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4D tracking - sensors without internal gain - 3D and intrinsic limitation

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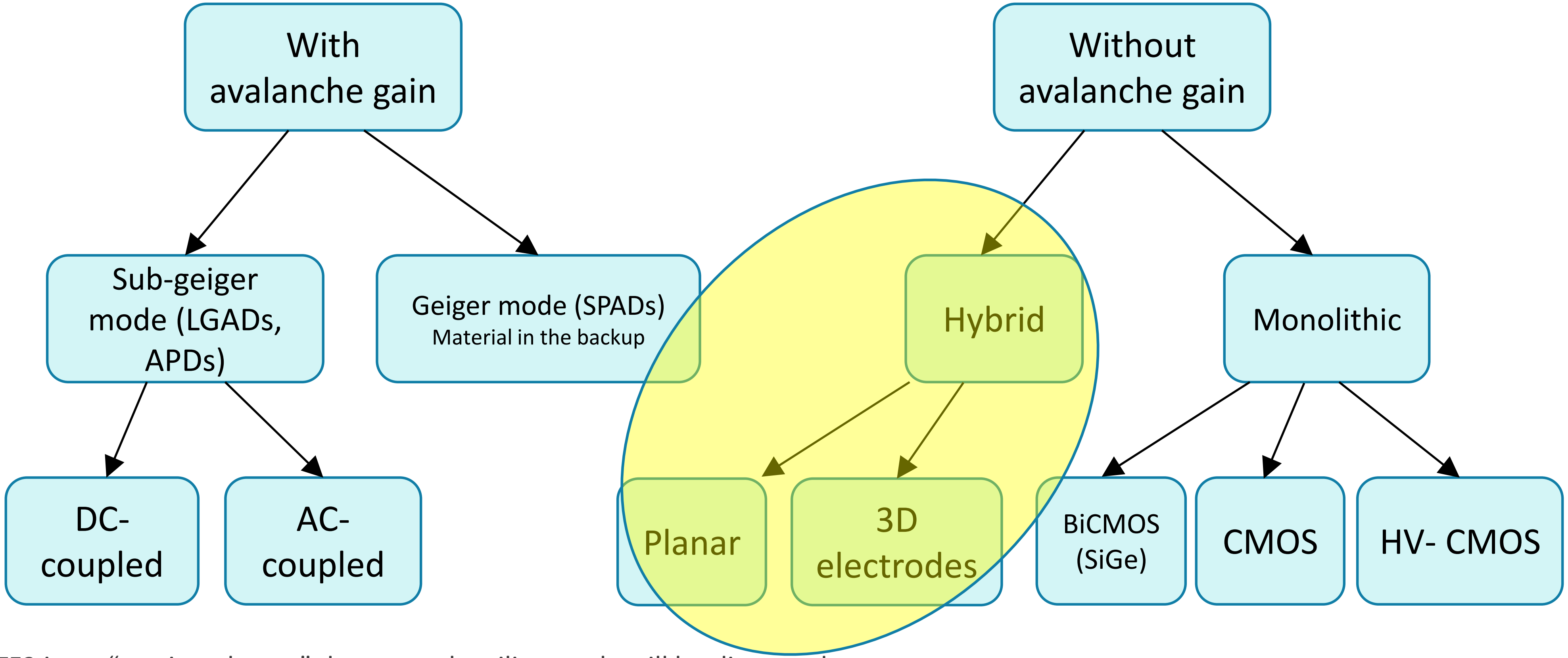
many thanks or all the input from the authors of preparatory talks – marvellous overview of what is ahead and also those who filled my knowledge gaps: A. Lai, F. Hartmann, S. Mazza, C. De La Taille, G. Pellegrini…



- Although TF3 is on “semiconductor” detectors the silicon only will be discussed:
  - For many years radiation hardness of the Silicon was questioned, but there are prospects that silicon detectors can be used well above >10^{16} cm^{-2} possibly >10^{17} cm^{-2}
  - The progress in other materials is fast and large, but for timing detectors high drift velocities are key. In terms of saturated drift velocities (v_e,v_h~100 μm/ns) developments only diamond can match the silicon (*A. Ox talk*)
  - Silicon is the far best studied and still not fully understood see (*M. Mikuž – extreme fluence , J. Schwandt talks - simulations*)
  - The nature has been “kind” and the projected damage from measurements at lower fluences is not so severe
- The talk will concentrate to detectors. The time resolution is governed by geometry of the detectors and key factors determining achievable time resolution are applicable also for any other semiconductor material .
- The capabilities will be discussed in the light of the particle physics and mip detection

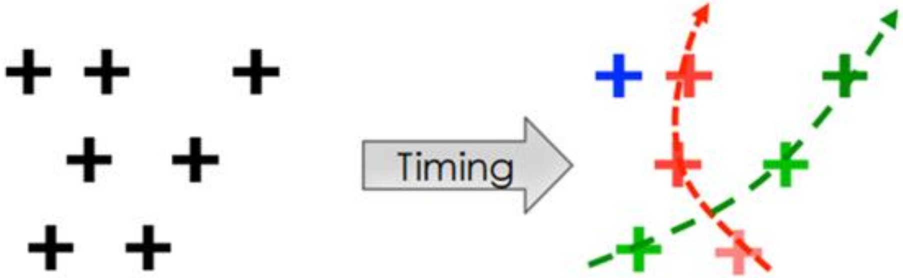
4D tracking

Benefits of more distant future full 4D tracking (each hit has precise 4D stamp):

- much better/simpler pattern recognition, ghost rate reduction
- better and faster tracks/physics reconstruction, better tracking algorithms
- less CPU power (improved cost and energy efficiency)
- effectively more luminosity

Near future: timing layer(s) – assigning the time stamp to the track

- Smaller spatial, but very good timing resolution (different technologies, harder integration)

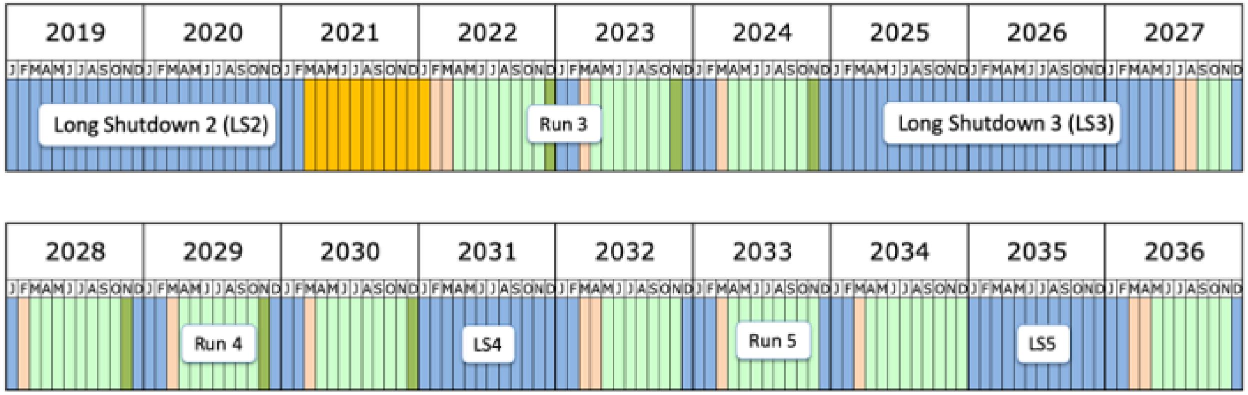


much easier tracking with “time compatible” points only
4D means going from now few ns (tens ns) to few tens ps – 2-3 orders of magnitude better, while retaining the superb spatial resolution

Facilities/experiments mainly expressing the interests:

- Beam monitors
- Future HL/HE/Hadron colliders also ee machines and rare decay experiments
  - Tracking
  - Calorimetry
- Outside HEP:
  - Medical imaging
  - Therapy beam monitoring

Needs on time scale ~10 y



Fixed targets

- NA61 Shine (beam monitor – measurement of each beam particle; p to Pb) (40 ps, 250 μm position resolution)

Rare decays

- NA62 (high intensity Kaon program at SPS)
  - GigaTracker upgrade (20-40 ps, ~few 100x100 μm2), $2 \cdot 10^{13}$ p on target/3s spill, extremely good efficiency required

Linear e-e machines

- Tracking: ~5 ns timing, but extremely low mass and position resolution (few μm)
- Forward Calorimetry: optional/beyond baseline (required GaAs/Si) to reduce the timing <1ns

Post LS3 LHC ($\Phi_{eq} > 10^{16}$ cm^{-2})

- LHC-B Velo II upgrade (>LS4)
  - $L = 1.5 \cdot 10^{34}$ cm^{-2}s^{-1} (7.5x occ.) , max fluence $5 \cdot 10^{16}$ cm^{-2} with huge fluence spread over the sensor -> desired full 4D tracking
  - ~55 μm pitch, <50 ps/hit resolution (ongoing optimization)
- CMS (LS >4,5)
  - possible addition of pixel disks with high precision timing in the forward region (~100x100 μm^2, ~30 ps)
- ATLAS (LS >4,5)
  - replacement of LGADs in the inner rings of HGTD
  - replacement of the inner-most pixel layers with possible timing information <50ps

Needs on time scale 20+ years (post LHC)

FCC-hh – Tracking

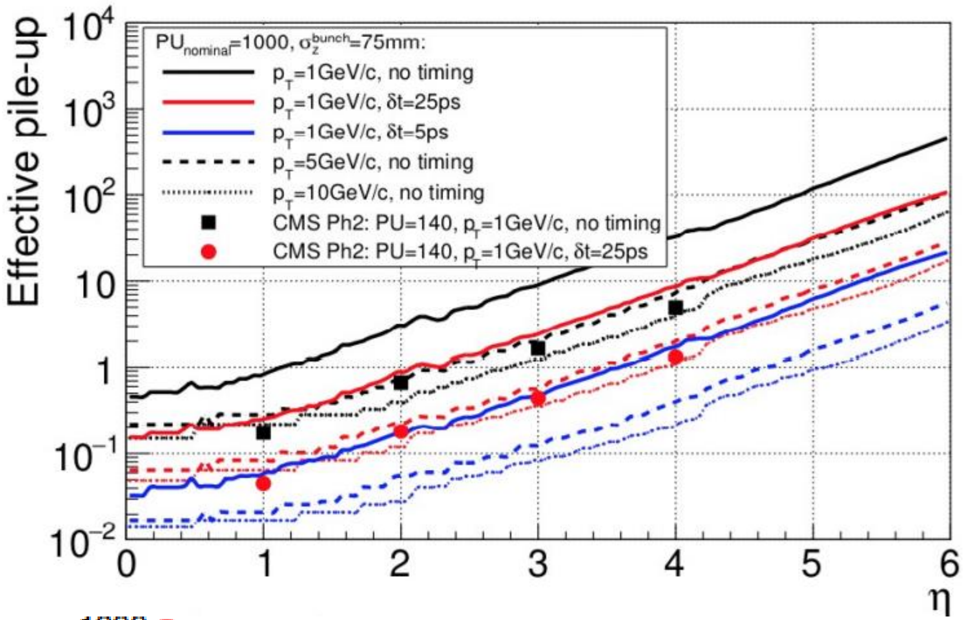
- very challenging requirements by today's standards almost impossible for r<30 cm:
- radiation hardness up to 10^{18} cm^{-2}, 300 MGy
- timing of tracks ~10 ps, 10 GHz/cm^2
- cell sizes of 25x50/25x25 μm^2
- surface inner tracker 15 m^2

FCC-hh – 5D Calorimetry (imaging calo + timing)

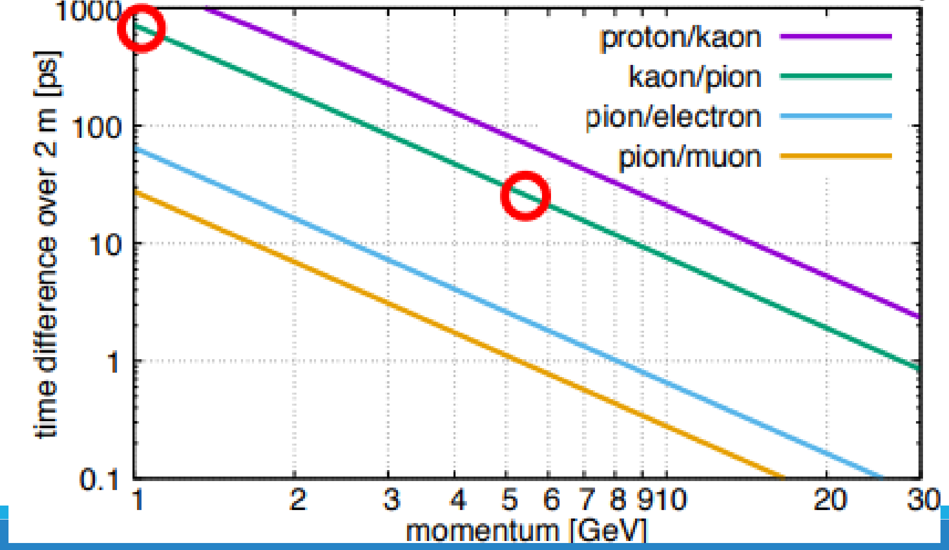
- Similar timing requirement as for tracking in terms of timing

FCC – ee

- as PID competing with Time of Flight RICH detectors - over distance 2m few ps to tens ps (large area, no extreme position resolution required)
- Calorimetry (optional)

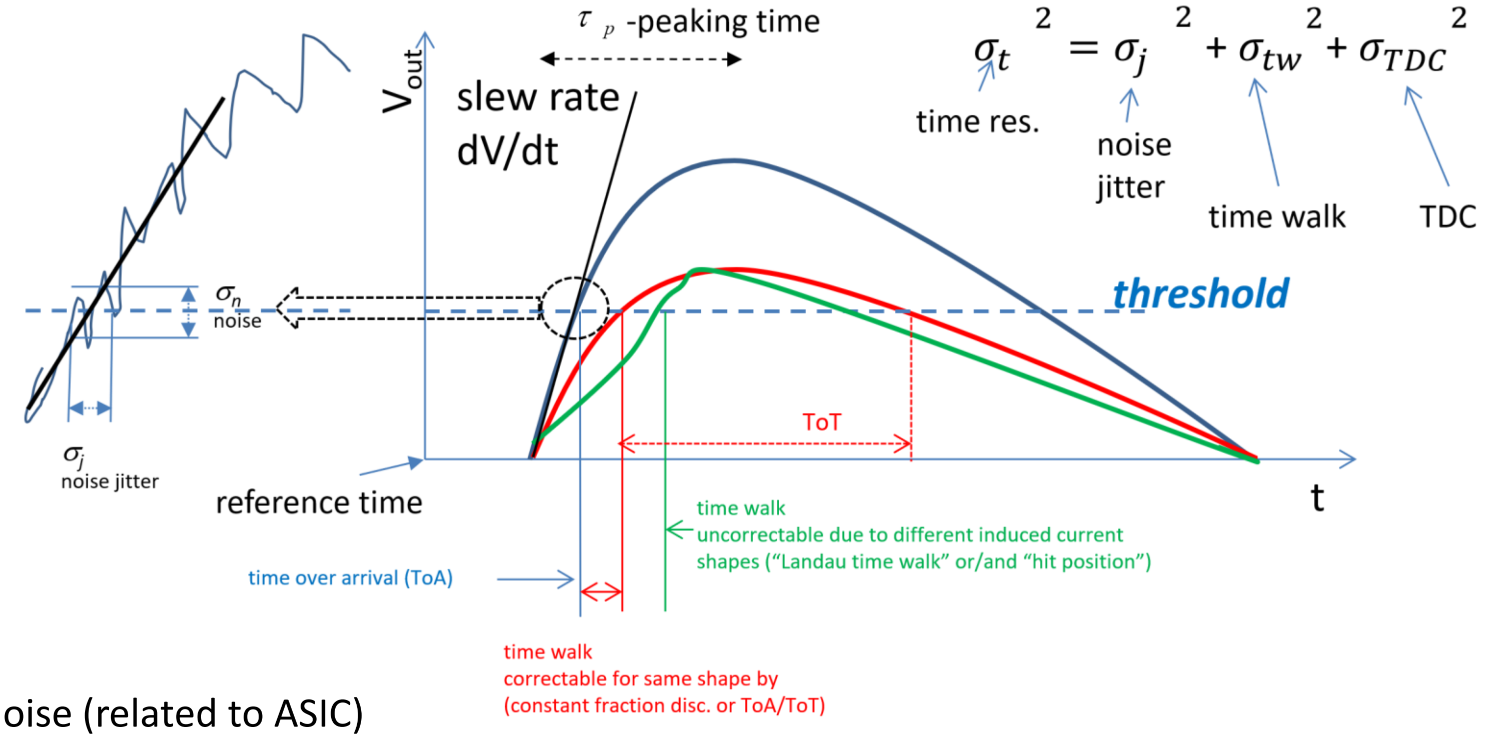


Effective pile up – number of vertices compatible with reconstructed tracks
Eff. pile-up = 1: Indication for unambiguous primary vertex identification



Time resolution

$$\boxed{\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} \approx \frac{\sigma_n}{\left|\frac{S}{\tau_p}\right|} = \frac{\tau_p}{S/N}}$$



$$\sigma_t^2 = \sigma_j^2 + \sigma_{tw}^2 + \sigma_{TDC}^2$$

- σ_j -jitter – fast rise time and high signal/noise (related to ASIC)
- σ_{TDC} – vey good granularity a challenge for ASIC

$$\boxed{\sigma_{tw}^2 = \sigma_{wf}^2 + \sigma_{lf}^2} + \cancel{\sigma_Q^2}$$

σ_{tw}-time walk component includes σ_{wf} σ_{lf} σ_Q, :

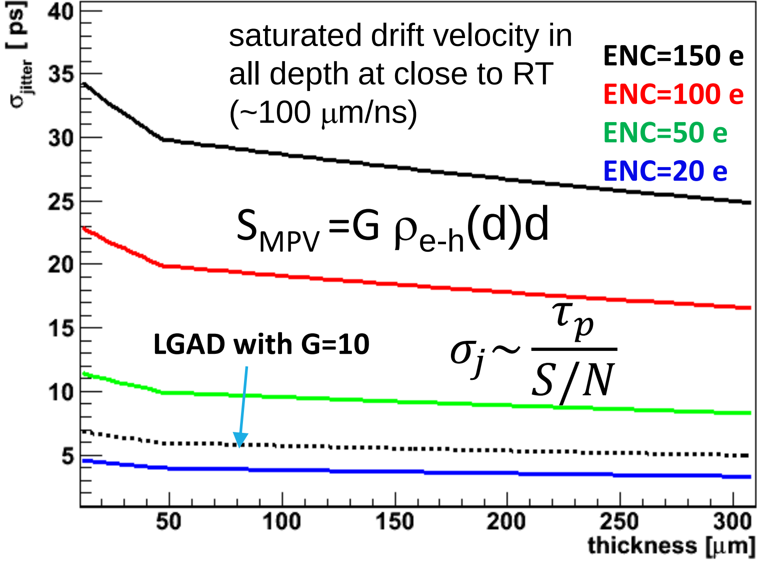
- σ_Q - fluctuations in amount of deposited charge –> correctable with ToA-ToT or CFD (not trivial)
- σ_{wf} / σ_{un} – weighting/electric field contribution (distortion component/un-perfection) -> depends on hit position in segmented devices
- σ_{lf} - Landau fluctuations in shape of the signal -> depends on hit position (segmented devices)

Limits for planar sensors

*NA62, NIM A958 (2020) 162127
**ATLAS HGTD TDR

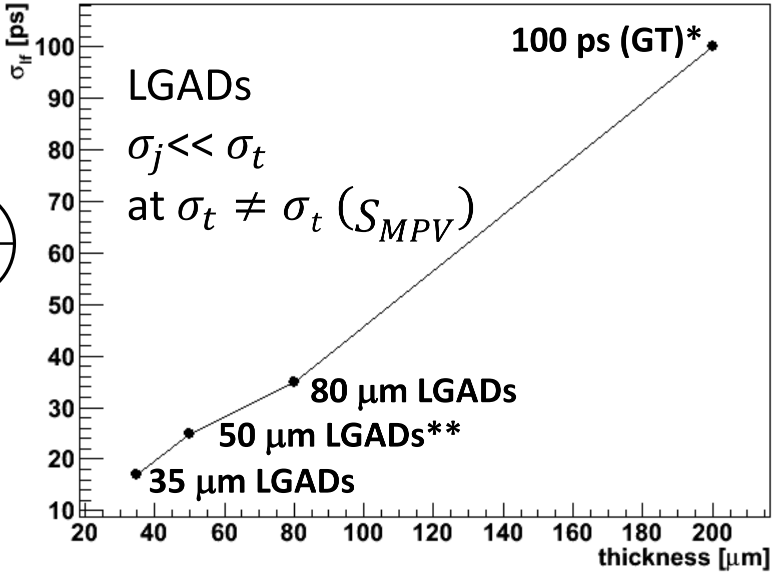
Planar sensors: NA62 giga-tracker (200 μm, p-n, TDCPix, 300x300 μm^2)*: σ_j~80 ps, σ_{wf}~ 80 ps , σ_{lf}~ 100 ps : σ_j~140 ps
This represents roughly the limits achievable with conventional planar detectors of that thickness.

σ_j - Jitter (τ_p= $t_{collection}$)



$\oplus$

σ_{lf} - Landau fluctuations



$\oplus$ σ_{wf} (segmentation pitch/thickness) $\approx$ **~10 ps** is (almost?) impossible in Si planar technology

LGADs (planar sensors with gain) seem to be ideal solution to reach superb resolution for large pixels/pads
- large capacitance (noise) can be offset by gain -> good S/N (with discrete electronics 80-100)
- σ_{wf} ~ 0
- Inter-pad no gain region is not critical (IP/cell size ~ 0)

Main LGAD limitations:
- Radiation hardness (currently **Φ_{eq}<3·10^{15}cm^{-2}**)
- Fill factor for small pixels

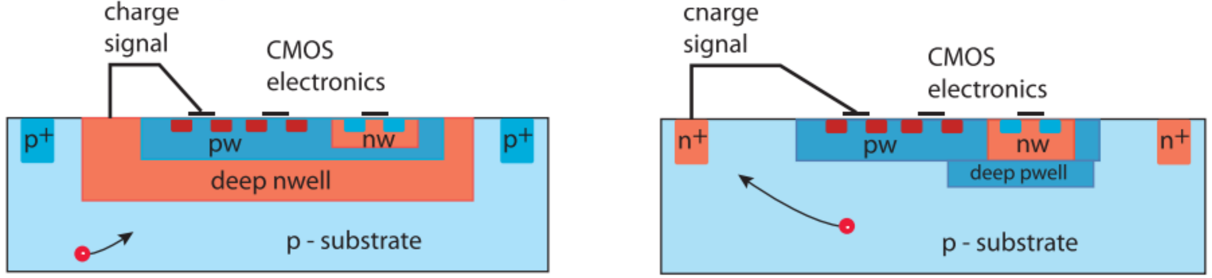
Depleted MAPS - planar

Depleted MAPS/HVCMOS offer an alternative to hybrid sensors as timing detectors – aiming for better S/N

$\tau \propto \frac{C}{g_\mathrm{m}}$, $ENC_\mathrm{thermal} \propto \frac{kTC}{g_\mathrm{m}}$ compensated by power (g_m)

(*there are several talks on D-MAPS and CMOS D-L. Pohl, W. Snoeys, P. Riedler*)

taken from N. Wermes



- Large electrode: $C \approx 300\,\mathrm{fF}$
- Strong drift field, short drift paths, large depletion depth
- Higher power, slower
- Threshold $\sim 2000\,\mathrm{e}^-$

- Small electrode: $C \approx 3\,\mathrm{fF}$
- Low analogue power
- Faster at given power
- Difficult lateral depletion, process modifications for radiation hardness
- Threshold $\sim 300\,\mathrm{e}^-$

σ_{wf} - small, σ_{j}, σ_{lf} - large

σ_{wf} - large, σ_{j}, σ_{lf} - small

The limits set for the planar detector are still valid:
CACTUS D-MAPS *(Y. Degerlia et al. JINST 15 (2020) P06011)*

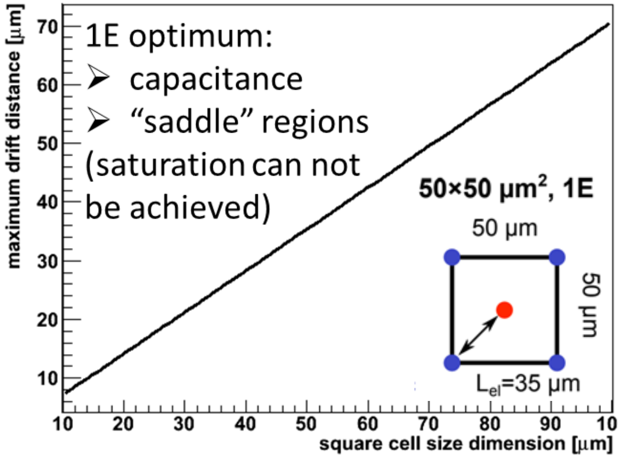
LFoundry-150 nm, high resistivity substrate
thickness=100 μm-> ~7500 e for m.i.p.
simulated channel noise ENC~ 300 e
τ_r~1 ns -> σ_j ~ 50 ps
σ_{wf}~0 (pixel of 1x1 mm^2)
σ_{lf}~50 ps

σ_t~70 ps -> also aimed by the designers (60 ps)

3D detectors for timing applications

3D technology as timing detectors:

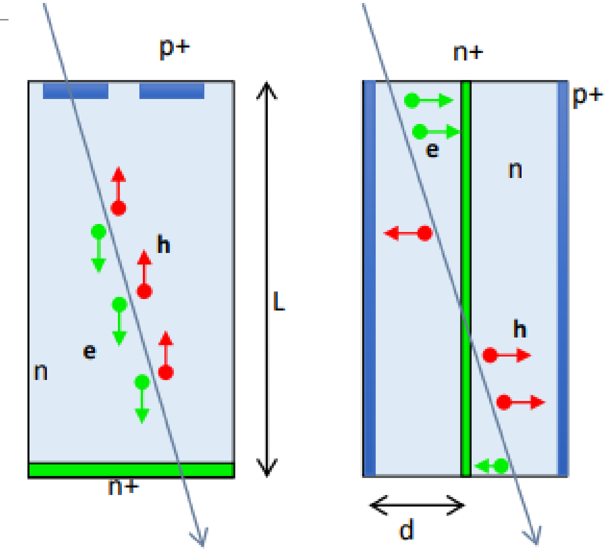
- They have fill factor ~100% (inclined tracks)
- The radiation tolerance of small cell size devices is large (for signal) and allows operation at higher bias voltages (next slide)



1E optimum:

- capacitance
- "saddle" regions

(saturation can not be achieved)



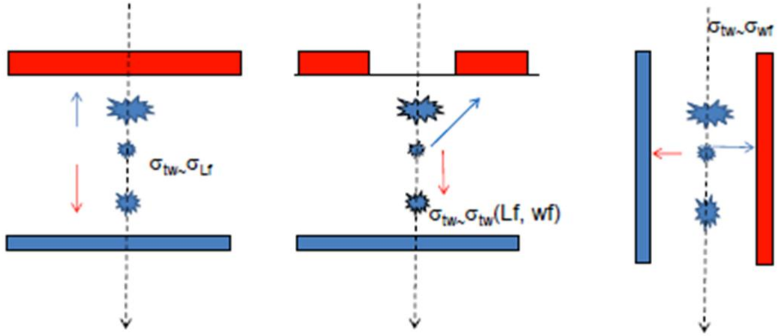
Planar sensor
d = L

3D sensor
d << L

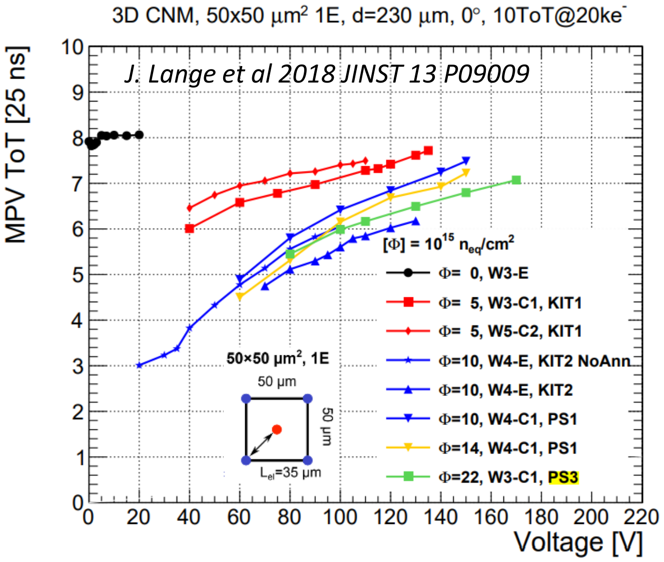
S. Parker et al, Nucl.Instrum.Meth.A 395 (1997) 328-343

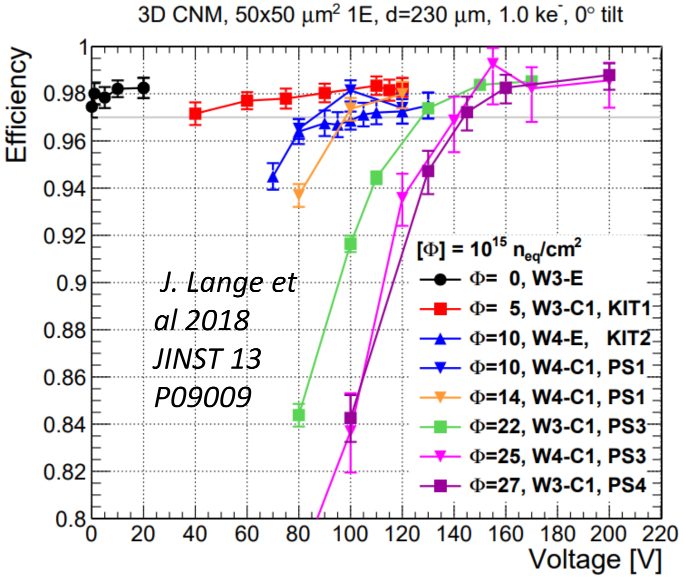
But/However:

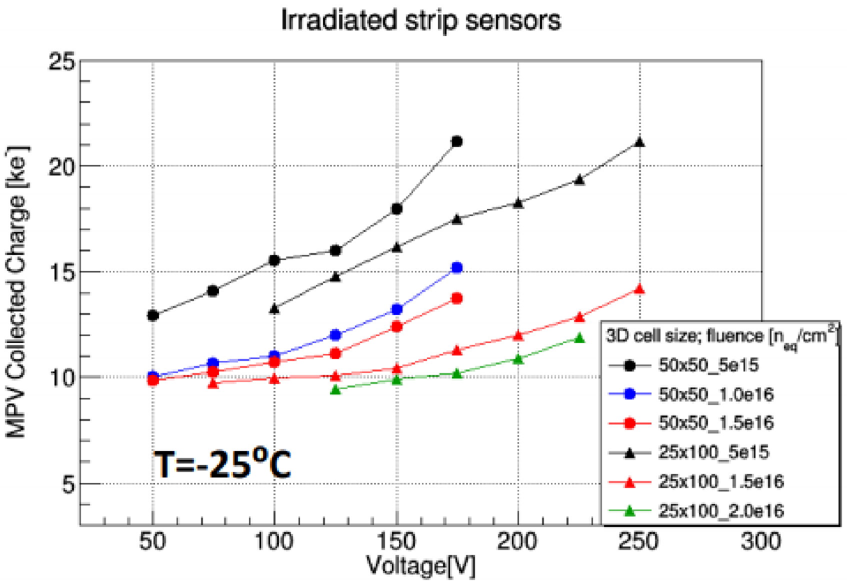
- 3D can be fast – ☺ short drift distance, but ☹saddle regions in the field
- the weighting field – hit position - will impact the signal ☹
- they can be thicker as Landau fluctuations play a minor role
- the capacitance will be much larger (hence noise and the jitter) particularly for thick sensors
- Lower operation voltages than for planar detectors (LGAD) and possibly lower current ($I_{LGAD}=G\cdot I_{gen}$) result in smaller power dissipation



Radiation hardness of 3D design (~10^{16} cm^{-2})





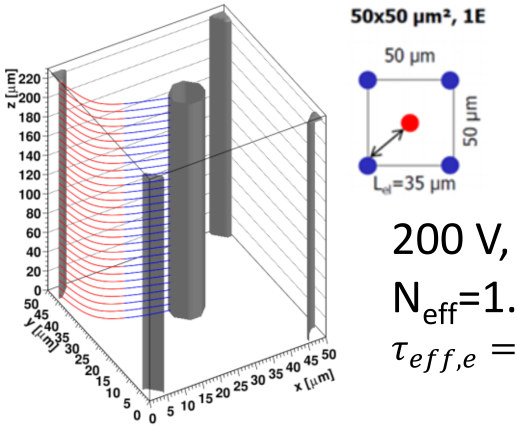


Good charge collection after large fluences - detection efficiency equal to the non-irradiated one after Φ_{eq}~$3\text{x}10^{16}$ cm^{-2} . The main reasons for encouraging performance (that also agrees with present understanding of radiation damage) are:

- short collection time and saturation of effective trapping times with fluence -> less trapping than expected
- small depletion depth and saturation of radiation induced space charge -> ability to deplete and establish high field in whole volume
- possible generation current saturation (difficult interpretation of the device)

Operation of 3D sensors at ~10^{17} cm^{-2}

Simulation with known damage parameters

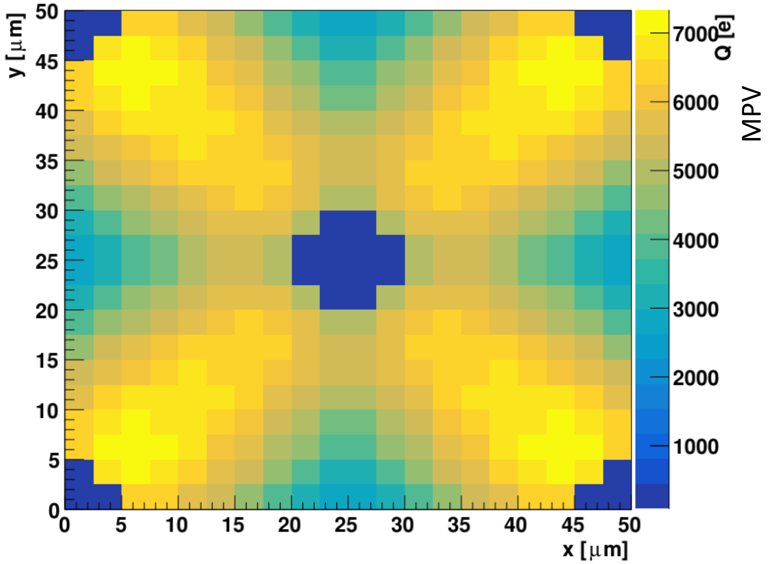


$\Phi_{eq}=10^{17}$ cm^{-2}

200 V, -20°C, 0°

$N_{eff}=1.5\cdot 10^{14}$ cm^{-3}

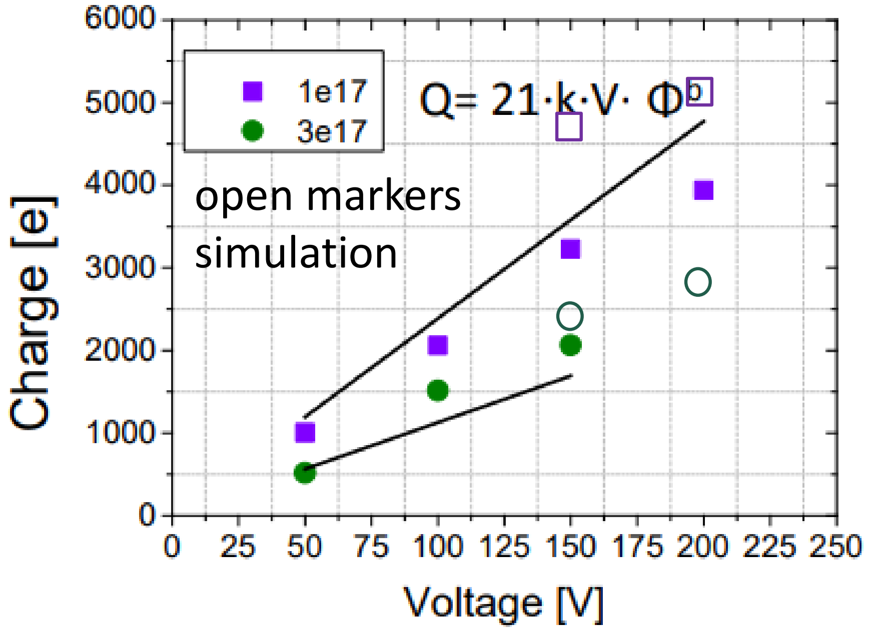
$\tau_{eff,e} = \tau_{eff,h} = 100$ ps



G. Kramberger, 11th HSTD, 2017

Measurements of 3D - Strip sensors irradiated to FCC-hh fluences using TCT/Alibava/CCE setups

M. Manna et al., NIMA 979 (2020) 164458.
M. Manna et al., 35th RD50 workshop,2019
I. Mandic et al., JISNT (2021) P11018



Signals around few 1000 e !

- Simulation and measurements are roughly compatible
- It seems that for 3D sensors the radiation damage at $\Phi_{eq}>10^{17}$ cm^{-2} is not an obvious show stopper, not for silicon, but maybe new/novel materials may offer better performance on the timescale of >20 years.

↓

What are the limits of 3D as a timing detector from the detector point of view

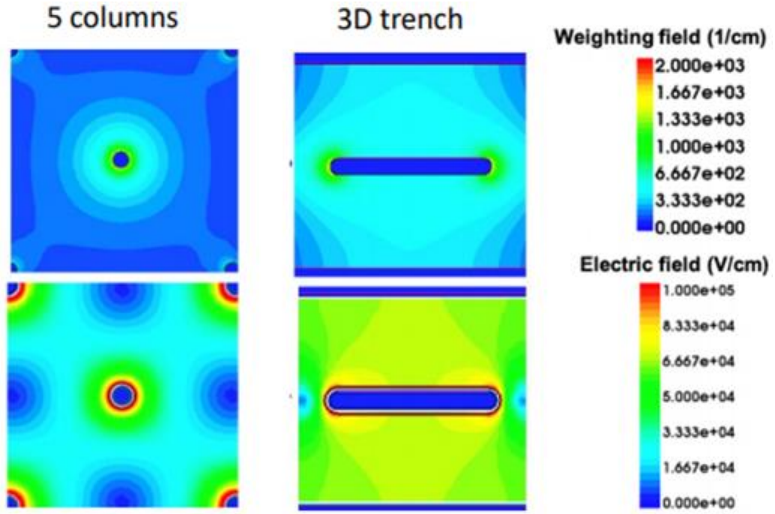
3D – for timing detectors

There are two approaches taken so far:

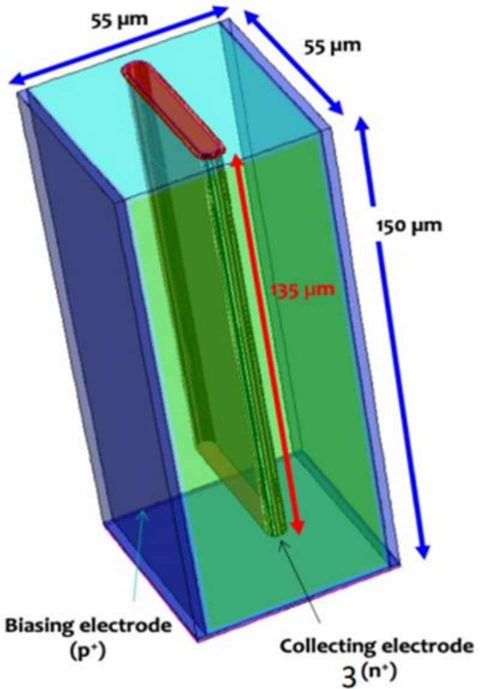
- Column 3D detectors (different patterns)
- Trench 3D detectors

(web.infn.it/timespot/)

$$i = q\,\vec{E}_w \cdot \vec{v}_d$$



TCAD simulation



Trying to achieve constant E_w and velocity – minimum σ_{wf} – figure of merit is the distribution of the collection time dependence on the hit position (σ_{tc}).

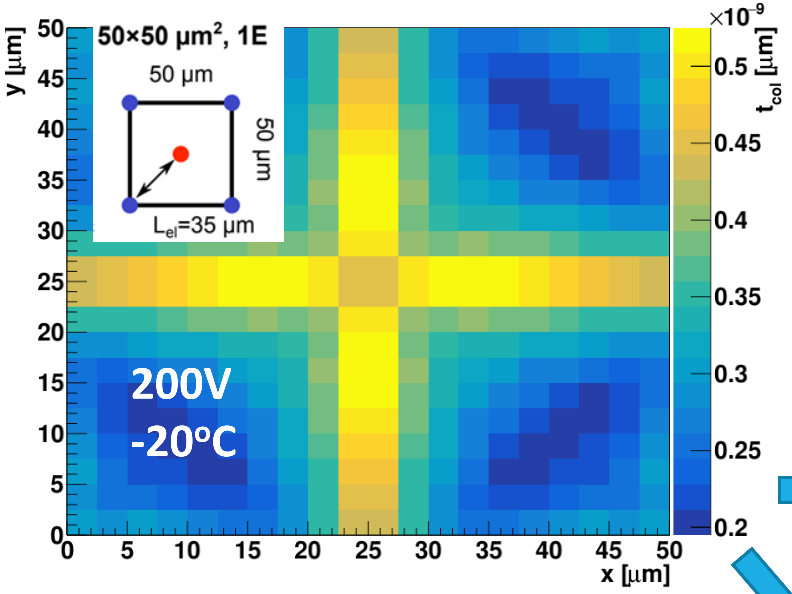
This can be seen as two pad detectors in back-to-back, rotated for 90° and stacked together

-> the optimum design and should lead to the minimum achievable σ_{wf} for a given cell size

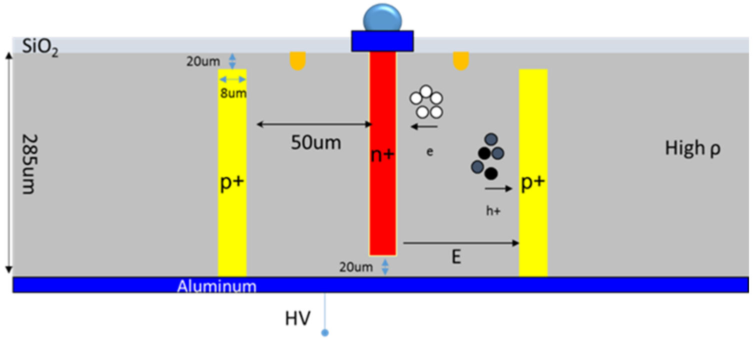
The price to pay:

- smaller fill factor which limits the cell size – hence efficiency and the position resolution
- significantly larger capacitance (**optimization σ_j vs σ_{wf} with power constrain is the key**)
- more complicated production – yield issues, scalability, ….

Column-3D detectors



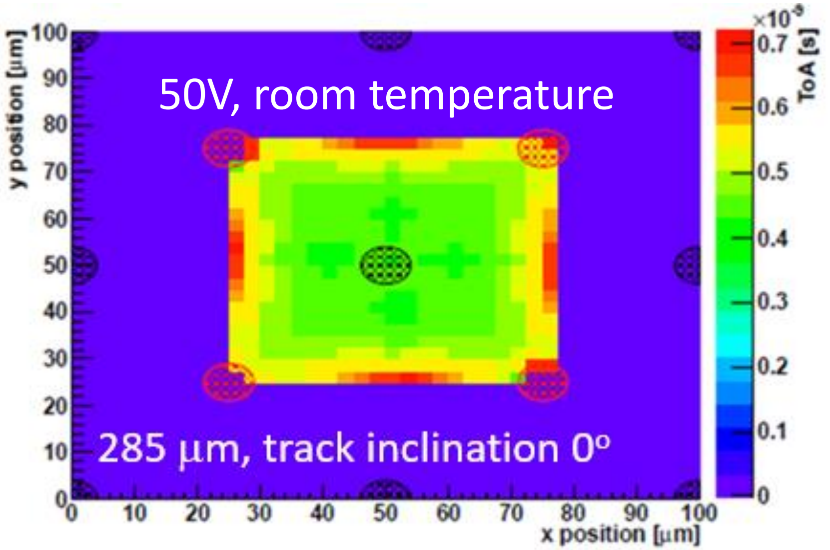
200V
-20°C



CSA τ=1.5 ns

CFD=25%

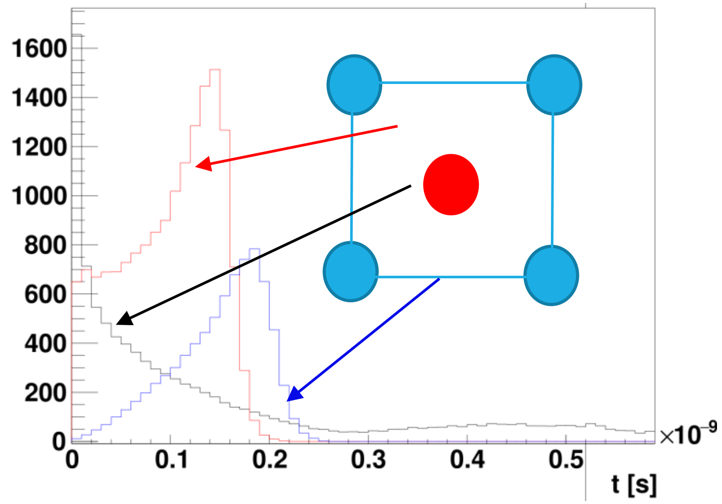
$$\sigma_{wf} \propto \sigma_{tc}$$

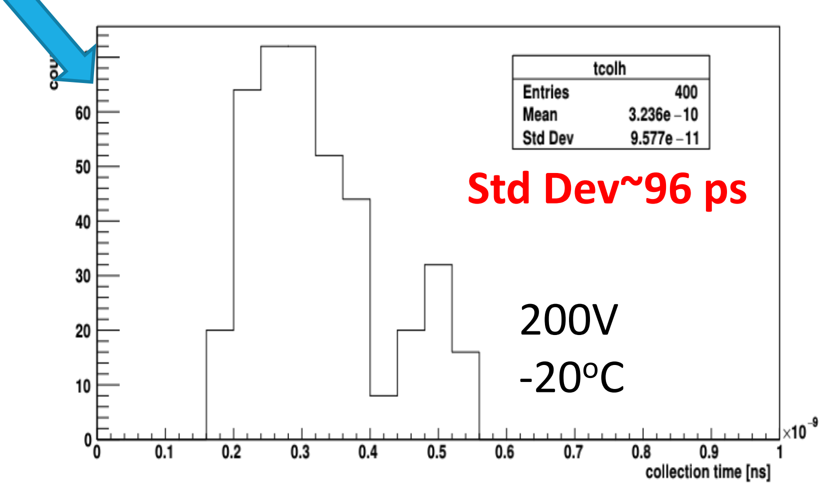


50V, room temperature

285 µm, track inclination 0°

G. Kramberger et al., NIMA 934 (2019) p. 26.





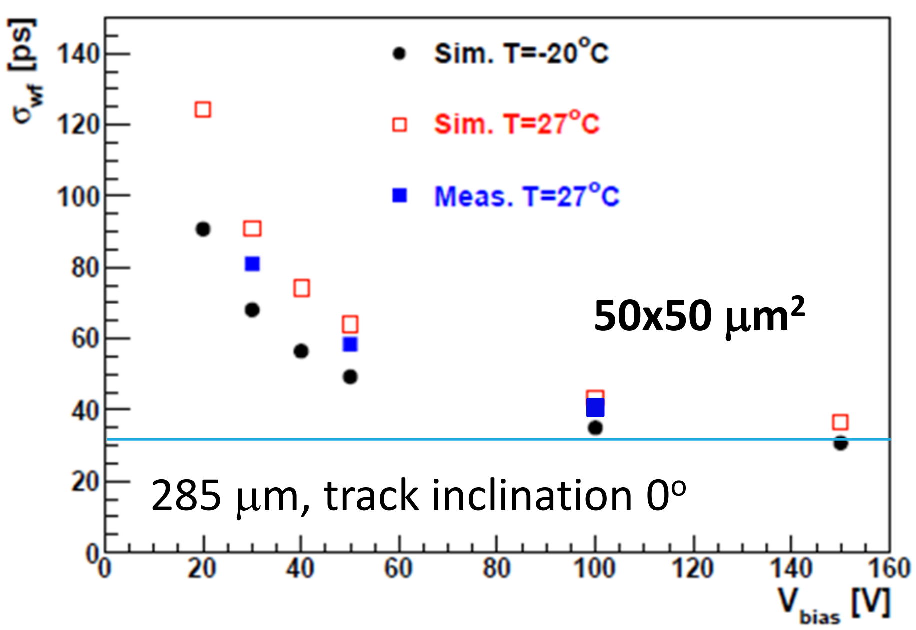
Std Dev~96 ps

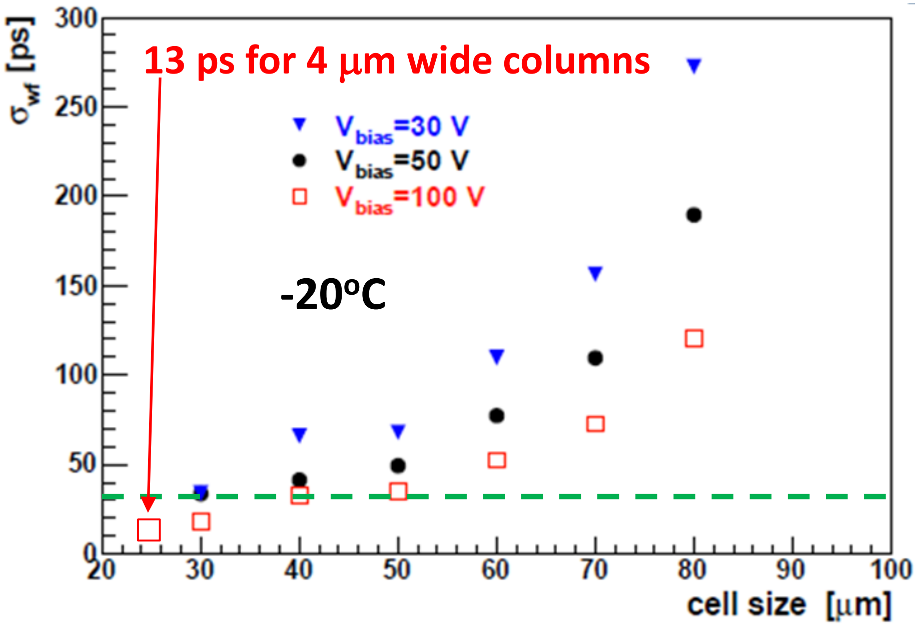
200V
-20°C

Low field regions (saddle) between ohmic columns worsen the timing resolution (spread in ToA)

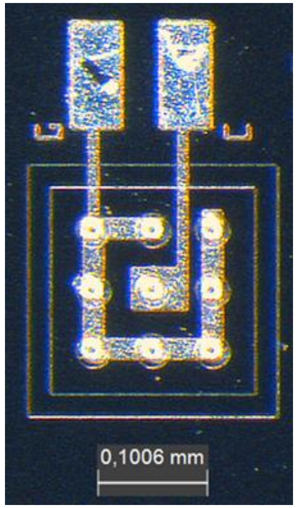
Column 3D - Measurements and simulations

G. Kramberger *et al.*, NIMA 934 (2019) p. 26.





Measured device (CNM)



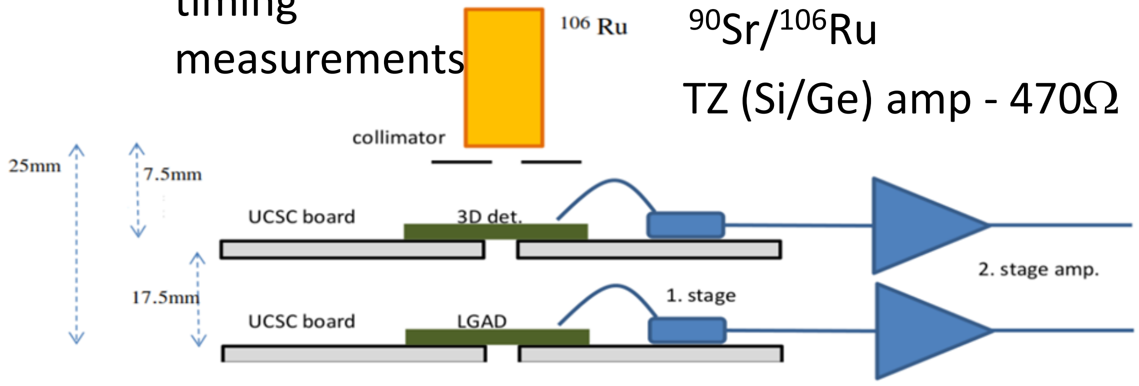
Single square cell readout σ_{wf} at -20°C and 100V

- **25x25 μm -> ~13 ps**
- **50x50 μm -> ~32 ps**

for multiple cell connected together and inclined tracks even better time resolution can be achieved

- around 20-25 ps for 50x50 μm^2 cell

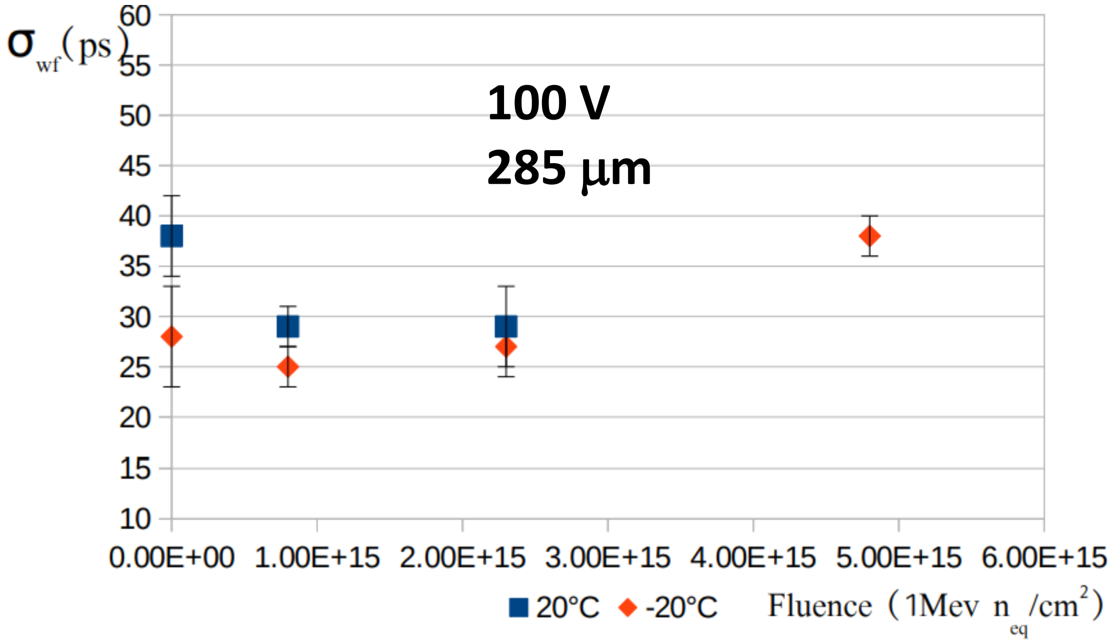
timing measurements



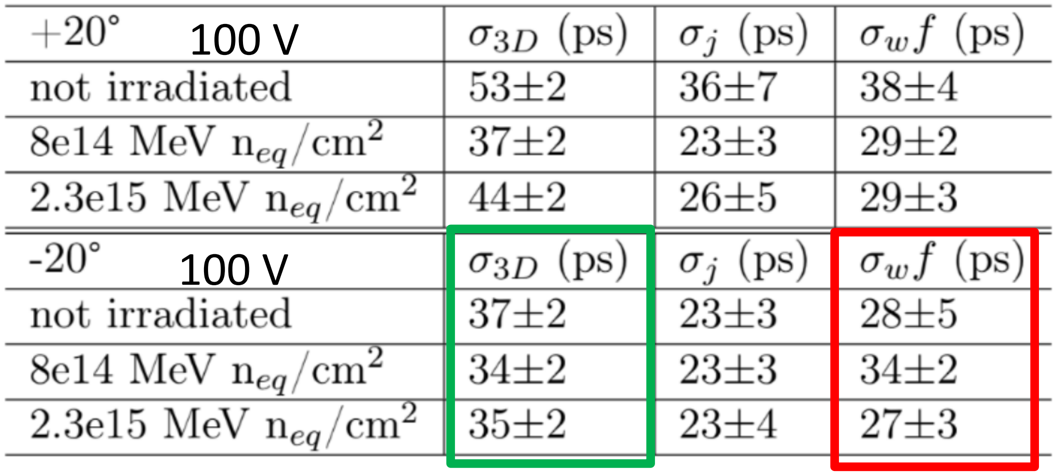
^{90}Sr/^{106}Ru

TZ (Si/Ge) amp - 470Ω

Column 3D - Measurements post-irradiations

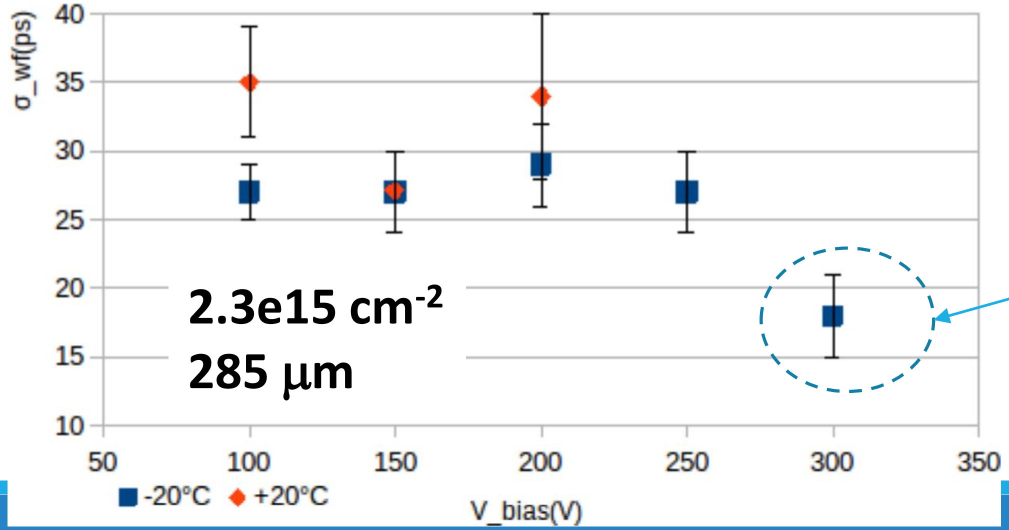


100 V
285 µm



+20° 100 V	σ_{3D} (ps)	σ_j (ps)	σ_{wf} (ps)
not irradiated	53±2	36±7	38±4
8e14 MeV n_{eq}/cm^2	37±2	23±3	29±2
2.3e15 MeV n_{eq}/cm^2	44±2	26±5	29±3
-20° 100 V	σ_{3D} (ps)	σ_j (ps)	σ_{wf} (ps)
not irradiated	37±2	23±3	28±5
8e14 MeV n_{eq}/cm^2	34±2	23±3	34±2
2.3e15 MeV n_{eq}/cm^2	35±2	23±4	27±3

- ➢No impact of irradiation on performance σ_{wf} and also σ_j.
- ➢At high bias voltages the charge multiplication (radiation induced – not by design) can lead to improvement due to charge multiplication?



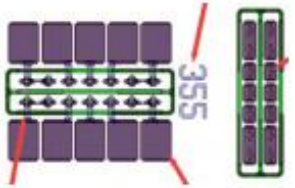
2.3e15 cm^{-2}
285 µm

D. De Simone et al, 37th RD50 workshop,2020
D. De Simone et al, 16th TRENTO workshop,2021

Trench - 3D detectors

- **55x55 µm²** pixels
- **150 µm** active thickness
- Collection electrode **135 µm** deep

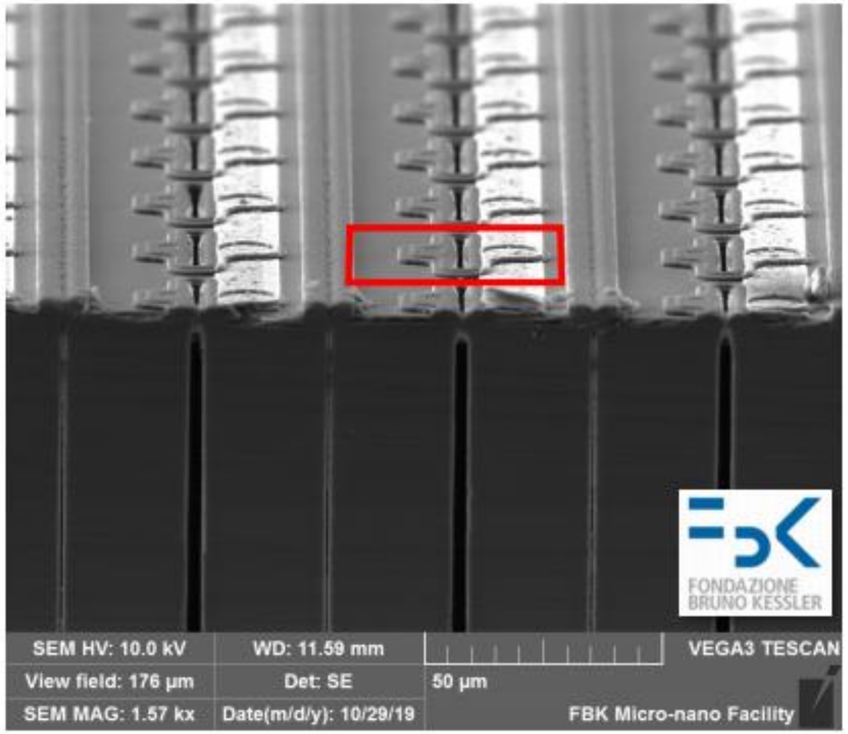
A. Lampis, 16th TRENTO workshop, 2021
M. Garau, 16th TRENTO workshop, 2021
web.infn.it/timespot/

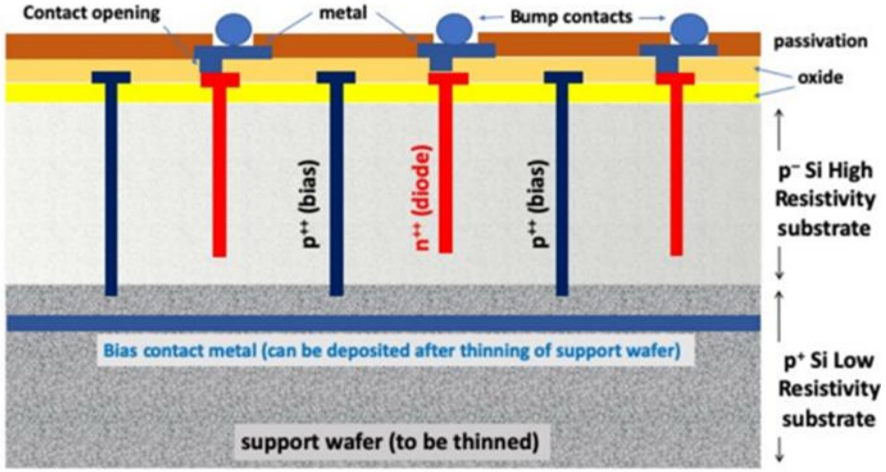


ingle and double pixels

pixel-strips

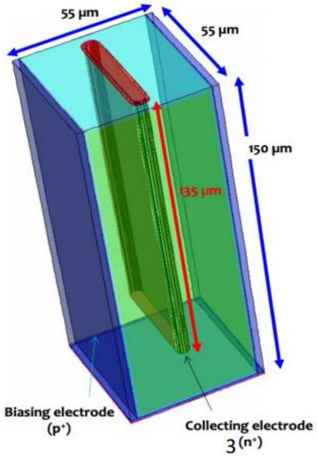
18x18 pixel matrix

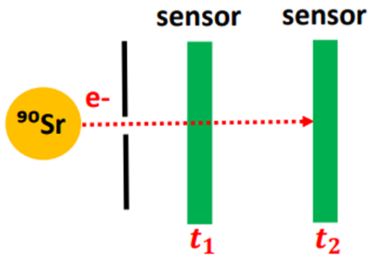


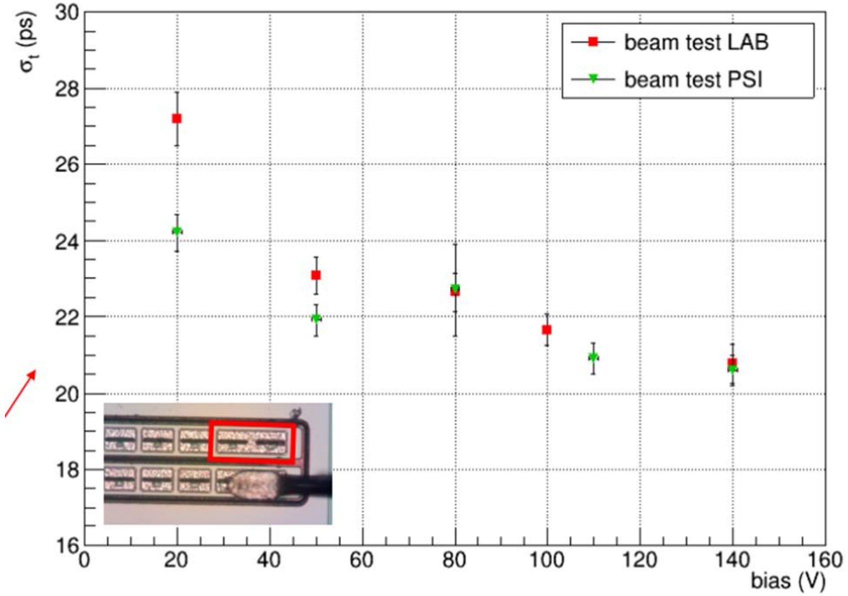


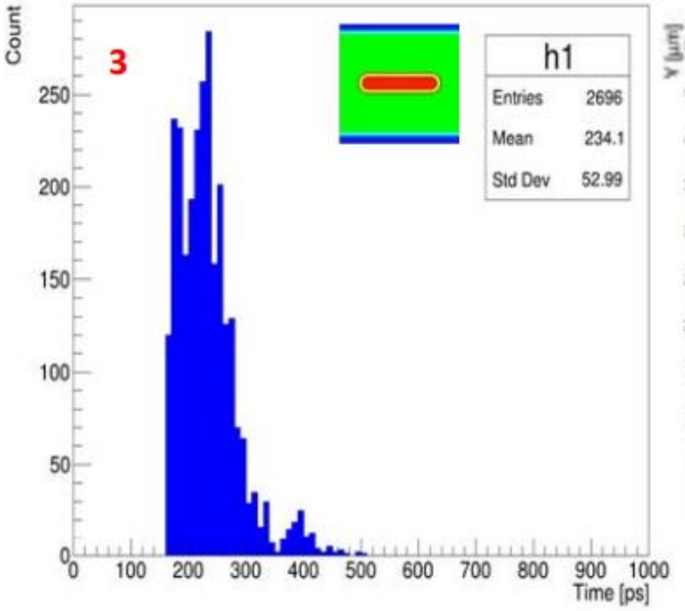
Trench - 3D detectors

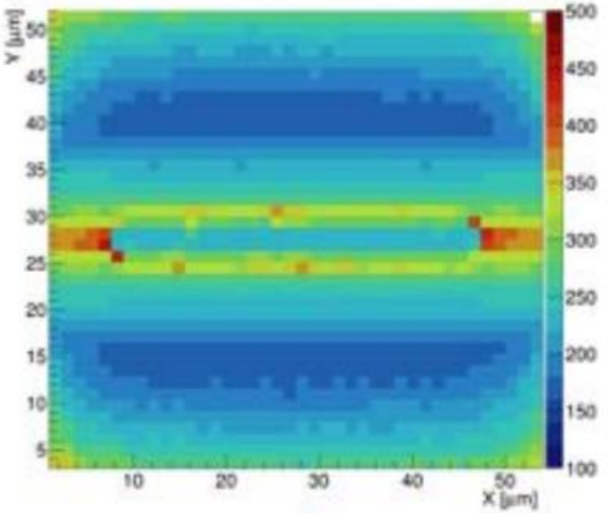
A. Lampis, 16th TRENTO workshop, 2021
M. Garau, 16th TRENTO workshop, 2021











The time resolution was found to be dominated by FE electronics σ_j ~18 ps

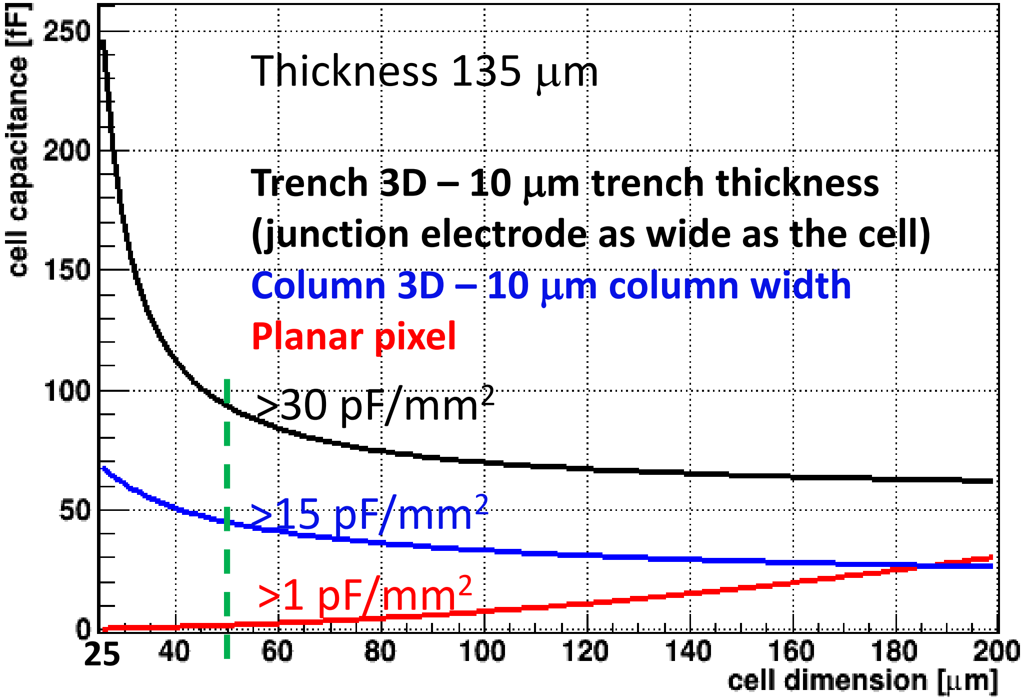
The σ_{wf} (intrinsic time resolution) of was found to be ~14-15 ps with accurate analysis **~10 ps.**

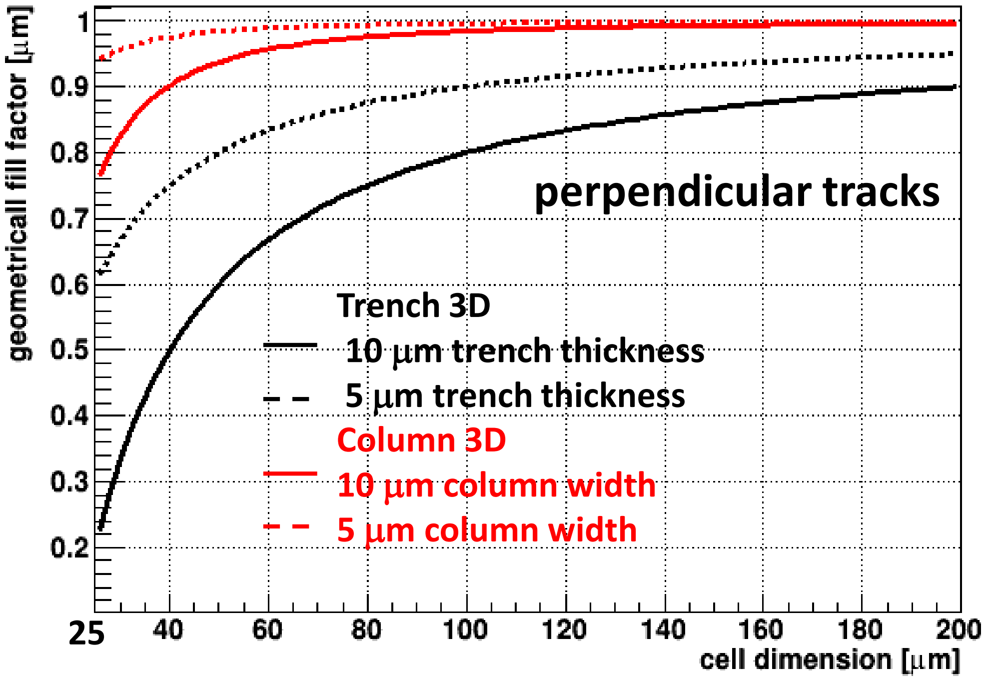
The tails in distribution due to low field regions in the space between the pads.

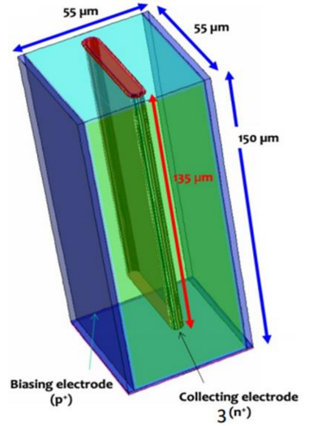
The reduction cell size may not improve the time resolution σ_t as the σ_{wf} may not be the limiting factor to the total time resolution.

around 15 ps better time resolution than for similar cell size with 3D-columns.

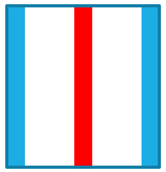
Drawbacks of 3D (Capacitance and fill factor)



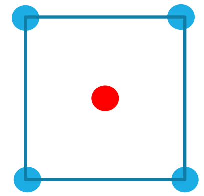




- Much larger capacitance of the trench design wrt. to column and planar (ASIC is crucial)
- At small cell sizes needed for superior timing resolution the fill factor can become a major issue:
  - For column like the direction of the inclined tracks is not very important
  - **For trench detectors the direction of tracks is crucial (detector design should be tailored to the application)**



not fully efficient for all φ at θ≠0

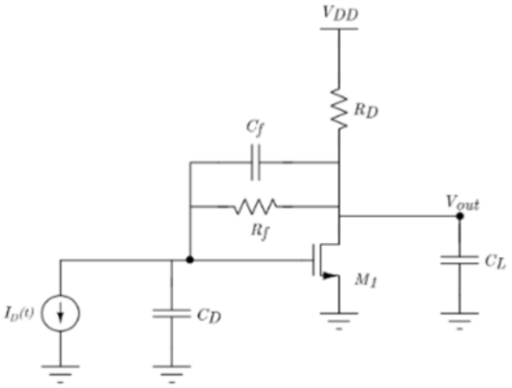


fully efficient at θ≠0

3D detectors – electronics readout

taken from A. Lai, INFN - Cagliari

Trans-Impedance-Amplifier with shunt-shunt feedback (FB–TIA).



Simplified schematic of the FB–TIA amplification stage

A) CSA-TIA, when the amplifier peaking time $\tau >> t_c$

It can be demonstrated(1) that in this case :

$$\sigma_t = \frac{\partial t_{thr}}{\partial t_c}\sigma_{tc} \approx \frac{1}{2}\left(1-\frac{V_{thr}\tau(1+G_0)}{Q_{in}R_fG_0}\right)\sigma_{tc} \boxed{\approx \frac{1}{2}\sigma_{tc}}$$

Limited by sensor

B) Fast-TIA, when the amplifier peaking time $\tau \approx t_c$

It can be demonstrated (1) that in this case

$$\sigma_t = \frac{\partial t_{thr}}{\partial t_c}\sigma_{tc} \approx \frac{\tau}{2}\sqrt{\frac{V_{th}}{I_0R_m}\frac{\sigma_{tc}}{t_c}} \approx \boxed{\left(\frac{1}{2}\frac{\tau}{t_c}\sqrt{\frac{N}{S}}\right)\sigma_{tc}}$$

The price to pay for speed and better time resolution is power consumption.

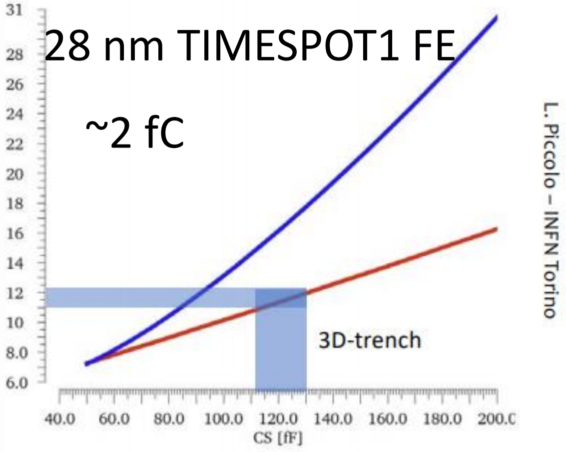
Currently the performance (ALTIROC, ETLROC, TimePix4, Fast2):

FOM ~ 20-40 ps fC/pF
σ_j = FOM·C_d/Q_{tresh}
σ_j = 20 ps 4fC/2fc~40 ps

at power consumption ~few mW/mm^2

C. De La Taille, AIDAINNOVA meeting, April 2021)

It is likely that new developments in electronics (fast SiGe BiCMOS, 28 nm -> CMOS) are going to be needed to exploit the sensor capabilities with peaking/rise times of ~ 1 ns.



σ_{ej} vs sensor capacitance

Outlook for the future – σ_t=10 ps goal

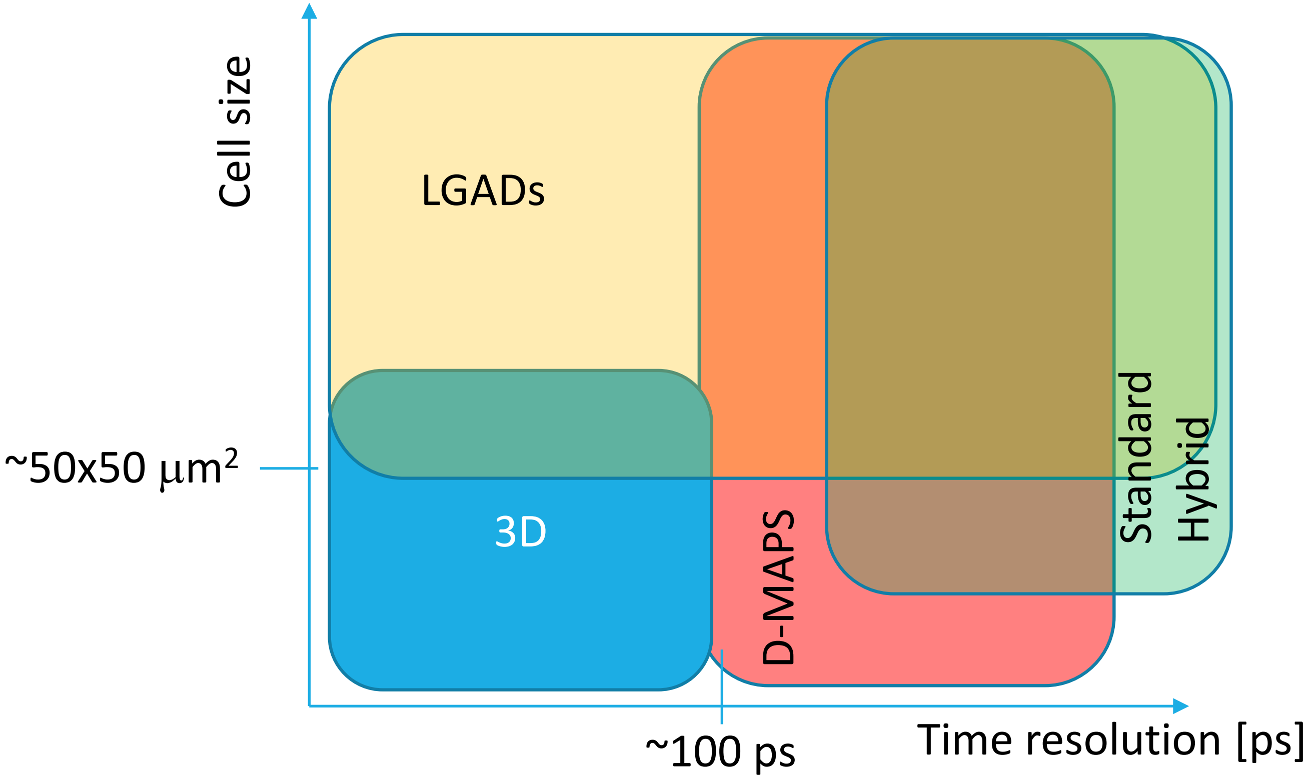
- Small cell size 25x25 μm^2 /25x50 μm^2 required for position resolution and high rates would allow also hit time resolutions close to 10-15 ps.
  - the column width reduction ~10 μm to <5 μm (reduction of capacitance, improvement of S/N, reduction of the jitter/power and increase of fill factor) – in the future column widths as low as ~1-2 μm may be possible allowing possible multi-cell configurations.
  - improved aspect ratio of Deep Reactive Ion Etching (DRIE) is crucial -> current aspect ratio of 25 should be improved, particularly for thicker detectors that may be required to improve the signal required in severe radiation hard environment - larger clusters become the problem.
  - The choice of design (Trench/Column) will be a matter of optimization σ_{wf} vs. σ_j vs. fill factor and there is no clear answer to which is better (it depends on application)
- New ideas will be important and may become possible and/or mature over the years:
  - “Marriage” of LGADs and 3D (either by trench filling, careful substrate selection with small interelectrode distance allowing charge multiplication without special processing of gain layer)
  - “Marriage” of CMOS and 3D.
- The scalability is a question for the producers:
  - single sided processing is a major step forward, the next is move to >=8” wafers, where thicker wafers are required
  - Yield improvement , robustness of the designs are key
- Operation conditions: cooling down as low as possible improves the performance in all respects not only power dissipation/leakage current, but also in speed and possible charge multiplication

Conclusions

The 3D design developments can lead to sensor solution for 4D tracking where ultimate radiation tolerance accompanied with small pixel size is required. The challenges ahead are very large, but there is no a clear show stopper.

Appropriate ASIC development is likely more challenging in terms of radiation hardness, power consumption connectivity and required functionality per pixel (not to mention cost).

Connectivity of sensors is something that is very important/challenging, but the progress is very rapid (ACF, 3D Wafer-Wafer bonding).



see AIDAINNOVA 2021 kick-off meeting
D. Dannhein, F. Hugging talks