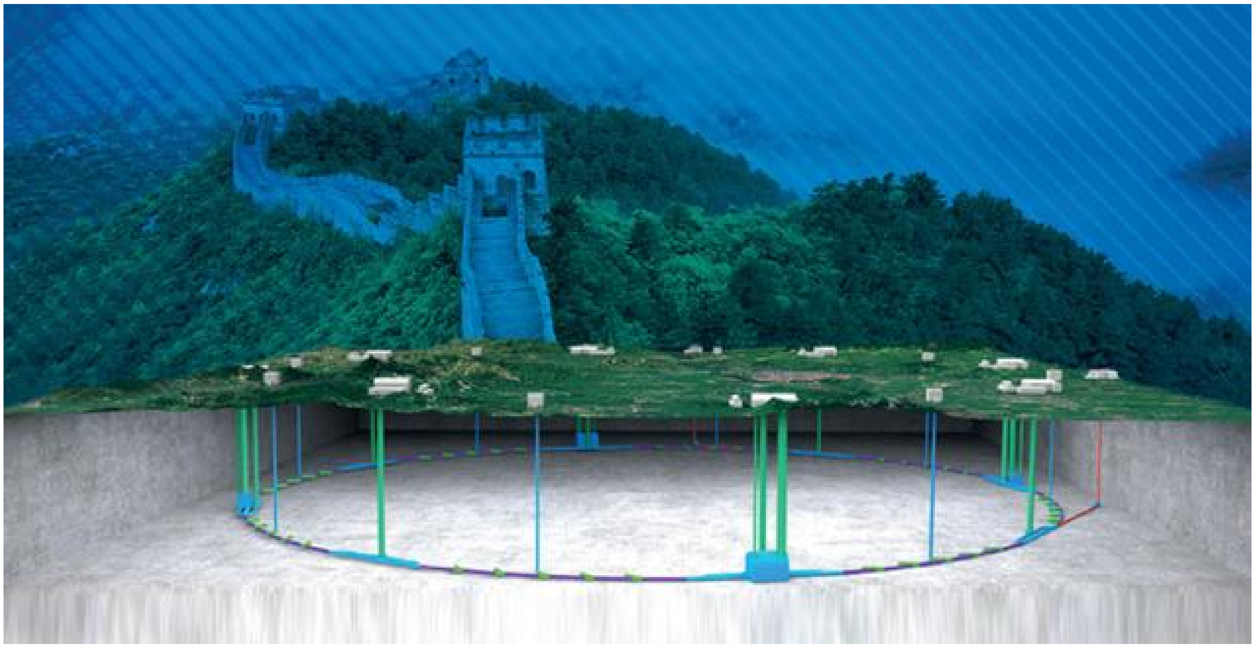
FIRST IDRC MEETING REPORT

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, Cristinel 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 running 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 1.92×10^{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 their extensive R&D efforts and the high-quality work they have achieved, especially considering the current team consists of only 90 staff members from IHEP and around 200 scientists from 35 domestic research institutes and universities. It is important to note that many of these staff members are not yet fully dedicated to the Reference Detector effort as they are still completing other projects. We recommend encouraging more personnel to join these activities as soon as possible. We acknowledge that CEPC management expects a rapid increase in staff following the completion of the JUNO project. Additionally, we appreciate the involvement of Chinese institutes in the DRD collaborations.

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. 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.

Machine Detector Interface

Findings

An evaluation of beam-induced backgrounds, mitigation strategies, and the design of the luminosity monitor was presented. The primary sources of beam-induced background include single-beam effects such as Touschek scattering, beam-gas interactions, beam-thermal photon scattering, and Synchrotron Radiation (SR). For beam-beam interactions, Beamstrahlung (including incoherent pairs) and radiative Bhabha processes are considered.

To mitigate these backgrounds, the plan involves the use of 16 strategically placed collimators and heavy-metal masks to block SR photons from final dipoles and quadrupoles. The beam pipe at the interaction point (IP) is a double-wall Beryllium pipe with a 10 mm radius, cooled by water or paraffin, designed primarily based on the profile of incoherent pairs. A gold coating inside the IP beam pipe is included in the simulation to absorb X-rays, along with simplified flanges, although cables have yet to be modeled. Beam particles are tracked for up to 200 turns.

The resulting occupancies and radiation doses in the detectors are found to be acceptable for Higgs operation, though further optimization is required for Z running. Additionally, beam background studies for failure scenarios have been conducted in collaboration with the accelerator group.

The LumiCal detector is designed to achieve a luminosity uncertainty in the range of 10^{-3} to 10^{-4}. The baseline design features two layers of silicon-strip disks, followed by a 23 mm-thick disk of LYSO crystals, and a 200 mm-long cylindrical section of LYSO crystals.

Comments

Beam backgrounds are notoriously difficult to predict, often leading to errors that can span one or more orders of magnitude. Therefore, it is crucial to adopt conservative estimates for background levels, especially in the initial stages of analysis.

A collimator was simulated under the assumption that any particle striking it would be fully absorbed without generating secondary particles. However, secondary particles can frequently lead to much higher background estimations. Currently, the SR masks used are those designed for the CDR detector, and they have not yet been optimized for the Reference Detector. A detailed optimization of the SR masks is essential, particularly for photons produced in the final dipoles and final focus quadrupoles. This includes considering effects like scattering at the mask tip and reflections within the beam pipe. To mitigate shower backgrounds caused by stray beam particles, heavy metal masks are often placed near the interaction point (IP), although no such study was discussed in the presentation. Additionally, the significant beamstrahlung generated at the IP during collisions must be carefully managed to ensure proper extraction into a dedicated beam dump, while also providing sufficient heat dissipation and radiation shielding.

The mechanical interface between the detector structure—including the large magnet system—and the final focusing magnet is critical. Close collaboration with the accelerator group is necessary to assess both magnetic field interactions and potential mechanical vibrations. Measurements of vibrations at the proposed CEPC site, along with an evaluation of their impact on beam offsets at the IP, are required. This assessment should consider the expected vibration modes in the mechanical transfer functions of the most sensitive magnetic components within the cryostat. The Committee also notes that the cantilevered cryostat for the final focusing magnet will require auxiliary support 3.3 meters from the IP, potentially resting on the electromagnetic calorimeter (ECAL), which could aid in stabilization. Nevertheless, a thorough evaluation of this setup is needed, particularly regarding the twisted mode, which poses the greatest risk for vertical beam offsets.

The estimated event rates for Bhabha scattering in the LumiCal detector fall within the nominal event rate. However, a dedicated high-rate LumiCal data stream will be necessary to accurately study beam backgrounds. The selected technology option appears to be technically feasible with current state-of-the-art capabilities and aims to achieve effective electron/gamma separation for radiative photons. Maintaining the required precision in luminosity measurement is challenging, as it demands the electron impact position (and inner radius) to be known to within 5-10 μm.

Recommendations

1. Optimize the collimators using simulations that account for secondary particle interactions.
2. Refine the SR masks for the Ref-TDR configuration, incorporating simulations of tip scatterings, bounces within the beam pipe, and SR originating from the beam halo in quadrupoles.
3. Explore the feasibility of placing heavy metal masks near the interaction point (IP) to absorb particle showers effectively.
4. We encourage continuing the design optimization of the LumiCal detector through simulation studies, with an emphasis on detailed mechanical design. In later stages, beam tests with detector prototypes should be performed.
5. A comprehensive review of the Machine-Detector Interface (MDI) would be highly beneficial. This review should involve experts from both the detector and accelerator teams to ensure all relevant aspects are thoroughly addressed.

TRACKING

Findings

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

Comments

The design and technology choices for the vertex detector, inner (ITK), and outer tracker (OTK) are particularly ambitious, incorporating the latest advances in silicon detector technology. This places the detector at the cutting edge of technological development but also necessitates the engagement of a much larger community to complete the prototyping and construction phases. The progress made by the groups working on the silicon trackers, considering the wide number of participating institutes, is truly remarkable.

Recommendations

- The current manpower dedicated to the design and R&D efforts should be expanded to ensure the successful completion of the project.
- It is essential to evaluate the Outer Tracker's (OTK) influence on the overall momentum resolution and its contribution to particle identification (PID). To achieve this, a comprehensive simulation is required that addresses the following key aspects:
    - **Alignment between ITK and OTK**: The relative alignment of the ITK and OTK plays a crucial role in determining global tracking precision. The simulation must incorporate realistic alignment tolerances and errors, reflecting the mechanical uncertainties expected during installation.
    - **Quantifying the Overall PID Enhancement**: The simulation should provide a quantitative analysis of how the inclusion of OTK-based time-of-flight (ToF) measurements improves PID compared to relying solely on the TPC's dE/dX measurements. This will clarify the OTK's role in extending the detector's PID capabilities across a wider momentum range, particularly in forward regions beyond the TPC's coverage. The importance of the OTK for PID in these forward regions is particularly noteworthy.
    - Establish the visibility of the Higgs peak independent of the Higgs boson decay by reconstructing the recoiling Z boson in $Z \rightarrow \mu\mu$ decays.

Vertex Detector

Findings

The Vertex detector aims to utilize Depleted Monolithic Active Sensors (DMAPS) to achieve a high position resolution of 3-5 μm, with a readout speed of approximately 43 MHz and an ultra-low material budget of <0.15% per layer, all while maintaining a power consumption of 40 mW/cm². This presents a significant technical challenge, but development can benefit from parallel efforts in ALICE ITS3, although the CEPC design is even more demanding, particularly with its tighter bending radius requirement of 11 mm.

The baseline solution involves a <65 nm process, which would reduce power consumption to acceptable levels and facilitate large-scale stitching. The availability of thin epi-layers favors a small electrode design with a modified or non-standard doping profile (low-doped n-layer). This technology is accessible through TowerJazz cooperation, and the 55 nm process with SIMC is also under investigation.

A notable achievement is the development of the TauichiPix3 sensor (engineering run with TowerJazz at 180 nm). While it does not fully meet the power requirements, it demonstrated excellent position resolution (<5 µm) and serves as an excellent test platform for further advancements. This sensor was used to construct a vertex detector prototype with ladders, which was successfully tested at DESY.

As a fallback, a solution using three double layers of DMAPS on ladders (providing six tracking points) is feasible if a thin, bent vertex detector cannot be achieved. This alternative would come with a slightly higher material budget and result in lower p_T resolution at lower energies. Mechanical tests of the baseline design, which consists of four bendable silicon layers and a ladder-based double layer, were successfully conducted using dummy thinned silicon (40 µm), bent to 12 mm, very close to the design goal.

Comments:

- The timeline of the CEPC project raises concerns that the process with the required features, such as modified doping profiles, may not be available when needed. Therefore, early communication with the vendor is essential, along with exploring potential developments with a secondary supplier. This proactive approach could also prove to be cost-effective in the long term.
- Regarding the mechanical design, it is still in the early stages of development. A significant challenge remains in cooling the vertex detector, especially with airflows exceeding several meters per second, which poses technical difficulties.

Recommendations:

- Thorough analysis and simulation of the background are essential, as they directly influence key aspects of detector design and operation, such as data rates and power consumption.

Inner Tracker (ITK)

Findings

The Inner Silicon Tracker (ITK) employs a combination of HV-CMOS pixels (with a 34 µm × 150 µm pixel size) and CMOS strips (2.1 cm x 2.3 cm size, 20 µm pitch) to achieve high spatial resolution, targeting under 10 µm in the bending plane and approximately 50 µm in the longitudinal direction for the barrel region. In the endcap sections, strip sensors are arranged at cross angles to enhance particle identification and momentum measurement, optimizing track resolution in the bending plane. The ITK is designed to sustain hit rates of up to 10^6 Hz/cm² in high-luminosity environments, covering a sensor area of around 20 m².

The ITK’s HV-CMOS (CAFFE chip), utilizing a so-called large pixel CMOS sensor design, is fabricated using a 55 nm process and standard reticle size (without stitching), and follows a standard pixel module design comprising modules, sensor with flex, and staves. This process enables the use of high-resistivity substrates (1-2 kΩ·cm), allowing for a greater depletion depth and bias voltages around 70 V, which supports larger depletion regions. Initial CAFFE tests using passive CMOS diodes have been successful, though tests with active cells and peripheral electronics are forthcoming.

The Depleted Active Micro Strips sensors use a separate process (CMSC 180 nm). Limited by reticle size, this design does not require stitching and is considered robust. CMOS passive strips have already been demonstrated; however, the small strip pitch and readout design within the periphery present significant challenges that remain to be resolved.

Comments:

- There is currently no dedicated effort focused specifically on developing CMOS strip sensors for the Inner Tracker (ITK).
- The 180 nm process may face limited availability in the coming years, presenting a potential risk.
- Additionally, integrating readout circuitry within the periphery of strip CMOS sensors is an innovative approach, likely to bring unforeseen challenges."

Recommendations:

- A detailed plan for the development of the ASICs for both CMOS strips and AC-LGAD (for OTK in this case) is essential. Given the demanding R&D timelines for these low-dissipation, high-time-resolution technologies, careful optimization of power consumption, timing precision, and seamless integration with the sensors is critical. ASIC development should proceed in parallel with sensor design. The process of designing, fabricating, and testing these ASICs is time-intensive, often requiring multiple iterations to achieve the desired performance. Any delays in this pipeline risk cascading effects on the broader project schedule.

Outer Tracker (OTK)

Findings

The outer tracker design includes 85 m^2 of AC-LGAD strip detectors positioned at a radius of 1.85 m and z-coordinates of ±2.35 m, measuring a single coordinate in the bending plane. These sensors will feature 100 μm-wide strips, ranging from 6 to 9 cm in length, targeting a position resolution of approximately 10 μm and a time resolution of 50 ps. Expertise in LGAD technology is largely drawn from the ATLAS HGTD detector, where IME serves as the sole producer of conventional LGADs, with sensor designs developed by IHEP and USTC.

The anticipated power consumption for the ASICs is 300 mW/cm^2, necessitating active CO_2 cooling. Achieving full coverage will require approximately 3,500 wafers, with two distinct sensor designs for the barrel and 21 different wedge-shaped detectors for the endcaps. The primary objective of the detector is to provide time-of-flight (ToF) measurements for tracks originating from the same vertex, facilitating particle identification (PID).

Initial prototypes using small AC-LGAD sensors (~5 x 2 mm²) have demonstrated promising results, achieving a time resolution of 37 ps and a position resolution of around 8 μm. While the ASIC for this application is yet to be designed, it is expected to closely resemble the current ASICs used for LGAD readout.

Comments:

- The large variety of sensor designs required for the endcap adds complexity to the construction process.
- Radiation damage may affect electron discharge through the n+ layer, potentially altering sensor performance over the detector's lifespan.
- Sensors may have high capacitance (up to ~10 pF), which could impact noise jitter and rise time, making it challenging to achieve the desired time resolution.
- The operation of AC-LGADs ma be suysceptible to effects from high particle rates, which should be thoroughly understood, especially regarding the size of the LGADs.
- With the specified pitch and thickness, a charge-sharing mechanism is expected to enhance position resolution; however, this should be carefully evaluated for different electrode dimensions, considering potential gain layer variations across the detector.
- The localized power dissipation at the ASIC level should be factored into the cooling design and overall performance assessment.

Recommendations:

- Reevaluate the size of the AC-LGADs, carefully balancing performance factors—such as rate effects, time resolution, and achievable position accuracy—with expected manufacturing yield to arrive at a cost-effective solution.
- Determine if redundancy is needed in the OTK barrel system.

TPC

Findings

The RDT selected an MPGD TPC as the central tracking detector—an excellent choice that leverages a proven, widely used technology with extensive operational history at LEP (ALEPH and DELPHI), LHC (ALICE), T2K, and various nuclear and non-accelerator experiments. This approach provides continuous 3D tracking over a large volume with minimal material interference, while also enabling particle identification via energy deposition in the gas.

Comments:

Selecting the appropriate gas and pad size is crucial. Gas choice should maximize ionization signal yield and minimize transverse diffusion, which depends heavily on the magnetic field ($\omega\tau$

factor). A high ωτ reduction factor calls for a 'hot' gas, often achieved with a small CF4 admixture, along with a high drift velocity at a low drift field. If cluster counting is desired to improve dE/dx or dN/dx measurements, small pad sizes are needed, though digital readout alone may suffice.

Mechanical alignment must be precise, within a few tens of microns, to avoid systematic errors in sagitta measurements. Electric and magnetic fields must be precisely parallel to prevent ExB distortions, necessitating a highly uniform magnetic field (see magnet specifications). Minimizing space charge buildup is also essential, as transverse electric fields can distort ionization electron paths, affecting track accuracy. Therefore, beam backgrounds must be controlled to prevent space charge accumulation, or corrective strategies must be implemented. However, at the Z peak with high luminosity, these issues make a TPC unsuitable.

Careful estimation of beam backgrounds is needed, as they produce TPC ionization, with low-energy X-rays and muons from beam halo interactions potentially generating low-pT particles (curlers) that deposit significant ionization. Ion feedback, where ions from amplification drift toward the cathode (over ~0.5 s), must be managed carefully. Operating at low gain with effective passive backflow mitigation, such as double misaligned meshes or graphene filters, is recommended. If space charge effects are unavoidable, correction techniques—drawing on ALICE's experience with lead-lead collisions—should be prepared.

A precise t_0 determination for each interaction, based on other tracking detectors, is essential. The readout chip must also be protected from sparks, which can be achieved by applying a resistive coating to each chip, with surface resistivity optimized for maximum protection without limiting rate capability.

Recommendations

- A full simulation is essential to optimize pixel/pad size. Microscopic pixels offer the benefit of low noise, enabling single-electron detection with digital readout. In contrast, larger pads (over 500 μm) support measurement of ionization on a track-by-track basis but require ADC-equipped electronics for each pad, which significantly increases power consumption.
- Space charge induced by beam background must be carefully estimated at the HZ energy. It is crucial to ensure that space charge distortions remain sufficiently low for a clear Higgs recoil mass peak.
- Prototyping will be needed to evaluate the pixel chip’s tolerance to sparks and to test protective measures.

CALORIMETRY

Findings

The electromagnetic (ECal) and hadronic (HCal) calorimeter teams are strong and productive, making steady progress in advancing their respective 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, along with effective particle flow reconstruction of hadronic showers. The other two technologies are well-developed and serve as viable backup options.

Similarly, three technologies were 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 superior energy resolution below 80 GeV, aligning well with the energy range of hadrons produced via Higgstrahlung at 240 GeV. R&D efforts on this technology have shown outstanding performance on a small scale, with the other two options remaining as 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, and 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;
- Optimization of ECal design granularity based on simulated physics performance;
- Homogeneity of MIP detection efficiency.

The HCal effort also faces significant challenges. While progress has been made, including prototype beam tests, further work is needed to bring the concept to the required maturity. The glass scintillator approach, although innovative, has limited precedent in particle physics detectors. Key areas of focus 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 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 innovative technologies selected for the baseline ECal and HCal present both opportunities and challenges. It is essential to maintain steady progress in prototyping and simulation to demonstrate their feasibility and readiness, along with finalizing specifications. One aspect that must be monitored and perfected is the reproducibility of glass scintillators.
2. 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?
3. Some specific performance issues that would be interesting to more fully understand. These include higher energy π^0 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, providing nearly complete coverage (0.98 × 4π) and a low pion-to-muon misidentification rate at high momentum (30 GeV/c). It might be considered for tagging Long Lived Particles. 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 – 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, robust rate capability, and cost-effectiveness. The μ-RWELL option was eliminated due to the large number of channels required.

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

Currently, the main focus of the R&D is on overcoming the issues 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**: local and 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 utilizing low-temperature superconducting (LTS) technology has been chosen as the baseline for further integration, with plans to demonstrate this technology prior to the Engineering Design Review (EDR).

The development of aluminum-stabilized superconductors, a critical component for the detector magnet, has advanced significantly through collaboration with the Chinese industry. The overall magnet design appears to be adequately optimized, featuring a crucial scaling parameter—the stored energy to cold mass (E/M) ratio—estimated at approximately 8.5 kJ/kg, which is essential for ensuring safe operation and redundancy.

However, the optimization of the superconductor design has not been sufficiently reported, potentially due to time constraints. There is concern that the strength of the aluminum-stabilized superconductor approaches the upper limit of the safety margin, reaching about two-thirds of the yield strength.

Additionally, no R&D plan for the coil winding has been presented; this should be included in the overall R&D strategy leading up to the EDR.

Comments

We were impressed with the progress in the development of aluminum-stabilized superconductors, which have successfully reached the applicable standards for large magnet systems. The committee extends its congratulations on the progress achieved in resuming this technology in China.

Given this significant progress, there is an opportunity to optimize the aluminum-stabilized superconductor and magnet design to enhance mechanical reliability and quench safety. Further research and development in mechanical reinforcement, possibly through the "cold work" process, could be beneficial if it has not yet been explored. This approach may significantly improve the mechanical safety margin of the magnet by adhering to the safety guideline of utilizing the conductor at less than two-thirds of the 0.2% yield strength.

Regarding the cooling design, the current LHe-pipe cooling path, which features multiple parallel cooling lines, could be streamlined by implementing a serpentine cooling path concept. This would reduce the number of aluminum cooling pipe welds—an area of concern for the team—thereby minimizing the risks associated with welding difficulties. Additionally, this design could facilitate the integration of both thermosyphon cooling and forced-flow cooling for enhanced performance.

The magnetic field design also warrants further optimization to improve field quality and suppress peak fields effectively.
The stability and safety of the superconducting conductor are critical. The design for quench safety and protection should proceed with careful attention.

Recommendations

1. Extend the R&D milestones for aluminum-stabilized superconductors, focusing specifically on enhancing mechanical strength while maintaining electrical stability through the residual resistance ratio (RRR). This is essential for ensuring the necessary

operational stability of the magnet and for demonstrating the complete conductor fabrication capability in a timely manner.

2. Confirm quench safety using the current NbTi superconducting cable and aluminum-stabilizer parameters, ensuring sufficient stability with a favorable temperature margin during coil operation under specified current and field conditions.
3. Optimize the conduction cooling design by incorporating a two-phase helium cooling channel. This includes refining the cooling paths, simplifying the fabrication process, and allowing for flexibility in operational modes.
4. Assess the field quality and uniformity to ensure compliance with the requirements for the TPC region, considering the current iron yoke (HCAL) and the final focusing magnet, including the compensation solenoid.
5. As a critical long-term R&D initiative, conduct a full-size (in radius) coil winding program to demonstrate coil fabrication, encompassing mechanical, electrical, and thermal characteristics to meet design specifications. This effort should be completed prior to the Engineering Design Review (EDR).

MECHANICAL INTEGRATION

Findings

The RDT presented initial concepts for the mechanical integration of the reference detector. They specifically outlined a proposed installation sequence for the various detector components and identified potential mitigation strategies to address the sagging of HCAL modules due to their self-weight, which measures 18.8 mm. This sag exceeds the available gap between the HCAL and ECAL modules, which is only 10 mm.

Comments

To date, there has been limited progress in integrating detector services. While it is essential to allocate adequate space within the detector for cables, fibers, cooling pipes, and hoses, the materials used in these services also significantly affect the detector's performance due to their material budget.

Additionally, it is crucial to estimate the total power budget, taking into account DC-DC power conversion efficiency and losses along the cables. This assessment will enable accurate sizing of the power plants and associated services, as well as clarify their impact on the overall detector design

Recommendations

1. Ensure that the service channels are appropriately sized, allowing for contingencies. Space and materials for services should be carefully incorporated into the simulations of the detector's performance.

2. It is also important to specify the cooling agents being considered (e.g., air, water, CO2) for all sub-detectors, as this has not yet been clearly defined.

Further investigations will be necessary beyond the reference TDR, including studies on air cooling for the vertex detector, to demonstrate that the cooling performance meets the required specifications, particularly 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. The BEE board receives data from the front ends, where it is buffered, processed, and then sent to the TDAQ system. Additionally, it transmits clock, trigger, and control signals to the front ends from the TDAQ TTC system.

The baseline choice for the Ref-TDR adopts a triggerless system, 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, in alignment with the recommendations of ECFA DRD6, simplifies the FE-ASICs by eliminating the need for local data buffering while awaiting 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

1. **Establish the timeline for <u>all</u> the FE ASICs development** for all the sub-detectors and their state of maturity.
2. 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.
3. **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 HZ 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 the Timing, Clock, and Control Distribution System (TCDS/TTC), as well as the Detector Control System (DCS) and Experiment Control System (ECS), are currently under development. The hardware trigger scheme is also in progress, with a preliminary design already presented. As more detailed information about data volumes from individual detectors becomes available, several key design decisions will need to be made to ensure optimal system performance

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

1. Prioritizing a straightforward simulation of subdetector-based trigger inputs using robust algorithms is essential. The simulation should include an appropriate safety factor for

beam-related backgrounds. This approach will enable a more detailed specification of the requirements for TDAQ hardware and help identify areas that require further attention.

2. 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 leverages established solutions developed for HEP, such as the Geant4 full simulation toolkit and ROOT, to provide essential components for detector geometry (DD4hep), event data model (EDM4hep) and application framework (Gaudi). CEPC has been an early adopter, actively contributing to the Key4hep stack since its inception at the Bologna Meeting in 2019. Noteworthy recent developments include the extraction of the Gaussino full simulation tool from LHCb for integration into Key4hep and the adoption of the ACTS tracking toolkit, which has led to an initial 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 incorporates novel detector technologies such as the crystal Ecal or the pixel-TPC, new reconstruction algorithms are also being developed. These include the CyberPFA algorithm and a particle identification (PID) algorithm utilizing cluster counting within the TPC.

Overall, the system is functional and built on well-established tools and components from a broader community. Its design is classical and robust, supporting detailed simulations and analyses for both detector performance studies and physics analyses. A simulation model for the reference detector has been successfully implemented in DD4hep.

Computing resources for CEPC are based on tools and structures that are well-established within the LHC and the broader HEP community, employing a tiered computing architecture along with job submission and monitoring tools like Dirac and Grafana. Currently, 2,000 CPUs are available at IHEP, with an additional 2,600 CPUs at other sites, adequately meeting the needs of CEPC studies.

Comments

Given the strong progress and recent advancements in the Key4hep ecosystem, we encourage the CEPC software team to integrate these developments back into the shared software stack. Collaboration with other Higgs factory concept groups on software tools, such as generative machine learning for fast simulation or ACTS integration, would be beneficial in reducing duplication of effort and maximizing resource efficiency.

Currently, the long-term vision for software and computing evolution seems somewhat undefined. The present approach largely integrates existing components and aims to develop detector-specific solutions that will facilitate high-quality physics performance for the Ref-TDR. However, it would be valuable to articulate a more cohesive strategy that aligns with future CEPC needs.

A key question remains on how a potential international collaboration is being considered within the software strategy. Furthermore, with CEPC likely to operate concurrently with major experiments such as the LHC, Belle-2, and EIC, it is essential to explore areas of mutual support, shared resources, and possibly unified frameworks for data analysis and computing. This strategic planning could enhance both technical and scientific synergies across these large-scale projects.

Recommendations

Given the rather ambitious timescale for the Ref-TDR, we recommend the following prioritized actions:

- Ensure that the reference detector model used for full simulation incorporates realistic material budgets in the tracking region, including supports, services, and cooling infrastructure.
- Focus on achieving a complete and well-tested full reconstruction for the reference detector in time for the Ref-TDR. This should demonstrate that key detector and software performance metrics, such as tracking and jet energy resolutions, are met. Where necessary, temporarily utilize existing software solutions (e.g., pad-based TPC reconstruction) if newer alternatives (such as pixel-based TPC reconstruction) are not ready on time.
- Use full reconstruction to create basic detector performance plots, with realistic assumptions on detector resolutions, such as:
    a. Track momentum resolution (for single muons) as function of p_T for different values of $\cos(\theta)$ or θ
    b. Impact parameter resolutions in $r-\phi$ and z
    c. Jet energy resolution as a function of $\cos(\theta)$, e.g., for uds di-jet events without ISR
    d. Flavour tagging performance
    e. PID performance (using dN/dx and TOF) including separation power for K/π and K/p

- Develop a realistic estimate of computing requirements for the reference detector, encompassing preparation, construction, and operational phases, ideally with an assessment of required human resources. Use data challenges to verify software and computing readiness.
- Prepare a forward-looking computing and software strategy for the post-Ref-TDR phase, addressing:
  - Data accessibility (open/shared) and long-term preservation
  - Integration of emerging technologies and their anticipated applications over the next 5-10 years
  - A systematic approach for documentation and knowledge capture
  - Initiatives for training and attracting new programmers, particularly for long-term sustainability.

DETECTOR PERFORMANCE

Findings and Observations

The planned performance studies include an ambitious set of channels, many with intricate topologies. Most of these benchmarks align well with international projects in the same domain (such as ILC, FCC). Compared to the CDR, several changes have been introduced to improve performance and incorporate recent hardware updates. While many studies have been redone, some are still pending. Given the limited human resources, the current list of channels may be too extensive for a few months of work.

It would be beneficial to clarify whether the focus is on optimizing detector performance or on exploring the physics reach. Given the time constraints, the primary goal should be to demonstrate that the reference detector achieves sufficient performance for physics studies. To this end, consider reducing the list of complex channels (e.g., b-physics) and adding simpler, fundamental channels, such as $Z\to\mu\mu$, that are essential for evaluating detector performance. It's important to prioritize basic object performance (leptons, photons, jets) as a function of energy and polar angle for the Ref-TDR. Full analyses and physics reach studies can be focused on a narrower set of channels, covering essential physics areas like Higgs, Z, W, and top physics.

A clear strategy is also needed for measuring absolute luminosity, crucial for accurate cross-section calculations and with significant applications (e.g., neutrino counting at the Z pole). It's essential to determine if the absolute luminosity measurement will rely solely on Bhabha scattering, the role of the luminometer, and whether the measurement will be complemented by $e^+e^-\to\gamma\gamma$ events.

Another critical aspect is the use of resonant depolarization to measure the Z and W masses with high precision. These are key observables that need enhanced accuracy to fully leverage precision Higgs measurements (e.g., Higgs couplings).

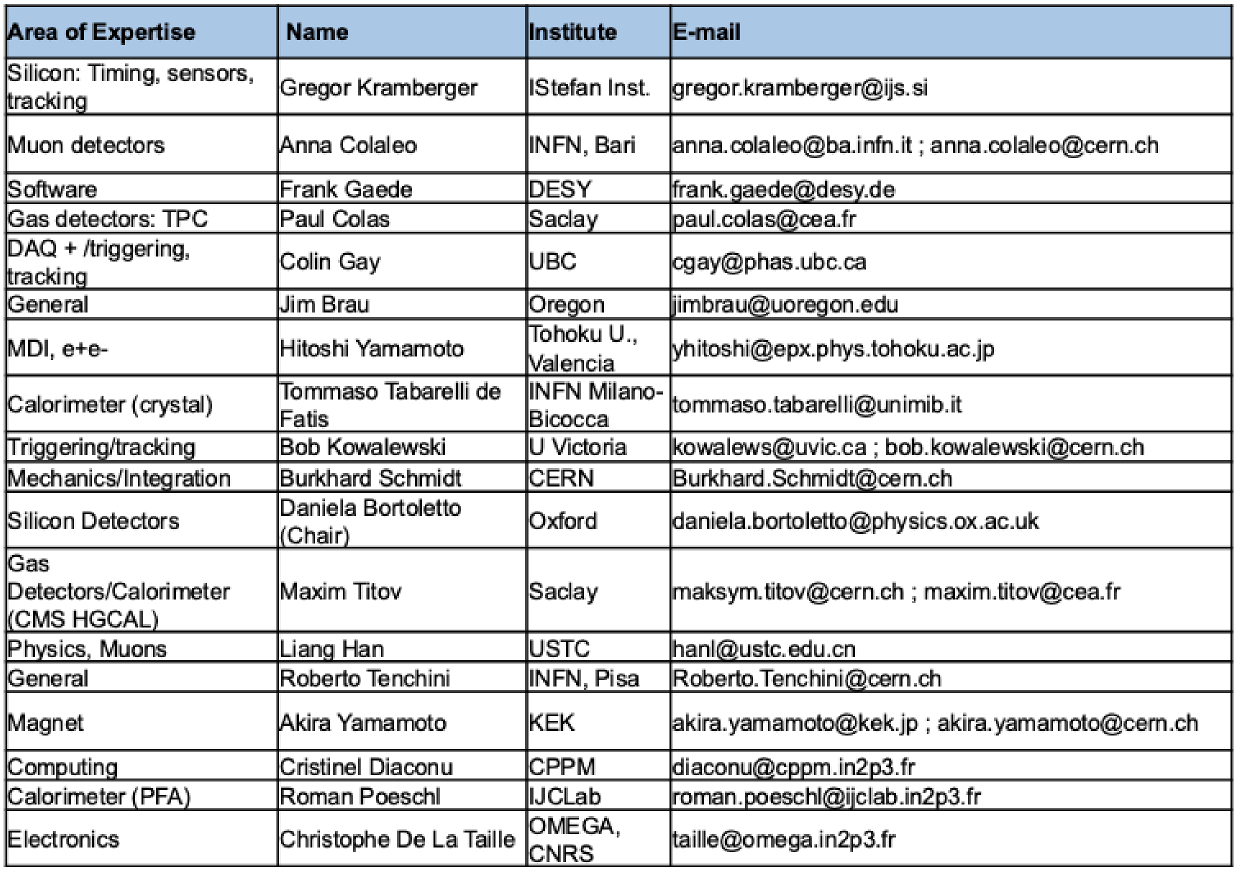
Regarding benchmark channels, a measurement of V_{cs} during the WW run may be more relevant than V_{cb}. Additionally, it would be helpful to clarify the chosen channel for measuring the electroweak mixing angle.

This refined approach will help focus resources effectively, ensuring the TDR delivers a comprehensive demonstration of detector performance in line with the project's timeline.

Recommendations:

1. Focus on a limited set of channels that will demonstrate the reference detector's performance adequacy for physics. Include channels with simpler topologies, such as $Z \rightarrow \mu\mu$, to provide foundational validation.
2. In the Ref-TDR, include results and figures showing detector performance metrics for fundamental objects like leptons, photons, and jets, plotted as a function of energy and polar angle.
3. Clearly outline the strategy for measuring absolute luminosity in the Ref-TDR, as this is essential for accurate cross-section measurements.
4. Include at least a brief description in the Ref-TDR regarding plans to use resonant depolarization for high-precision Z and W mass measurements.
5. (longer term) Outline the primary areas where detector configuration optimizations could be further explored beyond the initial Ref-TDR results, acknowledging the time constraints of the current study.
6. (longer term) Consider how performance study results could influence technology decisions, especially as they relate to detector component specifications and configurations.
7. Explain how calibration for each sub-detector will be achieved through physics processes, and document specific calibration methods in the Ref-TDR.
8. Ensure that the performance metrics for the crystal ECAL, specifically for boson mass resolution (see Page 20 of "Physics Benchmarks and Global Performance" presentation) and Jet Origin Identification (see Page 9), are simulated in a consistent way. Additionally, evaluate the impact of the crystal ECAL on PFA and jet flavor tagging capabilities to understand its potential contributions to the overall detector performance.

APPENDIX I



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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- **Kowalewski,** Tenchini, Gay
- Software - **Gaede,** Diaconu, Kowalewski

- Performance - **Tenchini**, Diaconu, Gay, Han