# Test of spatial resolution and trigger efficiency of a combined Thin Gap and Fast Drift Tube Chambers for high-luminosity LHC upgrades

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***Abstract*—The forthcoming luminosity upgrade of LHC to super-LHC (sLHC) will increase the expected background rate in the forward region of the ATLAS Muon Spectrometer by approximately the factor of five. Some of the present Muon Spectrometer components will fail to cope with these high rates and will have to be replaced. The results of a test of a device consisting of Thin Gap Chambers (TGC) and a fast small diameter Muon Drift Tube Chamber (sMDT) using the 180 GeV/c muons at the SPS-H8 muon beam at CERN are presented. The goal of the test was to study the combined TGC-sMDT system as tracking and triggering device in the ATLAS muon spectrometer after high-luminosity upgrades of the LHC. The analysis of the recorded data shows a very good correlation between the TGC and sMDT track position and inclination. This technology offers the combination of trigger and tracking and has good angular and spatial resolutions. The angular resolution is 0.4 mrad for each system individually, the spatial resolution for the combined system is 50 $\mu$m.**

***Index Terms*—ATLAS, LHC, drift tubes, TGC, muon chambers, sMDT**

## I. Introduction

During the second long shut-down, probably in 2017, the LHC will be upgraded to achieve the luminosity up to $2-3 \cdot 10^{34}$ $\mathrm{cm^{-2}s^{-1}}$. The expected background rates in the inner layer of the forward ATLAS [1] Muon Spectrometer [2] at the sLHC are expected to be higher by approximately a factor of five.

The present tracking detectors in the innermost layer of the forward ATLAS Muon Spectrometer (Monitor Drift Tubes (MDT) and Cathode Strip Chambers (CSC) for pseudorapidity $\eta > 2.0$) will not be able to cope with expected high rates. Furthermore, the present forward Muon Trigger system requires the inclusion of a measurement of the muon trajectories in the innermost layer of the forward Muon Spectrometer. This is presently possible by providing hits in the TGC of the inner layer but their pseudorapidity coverage extends only up to 2.0. To greatly improve the trigger capabilities in the forward region, one would need to include a detector that can provide a trigger signal in the pseudorapidity region $1.3 < \eta < 2.4$ with an angular resolution exceeding 1 mrad and a spatial resolution similar to a precision tracking device.

We propose to build a new tracking and trigger system for the innermost layer of the Muon Spectrometer which would replace the so-called Small Wheel. This device, which will be named the New Small Wheel (NSW), should bring a significant enhancement of the muon performance in the endcap region, in particular of the level-1 muon trigger as well the precision muon tracking, that would not be achieved by a simple modifications alone such as the improvement of radiation shielding or addition of new detector layers.

The results of a test of a device consisting of TGC and sMDT using the 180 GeV/c muons at the SPS-H8 muon beam at CERN are presented. The goal of the test was to study the combined TGC-sMDT system as tracking and triggering device in the ATLAS muon spectrometer after high-luminosity upgrades of the LHC.

## II. TGC design and performance

The TGC is a multiwire chamber with 50 $\mu$m diameter gold-plated tungsten wires, forming the anode plane. FR4 walls coated with resistive carbon serve as a cathode. The operational gas mixture is 55% of $CO_2$ and 45% of n-pentane. Each gas gap contains: a series of pad readouts for the first level trigger signal, strip readout for high precision accuracy and perpendicular wire readout for a second coordinate measurement. The schematic view of the TGC is shown in Figure 1 and the parameters of the TGC are shown in Table I. Two TGC quadruplets of $0.6 \times 0.4$ $\mathrm{m^2}$ size, each one containing four sensitive gaps were used for the test. The four gaps fit within a total thickness of 50 mm.

The position resolution of the TGC using fast digital readout from the strips and Time-over-Threshold method [3], as well as its dependence on the impact angle, were measured with the 180 GeV/c muons from the SPS-H8 test beam at CERN. Previous CERN pion test beam results, the muon test beam resolution measurements achieved with a larger prototype and the radiation tests are described in [4] and [5].

Each detector was equipped with 16 strip digital readout channels of a type similar to as those used in the ATLAS TGC [6]. The external trigger was provided by a coincidence of TGC pads from all the four layers of the quadruplet and two

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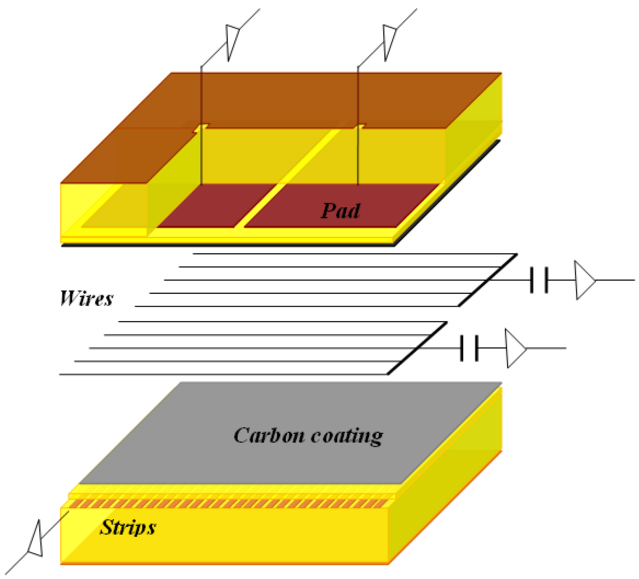


Fig. 1. The schematic view of the TGC.

| TGC geometry | |
|---|---|
| Wire-carbon gap | 1.4 mm |
| Wire-wire space | 1.8 mm |
| Strip-carbon gap | 0.1 mm |
| Strip pitch | 3.2 mm |
| Inter-strip gap | 0.5 mm |
| **TGC additional parameters** | |
| Wire length in layers | 0.4 mm |
| Number of wires ganged together | 5 |
| Strip length | 0.6 m |
| Pad size | $8.7 \times 8.7$ $cm^2$ |
| Carbon plan resistance | 70 kΩ/square |
| HV blocking capacitance | 470 pF |
| **TGC readout parameters** | |
| Preamplifier gain | 0.8 V/pC |
| Integration time | 16 ns |
| Main amplifier gain | 7 |
| Equivalent noise charge | 7500 electrons at $C_D$ = 150 pF |

TABLE I
THE PARAMETERS OF THE TGC.

plastic scintillators. The position resolution is directly related to the profile of the signal from the strips and on the accuracy of the time measurement. The time was measured with a VME 32CH TMC TEG3 KEK module.

The track hit position in each layer of the quadruplet was determined by a Gaussian fit. The typical signal from the TGC is shown in Figure 2. Then, a muon trajectory was fitted with a linear function using all the four layers hit positions, and the difference between the measured position and the expected position predicted from fit was defined as the residual, individually for each layer. The particular devices used in the present test show a differential non-linearity not present in the previous much larger prototypes constructed with a different design. Such a differential non-linearity has been corrected using a sinusoidal form. The final deviation was calculated from the fit curve and the residual distribution after such a correction is shown in Figure 3 for one of the TGC layers. The $\sigma$ value of the Gaussian fit of this distribution was defined as the resolution of the detector.

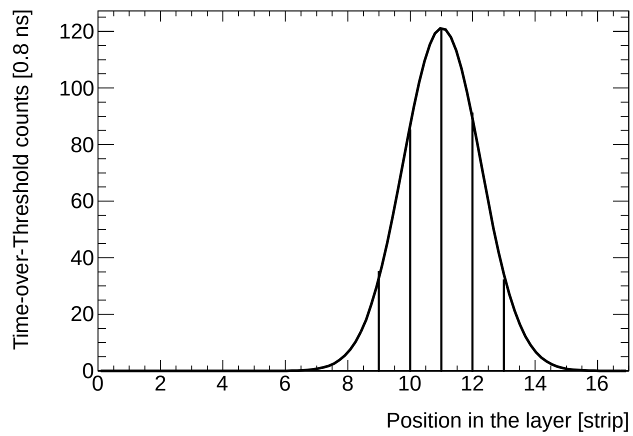


Fig. 2. The typical signal from the TGC fitted by Gaussian.

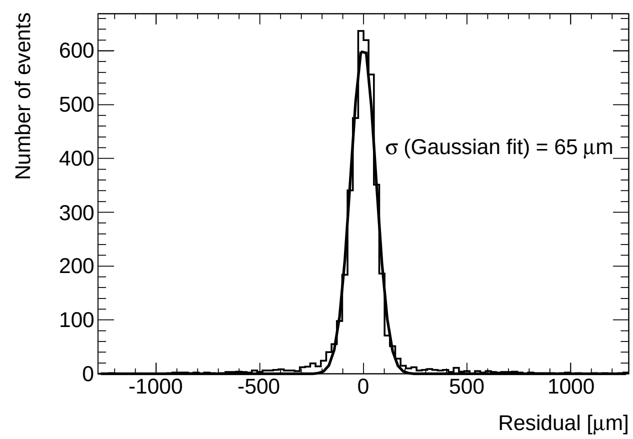


Fig. 3. The residual distribution for one of the TGC layers.

Ideally, not to introduce a bias, one should use only three layers for the linear fit, and look at the residual between the fit predicted position in the fourth layer and the track measured position in the fourth layer. However, in this method the correction of the non-linearity effect becomes nontrivial, so the linear fit using all the four layer hit positions was applied, as described above. The difference between the resolutions of the TGC when using three-out-of-four or all the four layers for the linear fit is no more than 10-15% as checked in the previous tests. The resolutions of each of the four layers for the different impact angles are shown in Figure 4. A single gap resolution value varies within the 60 $\mu$m-110 $\mu$m range.

## III. SMDT DESIGN AND PERFORMANCE

The ATLAS muon spectrometer relies on the MDT chambers for precision muon tracking. These chambers consist of 6 layers of aluminium drift tubes grouped into two multilayers. Each tube has a diameter of 30 mm and is filled with an $Ar{:}CO_2$ (93:7) gas mixture at 3 bar absolute pressure. The operation with an high voltage of 3080 V results in a maximum drift time of about 700 ns and an average resolution of 80 $\mu$m.

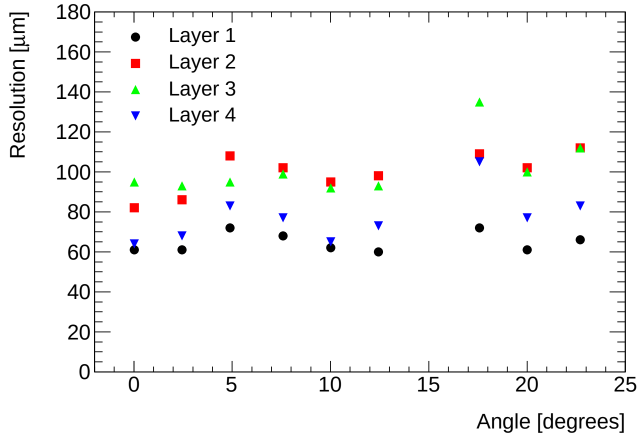


Fig. 4. The resolutions of each of the four TGC layers for the different impact angles.

With a sense wire position accuracy of 20 $\mu$m, the chamber provides the muon track with an accuracy of 35 $\mu$m [2]. These detectors were designed for the nominal luminosity of LHC. After the luminosity upgrade by a factor five the occupancy in the drift tube will be too high to allow an efficient muon tracking. To improve the high rate behaviour we proposed the use of thinner tubes, while keeping parameters like gas mixture, gas gain and chamber resolution constant [7] [8]. The parameters for the thinner tubes are listed in Table II.

| Drift tube parameters | |
|---|---|
| Wire diameter | 50 $\mu$m |
| Wire material | W-Re gold plated |
| Tube diameter | 15.0 mm |
| Tube wall thickness | 400 $\mu$m |
| **Drift tube operational parameters** | |
| Voltage | 2730 V |
| Gas mixture | Ar:$CO_2$ (93:7) |
| Pressure | 3.0 bar absolute |
| Gas gain | $2 \cdot 10^4$ |
| Maximum drift time | 185 ns |
| **Prototype chamber parameters** | |
| Number of tubes | 1152 |
| Number of tubes in readout | 384 (only long tubes) |
| Number of layers | 16 |

TABLE II
THE PARAMETERS OF THE 15 MM DIAMETER DRIFT TUBE CHAMBER.

To test the smaller diameter tubes we constructed a prototype chamber. This sMDT chamber consists of two times 8 layers (multilayers) of aluminium drift tubes of 15 mm outer diameter and 0.4 mm wall thickness. The high voltage of +2730 V applied between the anode wire and the tube wall was chosen to maintain the gas gain at the same value as for the 30 mm diameter ATLAS tubes. The average spatial resolution of individual drift tubes is 120±0.86 $\mu$m at low counting rates. The wire positions of the prototype were measured in a cosmic ray facility in Garching, Germany. The sigma of the distribution is 39 $\mu$m. Combining the single tube resolution and the construction accuracy, the spatial resolution is 34 $\mu$m per chamber and the angular resolution 0.4 mrad.

A photograph of the completed prototype chamber with visible services is shown in Figure 5.

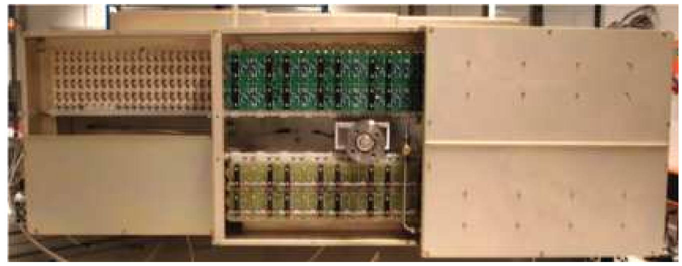

Fig. 5. Photograph of the prototype chamber showing the open Faraday cage, the gas system, and the HV and readout adapter cards.

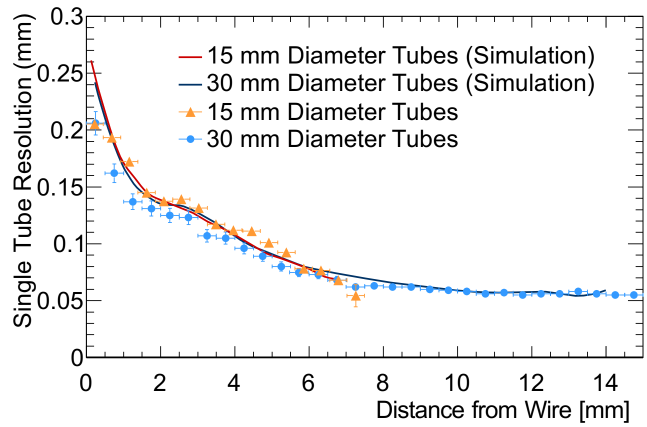


Fig. 6. Measured and simulated resolution of the sMDT. The average resolution for the 15 mm diameter tubes is 120 $\mu$m.

The performance of the sMDT prototype chamber was tested in 2010 at the SPS test beam facility at CERN. The resolution is shown in Figure 6 and reached the level we expected from the experience with 30 mm drift tubes already used in ATLAS and the Garfield simulations [7]. To measure the resolution, a track was fitted in the sMDT chamber, using all but one layer. The measured radius in this layer was then compared to the expectation from the track fit. These residuals are then corrected with the expected error on the track fit to compute the single tube resolution.

The efficiency was also studied as a function of the background radiation. The prototype chamber was irradiated at the Gamma Irradiation Facility (GIF) at CERN with a 750 GBq $^{137}$Cs source. The efficiency was measured by extrapolating a cosmic muon track reconstructed by a not irradiated part of the chamber in the analysis layer and checking if a hit in the tube was detected within 3$\sigma$ of the single tube resolution. The results are shown in Figure 7.

The maximum counting rate achieved in 1 m tubes is 1.2 MHz. The tube length installed in the hottest part of the small wheel will be 0.5 m, corresponding to 17 kHz/cm$^2$ for 1.2 MHz rate per tube. The highest counting rates expected after the LHC upgrade are 14 kHz/cm$^2$, or 1.05 MHz per 0.5 m tube.

The requirement by the ATLAS collaboration is a track segment reconstruction efficiency of more than 95% up to the highest expected rates. Calculation this quantity from the

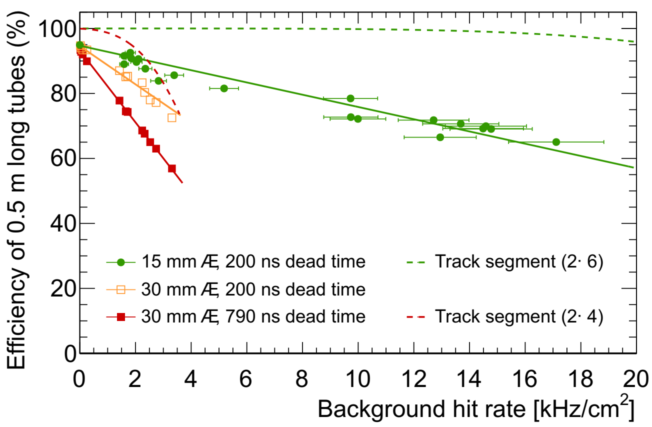


Fig. 7. Single tube efficiency and calculated track segment reconstruction efficiency for 30 mm and 15 mm diameter tubes for different background flux.

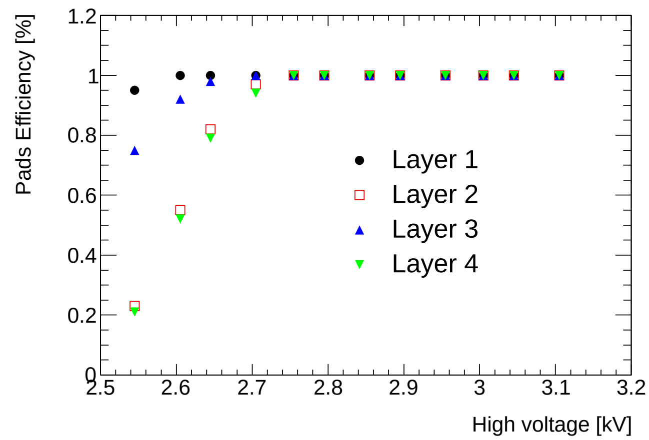


Fig. 9. The TGC pads efficiency versus operational high voltage.

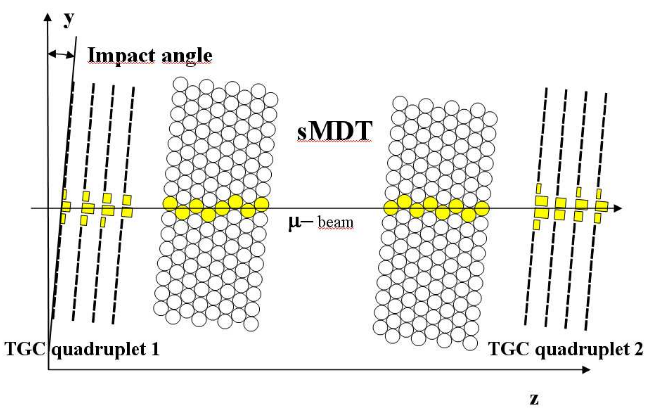


Fig. 8. The principal scheme of the combined TGC-sMDT test.

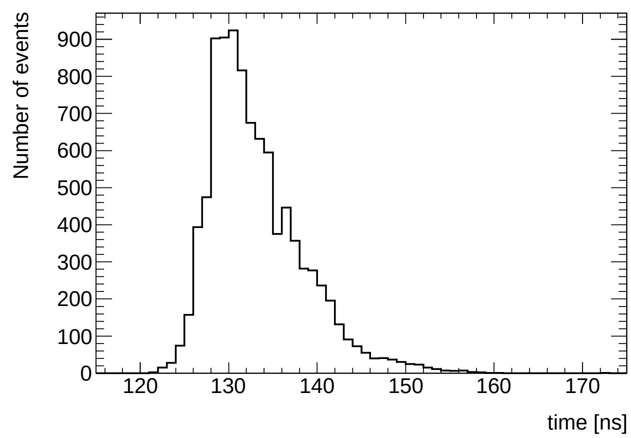


Fig. 10. The time difference between three-out-of-four pad trigger with respect to the beam scintillator.

measured single tube efficiency shows that the 15 mm diameter tubes can fulfil this requirement even for higher fluxes than the expected 14 kHz/cm$^2$ (see Fig. 7).

## IV. TGC-sMDT combined test

The combined TGC-sMDT test was performed in August 2011 using the 180 GeV/c muons at the SPS-H8 muon beam at CERN. The goal of the test was to study the combined TGC-sMDT system as tracking and triggering device. The principal scheme of the test is shown in Figure 8. The two TGC quadruplets were put on both sides of the sMDT at a distance of 40 cm between each other.

Signal coincidences from three-out-of-four TGC layer pads were used to provide the trigger for the combined TGC-sMDT device. The efficiency of the TGC pads as a triggering device was checked separately for each layer. While demanding the presence of the pads signals in the other three layers, the percentage of events in which the fourth layer also had a signal from pads was defined as the efficiency. Pads efficiency versus TGC operational high voltage is depicted in Figure 9 showing that the efficiency for all of the layers is more than 99% above the high voltage value of 2.75 kV. The operational high voltage used in the test was 2.9-3.0 kV. Another important issue is the timing of the trigger signal. The time difference between the three-out-of-four pad trigger with respect to the beam scintillator is shown in Figure 10. 98% of the distribution is within 25 ns which is a beam crossing time planned for the sLHC. Finally, signals from the pads were used as the second coordinate measurement; they were used both by the TGC and sMDT for calibration and alignment corrections. Pads signals from the two TGC quadruplets are very well correlated, as shown in Figure 11.

To test the TGC-sMDT as a tracking device, the angle of the muon trajectory and the the track position in the middle of the sMDT detector was measured by the TGC and sMDT separately, and the results compared with each other. In order to measure the angle by the TGC, all the eight hits in the two quadruplets were used and the linear fit applied, as described in Section II. The TGC-sMDT angle and position measurement correlations for the 0° impact angle are shown in Figures 12 and 13 respectively. By subtracting the sMDT measured angle and position from the TGC measured ones, the residual distributions were built, as shown in Figures 14 and 15. The $\sigma$ value of the Gaussian fit of the residual distribution and its dependence on the impact angle are shown in in

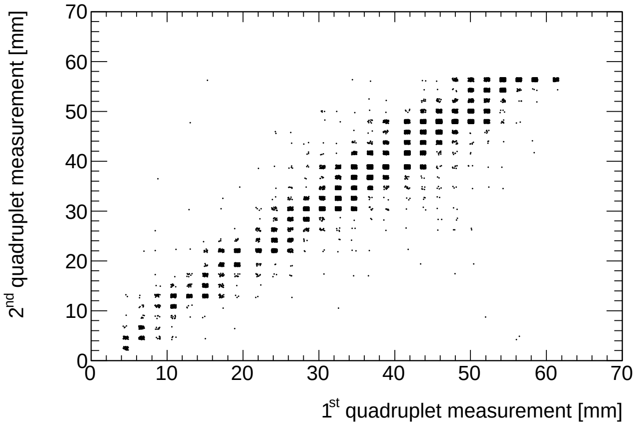


Fig. 11. Second coordinate position measurement: first TGC quadruplet versus the second one.

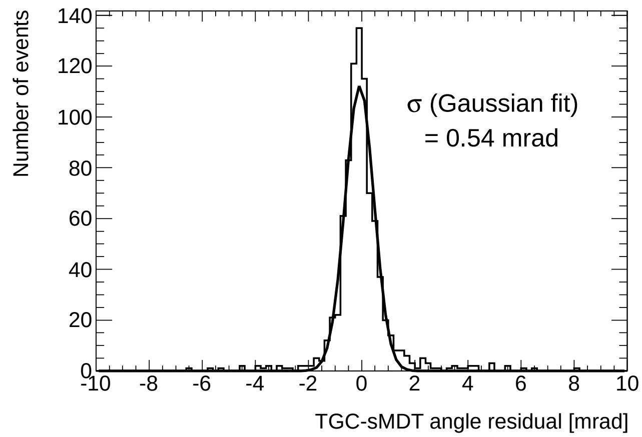


Fig. 14. The TGC-sMDT angle residual distribution.

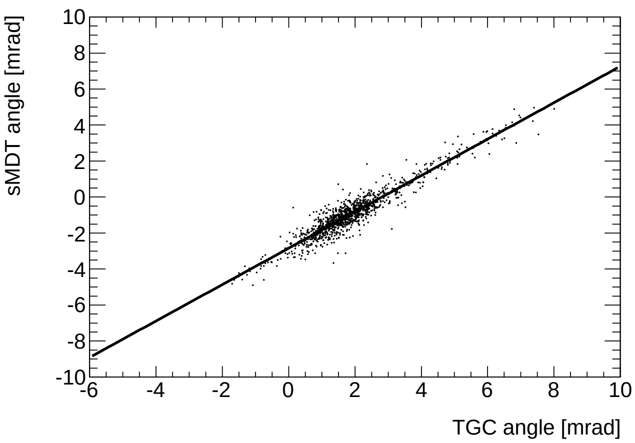


Fig. 12. The TGC-sMDT angle correlation.

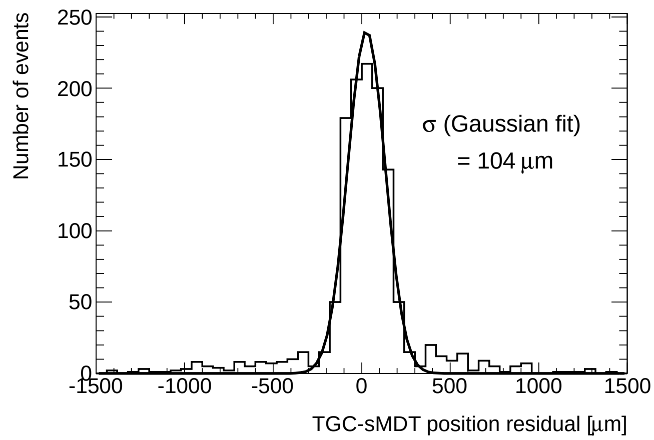


Fig. 15. The TGC-sMDT position residual distribution.

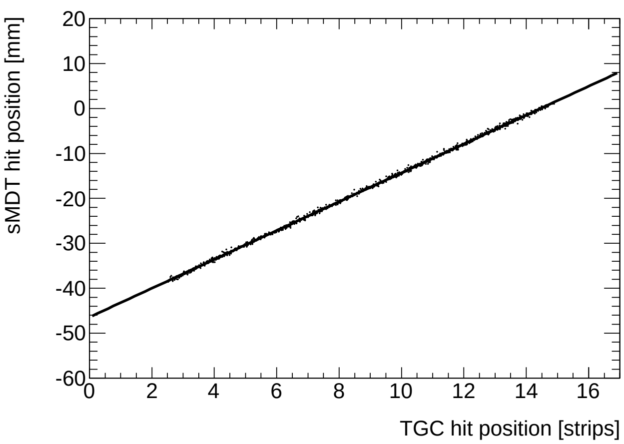


Fig. 13. The TGC-sMDT position correlation.

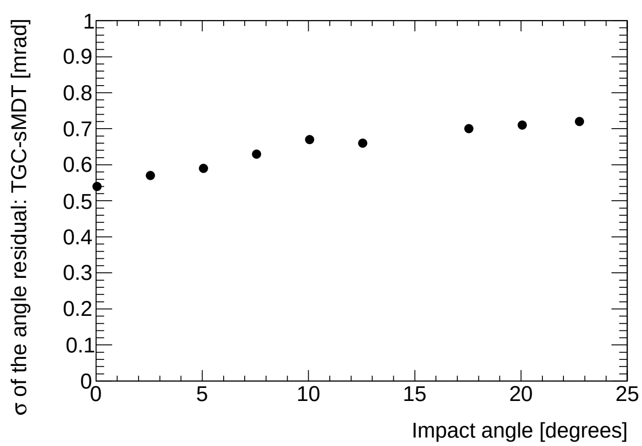


Fig. 16. $\sigma$ of the TGC-sMDT angle residual versus impact angle.

Figures 16 and 17 respectively.

As the TGC and sMDT systems demonstrate very similar angular resolutions, the individual resolutions of each of the systems are expected to be less by $\sqrt{2}$. Thus, the individual angular resolution is 0.54 mrad / $\sqrt{2}$ = 0.38 mrad. This is compatible with the expectation for the standalone sMDT system.

For the spatial resolution, the width of the track residuals is 104 $\mu$m for zero degree impact angle (Fig. 15). Therefore the combined system can be estimated as $104/2$ $\mu$m$=$ $52$ $\mu$m.

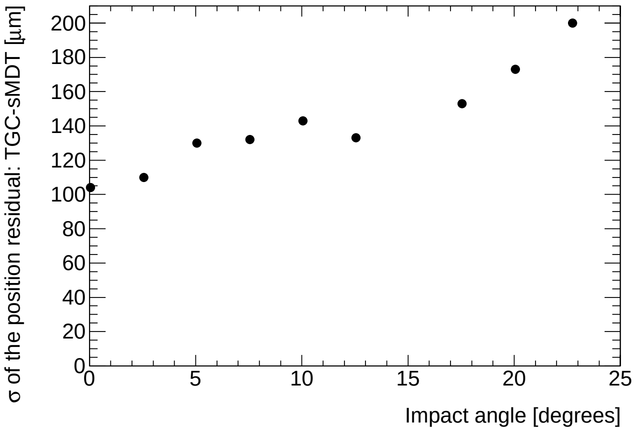


Fig. 17. $\sigma$ of the TGC-sMDT position residual versus impact angle.

## V. Conclusions

A muon test of the TGC-sMDT combined device was performed showing that such a system offers an attractive solution for triggering and measuring muons at the sLHC. The analysis of the recorded data shows a very good correlation between the TGC and sMDT track position and inclination. This technology has good angular and spatial resolutions: about 0.4 mrad for each system individually, the spatial resolution of the combined system is 52 $\mu$m at zero degree impact angle. The combined system has a very fast response and is a combination of trigger and tracking chambers, all at a reasonable cost.

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## References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST, s08003.

[2] ATLAS Collaboration, *ATLAS Muon Spectrometer Technical Design Report*, CERN/LHCC 97-22 (1997).

[3] T. Akesson *et al.*, *Particle identification using the time-over-threshold method in the ATLAS Transition Radiation Tracker*, Nucl. Instrum. Meth. A 474, (2001) 172-187.

[4] V. Smakhtin *et al.*, *Thin Gap Chamber upgrade for sLHC: Position resolution in a test beam*, Nucl. Instrum. Meth. A 598 (2009) 196.

[5] N. Amram *et al.*, *Position resolution and efficiency measurements with large scale Thin Gap Chambers for the super-LHC*, Nucl. Instrum. Meth. A 628 (2011) 177-181.

[6] O. Sasaki and M. Yoshida, *ASD IC for the thin gap chambers in the LHC Atlas experiment*, IEEE Trans. on Nucl. Science, Vol. 46,(1999) 1871 - 1975.

[7] B. Bittner *et al.*, *Development of muon drift-tube detectors for high-luminosity upgrades of the Large Hadron Collider*, Nucl. Instrum. Meth. A 617 (2010) 169 - 172.

[8] B. Bittner *et al.*, *Development of fast high-resolution muon drift-tube detectors for high counting rates*, Nucl. Instrum. Meth. A 628 (2011) 154 - 157.