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The CLIC Detector Concept

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Abstract

CLIC is a concept for a future linear collider that would provide e^+e^- collisions at up to 3 TeV. The physics aims require a detector system with excellent jet energy and track momentum resolution, highly efficient flavour-tagging and lepton identification capabilities, full geometrical coverage extending to low polar angles and timing information in the order of nanoseconds to reject beam-induced background. To deal with those requirements, an extensive R&D programme is in place to overcome current technological limits. The CLIC detector concept includes a low-mass all-silicon vertex and tracking detector system and fine-grained calorimeters designed for particle flow analysis techniques, surrounded by a 4 T solenoid magnet. An overview of the requirements and design optimisations for the CLIC detector concept is presented.

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Abstract

CLIC is a concept for a future linear collider that would provide e^+e^- collisions at up to 3 TeV. The physics aims require a detector system with excellent jet energy and track momentum resolution, highly efficient flavour-tagging and lepton identification capabilities, full geometrical coverage extending to low polar angles and timing information in the order of nanoseconds to reject beam-induced background. To deal with these requirements, an extensive R&D programme is in place to overcome current technological limits. The CLIC detector concept includes a low-mass all-silicon vertex and tracking detector system and fine-grained calorimeters designed for particle flow analysis techniques, surrounded by a 4 T solenoid magnet. An overview of the requirements and design optimisations for the CLIC detector concept is presented.

Keywords

CLIC; CLICdp; CLIC detector; new detector concepts.

1 Introduction

The LHC has pushed the energy frontier to new heights. For the precision frontier to keep up, a high energy lepton collider is needed. CLIC, the Compact Linear Collider, is a proposed concept for such a lepton collider. The study, hosted by CERN, aims to provide e^+e^- collisions at up to $\sqrt{s}$ = 3 TeV in the post-LHC era.

The rich physics programme for CLIC includes precision measurement of Higgs and top quark properties, precision measurements of new physics that are potentially discovered at the LHC as well as a unique sensitivity for particles produced in electroweak interaction. An overview of the physics potential of CLIC is given in [1] and a more detailed view on Higgs physics can be found in [2].

2 The CLIC Accelerator

In order to obtain a linear collider with multi-TeV energies at reasonable lengths, the accelerating structures have to operate at very high electrical field gradients. This excludes the use of superconducting RF structures because their maximum gradient is intrinsically limited by the critical field of the used material. Normal conducting cavities on the other hand have been shown to hold accelerating gradients of 120 MV/m with reasonable breakdown rates when operated at a frequency of several GHz [3]. For CLIC, the goal is to obtain gradients of 100 MV/m at a frequency of 12 GHz.

To power the accelerating cavities efficiently at this frequency, CLIC is based on a novel two-beam acceleration scheme that is shown in fig. 1. The idea is to use a high intensity but rather low energy electron beam, the so called drive beam, and restructure it into 12 GHz bunches via a series of delay loops and combiner rings. This beam is then decelerated in dedicated cavities and the extracted 12 GHz power is transferred via wave guides to power the accelerating cavities of the main electron and positron beams. The resulting beam structure shows a bunch spacing of 0.5 ns with 312 bunches making up one train. The repetition rate is 50 Hz.

To achieve the desired luminosity of $5.9 \cdot 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the beam sizes at the interaction point are focused to $\sigma_x \approx$ 45 nm and $\sigma_y \approx$ 1 nm at 3 TeV. The strong focusing together with the beam structure

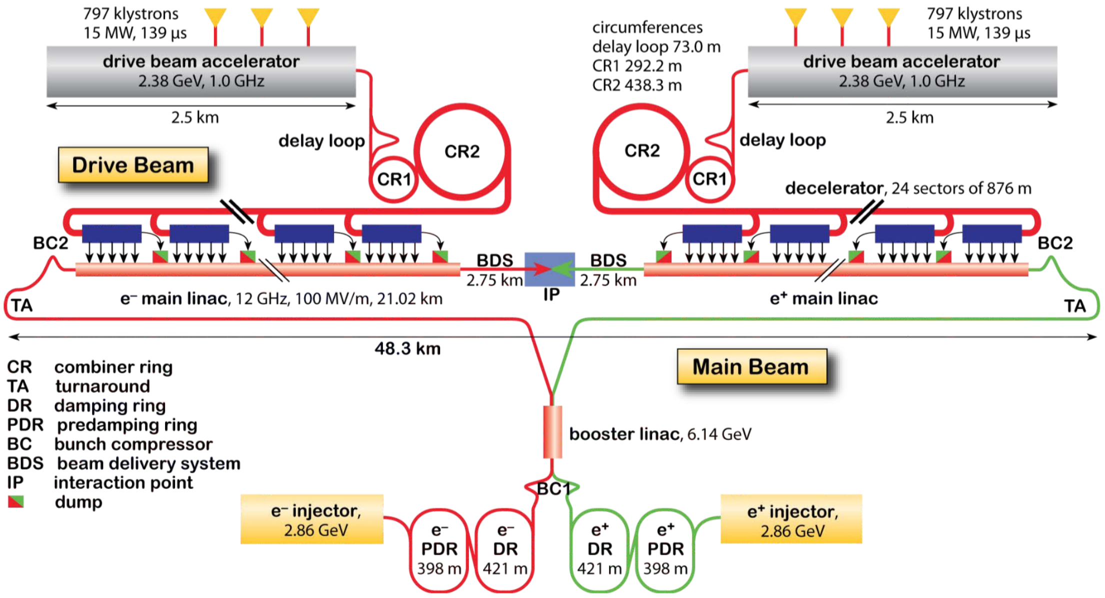

Fig. 1: The two-beam acceleration scheme for CLIC that is used to accelerate electrons and positrons to 3 TeV. A low energy but high intensity drive beam is bunched and decelerated to power the cavities for the main beam at the desired frequency of 12 GHz. This allows for accelerating gradients of 100 MV/m. Figure is taken from [3].

of the two-beam acceleration scheme creates very high charge densities. As a result, beamstrahlung takes place and reduces the energy of individual electrons and positrons. Collisions therefore take place over a wider range of energies. At 3 TeV, 35% of all collisions take place within 1% of the nominal $\sqrt{s}$ value [1]. This distribution, called luminosity spectrum, has to be measured and deconvoluted in every physics study.

Due to the wide range of the physics programme it is convenient to build CLIC in several energy stages, each one optimised for a certain part of the programme. The current baseline foresees three stages of 380 GeV, 1500 GeV and 3000 GeV. The energy of the first stage has recently been revisited and updated [4].

3 Detector Requirements

The design requirements for the detector are driven by the desired precision of the physics measurements. The track momentum resolution determines the feasibility and precision of many physics studies such as the measurement of the Higgs mass from the Higgsstrahlung process or the coupling of the Higgs to muons. The aim is set to $\sigma_{p_T}/p_T^2 \approx 2 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$. Another crucial parameter is the jet energy resolution. A value of $\sigma_E/E \approx 3.5\%$ for jet energies above 100 GeV allows for a 2.5σ separation of W and Z masses in multi-jet events. Also, efficient identification of secondary vertices for flavour tagging of heavy quark states is needed. The derived requirement is a transverse impact parameter resolution of $\sigma_{r\phi} \approx (5 \oplus 15\ /\ p[\mathrm{GeV}]\sin^{\frac{3}{2}}\vartheta)\ \mu\mathrm{m}$. Finally, tagging of very forward electrons plays an important role in many physics studies, e.g. for efficient background identification. Therefore, a large geometrical coverage in the forward region is desired.

In addition to the physics driven detector requirements, the strongly focussed beams and short bunch spacing set requirements on pile up mitigation and background suppression. Incoherent e^+e^- pairs and low p_T hadronic jets from the beamstrahlung interactions are the dominant background processes and require time stamping capabilities of 1 to 10 ns and a high granularity throughout the detector.

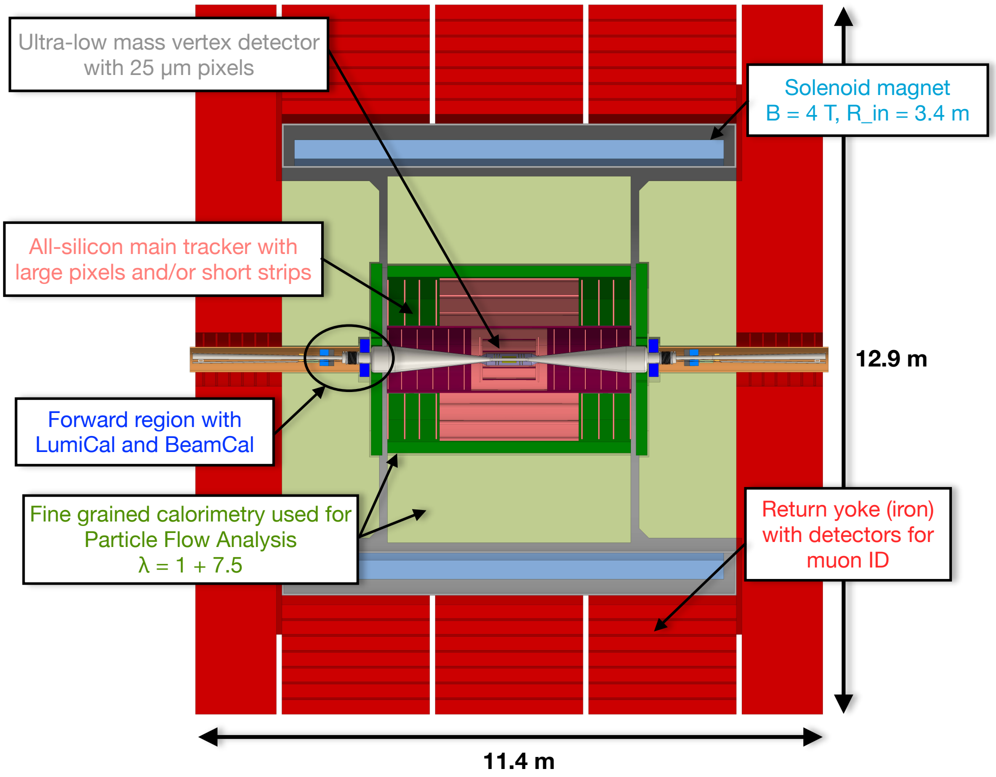

Fig. 2: Top view of the CLIC detector model.

4 The CLIC Detector

Starting from the ILD and SiD detector concepts [5, 6], adaptations were made towards CLIC specific requirements. The resulting two concepts were consequently merged into one optimised detector model that is displayed in fig. 2. The innermost layer of the CLIC detector is a low mass vertex detector followed by an all-silicon tracker. The detector is optimised for particle flow algorithms and as such, the calorimeters are required to be placed inside the magnet and as close to the tracker as possible. The electromagnetic calorimeter has a depth of 23 X_0 and the hadronic calorimeter is 7.5 λ_I deep. A superconducting solenoid that produces a 4 T magnetic field and an iron return yoke with interleaved muon chambers are located on the outside. The forward region is instrumented with two additional calorimeters for extended geometrical coverage and luminosity measurements. The overall dimensions of the detector are 11.4 m in length and 12.9 m in height.

4.1 Vertex Detector

The requirements for the vertex detector are determined mainly by the desired momentum resolution and flavour tagging capabilities as well as the need for efficient background suppression. To achieve the aims outlined in the previous chapter, the goal is to reach a single point resolution of $\sigma_{x,y} \approx 3$ μm and time stamping capabilities of better than 10 ns. Also, for occupancy reasons the pixel pitch should not exceed 25×25 μm^2. Another challenge comes from the low material budget. The goal of 0.2% X_0 per layer translates to an equivalent of roughly 200 μm of silicon for sensor, readout, cooling, support and cabling. The geometry of the vertex detector is shown in fig. 3. It is designed in 3 double layers and has an overall length of 560 mm. The innermost barrel layer is located 31 mm from the interaction point.

A concept based on hybrid silicon pixel detectors is under development to fulfil the requirements. Due to the low material budget, the sensors and ASICs are both foreseen to be thinned to 50 μm thickness.

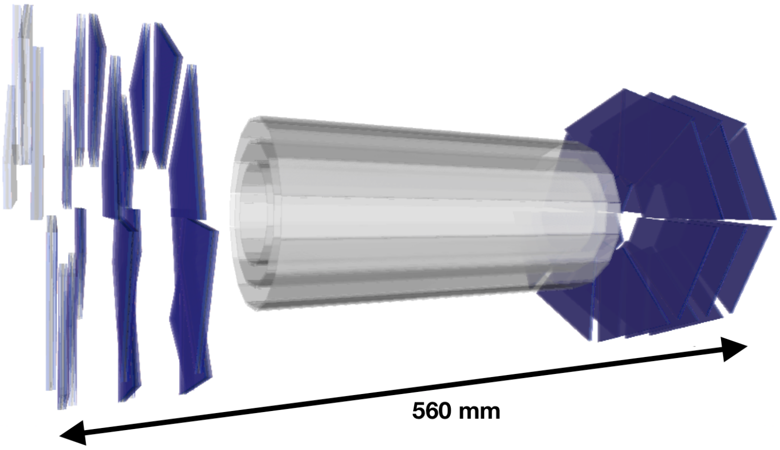

Fig. 3: The geometry of the CLIC vertex detector. A barrel design with spiral endcaps together with power pulsing of the electronics allow for forced gas flow cooling. This is necessary to fulfil the strict material budget.

As sensors, either capacitively coupled HV-CMOS sensors or bump-bonded active-edge planar sensors are considered. The capacitive coupling of the HV-CMOS sensors to the readout ASIC is realised via a layer of glue. CLICpix, a demonstrator chip in 65 nm technology and 25×25 μm^2 pixel pitch, has been developed for the readout. The chip allows for simultaneous time and energy measurements via time-over-threshold (ToT) and time-of-arrival (ToA) counters. An improved version, CLICpix2, is currently in the final verification stage.

To avoid the need for liquid cooling, the layout of the vertex detector is optimised for low power dissipation. This is achieved via power pulsing of the electronics: taking advantage of the pulsed beam structure, most of the electronics is powered down after every particle train and only switched back on a few µs before the next. Together with an optimised spiral geometry in the end caps this allows for forced air flow cooling.

4.2 Tracking Detector

The tracker requirements are mainly determined by the desired momentum resolution and background suppression. A single point resolution of $\sigma_{r\varphi} \approx 7$ µm in the rφ plane and time stamping capabilities of better than 10 ns are needed. Additionally, track reconstruction requires that occupancies should be kept below 3%. An all-silicon tracker is under development to meet these requirements. The maximum cell pitches needed are between 1 mm and 10 mm in the z direction, depending on the position inside the detector. In rφ, a 50 µm pitch is needed to reach the required single point resolution. Several monolithic silicon pixel technologies are being evaluated as possible sensor candidates.

The mechanical design is split in an inner and an outer region with separate supports. The inner tracker consists of 3 barrel layers and 7 forward disks, the outer tracker of 3 barrel layers and 4 forward disks. A radius of 1.5 m together with a 4 T magnetic field were chosen to achieve the required momentum and jet energy resolution at a reasonable field strength and bore radius. The variations of the magnetic field across the tracker volume are below 9%. The overall length of the tracker is 4.4 m.

A lightweight support is needed to meet a total material budget of $\approx 1.5\%$ X_0 per layer. To achieve this goal, a carbon fibre support frame is envisaged. A prototype to validate this concept has been built and is under evaluation.

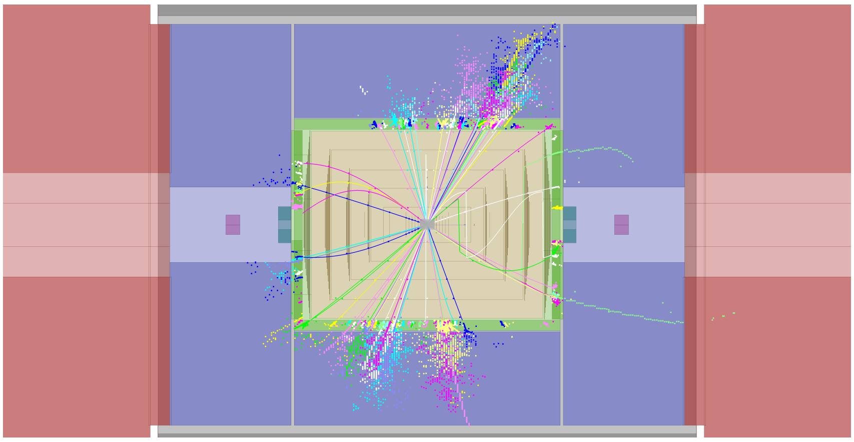

Fig. 4: Event display of a $t\bar{t}H$ decay event at $\sqrt{s} = 1.4$ TeV in the CLIC_SiD detector. The high granularity of the calorimeter allows for tracking of the shower development and can be used as input to a particle flow algorithm. Figure is taken from [2].

4.3 Calorimetry

In order to reach a jet energy resolution of approximately 3.5%, the CLIC calorimeter is optimised for particle flow calorimetry. The basic principle here is to improve the jet energy resolution by resolving energy depositions of the individual particles in a jet and using the most precise energy measurement available for that particle type. For example, the energy measurement for charged hadrons is typically far more precise in the tracker than in the hadronic calorimeter. The jet energy resolution is then strongly depending on the error contributions coming from wrongly associated depositions [7]. These contributions are represented by a newly introduced error term $\sigma_{\text{confusion}}$ and any detector dedicated to particle flow calorimetry must be carefully optimised to minimise them. Effectively, this approach changes the problem of summing up energy depositions in the calorimeters into a problem of pattern recognition. Dedicated software to reconstruct the particle flow is needed for the analysis. For CLIC, Pandora PFA is used [8, 9].

4.3.1 Electromagnetic and Hadronic Calorimeter

In order to resolve the individual shower components and minimise the confusion term, a high cell granularity and precise time information is required (see fig. 4). The granularity choices for the CLIC detector are 5×5 mm^2 in the electromagnetic calorimeter and 30×30 mm^2 in the hadronic calorimeter. The timing requirements are set to $\sigma_t \approx 1$ ns. Current technology choices are silicon pad sensors and tungsten absorbers for the electromagnetic and scintillating tiles with SiPM readout and steel absorbers for the hadronic calorimeter. The R&D and prototyping developments in this area are pursued within the CALICE collaboration [10] and have strong synergies with other projects, such as the planned upgrade of the CMS forward calorimeters [11].

4.3.2 Forward Calorimeters

The very forward region consists of two additional calorimeters that extend to very low angles. Fig. 5 displays this region. The BeamCal is used for forward tagging of high energy electrons and can deliver a fast luminosity estimation. For a precise luminosity measurement, the LumiCal is used. It measures the absolute luminosity via the number of Bhabha scattering events at low angles. For the shape of the luminosity spectrum, information on large angle scattering from tracker and calorimeter are used as well [12]. The LumiCal and BeamCal cover polar angles between 38 to 110 mrad and 10 to 40 mrad, respectively. The final focussing magnet QD0 is situated outside of the detector. Design efforts for both

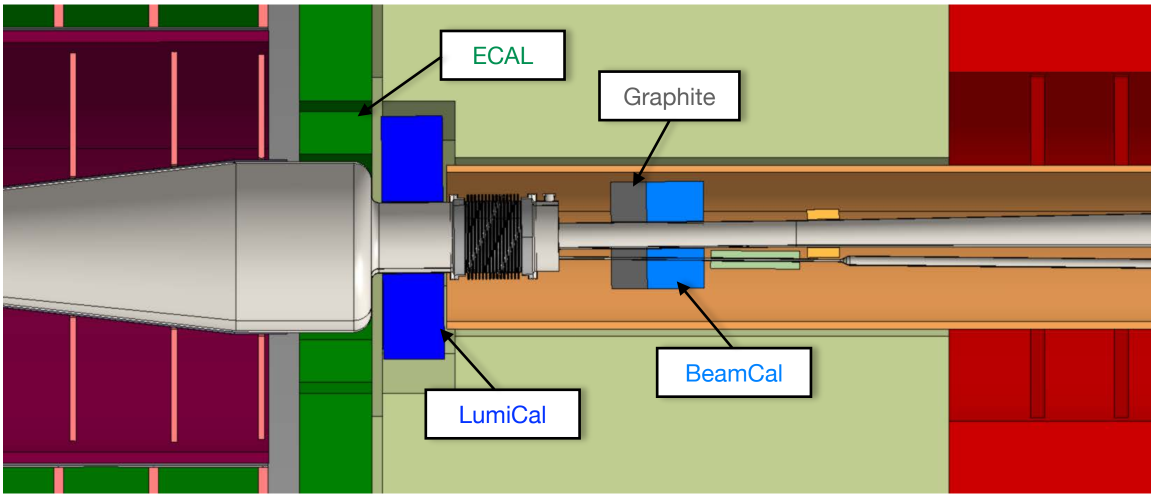

Fig. 5: The forward region of the CLIC detector. The BeamCal is used for tagging of forward boosted high energy electrons while the LumiCal delivers a precise luminosity measurement. A block of graphite is used to reduce the flux of backscattered particles into the interaction region.

forward calorimeters are performed within the FCAL collaboration [13].

One issue here is the flux of backscattered particles from the forward region into the interaction region. To minimise this flux, a graphite block is situated upstream of the BeamCal. For the BeamCal, radiation hard sensors are also important as this device will see radiation doses of several MGy in the innermost regions. Both GaAs and CVD diamond sensors are under consideration [14].

4.4 Muon ID System

The most import task of the muon system is to identify muons with high efficiency and purity. The system is arranged in 6 layers intervened in the return yoke. It does not improve the momentum resolution any further but the first layer acts as a tail catcher to improve the jet energy resolution. The time resolution needed is $\sigma_t \approx 1$ ns and cell sizes of 30×30 mm^2 are used to keep the muon tagging efficiency close to 1 and occupancies at manageable levels. RPCs or scintillating tiles with SiPM readout are considered to fulfil these requirements.

5 Conclusion

Challenging detector requirements are set by the physics goals and accelerator design. They include an excellent jet energy and track momentum resolution, efficient flavour tagging capabilities, large geometrical coverage and efficient suppression of beam-induced background. A detector concept optimised for particle flow calorimetry has been presented. It requires fast timing capabilities and high cell granularities throughout the detector.

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