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Latest Results from ALICE FoCal Prototypes

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The addition of a Forward Calorimeter (FoCal) to the ALICE experiment is proposed for LHC Run 4 to provide unique constraints on the low-x gluon structure of protons and nuclei via forward measurements of direct photons. A new high-resolution electromagnetic silicon-tungsten calorimeter using both low-granularity silicon pads and high-granularity silicon pixel layers is being developed to discriminate single photons from pairs of photons originating from π^0 decays. A conventional sampling hadron calorimeter is foreseen for jet measurements and the isolation of direct photons. This article reports on results from test beam campaigns in 2021 and 2022 at CERN with first prototypes for the electromagnetic and hadronic calorimeter.

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1. Introduction

Parton distribution functions (PDFs) describe the probability that a parton (quark or gluon) carries a certain momentum fraction x of protons and nuclei. Their properties depend on the energy scale Q^2 and are determined experimentally by reconstructing the kinematics in parton scattering processes. Through measurements of neutral current or Drell-Yann processes, the PDFs are very well constrained over several orders of magnitude of x for relatively large energy scales ($Q \approx 90\,\mathrm{GeV}$). At lower momentum transfers ($Q \gtrsim 1\,\mathrm{GeV}$), deep inelastic scattering processes are used for the determination of the PDFs. They provide constraints down to values of $x \gtrsim 10^{-3}$. The regime of $x \lesssim 10^{-5}$ is not yet explored and the behavior of the PDFs there is unclear. It is expected that the effect of gluon saturation becomes dominant, leading to non-linear and divergent terms for the evolution of the PDFs. Processes with production of prompt, isolated photons provide access to measuring the properties of the PDFs at low x since photons couple to quarks, but are not affected by the strong fragmentation process. Additionally, these processes exhibit a clear signature in the detector and have the potential to further explore the nature of the quark-gluon content in hadrons. When probing the parton content in hadron collisions, the momentum fraction x, reconstructed from the detected collision products, is approximately given by $x \approx 2p_\mathrm{T}\exp(-y)/\sqrt{s}$, with the transverse momentum p_T and the rapidity y of the photon, and the center-of-mass energy of the collision process $\sqrt{s}$. Hence, the sensitivity for low values of x can be significantly increased with a detector acceptance for low p_T and high rapidities y.
The main background for isolated photons in hadron collsions is the production of boosted π^0 which decay into a photon pair with small opening angle. The isolated photon signal has to be discriminated against this background which makes it necessary for the detector to resolve the two individual photons of the π^0 photon pairs. With the capability of a 2γ-separation better than 5 mm, a distance of 7 m from the interaction point, and a detector acceptance in regions up to $\eta > 5$, the domain of $x \approx 10^{-5}$ becomes experimentally accessible at LHC. The above considerations motivate the design and the installation of the ALICE FoCal detector [1].

2. ALICE FoCal Detector Concept

The design of the Forward Calorimeter for the ALICE experiment, ALICE FoCal, is driven, amongst other aspects, by the measurement of prompt isolated photons at low p_T in the very forward direction. The FoCal features a tungsten electromagnetic calorimeter with silicon sensors (FoCal-E), followed by a copper hadronic calorimeter with scintillating fibers (FoCal-H). A sketch of the FoCal design is shown in Fig. 1. It is built around the beam pipe and situated approximately 7 m away from the LHC interaction point, integrated in the ALICE detector. The minimum radial distance from the beam center is 4.5 cm, and the transverse extent in x-y-direction is approximately 90 cm × 90 cm, covering a pseudo-rapidity range of $3.4 < \eta < 5.8$. The installation of FoCal is foreseen for 2028 in order to be ready for data taking in LHC Run 4 starting from 2029.

For FoCal-E, a tungsten sampling calorimeter with 20 layers of W-plates is utilized. Each tungsten plate has a thickness of one radiation length $X_0 = 3.5$ mm, resulting in an overall radiation length of 20 X_0. The small Molière radius of tungsten ($r_\mathrm{M} = 0.93$ cm) is a key property for the two-gamma shower separation. There are 18 layers equipped with low-granularity silicon pads sensors,

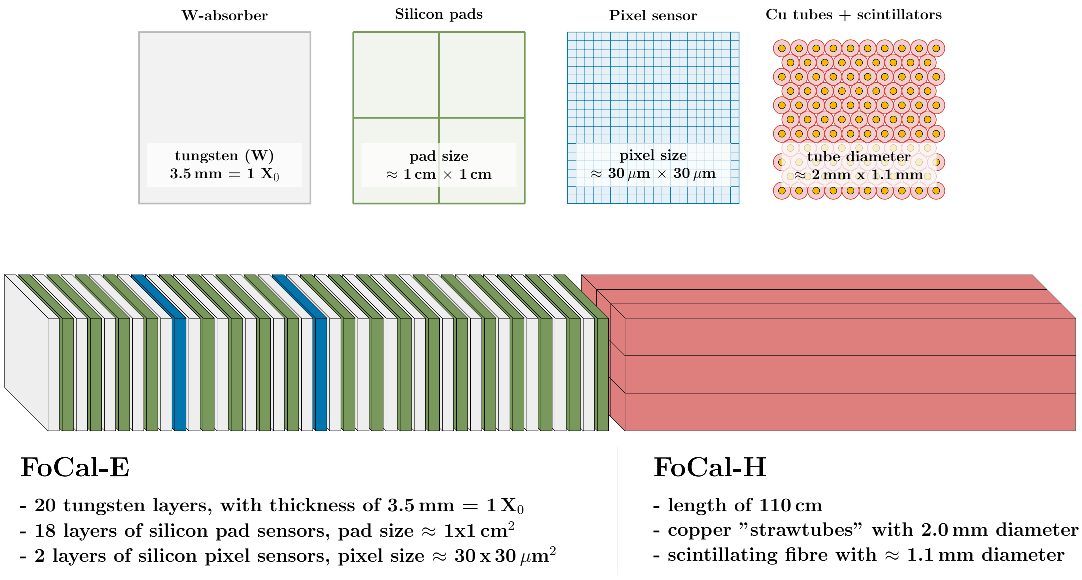

Figure 1: Detector design of the ALICE FoCal. A silicon-tungsten sampling electromagnetic calorimeter (FoCal-E) is followed by a scintillating-fibre-copper hadronic calorimeter (FoCal-H). Not to scale.

and two layers with high-granularity silicon pixel sensors in layer 5 and 10. In the transverse plane, the FoCal-E is composed out of 22 modules (two detector halves with 11 modules) with 20 layers each. Each module has a mass of about 56 kg, resulting in an overall mass of 1.2 t for FoCal-E.
The FoCal-E Pad layers utilize 320 µm thick n-in-p silicon sensors from 6"-wafers with 72 pads arranged in a 9 x 8 matrix, and a pad size of 1 x 1 cm^2. Each sensor is glued to a printed-circuit board (PCB) housing the HGCROC readout chip, which was developed for the CMS HGCAL project [3]. The HGCROC is connected through the PCB with wirebonds to the sensor pads and reads each pad out in one channel. For the charge measurement, the HGCROC uses the output from an analog-digital-converter (ADC) for low charge signals up to ≈200 fC, and for higher charges a time-over-threshold (TOT) measurement. By combining the ADC and TOT information, a high dynamic range in the charge measurement is achieved, from the order of ≈10 pC down to a minimum ionizing particle (MIP). The trigger functionality of the HGCROC makes it potentially possible for FoCal to implement a local triggering scheme in order to reduce the readout bandwidth. The deposited charge information is available per layer which makes an accurate reconstruction of the longitudinal shower profile in FoCal-E possible.
For FoCal-E Pixel, the ALPIDE monolithic active pixel sensor with an active size of of 3×1.4 cm^2 and a pixel size of 29×27 µm^2 is used [2]. In each layer, 1980 ALPIDE sensors are utilized. With the pixel layers, the transverse shower profiles are accurately resolved, making it possible to distinguish between one- or two-shower signatures. The longitudinal position of the pixel layers has been optimized with simulations. The placement at layers 5 and 10 represents a compromise between detecting narrow, well-separated showers early in the evolution of the shower, and larger signals later in the shower.
The FoCal-H is built with 110 cm long copper tubes, which are oriented parallel to the beam pipe. Scintillating fibres fill out the inner of the copper tubes, with their optimal diameter being studied.

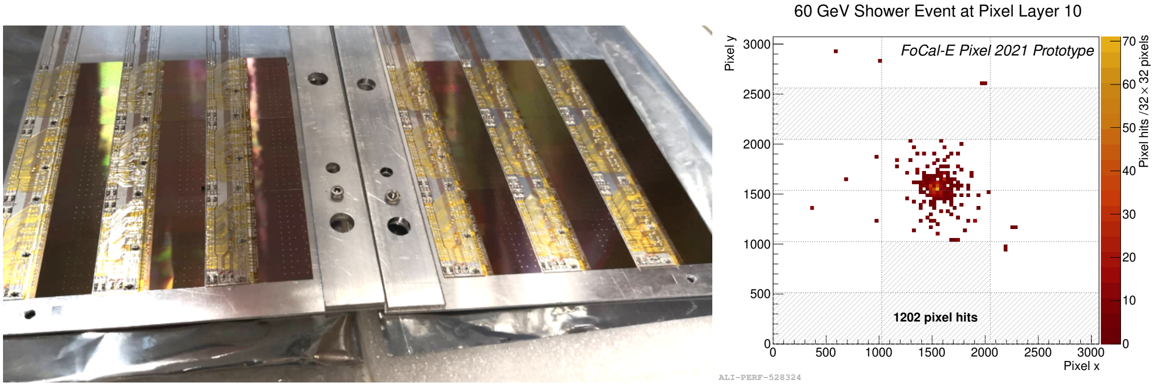

Figure 2: Left: Two pixel half-layers with ALPIDE chips mounted on flex PCBs. Together they form a full prototype pixel layer with 18 ALPIDE chips. Right: Display of an electron shower event at 60 GeV in FoCal-E Pixel layer 10. The shaded areas represent ALPIDEs which had to be excluded from data taking because of failures.

The fibres are bundled, providing a transverse segmentation of the FoCal-H. The bundles are read out with silicon photo-multipliers (SiPM) which are connected to the fibers at the back-end of the detector.

3. FoCal Detector Prototypes and Tests

An extensive FoCal detector prototype development and testing program has been conducted. For the FoCal-E, a tower with 20 layers of 3.5 mm thick tungsten plates was constructed. In October 2021, a FoCal-E Pixel prototype with two layers and a first FoCal-H prototype (Prototype 1) were tested in a test beam at CERN SPS H6 beam line. The tertiary beam at H6 provides a mixture of muons, hadrons, and electrons with momenta between 20 and and 80 GeV/c, which makes the test of the detector response for various particle types possible. In June 2022, an 18 layer FoCal-E Pad sensor prototype and a full-length (110 cm) prototype of FoCal-H (Prototype 2) were tested at the CERN PS T9 beam line with electron and hadron beams between 1 and 5 GeV/c and pure hadron beams between 5 and 9 GeV/c.

The FoCal-E Pixel prototype was built with two ALPIDE pixel sensors at layer 5 and 10 using a technique that has been established for the pCT project [4]. Figure 2 (left) shows two corresponding half-layers with three rows of three ALPIDE chips mounted on a flexible PCBs, glued to the aluminum carriers. One full pixel layer contains 18 ALPIDE chips and has an active size of $9 \times 8\,\mathrm{cm}^2$. Because of various failures of the ALPIDEs and the flexible PCBs after assembly (e.g. short circuits in the chips, or alignment and decoding errors), which have been investigated and understood, only 21 of 36 ALPIDE chips could be operated, leading to a limited acceptance per layer. Figure 2 (right) shows a shower event in Pixel layer 10 at a beam momentum of 60 GeV/c. In order to make sure that a shower is contained completely in the active pixel area, only events located in the central two ALPIDE rows were used for analysis. The number of pixel clusters produced by the particles traversing FoCal-E Pixel layer 10 are displayed in Fig. 3 (left), for beam momenta of 20, 40, 60, and 80 GeV/c. The signal of electromagnetic showers is located at the end of the spectra. The number of particles in the electromagnetic showers can be described with a Gaussian

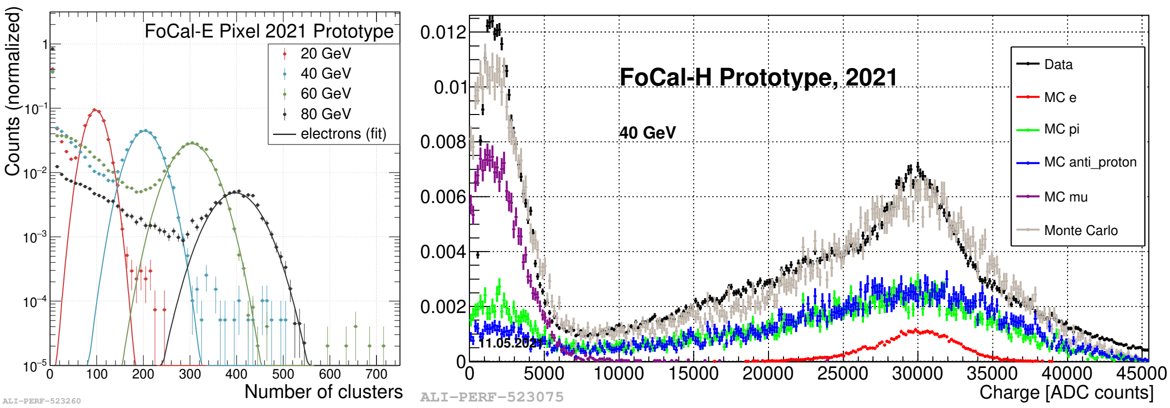

Figure 3: Left: Number of pixel clusters in FoCal-E Pixel layer 10 for energies of 20, 40, 60, and 80 GeV. The electromagnetic shower component is fitted with a gaussian function. Right: Measured signal in FoCal-H. A template fit with simulated signal of various particle types was applied to the dataset.

distribution function. Hadrons which start showering in FoCal produce a roughly exponentially distributed background to this electromagnetic signal. The peak in the first bin of the spectra relates to particles traversing FoCal-E without producing particles showers, i.e. muons or hadrons. The electron, muon, and hadron signals were simulated with a GEANT4 model of the detector prototype. While the muon and hadron response was only confirmed qualitatively, the measurement and the simulation of the electron signal agreed with an uncertainty of 10 % or better.

The FoCal-H Prototype 1 was composed of 1440 copper tubes with 2.5 mm (1.2 mm) outer (inner) diameter, each filled with a BCF10 scintillating fiber. Its transverse extent was $95 \times 95\,\mathrm{mm}^2$ and the length was 550 mm. The fibers, depicted in Fig. 1, were bundled in groups of 30 and coupled to 48 OnSemi C-Series 6035 silicon photo multipliers with a size of $6 \times 6\,\mathrm{mm}^2$, which are read out with a CAEN A1702 system. The light yield in FoCal-H in units of ADC counts is shown in Fig. 3 (right) for a beam momentum of 40 GeV/c, without the FoCal-E as an electron absorber in front. Signals from electrons, protons, pions, and muons were simulated with a GEANT4 model, and their fraction fitted to data with a template fit, describing the data very well. The limited dynamic range of the readout system and the short length of the FoCal-H Prototype 1 limit its performance at higher beam energies.

For the test of the 18 layers FoCal-E Pad prototype at CERN PS T9 energies, only the ADC of the HGCROC contributes to the energy measurement since the charge generation in the sensor is too low to activate the TOT. The MIP peak signal in the silicon sensor was measured, showing that it can be resolved from the pedestal. Figure 4 (left) shows an example of the ADC count distribution for a single pad channel after subtraction of the per-channel pedestal and the common noise of all HGCROC channels. A Landau function, describing the charge generation signal, convoluted with a Gaussian distribution describing noise effects is fitted to the MIP peak. Various preamplifier settings were tested leading to different positions and widths of the MIP peak. The evolution of the MIP peak away from the pedestal was measured in a sensor bias voltage scan from 0 V to −500 V (Fig. 4, middle). Figure 4 (right) shows the dependence of the mean position of the MIP peak on the sensor bias voltage for all channels of one HGCROC. The sensor is fully depleted at about −300 V and the MIP peak position reaches a plateau.

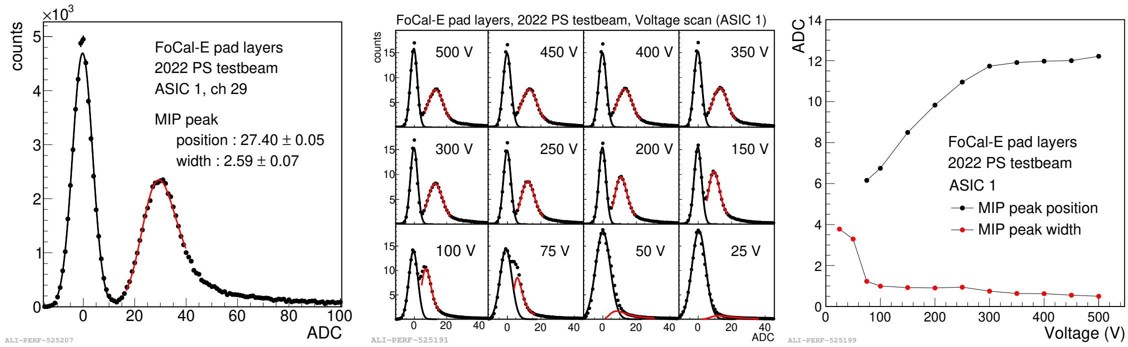

Figure 4: Left: MIP signal peak measured in ADC units. Center: Evolution of MIP signal peak for various sensor bias voltages between 0 and −500 V. Right: Mean position of the MIP peak with respect to sensor bias voltage for all channels of one HGCROC.

4. Outlook

After the individual subdetector prototypes were successfully tested at testbeam campaigns in October 2021 and June 2022, further tests are planned at CERN SPS for September and November 2022. The focus will be on tests of the full FoCal detector system, including all subdetectors, at beam energies larger than 20 GeV, where the TOT of the HGCROC in the FoCal-E Pad layers will be activated for energy measurement. A key implementation will be a common beam scintillator trigger system for FoCal-E and FoCal-H, as well as the common readout of FoCal-E Pads and Pixel. This will make it possible to investigate various particle signatures in FoCal, such as purely electromagnetic or purely hadronic events, or the measurement of longitudinal shower profiles in FoCal-E and the correlation between FoCal-E Pad and Pixel signals.

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