Proposal for test in CERN particle beams of large area MICROMEGAS chambers for hadronic calorimetry

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**Abstract**

A one square meter Micromegas chamber equipped with $10^4$ readout channels and MICROROC front-end electronics was constructed in 2011 and recently tested in SPS beams. Preliminary results reveal excellent performance of the prototype. Based on these, the need for beam time in 2012 is motivated.
1 Introduction

1.1 CALICE collaboration

The CAlorimetry for a Linear Collider Experiment (CALICE) [1] collaboration consists of 297 physicists from 53 institutions, located in 16 countries coming from the four regions (Africa, America, Asia and Europe). This R&D collaboration aims to design and develop highly granular calorimeters for experiments at the future International Linear Collider (ILC) [2]. The physics program of the ILC requires the reconstruction of multi-jet final states, and the separation of W and Z bosons in their hadronic decay mode by means of the di-jet invariant mass. This translates into an unprecedented jet energy resolution of about $30\%\sqrt{E}$. In the Particle Flow Algorithm (PFA), the overall detector performance is optimized by reconstructing each particle individually in the detector which gives the best measurement. Charged particles energy will be measured in the tracker and therefore the corresponding showers in the calorimeters have to be individually reconstructed. Separating out particles close together in hadronic jets requires excellent spatial resolution of the calorimeters and hence very high granularity and compactness never achieved so far.

1.2 Detector R&D

The CALICE collaboration is considering all types of sampling calorimeters and different technological designs in an integrated study.

- an electromagnetic calorimeter using silicon as the active detector and tungsten as the absorber: SiW ECAL;
- an electromagnetic calorimeter using scintillator as the active part readout by Multi-Pixel Photon Counter (MPPC, generically known as silicon photomultiplier) and tungsten as the absorber: ScECAL;
- a hadron calorimeter with steel absorber and scintillator tile with analog readout via novel photodetectors and moderate granularity: AHCAL;
- a hadron calorimeter with steel absorber and gas-based (GEM or RPC) option with very high granularity and one bit readout so called digital readout: DHCAL;
- a hadron calorimeter with steel absorber and gas-based (MICROMEGAS or RPC) option with very high granularity and two bits readout so called semi-digital readout: SDHCAL;
- a hadron calorimeter with tungsten absorber and scintillator-based or gas-based (MICROMEGAS or RPC) options: W-HCAL;
- a Tail Catcher Muon Tracker with scintillator strip read by Silicon PhotoMultiplier.

1.3 Digital and semi-digital HCAL concept

With about $3000^2$ active area and 30 million channels, a good choice for a sampling hadronic calorimeter at ILC is a gaseous active medium with embedded 1-bit readout (DHCAL) electronics. Such a calorimeter has to provide high Minimum Ionising Particle (MIP) efficiency, low multiplicity as well as no performance degradation due to high rate, hadronic showers and aging. Technologically, the challenges come from the large area (up to $1.8 \times 3.5 \text{ m}^2$) and the little thickness (below 8 mm) of a single gaseous detector, the ease of calibration and the low cost. At high jet energy, the number of hits recorded in the calorimeter saturates as an increasing number of particles are crossing the same cell, resulting in a drop of linearity and resolution. A semi-DHCAL (SDHCAL) with for instance 2-bit/channel can in principle attenuate this loss and extend the calorimeter linearity to higher energies.

1.4 This proposal

This subject of this proposal is the development of a MICROMEGAS-SDHCAL. In 2012 we aim to test several MICROMEGAS chambers of one square meter size with embedded semi-digital readout which is the first compulsory step towards a $1 \text{ m}^2$ SDHCAL of 40 stainless steel or tungsten layers (2 cm thick) interleaved with $1 \text{ m}^2$ active area (10 mm thick). The $1 \text{ m}^3$ SDHCAL will be a technological prototype that
will demonstrate the feasibility of a very low power consumption calorimeter with scalable active medium area as well as a physical prototype since no existing calorimeter provides such detailed information on the hadronic shower structure. The PFA relies on calorimeter simulation models which could only be validated and upgraded with the data taken with a 1 m³ prototype. In particular, prototypes with digital and semi-digital readout will have strong impact on the final detector architecture, optimization and cost estimation.

2 MICROMEGAS semi-digital HCAL project

2.1 The Micro Mesh Gaseous Structure

MICROMEGAS is a gaseous detector, based on the micro-pattern detector technology [3], used today by many experiments: COMPASS, CAST, NA48, n-TOF, T2K and ILC TPC project. It consists of a mesh which separates a drift region where the primary charge is produced by ionising particles from an amplification region where the primary electrons are drifted to and multiplied through an avalanche process. The mesh is maintained at a fixed distance from the anode place by periodically spaced insulating pillars. The anode plane is generally patterned into pads or strips on which the induced signals are picked-up.

2.2 MICROMEGAS for a DHCAL

Our prototypes consist of a commercially available 20 µm thick woven mesh which separates the drift gap (3 mm) from the amplification gap (128 µm). The manufacturing technique is called Bulk and is based on industrial PCB processes. The mesh, sandwiched in between two layers of photo-sensitive foils, is laminated onto an anode PCB with square pads of 1 cm². After exposure of the stack to UV light, most of the photoresist is dissolved and only pillars, on both sides of the mesh, remain. This manufacturing technique makes the detector robust. With a square pattern of pillars with 2.5 mm pitch, a gas gain uniformity over the whole mesh area of about 10% is easily achieved. This detector is a very appealing option for equipping a DHCAL with multi-threshold read-out for several reasons:

1. the Bulk technique is suited for the fabrication of MICROMEGAS of large area. It is available at the CERN workshop which in the near future will be able to process areas up to 1 × 2 m²;
2. the typical MIP charge collected on anode pads is roughly 20 fC which, with low noise electronics (1.5 fC threshold), can be detected with an efficiency higher than 97%;
3. the detector is operated in a mixture or argon with some quencher gas. Ar/CO₂ mixtures are non-flammable with working voltages below 500 V;
4. MICROMEGAS works in proportional mode and is best suited for a semi-DHCAL. Despite Landau fluctuations, some information on the number of particles traversing a given pad is available;
5. the intrinsic time resolution, governed by the arrival time of the first electron at the mesh, lies between 5–10 ns. Such precise time-stamping would be useful for an application at CLIC;
6. due to the fast collection of the primary charge and the short avalanche development (a few tens of ns), small gap MICROMEGAS chambers can operate up to very high rate without significant signal losses. They are well suited for equipping forward regions at collider experiments;
7. the limited transverse spread of the electron avalanche (10–20 µm) results in signals without physical cross talk and low pad multiplicity. This is crucial for the separation of showers within jets and the successful use of the PFA.
8. the pressure and temperature dependence of the detector pulse height is known and can be corrected for in real time by adjusting the mesh voltage;

In 2007 and 2008 small prototypes were realized and tested with an ⁵⁵Fe X-ray source and in particle beams at CERN. A broad test program including measurements of basic performance (gas gain, mesh transparency), ambient parameter signal dependence (gas flow, pressure, temperature), minimum ionising particle signals (Landau distribution, efficiency, pad multiplicity, uniformity) as well as study of the detector behaviour in low energy electromagnetic and hadronic showers (gain stability, shower profiles)
was carried out [4, 5]. In parallel to that, in 2008, a new design was proposed to reduce the detector thickness and match some requirements for an ILC HCAL (8 mm gaps between steel absorber, 1 µW power consumption per channel): the front-end chips are connected directly on the Bulk PCB rather than on separate boards, forming a so-called Active Sensor Unit (ASU). First, ASU of small size (8×8, 8×32 cm²) were built and tested at CERN [6]. Later on, in 2009, five ASU of 32×48 cm², each equipped with 24 HARDROC2 chips were fabricated and assembled inside a square meter chamber which was tested at SPS with muons and PS with pions in 2010 [7, 8]. The measured performance were clearly limited by the too fast shaping of the ASIC used and a lot of efforts were subsequently devoted to the development (in collaboration with the LAL/Omega group) of a new one called MICROROC optimised for the detection of Micromegas signals [9]. A first square meter prototype equipped with MICROROC chips was constructed in summer 2011 and successfully tested at the SPS. The prototype and the test in beam are described in what follows, the proposal for further test in 2012 are motivated in the last section of this document.

2.3 Square meter Micromegas prototype

2.3.1 Mechanical design

The one square meter prototype features 9216 readout channels (96×96 pads). It is assembled from six active sensor units glued on a stainless steel supporting plate and surrounded by a plastic frame (Figure 1). Another stainless steel plate holds a copper drift electrode. The 3 mm drift gap is defined by the frame height and is kept constant over all chamber area by tiny spacers placed between the ASU. Each ASU consists of woven mesh and a PCB with 48×32 readout pads of 1×1 cm² and 24 MICROROC chips. The readout of two ASU is chained serially and connected to the data acquisition system by three detector interface boards (DIF). The DIF is a mezzanine board which allows to configure the ASIC (e.g. thresholds), readout the data from the ASIC memory and also to provide system clock and low voltage. Another board, called inter-DIF, is placed between the DIF and the ASU to provide the high voltage to the drift and meshes. The gas is distributed by one inlet and outlet traversing the chamber frame. The total thickness of the chamber is about 1 cm.

![Figure 1: Photographs of an Active Sensor Unit and the 1 m² prototype during assembly.](image)

2.3.2 Front-end electronics

The prototype is equipped with a newly developed 64-channel ASIC called MICROROC. Each ASIC channel features a diode network embedded inside the silicon to protect against discharges, a charge preamplifier followed by 2 shapers of different gain and shaping time tunable between 75 and 200 ns, 3 discriminators allowing setting of 3 readout thresholds with 10-bit DACs (so-called semi-digital readout) and a 127 event depth memory with 200 ns timestamping of hits. The dynamic range of the low and high gain shaper are 200 and 500 fC respectively. The output of the high gain shaper is connected to 2 discriminators which are used to define the low and medium channel threshold while a third discriminator, linked to the low gain shaper, is available to set the high threshold. The three thresholds are common to the 64 chip channels, however a 4-bit offset can be used to vary the individual pedestal positions with respect to the thresholds. This feature virtually provides a channel to channel control of the 3 thresholds.
3 Results from 2011 test

3.1 Summer period - SPS/H4

3.1.1 Overview
A telescope and the square meter prototype were installed in H4 for a period of 18 days: 6 days standalone under CALICE collaboration followed by 13 days of RD51 running with the beam shared between four groups. At an average trigger rate of 100 Hz in spill, a total of 6 millions muons and pions in the ratio 85/15 were recorded. Muons were used to measure the prototype performance to MIPs (efficiency, multiplicity, uniformity) under various settings of the detector (voltages, shaping time, thresholds). Shower signals were measured with a collimated pion beam focused at a small iron block placed half a meter upstream of the prototype.

3.1.2 Set-up
Downstream of Goliath magnet, the set-up consisted of a telescope and the prototype each placed on a movable table, a gas distribution panel, two racks with trigger electronics and power supplies and a fast acquisition PC (Figure 2 left). The telescope is a mechanical structure holding small Micromegas tracking chambers equipped with pads or strips for tracking and three scintillators plus PMT for triggering. All the detectors were flushed with a non flammable gas mixture of Ar/CF$_4$/iC$_4$H$_{10}$ 95/3/2 at a total flow of 41/l/h.

3.1.3 Noise conditions
An iterative procedure to equalize the channel noise rate to 10 mHz was carried out at the beginning of the test, right after installation. Later, noise conditions were monitored with daily short dedicated runs during which the ASIC memory were read out every second. Very small deviations from the equalized value of 10 mHz could sometimes be observed. In such case, channel to channel pedestal corrections were applied to decrease/increase the noise back to its nominal value. This figure is to be compared to the particle rate per channel which reaches 10 Hz in the center of the muon beam, leading to a high signal to noise ratio of about $10^3$.

3.1.4 Performance to MIPs

Mesh voltage scan The efficiency is measured by finding a muon track in the telescope, extrapolating its impact point at the prototype and looking for hits inside a $3 \times 3$ pad area at the time of the trigger (window of 600 ns). The multiplicity is calculated as the average number of hits whenever at least one hit is present. Both quantities were measured at various mesh voltages and shaping times with the beam spreading over roughly hundred pads. A preliminary analysis lead to the trends showed in Figure 3 where a high efficiency is reached at all shaping settings. At 390 V mesh voltage (gas gain around 3000), 1 fC
hit threshold and 200 ns shaping, one records an efficiency of 98% and a multiplicity of 1.12. Both are very well compatible with small prototype performance previously measured in similar conditions [4].

**Figure 3:** Efficiency and pad multiplicity to 150 GeV/c muons at various operating conditions.

**Threshold scan**  Thanks to a careful calibration of the electronics before the test beam, a channel threshold scan could be performed (Figure 4 (left)). The slight inflexion point at half of the range follows from the Landau distribution turnover and indicates a MIP most probable charge of 22 fC. The lowest running threshold is about 1 fC; further increase to 2 fC leads to a dramatic drop of the noise rate by 3 orders of magnitude while leaving the efficiency almost unchanged.

**Angle scan**  Pad multiplicity is directly impacted by the angle of incidence of traversing muons. This fact is relevant when measuring shower secondary particles and was studied by rotating the prototype with respect to the beam direction. The measured trend appears in Figure 4 (right).

**Position scan**  A large part of the period was devoted to a position scan over the prototype area with the goal of assessing the performance uniformity with a precision on the efficiency better than 1% absolute. At the given beam size and rate, roughly two third of the prototype area could be scanned. Preliminary results show an expected drop at ASU boundaries and a very uniform response over active area.

**3.1.5 Performance with pions**  Directed at a 20 cm thick block of iron right downstream of the telescope, the 150 GeV/c pion beam was used to produce hadron showers which would propagate to the prototype placed half a meter downstream.
This set-up allows to get a first idea of the response of the prototype to high multiplicity events. In addition, the possibility to distinguish by use of the three thresholds multi-particles and single particle within 1 cm$^2$ cells can be looked at. Finally thanks to the possibly large spatial extend of some showers, a uniformity measurement can be carried out quickly.

**Uniformity** The superimposition of hits from $10^4$ pion events measured at a mesh voltage of 350 V (efficiency of 90 %) is depicted in Figure 5 (left). The pattern exhibits rings that correspond to non-showering pions in the center surrounded by the electromagnetic and hadronic components of the showers. The clear azimuthal symmetry results from the very good uniformity of the efficiency over the prototype area. The effect of dead zones at the ASU junctions is better seen when projecting the pattern along vertical and horizontal axis (Figure 5 middle and right). Pads at the ASU edges show a lower efficiency, as expected from the 2 mm wide Bulk coverlay line running along them.

![Figure 5: Integrated 2D and 1D image of $10^4$ pions of 150 GeV/c traversing a 1 $\lambda$ Fe block.](image)

**Hit multiplicity** Longer runs each containing $5\cdot10^4$ pion triggers were performed at various mesh voltages in order to measure the hit multiplicity that will later be compared to Monte Carlo predictions. Number of hits distributions obtained at 325, 350 and 375 V exhibit a sharp peak and a long tail from traversing and showering pions respectively (Figure 6 left). The tail extends to larger values at higher voltages while the population of the zero hit bin drops. At 375 V the expected MIP efficiency is 97 %, the measured maximum number of hits is quite large, roughly 300. Snapshots of such very high multiplicity events are showed in the Figure 7.

![Figure 6: Number of hits passing the three thresholds at various voltages. The distribution at 325 V and 375 V are scaled to the number of events of the 350 V distribution.](image)
Figure 7: High multiplicity events from showering pions (the color codes for the 3 thresholds).

Semi-digital readout  The three thresholds were set to 1 fC, 1 MIP and 5 MIP respectively where the charge of a MIP depends on the mesh voltage (e.g. 22 fC at 390 V). At 325, 350 and 375 V a different set of medium and high thresholds were therefore used so that the efficiency for passing medium and high thresholds is kept constant. Accordingly the corresponding number of hits distributions should be the same. The measurements plotted in Figure 6 (middle, right) agree well with this prediction, meaning that a good control of thresholds was achieved.

Figure 8: Fraction of hits passing medium and high threshold versus horizontal position.

A semi-digital readout should provide information on the number of particles crossing a cell. The particle density being higher in the shower core, the probability to cross medium and high thresholds should be larger for pads close to the shower axis. We thus calculated the ratio of the number of hits crossing the medium to low threshold $R_{1/0}$ and high to low threshold $R_{2/0}$ and plotted them versus position along the horizontal axis. A peak at the beam profile center is observed in Figure 8. This is especially clear for the $R_{2/0}$ ratio while a left shoulder is still to be understood in the $R_{1/0}$ distribution.

3.1.6 ASIC features
This beam test was the first occasion to check MICROROC main features: trigger-less mode, semi-digital and analogue readout and operation under power-pulsing. While the last point could not be verified during the allocated beam time, the others were successfully tested with muons and pions.

Trigger-less operation  When operated in trigger-less mode, the prototype is read out upon recieval at the DIF boards of a memory full signal from one of the 144 ASIC. A stable operation therefore requires very low noise and discharge rates which would fill memories up and generate dead time. This was easily achieved at 365 V as illustrated in Figure 9 by the recorded profile of the beam (efficiency of 95 %).
information from the detector is used in this plot and no cut is applied to the data. This is possible thanks to the the very quiet behaviour of the whole prototype (electronics and Bulk).

Figure 9: Muon beam profile obtained from raw data in trigger-less operation (left). Pion signal distribution measured on one pad with the analogue readout (right).

**Semi-digital readout** Hit information is coded on 2-bits in the ASIC memory according to three thresholds (so-called semi-digital readout). At a mesh voltage of 390 V the low, medium and high threshold were set to 1, 20 and 100 fC respectively using calibration constants measured at LAPP with test charges. The probability to cross the three thresholds can be inferred from the measured profiles in Figure 10 where a cut at the time of the trigger is applied (the acceptance of the scintillators is also seen). As expected, the higher the threshold, the lower the number of detected signals. The uniformity of the three thresholds is being worked out using the data from the position scan.

Figure 10: Beam profile viewed through the three readout thresholds.

**Analogue readout** The possibility to measure the shaper signal with a resolution better than 2-bit was implemented with dedicated routing lines on the PCB and a 12-bit ADC per DIF board. Focusing the pion beam on a four pad region, expected Landau distributions were measured. Figure 9 (right) shows one of them together with the pedestal peak. Several runs were performed at various timing settings in order to find the time of conversion at which the shaper signal reaches a maximum.
3.2 Fall period - SPS/H8

3.2.1 Overview

The square meter Micromegas prototype previously tested in summer was inserted inside a cubic meter steel structure together with 30–50 layers of Glass-RPC. The calorimeter was installed in H8 line for a period of 10 days from the 3rd to the 12th of October. The main goal was to validate the working point of the detector defined during the summer period (mesh voltage of 390 V) inside a HCAL structure by recording shower images at various hadron energies, sharing the data from GRPC and Micromegas detector and studying in details the spatial development of hadron cascades. That implied the use of a common acquisition system (CALICE DAQ) suitable for reading out very large number of channels (hundreds of thousands). Unfortunately, a stable running of the DAQ could not be achieved and the Micromegas chamber was read out through standalone USB. A total of one million pion triggers were recorded at the following momenta: 60, 80, 100, 120, 150, 180 GeV/c. Spatial and number of hits distributions after 5 interaction lengths of iron (layer 47) were recorded and for the first time, the behaviour of the prototype inside a calorimeter could be investigated.

3.2.2 Set-up

The calorimeter was installed in H8 upstream of the CALICE tungsten scintillator hadron calorimeter (AHCAL). A set of three scintillators with an overlap area of $6 \times 6 \text{cm}^2$ in front of the calorimeter was used for triggering the readout of the Micromegas prototype. All services (gas, LV and HV supply, electronics) were already described in section 3.1.2. The detector voltage throughout the test were kept at 480 V and 390 V for the drift and mesh respectively yielding fast collection time of the primary charge and high efficiency (98 %).

3.2.3 Hadronic showers

Number and space distribution

Without external tracking and common DAQ and reconstruction, the layer at which a shower starts as well as the shower axis are not known. It is however possible (as was done in summer) to measure spatial and number of hit distributions which can later be compared to Monte Carlo predictions. Preliminary plots in Figure 11 depict such distributions. The impact of dead area on efficiency is less pronounced than in Figure 5 probably because the mesh voltage is 10 V higher and the beam is directed at the center of the prototype. The maximum number of hits is also lower than what is shown in Figure 6 which can be explained by the larger amount of material in front of the chamber (5 against 1 λ) and the lower beam energy (100 against 150 GeV/c). Although only a fraction of the available statistics has been looked at yet, the preliminary plots are understood and the square meter prototype performed as well as during the summer period.

![Figure 11: Number and space distribution of hits from $2 \cdot 10^4$ pions of 100 GeV/c after 5 λ of iron.](image-url)
Trend with energy  As expected from the rising number of particle reaching the last layers of the calorimeter at higher beam energy, the average number of hits recorded at the prototype (layer 47) also increases. Interestingly, a linear relation is noted for the low, medium and high thresholds. This trend is illustrated in Figure 12 and will be compared to Monte Carlo predictions at a later stage of the analysis.

Figure 12: Average number of hits seen by the three thresholds versus pion momentum.
4 Proposal of beam test in 2012

At the end of October 2011, a second square meter prototype with MICROROC as a readout chip was constructed. At the moment of writing, 500 more chips have been ordered as well as PCB for two additional prototypes: one with a resistive coating over the pads and one with standard non-resistive pads. We thus expect to have four layers by the middle of 2012 which would undergo test inside a calorimeter (CALICE) and a test in muon and pion beam (RD51). Both are motivated below.

4.1 Calorimetry test inside the Fe/GRPC SDHCAL

Results on the first test of the MICROROC layer inside the Fe structure (section 3.2) promise that very interesting measurements will be carried out if a synchronisation between the GPRC and our detector(s) is realised and the data are shared. The synchronisation should be achieved thanks to a modified version of the CALICE DAQ which will allow the readout of both detector in a stable way. With common data reconstruction the Micromegas layers would sample the shower signals much more precisely as the starting point of the shower could be identified. Our tests, listed below, should be conducted at the SPS:

- measure showers with fine granularity (longitudinal and transverse development, hit density). This will prove that Micromegas is suitable for Particle Flow and will be an important input to Monte Carlo simulation models;
- assess the stability of the detector in a very high particle multiplicity environment especially at the maximum of the shower energy deposit. Summer 2011 test presented in section 3.1.5 are encouraging in that respect but a more qualitative study should be conducted;
- quantify the effect of temperature inside the calorimeter on electronics (pedestals, thresholds, gains) and gas density (gas gain). Because the thresholds are set very close to the pedestals, it is important to verify that both will not shift. For this purpose, each square meter layer is equipped with six temperature sensor and pedestal monitoring system;
- test of power-pulsing of the MICROROC. This could not be realised in 2011 and will be crucial to limit the power (and thus heat) dissipation inside the calorimeter to a minimum.

The three first objectives make it necessary that the Micromegas layers would be placed within the ten first layers of the calorimeter and not at the back. Concerning the desired statistics, we aim at collecting at four energy points between 100 and 200 GeV/c, one million pion triggers. The necessary time will obviously depend on the rate capability of the GRPC and we assume an event rate of 25 Hz and a duty factor of 20% of the SPS. As a result, the test should be completed in a period of 10 days. This period should be in continuation of the one of the GRPC group.

4.2 Performance test in muon and pion beam

The fabrication of a prototype with resistive coating is motivated by the need to simplify the chamber design by removing passive components which protect the ASIC against gas discharges and possibly reducing the cost. It is of course essential to validate the resistive scheme that will be adopted by measuring MIP performance and spark protection capability in a similar way as what was done in summer 2011. The test program is a position scan of the resistive chamber with muons at low intensity and some runs at higher intensity with pions to test the prototype against sparks (momentum of 150 GeV/c). Such beam requirements naturally fit within the needs of RD51 users which use the dedicated H4 line at SPS. In order to conduct all tests a period of 2 weeks in H4 is foreseen.
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