Intrinsic timing properties of simulated ideal 3D-trench silicon sensors with fast front-end electronics

Gian Matteo Cossu, Davide Brundu, Adriano Lai

INFN Sezione di Cagliari

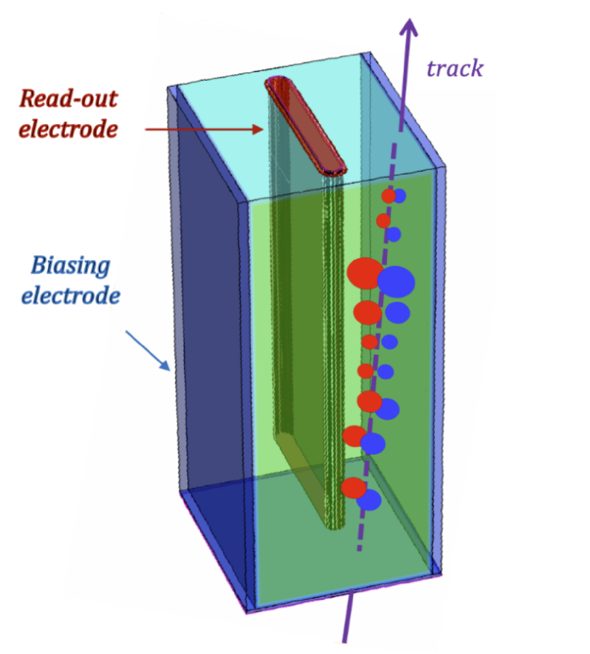
Introduction

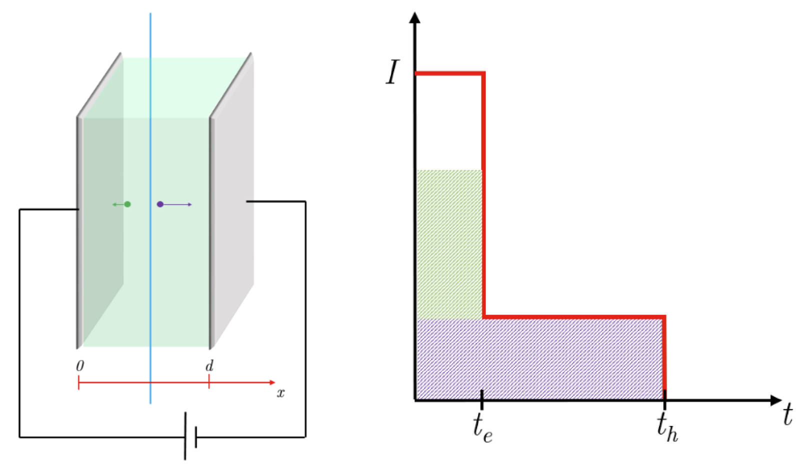
Silicon sensors with 3D-trench structure are a promising solution for future tracking systems, allowing to measure simultaneously time and spatial coordinates (4D-tracking). An analytical model of their intrinsic properties was missing in the literature and it is the aim of this work in the case of fast front-end electronics [1].

1. Ideal model of 3D-trench silicon sensor

We consider a 3D silicon sensor with a standard parallel electrode configuration and uniform electric field: two ohmic trenches at the two opposite sides of the pixel, a readout trench placed at the pixel centre, parallel to the two ohmic trenches. The transient current can be studied in half of the sensor (parallel-plate) and is given by

$$I(t) = \frac{Q_{in}v_e}{d}\theta\left(\frac{x}{v_e}-t\right)+\frac{Q_{in}v_h}{d}\theta\left(\frac{d-x}{v_h}-t\right),$$





where Q_{in} is the charge deposited, v_e and v_h the carriers velocities, t the time and θ the Heaviside function. We can define the two travel times for electrons and holes, t_e and t_h,

$$t_e = \frac{x}{v_e}, \quad t_h = \frac{d-x}{v_h}.$$

2. Properties of output signals and the synchronous region

To obtain the output signals we consider a front-end electronics of a simple ideal integrator across the capacitance C_D of the detector

$$V(t) = \frac{1}{C_D}\int^t I(t')dt'.$$

Let us focus on the discrimination properties: a threshold V_{th} is reached at time t_s when the induced charge Q_s is

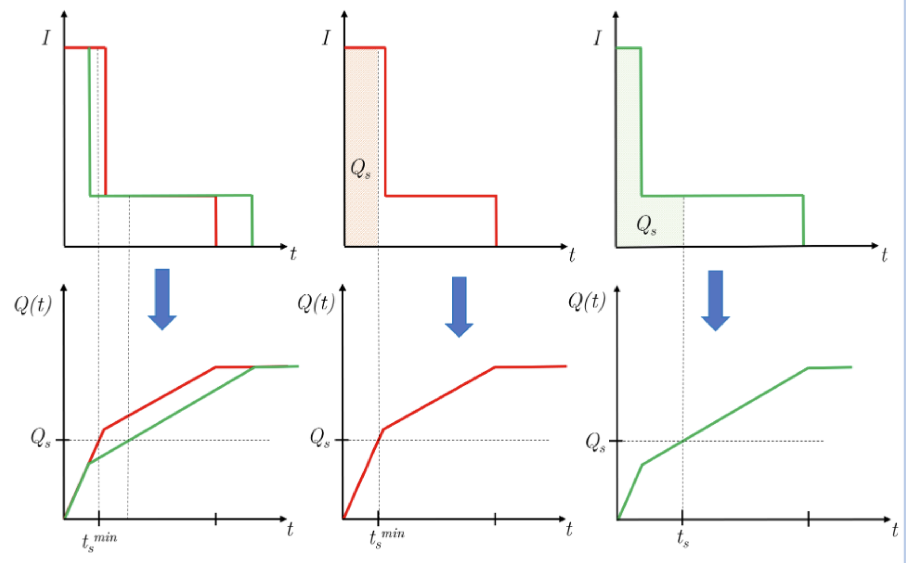
$$Q_s = \frac{Q_{in}v_e}{d}\Big[\Big(t_s-t_e\Big)\theta\Big(t_e-t_s\Big)+t_e\Big]+\frac{Q_{in}v_h}{d}\Big[\Big(t_s-t_h\Big)\theta\Big(t_h-t_s\Big)+t_h\Big].$$

If we consider the signals where the charge Q_s is reached with **both carriers** still contributing to the induction, we obtain a range of coordinates where the signals are all synchronous, i.e. a **synchronous region**:

$$t_s < t_e \quad \text{and} \quad t_s < t_h$$

$$Q_s = \frac{Q_{in}(v_e+v_h)}{d}t_s$$

$$x = \begin{cases} x \geq v_e t_s & \text{for electrons,} \\ x \leq d - v_h t_s & \text{for holes.} \end{cases}$$

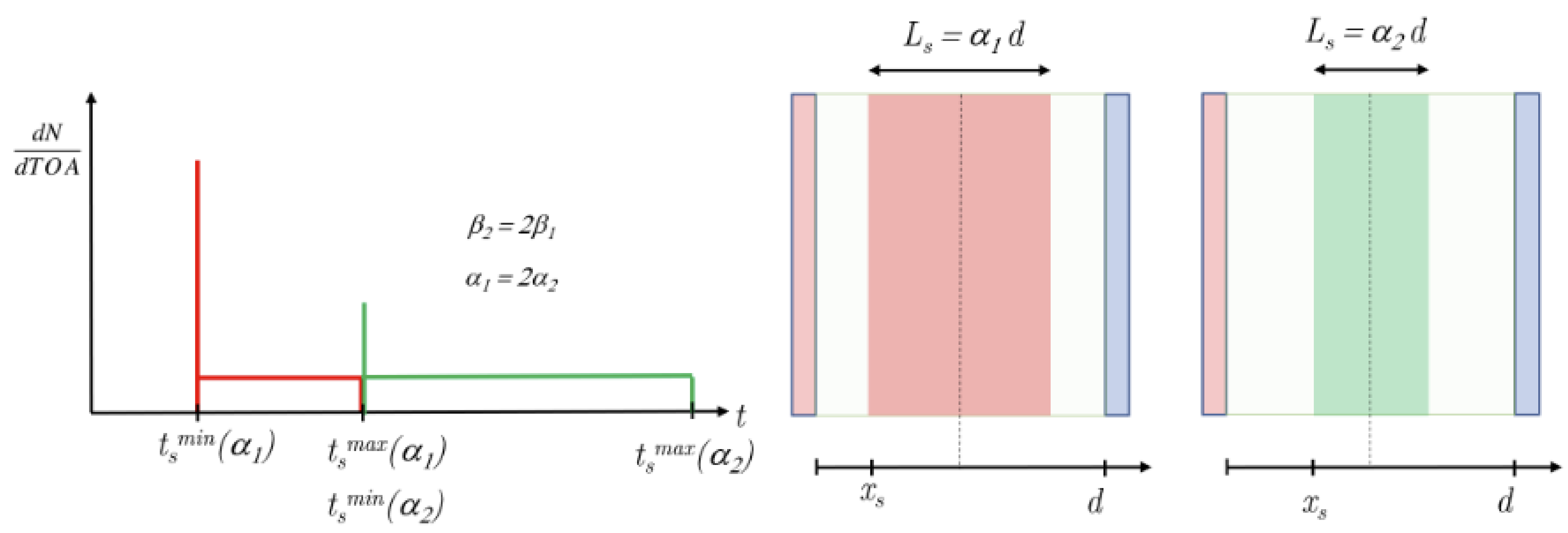


3. Time-of-Arrival (TOA) distribution and its intrinsic asymmetry

If we consider vertical tracks uniformly distributed on the coordinates x, we obtain a TOA as **a mixture of two distributions**:

- all the tracks impacting the sensor within the synchronous region are characterized by a peaking TOA distribution, corresponding to a fraction $\alpha = (Q_{in}-Q_s)/Q_{in}$, ideally with standard deviation $\sigma_\alpha = 0$,
- the remaining fraction $\beta = (1-\alpha)$ shows a uniform TOA distribution with width $\Delta t_s = t_s^{min}$ and standard deviation $\sigma_\beta = t_s^{min}/\sqrt{12}$.

Example in the case of $v_e = v_h$:



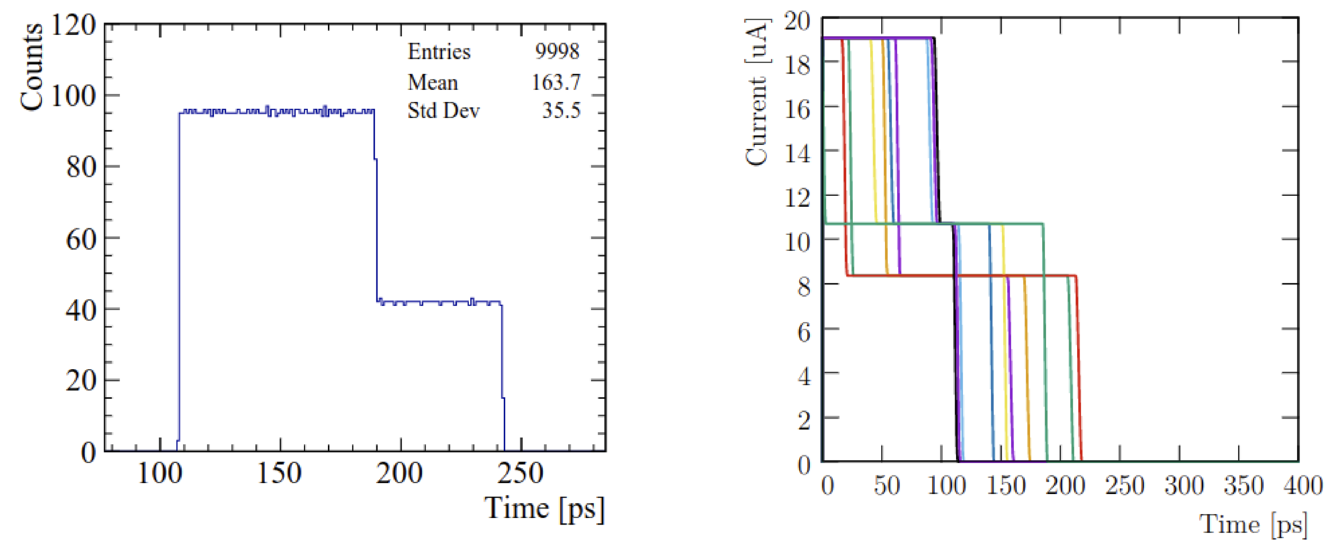
The TOA distribution is **intrinsically asymmetric, even if the field and velocities are constant and uniform.** In the case of different charge saturation velocities, the TOA asymmetry is even more prominent.

4. Simulation of Fast trans-impedance amplifier (fast TIA)

A more realistic electronics response can be modelled as a second-order trans-impedance amplifier (TIA), with DC trans-impedance R_{m_0}. The linear system composed of sensor and electronics is characterized by a finite bandwidth and a time constant τ. The transfer function can be written as

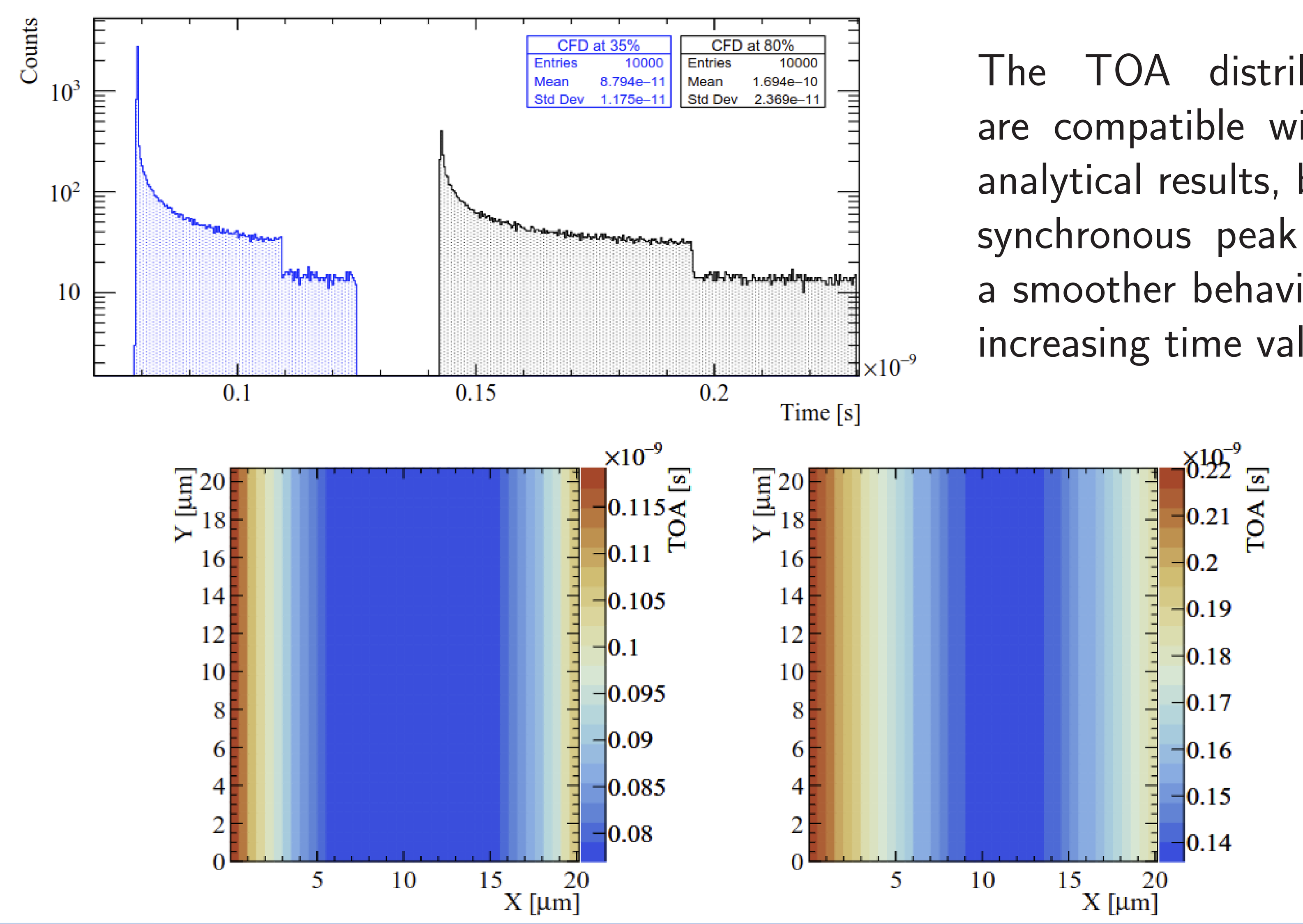
$$R_m(s) = \frac{R_{m_0}}{(1+s\tau)^2}.$$

We have simulated the electronics with $\tau = 160$ ps and $R_{m_0} = 2.3$ kΩ, representing a realistic front-end electronics. Moreover, we choose the electrode distance $d = 20$ μm, uniform electric field, both carriers with saturated drift velocity of $v_e = 0.107$ μm/ps and $v_h = 0.0837$ μm/ps.



5. Intrinsic asymmetry and synchronous region in case of fast TIA

The output signals obtained with the fast TIA have been discriminated with a CFD at different thresholds ($\beta = 0.35$ and $\beta = 0.5$).



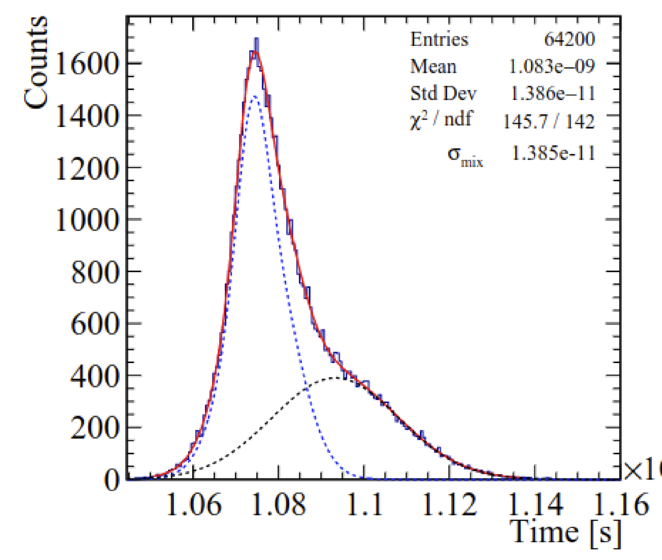
The TOA distributions are compatible with the analytical results, but the synchronous peak shows a smoother behaviour for increasing time values.

6. Time-of-Arrival distribution with fast TIA and noise

In the presence of electronics jitter $J(t)$ the intrinsic TOA distribution will be distorted and enlarged due to the noise convolution, $TOA_{out} = TOA_{intr} \otimes J(t)$. The total time resolution of the mixture distribution will be

$$\sigma_t^2 = \alpha(\Sigma_\alpha^2+\mu_\alpha^2)+\beta(\Sigma_\beta^2+\mu_\beta^2)-\mu^2.$$

For lower SNR, the TOA distribution becomes more and more symmetrical. In the realistic case of SNR $\sim$ 10-30, the final TOA distribution can be fitted with a mixture of two Gaussian distributions, in the approximation of quasi-Gaussian jitter.



For SNR > 10 the intrinsic asymmetry remains visible in the final TOA distribution, as observed in accurate simulations and experimental results [2,3].

[1] G.M.Cossu, D.Brundu, A.Lai, *Intrinsic timing properties of ideal 3D-trench silicon sensor with fast front-end electronics*, JINST 18 P07014.
[2] F.Borgato et al., *Charged-particle timing with 10 ps accuracy using TimeSPOT 3D trench-type silicon pixels*, Front. in Phys. 11 1117575.
[3] D.Brundu et al., *Accurate modelling of 3D-trench silicon sensor with enhanced timing performance and comparison with test beam measurements*, JINST 16 P09028.