

# The ALICE Electromagnetic Calorimeter: EMCAL

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**Abstract.** The ALICE Experiment (A Large Ion Collider Experiment) aims to study the properties of quark-gluon matter using Pb-Pb collisions at a center of mass energy (per nucleon pair) of  $\sqrt{s_{NN}} = 5.5$  TeV with the Large Hadron Collider (LHC) at CERN. The EMCAL detector is a large area electromagnetic calorimeter. ALICE's capability to perform jet reconstruction is greatly improved by measuring the neutral energy component of jets including photons and neutral pions. The calorimeter produces also a fast, high- $p_T$  trigger providing an enhancement in high- $p_T$  events, participates in the High Level Trigger (HLT), performing online reconstruction at the full data rates and generates trigger information based on reconstructed events. The performance of prototypes has been studied in test beam measurements at FNAL and CERN and are shown. Four EMCAL super-modules have been installed at CERN and are operational. First results from data taking are presented. Moreover, an extension of EMCAL for jet-jet and  $\gamma$ -jet physics will be discussed.

## 1. Introduction

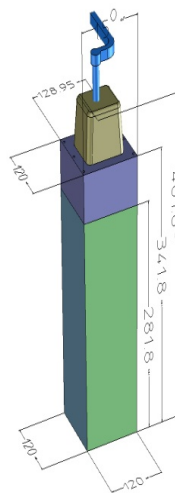
ALICE (A Large Ion Collider Experiment) at the LHC is designed to carry out comprehensive measurements of high energy nucleus-nucleus collisions, in order to study QCD matter under extreme conditions and to explore the phase transition between confined matter and the Quark-Gluon Plasma (QGP) [1,2].

ALICE contains a wide array of detector systems for measuring hadrons, leptons and photons. The ALICE detector is described in detail in [3]. The large acceptance Electromagnetic Calorimeter (EMCAL), which is foreseen to be fully installed in 2011, significantly enhances ALICE's capabilities for jet measurements. EMCAL is designed to provide the following functions: efficient and unbiased fast level L0 and L1 trigger on high energy jets; measurement of the neutral portion of jet energy; improvement of jet energy resolution; measurement of high momentum photons,  $\pi^0$  and electrons;  $\gamma/\pi^0$  discrimination up to 30 GeV (considering invariant mass and shower shape techniques only); electron/hadron separation for momenta larger than 10 GeV/c; high uniformity of response for isolated electromagnetic clusters.

This paper presents a description of the EMCAL with its characteristics, the final results of the performance of prototype modules in test beam measurements at FNAL and at CERN, the present status of EMCAL, the first results from data taking and an upgrade for EMCAL, expanding the acceptance of EMCAL for di-jet and hadron-jet correlation measurements.

## 2. EMCAL description and characteristics

The overall design of the EMCAL is heavily influenced by its integration within the ALICE [3] setup, which constrains the detector acceptance to a region of about  $110^\circ$  in the azimuthal angle  $\phi$ ,  $0.7 \leq \eta \leq 0.7$  in pseudo-rapidity and  $4.35 \text{ m} < R_{\text{EMCAL}} < 4.7 \text{ m}$  radial distance. The chosen technology is a layered Lead (Pb)-Scintillator (Scint) sampling calorimeter with wavelength shifting (WLS) fibers that run longitudinally through the Pb/Scint stack providing light collection (Shashlik) [4]. The basic building block is a module consisting of  $2 \times 2$  optically isolated towers which are read out individually. All modules in the calorimeter are mechanically and dimensionally identical. Each module has a rectangular cross section in the  $\phi$  direction and a trapezoidal cross section in  $\eta$  with a full taper of  $1.5^\circ$ , and spans  $\Delta\eta \times \Delta\phi = 0.014 \times 0.014$ . A scheme of the module is shown in Fig.1, together with the dimensions in mm. White, acid free, bond paper serves as a diffuse reflector on the scintillator surfaces and provides friction between layers. The scintillator edges are treated with  $\text{TiO}_2$  loaded reflector to improve the transverse optical uniformity within a single tower and to provide tower to tower optical isolation better than 99%. The requirement of a compact detector consistent with the EMCAL integration volume and the chosen detector thickness of about 20 radiation lengths, results in a lead to scintillator ratio by volume of about 1:1.22 corresponding to a sampling geometry of Pb (1.44 mm)/Scint (1.76 mm). The physical characteristics of the modules are summarized in Table 1.



Parameter	Value
Tower size (at $\eta=0$ )	$\sim 6.0 \times \sim 6.0 \times 24.6 \text{ cm}^3$
Tower size	$\Delta\phi \times \Delta\eta = 0.0143 \times 0.0143$
Sampling ratio	1.44 mm Pb / 1.76 mm Scint.
Layers	77
Scintillator	Polystyrene (BASF143E+ 1.5%pTP+0.04%POPOP)
Absorber	Natural lead
Effective RL $X_0$	12.3 mm
Effective MR $R_M$	3.20 mm
Effective density	5.68 g/cm <sup>3</sup>
Sampling fraction	1/10.5
Radiation length (RL $X_0$ )	20.1

Fig.1 (left): A single EMCAL module with the dimension in mm. Table 1 (right): EMCAL module physical parameters. Here, RL stands for Radiation Length and MR for the Moliere Radius.

Scintillation photons produced in each tower are captured by an array of 36 Kuraray Y-11 (200 M), double clad, wavelength shifting (WLS) fibers. Each fiber within a given tower terminates in an aluminized mirror at the front face of the module and is integrated into a polished, circular group of 36 fibers at the photo sensor end at the back of the module.

The 6.8 mm diameter fiber bundle from a given tower connects to the Avalanche Photodiode (APD) through a short light guide/diffuser. The selected photo sensor is the Hamamatsu S8664-55 avalanche photodiode chosen for operation in the high field inside the ALICE magnet. The APDs are operated at moderate gain for low noise and high gain stability in order to maximize energy and timing resolution. The number of primary electrons generated in the APD by an electromagnetic shower is  $\sim 4.4$  electrons/MeV. The reverse bias voltage of the APDs are individually controlled to provide an electron multiplication factor (M) of 30 resulting in a charge output of  $\sim 132$  electrons/MeV from the

APDs. All APDs used have been previously calibrated [5]. The charge output from the APD is integrated by a Charge Sensitive Preamplifier (CSP) with a short rise time of  $\sim 10$  ns and a long decay time of  $\sim 130$   $\mu$ s, i.e., approximately a step pulse.

The readout electronics is similar to that of the Photon Spectrometer (PHOS): a detailed description is given in [6].

Twelve modules are assembled with a structural strongback to form a strip-module, a self-supporting unit like the module. A collection of 24 strip-modules forms a super-module. EMCAL will be formed by ten super-modules. Pictures of a strip-module and of a full super-module are shown in Fig.2, on the left and right panel, respectively.

More details on the mechanical assembly can be found in [7].

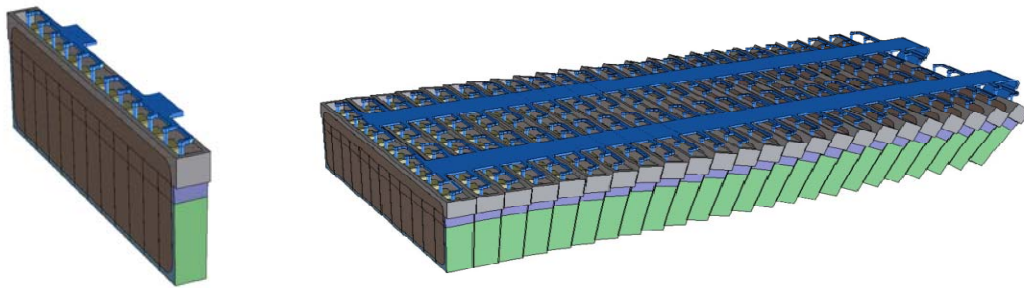


Fig.2: Single strip-module comprised of 12 EMCAL modules integrated onto a single strongback (left) and single super-module formed by 24 strip-modules (right).

### 3. Results from test beams

The performance of a 4x4 array of prototype modules and of a 4x4 array of final design modules for the ALICE EMCAL has been studied in test beam measurements at FNAL (2005) and CERN (2007), respectively. All towers were instrumented with the full electronics chain with shapers and APD gains operated as planned in ALICE. A LED calibration system was installed in order to monitor time-dependent gain changes. The readout of the front end electronics used the standard ALICE data acquisition system.

The final results are fully described in details in [8], showing an average light yield of  $(4.3 \pm 0.3)$  photoelectrons/MeV, a uniformity of the response within 1% for all towers and configurations; a good linearity of the response to electrons above 20 GeV, an only slightly deteriorated energy resolution when using the EMCAL default shaping time of 200 ns compared to 2  $\mu$ s for PHOS, a position resolution described by  $1.5 \text{ mm} + 5.3 \text{ mm} / \sqrt{E} \text{ (GeV)}$  and a hadron rejection factor  $> 600$  for an electron identification efficiency of 90%.

The energy resolution of  $\sigma(E) / E = (1.7 \pm 0.3) + (11.1 \pm 0.4) / \sqrt{E} + (5.1 \pm 0.3) / E$  (where E is in GeV) is shown in Fig.3 (left panel), together with the x and y position resolution as a function of the energy deposit for electrons (right panel).

In conclusion, the performance of the tested EMCAL modules reaches all design criteria.

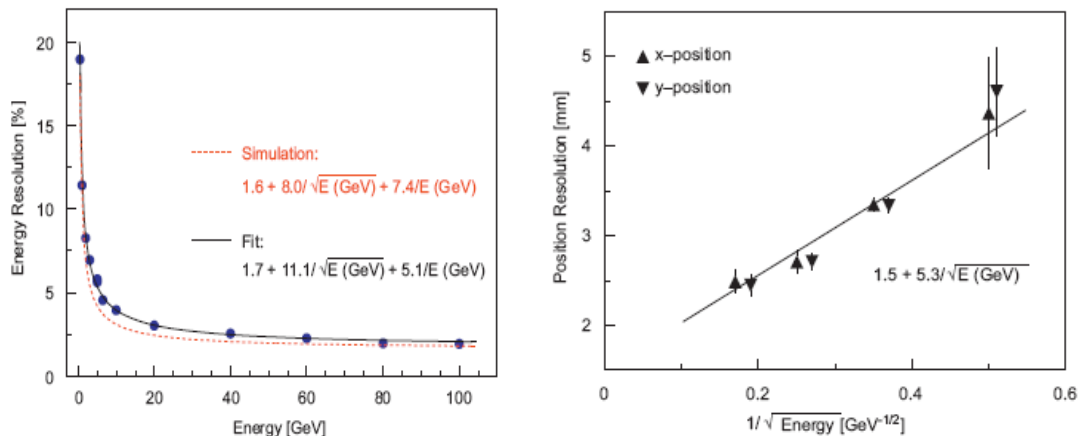


Fig.3: Left panel: energy resolution for electrons as a function of the incident beam energy. The beam energy spread was subtracted from the measured result and the dashed curve represents the resolution obtained from Monte Carlo simulations. Right panel: position resolution as a function of the deposited energy for electrons. The curve shows the best fit result.

#### 4. The EMCAL status

The assembly of EMCAL modules started at the end of 2008. In 2009 four super-modules have been installed in ALICE and presently they are operational and taking data. The corresponding angular coverage is  $\Delta\eta \times \Delta\phi = 1.4 \times 1.05$ . Extensive commissioning of the readout electronic, L0, L1 and HLT triggering has been carried forward together with APD bias optimization and gain monitoring. First physics events have been successfully reconstructed. Presently four further super-modules are ready and under test and calibration. All details about test and calibration are reported in a dedicated proceeding of this Conference [9]. The modules for the last two super-modules are in preparation and the assembly is expected to be completed before the end of the summer; the corresponding cosmic calibration will be completed during the fall 2010. As soon as a long LHC shutdown will be available, the full EMCAL will be installed, presumably in 2011.

A picture of the four super-modules installed in ALICE is shown in Fig.4 (left side), where only the two in the front side are visible.

#### 5. First results from data taking

After months of commissioning and running with cosmic rays, at the end of 2009 it was possible to see the response of EMCAL with the first proton-proton collisions at the center of mass energy  $\sqrt{s} = 900 \text{ GeV}$  and in 2010 at  $\sqrt{s} = 7 \text{ TeV}$ . Since the early commissioning phase of the LHC, it was possible to have the first events analyzed and displayed in the counting room by the offline reconstruction software and the online reconstruction software implemented in the high Level Trigger (HLT) analyzing the events in real time, indicating the start of the physics exploitation of the ALICE experiment. First results have been immediately obtained and published [10]. The four EMCAL super-modules are continuously present in the data taking. Invariant mass spectra of the  $\pi^0$  are obtained in different energy bins, an example is shown on the right panel of Fig.4.

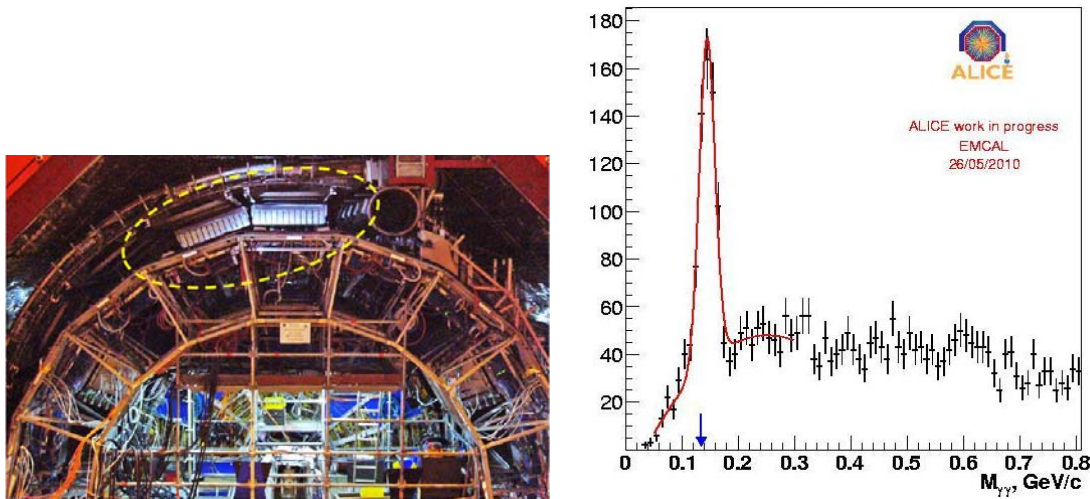


Fig.4 Left panel: four super-modules installed, only those two in front are visible. Right panel:  $\pi^0$  mass reconstruction in the transverse momentum bin  $5.0 < p_T < 5.5$  GeV.

## 6. The EMCAL upgrade: DCAL

Even though EMCAL was the last ALICE detector to be proposed, approved, assembled, and it is still only partially installed, the first upgrade approved by the ALICE collaboration (November 2009) is an extension of EMCAL, denominated DCAL (Di-jet Calorimeter) [11]. The DCAL expands the physics capabilities of the EMCAL by enabling back-to-back correlation measurements, which are impossible with the EMCAL alone, but are essential to obtain a complete picture of the physics addressed by the EMCAL. Together, the DCAL and EMCAL form a two-arm electromagnetic calorimeter. The EMCAL subtends  $110^\circ$  and the DCAL subtends  $60^\circ$  in  $\phi$ , with both detectors covering  $|\eta| < 0.7$ , thereby providing good acceptance for di-jets with radii  $R \leq 0.4$  up to transverse momenta  $p_T \sim 150$  GeV/c. Simulation studies of the DCAL have been carried out and have verified that the technology originally developed for and implemented in the EMCAL meets all the needs of the DCAL project. As a consequence, from a technical perspective, DCAL is an extension of EMCAL. DCAL super-modules are built exactly as they are in EMCAL, out of strip-modules, but with reduced length in  $\eta$ : in fact, each DCAL strip-module contains 16 modules instead of 24 present in EMCAL.

DCAL will be situated immediately adjacent to PHOS on both the ALICE A and C sides, causing unavoidably a small gap in  $\eta$  ( $\delta\eta \sim 0.02$ ) between the sensitive volumes of the two detectors, due to the super-module structure. DCAL+PHOS can be considered as one integrated detector system for the study of jets, consequently all simulations done include PHOS as well as DCAL super-modules.

The assembly of the DCAL modules will start in summer 2010, after completion of EMCAL. Before the end of the year, all 6 DCAL super-modules will be assembled and tested, ready to be installed in ALICE as soon as a long shutdown will be available, presumably on 2011.

On the left panel of Fig.5 is shown a schematic view of the 6 DCAL super-modules with the PHOS super-modules in between and on the right panel the beam view of EMCAL and DCAL is illustrated.

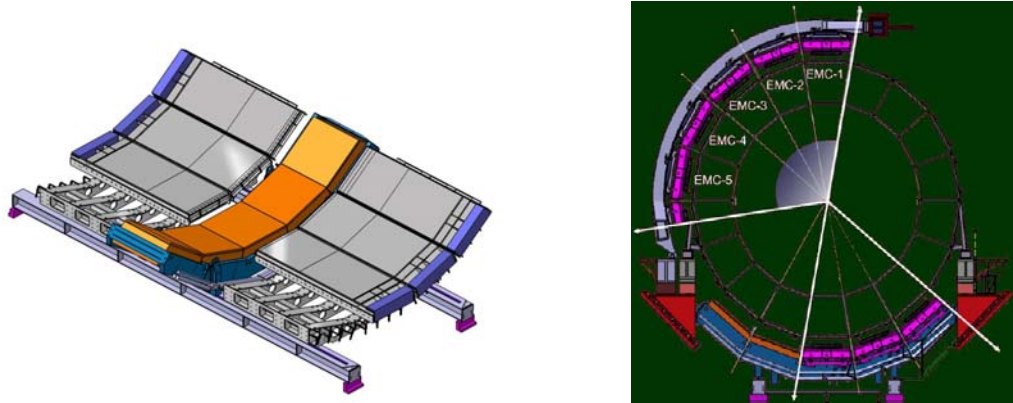


Fig.5: Left panel: 6 DCAL super-modules (in gray) with the PHOS super-modules (in orange) in between. Right panel: beam view of EMCAL and DCAL.

## 7. Conclusions

An accurate description of the ALICE electromagnetic calorimeter, with its characteristics has been given. Final results from measurements done in test beams in 2005 and 2007 have been reported, demonstrating that the performances of EMCAL satisfy all the design criteria. The status of the assembly and installation of EMCAL is illustrated: four super-modules are already installed in ALICE for  $\pi^0$ ,  $\gamma$  and first jet physics. The first results obtained from data taking are promising and encouraging: of course some investigation and optimization is still going on.

The assembly of EMCAL is expected to be completed in summer 2010 and the corresponding calibration in the fall in order to be ready for the full EMCAL installation for the next long shutdown available.

An upgrade for EMCAL, denominated DCAL for di-jet and hadron-jet physics, is illustrated: the corresponding assembly will start in the next months and will be completed before the end of the year, with possible installation together with the rest of EMCAL super-modules.

## References

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