**CLICdp-Note-2017-002**
**25 April 2017**

# Requirements for the CLIC tracker readout

D. Dannheim*, A. Nürnberg[1)]*

* *CERN, Switzerland*

## Abstract

The requirement of precision physics and the environment found in the proposed future high-energy linear $e^+e^-$ collider CLIC result in challenging constraints for the silicon tracking detector. A track-momentum resolution of approximately $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}\,\text{GeV}^{-1}$ for high-momentum tracks has to be achieved in an environment with high rates of beam-induced background events. The current layout foresees a multi-layer tracking detector system arranged in a barrel and endcap geometry with a total surface of approximately $100\,\text{m}^2$. This note describes the specifications for the tracker sensors and readout electronics.

*This work was carried out in the framework of the CLICdp collaboration*

[1] andreas.nurnberg@cern.ch

# 1 Introduction

The proposed CLIC linear $e^+e^-$ collider with a center-of-mass energy up to 3 TeV requires high-precision track-momentum measurements in an environment with high rates of beam-induced background events [1]. The current design of the CLIC detector foresees an all-silicon tracker surrounding the vertex detector [2]. The tracker is divided into an “Inner Tracker” and “Outer Tracker”, separated by the support cylinder of the beam vacuum tube. The Inner Tracker contains three tracker barrel layers and, on each side of the barrel, seven inner tracker disks. The Outer Tracker is built from three large barrel layers complemented on either side by four outer tracker disks. A cross-section of a single quadrant of the CLIC tracking systems in the xz-plane is depicted in Figure 1. In total, the active sensor area is in the order of $100\,\mathrm{m}^2$. Short strips/long pixels (strixels) are envisaged to meet the requirements in terms of precision and occupancy throughout the detector. Given the large detector area and the high readout granularity, monolithic technologies can offer advantages in assembly and system design. This document summarizes the requirements on a readout chip for application in the CLIC tracker at the highest center-of-mass energy stage of 3 TeV.

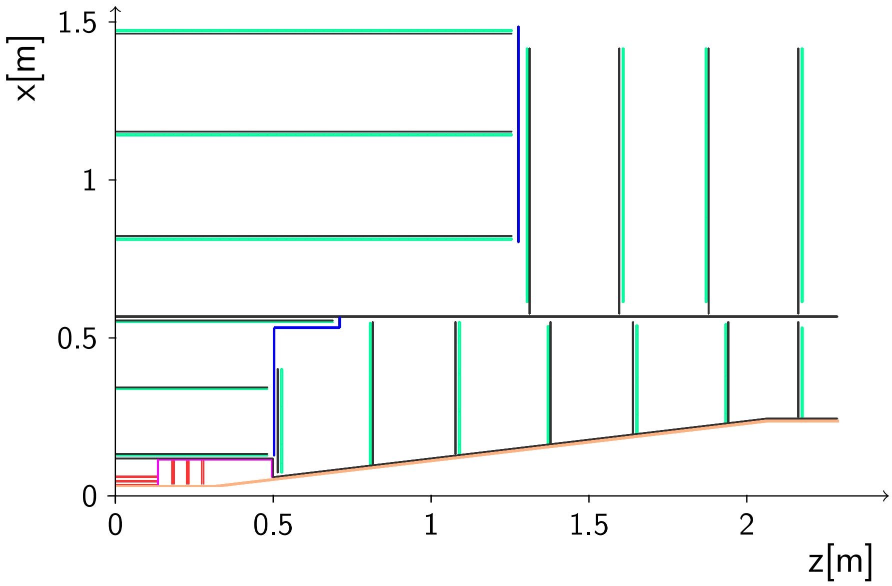



Figure 1: One quarter of the CLIC tracker layout [2].

# 2 Requirements

## 2.1 Point resolution

A transverse-momentum resolution of $\sigma_{p_\mathrm{T}}/p_\mathrm{T}^2 \approx 2\times10^{-5}\,\mathrm{GeV}^{-1}$ for high-momentum tracks in the central part is required for accurate physics measurements of e.g. the Higgs strahlung process [1]. In combination with the choice of the magnetic field strength of 4 T and the large tracker radius of 1.5 m, this poses constraints on the required single-point resolution of the sensors in the bending direction of the magnetic field. GEANT4 [3, 4] based full detector simulations of the CLIC detector concept were performed in order to assess the performance of the tracker as a function of the single-point resolution of the detection layers. In these simulations the response of the sensor layers is obtained by a Gaussian smearing of the true hit position with a width corresponding to the assumed single-point resolution. The resulting transverse-momentum resolution for individual muons in the central region of the tracker is shown in

Figure 2 for different resolutions in the transverse plane of the detector layers. The $p_T$ resolution as a function of $p$ has been fitted to the parameterization:

$$\sigma\left(\Delta_{p_T}/p_T^2\right) = a \oplus \frac{b}{p\sin\theta} \tag{1}$$

where parameter $a$ corresponds to the contribution from the curvature measurement and parameter $b$ to the multiple scattering contribution. The fit results for different single point resolutions are given in Table 1. From this study it is clear that a single point resolution of 7 µm or better is needed to reach the transverse-momentum resolution goal.

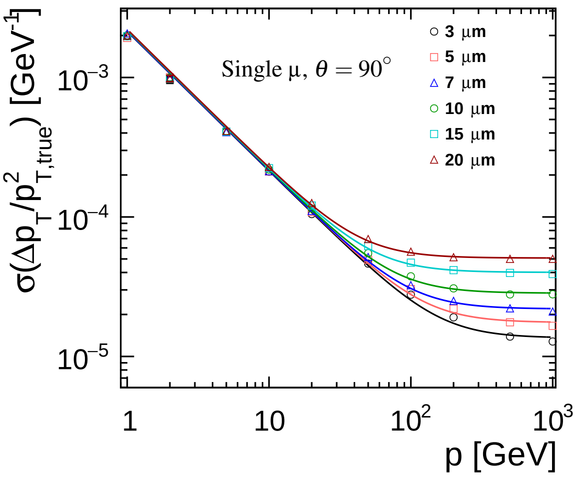


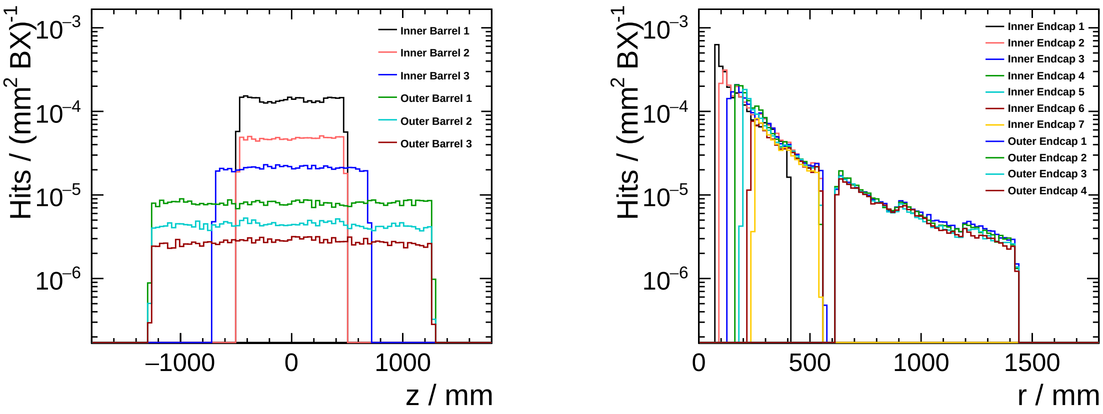

Figure 2: Transverse-momentum resolution for single muons in the CLIC barrel tracking detector as a function of particle momentum and for various single point resolutions in the transverse direction.

Table 1: $p_T$ resolution $\sigma\left(\Delta_{p_T}/p_T^2\right)$ for single muons in the central detector at $\theta = 90^\circ$, parameterized by Equation (1).

| Single point resolution / µm | $a$ / GeV$^{-1}$ | $b$ |
|---|---|---|
| 3 | $1.36 \times 10^{-5}$ | $2.14 \times 10^{-3}$ |
| 5 | $1.75 \times 10^{-5}$ | $2.16 \times 10^{-3}$ |
| 7 | $2.19 \times 10^{-5}$ | $2.15 \times 10^{-3}$ |
| 10 | $2.84 \times 10^{-5}$ | $2.18 \times 10^{-3}$ |
| 15 | $4.01 \times 10^{-5}$ | $2.20 \times 10^{-3}$ |
| 20 | $5.08 \times 10^{-5}$ | $2.21 \times 10^{-3}$ |

### 2.2 Strixel granularity

The accuracy in the position measurement in the direction perpendicular to the bending in the magnetic field, corresponding to the direction of the strixels, does not contribute to the momentum measurement. The readout segmentation in this direction, corresponding to the length of the strixels, is constrained by the need for efficient pattern recognition in the presence of hits from beam-induced backgrounds. Figure 3 illustrates the hit rate per unit area and bunch crossing in the barrel and endcap region, taking




(a) Barrel

(b) Endcaps

Figure 3: Expected hit rate in the CLIC tracker due to beam induced background hits from incoherent pair production and $\gamma\gamma \to$ hadrons background processes. Safety factors for the simulation uncertainties are not included. In contrast to the detector model described in [2], the thickness of the silicon sensors studied in this paper has been kept at 300 µm.

into account both incoherent pair production and $\gamma\gamma \to$ hadrons background processes from a GEANT4 based full detector simulation.

The resulting hit rates in each layer allow for an estimate of the required readout granularities (strixel pitch p and strixel length l) needed to limit the occupancy to a certain level:

$$\text{Occupancy/train} = \sum_{proc.} \text{Hits}_{\text{proc.}}/(\text{mm}^2 \cdot \text{BX}) \times n_{\text{bunches}} \times \text{p} \times \text{l} \times \text{cs} \times \text{sf}_{\text{proc.}} \tag{2}$$

In the following it is assumed that

- a maximum readout occupancy, integrated over the full bunch train ($n_{\text{bunches}} = 312$ bunch crossings spaced by 0.5 ns), of 3% can be tolerated,
- the granularity in the transverse direction (pitch p) is 50 µm,
- the average number of readout cells responding to each hit[2] (cluster size cs) is 2.6.

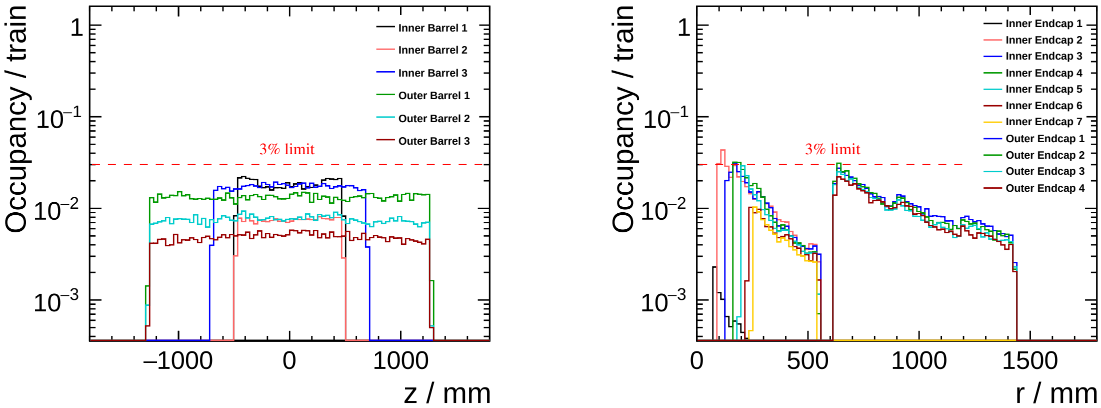
Safety factors (sf) for the uncertainties related to the production and simulation of the individual background processes (proc.) of 5 for the incoherent pair production and 2 for $\gamma\gamma \to$ hadrons have been applied [5, 6]. In contrast to the detector model described in [2], the thickness of the silicon sensors studied in this paper has been kept at 300 µm, in order to be consistent with previous studies. The influence on the detector background occupancy from the reduction of the sensor thickness to 100 µm remains to be studied. Table 2 summarizes the required strixel granularity in the tracking detector obtained for the assumptions presented above. The resulting occupancy of the detector per bunch train using Equation (2) is illustrated in Figure 4, demonstrating that the chosen cell sizes between 1–10 mm limit the occupancy to levels below 3%.

The required granularity of only 25 µm × 25 µm for the first inner disk was obtained from a separate optimization study [7, 8]. It is motivated by the need for efficient track extrapolation into the high-occupancy inner vertex-detector region during track reconstruction. The first inner disk should therefore be considered as part of the vertex detector in terms of sensor and readout technology.

[2]Can depend on technology, sensor thickness and pitch

Table 2: Minimal strixel granularity in the tracker layers required to limit the occupancy due to background particles to 3% per bunch-train.

| Detector layers | Total area / $m^2$ | Strixel length / mm | Strixel width / mm |
|---|---|---|---|
| Inner barrel 1–2 | 2.99 | 1 | 0.05 |
| Inner barrel 3 | 5.22 | 5 | 0.05 |
| Outer barrel 1–3 | 60.66 | 10 | 0.05 |
| Inner disc 1 | 0.63 | 0.025 | 0.025 |
| Inner discs 2–7 | 6.09 | 1 | 0.05 |
| Outer discs 1–4 | 26.76 | 10 | 0.05 |




(a) Barrel

(b) Endcaps

Figure 4: Bunch train occupancies in the CLIC tracker due to beam induced background hits from incoherent pair production and $\gamma\gamma \rightarrow$ hadron background processes. Here, cluster size and safety factors are taken into account. In contrast to the detector model described in [2], the thickness of the silicon sensors studied in this paper has been kept at 300 µm.

## 2.3 Energy measurement

In the presence of significant charge sharing among several cells, the hit resolution can be improved by using the weighted mean of the energy deposits. Since the fraction of hits with shared charge depends strongly on the cell size and the choice of sensor technology, no requirement for energy measurement is derived from the hit resolution target. However, the energy measurement may be needed to mitigate the effect of time walk (see Section 2.4). Moreover, the relevance of the measurement of the specific energy loss dE/dx for particle identification is currently under study. If found to be beneficial, energy measurement of the individual hits might be needed, independent of its impact on the hit reconstruction. To study the signal development in the first generation of prototype detectors, an energy measurement with moderate resolution of 5 bits, e.g. by means of time-over-threshold determination, should be implemented.

## 2.4 Trigger and time tagging

Given the low duty cycle of the CLIC accelerator, and the fact that at most one hard interaction per bunch train is expected, a trigger-less readout of the CLIC detector is foreseen. The hits originating from the

312 bunch crossings per bunch train of 156 ns duration are integrated and read out after the active period as one event. No multi-hit capability per readout cell during the bunch train is envisaged.

To suppress out-of-time hits from beam-induced background particles and thus to simplify the event reconstruction, time slicing with a bin size of 10 ns is foreseen in the tracking detectors. For that, the least significant bit of the time-of-arrival (TOA) measurement relative to the bunch train should be 10 ns, with a dynamic range of at least 4 bits. For easier testing at test beams, a higher dynamic range of the TOA measurement of approximately 8 bits or more would be beneficial.

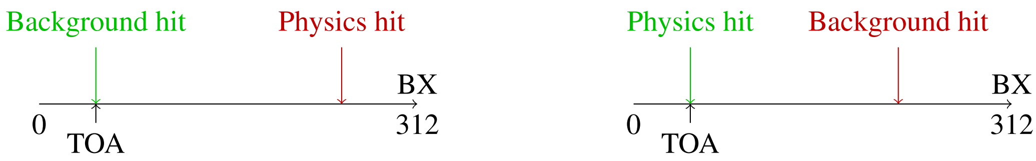
To achieve the 10 ns time slicing, the influence of time walk[3] on the TOA measurement has to be taken into account. In case the detector front-end is designed in a way, that the time walk effect contributes significantly to the TOA precision, time walk can be corrected during the event reconstruction. For that, the measurement of the signal amplitude is essential (see Section 2.3).

## 2.5 Hit efficiency and noise rate

The occupancy from beam-induced background particles of up to 3% (see Section 2.2) and the envisaged trigger-less readout scheme without multi-hit capability within a bunch train (see Section 2.4) influence the requirements on the detection efficiency and the tolerable noise rate.

Depending on the position of the hard interaction in the 156 ns bunch train, a certain fraction of the detector cells have already been hit by a background particle (see Figure 5(a)), and the time of that background hit has already been assigned to the readout cell. These cells are no longer sensitive to the hit originating from the physics event, and any further hit is discarded due to the timing cut in the reconstruction. This results in a decreasing detection efficiency over the duration of the bunch train.

Considering the reverse case: a cell is first hit by a particle originating from a physics event and later in the bunch train again by a second particle, this time originating from a background process (see Figure 5(b)). In this case, the correct timestamp is assigned to the hit. However, the energy deposited by both particles overlay (e.g. by increasing the time-over-threshold). This effect can bias the energy resolution and by that, in the presence of charge sharing, also the position resolution.




(a) Background first

(b) Physics first

Figure 5: Combinations of background and physics hits in a readout cell within the bunch train.

The coverage of the combined vertex and tracking system provides at least eight hits for all tracks with a polar angle down to about $8^\circ$ [2]. For that reason, the above mentioned effects of missing or biased hits are not expected to significantly degrade the efficiency of the pattern recognition or the quality of the final track fit in the detector. However, the intrinsic hit detection efficiency for isolated particles should not add a dominant contribution to the above mentioned effects. As a goal, the intrinsic detector readout inefficiency of a single detection layer should therefore be about one order of magnitude below the background hit rate of approximately 1–3%, which translates into a requirement on the readout hit detection efficiency of 99.7–99.9%.

Besides the beam background, electronic noise contributes to the overall detector occupancy and the above mentioned effect. Also this contribution should be kept at least one order of magnitude below the beam background contribution. This translates to $10^{-3}$ noise hits per readout cell and bunch train of

[3]For a fixed rise time of the front-end amplifier, the time delay between the particle hit and the time of the threshold crossing (which defines the TOA) depends on the signal amplitude.

156 ns. The noise rate should thus be below $10^{-3}/156\,\text{ns} \approx 6.5\,\text{kHz}$. This quite high number reflects the maximum tolerable noise rate for operation in the CLIC tracker, taking the low duty cycle of $\approx 10^{-5}$ of the accelerator into account. For testing of the sensors with particle sources and beams, where detectors are operated usually with higher duty cycle up to 1, and for applications beyond CLIC, a much lower noise rate is required.

### 2.6 Material budget and power consumption

The material budget currently foreseen in the CLIC tracker is in the order of 1–1.5 $\%X_0$ per detection layer in total, including the sensors, the support structures, additional readout electronics and services for powering and cooling. This budget allows for 200 μm thick silicon layers, shared between the active detection material and the readout circuits [2].

It is assumed that the detectors can be operated at or above room temperature. Air flow cooling as foreseen for the vertex-detector region is deemed not to be feasible, due to the large volume of the tracker. Water cooling of the tracker is therefore currently foreseen. Due to the low duty cycle of the CLIC machine (156 ns bunch trains every 20 ms), pulsed power operation of the analog and digital parts of the front-end electronics is a possible way to reduce the average power consumption of the detector. With such a power-pulsing scheme, an average power consumption of below $150\,\text{mW}\,\text{cm}^{-2}$ is aimed for.

### 2.7 Radiation levels

The radiation levels expected from beam-induced background events have been estimated in full-detector simulation studies with a previous version of the detector model [5]. In most parts of the detector, the non-ionizing energy loss and dose level is several orders of magnitude below the ones for the corresponding detector regions in the LHC experiments. In the CLIC tracker region the expected Non-Ionizing Energy Loss (NIEL) is below $10^{10}\,n_{eq}\,\text{cm}^{-2}\,\text{yr}^{-1}$ and the Total Ionizing Dose (TID) is below $1\,\text{Gy}\,\text{yr}^{-1}$. This is the expected radiation level in the detector parts which are located close to the beam pipe, dropping by approximately one order of magnitude over the radial extend of the tracker. Radiation hardness is therefore not considered to be a major concern for the silicon tracking detectors at CLIC.

## 3 Summary

The following list summarizes the requirements for the readout of the CLIC tracker, as detailed in the previous sections:

- A single point resolution of 7 μm or better in the transverse plane is needed to meet the requirement on the track-momentum resolution.
- The maximum strixel length is ranging from 1–10 mm. Here, 50 μm wide strips/pixels and an average multiplicity of 2.6 have been assumed, following earlier studies. Scaling to other geometries or technologies can be performed with Equation (2).
- The energy measurement per strip/pixel should be performed with approximately 5 bits precision.
- Hits should be time-tagged within 10 ns time slices, to suppress out-of-time hits from beam-induced background. A dynamic range of several μs, corresponding to 8 bits or more, is foreseen for testing the detectors with particle sources and beams. For operation in CLIC, the minimal dynamic range is 156 ns, corresponding to 5 bits.
- The hit detection efficiency should be >99.7–99.9%, and the noise occupancy $< 10^{-3}$ per bunch train. This results in a quite high tolerable noise rate requirement per cell $< 6.5\,\text{kHz}$ for operation

in CLIC at a low duty cycle of $\approx 10^{-5}$. For testing with particles sources and beams, at a higher duty cycle, a much lower noise rate is required.

- The average power consumption should be below $150\,\mathrm{mW\,cm^{-2}}$. Power pulsing of the analog and digital electronics in the inactive time between bunch trains can be exploited.
- The total silicon thickness should be $\leq 200\,\mu\mathrm{m}$. This holds for monolithic and hybrid solutions.
- The detector should withstand NIEL $> 10^{10}\,\mathrm{n_{eq}\,cm^{-2}\,yr^{-1}}$, and TID $> 1\,\mathrm{Gy\,yr^{-1}}$. This numbers are several orders of magnitude lower than in the corresponding detector regions in the LHC experiments.
- Integration of the full 156 ns bunch train is envisaged, and no multi-hit capability during the bunch train is foreseen. The readout should be performed within the 20 ms between bunch trains, with a maximum cell occupancy of 3%.

## References


[1] L. Linssen et al., eds., *CLIC Conceptual Design Report: Physics and Detectors at CLIC*, CERN-2012-003, CERN, 2012, arXiv: 1202.5940 [physics.ins-det].

[2] N. Alipour Tehrani et al., *CLICdet: The post-CDR CLIC detector model* (2017), CLICdp-Note-2017-001, URL: http://cds.cern.ch/record/2254048.

[3] S. Agostinelli et al., *Geant4 - a simulation toolkit*, Nucl. Instr. Meth. Phys. Res. A **506** 3 (2003) 250, DOI: 10.1016/S0168-9002(03)01368-8.

[4] J. Allison et al., *Geant4 developments and applications*, IEEE Transactions on Nuclear Science **53** 1 (2006) 270, DOI: 10.1109/TNS.2006.869826.

[5] D. Dannheim, A. Sailer, *Beam-Induced Backgrounds in the CLIC Detectors* (2012), LCD-Note-2011-021, URL: http://cds.cern.ch/record/1443516.

[6] A. Nürnberg, *Background hit rate in DD4hep*, CLICdp Tracker WG meeting, 2016, URL: https://indico.cern.ch/event/476939/contributions/1155157/attachments/1210660/1765704/20160113_HitrateDD4hep.pdf.

[7] S. Aplin et al., *Forward tracking at the next e+e- collider part II: experimental challenges and detector design*, JINST **8** 06 (2013) T06001, DOI: 10.1088/1748-0221/8/06/T06001.

[8] R. Simoniello, *Tracker optimization*, CLIC Workshop, 2016, URL: https://indico.cern.ch/event/449801/contributions/1945360/attachments/1213105/1770052/tracker-opt-CLICworkshop-2016.pdf.