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The Muon Counter in the Beijing Spectrometer

Zhu Yongsheng, Zhang Liangsheng, Gao Wenxiu, Zhang Yingping, Zhao Pingde, Zhang Jiawen, Li Fang, Chen Lejun, and Xu Zhiqing

(Institute of High Energy Physics, Chinese Academy of Sciences, Beijing)

The arrangement and design performance of the muon identifier in the Beijing Spectrometer (BES) are described. The gas gain, plateau feature, drift time, detection efficiency, charge division for the hit location and other characteristics of the muon counter modules have been measured.

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1. INTRODUCTION

The BES[1] is a general purpose magnetic spectrometer for experimental research of e^+e^- physics in the first e^+e^- collider (BEPC) built in China. The muon identifier is an important part of it. By measuring the hit locations in several layers of the muon identifier, the track of a charged particle can be determined. Connecting with the track determined by the inner detectors of the BES (main drift chamber and layered shower counter), the muon can be distinguished from other particles and its momentum measured.

2. ARRANGEMENT OF THE MUON IDENTIFIER

The muon identifier consists of several absorber layers and an array of muon counter modules. Its arrangement in the BES is shown in Fig.1. The BES looks like an octagon. 189 muon counter modules line up in three layers behind the three-layer magnetic iron yoke. There are 1512

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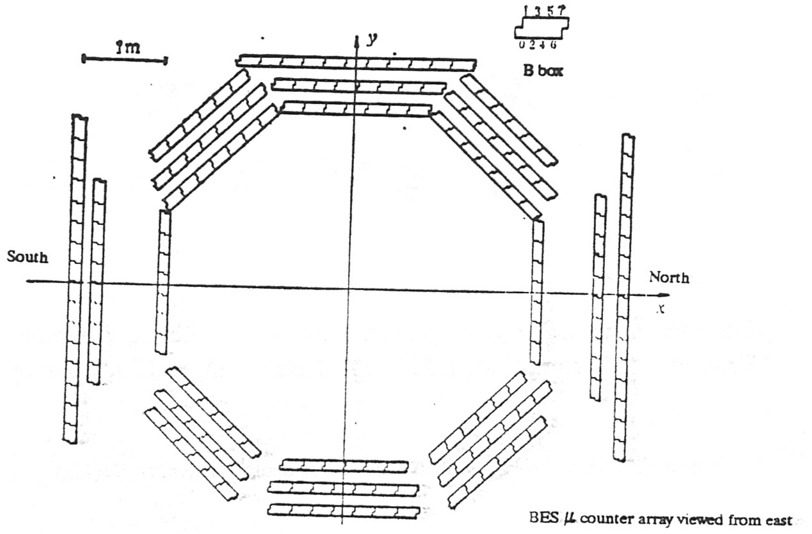


FIG. 1
Arrangement of 189 muon counter modules on BES.

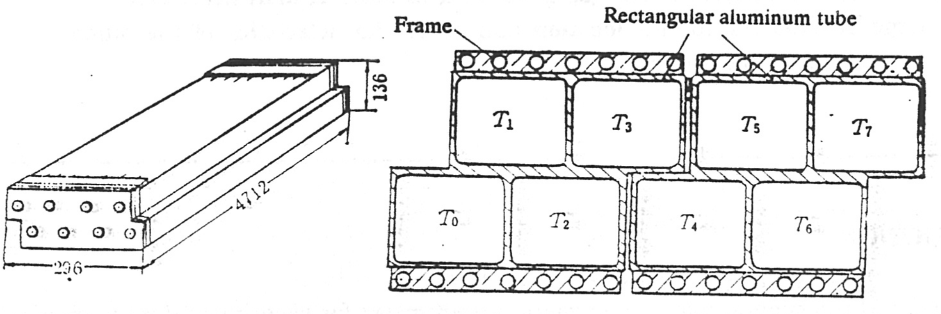


FIG. 2
Sketched structure of the muon counter module.

proportional tubes altogether, as each module contains 8 tubes. The structure of the module is sketched in Fig.2. The length of the tubes in the 1st layer is 4212 mm and that in the 2nd and 3rd layer is 4638 mm. The tubes in the upper row and the lower row in each module are shifted by half the tube width (~ 3 cm) to solve the "left-right ambiguity". Therefore the hit location accuracy in the $r-\phi$ plane reaches ~ 3 cm. The anode of the proportional tube is a stainless wire of 48 μm with a specific resistance ~ 727 Ω/m. The hit location along the anode wire (z direction) is determined by charge division. The design principle of the muon identifier refers to Refs.[2,3]. The details of the construction, cleaning, assembly and preliminary measurement of the muon counter module have been reported in Ref.[4].

3. PERFORMANCE OF THE MUON COUNTER MODULE

249 modules have been constructed, with the wire tension, gas leakage rate and plateau curve of each module being measured one by one. The dark current, O_2 content in the filling gas, the gas gain, drift time, hit location of charge division, distribution of the pulse height of the signal and noise and detection efficiency of the modules have been sampled.

3.1 The Electric Insulation and Dark Current of the Proportional Tube

The insulation between the anode wire and the cathode wall for each tube of a module is measured by a 2.5 kV megohm meter, all resistance values being greater than 500 MΩ. Connecting a 56 MΩ protection resistance and a nanoampere meter in series between the anode wire and the cathode wall and applying high voltage, the dark current of nA order appears near 3.8 kV and increases to ~ 100 nA at 3.82 kV.

3.2 Wire Tension, Gas Leakage Rate and O_2 Content in the Filling Gas

The metal wire in the magnetic field will vibrate if an alternative current is fed into it and the wire tension can be deduced from its resonant frequency. The measured data of the tensions of 1992 wires in 249 modules show that the average value is 128.4 g, but the tensions of 91.5% of the wires deviate from the average value by ± 5%. It can be seen that the wire tensions in all modules are consistent.

Efficient gas tightness of the modules can ensure that the component ratio of the filling gas will not change due to gas leakage and will keep the proportional tubes in stable operation with a relatively low flow rate of the filling gas. Low flow rate will save great amounts of filling gas, as the muon counter system has 20 m^3 volume in total and will run at least for 4--5 years. The leakage rate of the muon module is measured by a U-tube pressure meter filled with silicon oil. 94.4% of the 249 modules have the leakage rate below 4 cm H_2O per day at an overpressure ~ 35 cm H_2O of working gas in muon counter. This rate corresponds to the leakage of gas by 0.4% in the module per day. The overpressure of the muon counter in normal operation mode of the BES actually is ~ 10 cm H_2O. Therefore the leakage rate is much lower than the value pointed out above.

The O_2 content in the filling gas substantially affects the performance of the proportional tube. The working gas of the muon counter module is composed of Ar/CH_4:90/10 with the proportion accuracy being ~ 0.5% and O_2 content being 100 ppm. The measured value of the O_2 content is ~ 52 ppm at such a flow rate that the total amount of gas in the muon counter system is renewed completely in one day. Apparently the measured O_2 content is lower than the required value.

3.3 Gas Gain

To determine the hit location by charge division, the required number of electronics channels are 3024 for all 1512 proportional tubes. Every two anode wires are connected in series with the mode of T_0-T_4, T_1-T_5, T_2-T_6, T_3-T_7 in each module. Such a connection mode can save half the number of electronics channels and thus ensure that a particle from the interaction region of the e^+e^- collider cannot hit simultaneously the two proportional tubes whose wires are connected to each other.

The gas gain of the proportional tube is measured by a cosmic ray, the main component of which is muon. The hit positions of the cosmic particles on the tube are randomly distributed. By measuring the signals at each end of the paired wires (connected in series) and then adding them up,

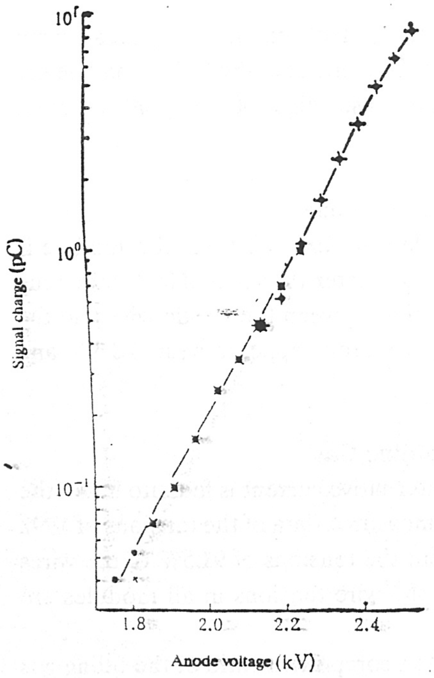


FIG. 3
Gas gain of muon paired tubes.
·○ September 2, 1987;
× + September 24, 1987.

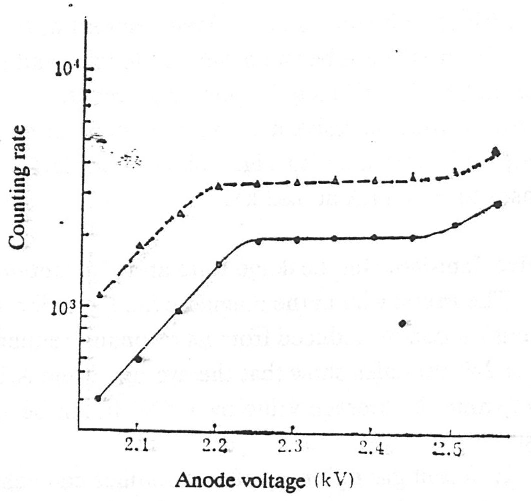


FIG. 4
Plateau curve of muon paired tubes.
○ cosmic ray T_1+T_5; △ Sr^{90} source T_5.

we obtain a wide distribution of the pulse height, the peak value of which corresponds to the most probable charge in the hit tube. The typical gas gain feature of the muon tubes is shown in Fig.3. It appears that the gas gain has a linear relation with the anode wire voltage below 2.4 kV. The signal charge is 5 pC at 2.4 kV. The gas gain curves of different paired wires are rather consistent and reproducible in different measurements.

3.4 Plateau Curve

In general the plateau curve of a proportional tube is measured when particles pass through a fixed position of the tube. However in the BES all the particles which pass through the effective detection region of the muon counters have to be registered. Furthermore, the distance between the hit point and the output end directly determines the pulse height of the signal. Therefore, it is inadequate to measure the plateau curve in the mode of particles incidence on the fixed position of the tube. Measuring the counting rates of the "summed signal" at both ends of the paired wires generated by cosmic particles whose hitting positions on the tube distribute randomly without position selection by a scintillator telescope at ascending anode voltages, we obtain the plateau curve as shown by the solid line in Fig.4. The plateau starts from ~ 2.25 kV and extends for ~ 250 V. The dash line in the figure is the plateau curve of particle incident on a fixed position of the tube, which has a starting voltage of ~ 2.2 kV and extends for > 300 V. The high end voltages of the S-C two

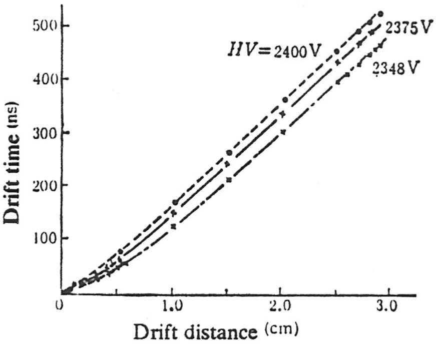


FIG. 5
Relation curve of drift time and drift distance of muon tube.

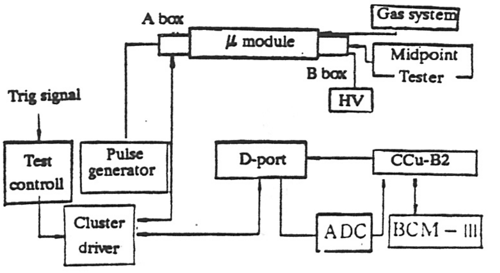


FIG. 6
Sketch diagram of charge division measurement system.

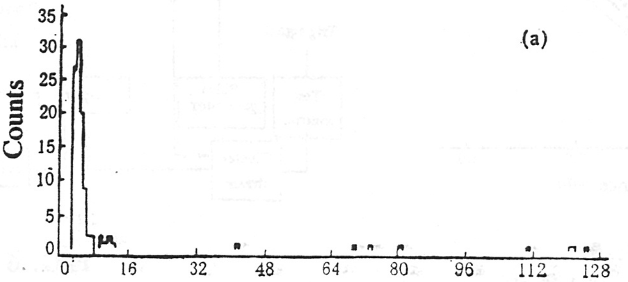
plateau regions are nearly the same. This reflects the fact that the anode voltage, when the gas gain of a proportional tube transits from the proportional mode to the limited proportional mode, is irrelevant to the hitting position of a particle in the tube. The plateau curves of all the 996 paired wires are rather coincident with the differences of plateau lengths and starting voltages within 25 V. Therefore the anode voltage could be any value between 2375--2400 V, which guarantees the most effective operation of all the muon counter modules.

3.5 Drift Time

The drift time of the muon proportional tube is one of the basic parameters for the trigger arrangement in the BES.

The principle of the drift time measurement of the muon tube is as follows: the collimated beta particles emitted by a ^{90}Sr source pass through the upper and lower thin windows of the tube and are then recorded by a scintillation counter located under the tube. The output signals of the scintillator and proportional tube are taken as the start and stop signals of TAC respectively. The time difference between the start and stop signals corresponds to the pulse height of the TAC output. Varying the ^{90}Sr position by a precise moving device and measuring the corresponding pulse height of the TAC output, the curve showing the relation between the drift distance of and the drift time is obtained.

Three measured curves at three anode voltages are shown in Fig.5. The linear relation appears in the region of a drift distance greater than 10 mm, where both the electric field and drift velocity are relatively low. The velocities are 52.5, 53.5 and 55.0 μm/ns for the anode voltages of 2400 V, 2375 V and 2348 V respectively. The non-linear relation appears, however, in the region of a drift distance less than 10 mm where the electric field becomes very high particularly near the anode wire. The drift times for the anode voltages of 2348 V, 2375V and 2400V are 460, 500, 520ns respectively, provided that the hit point is near the tube wall (~ 29 mm away from the wire). The BES demands that the signal collecting time for the muon counter be shorter than 550 ns. Apparently this requirement can be satisfied at these three anode voltages.



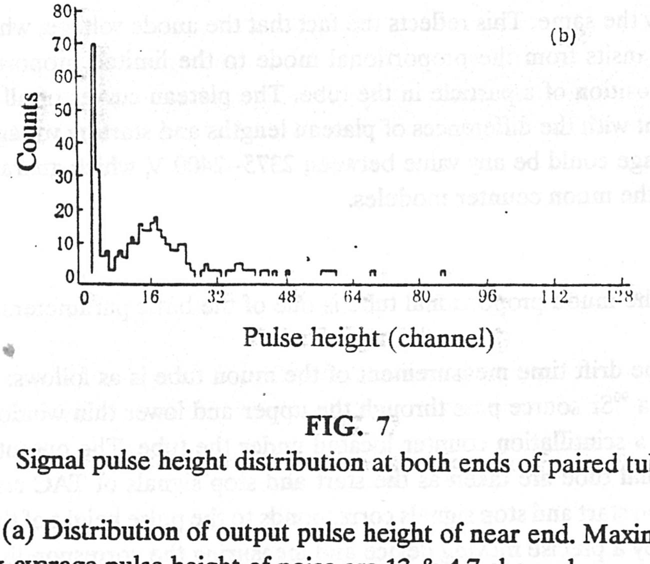


FIG. 7
Signal pulse height distribution at both ends of paired tubes.

(a) Distribution of output pulse height of near end. Maximum & average pulse height of noise are 13 & 4.7 channel, respectively.

(b) Distribution of output pulse height of far end.

3.6 Hit Location by Charge Division

To connect the particle track determined by the muon counters with that determined by the inner detectors of the BES for particle identification and momentum measurement, the hit points in the muon counters have to be located with sufficient accuracy. There exists ~ 13 r.l. material between the 1st layer of the muon modules and the last hit point in sampling the shower counter whose location can roughly be known. The multiple scattering of 500 MeV/c muon (the lowest measurable muon momentum in the BES) will introduce ~ 7 cm uncertainty (r.m.s. value) of the hit position on the 1st layer of the muon modules. Therefore, ~ 5 cm is the adequate choice for the

TABLE 1

No. of module	Average fitting deviation (cm)	No. of module	Average fitting deviation (cm)
0-067(L)	1.624	1-135(R)	1.239
0-067(R)	1.040	1-141(L)	2.132
0-048(L)	1.624	1-141(R)	1.845
0-048(R)	1.040	1-172(L)	2.132
0-065(L)	1.624	1-172(R)	1.845
0-065(R)	1.040	1-078(L)	2.132
0-050(L)	0.598	1-078(R)	1.467
0-050(R)	1.450	1-059(L)	2.092
0-038(L)	1.362	1-059(R)	1.227
0-038(R)	1.298	1-056(L)	1.594
0-060(L)	1.362	1-056(R)	2.222
0-060(R)	1.298	1-073(L)	2.182
1-112(L)	1.918	1-073(R)	2.476
1-112(R)	1.366	1-136(L)	2.819
1-135(L)	2.626	1-136(R)	2.410

Note: In a module, L represents the wires with smaller order numbers (0, 1, 2, 3) and *R* the wires with bigger order numbers (4, 5, 6, 7).

location accuracy of *z*-direction in the muon counter, whereas the location accuracy in the r—ϕ plane reaches 3 cm as stated in Section 2, which is already good enough.

The block diagram of the measurement system for charge division is sketched in Fig.6 in which box as A and B are the front end electronics. A telescope which is composed of two scintillator strips with a size of 250 × 30 mm² selects the cosmic particles penetrating the muon counter at a fixed position. The coincident output of the telescope is taken as the trigger signal. An on-line program of BCM III micro-computer controls the Test-control, Cluster-driver and D-port through a CAMAC crate control unit CCU-B2 to implement the transfer and register of the signals and their addresses, and the control of the trigger mode in order to record the pulse height of the signals of the muon counter module into ADC. Thus we can obtain the signal charges of both ends for the paired wires. This measurement system can carry out the storage, read, write, print, plot and accomplish other various operations of charge division and some other measurements, not only for single module but also for all the 189 modules if connected to a VAX 785 computer.

Fig.7 shows the distributions of the pulse height from two ends of the paired wire when the hit position of cosmic particles incident on the muon tube is 15 cm away from the near-end, and 921.6 cm away from the far-end, and the anode voltage is 2.4 kV. It can be seen that the near-end signals have more charge (the pulse height of most signals is beyond the scope of the abscissa of Fig.7a), and thus the signal can be easily distinguished from the noise. However, the far-end signal has less charge, and has been mixed up with noise in the low pulse height region. But the distributions of the noise pulse height of both ends are similar, with the maximum being 13 ch. and the average 4.7 ch. which correspond to 0.127 and 0.046 pC charges respectively.

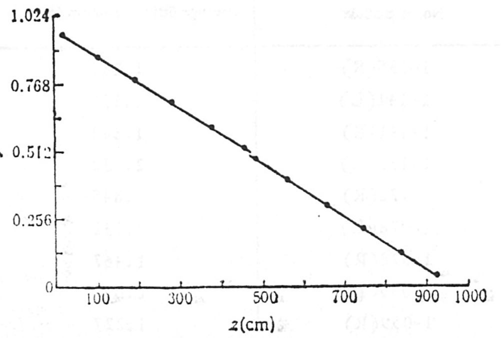


FIG. 8
Results of charge division measurements and their fitting curves.

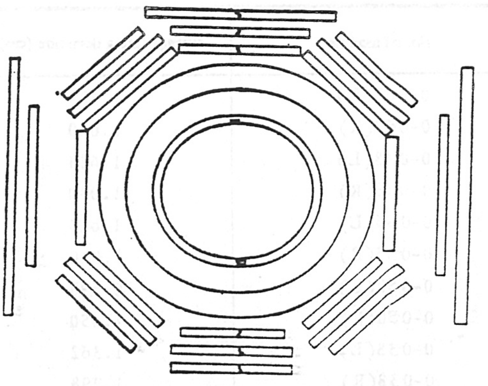


FIG. 9
A cosmic ray event.

By measuring the signal pulse height at both ends of the paired wires at different positions z_i, we can obtain the corresponding charge ratio f_i of signals at both ends. f_i appears as a Gaussian distribution and its peak $\bar{f}_i$ can be considered as the most probable value of f_i. The z_i—$\bar{f}_i$ plots of 60 paired wires of 15 modules have been measured. The typical result is shown in Fig.8 where the break-point corresponds to the connecting point of the paired anode wires. The existence of the break-point probably reflects the fact that although the resistance of the connecting wire is very small, the impudence induced by the wire with its surrounding environment affects the signal transmission considerably. To avoid the difficulty induced by the break-point we fit the $z-f$ relation in two segments for the paired wires with the following formula:

$$f = Az + Bz^3 + C. \tag{1}$$

The typical values of A, B, C (for module 1--073) are

$$A_L = -0.9266 \times 10^{-3}/\text{cm}, \quad B_L = -0.5 \times 10^{-9}/\text{cm}^3, \quad C_L = 0.9801368;$$
$$A_R = -1.1781 \times 10^{-3}/\text{cm}, \quad B_R = -0.1 \times 10^{-9}/\text{cm}^3, \quad C_R = 1.0400384.$$

Table 1 lists the average deviations between the data and the fitting values of z_i for 15 modules, which are all less than 2.9 cm.

There nearly exists a linear relation between the hit position z and charge ratio $f = Q_1/(Q_1 + Q_2)$ according to the charge division principle[9]. In fact it can be seen that the coefficient B of the cubic term is very small, so we have approximately

$$\sigma_z \cong \sigma_f / A, \tag{2}$$

TABLE 2 Performance of Muon Counter Modules of BES (Typical Values)

HV	Length plateau	Signal charge	Average moise level	Detection efficiency	Location error in z direction	Max. drift time	O_2 content
2.35—2.40kV	~250V	~5pC*	~0.046pC*	⩾98%	⪅4.5cm	~500ns	~50ppm

* HV2.40kV.

namely the uncertainty of z_i is mainly determined by the standard deviation of f_i. The typical value of σ_z is ~ 4.5 cm. The total uncertainty of z for the muon counter module includes the contributions of σ_z, the fitting error σ_{fit} and the subtraction of the contribution of 3 cm width of the strip scintillator for the hit position selection of cosmic particles

$$\sigma_t \cong [\sigma_z^2 + \sigma_{fit}^2 - (3\text{cm})^2]^{1/2} \lesssim \sigma_z \cong 4.5\text{cm}, \tag{3}$$

namely, the total error is less than 4.5 cm.

3.7 Detection Efficiency

Two strip scintillators which are perpendicular to each other and parallel to the anode wire are put on the upper side of a muon module, one of which is parallel to the 3rd strip scintillator located below the module. All these strips have a width of 3 cm. Their tri-coincidence output is taken as the trigger signal, and this arrangement ensures that the cosmic particle generating the trigger signal can definitely pass through the sensitive region of the muon tube. The detection efficiencies obtained in three measurements are all greater than 98% at z = 267 cm and with the anode voltage at 2.35 kV.

3.8 System Integration Test with the Cosmic Ray

189 modules with their front end electronics have been assembled on the BES and connected to the trigger system and the VAX-785 on-line data acquisition system of BES. The system integration test with the cosmic ray has been successfully implemented. Fig.9 is a cosmic particle event displayed on the on-line system. The trigger requirement is that there must be a coincidence between the output of the scintillator located at the center of the BES and the output of one of the 48 units of barrel TOF. The particle track is shown clearly by 12 hits in the muon counter modules and 2 hits in TOF. The number of relative events recorded in each module can be calculated in terms of the Monte-Carlo simulation program based on the geometric position of each module and cosmic ray $\cos^2\theta$-intensity-distribution. The experimental data of the cosmic ray run are in good agreement with the Monte-Carlo simulation.

4. CONCLUSION

1) All the 249 muon counter modules have shown adequate consistency in their performance. This allows the interchange between any of them.

2) The actual performance of the modules (see Table 2) is better than the design requirement. The muon identifier of the BES composed of these modules and several absorber layers has achieved the same performance as that of MARK III[2].

3) The system integration test of the muon detectors, trigger system and on-line computer has been successfully implemented, and the experimental data of the cosmic ray run are in good agreement with the Monte-Carlo simulation. The muon identifier is now ready for e^+e^- collision experiments.

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