

# **4D Sensors: Unifying the Space and Time Domain with Ultra-Fast Silicon Detectors UFSD**

Hartmut F.W. Sadrozinski

with

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*SCIPP, Univ. of California Santa Cruz*



# “4D”

Ultra-Fast Silicon Detectors (UFSD) incorporate the time-domain into the excellent position resolution of semiconductor sensors

They provide in the same detector and readout chain

- **ultra-fast timing resolution [10's of ps]**
- **precision location information [10's of  $\mu\text{m}$ ]**

A crucial element for UFSD is the **charge multiplication** in silicon sensors investigated by RD50, which permits the use of **very thin** detectors without loss of signal-to-noise.

Hartmut Sadrozinski, “Exploring charge multiplication for fast timing with silicon sensors”,  
20<sup>th</sup> RD50 Workshop, May 30 to June 2, 2012, Bari, Italy

<https://indico.cern.ch/getFile.py/access?contribId=18&sessionId=8&resId=1&materialId=slides&confId=175330>



# “4D”

**We “just” need 3 items:**

- I. Charge Multiplication**
- II. Thin segmented sensors**
- III. Fast readout**

**2 questions need to be addressed for UFSD:**

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

**In this talk:**

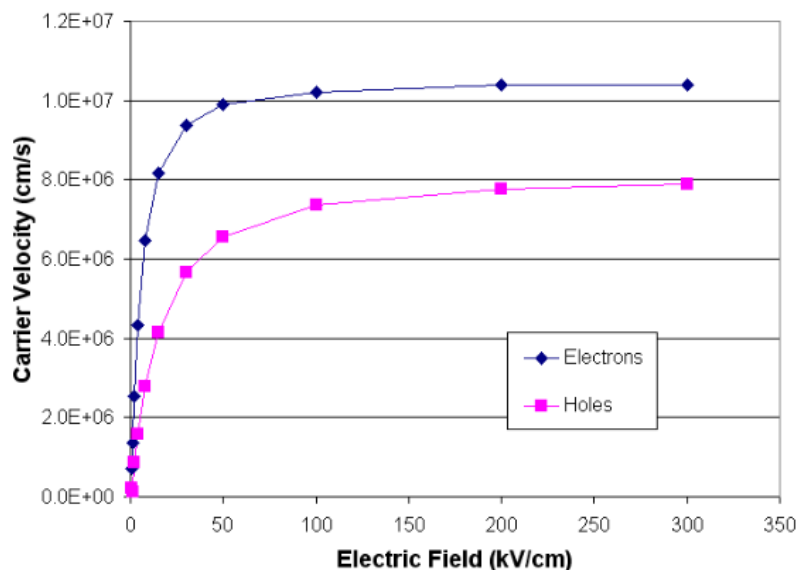
- **Charge collection in thin sensors**
- **Low-Gain Avalanche Detectors (LGAD)**
- **Charge multiplication data on pad detectors**
- **Estimation of Time resolution**
- **Motivation**

# Collection of Charges in Silicon Sensors



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Carrier Drift Velocities in Si at 300K



Drift velocity saturates for both electrons and holes!

-> need thin sensors for fast charge collection

Collection time is close to minimum when  $E\text{-Field} \geq 20 \text{ kV/cm}$

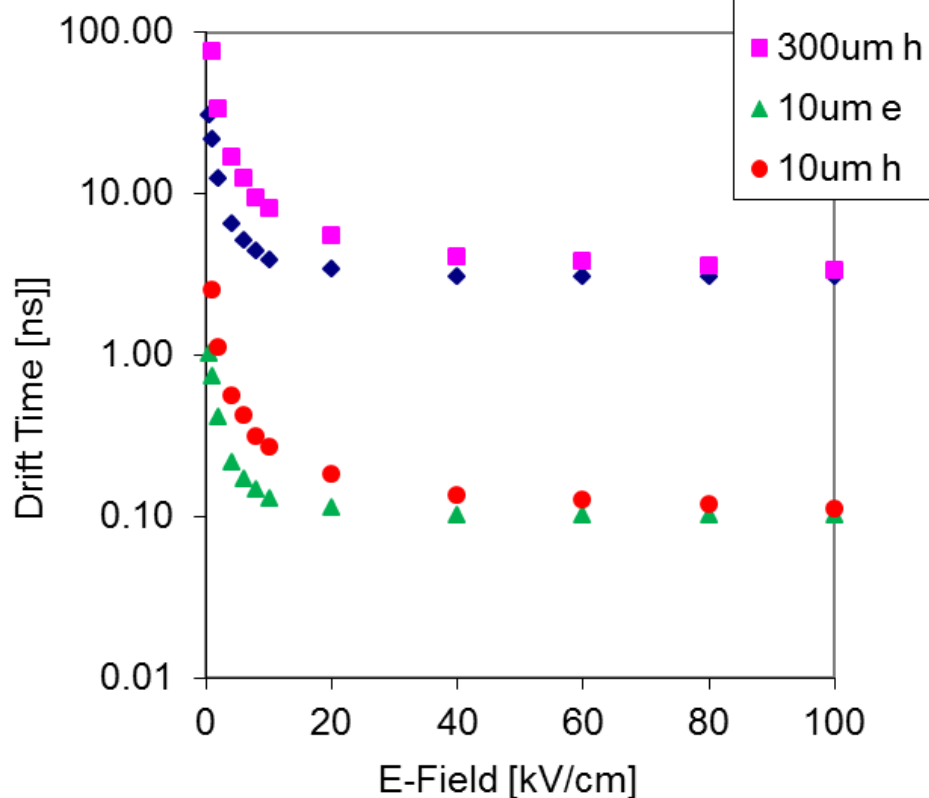
For 300 $\mu\text{m}$  Si

Collection time  $\sim 5 \text{ ns}$  (h),  $\sim 3 \text{ ns}$  (e)

For 10 $\mu\text{m}$  Si

Collection time  $\sim 0.3 \text{ ns}$  (h),  $\sim 0.1 \text{ ns}$  (e)

Drift Time in Si

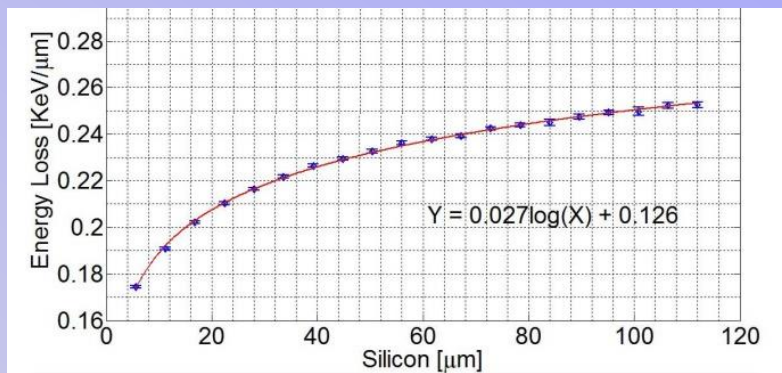




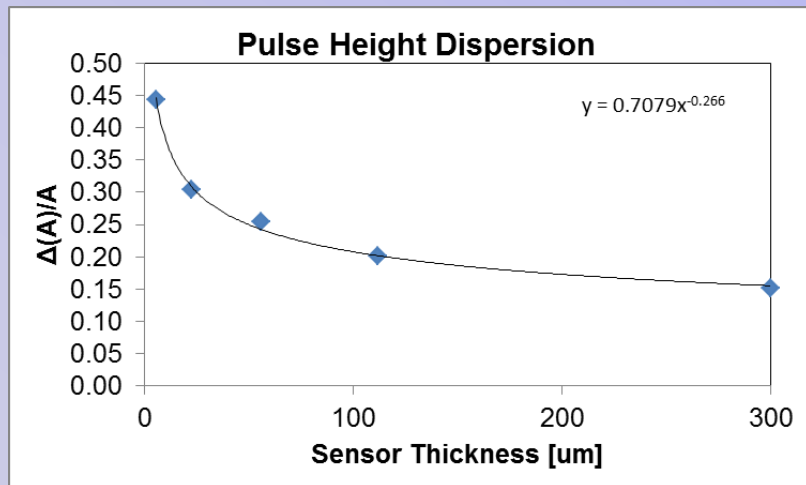
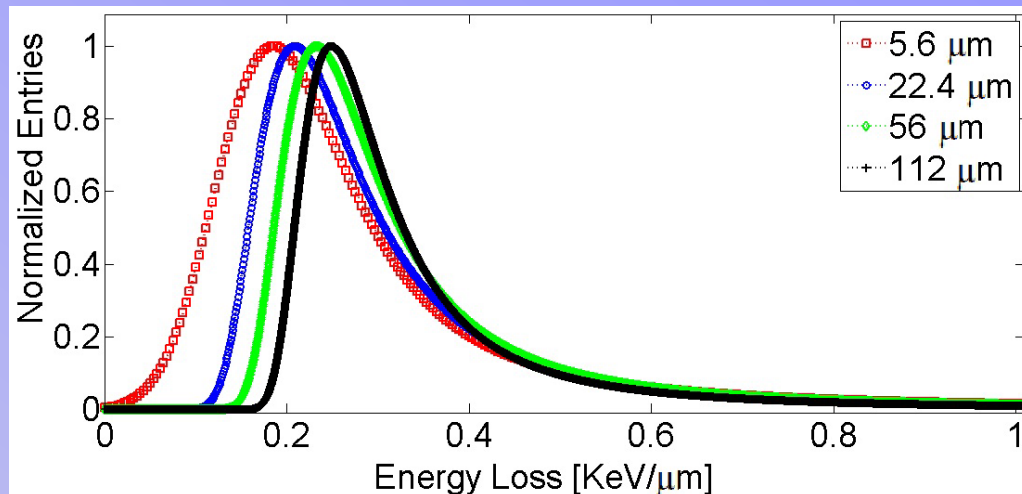
# Details of Collected Charge in Thin Sensors

Energy loss measurement for charged particles in very thin silicon layers

S. Meroli, D. Passeri and L. Servoli 11 JINST 6 P06013



Energy loss for 12GeV protons passing through several si



Charge yield per um  
for very thin silicon sensors::

- Reduced measured MPV
- Increased relative dispersion (see later)



# Can 4D-UFSD work? Correct Collected Charge

Collection time = thickness/ $v_{sat}$  ( $v_{sat} = 80 \mu\text{m/ns}$ ) (holes)

Realistic gain & cap



Good time resolution



| Thickness<br>[um] | BackPlane Capacitance |                | Signal<br>[# of e-] | Coll. Time<br>[ps] | Gain required |             |
|-------------------|-----------------------|----------------|---------------------|--------------------|---------------|-------------|
|                   | Pixels [fF]           | Strips [pF/mm] |                     |                    | for 2000 e    | for 12000 e |
| 1                 | 250                   | 5.0            | 35                  | 13                 | 57            | 343         |
| 2                 | 125                   | 2.5            | 80                  | 25                 | 25            | 149         |
| 5                 | 50                    | 1.0            | 235                 | 63                 | 8.5           | 51          |
| 10                | 25                    | 0.50           | 523                 | 125                | 3.8           | 23          |
| 20                | 13                    | 0.25           | 1149                | 250                | 1.7           | 10.4        |
| 100               | 3                     | 0.05           | 6954                | 1250               | 0.29          | 1.7         |
| 300               | 1                     | 0.02           | 23334               | 3750               | 0.09          | 0.5         |

For pixel thickness > 5 um, Capacitance to the backplane  $C_b < C_{int}$  (200 fF)

For pixel thickness = 2 um,  $C_b \sim \frac{1}{2}$  of  $C_{int}$ , and we might need bipolar (SiGe)?

Viable sensor thickness 2  $\mu\text{m}$  – 10  $\mu\text{m}$  (i.e. 20-100 ps)

Needed Gain: **4 – 25** for pixels, **20- 150** for 1 mm strips

(much less than APD's or SiPM)

**Note: CNM (Barcelona) and HLL (Munich) have been producing ~10  $\mu\text{m}$  thick sensors.**



# Charge Multiplication

A. Macchiolo, 16th RD50 Workshop Barcelona, Spain, May 2010

Charge multiplication in path length  $\ell$  :

$$N(\ell) = N_0 * \exp(\alpha * \ell) = g * N_0$$

$$\alpha_{e,h}(E) = \alpha_{e,h}(\infty) * \exp\left(-\frac{b_{e,h}}{|E|}\right)$$

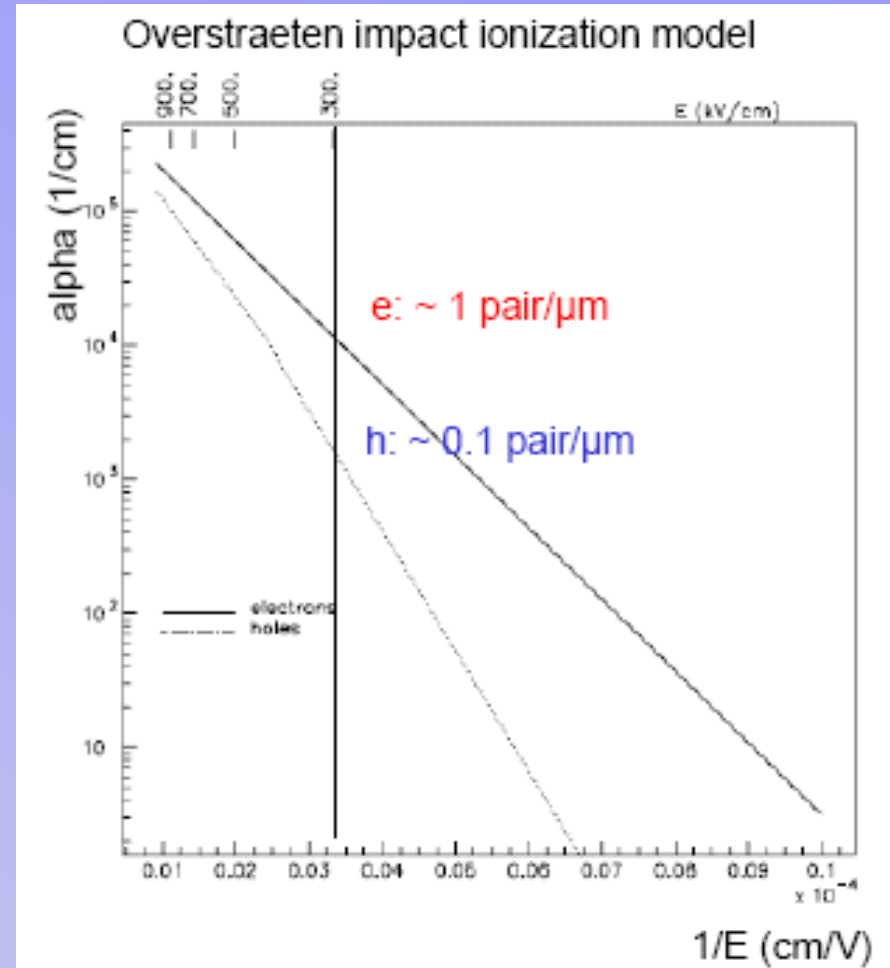
At the breakdown field in Si of 270kV/cm:

$$\alpha_e \approx 0.7 \text{ pair}/\mu\text{m}$$

$$\alpha_h \approx 0.1 \text{ pair}/\mu\text{m}$$

→ gain  $g = 33$  possible in  $l = 5 \mu\text{m}$ .

→ In the linear mode (gain  $\sim 10$ ), consider electrons only



**Need to raise E-field as close to breakdown field as possible for high gain but not too much to prevent breakdown!**



# Development of Si sensors with gain (RD50)

See Giulio Pelligrini's talk

RD50 Groups have been investigating charge multiplication (CM) in heavily irradiated silicon sensors.

Un-irradiated sensors manufactured without drastic changes to the doping profile exhibit very little gain before breakdown.

**RD50 Common Project to manufacture Low-Gain Avalanche Detectors (LGAD) based on the principle of SiPM or APD, but with moderate gain.**

Principle:

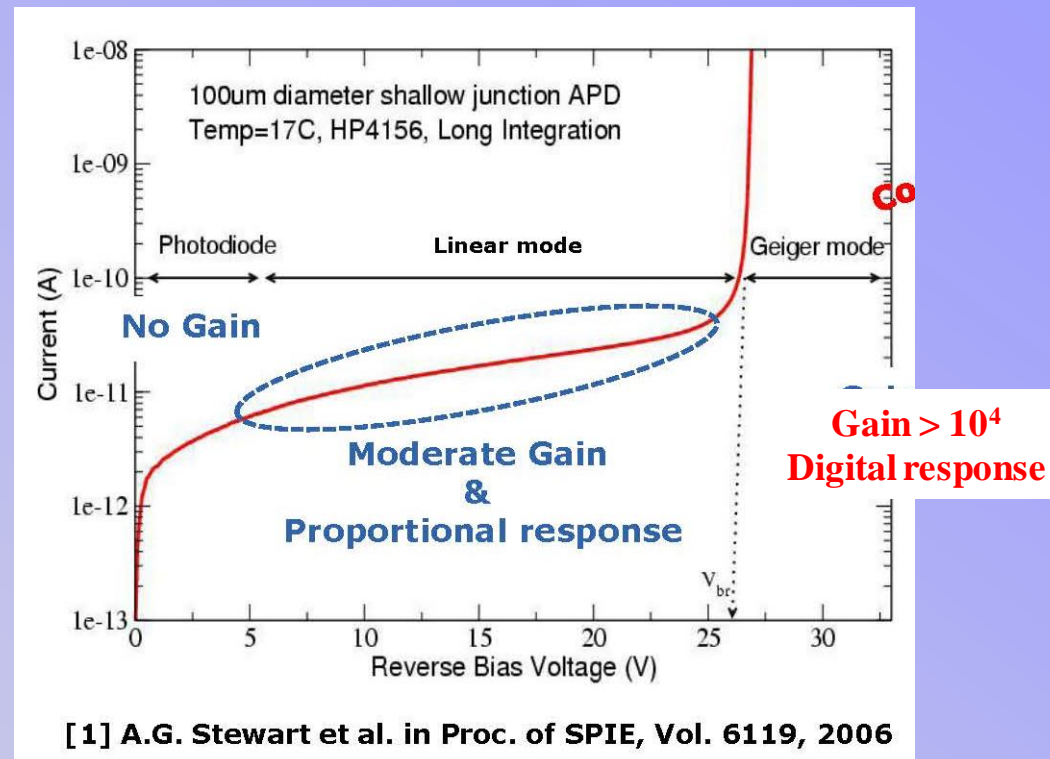
Deep n-implants and extra p-layer increase the E-field so that **moderate** charge multiplication occurs without breakdown.

**CNM Barcelona**

First step: Pad detectors/simple diodes

- verify gain,
- optimize parameters
- radiation hardness

Second step: strip/pixel sensors

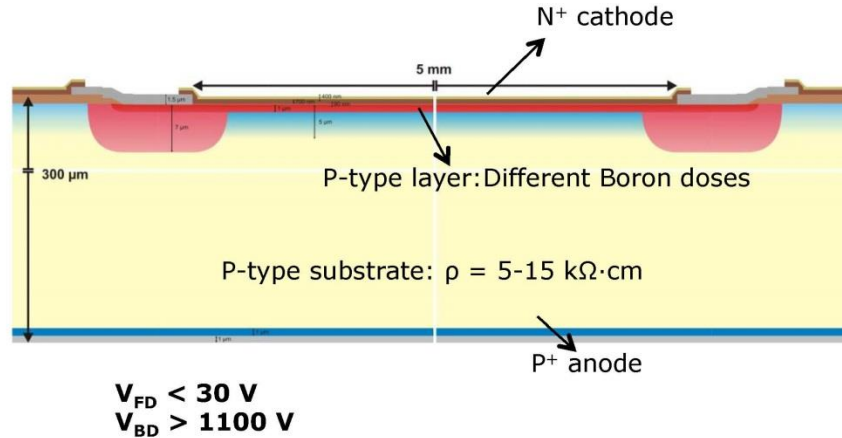




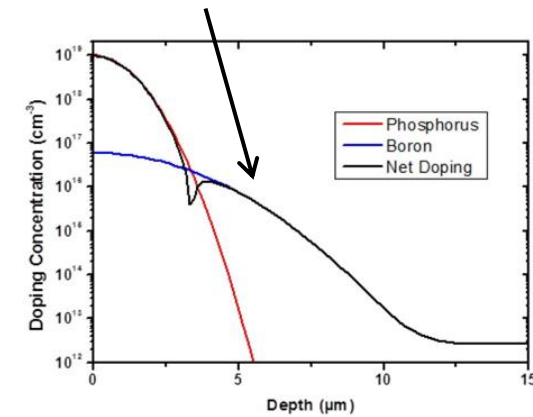
1. Thin p-type epitaxial substrates
2. Low gain avalanche detectors

# Pads detectors with multiplication

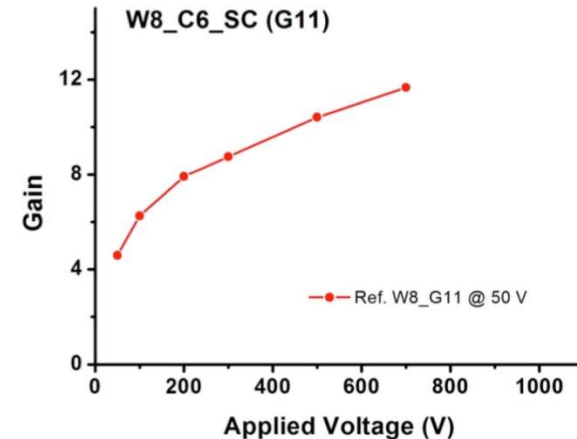
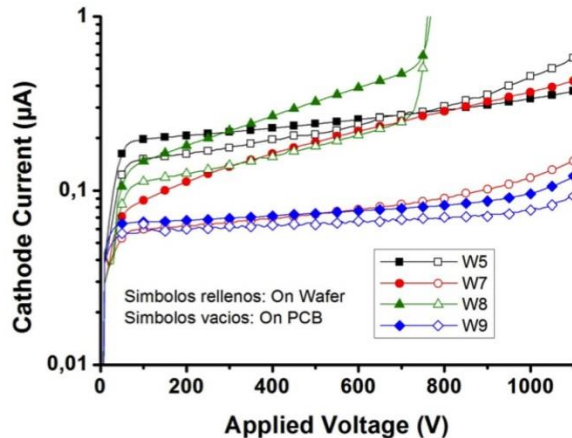
## Low-Gain Avalanche Detector (LGAD)



## High-Field: Gain



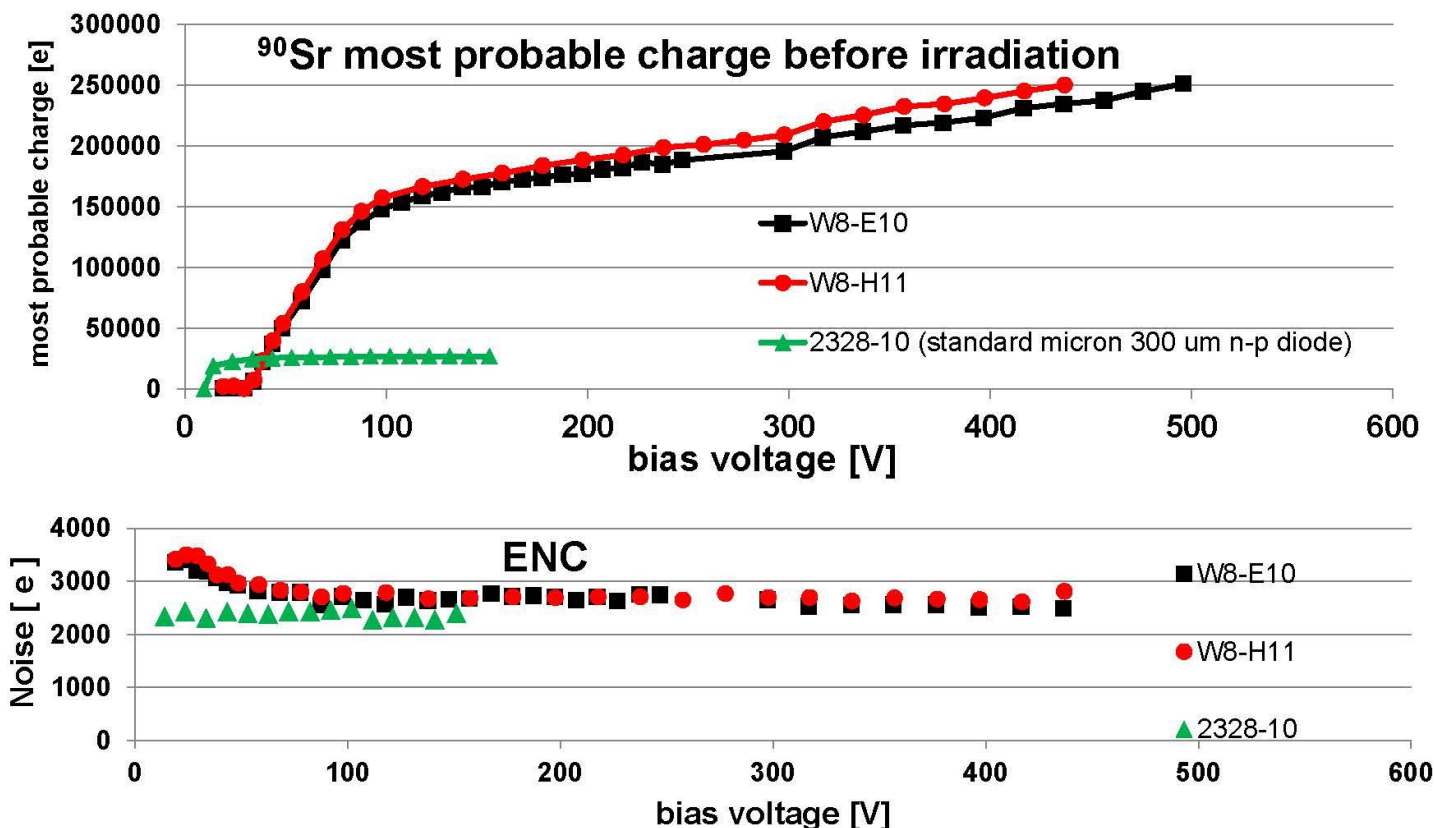
Marta Baselga,  
Trento Workshop  
Feb. 2013





# Gain with MIP's

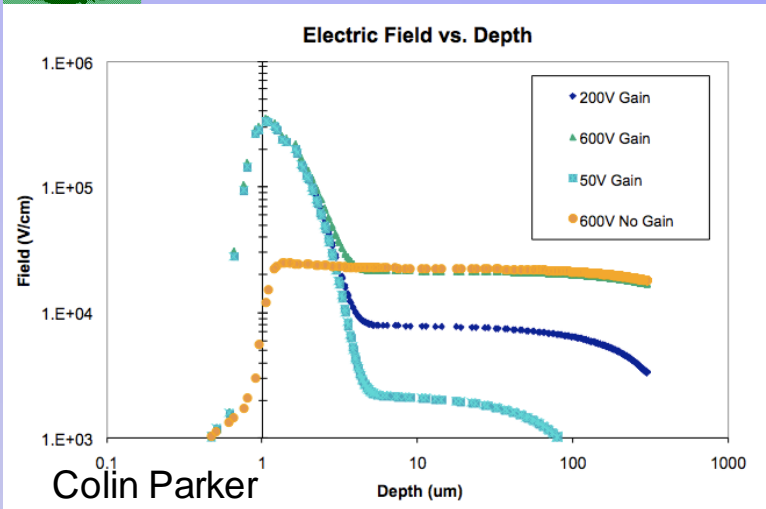
## Most probable signal and noise



- Improvement of signal **for a factor 8 at 300 V** before irradiation
- No significant increase of noise – dominated by series noise

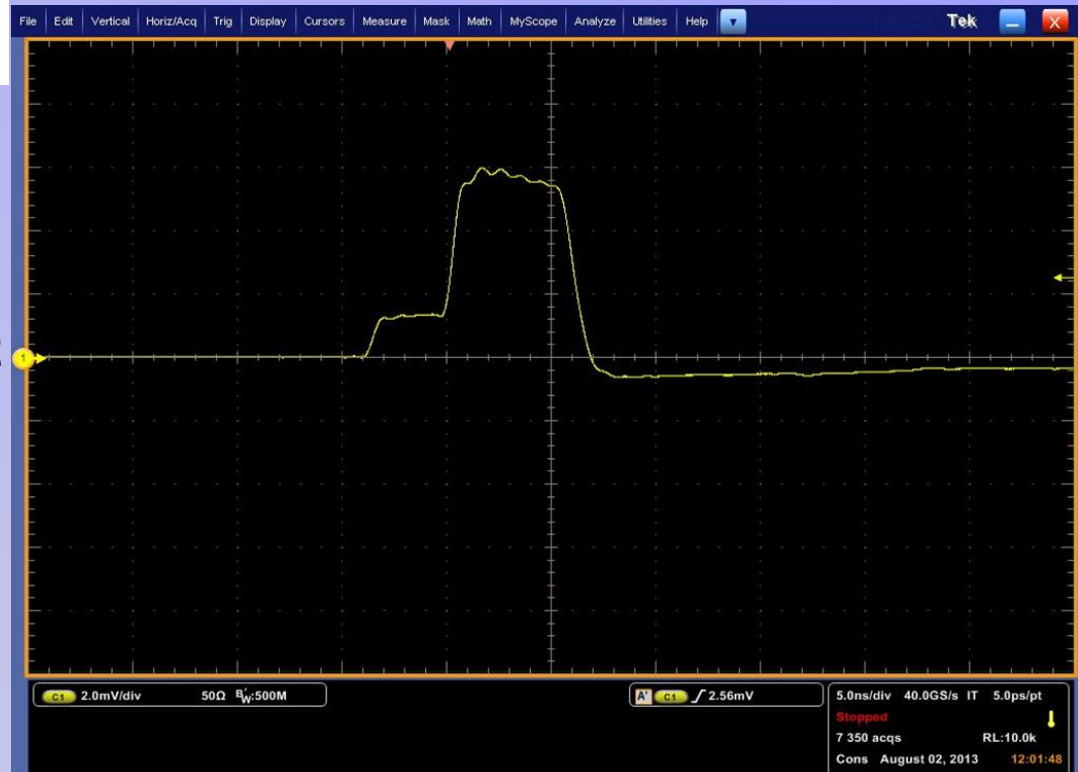


# Charge Collection with $\alpha$ 's from Am(241)



$\alpha$ 's  
←  
←  
←  
←

**Am(241)**  
illuminating the back side,  
range ~ few  $\mu\text{m}$ 's  
“electron injection”  
signal drifts and is then  
amplified in high field



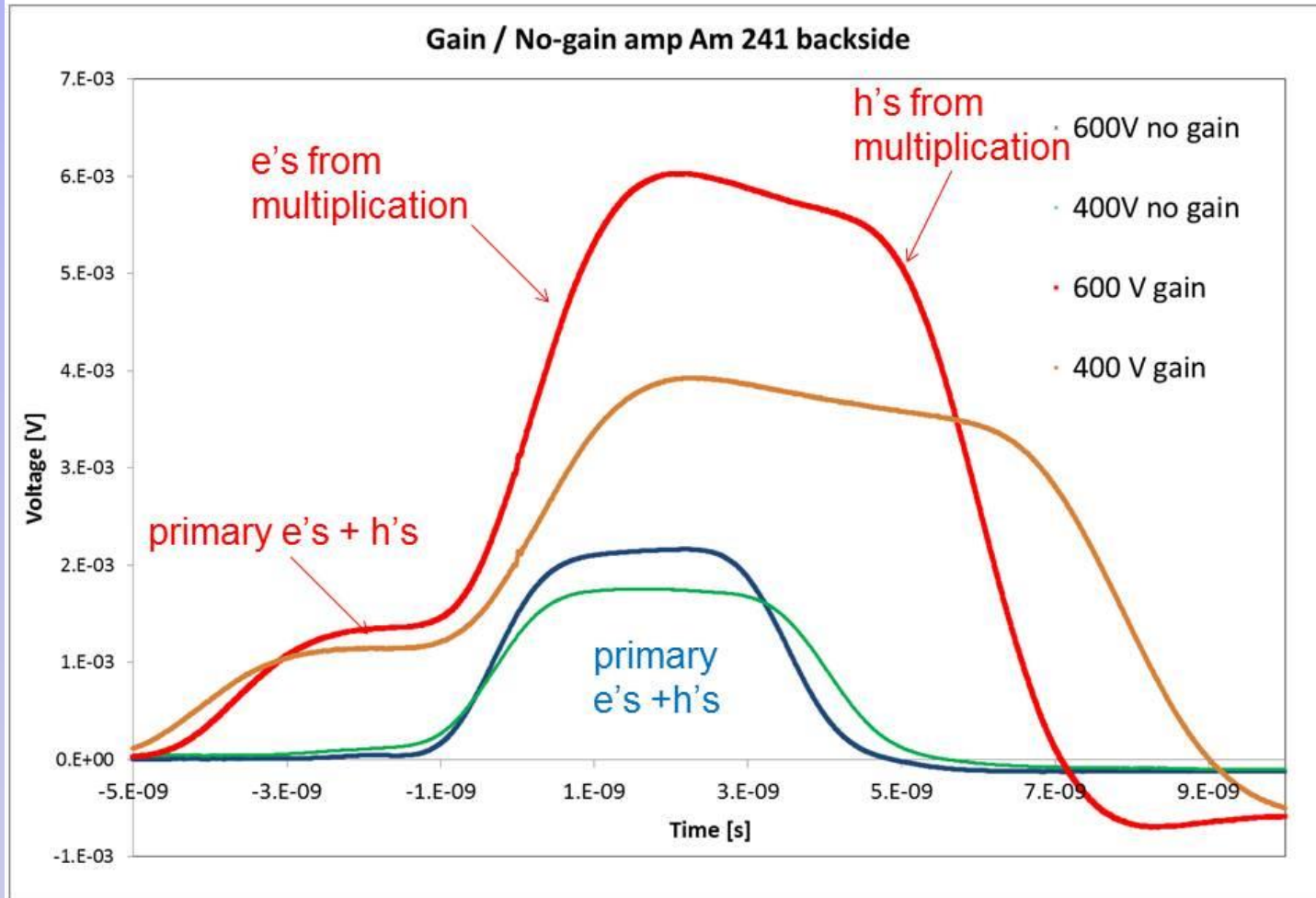
**Fast signals!**

**Observed rise times  $\approx 400$  ps  
allowing time-resolved current  
transient (TCT) analysis .**

**Don't know yet where the  
lower limit is, since we are still  
improving the BW of the  
system.**



# Observed TCT shapes from $\alpha$ 's



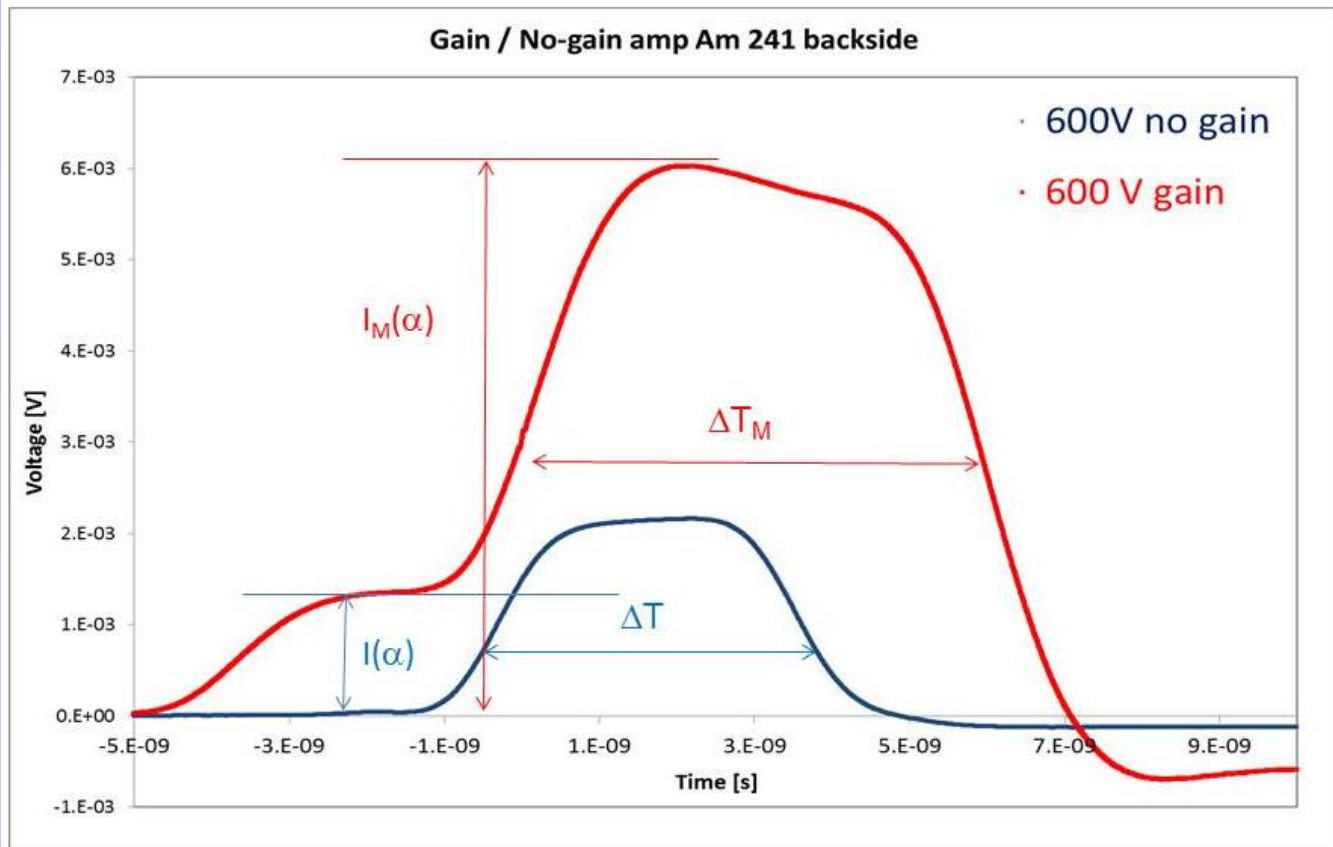
Total collection time =  
 $\Sigma$  of drift times of primary e's and of h's from multiplication



# Estimation of Gain with $\alpha$ TCT

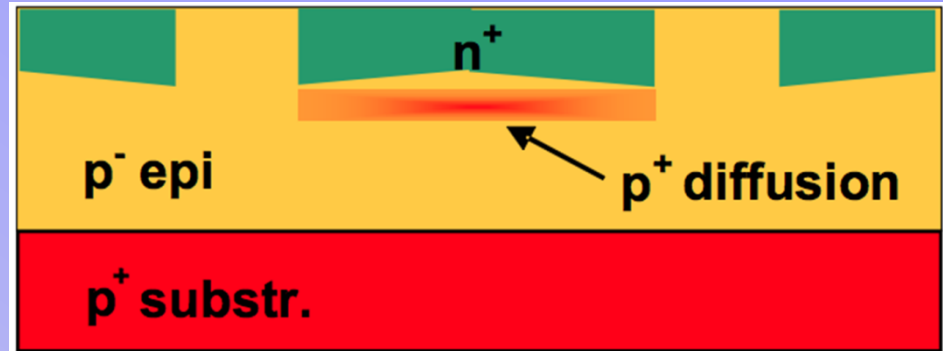
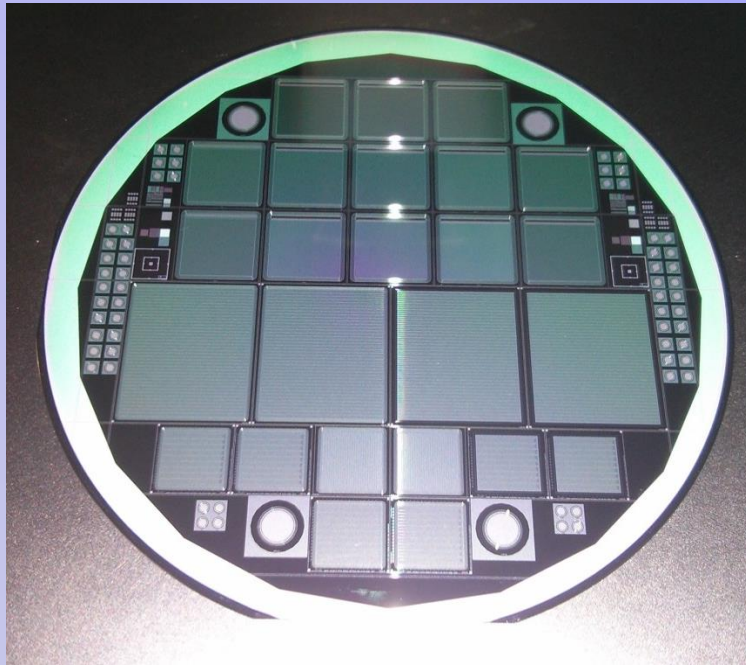
$$\text{Total Gain} = I_M(\alpha) / I(\alpha) * \Delta T_M / \Delta T \sim 5 * 2 = 10$$

(N.B.: For thin sensors, both  $\Delta T_M$  and  $\Delta T$  are shortened)





# From pads to strips and pixels



## New CNM production (RD50) 14 p-type wafers

| Thick<br>( $\mu\text{m}$ ) | Resistivity<br>( $\Omega\text{cm}$ ) | Substrate<br>resistivity ( $\Omega\text{cm}$ ) | Substrate<br>thickness ( $\mu\text{m}$ ) |
|----------------------------|--------------------------------------|--|--|
| 9.8                        | 110.5                                | 0.006  | 525                                      |
| 50.4                       | 96.7                                 | 0.006  | 525                                      |
| 75.2                       | 104.6                                | 0.006  | 525                                      |
| 285 (FZ)                   | 12000 $\pm$ 7000                     |  |  |

Width/Pitch varies from 0.3 to 0.8



# Fast Rise Time Sensors for Timing

Why thin sensors for fast timing? Thin sensors allow fast rise time because of the fast collection time. But their S/N is reduced.

Why not use thick sensors, and collect only the early part of the electrons or integrate the charge over longer time, reduce noise and trigger low on the rising pulse, like in LHC pixel sensors?

In general: induced pulse development is fairly complicated (i.e. bipolar pulses in neighboring strips, possibility of increased “cross-talk”) so shaping at the collection time seems to be a safe thing to do.

## Time resolution due to noise and time walk (amplitude dispersion of Landau):

Assume pulse of amplitude  $A$  with dispersion  $\Delta A$ , electronic noise  $\sigma_A$  and rise time  $\tau_R$  :

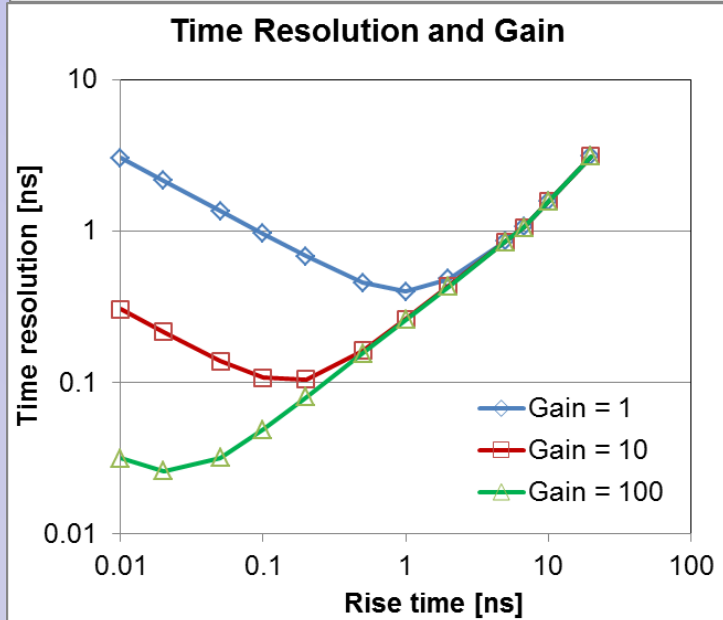
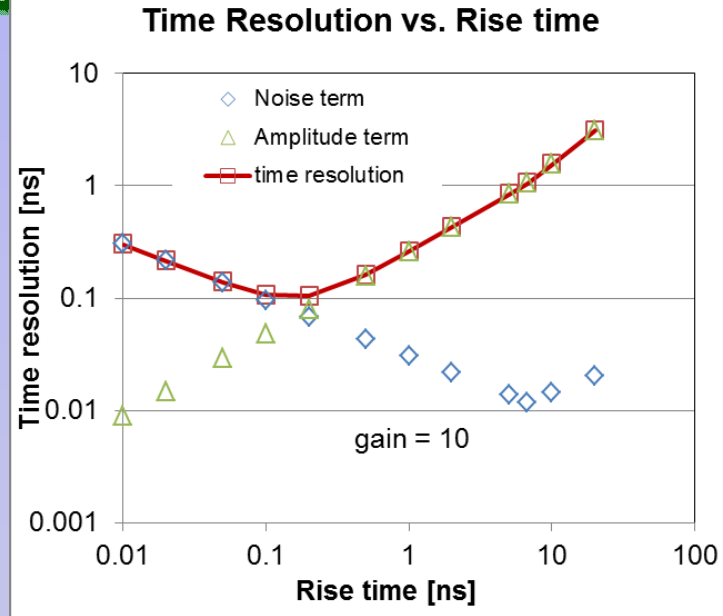
$$\sigma_t = \left[ \left( \frac{\sigma_A}{\partial A} \right)^2 + \left( \frac{\Delta A}{\partial A} \right)^2 \right]^{1/2} \approx [(\sigma_A)^2 + (\Delta A)^2]^{1/2} \frac{1}{A} \tau_R$$

$$\sigma_A \sim \frac{1}{\sqrt{\tau_R}}, \quad \Delta A = f * A \quad \sigma_t \approx \left[ \left( \frac{\sigma_A}{A} \tau_R \right)^2 + \left( \frac{\Delta A}{A} \tau_R \right)^2 \right]^{1/2} = \left[ \left( \frac{1}{S/N} \tau_R \right)^2 + \left( \frac{\Delta A}{A} \tau_R \right)^2 \right]^{1/2}$$

For fast shaping, thin sensors: amplitude  $A \sim \tau_R$ , for  $\tau_R \leq 8\text{ns}$ ,  $f = 0.16 - 0.4$

# Time Resolution vs. Rise Time & Gain

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Assumes

S/N = 100 @ 20ns shaping  
like at LHC (before gain)

Shaping time dependence of noise :  $1/\sqrt{\tau}$

A gain of 10 (100) results in  
a time resolution of ~100 (30) ps

Improvement of noise

-> thinner sensors

Improvement of time walk

-> thicker sensors

Hopefully Angelo Rivetti will tell us  
how to improve on this with a  
Constant-Fraction-Discriminator  
CFD

Stay tuned for pulse and SPICE  
simulations.





# Integrated Circuit Design for Time-of-Flight PET with Silicon Photomultipliers

Manuel Dionisio Rolo, Angelo Rivetti, Ricardo Bugalho,  
Carlos Gastón, Gianni Mazza, Richard Wheadon,  
Jose Carlos da Silva, Rui Silva, Joao Varela

LIP - Laboratorio de Instrumentação e Física Experimental de Partículas  
INFN - Istituto Nazionale di Fisica Nucleare sez. Torino

"The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/ 2007-2013) under Grant Agreement n°256984."

8th "Trento" Workshop on Advanced Silicon Radiation Detectors  
(3D and p-type)

February 18-20 2013, FBK Trento, Italy





# 4D Sensors: Unifying the Space and Time Domain with Ultra-Fast Silicon Detectors UFSD

**Sensor Production:** CNM Barcelona

**Sensor Testing:** UC Santa Cruz, Freiburg U., Florence U., SJI Ljubljana, Trento U.

**Readout ASIC:** INFN Torino, UC Santa Cruz,

**Data Acquisition DAQ:** HEPHY Vienna





# Conclusions

Timing precision in silicon sensors has been the Cinderella (before meeting the prince) of instrumentation, in contrast to photon detectors. (Sherwood Parker has been the only voice in the wilderness).

With Ultra-Fast Silicon Detectors we want to reach the same happy ending as the fairy tale!

## **We made quite a lot of progress in one year:**

- |                            |  |
|----------------------------|--|
| I. Charge Multiplication   | Achieved gain 10 -15 with pad detectors  |
| II. Thin segmented sensors | Received 10 um – 75 um epi strips/pixels |
| III. Fast readout          | Area of next big push                    |



# Acknowledgments

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This work was carried out in the framework of RD50 Common Projects and funded by the US Dept. of Energy.

Special thanks to Giulio Pellegrini and Salvador Hidalgo (CNM) for expert design and production of LGAD, and Gregor Kramberger for expert CCE and TCT measurements.

Thanks to Harris Kagan for telling me over and over again that Silicon is not perfect, and to Abe Seiden and Nicolo Cartiglia for asking me if that can be true..



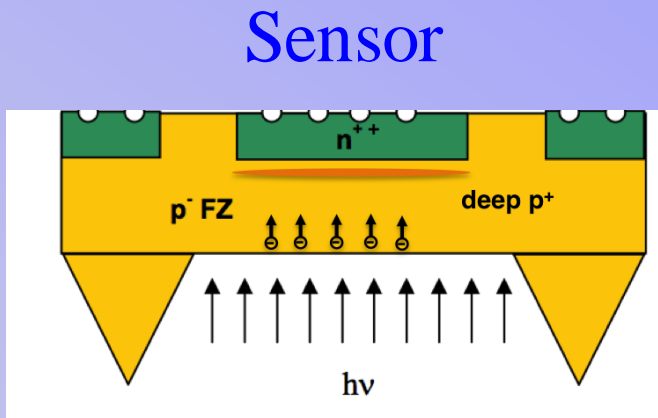
# More Applications for 4D UFSD

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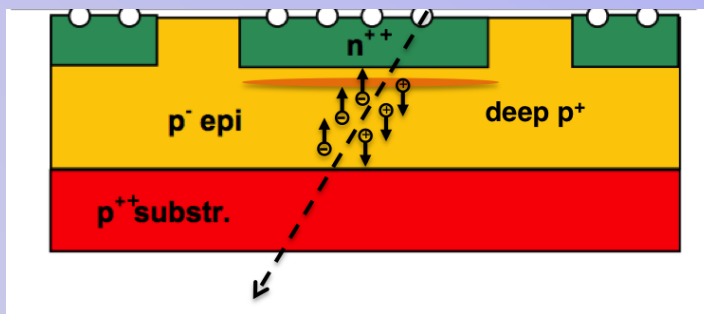


# Thin 4D Sensors

Thinned FZ sensors with “ribs” for strength (HLL-MPI, CNM): even photons



Epitaxial sensors  
Ideal for prototyping



## ASIC

Position and Energy

Position and Time

Counter Chip



# Motivation for 4D Detectors

- Up to now, semiconductor sensors have supplied precision data only for the 3 space dimensions (diodes, strips, pixels, even “3D”), while the time dimension has had limited accuracy (e.g. to match the beam structure in the accelerator).
- We believe that being able to resolve the **time dimension with ps accuracy** would open up completely new applications not limited to HEP
- An example in HEP are forward physics projects at the LHC, like the AFP. Scattered protons are tracked from stations 100’s of meters downstream back to the interaction region and the z-vertex is determined from the timing information. A **time resolution of 10ps** results in a resolution in the vertex resolution of 3 mm. 4D sensors can give the required good resolution both in position resolution and timing in one sensor, while at the moment two different detector technologies are required (e.g. pixels and Micro-channel plates).
- **Proposal: Combined-function pixel detector will collect electrons from thin n-on-p pixel sensors read out with short shaping time electronics.**
- 4D sensors rely **on internal charge multiplication** to increase the collected signal





# Benefits of Ultra-Fast Silicon Detectors

- **Tracking:** Identifying with high precision the temporal signature of different events allows for their association and it reduces random coincidences. Traditional tracking is often overwhelmed by combinatorial backgrounds, which can be dramatically reduced by adding a 4th dimension (time) per point.
  - **Vertex Locator:** Forward physics in AFP (ATLAS) and HRS (CMS)
  - **Time of Flight (ToF):** ToF is already used in many commercial applications such as ToF-enhanced PET and Mass Spectroscopy ToF, however with precision one order of magnitude higher than the goal of UFSD ( $\sim 500$  ps vs.  $\sim 50$  ps). ToF is also used in particle physics as a tool for particle identification.
  - **ToF can also be used in 3D and Robotic Vision:** the ability to accurately measure the travel time of light pulses reflected by an object at unknown distance is of paramount importance to reconstruct 3D images, fundamental in imaging and robotic vision. UFSD will offer a spatial precision of a few mm at low illumination power, allowing for battery operated, portable systems.
  - **Particle counting:** UFSD performance would allow developing new tools in single particle counting applications with unprecedented rate capabilities. For example, in the treatment of cancer using hadron beams, such a tool would measure the delivered dose to patients by directly counting the number of hadrons.
- Material science experiments using soft x-rays will benefit from the combination of high rate and precision location that UFSD offers.

# Internal Gain in Detectors



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- Charge multiplication (CM) in silicon sensors (investigated by RD50 institutions) can have much wider applications than off-setting charge lost due to trapping during the drift of electrons or holes in irradiated sensors.
- 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.

## Recall our experience with DC:

- Need to balance the need of high E-field around a wire to have charge multiplication with the need to keep the E-field low to prevent breakdown (wire diameter, field shaping wires,..) and give proper drift field.
- The drifting electrons contribute mainly to the collected charge after they have undergone charge multiplication, which means that the pulse develops (in principle) in a short time.
- The very large charge density in the “plasma cloud” prevents the electron to move until the ions have drifted away! So electron signal is given by hole dynamics!?

## Basic question for use of CM

- **What field strength do we need?**
- **Can the sensor geometry and doping profile be engineered so that the amplification field can be kept high, but just below the breakdown field?**

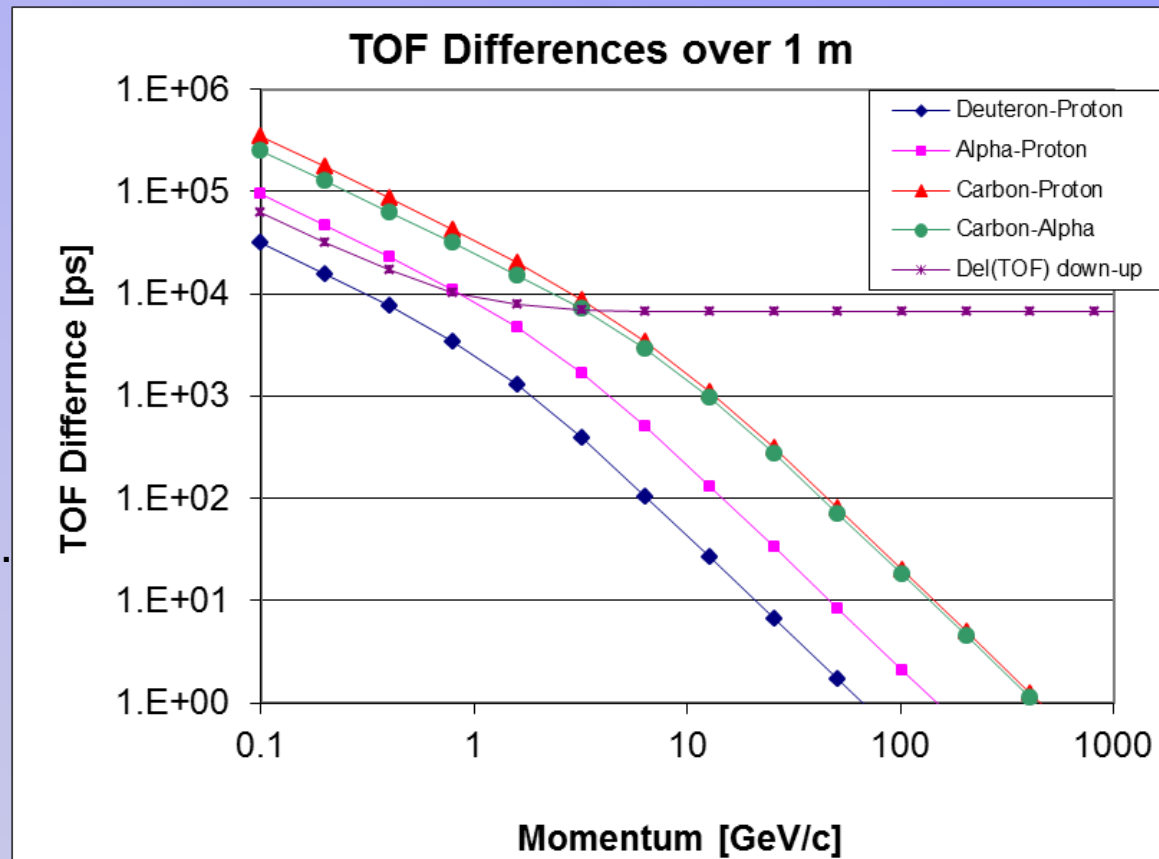


# Time of Flight for Particle Identification in Space.

The Alpha Magnetic Spectrometer (AMS) detector, operating in the International Space Station since 2011, performs precision measurements of cosmic ray composition and flux.

The momentum of the particles is measured with high-resolution silicon sensors inside a magnetic field of about 1 m length.

A time resolution of 10 picoseconds, the “Holy Grail” of Cosmic Ray Physics: the distinction between anti-carbon ions and anti-protons can be achieved up to a momentum of 200 GeV/c.



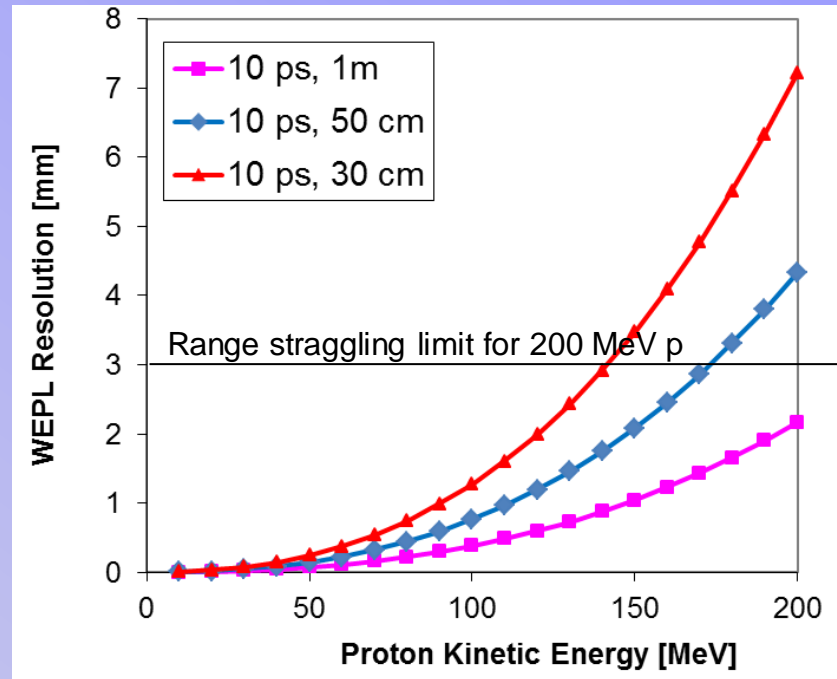
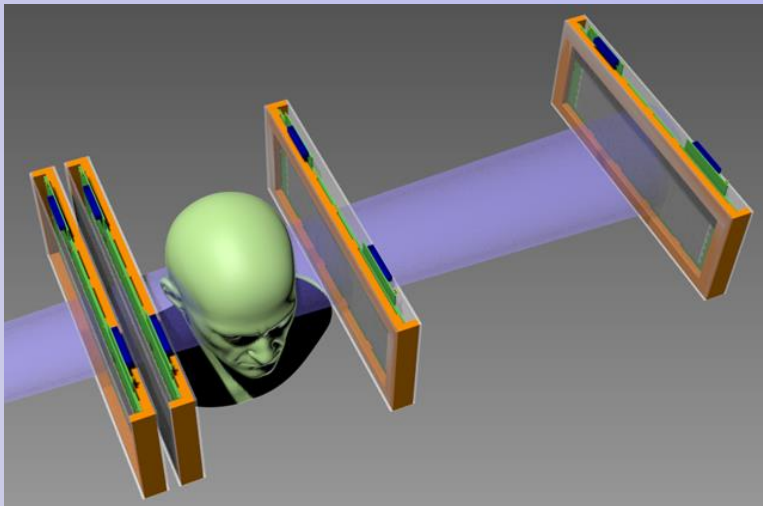
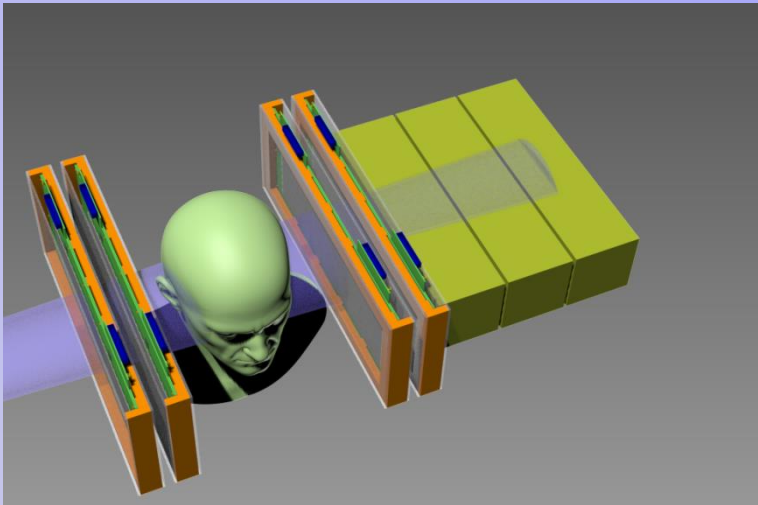


# Future: 4-D Ultra-Fast Si Detectors in pCT

Protons of 200 MeV have a range of  $\sim 30$  cm in plastic scintillator. The straggling limits the WEPL resolution.

**Replace calorimeter/range counter by TOF:**

Light-weight, combine tracking with WEPL determination



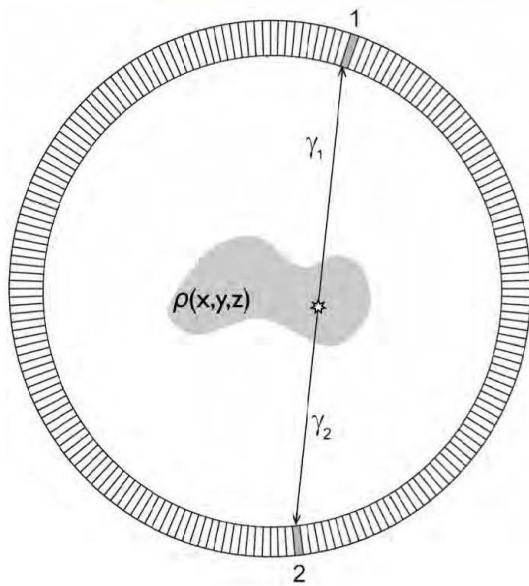


# Positron Emission Tomography PET

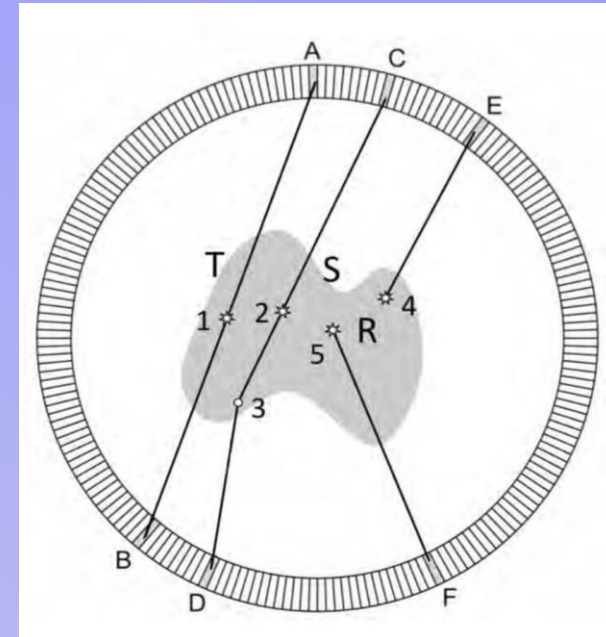
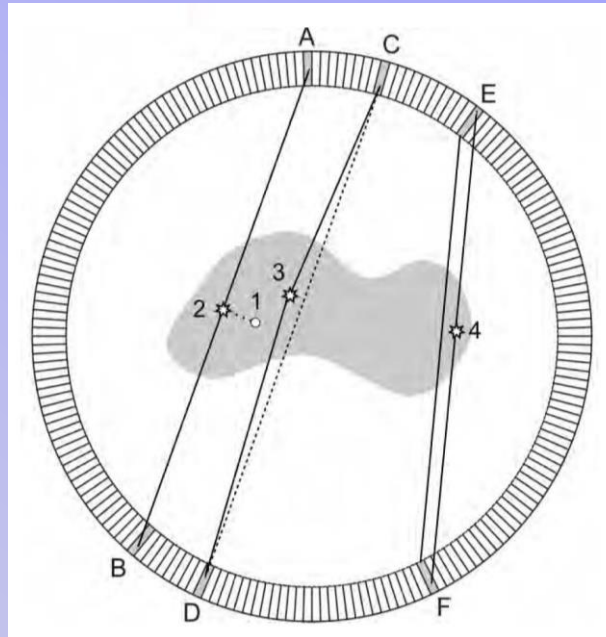
Study accumulation of radioactive tracers in specific organs.

The tracer has radioactive positron decay, and the positron annihilates within a short distance with emission of 511 keV  $\gamma$  pair, which are observed in coincidence.

Perfect Picture:



Resolution and S/N Effects:



$$FWHM = 1.2 \sqrt{\left(\frac{d}{2}\right)^2 + b^2 + (0.0022D)^2 + r^2 + p^2}$$

|         |                                  |
|---------|----------------------------------|
| 1.2     | from analytical algorithm (FBP)  |
| d/2     | from the detector pitch          |
| b       | from the coding                  |
| 0.0022D | from the 2 photon a-collinearity |
| r       | from the positron range          |
| p       | from parallax                    |

Resolution of detector (pitch)  
 Positron range  
 A-collinearity  
 Parallax (depth)

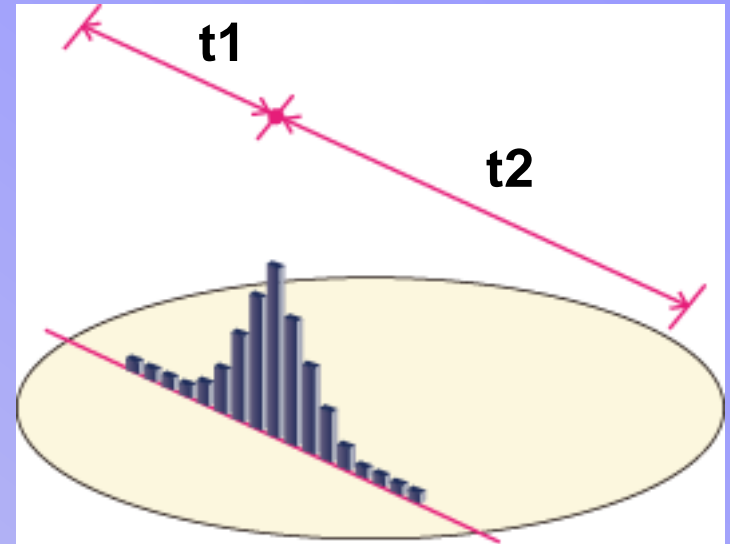
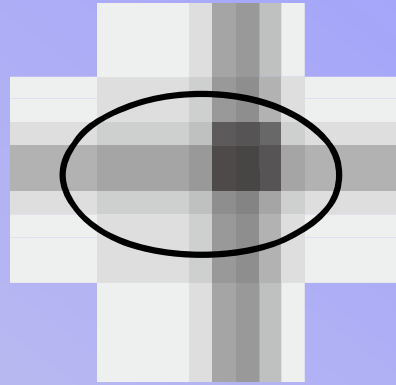
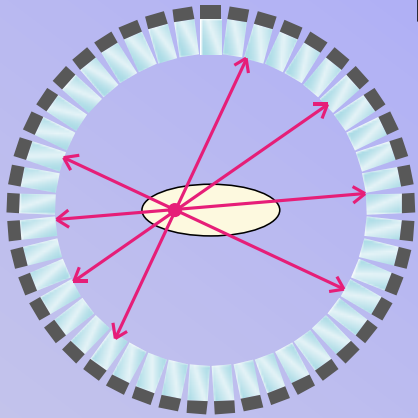
T: true event  
 S: Compton Scatter  
 R: Random Coincidence

A. Del Guerra, RESMDD12

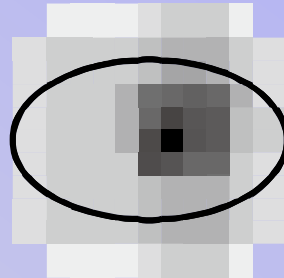
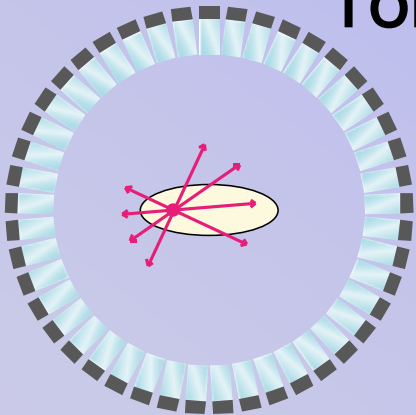


# Reduce Accidentals & Improve Image: TOF-PET

PET



TOF-PET



Localization uncertainty:

$$\Delta d = c \times \Delta t / 2$$

When  $\Delta t = 200 \text{ ps}$

$$\rightarrow \Delta d = 3 \text{ cm}$$

@ VCI

K. Yamamoto 2012 IEEE NSS-MIC



# ToF – PET SNR Improvement

The improved source localization due to timing

$$\sigma_x = c \cdot \sigma_t / 2$$

leads to an improvement in signal-to-noise

$$SNR_{TOF} = \sqrt{\frac{D}{\sigma_x}} \cdot SNR_{Non-TOF}$$

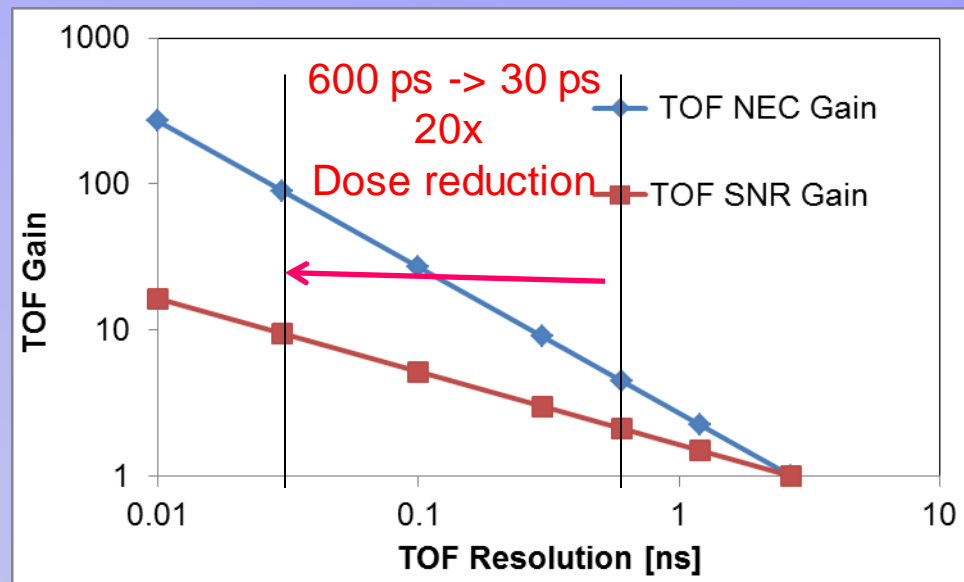
and an increase in Noise Equivalent Count NEC

$$NEC \cdot Gain = \frac{D}{\sigma_x}$$

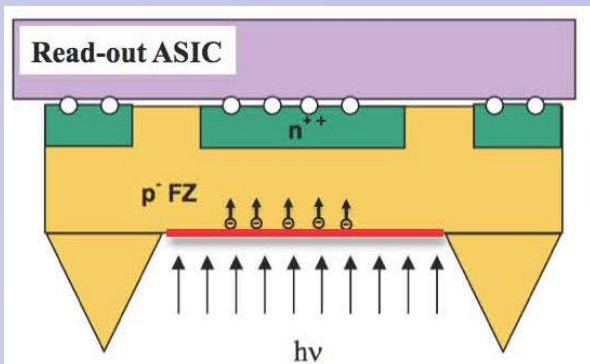
1. For a given acquisition time and dose to the patient, TOF can provide better image quality and improved lesion detection.

OR

2. with TOF the scan time and dose can be reduced while keeping the same image quality ( better clinical workflow and added comfort for the patient).



M. Conti, Eur. J. Nucl. Med. Mol Imaging (2011) 38:1147-1157



## Photon Timing improvement is a major R&D Field