Chasing time

Citation for published version (APA):

Geertsema, R. E. (2024). *Chasing time: Characterisation and application of precision temporal measurements with silicon pixel detectors*. [Doctoral Thesis, Maastricht University]. Maastricht University. https://doi.org/10.26481/dis.20240110rg

Document status and date:
Published: 01/01/2024

DOI:
10.26481/dis.20240110rg

Document Version:
Publisher's PDF, also known as Version of record

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
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Summary

The research presented in this dissertation aims to develop temporal information for high energy physics experiments at the European Organization for Nuclear Research (CERN). These experiments are designed to investigate the fundamental building blocks of nature, described by the Standard Model. They utilise a particle accelerator complex that accelerates particles, protons most of the time, to near the speed of light and smash them together at dedicated interaction points. The resulting collisions produce new particles that are studied by the experiments.

Substantial progress in the understanding of these fundamental building blocks of nature has been made since the first discovery of elementary particles, starting with the discovery of the electron by Joseph Thomson [1] using particle accelerators. Ever since, different designs of particle accelerators have emerged, and their development led to the Large Hadron Collider (LHC) which started operation in 2008. The LHC is a circular accelerator and contains two beam pipes next to each other to guide two beams in opposite directions, one beam per pipe, around a circle with a length of 27 km. The two beams contain so-called *bunches*, a cloud which contains a large number of protons: around 1.15×10^{11}. At four dedicated *interaction points* the two beams are crossed in such a way that protons from the two different beams can collide every 25 ns. Such a collision is called a *bunch crossing*, in which the individual proton-proton collisions occur spread over around 200 ps due to the spatial characteristics of the bunches. The energy frontier of the LHC has been pushed tremendously after the start of the LHC. When the LHC started the energy contained within a single collision was 7 TeV and has been increased in steps to the current energy of 13.6 TeV. The statistical frontier of the LHC has been developed alongside the energy frontier of the LHC. The increase in the proton-proton collision rate also directly increases the statistics of the physical processes to be studied. These physical processes of interest can often contain novel hints towards the validity and understanding of the Standard Model and thus are of prime interest for particle physicists.

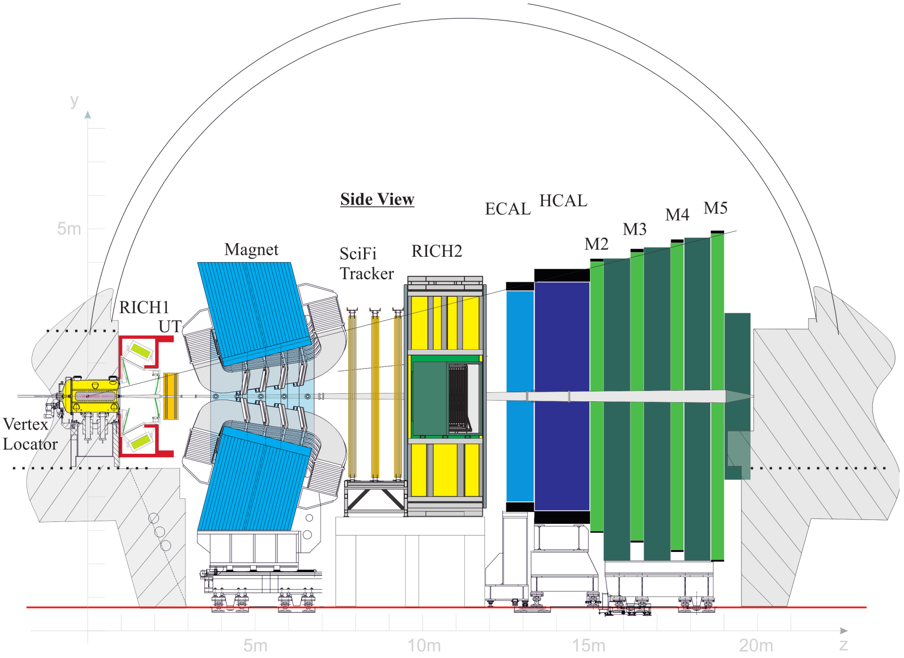

Figure 1: An illustration of the LHCb detector after its first upgrade (2022). The different subdetectors are indicated in various colours, as well as the outline of the cavern (grey lines and striped grey area) and the magnet (blue). The proton-proton interactions take place in the VELO, around $z = 0$. Figure taken from [2].

LHCb's Upgrade 2

One of the experiments operating around an interaction point at the LHC is LHCb (LHC beauty - shown in fig. 1), which is a so-called *forward single-arm spectrometer*, in other words, it focuses its detection at low azimuthal angles with respect to the beamline. Similarly to the other experiments operating at the LHC, it is planning to increase the proton-proton collision rate at the experiment currently planned to start in 2035 and referred to as Upgrade 2. This rate increase is required such that more interactions can be measured over its lifetime. Such a drastic change also requires a complete redesign and upgrade of the various subdetectors in the experiment in order to cope with the increase in rate, radiation damage, data volume and much more. The aim is to increase the average number of visible collisions each 25 ns, in other words, 40 million times per second, from 7 to 42 after the upgrade, resulting in an increased pile-up (the number of collisions occurring within the same event). This increase in pile-up allows LHCb to extend its physics potential beyond what is currently possible.

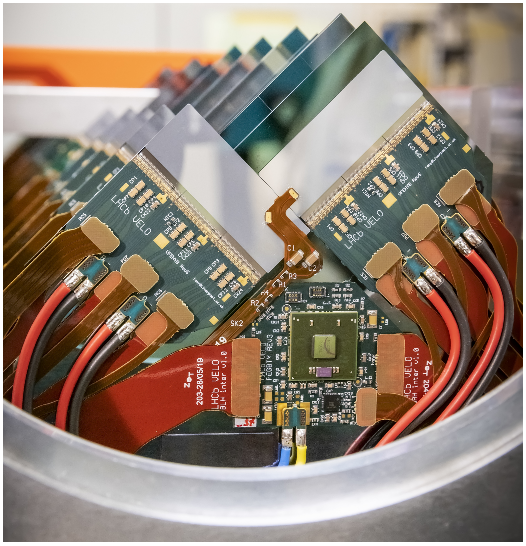

Figure 2: Picture of one side of the VELO detector. The first detector plane is visible along with multiple planes behind it. Picture by [3].

The tracking system of the LHCb detector, needed to reconstruct the trajectories of the various particles emerging from the proton-proton collisions (also called primary vertices), consists of various subdetectors. The subdetector that surrounds the proton-proton collisions, and is the closest to these collisions, is the *VErtex LOcator* (VELO - partially shown in fig. 2). This detector is based on multiple layers of silicon pixel detectors and serves the purpose of tracking the particles emerging from the proton-proton collisions, as well as the reconstruction of the position of these collisions. With the increase in collision rate, the VELO will lose discriminating power in the parameters it provides to the physics analyses, which makes it impossible to perform these analyses. Therefore, temporal information will be included in the VELO, which is information about the time-of-arrival of particles in each pixel detector. This information will be included in its reconstruction to regain the loss in performance. This addition of temporal information enables disentangling overlapping physics processes and collisions.

Since the proton-proton collisions taking place during a bunch crossing are not instantaneous, the timestamp of the collisions and their products can be utilised in the reconstruction. This dissertation investigates how this addition can aid in improving the performance of the VELO. Therefore the impact of this temporal information to two different parameters used in the VELO is studied. Using simulation, the impact of a time resolution of 50 ps per hit is studied. In fig. 3 the impact of temporal information on a typical bunch crossing is shown. The lower plot shows a typical bunch crossing at LHCb during Upgrade 2 with around 42

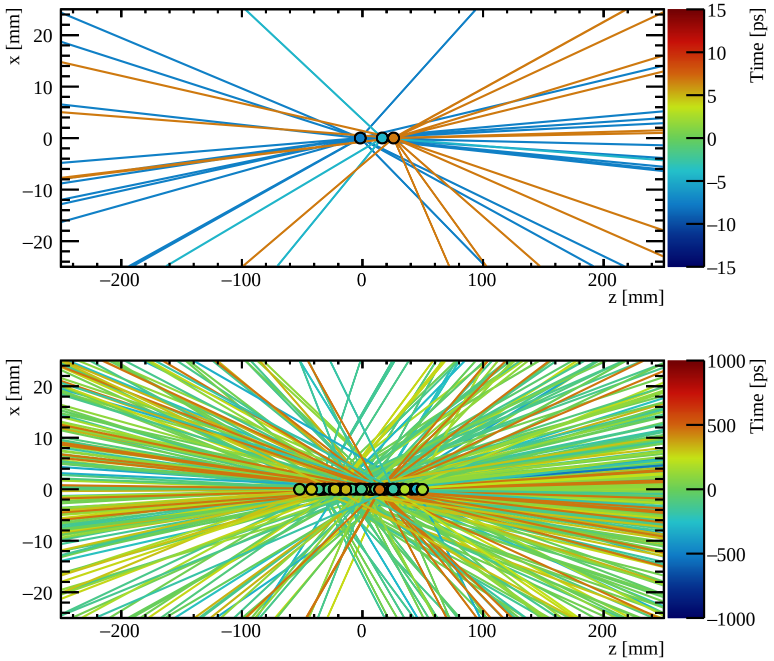

Figure 3: Two figures that indicate the impact of temporal information on pile-up suppression for the VELO. The circles visible in the figures are the proton-proton collisions (primary vertices) and the lines indicate the particle trajectories originating from these primary vertices. The colours indicate the timestamp associated with the vertices and tracks. A typical bunch crossing for Upgrade 2 is shown in each figure, with on average 42 visible collisions. By including temporal information, and selecting a smaller window in time, the effective pile-up is artificially reduced, visible by a reduction of vertices and tracks. The bottom figure shows the full bunch crossing and the top figure shows one of the time slices of 30 ps.

visible proton-proton collisions. The circles in these figures indicate the position of the vertices (the individual proton-proton collisions) and the lines indicate the trajectories of the particles that are created during these collisions. The colours are associated with the individual collisions and the lines indicate the relative time at which they are created. This creation time, referred to as timestamp, enables associating tracks to collisions and depending on the timestamp precision, even without spatial information. One can see that within a time window of around 2 ns, the individual vertices and the particles that emerged from them are difficult, if not impossible, to distinguish. However, when the timestamp of the collisions and particles is considered, a smaller window in time can be selected. Since the individual collisions are spread out in time, the smaller window selected contains fewer collisions and therefore the individual collisions can easily be identified. This is indicated in the top figure in fig. 3, where a 30 ps window is shown out of the full bunch crossing. The colours, or timestamps, can also be used to relate the created particles to their respective collisions, as visible in this top figure.

These simulations indicate that with a per-hit time resolution of 50 ps the adverse effects of higher pile-up are suppressed. These simulations, therefore, sets a stringent goal for the time resolution of silicon pixel sensors that needs to be achieved in the coming years.

DEVELOPMENT OF SILICON PIXEL DETECTORS AND DEDICATED CHARACTERISATION SYSTEMS

At this moment, all existing detectors do not achieve the requirements set for the VELO Upgrade 2. However, extensive R&D programs are ongoing that explore a wide range of possible novel technologies for both the silicon sensor and the electronics. As part of this program, we develop new measurement techniques and equipment to characterise these novel techniques and equipment.

To measure, and more importantly, characterise the temporal performance of novel silicon sensors and detectors that are developed in view of the VELO Upgrade 2, dedicated characterisation systems are developed. In this dissertation, two separate systems are developed. This first system is a beam telescope that uses charged particle beams to study the sensor response. The second system is a laser-based two-photon absorption system that uses photons to induce signals to study the sensor response.

The beam telescope consists of eight planes of silicon detectors, equipped with Timepix4 *Application-Specific Integrated Circuits* (ASICs), and tracks these particles as they traverse the system. Such a system is often called a telescope, and in this specific case is called the Timepix4 telescope. The Timepix4 telescope is developed to provide both precise position tracking and a precise time resolution of the tracked particles. This system in turn allows to compare the reconstructed information of the particles traversing the telescope to the measurements of the particles by an external detector, which enables the characterisation of the different detectors by comparing the measured signals.

The Timepix4 telescope is built in stages and therefore different versions of the Timepix4 telescope have existed. The temporal performance of the four plane system with two thin silicon sensors and two thick silicon sensors (half of the envisioned telescope) and based on the first version of the Timepix4 ASIC is determined at different bias voltages and threshold values. A summary of the results of the time resolution for bias scans (left) and threshold scans (right) of the telescope planes are shown in fig. 4 and are used to find the optimal operating conditions.

The best time resolution of this four plane telescope is determined to be 340 ± 5 ps. However, it was also noted that this resolution will be improved significantly when the final version of the Timepix4 ASIC is implemented in the system as well as adding a further four planes. The resolution will also further improve when the so-called timewalk calibration and clock synchronisation have been further optimised. A time resolution below 100 ps is expected to be achieved by the complete telescope. This resolution will be enough to test the first generation of novel ASICs but is not sufficient to test silicon sensors themselves to their limit. The telescope, however, can also provide a more precise timestamp at a lower rate using a dedicated timing system to timestamp the tracks to a precision of below 20 ps which is sufficient to test the performance of the novel sensors.

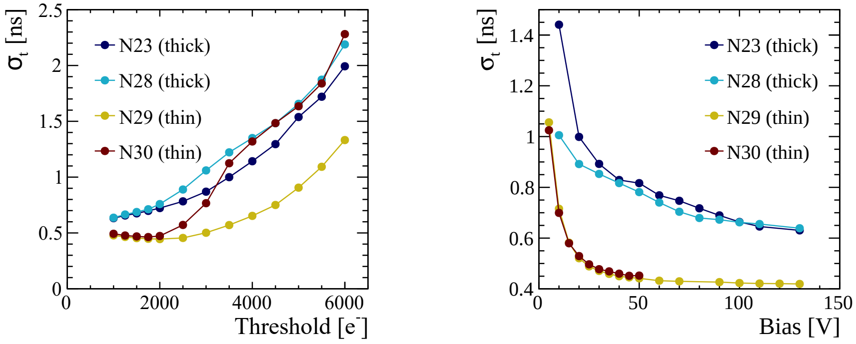

Figure 4: Left: the time resolution of the four telescope planes for a variety of threshold values. Right: the time resolution of the four telescope planes as a function of the bias voltage. Two of the planes reach their best resolution at a threshold of around 2000 e$^-$, and the time resolution improves for higher bias voltages for all planes. Figures adapted from [4].

Employing the predecessor of the Timepix4 telescope, the Timepix3 ASIC based telescope called the Timepix3 telescope, the charge collection and temporal characteristics have been measured for a variety of sensor designs in view of the first upgrade of the VELO that is currently installed. These studies provided information on the impact of radiation damage which sensors need to handle with close to the interaction point. In these studies, it was concluded that the radiation damage that the VELO will have received at the end of its lifetime will reduce the collected charge from 16 ke$^-$ to 6 ke$^-$, which is sufficiently high to achieve the required performance. A small amount of charge multiplication has been discovered in a subset of sensors that received the highest amount of radiation damage, which slightly increased the collected charge. The time resolution was also studied as a function of radiation damage and has been found to degrade with increasing damage. No improvement in the time resolution was found when charge multiplication occurred. These studies however were performed with the

Timepix3 ASIC, which has an intrinsic time resolution of at least 451 ps and thus dominates the time resolution. Therefore, small changes in the time resolution, due to for example charge multiplication, might not have been identified.

Besides the telescope, the development of a laser-based system is also described in this dissertation. This system consists of a fibre-based 1550 nm laser that can create signals in silicon sensors through the *Two-Photon Absorption* (TPA) effect. This process relies on the fact that two photons are absorbed in the silicon sensor within a short period of time at the same position. This technique therefore enables the localised characterisation of charge collection within the silicon bulk. Since the duration of the laser pulses is short, between 380 to 540 fs, this allows to create a precise time reference signal, which is estimated to have a jitter of less than 30 ps, limited by the device that was used to verify the time resolution. This makes the TPA system ideal to characterise the spatial, charge collection and temporal performance of silicon sensors and detectors in a controlled way.

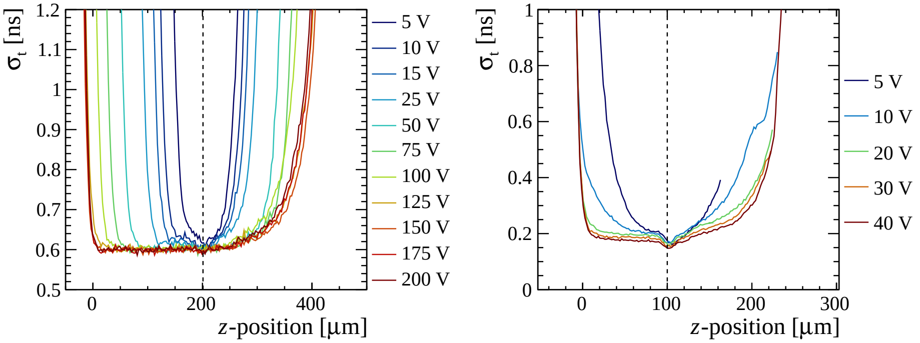

Figure 5: Left (Right): the time resolution of a 200 µm (100 µm) silicon sensor connected to a Timepix3 (Timepix4) ASICx as a function of the height within the sensor for different bias voltages indicated by the different colours. The dashed line indicates the front of the sensor and the 0-point on the horizontal axis indicates the back of the sensor. Left figure taken from [5].

The two-photon absorption system constructed at Nikhef has been commissioned and the results are discussed in this dissertation. Initial measurements indicate a variation in the TPA signal intensity due to fluctuations in the temporal width of the laser pulses over a timescale of several minutes. These fluctuations can partially be corrected offline using a separate silicon sensor as an intensity reference. Using this system, both planar sensors on Timepix3 and Timepix4 ASICs have been investigated. Two planar sensors have been investigated on Timepix3 ASICs and it is concluded that the time resolution is dominated by the contributions from the ASIC and not the sensor, in line with the findings from the Timepix3 telescope. Nonetheless, a resolution of around 600 ps is achieved. For the initial results with the Timepix4 ASIC, a resolution of 147.4 ± 1.1 ps has been achieved, which is substantially better compared to the results with Timepix3 ASICs. This improvement can be attributed to the improved analogue front-end and digital time measurement of the Timepix4 ASIC. Small improvements are envisioned to be implemented that can improve this time resolution further. Two measurements, left with Timepix3 and right with Timepix4 ASIC, are shown in fig. 5. These measurements show the time resolution of the sensors as a function of depth within the sensor volume. The dashed line indicates the front side of the sensor and the 0-point indicates the back side. Both show similar response curves independent of their different thickness, however, the time resolution scale is significantly different with the Timepix3 ASIC reaching a saturation at around 600 ps compared to the Timepix4 ASIC at just below 200 ps.

These initial measurements with the TPA system indicate that the characterisation of novel silicon detectors can be performed and that this system is a valuable tool and testbed for developing fast-timing silicon detectors in the coming years. We have seen that the current limiting factor for fast silicon sensors is the analogue front-end and digitisation (TDC). However, with the current trend of improvements over the past few years, this limiting factor will most likely disappear in the near future. Novel silicon sensor techniques have already proven that a time resolution below 30 ps is achievable, however full-scale implementation of them in the VELO are still under study. At this moment, it seems that the sensor will not be the limiting factor of these development in the near future.

The time resolution of the detectors that have been covered in this dissertation is far away from the required 50 ps for the VELO. However, as can be seen from the transition of the Timepix3 ASIC to the Timepix4 ASIC, significant steps are already achieved. This trend needs to continue in the coming years to achieve the goal of a per-hit time resolution of 50 ps. The two characterisation systems discussed in this dissertation will become crucial tools in the development of silicon based fast-timing detectors.

BIBLIOGRAPHY

[1] J. Thomson, *Cathode rays*, *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **44** (1897) 293.

[2] LHCb Collaboration, *LHCb Tracker Upgrade Technical Design Report*, tech. rep., CERN, Geneva, 2014.

[3] McCoy Wynne photography partnership. Personal communication.

[4] K. Akiba et al., *Reconstruction of charged tracks with Timepix4 ASICs*, *Journal of Instrumentation* **18** (2023) P02011.

[5] R. Geertsema et al., *Charge and temporal characterisation of silicon sensors using a two-photon absorption laser*, *Journal of Instrumentation* **17** (2022) P02023.