VCI
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Innovative DC-coupled Resistive Silicon Detectors for 4D tracking

R. Arcidiacono (Università del Piemonte Orientale & INFN Torino)

on behalf of the 4DSHARE project

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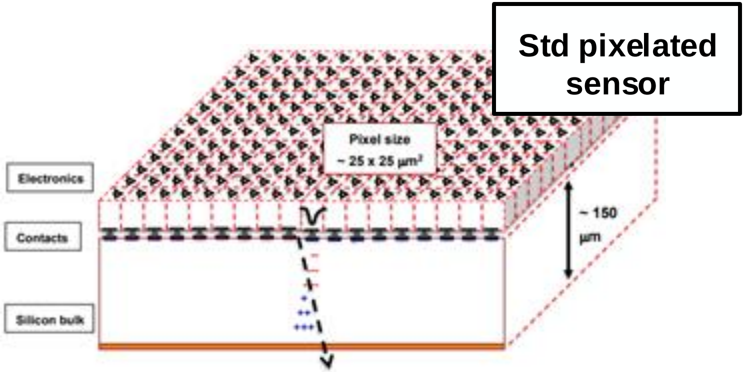
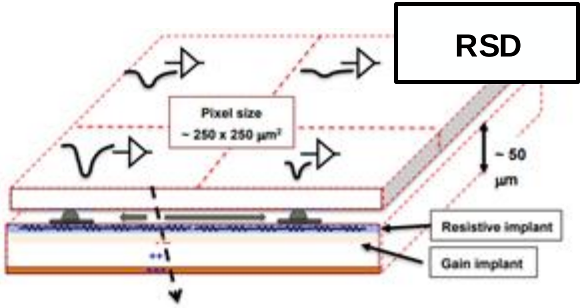
UPO UNIVERSITÀ DEL PIEMONTE ORIENTALE

The paradigm for silicon trackers using “resistive LGAD”





- **Binary read-out: σ_{Pixel} ~ 0.3·pitch**
- **resistive LGADs: σ ~ 0.03- 0.05 ·pitch**
- **resistive LGADs** time resolution with thin detectors→ **30-40 ps** for **50 micron thick**

similar space resolution with reduced number of read-out channels (a factor of ~100 less)
smaller material budget

excellent time resolution

Space resolution with RSDs

AC-coupled resistive LGADs → RSD

FBK RSD2 (2021) best design: Swiss cross electrodes.

Position performance have been explored with laser and at several test beams.

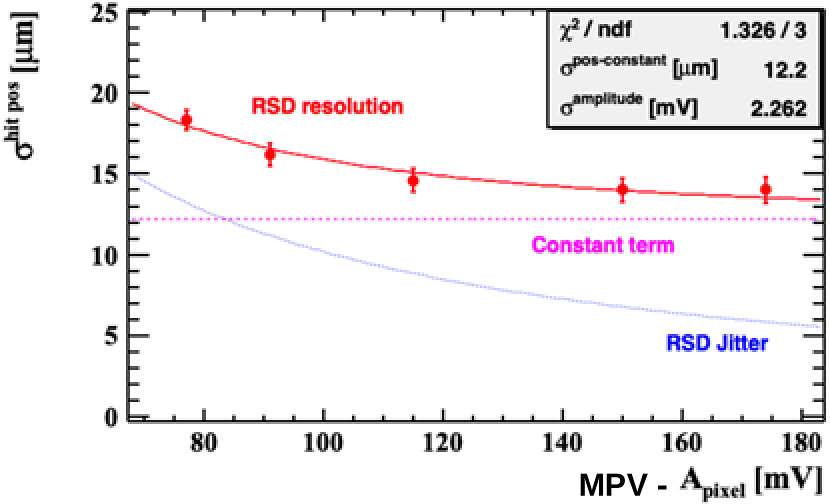
Results with electron testbeam (DESY)

RSD2-450, pixel 450 x 450 um^2 - 16 electrodes read out
16ch FAST2 Board (INFN Torino) + CAEN Digitizer

The constant term dominates the resolution $\sigma_{constant}$ ~ 13 µm
It includes mis-alignment RSD-Tracker, sensor and electronics non uniformity, etc…

Resolution around **3%-4%** **of the pitch.**

RSD2-450-micron pitch



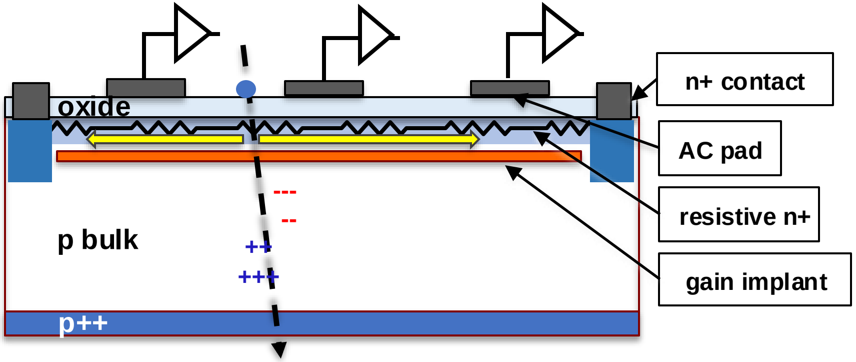
$$\sigma^{\text{hit pos}} = \sqrt{(\sigma^{\text{pos-constant}})^2 + (\frac{\sigma^{\text{amplitude}} \times \text{pitch}}{\Sigma_i^4 A_i})^2}.$$

L. Menzio et al, "First test beam measurement of the 4D resolution of an RSD 450 microns pitch pixel matrix connected to a FAST2 ASIC",)NIMA 1065 (2024), 169526

Next evolution: DC-coupled RSD

RSD sensors show **some non-ideal features**:

- Signal spread may involve a large (>4) and variable number of electrodes, leading to slight deterioration and a non-uniform spatial resolution over the sensor surface
- Baseline fluctuations (leakage current collection only at the edge) in large and/or irradiated devices
- Signals are bipolar with rather long tails during the discharge



RSD (AC-LGAD)

DC-coupled Resistive Silicon Detectors

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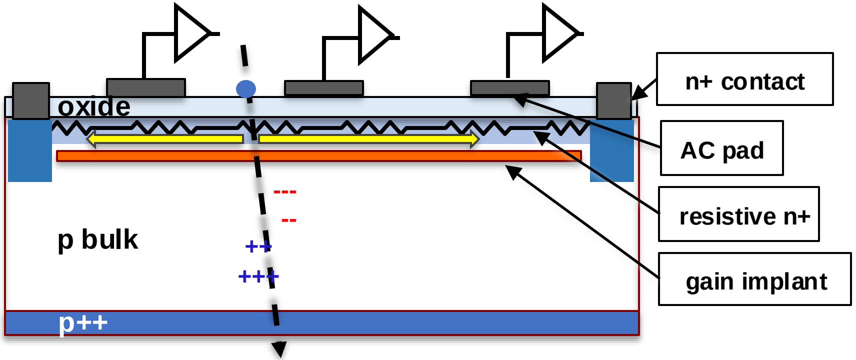
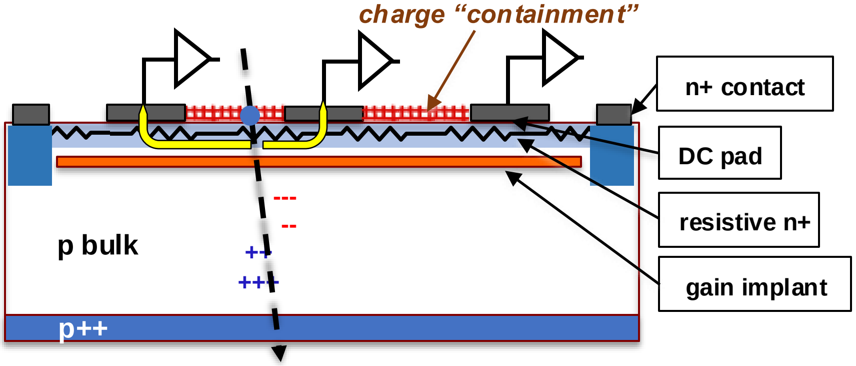


RSD (AC-LGAD)

Evolution of the RSD design:

DC collection of signals, with low resistivity paths to readout pads **+ charge "containment"** structures (isolating trenches for now) $\Longrightarrow$ **DC-RSD design**



DC-RSD

DC-coupled Resistive Silicon Detectors

In the DC-RSD design

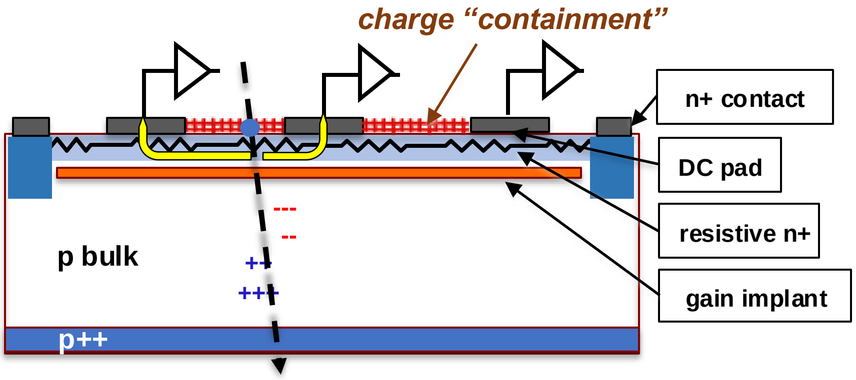
- Signal is confined: charge sharing in a predetermined number of pads
- the leakage currents is removed locally at each electrodes
- No bipolar signal → 1-2 ns-long pulses

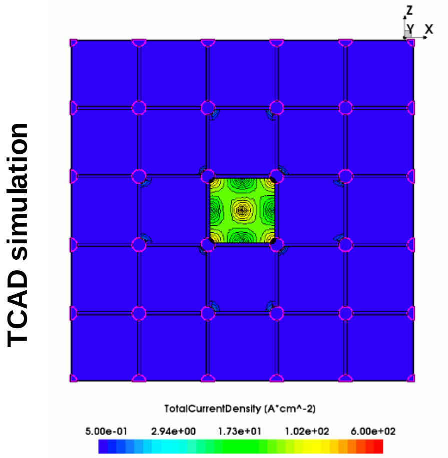
→ expected more uniform performance and design scalable to large devices

Extensive simulation studies performed to optimize design: resistive path, charge sharing, electrodes geometry, confinement method…

F. Moscatelli et al, https://www.sciencedirect.com/science/article/pii/S0168900224003061

A. Fondacci's talk at Pixel2024





DC-RSD with trenches

current density over device surface, generated by a hit in the center of the pixel → expected **signal confinement**

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DC-RSD1: “proof-of-concept” production

DC-RSD developments: supported by 3 national **Grants** [4DinSiDe, 4DSHARE projects] so far.

The first production was completed @FBK in November 24: **DC-RSD1**

- The solution selected to achieve **charge containment**: use of Isolating Trenches (like TI-LGADs or SiPM)

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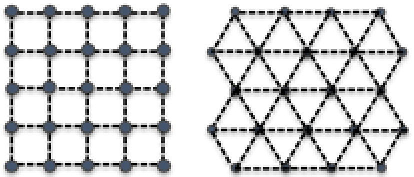
- The solution selected to achieve **charge containment**: use of Isolating Trenches (like TI-LGADs or SiPM)

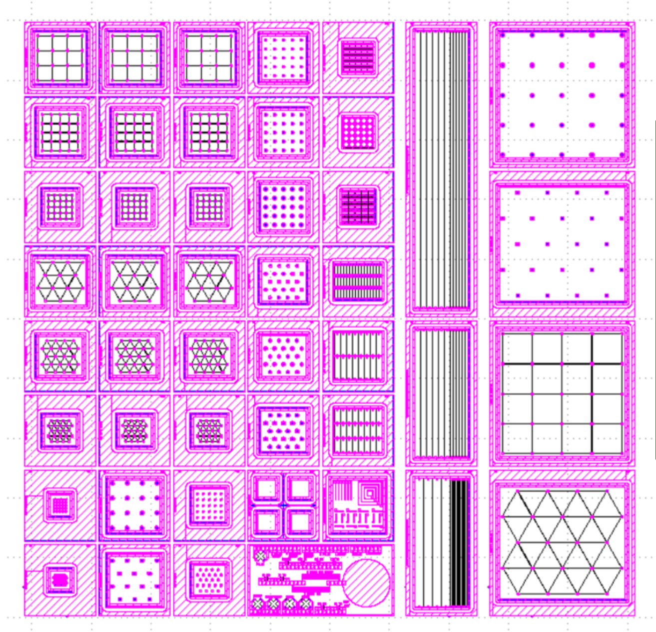
Several test structures implemented:

- devices with squared or hexagonal matrix of electrodes (dot-shaped), with and without isolating trenches, multiple pitch options
- strips with multiple pitch options and multiple length



"square" or "triangle" pixel shape

- devices without isolating trenches have been implemented to allow comparison with the equivalent designs in AC-LGADs



DC-RSD1 reticle

DC-RSD1: “proof-of-concept” production

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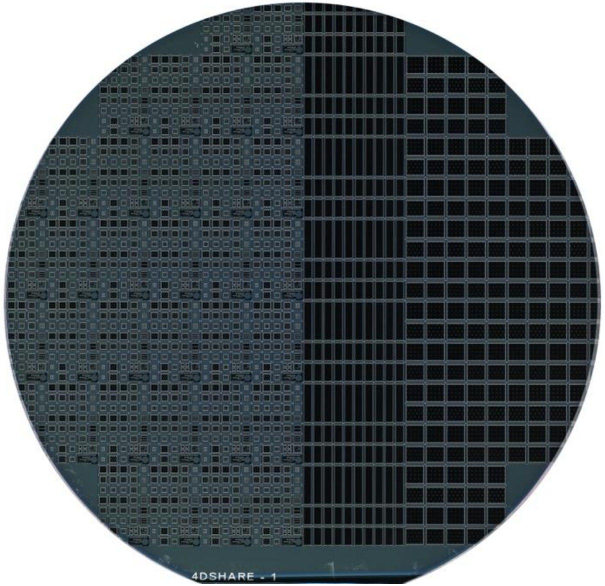
Split table:

Wafer	NPLUS dose	CONHO_IMP	Trench depth	Trench process	PGAIN dose	Thickness
1	0,25		D2	P2	1.02	55
2	0,25	Y	D2	P2	1.02	55
3	0,25	Y	D2	P2	1.06	55
4	0,25	Y	D2	P2	1.06	55
5	0,5		D2	P2	1.02	55
6	0,5		D2	P2	1.06	55
7	0,5	Y	D2	P2	1.06	55
8	0,5	Y	D2	P2	1.02	55
9	1		D2	P2	1.02	55
10	1		D2	P2	1.06	55
11	1	Y	D2	P2	1.02	55
12	1	Y	D2	P2	1.06	55
13	0,25	Y	D2	P2	1.06	55
14	0,5	Y	D2	P2	1.02	55
15	1	Y	D2	P2	1.06	55

wafer selected for lab and testbeam measurements



DC-RSD1 wafer

see M. Centis Vignali’s Talk at TREDI2025 for more information on the DC-RSD1 production

DUTs @DESY testbeam

Today: preliminary results on space and time resolutions of these devices

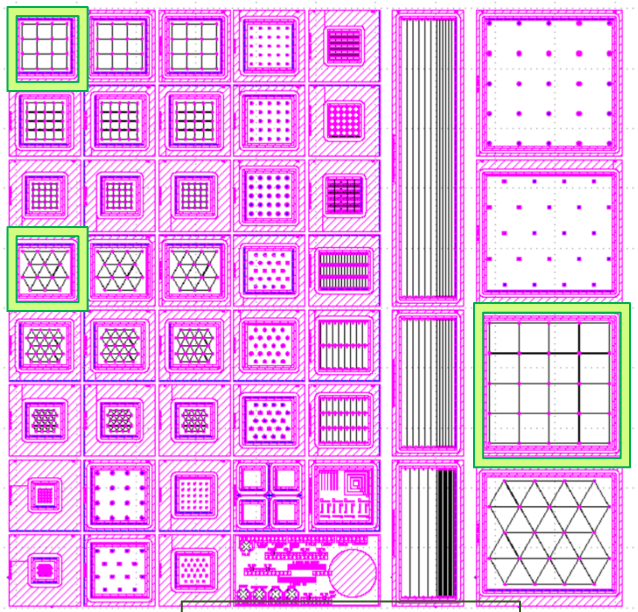
measured with a 5 GeV electron beam (DESY)

“Square” pixels

- 3x3 pixel matrix
- 16 electrods
- 500- and 1000-micron pitch

“Triangle” pixels

- 5x3 pixel matrix
- 14 electrodes
- 500-micron pitch



DC-RSD1 reticle

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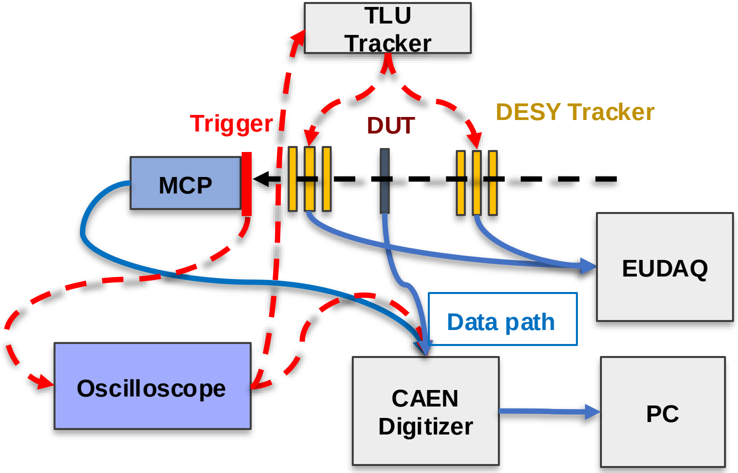
The DESY test beam set-up

Two different data taking modes

Studies of spatial resolution

Read many pixels using a CAEN digitizer

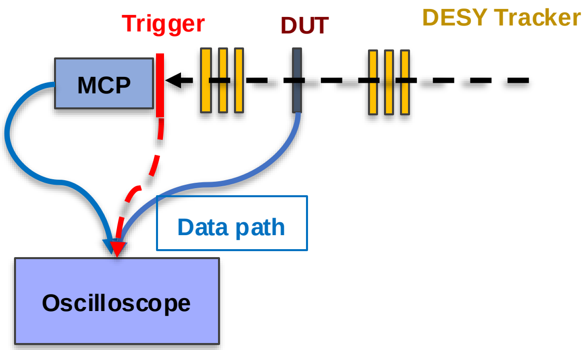
- Up to 16 electrodes



Studies of time resolution

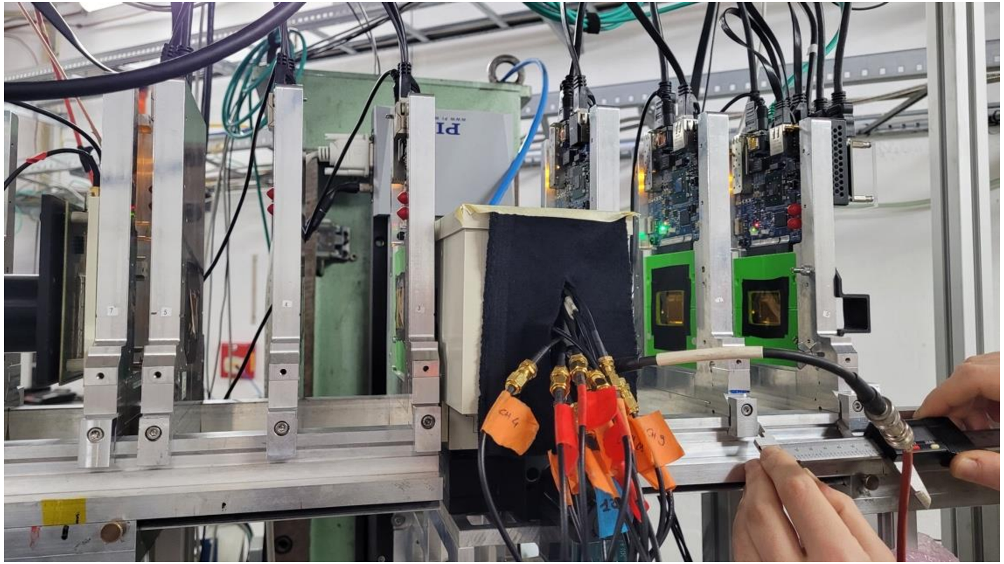
Read 2 pixels using an 8-ch oscilloscope

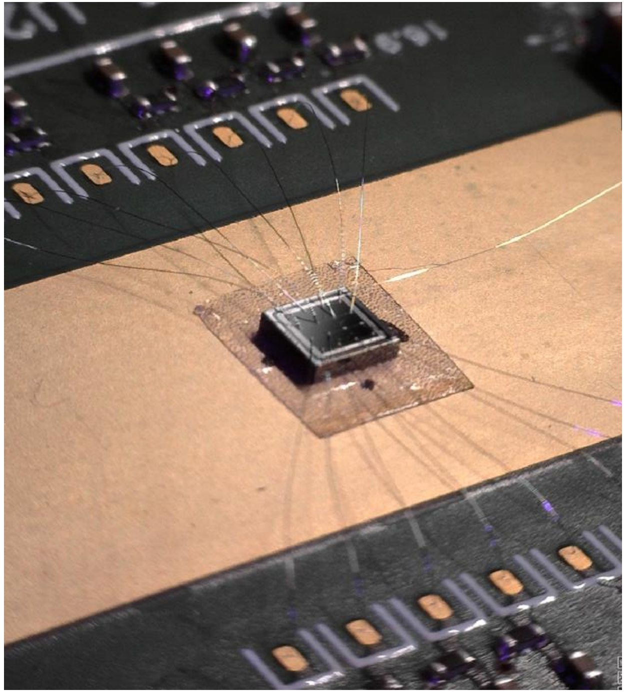
- Up to 7 electrodes + MCP (time reference)
- High time resolution



The DESY test beam set-up

in pictures….



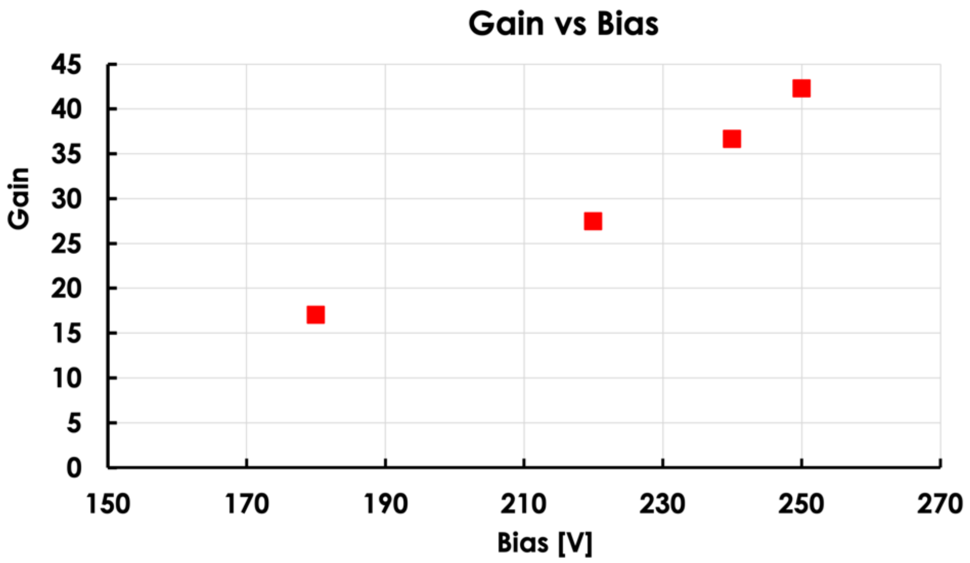


DC-RSD1 W3: gain studies

Wafer 3: "high" p-gain dose, highest n+ resistivity ("slower" propagation on the resistive layer)

High-statistics runs taken at different reverse bias voltages.

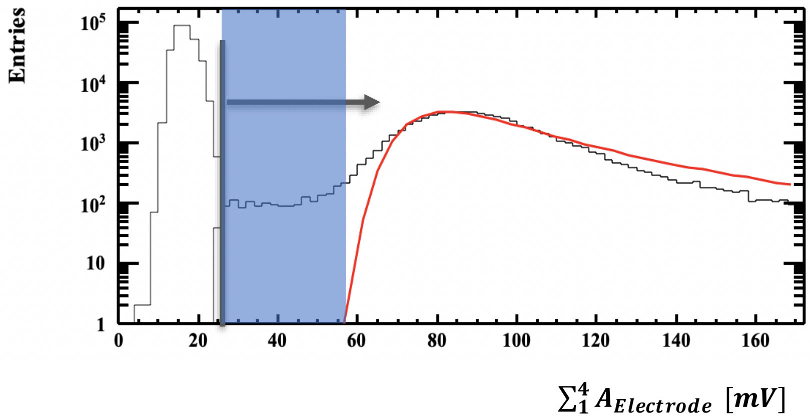
Gain estimated by comparing the signal area measured at a given bias, with the theoretical signal area in a PIN (uncertainty ~10%)



Gain range used in the analysis: 15 - 45

Signals collected by a pixel

The signal collected by a "pixel" is estimated **summing the amplitudes seen by the four** (three) **electrodes** defining the squared (triangular) pixel



Clear separation between signal (Landau in red) and noise.

Event Selection criteria: $A_{pixel} > 25\, mV$

Events with lower amplitudes are located close to trenches

Signals collected by a pixel: inefficiencies?

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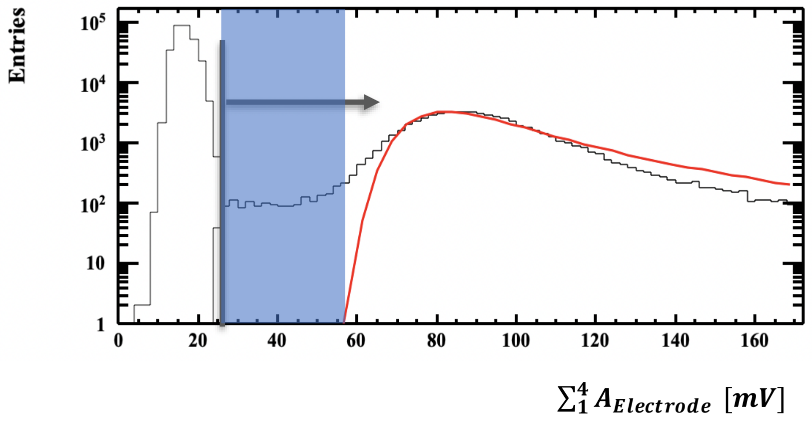


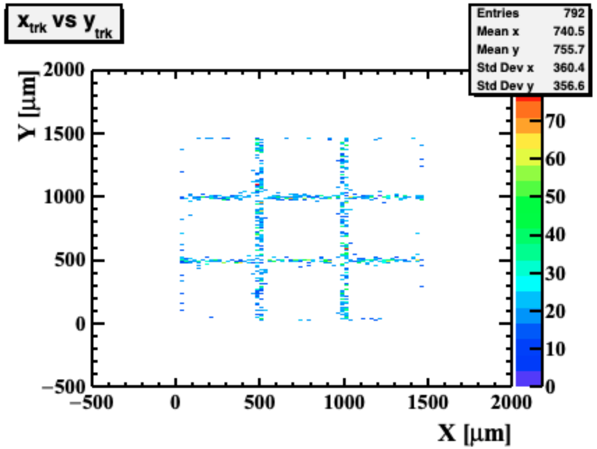
Clear separation between signal (Landau in red) and noise.

Event Selection criteria: $A_{pixel} > 25\,mV$

Events with lower amplitudes are located close to trenches

Is the DUT inefficient?

Events with tracks inside the active area and $A_{pixel} < 25\,mV$



mostly aligned with the trenches!
this is not inefficiency but acceptance (fill factor ~ 99%)

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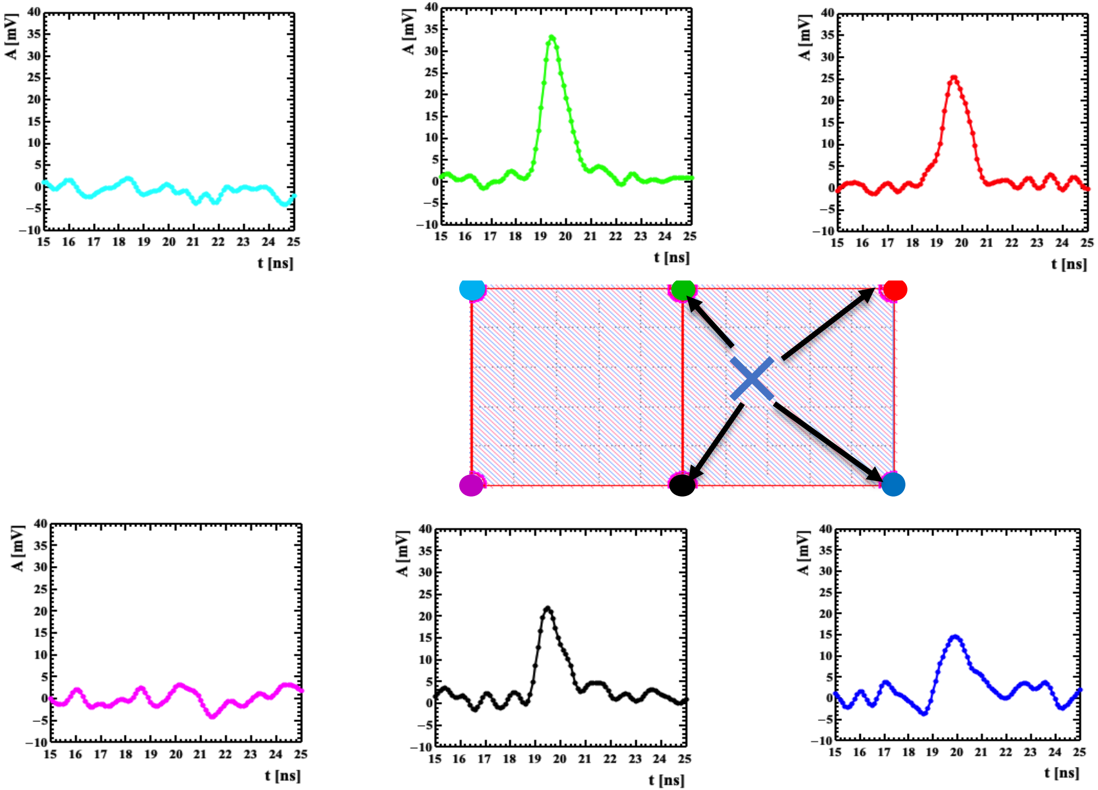
Signal shape: square pixel, 500-micron pitch

Amplitudes recorded by 6 electrodes (see sketch)

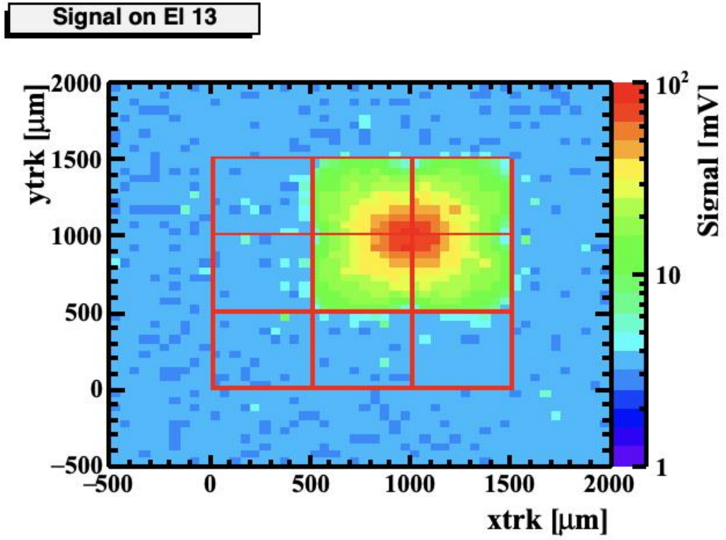
- **The signal is fast**, unipolar, same shape of a standard LGAD.
- **Perfect isolation**: the signal is seen only in the electrodes belonging to the hit pixel.

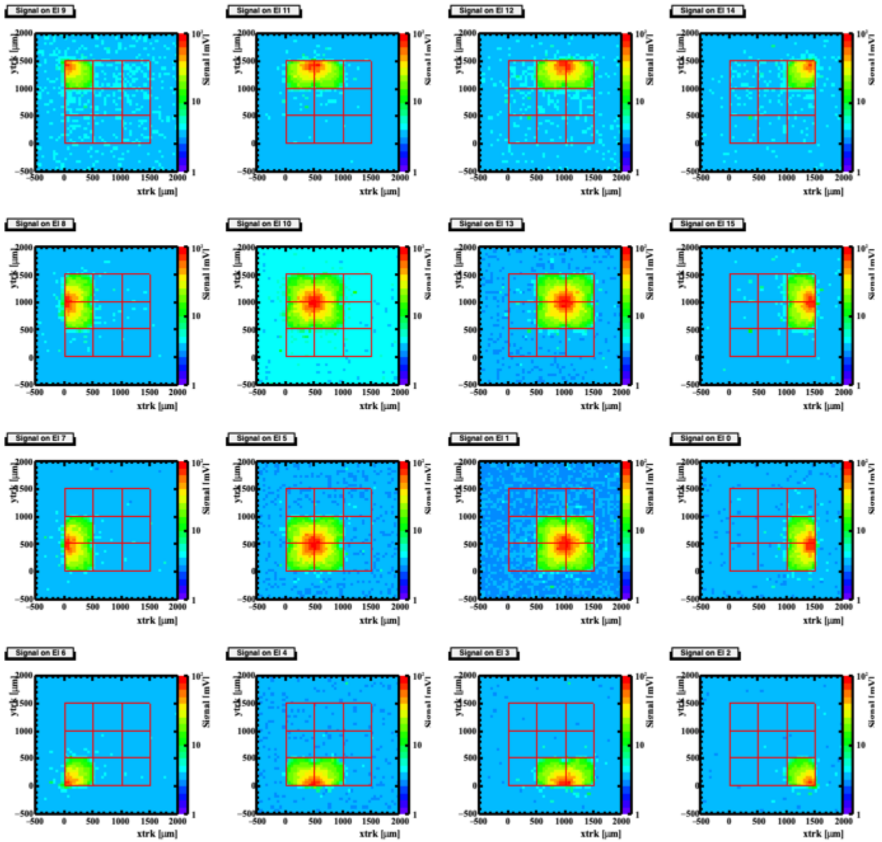


DC-RSD signal containment

Average signal amplitude seen by each electrode as a function of the $(X,Y)_{TRACKER}$

(Square pixels 230V)

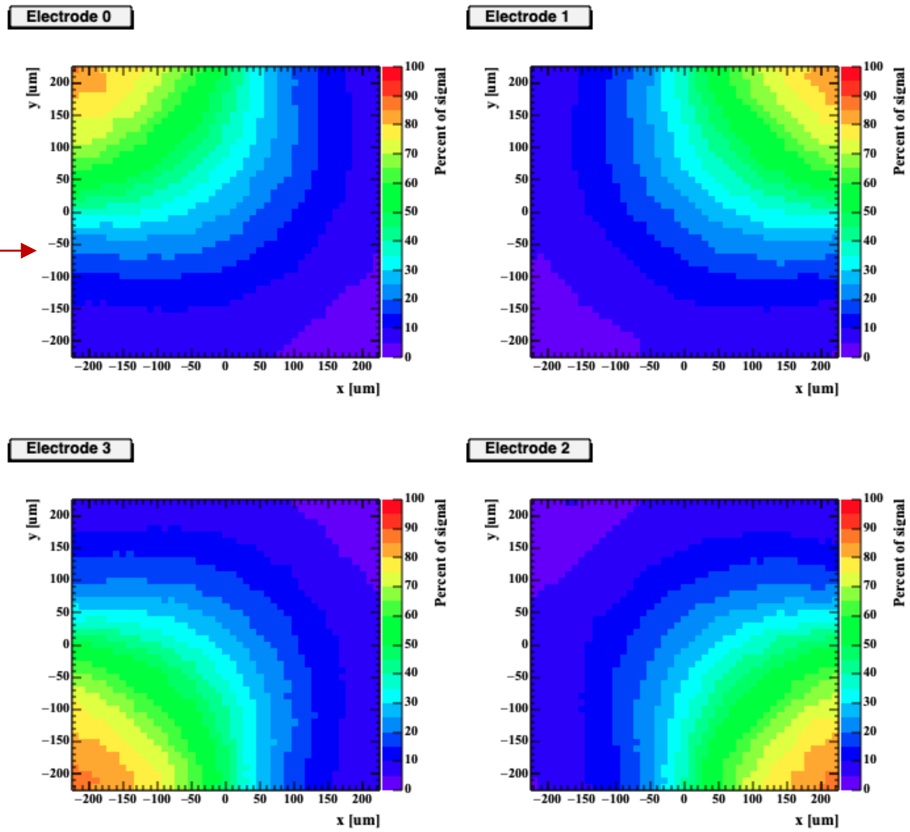




Position reconstruction method: sharing template

Position reconstruction procedure:

1) Produce look-up tables with the signal-sharing pattern among the 4 electrodes (done with test beam data).
   These plots show the signal percentage seen by a given electrode as a function of position (tracker)
2) For each event, compare the measured signal sharing with the look-up table to find the location that best reproduces the measured sharing



NB:

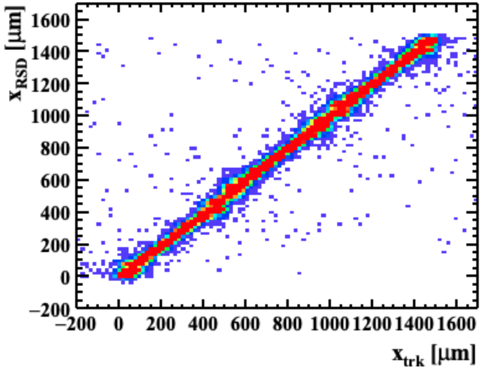
- **DUTs** have been **aligned w.r.t. the tracker**
- **Rotations** have been estimated and **corrected for**
- **electrodes amplification** (FNAL board) **inter-calibrated**, equalizing the MPV of the amplitude distributions

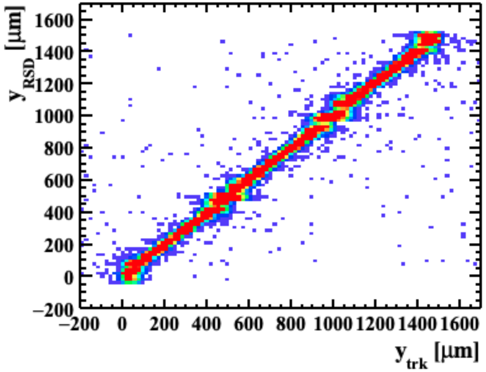
DC-RSD position resolution

Square matrix, 500-micron

Bias = 240 V (gain ~37)

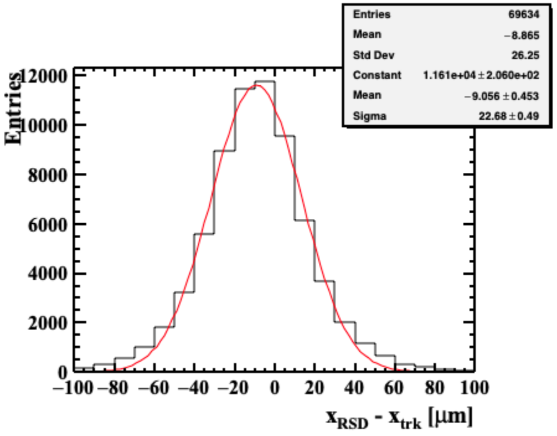
Correlation between the positions of tracker and DC-RSD over the whole 3x3 matrix.

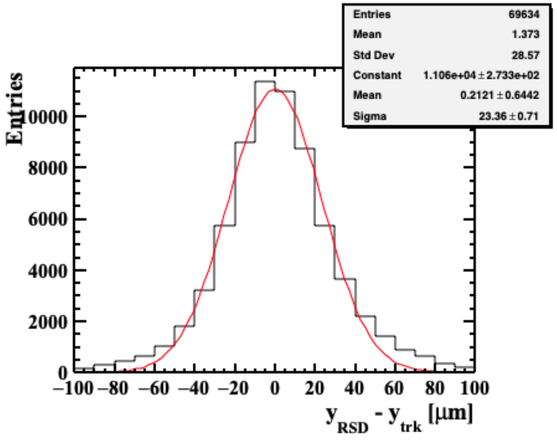




Measurement of the position resolution $(X, Y)_{DC\text{-}RSD} - (X, Y)_{TRK}$

$$\sigma_{x,y} \sim 23\ \mu m$$

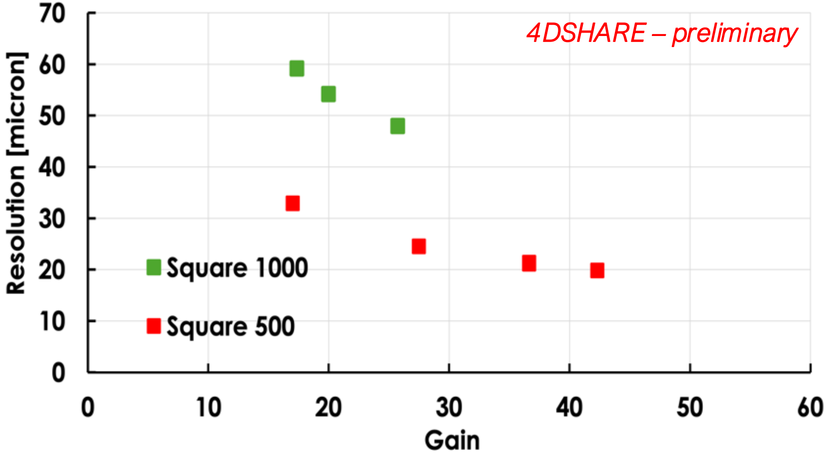




Position resolution: summary of results

Resolution for the 500- and 1000-micron pitch squared pixel matrix

(tracker resolution ~8 micron subtracted)



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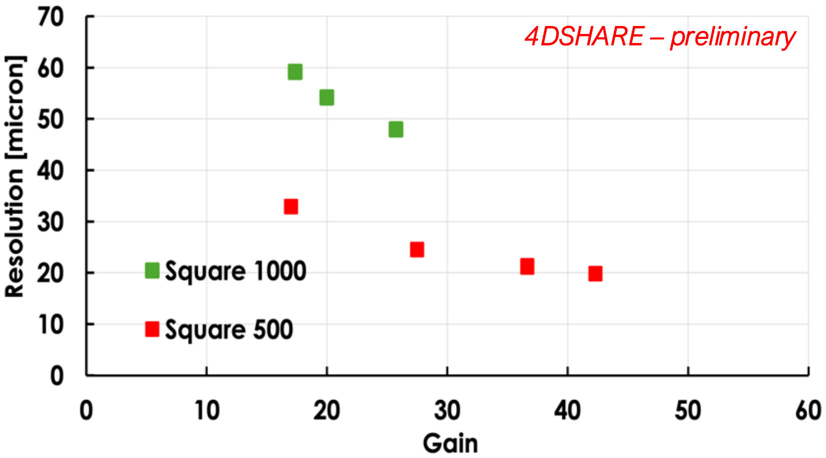
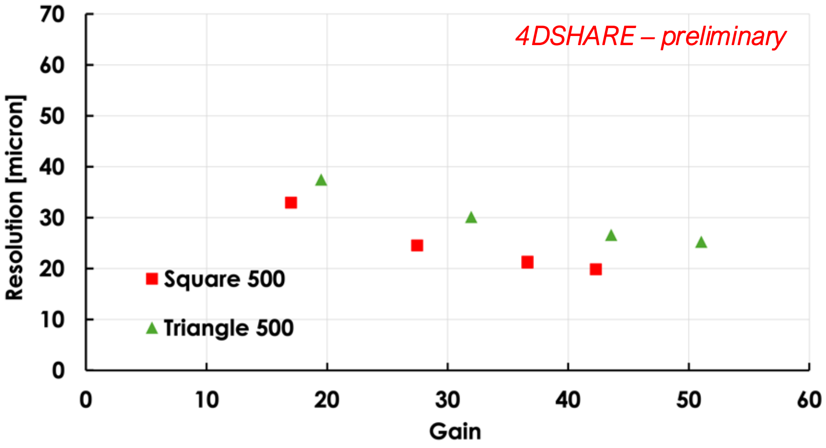


Resolution for the 500-micron pitch squared and triangular pixel matrix

(tracker resolution ~8 micron subtracted)



Both sensors reach very good position resolution, below 5% of their pitch

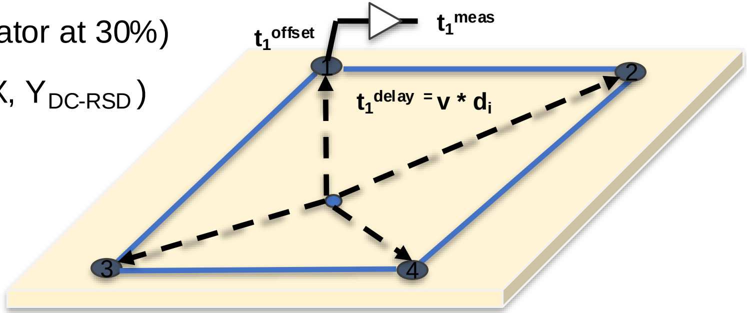
Square pixels are better performing than triangular pixels

Time reconstruction procedure

For each electrode, estimate the time of the hit t_i^{hit}

- Measure the time of arrival t_i^{meas} (constant fraction discriminator at 30%)
- Correct for signal delay $t_i^{delay} = v * d_i$ (d computed using X, $Y_{DC\text{-}RSD}$)
- Correct for set-up offset t_i^{offset}

$$t_i^{hit} = t_i^{meas} + t_i^{delay} + t_i^{offset}$$



The delays are calculated assuming a given signal propagation velocity on the n+ layer

The **particle time is computed combining the 4 measurements**, weighted with the squared amplitude

$$t^{hit} = \frac{\sum_1^4 t_i^{hit} A_i^2}{\sum_1^4 A_i^2}$$

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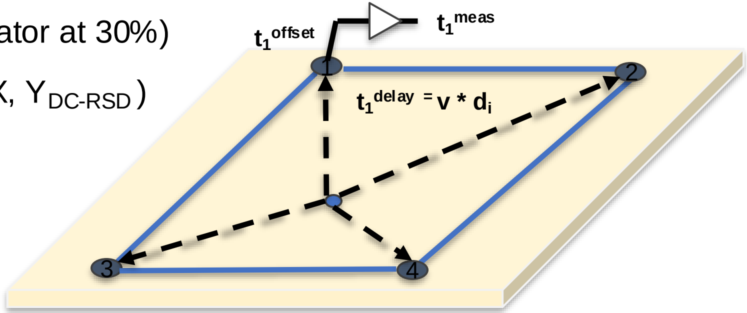
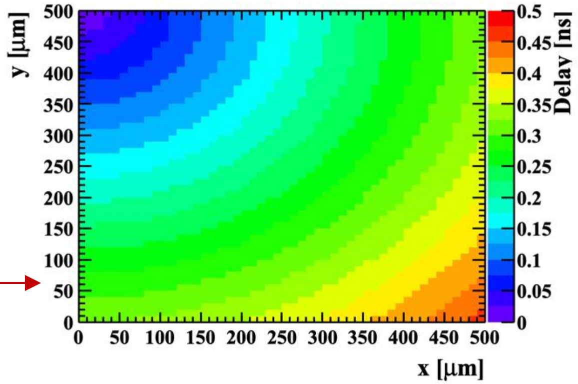


The **particle time is computed combining the 4 measurements**, weighted with the squared amplitude

$$t^{hit} = \frac{\sum_1^4 t_i^{hit} A_i^2}{\sum_1^4 A_i^2}$$

The delays are calculated assuming a given signal propagation velocity on the n+ layer, **which can also be measured using the data**

signal delay as a function of the hit position



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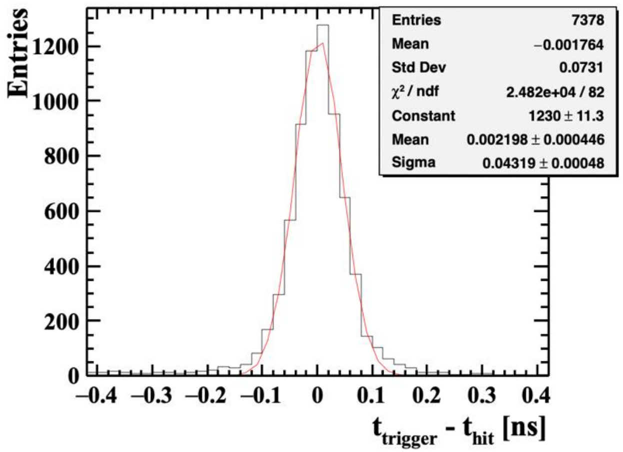
DC-RSD Time resolution

$$t^{hit} = \frac{\sum_1^4 t_i^{hit} A_i^2}{\sum_1^4 A_i^2}$$

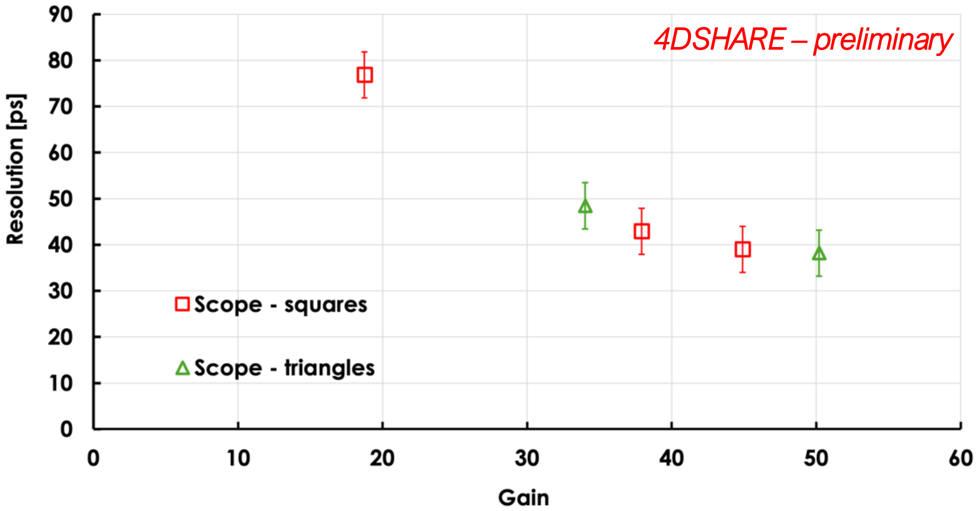
Distribution of $t^{MCP} - t^{hit}$ for 500-micron square matrix, bias = 240 V

$\sigma_t \sim 43\ ps$



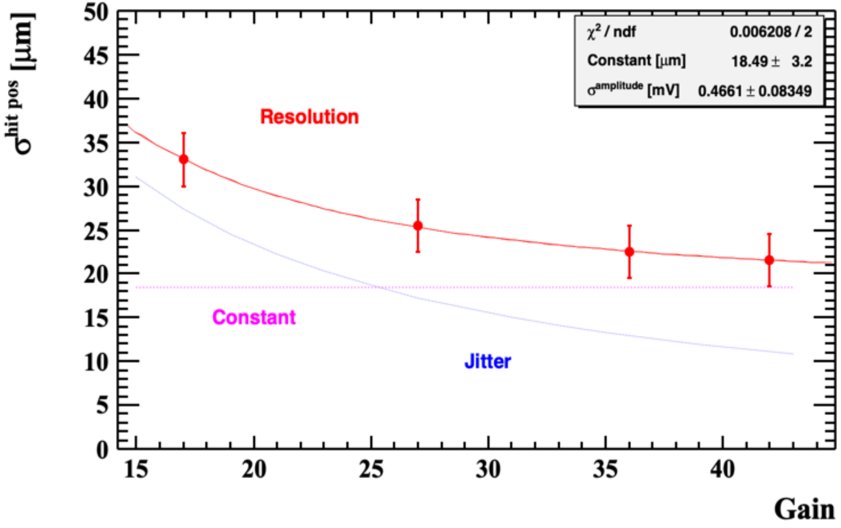
Time resolution for the 500-micron pitch squared and triangular pixel matrix

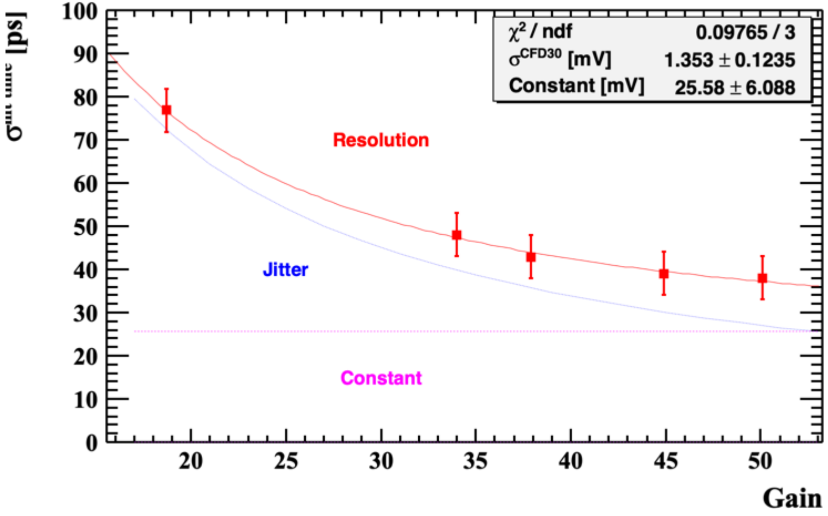
(time resolution MCP estimated to be 5 ps – subtracted)



Performance DC-RSD "squares" pitch 500

20 micron – 40 ps





Summary and Outlook

The **first prototype run of DC-RSD has been completed** and works very well!

Initial measurements done @FBK on-wafer gave us very important feedback on the success (or problematic points) of the process flow

The main goal of the production, **the realization of matrices of trench-isolated DC-RSD**, has been achieved, with fast and unipolar signals (similar to standard LGADs)

DC-coupled electrodes are alive, the charge is contained by the trenches

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Summary and Outlook

The **first prototype run of DC-RSD has been completed** and works very well!

Preliminary measurements of space and time resolution are excellent!

All devices tested ("square" pixels with 500-, 1000-micron pitch and "triangle" pixels with 500-micron side) achieve a **position resolutions better than 5% of the pitch**.
For the square matrix:

- 500-micron pitch: $\boldsymbol{\sigma_{x,y} \sim 20\ \mu m}$
- 1000-micron pitch: $\boldsymbol{\sigma_{x,y} \sim 48\ \mu m}$

Time resolution is $\boldsymbol{\sigma_t \sim 40\ ps}$ for gains > 40

We are preparing for the second **DC-RSD Test Beam** at **DESY, adding DUTs with different pitch size and resistivity.**
Full systematic studies of the production in lab with TCT, beta-source setup are ongoing.

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Acknowledgements

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- European Union's Horizon Europe research and innovation program under grant agreement no. 101057511 (EuroLABs)

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Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

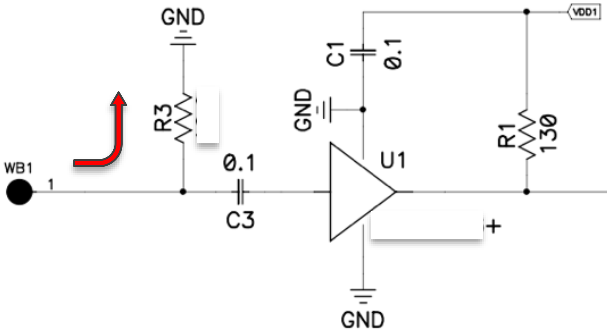
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

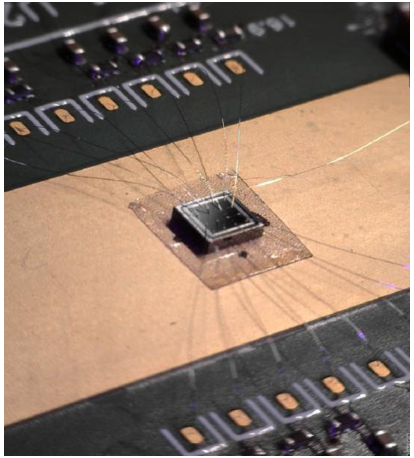
Thanks for the attention!

Back-up material

Front-end board

- 16-ch fast TIA pre-amplifier analog board, developed at FNAL (2-stage amplifier chains based on the Mini-Circuits GALI-66+)
- ~25 ps jitter, fixed gain = 70
- About 1 GHz BW
- Noise ~ 1.5 mV
- Well-suited for DC-RSD read-out (RC input circuit)





DC-RSD wirebonded to FNAL board

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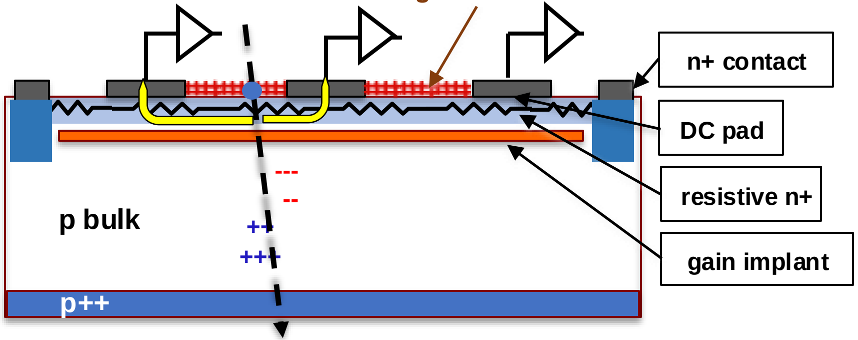
DC – RSD front-end amplifiers

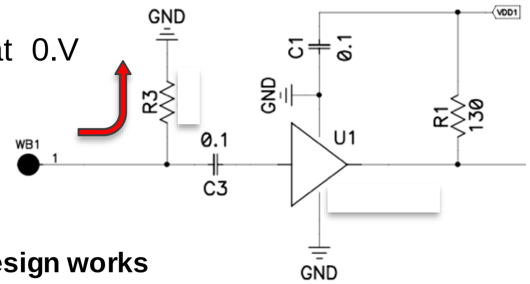
The amplifiers are connected to the same n+ sheet.

For the read-out to work, **the amplifiers should polarize the sensor to the same reference level.**



Input into an RC

DC level uniform at 0.V

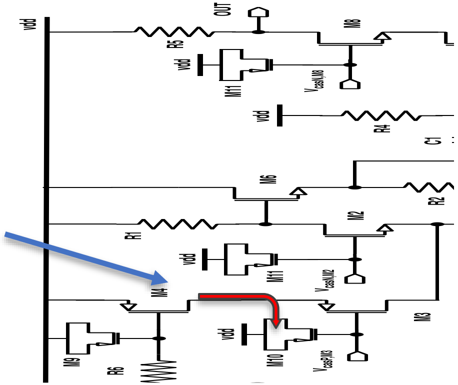


This design works

Input into a transistor,

DC level non uniform,

about 0.7 V



This design does not work

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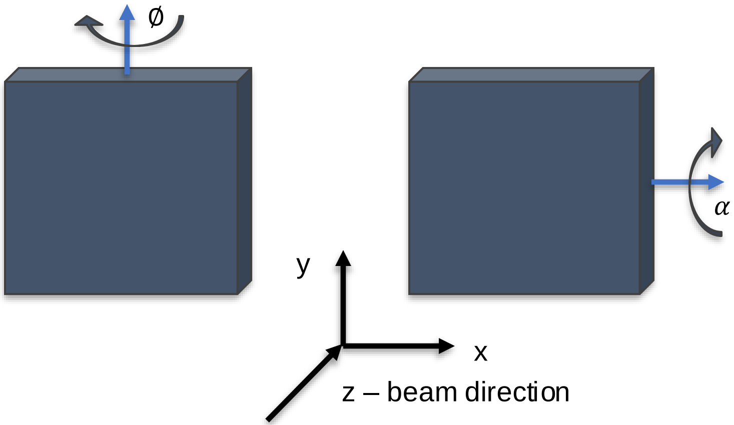
Data correction: rotations

The DUT can have a rotation in the x-y plane

Such a rotation will “deform” **the DC-RSD pixel size seen by the tracker**



For a pixel:

RSD dimension: pitch

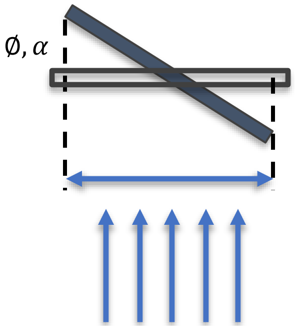
Tracker dimension: pitch*cos(Ø)

Rotations measured on the 500-microns:

x- rotation: 15 – 20 degrees

y rotation: 0 degrees

With a rotation, the RSD coordinates are larger than the tracker’s



Tracker range: pitch*cos(Ø)

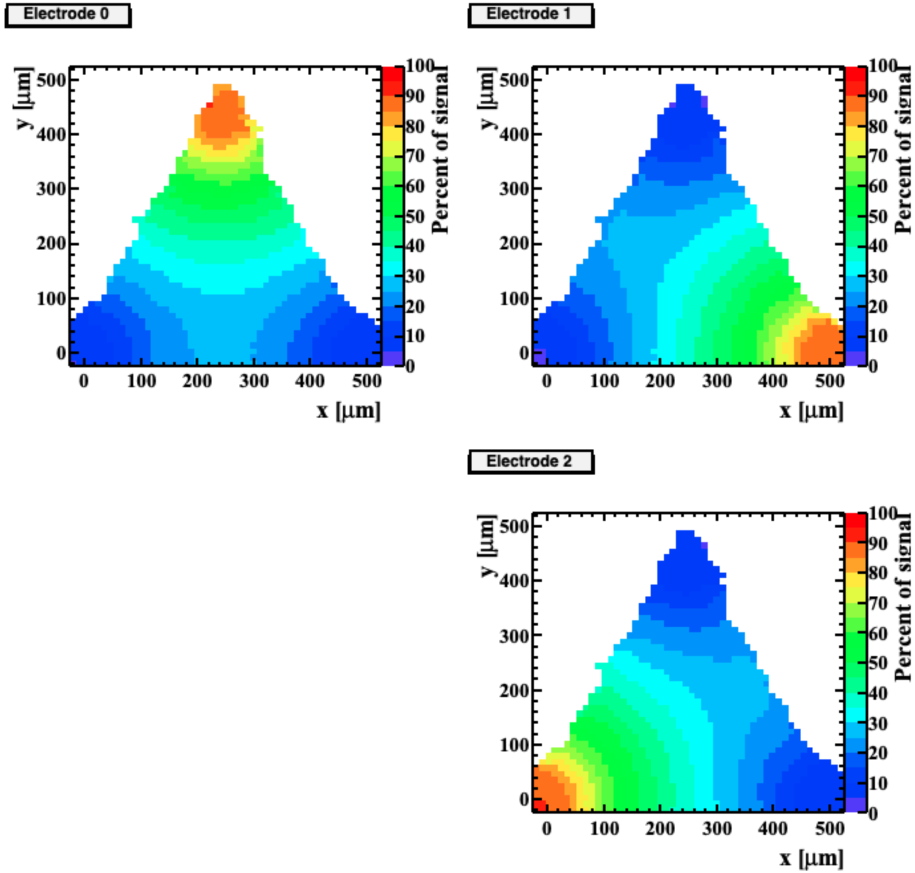
Rotations measured on the 1000-microns:

x- rotation: 15 – 20 degrees

y rotation: 5 - 10 degrees

Sharing Template for triangular pixels

Sharing templates for the triangular pixel (500-microns pitch)



Tracker – DC-RSD position correlation

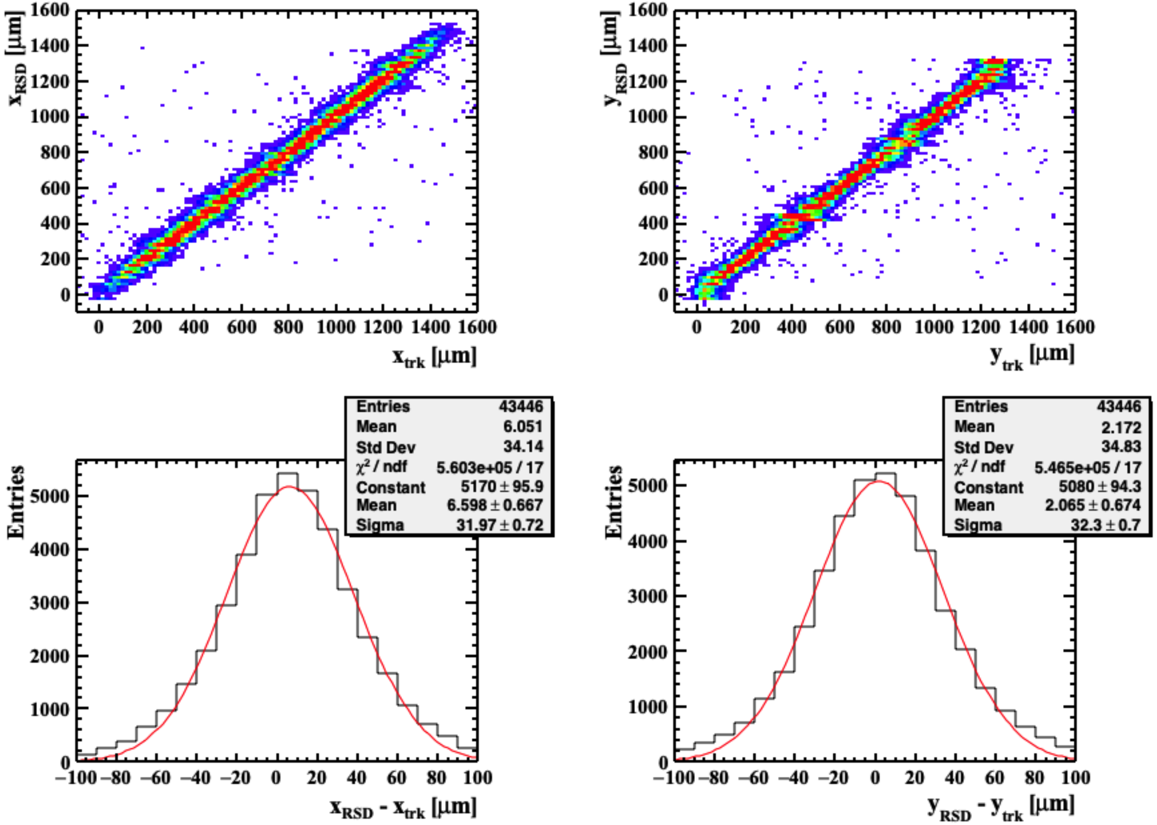
Triangular matrix, 500-micron

Bias = 240V

- Triangular pixels have a worse resolution with respect of squared pixels

- Sharing among 3 electrodes instead of 4 gives less handles to estimate the positions.

$$\sigma_{x,y} \sim 32\ \mu m$$



DC- RSD setup: DESY tracker resolution

Resolution estimated with the tracker resolution simulation tool developed for the *Mimosa* telescope in T22.

Changed the description of the telescope planes:

- set the expected resolution of the telescope at the energy we were using (5 GeV) for a configuration without DUT, with planes closest to our setup: 6.5 μm.
- set the ALPIDE planes material budget with 70 μm thick silicon and 25 μm thick Kapton on each side
- set the DUT description with 1 mm PCB, 500 μm thick silicon at Z=222.5 mm

By varying the total material budget of the DUT by ±50% and scanning over the Z position by ±2.5 mm, obtained

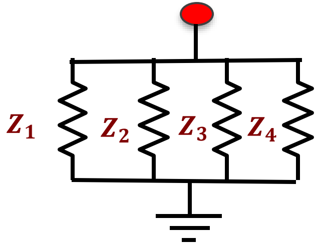
$$\sigma_{trk} = (7.85 \pm 0.5)\mu m$$

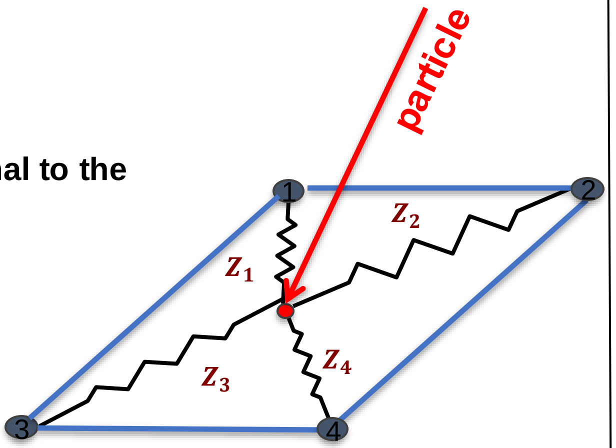
Modeling the spatial resolution

What is currently limiting the spatial resolution that we measure in DC-RSD (and RSDs) ?

Simple analytical model (fit better the DC-RSD design). Assumptions:

1) The **impedance** between the hit position and each electrode is **proportional to the distance** $Z_i \propto d_i$
2) The signal is **shared as in a perfect resistive divider**





With this model, given a $(X, Y)_{TRUE}$ we can compute
the ideal amplitude sharing among the electrodes,
add random noise to each amplitude, compute the sharing fractions.
In a second step, the "noisy sharing fractions" are given to Minuit to find the position $(X, Y)_{RSD}$ that best fit these inputs.
The spatial resolution sigma [$(X, Y)_{TRUE}$ - $(X, Y)_{RSD}$] is computed

Modeling the spatial resolution

What is currently limiting the spatial resolution that we measure in DC-RSD (and RSDs) ?

The model has one free parameter, the noise of the amplitude reconstruction

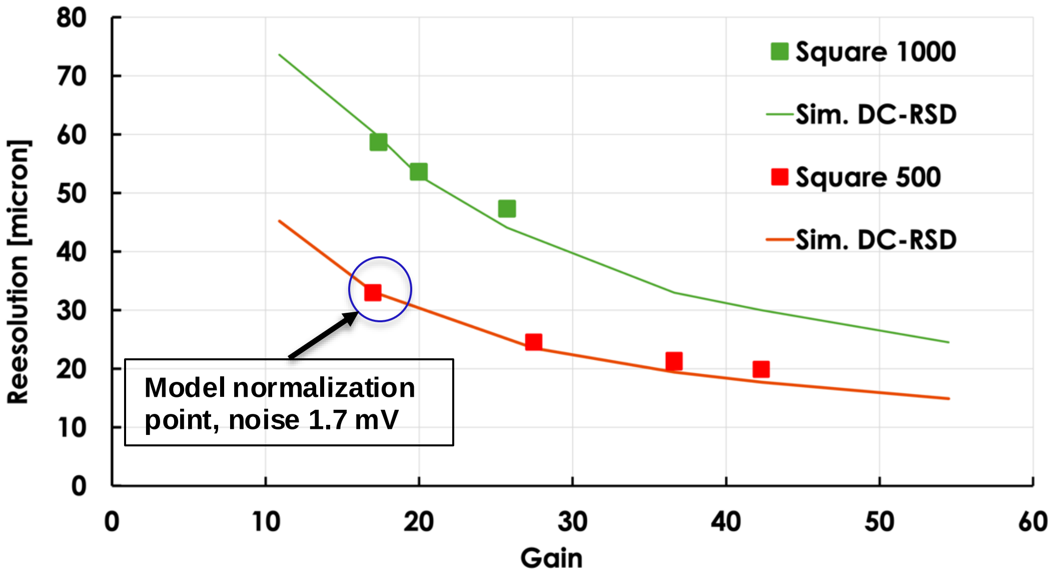
Noise value is determined fitting the data in a given point. Noise on Amplitude = 1.7 mV

The model has one scale: the pitch.

The model fits the data pleasingly well!

The resolution depends on 3 parameters:

- The signal amplitude
- Noise
- Pitch



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