Calculation of geometrical parameters of 3D sensors for timing application

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Motivation

- Time resolution 10 - 50 ps
- Pixel pitches down to 25µm
- Fluences up to $10^{17} n_{eq}/cm^2/y$
- Max hit rate up 20 $G/cm^2/s$

[fineprint in CERN-OPEN-2018-006]	HL-LHC	SPS	FCC-ee	FCC-hh
Total fluence [$n_{eq} cm^{-2} s^{-1}$]	5×10^{16}	10^{17}	10^{10}	10^{17}
Max Hit rate [$cm^{-2} s^{-1}$]	2-4G	8G	20M	20G
Material budget per layer [X_0]	0.1-2%	2%	0.3%	1%
Pixel size [μm^2] inner trackers	50x50	50x50	25x25	25x25
Temporal hit resolution [ps] inner trackers	~50	~40	-	~10

Achieving several of these requirements in parallel is a challenge for sensor and front-end electronics

ASIC Jitter as a function of input charger and capacitance

Simulation results of an analog front-end.

(More about this in j.nima.2022.167489)

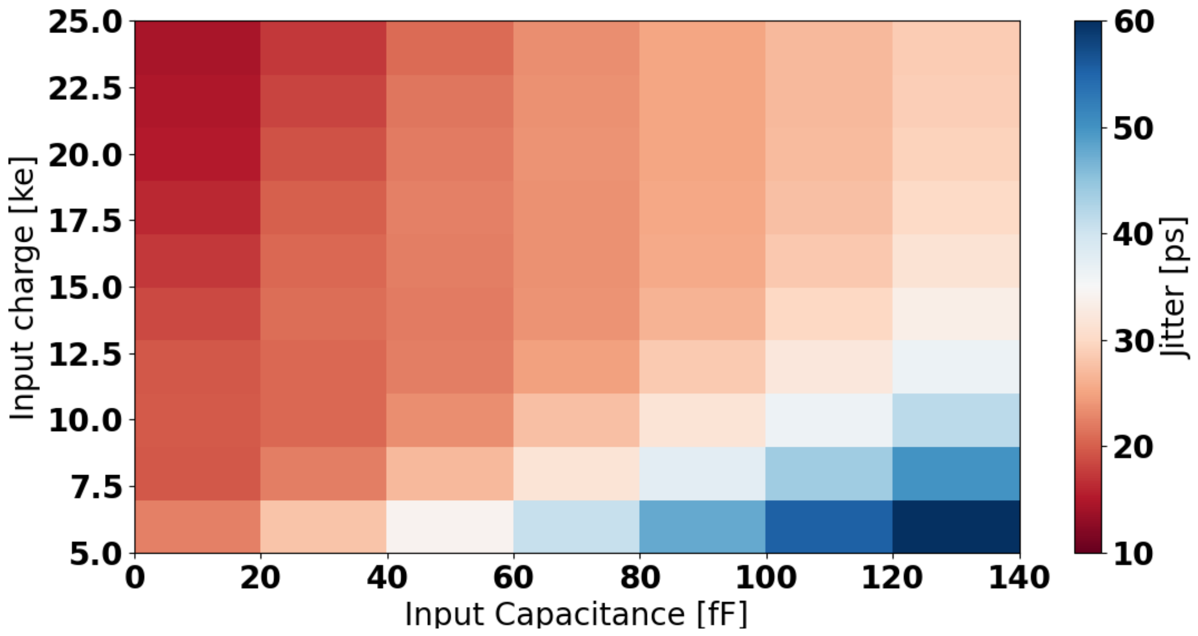
Two important features from these data:

•Larger the capacitance, larger the jitter

•Larger the input charge, smaller the jitter

This jitter comes from the **ASIC** side but depends on the **sensor's** characteristics.

Limitation induced by the ASIC readout to be taken into account in the sensor specification for sensor targeting fast timing applications.



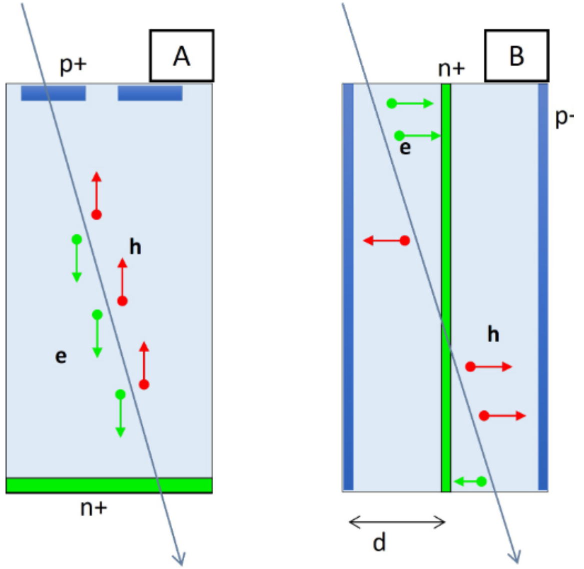
3D sensor for high precision timing measurements

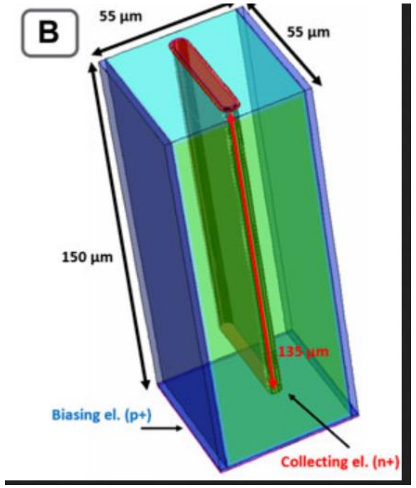
3D sensors are a good candidate for timing measurements:

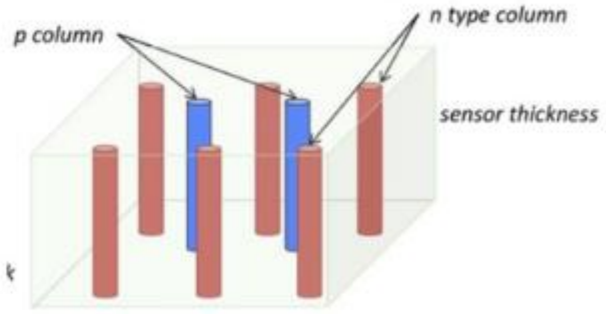
- Smaller drift distances, larger induced charge
- Low leakage current and full depletion voltage
- Radiation tolerant

Different designs for 3D sensors:

- Column-based and Trench-based designs







Calculation of input charge and capacitance for a 3D sensor

The capacitance of a single pixel is calculated as:

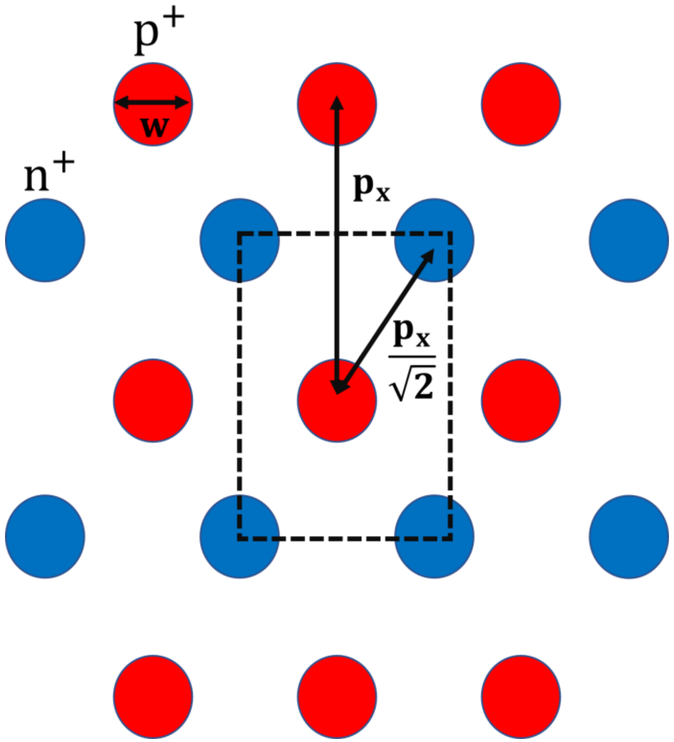
$$C_{pix} = 2C_{p^+p^+} + C_{p^+n^+}$$

Where $C_{p^+p^+}$ and $C_{p^+n^+}$ depends on column width (w) and the aspect ratio of the sensor (A.R).

The deposited charge of a single pixel is calculated as:

$$Q_{in} = 0.072\ \text{ke} \times \text{AR} \times \text{w}$$

Using these equation one can calculate the parameters of a sensor which correspond to a certain time resolution (e.g. 30 ps).



Calculation of acceptance region in w-A.R space

For a given (AR_i, w_i) pair, the sensors capacitance and charge is calculated (as shown in the previous slide):

$$C_i = F_1(AR_i, w_i)$$
$$Q_i = F_2(AR_i, w_i)$$

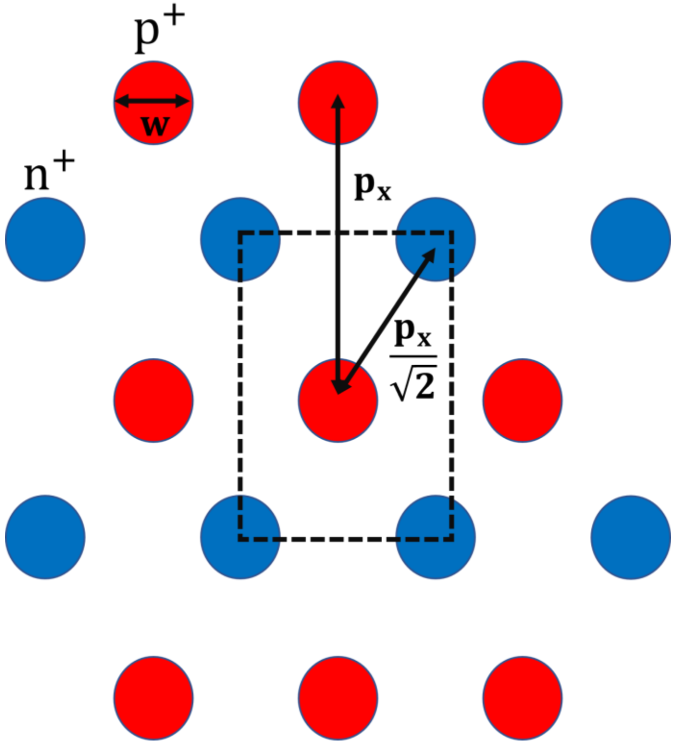
Then, the minimum charge which gives a jitter less than 30 ps for the sensor with the capacitance of C_i is found, Q_{min}.

The sensor with the parameters of (AR_i, w_i) has a timing jitter if:

$$Q_i \geq Q_{min}$$

For a given C_i, the requirements on the minimal charge to achieve 30ps resolution are tighter than to "just" detect the presence of a particle, i.e.:

$$Q_{min} > Q_{thr}$$



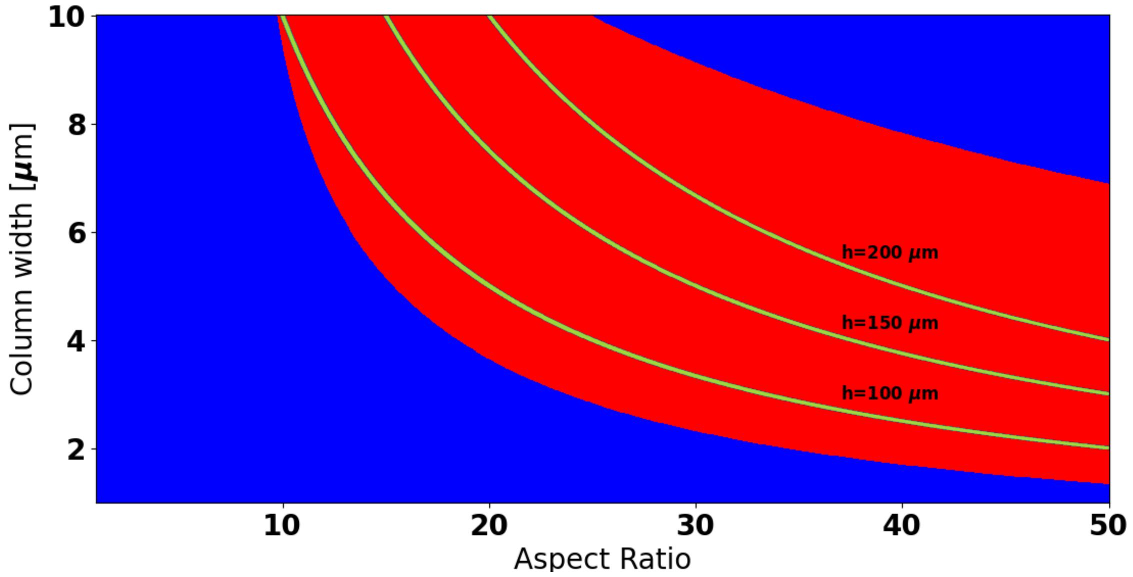
Acceptance region in w-A.R phase space

By combining the capacitance and charge calculations with results of the jitter simulation, the acceptance region in w-A.R space which gives a timing jitter less than 30 ps is found.

The red region shows the accepted range for a w-A.R pair and green lines show different iso-thickness.

This pictures becomes more complicated if the tracks are not parallel, $\theta \neq 0$, and/or limits on fill factor are considered.

$$\theta = 0°, \sigma_t \leq 30 \text{ ps}$$



Definition of “geometrical fill factor”

Geometrical fill factor is calculated as follows:

For a given $(A.R, w)$, in-pixel charge map $Q_{R,w}(x, y)$ is calculated.

The efficiency at the position of (x, y) is calculated as:

$$\mathrm{Eff}^{g}_{A.R,w}(x, y) = \begin{cases} 1 & \text{if } Q_{A.R,w}(x, y) > Q_{thr} \\ 0 & \text{if } Q_{A.R,w}(x, y) < Q_{thr} \end{cases}$$

Where, Q_{thr} is the threshold charge (in this talk 1000 e^{-}).

The geometrical fill factor is defined as the average of the efficiency map:

$$\mathrm{FF}^{g}_{A.R,w} = \overline{\mathrm{Eff}^{t}_{A.R,w}(x, y)}$$

Definition of “timing fill factor”

Timing fill factor is calculated as follows:

For a given $(A.R, w)$, in-pixel charge map $Q_{A.R,w}(x, y)$ is calculated.

The timing efficiency at the position of (x, y) is calculated as:

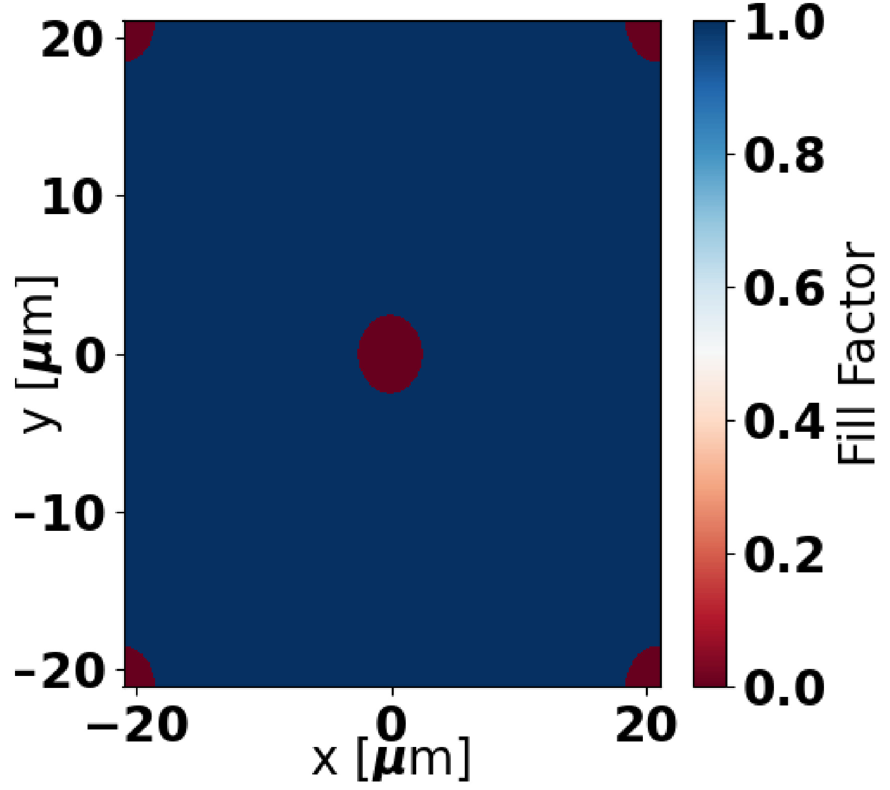
$$Eff^{t}_{A.R,w}(x, y) = \begin{cases} 1 & \text{if } Q_{A.R,w}(x, y) > Q_{min}(A.R, w) \\ 0 & \text{if } Q_{A.R,w}(x, y) < Q_{min}(A.R, w) \end{cases}$$

Where, $Q_{min}(R, w)$ is the minimum charge required to have a jitter below 30 ps.

The timing fill factor is defined as the average of the efficiency map:

$$FF^{t}_{A.R,w} = \overline{Eff^{t}_{A.R,w}(x, y)}$$

$w = 5\mu m, A.R = 30, \theta = 0°$

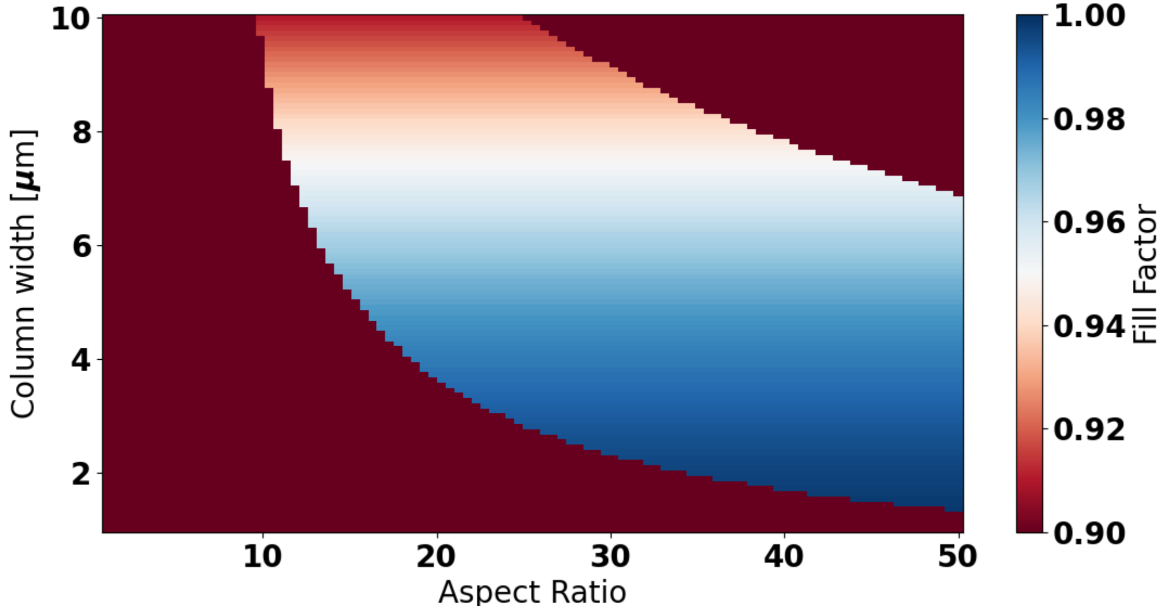


Timing fill factor in w-A.R phase space

The timing fill factor, FF^t, can be estimated for pairs of $(w, A.R)$ values.

$$\theta = 0°, \sigma_t \leq 30\ ps$$

The results for perpendicular tracks are shown in this plot.



There is a rather small region where FF^t >0.98.

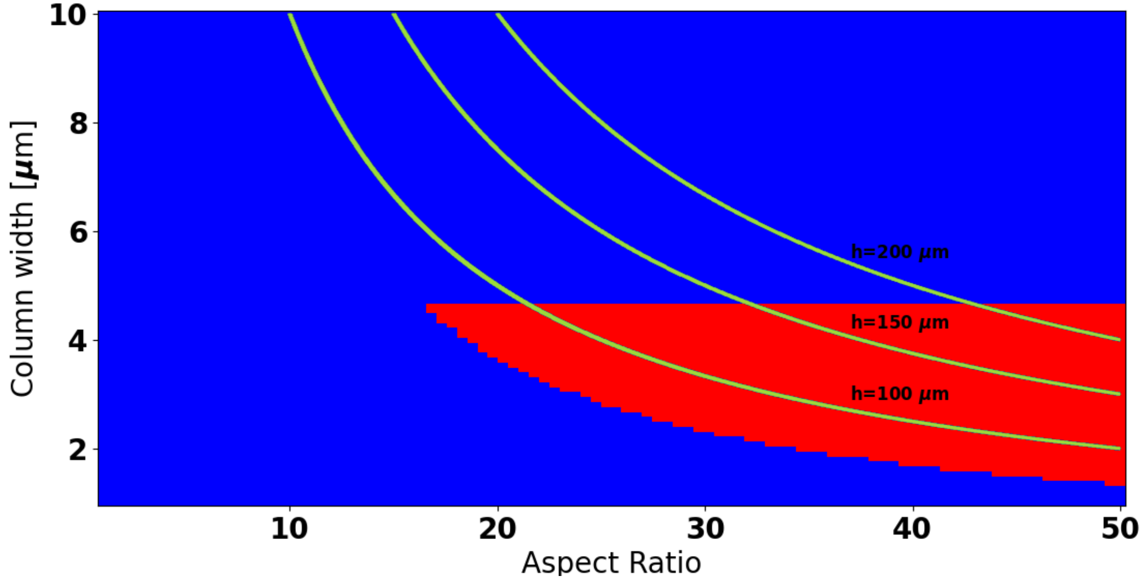
Acceptance region in w-A.R phase space for $\mathrm{FF}^t > 0.98$

$$\theta = 0°, \sigma_t \leq 30\ \mathrm{ps}, \mathrm{FF}^t > 0.98$$

Applying the requirement for the timing fill factor, reduces the acceptance region in w-A.R space, significantly.

The vertical incidence, $\theta = 0°$, is the best-case scenario for timing since the charge sharing between pixels is minimum.

By increasing θ from zero, the charge is spread over more pixels which means the timing jitter increases.



Inclined tracks with respect to the sensor plane

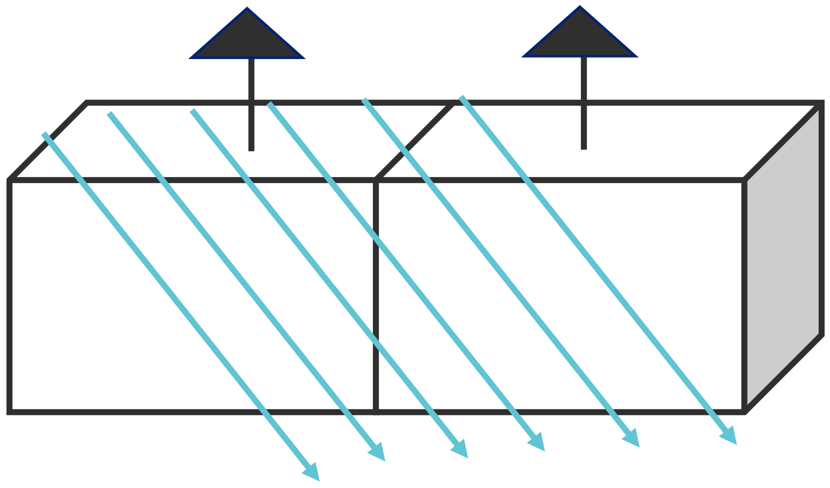
By turning the sensor, the fill factor in the column regions improve.

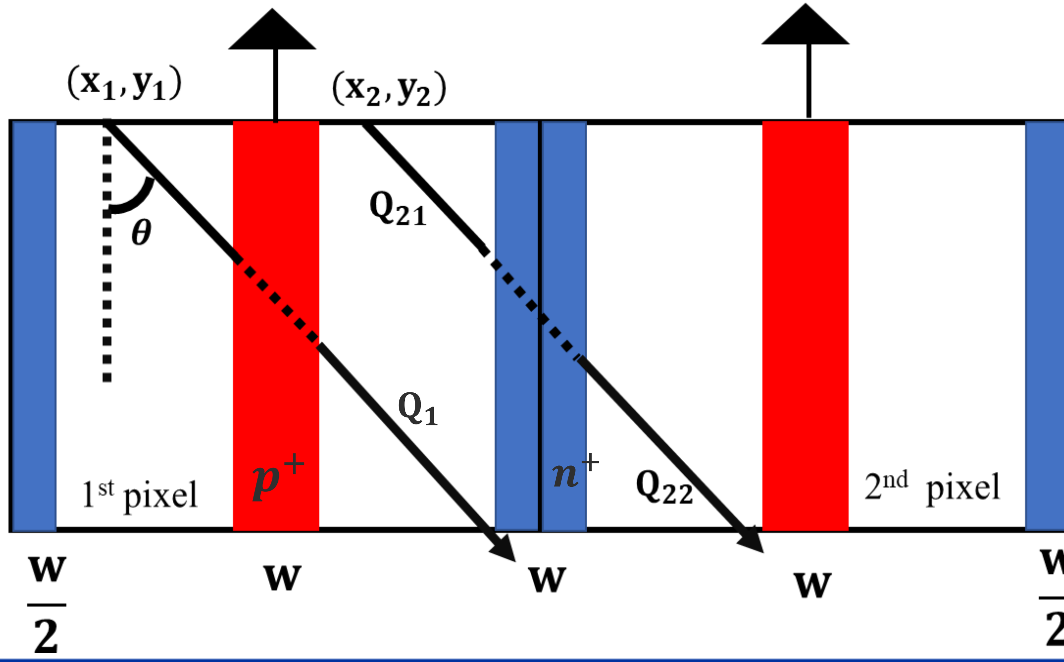
However, the charge is shared between pixels, → less charge is deposited in a single pixel →higher timing jitter

In the electronic, the pixel with the maximum charge is used for timing measurement:

$$\begin{cases} Q_{sig}(x_1, y_1) = Q_1 \\ Q_{sig}(x_2, y_2) = \max(Q_{21}, Q_{22}) \end{cases}$$

Depending on the entry point of the track in the pixel, a different charge is recorded→ position dependent jitter.





Charge map for inclined tracks

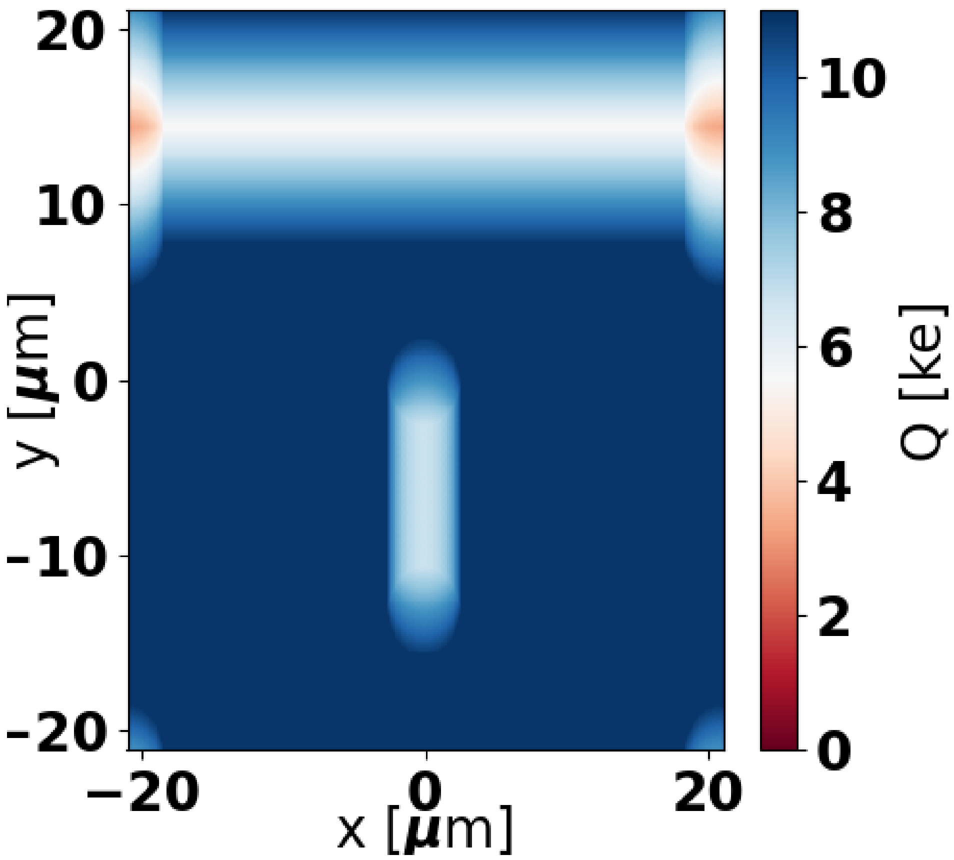
By turning the sensor, the charge loss inside the inactive columns decreases→ better geometrical fill factor.

However, due to the inclined tracks, a “band” of charge sharing is created close to the boundary of the pixel with its neighbor.

The deposited charge in this band is less than the rest of the pixel.

Therefore, the “timing fill factor” of the sensor is reduced for inclined tracks.

$w = 5\mu m, A.R = 30, \theta = 5°$



Charge profile for vertical and inclined tracks

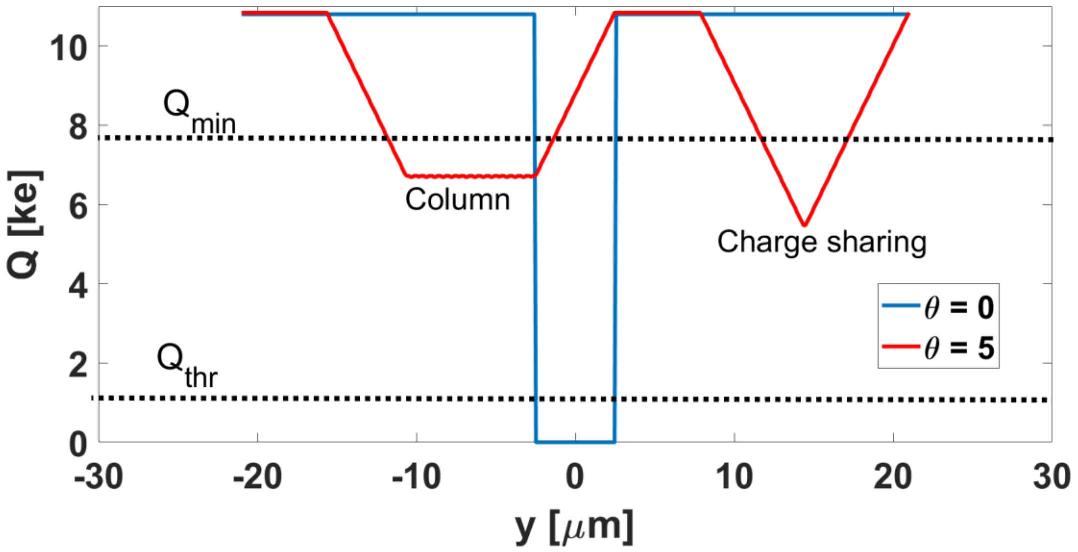
By turning the sensor, the charge loss inside the inactive columns decreases→ better geometrical fill factor.

However, due to the inclined tracks, a “band” of charge sharing is created close to the boundary of the pixel with its neighbor.

The deposited charge in this band is less than Q_{min} but still higher than Q_{thr}.

Therefore, while the “geometrical fill factor” of the sensor increased for inclined tracks, the “timing fill factor” is reduced.

$\mathrm{w} = 5\mu\mathrm{m}, \mathrm{A.R} = 30$



$\text{cut at } \mathrm{x} = 0\ \mu\mathrm{m}$

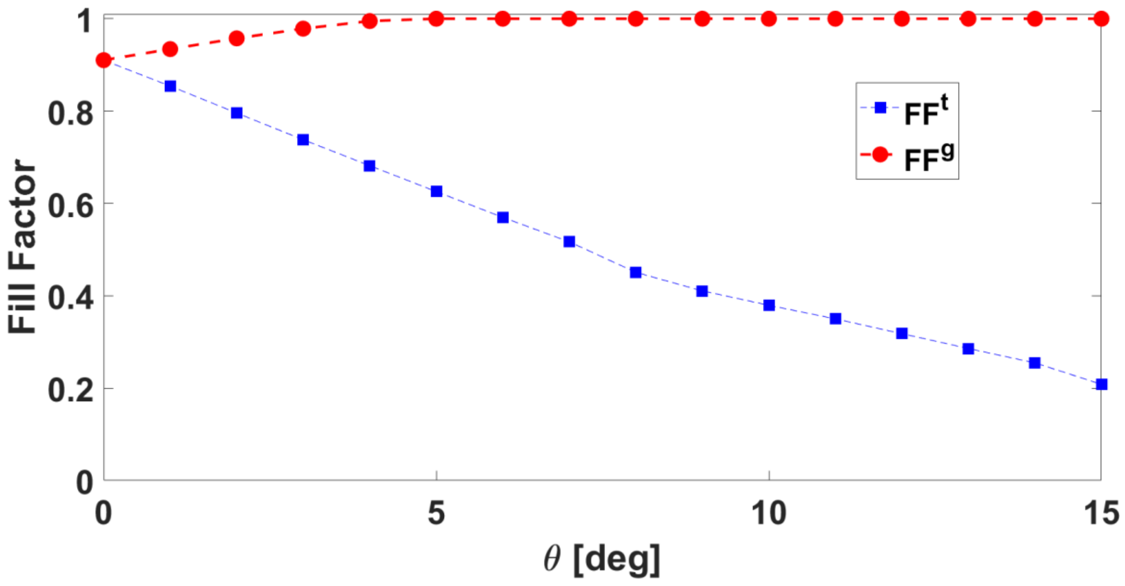
Fill factor as a function of turn angle

As expected, turning the sensor increases the geometrical fill factor.

However, due to increased charge sharing between pixels, the timing fill factor decreases significantly.

This is due to the fact the mean deposited charge in a single pixel decreases which increases the timing jitter.

$$w = 5\mu m, A.R = 30$$



Timing fill factor in w-A.R phase space for inclined tracks

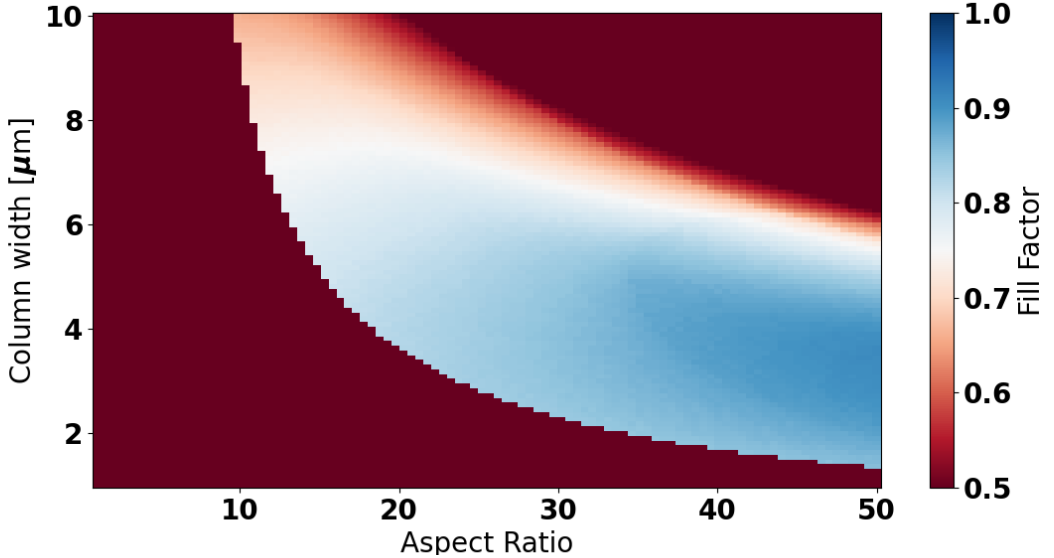
For inclined tracks, $\theta = 5°$, no region in w-A.R with a timing fill factor above 0.90.

The timing fill factors becomes even lower as the inclination angle increases since the charge sharing between increases.

When using 3D sensor for timing measurements, using angle to recover geometrical fill factor will penalise the timing measurement:

$$\text{increase in } \theta \rightarrow \begin{cases} \text{incease in } FF^{g} \\ \text{decrease in } FF^{t} \end{cases}$$

$$\theta = 5°, \sigma_t \leq 30 \text{ ps}$$



Summary and conclusion

- The timing jitter of analog front-end has been simulated as a function of input charge and capacitance.
- The simulation results show the jitter increases with the sensor's capacitance and decreases with the sensor's charge.
- A first-order calculation of the capacitance and charge of 3D column sensors in $\mathrm{w - A.R.}$ space has been done.
- A region in $\mathrm{w - A.R.}$ space which satisfies the requirement of a timing jitter below 30 ps is found.
- The acceptance region in $\mathrm{w - A.R.}$ space for jitter below 30 ps becomes much smaller by adding the fill factor requirement.
- For inclined tracks with $\theta = 5°$, no region in $\mathrm{w - A.R.}$ space is found with a fill factor above 0.9.
- The results presented in this talk should be double-checked with TCAD and Monte-Carlo simulations.