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CMS CR -2009/100

The Compact Muon Solenoid Experiment

Conference Report

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12 May 2009

Calibration of the Barrel Muon Drift Tubes System in CMS

Silvia Maselli on behalf of CMS Collaboration

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In this report, results on the calibration process of the Drift Tubes (DT) system of the Compact Muon Solenoid experiment are presented. The full commissioning of the calibration procedure has been deployed in year 2008 with the CMS Computing, Software and Analysis challenge (CSA08), which has tested the full work-flow needed for CMS data-taking during the LHC start-up operations. In autumn 2008, the same Calibration work-flow was applied to a high statistics cosmic ray muon data taking period: the Cosmic Run At Four Tesla (CRAFT) period. The accurate measurement of the main calibration conditions corresponding to the Time Pedestals and the Drift Velocity provide the necessary space-time relationship used in the first stage of the muon local reconstruction.

Presented at *CHEP*

Calibration of the Barrel Muon Drift Tubes System in CMS

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Abstract. In this report, results on the calibration process of the Drift Tubes (DT) system of the Compact Muon Solenoid experiment are presented. The full commissioning of the calibration procedure has been deployed in year 2008 with the CMS Computing, Software and Analysis challenge (CSA08), which has tested the full work-flow needed for CMS data-taking during the LHC start-up operations. In autumn 2008, the same Calibration work-flow was applied to a high statistics cosmic ray muon data taking period: the Cosmic Run At Four Tesla (CRAFT) period. The accurate measurement of the main calibration conditions corresponding to the Time Pedestals and the Drift Velocity provide the necessary space-time relationship used in the first stage of the muon local reconstruction.

1. Introduction

The CMS Muon spectrometer [1] has been built to provide a fast trigger and a precise momentum measurement of the muon momentum up to 1 TeV/c. The Drift Tubes (DT) muon station structure is shown in Fig .1 and contains two Super Layers formed by four Layers of adjacent drift tubes each, which measure the *r-phi* coordinate. The first three stations also contain one Super Layer of orthogonal drift tubes measuring the *r-theta* coordinate. The basic element of the DT detector is the drift cell, shown in Fig. 2 together with a schematization of the electric field within it.

The spatial measurement precision in the DT system depends strongly on the exact time that a signal is obtained. Electrons produced by incoming particle reach the anode wire after a certain drift time which is measured by the TDC. The precise knowledge of the space time relationship and therefore of the drift time and drift velocity requires an accurate calibration of the DT system. This is achieved computing the Time Pedestal and Drift Velocity calibration.

In the present paper, the procedure and the results of the calibration of the DT system are presented for the simulation of *pp* collision data set collected during the Computing, Software and Analysis challenge (CSA08), and for the Cosmic Run At Four Tesla (CRAFT) run periods; in both cases the calibration procedure has demonstrated to be robust and has produced on schedule the conditions fundamental for the further offline processing of the data.

This paper is organized as follows: in Section 2 the data sets used in this note, the calibration work-flow and the monitoring process is summarized, Section 3 provides the definition and the methods of the DT Calibration. In Section 4 and Section 5, the main results of the DT calibration for the CSA08 and CRAFT data periods are reported.

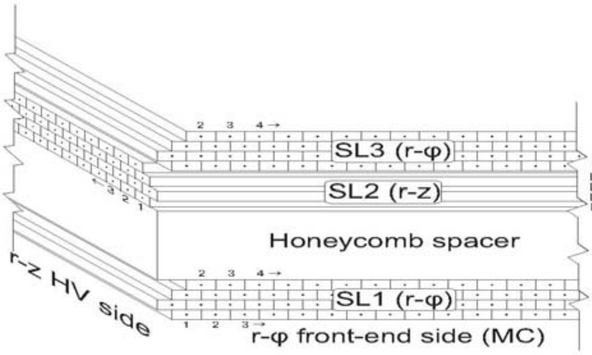


Figure 1. Schematic view of a DT chamber.

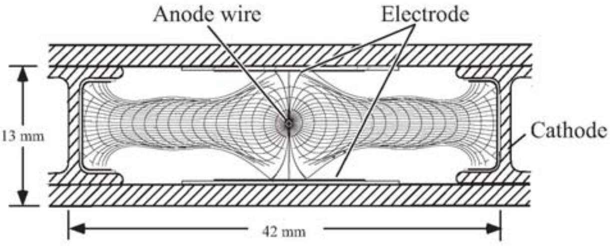


Figure 2. Section of a drift tube cell showing drift lines and isochrones.

2. The Input Data Sets and the Calibration Work-Flow

The CSA08 data sample consists of simulation of *pp* collision data generated considering two initial luminosity scenario of the LHC start up (1pb-1 and 10pb-1). The DT Calibration procedure was applied on special data sets which are a skim of the original data set (the so-called AlCaReco samples) which keeps the information of the digitized signal necessary for the DT Calibration (AlCaReco step2). The AlCaReco producers used in CSA08 for the DT Calibration exercise were essentially two data sets selecting single muon events with two different transverse momentum cut (pt >5 GeV/c and pt >11 GeV/c). A detailed description of all steps and achievements of the CSA08 challenge is given in [2].

The Cosmic Run at Four Tesla (CRAFT) represents the more extensive data-taking period of cosmic ray events collected up to now by the CMS experiment. Most of the CMS sub-detectors participated, and data were taken both with the magnetic field switched off and on. About 300 million events were collected with a magnetic field value inside the solenoid of 3.8 Tesla. In this experimental condition, longitudinal and radial components of the stray magnetic field in the gas do not exceed 0.4 and 0.8T, respectively. As in the case of the CSA08 exercise an AlCaReco step2 sample was produced selecting events with a transverse momentum > 10 GeV/c.

There is a crucial difference between the two considered data sets which is explained in the following. The DT system and its trigger have been designed to collect collision data coming from the interaction point. With this configuration the muons coming from collision are synchronized with the LHC clock, and the calibration procedure performed at CSA08 represents therefore what we expect with real collision data at LHC. On the other side, during cosmic ray data taking periods, the time of arrival of cosmic ray events is uniformly distributed between two consequent bunch crossings. This characteristic represents an intrinsic limit for the calibration procedure and it affects the resolution obtained by the local pattern recognition.

The DT Calibration work-flow is part of the general CMS calibration procedures described in details in [2]. The main steps followed during the DT Calibration process can be summarized as follows:

- the central offline processing produces AlCaReco samples datasets;
- these samples are saved to the Central Analysis Facility (CAF) and are taken as input to the calibration process;
- the calibration algorithm runs on the CAF and produces a set of constants, usually in the form of a temporary Data Base;
- the constants undergo validation on the CAF, and they are transferred to the central CMS Conditions Data Base.

The quality and stability of the calibration constants are a crucial part of the procedure and must be continuously monitored. Validation procedures have been therefore set up within the central CMS Data Quality Monitoring (DQM) framework. Quality tests are applied to the residual distributions calculated at different steps of the calibration work-flow. In addition every time a new Condition Data Base is produced and validated it is compared with its reference Data Base to monitor the possible variations.

3. The DT Calibration Conditions

The main goal of the calibration process is to determine the Time Pedestals of the signal which is needed to extract the drift time from the TDC measurement and the effective Drift Velocity within the cell. The TDC time contains the drift time of the ionization electrons in the cell plus contributions from:

- the Time-Of-Flight (TOF) of the muon from the interaction point to the cell;
- the propagation time of the signal along the anode wire;
- the delays due to the cable length and read-out electronics (referred in the following as the inter-channel synchronization);
- the time latency due to the Level-1 trigger.

The major contribution is coming from the Level-1 trigger latency and therefore the Time Pedestal are often referred as *tTrig* conditions. The contribution coming from the inter-channel synchronization time, and the list of noisy channels cannot be studied with simulated data. Therefore the calculation of these conditions are performed only for the CRAFT data.

The Time Pedestals are computed with a Super Layer granularity and they are estimated directly from the distribution of the digitized times, usually referred as Time Box. The complete description of the *tTrig* calibration is given in [3] and it is based on the fit to the rising edge of the Time Box using the integral of a Gaussian. An example of Time Box distribution for cosmic ray events is shown in Figure 3 together with the fit to the rising edge. The optimal value of the *tTrig* should correspond to the beginning of the rising edge. This is computed through the relation:

$$tTrig = Tmean - k \cdot Tsigma, \qquad (1)$$

where k is a factor used to tune the delay: the fine tuning of the *tTrig* is performed requiring the minimization of the residuals on the reconstructed hit position.

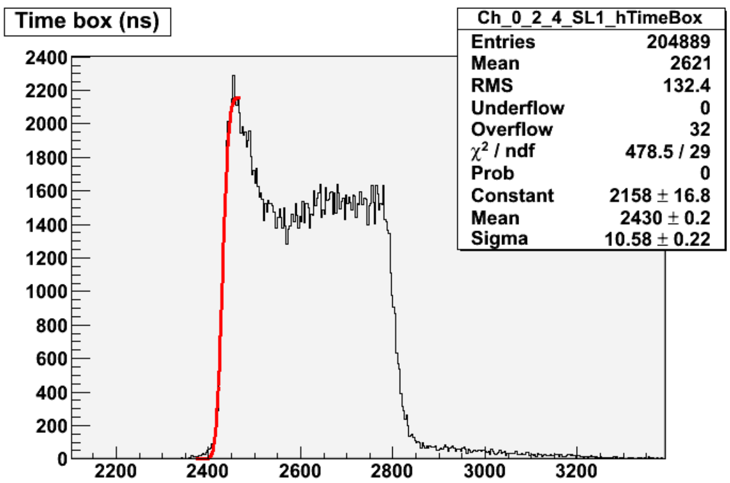
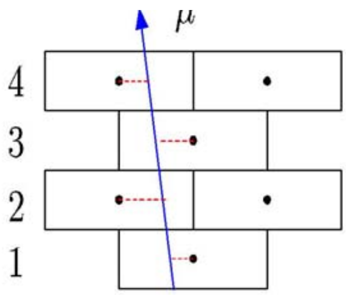


Figure 3. Distribution of the signal arrival time recorded by the TDC; the arrival time in all the cells from a single Super Layer in a chamber are superimposed, after the cell-to-cell equalization based on electronic test-pulse calibration. The continuous line indicates the fit to the time box rising edge with the integral of a Gaussian.

Once the Time Pedestal is computed the direct calculation of the drift time can be performed and a drift velocity has to be chosen for the first local pattern reconstruction of the hits. Two alternative algorithms can be used to estimate the effective drift velocity within the drift cell: a parameterized drift velocity which compute analytically the velocity as a function of the drift times, the stray magnetic field and the impact angle, or a linear constant drift velocity which computes the best effective average drift-velocity with a granularity suited to take into account local variations of the track angles and residual magnetic field. Both algorithms have been implemented in the framework of the official CMS reconstruction code and an analysis of the reconstruction using the parameterized drift velocity is given in [4].

Since the residual magnetic field within the return yoke is usually low and approximately constant a linear constant drift velocity is assumed to be a good approximation. In this case an accurate calibration is needed and it is achieved using the combined information of the Time Pedestals and the geometrical structure of the CMS Drift Tubes system. The results presented in this report are obtained with a linear constant drift velocity and the method is briefly recalled in the following.

The Drift Velocity calibration algorithm is based on the so-called Mean Timer technique which is described in details in [3]. This method estimates the maximum drift time (*Tmax*) considering nearby cells of adjacent layers and with a linear expression it computes the average drift velocity. Many different patterns of segments are considered. The easiest case is shown in Fig.4 where the track crosses a semi-column of cells, and the maximum drift time expression (*Tmax*) can be calculated by the formulas shown in the figure. In general, the Mean Timer relation depends on the track angle and on the pattern of cells hit by the track, and the maximum drift time is obtained with a weighting procedure of all geometrical possibilities.



$$T_{max}^{123} = \frac{t_1 + t_3}{2} + t_2$$

$$T_{max}^{234} = \frac{t_2 + t_4}{2} + t_3$$

Figure 4. Schematic view of a Super Layer section showing the pattern of semi-cells crossed by the track.

4. The CSA08 results on Simulated data

The Time Pedestals are computed with a Super Layer granularity using the expression (1) where the *Tmean* is the mean of the fit to the rising edge of the Time Box while the *TSigma* is the standard deviation of the fit which reproduces its slope. The *k* factor is used to tune the Time Pedestal; it is obtained by the minimization of the residuals on the reconstructed hit position, and it is function of the assumed drift velocity.

The distributions of the *Tmean* and the slopes *TSigma* from the fit to the time box rising edge are illustrated in Fig.5 and Fig.6. The values of the most internal Super Layer for each chamber/sector and for all wheels are shown. The means are homogeneously distributed around an average value of 507 nsec. The slope of the rising edge is originating from different contributions like the fluctuations of the drift paths of the electrons, the propagation time along the wire and the time of flight within the Super Layer. Fig. 6 illustrates a constant average value of 4 ns for all the wheels with a spread of less than 1 nsec, which is comparable to the experimental precision reached by the TDC counts (the finite step size of the TDC is 0.78 ns). The resulting Time Pedestals, computed using eq. (1) using a $k=2$, are very close to the ones used at the generation step of the DT digitized hit (500 nsec).

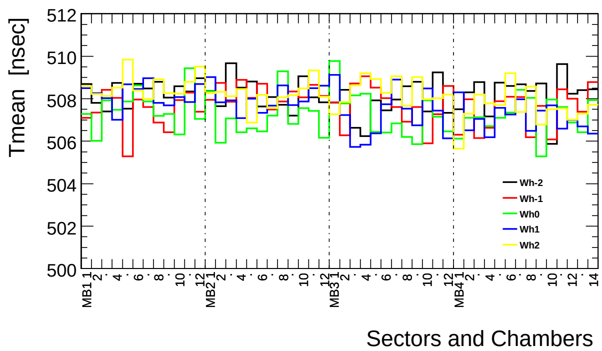


Figure 5. Distribution of the mean value (*Tmean*) of the fit of the rising edge of the Time Box.

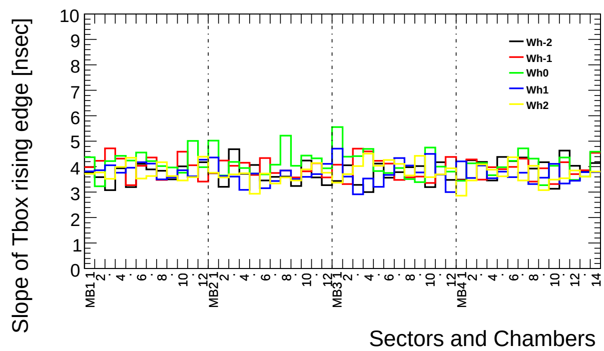


Figure 6. Distribution of the standard deviation of the fit to the rising edge of the time box, which measure the slope of the rising edge.

To compute the effective drift velocity we use the Mean Timer method summarized in Section 3. In Fig. 7 the drift velocity is shown for the most internal Super Layer for each chamber/sector/wheel. An average value of approximately 54.2 microns/nsec is observed for all chambers except for the MB1 chambers in the wheels near the end cap regions, where the value of the drift velocity is lower by 2.2% as expected when the CMS magnet is on. This result confirms the good stability of the drift velocity in the whole DT system and validates the assumption of a constant linear drift velocity value for all Super Layers.

In Fig.8, the standard deviation of the fit to the residuals computed with local reconstruction is shown for the full DT system. This quantity is related to the chamber resolution. Resolution values of the order of 200 microns is found for the MB2 and MB3 chambers in all the wheels and for MB1 chambers in the central wheels. The resolution deteriorates for the MB1 chambers in the wheels close to the end-caps where the non-linearity effects, due to inhomogeneous stray fields, become important. In addition, a worse resolution for the MB4 chambers is observed because only one reconstruction projection (*r-phi*) is present in the detector.

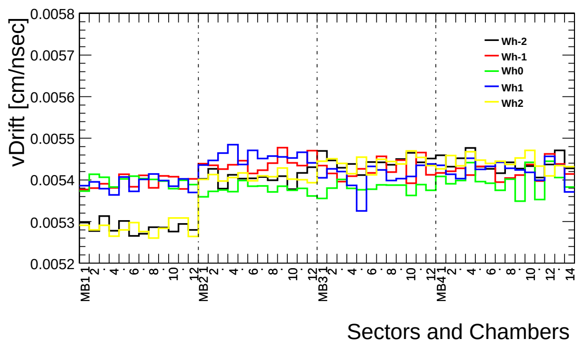


Figure 7. Distribution of the drift velocity (*vDrift*) computed using the Mean Timer technique.

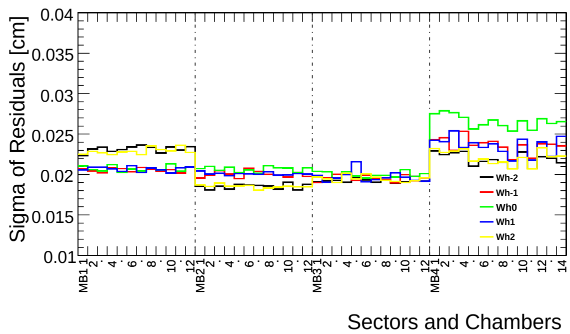


Figure 8. Distribution of the standard deviation of the fit to the residuals computed with respect to the reconstructed segments, using the constant calibrated *vDrift*.

5. The CRAFT results on Real Cosmic Ray Events

The extraction of the Time Pedestals from the real data TDC measurements proceeds mainly in two steps. Firstly the inter-channel synchronization of each channel (~170000) is considered and the noisy channels are subtracted so to have a clean structure of the Time Box distribution and all digitization signals synchronized within each chamber. Secondly the same Time Pedestal and the Drift Velocity calibration work-flow described in Section 4 is applied.

5.1. Inter-channel synchronization

This operation is performed using special Test Pulse calibration runs and the computed correction has a channel granularity. The main aim is to synchronize all the signals within each chamber taking into consideration the cable lengths of the readout electronics.

Fig.9 shows an example of distribution of these relative times offset for all the layers of the 4 chambers of one sector as a function of the channel number. The synchronization correction, which depends only from the hardware conditions, is usually small and below 10 nsec. During the CRAFT data taking period the inter-channel synchronization has been monitored and showed a good stability in time.

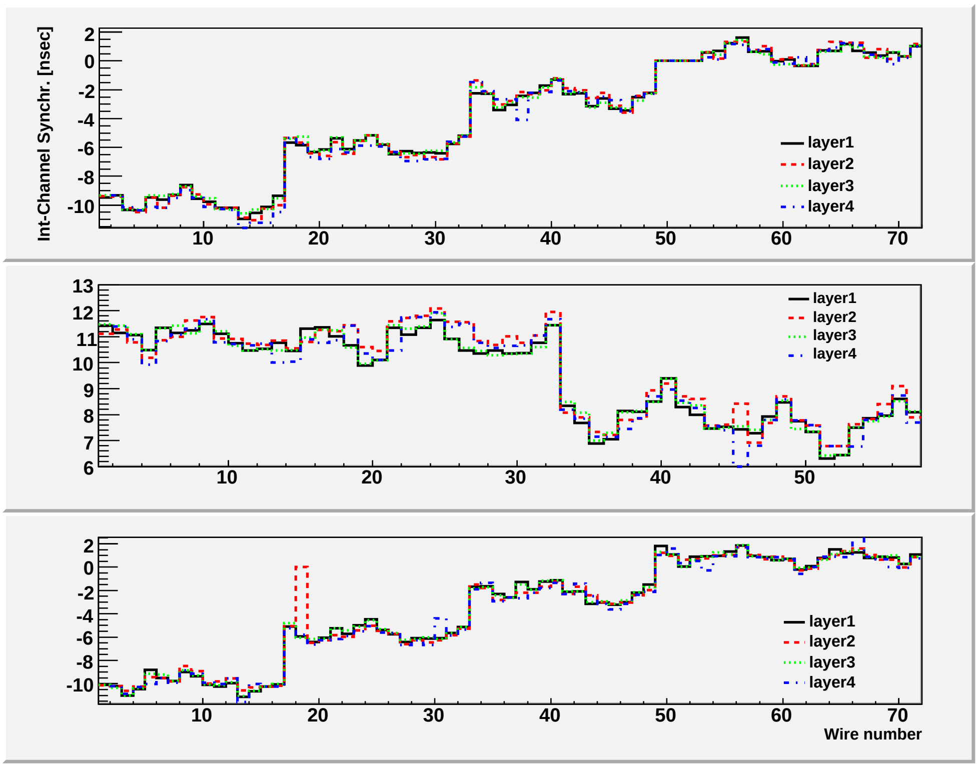


Figure 9. Distribution of inter-channel synchronization constants calculated from a Test Pulse run. Results are shown for a single Sector and for chamber MB3. The distribution for the 3 Super Layers and for the 4 Layers for each Super Layer is shown as a function of the Wire number.

5.2. Noise calculation

A DT cell is defined as "noisy" if its rate of noise hits is higher than 500Hz. A good stability in time of the number of noisy cells within the DT system has been observed during the full CRAFT data taking period also considering different experimental conditions (e.g. different triggering sub-detectors) and different magnetic field conditions. For all the runs analyzed, the number of noisy cells is below the 0.1 % of all the DT system channels and the average noise rate is 4Hz as it is illustrated in Fig.10.

The noisy cells have been observed usually in the inner most layer of the DT chambers, they are characterized by a very high noise rate, and they are positioned at the extremities of the layers, where there are the input high voltage cables.

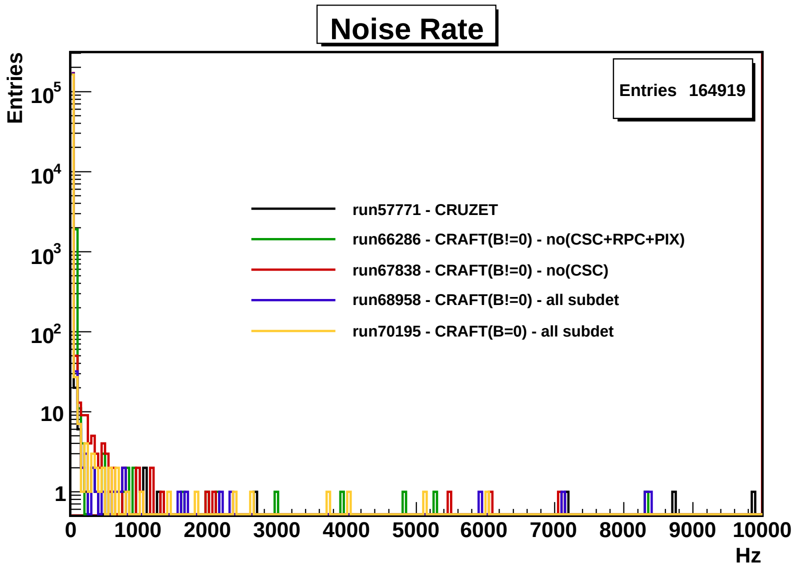


Figure 10. Cell noise rate distribution computed for different condition of data taking.

5.3. Time Pedestal Calibration

Once the inter-channel synchronization corrections are applied and the noisy channels are subtracted, the Time Pedestal may be computed from the starting point of the Time Box distribution with the method described in Section 3.

The results of the Time Pedestal calibration procedure for a typical run of the CRAFT data taking period are shown in Fig. 11 and Fig. 12 as a function of the chamber and sector number for all the wheels of the muon DT system.

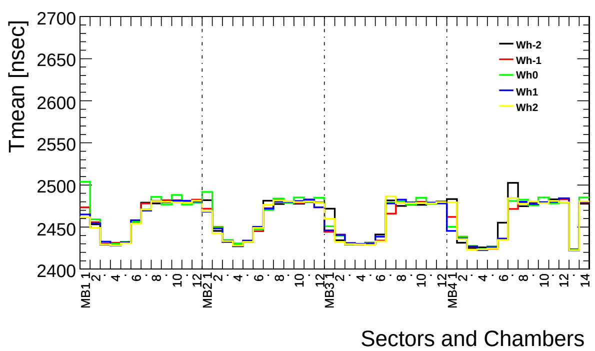


Figure 11. Distribution of the mean of the fit to the rising edge of the Time Box using the integral of a Gaussian for the *r-phi* Super Layers for all wheels. Triggering sectors (3, 4, 5 and 9, 10, 11) are better synchronized among them.

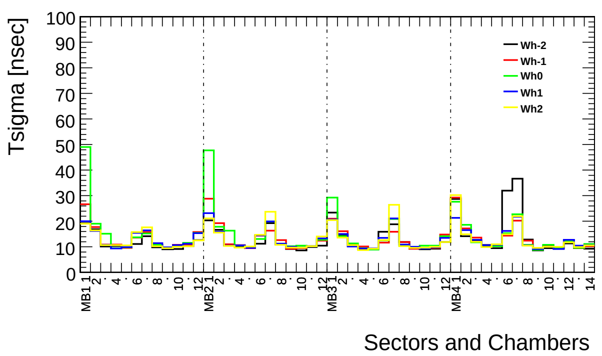


Figure 12. Distribution of the sigma of the fit to the rising edge of the Time Box using the integral of a Gaussian for the *r-phi* Super Layers for all wheels. In The vertical sectors have a rising edge less defined and the Time Pedestals are estimated less precisely.

The values of *Tmean* are stable for all the wheels showing that, a part specific hardware instability correlated to particular runs, the Time Pedestals calculated for one wheel can be replicated for all the other wheels.

A periodic structure is evident which corresponds approximately to the TOF of the cosmic muon from the upper sector to the lower sector which is not included in the calculation of the Time Pedestals. The time offset corresponds approximately to 40 nsec which is the cable distance between the sector collector of the above sectors and the one of the below sectors. This is the time of flight of a particle crossing two chambers of the more external layer (MB4) in opposite sectors.

The distribution of the slopes of the rising edge of the Time Box is shown in Fig 12. As in the case of the *Tmean*, also the *Tsigma* distribution is stable for all the wheels. Furthermore it illustrates another characteristic of the cosmic ray event data taking: the periodic structure shows in fact peaks corresponding to the Super Layers of the vertical sectors (1 and 7) which collect the tracks with wider angle with respect to the normal of the chamber plane, and have a poorly defined rising edge. A part of those particular sectors the quantity *Tsigma* has an approximately constant value of 10 nsec. This value, which is more than two times the one observed in simulated data (Fig.6), is originating mainly from the uncertainties of the arrival time of the cosmic ray events within the bunch crossing structure.

5.4. Drift Velocity Calibration

The drift velocity calibration algorithm is based on the Mean Timer computation which is summarized in Section 3 and it is calculated with a Super Layer granularity. Fig.13 and Fig.14 show two examples of drift velocity distributions calculated as a function of chambers and sectors and for all the wheels of the DT system. Fig. 13 shows the distribution of the drift velocity for a run with the magnetic field off, while Fig. 14 shows the distribution for a run with magnetic field on and at its nominal value of 3.8 Tesla.

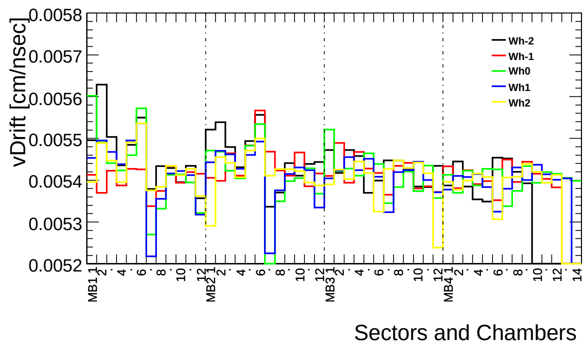


Figure 13. Distribution of the Drift Velocity for a CRAFT run with magnetic field switched OFF. The *vDrift* is computed using the Mean Timer method for the *r-phi* Super Layers.

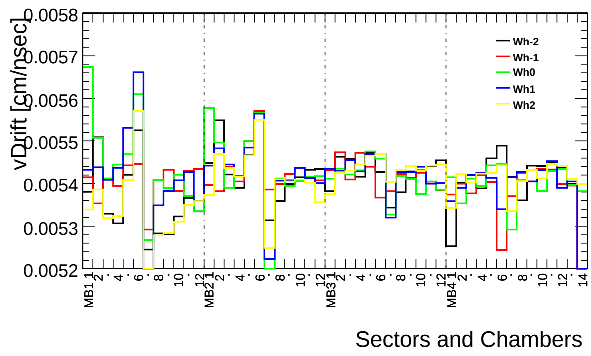


Figure 14. Distribution of the Drift Velocity for a CRAFT run with magnetic field switched ON. The *vDrift* is computed using the Mean Timer method for the *r-phi* Super Layers.

The figures show an approximately constant value of 54.3 microns/nsec, although some fluctuations are present due to the contribution of tracks which have a worse reconstruction because of their large angles. For the same reason the vertical sectors (1 and 7) have a drift velocity very poorly defined.

In addition, an effect is observed for the presence of the residual magnetic field in the results shown in Fig.14. The distribution of the radial component of the residual magnetic field present in the yoke, where the DT chambers are positioned, is shown in Fig.15. The residual magnetic field has its largest values for the more internal chamber layer (MB1) especially in the more external wheels (Wheel+-2). For those chambers a lower value of drift velocity is expected on average. This is approximately observed in Fig. 14.

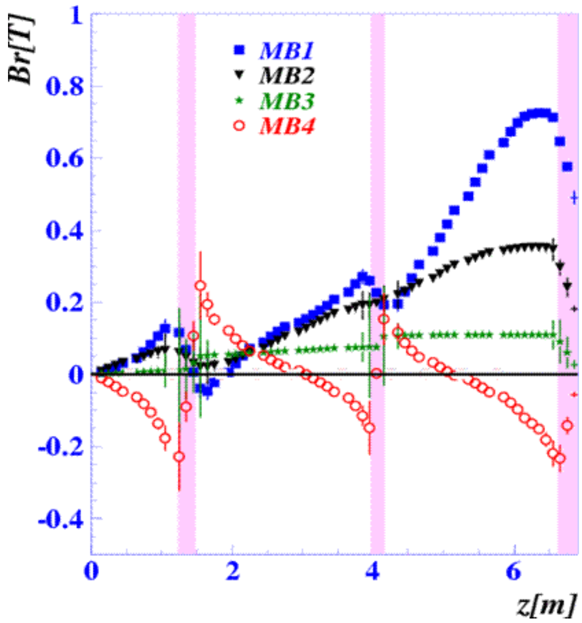


Figure 15. The radial component of the magnetic field in the Muon Barrel chambers for the different wheels, as a function of Z.

Once the Time Pedestal and the Drift Velocity calibrations have been computed, they are used in the local reconstruction and the calibration procedure proceeds with the validation step studying the effect of the calibration on the reconstruction algorithm. The analyzed quantities are the residuals computed as the difference between the distance of the hit and the reconstructed segment.

The distribution of the standard deviation of the fit to residuals is a first indication of the resolution of the DT system on cosmic rays. This is illustrated in Fig 16.

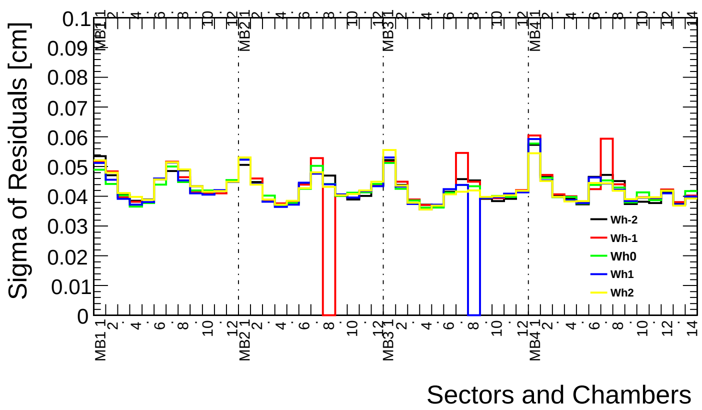


Figure 16. Distribution of the standard deviation of the fit to the residuals computed with respect to the reconstructed segments, using the Time Pedestals and the calibrated Drift Velocity.

As in the case of the other calibration quantities studied up to now a periodical structure is observed which shows a worsening of the resolution for the vertical sectors.

On average the resolution values vary between 380-550 microns, which are in the best case almost a factor two the nominal resolution expected in the DT chambers. Such values are expected at the level of local pattern recognition because of the convolution of the non bunched structure of the arrival time of cosmic muons.

6. Conclusion

Results on Calibration procedures for the Drift Tubes system of the CMS experiment have been presented for simulated collision events (CSA08) and for cosmic ray event data taking (CRAFT).

During the CSA08 exercise, which has been the first full-scale offline and computing CMS enterprise, the DT calibration work-flow focused on the production, validation and publication of calibration and alignment conditions within the time constraints expected at the LHC start up.

The same Calibration work-flow has been applied to the data collected during the CRAFT running period, providing the local reconstruction with constantly updated Condition Data Bases and exercising the monitoring of the stability in time of the produced conditions.

The main results on Time Pedestal offsets and on effective Drift Velocity have been shown. For the simulated collision data the Time Pedestal offsets reproduce the pedestals introduced at the generation level with an uncertainty which is of the order of 1-2 nsec. The same quantity calculated for the cosmic ray events shows, subtracting the contribution coming from the TOF between upper and lower sectors, a constant behavior for all the DT system. Due to the particular topology of the cosmic ray events, the Time Pedestals are less defined for the vertical sectors where tracks with large angles are present. For all the other sectors an uncertainty of the order on 10 nsec is observed. This value is originating from the uncertainty of the arrival time of cosmic ray events within the bunch crossing structure.

The Drift Velocity calibration results have shown for the simulated collision data an approximately constant value of 54.3 microns/nsec for all the chambers of the spectrometer except those chambers positioned in the more inner layer in the external wheels. The drift velocity for these chambers results to be lower, of the order of 53.4 micron/nsec as expected when the CMS magnet is on. These conditions, when computed with the cosmic ray events, appear to be less defined due to the arrival time structure of these events. Although big fluctuations are present, the drift velocity also for real data shows approximately the same values observed in simulation.

Finally, the application of the calibration conditions to the local reconstruction algorithm gives a first and direct estimation of the chamber resolution. While for the simulated collision data a resolution very close to the nominal expected resolution of 200 microns is observed, for the real cosmic ray data a spatial resolution which is at best 380 microns is observed which is in agreement with the uncertainty expected because of the random arrival time of cosmic muons with respect to the system clock running at LHC frequency.

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