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Detector challenges at the CLIC multi-TeV e^+e^- collider

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The beam parameters of the proposed CLIC concept for a linear electron-positron collider with a centre-of-mass energy of up to 3 TeV pose challenging demands for the design of the detector systems. This paper introduces the CLIC machine and the requirements for the detectors and gives an overview of the ongoing detector studies.

1. Introduction

The LHC experiments have the potential to discover new physics at the TeV scale. A lepton collider operating at these energies will then be required to complement the results of the LHC experiments and to measure the properties of new particles with high precision. The proposed **C**ompact **LI**near **C**ollider (CLIC) concept of a linear electron-positron collider with a center-of-mass energy of up to 3 TeV will be a suitable machine for such measurements [1]. The detector requirements for precision physics in combination with the challenging experimental conditions at CLIC have inspired a broad detector R&D program.

2. The CLIC accelerator

The CLIC project studies the feasibility of a linear electron-positron collider optimized for a center-of-mass energy of 3 TeV with an instantaneous luminosity of a few $10^{34}cm^{-2}s^{-1}$, using a novel technique called two-beam acceleration [2]. Figure 1 shows the two-beam acceleration principle. A drive beam of rather low energy but high current is decelerated, and its energy is transferred to the low-current main beam, which gets accelerated with gradients of 100 MV/m. The two-beam acceleration scheme thus removes the need for individual RF power sources. It is expected that the machine will be built in several stages with centre-of-mass energies ranging from 500 GeV up to the maximum of 3 TeV, corresponding to an overall length of the accelerator complex between approximately 14 and 48 km.

In order to reach its design luminosity of $6 \times 10^{34}cm^{-2}s^{-1}$ at a maximum centre-of-mass energy of 3 TeV, CLIC will operate with very small bunch sizes ($\sigma_x \times \sigma_y \times \sigma_z \approx$ 40 nm x 1 nm x 44 µm), leading to strong electromagnetic radiation (Beamstrahlung) from the electron and positron bunches in the field of the opposite beam. The resulting luminosity spectrum has a peak at 3 TeV with a tail towards lower center-of-mass energies. About one third of the total luminosity is contained in the most energetic 1% fraction of the spectrum.

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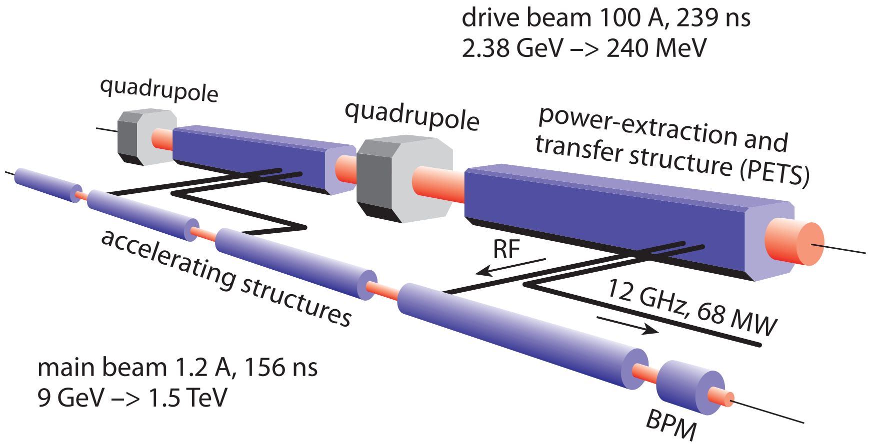

Figure 1: CLIC two-beam acceleration scheme

The beam parameters and machine requirements are very challenging. 12 GHz accelerating structures drive the two main beams and collisions occur every 0.5 ns for a train duration of 156 ns. The train repetition rate is 50 Hz. The components have to be stable on the nm level while strong final focusing inside the experimental areas is required.
Several test facilities (the most recent one CTF3) have been built over the past years, which have succeeded in demonstrating the feasibility of the two-beam acceleration principle.

3. Detector Requirements and Challenges

The performance requirements for the detector systems at CLIC are driven by the physics goals of performing precision measurements of newly discovered particles up to the TeV scale, for example the Higgs boson or SUSY particles. The CLIC experiments shall probe the parameter space of theories beyond the Standard Model over a large range, thus allowing discrimination between competing models. The jet-energy resolution should be adequate to distinguish between di-jet pairs originating from Z or W bosons as well as light Higgs bosons. This can be achieved with a resolution of $\sigma_E/E \approx 3.5\% - 5\%$ for jet energies from 1 TeV down to 50 GeV. The momentum-resolution requirement for the tracking systems is driven by the precise measurement of leptonic final states, e.g. the Higgs mass measurement through Z recoil, where $Z_0 \rightarrow \mu^+\mu^-$, or the determination of slepton masses in SUSY models. This leads to a required resolution of $\sigma(p_T)/p_T \approx 2 \times 10^{-5}$ GeV^{-1}. High-resolution pixel vertex detectors are required for efficient tagging of heavy states through displaced vertices, with an accuracy of approximately 5 µm for determining the transverse impact parameters of high-momentum tracks and a multiple scattering term of approximately 15 µm. The latter can only be achieved with a very low material budget of less than 0.2% of a radiation length per detection layer, corresponding to a thickness of less than 200 µm of silicon, shared by the active material, the readout, the support and the cooling infrastructure.
The time structure of the collisions, with bunch crossings spaced by only 0.5 ns, in combination with the expected high rates of beam-induced backgrounds, poses severe challenges for the design of the detectors and their readout systems. Of the order of one

interesting physics event per 156 ns bunch train is expected, overlaid by an abundance of particles originating from two-photon interactions. These background particles will lead to large occupancies (number of hits per readout cell) in the inner and forward detector regions and will require time stamping on the nano-second level in most detectors, as well as sophisticated pattern-recognition algorithms to disentangle physics from background events. The gap of 20 ms between consecutive bunch trains will be used for trigger-less readout of the entire train. Furthermore, most readout subsystems will be operated in a power-pulsing mode with the most power-consuming components switched off during the empty gaps, thus taking advantage of the low duty cycle of the machine to reduce the required cooling power.

4. Detector Concepts

The detector concepts ILD [3] and SiD [4] developed for the **I**nternational **L**inear **C**ollider (ILC) [5] with a center-of-mass energy of 500 GeV form the starting point for the two general-purpose detector concepts CLIC_ILD and CLIC_SiD. Both detectors will be operated in one single interaction region in an alternating mode, moving in and out every few months through a so-called push-pull system. The main CLIC-specific adoptions to the ILC detector concepts are an increased hadron-calorimeter depth to improve the containment of jets at the CLIC centre-of-mass energy of up to 3 TeV and a redesign of the vertex and forward regions to mitigate the effect of high rates of beam-induced backgrounds.

Figure 2 shows cross-section views of CLIC_ILD and CLIC_SiD. Both detectors have a barrel and endcap geometry with the barrel calorimeters and tracking systems located inside a superconducting solenoid providing an axial magnetic field of 4 T in case of CLIC_ILD and 5 T in case of CLIC_SiD. The highly granular electromagnetic and hadronic calorimeters of both detectors are designed for the concept of particle-flow calorimetry, allowing to reconstruct individual particles combining calorimeter and tracking information and thereby improving the jet-energy resolution to the required excellent levels. The total combined depth of the electromagnetic and hadronic calorimeters is about 8.5 hadronic interaction lengths. The hit-time resolution of the calorimeters is of the order of 1 ns.

In the CLIC_ILD concept, the tracking system is based on a large Time Projection Chamber (TPC) with an outer radius of 1.8 m complemented by an envelope of silicon strip detectors and by a silicon pixel vertex detector. The all-silicon tracking and vertexing system in CLIC_SiD is more compact with an outer radius of 1.3 m.

Both vertex detectors are based on semiconductor technology with pixels of 20 μm x 20 μm size. In case of CLIC_ILD, both the barrel and forward vertex detectors consist of three double layers which reduce the material thickness needed for supports. Figure 3 shows a sketch of the vertex-detector region of CLIC_ILD. For CLIC_SiD, a geometry with five single barrel layers and 7 single forward layers was chosen. The high rates of incoherently produced electron-positron pair background events constrains the radius of the thin beryllium beam pipes and of the innermost barrel layers. For CLIC_ILD the beam pipe is placed at a radius of 29 mm, while the larger magnetic field in CLIC_SiD leads to a larger suppression of low-p_T charged particles and therefore allows for a reduced radius of the beam pipe of 25 mm. The material budget of 0.1% - 0.2% of a radiation length per detection layer assumes that cooling can proceed through forced air flow without additional material in the vertex region. The resulting impact-parameter resolutions are as precise as 3 μm for high-momentum tracks and the momentum resolution of the overall tracking systems reach the required value of $\sigma(p_T)/p_T^2 \approx 2 \times 10^{-5}$ GeV^{-1}. Time stamping of the pixel and strip hits with a precision of 5 - 10 ns will be used to reject out-of-time background hits.

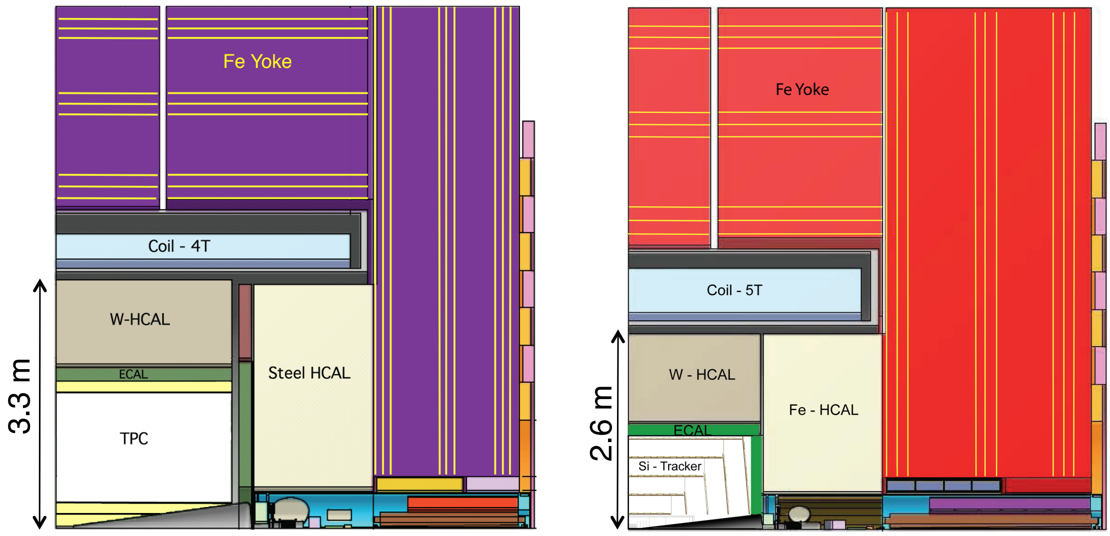

Figure 2: Longitudinal cross section of the top quadrant of CLIC_ILD (left) and CLIC_SiD (right)

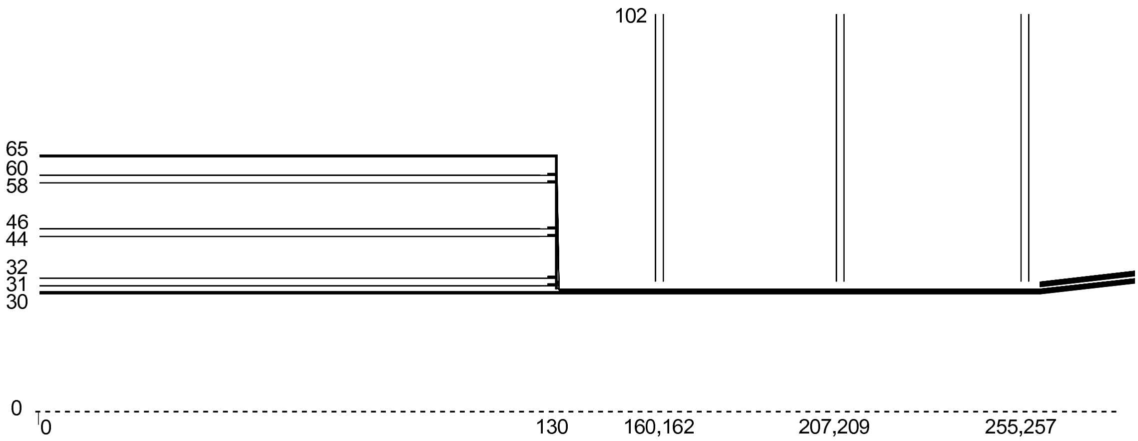

Figure 3: Longitudinal cross section of the barrel and forward vertex region of the CLIC_ILD detector. Dimensions are given in millimeters.

The superconducting solenoids are surrounded by instrumented iron yokes allowing to measure punch through from high-energy hadron showers and to detect muons. Two small electromagnetic calorimeters cover the very forward regions down to 10 mrad.

They are foreseen for electron tagging and for an absolute measurement of the luminosity through Bhabha scattering.

5. Backgrounds in the Detectors

Beamstrahlung off the colliding electron and positron bunches will lead to high rates of electron-positron pairs, mostly at low transverse momenta and small polar angles. In addition, hadronic events are produced in two-photon interactions with larger transverse momenta and polar angles. Figure 4 (right) compares the polar-angle distributions of the main sources of beam-induced background events. Electron-positron pairs produced coherently and through the so-called trident cascade do not affect the detectors, as they leave the detector towards the past-collision line with a design acceptance of $\theta<10$ mrad. The incoherently produced electron-positron events affect mostly the forward regions and the inner tracking detectors. Approximately 60 particles from incoherent pair events per bunch crossing will reach the inner layers of the vertex-detector. The $\gamma\gamma\rightarrow$hadron events will result in approximately 54 particles per bunch crossing in the vertex detectors. Figure 4 (left) shows the expected hit rates in the barrel vertex-detector layers of the CLIC_ILD detector, as obtained with two different simulation setups. Readout train occupancies of up to 2% are expected in the barrel layers and of up to 3% in the forward layers, including safety factors for the simulation uncertainties and cluster formation.

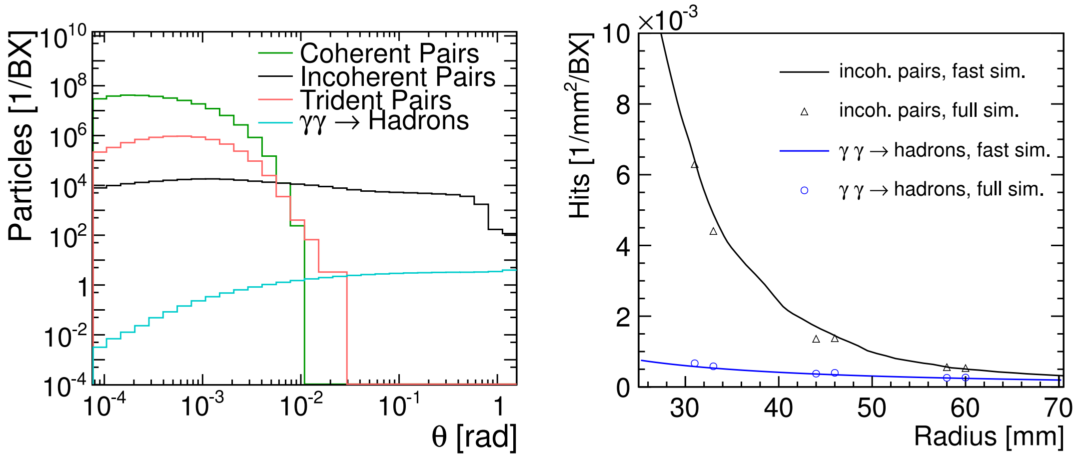

Figure 4: Polar-angle distribution of the main sources of beam-induced backgrounds, normalised to one bunch crossing (left); average hit densities in the CLIC_ILD barrel vertex detectors for particles originating from incoherent electron-positron pairs and from gg-->hadrons (right).

Due to their harder p_T spectrum, the $\gamma\gamma\rightarrow$hadron events will also lead to large occupancies and significant energy deposits in the calorimeters. The expected train occupancies are up to 50% in the electromagnetic endcap calorimeters and up to 1000% in the hadronic endcap calorimeters. Multiple readouts per train and possibly a higher granularity for the high-occupancy regions will be required to cope with these high rates. The total energy deposition in the calorimeters from electron-positron pairs and from

$\gamma\gamma \rightarrow$hadron events is 37 TeV per train, posing a severe challenge for the reconstruction algorithms. Cluster-based timing cuts in the 1-3 ns range are applied offline to mitigate the effect of the backgrounds on the measurement accuracy for high-p_T physics objects. The radiation exposure of the main detector elements is expected to be small, compared to the corresponding regions in high-energy hadron-colliders. For the non-ionizing energy loss (NIEL), a maximum total fluence of less than 10^{11} n_{eq} / cm^2 / year is expected for the inner barrel and forward vertex layers. The simulation results for the total ionizing dose (TID) predict approximately 200 Gy / year for the vertex detector region.

6. Detector R&D

Hardware R&D for the proposed CLIC detectors has a large overlap with the corresponding developments for the ILC detectors. In several areas, however, CLIC-specific requirements need to be addressed. The following list contains examples of ongoing R&D projects for the CLIC detectors.

- *Hadronic calorimetry*. The higher jet energies expected at CLIC require a denser absorber material for a given maximal radius of the barrel hadronic calorimeter, compared to ILC conditions. Tungsten is therefore foreseen as absorber for the barrel hadronic calorimeter. Prototypes of highly granular tungsten-based calorimeters with either analog or digital readout are currently under study in test beams performed within the CALICE collaboration. One of the main goals of these tests is to improve the simulation models describing the enlarged slow component of the hadronic showers in tungsten, compared to the ones in steel absorbers.
- *Vertex detector*. The vertex detectors have to fulfill a number of competing requirements. Small pixels and therefore small feature sizes are needed to reach very high measurement accuracy and to keep the occupancies low. Time stamping in the 5-10 ns range requires fast signal collection and shaping. The amount of material has to stay within a budget of 0.1% - 0.2% of a radiation length per detection layer, asking for ultra-thin detection and readout layers and low-mass cooling solutions. Two principal lines of vertex-detector R&D are pursued to reach these ambitious goals: In the *hybrid-detector* approach, thinned high-resistivity fully depleted sensor layers will be combined with fast low-power and highly integrated readout layers through low-mass interconnects. The *integrated technology* option combines sensor and readout in one chip. The charge collection proceeds in an epitaxial layer. Hybrid solutions factorize the sensor and readout R&D and take advantage of industry-standard processes for the readout layers. Drawbacks are the higher material budget, the additional material and cost for interconnects and the additional complication of handling the thinned structures. Integrated technologies can reach lower material budgets and very low power consumption. On the other hand, fast signal collection and readout has not been demonstrated yet in these technologies. A concern for a future application at CLIC is also the limited availability of the custom-made integrated CMOS processes.

- *Low-mass cooling solutions*. A total power of approximately 500 W will be dissipated in the vertex detectors alone. The small material budget for the inner tracking detectors constrains severely the permitted amount of cooling infrastructure. For the vertex barrel layers, forced air-flow cooling is therefore foreseen. Figure 6 shows a calculation of the temperature distribution inside the barrel layers of the CLIC_SiD vertex detector in dependence of the air-flow rate. A flow rate of up to 240 liter / s, corresponding to a flow-velocity of 40 km/h, is required to keep the temperatures at an acceptable level. Further R&D is required to demonstrate the feasibility of this air-flow cooling scheme. Possible vibrations arising from the high flow velocities are of particular concern. Supplementary micro-channel cooling [6] or water-based under-pressure cooling may be required in the forward vertex regions.
- *Power pulsing* and *power distribution*. The ambitious power-consumption targets for all CLIC sub detectors (for example < 50 mW / cm^2 in the vertex detectors) can only be achieved by means of pulsed powering, taking advantage of the low duty cycle of the CLIC machine. The main power consumers in the readout circuits will be kept in standby mode during most of the empty gap of 20 ms between consecutive bunch trains. Furthermore, efficient power distribution will be needed to limit the amount of material used for cables. Low drop-out regulators or DC/DC converters will be used in combination with local energy storage to limit the current and thereby the cabling material needed to bring power to the detectors. Both the power pulsing and the power-delivery concepts have to be designed and thoroughly tested for operation in a magnetic field of 4-5 T.
- *Solenoid coil*. Design studies for high-field thin solenoids are ongoing, building up on the experience with the construction and operation of the LHC detector magnets. Principal concerns are the uniformity of the magnetic field, the ability to precisely measure the field map and the requirement to limit the stray field outside the detector.
- *Overall engineering design and integration studies*. Various CLIC-specific engineering and integration studies are ongoing. The main areas of these studies are the design of the experimental caverns including centralized infrastructure for cooling and powering, access scenarios in the push-pull configuration and integration issues related to the machine-detector interface.

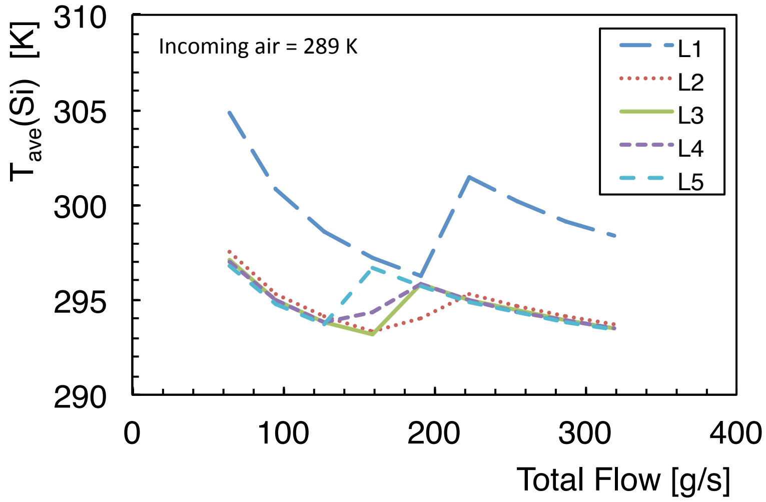

Figure 6: Calculated average temperatures of the five barrel layers of the CLIC_SiD vertex detector in dependence of the total air-flow rate.

7. Conclusion

The detectors of the multi-TeV CLIC machine will have unsurpassed physics reach for discoveries and for precision measurements complementing the results expected from the LHC experiments. The proposed CLIC detector concepts will be able to measure the physics with good precision, despite the high energies and challenging background conditions. Detector R&D studies are ongoing worldwide, in collaboration with the ILC detector community, aiming to meet the required performance goals.

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