Performance Study of Monitored Drift Tube Chambers with Cosmic Rays*

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Abstract The performances of monitored drift tube chambers for the ATLAS experiment are studied with cosmic rays. The main features of the chamber and the test facilities are described briefly. The criteria and test procedures for the BEE chambers are presented, including the dark current, the noise level, the drift time spectra, the charge distribution and the relative efficiency. The results are within the specifications required by ATLAS.

Key words monitored drift tubes, MDT chamber, ATLAS muon spectrometer, cosmic ray test

1 Introduction

ATLAS (A Toroidal LHC ApparatuS)[1], a general-purpose high-energy physics experiment at the CERN Large Hadron Collider (LHC), is designed to exploit the full discovery potential of the TeV energy scale by providing precise momentum and energy measurement of hadrons and charged leptons over a large pseudo-rapidity range.

The Monitored Drift Tube (MDT) chambers in the ATLAS muon Spectrometer[2] are used to provide the precise measurements of the muon tracks in the principal bending direction of the magnetic field, with the spatial resolution of 50μm and the relative alignment accuracy of 30μm, in order to achieve the momentum resolution of 10% for transverse momentum up to 1TeV/c. This requires that the drift tube, the basic detection cell of the chamber, work at 3 bar gas (Ar-CO_2 (93%-7%)) pressure to provide a single tube resolution of about 80μm and a systematic timing error for the tube of about 500ps, which has a maximum drift time of 700ns[1, 3, 4].

The MDT chambers are constructed on 13 production sites in China, Europe and USA[5], and among those, 16 BIS (Barrel Inner Small) and 32 BEE (Barrel Endcap Extra) chambers were built at the Institute of High Energy Physics (IHEP), the Chinese Academy of Sciences, which have met the big challenge to the required mechanical precision of 20μm[6]. At IHEP, the BEE chambers, which will be located in the transition region between barrel and endcap, were equipped with the gas distribution system, the high voltage and read-out electronics system as well as the Faraday cages for shielding. A complete test for the chamber quality control was done and the fundamental performances have been studied, including the gas tightness, the dark current, the noise, the time spectra, etc. with the cosmic-ray test stand and other facilities.

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2 The BEE chamber structure and operating conditions

The MDT chambers are mainly composed of aluminum drift tubes of 30mm in diameter and 0.4mm in wall thickness. For every tube a gold-plated tungsten–rhenium anode wire of 50μm in diameter is strung between the tube end-plugs and tensioned at 350g. Each BEE chamber consists of 192 drift tubes, with four layers of staggered tubes (named as one multi-layer) and 48 tubes per layer (shown in Fig. 1(a)), which were glued together with epoxy by means of precision assembly tooling to keep the accuracy of all wire locations inside the chamber better than 20μm. Every tube is 911mm long and is filled with a gas mixture of 93% Ar and 7% CO_2 at an absolute pressure of 3 bar and operated with a low gas gain of 2×10^4 to minimize the fraction of streamers. The corresponding high-voltage setting is 3080V. The choice of high gas pressure is to improve the spatial resolution by minimizing the longitudinal diffusion and the fluctuations. The performance of signal amplitude[7] and the drift time spectra[8] of single tube have been studied, and the manufacturing techniques of tube and chamber described[6].

To be a full chamber, all of the on-chamber service systems are installed step by step. Those include: (1) two aluminum gas manifolds (called gas-bar) to provide the gas inlet and outlet at two ends of the chamber respectively, which are connected to tubes via stainless steel tublets; (2) the printed circuit boards to provide high voltage and signal distribution; (3) the front-end electronics; (4) two Faraday cages to provide shielding at two ends of the chamber; (5) the magnetic field sensors. Fig. 1 shows a full chamber without the Faraday cage.

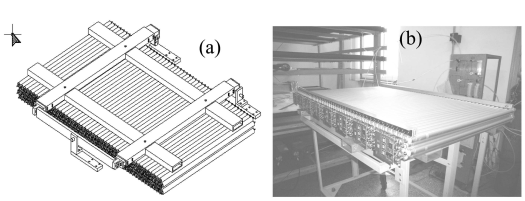

Fig. 1. (a) Schematic drawing; (b) Picture of BEE chamber with gas manifolds.

The positive HV is supplied to the wires by connecting 8 printed circuit boards (HV hedgehog) to the wire pins of the drift tubes. Each board serves a group of 6×4 tubes via filters consisting of a 1MΩ resistor, a 500pF capacitor and a 383Ω termination resistor. On the readout side, the tube wire pins are connected to 8 signal hedgehog boards and each contains 6×4 500pF decoupling capacitors. Both the HV and the signal hedgehog boards are shielded from external RF noise by the Faraday cages. The front-end electronics are housed in a mezzanine card that serves 24 read-out channels connected with the amplifier-shaper-discriminator (ASD) and TDC chips[9]. The mezzanine card is connected directly to the signal hedgehog board via a multi-pin connector, and located outside the signal hedgehog in the convex part of the Faraday cage, in order to shield the hedgehog board circuit from RF noise when signals are processed in the TDC.

3 Experimental setup and operation

Before the cosmic-ray test, the gas leak rate of each chamber should be verified by measuring the pressure drop in 60 hours. According to the specification of the chamber commission procedure[10], the leak rate for one BEE chamber must be below 4×10^{-6}bar·l/s when the chamber is pressured to 3bar, with equivalent pressure drop of about 3mbar per day, taking into account the gas volume of the whole chamber. The check of wire and hedgehog board electric continuity is performed via the MECCA system[11] developed by University of Michigan. For noise and drift time spectra test of each tube under the cosmic rays, the procedure is described as follows.

3.1 Gas system and environment monitoring

The gas supply is monitored by two pressure sensors, with the range of 0—6bar and sensitivity of 6mbar, located at the gas inlet and outlet respectively, together with four temperature sensors and one humidity sensor readout by a LabView—one wire slow control system[12]. The chamber is flushed with the Ar/CO_2 (93%-7%) gas mixture to four volume exchange for two and half hours (about 4000ml/min) and then keeps lower gas flow with one volume per day (about 30ml/min) at the working pressure of 3bar.

3.2 High voltage system and dark current

The high voltage is supplied by a CAEN-127 module (6kV, with 100nA leak current sensitivity) via a splitter box connected to four tube layers of the chamber. The voltage is slowly increased up to 3400V (10% higher than the operation voltage of 3080V), and kept for about 15 minutes, the leak current drawn by the chamber should be less than 430nA summed from 192 tubes and 16 hedgehog boards of one BEE chamber[10].

3.3 Trigger system

A cosmic-ray muon telescope (shown in Fig. 2) used as the trigger system consists of 6 large scintillating counters (SC) with the size of 1.5m×15cm×5cm for each one. The trigger configuration is mainly composed of OR signal from three upper SCs and three lower SCs respectively, then AND together output as the trigger signal for the MDT chamber data acquisition system. Based on the muon intensity of I_0=70m^{-2}·sr^{-1}·s^{-1} and the large angle (θ in Fig. 2) acceptance, the trigger rate is 39.4Hz[13], showing agreement with the experimental results. A tighter triggering acceptance (θ_1 in Fig. 2) has also been used, in order to have more vertical tracks for better drift time spectra, by choosing AND signal from three vertically coupled SCs respectively, then outputting OR signal together, but the trigger rate is too low for our test. The length of the SC can cover the whole chamber, with the tube direction perpendicular to the SC.

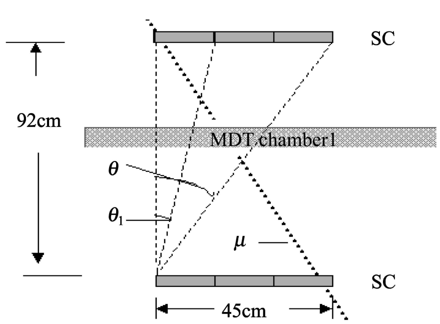

Fig. 2. The trigger system for cosmic-ray test.

3.4 Data acquisition system

The scheme of the readout for the cosmic-ray test is shown in Fig. 3. For each mezzanine card, the output signals from 24 channels are readout by three 8-fold ASD chips and one ATLAS Muon TDC (AMT) chip with 24 channels, and then transmitted to a Chamber Service Module (CSM, version 0), a VME module interfaced with the PC running an on-line software package, Mini-DAQ3.0, developed in ANSI C language of LabWindows/CVI[14] One CSM0 could serve up to 18 Mezzanine cards, but only 8 cards used for our test on each BEE chamber.

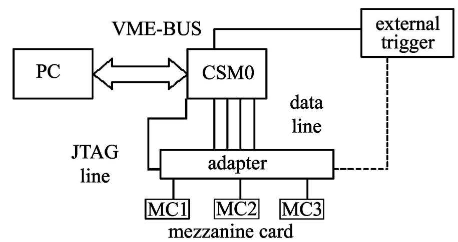

Fig. 3. The read-out electronics for the MDT chamber.

The discriminator thresholds and other control functions are programmable via a JTAG interface hosted on the CSM0. The threshold for every eight channels has to be set one by one according to the database provided by Harvard University. The adapter distributes the low voltage power supply and control signals JTAG to every mezzanine card and as interface communicating data with PC.

4 Results of performance test

All the testing schemes and procedures of MDT chamber have been defined by the collaboration[10]. After the gas tightness, grounding and electric continuity between the hedgehog board and the tube are checked, every chamber should be tested under the cosmic-ray stand for the following items.

4.1 Dark current

The ATLAS specification of dark current for single tube with 3 bar working gases is 2nA/m at 3.4kV. For every chamber, the allowed dark current I_{dark} is the sum induced from all tubes and Hedgehog boards[10]

$$I_{\mathrm{dark}}(\mathrm{nA}) = 2\times N_{\mathrm{tube}}\times L_{\mathrm{tube}}(\mathrm{m})+5\times N_{\mathrm{card}}\ , \quad (1)$$

where N_{tube}, L_{tube} and N_{card} are the number of tubes, the average tube length and number of hedgehog boards in a multilayer respectively. For BEE chamber, I_{dark} should be lower than 430nA and not higher than 2nA for every tube. The tubes with dark current higher than 2nA have been treated with negative high voltage. Among all of BEE chambers, 48% of them gave the dark current lower than 200nA, 40% were between 200nA and 400nA, and only one chamber showed a large current. In order to debug the leaking source, HV was supplied for each layer and each HV hedgehog board separately. One tube was identified to exceed the limit and disconnected electrically from HV as a dead channel.

4.2 Noise test

4.2.1 Threshold settings

The noise level mainly depends on the FEE thresholds, the tube characteristics, the grounding and the Faraday cage shielding. It will reduce with increasing the effective FEE thresholds in a semi-Gaussian shape according to the study of ATLAS MDT community.

The effective thresholds V_{eff} have to be set for every eight channels of each mezzanine card, which is defined by Eq. (2)[10].

$$V_{\text{eff}} = V_{\text{main}} - V_{\text{hys}} + V_{\text{ofs}} \ , \tag{2}$$

where V_{hys} means the compensation of time hysteresis (delay) influencing the discriminator level and should be 8.75mV; V_{ofs} is the voltage offset generated by the ASD chip input, the value for every channel is extracted from the database at Harvard University. In the noise test, V_{eff} should be set to -50mV, and then according to Eq. (2), the corresponding three V_{main} of three ASDs should be input respectively for every mezzanine card.

4.2.2 Test with HV off

The main purpose of testing with HV off is to identify the electronics noise level caused by the mezzanine cards, the grounding and the shielding effects of the Faraday cage. The way to take noise data to use a random software trigger generated from CSM. The noise level f could be expressed by counts or hits N in the time interval generated by the software trigger with the following relation:

$$f = \frac{N}{(n \times \Delta t)} \ , \tag{3}$$

where n is the number of triggers and Δt is the width of the time window for each trigger, and we fix Δt=1.6μs.

During the noise test for the BEE chambers, 1×10^6 trigger events in total are used. The results for almost all channels of the BEE chambers are f <20Hz, showing much lower than the specification (below 5kHz per tube)[10].

4.2.3 Test with HV on

With HV on the noise test, one may distinguish the effects of acting tube from the FEE electronics and choose the noisy tubes. Setting conditions and specification value are the same as that of HV off test, except the chamber should be pressured with working gas. In general, the noise rate for most channels of the chambers is 0—20Hz. A few channels have 20—100Hz, significantly lower than specification of 5kHz per tube.

4.3 Drift time and charge distribution in cosmic-ray test

The external trigger is used during the cosmic ray data taking. The operation conditions of the chamber are the same as that in HV during the noise test, except the effective threshold of mezzanine card is set to -40mV. The data acquisition taking about 12 hours is needed for one run with 120000 trigger events, in order to guarantee at least 15000 hits per tube so as to obtain good time spectrum with satisfied fit expressed by empirical parameterized function[3, 6]

$$f(t) = p_1 + \frac{p_2\left[1 + p_3 \exp\left(\frac{p_5 - t}{p_4}\right)\right]}{\left[1 + \exp\left(\frac{p_5 - t}{p_7}\right)\right]\left[1 + \exp\left(\frac{t - p_6}{p_8}\right)\right]}, \tag{4}$$

where p_1 represents the background resulted from noise, p_2, p_3, p_4 stand for the exponential decay function versus time in the middle region of the drift time spectrum. The leading edge and the trailing edge of the time distribution in this function are described by two Fermi-Dirac functions. The leading edge and the trailing parameter p_5 and p_6 are the values of t_0 and $t_{\max}$ respectively. p_7, p_8 are the steepness of ascending and descending of two functions respectively. A typical drift time spectra of one tube is shown in Fig. 4(a), with the eight parameters determined with the maximum likelihood method.

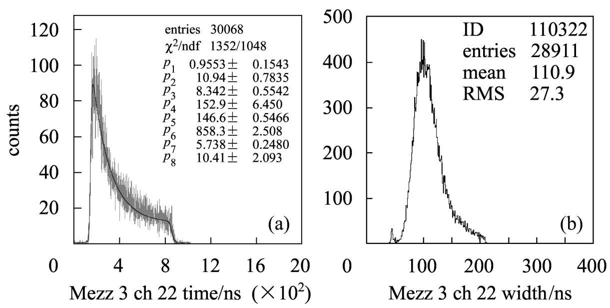

Fig. 4. (a) The drift time spectrum of one channel; (b) The charge distribution of the same channel.

The MDT front-end electronics with Wilkinson ADC circuit provides the possibility to measure the sampled charge distribution (ADC spectra). It is used to inspect the tube characteristics, which is designed to compensate the discriminator in TDC. Fig. 4(b) shows the typical charge distribution of the same channel as that of Fig. 4(a), having a Gaussian form with small Landau tail, and the noise amplitude is lower by a factor of 2 compared with the peak.

Both the drift time and the charge distribution of the single tube make possible to monitor the data quality. The t_0 and the $t_{\max}$ correspond to the measured drift time of particle passing very closely the wire and the tube wall respectively . The value of t_0 depends on the time delay of the signal cables and the front-end electronics as well as on the discriminator threshold and the HV setting, and the difference $t_{\rm tot} = t_{\max} - t_0$ represents the maximum drift time. The width of $t_{\rm tot}$ distribution is very sensitive to the gas properties, such as mixture composition, pressure and temperature, and is a key parameter in evaluating the chamber behavior. Fig. 5 shows the distribution of $t_{\rm tot}$ in one BEE chamber, with the average value of around 718ns, which is consistent with the expected specifications. From the charge distribution, one can find if the tube is noisy, or has high gain with higher ADC spectra peak. In some cases, the noisy channel will lead a failed fit on TDC spectrum, so we have to reduce the noise by applying the ADC cut in the data analysis.

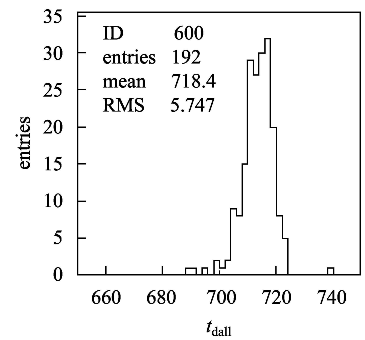

Fig. 5. The $t_{\rm tot}$ distribution in one chamber.

4.4 Relative efficiency

The tube mapping, also called the tube occupancy distribution[3], is described by the hit-map of entry number for each tube row, and the relative tube efficiency is defined as the ratio of the measured number of hits and the expected number of a fit. Fig. 6 shows a measured tube occupancy map for one tube row, and a fitted curve with convex shape of lower number of entries at two ends reflects the angular trigger distribution in the cosmic-ray stand. It can be clearly seen from the tube occupancy distribution for tube problem debugging, such as hot, dead or low efficiency channels.

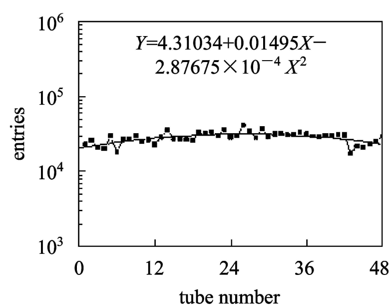

Fig. 6. The tube occupancy mapping in one tube row.

For every procedure of the test described above, all the parameters and results are input into the commissioning database, written in Microsoft ACCESS interfaced with Visual Basic, for the purpose of information records that can be checked in further commissioning tests.

5 Conclusions

The quality control tests, such as the gas leak rate, the dark current and the drift time spectra are very crucial for achieving high performance of MDT chambers. The fundamental performance studies are done on the BEE chambers with the cosmic rays, and the results of some key features, including the noise with HV-off/on, the drift time spectra, the charge distribution and the relative tube efficiencies, are certified to meet the design specifications.

All BEE chambers have been transported to CERN where the final version of the CSM readout electronics and detector control system will be equipped, and they should be tested with the cosmic rays for certification before installing in ATLAS.

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监控漂移管宇宙线实验性能研究*

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摘要 利用宇宙线对ATLAS实验上的监控漂移管室进行了性能研究，根据BEE室的测试标准及步骤简要的测量了漂移管的主要特性. 包括: 漏电流、噪声水平、漂移时间分布、电荷分布及探测效率. 测试结果表明都在ATLAS规范要求之内.

关键词 监控漂移管 MDT室 ATLAS 宇宙线测试

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