A particle counting EM calorimeter using MAPS

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Abstract. The availability of full size MAPS sensors makes it possible to construct a calorimeter with pixelsize of a few tens of micrometers. This would be small enough to count individual shower particles and would allow a shower shape analysis on an unprecedented, small scale. Interesting features would be tracking capability for particle flow algorithms and a superior discrimination of single photons from neutral and charged pions at high momenta. A small Molière radius together with high transverse resolution would allow to separate close showers, induced by photons from neutral pion decay. A full scale (4 R_M, 28 X_0) prototype was constructed to demonstrate this. It features 30 micron pixelsize and a longitudinal sampling at 1 radiation length. We will show results from beam tests of this prototype at electron energies of 2 to 200 GeV.

1. Introduction
To cope with the availability of accelerators of increased energy, better detector performance, like spatial resolution, electronics readout speed and energy resolution are required. This might enable new measurement approaches. In calorimetry for example, instead of measuring the deposited energy of the showering particles it would be more convenient to count all the particles traversing the detectors. This would be an advantage in particle identification and in the separation of close showers. This entails fine detector granularity, namely a large number of channels. This is only feasible with digital signals.

We built a fully digital electromagnetic calorimeter equipped with Monolithic Active Pixels Sensors (MAPS) [1] with a longitudinal segmentation of 1 X_0 and an expected lateral resolution of few hundreds micron.

The main goal of such a device is the discrimination of direct photons from the photons produced by the π⁰ decay at forward angles in high-energy physics experiments as at the LHC. The shower core density would be 10^3 mm⁻² and to study the shower shape longitudinally and transversely, the pixel size is bound to be of the order of 30 - 50 μm for an average occupancy of 1 particle/pixel. Moreover to fully exploit such a small pixel size, a compact design of alternated tungsten planes with active planes has been realized with a calculated Molière radius of 11 mm.

The prototype was tested with particle beams proving the feasibility of a digital calorimeter [2] and demonstrating the integration of cooling without worsening the Molière radius.

Performance results from the test beams are reported.
2. The Detector
The prototype (Figure 1) has 24 layers with a thickness of 4 mm of which the sensor part, including the read-out board, is 1 mm. This leaves an air gap of only 0.1 mm between the overlapping sensors. The radiation thickness of one layer is 0.97 $X_0$. The active area of a layer (Figure 2) is $4 \times 4 \text{ cm}^2$, composed of four sensors, while the absorber measures $5 \times 5 \text{ cm}^2$. To compensate for some of the dead zones sensors overlap in one spatial direction. For ease of construction there remains a dead zone of 0.1 mm between each pair of chips in the other direction. The Molière radius calculated for this setup is 11 mm, which means that the tower is wide enough to study the lateral shower development. The first active layer has only 0.02 $X_0$ in front, to act as a charged particle detector. Between layers 21 and 22 6.7 $X_0$ of tungsten are placed to obtain a total depth of 28 $X_0$. At a dissipation of 70 W in 150 cm$^3$ a heat resistance of 0.3 K/W from chip to cooling water was measured.

The sensor chosen for the prototype is PHASE2/MIMOSA23 from IPHC [3]. This is the only full size MAPS (640 * 640 pixels), which allows the continuous read-out of all pixels, thanks to four outputs at 160 MHz. The 1 MHz rolling shutter implies an integration time of 640 $\mu$s. The resulting low event rate is no problem in the case of test experiments. The small pixel pitch of 30 $\mu$m allows very fine sampling of the shower core. In the detector there are sensors with different epilayer thicknesses and resistivity: 15 and 20 $\mu$m with resistivity of (400 Ωcm) and 14 $\mu$m with 10 Ωcm resistivity.

As each full detector read-out - a so-called frame - contains 39 M pixels, the raw data rate of the prototype is 61 Gb/s. Several FPGAs are used to manage this, as described in [4]. Incoming trigger bits are time-stamped with the read-out clock and stored separately.

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**Figure 1.** The electromagnetic MAPS prototype measures $4 \times 4 \times 12 \text{ cm}^3$, hence it is a compact detector. In the picture the prototype is located in the centre and on the sides there are the printed circuit boards with the flat cables for the chip operation. At the time of this picture the cooling was not implemented yet.

**Figure 2.** Picture of half module. On the tungsten plate two chips positioned side by side are connected to their printed circuit board.
3. Test beam results

Several test beam campaigns have been performed in the last couple of years: at DESY (in 2012 and 2014) with pure electron beam from 2 to 5.4 GeV and at CERN PS and SPS (in 2012) with mixed beams from few GeV till 200 GeV. In the meanwhile cosmic ray data have been taken and used to tune the sensors.

3.1. Energy Calibration

Due to diffusion, the charge created by a particle will lead to a cluster of pixel hits. The size of the cluster will depend on the charge created by the particle (Landau distribution) and the threshold of the discriminators. For application in trackers the discriminators are usually adjusted such that an acceptable fake rate, measured as clusters not belonging to a track, is achieved. In the case of a calorimeter it is a priori not known whether the clusters will be well-separated, especially in the core of the shower, Figure 3. Therefore it was decided to use the number of hit pixels as a measure of the energy, instead of trying to derive the number of particles from the hit distributions. This means however, that the discriminators should be set such that, in the absence of particles, an acceptable number of individual pixel hits is achieved, as opposed to clusters of hits. Figure 4 shows the average uncorrected response of the detector as a function of energy for the measurements at DESY. The figure also illustrates the total noise: this value is around 300 hits, which corresponds to a noise level of $10^{-5}$ per frame. Although the detector was not designed for such low energies a linear behaviour in number of hits per event is reported.

![Figure 3](image3.png)

**Figure 3.** Close look at the shower core in $2 \times 2$ mm range. The individual pixel corresponds to a single circle.

![Figure 4](image4.png)

**Figure 4.** The average number of hits per event as function of the energy for raw data is shown. The point at zero corresponds to the integrated noise of the whole detector.

3.2. Longitudinal profile

The longitudinal profile averaged over more than 2000 shower events is depicted in Figure 5 for two energies: 2 and 5.4 GeV. The shower maxima are displaced according to the shower energy as expected. There are visible instrumental effects like, for example, in layer 5 where there is a decrease in number of hits for both energies. The decrease is caused by non working channels as illustrated in Figure 6. Unfortunately more than third of the detector is affected by such a
problem that, as consequence, spoils the longitudinal profile and broadens the energy resolution.

![Figure 5](image1.png)

**Figure 5.** Longitudinal profile averaged over 2000 showers for 2 and 5.4 GeV electron beam. The not perfect longitudinal profile is due instrumental effects.

![Figure 6](image2.png)

**Figure 6.** As example of not working channels, the hits map of layer 5 integrated over several shower events is reported. The white bands correspond to the missing channels that cause the decrease in the number of the counted hits in such a layer.

### 3.3. Lateral Profile

The lateral profile \( \frac{4N}{2\pi rdr} \) has been estimated as the average over a few hundred showers. No calibration has been performed and only a preliminary alignment of the chips within 0.1 cm has been performed. In Figure 7 the average shower development for 5.4 GeV is plotted. The incoming particle leaves a track signal in layer 0 (there is no absorber in front of the sensor) and the shower develops leading to a maximum in layer 4. The distributions of layer 9 and layer 14 decrease at large \( r \) to an asymptotic value of 1 hit cm\(^{-2}\), which is the noise level.

From the lateral distribution integrated over all the layers the Molière radius is calculated (see Figure 8). We obtain: \( R_M = 11 \pm 1 \) mm, which confirms the detector design expectations.

### 3.4. Energy Resolution

The energy resolution is a key quantity for a digital calorimeter. GEANT based simulation provides an estimate of the expected energy resolution, see Figure 9. Although the detector description is implemented to represent the real detector as closely as possible, e.g. also excluding the not working channels, there is still the approximation of identical sensors. This definitely contributes to a deteriorated energy resolution as measured from the data collected at the test beam at 30-50-100 GeV, which is about a factor of two worse than expected. In Figure 10 the detector response for data calibrated with MIP response are plotted. Further studies of the resolution including improvements of both the description in the simulation and a possible response correction of the experimental data are in progress.

### 3.5. Particle Identification

Despite the digital output it is possible to identify particles with unprecedented detail. In Figure 11 the number of hits as a function of the depth in units of radiation length (\( X_0 \)) for two
Figure 7. Lateral profile averaged over hundred showers at 5.4 GeV.

Figure 8. Hits fraction versus the distance from the shower core. From this measurement the estimate of the Molière radius for such a detector is 11 ± 1 mm as estimated from in the detector design.

Figure 9. Simulations of the detector response for 30, 50 and 100 GeV with an energy resolution of 4.1%, 3.4% and 2.7% respectively.

Figure 10. Calibrated detector response with pion for 30, 50 and 100 GeV. The calculated energy resolution for the same energies is: 8.1%, 6.8% and 5.3%.

showers at 50 GeV and 200 GeV, respectively is shown. These showers appear similar according to the total number of hits. The extremely high sensor granularity allows us to sample the lateral and longitudinal shower evolution in detail and to use this for the discrimination between electromagnetic and hadronic showers, as illustrated in Figures 12 and 13.

4. Conclusions
In this article the construction feasibility of digital electromagnetic calorimeter with sampling of 1X₀ and spatial resolution down to few hundreds micron has been demonstrated. The sensors equipping the prototype are MAPS that have the front-end embedded in the sensor with very small pixel size, 30 µm. The 39 M pixels are read out at the GB/s rate. The sensor type is not the final one, but this large MAPS application shows the technology and integration feasibility,
Figure 11. Cumulative number of hits as a function of the depth for an electromagnetic and a hadronic shower at 50 GeV and 200 GeV. The hits distribution for the same showers is displayed in figures 12 and 13.

Figure 12. Event display of an electromagnetic shower at 50 GeV integrated over the full depth of the detector.

Figure 13. Event display of a hadronic shower at 200 GeV integrated over the full depth of the detector.

allows the MAPS characterisation study in terms of the signal saturation and study of the shower development.

The particle counting approach has been demonstrated to work for a fully digital electromagnetic calorimeter. Results on particle identification and the transverse and longitudinal shower development is reported. A very small Molière radius of 11 mm has been demonstrated, which is in perfect agreement with the design expectations.

The simulated energy resolution for 30, 50 and 100 GeV is a factor of two off from the measurements. This is partially explained by the missing implementation of the single chip response in the simulation. However it is work in progress.

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