PROCEEDINGS OF SCIENCE

ALICE Forward Calorimeter upgrade (FoCal): Physics program and performance

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A new high-precision forward calorimeter (FoCal) is about to be installed in the ALICE experiment at the LHC during Long Shutdown 3 for data-taking in the LHC Run 4 that is currently scheduled for the period 2030-2033. FoCal consists of a Si+W sampling electromagnetic calorimeter with longitudinal and transverse segmentations (FoCal-E) and a conventional Cu+scintillating-fiber hadronic calorimeter (FoCal-H). FoCal has a front face of approximately 90×90 cm^2 and is placed at $z = 7$ m from the nominal interaction point. It covers the pseudo-rapidity range of $3.2 < \eta < 5.8$. FoCal has unique capabilities to measure the direct photon production at the forward rapidity that probes the gluon distribution in protons and nuclei at small-x. Furthermore, FoCal will enable to carry out inclusive and correlation measurements of photons, neutral mesons and jets in hadronic pp and p-Pb collisions as well as J/ψ production in the ultra-peripheral p-Pb and Pb-Pb collisions. We developed a full-length detector prototype and studied its performance such as a response to minimum ionizing particles and a longitudinal shower profile of electromagnetic showers at the CERN PS and SPS complexes in 2022-2023. We tested the silicon pad sensors for FoCal-E at the RIKEN Accelerator-driven compact neutron systems (RANS) facility in Japan in 2022-2024 and they have the radiation tolerance to withstand the full operation at the LHC Run 4. Mass production of FoCal will begin soon.

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1. Introduction

As an upgrade project of A Large Ion Collider Experiment (ALICE) at the Large Hadron Collider (LHC), an extensive R&D program of a new high-precision forward calorimeter (FoCal) was carried out [1-6]. FoCal consists of a longitudinally and transversally segmented silicon-tungsten electro-magnetic calorimeter (FoCal-E) in the front and a conventional copper+scintillating-fiber hadronic calorimeter (FoCal-H) just behind FoCal-E as shown in Fig. 1. The front face of FoCal will be approximately 90×90 cm^2 and placed at 7 m from the nominal interaction point, in front of the compensator magnet and outside the magnet doors of the ALICE solenoid on the A-side, opposite the muon arm. FoCal will cover the pseudo-rapidity ranges of $3.4 < \eta < 5.5$ over the full azimuth and $3.2 < \eta < 5.8$ with the partial azimuthal coverage. FoCal is mainly designed for the measurement of isolated photons at the forward rapidity in pp and p-Pb collisions, specifically the precise discrimination of neutral-pion decay photons and prompt photons. To satisfy the requirements, a sampling calorimeter design is well suited for both FoCal-E and FoCal-H.

2. Physics programme

The gluon density of matter is expected to saturate at low momentum fraction x, and QCD evolution is expected to be non-linear. Measurements of prompt and isolated photons at small x and Q^2 provide incisive probes of the small x structure of matter and a key role in the search for evidence of non-linear QCD evolution at small-x [2,3]. FoCal has unique capabilities for forward measurements of direct photons, neutral mesons, vector mesons, jets, Z-bosons and their correlations in hadronic pp and p-Pb collisions and in ultra-peripheral p-Pb and Pb-Pb collisions. One of the key challenges for the measurement of prompt-photon production is the discrimination of signal photons, and FoCal will utilize three techniques to enhance the signal contribution; (1) Isolation: Measurement of the isolation energy in FoCal-E and FoCal-H in a cone of given radius around the photon candidate, with rejection of candidates with isolation energy above a specified threshold. (2) Invariant mass tagging: Rejection of photons originating from π^0 decays using the invariant mass of cluster pairs. (3) Shower shape tagging: Rejection of elongated clusters originating from decay photons with small opening angle. In addition to prompt photons, FoCal will perform measurements of neutral and vector mesons, two-particle azimuthal correlations for the π^0-π^0 and photon-π^0 systems, but also vector meson photoproduction in ultra-peripheral collisions. FoCal will also carry out long-range correlation measurements in conjunction with the detector systems of the ALICE central barrel located at mid-rapidity ($-0.9 < \eta < 0.9$), and the muon arm on the opposite side of ALICE ($-4 < \eta < -2.5$).

3. Detector design

3.1 FoCal-E

We are going to challenge the measurements of both direct photons in pp and p-Pb collisions at the forward rapidity and high transverse-momentum neutral pions in Pb-Pb collisions. To optimize the photon shower separation and to minimize occupancy effects, FoCal should have a small transverse-shower size together with the minimum production costs. Consequently, FoCal-E

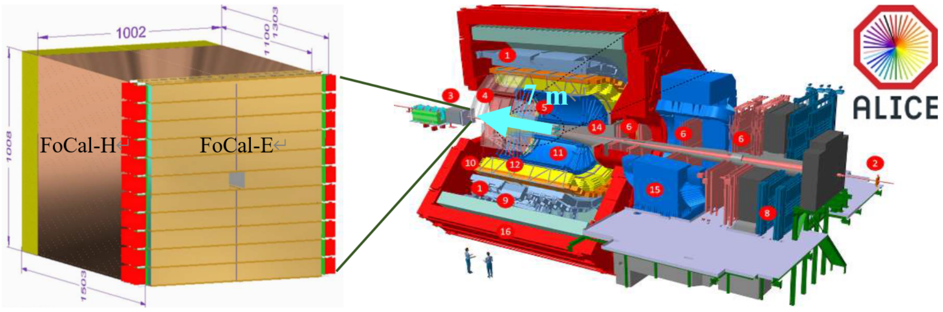

Figure 1: A new high-precision forward calorimeter (FoCal: FoCal-E & FoCal-H) for the ALICE experiment at the LHC. Figure taken from Ref. [6].

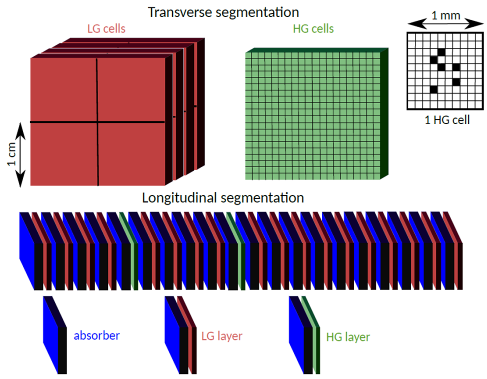

Figure 2: A basic design of FoCal-E with 18 low-granular layers for the analog readout and 2 high-granular layers for the digital readout. Figure taken from Ref. [6].

is a compact sampling calorimeter using two different silicon-sensor technologies and the tungsten absorber which has a small effective Moliére radius (R_{M} = 0.9 cm) and one radiation length (X_0 = 3.5 mm). Fig. 2 shows a basic design of FoCal-E with 20 layers, corresponding to 20 X_0 in a total depth, to provide sufficient linearity at large energies. The two layers located at the 5th and 10th positions are the high-granular (HG) layers using silicon pixel sensors with digital readout, and they provide crucial information for the π^0 identification and the capability to resolve multiple hits in a high multiplicity environment. Others are the low-granular (LG) layers using the large-size silicon pad sensors with the analog readout to measure the energy of electromagnetic showers and provide the important information about the longitudinal electromagnetic shower profiles.

3.2 FoCal-E Pad (LG layers)

The LG layer within FoCal-E is made out of the tungsten alloy plate, five silicon pad sensors and five printed circuit boards (PCBs) hosting the HGCROC-series front-end chips each. The dimensions of the plate as a passive absorber are 464 mm (length) × 84 mm (width) × 3.5 mm (thickness) corresponding to one X_0. Chemical compositions, density and hardness of the plate are Tungsten (94%), Nickel (4%) and Copper (2%), 17.8 g/cm^3 and 103 HRB, respectively. In order to assemble the layers into a module properly, good parallelism and flatness of the plate are required, and M2 threaded screw holes are formed on the side of the plate for fixing and positioning. The quality of the full-size prototypes by Nippon Tungsten Co., Ltd. was satisfactory, and mass production of 440 plates in total is foreseen in 2025-2026. We will check all plates using high-precision thickness sensors and edge-extractable close-up cameras after delivery.

Another key component for the LG layer is the large-size silicon pad sensor with the high radiation tolerance. The estimated radiation dose in the innermost part of FoCal-E is approximately equal to 7×10^{13} 1 MeV n_{eq} / cm^2 over the full Run 4 period including a safety factor. Several types of p- and n-substrate silicon pad sensors were manufactured by way of trial and those characteristics were studied through irradiation tests at the RIKEN Accelerator-driven compact neutron systems (RANS) facility in Japan and beam tests including temperature dependence. We try to operate the sensors at room temperature even after a leakage current of the sensor increases by radiation damage. Finally, the p-substrate silicon PIN photodiode array from the 6-inch double-sided polished wafer with <100> orientation by Hamamatsu Photonics K. K. has been proven to be able to operate in such environment. The sensor contains $9 \times 8 = 72$ main photodiode cells and 2 small calibration cells with pitch sizes of 10×10 mm^2 and 3×3 mm^2, respectively, as shown in Fig. 3. The external dimensions of the sensor are 92.6×82.6 mm^2 including guard rings, and it is designed to withstand up to a reverse bias voltage of 1 kV at the maximum. The calibration cell is electrically isolated from the main cell in the same area, and it is mainly used to track a Minimum Ionizing Particle (MIP) position as it has a better signal-to-noise ratio (S/N) than the main cell due to its smaller pitch. Both the light shield with an aluminum coating on the surface and a low-impedance ground connection to the substrate from the back of the sensor are effective to improve the overall S/N and stability. While the sensor thickness is 320 µm, the depth of the active area, where the depletion region is produced, is about 290 µm. We developed a new probe station with 82 probe pins for the detailed quality check of all the 1,980 silicon pad sensors as shown in Fig. 4.

The front-end electronics for the LG layer should have 74 input-channels with an expected small signal of 3 fC for the MIP and a wide dynamic range of about 1-to-1000 MIPs. Furthermore, it must work with the 40 MHz bunch crossing structure of the LHC and have a radiation tolerance with good reliability to guarantee the uninterrupted operation of FoCal-E. The front-end chip which satisfies these requirements is the HGCROC-series ASIC [8], developed by the Omega group for the CMS High Granularity Calorimeter. To test the full-length FoCal-E prototype, we used the HGCROC V2 chips that each input-channel has a charge-sensitive preamplifier with a configurable feedback network, shaping filters, a 12-bit ADC and two independent discriminators with respective TDCs for the Time-Of-Arrival (TOA) and the Time-Over-Threshold (TOT). The TOA is used to compute the TOT, which is used to extend the dynamic range beyond saturation of the ADC and of the preamplifier. We will use the later version of HGCROC-series ASICs in the final design. The front-end PCB hosting the HGCROC-series ASIC together with low drop-out linear regulators, bias resistors and high-voltage DC-cut capacitors is glued on the surface of the silicon pad sensor, and they are electrically connected with each other by aluminum bonding wires through holes of the PCB. The LG layer is formed by aligning five pairs of the sensors and PCBs horizontally on the tungsten alloy plate, and four LG layers constitute the "Pad only segment" as shown in Fig. 5.

3.3 FoCal-E Pixel (HG layers)

The tungsten alloy plates are the common components for both HG and LG layers, and the silicon sensor for the HG layer is the ALICE Pixel Detector Monolithic Active Pixel Sensor [9], which was developed for the ALICE upgrade of the Inner Tracking System and the Muon Forward

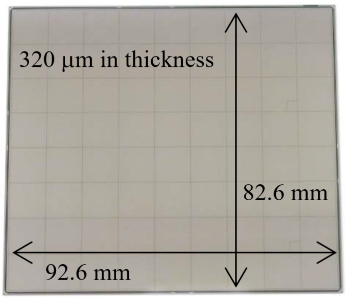

Figure 3: The p-substrate silicon pad sensor with 72 main cells and 2 calibration cells for the LG layers.

Figure 4: A new probe station for the quality check of the silicon pad sensors.

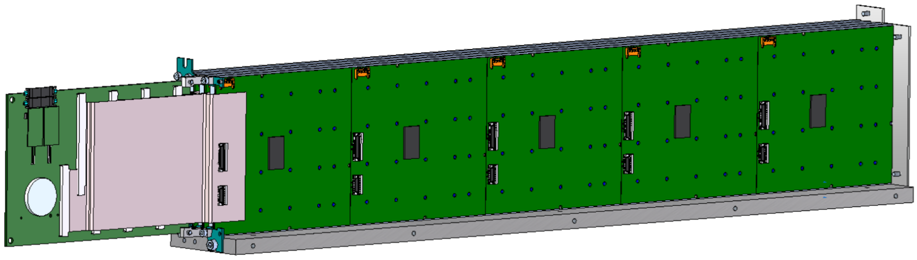

Figure 5: The "Pad only segment" with four LG layers. Figure taken from Ref. [6].

Tracker. The total area of the sensor is 30 × 15 mm^2, of which 29.94 × 13.76 mm^2 is the pixel area, with the remainder at the lower edge containing digital circuitry for readout and control. The size of an individual pixel is 29.24 × 26.88 μm^2, containing the charge collection diode, amplification circuit and discriminator. For assembling one HG layer, three 15-chip strings are glued onto an aluminum carrier next to each other, and two carriers are assembled together back-to-back. A unit that one HG layer is placed in front of the "Pad only segment" is called the "Pad & Pixel segment". Two "Pad only segments" and two "Pad & Pixel segments" are used to assemble a full-length module with 20 layers in total, and we are going to produce 22 modules to realize FoCal-E.

3.4 FoCal-H

FoCal-H, that is the hadronic section of FoCal, covers the same pseudo-rapidity range as FoCal-E. In contrast to FoCal-E, FoCal-H has transverse but not longitudinal segmentation. FoCal-H consists of copper capillary tubes filled with plastic scintillating fibers. An outer diameter and a depth of the tube are 2.5 mm and 1,100 mm, respectively, corresponding to a total thickness of approximately 5 λ_{int}. The weight of FoCal-H is estimated to be about 7,000 kg. The number of fibers, which cover a lateral area of approximately 10 × 10 mm^2, are gathered into a bundle to be read out by a silicon photomultiplier (SiPM). The number of SiPMs which cover the whole area of FoCal-H amounts to about 10,000. For reading signals of SiPMs, we will use the H2GCROC chip (or its later version). The H2GCROC chip was developed by the Omega group for the CMS High Granularity Calorimeter as well, and "H2" denotes the version developed for SiPMs. Most of the functionalities of the H2GCROC chip are common with the HGCROC V2 chip. Some candidates of plastic scintillating fibers and SiPMs were tested, and two FoCal-H prototypes were developed so far.

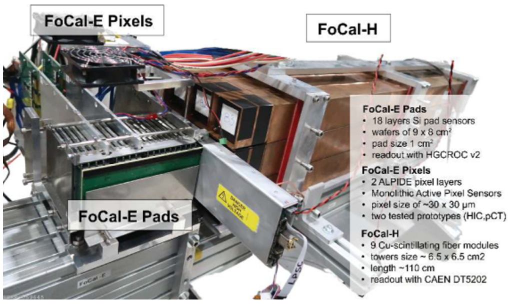

Figure 6: A new full-length FoCal prototype. Figure taken from Ref. [6].

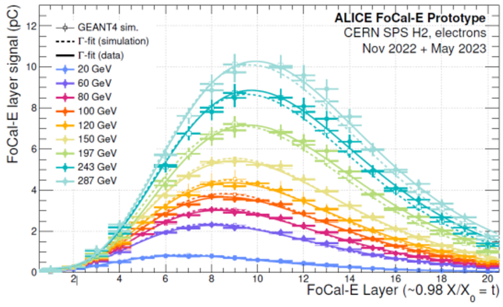

Figure 7: Longitudinal electromagnetic shower profiles for 20-to-300 GeV. Figure taken from Ref. [5].

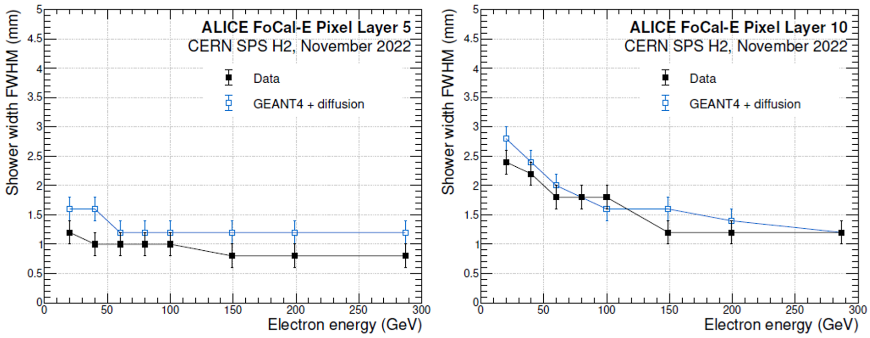

Figure 8: The measured and simulated FWHM versus electron energy. Figure taken from Ref. [5].

4. Beam test campaign

Fig. 6 shows a new full-length detector prototype with a single tower of FoCal-E and 3×3 towers of FoCal-H, which was developed to investigate performance of the actual detector. Data taking was carried out at the CERN PS and SPS complexes in 2022 and 2023 as a FoCal beam test campaign. For FoCal-E, comprehensive studies of the response to MIPs across the LG layers exhibited very clean signals and good stability. Longitudinal shower profiles for 20-to-300 GeV from measurements with electrons gave good agreement with simulations as shown in Fig. 7. Linearity of the electron response was also found to be in good agreement between data and simulations, over the full range of available energies. The relative energy resolution was found to be less than 3 % at energies larger than 100 GeV. Though one LG layer was missing at the time, data up to 300 GeV demonstrated that the energy resolution fulfilled the physics requirements. The electromagnetic transverse shower profiles in the 1st and 2nd HG layers, at the 5th and 10th positions, respectively, in FoCal-E, were measured, and its width was quantified using the Full Width Half Maximum (FWHM) between 1 mm and 3 mm according to an increase of electron energy as shown in Fig. 8. It was found to be well described by simulations demonstrating the ability of the calorimeter to resolve two-showers on that scale. For FoCal-H, the response to hadrons at various energies was measured, and it was found to be linear. The corresponding resolution was 16 % at 100 GeV and 11 % at 350 GeV. The constant term of the resolution is estimated to be 10 %, likewise meeting the physics requirements.

5. Summary

A new high-precision forward calorimeter (FoCal) will be installed on the A-side of the ALICE experiment as an upgrade project. FoCal consists of a Si-W sampling electromagnetic calorimeter (FoCal-E) and a conventional Cu+scintillating-fiber hadronic calorimeter (FoCal-H). FoCal-E has a hybrid design with analog-readout silicon pad sensors (LG layers) and digital-readout silicon pixel sensors (HG layers). After an extensive R&D program, a full-length detector prototype was developed, and its performance was studied at the CERN PS and SPS complexes in 2022 and 2023. The test beam results confirmed that the detector prototype fulfills the physics requirements such as very clean signals and good stability for the MIP measurement, longitudinal electromagnetic shower profiles with a good energy resolution, the ability of the calorimeter to resolve two-showers, and a good response to hadrons at various energies. Irradiation tests of the silicon pad sensors and electronics components for the LG layers were carried out at the RIKEN RANS facility in Japan as well. We developed the detailed quality check systems for the silicon pad sensors and tungsten alloy plates. Mass production will begin soon and the installation of FoCal is foreseen for the end of the LHC Long Shutdown 3. FoCal will be ready to record data from pp, p-Pb and Pb-Pb collisions for both hadronic interactions and ultra-peripheral collisions during the LHC Run 4 that is currently scheduled for the period 2030-2033.

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