CEPC ECAL

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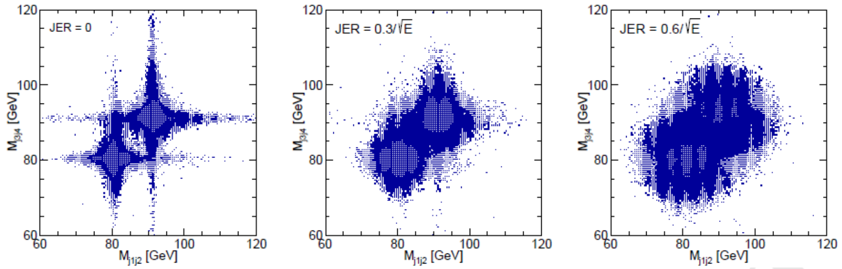
Performance Requirements

- Photon energy resolution imposed by both Jet energy measurement and $H \rightarrow \gamma\gamma$ measurement
  - $20\%/\sqrt{E} \oplus 1\%$
- Boson mass resolution (BMR) < 4% is required for W/Z separation in their hadronic decays.
  - Jet energy resolution ~ 30% /√E (E<100GeV)



(a) (b) (c)

Figure 5.1: Separation of W and Z bosons in their hadronic decays with different jet energy resolutions: $0/\sqrt{E}$ (a), $30\%/\sqrt{E}$ (b), and $60\%/\sqrt{E}$ (c). A jet energy resolution of $30\%/\sqrt{E}$ is required to separate the hadronic decays of W and Z bosons.

Particle Flow Algorithm

- Particle Flow Algorithm (PFA) is a promising approach to achieve the unprecedented jet energy resolution of 3%-4%.
  - All particles (both charged and neutral) in an event be individually reconstructed.
  - The energy/momentum of each particle in a jet is determined by making use of the optimal sub-detector.
- A highly granular and full-contained calorimeter system is required, and combined with a transparent and high-resolution tracking system.

PFA calorimeters

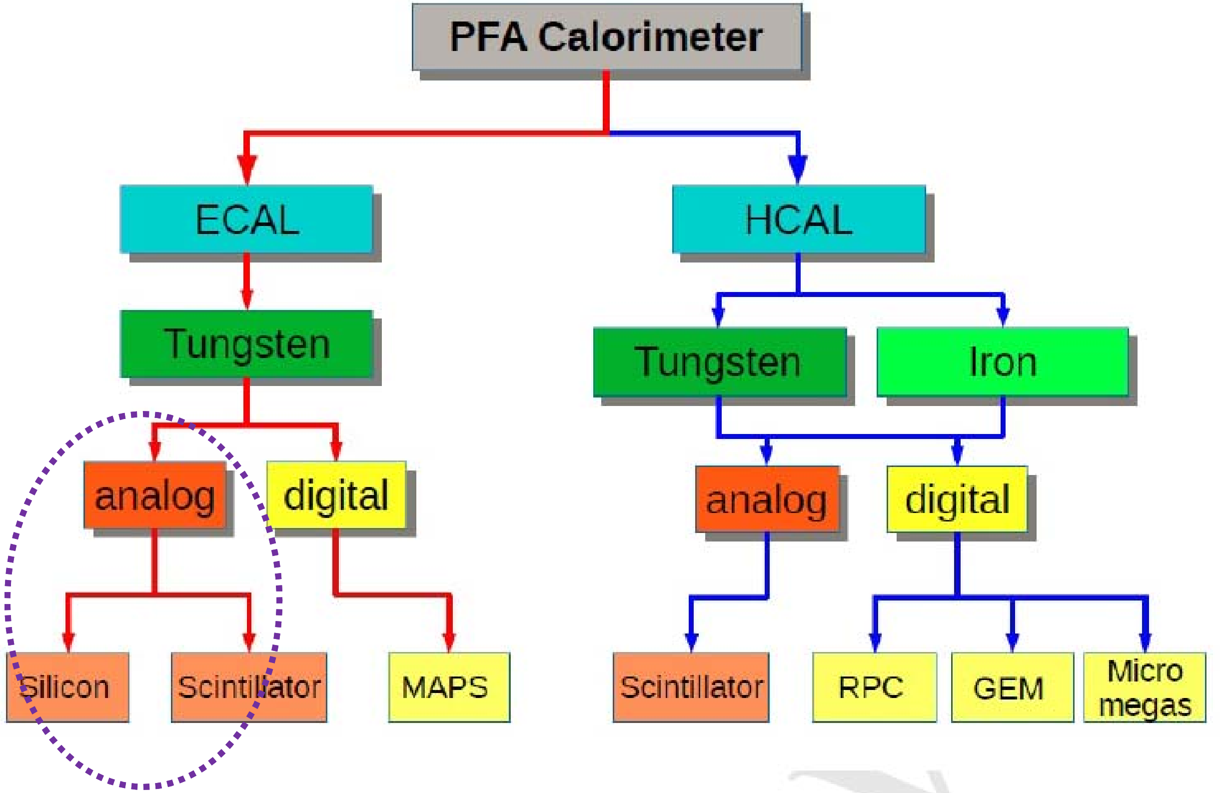


Figure 5.2: PFA: Overview of development of imaging calorimeters in the CALICE collaboration. Various technology options have been explored in aspects including absorber material, active medium and readout scheme.

- Analog ECAL options are considered for CEPC.

General Design Considerations

- A sampling calorimeter consisting of sensitive layers of either silicon pads or scintillator tiles interleaved with tungsten absorber plates.
  - Tungsten (W): short radiation length, small Moliere radius, large ratio of interaction length over radiation length.
  - Two options from two active materials: Si-W, Sci-W
- They are all highly segmented both transversely and longitudinally for excellent particle shower separation capability.
- Si-W is adopted as the ECAL baseline option.

Design Optimisation (I)

- Absorber thickness → 84 mm

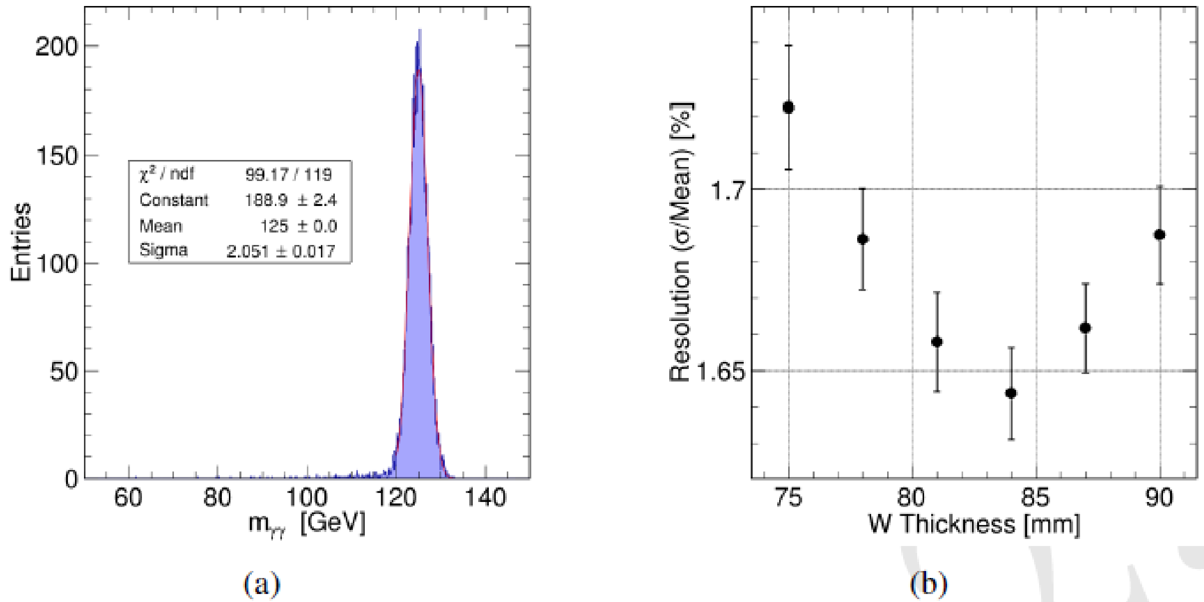


Figure 5.3: A typical distribution of Higgs boson mass reconstructed with the ECAL alone for $\nu\nu H(\rightarrow \gamma\gamma)$ events (a) and the resolution of the reconstructed Higgs boson mass for different total tungsten absorber thickness of the ECAL (b). The mass resolution is extracted from a Gaussian fit to the mass distribution. The best Higgs mass resolution is achieved when the total thickness of tungsten absorber of the ECAL is 84 mm.

Design Optimisation (II)

- Number of sampling layers → 30

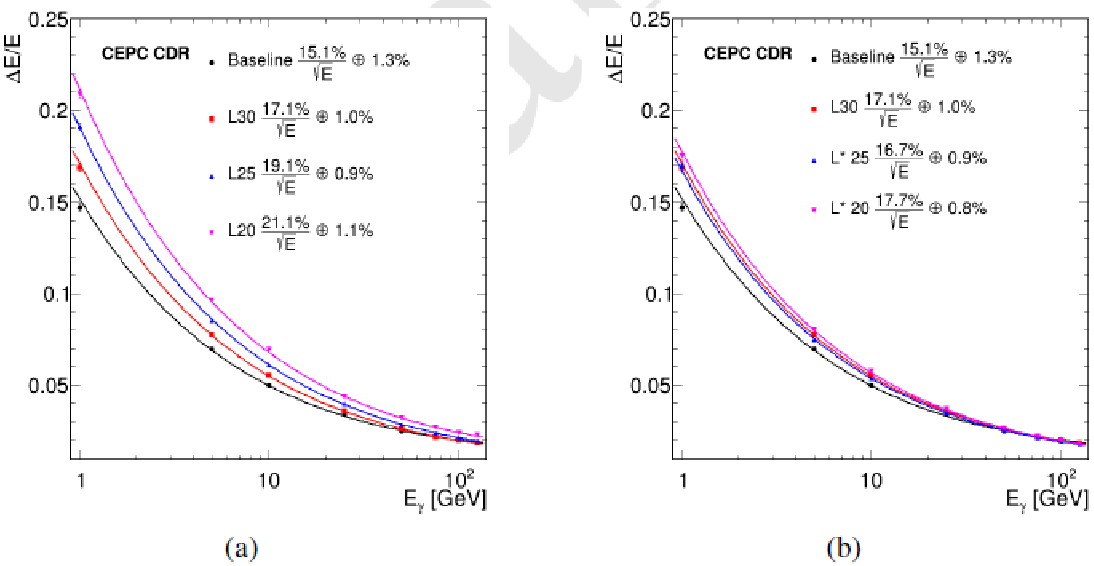


Figure 5.4: Photon energy resolution of the silicon-tungsten ECAL as a function of photon energy for different numbers of sampling layers of the ECAL(a) and together with different thicknesses of silicon sensors (b), where the thickness of silicon sensors for 30 layers is 0.5 mm, while they are 1.5 mm and 1.0 mm for 20 and 25 layers, respectively. The baseline geometry uses inhomogeneous absorber thichness, 2.1 mm tungsten for first 20 layers and 4.2 mm for last 10 layers, which is same with the CEPCv4). This design can improve the energy resolution of low energy photons. Photons are incident randomly for 4π sterad. The photon energy resolution degrades by 12% and 23% when the number of sampling layers is reduced from 30 to 25 and 20, respectively. The resolution degradation can be compensated by increasing the thickness of silicon sensors.

Design Optimisation (III)

- Cell size $\rightarrow$ 10×10 mm^2

Silicon sensor size (mm)	Higgs boson mass resolution (with statistic error)
5	3.74 ± 0.02 %
10	3.75 ± 0.02 %
20	3.93 ± 0.02 %

Table 5.1: Higgs mass resolution for the $\nu\nu$H, $H \rightarrow gg$ events for different ECAL sensor sizes. No significant impact of the sensor size on the Higgs mass resolution is found in the $\nu\nu H$, $H \rightarrow gg$ process.

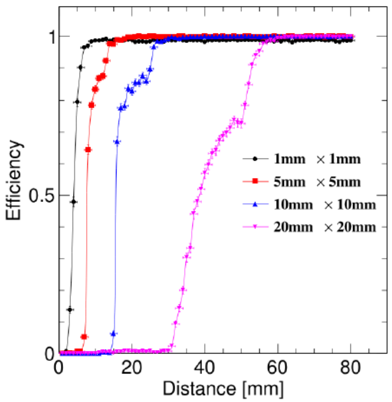


Figure 5.5: Reconstruction efficiency of events with two parallel 5 GeV photons as a function of the distance between the two photons for different ECAL sensor sizes. The reconstruction of the di-photon events is fully efficient once the sensor size is smaller than half of the distance between the two photons.

Cell size (mm)	Percentage of inseparable photons
1	0.07%
5	0.30%
10	1.70%
20	19.6%

Table 5.2: Percentage of photons in τ decays that can't be separated from neighboring particles in the ECAL for $Z \rightarrow \tau\tau$ events for different ECAL sensor sizes. Almost all photons in the τ decays can be well reconstructed for a ECAL sensor size up to 10 mm. A significant portion of the photons fail to be separated from other particles in the ECAL when the sensor size exceeds 10 mm.

ECAL Baseline Design Profile

- A Si-W sandwich calorimeter
- Absorber
  - W, 84 mm thick in total (24 X_0)
  - 30 layers (first 20 layers of 2.1mm W plates + the remaining 10 layers of 4.2mm W plates)
- Active medium
  - Si plates, each 0.5 mm thick, divided into square cells, cell size 10*10 mm^2

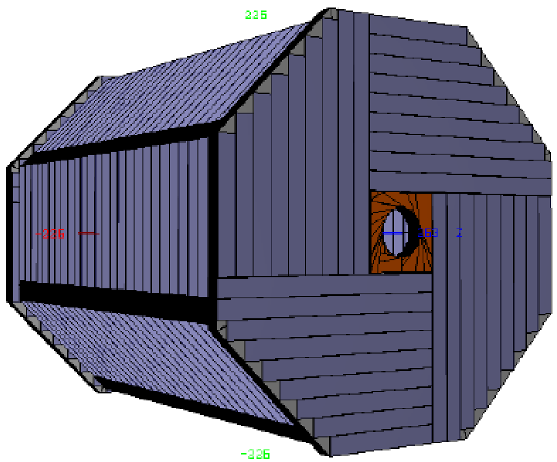
Sensor

- Silicon PIN diodes

  - Stability: under a reasonable bias voltage, a completely depleted silicon PIN diode has unity gain, and a signal response to a Minimum Ionizing Particle (MIP) mostly defined by the sensor thickness, with a relatively low dependence on the operating environment including temperature, humidity, etc.
  - Uniformity: the control of the sensor thickness within large production batches (typically to less than a percent) ensures uniform responses within a wafer and between different wafers. The non-sensitive area between wafers has recently been reduced by the use of laser cutting, thinned guard-ring design [3], and would benefit from the use of larger ingot size (8″ becoming the standard).
  - Flexibility: the dimension and geometry of the cells can be flexibly defined. The readout pads on the PCB need to be compatible.
  - High signal-to-noise (S/N) ratio: for a MIP, the most probable number of electron-hole pairs generated in 1 μm thick silicon is around 76 (while the average number is 108), which yields an excellent S/N ratio of silicon sensors. Thus, MIP tracks can be easily tracked in the calorimeter, which is critical to the good performance of the ECAL.

Geometry and mechanical Design

- One cylindrical barrel + two disk-like endcaps
- 8 barrel sections, each consisting of 8 staves
- Each endcap consists of 4 quadrants, each consisting of 2 modules.



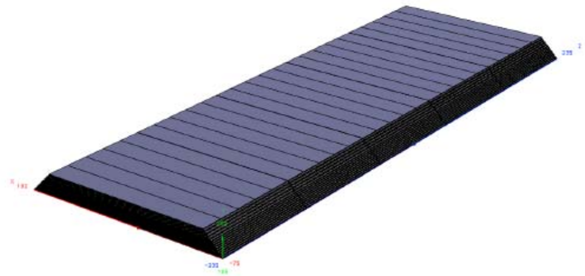


Figure 5.7: Schematic of the structure of one ECAL stave. Each stave is made up of 5 trapezoidal modules, and each module contains up to 5 columns.

Figure 5.6: Schematic of the CEPC ECAL layout in its baseline design. The ECAL is organized into one cylindrical barrel and two disk-like endcap sections, with 30 layers in each section. The barrel section is arranged into 8 staves, each consisting of 5 trapezoidal modules. Each of the two endcap sections is made of four quadrants, each consisting of 2 modules. The ECAL barrel overall radius is 2028 mm in X-Y plane, the two endcaps are located at ±2635 mm.

Electronics Parameters

Dynamic range: A MIP going through a 500 μm silicon diode will produce around 60000 electron-pairs holes (or a charge of 9.6 fC) as the most probable value (MPV). To record MIPs with an efficiency higher than 95%, this determines the lower limit of the dynamic range to a 1/3 of the MPV. The higher limit is given by the number of MIP equivalents at the core of the high-energy EM showers, which can reach up to 10000 MIPs (or 96pC) within a $11 \times 11\ \text{mm}^2$ cell.

Timing: Time measurements of energy depositions in the calorimeters can be useful to Particle Flow algorithms to help disambiguate particle contributions. For the CEPC as a lepton collider, normally with a single primary vertex, precision timing of individual cells - or group of cells - could still be useful to reduce the confusion in the calorimeters and improve the energy resolution, which however needs further studies to quantitatively explore this potential. A SiW-ECAL ASIC with the most recent version (SKIROC2A) has been tested on a test board and reached a measure of timing resolution close to 1.1 ns for a signal amplitude corresponding to 5 MIPs [4].

Power consumption: The running conditions of a circular collider exclude pulsed operation as is planned for the linear colliders. As a point of reference, the current power consumption for the SKIROC2 chip is around 5 mW per channel in the continuous operating mode.

Occupancy: The occupancy of the calorimeters is expected to be very low. This offers room for an ultra-low power electronics design when there is no signal.

Power consumption and cooling

- Both passive and active cooling schmes are considered since CPEC ECAL is at the boundary of the two options.
  - Passive cooling requires a reduced number of channels
  - Active cooling is the baseline cooling scheme. A two-phase, low mass CO_2 cooling system is a promising technology option.

An alternative ECAL: Sci-W

- Advantage in cost
- Layout and structure quite similar to Si-W
- Same is for major design parameters
- The primary difference is in the thickness of active layers
  - 2 mm thick scintillator tiles
- Explore strip configuration to get a higher effective granularity

Layout of a Sci-W module

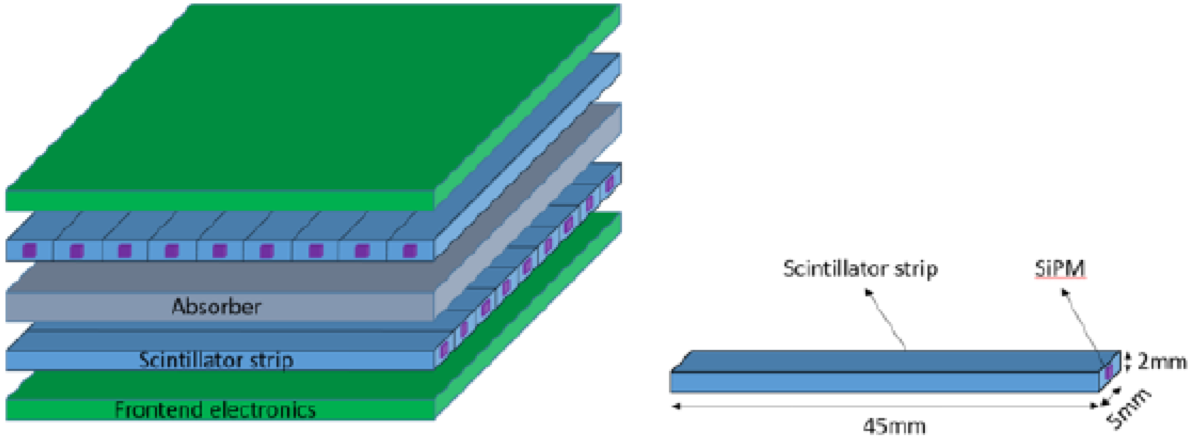
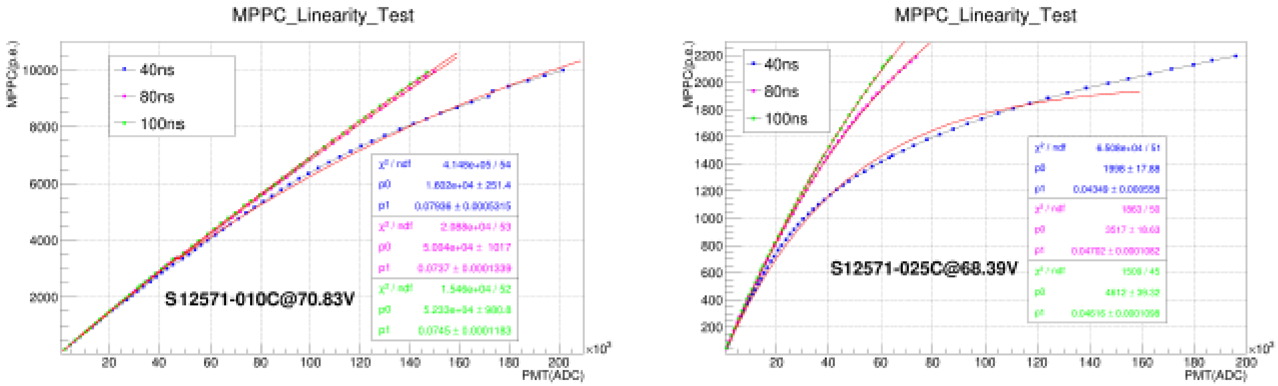


Figure 5.8: Layout of a scintillator-tungsten ECAL module and dimensions of a scintillator strip. The scintillator strips in adjacent layers are perpendicular to each other to achieve a small effective transverse readout cell size.

- Studies required to demonstrate the effectiveness of the strip configuration

SiPM dynamic range

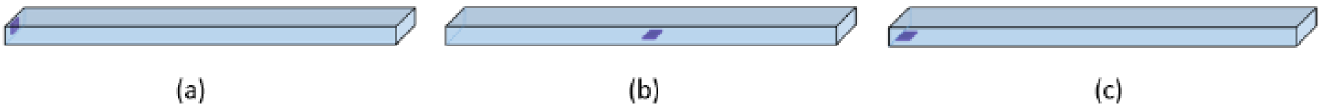


(a) (b)

Figure 5.9: Response linearity (the number of photo-electrons detected with a SiPM as a function of the number of incident photons) of SiPMs with different numbers of pixels [(a): 10000-pixel SiPM, (b): 1600-pixel SiPM] for light pulses with different widths (blue: 40ns, red: 80ns and green: 100ns). The linearity of SiPM response with 10000 pixels is better than that with 1600 pixels. And the range for linear response of SiPM gets larger for a wider light pulse.

- A dynamic range up to ~800 MIPs is required for H$\rightarrow\gamma\gamma$ measurement.
- Small pitch (e.g. 10 μm) and large-area SiPM is needed.

Scintillator Sensitive Unit



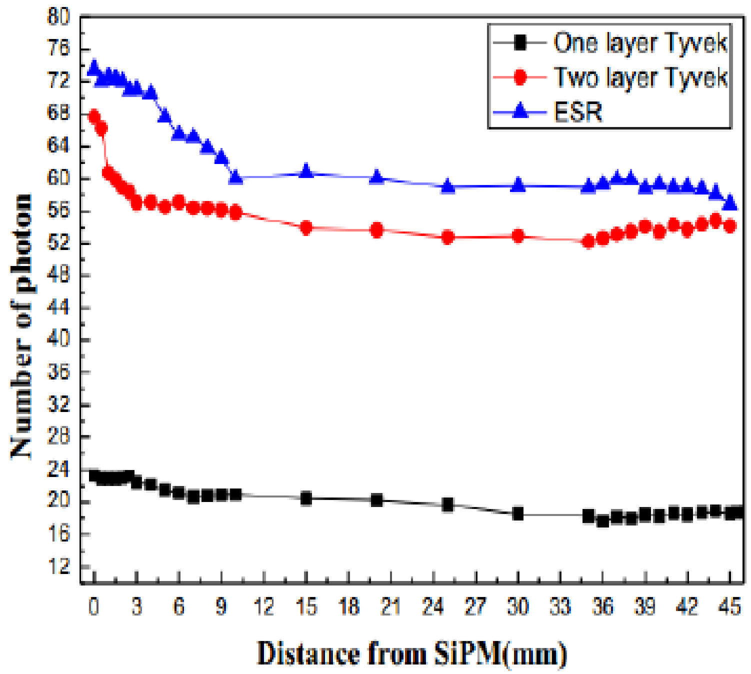


Figure 5.12: Light yields of scintillator strips with different reflectors versus the distance of an incident particle from SiPM . The scintillator with ESR gives the highest light yield.

Sensitive Unit Performance

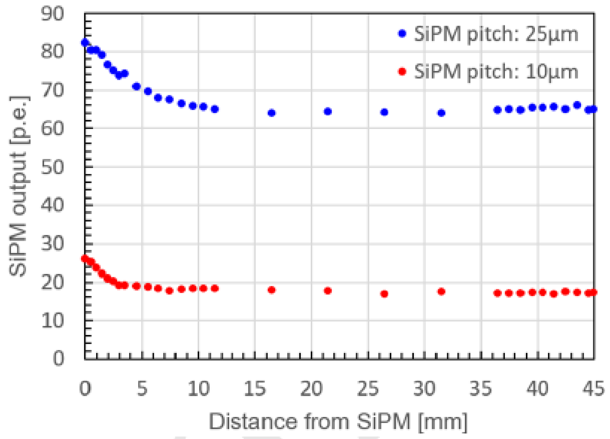


Figure 5.13: Light yields of scintillator strips coupled with SiPMs with different pitch sizes (red: 10 μm, blue: 25 μm). The SiPM with the larger pitch size of 25 μm has a significant higher light yield (about 65 p.e.) than that with the smaller pitch size of 10 μm (about 18 p.e.) due to a higher photon detection efficiency.

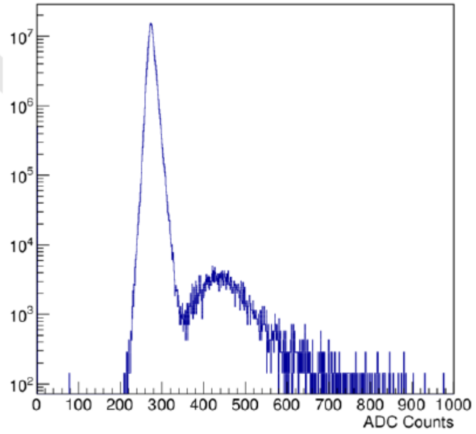


Figure 5.14: The pulse height distribution for cosmic-ray signals of the scintillator sensitive unit with a 10 μm SiPM. Cosmic-ray signals can be found well separated from noise demonstrating the sensitivity of the scintillator sensitive unit to M.I.Ps.

SiPM Readout and Calibration

- SPIROC chip is a good reference as a SiPM readout chip for the CEPC ECAL.
  - Large dynamic range and good charge resolution
  - Sub-ns timing resolution
- A SiPM monitoring and calibration system consisting of pulse generators, chip LEDs, and notched fibers

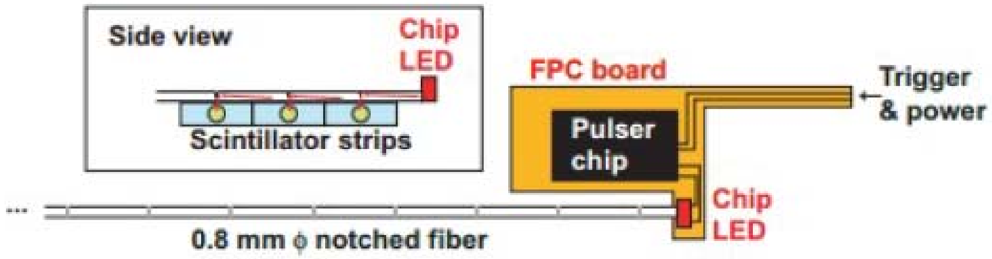


Figure 5.16: Schematic of the SiPM gain monitoring system with LED and notched fiber. Light pulses from the LED are scattered and distributed into each strip.

Summary

- Baseline PFA ECAL for CEPC
  - Si-W, 30 sampling layers
  - Absorber layers
    - 84 mm thick W (24 X_0), 20 layers of 2.1mm W plates + 10 layers of 4.2mm W plates
  - Active layers
    - 0.5 mm thick Si plates divided into square 10*10 mm^2 cells
- Alternative option
  - Sci-W
  - 2mm thick scintilator readout with SiPM