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Performance study of MicroMegas chambers for the ATLAS muon spectrometer upgrade

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Summary. — MicroMegas (MM) chambers have been chosen as new precision tracking detectors for the upgrade of the forward muon spectrometer of the ATLAS experiment at the Large Hadron Collider (LHC). These chambers have been designed to allow operation in the high rate environment expected with the high luminosity, significantly exceeding the design one, during the third run of the LHC and the High Luminosity LHC (HL-LHC) operation. They must provide a space resolution below $100\,\mu$m and a tracking efficiency better than 97% per single plane. During the last years several tests have been performed on MM prototypes in order to verify that the requirements on efficiency and resolution can be achieved. The methodology and some of the results of performance studies done in beam tests at CERN are presented in this paper.

1. – Introduction

MicroMegas (MM) is an abbreviation for MICRO MEsh GASeous Structure, an innovative design concept for Micro-Pattern Gaseous Detectors first introduced by Charpak and Giomataris during the 1990s [1]. These high-resolution devices have been chosen as new precision tracking detectors for the ATLAS muon spectrometer upgrade [2,3], which will take place during the second long shut-down of the LHC in view of the increase of the luminosity for the third data-taking period, foreseen in 2021, and for the High Luminosity LHC (HL-LHC) where the peak luminosity will reach values up to $7.5\times10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ exceeding the project luminosity by about an order of magnitude. Such a high luminosity is a great opportunity for physics searches and measurements, but is very demanding in particular for the detector regions where a large flux of particles is expected, like the forward regions.

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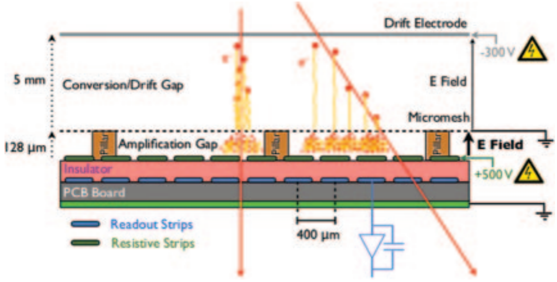

Fig. 1. – Working principle of a MicroMegas with numbers referred to the ATLAS MM project.

There are two main issues that would represent a serious limitation on the ATLAS performance beyond the design luminosity with the current detector: the decrease of the muon tracking efficiency in the forward regions and an unacceptable Level-1 muon trigger rate due to the increase of fake triggers coming from the forward direction. The present main tracking detectors of the muon spectrometer are the MDT chambers. For these chambers, in dedicated high-rate tests, single tube inefficiencies higher than 35% have been observed for rates exceeding 300 kHz/tube (which is the rate expected at the design luminosity). Those inefficiencies would significantly affect the overall chamber resolution resulting in a degradation of the spectrometer performance. The present Level-1 forward muon trigger is based on the coincidence of different layers of the TGC chambers in the middle muon station (the inner Big Wheel). This trigger is strongly affected by background particles and the trigger rate will increase with the increase of the luminosity exceeding the muon trigger rate sustainable by the readout system. An additional trigger station at the Small Wheel location would give the possibility to select the tracks pointing to the interaction region and therefore significantly reduce the fake trigger rate produced by forward tracks allowing to keep the single muon p_T threshold at 20 GeV.

For these reasons the complete replacement of the Small Wheel (the first station of the forward muon spectrometer) has been decided. Two different detector technologies have been chosen for the New Small Wheel (NSW): the small Thin Gap Chambers (sTGC) for triggering and the MM for precision tracking [2]. The NSW will have a diameter of about 10 m and will be composed of 16 sectors, 8 large and 8 small sectors. Each sector will have modules of sTGC and MM detectors, arranged in the configuration sTGC-MM-MM-sTGC, with each module being a quadruplet of detector layers. An overall active area of about 1200 m^2 will be provided by each one of the two technologies with chambers of unprecedented size up to 3 m^2.

2. – The MicroMegas technology for the New Small Wheel

The principle of operation of MicroMegas detectors is shown in fig.1. A 5 mm gap between two parallel electrodes is filled with a 93:7 Ar:CO_2 gas mixture and a thin metallic *micromesh* is placed between the two electrodes, held by pillars with a pitch of few millimetres and a height of about 100 μm. The *drift electrode*, with a -300 V voltage applied, and the mesh, which is grounded, define the *drift region*, where the ionisation takes place and the low electric field ($\simeq$ 600 V/cm) leads the produced electrons towards

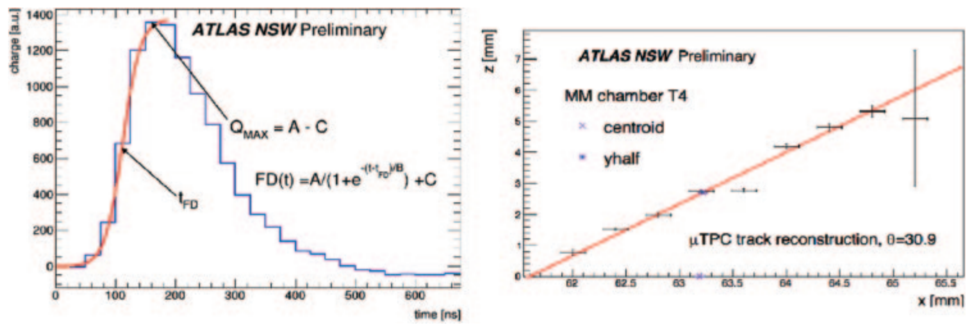

Fig. 2. – Example of hit reconstruction in a MM chamber on a track inclined by 30°. Left: single strip signal with Fermi-Dirac fit. Right: track reconstructed with the μTPC method.

the mesh. Following the field lines the electrons enter the very thin *amplification region* between the mesh and the *readout electrode*, which is segmented into strips with a pitch of about 400 μm, where a 530–580 V voltage is applied. Due to the very high electric field (40–60 kV/cm) the electrons produce avalanches with a gain of the order of 10^4. The thin amplification gap allows a fast ions evacuation, which occurs in about 100 ns, and allows MM to operate in highly irradiated environments. The produced signal is then read with readout strip. One of the most important innovations introduced for the ATLAS MM chambers is the introduction of a spark protection system provided by the usage of resistive strips placed on the readout electrode. The signal is read by the readout strips capacitively coupled to the resistive ones and this configuration significantly reduces the performance degradation due to discharges in the detector [4].

3. – Test beam results

In the last years several tests have been performed on beams at CERN on MM prototypes with different dimensions (from $10 \times 10\,\text{cm}^2$ up to $1 \times 0.5\,\text{m}^2$) and construction characteristics (strip pitch, pillar height, mesh construction technology) operating in different conditions, to determine the performance in terms of efficiency and resolution and develop and improve the track reconstruction algorithm. The results reported in this paper have been obtained using $10 \times 10\,\text{cm}^2$ chambers with 400 μm strip pitch.

3·1. *Reconstruction*. – For all tests presented in this report, signals from the readout strips were read using APV25 front-end readout electronics [5] which provides the collected charge as a function of the time in 25 ns bins. In fig. 2 (left) is shown an example of a single strip signal. By fitting the risetime of the distribution with an inverse Fermi-Dirac function, the time of the arrival of the signal, defined as the inflection point of the function, and the charge induced on the strip, defined as the maximum of the distribution subtracted by the baseline level, can be measured. For each strip i the time t_i and the charge q_i are therefore measured and clusters are reconstructed as groups of neighbouring strips according to dedicated clustering algorithms. In MM chambers the position of the cluster, which provides the hit position that will be used for the muon tracking in the NSW, can be measured with two different methods: the method of the centroid of charge and the μTPC method.

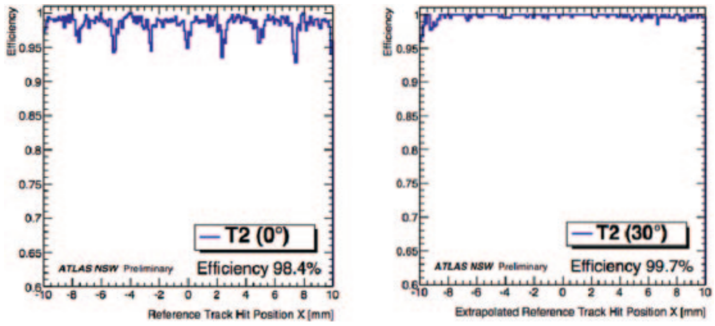

Fig. 3. – Efficiency measured as a function of the extrapolated position for perpendicular tracks (left) and tracks inclined by 30° (right).

The method of the centroid of charge is the simplest position reconstruction where the position is measured as the average of the position of the strips x_i in the cluster weighted by their charge measurement q_i:

$$x_{centroid} = \frac{\sum_i x_i \cdot q_i}{\sum_i q_i} \,. \tag{1}$$

The μTPC method consists in the local reconstruction of the track in the drift gap by using the measurement of the time of arrival of the signals t_i and the drift velocity of the electrons v_{drift} (4.7 cm/μs). For each strip hit the z coordinate is measured as $z_i = v_{drift} \cdot t_i$, which corresponds to the position of the primary ionisation, and a linear fit ($z = mx + q$) is used to reconstruct the track. The best position measurement is then given by the x coordinate (x_{half}) of the reconstructed track at half gap (z_{half}):

$$x_{half} = \frac{z_{half} - q}{m} = \frac{2.5\,\text{mm} - q}{m} \,. \tag{2}$$

An example of μTPC reconstruction is shown in fig. 2 (right). The two methods are complementary: the centroid method provides a better resolution for tracks with small inclination angles that generate small clusters while the μTPC provides a better resolution for more inclined tracks that fire a larger number of strips.

3˙2. *Efficiency*. – The chamber efficiency can be measured using several MM chambers as a telescope to reconstruct the track that is then extrapolated to the chamber of interest. In fig. 3 results are shown as a function of the extrapolated position for perpendicular tracks (left) and tracks inclined by 30° (right). For perpendicular tracks inefficiencies points are visible every 2.5 mm, reflecting the mesh pillars structure, but the overall efficiency is at 98% level. For inclined tracks the pillars structure does not affect the efficiency that results to be nearly 100% independently of the position.

3˙3. *Spatial resolution*. – The spatial resolution can be measured from the width of the distribution of the difference between the hit positions reconstructed in two adjacent chambers divided by $\sqrt{2}$, given the negligible effect of the beam divergence. In fig. 4 (left) such distribution is shown for perpendicular tracks. A fit with a double-Gaussian

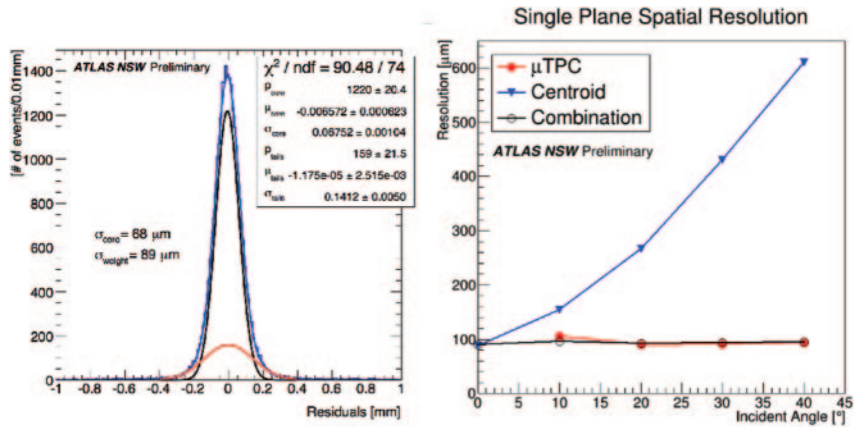

Fig. 4. – Left: Distribution of the difference of the hit positions reconstructed by two chambers divided by $\sqrt{2}$. Right: Spatial resolution obtained for the centroid and μTPC methods as a function of the track inclination angle.

function, to take into account the tails of the distribution, is performed to extract the resolution from the weighted average of the standard deviations of the two Gaussian functions. In fig. 4 (right) the resolution obtained with this technique for the centroid and μTPC position reconstruction methods is shown as a function of the inclination angle of the tracks. As expected the centroid method is best performing for perpendicular tracks while the μTPC method for inclined tracks. By combining the two methods a flat resolution at the level of $100\,\mu$m is obtained for tracks with all inclinations and in particular for angles between 8° and 32° which is the range for tracks in the NSW.

4. – Summary and outlooks

MM chambers have been chosen as precision tracking detectors for the NSW of the ATLAS detector. In the past years several tests have been performed on many prototypes and the results of the performance studies show that MM detectors have efficiency above 97% and resolution of about $100\,\mu$m per plane, well within the requirements for the NSW of the ATLAS experiment. The Collaboration is now building the Module-0, the first chamber with the dimensions and characteristics of the final chambers for the NSW, and tests will be performed on this chamber by the end of 2016 to verify its performance.

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