Performance of triple GEM tracking detectors in the COMPASS experiment

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Abstract

COMPASS is a high-luminosity fixed target experiment at CERN’s SPS, which has been taking data with a 160 GeV/c muon beam since 2001. The tracking of charged particles in the near-beam area is achieved by a set of twenty novel large-area micropattern gas detectors based on the Gas Electron Multiplier (GEM). Owing to a two-dimensional readout of signals, each of these detectors delivers two track projections. Distributed over a distance of 30m throughout the spectrometer, the GEM detectors constitute the backbone of the small-area tracking system of COMPASS. The performance of these detectors in the high intensity muon beam with particle rates up to 25 kHz/mm\textsuperscript{2} is investigated.

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1. Introduction

The aim of the COMPASS experiment [1] at CERN’s SPS is the study of the structure of nucleons and the spectroscopy of strongly interacting particles. The present focus lies on the investigation of the spin structure of the nucleon, in particular the measurement of the gluon contribution to the nucleon spin and the transversity structure function. This is achieved by deep-inelastic scattering of polarized $\mu^+$ from polarized deuterons in a $^6$LiD target, and determining the asymmetry of open charm production as a function of the relative orientation of muon and deuteron spins. In its first 2 years of operation with a muon beam more than 500 TB of physics data have been written to tape. In 2004, a pilot run with hadron beams is scheduled, which will yield data on the polarizability of $\pi$ and K mesons as well as on diffractive production of exotic mesons. Due to

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the small cross sections of the processes under investigation, a very high flux of beam particles up to $5 \times 10^7$ on the one hand, and a large spectrometer acceptance at high momentum resolution on the other hand are mandatory. Especially in the near-beam region, the tracking detectors have to be able to digest particle rates up to several tens of kHz/mm$^2$, maintaining good spatial and time resolution.

2. The triple GEM tracking detectors

COMPASS is the first high-luminosity particle physics experiment to rely on purely GEM-based [2] micropattern gas detectors for tracking in the near-beam area. As shown in Fig. 1, the COMPASS GEM detectors consist of three $31 \times 31$ cm$^2$ large GEM foils, stacked on top of each other and separated by thin spacer grids [3]. The triple amplification, together with a number of other features like segmented GEM foils and asymmetric gain distribution, is the key to a safe operation without electrical discharges in a high-intensity particle beam.

![Fig. 1. Exploded view of a COMPASS triple GEM detector.](image)

The electron cloud emerging from the last GEM is collected on a readout anode comprising two perpendicular sets of strips of 400 μm pitch. The two projections of a particle trajectory determined this way can be correlated by their signal amplitudes, a feature of great importance to disentangle ambiguities in multi-hit events. To this end, the analogue signal from each strip is preamplified, shaped, and sampled at a frequency close to 40 MHz by the APV25 front-end chip [4]. After the trigger decision, the corresponding samples are digitized by a 10 bit ADC, which also performs common mode noise correction and zero suppression.

In COMPASS, GEM detectors are mounted in pairs onto a large-area tracking detector to cover its dead zone, with one detector rotated by 45° with respect to the other. This way, four projections ($X/Y$ and $U/V$) are measured for each track crossing both GEM detectors of one station.

3. Performance in the COMPASS muon beam

3.1. Analysis procedure

While the basic characteristics like efficiency plateaus and intrinsic spatial resolution of these detectors have been studied both in test beams and within COMPASS using a low intensity muon beam [5], this is the first conclusive study of the performance of the full set of 20 detectors during a physics run at nominal beam intensity. Using the standard COMPASS reconstruction software based on a Kalman filter, with the GEM detector under investigation disabled from tracking in order not to bias the result, 1 tracks with a reduced $\chi^2 \leq 2$ and a track time within a window of ±3 ns around the trigger time were selected.

3.2. Efficiency

Considering the high rate of particles crossing a GEM detector, the apparent efficiency $e_{\text{app}}$, as

$e_{\text{app}} = \frac{N_{\text{rec}}}{N_{\text{true}}}$

For a few detector locations, however, this procedure results in a bias of the efficiency towards lower values due to redundancy problems, when a detector at this particular location was not used for tracking.
calculated simply from the probability of at least one detector hit within a given window (here chosen to be \( \pm 1 \text{ mm} \)) around the expected track trajectory, may be biased towards larger values by pile-up tracks. With \( b \) being the probability of at least one background hit, determined from accidental hits outside this window, the apparent efficiency is given by the sum of the true efficiency \( e \) and the probability \((1 - e) \cdot b\) that a track remained undetected while a background hit was present:

\[
e_{\text{app}} = e + (1 - e) \cdot b. \tag{1}
\]

This equation can be solved for \( e \), yielding the background corrected efficiency for a single projection, \( e_{1\text{D}} \), or for both projections of a GEM detector, \( e_{2\text{D}} \), by requiring hits on one or on two projections, respectively. Fig. 2 shows a map of \( e_{2\text{D}} \) for one typical COMPASS GEM detector. Not taking into account local inefficiencies due to the spacer grids, which account for a loss of \(<2\%\), all detectors show a very uniform performance with an average efficiency for single projections of \( \langle e_{1\text{D}} \rangle = 97.2\% \). The average 2D-efficiency is found to be \( \langle e_{2\text{D}} \rangle = 95.6\% \). The effect of track multiplicity on the efficiency is small, as can be seen from Fig. 3.

### 3.3. Spatial resolution

Since the GEM detectors are the most precise tracking devices behind the first spectrometer magnet of COMPASS, their spatial resolution in the high-intensity muon beam was determined employing tracks through GEM detectors only, so that the track error could easily be deconvoluted. Fig. 4 shows the distribution of residuals, i.e. the difference along one coordinate of expected track and measured hit position, plotted for all hits seen by one of the GEM detectors. The distribution is fitted by a constant background, taking into account uncorrelated hits due to pile-up, and the sum of two Gaussians, necessary to account for the tails of the distribution due to local distortions of the spatial resolution by e.g. spacer grids. The spatial resolution \( \sigma \) of a given detector is then determined from the weighted average rms width \( \sigma_{\text{res}} \) of the two Gaussians by deconvoluting the error \( \sigma_{\text{rec}} \) from track reconstruction:

\[
\sigma^2 = \sigma_{\text{res}}^2 - \sigma_{\text{rec}}^2. \tag{2}
\]

The spatial resolutions determined this way for all 40 planes are found to be very uniformly distributed around an average value of \( \langle \sigma \rangle = 71.6 \mu\text{m} \), with the spacer grid accounting for a degradation by \( \sim 4 \mu\text{m} \). Discarding large-angle
tracks (\(>0.2^\circ\)), an average spatial resolution of 69.6\(\mu\)m is reached. Probing the spatial resolution in regions with low particle rates, resolutions lower by 10–15\(\mu\)m are obtained, depending on the rate. These values are compatible with results of low-intensity beam tests using high-resolution Silicon trackers [6], where an average intrinsic resolution of 50\(\mu\)m had been found.

### 3.4. Amplitude correlations

In order to be able to profit from amplitude correlations between signals measured on both coordinates of one detector, a feature of great importance to disentangle ambiguities in a multi-hit environment, an analogue readout was chosen for the COMPASS GEM detectors. Fig. 5 shows an example of the clean correlation of amplitudes measured on both coordinates of a GEM detector. These distributions, established for each detector using a sample of good tracks, serve as look-up table for a correlation likelihood for every pair of amplitudes recorded on the two projections of a particular detector. The combined likelihood of all GEM detectors participating in a given track candidate can then be used to discard track candidates at a very early stage of the reconstruction algorithm, without time consuming fits.

### 3.5. Time resolution

Although no direct time information is available from the GEM detectors, the hit time can be determined by reading and digitizing three
consecutive samples of the signal on its rising edge, and extrapolating backwards in time using the known average signal shape of a minimum ionizing particle. With this method, an average time resolution of $\langle \sigma_t \rangle = 12$ ns was found for the GEM detectors in the high intensity muon beam, as can be seen from Fig. 6. It should be noted that this number is the convolution of the intrinsic time resolution of a GEM detector and the time resolution limited by the front-end electronics due to the 40 MHz sampling and a trigger which is asynchronous to this clock.

4. Conclusions

The tracking of particles near the beam in COMPASS is performed by a set of 20 large-size triple GEM detectors. The detectors are shown to operate at an average single plane efficiency $>97\%$ in standard physics conditions. The spatial resolution is found to be around $70\mu m$ for all detectors. By sampling the analogue signals of each strip a time resolution of $\sim 12$ ns is reached. Strong correlations between amplitudes measured on both projections within one detector considerably improve the tracking efficiency and speed by removing ambiguities in multi-hit events. No degradation of performance was observed over the 3 years of operation of the GEM detectors in COMPASS.

References