Performance of the ATLAS Precision Muon Chambers under LHC Operating Conditions

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For the muon spectrometer of the ATLAS detector at the large hadron collider (LHC), large drift chambers consisting of 6 to 8 layers of pressurized drift tubes are used for precision tracking covering an active area of 5000 m\textsuperscript{2} in the toroidal field of superconducting air core magnets. The chambers have to provide a spatial resolution of 41 \(\mu\)m with Ar:CO\textsubscript{2} (93:7) gas mixture at an absolute pressure of 3 bar and gas gain of \(2 \cdot 10^4\). The environment in which the chambers will be operated is characterized by high neutron and \(\gamma\) background with counting rates of up to 100 s\textsuperscript{-1} cm\textsuperscript{-2}. The resolution and efficiency of a chamber from the serial production for ATLAS has been investigated in a 100 GeV muon beam at photon irradiation rates as expected during LHC operation. A silicon strip detector telescope was used as external reference in the beam. The spatial resolution of a chamber is degraded by 4 \(\mu\)m at the highest background rate. The detection efficiency of the drift tubes is unchanged under irradiation. A tracking efficiency of 98\% at the highest rates has been demonstrated.

1. Introduction

The ATLAS detector is a multi-purpose detector built for the search for the standard model Higgs boson and new physics at the large hadron collider (LHC) at CERN. A striking feature of its design is the muon spectrometer, which is designed to measure muon momenta in the 0.4 T field of a superconducting air-core toroid magnet with an accuracy of 3\% over a wide momentum range; at 1 TeV/c a momentum resolution of 10\% is achieved.

The muon trajectories will be measured by three stations of monitored drift-tube (MDT) chambers. These chambers consist of two triple- or quadruple-layers of pressurized aluminium drift tubes of 0.4 mm wall thickness and 29.970 mm diameter which are filled with a gas mixtures of Ar:CO\textsubscript{2}(93:7) at an absolute pressure of 3 bar. Operated at a gas gain of \(2 \cdot 10^4\), the tubes must provide an average spatial resolution of better than 100 \(\mu\)m. In a six-layer chamber with six tubes hit, this corresponds to a spatial resolution of the chamber of better than \(100 \mu m/\sqrt{6}=41 \mu m\).

The operating conditions of the ATLAS muon chambers at the LHC are characterized by unprecedentedly high neutron and \(\gamma\) background. The chambers will experience background counting rates ranging from 8 s\textsuperscript{-1}cm\textsuperscript{-2} to 100 s\textsuperscript{-1}cm\textsuperscript{-2}. In summer 2002, one of the largest MDT chambers constructed for the muon spectrometer with 432 drift tubes of 3.8 m length \cite{1,2} was tested in the \(\gamma\) irradiation facility at CERN with a 740 GBq \({}^{137}\text{Cs}\) source and a 100 GeV muon beam. To take into account uncertainties in the background estimates, the chamber was irradiated with photon counting rates of up to 183 s\textsuperscript{-1}cm\textsuperscript{-2}. A silicon strip tracking detector was used as external reference 50 cm in front of the muon chamber (see Figure 1).

2. The Spatial Resolution of the Drift Tubes

The hits detected by the silicon detector telescope (STEL) are used to reconstruct the straight
trajectories of the muons. The extrapolation of these trajectories into the triple-layer of the chamber closest to the telescope determines the impact radii $r_{STEL}$ in the tubes traversed by the muons with an accuracy of 20 $\mu$m. The knowledge of the impact radii $r_{STEL}$ allows a precise determination of the space-to-drift-time relationship $r(t)$. After $r(t)$ has been determined, the spatial resolution of a single drift tube is given by

$$
\sigma(r_{STEL}) := \sqrt{\text{Var}(r(t) - r_{STEL})}.
$$

Figure 2a shows the spatial resolution of a drift tube as a function of the impact radius and the $\gamma$ irradiation rate. The spatial resolution is degraded with increasing irradiation rate for large impact radii because of the space charge effect. When a photon is converted into an electron causing a hit in a drift tube, positive ions are drifting from the avalanche region around the wire towards the tube wall. The space charge of the ions change the electric field inside the tube and, hence, the drift velocity of the ionization electrons. If the irradiation rate is low, the muon hits in the tubes rarely overlap in time with the positive ions from the photon conversion. At high irradiation rates, however, the probability increases that ions from background photon conversions are still present, when muons hit the tubes. The presence of the ions causes increasing fluctuations in the space-to-drift-time relationship. Since for the track position measurement, only one space-to-drift-time relationship common to all events can be used, this leads to a decreasing spatial resolution. Because of the longer drift time, the degradation is worse for large impact radii. The space charge effect in drift tubes for MDT chambers was first measured in [4]. The results presented here are in accord with these measurements.

Figure 1b) shows the average spatial resolution of the drift tubes defined by

$$
\bar{\sigma} := \frac{1}{14.6 \text{ mm}} \int_{0}^{14.6 \text{ mm}} \sigma^2(r) \, dr.
$$

At the highest irradiation rate of 100 s$^{-1}$cm$^{-2}$ expected during the ATLAS operation, the spatial resolution is degraded by only 10 $\mu$m compared to the case without irradiation (see Figure 2b). The average resolution achieved with a non-irradiated chamber is slightly above 100 $\mu$m. With the testbeam data we could show that the discriminator threshold of the read-out electronics can be lowered from the 28th to the 25th primary ionization electron without introducing excess noise. This results in an improved average spatial resolution of 99 $\mu$m instead of 104 $\mu$m. A further reduction of the threshold is under study. We also found that
Figure 2. a) Spatial resolution of a single drift tube as a function of the impact radius $r$ for different levels of irradiation. b) Average spatial resolution as a function of the irradiation level.

Table 1
Single-tube and tracking efficiencies as a function of the irradiation rate.

| Irradiation Rate (Hz) | Efficiency | Probability for a Correct Hit | Track Reconstruction Efficiency |
|-----------------------|------------|-------------------------------|--------------------------------|
| none                  | 0.9970±0.0002 | 0.933±0.002                   | 0.9997±0.0090                  |
| 63 Hz                 | 0.9962±0.0002 | 0.898±0.002                   | 0.999±0.008                    |
| 121 Hz                | 0.9960±0.0002 | 0.861±0.002                   | 0.996±0.007                    |
| 183 Hz                | 0.9955±0.0003 | 0.803±0.003                   | 0.984±0.007                    |
raising the gas gain instead is not profitable due to the increased space-charge effect.

3. Detection Efficiencies

Not only the spatial resolution, but also the efficiency of a drift tube may deteriorate under irradiation. The knowledge of the impact radii in the drift tubes allows for the measurement of the detection efficiency of the tubes. The results of our measurements are summarized in Table 1. The efficiency is always above 0.995 independently from the irradiation rate.

In the offline analysis, always the first hits after the trigger time are selected. Therefore the probability of choosing a wrong hit increases with the photon background rate. At the irradiation rate of $183 \text{s}^{-1}\text{cm}^{-2}$ in the test which corresponds to a hit rate of 209 kHz for 3.8 m tubes, this probability is 11%. It is less than 1 because of $\delta$ rays created in the tube walls by the traversing muons.

Because of the redundancy of a chamber – at least six tubes are traversed by a muon – a high track-reconstruction efficiency of greater than 98% is maintained up to the highest background rates, if one requires at least 3 correct hits in the muon chamber.

4. Summary

A large monitored drift-tube chamber was operated at LHC background conditions and above in the gamma irradiation facility at CERN. The measurements show that all chamber will have a spatial resolution of better than 50 $\mu$m and that the track reconstruction is not significantly deteriorated.

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