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Large area Micromegas chambers with embedded front-end electronics for hadron calorimetry☆

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Abstract

Micromegas (Micro-mesh gaseous structure) is an attractive technology for applications in particle physics experiments (TPC, calorimeters, muon systems, etc.). The most important results of an extensive R&D program aiming to develop a new generation of a fine-grained hadron calorimeter with low power consumption digital readout using Micromegas chambers as an active element are presented. In 2010, the first large scale prototype of Micromegas chamber with almost 8000 readout channels has been built and tested with high energy particle beams at CERN. The fundamental results, such as detection efficiency, hit multiplicity, gain stability, response uniformity and effect of power pulsing of the detector front-end electronics are reported. Eventually, the development and test of the second generation of the large scale prototype with new readout electronics and some important improvements of its mechanical design is described and the prospective towards the construction of a technological prototype of a 4.5 λ deep digital calorimeter for a future linear collider is also given.

Keywords: Gaseous Detectors (MPGD), MICRO MEsh GAseous Stucture (MICROMEGAS), Calorimeters, Large detector systems for particle and astroparticle physics

1. Introduction

Calorimetry at the future linear collider will be optimized for Particle Flow. This approach has been chosen to achieve an excellent jet energy resolution of about 3–4 % over the whole jet energy range, which allows to distinguish between gauge bosons in multi-jet final state events and make thus possible to study many interesting reactions in e^+e^- collisions. In order to have maximal benefit from this approach, the calorimeters must have capability to separate showers of individual particles in a jet. This requires development of new advanced reconstruction algorithms as well as the utilization of the calorimeter with very fine granularity. Intensive R&D program on different detector technologies for hadron calorimeter is currently underway. One of the considered technology is a Micromegas (Micro-

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mesh gaseous structure) detector with 1×1 cm^2 lateral segmentation and embedded readout electronics providing 2-bit information per channel, which allows not only counting hits in a hadron shower, but also making a coarse estimation of energy deposited in a cell in order to improve linearity of the calorimeter. The first large scale prototype (1×1 m^2) of the Micromegas chamber developed for a hadron calorimeter was constructed and tested in a beam last year. The second generation chamber prototype with new readout electronics has been produced this year. Finally, a technological prototype of the digital hadron calorimeter with 40 Micromegas chambers interlayed by stainless steel or tungsten absorber planes is expected to be built to evaluate its physics performance and to choose the final technology for the future hadron calorimeter.

1.1. Micromegas basic characteristic

The Micromegas chambers designed for a hadron calorimeter have 1×1 cm^2 readout pads with embedded readout electronics to ensure very fine lateral and longitudinal segmentation of the calorimeter. The chamber gas volume is divided by woven mesh into the 3 mm thick drift and 128 μm application gaps. Typical voltages providing an optimal drift and amplification electric fields for Ar/iC_4H_{10} gas mixture are 0, 430, and 480 V on the anode, mesh and cathode, respectively. Properties of the chamber has been evaluated with several small size prototypes (from 8×8 up to 32×12 cm^2), firstly, by used of the analog readout for detail detector characterizations, and secondly, with digital readout to test the embedded very-front-end electronics and to measure the most important quantities for digital hadron calorimetry. Important results has been achieved during several test beam campaigns at CERN with the small size prototypes [1]. Measured deposited charge with a most probable value around 22 fC with a variation of 11.3 % over 617 readout channels has been measured. At 1.5 fC readout threshold, the detection efficiency better than 97 % with an efficiency disparity less than 1 %, and hit multiplicity smaller than 1.1 have been obtained. These characteristics make Micromegas very attractive technology for hadron calorimetry as well as for other applications.

2. First large scale prototype – 1 m^2 chamber

2.1. Engineering design and data readout

The first large scale prototype is a 1 m^2 chamber with 9216 readout channels (96×96 pads). The chamber is assembled from six active sensor units (ASUs) which are glued on the stainless steel supporting plate. They are surrounded by a plastic frame and covered by another stainless steel plate which holds a copper cathode. 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 ASUs. Each ASU consists of woven mesh and a PCB with 48×32 readout pads of 1×1 cm^2 and 24 HARDROC [2] chips. The readout of two ASUs is chained serially and connected to the data acquisition system by detector interface boards (DIF). The DIF is a mezzanine board which allows to configure HARDROCs by setting readout thresholds and preamplifier gains, to readout the HARDORC data, and also to provide the distribution of the system clock and high voltages through another dedicated board, called inter-DIF, which is placed between the DIF and the ASU. The gas distribution is provided by one inlet and outlet in the chamber frame. Total thickness of the chamber is 12 mm and corespondents to an effective thickness[1] of 8 mm which complies well with ILC specifications. Finally, it must be noted that due to the lack of the readout electronics, the first 1 m^2 prototype has been equipped only by 5 ASUs and thus total number of readout channels was 7680 instead of 9216.

Before the prototype assembly, the readout electronics of each ASU has been verified and procedure for its calibration has been established. The calibration includes the setting of pedestals, determination of the noise level and preamplifier gain equalization to obtained the lowest detection threshold and thus the highest detection efficiency. The overall functionality of each ASU has been then extensively tested in the dedicated test gas chamber using an ^{55}Fe source and cosmic particles. Methodology and results of these tests can be fount in Ref. [3].

2.2. Test beam

The 1 m^2 chamber was tested in a particle beam at CERN during two test beam periods in 2010. The first one was performed at CERN SPS/H4 where chamber performance was evaluated with high energy muons. The second period was a combined test of the Micromegas prototype and scintillator hadron calorimeter with tungsten absorbers at CERN PS/T9 to evaluate the chamber behavior and its stability in hadronic showers.

[1]The effective thickness doesn't include 4 mm of the supporting plates material, which will be considered as a part of the absorber.

2.2.1. Muon data

The Micromegas chamber was exposed to 150 GeV/c muon beam. The main objective was to validate its technological chooses, functionality test of the readout electronics and DAQ, and to evaluate the chamber general performance. Due to the very short shaping time of the HARDROC chip, which is optimized for RPC (Resistive Plate Chamber) signal and not for Micromegas, only about 10 % of the signal has been seen. That is why a detection efficiency of only about 43 % has been measured as is shown for one chip in Fig. 1 left. It must be pointed out that the utilization of the HARDORC chip for the 1 m^2 chamber was because no other electronics was available at that time. It is expected that for readout electronics well suited for Micromegas signal, the efficiency close to 100 % should be reached. The hit multiplicity has been measured to be about 1.05.

The ILC beam structure allows to power pulse the readout electronics and thus reduce significantly its power consumption. To test this approach, all the chips of the prototype has been power pulsed during the beam spill. The results obtained shows that the chamber performance doesnt change significantly during the power pulsing. An example of the detector efficiency measured with and without power pulsing is displayed in Fig. 1 right.

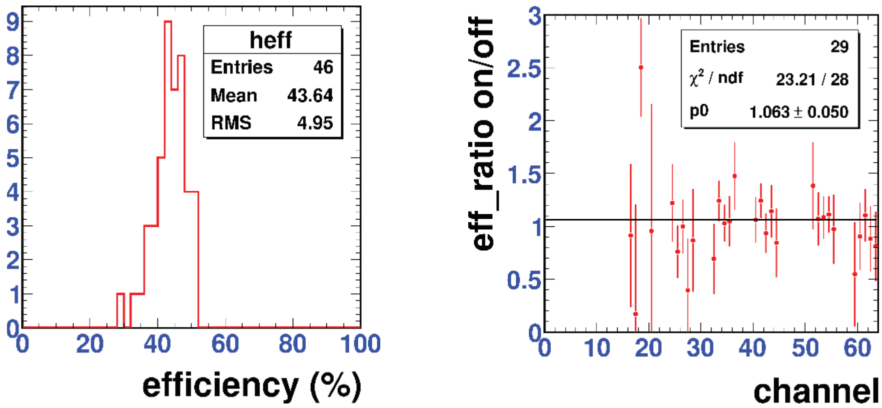

Figure 1. Left: Detector efficiency measured in one chip. Right: Comparison of the detector efficiency measured with and without power pulsed readout electronics.

2.2.2. Hadron data

To evaluate the chamber behavior and its stability in multi-hit events, the prototype was placed in the last position of the tungsten hadron calorimeter prototype instrumented by 30 layers with scintillator planes and exposed to hadron showers initialized by pions with momentum up to 10 GeV. A total amount of tungsten in front of the Micromegas chamber was about 4.5 λ. As expected, the number of hits measured in chamber increases with energy of incident particles, see Fig. 2 right. The lateral profile of the hadron shower is displayed in Fig. 2 middle. Thanks to the very fine lateral segmentation of the chamber, the electromagnetic and hadronics parts can be easily distinguished as it is shown in a profile histogram in Fig. 2 left. In this figure is also clearly seen the contribution of the muons by which the hadron beam was contaminated. In addition, the DAQ between scintillator calorimeter and Micromegas prototype has been synchronized. This allows to compare the response in scintillator with Micromegas, and furthermore the tungsten calorimeter can be use as an efficient tool for event selection (e. g. depending on the shower start position) for further data analysis.

3. Second large scale prototype – 1m^2 chamber

The second large scale prototype has been build in 2011 and the first beam test has been performed in August of the same year. Although the lateral dimension of the chamber are identical to the previous prototype (1×1 m^2), many improvements in chamber engineering design and readout electronics have been made.

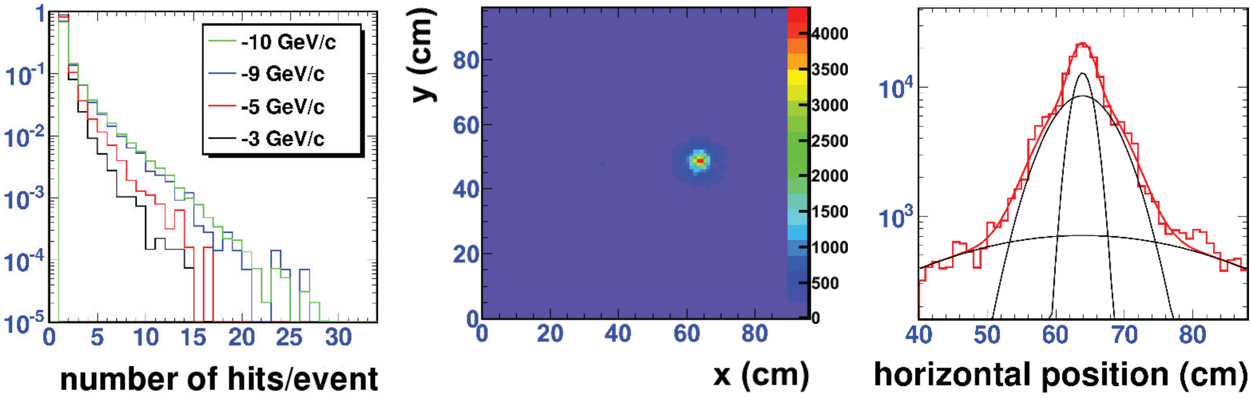

Figure 2. Left: Normalized number of hits collected in hadron showers for different incident pion energies. Center: Hit map of hadron showers in the Micromegas chamber. Right: Lateral shower profile showing three components: electromagnetic, hadronic and muon contamination of the hadron beam.

3.1. Engineering design

Main improvements with respect to the first 1 m^2 prototype are following. The stainless steel back-plate protecting very-front-end electronics is now screwed instead of glued, which allows to access easily the readout electronics in case that an intervention is needed. Moreover, gas tightness is now made by ASU and mask on one side, and the drift plate on the second side. Because of this, the back-plate may be removed, which can improve absorber stiffness by increasing its thickness by additional 2 mm of stainless steel. The active chamber thickness has been reduced from 8 to 7 mm by necking of the mask thickness. Thus the total thickness of the chamber is 1.1 cm and 0.9 cm with and without supporting back-plate respectively. Finally, the easier access to DIF connectors and low/high voltage patch panels when the chambers are inserted inside structures, has been made. A sketch and photography of the second 1 m^2 showing those new technological solutions in displayed in Fig. 3.

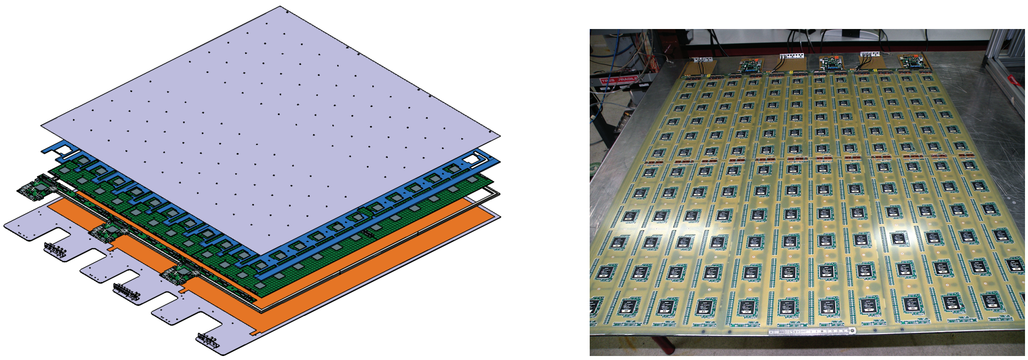

Figure 3. Left: Engineering design of the second generation of the Micromegas chamber. Right: Photography of the chamber showing side of the readout electronics and protective mask.

3.2. Read-out electronics

The second 1 m^2 chamber has been equipped with a newly developed 64-channel ASIC called MICROROC. The MICROROC has the same digital part as the HARDROC and is also pin-to-pin compatible which minimize modifications on the PCB. A simplified schema of the channel architecture is in Fig 4.

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 time-stamping 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.

A detailed characterization of the detector can be performed thanks to the calibration test input and a multiplexed analogue output. The former is connected to the preamplifier input via a capacitor while the analogue signal is picked up at the low gain shaper output. The MICROROC, like the HARDROC, is auto-triggered: hits are recorded to the memory whenever a chip threshold is passed. The memory is read out either when it is full or upon the receival of an external trigger signal. Also different parts of the ASIC can be power pulsed so as to reduce the power consumption. Finally, to monitor a temperature of the readout electronics, a temperature sensor has been placed on each ASU.

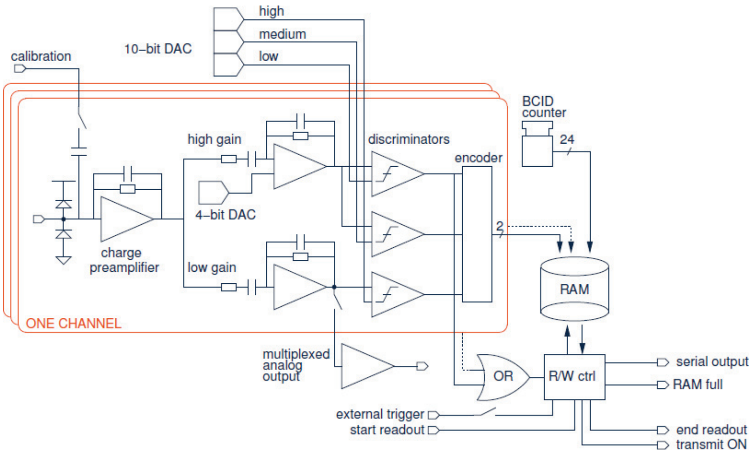

Figure 4. Schema of the MICROROC asic architecture.

3.3. Electronics calibration

The aim of the calibration is to verify the overall functionality of the chips (shaper gain, noise) and determine optimal settings (thresholds and pedestal offsets) for maximum detector efficiency and negligible noise hit rate. This procedure was carried out for six ASU each equipped with 24 MICROROC circuits (9216 channels).

The shaper gain of a given channel is determined by injecting voltage pulses to the test capacitor for decreasing threshold values. The obtained hits versus threshold trend is called an S-curve. Measuring the S-curve inflexion point (in DAC units) for different input charges (in fC) yields the gain of the shaper (in DAC/fC). For the high gain shaper, the average gain over the 9216 channels is 7.1 DAC/fC with variations of 2.5 % RMS (Fig. 5 left). Smaller variations of 1 % are observed at the chip level. Measurements of the low gain shaper performance show a gain of 1.6 DAC/fC with 3.3 % variation RMS (Fig. 5 right).

The noise is measured as the width of the S-curve obtained for a test charge of 12.5 fC. The width in DAC units is translated into charge using the shaper gain. The average value over all channels is 0.16 fC with variations of 0.02 fC RMS (Fig. 5 center). This value is very small compared to the expected detector signal (2025 fC MPV for MIPs at a mesh voltage of 420 V in Ar/iC_4H_{10} 95/5), therefore the MICROROC m^2 prototype should has a very high detection efficiency.

The low threshold of a chip is set just above the noise level of the 64 channels. This is done is two steps. Firstly, all pedestal S-curves are measured at equal offset settings (Fig. 5 left). The low threshold is then set just above the highest pedestal[2]. Secondly, the channel offsets are tuned so as to move all pedestals as close as possible to the threshold while keeping the noise hit rate under a tolerable value, for instance 0.1 Hz. Thanks to this procedure, the S-curves are aligned and the channel threshold dispersion is reduced. This is illustrated Fig. 5 center and right.

[2]More precisely, 10 times the S-curve width which is less than 1 fC.

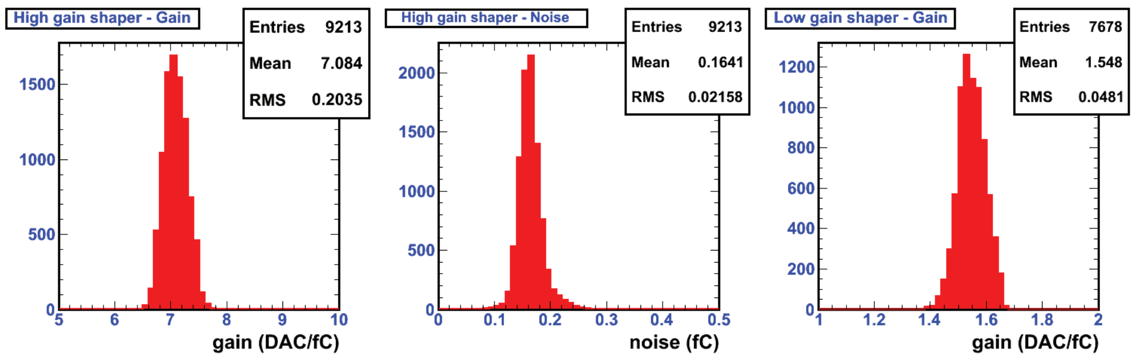

Figure 5. Gain (left) and noise (center) of MICROROC high gain shaper measured over all six ASU channels but three noisy channels. Gain of the low gain shaper measured over a smaller number of chips (right).

While the low threshold is set to a minimum value, there is no pre-defined values for medium and high thresholds. Their final values in a hadron calorimeter should be optimized for best performance. This work being still on-going, they are set for the time being at 1 and 5 MIPs which at 420 V in a mixture of Ar/iC_4H_{10} 95/5 equal to roughly 20 and 100 fC, respectively. In any case, setting the thresholds obviously makes use of the measured pedestals and shaper gains. Using calibration results, they hence can be set precisely over the full dynamic range of the shapers (200 and 400 fC for the medium and high threshold, respectively).

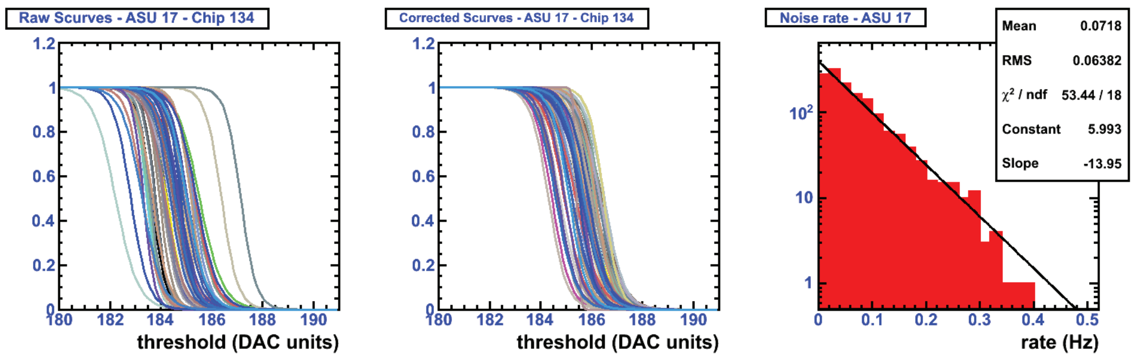

Figure 6. Pedestal S-curves measured on a MICROROC before (left) and after (center) channel offset correction. The alignment procedure consists in adjusting the offsets so as to obtain a noise rate as uniform as possible over the ASU channels. On the right is the rate measured over all ASU channels, the target rate in this case was 0.1 Hz (right).

3.4. Test in gas

Prior to the 1 m^2 assembly, tests in gas are carried out to improve the high voltage stability of each ASU and to check the full detection chain from signal generation in gas to hit reconstruction with off-line software.

Freshly manufactured ASU can be contaminated by dust particles or other impurities resulting from the fabrication process which are trapped between the ASU anode pad plane and the mesh. They eventually limit the possible gas gain by lowering the breakdown voltage of the detector. A standard cleaning procedure is to let the detector to spark in air while progressively increasing the mesh voltage until a value of 800 V (given by the Paschens law) is reached. This operation is conducted in a clean room and takes about 15 minutes per ASU.

After the cleaning procedure, each ASU is placed into a gas chamber designed to measure the response to ^{55}Fe quanta of individual channels (Fig. 7 left). To this end, the chamber cover is perforated above each anode pads. Also a very thin window limits the absorption of X-rays which mostly convert in the 1 cm thick drift gas gap. An ^{55}Fe source with a collimator encompassing 4 cover holes is centered above the junction between 4 pads each wired to a different chip. In this way, a quick qualitative test can be conducted over the 24 ASU chips by moving the source over 6 positions and measuring the hit profile from quanta conversions (Fig. 7 center).

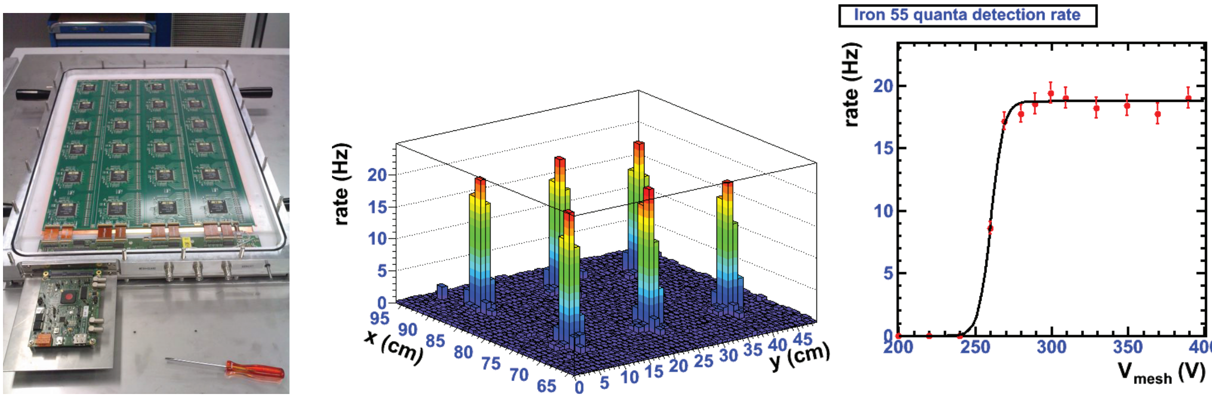

Figure 7. Left: Photography showing an ASU placed inside the test chamber before closure. Outside the chamber, the DIF readout board as well as HV connectors for mesh, guard and cathode are visible. Center: Profile of hits obtained after merging 6 acquisitions with the ^{55}Fe source at different positions above the ASU. At each position, the source illuminates mainly 4 pads of 4 different chips. Right: Hit rate versus mesh voltage in an Ar/iC$_4$H$_{10}$ 95/5 mixture. The inflexion point at 260 V corresponds roughly to the photoelectric peak (230 primary electrons).

Quantitative study of the threshold and mesh voltage has been performed on a single channel by collimating the source to a single pad and counting the number of hits recorded in the MICROROC memory. As an example, Fig. 7 (right) shows the trend of the number of detected quanta with mesh voltage in a double mixture of Ar/iC$_4$H$_{10}$ 95/5. The inflexion point corresponds roughly to the photoelectric peak (230 primary electrons), it is reached at 260 V at which a gas gain of roughly 50 is expected. This is a promising result as it can be inferred from, that a relatively low gas gain of a few thousands should be sufficient to detect MIP charges down to a few primary electrons.

4. Simulation studies

In order to evaluate the physics performance of the digital hadron calorimeter with very fine lateral and longitudinal segmentation, a detail simulation of the technological prototype instrumented with 40 1 m^2 Micromegas chambers has been performed. The fundamental characteristics, such as longitudinal and lateral shower profiles, energy containment, calorimeter response and its linearity, energy resolution, etc., have been studied and compared to a conventional calorimeter with an analog readout. The results confirmed that the digital calorimeter offers similar performance as the analog one [4].

Current work is focused on the optimization of the semi-digital readout (2-bit readout giving coarse estimation of deposited energy) to improve energy resolution and linearity of calorimeter response for higher energies of impacting particles, where the pure digital calorimeter (1-bit readout) suffers by the saturation effect. In Fig. 8 is show the preliminary results for the energy resolution measured by use of the analog, digital and semi-digital readout.

Moreover, several dedicated studies towards the optimization of the calorimeter design have been performed and alternative geometries improving calorimeter mechanical properties and stability have been proposed [5]. Finally, two designs for the SiD hadron calorimeter, one with off-pointing and second with tilted geometry, have been investigated. The first geometry, which is a Sid base-line design, has no cracks in calorimeter, but has more challenging design. On the other hand, the tilted calorimeter is easier to build (all the modules have identical shape), but part of the information is lost in the cracks between modules. The advantages and drawbacks of these geometries for Sid detector performance can be find in more detail in Ref. [6].

5. Summary and conclusions

Two 1 m^2 Micromegas chamber has been developed for application in hadron calorimetry. The first chamber has validated several important technological aspects of the project, such as choose of materials, chamber gas tightness,assembly and calibration procedures, etc. The chamber has been studied in laboratory with radioactive source

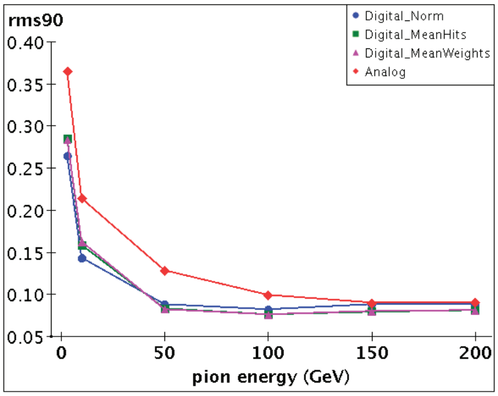

Figure 8. Energy resolution as a function of the beam energy for hadron calorimeter with analog (red), digital (blue) and semi-digital (green and pink) readout, respectively.

and cosmics particles, as well as in particle beams at CERN PS and SPS. The maximal performance of the chamber could not be reached due to the readout electronics, which was not designed for the Micromegas signal. Nevertheless, the calibration procedure to obtain the maximum detection efficiency has been established. Very good hit multiplicity and gain stability have been measured. The chamber also proved its robustness when exposed to hadronic showers. The substantial progress in development of the new readout electronics (MICROROC chip) and DAQ for Micromegas hadron calorimeter has led to the construction of the second large scale prototype to demonstrate its full potential. Beside the new electronics, some important improvements on engineering site has been made. Electronics calibration and functionality test of the chamber sub-modules (ASU) has been performed in laboratory by use of radioactive source and cosmics particles. The fabrication of the second 1 m^2 chamber is completed and has passed the first test in particle beams at CERN SPS in August 2011. Finally, it can be concluded that the successful construction and current performance of the 1 m^2 Micromegas chamber is the corner stone towards the construction of the sizable module - the technological prototype of the hadron digital calorimeter for a future linear collider.

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References

[1] C. Adloff et al., Micromegas chambers for hadronic calorimetry at a future linear collider, Tech. Rep. arXiv:0909.3197 (Sep 2009).
[2] S. Callier et al., Hardroc, readout chip of the digital hadronic calorimeter of ilc.
[3] C. Adloff et al., Micromegas for imaging hadronic calorimetry, Tech. Rep. arXiv:1102.1320, comments: 6 pages, 9 figures, CALOR2010 conference (Feb 2011).
[4] C. Adloff et al., Monte carlo study of the physics performance of a digital hadronic calorimeter, Tech. Rep. arXiv:0910.2636, comments: 8 pages, 5 figures, MPGD09 conference (Oct 2009).
[5] J. Blaha, Y. Karyotakis, Optimization of the hadron calorimeter geometry for the sid detector, Tech. Rep. LAPP-TECH-2011-03, comments: 14 pages (Sep 2011).
[6] J. Blaha, N. Geffroy, Y. Karyotakis, Impact of dead zones on the response of a hadron calorimeter with projective and non-projective geometry, Tech. Rep. arXiv:1102.1363, comments: 12 pages, 8 figures (Feb 2011).