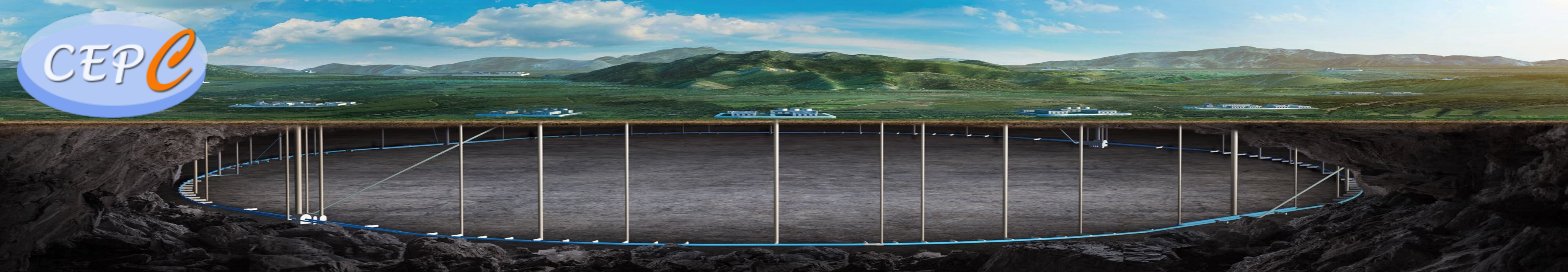

Feedback of 2025 IDRC Review Report

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ELECTROMAGNETIC CALORIMETER

Findings

- The high-granularity crystal ECAL is a recently proposed concept designed to be compatible with particle flow algorithm (PFA) reconstruction of jet energy within a homogeneous structure. The calorimeter is modular, with the fundamental detection units consisting of long orthogonal BGO crystal bars, read out at both ends by SiPMs.
- Achieving high granularity at an affordable cost requires making strategic choices and compromises, guided by specific performance benchmarks. The **team has made steady progress** in understanding the performance and optimizing the performance-cost balance, using the ECAL standalone energy resolution and PFA jet resolution as primary benchmarks.
- The baseline granularity was recently updated to $15 \times 15 \times 40\ cm^3$, resulting in a significant reduction in the number of readout channels and associated power needs. Simulations indicate that, even with this updated configuration, the calorimeter meets the target requirements for boson-mass resolution and standalone electromagnetic energy resolution. The **overall performance remains excellent**, despite some degradation in π^0/γ identification and two-photon separation; the latter may potentially be recovered through improvements in offline reconstruction methods.
- A **full-scale prototype** with the updated granularity is planned. Current simulation studies and experimental results from similar granularities provide confidence that the ECAL performance and component requirements are sufficiently understood, despite limitations in previous test beams due to electron beam spread. The team is also aware of the need for further progress beyond the reference TDR, particularly in **defining QA/QC aspects** for the components.

Comments (1)

- The ECAL standalone energy reconstruction requires an energy threshold of 0.1 MIPs (as shown in Fig. 7.17), whereas the PFA jet reconstruction, based on fast simulation, adopts a higher threshold (Fig. 8.2). The ECAL team acknowledges the need to further develop and refine particle flow algorithms, photon identification at low energies, and π^0/γ separation to fully exploit the calorimeter's potential.
- The timing specification of 0.5 ns for MIPs was not strongly motivated. This corresponds approximately to the time spread across a full bar and is insufficient to provide significant benefits for event reconstruction. Additionally, the current time resolution analysis appears suboptimal. The team acknowledges that a deeper understanding of timing response and its potential use is needed, although this is not a priority at this stage.
- Crystal transparency variations are significant. While progress has been made toward developing a calibration plan using collision events, a quantitative demonstration that the precision and event rates are sufficient for monitoring response evolution across the detector is still missing.
- The non-linearity of the SiPMs poses a potential risk to the constant term in the energy resolution. Although compact photon detectors with more linear responses (such as APDs) were noted, SiPMs are preferred for cost and design uniformity reasons. However, SiPMs will require per-channel calibration, and possibly sorting during construction, along with continuous in-situ monitoring and corrections.

Comments (2)

- Prototyping with close-to-final components is essential to confirm performance. Using existing readout ASICs can help decouple detector characterization from electronics debugging and allow parallel progress rather than sequential steps.

- The committee was pleased to see a substantial effort in understanding the impact of gaps between modules. However, the mechanical design and service layout within the gaps remains sketchy, and some components, such as the cooling plates, could be prone to underperformance.

- From a stylistic perspective, the TDR would benefit from an upfront presentation of the key performance benchmarks and detector specifications, followed by a focused discussion of the performance-cost optimization supported by R&D and simulation evidence. The detailed discussion of alternative options currently in Section 7.2 could be summarized briefly and moved to an appendix.

Recommendations

- Continue developing a **full-scale prototype** with the final geometry (using existing readout ASICs) and aim to confirm performance in an electron beam with low momentum spread.

- Further **refine calibration strategies** to ensure that necessary stability in transparency, linearity, and uniformity can be achieved in situ, without relying on a dedicated monitoring system.

- Advance preliminary engineering of the gaps between modules and fully assess their impact on reconstruction performance.

Comments on Draft v0.4.1

- General comment:
- There is no mention of separation of showers or individual particle depositions. The parameters mentioned are energy resolutions without mentioning the segmentation (granularity) needed to achieve particle flow performance. We suggest adding mention of needed segmentation or granularity.
- Line by line comments:
- line 1475, 1481: - reference to just LEP for last gen e+e-. Suggest "LEP and SLD at SLC"
- line 1490: "the key ingredient" I suggest "a key ingredient"
- lines 1493-1494: We suggest expanding the sentence to "We propose to use BGO crystals as full absorption ECAL which will significantly improve energy resolution, which is essential for optimal H-> gamma gamma detection, for example."
- line 1496: "18 longitudinal layers providing 24 radiation lengths" → "providing 24 or more radiation lengths", since there are more than 24 radiation lengths. for much of the barrel
- line 1499: "fully contain electromagnetic showers." → "maximize containment of electromagnetic showers.", because, strictly speaking, there is still some leakage.
- line 1524: "typical" would be better as "the typical" and "result" should be plural "results".

Comments on Draft v0.4.1

- The EM calorimeter chapter has been substantially restructured. It now presents directly the design choice and comments on alternatives at the end of the chapter. This addresses one of the comments that were raised in the April review and benefits the clarity of the information flow. The text has been polished and shortened in several parts, improving readability. However, the large restructuring poses a challenge to the review process, as we are largely facing a new document.
- The overall design and specifications are essentially the same, except a few notable changes, which require further considerations:
- The MIP requirement for the MIP light output has been raised from 200 to 300 p.e./MIP. While this makes the 0.1 MIP threshold for signal-to-noise ratio easier to achieve, it makes the requirement for the linearity up to 3000 MIPs (set by the maximum energy deposition from e showers for the CEPC operated at 360 GeV) more difficult to be met. Additionally, tests with prototypes show that the light yield of bars in the baseline bar configuration (1.5x1.5 x 40 cm3) are 400 pe/MIP (L.6527), thereby requiring linearity up to 106 pe and beyond. Simulation studies show that the linearity requirements are met (Section 7.3.5). However, these studies assume the nominal 300 pe/MIP and not the measured output of 400 pe/MIP for the baseline design choice for the BGO bars. Additionally, the study is limited to photons from the H → γγ decay for operation at 240 GeV, which have an energy deposition up to about 1500 MIPs (Fig. 7.5b). The SiPM dynamic range is further discussed in Section 7.4.2.2, with numbers that appear inconsistent with other parts of the TDR. For example, it is stated (L.6586) that a maximum deposition per bar of 45 GeV corresponds to 5x105 pe. However, at L.5984 it is stated that the MPV for a MIP is 13.3 MeV, which converts into 3383 MIPs for a 45 GeV energy deposition. At 300 pe/MIP, this gives already 106 pe. At 400 pe/MIP this is above 1.3x106. In summary, the effect of non linearity over the full range and up to 106 p.e. (or beyond) with SiPMs having 250k pixels does not appear to be sufficiently documented.
- The specification about radiation hardness requirements has been dropped from the list (Table 7.1). A statement on the response stability of the BGO vs the ionization dose is needed in the section where the crystal choice is discussed, even if this is not translated into a specification.

Comments on Draft v0.4.1

- There are a few inconsistencies in the requirements about energy resolution. At line 5932 it is "$\sigma E/E$ ≤ 2%/root(E)" while at L.1501 it is required an "energy resolution of <3%/root(E)". In other places the energy resolution is required to be less than 3% (Table 7.1) without specifying any energy dependency. Then there are instances where both the stochastic and the constant term are indicated (L. 6851 and L.1321, again with some inconsistency between 2% and 3%). Please clarify and distinguish clearly between the requirement and what is achieved. For example at L.6851, if the requirement is 3% and you achieve <2%, you can simply state that the requirement of <=3% is achieved.

Comments on Draft v0.4.1

- The discussion about timing performance (Section 7.4.3) remains confusing. The time resolution is defined as "the standard deviation of the time difference of the time stamps of SiPM signals from the two ends of a crystal". This quantity is not independent of the hit position and does not correctly quantify the precision with which the position of a deposition can be reconstructed. A deposition in the centre of the bar, would give a Δt = 0 with an RMS from the resolution of the device. A deposition near the ends of the bar would give a distribution with the same RMS centered at Δt = +/- L/2v, where L is the bar length and v the velocity of the light in the crystal. For a uniform hit distribution, the RMS will therefore get a contribution from the propagation path of L/(v sqrt(12)) ~ 0.6 ns for L=40 cm, v = 1.5c. This should be added in quadrature to the genuine time resolution from the detector and readout. In Fig. 7.31 at L=40 cm, the resolution is 0.7 ns, which is consistent with 0.6 ns from propagation (+) 0.4 ns intrinsic to the detector, which you can read from the measurement with L=2 cm crystals. At L=60 cm, your measured resolution is almost 1 ns, which is again consistent with an L/(v sqrt(12)) ~ 0.9 ns (+) 0.4 ns. So, while your data show the expected behaviour, your interpretation of the results is different. At L 6602, you conclude that at L=40 cm, the resolution is 700 ps (500 ps per end), while your data indicate a resolution is 400 ps/MIP (280 ps per end), which would scale to a resolution of 100 ps already at 200 MeV (per crystal). A better measure of the time resolution is provided by the RMS of the sum of the two timestamps, because the sum of the two propagation times is independent of the hit position. A plot of this quantity should clarify what is the actual resolution. You may still have some dependence on the bar length, because the light output is lower for longer bars.

Comments on Draft v0.4.1

- Line by line comments (not exhaustive):
- -line 5914 - "It also detects neutral pions $\pi 0$ ...." → "It detects neutral pions $\pi 0$ ...." The current formulation (with “also”) is a bit strange to me since it actually detects the gammas from neutral pions and those were already mentioned in the previous lines.
- -line 5920 - "Moliere Radius" → "Moliere radius"
- -line 5935 - "at two ends." slightly better would be "at both ends."
- -line 5939+ and Fig 7.1: "contains over 400 long crystal bars”. It would be helpful here to re-state number of crystals in depth (18 specified much earlier on line 1496)
- -line 5963 - "ers.`necessitating" looks like a typo ".`" should be ", "
- -Figure 7.1: Here the "module" is shown as a "supercell". This is the first use of the term "supercell". Supercell is later referred to in section 12, but not until then. A clarification of these two different references should be added.
- -Table 7.1 "EM energy resolution < 3%". Shouldn't this be energy dependent? Perhaps, add <3% above xx GeV.
- -lines 6009 - 6010: "A typical 40 × 40 cm2 module employs 1.5 × 1.5 × 40 cm3 crystal bars". It would be helpful here to state there are 18 layers.
- -lines 6861-6863: "~ 285,000 crystals" "571,000 SiPMs". As there are two SiPMs per crystal by design, make the two figures a factor two: either ~285,000 and ~570,000 or 285,500 and 571,000.
- -line 6851 "to achieve an EM energy resolution of $\sigma E/E$ ≤2%/root(GeV) $\oplus$1%" should be root(E(GeV)). Please correct also the requirement on line 1321 "$\sigma E/E$ ≤ 3%/ root(E(GeV)) $\oplus$ 1%," (and make them consistent)
- -lines 11299-11301: "The ECAL supercells, mentioned in Section 7.2, are used for the preliminary trigger studies.". We don’t find mention of supercells in section 7.2, where discussion of ECAL elements are modules. If the ECAL supercells are identical to "modules" the terminology used in Section 7, it would be helpful to state that here.

Feedback to IDRC Recommendations (1)

- Continue developing a **full-scale prototype** with the final geometry (using existing readout ASICs) and aim to confirm performance in an electron beam with low momentum spread.
  - Developing a full-scale technological prototype is planned for next 3-4 years, by integrating crystal bars, readout boards embedded with SiPMs and ASICs, a cooling system within a light-weighted mechanical structure
  - Electron beams with low momentum spreads: a very stringent requirement
    - Crystal ECAL prototype shows EM resolution better than 2%, which requires beam spread well below 1%.
    - Can also use tracker + magnetic field to measure beam momentum spreads
    - (e.g. DESY 1-6 GeV electron beams: momentum spread on the order of 10% at 1 GeV)
  - Test beam facilities
    - CERN PS-T09 is the primary option (with our best understandings and hands-on experiences). But due to the Long-Shutdown 3 (LS3), we will also need to consider other options.
    - Light sources in China: need to investigate synchrotron radiation light sources (e.g. BSRF, HEPS)
    - KEK 1-6 GeV electrons: need to understand lowest possible momentum spreads
  - International Collaboration in DRD-Calo (DRD6): subtask of WP3 (i.e. WP3.1.1 HGCCAL)

Feedback to IDRC Recommendations (2)

- Further **refine calibration strategies** to ensure that necessary stability in transparency, linearity, and uniformity can be achieved in situ, without relying on a dedicated monitoring system.

  - Factors with significant impacts to the ECAL performance
    - Crystal: (1) response uniformity along the bar length, (2) batch uniformity in mass production and quality control
    - SiPM: (1) response linearity, (2) batch uniformity in mass production
    - ASIC: (1) ADC linearity, (2) switch between different gain modes, (3) batch uniformity in mass production
    - BIB: (1) extra hits mixed in signals, (2) crystal transparency degrade after calibration, (3) SiPM degrade due to NIEL
    - Temperature: (1) gradient (monitoring data for corrections), (2) fluctuation (stability)
    - Geometry effects: (1) gaps between crystals and modules, (2) insensitive materials, (3) longitudinal shower leakage
  - **Updates in Section 7.2.6 Calibration and Monitoring**
    - On-detector calibration: (1) pedestal and noise, (2) SiPM non-linearity, (3) ASIC, (4) Beam-Induced Backgrounds
    - Collision data calibration: (1) Bhabha, (2) $Z \to ee$, (3) π^0, (4) MIP, (5) others: $J/\psi \to ee$, $W \to e\nu$, $Z \to \mu\mu\gamma$
  - SiPM non-linearity calibration scheme (details in next page)

Feedback to IDRC Recommendations (2)

Detailed calibration scheme on SiPM non-linearity effects

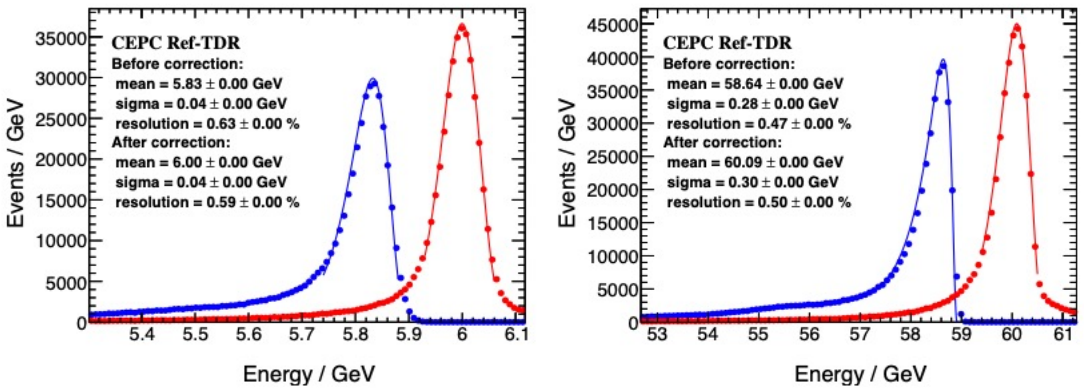
- SiPM non-linearity effects are studied by including SiPM pixel recovery during the relatively slow BGO scintillation time (typ. 300 ns), which further increases the effective number of SiPM pixels (i.e. many pixels can be fired multiple times during this scintillation process)
- Calibration is first done in an off-detector way, by extracting key parameters related to the SiPM non-linearity effects via the SiPM QA/QC database (e.g. breakdown voltage, interpixel crosstalk, etc.)
- Apply these parameters to all SiPMs in ECAL after detector assembly and use them for commissioning
- Use Bhabha events as an in-situ calibration source to monitor and calibrate SiPM non-linearity
- **Updates in Section 7.2.6 Calibration and Monitoring**

Plans beyond Ref-TDR scope

- To validate the SiPM non-linearity simulation model either using laser or in beam tests
- To test batches of SiPMs for non-linearity calibrations: to extract QA/QC parameters and to validate the proposal above

Feedback to IDRC Recommendations (3)

- Advance preliminary engineering of the gaps between modules and fully assess their impact on reconstruction performance.
- Current status
  - Engineering designs, including readout boards, cooling sheets and active cooling pipes, are added
  - An energy-correction algorithm has been developed to correct cluster energy loss in module cracks
  - Plots of EM performance have been updated, where incident photons are uniformly distributed around ECAL modules including crack regions
  - Updates in Section 7.2.5 and 7.3.4

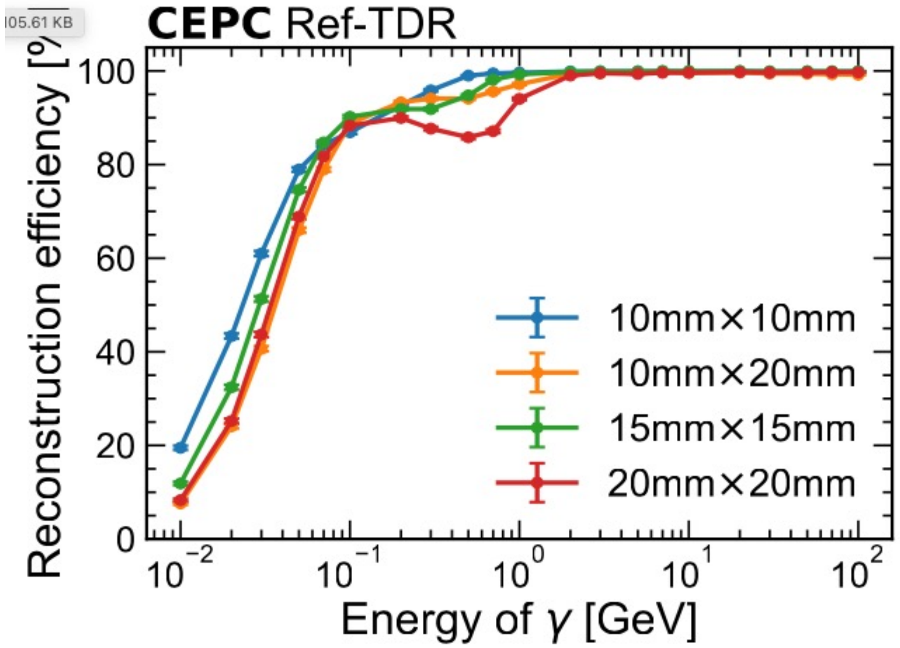


(a) 6 GeV **(b)** 60 GeV

Figure 7.21: Energy deposition of 6 GeV and 60 GeV photon with and without the energy correction. The directions of the photons are $\theta \in [40°, 140°]$ and $\varphi \in [0°, 360°]$.

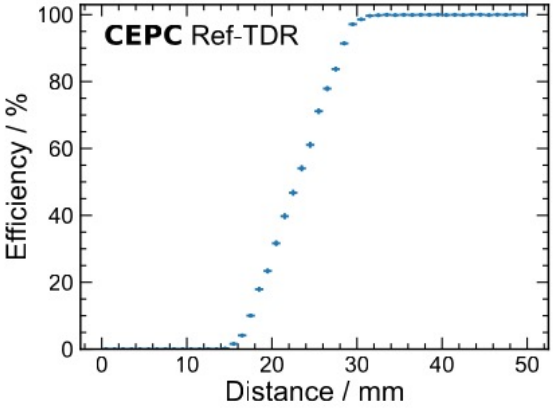
Feedback to IDRC comments

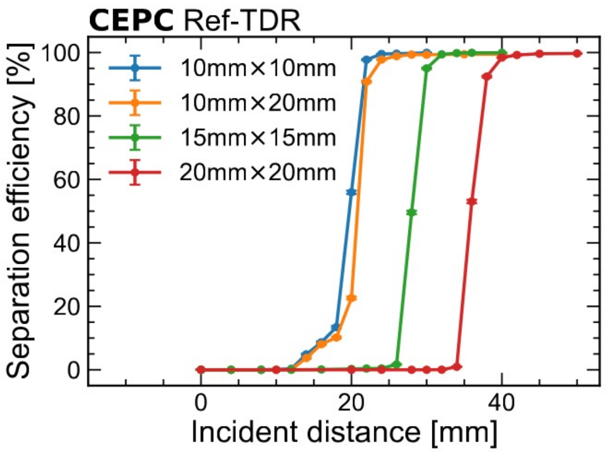
- Single photon reconstruction performance
  - IDRC review: need to describe in a more clear and consistent way how to reconstruct photons
- Current status
  - Updated CyberPFA for photon reconstruction: significant performance improvement
  - Descriptions on this part are also updated: Section 7.3.2

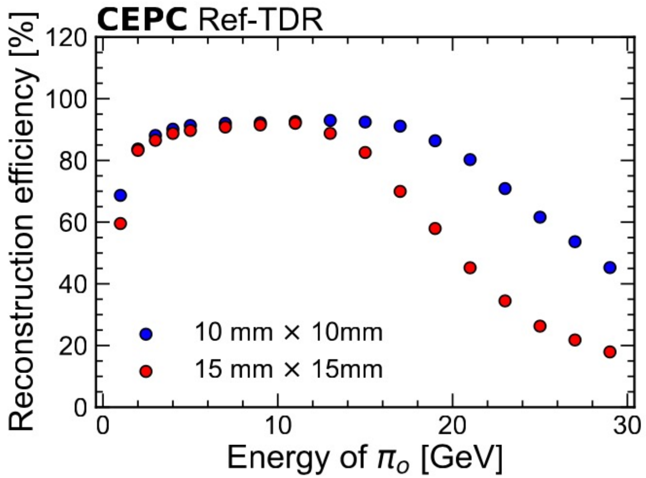


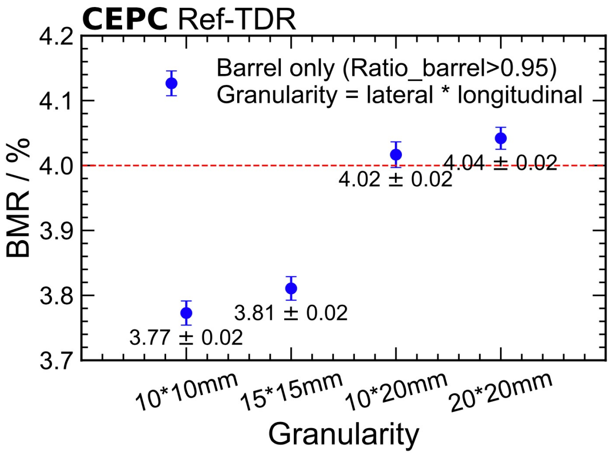
Feedback to IDRC Comments on Draft v0.4.1

- General comment
  - There is no mention of separation of showers or individual particle depositions. The parameters mentioned are energy resolutions without mentioning the segmentation (granularity) needed to achieve particle flow performance. We suggest adding mention of needed segmentation or granularity.
- Feedback
  - The two-particle separation performance (separation efficiency) is updated in Section 7.2.2 and 7.3.2
  - The required granularity of 15x15 mm is added in the updated version.









Feedback to IDRC Comments on Draft v0.4.1

- Detailed comment
  - The MIP requirement for the MIP light output has been raised from 200 to 300 p.e./MIP. While this makes the 0.1 MIP threshold for signal-to-noise ratio easier to achieve, it makes the requirement for the linearity up to 3000 MIPs (set by the maximum energy deposition from e showers for the CEPC operated at 360 GeV) more difficult to be met. Additionally, tests with prototypes show that the light yield of bars in the baseline bar configuration (1.5x1.5 x 40 cm3) are 400 pe/MIP (L.6527), thereby requiring linearity up to 106 pe and beyond. Simulation studies show that the linearity requirements are met (Section 7.3.5). However, these studies assume the nominal 300 pe/MIP and not the measured output of 400 pe/MIP for the baseline design choice for the BGO bars. Additionally, the study is limited to photons from the H → γγ decay for operation at 240 GeV, which have an energy deposition up to about 1500 MIPs (Fig. 7.5b). The SiPM dynamic range is further discussed in Section 7.4.2.2, with numbers that appear inconsistent with other parts of the TDR. For example, it is stated (L.6586) that a maximum deposition per bar of 45 GeV corresponds to 5x105 pe. However, at L.5984 it is stated that the MPV for a MIP is 13.3 MeV, which converts into 3383 MIPs for a 45 GeV energy deposition. At 300 pe/MIP, this gives already 106 pe. At 400 pe/MIP this is above 1.3x106. In summary, the effect of non linearity over the full range and up to 106 p.e. (or beyond) with SiPMs having 250k pixels does not appear to be sufficiently documented.
  - The specification about radiation hardness requirements has been dropped from the list (Table 7.1). A statement on the response stability of the BGO vs the ionization dose is needed in the section where the crystal choice is discussed, even if this is not translated into a specification.
- Feedback
  - Descriptions of the MIP response in the specification (300 p.e./MIP): updated in Chapter 7 for better consistency
  - Beam-test measurements: 307 p.e./MIP for 1x1x40cm BGO crystal bar rescaled with target 3x3mm SiPM and time window of 300ns
  - Total Ionization Dose (TID) for BGO crystals: a reference and conclusions are added in Chapter 7

Comments on Draft v0.4.1

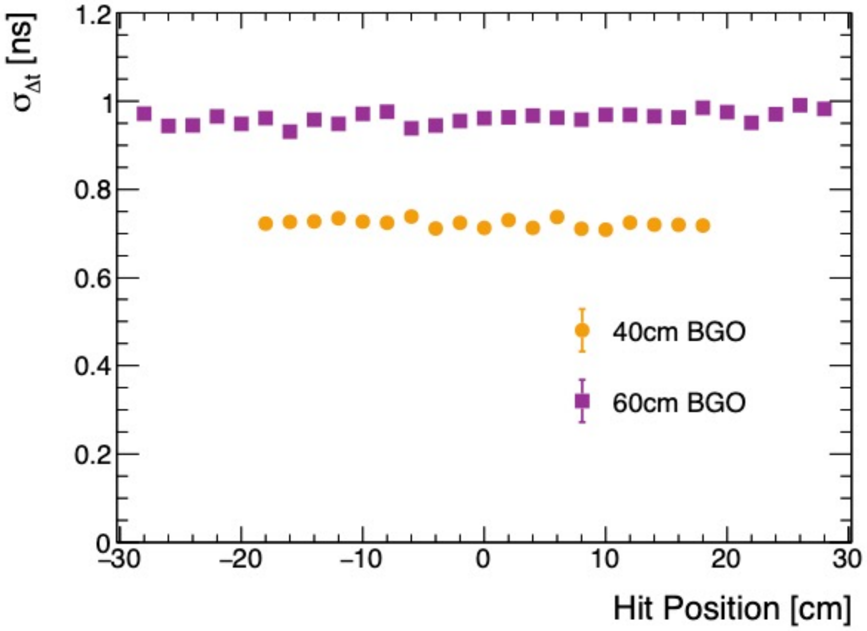
- Detailed comment
  - There are a few inconsistencies in the requirements about energy resolution. At line 5932 it is "$\sigma E/E \leq 2\%/\text{root}(E)$" while at L.1501 it is required an "energy resolution of <3%/root(E)". In other places the energy resolution is required to be less than 3% (Table 7.1) without specifying any energy dependency. Then there are instances where both the stochastic and the constant term are indicated (L. 6851 and L.1321, again with some inconsistency between 2% and 3%). Please clarify and distinguish clearly between the requirement and what is achieved. For example at L.6851, if the requirement is 3% and you achieve <2%, you can simply state that the requirement of <=3% is achieved.
- Feedback
  - Descriptions of the EM resolution requirement and performance are updated in TDR for consistency in the whole chapter

Comments on Draft v0.4.1

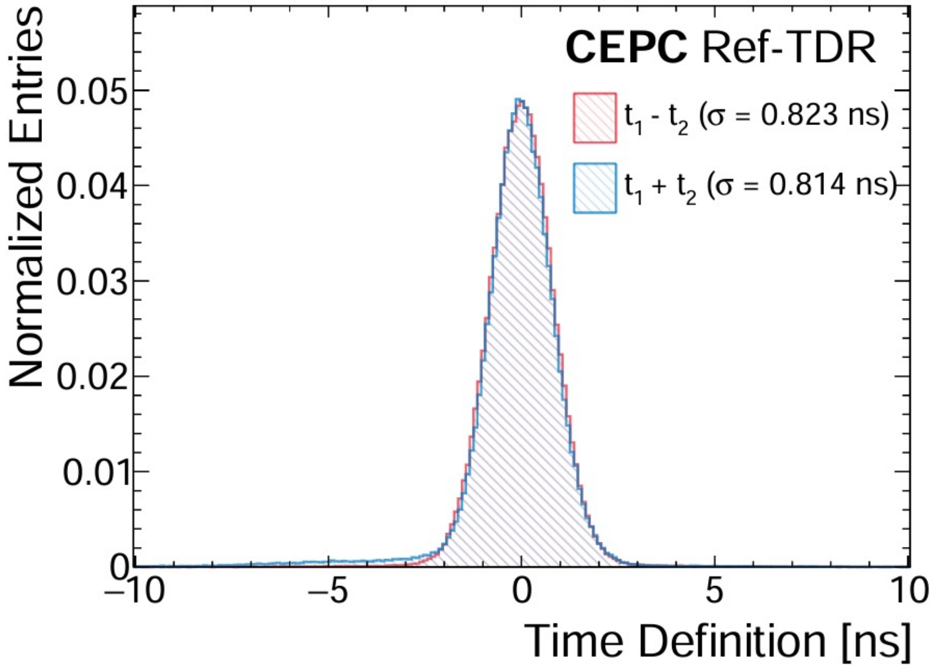
- Detailed comment
  - The discussion about timing performance (Section 7.4.3) remains confusing. The time resolution is defined as “the standard deviation of the time difference of the time stamps of SiPM signals from the two ends of a crystal”. This quantity is not independent of the hit position and does not correctly quantify the precision with which the position of a deposition can be reconstructed. A deposition in the centre of the bar, would give a Δt = 0 with an RMS from the resolution of the device. A deposition near the ends of the bar would give a distribution with the same RMS centered at Δt = +/- L/2v, where L is the bar length and v the velocity of the light in the crystal. For a uniform hit distribution, the RMS will therefore get a contribution from the propagation path of L/(v sqrt(12)) ~ 0.6 ns for L=40 cm, v = 1.5c. This should be added in quadrature to the genuine time resolution from the detector and readout. In Fig. 7.31 at L=40 cm, the resolution is 0.7 ns, which is consistent with 0.6 ns from propagation (+) 0.4 ns intrinsic to the detector, which you can read from the measurement with L=2 cm crystals. At L=60 cm, your measured resolution is almost 1 ns, which is again consistent with an L/(v sqrt(12)) ~ 0.9 ns (+) 0.4 ns. So, while your data show the expected behaviour, your interpretation of the results is different. At L 6602, you conclude that at L=40 cm, the resolution is 700 ps (500 ps per end), while your data indicate a resolution is 400 ps/MIP (280 ps per end), which would scale to a resolution of 100 ps already at 200 MeV (per crystal). A better measure of the time resolution is provided by the RMS of the sum of the two timestamps, because the sum of the two propagation times is independent of the hit position. A plot of this quantity should clarify what is the actual resolution. You may still have some dependence on the bar length, because the light output is lower for longer bars.
- Feedback
  - We have thoroughly reanalyzed the testbeam data using the definition in TDR and the suggested definition in the IDRC review. Plots are not put in the TDR but will be provided separated (next page).
  - Conclusions: the 1-MIP timing resolution along crystal length is quite uniform; the 1-MIP timing resolutions from two definitions are mostly the same.

Comments on Draft v0.4.1

Timing Resolution vs Hit Position in BGO (testbeam data)



40cm BGO scan (testbeam data)



- $\Delta T = T1 - T2$: used in Ref-TDR
- Uniform sigma(ΔT) with hit positions

Two definitions of timing resolution compared: similar performance

- T1-T2 used in Ref-TDR
- T1+T2 suggested by IDRC: to eliminate position dependence