FIRST IDRC MEETING REPORT

IHEP

21-23 October 2024

Introduction

The IDRC held its inaugural meeting from October 21-23, 2024, with active participation from its membership (see Appendix I for the full composition). The meeting was well-attended both in person and virtually. Attending in person were Daniela Bortoletto (Chair), Jim Brau, Paul Colas, Anna Colaleo, Frank Gaede, Colin Gay, Liang Han, Bob Kowalewski, Gregor Kramberger, Burkhard Schmidt, Maxim Titov, Tommaso Tabarelli de Fatis, and Hitoshi Yamamoto. Remote participants included Christophe De La Taille, Cristenel Diaconu, Roman Poeschl, Akira Yamamoto, Roberto Tenchini and Ivan Vila, who were able to engage in the meeting, at least partially, online.

The meeting's charge, prepared by the CEPC Reference Detector Management, can be found in Appendix II. The presentation delivered by the CEPC Reference Detector Team (RDT) is accessible at: https://indico.ihep.ac.cn/event/23265/.

To facilitate focused discussions, the IDRC organised itself into smaller working groups, each concentrating on specific components of the presentation and related discussions (team compositions are listed in Appendix III). After in-depth discussions, the full committee convened to reach a consensus on the meeting report and its recommendations.

This inaugural meeting served as an excellent opportunity for the IDRC to familiarise itself with the ongoing planning and developments of the CEPC Reference Detector. The committee also had the chance to visit several laboratories at IHEP, which highlighted the institute's capabilities in supporting major international experiments, including AMS, ATLAS, CMS, and LHCb.

We commend the Reference Detector Team (RDT) for the excellent presentations given during the meeting. We express our appreciation for the work done by the RDT participants and the IHEP assistance and support in making this meeting possible and productive.

Executive Summary

The CEPC leadership has reached a consensus on the design of the Reference Detector, which was thoroughly presented during the meeting. This design marks a significant advancement from the preliminary concept outlined in the CEPC Physics and Detector Conceptual Design Report (CDR), initially developed by scientists from the Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences (CAS), along with contributions from numerous universities and research institutes both in China and abroad.

The Reference Detector is designed to deliver outstanding performance, with the goal of conducting detailed studies of the Higgs boson during CEPC's first decade of operation, when the collider will focus primarily on Higgs physics. However, the IDRC has noted that the running plan is complex. Two power options (30 MW and 50 MW) are under consideration. While we understand that the collider is expected to operate mainly at the ZH energy level during the first 10 years, it is not clear if there will be any physics Z pole runnings during this period or if running at the Z will just be required for calibration. We recommend that the Reference Detector Team (RDT) review the detector, electronics and TDAQ performance for potential bottlenecks at the Z mass (for a luminosity of 20% of $1.92x10^{36}$). The RDT will also have to clarify if operation at 3 T is feasible at the Z pole.

The IDRC extends its congratulations to the RDT for the excellent presentations delivered at the meeting. We also commend the team for the extensive R&D and the high-quality work they have accomplished, particularly given that the current team consists of only 90 staff members from IHEP and approximately 200 scientists from 35 domestic research institutes and universities. Notably, this staff is not fully engaged in the reference Detector effort since they are still completing other projects. We recommend that more personnel is encouraged to join these activities as soon as possible. We note that the CEPC management anticipates a rapid increase in personnel following the completion of the JUNO project.

The technical specifications of the Reference Detector are ambitious, incorporating cutting-edge technologies to meet and exceed the physics goals set out in the CDR. These include the development of an ultra-low mass vertex detector, innovative glass scintillator materials to enhance the performance of the hadronic calorimeter, and a novel Crystal ECAL option compatible with Particle Flow. While the use of these advanced technologies is essential for securing project approval, it introduces additional risks and uncertainties, including in the costing. The RDT has wisely adopted conventional backup technologies to mitigate these risks. However, we encourage the team to further justify their decisions and demonstrate how these technologies will enhance the detector's physics capabilities. This will require achieving the necessary level of simulation to evaluate low-level object performance, which is critical and should be prioritized. Additionally, the RDT must define a comprehensive system configuration to establish a solid foundation for the project, even as further optimization of individual detector components continues. These steps are essential for the forthcoming Ref-TDR.

Our initial evaluation of the information that we have received has not shown any showstoppers, but R&D remains to be completed, and the industrialization of some of the more novel technologies has yet to be demonstrated. We appreciate the involvement of Chinese institutes in the DRD collaborations. Furthermore, full-size prototypes are essential to confirm that the required performance can be achieved. The integration of services with the mechanical design will also require further work. In addition the interfaces between detectors require special attention. A key challenge is the development of multiple Front-End ASICs, a process that demands long-term investment and has proven difficult during upgrades of LHC experiments for the HL-LHC.

We have included in the report our recommendations for the steps that should be addressed before the submission of the Ref-TDR.

MDI

Findings

An evaluation of beam-induced backgrounds and mitigation plans as well as the design of luminosity monitor were presented. As sources of beam-induced background, single-beam sources include Touschek, beam-gas, beam-thermal-photon, and Synchrotron Radiation (SR). For beam-beam background, Beamstrahlung (including incoherent pairs) and radiative Bhabha are taken into account. In order to control these beam-induced backgrounds, the plan employs 16 sets of collimators strategically-placed for background mitigation and heavy-metal masks to block SR photons from final dipoles and quadrupoles. The IP beam pipe is a double-wall Beryllium beam pipe cooled with water or paraffin with radius of 10 mm as mainly defined from the profile of incoherent pairs. The gold coating inside the IP beam pipe to absorb X-rays and simplified flanges are included in the simulation while cables are not yet simulated. The beam particles are traced up to 200 turns. The occupancies and doses in the detectors are found to be acceptable for Higgs running, but it is still under optimisation for Z running. In addition, beam background studies for beam failure scenarios have been performed together with relevant accelerator group.

The LumiCal detector is to deliver the required 10-3 -10-4 luminosity uncertainty. A baseline design was presented that incorporates two layers of Si-strip disks followed by a 23 mm thick disk of LYSO crystals followed by a 200 mm long cylinder of LYSO crystals.

Comments

Beam backgrounds are notoriously difficult to predict and errors by one or more orders of magnitude are common. Thus, one needs to be on the safe side at least initially in estimating the level of the backgrounds.

A collimator is simulated assuming that when a particle hits it, the particle is completely absorbed without producing any secondary particles. The secondary particles could often result in background estimation much larger than otherwise. SR masks are as used for the CDR detector and not yet optimized for the ref-TDR. It is essential to perform detailed optimisation of SR masks for photons generated from the final dipoles and final focus quadrupoles including the effect of scattering at the tip of the mask as well as bounces inside the beam pipe. For mitigating shower background generated by stray beam particles, often heavy metal masks are placed near the IP. However, there was no description of such study in the presentation. The significant amount of beamstrahlung emitted at the IP during collisions is important also to ensure safe extraction from the vacuum pipe into a dedicated beam dump, for suitable heat extraction and radiation containment.

Mechanical interface between the detector structure with a large magnet system and the final beam focusing magnet should be critically important to be carefully studied in communication with the accelerator group in both viewpoints of magnetic field interaction and mechanical vibration. Measurements of vibrations at the proposed CEPC site and evaluation of their impact on offset between the beams at the IP, taking into account expected vibration modes in the mechanical transfer functions of the most sensitive magnetic elements within the cryostat, are needed. The Committee notes that the cantilevered cryostat for the final focusing magnet system will also involve an auxiliary support 3.3 m from the IP, on the ECAL, which may be beneficial for stabilization. It is nevertheless important to pursue a detailed evaluation, in particular for the twisted mode, which is the most dangerous mode for the vertical offset between the beams.

The estimated rates for Bhabha events in the LumiCal detector are within the nominal event rate. However, a dedicated high-rate LumiCal data stream has to be envisioned to study the beam backgrounds.The chosen technology option should, in principle, be technically feasible with a present state-of-the-art technology. It aims for electron/gamma separation of radiative photons. In order to keep the required luminosity precision, the electron impact position (and the inner radius) must be known to within 5-10 um that represents a challenge.

Recommendations

1. Optimize the collimators with simulations including secondary particles.
2. Optimize the SR masks for the ref-TDR configuration including the tip scatterings and bounces inside the beam pipe as well as the SR from the halo of the beam in quadrupoles.
3. Study the possibility to use heavy metal masks near the IP to absorb particle showers.
4. For the LumiCal detector, we encourage continuation of the design optimization based on simulation including more detailed mechanical design, and to perform beam tests with detector prototypes, at a later stage.
5. A dedicated review on the MDI, inviting members from both detector and accelerator groups with sufficient expertise and experience to cover all the relevant aspects, would be very beneficial.

TRACKING

The reference detector includes four tracking systems: the vertex detector, the Inner tracker (ITk), the TPC, and the outer tracker. These systems provide excellent position and momentum resolution. They are also crucial for Particle Identification.

The design and choice of technologies for Vertex detector, ITK and OT are very ambitious. The latest advances in Silicon detector technologies were implemented. This puts the detector design at the forefront of technological developments but also means that a much larger community needs to be engaged to complete the prototyping phase and eventually construct the detector(s). The achievements of groups involved in the silicon tracker, given the number of institutes involved, are impressive.

Recommendations

The manpower so far engaged in the design and R&D studies should be enlarged in order to ensure the successful completion of the project.

It is critical to assess the Outer Tracker (OTK) influence on the global momentum resolution and its impact to PID. To achieve this, **a realistic full simulation** is needed that accounts for the following aspects:

- **Alignment between ITK and OTK:** The relative alignment of the ITK and OTK has a significant impact on the global tracking precision. The simulation must incorporate realistic alignment tolerances and errors, reflecting expected mechanical installation uncertainties.
- **Quantifying the Overall PID Improvement:** The simulation should ultimately demonstrate the quantitative improvement in PID when incorporating OTK-based ToF compared to using TPC dE/dX alone. This will provide a clear understanding of the role the OTK plays in broadening the detector's PID capabilities across a broader spectrum of momenta. OTK importance to PID in forward regions outside TPC coverage is particularly important.

VERTEX

The Vertex detector plans to use Depleted Monolithic Active Sensors for achieving the desired position resolution of 3-5 mm with a readout speed of ~43MHz very low mass of >0.15% per layer with a power consumption of 40 mW/cm2. This presents a big challenge at the moment, but the developments can benefit from similar developments for ALICE ITS3, although CEPC design is even more demanding in terms of bending radius (11 mm).

The baseline solution would require <65 nm process, which would bring the power consumption to an acceptable level and allow for large-scale stitching. The availability of the thin epi-layers prefers the small electrode design with modified/non-standard doping (low doped n layer) profile. Access to such technology is available through TowerJazz cooperation. At the same time 55 nm line with SIMC is also being investigated.

The big success was the development of TauichiPix3 sensor (engineering run with TJ in 180 nm) which although doesn't fulfill mainly the power requirement (excellent position of <5um resolution was demonstrated) serves as an excellent test bed for further developments. It was used to build a vertex detector prototype with ladders which was successfully tested at DESY.

The backup solution of 3 double layers on DMAPS on ladders (6 points/track) therefore seems doable in case a thin foldable vertex detector can't be done at the cost of a somewhat larger material budget (lower pT resolution at lower energies). The baseline design with 4 foldable silicon layers and a ladder-based double layer was mechanically tested with dummy thinned silicon (40 um) successfully bent to 12 mm which is close to the design requirement.

Comments:

- The time scale of the CEPC is such that the availability of the process that has all the required features (modified doping profiles) may not be around. Therefore early communication with the vendor and potential developments with the second vendor are needed. This may also be proven to be cost-effective.
- The mechanical design is still in the early phase of development and the ability to cool down the vertex detector with flow or air with speeds exceeding several m/s remains very challenging.

Recommendations:

- The studies and simulations of the background should be carefully followed as they impact the detector design and operation (data rate and power consumption).

ITK

The **Inner Silicon Tracker (ITK)** uses a combination of **HV-CMOS pixels** (34 µm × 150 µm pixel size) and **CMOS strips** (2.1 cm x 2.3 cm size, 20 um pitch) to provide excellent spatial resolution, with a target of less than 10 µm in the bending plane and around 50 µm in the longitudinal direction for the barrel region. The endcap sections are optimized for particle identification and momentum measurement, featuring strip sensors arranged with a cross angle to maximize track resolution in the bending direction. The ITK is designed to handle hit rates of up to **10^6 Hz/cm²** in high-luminosity environments, with a total sensor area of about **20 m²**.

The ITK HVCMOS (CAFFEE chip) utilizes a so-called large pixel CMOS sensor design and was realized in 55 nm process and standard reticle size (no stitching) and follows standard pixel module design (modules, sensor+flex, on staves). The advantages of this process are the use of high resistivity substrates (1-2 kOhm cm) which allows for higher depletion depth and also bias voltages of ~70 V assuring large depleted regions. First CAFFE tests were successful with passive CMOS diodes while active cells and active cells with periphery electronics are yet to be tested.

The Depleted Active Micro Strips sensors would use a different process (CMSC 180 nm). As sensor size is limited to reticle size, it doesn't require stitching and seems a safe design. The

CMOS passive strips have already been demonstrated, however, the small strip pitch and the design of the readout part in the periphery are very challenging and have yet to be demonstrated.

Comments:

- There is no dedicated effort mentioned in the current development of the CMOS strip sensors specifically for the Inner Tracker (ITK).
- 180 nm process may not be available over the next several years and presents a risk.
- Strip CMOS sensors with readout circuitry in the periphery of the sensors is novel and surprises are likely.

Recommendations:

- A detailed plan for the development of the ASIC for both CMOS strips and AC-LGAD (for OTK in this case) is needed, as the R&D timescales for these ASICs technologies with low-dissipation, high-time resolution is particularly challenging, requiring careful optimization of power consumption, timing precision, and integration with the sensors. They should be developed alongside the sensors. ASIC design, fabrication, and testing are time-intensive processes, often requiring multiple iterations to meet the performance requirements, and any delays in this pipeline could have cascading effects on the overall project timeline.

OTK

The outer tracker is planned with 85 m2 of AC-LGAD strip detectors located at r=1.85, z=+/-2.35 m and measuring a single coordinate in the bending plane. The sensors should have 100 um wide strips that would be 6-9 cm long and deliver around 10 um position and 50 ps time resolution. The much-needed expertise in LGAD technology comes from ATLAS HGTD detector where IME is the sole producer of conventional LGADs and the IHEP and USTC designed the sensors.

The envisaged power consumption is 300 mW/cm2 (ASIC) and requires active CO2 cooling. The full coverage will require ~3500 wafers with 2 different sensor designs in the barrel and 21 different detectors in endcaps (wedge-shaped). The purpose of the detector is to provide a ToF point for the tracks originating at the same vertex (PID).

First prototypes on small sensors ~5x2 mm2 AC LGADs showed a time resolution of 37 ps and position resolution of around 8 um. The ASIC has not been designed yet, but it is planned to mimic the current ASICs for LGAD readout.

Comments:

- The number of different sensor designs is large in the endcap and can complicate the construction.
- The discharge of generated electrons through n+ layer may be affected by radiation damage and can change during the lifetime of the detector.
- The capacitance of some sensors will be large (up to ~10 pF) which will make the noise jitter and rise time such that it will be difficult to achieve the desired time resolution.
- Operation of AC-LGADs can be susceptible to high particle rate effects and make sure that you understand that well (also related to size of LGADs).
- For the given pitch and thickness a charge-sharing mechanism and by that the position resolution should be carefully studied for different electrode dimensions taking possible variations of gain layer properties across the large detector into account.
- The localized power dissipation at the ASIC should be taken into account in the cooling design and performance evaluation.

Recommendations:

- Reconsider the size of the AC-LGADs and take both the performance (rate effects, time resolution and achievable position resolution) and expected yield into consideration in order to reach a cost effective solution.

TPC

The CEPC reference detector collaboration chose a MPGD TPC as the central track detector. This in an excellent choice, building up on a very successful technique, recording a long experience at LEP (ALEPH and DELPHI), at LHC (ALICE) and, more recently, equipping the T2K near detector, as well as dozens of nuclear and non-accelerator experiments. This concept offers continuous tracking in 3 dimensions over a large volume with a minimal amount of matter, and a possibility of identifying particles by their energy deposition in the gas.

The gas and the pad size have to be chosen with care. The choice of gas is important, with consideration of its ionization signal yield, and its transverse diffusion property, strongly influenced by the magnetic field (the omega.tau). A large omega tau reduction factor requires a ‘hot’ gas (a few percent CF4 admixture is an easy way of giving this property), and not to neglect a maximal drift velocity at a low enough drift field. If one is willing to allow cluster counting to help to measure the track dE/dx or dN/dx, the pads have to be small enough, but a digital readout is sufficient.

The mechanical alignment of the modules has to be excellent (a few tens of microns) to avoid systematics on the sagitta measurement. The electric and magnetic fields have to be precisely parallel to avoid ExB distortions. This calls for a very uniform magnetic field (see magnet section).

The build-up of a space charge has to be very limited to avoid a transverse electric field which causes distortion of the trajectories of the ionization electrons, leading to track distortions. Beam backgrounds have to be kept to a minimum to avoid this space charge build-up, or mitigation and correction techniques have to be designed to limit these distortions. This problem makes a TPC improper at the Z peak at very high luminosity.

Beam backgrounds have to be estimated carefully, as they produce ionization in the **TPC**. Especially low-energy X-rays and muons from thermal neutron interaction (the beam halo) can lead to low-pT particles (curlers) which deposit a huge ionization in the gas. These effects are amplified by ion feedback : ions created in the amplification gap can escape and drift all the way to the cathode. This takes typically half a second. Thus ion feedback has to be very well controlled. For this, low gain operation must be preferred and passive backflow mitigation must be searched for and well established (double misaligned meshes, graphene filter…) .

Also, in case the space charge effects cannot be avoided, correction methods should be developed, following the experience of ALICE lead-lead collisions.

A precise t0 has to be determined for each interaction using the other tracking detectors.

The readout chip itself has to be protected against damage from sparks. An adequate resistive coating has to be applied on each chip, with a surface resistivity tuned for maximal protection without excessive rate limitation.

Recommendations

- A full simulation is necessary to optimize the pixel/pad size. Microscopic pixels present the advantage of low noise, allowing single electron efficiency for a digital readout. Larger pads (more than 500 µm) allow a measurement of the ionization track element by track element, but require an electronics with an ADC for each pad, and this part is power consuming.
- The space charge induced by beam background has to be estimated at the HZ energy and it must be checked that the distortions from space charge are limited enough to allow for the Higgs recoil mass peak to appear clearly.
- Prototyping is necessary to assess the tolerance of the pixel chip to sparks and test the protection.

CALORIMETRY

Findings

The electromagnetic calorimeter (ECal) and hadronic calorimeter (HCal) teams are strong and productive. They are generally making good progress on their technologies.

Three technologies have been investigated and considered for the ECal:

- silicon-tungsten sampling calorimetry;
- scintillator-tungsten sampling calorimetry;
- and, most recently since 2020, crystal calorimetry.

Based on the potential for best performance, the crystal calorimetry has been chosen for the baseline, with crystals of 1 cm x 1 cm x 40 cm initially proposed. A prototype calorimeter based on this crystal baseline choice has been built and tested. The concept provides excellent electron and photon resolution, but must also contribute to the particle flow reconstruction of hadronic showers. The other two technologies are mature and provide backup alternative options.

Three technologies have also been investigated and studied for the HCal:

- semi-digital RPC-based calorimeter;
- plastic scintillator calorimeter;
- and glass scintillator calorimeter.

The glass scintillator has been chosen for the hadron calorimeter baseline based on its significantly better energy resolution below 80 GeV, where the hadrons populate from Higgstrahlung at 240 GeV. R&D has demonstrated excellent performance on a limited scale. The other two approaches have been developed and are potential alternatives.

The simulated jet reconstruction using PFA based on these two ECal and HCal baseline choices shows excellent performance.

Comments

The ECal team recognizes that they have several challenges in front of them to bring their chosen technology to maturity. They should sustain steady progress addressing these including:

- Developing and perfecting the Particle-flow algorithms including the effective pattern recognition and minimization of ambiguity issue;
- Dealing technical issues (ASICs, hermiticity, minimized power, mass production) with the very large number of channels in the very finely grained concept;
- Successfully overcoming beam-induced backgrounds and radiation damage;
- Understanding the impact of design choices on the performance to define specifications for the SiPMs linearity, crystal granularity and uniformity, readout threshold and noise, calibration needs;
- Developing and optimizing the in-situ calibration system.

There are ECal issues that need clarification such as

- The 0.1 MIP ECal threshold is chosen based on a balance between S/N and dynamic range - a more quantitative explanation of this is missing from presentation;
- SiPM dynamic range and linearity needs specification;
- The noise levels of the ECal including SiPMs and readout electronics;
- Anticipated level of crystal degradation with time, and its impact on physics performance;
- Homogeneity of MIP detection efficiency.

The HCal effort also confronts large challenges. While significant progress has been made, including beam testing of a prototype detector, much remains to achieve the maturity that is required. The glass scintillator concept is innovative, with limited experience in the particle physics detector community to draw from. Some of the critical aspects that need urgent attention include:

- Mature development of the glass scintillator technology, demonstrating mass production and cost containment with uniform properties such as high density, high light yield, large attenuation length, and short decay time;
- Optimization of ECal design granularity based on simulated physics performance;
- Optimization of other aspects including GS-SiPM coupling, mechanics, cooling, and electronics;
- Preparation and beam testing of full-size HCal prototype.
- The ECal-HCal transition region must be evaluated with attention to physics performance.

Given the short time scale, management oversight and support is essential to ensure successful achievement of these goals.

Recommendations

1. The new technologies chosen for the baseline ECal and HCal technologies are innovative and challenging. Steady progress must be maintained in prototyping and simulation. The concepts are feasible and attractive, but need steady and significant preparation to prove readiness, along with final specifications.
2. One aspect that must be monitored and perfected is the reproducibility of glass scintillators.
3. Design choices should be thoroughly justified by physics goals achieved with simulation of a full detector model. Alternative parameter choices should be considered and evaluated for physics outcomes. For example, ECal crystals of 1 cm (transverse) x 2 cm (depth) would reduce channel count and cost. Does it impact physics performance?
4. Some specific performance issues that would be interesting to more fully understand. These include higher energy pi zero reconstruction, which may benefit, for example, from a staggered bar arrangement or finer granularity in the first few layers. Also electron ECal resolution when the bending of electrons match the 12 degree incline angle. Does this impact electron measurements?

MUON SYSTEM

Findings:

The Muon Detector is designed for high efficiency and precise muon identification, offering nearly complete coverage (0.98 × 4π) and a low pion-to-muon misidentification rate at high energy levels (30 GeV/c). It might be considered for tagging LLPs. Trigger capabilities will be explored.

The muon system does not face significant challenges in terms of particle fluxes or radiation environment, with a rate capability of 60 Hz/cm², which is well within the limits of current technologies.

Several technologies are being considered for the detector, including Plastic Scintillators (PS), Resistive Plate Chambers (RPC), and μ-RWELL. The baseline choice is PS bars with SiPMs due to their simplicity, rate capability, and cost-effectiveness. The μ-RWELL option was ruled out because of the excessive number of channels required.

The current R&D shows promising results, particularly with Plastic Scintillators and SiPMs. Tests have demonstrated strong performance with shorter PS bars around 1.5 meters. However, extending the length to 4.2 meters presents challenges related to fiber attenuation.

Currently, the main focus of the R&D efforts is precisely on addressing the challenges associated with fiber attenuation in the longer PS bars.

Comments:

1. **Rate Capability**:
    - The 60 Hz/cm² rate for the PS system is achievable with modern detectors like **PS+SiPM** and **RPCs**, so *it's unclear why high-rate capability is emphasized as a significant challenge.*
2. **Detector Design and Technology Choices**:
    - The CEPC team proposes **PS bars with SiPMs** as the baseline. Ongoing R&D aims to improve light collection and fiber embedding (groove vs. hole). *The 4.2-meter-long PS bars face fiber attenuation issues, as the current fiber attenuation length (2.63 meters) is insufficient.*
3. **Prototype Performance**:
    - **Cosmic Ray (CR) tests** on a 1.5-meter PS bar prototype demonstrated >98% detection efficiency and <1.5 ns timing resolution. While NDL SiPMs and MPPCs have shown both good performance, the CR results show better performance of

    MPPC in terms of gain and DCR. So *the decision to use NDL SiPMs should be better justified, especially given the performance advantages of MPPCs in dark count rate (DCR) and gain.*

4. **Prototypes and Future Testing**:
    - ○ The prototype testing on shorter PS bars shows promise. However, the transition to longer bars (4.2 meters) introduces challenges with light collection. *There is no clear plan for the* ***longer bar prototype*** *construction or testing in the TDR.*
5. **RPC as a Suitable Option**:
    - ○ **RPCs** could be a viable option provided an eco-friendly gas mixture is developed. If the team decides to pursue the RPC option, *they should take advantage of the ongoing studies within the DRD1 Collaborative framework, particularly regarding eco-friendly gas mixtures.*

Recommendations:

1. In the TDR, provide a clear plan and timeline to address fiber attenuation and prototype scaling:
    - **Optical Glue**: Outline the testing process for various optical glues, including supplier options and performance criteria to improve fiber-scintillator coupling.
    - **Larger Diameter Fibers**: Specify steps for sourcing 2 mm diameter fibers, identifying suppliers.
    - **Prototype Scaling**: Plan for constructing and testing longer PS bars (e.g., 4.2-5 meters), focusing on stability, long-term SiPM performance, including radiation hardness tests if needed.
    - **Double-Sided Readout**: Consider a dual-end readout as a solution to mitigate attenuation and enhance redundancy.
2. **Electronics:**
    - ○ Justify the choice of NDL SiPMs, given MPPCs' superior DCR and gain. Clarify the operation temperature of SiPM.
3. **Muon Performance Studies**:
    - ○ **Hit rate vs. θ map**
    - ○ **Momentum Resolution**: global resolution (combined muon and tracking tracks)
    - ○ **Muon Identification and Fake Rate Studies**
    - ○ **Muon Rates**: single/multi-muon rates to optimize trigger performance.

MAGNET

Findings

A detector magnet design based on low-temperature superconducting (LTS) technology has been selected as the baseline to be further integrated and the technology to be demonstrated prior to the EDR.

Al-stabilized superconductor development, as a key technology for the detector magnet, has progressed much in cooperation with the Chinese industry.

The general magnet design is found to be adequately optimized, with an important, fundamental scaling parameter represented by stored energy / cold mass (E//M) ratio to be ~ 8.5 kJ/kg for ensuring safe operation and redundancy.

On the other hand, superconductor design optimization was not sufficiently reported (because of time limit?). It might be a concern that the Al-stabilized superconductor strength seems to reach the edge of the ordinal safety limit against ⅔ of yield strength.

No R&D plan for the coil winding was presented, and it should be included in the R&D plan towards the EDR.

Comments

We have been impressed with the progress in the Al-stabilized superconductor development successfully achieving the applicable level to a large magnet system. The committee (we) congratulates the progress in resuming this technology in China.

Based on this excellent progress, the Al-stabilized superconductor and magnet design may be optimized to accomplish mechanical reliability and quench safety and protection. Further R&D for mechanical reinforcement possibly by using the “cold work” process may be a good approach if it has not been done. It may contribute to sufficiently improving the mechanical safety margin of the magnet by satisfying an ordinal safety guideline of the use of the conductor at < ⅔ of 0.2% yield strength

Concerning the cooling design, LHe-pipe cooling path with many parallel cooling paths may be simplified by using a serpentine cooling path concept for minimise the number of Al-cooling pipe welding, concerned by the team, and for minimizing risks for welding difficulty of Al. It may provide further advantages to adapt both thermosyphon cooling and forced flow cooling.

Magnetic field design may be further optimized to optimize the field quality and the peak field to be suppressed.

The superconductor conductor stability and safety are very important and the quench safety and protection design shall proceed.

Recommendations

1. Extend Al-stabilized superconductor R&D mile-stone particularly for improving mechanical strength while keeping electrical stability with the residual resistance ratio (RRR) for necessary magnet operational stability, and for demonstrating the full conductor fabrication capability in a timely manner.
2. Confirm the quench safety with the current NbTi superconducting cable and Al-stabilizer parameter while providing sufficient stability with the temperature margin at the coil operational current and field.
3. Optimize the conduction cooling design with 2-phase helium cooling channel, by further optimizing the cooling paths, simplifying the cooling path in the fabrication and enabling flexibility of the operational modes.
4. Confirm the field quality / uniformity enabling to satisfy necessary field quality required for the TPC region under the current iron yoke (HCAL) and the final focusing magnet including the compensation solenoid.
5. As a critical and longer term R&D program, a full-size (in radius) coil winding R&D to demonstrate the coil fabrication including mechanical, electrical, and thermal characteristics to meet the design requirement. It shall be realized prior to the EDR.

MECHANICAL INTEGRATION

Findings

The study team presented the first ideas about the mechanical integration for the reference detector. In particular, they developed a concept for the installation sequence of the various detector elements and possible mitigation measures to compensate for the sagging of HCAL modules due to their self-weight (18.8mm), which is larger than the gap between HCAL and ECAL (10mm).

Comments

Not much work has been done so far in terms of the integration of detector services. Beyond sufficient space to be foreseen in the detector for cables, fibres, cooling pipes and hoses, but the services also have an impact on the detector's performance through their material budget.

Moreover, an estimate of the total power budget including power conversion efficiency and losses along the cables is necessary to correctly define the size of the power plants and of the services, and the impact of the services on the detector design.

Recommendations

1. Correctly size the service channels accounting for contingency. Space and material for services should also be duly considered in the simulations of the detector performance.
2. It would be important to define the considered cooling agents (air, water, CO_2 etc.) for all sub-detectors, which doesn't seem to be the case yet.

Further investigations going beyond the reference TDR will be needed at a later stage, including air cooling studies for the vertex detector to demonstrate the required cooling performance within the specifications in terms of vibrations.

ELECTRONICS

Findings

The electronics program has several components — A set of 6 Front End Electronics ASICs (FE-ASICs) for the subdetectors, a set of 4 radiation tolerant components for data readout and power, which are common to all subsystems, and a common Back End Electronics (BEE) board that receives data from the front ends before being buffered, processed and sent to the TDAQ system, and sends clocking, trigger and control signals to the front ends from the TDAQ TTC system.

The baseline choice for the reference TDR is that the system is triggerless, simplifying the FE-ASIC design, but increasing the readout bandwidth needed. A backup plan suggested is to use a triggered readout design. The rad tolerant readout chain includes 3 custom components mirroring the GBT system designed by CERN. These are a data aggregation ASIC (TaoTie), a Data Interface (GBTx-like), ChiTu, and an Optical Module (VTRx-like), KinWoo. The powering scheme is based upon a parallel powering plan based upon a DC-DC converter under design.
The BEE consists of a common board that aggregates data from various subsystems, buffers data during trigger processing, and interacts with the TDAQ system.

The readout system baseline uses optical links, with a backup plan to use a wireless readout technology.

Comments

Using common components for the readout of all the subsystems is an excellent choice and leverages the available engineering FTEs very effectively.

The triggerless data-driven readout baseline choice, which goes along the recommendations of ECFA DRD6, simplifies the FE-ASICs in that they don't need to locally buffer data while waiting for the trigger, decoupling these ASICs from details of the trigger logic. The buffering of data is instead moved to the BEE board, where it is much simpler to implement and more flexible with regards to changes in the trigger decision timing. Moving to a triggered readout scheme is listed as a backup plan, however it is unlikely that this would be viable once the project is well underway due to the impact on the FEE-ASIC designs as the backend is radically different.

The common BEE board uses well-established technology (standard optical links, modest sized FPGA, DRAM, Ethernet, I2C). In fact, the electronic team has already built a version of the board with 12 optical inputs for use with the prototype VTX detector. Once the amount of

DRAM needed for buffering data during the trigger decision time is set, and a target FPGA is selected (currently envisioned to be an XC7V690T) . The team has a strong history of delivering boards similar in scope to the BEE, and this element of the project has very low risk.

By far the highest risk in the electronics is designing and delivering the 6 FEE-ASICs needed. For the 6 FEE-ASICs needed to readout the detector subsystems, there is significant effort needed.

There are design teams already working on 2 of the chips (for VTX and TPC detectors) and another has been identified for the ITK.

For several detectors (tracker, AC-LGAD, calorimeters..) the detector design cannot be done independently of the readout electronics, as there is a close interplay on the overall performance. Granularity, sensor capacitance, power dissipation, occupancy are key ingredients for the detector and chip design. Some of the ASICs need the detector to be better defined to start the design. Although this is well understandable, chips tend to have a long development time and often end up in the critical path of the experiment. It is planned that most chips would share the same technology node (55 nm) and possibly share some blocks, which is very efficient but not so easy in practice.

The FE-ASIC progress should be closely monitored by the electronics coordinators. Although the analog front-end is detector-specific and needs to be developed in close collaboration with the detector team, the backend needs to be harmonized between detectors. The timeline and development path should be clearly specified (number of intermediate prototypes, variants…)

The design of the 3 data readout components mirrors the GBT system developed by CERN which is being used for a wide variety of applications. Modifications of the CERN design are needed for CEPC use due to the slightly different base clock (43 MHz). As well, the design can be simplified, with some capabilities of the CERN components removed as they are not needed for CEPC. This is underway for the CEPC ChiTu (GBTx-like) ASIC. The TaoTie pre-aggregation ASIC, which takes inputs with different data rates and channel counts from various front ends and merges them into fixed width and rate lines has not been started, but is less complex than the ChiTu. The KinWoo optical module (VTRx-like) has already been built and tested.

The development of these common chips by a strong central group is a good choice. However, it’s a heavy load and the manpower needed for full verification and testing should not be underestimated. The manpower absorbed by this common task may deprive other developments, in particular for the FE ASICs. If all the chips need to be developed in China (to be discussed with management), the resources are probably insufficient, especially if they are distributed over several labs. In any case a strong central facility (like CERN-MIC does for LHC) is essential. Otherwise look at existing chips and whether they could be adapted to CEPC.

The DC-DC converter is at an early stage. The GaN transistor has been selected, though needs testing for radiation tolerance. The switching frequency of the design is currently 5MHz, but the group is investigating moving to a higher frequency to improve the conversion efficiency. The converter circuitry itself is an established design. The parallel power scheme baseline plan is low risk, but serial powering has benefits if it can be used. The team should monitor developments elsewhere in case progress makes a serial scheme viable.

The wireless data transmission option is a backup plan, however it is not a low-risk backup. Significant R&D remains in miniaturizing and shielding, which is envisioned being driven by an industrial partner. One use case for this readout scheme would be to reduce the cabling costs for the ECAL. Replacing these cables would require developing repeater modules, in addition to the transmitters and receivers. Use inside the detector for readout of, eg, the silicon system would also require development of shielding and significant testing of the level of noise pickup the transmitters might induce in the detector elements. However, the wireless readout development should not take resources from the baseline electronics effort.

Recommendations

- **Establish the timeline for <u>all</u> the FE ASICs development** for all the sub-detectors and their state of maturity.
- Establish early enough the readout scheme (triggerless) so that no efforts are wasted on developments that will not be retained, chips unlikely to accommodate both R/O schemes.
- **For the triggerless readout, show the maximum rates that can be handled**, the safety margin that is included and what happens if the occupancy gets higher. What throttle scheme can be used?

TDAQ

Findings

The requirements for the TDAQ system are dictated by the need to collect all ZH, WW and Z pole events and provide the bandwidth needed to store these data. The data rates, before trigger, range from <1 TB/s for ZH running up to several TB/s at the Z peak with an expected event size below 2MB. The storage rate after the trigger ranges from 0.1 for ZH to 100 kHz at the Z pole. Contributions from beam-related backgrounds (for both single-beam and sources that scale with luminosity) are based on dedicated simulations and are included in rate estimates and preliminary trigger design.

The baseline plan is to transmit the full raw data to the front-end electronics and connect the trigger to the back-end electronics. This strategy is sound. Similar strategies have been successfully implemented in CMS and LHCb, where data rates are much higher. A hierarchical trigger scheme is foreseen to bring event data rates down from ~3MHz to ~1kHz in ZH running and ~40MHz to ~100kHz at the Z pole.

Early trigger studies are based on primitives from the calorimeter and muon detector which show promise for selecting desired physics at high efficiency while rejecting beam backgrounds. These studies do not yet include any high-level trigger information, which should be very effective at further refining the selection.

The system design foresees a common hardware trigger board to collect trigger primitives from the BEE common boards and send trigger accept signals to the BEEs. High-throughput DAQ and processing building on the RADAR framework used in previous projects will be extended to meet the requirements at CEPC. Initial designs for TCDS/TTC, DCS and ECS are in development. The scheme for a hardware trigger is in development and a preliminary design was presented. Many design decisions will need to be taken as more detailed information on data volumes from individual detectors is clarified.

The RDT has extensive experience in TDAQ and has designed and built hardware boards, firmware and software for several leading projects: BESIII, PANDA at GSI, Belle2 and CMS as well as several neutrino experiments, and have implemented machine learning (a NN for tau reconstruction) in the ATLAS global trigger upgrade. Their expertise is consistent with providing the TDAQ for the CEPC reference detector, and they are planning to increase capacity by adding additional members.

Comments

The detailed (bottom-up) design of the TDAQ must await further details on the subdetector design.

Work on the trigger primitives is needed to bring the rate down to an acceptable input for the second-level trigger, and to inform further planning for the processing farms in the DAQ design. Should it be needed, a track trigger could provide a powerful additional primitive.

High-level triggering will also need to weigh the physics-versus-bandwidth tradeoff for lower-energy events, e.g. from gamma-gamma collisions.

Recommendations

- A simple simulation of sub detector-based trigger inputs using simple, robust algorithms should be prioritized to allow more detailed specification of the requirements for TDAQ hardware and identify areas that need further attention. This should include an appropriate safety factor for beam-related backgrounds.

- Further work should include an evaluation of benefits of implementing a track trigger as a complement to the calorimeter and muon primitives, and to clarify the bandwidth foreseen for gamma-gamma events.

SOFTWARE AND COMPUTING

Findings

Key4hep is a common software ecosystem that is collaboratively developed by all future collider communities, i.e. mainly CEPC, CLIC, FCC and ILC. It is based on standard solutions developed for HEP such as the Geant4 full simulation toolkit or ROOT, and provides core solutions for detector geometry (DD4hep), event data model (EDM4hep) and application framework (Gaudi). CEPC is an early adopter and very actively contributing to the Key4hep stack from the beginning of the Key4hep project (Bologna Meeting in 2019). In particular worth mentioning here are some recent pioneering developments like extracting the Gaussino full simulation tool from LHCb to be used inside Key4hep or adopting the ACTS tracking toolkit and implementing a first version of track fitting for the CEPC reference detector. They started very promising activities, addressing optimized compute performance and hence sustainability, like the use of generative machine learning for fast calorimeter simulation or TPC digitisation.
As the reference detector introduces some novel detector technologies such as the crystal Ecal or the pixel-TPC, also novel reconstruction algorithms are under development, like the CyberPFA algorithm or a PID algorithm using cluster counting in the TPC.
In general, the system is functional and relies on well-known tools and components developed by a larger community. The overall design is classical, robust and able to support detailed simulations and analyses for detector performance studies and physics analyses.
A simulation model for the reference detector has been implemented in DD4hep.

The development team of 20 FTE for software seems adequate for the current situation !?

The computing for CEPC is based on tools and structures well established at the LHC and the overall HEP community, e.g. a Tier based computing architecture and job submission and monitoring tools such as Dirac and Grafana. For current CEPC studies, 2000 CPUs are available at IHEP and 2600 at other sites fulfilling the needs of CPEC.

The staff of 8 FTEs at IHEP for computing seems adequate for the current situation ?

Comments

Given the very nice work and recent developments in the Key4hep context, we encourage the CEPC software group to ensure that these find their way back into the common software stack. Seek collaboration with other Higgs factory concept groups on software tools were adequate in order to avoid duplication of effort, e.g. generative machine learning for fast simulation or ACTS integration

The long term vision of the software/computing evolution is not very clear, for the time being it looks more like an aggregation of existing components and efforts to implement best possible detector based solutions, so that physics performance for the TDR can be effectively performed.

How is the context of a potential international collaboration taken into account?

When CEPC goes ahead it will run in parallel with LHC, Belle-2 and EIC data analysis: what is the entanglement, mutual support and possibly common data analysis and computing frameworks ?

Recommendations

Given the rather ambitious timescale for the RefTDR, we make the following prioritized list of recommendations:

1. Ensure that the reference detector model used for the full simulation uses realistic material budgets in the tracking region containing/representing supports, services, cooling etc.
2. Focus on a complete and well tested full reconstruction for the reference detector in time for the RefTDR in order to demonstrate that detector/software performance goals like tracking and jet energy resolutions have been met. Where needed, one could fall back for now to already existing software for alternative technologies (e.g. use pad based TPC reconstruction if pixel based will not be available on time). Use full reconstruction to create basic detector performance plots, with realistic assumptions on detector resolutions, such as (non exclusive list)

    a. Track momentum resolution (single muons) as function of p_t for different values of cos(theta)/ or theta
    b. Impact parameter resolutions in r-phi, z
    c. (jet) energy resolution as a function of cos(theta), e.g. w/ uds di-jet events w/o ISR
    d. Flavour tagging performance
    e. PID performance (using dN/dx and TOF) including separation power for K/pi, K/p

3. Prepare a realistic estimate of the computing needs for the reference detector for the preparation, construction and running phase, ideally including the necessary human

resources. Consider data challenges in order to verify software and computing readiness.

4. Prepare a computing and software design for the phase beyond the RefTDR, addressing also:
    a. the data (open/shared) access and its long term preservation
    b. the incorporation of emerging technologies and their potential usage at 5-10 years
    c. a systematic approach for the knowledge collection and robust documentation.
    d. training and attractiveness for (young) programmers in the context of a long term target.

DETECTOR PERFORMANCE

Findings and Observations

The planned performance studies are based on an ambitious list of channels, often with complex topologies. Most of these benchmarks are aligned with the relevant international projects in the same area (ILC, FCC…). There are several changes with respect to the CDR, with the goal to improve performance and take into account the recent h/w updates. Many studies are redone, and some are still to come. The team has limited human resources, and the planned list of channels looks a bit too high for a few months of work.

It looks important to clarify whether the strategy is to optimize detector performance or study the physics reach. Given the limited amount of time it is better to focus on demonstrating that the reference detector reaches adequate performance for physics. With this aim the list of complex channels should be reduced (e.g. the b-physics part) and some basic channels (e.g. Z→ mumu) added in. The performance on basic objects (leptons, photons, jets) as a function of energy and polar angle is an essential part of the TDR. Full analyses and physics reach can be limited to a restricted list of channels, encompassing Higgs, Z, W and top physics.

It is also important to devise a strategy for the measurement of absolute luminosity, which is necessary for absolute cross-sections and has relevant applications (e.g. neutrino counting at the Z). Is the measurement of absolute luminosity based only on Bhabha, how the luminometer is going to be used, is the measurement complemented by ee→gamma-gamma events ?

Another key point is the use of resonant depolarization to measure the Z mass and W mass with high precision. These are key observables, whose precision must be improved in order to make full use of Higgs precision measurements (e.g. Higgs couplings).

Again on benchmark channels, a measurement of V_cs during the WW run is probably a more relevant benchmark than V_cb ; in addition which channel to be used for the measurement of the electroweak mixing angle should be clarified.

Proposed recommendations:

- Physics benchmarks: select fewer channels, aimed at demonstrating that the reference detector reaches adequate performance for physics. Include some simple topology (e.g. Z→mumu)
- Foresee in the TDR results and figures about performance on basic objects (leptons, photons, jets) as a function of energy and polar angle
- Clarify in the TDR the strategy on the measurement of absolute luminosity
- Include in the TDR at least a brief description of the plans related to the use of resonant depolarization for Z and W mass
- (longer term) Note down the main points of detector configuration optimisations that can be further explored versus the presented performance for the RefTDR, given the limited time available
- (longer term) Address the impact of the performance studies on the technology choices?
- explain how the various sub-detector will be calibrated with physics processes.
- The performance of crystal ECAL on boson mass resolution (Page 20 of “Physics Benchmarks and Global Performance” talk), and Jet Origin ID (Page 9 of the same talk), should be simulated in a consistent way. The impact of crystal ECAL on PFA and jet flavor tagging capability should be estimated.

CONCLUSIONS

APPENDIX I

Appendix II

CEPC International Detector Review Committee Charge

Meeting: October 21-23, Beijing

The Circular Electron Position Collider (CEPC) project, a Higgs factory proposed to be constructed in China, plans to have two experimental interaction regions. After the CEPC project approval, the final two detectors will be developed as International Collaborations. In the meantime, a Reference Detector is being designed to demonstrate the readiness and feasibility of detector technologies.

Following the successful publication of the CEPC Accelerator Technical Design Report (TDR) in December 2023, the CEPC Design Group is devoting its attention to the CEPC Reference Detector TDR. This Reference Detector TDR, together with the accelerator-engineering designs, will complete the preparation of the CEPC proposal to the governments (central and local) for project approval in China.

The Reference Detector described in this TDR could be but does not necessarily need to be, one of the two detectors that will eventually be installed in the CEPC. The technologies used in the Reference Detector are forward-looking, and although not necessarily at hand today, they could be achieved within the timescale of the start of construction. The reference TDR also includes alternative options for each sub-detector, which are often more conservative, based on technologies available today, and for which more advanced prototypes might have already been produced.

The primary focus of the first meeting of the CEPC International Detector Review Committee (IDRC), scheduled for October 2024, is to inform the committee of the current status of the project, set the groundwork for the comprehensive review process to happen in 2025, ensure alignment with the project objectives, and provide initial feedback on the R&D progress of the Reference Detector. The CEPC Design Group will make presentations to cover each chapter of the Reference TDR. The presentations will cover the current status of research and development (R&D), including a technology survey, technical challenges, details of the current design and justification for the adopted solutions. In this first meeting, the CEPC International Detector Review Committee (IDRC) is charged with:

Review the overall status of the research and development (R&D) efforts for the CEPC detectors, which will be highlighted in the presentations.

- Offer initial observations or suggestions for improvements across the project.
- Identify technical risks associated with the detector design and propose mitigation strategies.
- Discuss the feasibility and readiness of critical technologies and components for the detector system, considering the proposed Reference Detector and alternative technologies, and taking into account the overall detector performance and physics performance expectations.
- Prepare for subsequent review meetings by establishing the framework for ongoing evaluation and feedback processes.
- Other -- any comments and suggestions pertaining to the Reference Detector TDR.

The first draft of the Reference TDR is expected to be available in early 2025, and subsequent meetings of the IDRC will explore specific aspects of detector design and technological integration as the project is further refined.

APPENDIX III

- MDI - **H. Yamamoto,** Kramberger, Titov

- Vertex Detector, Silicon Tracker, Gaseous Detector- **Kramberger,** Colaleo, Colas, Titov, Vila
- Calorimetry - **Brau,** Tabarelli de Fatis, Poeschl
- Muon detector- **Colaleo**, Colas, Han, Titov
- Magnet – **A. Yamamoto,** H. Yamamoto, Brau
- Mechanics - **Schmidt,** Kramberger, Tabarelli de Fatis
- Electronics - **Gay,** De la Taille, Titov
- TDAQ- **Kowaleski,** Tenchini, Gay
- Software - **Gaede,** Diaconu, Kowaleski
- Performance - **Tenchini**, Diaconu, Gay, Han