Feedback of IDRC Review Report

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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.
- Answer: The failure case already been studied in the design of the passive machine protection system with acc. 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.

- Answer: The secondaries generated by collimators has been studied yet and since all the collimators are far away from the IP, there will be no impact on detectors. The SR masks has been updated, and the effects has been studied. The heavy metal shielding outside of the cryo-module have been added. The photon dump is under design.

Comments

Machine Detector Interface

- 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.
- Answer: The investigation on the vibrations is on going, and our acc colleague will perform the study with those data.
- 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.
- Answer: We've added the detailed design in the report.

Recommendations

1. Optimize the collimators using simulations that account for secondary particle interactions.

Answer: The collimators has been updated with the secondaries considered.

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.

Answer: The SR masks has been updated and included in simulation. The SR originating from beam halo in quadrupoles has been studied together in the simulation.

3. Explore the feasibility of placing heavy metal masks near the interaction point (IP) to absorb particle showers effectively.

Answer: The heavy metal shielding has been added outside of the cryo-module. The BG level has been mitigated with such shielding.

Recommendations

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.

Answer: The updated design of the lumical has been updated, and the prototypes are on schedule in the EDR phase.

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.

Answer: We plan to have such a review in April/May. The review will cover all the MDI related topics from both accelerator and detector side. The preparation of the review is on going.

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.
- Work plan
  - expanding international collaboration (DRD3 …) and explore synergies with other projects, to enlarge our community

Recommendations

TRACKING

1. The current manpower dedicated to the design and R&D efforts should be expanded to ensure the successful completion of the project.
2. 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→ $\mu\mu$ decays.

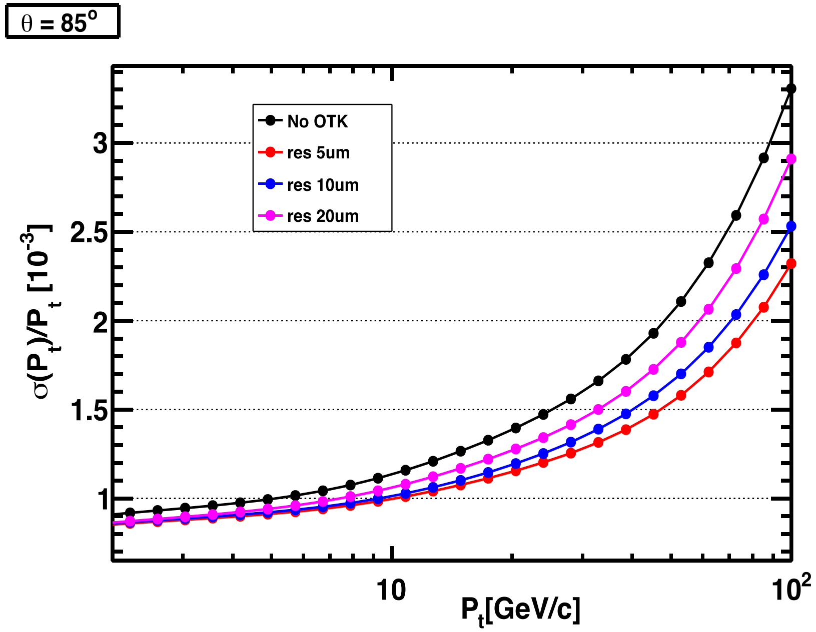
Responses-I

- 1. The current manpower dedicated to the design and R&D efforts should be expanded to ensure the successful completion of the project.

Responses-II

2.1 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:

- A: OTK‘s influence on overall momentum resolution is evaluated by fast simulation. The results show that the OTK plays an important role for the tracks with high transverse momentum (pt >20 GeV) when the spatial resolution along bending direction is at ~10 μm. Validation of this results with full simulation is ongoing.



Responses-III

- **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 expeced during installation.

A:

We thank the referees for this important comment. Alignment is indeed crucial for achieving ultimate track position resolution at the micron level. Alignment involves two key steps: the optical survey (mechanical assembly precision) and track-based mathematics alignment.

The assembly of both ITK and OTK follows a hierarchical structure, starting from small modules and building to larger ones. Based on our experience, the mechanical assembly (or optical survey) precision for small modules, such as sensors on ladders (staves or sectors), should be within tens of microns. For the large modules, such as ladders (staves or sectors) on the supporting frame, precision should be within hundreds of microns. While we have extensive experience with small module assembly. For large module assembly, we plan to develop detailed mounting procedures and alignment system to achieve the required precision.

For track-based alignment, we plan to use a composite global alignment procedure, which aligns all detector modules from different hierarchy levels simultaneously, considering all correlations (*Eur. Phys. J. C* **83**, 245 (2023)). Additionally, we will simulate alignment precision under various mechanical tolerance scenarios using this approach.

Dedicated studies on alignment for each sub-system and the alignment uncertainties, even rough estimation, are necessary.

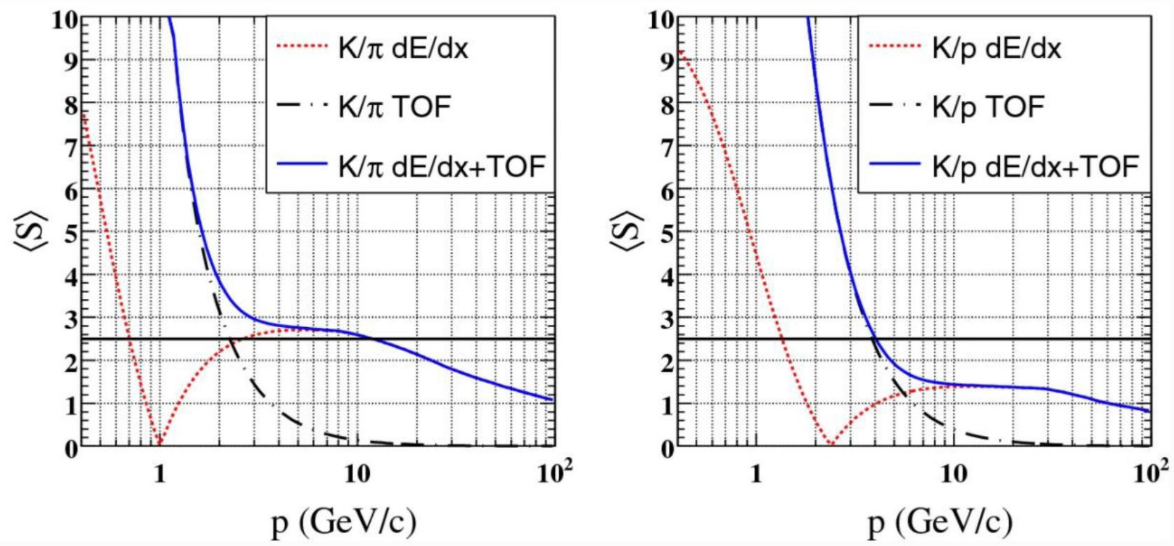
Implement alignment effects into simulation need to be scheduled …

Responses-IV

2.2 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.

We thank the referees for this important comment.

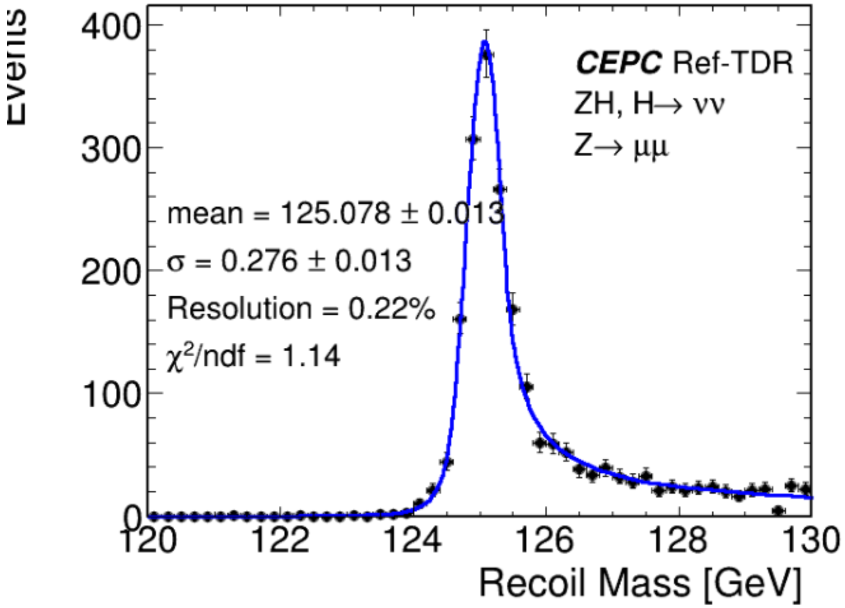
We provide Figure for the referees, illustrating a PID study for K/pi and K/proton separation using TPC alone, ToF alone, and a combination of both. As shown, ToF offers dominant performance for K/pi separation below 2.5 GeV/c and K/proton separation below 5.5 GeV/c…. (Contacted with TPC group, and this plot will be updated accordingly.)



Responses-V

2.3 Establish the visibility of the Higgs peak independent of the Higgs boson decay by reconstructing the recoiling Z boson in Z→ $\mu\mu$ decays.

The model independent analysis based on full simulation is ongoing. The preliminary results show that the mass resolution reaches the design goal : ~0.2% and it is consistent with fast simulation. Further checks & validations are needed.



Vertex Detector

Vertex finding 1

- 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.

Vertex finding 2

1. 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.
2. 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 pT 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.

Comment 1 on vertex

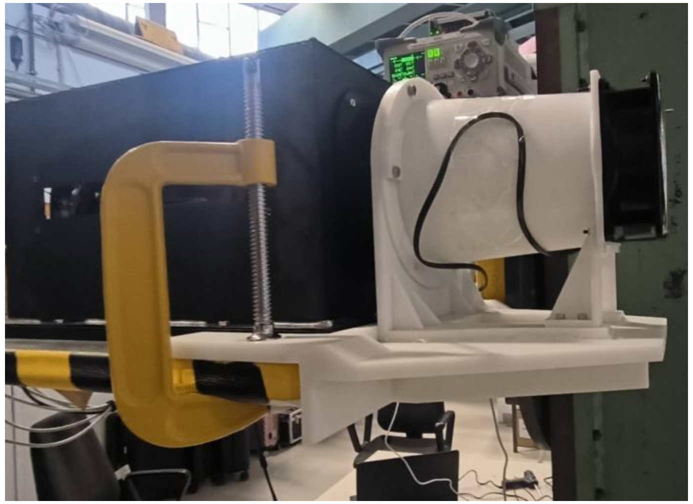
- The timeline of the CEPC project raises concerns that the process with the required features, such as modified doping profiles, may not be available when needed. Therefore, early communication with the vendor is essential, along with exploring potential developments with a secondary supplier. This proactive approach could also prove to be cost-effective in the long term.
    - Plan to work with TPSCo 65 nm in next few years to develop stitched MAPS
    - Exploring potential of domestic 65nm/55nm foundry as secondary supplier
    - We have early communication with both TowerJazz and domestic foundry

Comment 2 on vertex

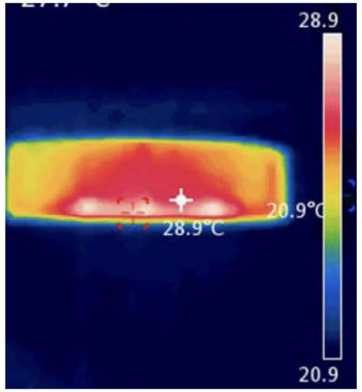
- Regarding the mechanical design, it is still in the early stages of development. A significant challenge remains in cooling the vertex detector, especially with airflows exceeding several meters per second, which poses technical difficulties.
- Work plan
  - Air cooling experiments performed in vertex prototype in DESY testbeam
  - Do more experiments with dummy wafer and thermal mockup system

R&D efforts: Air cooling in vertex prototype

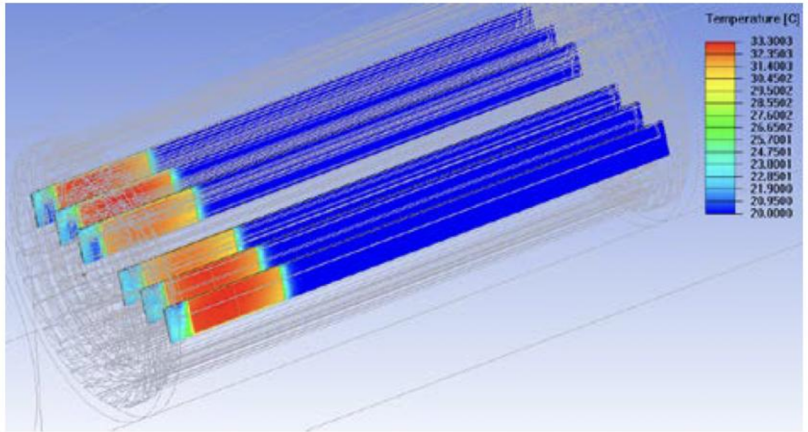
- Dedicated air cooling channel designed in prototype.
  - Measured Power Dissipation of Taichu chip: ~60 mW/cm^2 (17.5 MHz in testbeam)
  - Before (after) turning on the cooling, chip temperature 41 °C (25 °C)
    - In good agreement to our cooling simulation
    - No visible vibration effect in spatial resolution when turning on the fan



Chip temperature under cooling during beam test: Max 28.9 ℃



Prototype cooling simulation： Max 33.3 ℃



Recommendations 1 for vertex

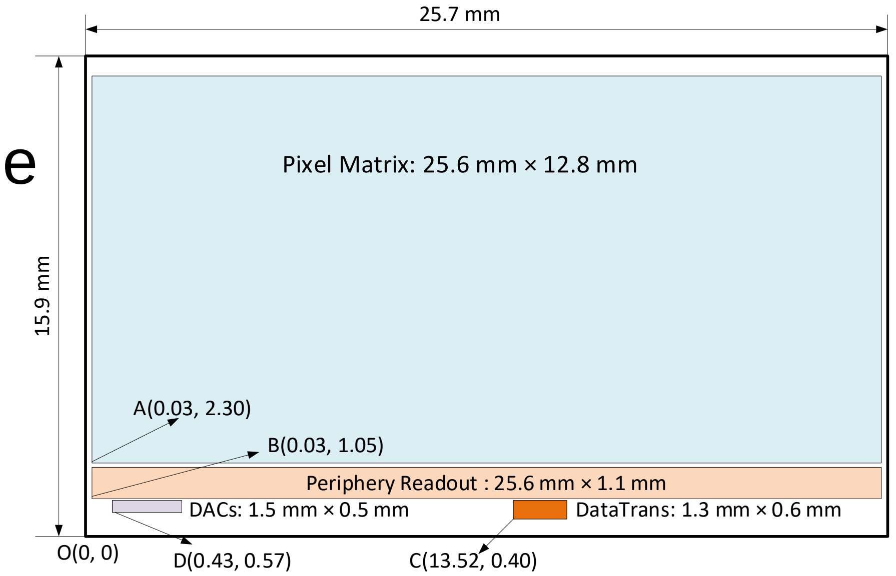
1. Thorough analysis and simulation of the background are essential, as they directly influence key aspects of detector design and operation, such as data rates and power consumption.

- Work plan: joint efforts with MDI and electronics teams
  - Have Explore carefully all kind of background for low-lumi Z operations
    - Including pair production, beam gas …
  - The impact of data rates and power consumption are being evaluated
  - Work with electronics team to refine power consumption estimation

backup

Chip design for ref- TDR and power consumption

- **Power consumption**
  - **Fast priority digital readout** for 43.3MHz at Z pole
  - 65/55nm CIS technology
  - Power consumption can reduced to ~40mW/cm^2
- **Air cooling feasibility study**
  - Baseline layout can be cooled down to ~20 ℃
    - Based on 3 m/s air speed, estimated by thermal simulation



	Matrix	**Periphery**	**DataTrans.**	**DACs**	**Total Power**	**Power density**
TaiChu3 180nm chip @ triggerless	304 mW	135 mW	206 mW	10 mW	655 mW	160 mW/cm^2
65nm for TDR @ 1 Gbps/chip (TDR LowLumi Z)	60 mW	80 mW	36 mW	10 mW	186 mW	~45 mW/cm^2

Timeline for all the FE ASICs - VTX

- 2025：
  - Taichu debugging and finalization
  - Stitching design on TJ180, based on Taichu’s previous design, for low cost
  - Bending chip electrical test based on Taichu3-most2, at single chip level.
- 2026：
  - Taichu-Stitching-180 chip test
  - TJ65 design kit finalization (expected)
  - Taichu4 prototype design on TJ65 for process evaluation (MPW or combined-engineering), at single chip level
- 2027：
  - Taichu-Stitching-180 mechanical prototype and test
  - TJ65 chip prototype test.
- 2028~2029：
  - TJ65-stitching based on previous experience of TJ180-stitching & TJ65 prototype
- Comment:
  - Stitching on TJ65 currently is not cost-effective and high risk, given that the design kit is not finalized. Two parallel design to verify the final scheme: Stitching on TJ180; prototype on TJ65

Inner Tracker (ITK)

Findings

ITK

- 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 bias voltages around 70 V for a greater depletion depth. 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

ITK

- There is currently no dedicated effort focused specifically on developing CMOS strip sensors for the Inner Tracker (ITK).

In our upcoming Ref-TDR, we delicate an entire Section to describe efforts for the development CMOS strip sensor. In addition, the tape-out for the first CMOS chip (CSC1) is scheduled on March 5.

- The 180 nm process may face limited availability in the coming years, presenting a potential risk.

We spoke with the CSMC foundry, and they preliminarily confirmed that 180 nm process will be maintained for a least the next 20 years. In parallel, we also have a plan to migrate to 65 nm or 28 nm, after the functional test of the 180 nm process.

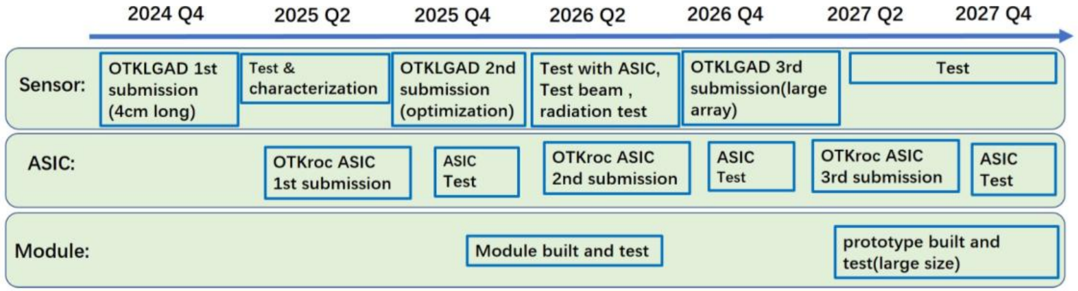
- Additionally, integrating readout circuitry within the periphery of strip CMOS sensors is an innovative approach, likely to bring unforeseen challenges.

There are no fundamental barriers to the development of readout circuits in the periphery of strip sensors, as the key components for the strip CMOS sensor has already been incorporated into CSC1 design (full wafer). After the CSC1 tape-out, we will have further insights into the details of the readout circuitry and validate the electric isolation design.

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.

We fully agree on the importance of having a detailed plan for the development of ASICs for both CMOS strips and AC-LGAD. To ensure that ASIC development aligns with sensor design, we have established parallel development tracks for both ASICs and sensors, as out



We are also leveraging existing R&D work to accelerate the process. Our ASIC development team has prior experience in developing high-performance time measurement ASICs, such as FPMROC. Many key design components from these previous projects can be incorporated into the current ASIC design, helping to shorten the development timeline.

Given the time-intensive nature of ASIC design, fabrication, and testing, we will conduct regular reviews and maintain close coordination between the various ASIC teams and sensor teams to mitigate potential risks, ensuring smooth progress and preventing delays that could impact the broader project timeline.

Outer Tracker(OTK)

Findings

OTK

- 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).

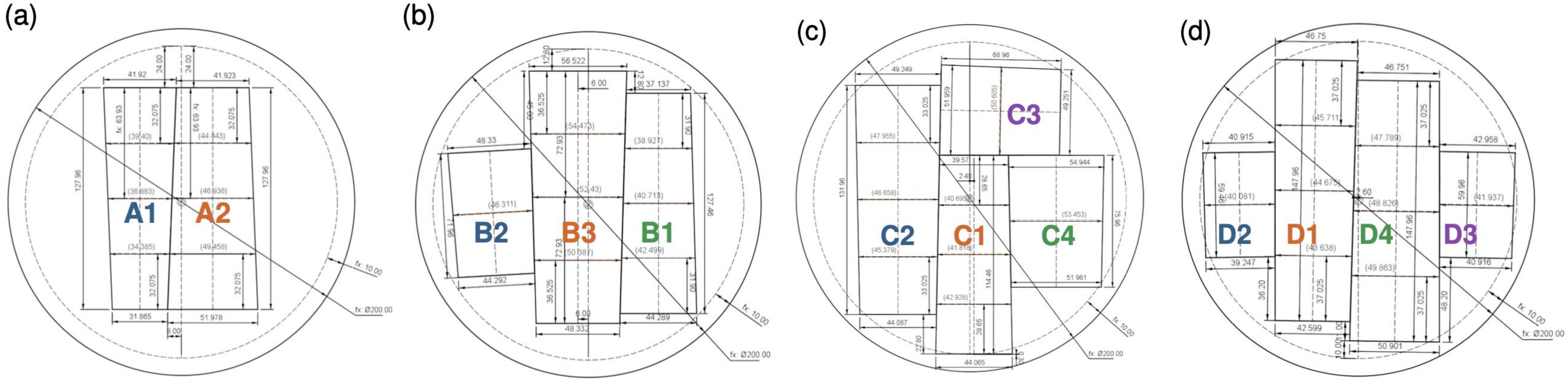
- Initial prototypes using small AC-LGAD sensors (~5 x 2 mm^2) have demonstrated promising results, achieving a time resolution of 37 ps and a position resolution of around 8 μm. While the ASIC for this application is yet to be designed, it is expected to closely resemble the current ASICs used for LGAD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

Comments

OTK

- The large variety of sensor designs required for the endcap adds complexity to the construction process.

The complexity of OTK endcap construction has been carefully considered in the design. With dimensions ranging from 406 mm to 1816 mm in radius, the OTK endcap is quite substantial. To simplify sensor production and assembly, the current design uses only four masks for the silicon wafers, with trapezoidal-shaped sensors. This approach helps reduce the complexity of sensor production and assembly, as well as the costs, while ensuring effective full detector coverage.



Comments

OTK

- Radiation damage may affect electron discharge through the n+ layer, potentially altering sensor performance over the detector’ s lifespan.

Radiation damage can affect electron discharge through the n+ layer, potentially altering sensor performance over the detector’s lifespan. However, this should not be a major concern. Our team has already delivered high-irradiation-tolerant LGAD sensors, optimized for n+ layer depth and carbon doping, which are capable of surviving in proton-proton collisions. The situation is even more favorable for e+e-colliders.

- 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.

We appreciate the referee's concern. Indeed, the relationship between time resolution and capacitance requires further study. To address this, we plan to tape out several prototypes in the coming years to explore this effect more thoroughly. Additionally, our upcoming sensor design includes options to reduce capacitance, such as increasing the thickness of the EPI layer or introducing an isolated structure.

Comments

OTK

- The operation of AC-LGADs may be susceptible to effects from high particle rates, which should be thoroughly understood, especially regarding the size of the LGADs.

In our Ref-TDR, we have a dedicated section discussing the estimated particle rates in the ITK and OTK. The results show that the current baseline design provides a sufficient safety margin to operate in various modes, including the High Luminosity Z regime ($L = 192 \times 10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$).

- 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.

We have included a detailed discussion of this in our Ref-TDR and will conduct further R&D to investigate it.

- The localized power dissipation at the ASIC level should be factored into the cooling design and overall performance assessment.

We appreciate referees' suggestion. Localized power dissipation at the ASIC has been considered in our cooling design, including the use of thermal vias in PCBs.

Recommendations

OTK

1. 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.

We appreciate the referees' suggestion. Considering the various factors mentioned, along with the evolution of detector technology, we have adjusted the sensor size to ~4 cm x 5 cm in the baseline design, while accommodating the 2 cm x 2 cm size as a backup for the OTK. Given the CEPC project timeline of over 5 years from construction, the project remains flexible enough to adjust its technical approach and has robust backup plans in place for the engineering phase.

1. Determine if redundancy is needed in the OTK barrel system.

Yes.

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 -1

- 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 (ωτ 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.

- Comments and work plan:
  - Full simulation framework of the detector developed and the performance simulation started
  - Ne gas can be optimized

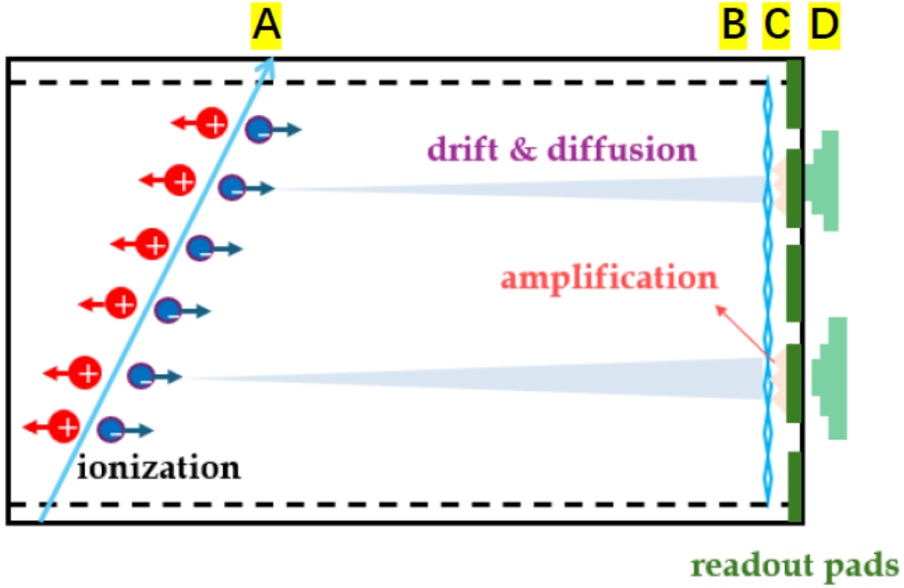
Full Simulation of Pixelated readout TPC

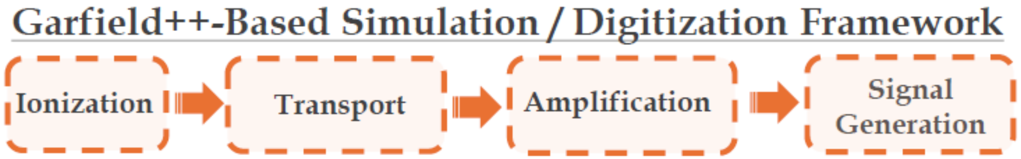
Guang Zhao's talk in 3rd DRD1 meeting

https://indico.cern.ch/event/1442324/contributions/6262871/attachments/2984481/5255933/DRD1_CM3_TPC_SIM_Guang.pdf

Simulation:

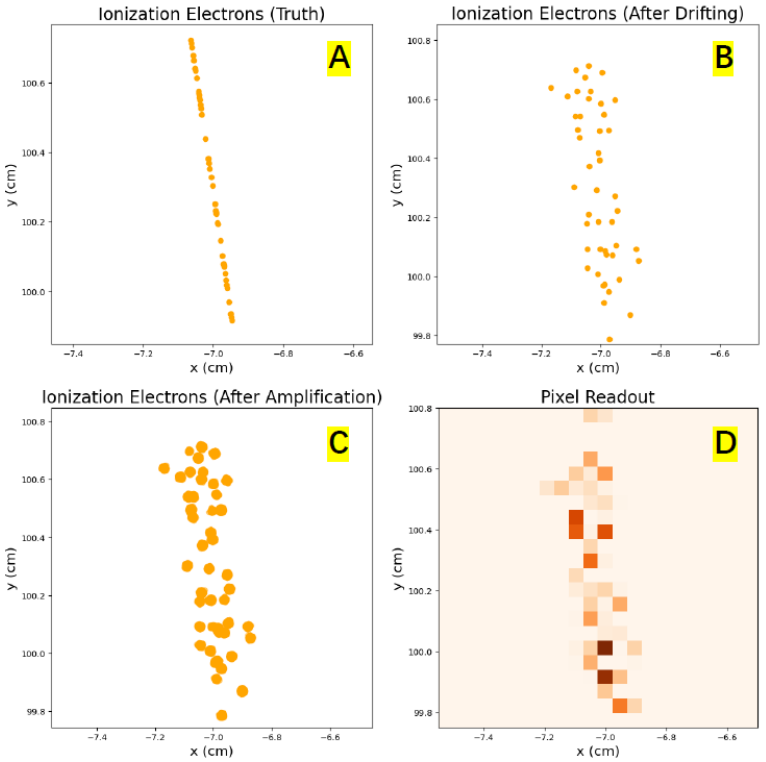
- With the full TPC geometry
- Ionization simulated with Garfield++
- Drift and diffusion from parameterized model based on Garfield++





Digitization (Refer to the TPC module and prototype):

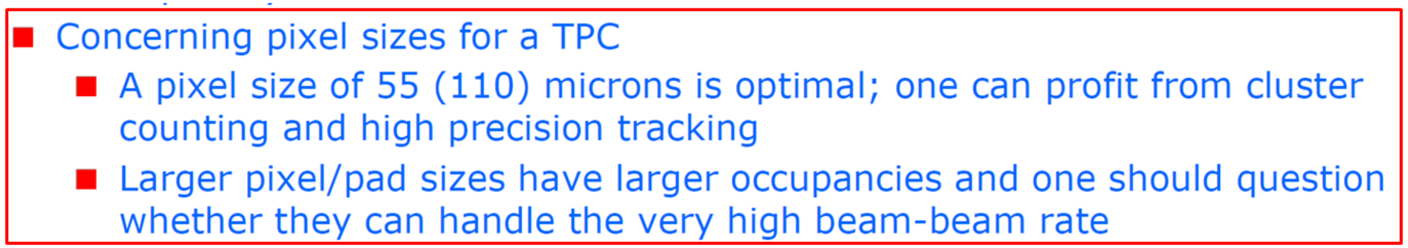
- Electronic noise: 100 e-
- Amplification:
    - Number of electrons: 2000
    - Profile of signal size : 100µm



Simulation of TPC detector under 3T/2T and T2K mixture gas

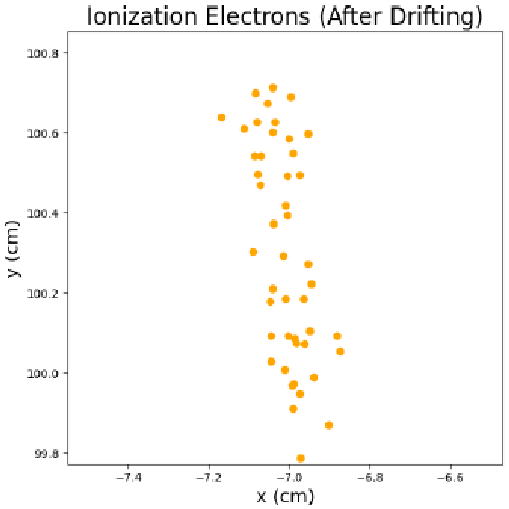
Full Simulation of Pixelated readout TPC – Readout size

- Simulation of the readouts in pixel sizes
  - Actually, TPX3/4 option existing and the power consumption will be optimized.
  - Optimization started in this ref-TDR at IHEP to meet **Higgs/Z at 3T**.

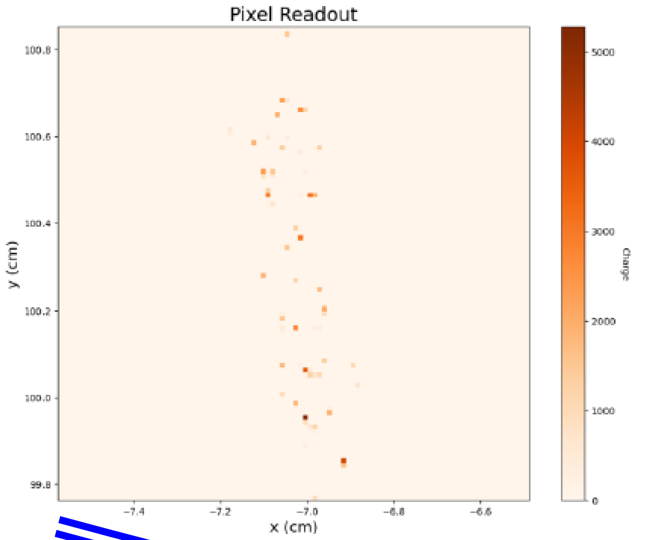


- Concerning pixel sizes for a TPC
  - A pixel size of 55 (110) microns is optimal; one can profit from cluster counting and high precision tracking
  - Larger pixel/pad sizes have larger occupancies and one should question whether they can handle the very high beam-beam rate

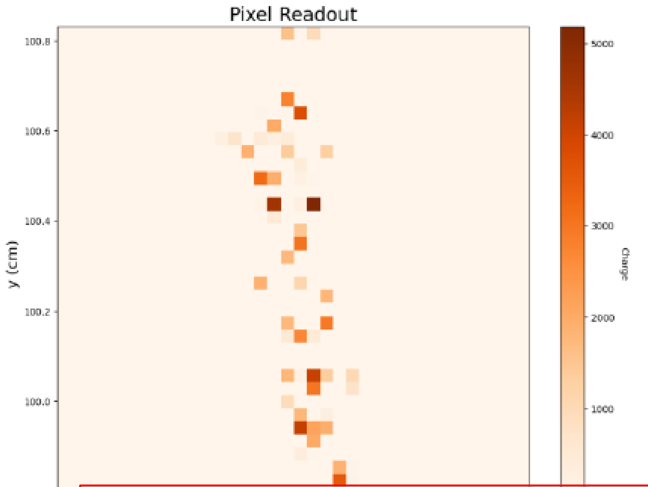
Peter's comment
in CEPCWS at Hangzhou.



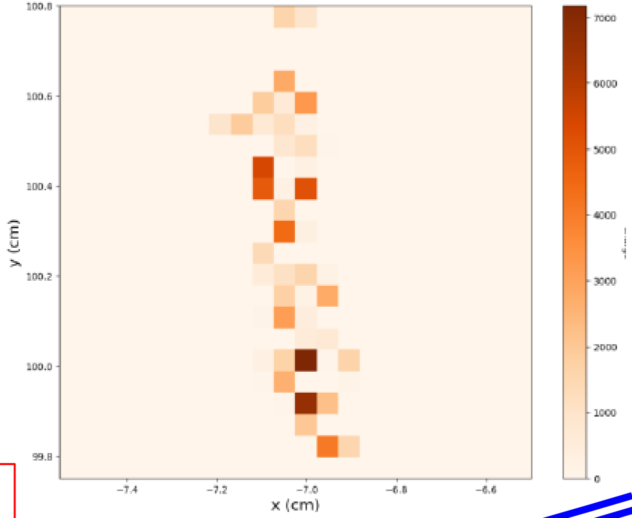
Pixel size = 110 um



Pixel size = 300 um



Pixel size = 500 um

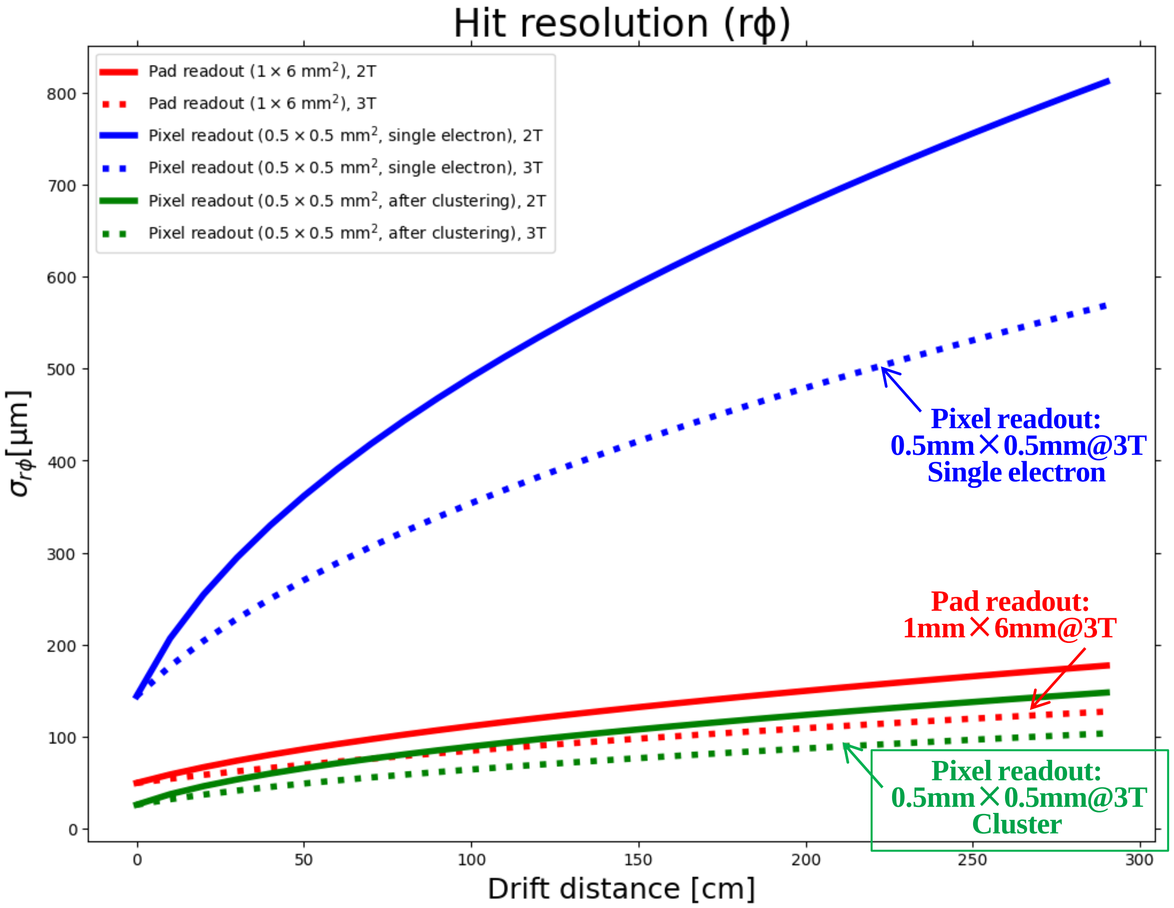


Optimization of readout size
Balancing of performance, cost power consumption, etc.

Full Simulation of Pixelated readout TPC – Spatial resolution

Estimation of the **spatial resolution using pixelated readout**.

- The granularity readout and the transverse diffusion are also taken into consideration..
- TPC can operates effectively at 3T B-field.
- Pixelated readout TPC can achieves superior spatial resolution at 3T compared to 2T.



Pad readout:

$$\sigma_{r\phi}^{\mathrm{pad}} = \sqrt{(\sigma_{r\phi0}^{\mathrm{pad}})^2 + \sigma_{\phi0}^2 \sin^2(\phi_{\mathrm{track}}) + L\frac{D_{r\phi}^2}{N_{\mathrm{eff}}}\sin(\theta_{\mathrm{track}})}$$

Pixel readout:

$$\sigma_{r\phi}^{\mathrm{pixel}} = \sqrt{(\sigma_{r\phi0}^{\mathrm{pixel}})^2 + LD_{r\phi}^2}$$

Comments -2

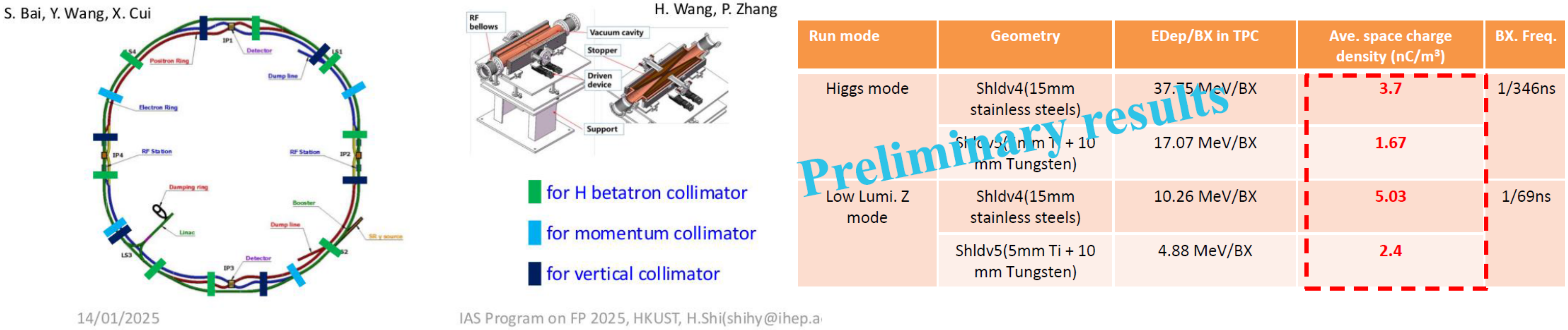
- Mechanical alignment must be precise, within a few tens of microns, to avoid systematic errors in sagitta measurements. Electric and magnetic fields must be precisely parallel to prevent ExB distortions, necessitating a highly uniform magnetic field (see magnet specifications). Minimizing space charge 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.

- Comments and work plan:
  - Collaboration with Mechanical and magnet group

Background at Higgs/ Low luminosity Z @3T

- Collimators were implemented to reduce Interact Region(IR) loss caused by Single-Beam
- With the implementation of collimators, single-beam backgrounds can be shielded effectively @ Low Lumi. Z run
  - ~20 sets of collimators were installed for passive machine protection and will also contribute to mitigate beam-backgrounds
  - After adding collimators, the beam loss rate can be reduced
  - The space charge density in TPC @ Low Lumi. Z is close to Higgs mode

Slides from Haoyu Shi



S. Bai, Y. Wang, X. Cui

H. Wang, P. Zhang

🟩 for H betatron collimator

🟦 for momentum collimator

■ for vertical collimator

Run mode	Geometry	EDep/BX in TPC	Ave. space charge density (nC/m³)	BX. Freq.
Higgs mode	Shldv4(15mm stainless steels)	37.75 MeV/BX	3.7	1/346ns
	Shldv5(5mm Ti + 10 mm Tungsten)	17.07 MeV/BX	1.67	
Low Lumi. Z mode	Shldv4(15mm stainless steels)	10.26 MeV/BX	5.03	1/69ns
	Shldv5(5mm Ti + 10 mm Tungsten)	4.88 MeV/BX	2.4	

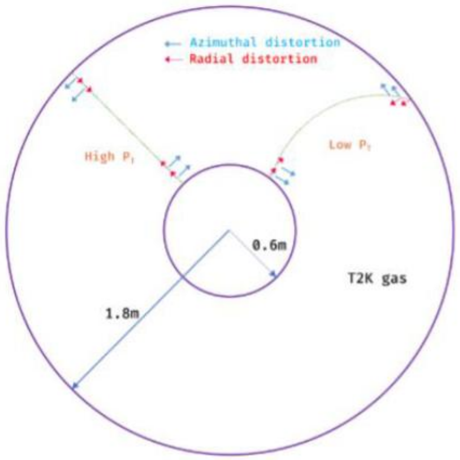
Preliminary results

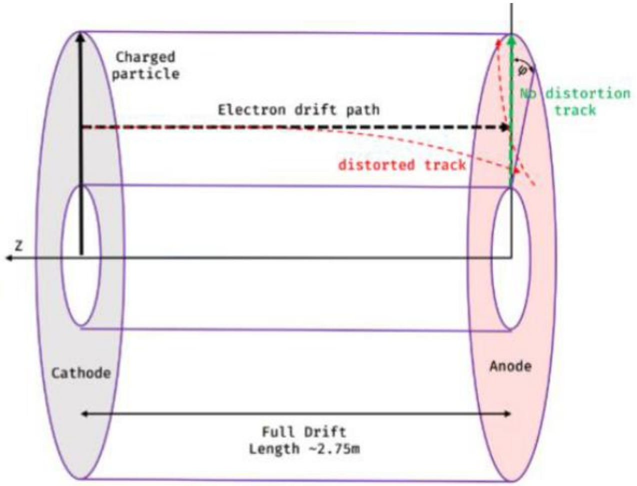
14/01/2025

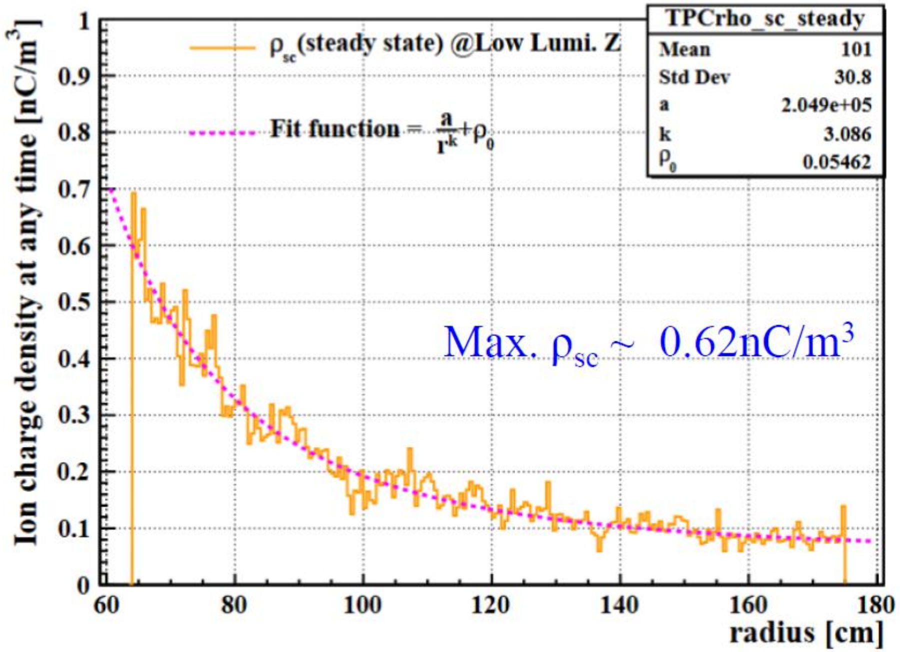
IAS Program on FP 2025, HKUST, H.Shi(shihy@ihep.a

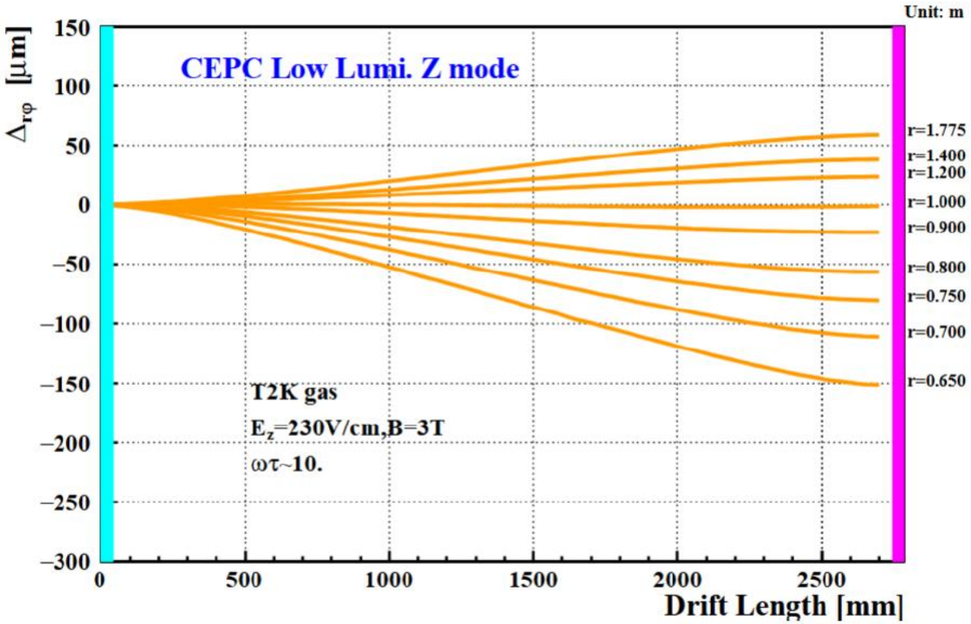
Distortion w.o. the low energy Photons at Higgs/ Low luminosity Z @3T

- The space charge density is only 0.62 nC/m^3 @Low Lumi. Z mode if we can shield all low energy photons(<10MeV) → **Ideal Situation**
- The max. r-phi distortion is about 150 um under 2.75m drift length.







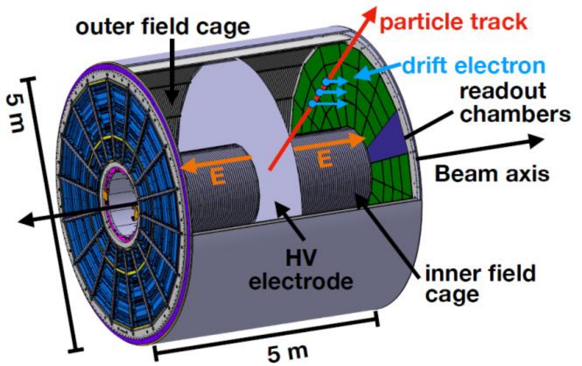


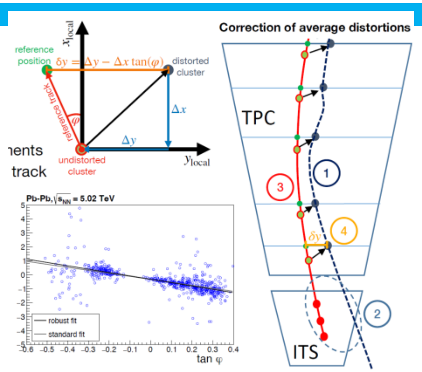
Comments -3

- 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.

- ■ Comments and work plan:
  - To optimize at low luminosity Z peak. (0.5× or 0.1×) ！ 10^{-35}
  - Double misaligned meshes (NIKHEF)
  - graphene filter(Shandong University)

Validation of effective trajectory distortion correction





Drift-field distortions in the ALICE TPC in LHC Run 3

Matthias Kleiner
Goethe-Universität Frankfurt
LCTPC Collaboration Meeting
January 29-31, 2025

OETHE
NIVERSITÄT
ANKFURT AM MAIN

Data driven approach to extract corrections

ALICI

Correction of average distortions

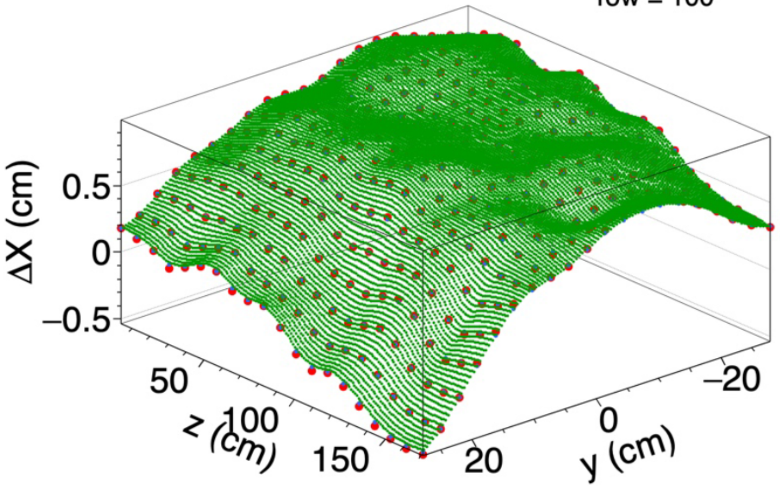
- Already performed during LHC Run 2

Procedure

1. Reconstruction of distorted TPC track
    - Tracking with relaxed tolerances
2. Track matching with ITS (and TRD-TOF) track segments
3. Residuals between TPC clusters and reference ITS track
    - Measurement of $\delta y, \delta z$
    - Storage in 3D map
4. Collect data for full TPC volume $\left(\mathcal{O}(\mathrm{s})\right)$
    - $\delta y, \delta z \rightarrow \Delta x, \Delta y, \Delta z$
5. Smooth parametrisation of extracted corrections with 2D splines

- 2D spline in y-z-plane for each pad row

Example of 2D spline for one pad row

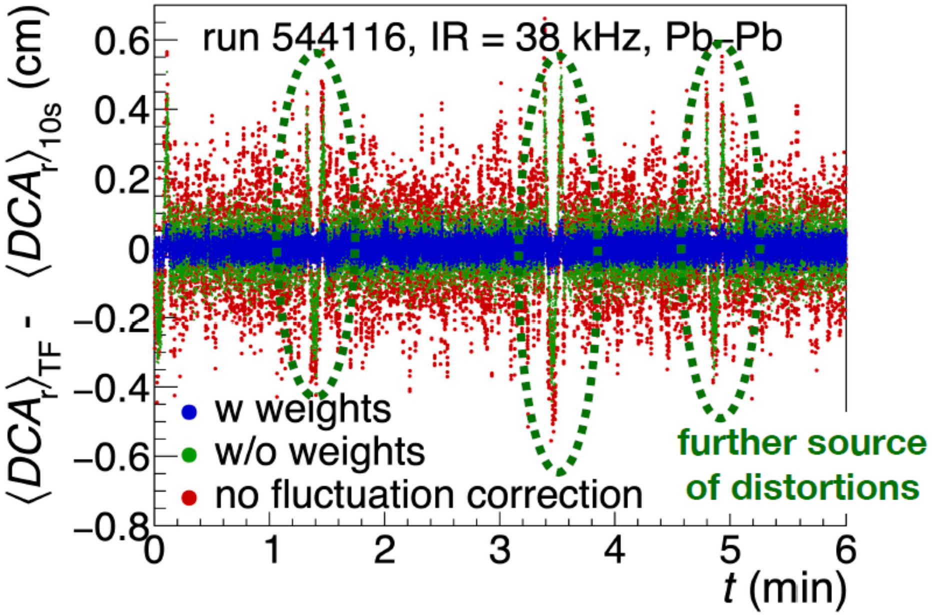


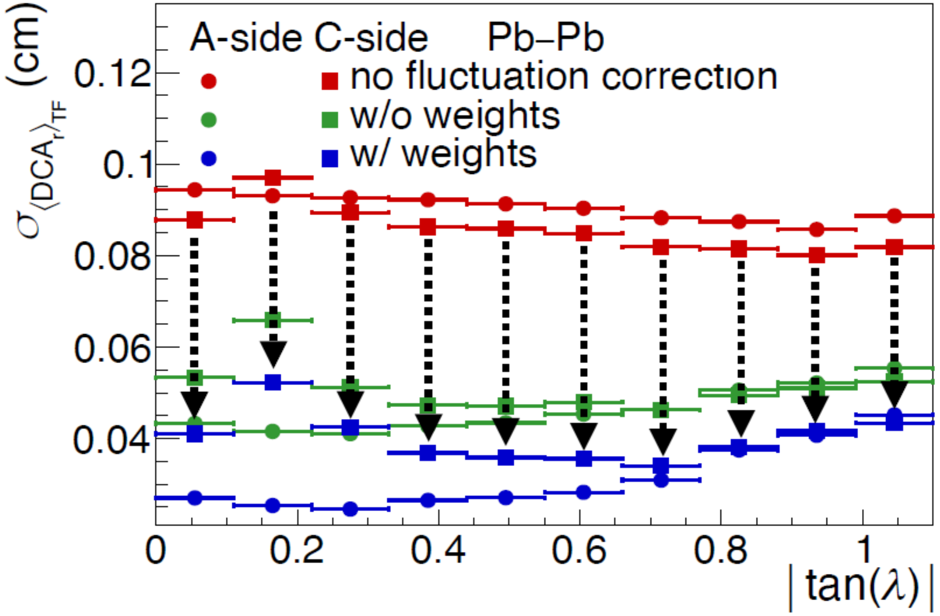
Validation of effective trajectory distortion correction

Space-charge correction precision

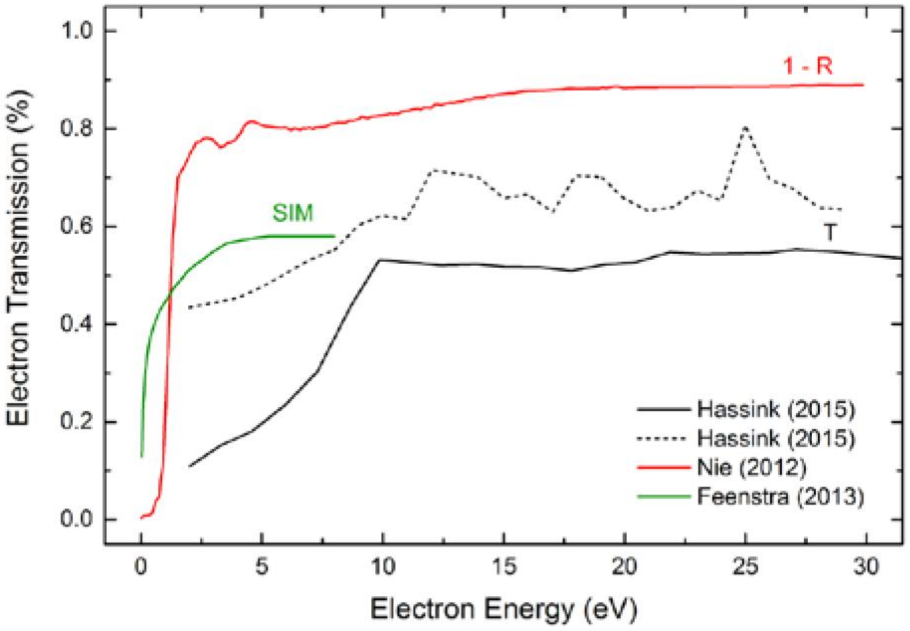
Schätzung für die Verzerrungskorrektur

- $\sigma_{\langle \mathrm{DCA_r} \rangle_{\mathrm{TF}}}$: Width of the DCAs a measure for the precision of the correction procedure
- Up to 3x smaller fluctuations of the DCAs

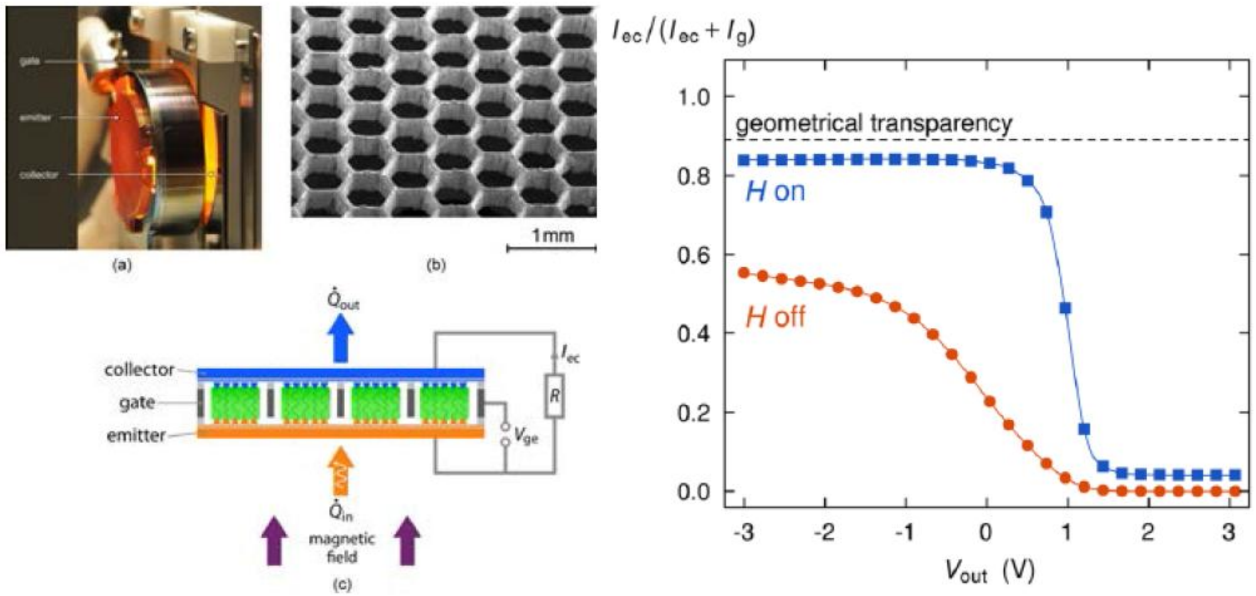




Ions suppression using Graphene filter



Transmission rates of electrons of different energies in graphene



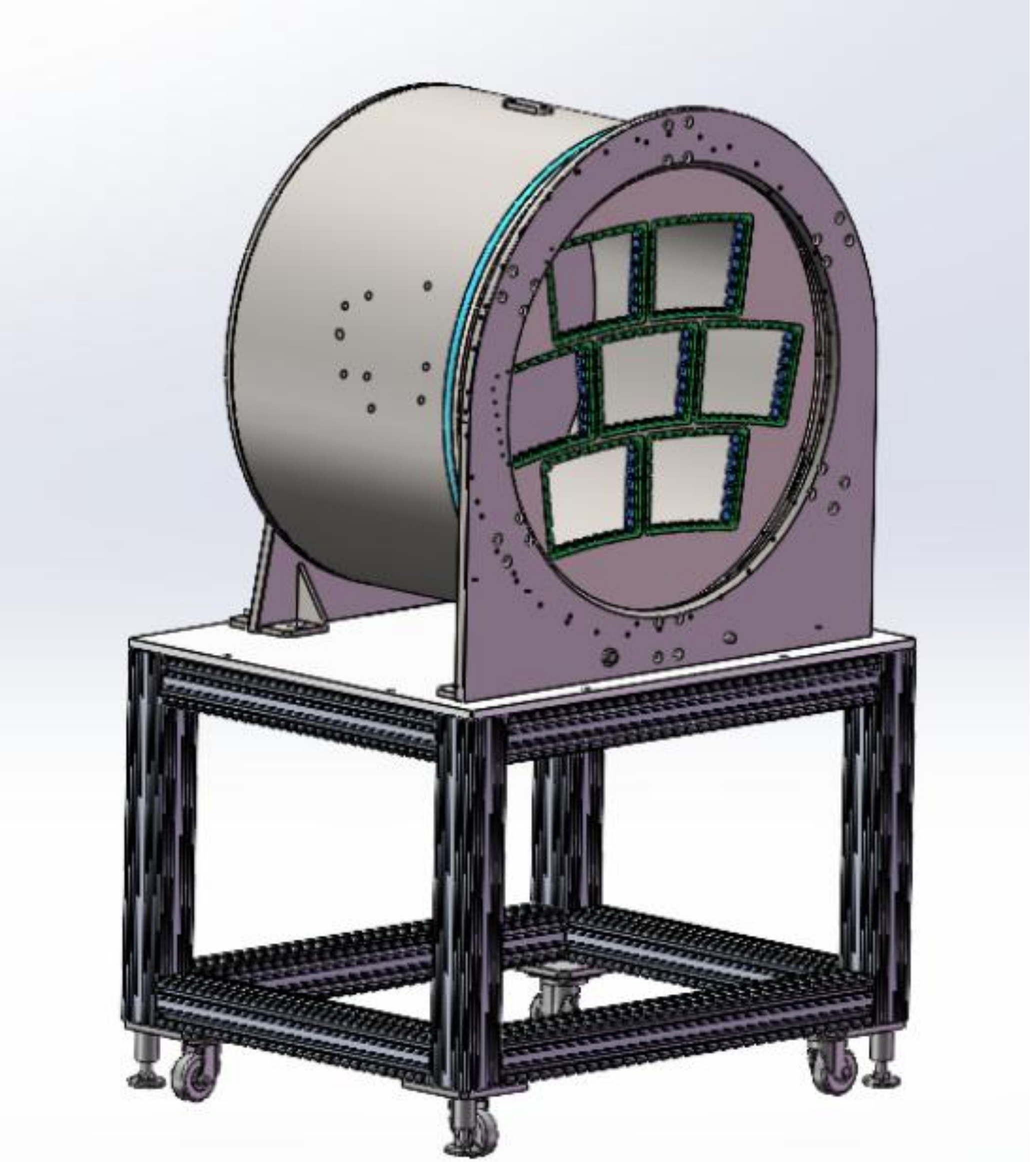
Transmittance results in graphene irradiated by electron spectroscopy

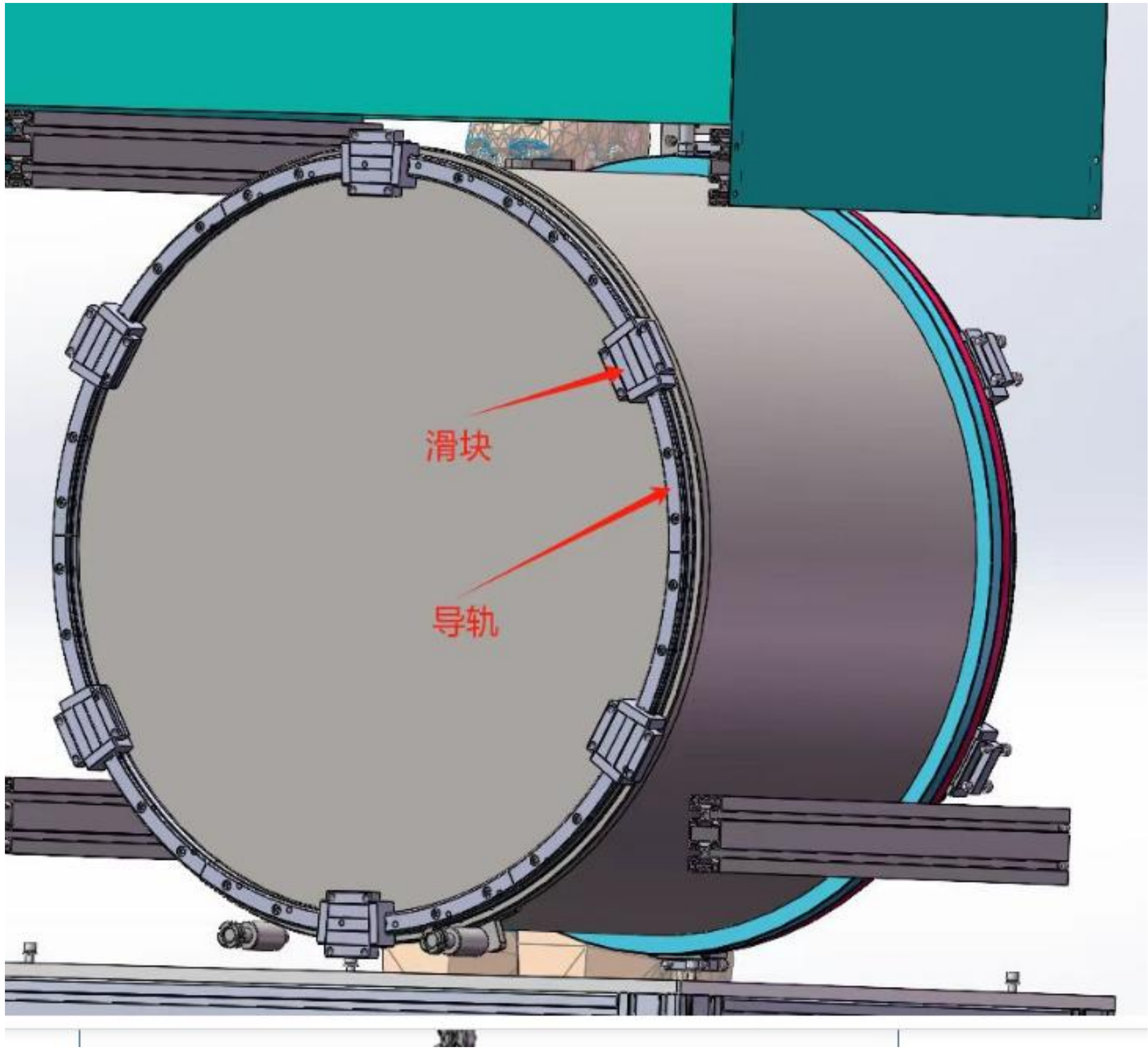
Comments -4

- 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.

- Comments and work plan:
  - Prototyping of chip + mesh + protection
  - Discussion with Tsinghua, the protection resistive layer can be coated with ASIC chips.

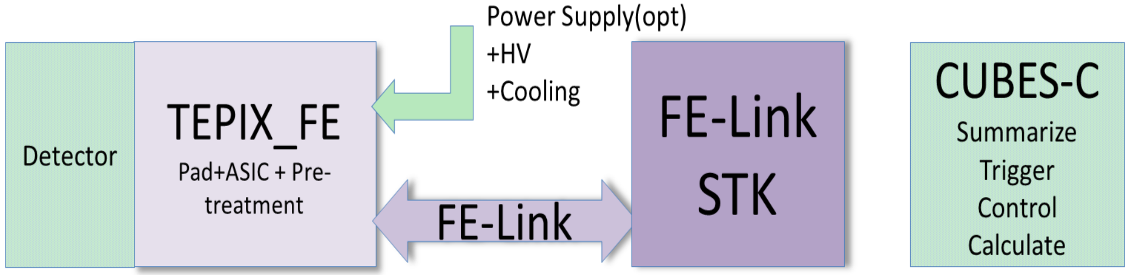
Prototype of TPC





Validation and commissioning of TPC prototype

- **R&D on Pixelated TPC readout for CEPC TDR.**
  - ASIC chip developed and **2nd prototype wafer has been done** and tested.
  - The TOA and TOT can be selected as the initiation function in the ASIC chip
- **Beam test of the pixelated readout TPC prototype in preparation. (May , 2025 at DESY)**



Detector

TEPIX_FE

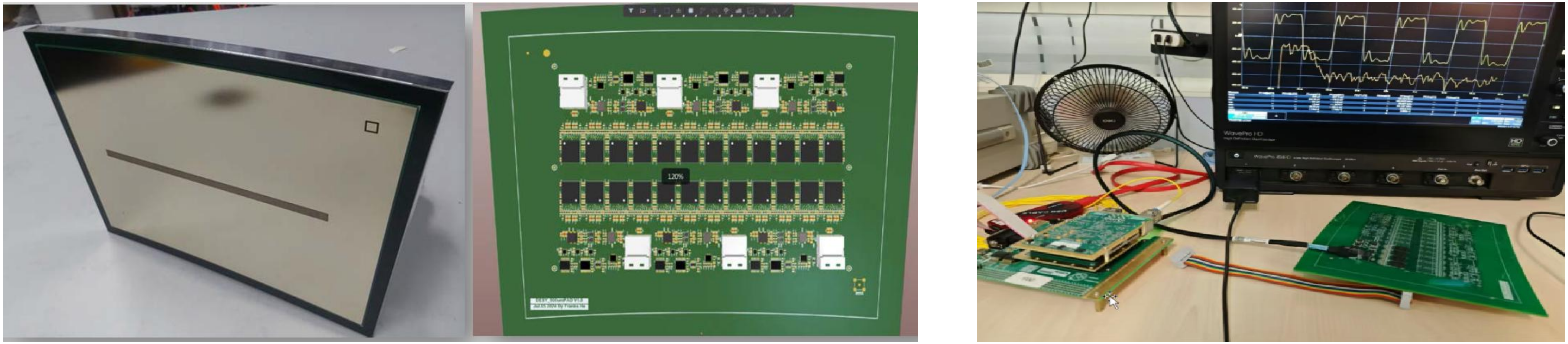
Pad+ASIC + Pre-treatment

Power Supply(opt)
+HV
+Cooling

FE-Link

FE-Link
STK

CUBES-C
Summarize
Trigger
Control
Calculate



Photos TPC modules assembled for the beam test

Recommendations

TPC

√

1. 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.

√

2. **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.

√

3. **Prototyping** will be needed to evaluate the pixel chip’s tolerance to sparks and to test protective measures.

CALORIMETRY

Findings

CALORIMETRY

- 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.

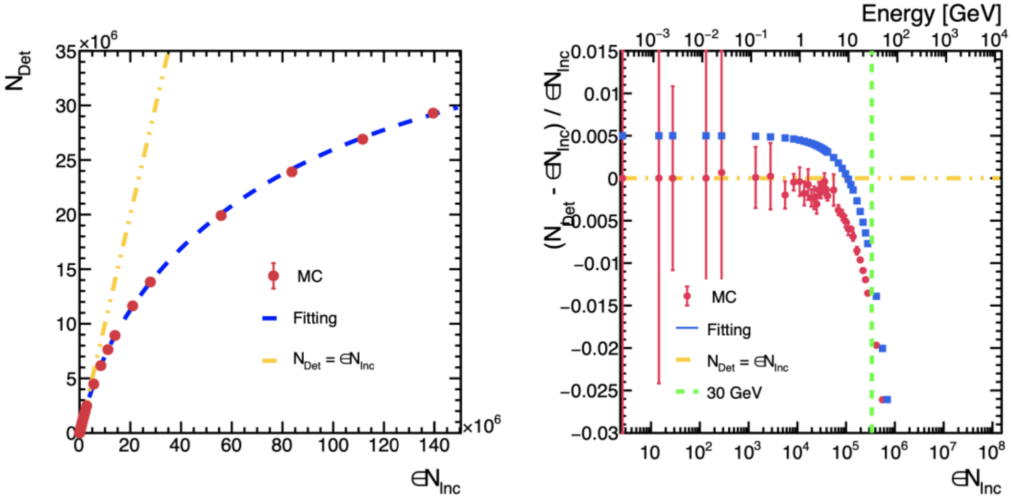
Comments

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;
  - Extensive results from simulation and measurements be summarized to better explain this spec.
- SiPM dynamic range and linearity needs specification;
  - Next page
- The noise levels of the ECal including SiPMs and readout electronics;
  - Noises from SiPM and electronics are expected to be significantly lower than trigger threshold.
- Anticipated level of crystal degradation with time, and its impact on physics performance;
  - Crystal majorly degrades with TID. Detailed TID input will be required to be provided by the MDI team. Relation TID and crystal transparency (based on measurements) can be modelled in simulation.
- Optimization of ECal design granularity based on simulated physics performance;
  - Addressed in previous pages.
- Homogeneity of MIP detection efficiency.
  - Beam test results will be summarized.

SiPM and electronics: linearity specification

- SiPM response linearity to BGO scintillation light
  - SiPM pulse simulation done: 6um-SiPM non-linearity <1% at 30GeV
- Front-end electronics linearity
  - Already modelled in the ECAL digitisation
    - Target: ASIC non-linearity effect should be smaller than SiPM non-linearity
  - HGCROC: a state-of-art chip for CMS HGCAL, considered as a first reference



Including BGO scintillation and pixel recovery effects

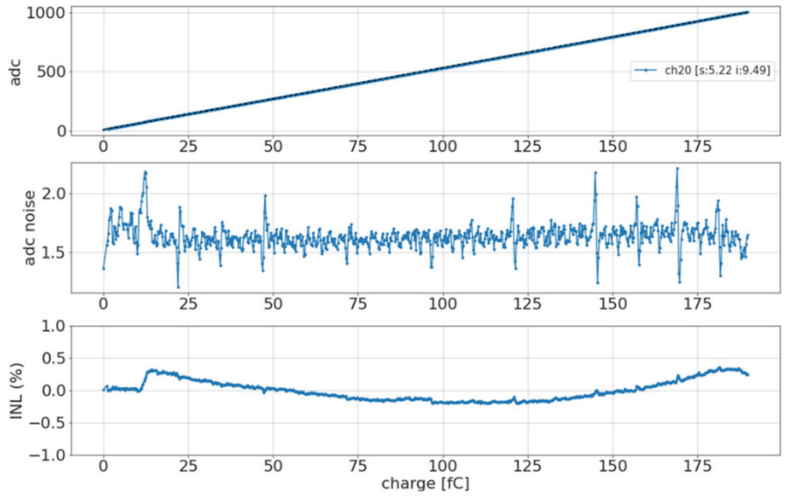


Figure 2. ADC characterisation. Top: charge conversion in ADC units versus injected charge. Middle: noise in ADC units for each charge. Bottom: integral non linearity (INL).

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 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 is the electron ECal resolution impacted when the bending of the electron matches the 12 degree incline angle?

Feedback to Recommendations

ECAL

- 1. Prototyping and simulation to demonstrate feasibility and readiness
  - For the crystal ECAL, a physics prototype has been successfully developed and tested with beam particles. Key EM performance (linearity and resolution) has been demonstrated to meet requirements in the energy range of 1-10 GeV. Further considerations will be focused on the higher energy range and also developments of a full-scale technological prototype.
  - While fully exploiting beam test data, beam momentum spreads should be well controlled to avoid significant impacts to EM resolution (in collaboration with CERN beamline experts).
  - Knowledge and results from beam tests in 2023/24 have been implemented in digitisation for crystal ECAL simulation. Simulation studies are ongoing to further evaluate EM performance including beam-induced backgrounds and noises from SiPM.

Feedback to Recommendations

2. ECAL granularity optimisation: balance of physics performance and cost/power

- Dedicated optimisation studies have been done for crystal granularity of 10 mm and 15 mm to evaluate the physics performance including jets and π^0 with PFA
- Jet performance of 15 mm crystals can also meet BMR<4%
- π^0 performance not significantly degrade in lower energy region
- γ/π^0 discrimination technique shows promising potentials to improve π^0 performance in higher energy region
- Details in the talk presented in CEPC Day in Jan, 2025
- This part is also related the Recommendation 3.

Feedback to Recommendations

ECAL

3. π^0 performance and electrons performance

- π^0 performance has been presented previously
- Electron performance in ECAL when theelectrons bending track hits module gap
  - This is mostly related to the electron PID.
  - In PFA, electron beam energy is determined in tracker rather than in ECAL. Tracking detectors are expected to achieve excellent PID performance for electrons, e.g. based on dN/dX technique.
  - Potential impact could be in the tracker-calorimeter matching. In case electron clusters loss significant energy in module gaps, the matching efficiency can be degraded. This is expected to be at a low level. But simulation studies will be performed in order to quantify this effect.

To address technical challenges (1)

ECAL

- *“Developing and perfecting the Particle-flow algorithms including the effective pattern recognition and minimization of ambiguity issue”*
- Work Plan: joint efforts with software team
  - This suggestion is related to further optimisations of the particle-flow algorithm CyberPFA.
  - The work plan include the performance evaluation with the full detector geometry (including both barrel and endcaps) and also the tracking performance, especially its matching with calorimeter clusters.
  - Besides, the calorimeter calibration for the jet energy scale needs in-depth studies, to ensure correct reconstruction of the Z and H boson masses in a consistent way.

To address technical challenges (2)

ECAL

- *"Dealing technical issues (ASICs, hermiticity, minimized power, mass production) with the very large number of channels in the very finely grained concept."*
- Work plan: joint efforts with electronics, software, mechanics teams
  - This is related to the general detector design for ECAL, optimisation and validation, including mechanics, cooling, embedded electronics and their integration.
  - ASIC development requires joint efforts of CEPC electronics team, while keeping an eye on DRD6/7 collaborations on new calorimetry-specific ASIC developments.
  - Modularity is a major prerequisite to demonstrate mass production capability. We plan to further optimize and validate modular designs for barrel and endcaps, and would also need to propose protocols on Quality Assurance and Quality Control (QA/QC) for key components, including crystals, SiPMs, ASICs, mechanics, cooling, etc.
  - Further studies on integration of modules and cooling (in barrel and endcaps) is planned.

To address technical challenges (3)

- *"Successfully overcoming beam-induced backgrounds and radiation damage."*
- Work plan: joint efforts with software and MDI teams
  - This is related to simulation studies of beam-induced backgrounds and modelling of radiation damages to crystals and SiPMs.
  - Key information is needed from the MDI team: mappings of **TID (Total Ionisation Dose)** and **NIEL (Non-Ionisation Energy Loss**) in ECAL (esp. in ECAL endcaps), which is a crucial input for study radiation damages to crystals and SiPMs
  - Based on ongoing developments of modelling (including TID vs crystal transparency, NIEL vs SiPM noises), we plan to quantify the impacts of radiation damage to the EM performance and also to the cooling system design (e.g. SiPM operational temperature)
  - We also plan to further study extra hits from beam-induced backgrounds and evaluate their impacts to EM performance by mixing calorimetric signals and backgrounds. This would also be related to the optimization of ECAL time window for signal readout.

To address technical challenges (4)

ECAL

- *"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."*
- Work plan: joint efforts with software and electronics teams
  - SiPM noise, linearity, readout threshold and crystal uniformity have been extensively studied in the lab and in simulation. We would need to prepare a comprehensive summary of these results and thus define specifications, which would be also an input to the SiPM-readout chip design.
  - Crystal granularity: longer crystal bars (60cm) and coarser transverse granularity (15x15mm) were already tested in beams. Performance studies with granularity of 15mm were done.
  - Calibration needs: we plan to study calibration precision to meet the specifications.

To address technical challenges (5)

ECAL

- *“Developing and optimizing the in-situ calibration system.”*
- Work plan: joint efforts with electronics and software teams
  - In-situ calibration system in general would be indispensable to the success of ECAL that can finally achieve optimal EM performance
  - Bhabha and di-muon events at CEPC would be ideal for in-situ ECAL calibration. We would need to estimate typical numbers of events and running times that are required to achieve the calibration precision
  - We are evaluating the impacts to EM performance from beam-induced backgrounds that could be mixed in the events in the pile-up way. Dedicated calibration scheme to mitigate BIB will be proposed.

Findings

HCAL

- 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.
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- 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 **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.

- **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;**

--> The GS collaboration Group has already produced the two types of the small size sample with performance:

① Size=5*5*5 mm^3 ;Density=6.0 g/cm^3; LY=985 ph/MeV; Decay=16ns (8%), 105ns;

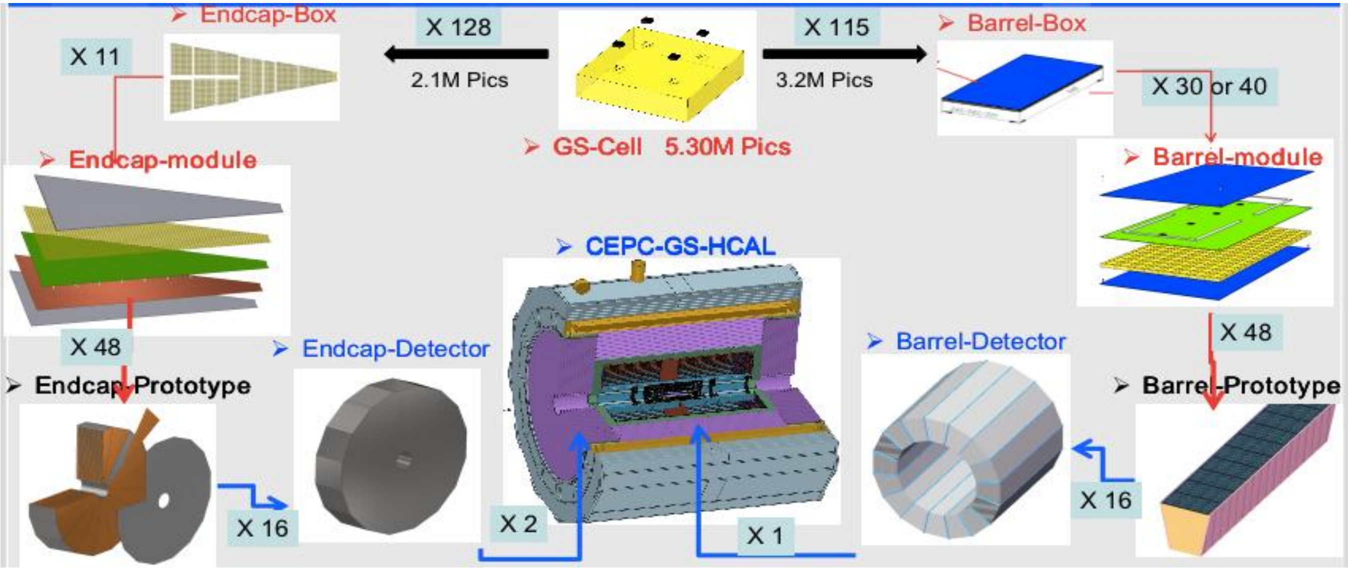
② Size=5*5*5 mm^3 ;Density=6.0 g/cm^3; LY=2455 ph/MeV; Decay=1456ns;

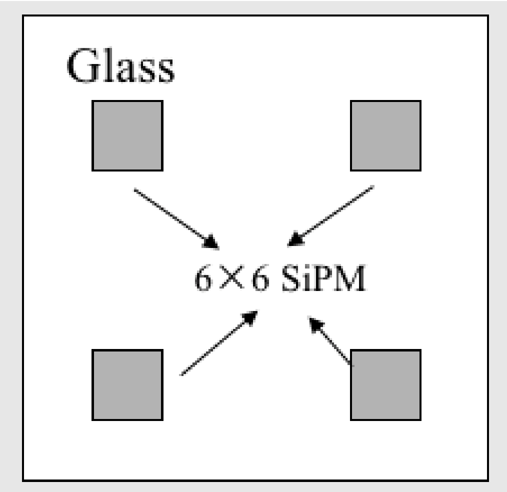
--> The GS collaboration Group has already produced the large size samples for the prototype of HCAL:

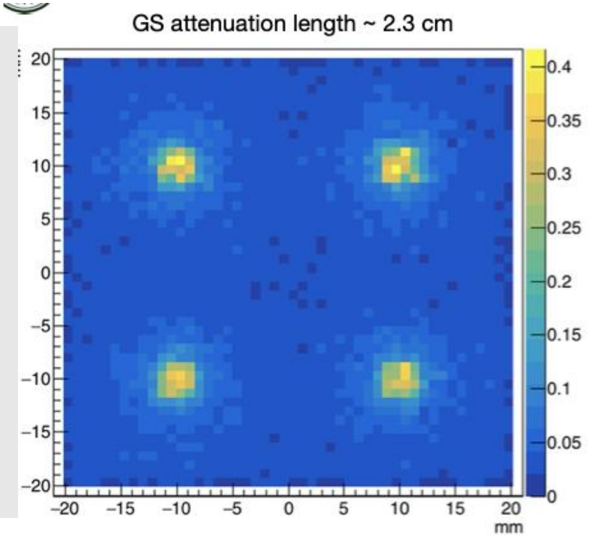
Size=40*40*10 mm^3 ;Density=6.0 g/cm^3; LY=1025 ph/MeV; Decay=81ns (7%), 520 ns;

- **Optimization of other aspects including GS-SiPM coupling, mechanics, cooling, and electronics;**

--> these suggestion have already considered for the optimization work, especially the coupling design. For the short attenuation length of GS is only 2.3cm, so there are four small SiPMs coupling one GS for better photo detection.





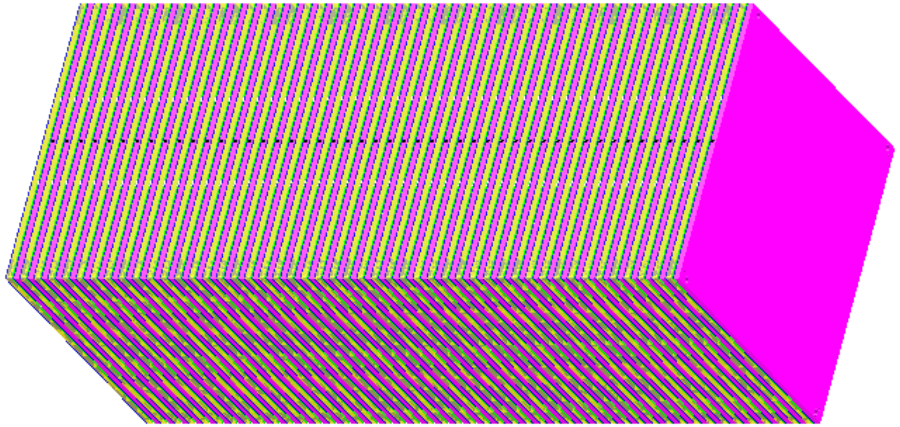


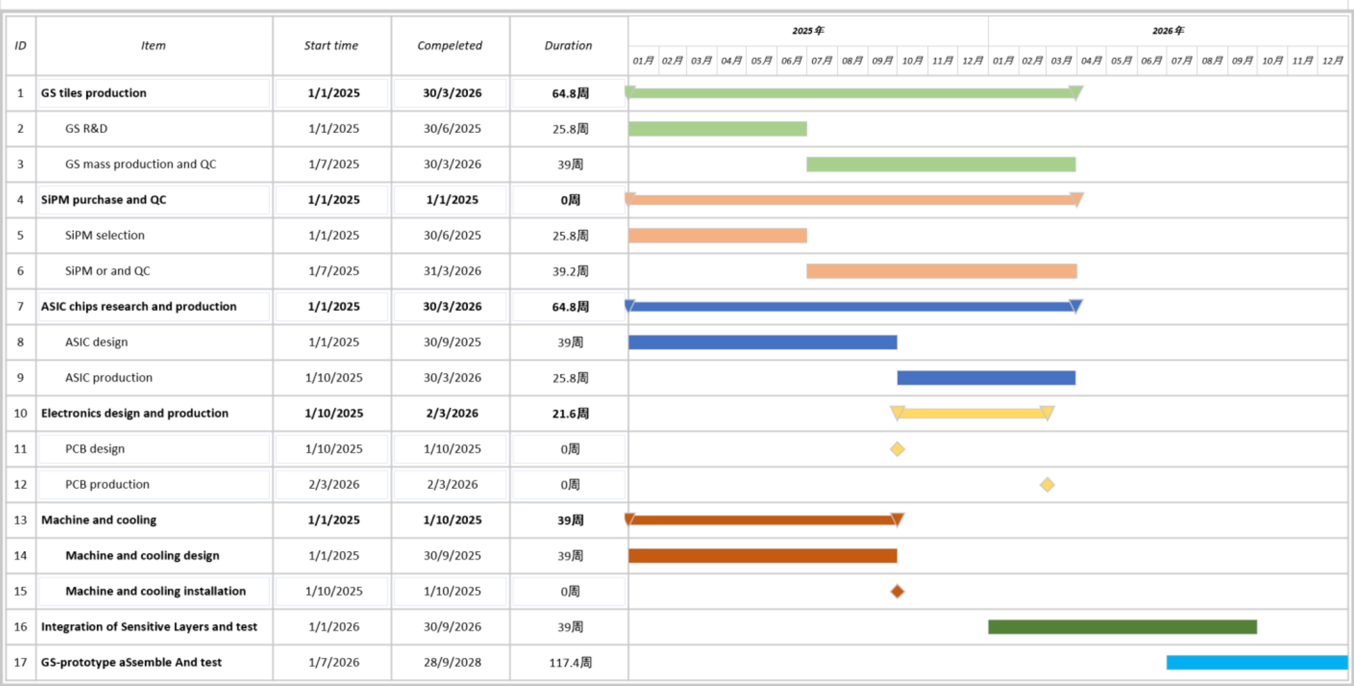
- **Preparation and beam testing of full-size HCal prototype.**

--> There is the plan to produce the GS-HCAL prototype with 48 layers and 15pics X 15 pics cell size.

--> The Plan of the Prototype of GS-HCAL in the next two years (2025-2026).

Prototype design





ID	*Item*	*Start time*	*Compeleted*	*Duration*
1	**GS tiles production**	**1/1/2025**	**30/3/2026**	**64.8周**
2	GS R&D	1/1/2025	30/6/2025	25.8周
3	GS mass production and QC	1/7/2025	30/3/2026	39周
4	**SiPM purchase and QC**	**1/1/2025**	**1/1/2025**	**0周**
5	SiPM selection	1/1/2025	30/6/2025	25.8周
6	SiPM or and QC	1/7/2025	31/3/2026	39.2周
7	**ASIC chips research and production**	**1/1/2025**	**30/3/2026**	**64.8周**
8	ASIC design	1/1/2025	30/9/2025	39周
9	ASIC production	1/10/2025	30/3/2026	25.8周
10	**Electronics design and production**	**1/10/2025**	**2/3/2026**	**21.6周**
11	PCB design	1/10/2025	1/10/2025	0周
12	PCB production	2/3/2026	2/3/2026	0周
13	**Machine and cooling**	**1/1/2025**	**1/10/2025**	**39周**
14	**Machine and cooling design**	1/1/2025	30/9/2025	39周
15	**Machine and cooling installation**	1/10/2025	1/10/2025	0周
16	**Integration of Sensitive Layers and test**	1/1/2026	30/9/2026	39周
17	**GS-prototype aSsemble And test**	1/7/2026	28/9/2028	117.4周

- **The ECal-HCal transition region must be evaluated with attention to physics performance.**

--> Yes, the simulation and design work have already get the full simulation result by the ECAL and HCAL together.

--> Understanding the “big” HCAL constant term of the GS-HCAL design.

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 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 is the electron ECal resolution impacted when the bending of the electron matches the 12 degree incline angle?

MUON

Findings

MUON

- 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.

- The CEPC Muon Detector design consists of:

- **Barrel**: Six layers in a helix dodecagon configuration, each layer containing two long rectangular modules inserted between iron plates. Modules measure **4.275 to 4.625 meters in length** and vary from 1.1 to 3.5 meters in width.
- **Endcaps**: Six layers, with each layer divided into four sectors. Each sector houses two modules (inner and outer), with the longest PS bars in the outer modules extending up to **4.2 meters.**
- Overall, the detector encompasses 43,176 channels, covering a sensitive area of 4782 m², and requires 119,563 meters of fiber for light collection.

- Current R&D efforts shows promising results, particularly with Plastic Scintillators and SiPMs. Tests have shown strong performance using shorter PS bars (approximately 1.5 m in length). However, extending the bar 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

MUON

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.*

It is not a significant challenge. We will remove it.

1. **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.*

2.63m is an effective attenuation length from the testing. According to Kuraray, it could be about 6m. Meanwhile, this is of 1.2mm fiber, but we are considering the new one with 2.0mm diameter fiber. We will test the new fiber.

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

The NDL SiPM is under development, and the new product has much better performance in DCR. Meanwhile, it has a good advantage in cost.

1. **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.*

We are planning the prototype testing. It will be tested soon.

1. **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.*

We take this suggestion.

Recommendations

MUON

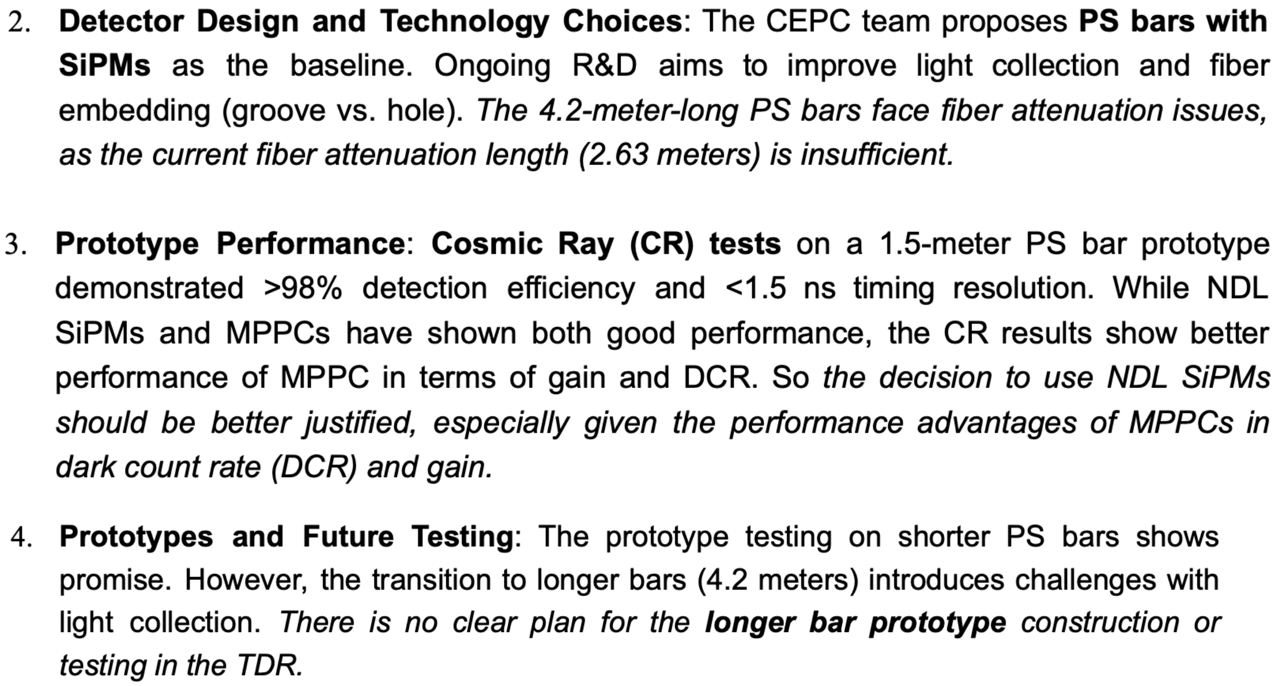
1. In the TDR, provide a clear plan and timeline to address fiber attenuation and prototype scaling:

- **Optical Glue**: Outline the testing process for various optical glues, including supplier options and performance criteria to improve fiber-scintillator coupling. →We will do it.
- **Larger Diameter Fibers**: Specify steps for sourcing 2 mm diameter fibers, identifying suppliers. →Kuraray
- **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. →OK
- **Double-Sided Readout**: Consider a dual-end readout as a solution to mitigate attenuation and enhance redundancy. →OK. Especially for the very long strips.

1. **Electronics:**
    - ○ Justify the choice of NDL SiPMs, given MPPCs' superior DCR and gain. Clarify the operation temperature of SiPM. →Operation temperature should be room temperature, and we will insert temperature sensor in the electronics.
2. **Muon Performance Studies**: →We take these in the plan for software and simulation subgroup.
    - ○ **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.

IDRC Comments for Muon Detector

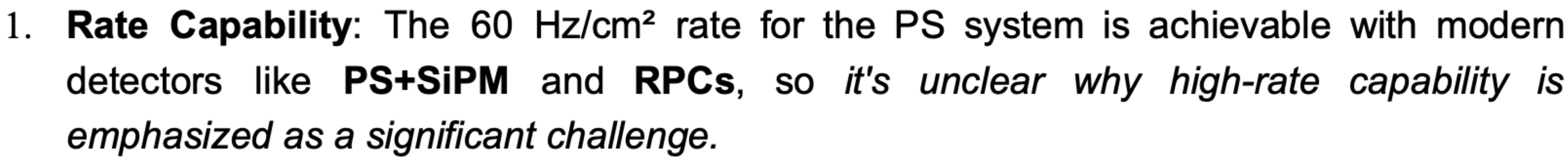
- Currently, the main focus of the R&D is on overcoming the issues associated with fiber attenuation in the longer PS bars.



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.*

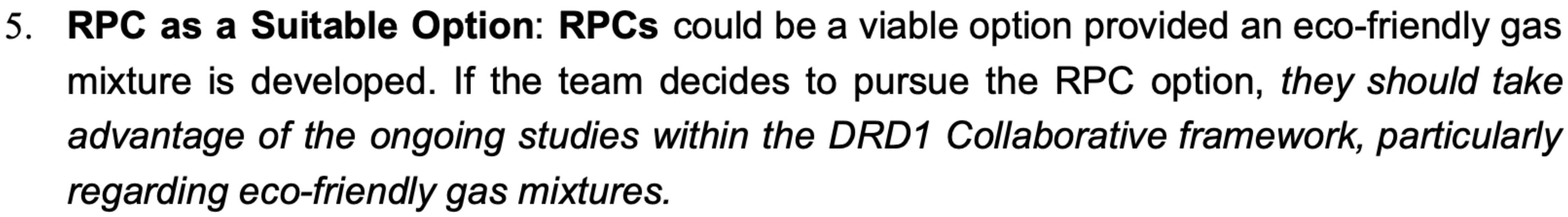
For this, we have recently found domestic manufacturer to be able to produce the 4 meters long fiber + WLS's + assemble them together.
The production and test of such a prototype will be the next step.

IDRC Comments for Muon Detector



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.*

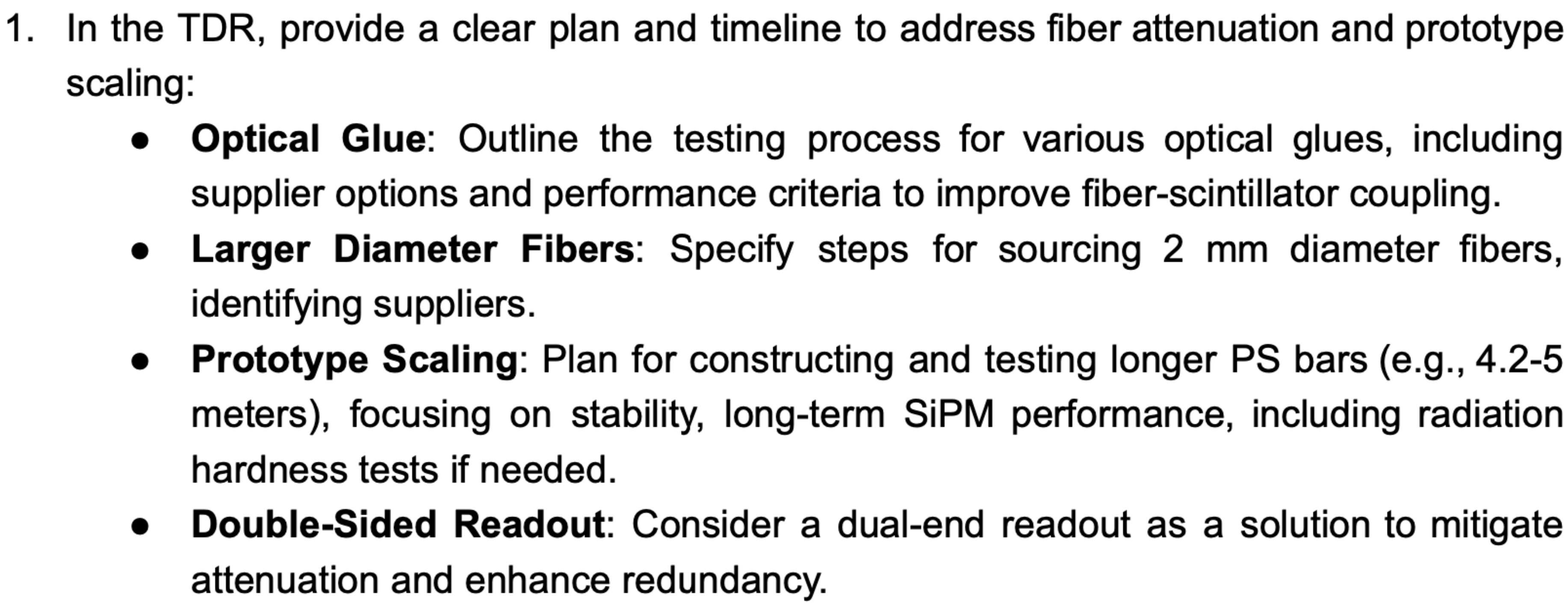
We didn’t emphasized it is a challenge, detailed studies are carried out by Junhao Yin.



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.*

Right, Shanghai Jiaotong U. is going to continue with the RPC option.

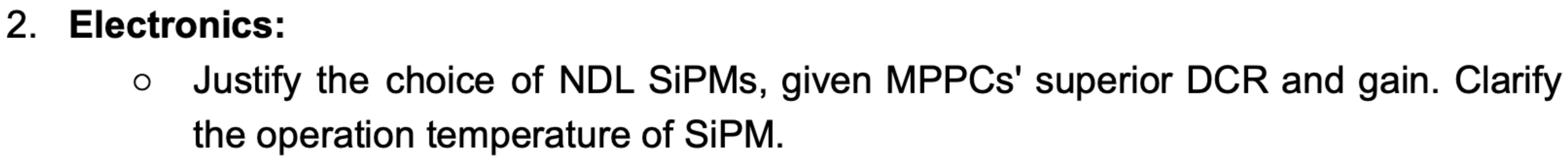
IDRC Recommendations for Muon Detector



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.

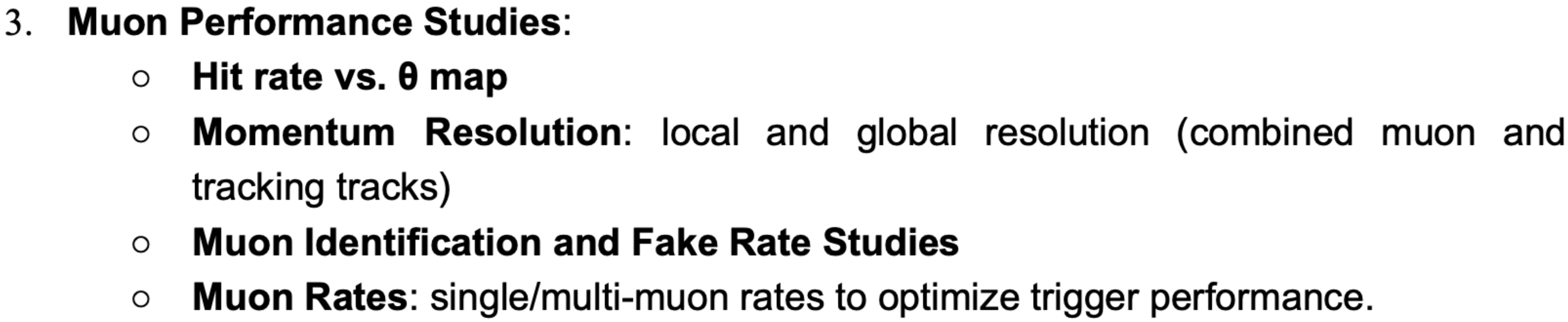
We agree these are good suggestions that will follow, once we have our 4-meter prototype ready. We will go with these tests.

IDRC Recommendations for Muon Detector



2. **Electronics:**
    - Justify the choice of NDL SiPMs, given MPPCs' superior DCR and gain. Clarify the operation temperature of SiPM.

Agree, we will integrate the temperature sensors in FEE



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.

Agree, these are agreed approach we are currently working on.

SYSTEM 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

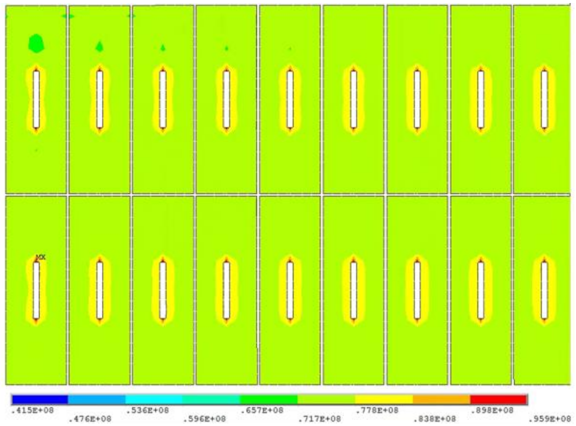
1. Extend the R&D milestones for aluminum-stabilized superconductors, focusing specifically on enhancing mechanical strength while maintaining electrical stability through the residual resistance ratio (RRR). This is essential for ensuring the necessary operational stability of the magnet and for demonstrating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

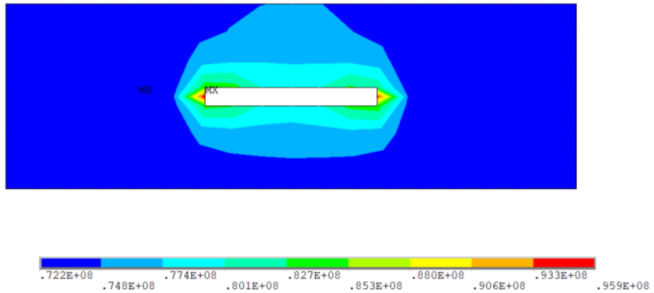
Feedback 1

- 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.
- 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.

✓ The maximum von mise stress on the aluminum stabilizer (96MPa) is close to the yield strength of the material (105MPa). The safety margin is less than 1/3 of 0.2% yield strength. But the maximum stress on the aluminum stabilizer is only in a very small local area, near the Rutherford cable, with the majority of the region within the stress 70-80 MPa, below 1/3 of 0.2% yield strength, indicating that the coil can operate safely.

✓ We are still doing the R&D of aluminum stabilizers, aiming to achieve higher strength by combining the required RRR values for quench simulations. And in fact, we have used the cold work process to reinforce the mechanical strength.





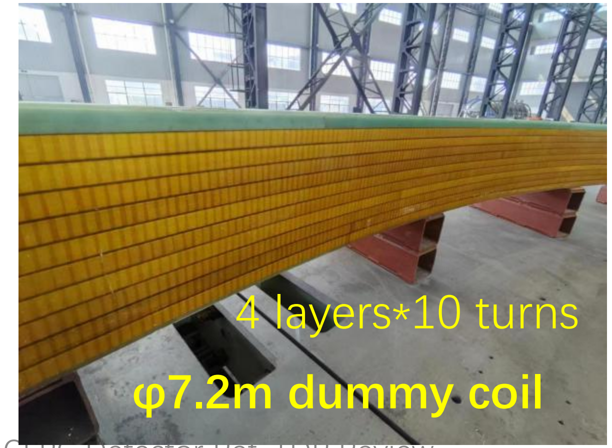
Feedback 2

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

✓ We have built a large superconducting coil winding platform with company, and developed a full-size dummy coil. This can demonstrate the winding process of the coil, but cannot demonstrate the mechanical, electrical, and thermal performance.

✓ We are developing the full-size aluminum stabilized NbTi Rutherford cable toward the TDR. And plan to develop a full-size superconducting coil prior to the EDR.


Large scale superconducting coil winding platform


4 layers*10 turns

φ7.2m dummy coil

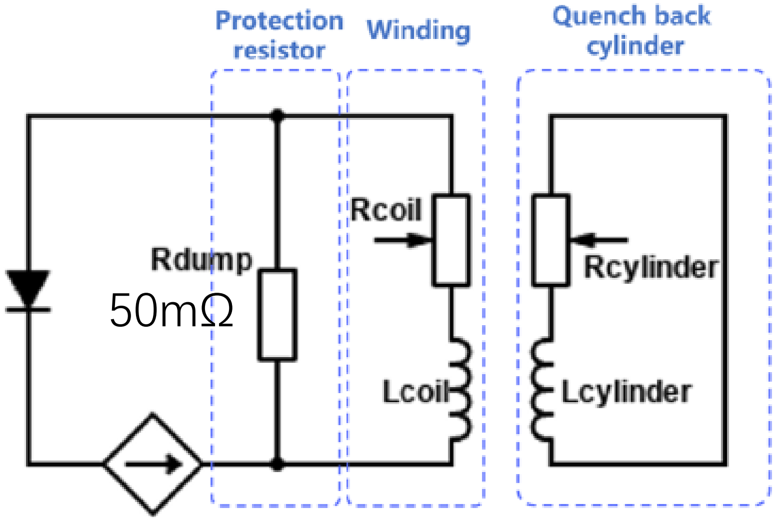

Dummy coil

Feedback 3

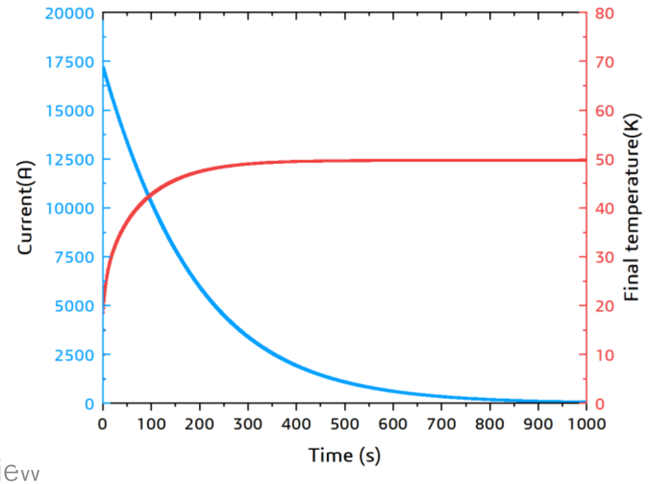
- The superconductor conductor stability and safety are very important and the quench safety and protection design shall proceed.
- Confirm the quench safety with the current NbTi superconducting cable and Al-stabilizer parameter while providing sufficient stability with the temperature margin at the coil operational current and field.

- The report did not display any content on quench protection, but we have conducted simulations of magnet quench protection.

The coil protection system is based on a 50 mΩ dump resistor. The maximum voltage and temperature rise of the coil after quench have been controlled within a safe range.



Fast dump discharge



Feedback 4

- Concerning the cooling design, LHe-pipe cooling path with many parallel cooling paths may be simplified by using a serpentine cooling path concept for minimize 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.
- 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.

✓ After detailed calculations and simulations, we have ultimately chosen the thermosyphon cooling method. Based on the small temperature difference and high heat exchange capability, we have to use the parallel cooling paths.

✓ At the same time, we are seeking support from companies to reduce the risks for aluminum welding.

	Thermosyphon	Force flow
Difference	Need more space to install the phase separator	A liquid helium circulating pump is required
heat exchange capability	1200 W/(K·m^2)	412.1 W/(K·m^2)
Coil maximum temperature	4.982 K	5.383 K
Coil average temperature	4.591 K	4.972 K
Inner diameter of Liquid helium pipes	Φ15 mm	Φ 20 mm

Feedback 5

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

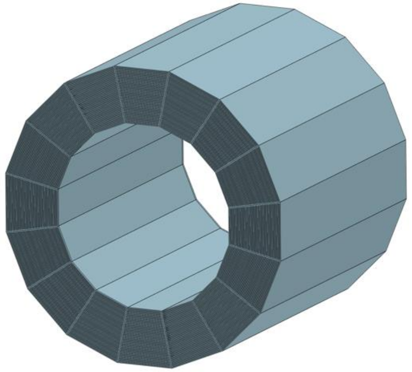
✓ The magnetic field distribution with anti-solenoid has been simulated. The anti-solenoid has a very small effect on the magnetic field uniformity of the TPC area.

✓ The most important is not the uniformity of the magnetic field, but rather the gradient of the magnetic field and the accuracy and magnetic field mapping density.

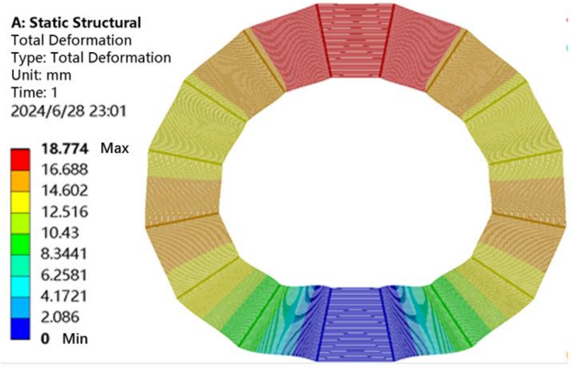
MECHANICAL INTEGRATION

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.



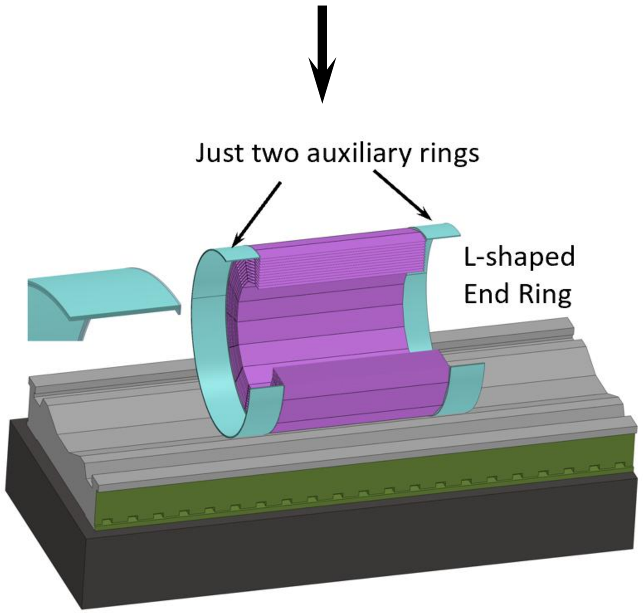
HCAL Structure

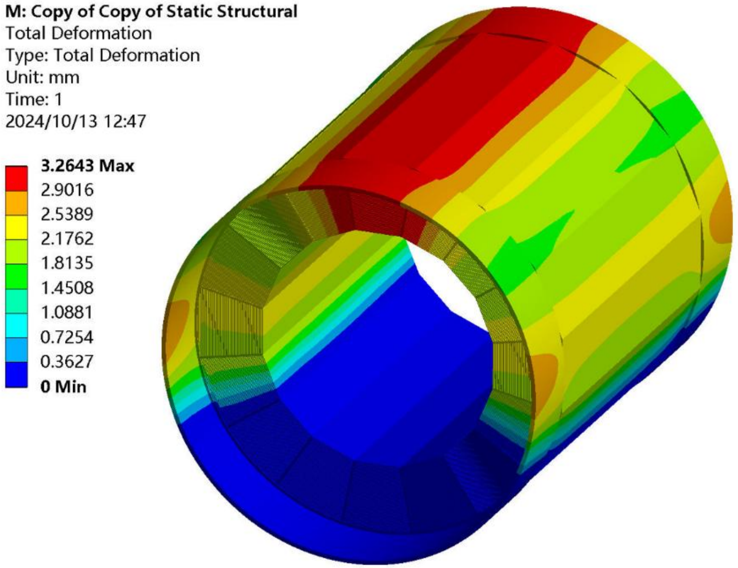


HCAL deformation calculation results

From **18.8**

Solution





to 3.3 mm
(< 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.

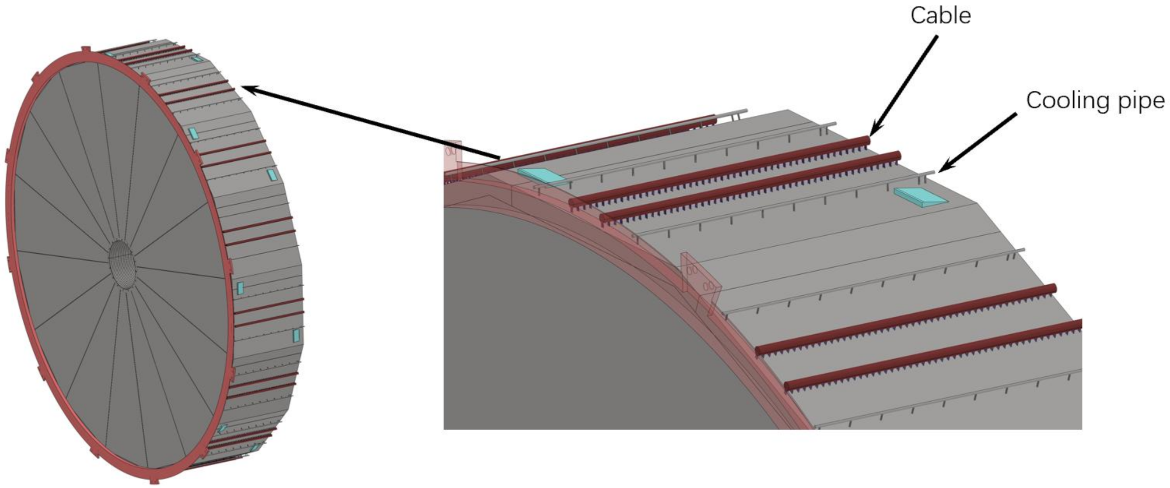
The detector electronics and cooling design have been completed

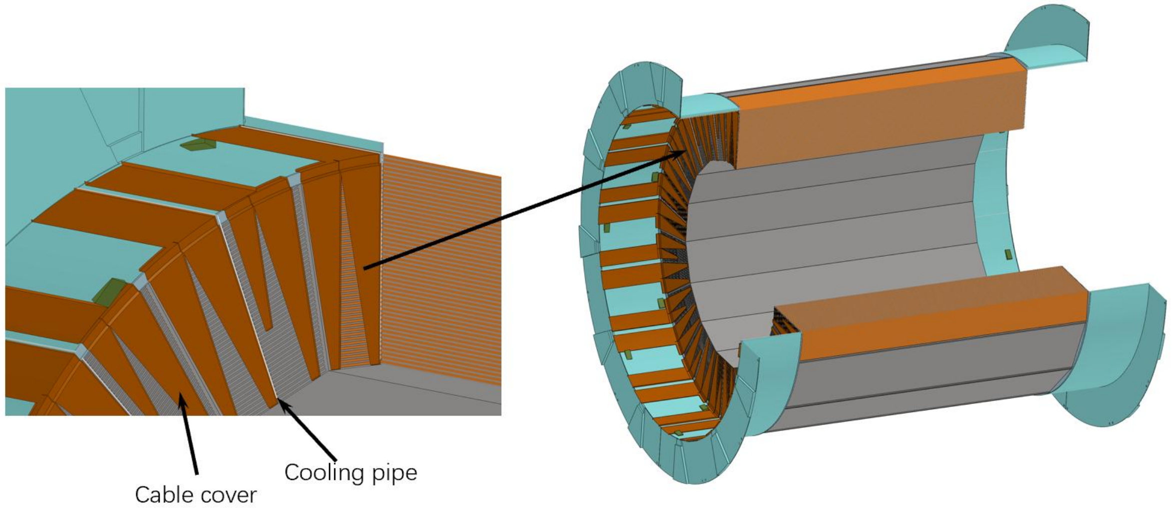
- Additionally, it is crucial to estimate the total power budget, taking into account DC-DC power conversion efficiency and losses along the cables. This assessment will enable accurate sizing of the power plants and associated services, as well as clarify their impact on the overall detector design

Total power of electronics : 1000kW

Comments

Cooling Design

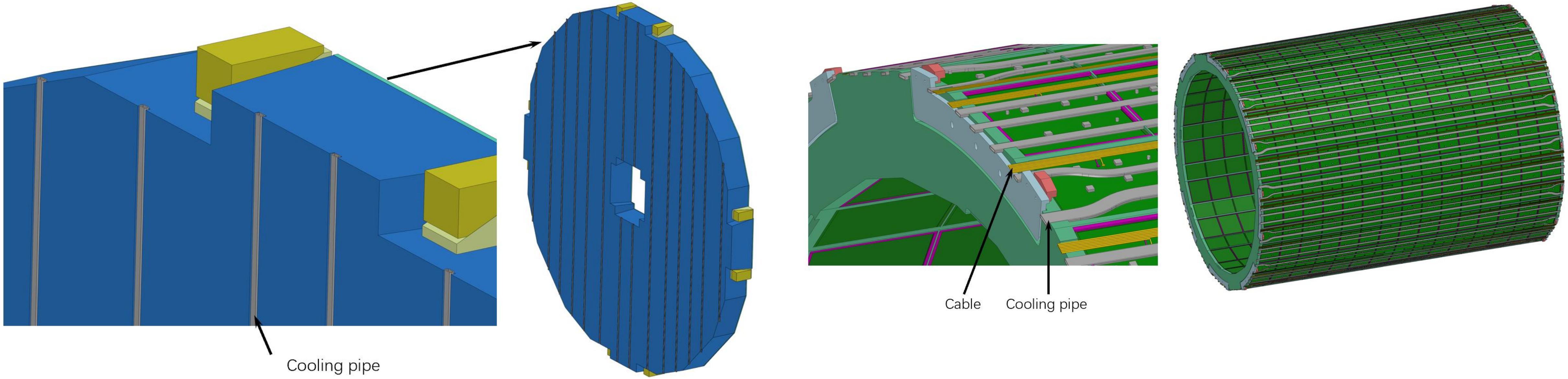




HCAL

Comments

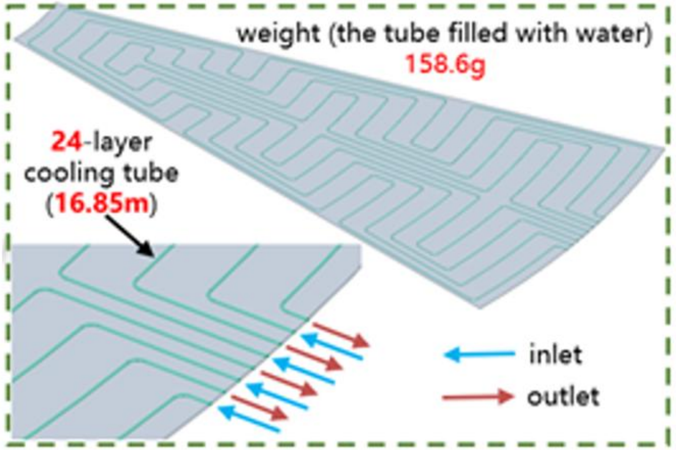
Cooling Design



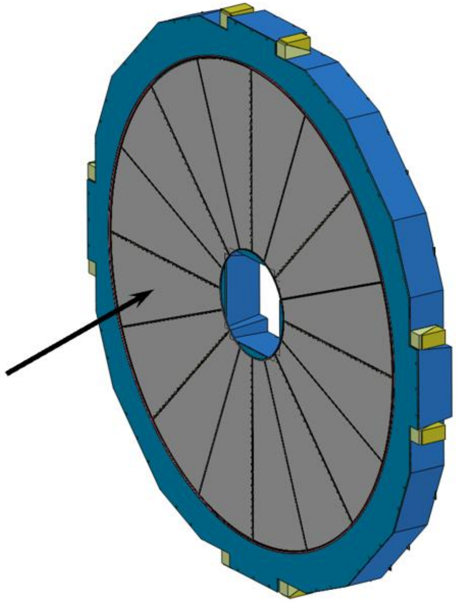
ECAL

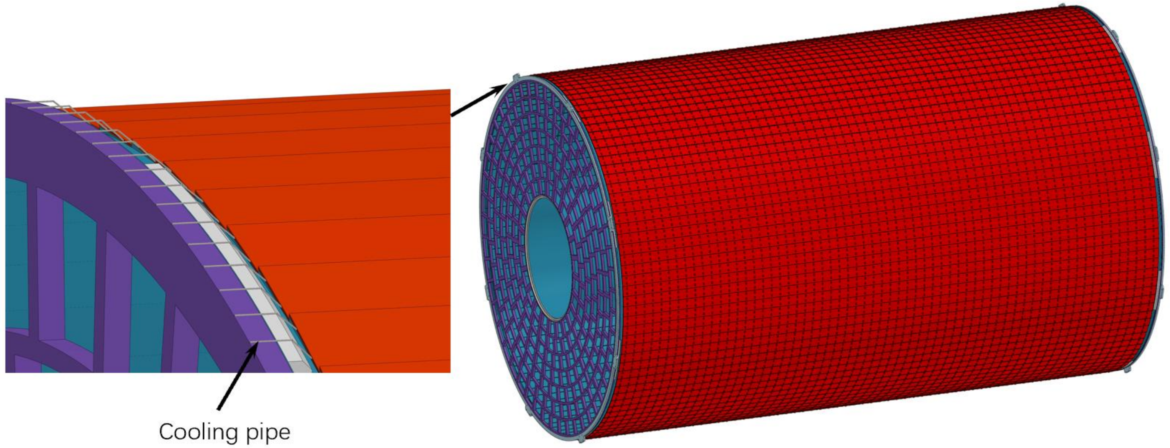
Comments

Cooling Design



Cooling design

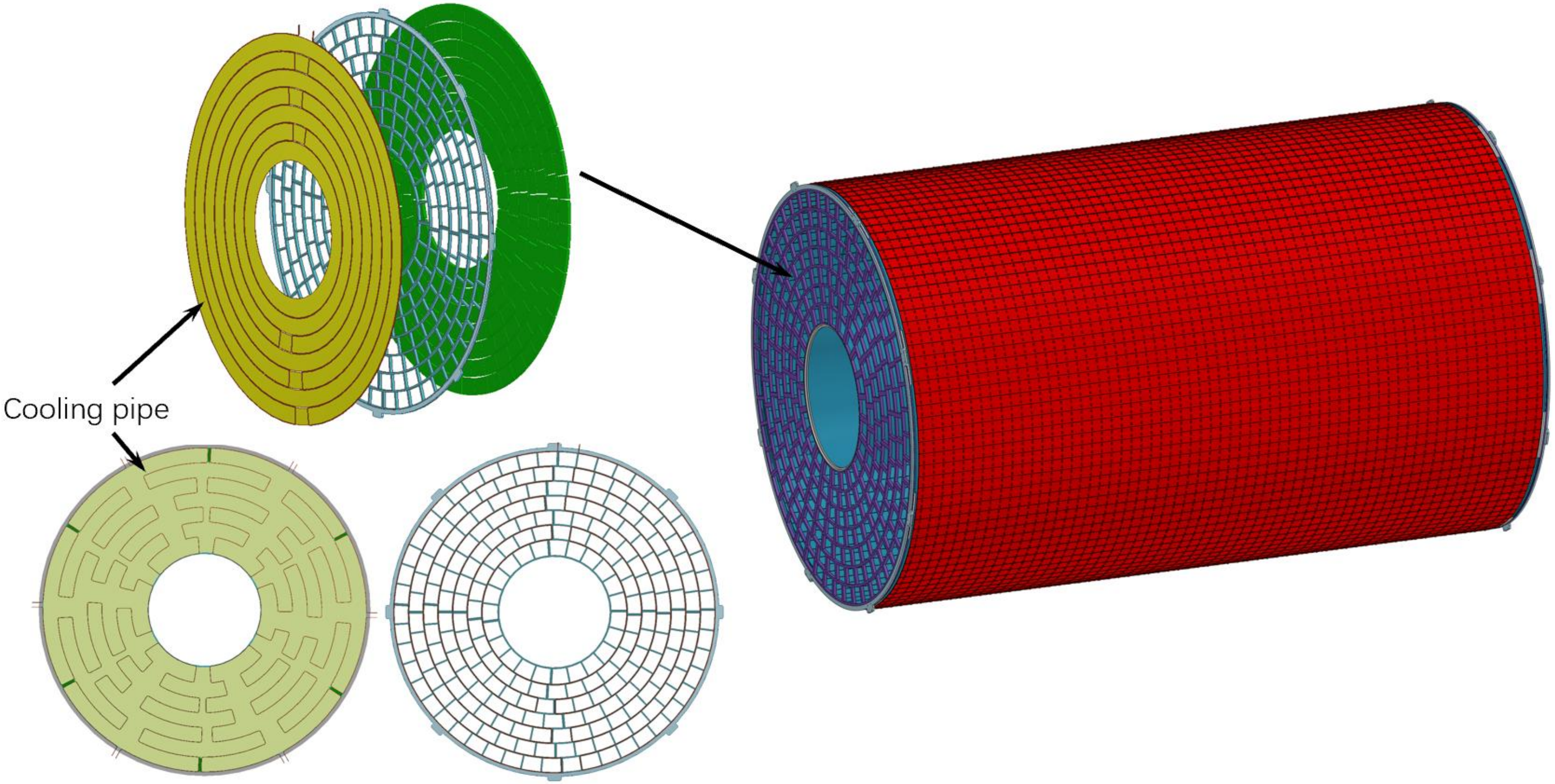




OTK

Comments

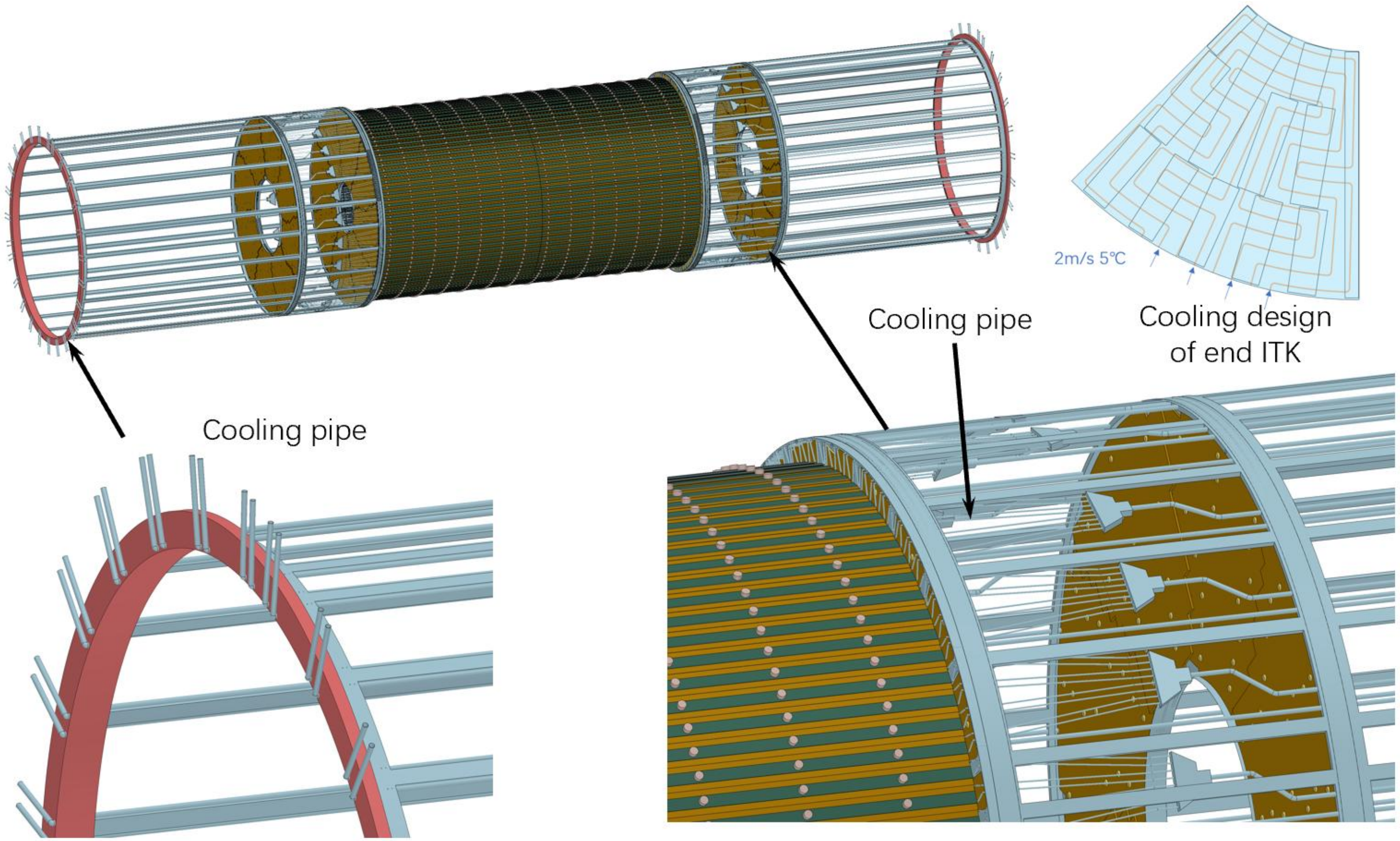
Cooling Design



TPC

Comments

Cooling Design



ITK

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.

Completed, continuing to optimize……

2. It is also important to specify the cooling agents being considered (e.g., air, water, CO_2) for all sub-detectors, as this has not yet been clearly defined.

Completed

1. Water-cooling system

	Inlet temperature
ECAL HCAL TPC Beampipe	15℃
ITK OTK	5℃

2. Air-cooling system

Vertex	5℃

- 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.

Recommendations

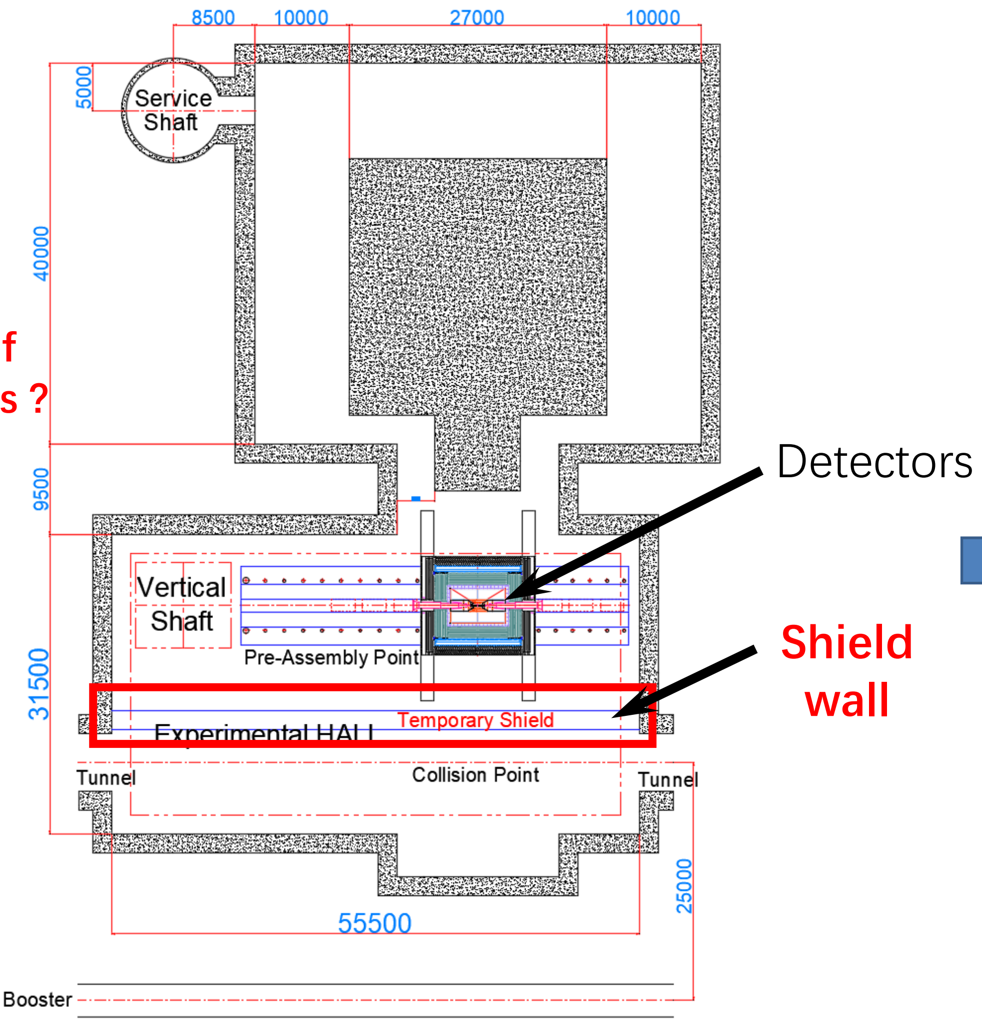
How to make full use of temporary shielding walls ?

↓

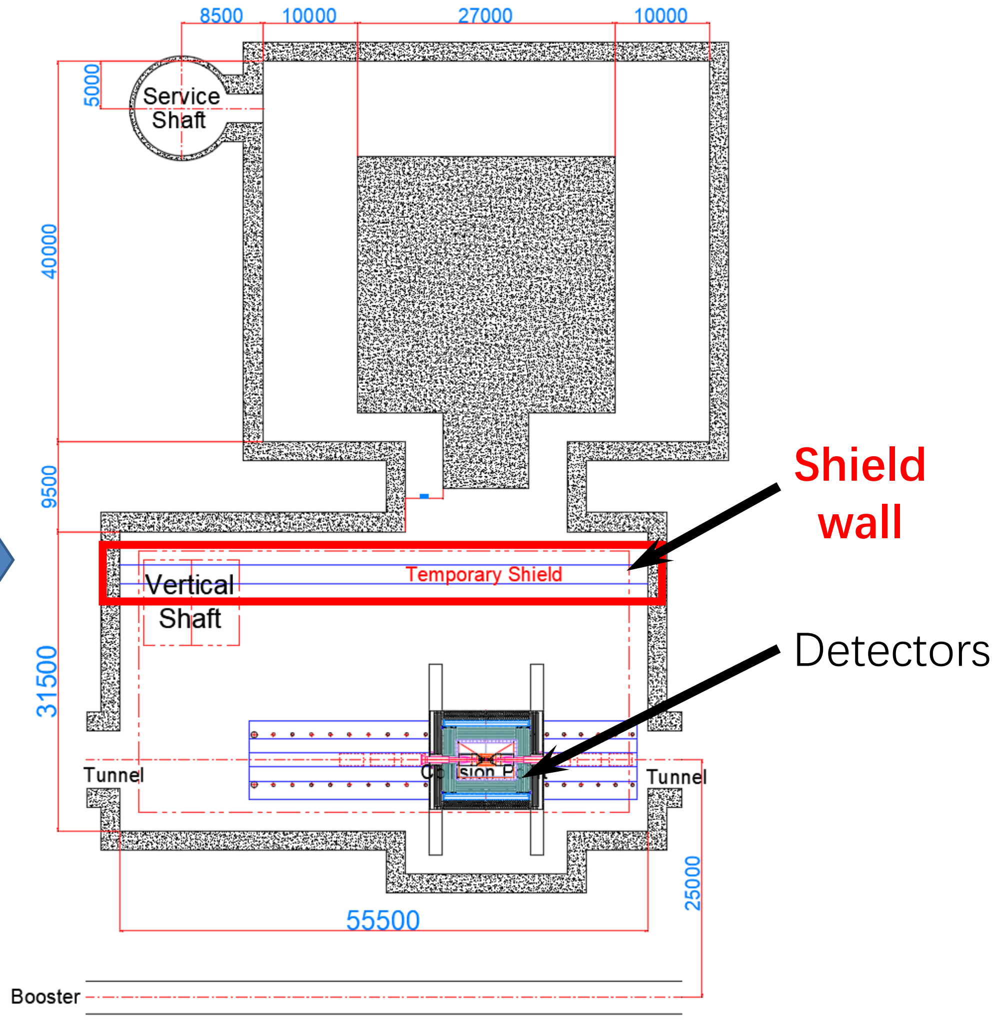
Optimization

Layout ?

Size ?



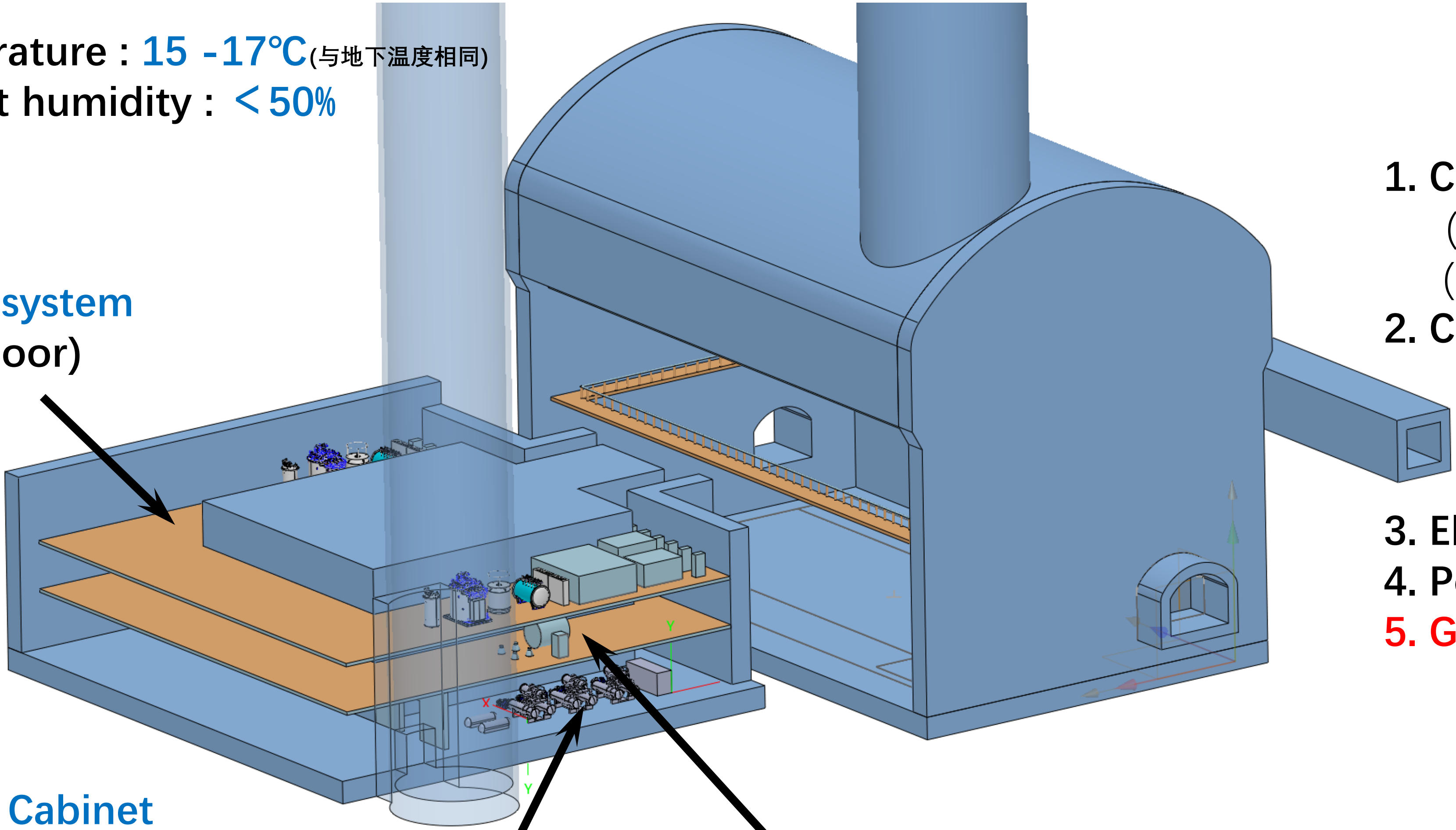
Pre-Assembly Point layout



Collision Point layout

Recommendations

ambient temperature : 15 -17℃(与地下温度相同)
ambient humidity : ＜50%



Cryogenic system
(Third floor)

Electronics Cabinet
&Power Cabinet
(Remaining)

Cooling system
(First floor)

Gas system
(Second floor)

1. **Cooling system**
   (air and water)
   (5℃ and 15℃)
2. **Cryogenic system**

3. **Electronics**
4. **Power (Support)**
5. **Gas system**

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

ELECTRONICS

- 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 leverages well-established technologies, including standard optical links, modest-sized FPGAs, DRAM, Ethernet, and I2C. Notably, the electronics team has already developed a version of the board with 12 optical inputs for use with the prototype VTX detector. Once the required DRAM capacity for buffering data during the trigger decision period is determined and a target FPGA is selected (currently anticipated to be an XC7V690T), the design can proceed. Given the team’s strong track record of delivering similar boards, this aspect of the project is considered to have minimal 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…)

Comments

- 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, 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 a comprehensive timeline for the development of all FE ASICs across sub-detectors, along with an assessment of their current maturity levels.
2. Determine the readout scheme (e.g., triggerless) at an early stage to prevent wasted efforts on developments that will not be adopted, particularly as some chips may not support both readout schemes.
3. Provide a detailed analysis of the maximum rates that the triggerless readout can handle, including the safety margin incorporated. Additionally, outline contingency plans for scenarios with higher-than-expected occupancy and describe the throttle scheme to manage such situations effectively.

Answer

1. Triggered Readout Scheme (R.2)

IDRC Comment: Switching to a triggered readout mid-project is high-risk due to impacts on FEE-ASIC design.

Response: Baseline is triggerless readout. Final scheme pending MDI background rate results. VTX cooling capability under monitoring; fast trigger may be added if needed.

2. FE-ASIC Development Risks (R.1)

IDRC Comment: Designing/delivering 6 FE-ASICs is the highest risk. Centralized development may strain resources.

Response: IHEP as central facility; design tasks distributed across teams.
Actively seeking international collaboration.
Existing chips (e.g., SiPM ASIC) evaluated but deemed cost-prohibitive; self-R&D prioritized.

3. DC-DC Converter & Powering

IDRC Comment: Early-stage DC-DC converter (GaN transistors). Monitor serial powering viability.

Response: Parallel powering baseline retained. R&D for serial scheme ongoing; progress tracked.

4. Wireless Data Transmission

IDRC Comment: Wireless readout is high-risk due to shielding/miniaturization challenges.

Response: R&D resources allocated independently to avoid impacting baseline electronics.

5. ASIC Verification & Resource Management

IDRC Comment: Centralized development risks resource depletion; recommend CERN-MIC-like facility.

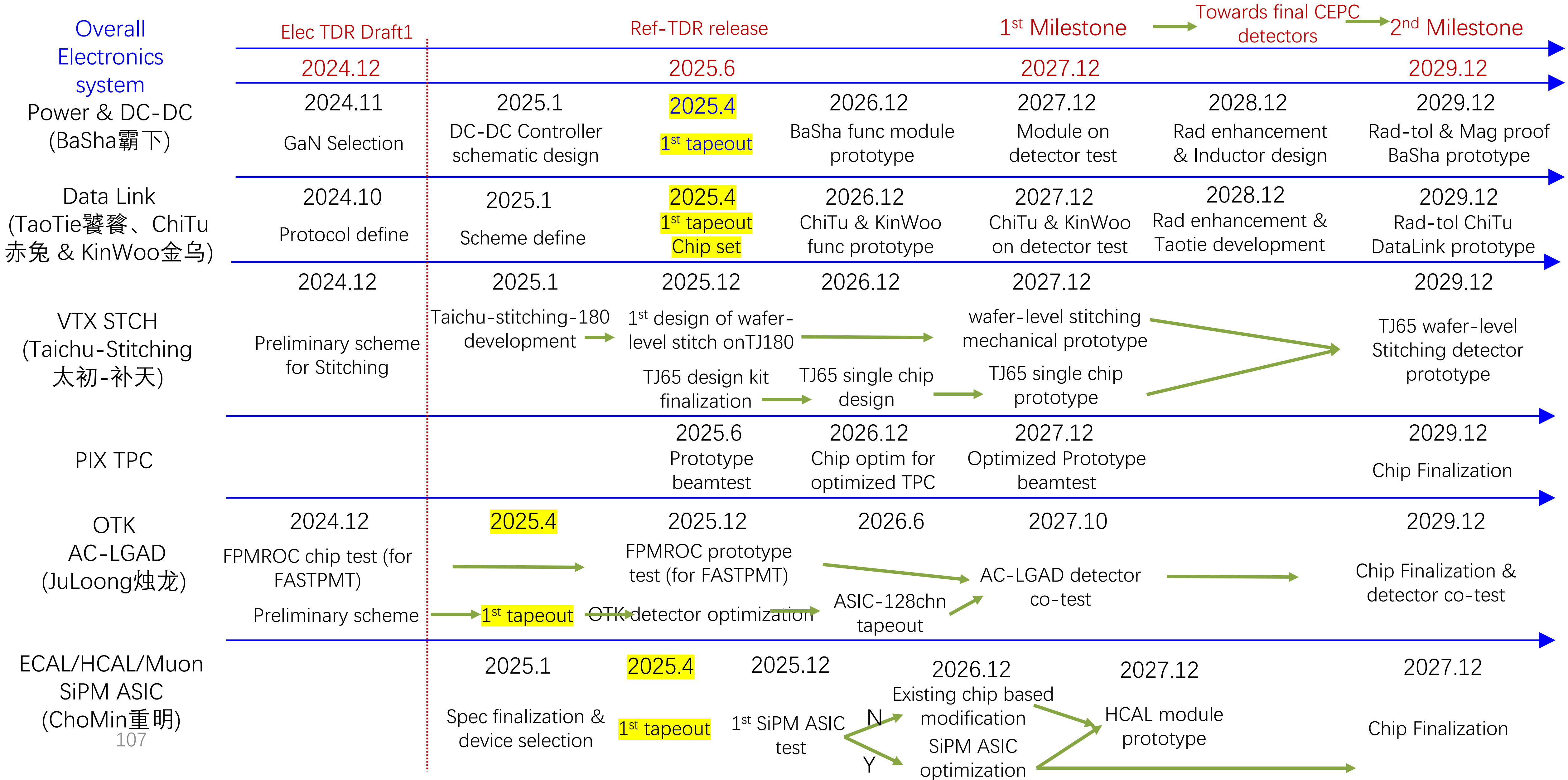
Response: IHEP coordinates ASIC development with distributed design teams. Supplement files detail resource allocation.

6. Occupancy & Safety Margins (R.3)

IDRC Comment: Clarify triggerless readout’s max rate, safety margins, and throttle mechanisms.

Response:Rates calculated based on MDI studies; most sub-detectors use low-load data links.
FE-ASICs include zero-suppression/event-driven designs. VTX data rate (~1–2 Gbps/RSU) under close R&D scrutiny.

Timeline for all the FE ASICs – common ASIC – long term



Overall Electronics system	Elec TDR Draft1 2024.12		Ref-TDR release 2025.6		1st Milestone 2027.12	→ Towards final CEPC detectors →	2nd Milestone 2029.12
Power & DC-DC (BaSha霸下)	2024.11 GaN Selection	2025.1 DC-DC Controller schematic design	2025.4 1st tapeout	2026.12 BaSha func module prototype	2027.12 Module on detector test	2028.12 Rad enhancement & Inductor design	2029.12 Rad-tol & Mag proof BaSha prototype
Data Link (TaoTie饕餮、ChiTu赤兔 & KinWoo金乌)	2024.10 Protocol define	2025.1 Scheme define	2025.4 1st tapeout Chip set	2026.12 ChiTu & KinWoo func prototype	2027.12 ChiTu & KinWoo on detector test	2028.12 Rad enhancement & Taotie development	2029.12 Rad-tol ChiTu DataLink prototype
VTX STCH (Taichu-Stitching 太初-补天)	2024.12 Preliminary scheme for Stitching	2025.1 Taichu-stitching-180 development →	2025.12 1st design of wafer-level stitch onTJ180 → TJ65 design kit finalization →	2026.12 TJ65 single chip design →	2027.12 wafer-level stitching mechanical prototype TJ65 single chip prototype		2029.12 TJ65 wafer-level Stitching detector prototype
PIX TPC			2025.6 Prototype beamtest	2026.12 Chip optim for optimized TPC	2027.12 Optimized Prototype beamtest		2029.12 Chip Finalization
OTK AC-LGAD (JuLoong烛龙)	2024.12 FPMROC chip test (for FASTPMT) → Preliminary scheme →	2025.4 1st tapeout →	2025.12 FPMROC prototype test (for FASTPMT) → OTK detector optimization →	2026.6 ASIC-128chn tapeout →	2027.10 AC-LGAD detector co-test →		2029.12 Chip Finalization & detector co-test
ECAL/HCAL/Muon SiPM ASIC (ChoMin重明)		2025.1 Spec finalization & device selection	2025.4 1st tapeout	2025.12 1st SiPM ASIC test N Y	2026.12 Existing chip based modification → SiPM ASIC optimization →	2027.12 HCAL module prototype	2027.12 Chip Finalization

TDAQ

Findings

TDAQ

- 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 ~40 MHz to ~100 kHz 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

TDAQ

- 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.

Answer:

- We closely follow the design of detectors. Especially background study and data rate estimation from each sub detectors.
- We did most simulation works on trigger primitive from Ecal, Hcal and Muon detectors for L1. We did some simulation works on track trigger at HLT.
- Lower-energy background events from gamma-gamma collisions could be reduce to 1% by L1 and 0.2% by HLT both for Higgs and low lum. Z.

Recommendations

TDAQ

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.

Answer:

1. According to primary simulation with all detectors, calorimeter energy and muon hit trigger condition are good efficiency at L1 and tracking trigger at HLT to select physics event and reduce background without considering detector and electronics noise. A 10-fold safety factor for beam related backgrounds has been investigated and a 100-fold factor is under investigation.
2. Lower-energy background events from gamma-gamma collisions could be reduced 80% with tracking trigger at HLT

SOFTWARE AND COMPUTING

Findings

SOFTWARE AND COMPUTING

- 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.

  国际合作

- 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.

  独创/特色软件

- 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.

  软件系统

- 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 current needs of CEPC studies.

  计算系统

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.

Agree, but not too much till now. main reason is manpower and time

- 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.

Needs further clarify the requirements.

- 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.

Agree, further expand cooperation with major experiments, need more time

Recommendations

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

1. Ensure that the reference detector model used for full simulation incorporates realistic material budgets in the tracking region, including supports, services, and cooling infrastructure. Done / Asking for timely notice from hardware and mechanism
2. 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 in time. Almost Done / Tracking: effective pad-based PID: pixel based
3. Use full reconstruction to create basic detector performance plots, with realistic assumptions on detector resolutions, such as: In processing lead by Mingshui, no serious problem foreseen
   a. Track momentum resolution (for single muons) as function of p_T for different values of cos(θ) or θ
   b. Impact parameter resolutions in $r-\phi$ and z
   c. Jet energy resolution as a function of cos(θ), e.g., for uds di-jet events without ISR
   d. Flavour tagging performance Optimizing
   e. PID performance (using dN/dx and TOF) including separation power for K/π and K/p

Recommendations

SOFTWARE AND COMPUTING

1. 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. In processing / no matter for principle
2. Prepare a forward-looking computing and software strategy for the post-Ref-TDR phase, addressing: Long term strategy
   a. Data accessibility (open/shared) and long-term preservation
   b. Integration of emerging technologies and their anticipated applications over the next 5-10 years
   c. A systematic approach for documentation and knowledge capture
   d. Initiatives for training and attracting new programmers, particularly for long-term sustainability.

DETECTOR PEREORMANCE

Findings

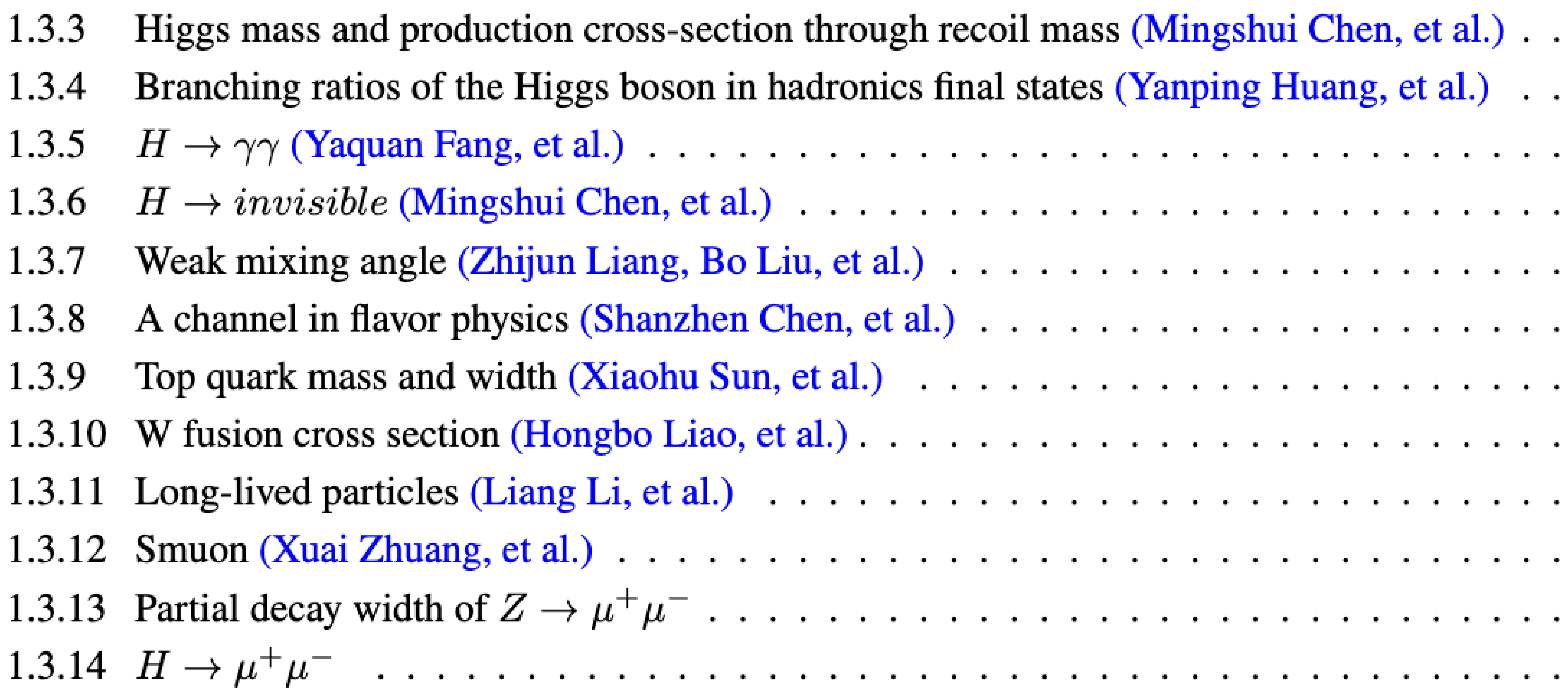
- The planned performance studies include an ambitious set of channels, many with intricate topologies. Most of these benchmarks align well with international projects in the same domain (such as ILC, FCC). Compared to the CDR, several changes have been introduced to improve performance and incorporate 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→μμ, 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 $e^+e^-\rightarrow\gamma\gamma$ 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

DETECTOR PEREORMANCE

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→μμ, to provide foundational validation.

A: Narrower list. Potentially the number of channels would be further reduced. **Just started.**



Recommendations

DETECTOR PEREORMANCE

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.

A: **Reconstruction/identification efficiency and/or energy/angular resolution as a function of energy and cos(theta) for tracking, photon, electron, muon, vertex, jets, PID of charged particles.**

These are the Priority. First draft of text available. Plots to be updated.

3. Clearly outline the strategy for measuring absolute luminosity in the Ref-TDR, as this is essential for accurate cross-section measurements.

A: first draft available by Ivanka Bozovic

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.

A: first draft available by Zhe Duan

Recommendations

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.

A: Number of ITK layers, transverse granularity of long crystal bars, thickness of HCAL vs. polar angle? Number of muon layers

6. (longer term) Consider how performance study results could influence technology decisions, especially as they relate to detector component specifications and configurations.

A: TOF of ITK: AC-LGAD for the outmost layer of ITK? PID in ITK strip? TPC vs. DC at high lumi Z? HTS ultra thin magnet?

7. Explain how calibration for each sub-detector will be achieved through physics processes, and document specific calibration methods in the Ref-TDR.

A: being worked on by Jin Wang

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.

A: In progress