Ultra-Fast Silicon Detectors

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with

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and

CNM Barcelona (G. Pellegrini et al), IJS Ljubljana (G. Kramberger et al)

- Principle of UFSD
- Time resolution
- Beam Test results
- Applications
- Segmented UFSD

Ultra-Fast Silicon Detectors

Since 2012, we are developing a new type of sensor and its associated readout electronics, called an ultra-fast silicon detector (UFSD), allowing detection of charged particles over large areas, with very high data rates, and very high spatial precision and time resolution.

The sensor is based on silicon detectors (LGAD) with a new implantation scheme during the sensor fabrication to achieve internal gain without electrical breakdown. It allows an improvement of the time measurement for large area detector arrays by about a factor of 1000 from ~ 10 nano-seconds to ~ 10 pico-seconds.

We expect profound impact in many fields where the timing of charged particles is important. To name a few:

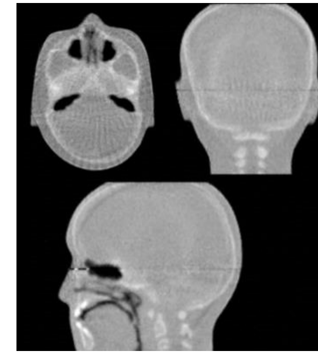
Tracking: Reduction of random coincidences, by adding a 4th dimension (time).
Vertex Locator: Forward physics in AFP2, HGTD (ATLAS), CT-PPS (CMS)
Time of Flight (ToF): Mass Spectroscopy, Particle ID, Remote Vision
Particle counting: Dose in hadron beams
Energy of low-energy protons: Proton CT **(**pCT) and Interaction Vertex Imaging (IVI) in hadron therapy (see Poster # 41 about present state of pCT)

Hartmut Sadrozinski, “Exploring charge multiplication for fast timing with silicon sensors”, 20th RD50 Workshop, https://indico.cern.ch/getFile.py/access?contribId=18&sessionId=8&resId=1&materialId=slides&confId=175330

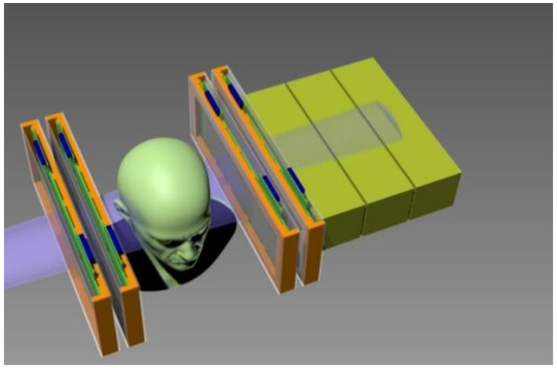
4-D Ultra-Fast Si Detectors in pCT

In support of Hadron Therapy, the relative stopping power (RSP) is being reconstructed in 3D.
The UCSC-LLU pCT scanner uses Si strip sensors to locate the proton and heavy scintillator stages to measure its energy loss (WEPL).

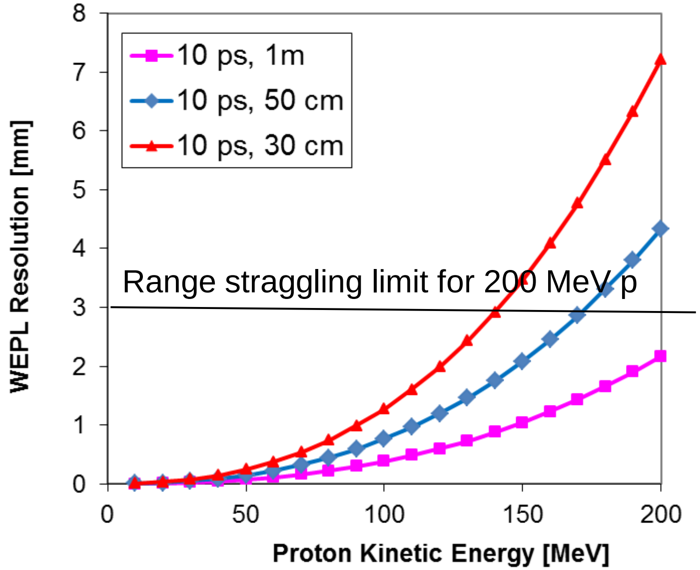
Poster 41



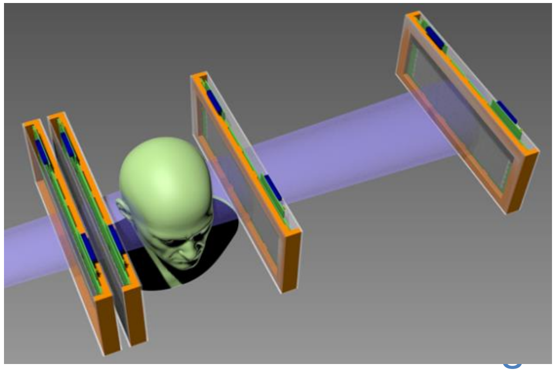
Protons of 200 MeV have a range of ~ 30 cm in plastic scintillator. The resulting straggling limits the WEPL resolution.



Replace calorimeter/range counter by UFSD:
Combine tracking with WEPL measurement where the ToF of the proton measures the residual energy., with comparable or better resolution than the scintillator.

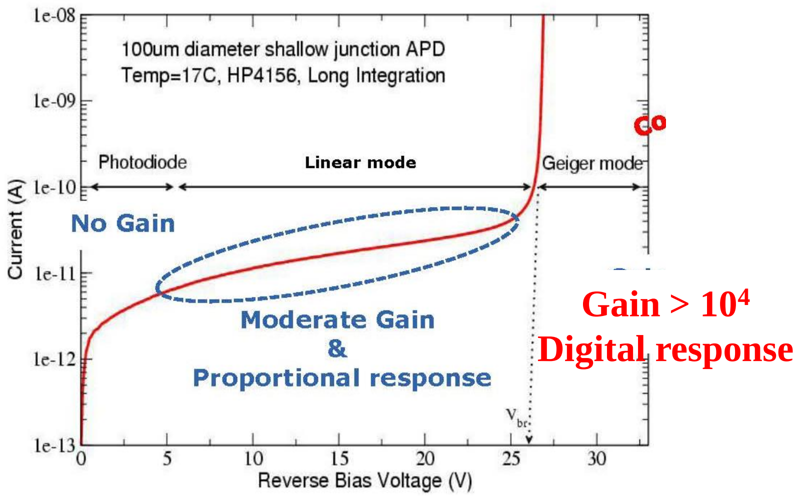


Light-weight,
all silicon
construction
ideal for
installation
Into the gantry



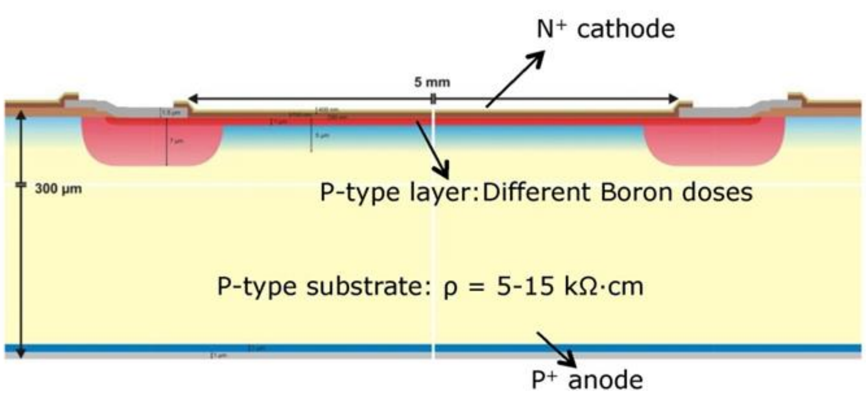
Low-Gain Avalanche Detectors (LGAD)

RD50 Common Project to manufacture Low-Gain Avalanche Detectors (LGAD) based on the prinicple of SiPM or APD, but with moderate gain (CNM Barcelona).
Up to now 5+ iterations. **See Giulio Pellegrini's talk.**

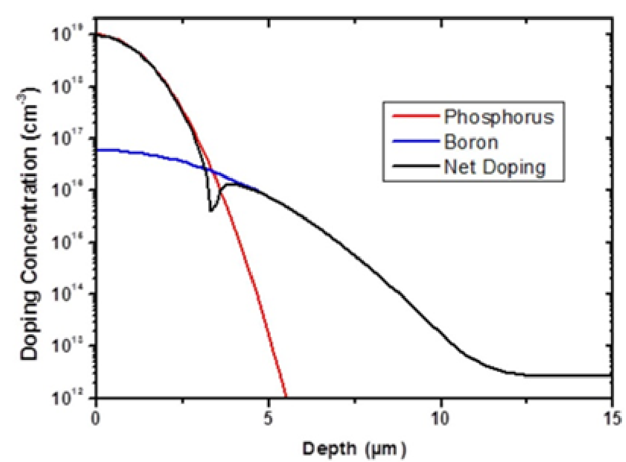


[1] A.G. Stewart et al. in Proc. of SPIE, Vol. 6119, 2006

Principle:
Combination of extra p-layer (increases the E-field) and deep n-implants generate **moderate** charge multiplication without breakdown.

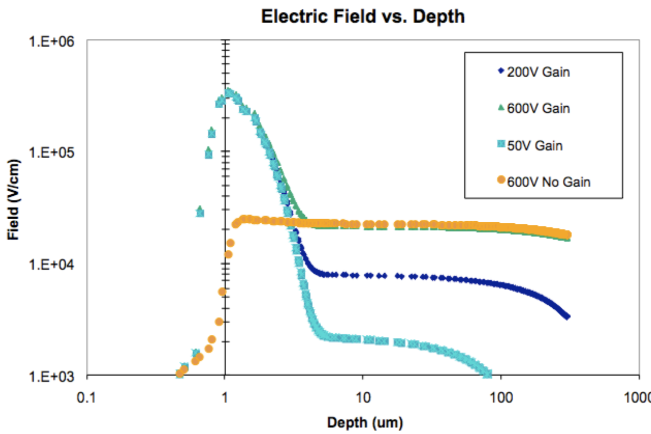


High-Field: Gain

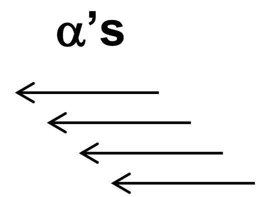


G. Pellegrini, et al., Nucl. Instrum. Meth. A765 (2014) 12.

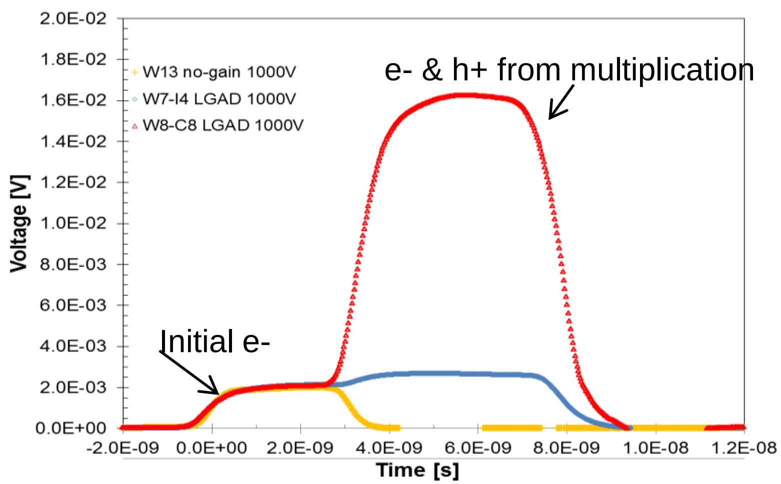
Gain Calibration with α's from Am(241)



Colin Parker, M.S. Thesis UCSC



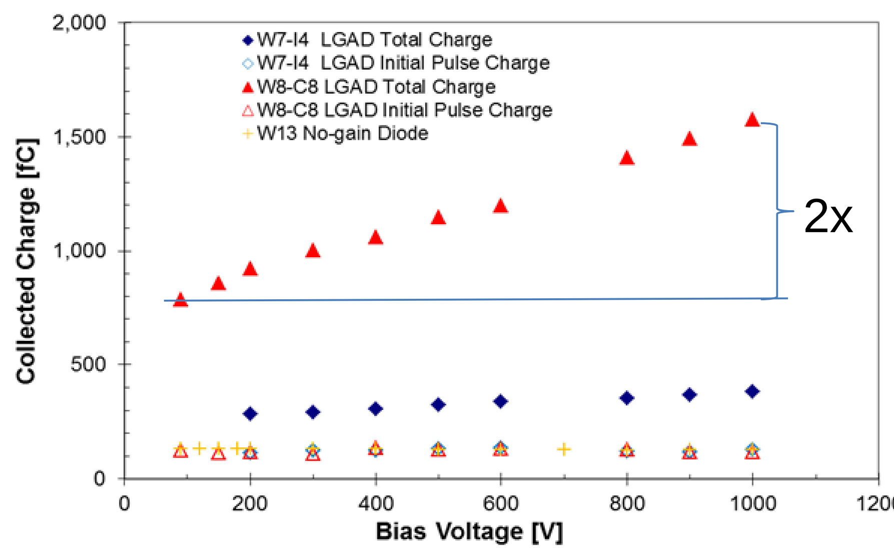
"Electron injection" with α's from Am(241) illuminating the back side, range ~ few um's signal drifts and is then amplified in high field



$$Gain = \frac{electrons + holes}{initial \cdot electrons}$$

Sensitivity to process variations in the p+ concentration in the thin gain layer is well under control.

Gain of 15 observed, can be tuned within factor 2x with bias voltage.



Time Resolution and Slew Rate

The time resolution σ_t depends on the rise time τ_r ,
and τ_r depends on the collection time (i.e. the detector thickness).
The time resolution has 3 terms: **time walk** due to amplitude variation, **time jitter** due to noise, **binning** resolution:

$$\sigma_t^{\,2} = \left(\left[\tau_r \frac{V_{th}}{S}\right]_{RMS}\right)^2 + \left(\tau_r \frac{1}{S/N}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$$

Introducing the **slew-rate S/τ_r = dV/dt**

$$\sigma_t^{\,2} = \left(\left[\frac{V_{th}}{dV/dt}\right]_{RMS}\right)^2 + \left(\frac{N}{dV/dt}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$$

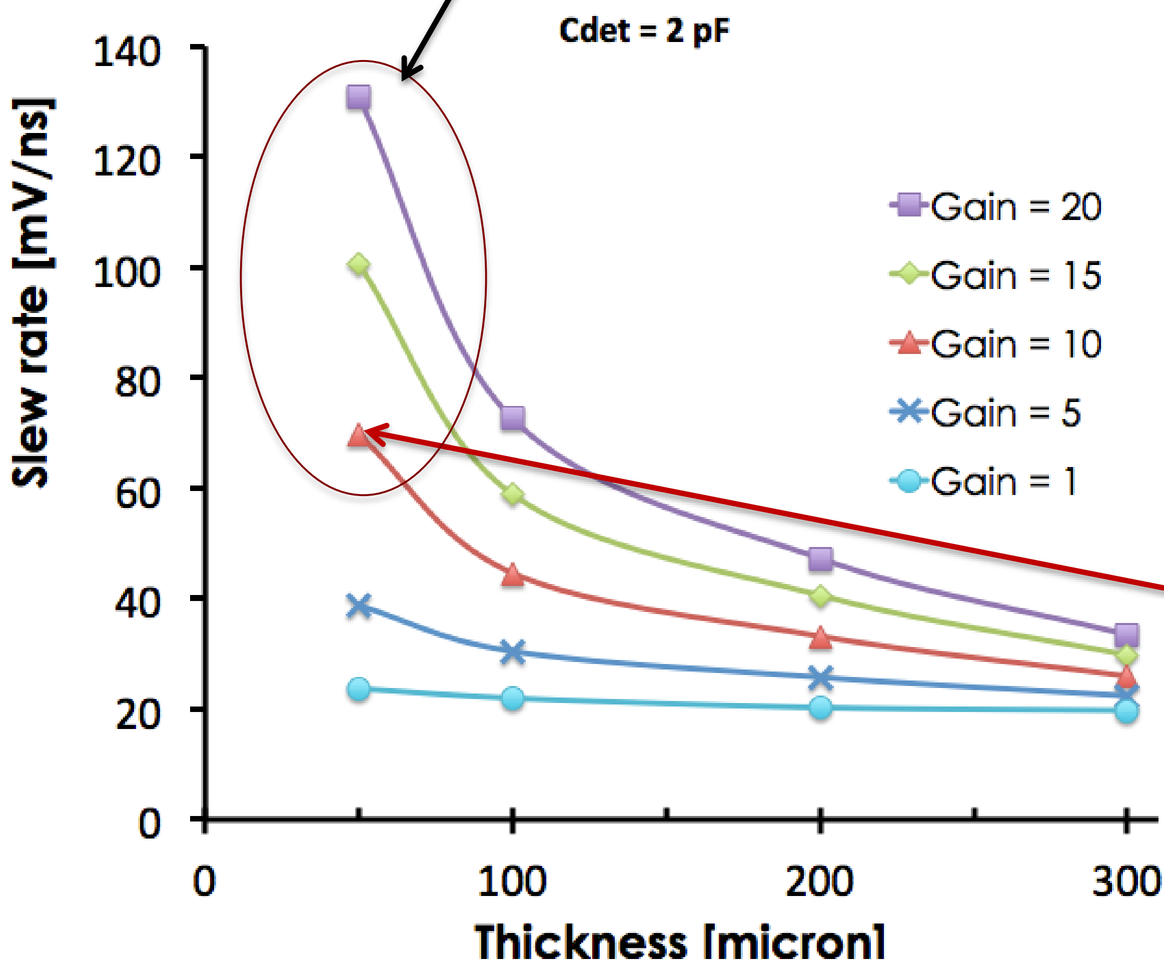
18ps (measured), vs 14ps (expected)

(Is there another term connected to the Landau fluctuations?)
(binning error is negligible at 50 ps sampling rate)
We find that for constant noise N, to minimize the time resolution, we need to maximize the slew-rate dV/dt of the signal (and threshold in the simple case)

Need both large and fast signals.

Slew-rate as a Function of Sensor Thickness

Large slew rate, good time resolutions



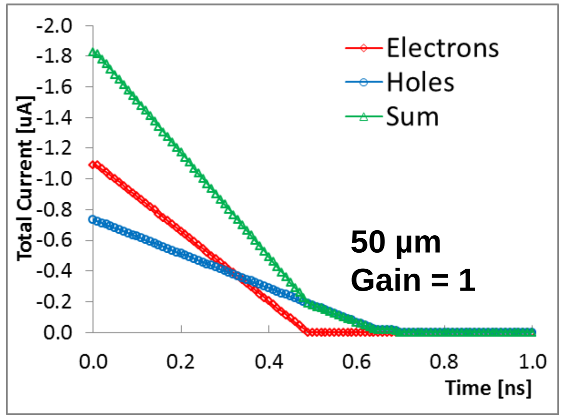
50 micron:
~ 3x improvement
with gain = 10

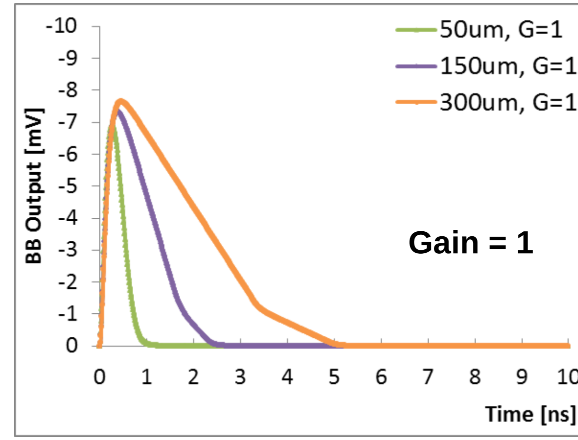
Significant improvements in time resolution require thin and small detectors

Signal Characteristics vs. UFSD Thickness & Gain

Pulse duration scales with thickness due to saturated drift velocity in high fields

Sensors without gain: rise time independent of thickness

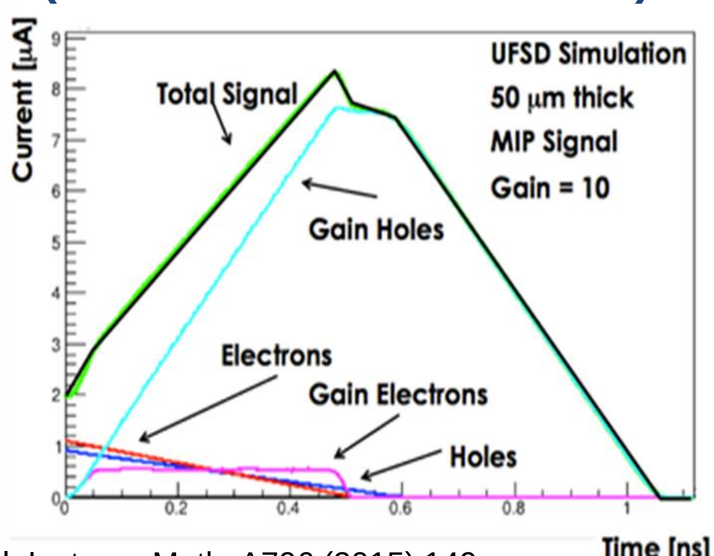


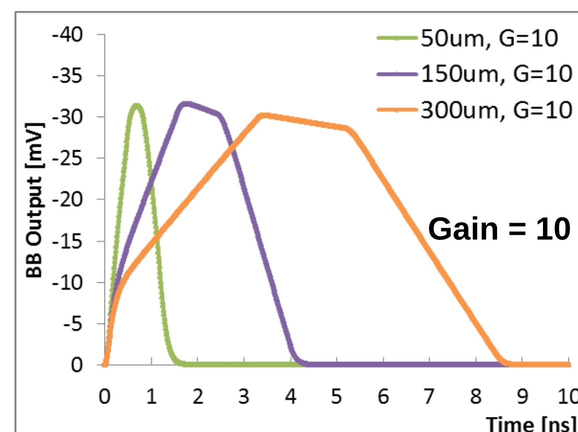


LGAD:
Thickness determines
the peaking time (~ electron collection time) and slew-rate

WF2

simulations

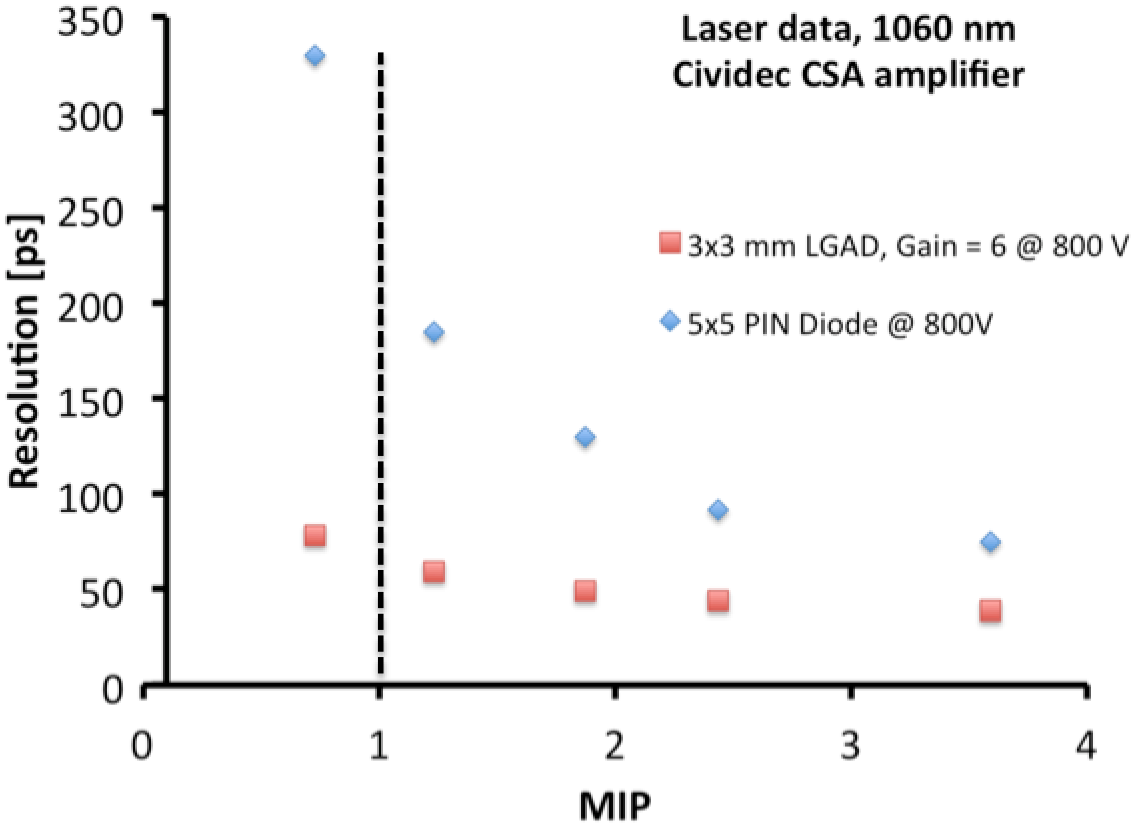




F. Cenna, et al., Nucl. Instrum. Meth. A796 (2015) 149

Measured Time Resolution of UFSD: IR Laser

Laser measures the intrinsic time jitter of the LGAD, depending on the noise and the slew-rate



$$\sigma_{Laser} = \left(\frac{N}{dV/dt}\right)$$

For 1 MIP, an UFSD with gain ~ 6 shows a factor of 3 better time resolution than PIN diodes: 70 ps vs 200 ps

For many MIPS the difference is decreasing (important for timing calorimeter)

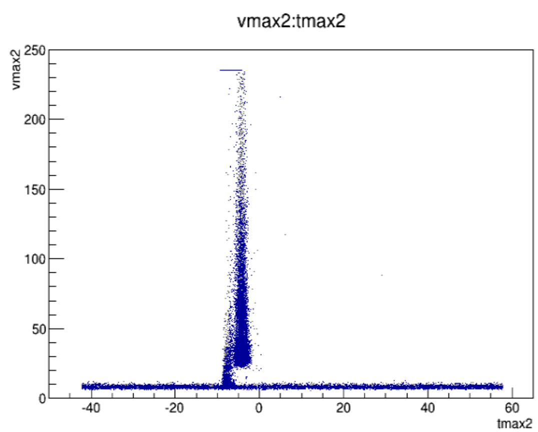
Beam Tests with UFSD

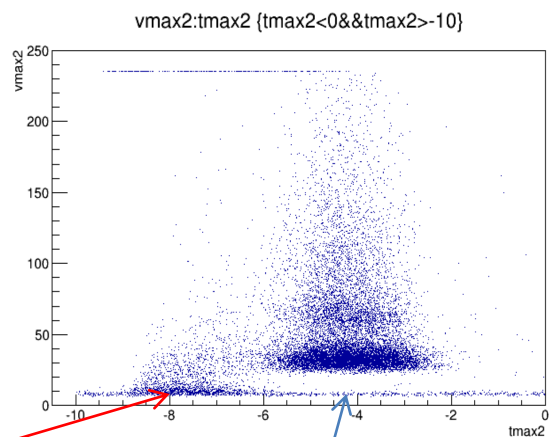
2014 Frascati: 2 LGAD 7x7mm^2 300µm (C = 12pF, Gain =10), CSA or BB
2014 CERN: 2 LGAD 7x7mm^2 300 µm (C = 12pF, Gain =10), CSA and BB
2015 CERN: 2 LGAD 3x3mm^2 300 µm (C = 4pF, Gain =10 & 6), CSA or BB

CSA: charge sensitive amplifier with gain of ~100, effective shaping ~200 Mhz
BB: Broad-band current amplifier with gain of ~100, BW 2.5 GHz
Pulse forms were recorded in a 2.5 GHz Digital scope with 50 ps bins

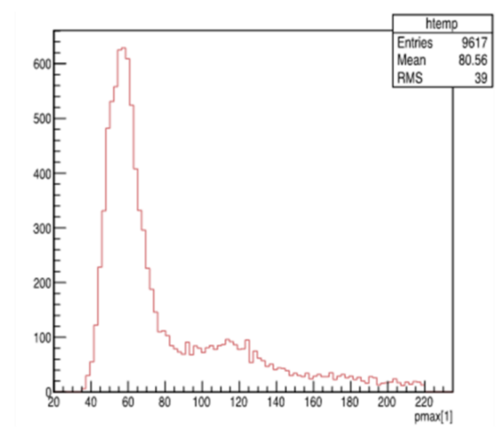
Goal: Study timing method, shaping time, noise, capacitance, gain, ..

No tracking information was available: Need to recognize no-gain events from the periphery
Scatter pulse maximum amplitude (vmax2) vs. its time stamp (tmax2).
Events from the gain region and the periphery have similar start times, but very different peak times.





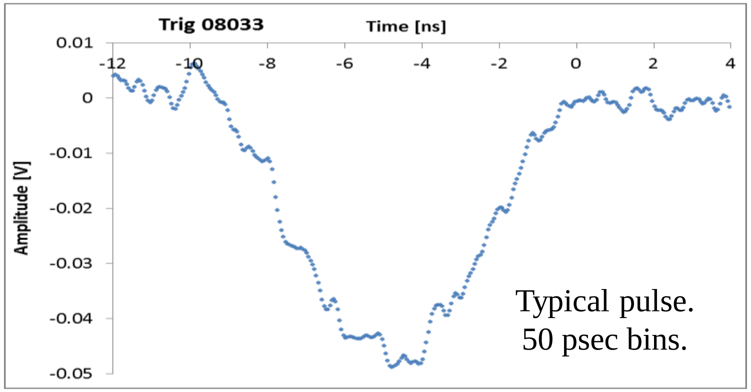
Pulse height spectrum indicates about 10% two-MIP events

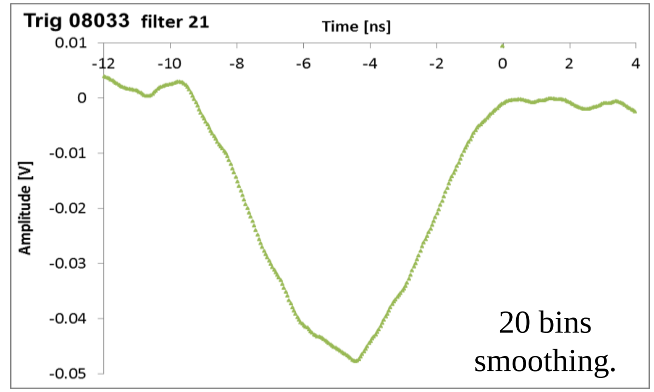


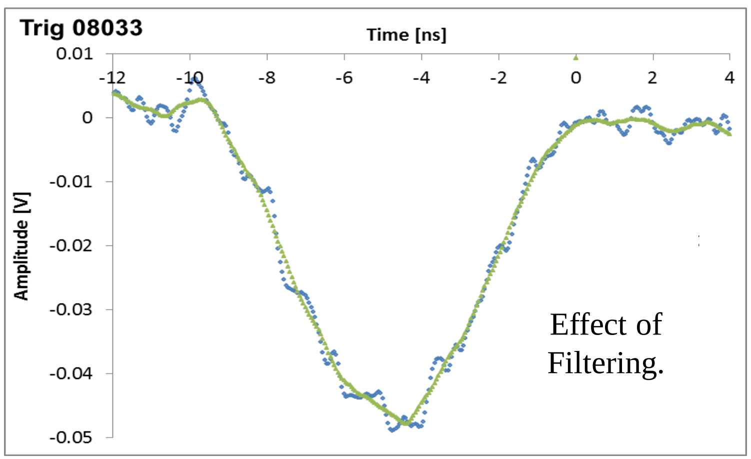
Clear separation of two contributions:
at -8 ns = no-gain, at -4.5 ns = events with gain

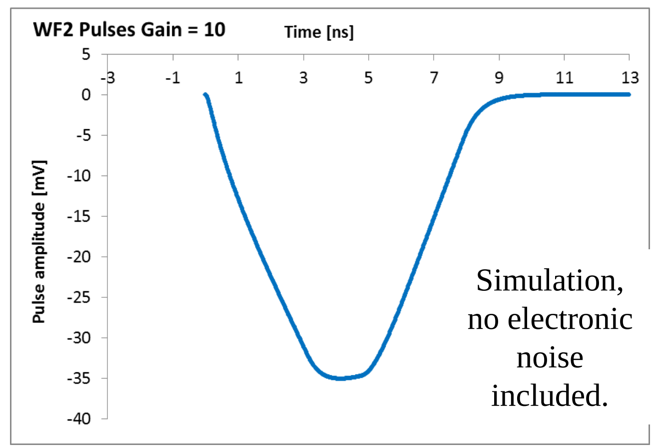
Filtering the Pulses (Running average or FFT)

FZ LGAD 300 µm, C = 12 pF, G=10, BB, 1000V, noise about 3 mV









Timing with Fixed Threshold

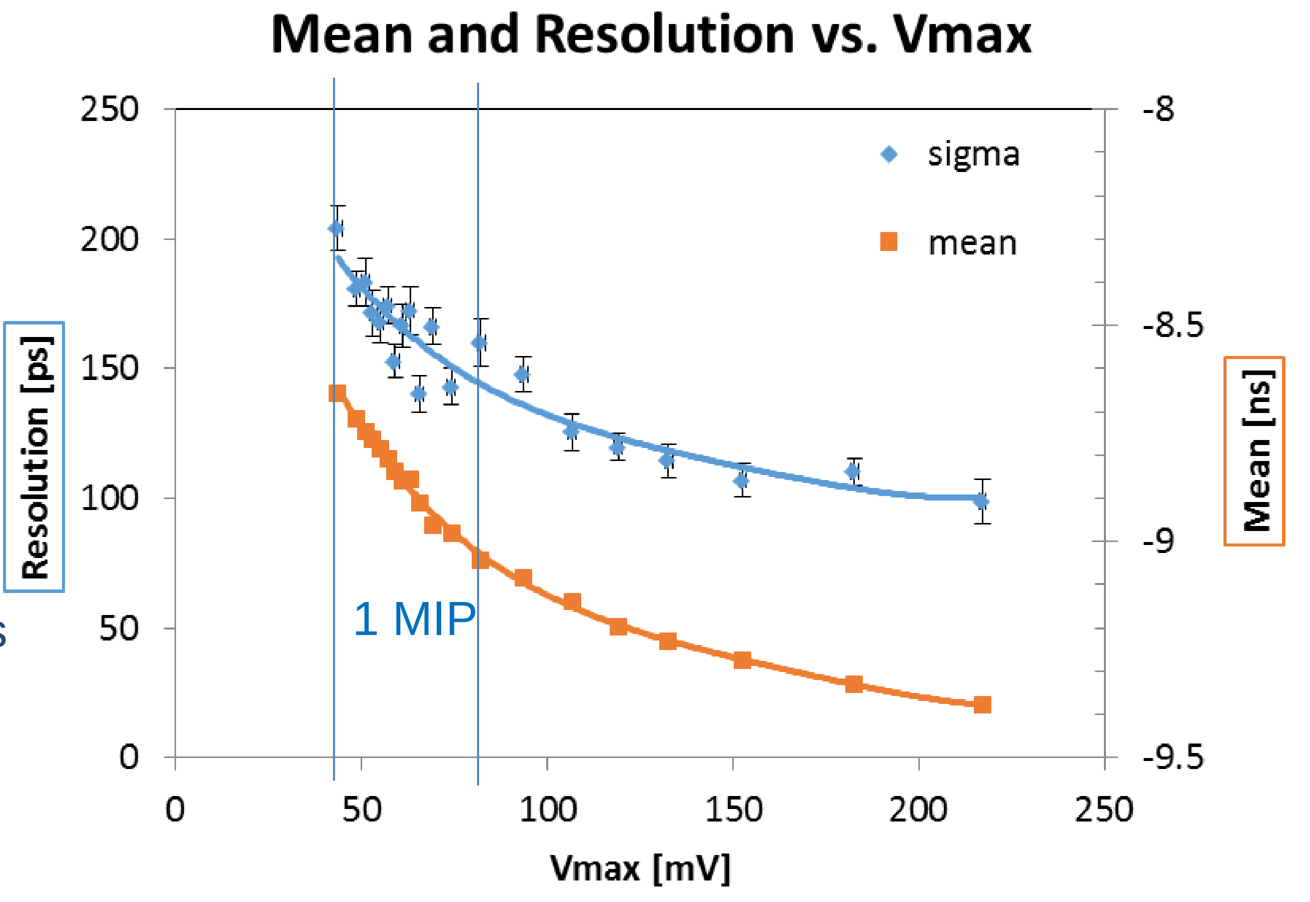
Analysis of FZ LGAD 300 µm, C = 12 pF, G=10, BB
Bias 1000V, fixed threshold = 10 mV, filtered with 20 bins

Time walk is large (700ps)!

Resolution ~ 1/√V shouldn't it be 1/V?

Resolution 150 – 200 ps

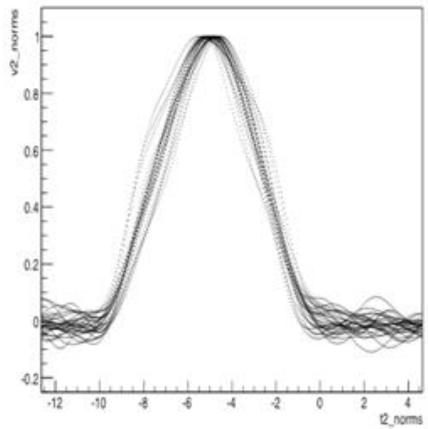
Precise time walk projection looks non-trivial to incorporate into an ASIC.



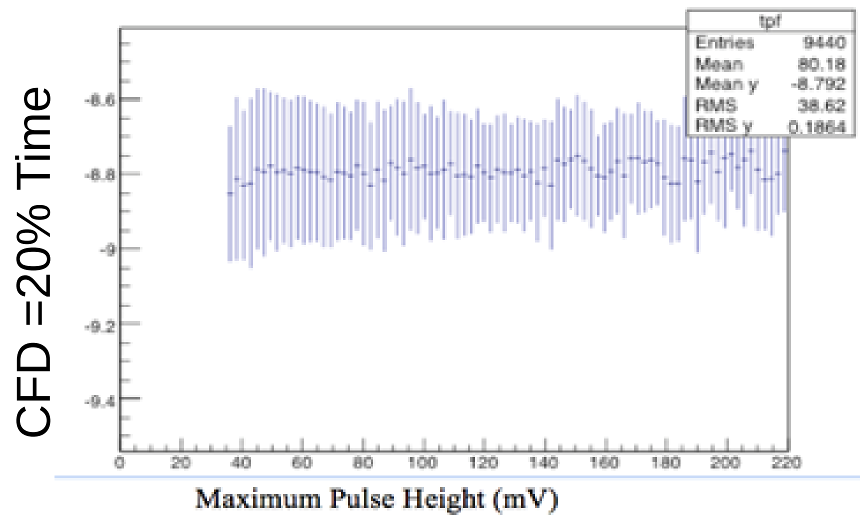
Analysis: Chi Wing Ng (Tom) & Sze Ning Mak (Hazel)

Case for Constant Fraction Discriminator CFD

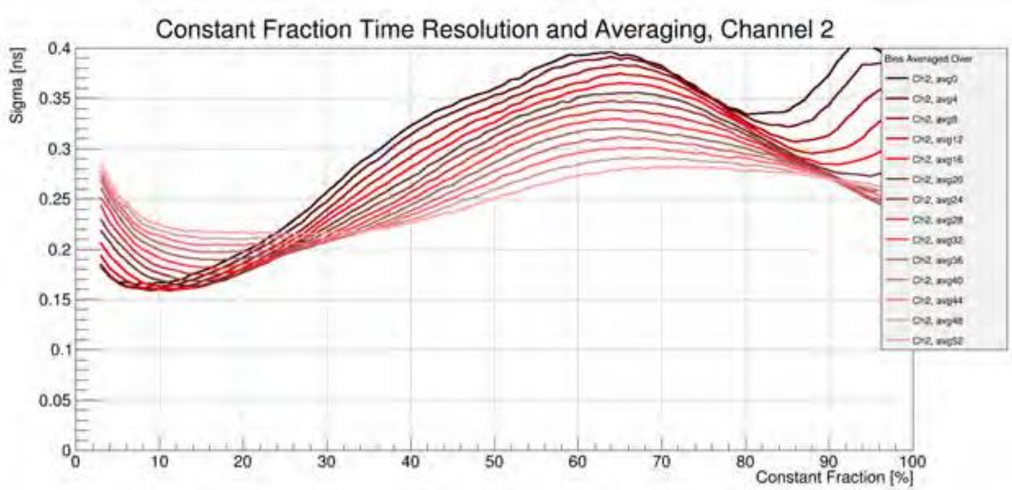
Abe’s unified pulse shape indicates uniformity of pulse shapes.
A low CDF has best resolution.



CDF = 20% has no time walk



Timing resolution vs. CFD threshold for varying BW cut-off.
Optimize the filter (i.e. shaping time) for each CFD threshold



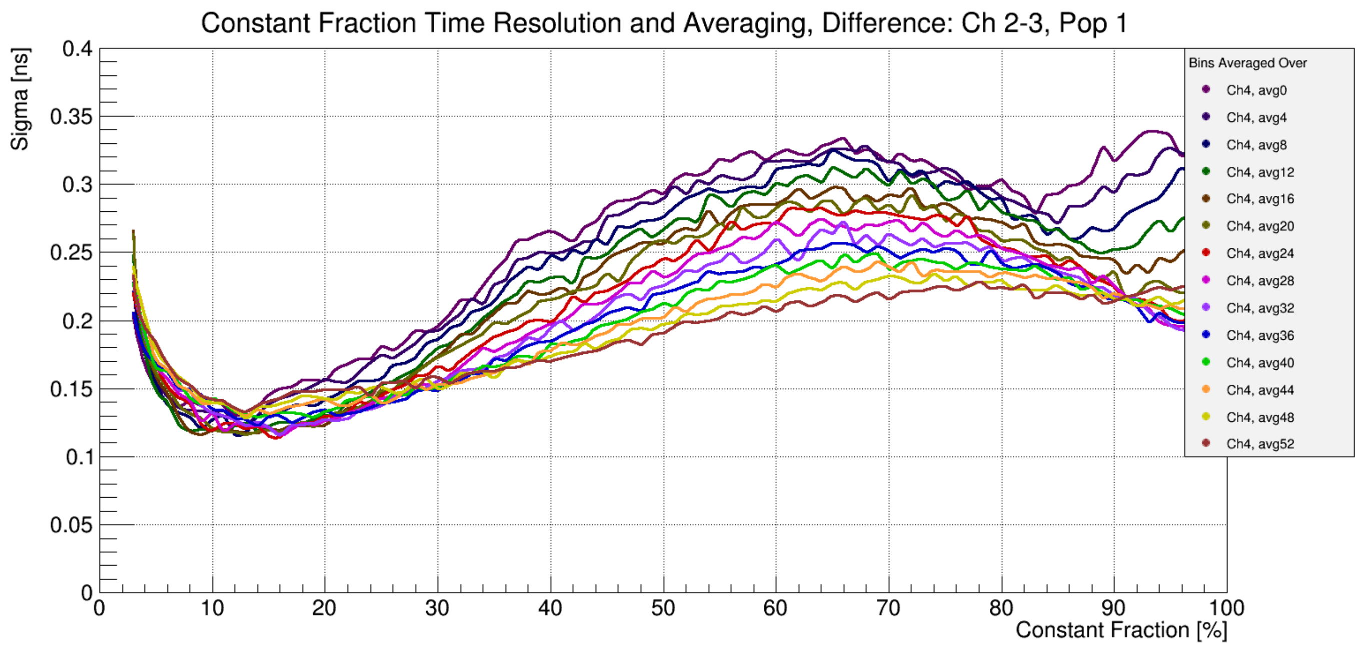
Best time resolution (160 ps):
Low CFD threshold
BW higher than expected from rise time

CFD is easy to incorporate into an ASIC.

Analysis: Abe Seiden, Natasha Woods, Ben Gruey

UFSD Timing with Reduced LGAD Capacitance

July 2015 beam test, 2 FZ LGAD 300 µm, C = 4 pF (instead of 12 pF before, G=10 & 6, BB
Bias: 900V, CFD: 0->100%, filtered with variable BW.
Resolution: Time difference between two channels divided by sqrt(2).



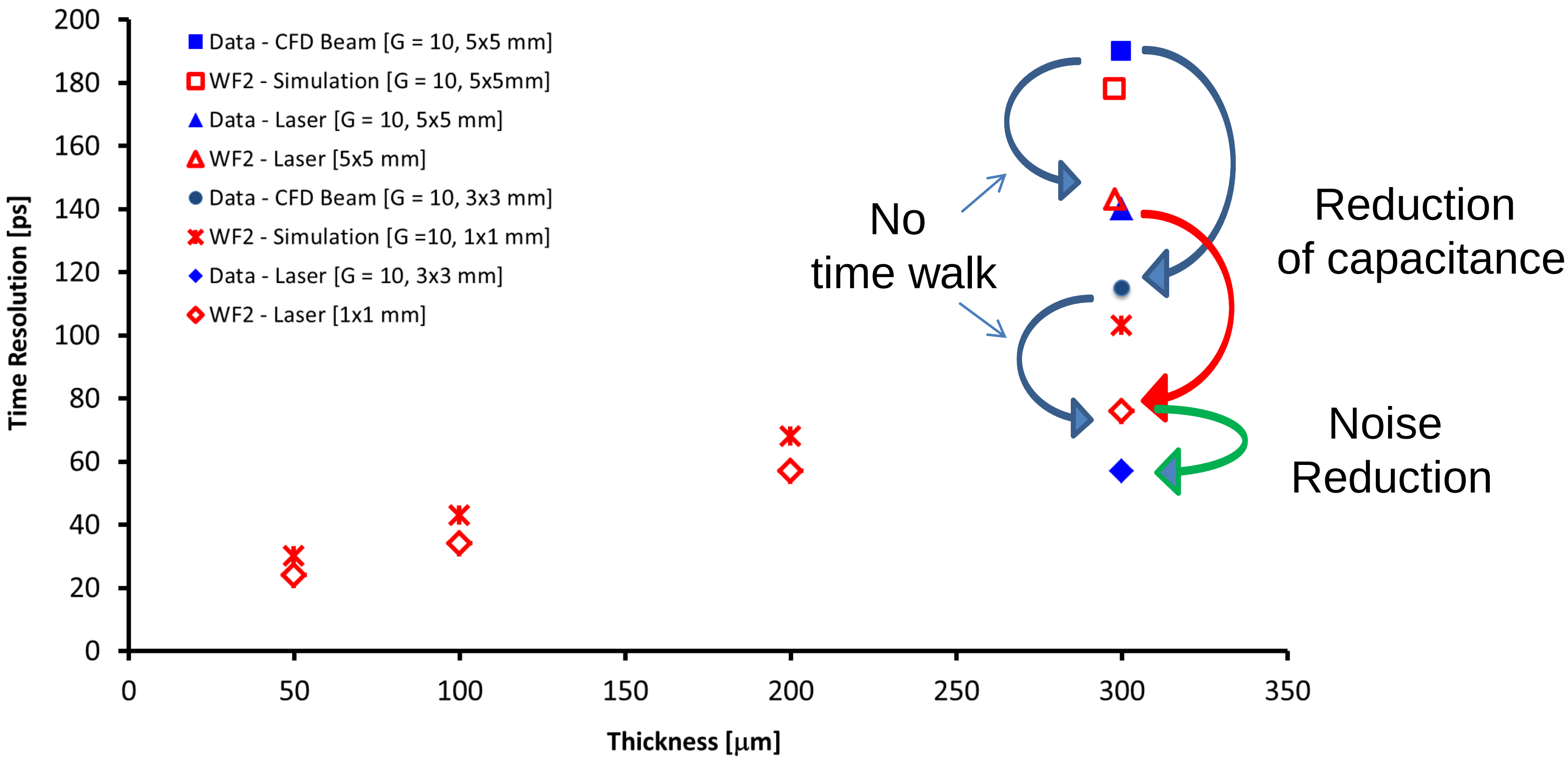
Best resolution 115 ps with CFD @ 8 -15% with BW cutoff higher than given by rise time.

The two LGAS have different gain. It's difficult to assign correctly the two time resolutions, Using simply the inverse of the gain, we get:
Gain = 6 σ =140 ps, Gain = 10 σ = 80 ps.

Analysis: Abe Seiden, Natasha Woods, Ben Gruey

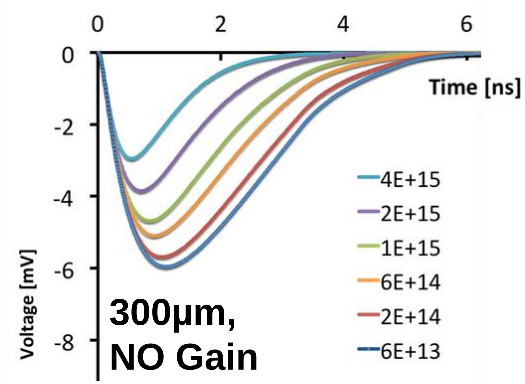
Timing Resolution of UFSD

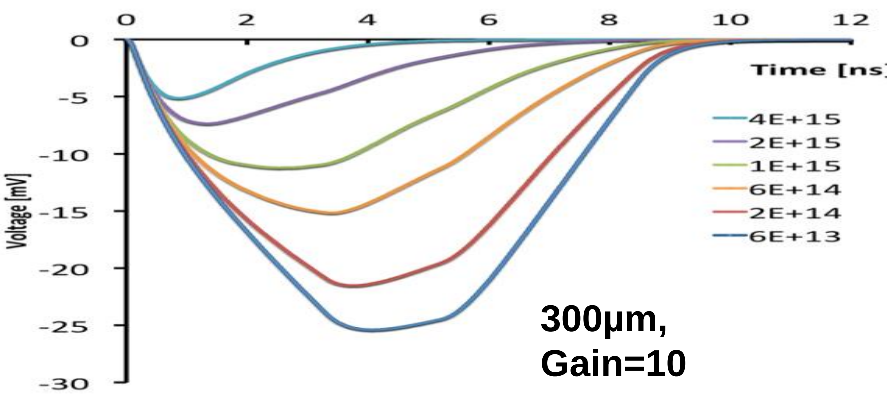
Up to now the only MIP data available are for 300 µm LGAD.
Good agreement between data (beam & laser) and simulations.
Laser data have no time walk.
Improvements are due to reduction of capacitance which increases the pulse height and reduces the noise.



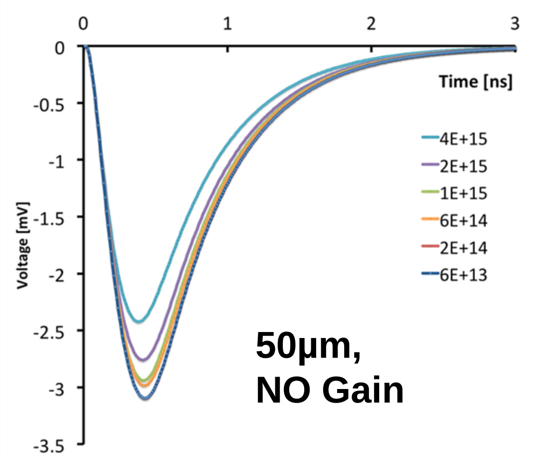
WF2 Simulation: Radiation Damage (Trapping)

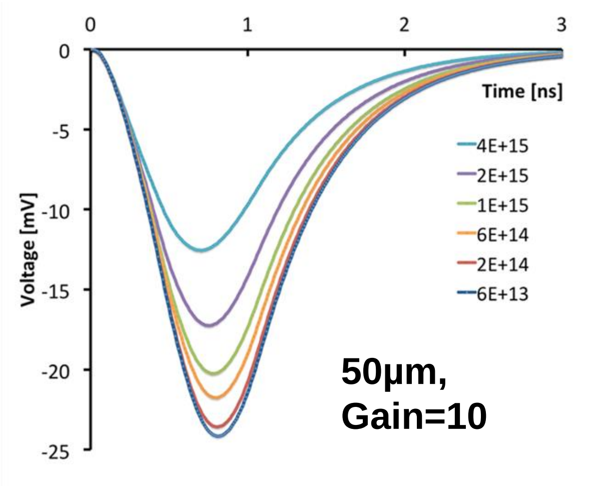
Effect of trapping in thick and thin detectors at large fluences

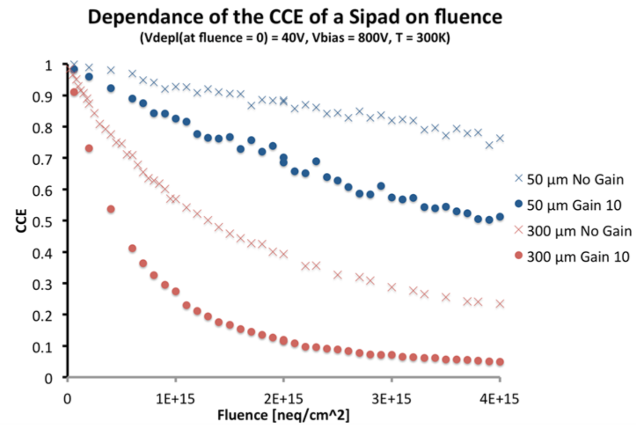




The radiation induced change of the peaking time (and CFD time) of thick (300µm) sensors bodes ill for timing.





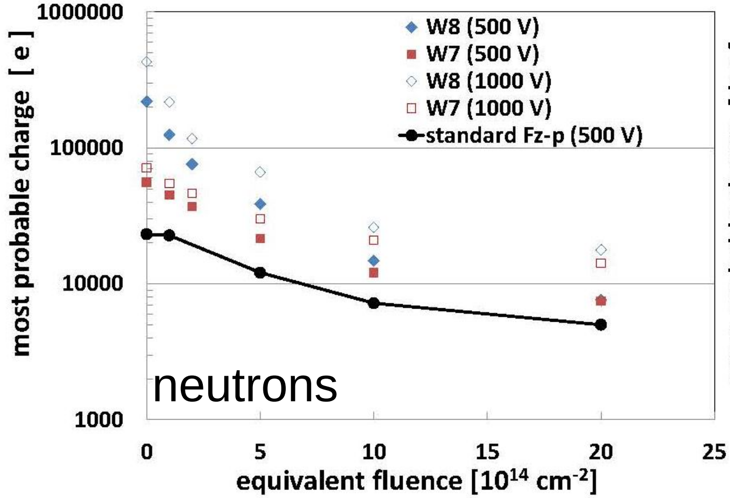


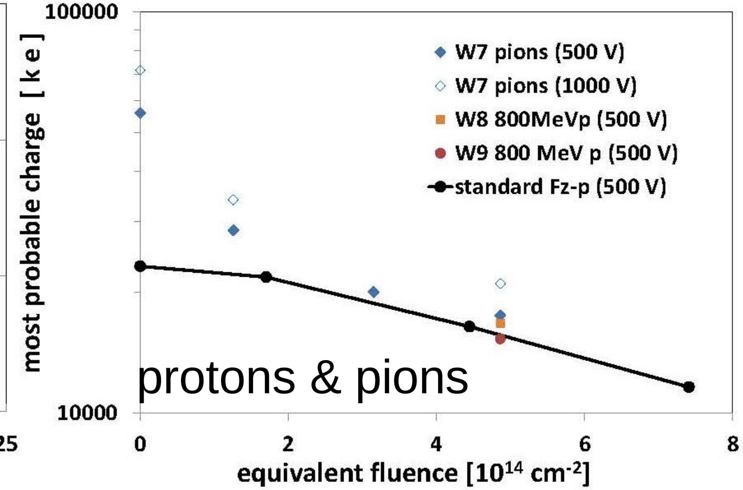
The peaking time (and CFD time) of thin (50µm) sensors is stable with radiation.
The rising edge of thin sensors is insensitive to trapping.

Weightfield 2 (WF2) Implementation and Simulation: Bianca Baldassari

Radiation Damage in UFSD: Change in Gain

Measurement of collected charge (CCE) in 300 µm LGAD





G. Kramberger et al, 2015 JINST 10 P07006)

As expected, a 300 µm LGAD shows larger CCE degradation than a no-gain diode, since the gain signal is mainly due to late drifting holes which have large trapping effects.
Thick sensors would benefit from LGAD up to fluences of few 10^{14}.
This “Acceptor Removal” seems to be larger for larger gain, and leveling off at higher fluences.

- Need to measure the gain (with red laser or α’s) as a function of fluence for thin LGAD with different gain.
- Investigate to restore gain loss after irradiation with increasing the bias voltage.
- On-going program to improve radiation tolerance by replacing **Boron** with **Gallium**

Applications of UFSD

Where-ever the time resolution of charged particles matters

- **Flight Path for Longitudinal Vertex Identification**
  Suppression of pile-up through TOF (AFP2, CT-PPS, HGTD)

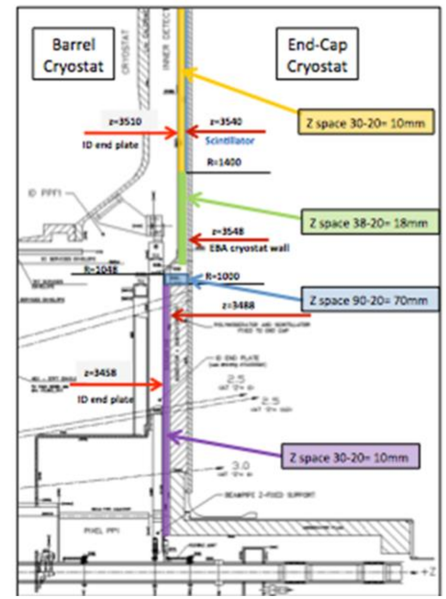
- **Particle Mass in Spectrometers:**
  Mass Spectrometers, Astro-Physics Instruments ("AMS") get superior mass analyzer resolution with TOF.

- **Proton Energy in Hadron Therapy:**
  Proton Energy for pCT, IVI using TOF

Identification of Longitudinal Vertex

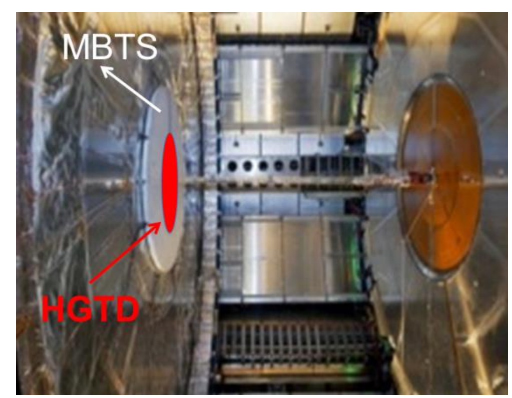
Suppression of pile-up with High-Granularity Timing Detector HGTD (Run 2)

4 active layers per side (~10 m^2 in total) in front of FCAL
HGTD baseline dimensions:
Z =[3475, 3545] mm ; **ΔZ=70mm**
Rmin ~ -90 mm (ηmax≃4.3)
Rmax ~ 600 mm (ηmin≃2.4)
Possible to extend η=5.0 (Rmin ~ 50mm)
Required timing resolution: 50 – 100 ps
There are several (6?) technologies being considered.

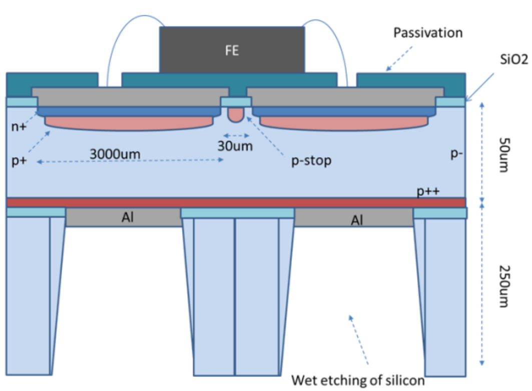


Radiation Levels: (scaled to 3000 fb^{-1}):
- $(1\text{-}3)\times10^{15}$ n/cm2 ;
- $(0.3\text{-}2.4)\times10^{15}$ hadrons/cm2 (>20MeV)
- ~100 Mrad

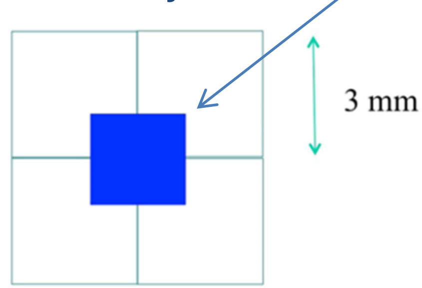
A challenging project for the radiation resistance of UFSD.

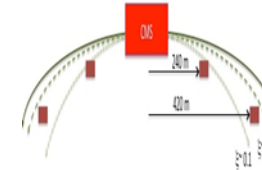


CNM started to work on the UFSD Implementation



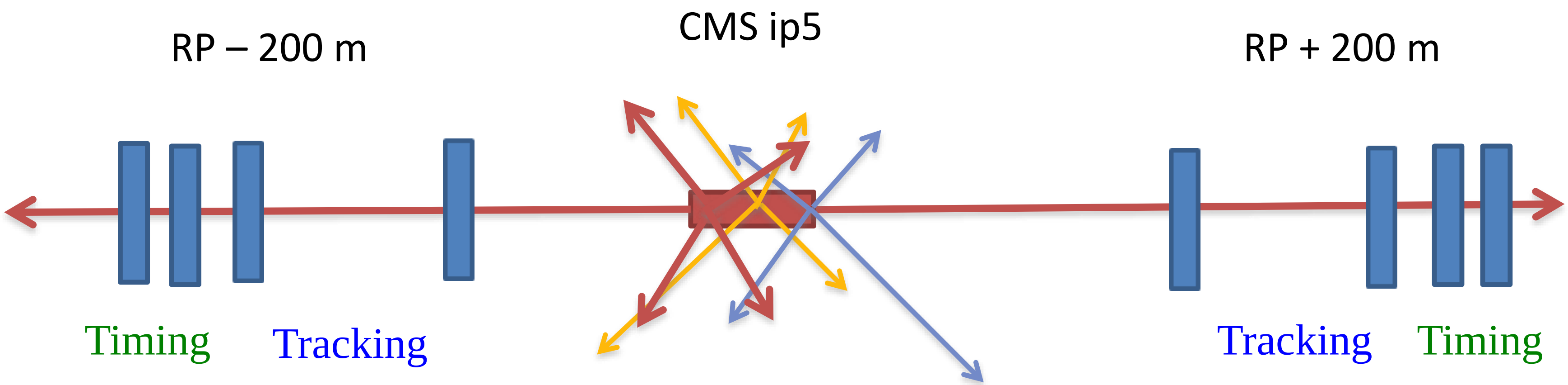
2x2 array with 1 ASIC

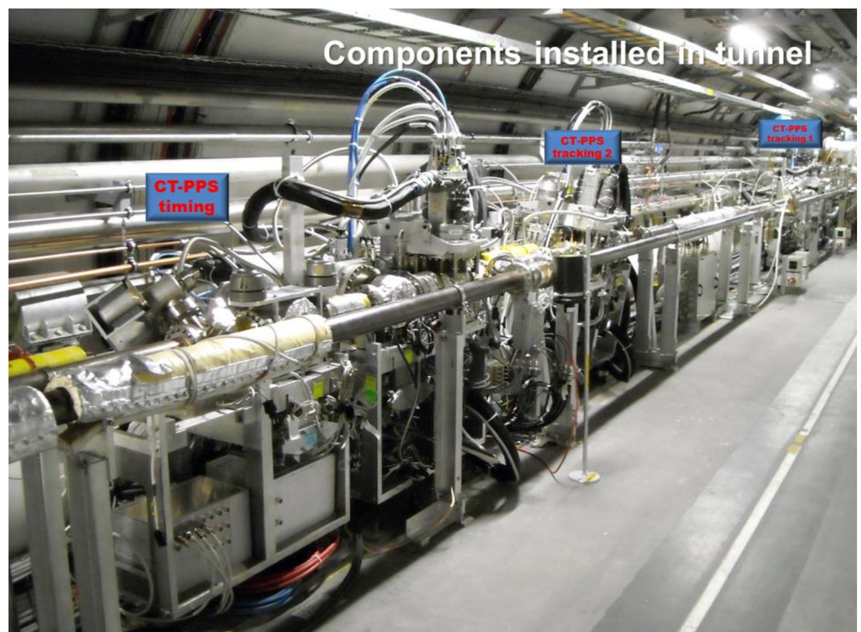




PPS by CMS & TOTEM= CT-PPS

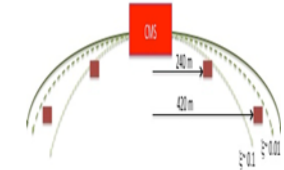
A Totem-CMS combined spectrometer to detect high momentum – high rapidity protons.

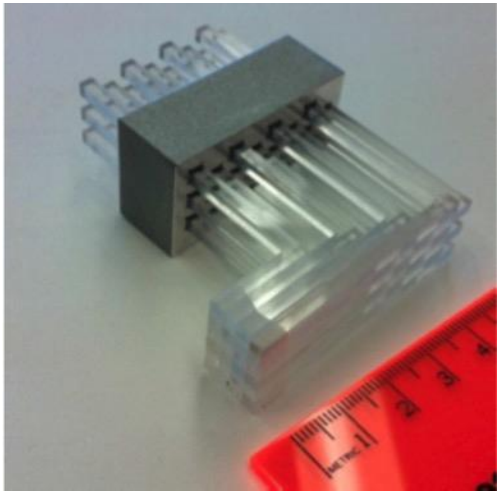




Tracking and timing detectors positioned inside roman-pots

CT-PPS Basic Design: Timing





Vertex z-by-timing: ~ 2 mm:

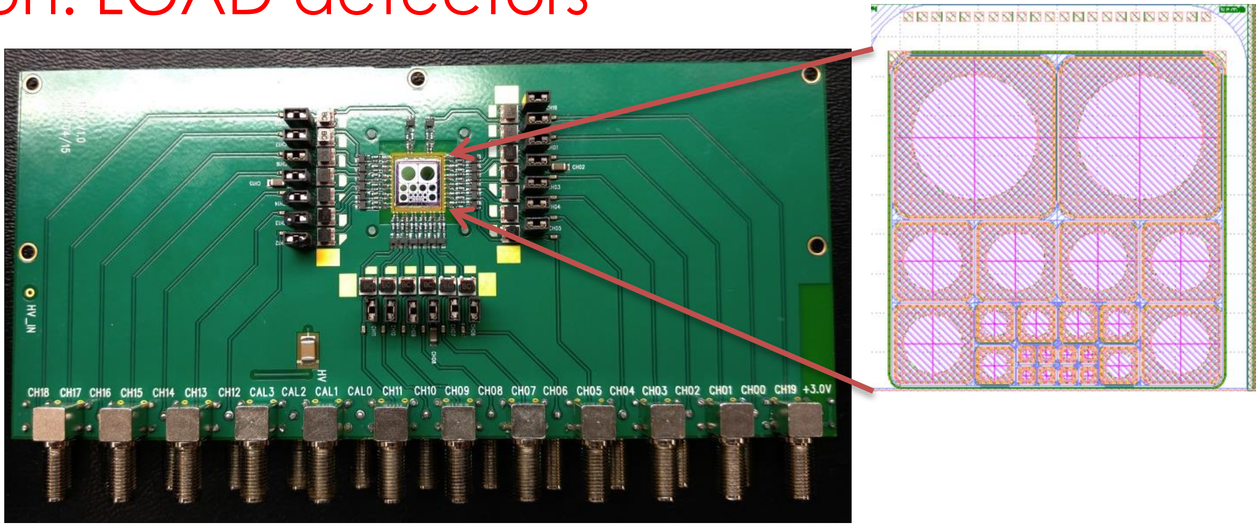
Time resolution ~10 ps
Segmentation: 1 - 3 mm
Edgeless, active to ~ 200 micron from edge
Radiation hard:
Lifetime > ~ 1 year at LHC at 10^{34} (~$5*10^{15}$ p/cm^2)
Rate: 25 ns sensitivity

➔ Current solution: quartz bars

➔ Upgrade solution: LGAD detectors

Use a segmented LGAD sensor, with variable pad/pixel size.

LGAD and Read out Ready for beam test



Nicolo Cartiglia, INFN, Turin

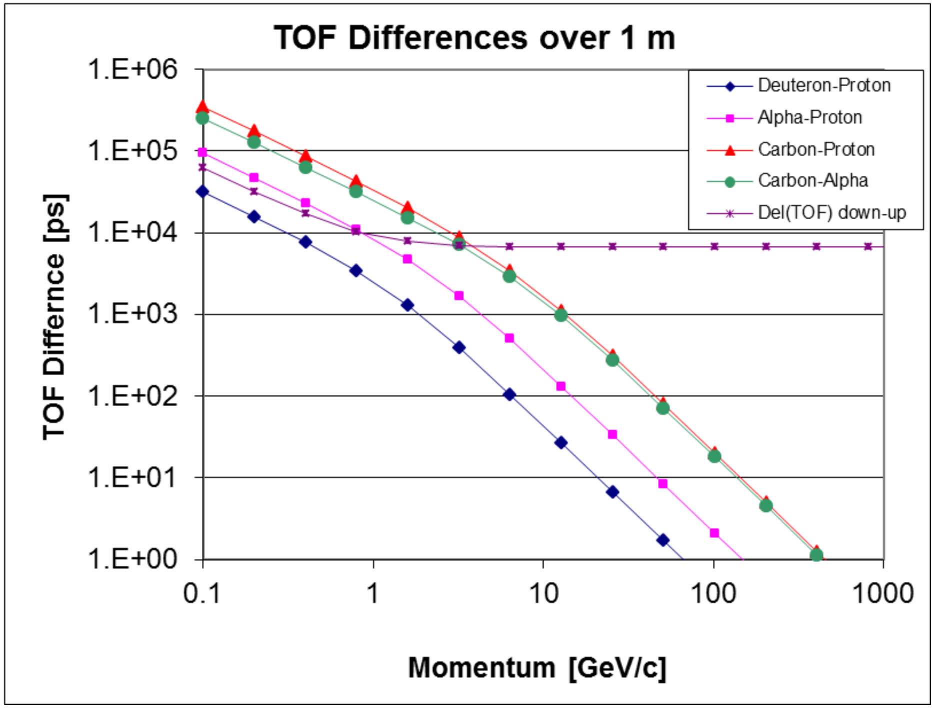
TOF: Mass Spectroscopy MALDI & in Space

Time-of-Flight (TOF) Mass Spectroscopy is used in commercial products in the form of matrix assisted laser desorption/ionization (MALDI).
The superior time and position resolution of UFSD will allow smaller instruments and/or better analyzer resolution of M/ΔM.

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 TOF system of UFSD with a time resolution of 10 ps could reach the "Holy Grail" of Cosmic Ray Physics: the distinction between anti-carbon ions and anti-protons or α's can be achieved up to a momentum of 200 GeV/c.

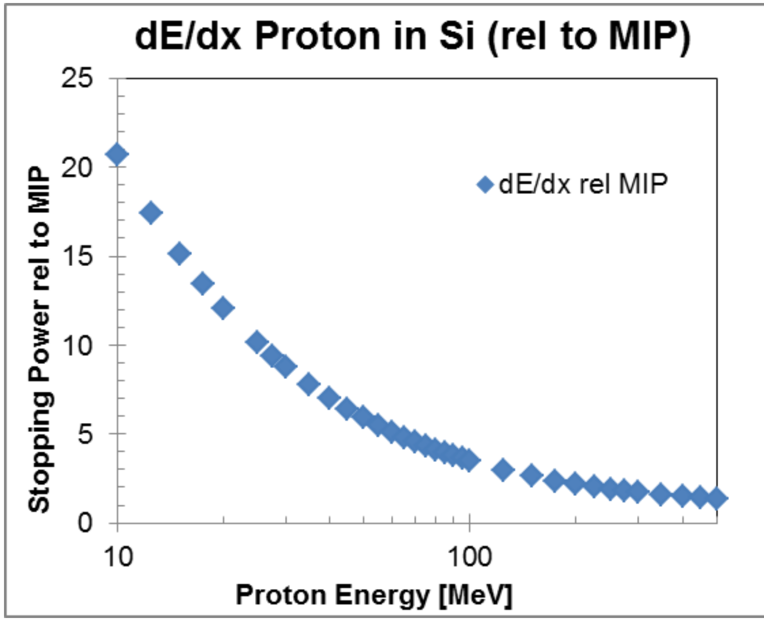


Conclusions

- We made progress in understanding the principle and the expected performance of UFSD
- The timing resolution in beam and laser tests are confirmed by the Weightfield 2 simulations.
- Thin sensors are predicted to have many advantages. We expect results from 50um UFSD this year.
- I acknowledge the contributions from our RD50 colleagues, and support from US, Italian and Spanish funding agencies.
- I would like to express my appreciation for the local organizers to have HSTD10 in Xian.

Time Resolution for low-Energy Protons

Large dE/dx increases the slew-rate dV/dt



Predictions from simulations:

For MIPs in 50 um sensors

time resolution: 30 ps with gain = 10

time resolution: 84 ps without gain

Predicted time resolution for protons in Ultra-fast Silicon Detectors without gain:

E [MeV]	rel. dE/dx	Time res. [ps]
10	20.7	4.1
20	12.1	6.9
50	5.9	14.2
100	3.6	23.3
200	2.2	38.2

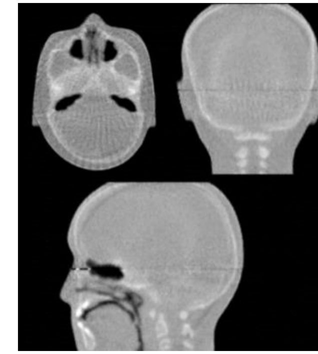
With USFD with gain = 10, the time resolution is improved by another factor3 !

Low-energy protons afford very good time resolution, allowing the measurement of the proton energy by time-of-flight TOF.

UFSD for Low-Energy Protons

- Ultra-fast silicon detectors (UFSD) afford very good time resolution for low-energy proton (or ions) since they have very high slew-rare.
- The large slew rate due to the high specific energy loss of low-energy protons is enhanced by a factor 3 when a UFSD with gain = 10 is used. Timing resolution of < 10 ps for protons with E < 200 MeV are predicted.
- The fact that UFSDs have their best timing capability when the sensor is thin (< 50 um) goes hand-in-hand with the fact that tracking of low-energy protons need thin sensors to reduce MCS (Multiple coulomb scattering).
- Smaller UFSD with 200um thickness and 50um thickness are being produced at CNM.

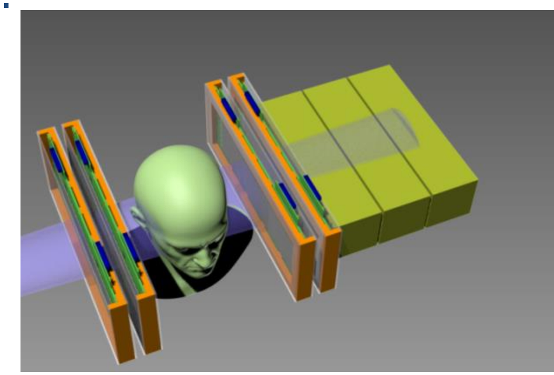
4-D Ultra-Fast Si Detectors in pCT



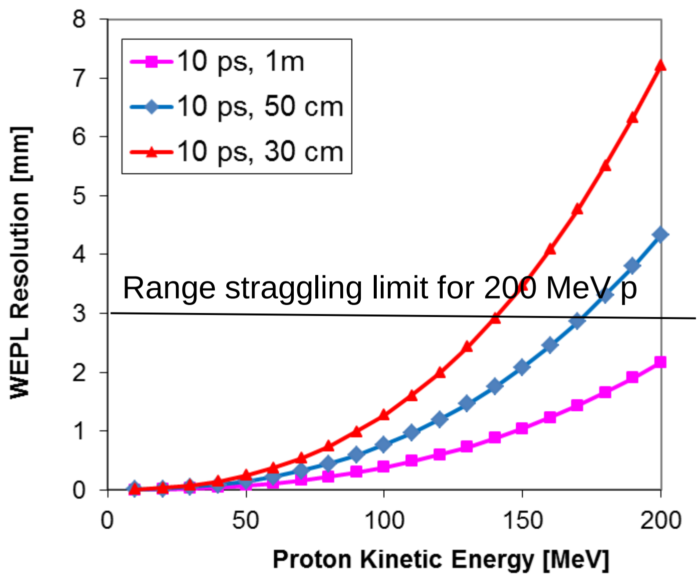
In support of Hadron Therapy, the relative stopping power (RSP) is being reconstructed in 3D.
The UCSC-LLU pCT scanner uses Si strip sensors to locate the proton and heavy scintillator stages to measure its energy loss (WEPL).

Poster 41

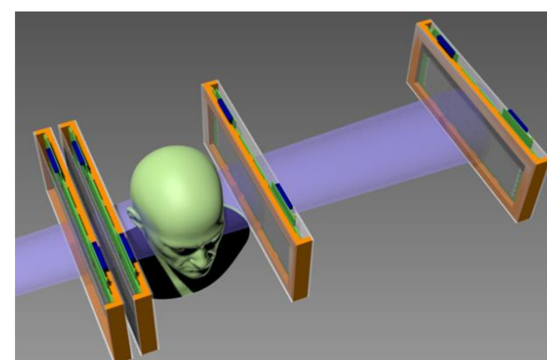
Protons of 200 MeV have a range of ~ 30 cm in plastic scintillator. The resulting straggling limits the WEPL resolution.



Replace calorimeter/range counter by UFSD:
Combine tracking with WEPL measurement where the ToF of the proton measures the residual energy., with comparable or better resolution than the scintillator.

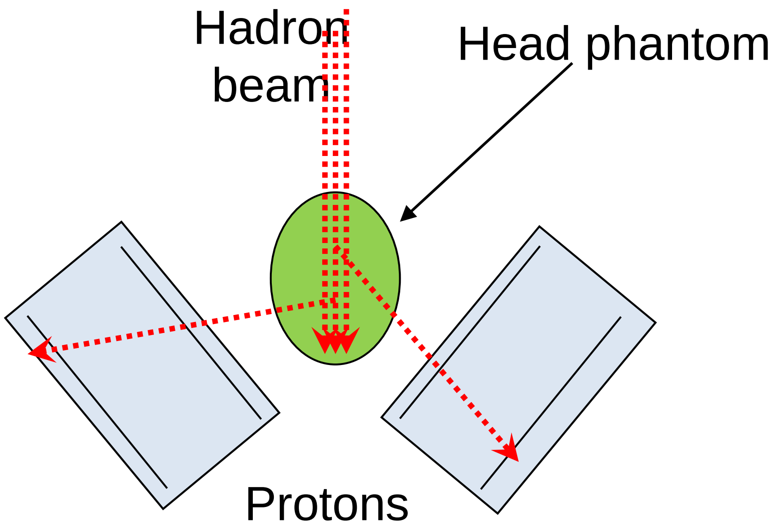


Light-weight, all silicon construction ideal for installation Into the gantry

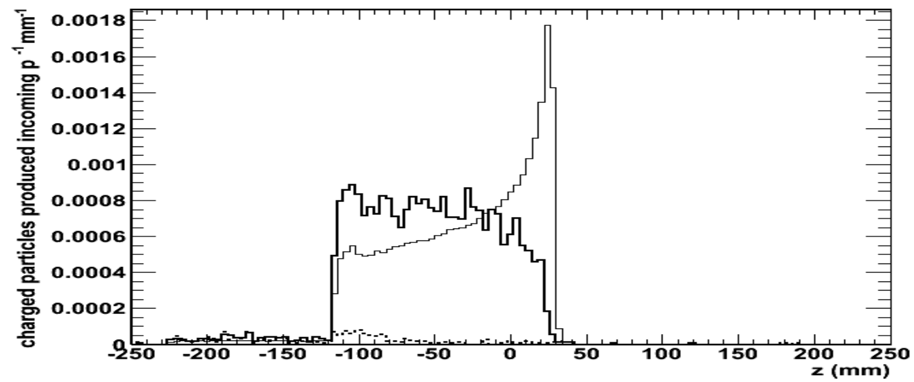


Interaction Vertex Imaging (IVI) with UFSD

Direction and energy of (low-energy!) secondaries are measured in telescopes of UFSD and projected back to identify the beam location.



Longitudinal distribution of energy deposition (Bragg peak) and number of secondaries

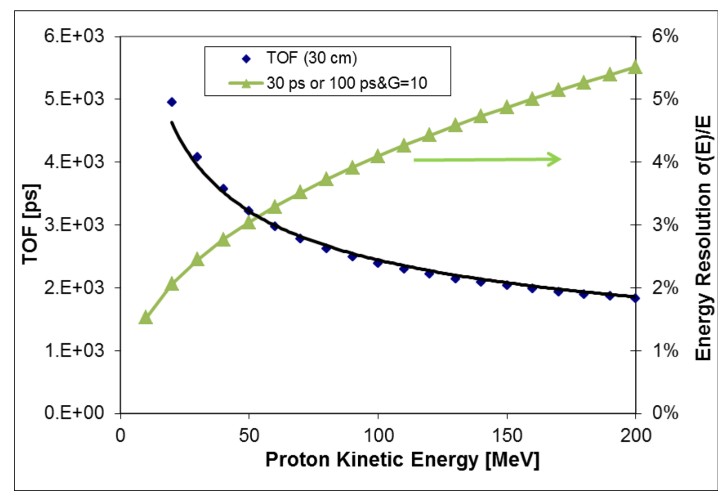


UFSD: 50 um thin, pixels 300um x 300 um,
Time resolution of 30 ps,
i.e. (“100ps & Gain = 10”)
allows energy measurement by TOF

Energy resolution on secondaries:

100 MeV pions: **16%**

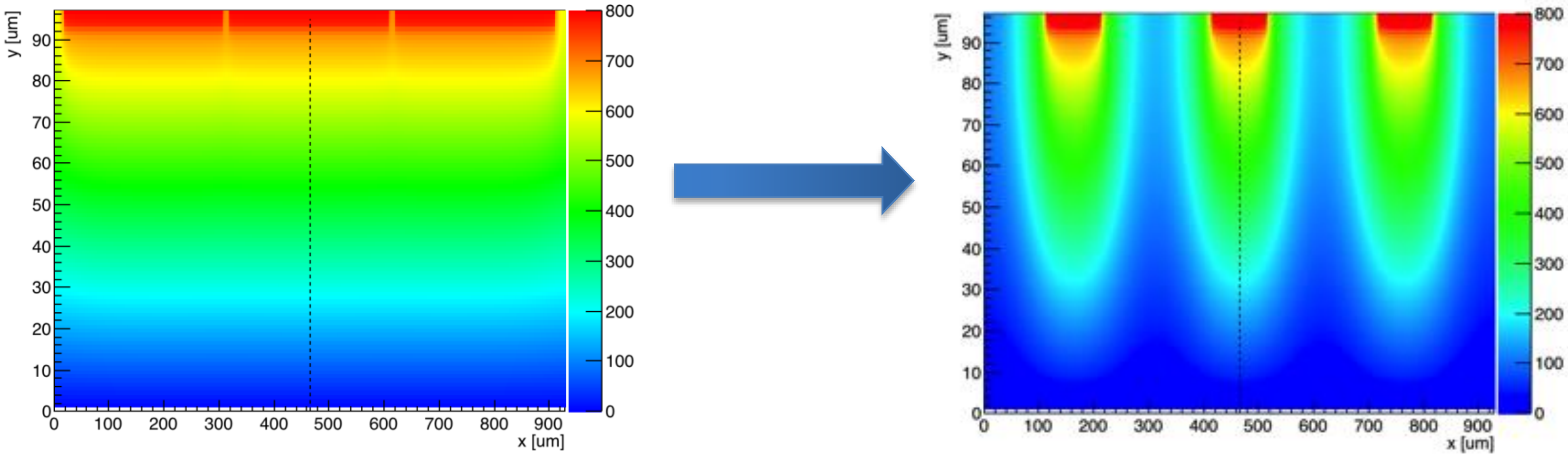
100 MeV protons : **4%**



UFSD can operate at 10+ MHz rate and provide real-time beam diagnostics.

Segmented LGAD: Pixels/Strips

How can we achieve uniform multiplication in segmented detectors?
Electrode segmentation makes the E field very non uniform, and therefore ruins the gain and timing properties of the sensor



Non uniform E field and Weighting field

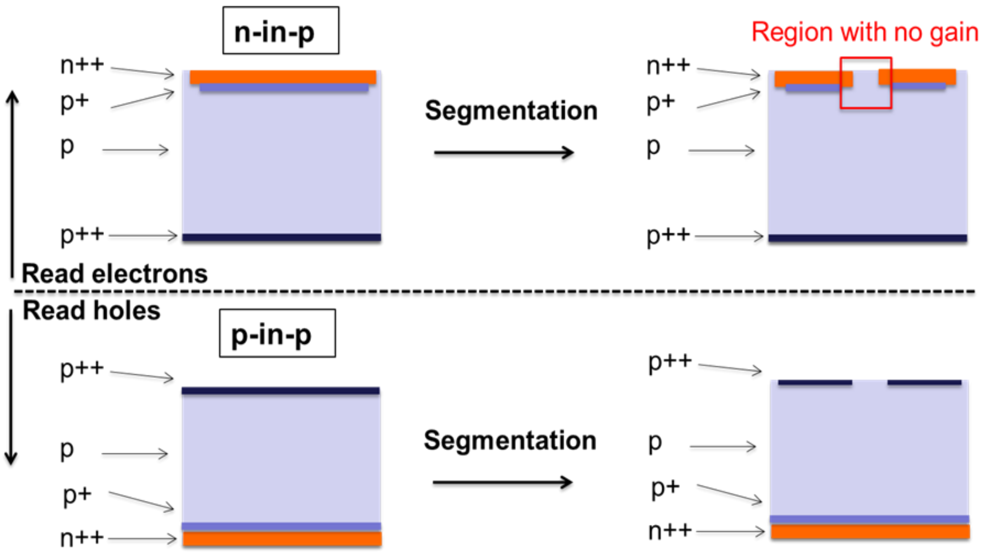
We need to find a design that produces very uniform E field, while allowing electrode segmentation.

1. Separation Timing and segmentation leads to p-on-p LGAD
2. Un-segmented gain layer (resistive sheet) with AC coupling

Segmented LGAD: p-on-p

Gain on LGAD **pad** detectors is well developed.
Segmented no-gain sensors (pixels & strips) are routinely fabricated.
But implementation of **uniform gain** on the **segmented** side of LGAD pixel or strip detectors appears difficult.

Options for electron multiplying structures



Divide functions between the two sides of p-in-p:

- **Position measurement in the small pixel (p)**
- **Time measurement on the gain side (n)**
  (with segmentation of macro – pixels ~1mm^2, C ~1pF)

Segmented LGAD: p-on-p

Reading from both sides gives the best of both environments:

1) Position determination:

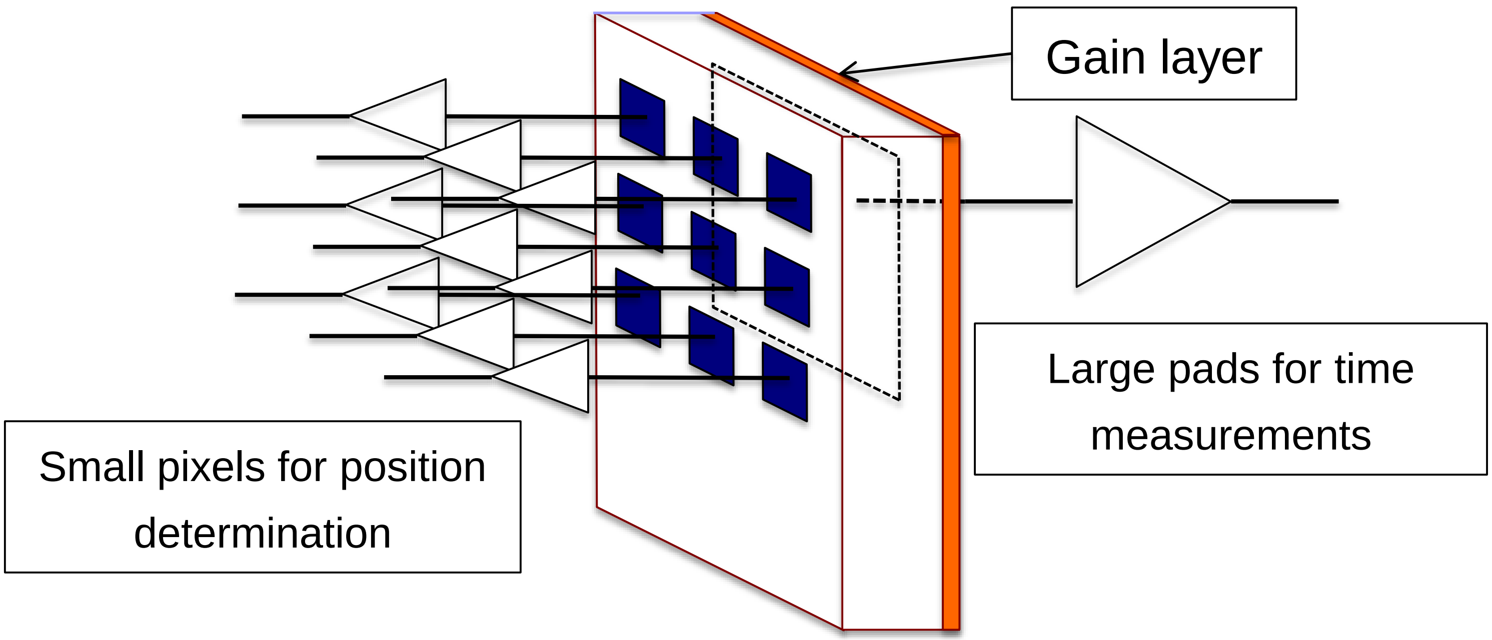
finely pixelated electrodes, opposite to the gain layer.

It can use present chips, for example PSI46, FEI4

2) Time determination:

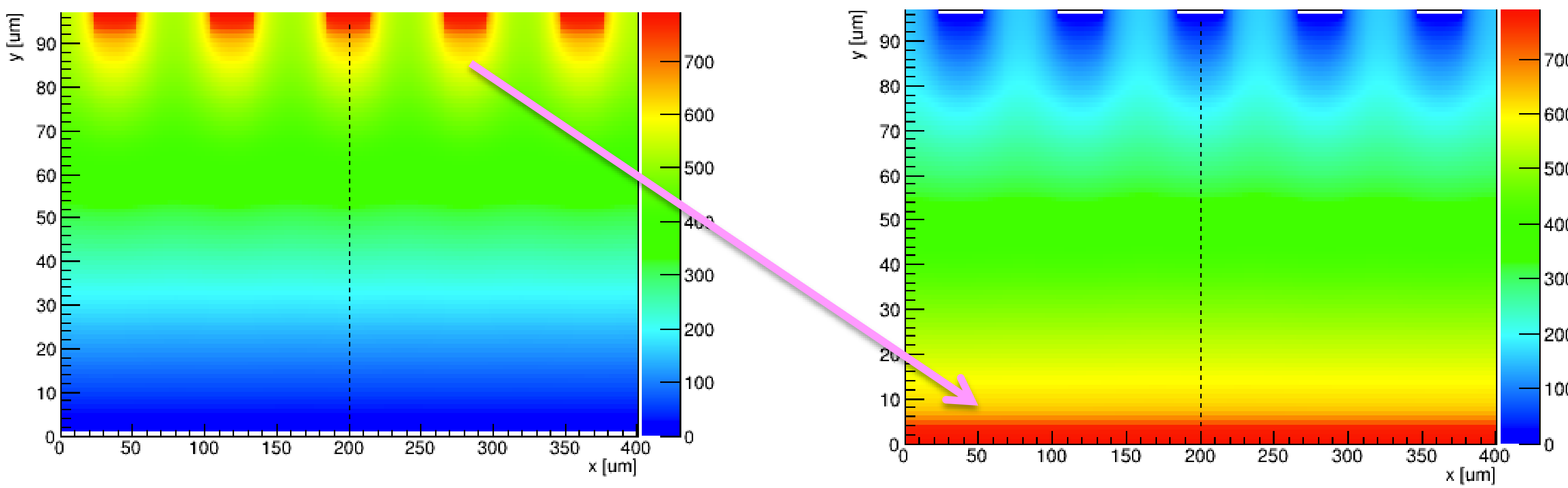
large pads, near the gain layer

Much fewer channels (~1/10)



Segmented LGAD: p-on-p

Segmentation makes the effect of gain more difficult to predict,
and most likely very dependent on the hit position

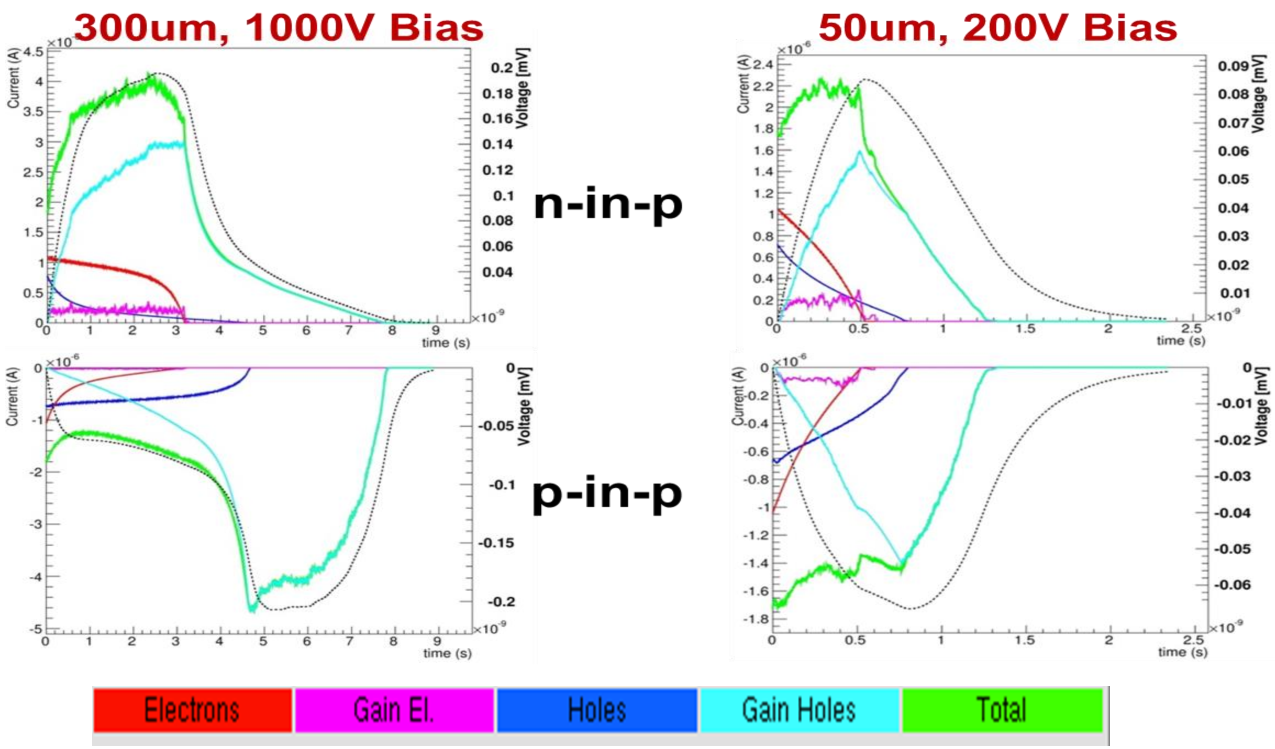


Reversed–LGAD design: the gain is on the opposite side of the read-out

G.-F. Dalla Betta, et al., Nucl. Instrum. Meth. A796 (2015) 154

Segmented LGAD: p-on-p

Will p-on-p work since holes are collected which are slower?



Thick p-type LGAD relies on late hole collection: p-in-p not viable.

Thin p-in-p LGAD has a very fast slew rate, comparable to n-in-p

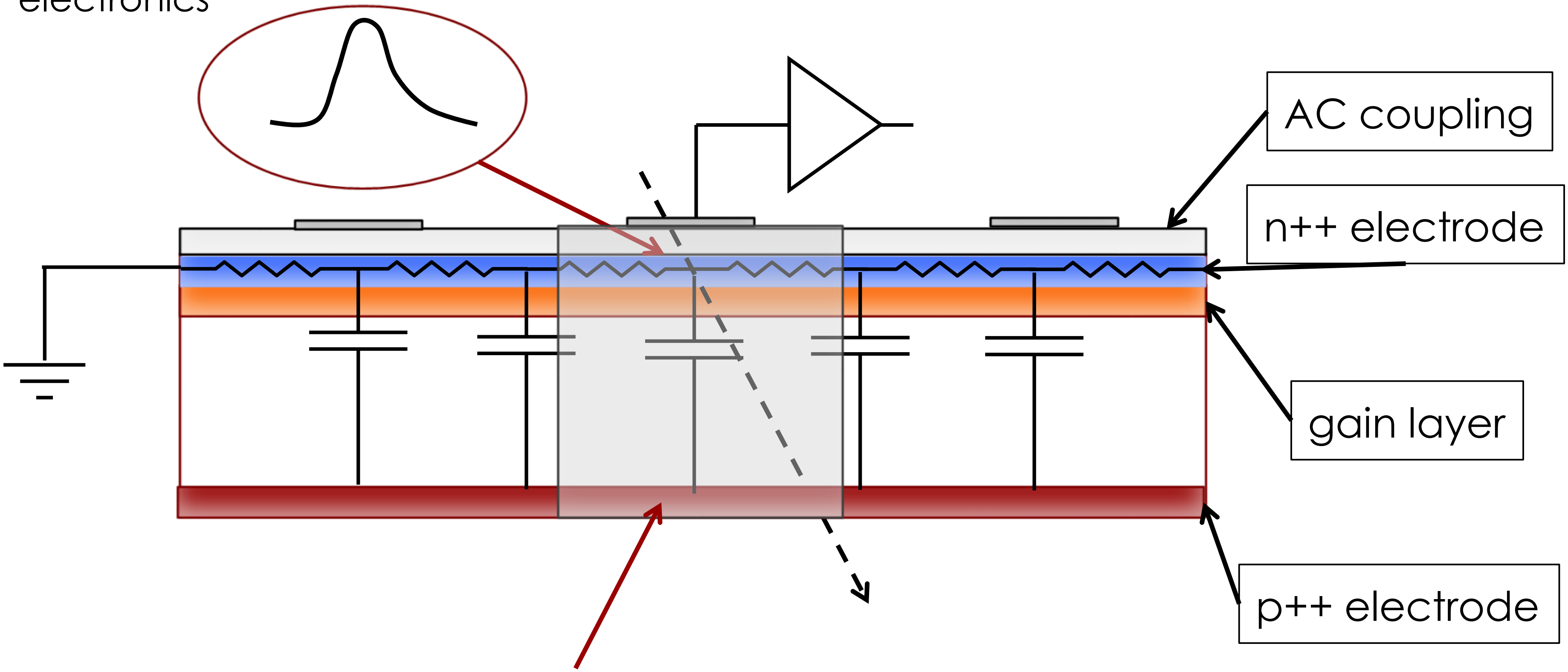
Yes, for thin LGAD!

Resistive sheet with AC-coupled Pixels

The signal is "frozen" on the resistive sheet, and it is AC coupled to the electronics

➔ E and E_w fields are very regular

➔ Segmentation is achieved via AC coupling



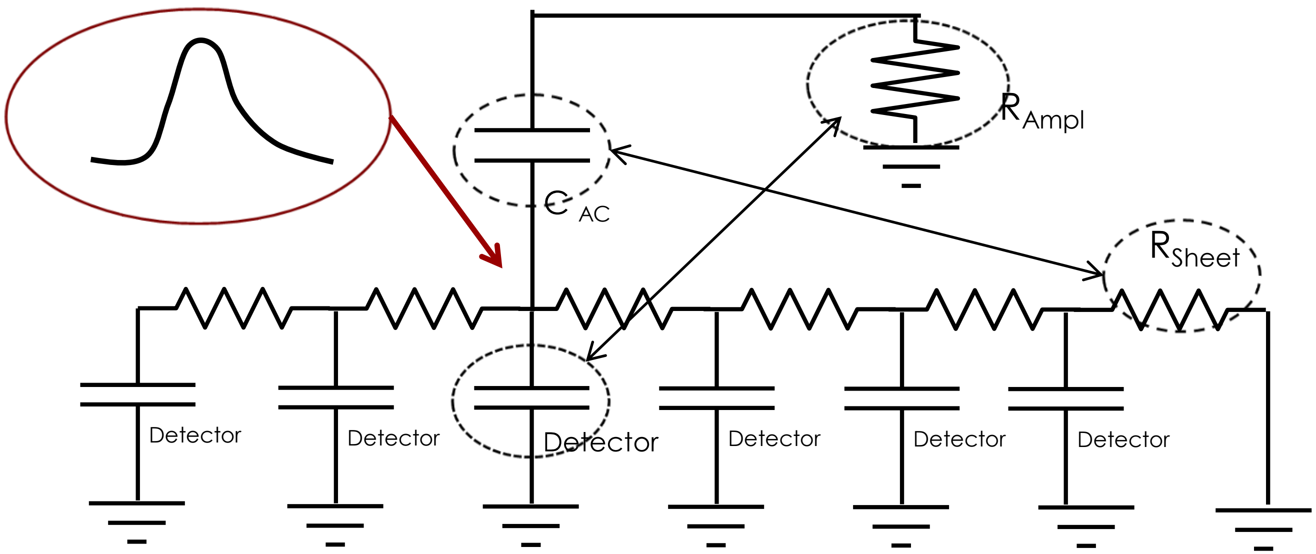
The AC read-out sees only a small part of the sensor: small capacitance and small leakage current.

Resistive sheet with AC-coupled Pixels

Details of AC coupling - I

Additional Rise time

$R_{Ampl} * C_{detector} \sim 100\ \Omega * 1\text{pF} \sim$ **100 ps**



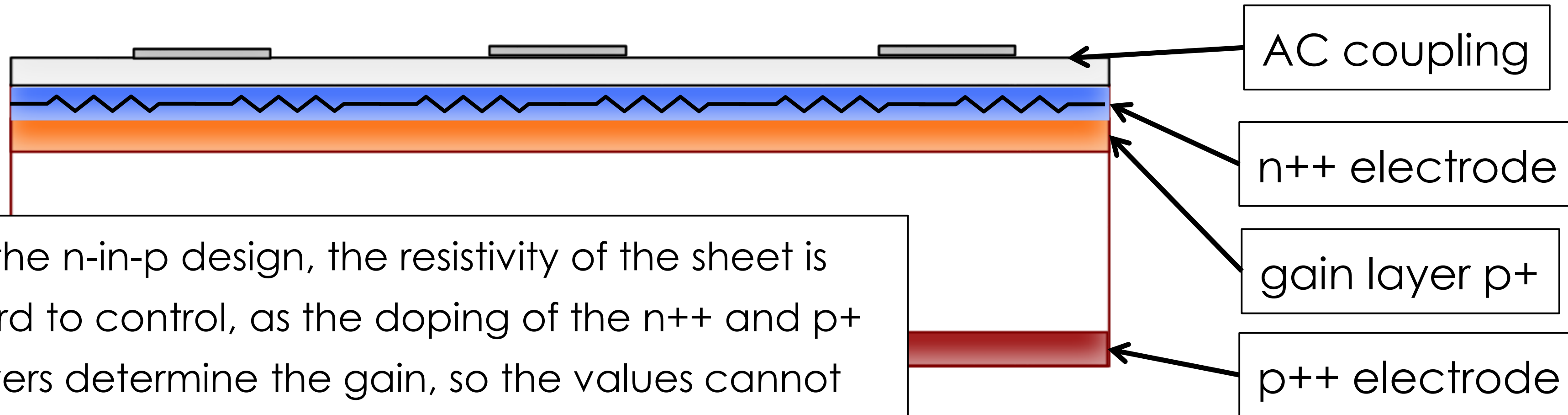
Freezing time

$R_{Sheet} * C_{AC} \sim 1\text{k}\Omega * 100\text{pF} \sim 100$ ns

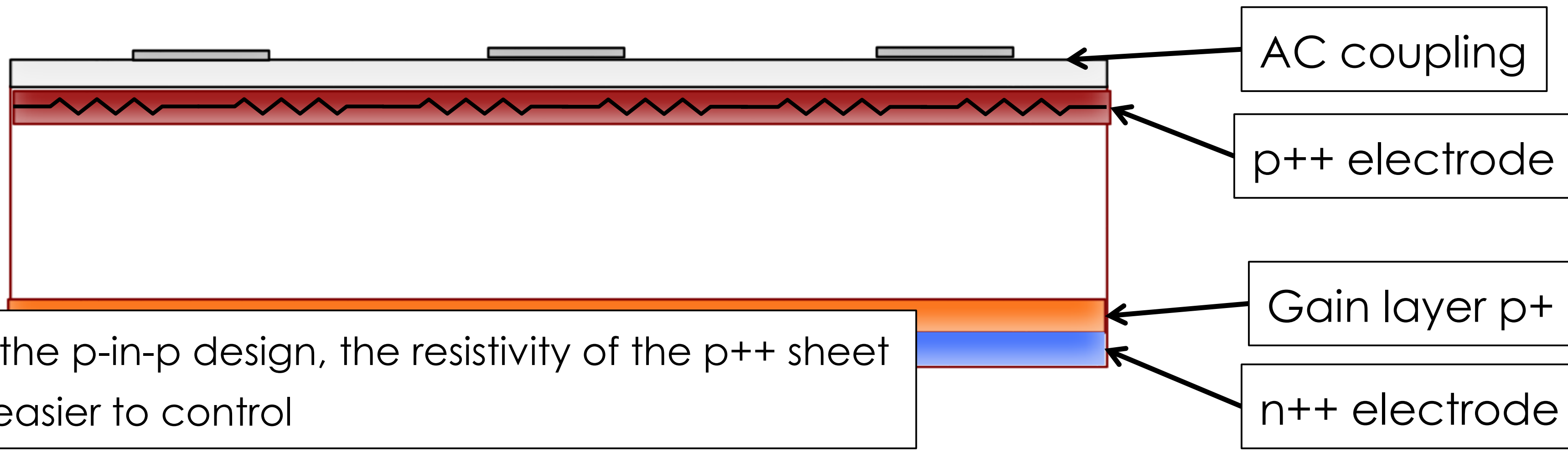
Only a small part of the detector is involved

Resistive sheet with AC-coupled Pixels

Details of AC coupling - II



In the n-in-p design, the resistivity of the sheet is hard to control, as the doping of the n++ and p+ layers determine the gain, so the values cannot be chosen as we like.



In the p-in-p design, the resistivity of the p++ sheet is easier to control