PROCEEDINGS OF SCIENCE

ALICE Forward Calorimeter (FoCal) upgrade: physics program and expected performance

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FoCal is a high-granularity forward calorimeter to be installed as an ALICE upgrade during the LHC Long Shutdown 3 for data taking in Run 4. Covering $3.4 < \eta < 5.5$ with full azimuthal acceptance, it will probe QCD at Bjorken-x values down to $\sim 10^{-6}$, where non-linear dynamics are expected to become significant. The detector features a compact silicon–tungsten electromagnetic calorimeter with pad and pixel readout for precise photon measurements, complemented by a hadronic section based on copper capillaries instrumented with scintillating fibers. This design enables measurements of key observables such as isolated photons, jets, ultra-peripheral photo-production of vector mesons, and angular correlations at forward rapidity. Following the completion of its Technical Design Report, the FoCal project is moving into the production phase for installation in 2028. We present an overview of the FoCal physics programme, the detector design, and the expected performance based on recent test-beam results from small-scale prototypes.

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1. Introduction

The Large Hadron Collider (LHC) at CERN will finish its Run 3 data taking in mid-2026, and a long technical stop (Long Shutdown 3, LS3) will follow until 2030. During LS3, the ALICE experiment, designed to study the Quark-Gluon Plasma (QGP) in heavy-ion collisions, will undergo a major upgrade to enhance its physics capabilities. The upgrade includes the Inner Tracking System 3 (ITS3) [1], and the new Forward Calorimeter (FoCal) [2, 3].

The ALICE FoCal is a high-granularity calorimeter, which will be installed in the forward region of ALICE. It consists of three components: FoCal-E Pixel layers, FoCal-E Pad layers, and FoCal-H. This contribution presents the physics program, the detector design, and recent developments of the FoCal sub-detectors.

2. Physics Program

One of the main physics goals of FoCal is to study gluon saturation, which is expected to occur at small Bjorken-x where the gluon density becomes very high. At small x, the partons will start to recombine, leading to a reduction of the gluon density compared to predictions from linear QCD evolution. By combining measurements of multiple probes in different collision systems, both linear and non-linear QCD dynamics can be interpreted and constrained effectively.

The nuclear parton distribution functions (nPDFs) provide essential input for quantifying the initial-state partonic structure in heavy-ion and proton–nucleus collisions, and FoCal will provide unique constraints on the associated PDF uncertainties. Figure 1 compares the nuclear modification factor R_{pPb} for prompt photons as a function of p_{T} using INCNLO with the nNNPDF3.0 set, showing the impact of FoCal pseudo-data on the nPDF uncertainties [4]. With FoCal pseudo-data, a reduction of the nPDF uncertainties of about 50% is observed, which is of the same order as that obtained from forward D-meson measurements by LHCb [5].

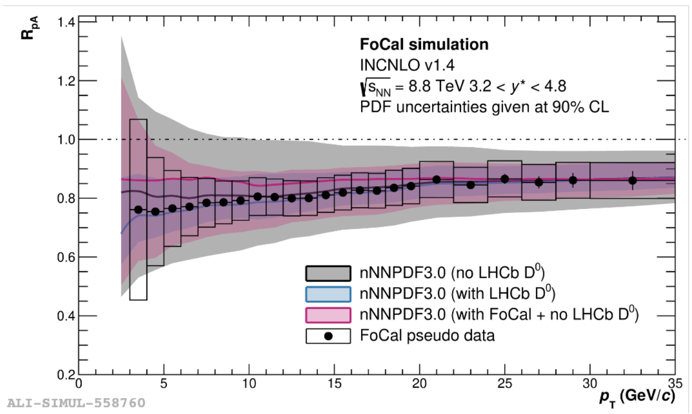

Figure 1: Distribution of R_{pPb} for prompt photons at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV using FoCal pseudo data [4].

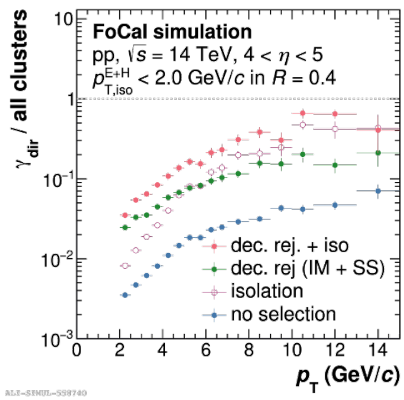

Figure 2: Signal ratio w./w.o. background suppression [4].

For direct-photon measurements, the main background originates from decay photons of neutral mesons, predominantly from π^0 decays. Several techniques are used to suppress this background, including isolation cuts, shower-shape cuts, and invariant-mass cuts. With these methods, simulations show an improvement of the signal-to-background ratio by a factor of about 11, as shown in Figure 2.

With its hadronic calorimeter, FoCal can also measure forward jets, dijets, and γ-jet events to study transverse-momentum-dependent (TMD) gluon distributions. By probing the momentum imbalance of dijet and γ-jet pairs, the gluon TMDs in both the proton and the nucleus can be accessed. For jet-quenching studies, FoCal will provide neutral-meson and jet measurements at high p_{T} in a rapidity region not covered by other ALICE detectors.

3. Detector Design

The ALICE FoCal consists of both hadronic and electromagnetic parts: FoCal-E with high-granularity Monolithic Active Pixel Sensor (MAPS) layers (FoCal-E Pixel layers) and silicon pad sensors layers (FoCal-E Pad layers), followed by FoCal-H which is made of scintillator fibers and copper absorber. As shown in Figure 3, FoCal-E is segmented longitudinally and will be placed in front, while FoCal-H is segmented laterally and will be located behind FoCal-E as seen from the interaction point.

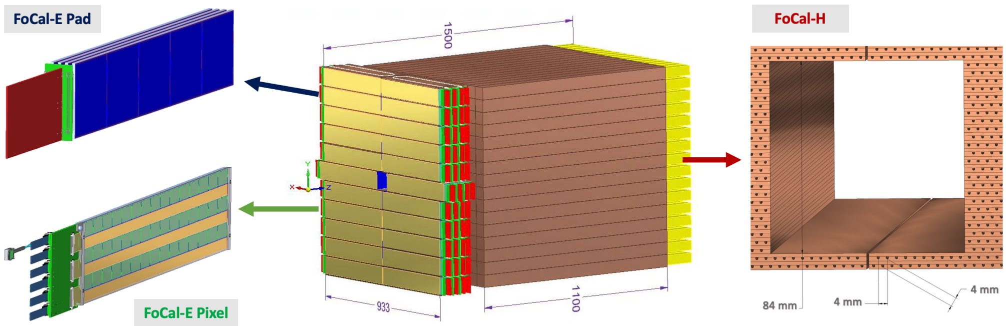

Figure 3: Schematic view of the ALICE FoCal detector design.

3.1 FoCal-E

The electromagnetic part of the FoCal detector is a sandwich sampling calorimeter with tungsten absorber and MAPS/silicon sensors as active layers. There will be 18 layers of silicon pad sensors (FoCal-E Pad), and 2 layers of ALPIDE sensors [6] (FoCal-E Pixel) placed as the 5th and the 10th layers. The full FoCal-E will have a transverse size of 93×101 cm^2.

To construct the system, a modular design is proposed, which uses 22 FoCal-E modules to form the full FoCal-E detector. The modules are arranged in 2 columns and 11 rows, with the two central modules being shorter to accommodate the beam pipe. Each module consists of several active and passive layers, and integrated with the front-end readout and the cooling plates.

3.2 FoCal-H

FoCal-H is the hadronic component, located behind FoCal-E as seen from the interaction point. Instead of being segmented in the longitudinal direction, FoCal-H is segmented laterally and thus has only one readout plane giving 2D spatial information in the plane transverse to the beam direction. The transverse size will be 100×101 cm^2 and the longitudinal size will be 110 cm ($\sim 5\lambda_{\mathrm{int}}$).

The development of the FoCal-H prototype has proceeded through two iterations, and we are currently building the third prototype, which will use milled copper sheets as absorber and scintillator fibers as active medium. The fibers will be put into the grooves on the copper sheets, and then bundled together and epoxied in 3D printed sleeves, which are arranged in a custom frame. The PC boards carrying the SiPMs are attached to this frame, with each SiPM reading out a 4×4 array of scintillating fibers.

3.3 Readout Electronics

Due to the complexity of the different sub-detectors, three front-end readout solutions are proposed for FoCal:

- ALPIDEs used in the FoCal-E pixel layers have in-pixel amplification and discrimination.
- HGCROC3 ASICs for the FoCal-E pad layers.
- H2GCROC3 ASICs for FoCal-H.

Both HGCROC3 and H2GCROC3 are being developed by the OMEGA group at École Polytechnique (Paris) and share the same digital architecture [7], which simplifies the design of the readout system. For the FoCal-E pixel layers, a dedicated readout unit is being developed to handle the data transmission and control of the ALPIDE chips. It will use a main FPGA together with a flash-based auxiliary FPGA to manage the high data rate and ensure radiation tolerance. The pad layers will utilize the ECON-D ASIC [8] for data concentration and then transmit the data via the lpGBT ASIC and optical links to the back-end readout system. Similarly, FoCal-H will also use lpGBT for data transmission, but not the ECON-D ASIC due to its relatively lower channel count.

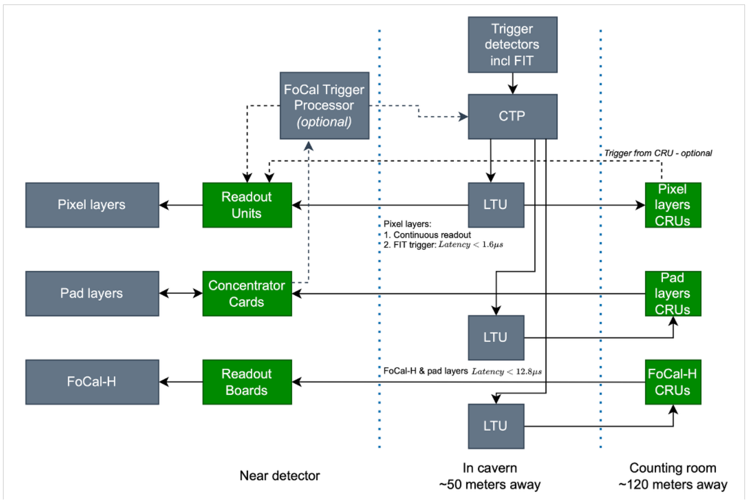

Figure 4: Schematic view of the ALICE FoCal readout electronics [2].

For the back-end data concentration, as shown in Figure 4, the standard ALICE readout chain will be used, which consists of the Central Readout Unit (CRU), the Local Trigger Unit (LTU), and the Central Trigger Processor (CTP). Each CRU can take up to 24 lpGBT links; therefore, 7 CRUs will be used to read out the FoCal-E pixel layers, 10 CRUs for the pad layers, and 2 CRUs for FoCal-H. With a total of 19 CRUs, an aggregate data throughput of up to about 834 Gbps is foreseen [2]. The concentrated data will be processed by the First-Level Processors (FLPs) and Event Processing Nodes (EPNs) using the ALICE O^2 framework [9].

4. Beam Test Campaigns

During the past years, several beam test campaigns were performed to validate the detector design and the readout electronics.

The energy resolution of each sub-detector is evaluated using the following formula:

$$\frac{\sigma_E}{E} = \frac{\sigma_{\text{stoch.}}}{\sqrt{E/\text{GeV}}} \oplus \sigma_{\text{const}} \oplus \frac{\sigma_{\text{noise}}}{E/\text{GeV}} \tag{1}$$

where $\sigma_{\text{stoch.}}$ is the stochastic term, σ_{const} is the constant term, and σ_{noise} is the noise term. The beam tests in 2023 and 2024 show an energy resolution of $\sigma_{\text{stoch.}} = (33.6 \pm 1.4)$ %, $\sigma_{\text{const}} = (2.27 \pm 0.10)$ %, and $\sigma_{\text{noise}} = (59.2 \pm 35.3)$ % for the FoCal-E pad layers [10].

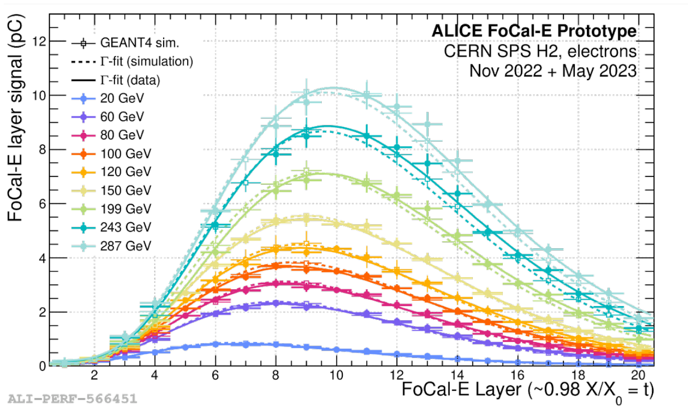

Figure 5: FoCal-E longitudinal shower profile for 20 GeV to 300 GeV electron beams [10].

The energy deposition in each layer is also studied and is shown in Figure 5. The test data agree well with the Geant4 simulations and show that the layer with the maximum energy deposition is around layer 5 for low-energy beams, while it shifts to around layer 10 for high-energy beams, where the pixel layers are located.

The FoCal-H prototype 2 was tested in September 2024 at the CERN SPS beam line. The test was carried out using the commercial CAEN DT5202 digitizer [11], which was triggered by dedicated trigger scintillators. During the test, electron beams with a maximum energy of 250 GeV and hadron beams with a maximum energy of 350 GeV were used. The energy resolution was evaluated using the same formula, yielding a stochastic term of $\sigma_{\text{stoch.}} = \left(148 \pm 2_{\text{stat.}} \pm 22_{\text{syst.}}\right)$ % and a constant term of $\sigma_{\text{const}} = \left(10.0 \pm 0.13_{\text{stat.}} \pm 0.7_{\text{syst.}}\right)$ % [10].

The prototype was also tested in a beam setup equipped with the H2GCROC3 ASICs. An AMD KCU105 FPGA board with customized firmware and software was used to read out the data. Preliminary results show that the H2GCROC3 ADC measurements exhibit a performance similar to that of the DT5202 digitizer, and further tests are planned to validate the full readout chain.

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5. Conclusion

The ALICE FoCal upgrade has a unique capability of studying non-linear QCD dynamics at small x. Test-beam campaigns of the FoCal-E and FoCal-H prototypes have validated the detector concept, demonstrating good energy resolution and excellent agreement with Geant4 simulations. In parallel, the mechanical structure and cooling system are progressing well, and the collaboration is preparing for the production phase.

With its combined photon, jet, and hadron measurement capabilities, FoCal will provide critical constraints on nuclear PDFs and transverse-momentum-dependent gluon distributions. Overall, FoCal is expected to play a central role in advancing our understanding of strong-interaction dynamics at the Large Hadron Collider.

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