The ability to provide fast muon triggering and efficient offline muon identification is an essential feature of the LHCb experiment. The muon detector is required to have a high efficiency over a large area and an appropriate time resolution to identify the bunch crossing for level–0 triggers. The LHCb muon detector consists of five stations equipped with 1368 Multi Wire Proportional Chambers and 12 Gas Electron Multiplier chambers. The technical design of the chambers is briefly presented and the Quality Control procedures during the various construction steps are described. The method developed for gas gain uniformity measurement is also described together with the results on efficiency of detectors fully equipped with the front–end electronics, obtained from tests with cosmic rays.

1. Introduction

The LHCb experiment, that will operate at the Large Hadron Collider (LHC) at CERN, has been designed to study CP violation in B meson decays. Muon triggering and offline muon identification are essential to reach these objectives as muons are present in the final states of many CP–sensitive decays. In addition, muons provide a very efficient flavour tagging through $b \rightarrow \mu X$ semileptonic decays.

The main goal of the LHCb muon detector is to provide an efficient and robust level–0 muon trigger through a 5–fold coincidence of hits in all stations. Therefore an efficiency greater than 99% per station is required in a gate of 20 ns and, therefore, a time resolution better than 4 ns. Due to the high rate of incident particles (up to 0.1 MHz/cm$^2$ for inner chambers) the muon system is required to have good rate capability and aging resistance to ensure full functionality for the 10 years lifetime of the experiment. The design of the muon system has been optimized in order to fulfill all these requirements and allows to reach a trigger efficiency of 46% for inclusive $b \rightarrow \mu X$ events inside the geometrical acceptance.
2. Muon system layout

The muon detector consists of five muon tracking stations placed along the beam axis for a total active area of 435 m$^2$. The first station, M1, is placed in front of the calorimeters, while stations M2 to M5 are interleaved with three iron filters and placed downstream the calorimeters. The acceptance of the muon detector is about 20% for muons from inclusive b decays. Each station is subdivided into four regions (R1–R4) with dimensions and granularity shaped in order to keep the occupancy roughly constant over the detector channels.

The muon detector is fully equipped with Multi Wire Proportional Chambers (MWPCs) except for Region 1 of Station 1 (1% of the area), where triple–GEM (Gas Electron Multiplier) are used. A MWPC is made of four gaps (two in station M1), each one with a plane of anode wires between two cathode planes (Fig. 1).

The anode–cathode distance is as short as 2.5mm to have a fast charge collection. The cathode panels are composed of two copper/gold clad FR4 laminates filled with a rigid polyurethanic foam. The anode plane is composed of 30$\mu$m diameter gold–plated tungsten wires with a pitch of 2 mm. The chambers are filled with an Ar/CO$_2$/CF$_4$ gas mixture (40%, 55%, 5%).

The readout is performed through a combination of cathode and/or wire pads depending on the granularity and particle fluxes foreseen in each region. To ensure a good efficiency the four gas gaps are hard wired in pairs to form two independent double gaps before the connection to the front–end readout where the two double–gaps are logically OR-ed. This structure provides adequate redundancy and robustness to the system.

The electronics is based on custom chips especially developed for the Muon System in 0.25$\mu$m CMOS radiation hard technology. Short peaking time (10 ns) and low noise (ENC $\approx$ 2000+40 e$^-$/pF) ensure a good time
resolution. Several tests have demonstrated\textsuperscript{5} that chambers equipped with such final electronics easily achieve the required time resolution of about 4ns, with 99% efficiency within a 20ns gate.

3. Construction and Quality Control

The Muon detector consists of 1380 chambers, with 20 different sizes and readout types, that have to be built within two years in six production centers. To guarantee the construction of such a large number of chambers with high quality and reproducibility with limited manpower, several automatic procedures have been developed for all the production phases. Stringent mechanical constraints are imposed by the requirement of chamber response uniformity within a relatively small plateau (\(\sim 150V\) around a nominal working point of 2620V, see ref.\textsuperscript{5}) limited from below by the 99% efficiency threshold and from above by a maximum allowed cluster size of 1.2, as imposed by the trigger algorithm. To be conservative, a maximum voltage change of \(\pm 50V\) is allowed, corresponding to a gain change of a factor 1.4. A full Monte Carlo simulation of the chambers was performed to evaluate the sensitivity of gas gain to the chamber imperfections\textsuperscript{6}. The results have been confirmed on several prototypes tested on particle beams and have set limits to the allowed chamber imperfections, in particular on wire position, wire tension and gap size. In order to check that the produced chambers fulfill these constraints a series of quality tests have been devised.

The gap size is one of the more sensitive parameters with respect to gas gain stability. The first consequence is a stringent requirement on panel planarity stating that at least 95% of the surface should be within 50\(\mu\)m and the maximum allowed deviation is 100\(\mu\)m. In addition the wire fixation bars thickness (that determines the half gap size) should be within \(\pm 0.05mm\) from the nominal value of 2.5mm.

The requirement for the wire pitch is \(2\pm 0.05\) mm. The wire position is precisely determined by the pitch of the wiring machine combs; however it is important to check that no wire is out of acceptance. The wire pitch measurement is performed with two CCD cameras, viewing the two ends of the wires close to the fixation bars, moved with a step motor. A scan of the whole panel is performed taking pictures of a group of wires at each step. The mutual position of the wires is obtained by an analysis of the acquired pictures. A typical result of the pitch measurement for a whole panel with 760 wires is shown in Fig. 2; the precision obtained with this method is
about 10µm.

Figure 2. Typical result of an automated wire pitch measurement for a panel of with 760 wires.

To avoid mechanical instabilities due to electrostatic repulsion, the mechanical wire tension T must be larger than 0.3N. The upper limit on T is set by the wire elastic limit which is 1.2N. A safe condition is then 0.5N < T < 0.9N. The wire tension is controlled by a brake motor during the wiring procedure; however a test on the whole panel is needed to detect any possible failure occurring during the wiring process. The total number of wires of the muon system is about 3.2 millions: this implies that a fast, automated and reliable system is needed to check their mechanical tension. The wire mechanical tension T is related to its mechanical resonance frequency F through the equation

\[ T = \mu (2IF)^2 \]

where \( \mu \) is the wire linear density and \( l \) is its length. The adopted method consists in hitting the wire with a light Mylar hammer and let it vibrate with its own fundamental frequency. The light of a few mW laser beam is reflected on the wire and then detected by a photo-diode producing a signal of the same frequency of the vibrating wire. This signal is sent to a standard PC sound card and the wire fundamental frequency is evaluated by applying a Fast Fourier Transform algorithm. This innovative method allows to measure the wire tension in a few seconds with an accuracy of 0.2%. In Fig. 3 the mean value of the wire tension is shown for several panels.

To check the gas tightness, a small (5mbar) over-pressure is applied to the chamber under test and the pressure difference with respect to a reference hermetically closed chamber is recorded for one hour. The measured curve is then fitted to an exponential function. The maximum allowed gas leakage rate is 2mbar/hour.
An automated training procedure is performed on all chambers before applying the operating voltage. The chamber is accepted if all the gaps are able to stand a voltage of 2850V for a few hours with a total dark current smaller than 50nA.

As mentioned before, the gas gain uniformity is fundamental to ensure that the working voltage is within the voltage plateau. The test consists of an automatic scan of the wire planes with a radioactive source ($^{90}$Sr or $^{137}$Cs), recording the measured current at each position. The total measured double-gap current is then compared with the average double-gap current evaluated over the whole set of produced chambers. The maximum gain variation should not deviate by more than a factor 1.4 from the average value. In Fig. 4 the normalized double gap gain is shown as a function of chamber number for chambers of Region 3 of Station M5.

Finally, a sample ($\sim 10 \div 20\%$) of the chambers that satisfy all the previous specifications, equipped with the final readout electronics, is tested with cosmic rays to determine the efficiency plateau and time resolution. Up to six chambers are piled up on a stand with two plastic scintillator planes to provide triggers. All double gaps tested up to now are well within
the required time resolution and detection efficiency.

4. Conclusions

The LHCb muon detector requirements are good time resolution, high efficiency, high rate capability and aging resistance. Extensive tests have shown that the detector design satisfies all these requirements. Several tests are performed on the produced chambers to verify that all the specifications are satisfied. Due to the high number of chambers to be built, automatic procedures have been developed for all the production and test phases. The construction is currently well advanced and the detector should be ready for the first LHC beam.

References
6. W. Riegler, LHCb 2000–060