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# Conceptual design studies for a CEPC detector

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The physics potential of the Circular Electron Positron Collider (CEPC) can be significantly strengthened by two detectors with complementary designs. A promising detector approach based on the Silicon Detector (SiD) designed for the International Linear Collider (ILC) is presented. Several simplifications of this detector for the lower energies expected at the CEPC are proposed. A number of cost optimizations of this detector are illustrated using full detector simulations. We show that the proposed changes will enable one to reach the physics goals at the CEPC.

*Keywords*: $e^+e^-$; jets; Monte Carlo; CEPC.

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## 1. Introduction

The Circular Electron Positron Collider (CEPC) project is currently planned in China as a Higgs factory. Operating at the center-of-mass (CM) energy of 250 GeV (or above), the CEPC experiment will take advantage of the clean environment of $e^+e^-$ collisions needed for high-precision measurements of the Higgs boson. CEPC experiments can significantly strengthen our understanding of the fundamental processes at the electroweak sector of the Standard Model (SM), and can lead to discoveries of new physics through the precision measurements of the SM.

In order to achieve the physics goals at the CEPC, a detector should be well optimized for measurements of $e^+e^-$ annihilation. In particular, the studies of physics processes in the Higgs sector are considered to be the primary goal of the new experiment. A promising approach for a detector at the CEPC can be based on the Silicon Detector (SiD) concept[1] developed for the International Linear Collider (ILC).[2,3] The design of this detector has a long history, and the experience gained during the R&D phase of this detector can be extremely valuable during the preparation to the CEPC concept.

The abbreviation "SiD" stands for "silicon detector" — a compact general-multipurpose detector designed for high-precision measurements of $e^+e^-$ annihilation at a CM energy of 500 GeV, which can be extended to 1 TeV. Radiation hardness of silicon sensors used for vertexing, tracking and Electromagnetic Calorimeter (ECAL) ensures the required robustness to beam background or beam loss, while a high-granular calorimeter is well suited for the reconstruction of separate particles.[1] Some key characteristics of the SiD detector are:

(1) $4\pi$ solid angle coverage for reconstructed particles.
(2) Full five-layer silicon tracking system with 50 $\mu$m readout pitch size.
(3) Silicon pixel detector with 20 $\mu$m readout pitch size. The detector has excellent flavor-tagging capabilities through a measurement of displaced vertices.
(4) Superconducting solenoid with a 5 Tesla (T) field.
(5) Highly segmented silicon-tungsten ECAL with the transverse cell size of 0.35 cm.
(6) Highly segmented Hadronic Calorimeter (HCAL) with a transverse cell size of $1 \times 1$ cm. The depth of the HCAL in the barrel region is about 4.5 interaction length[a] ($\lambda_I$). The calorimeter has 40 longitudinal layers in the barrel and 45 layers in the endcap region; Resistive-Plate Chambers (RPCs) are the baseline for the active media, although other options, such as Gas-Electron Multipliers (GEM), micromegas, scintillator/SiPM are being considered.
(7) High-resolution muon detector based on scintillator strips with SiPM readout. Bakelite RPC is an alternative option for the muon-detector readout.

Both ECAL and HCAL calorimeters are finely segmented longitudinally and transversely. This is required for "imaging" capabilities of the calorimeter system: Together with the efficient tracking, the fine segmentation of the calorimeter system optimizes the SiD detector for particle-flow algorithms (PFAs) which allow identification and reconstruction of separate particles. The PFA objects can be reconstructed using the Pandora PFA.[4,5]

The response of the SiD detector to physics processes is simulated using the "Simulator for the Linear Collider (SLIC) software package"[6] developed for the ILC project. The main strength of this software lies in the fact that it can easily be configured using XML option files, and it has a platform-independent reconstruction which can be easily deployed on computers with different operating systems.

The M&S cost of the baseline design of the SiD detector is estimated to be around \$320M,[1] with 32% being allocated for the calorimeter, and 37% for the magnet (estimated in 2009).

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[a]Nuclear interaction length, ($\lambda_I$), is the average distance traveled by a hadronic particle before undergoing an inelastic nuclear interaction.

## 2. SiD for the CEPC

For the CEPC physics goals, the SiD detector is over-designed. For example, the cost can be substantially reduced by simplifying the calorimeters and by reducing the magnetic field of the solenoid. Due to the lower CM energy of 250 GeV at the CEPC, a number of optimizations of the SiD detector are proposed:

(1) 5 T solenoid field can be reduced to 4 T;
(2) 40 layers of HCAL can be reduced to 35 by removing five outer HCAL layers in the SiD design. The remaining 35 layers of the steal absorber correspond to about 4.1 nuclear interaction length;
(3) 45 layers of the HCAL endcap can be reduced to 35 layers. This makes the CEPC detector fully uniform from the point of view of the HCAL depth.

The reason for the reduction of the solenoid field lies in the fact that the typical track momentum measured at CEPC is a factor of two (four) smaller compared to the 500 (1000) GeV $e^+e^-$ collisions at the ILC. The magnetic field could be further reduced, but this will require a more detailed study than shown in this paper. Similarly, the reduction of the calorimeter depth is motivated by the fact that the maximum jet transverse momentum at the CEPC is 125 GeV, which is a factor two (four) smaller than for the 500 (1000) GeV $e^+e^-$ machine. In terms of the HCAL interaction length, the proposed $4\lambda_I$ calorimeter is similar to that of the OPAL experiment.[7] The total absorber (steal and tungsten) of the ECAL and HCAL calorimeter systems corresponds to about $5.1\lambda_I$.

In order to explore the possibility of optimization of the SiD detector to a lower CM energy, we use the HepSim Monte Carlo repository[8] with several benchmark processes for $e^+e^-$ collisions. The $e^+e^-$ events at the 250 GeV CM energy were generated using the PYTHIA6 model.[9] The following processes were generated:

• Fully inclusive QCD dijet process;
• $Z$-boson production with the decays $Z \to e^+e^-$, $Z \to \mu^+\mu^-$, $Z \to \tau^+\tau^-$, $Z \to b\bar{b}$;
• Higgs production ($Z^0H$) with the decays $H \to 4l$, $H \to \gamma\gamma$, $H \to \tau^+\tau^-$, $H \to b\bar{b}$. The Higgs mass was set to 125 GeV.

The events were simulated using the SiD detector geometry, and reconstructed using the SLIC package with Pandora PFA. The simulation and reconstruction steps were performed using the Open-Science Grid.[10] Events before and after the simulation of the detector response were registered in the HepSim data catalogue.

In the following, the original SiD detector geometry will be called SiDloi3. The number of reconstructed events after the SiDloi3 detector simulation and reconstruction was about 10,000. Most representative observables which are expected to be sensitive to the tracking and calorimeter performance of the SiD detector were analyzed. The obtained results (not shown) were found to be within the specification of the SiD detector.[3]

The same data samples were simulated and reconstructed using the CEPC-optimized geometry discussed in the beginning of this section, i.e. with the solenoid

field changed from 5 T to 4 T, and the HCAL calorimeter depth reduced from 40 (45) to 35 layers. In the following, the SiD geometry after such modifications called SiDcc1. Full details of this detector geometry are available from the HepSim repository. To reduce computation time, the number of simulated and reconstructed events for the SiDcc1 detector were a factor two smaller than for the SiDloi3 simulation.

The distributions of several observables which are particularly sensitive to the change in the strength of the solenoid field and the HCAL absorber depth is shown in Figs. 1 and 2. The distributions were reconstructed from the PFA objects

(a)



(b)
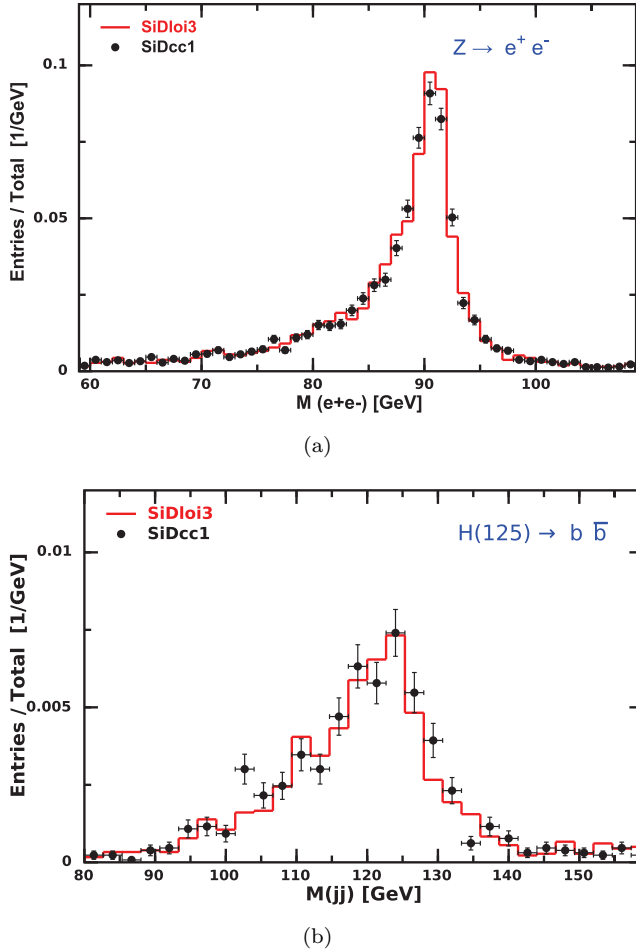
Fig. 1. The invariant mass of two reconstructed electrons for the $Z \to e^+ e^-$ process (a) and the invariant mass of two jets for the process $H(125) \to b\bar{b}$ (b). The distributions were reconstructed from the PFA objects. The figure shows the original SiD setup (SiDloi3) and a CEPC optimized version of the SiD detector (SiDcc1). The distributions of the latter setup are shown as solid dots with statistical uncertainties.
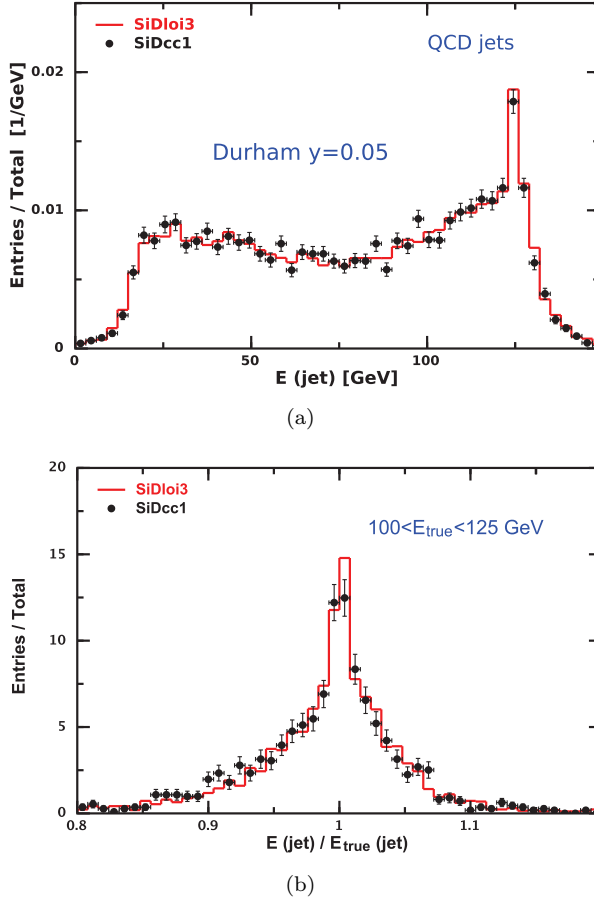
(a)



(b)

Fig. 2.    The distribution of QCD jets in $e^+e^-$ collisions using the Durham algorithm with $y_{\text{cut}} = 0.05$ (a), and the jet energy response for jets with energy close to the kinematic peak of 125 GeV. The jets were reconstructed from the PFA objects. The figure shows the original SiD setup (SiDloi3) and a CEPC optimized version of the SiD detector (SiDcc1). The distributions of the latter detector setup are shown as solid dots with statistical uncertainties.

which combine the information from four-momenta of tracks and calorimeter energy deposits. For example, the $Z$ boson mass reconstructed from the invariant mass of two electrons (Fig. 1(a)) is sensitive to the performance of tracking system to high-momentum tracks ($e^+/e^-$). The energy distribution of hadronic jets reconstructed from the PFA objects is sensitive to both the performance of the tracking system, and to the HCAL longitudinal segmentation. Figure 1(b) shows the invariant mass of two jets for the process $H(125) \to b\bar{b}$. The jets were reconstructed with the Jade algorithm[11] by forcing two jets per event, and requiring the transverse momentum of jets to be above 20 GeV.

To take a closer look at the hadronic jets, Fig. 2 shows the distribution of the jet transverse momentum for inclusive QCD processes in $e^+e^-$ at 250 GeV.

The jets were reconstructed using the Durham algorithm[12] with the parameter $y_{\text{cut}} = 0.05$. Unlike the Jade algorithm which uses the invariant mass-squared of the pair of particles for the clustering procedure, the Durham algorithm uses the relative transverse momentum-squared. Such a choice for two-particle distance measure better reflects the nature of jet evolution. As before, the input to this algorithm are the PFA objects. Jets were selected with a minimum transverse momentum of 20 GeV. Figure 2(b) shows the jet energy response by taking the ratio of the reconstructed jet energy to the energy of jets reconstructed from stable particles, which are defined if their lifetime $\tau$ are smaller than $3 \cdot 10^{-10}$ s. Neutrinos were excluded from consideration. As expected, the distributions for this ratio peaks at one, indicating that no energy leakage is observed for both the SiDloi3 and SiDcc1 detectors.

Figure 3 illustrates a typical $Z \to e^+ e^-$ event in the Jas3/Wired4 event display. A prominent feature of this event is the energy deposits in the ECAL corresponding to the electrons from the $Z$ decay. The space between the outer layer of the HCAL and the solenoid is due to the removal of 5 HCAL layers from the original design of the SiD detector.

In summary, this paper suggests that the SiD detector (or its sub-detectors) can be repurposed for the CEPC. We have illustrated a few directions to optimize the SiD detector for lower CM energies. The results obtained with the SiDloi3
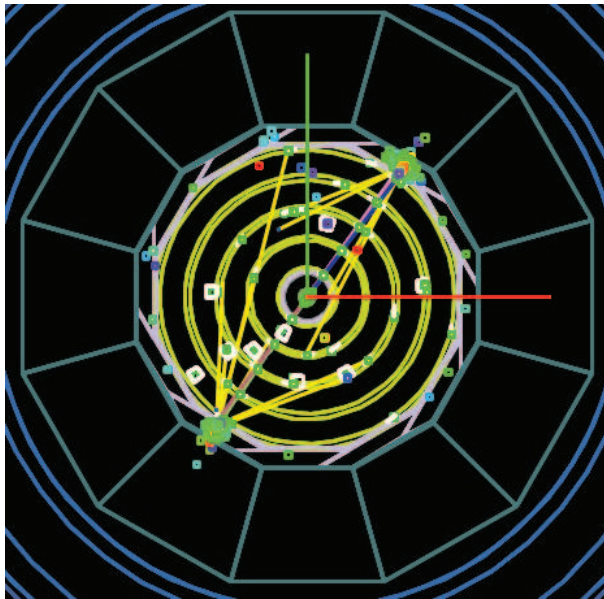


Fig. 3. (Color online) An event display of an $Z \to e^+ e^-$ event using the optimized SiDcc1 setup. Clusters of the green points on the surface of the ECAL correspond to the reconstructed $e^+/e^-$ from the $Z$ decay. The space between the outer layer of HCAL (shown with the trapezoid segments) and the inner radius of the cylindrical solenoid is due to removed 5 outer HCAL layers of the original SiD detector.

and SiDcc1 detector concepts show good agreements (within statistical errors), thus the optimized SiDcc1 detector will enable to reach the physics goals at the CEPC. It should be noted that the changes to the SiD concept listed above are just a few possible options to reduce the cost of a detector for the CEPC energy, without compromising the physics goals at the CEPC. It is very likely that a more substantial optimization can be made after dedicated performance studies.

## References

1. H. Aihara *et al.*, SiD Letter of Intent, presented to ILC IDAG, arXiv:0911.0006 [physics.ins-det].
2. C. Adolphsen *et al.*, The International Linear Collider Technical Design Report — Vol. 3, II: Accelerator Baseline Design, arXiv:1306.6328 [physics.acc-ph].
3. H. Abramowicz *et al.*, The International Linear Collider Technical Design Report — Vol. 4: Detectors, arXiv:1306.6329 [physics.ins-det].
4. M. J. Charles, PFA performance for SiD, in *Proc. Int. Linear Collider Workshop, LCWS08 and Int. Linear Collider Meeting, ILC08*, Chicago, USA, 16–20 November 2008 (2009), arXiv:0901.4670 [physics.data-an].
5. J. S. Marshall and M. A. Thomson, Pandora particle flow algorithm, in *Proc. Int. Conf. on Calorimetry for the High Energy Frontier* (*CHEF 2013*) (2013), pp. 305–315, arXiv:1308.4537 [physics.ins-det].
6. N. Graf and J. McCormick, *AIP Conf. Proc.* **867**, 503 (2006).
7. OPAL Collab. (K. Ahmet *et al.*), *Nucl. Instrum. Methods A* **305**, 275 (1991).
8. S. Chekanov, *Adv. High Energy Phys.* **2015**, 136093 (2015), available at http://atlaswww.hep.anl.gov/hepsim/.
9. T. Sjöstrand, S. Mrenna and P. Z. Skands, *J. High Energy Phys.* **0605**, 26 (2006).
10. R. Pordes *et al.*, *J. Phys. Conf. Ser.* **78**, 012057 (2007).
11. JADE Collab. (W. Bartel *et al.*), *Phys. Lett. B* **123**, 460 (1993).
12. Y. L. Dokshitzer, *J. Phys. G* **17**, 1537 (1991), Contribution in Report of the Hard QCD Working Group, in *Proc. Workshop on Jet Studies at LEP and HERA*, Durham, December (1990).