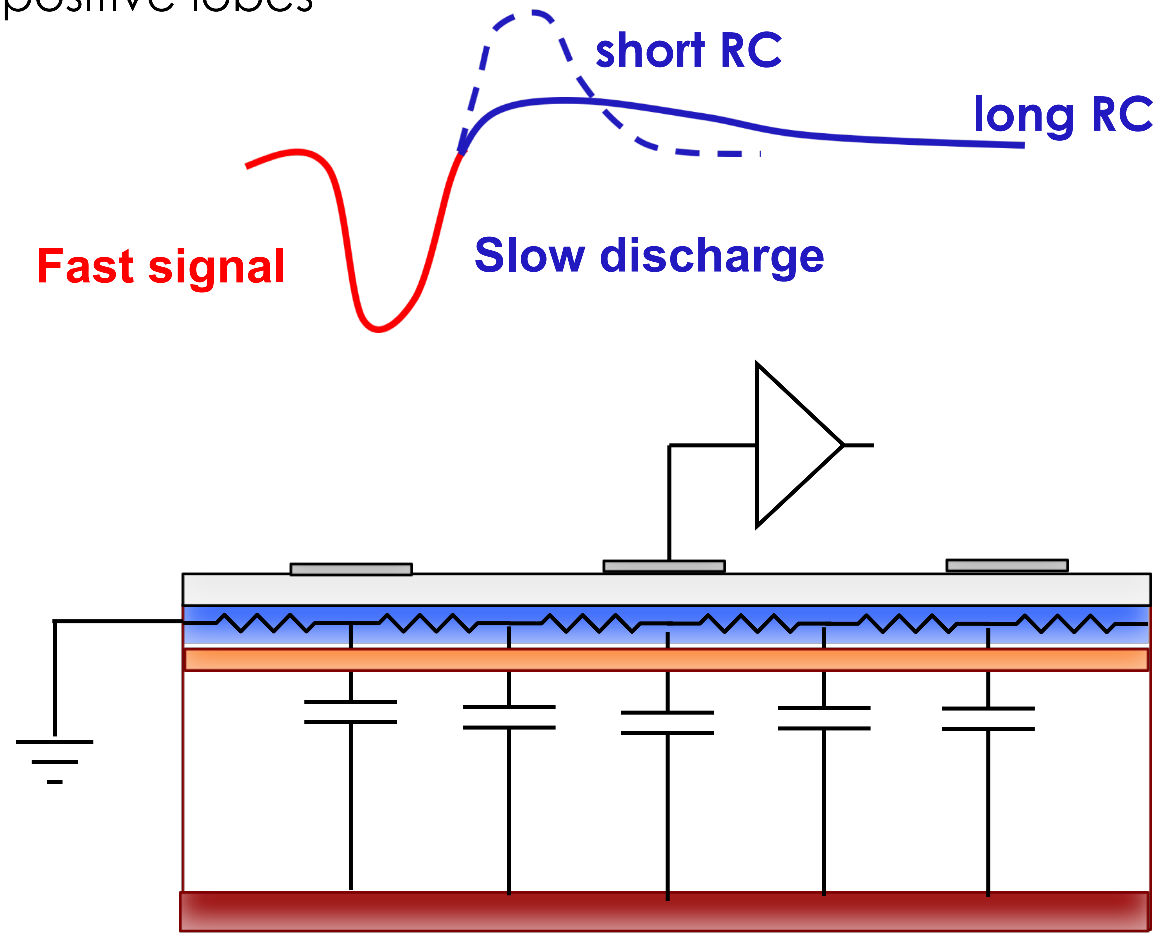
A

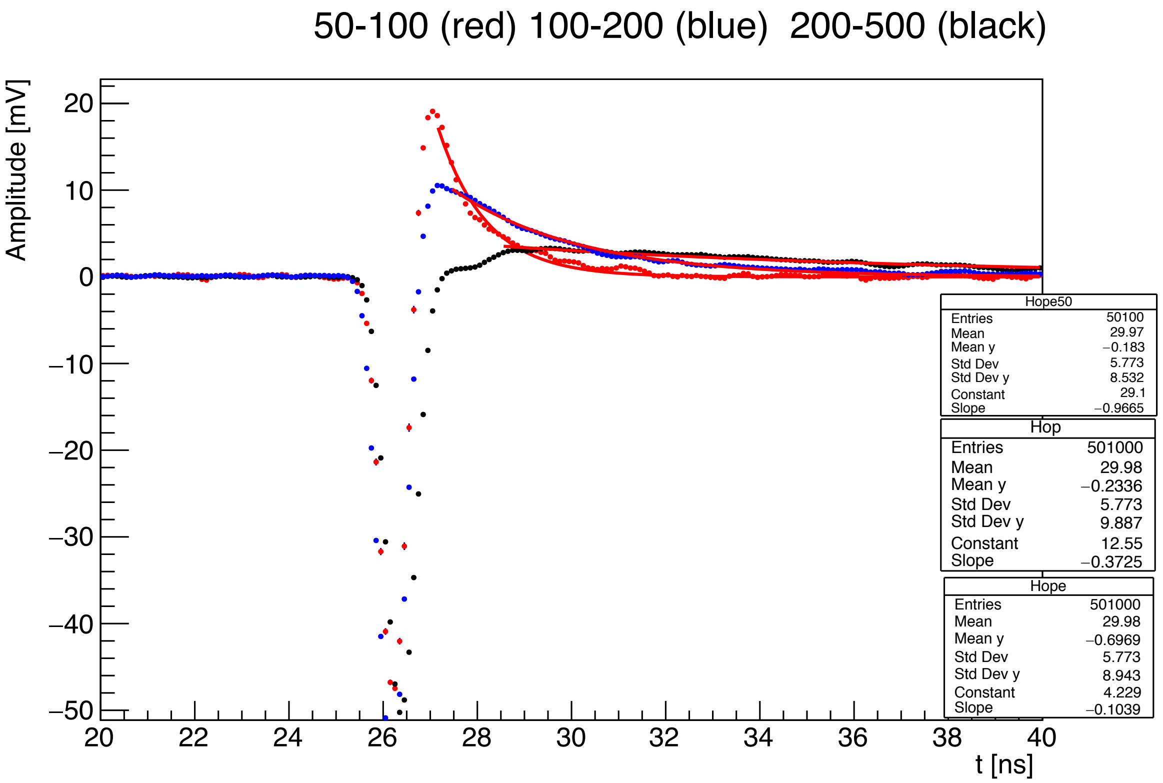
The exploitation of this effect is the key to excellent position resolution. Results will be presented by R. Arcidiacono and G. Paternoster in the next talks.

NC, MT, MM: RSD signal formation

RSD Signal formation: slow discharge

Act 3: the signal discharges, according to the read-out RC. Small RC have larger and shorter positive lobes





Putting things together

Timing: hopefully, good time resolution can be extended up to about 5E15 n/cm^2

Position Sensors at 1E16 – 1E17 n/cm^2 : we are exploring the use of thin Silicon with bulk multiplication. A strong R&D about gain in irradiated detector is needed, too early to make predictions.

Excellent position resolution (<10 um): the AC evolution of LGAD provides natural sharing of signals among several pads. The exploitation of signal sharing is necessary to overcame the rule pitch/sqrt(12)

Conclusions: the requests put forward by the next projects are very challenging. The next 5-10 years are going to be very intense and a lot of fun.

Acknowledgments

We kindly acknowledge the following funding agencies, collaborations:

- INFN - Gruppo V
- Horizon 2020, grant UFSD669529
- Horizon 2020, grant no. 654168 (AIDA-2020)
- U.S. Department of Energy grant number DE-SC0010107
- Dipartimenti di Eccellenza, Univ. of Torino (ex L. 232/2016, art. 1, cc. 314, 337)

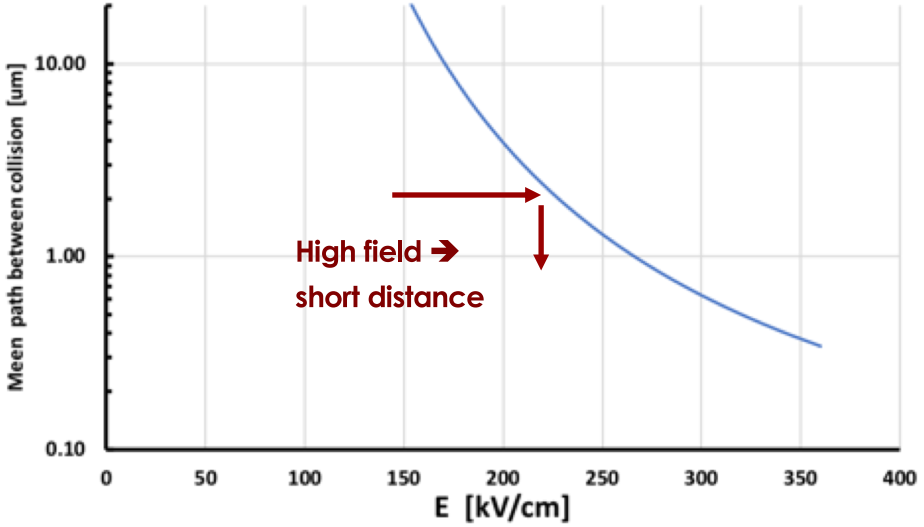
Gain in Silicon

$$G(E,T,\emptyset,d) \propto e^{\alpha(E,T,\emptyset)*d}$$

$\alpha(E,T,\phi)$ impact ionization coefficient

d = length of high E field

$\lambda(E,T,\phi) = \alpha^{-1}(E,T,\phi)$ it is the **mean free path** necessary to achieve multiplication.



1) The distance to acquire enough kinetic energy **is shorter in high E field: higher E field ➔ shorter $\lambda(E,T,\phi)$**

2) The presence of **phonons and/defects create scattering centers, slowing the carriers down:**
Scattering center ➔ longer $\lambda(E,T,\phi)$

3) The effect of the scattering centers can be compensated using higher E field (i.e. shorter mean free path) :
Higher E ➔ compensate scattering center

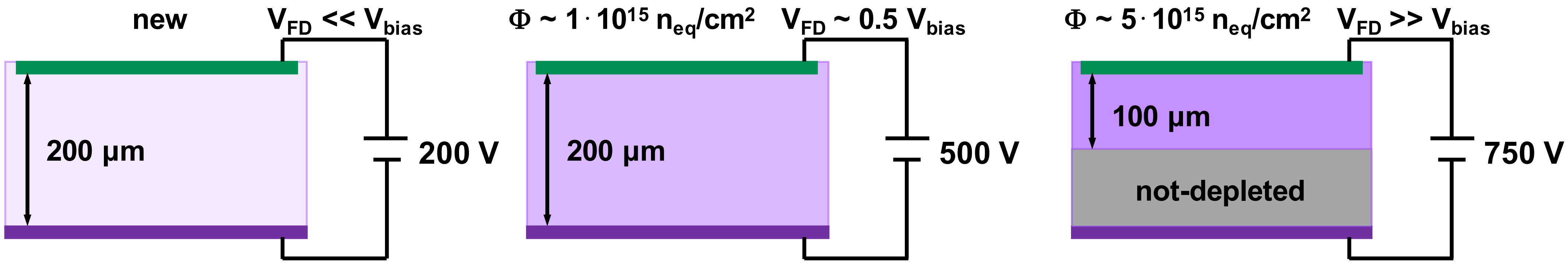
Silicon at fluences about 1E16 – 1E17 n/cm^2

Irradiation causes 3 main effects:

- **Decrease of charge collection efficiency due to trapping**
- **Doping creation/removal**
- **Increased leakage current, shot noise**

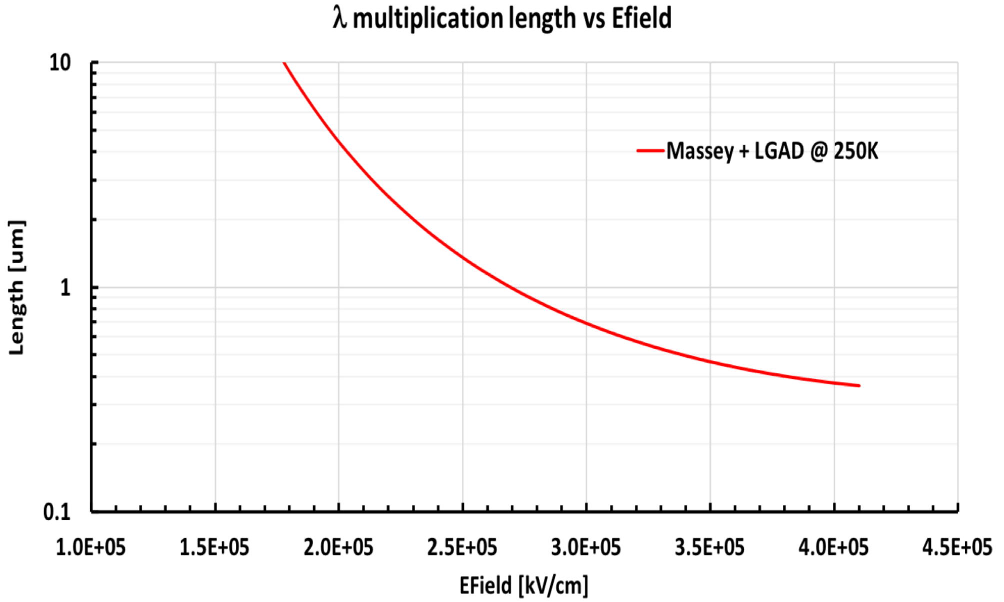
Irradiation models developed in the fluence range 1E14 – 1E15 n/cm2 predict standard silicon detectors (~ 200 um thick) will be almost impossible to operate

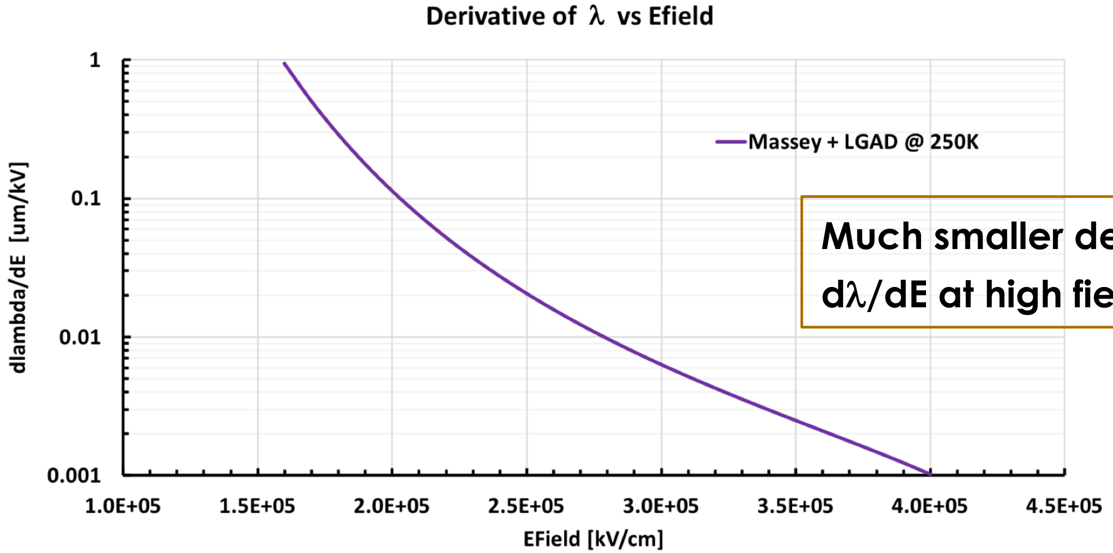
following Gregor's statement @ HSTD12: looks like mission impossible



Fully depleted at low V_{bias} **Fully depleted at high V_{bias}** **Partially depleted at very high V_{bias}**

Higher bias to recover gain





Much smaller derivative dλ/dE at high field

If the gain decreases (for temperature increase or fluence), the bias need to be increased to compensate

$$G \propto e^{\alpha(E,T)*d}$$

$$\alpha \propto e^{-(a+b*T+c*\emptyset)/E}$$

In the "gain model" currently implemented in simulators, there is no explicit dependence on the fluence

➔ need to add a term to quench the gain in irradiated sensors