Nuclear Instruments and Methods in Physics Research A ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Tracking in 4 dimensions

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ARTICLE INFO

Article history:
Received 12 March 2016
Received in revised form
17 May 2016
Accepted 20 May 2016

Keywords:
Tracking
UFSD
LGAD
Ultrafast
Particles
Silicon

ABSTRACT

In this contribution we will review the progresses toward the construction of a tracking system able to measure the passage of charged particles with a combined precision of ~10 ps and ~10 μm, either using a single type of sensor, able to concurrently measure position and time, or a combination of position and time sensors.

1. The effect of timing information

The inclusion of timing information in the structure of a recorded event has the capability of changing the way we design experiments, as this added dimension dramatically improves the reconstruction process. Depending on the type of sensors that will be used, timing information can be available at different stages in the reconstruction of an event, for example (i) at tracking reconstruction, if timing is associated to each point or (ii) during the event reconstruction, if timing information is associated to each track. In the first case, the 4th dimension brings a simplification already in the reconstruction algorithm as only time-compatible hits are used in the pattern recognition phase, however the electronics is very demanding as it needs to be able to accurately measure timing in each pixel. The second case is simpler as it requires the implementation of a dedicated timing layer, either inside or outside the main silicon tracker volume, to assign the timing information to each crossing track without changing the vast majority of the tracker hardware. The timing information can then be used to improve Level 1 trigger decisions, as it can be obtained faster than tracking reconstruction, and to separate events with overlapping vertices.

Considering a specific situation, at HL-LHC the number of events per bunch crossing will be of the order of 150–200, with an average distance between vertexes of 500 micron and a timing rms spread of 150 ps. Considering a vertex separation resolution of 250–300 micron along the beam direction (present resolution for CMS and ATLAS), there will be 10–15% of vertexes composed by two overlapping events. This overlap will cause a degradation in the precision of the reconstructed variables, and lead to loss of events. Examples where timing information is crucial to avoid loss of measuring accuracy are a) the correct assignment of each particle to its event when two interactions overlap, b) the

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http://dx.doi.org/10.1016/j.nima.2016.05.078
0168-9002/

Please cite this article as: N. Cartiglia, et al., Nuclear Instruments & Methods in Physics Research A (2016), http://dx.doi.org/10.1016/j.nima.2016.05.078

identification of the correct $H \to \gamma\gamma$ vertex , and c) the association of displaced tracks to the correct vertex. We can therefore conclude that timing information at HL-LHC is equivalent of having additional luminosity.

2. Time-tagging detectors

In the following we will use a simplified model to explore the timing capabilities of various detectors (for a review of current trends in electronics see for example [1]): the sensor, thought as a capacitor (C_{Det}) with a current source in parallel, is readout by a pre-amplifier that shapes the signal. The pre-amplifier's output is then compared to a fixed threshold (V_{Th}) to determine the time of arrival. The time resolution σ_t can be expressed as the sum of several terms: (i) Jitter, (ii) Landau Time Walk (iii) Landau noise due to shape variation, (iv) signal distortion, and (v) TDC binning:

$$\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{Land.\ TW}^2 + \sigma_{Land.\ noise}^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2. \quad (1)$$

We will assume in the following two simplifications:

- We consider the effect of time walk (see [2] for details) compensated by an appropriate electronic circuit (either Constant Fraction Discriminator or Time over Threshold). With this assumption, the effect of Landau variations in signal amplitude are compensated, but not that of shape variation. This second contribution is indicated as Landau noise ($\sigma_{Land.\ Noise}^2$) in Eq. (1).
- The contribution of TDC binning to be below 10 ps and therefore negligible.

2.1. Jitter

The jitter term represents the time uncertainty caused by the early or late firing of the comparator due to the presence of noise. It is directly proportional to the noise N and it is inversely proportional to the slope of the signal around the value of the comparator threshold. Assuming a constant slope we can write $dV/dt = S/t_r$ and therefore:

$$\sigma_J = \frac{N}{dV/dt} = \frac{t_r}{S/N}. \quad (2)$$

2.2. Landau fluctuations: time walk and Landau noise

The ultimate limit to signal uniformity is given by the physics governing energy deposition: the charge distribution created by an ionizing particle crossing a sensor varies on an event-by-event basis. These variations not only produce an overall change in signal magnitude, which is at the root of the time walk effect (that we assumed perfectly corrected by electronics), but also produce an irregular current signal (Landau noise). The left part in Fig. 1 shows 2 examples of the simulated [3] energy deposition of a minimum ionizing particle, while the right part the associated generated current signals and their components: the variations are rather large and they can severely degrade the achievable time resolution.

2.3. Signal distortion: weighting field and drift velocity

In every particle detector, the shape of the induced current signal can be calculated using Ramo's [4] theorem that states that the current induced by a charge carrier is proportional to its electric charge q, the drift velocity v and the weighting field E_w: $i(t) \propto qvE_w$. This equation indicates two key points in the design of sensors for accurate timing. First, the drift velocity needs to be constant throughout the volume of the sensor. Non-uniform drift velocities induce variations in signal shape as a function of the hit position, Fig. 2a, spoiling the overall time resolution. The easiest

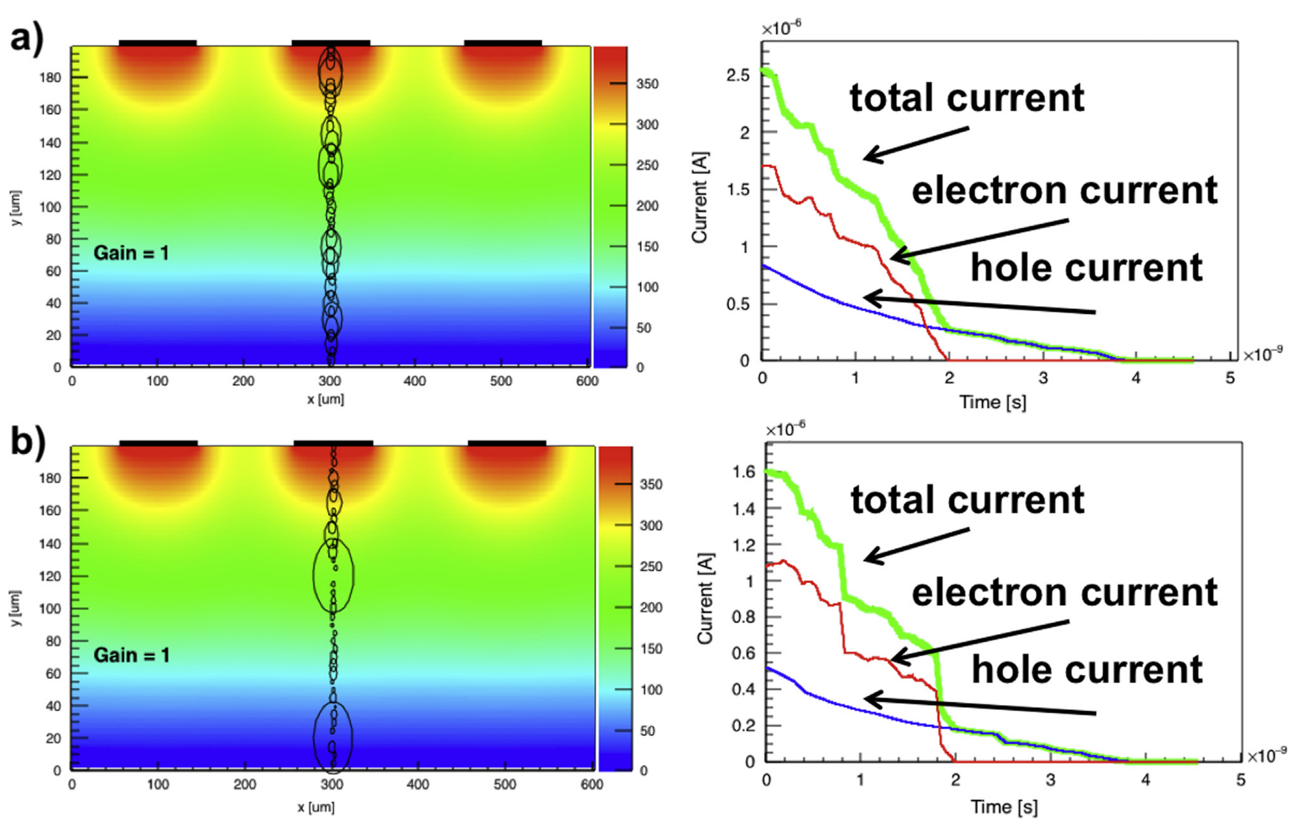

Fig. 1. a) Energy deposits in a silicon detector with gain =1, and (b) the corresponding current signals.