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A new surface treatment for the prototype RPCs of the BESIII spectrometer

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Abstract

The prototype resistive plate chambers (RPCs) for the BESIII spectrometer were constructed by using resistive electrodes made from a special type of phenolic paper laminates developed by us. The surface quality of these laminates is superior to other bakelite plates that have been used to construct RPCs elsewhere. A method for adjusting the resistivety of these laminates was also developed. Extensive studies were conducted by using a number of prototype RPCs in the last several years. Tests have shown prototype RPCs made by using our resistive plates without the linseed oil treatment can achieve the level of performance comparable to RPCs with linseed oil treated bakelite or resistive glass electrodes. In this paper, we will discuss the construction of these prototype RPCs. The test results of a prototype RPC that have been monitored for a year will be reported. Based on favorable test results of prototypes, the RPC production for the muon identifier of the BESIII spectrometer has started at the Beijing Gaonengkedi Science and Technology Co. Ltd. in early 2004 using the technology that we developed.

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Keywords: Resistive plate counter; Resistive plate chamber; Bakelite; Muon spectrometer; Muon identifier

1. Introduction

Resistive plate chambers (RPCs) are inexpensive to build and have excellent time resolution. Currently, three large CERN LHC experiments,

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ALICE, ATLAS and CMS, are constructing RPC-based muon triggering systems. For cosmic ray and neutrino experiments that need to cover large surface areas, RPCs are also an excellent detector choice. The OPERA experiment at Gran Saso and YBJ-ARGO at Yangbajing International Cosmic Ray Observatory in China are building RPC-based detector systems. The two B-factory experiments, BaBar at SLAC and Belle at KEK, both use RPCs to instrument their flux return for muon triggering and identification.

Phenolic paper laminates commonly referred as bakelite have been the standard resistive plate material since the invention of the RPC in the early 1980s [1]. Among the large RPC systems mentioned above, only the RPCs of Belle experiment use resistive glass electrodes [2]. All others use bakelite. A large fraction of the bakelite RPCs used in these experiments are made by General Tecnica in Italy [3].

Treating the inner surfaces of the bakelite electrodes by linseed oil has been an essential process for their optimum performance [4]. Bakelite plates used as electrodes for RPCs are made by a high-pressure lamination process in which paper layers, after going through a resin bath and a roller system, are placed in a large press on a polished steel plate. Another steel plate is placed on top of the paper layers. A stack of such processed paper layers and steel plates are then held in the high-pressure press for up to several hours at elevated temperature. The hardened laminates are then removed from the press and cut to size. The resin used is usually phenolic or a mixture of phenolic and melamine resin. The proportion of the phenolic and melamine is adjusted according to the desired bulk resistivity of the finished products. The chemical formulation of the resin and the physical parameters of the lamination process determine the resistivity and other properties of the bakelite plates.

In order to improve the surface quality, the outside layer of the bakelite plates are substituted with a more refined paper layer that has been processed with a melamine, a phenolic or a mixture of melamine and phenolic bath. The surface quality and the cleanness of the steel plates that are repeatedly used also play a critical role in determining the surface quality of the finished bakelite plates. Some discussions about the production process of the standard bakelite plates used for RPC electrodes can be found in Ref. [5].

Controlling the surface quality and avoiding defects on the laminated plates in the high-pressure lamination process is quite difficult in lamination plants that are not set up to meet our special requirements. The roughness and defects on the inner surfaces of RPC resistive electrodes can cause high dark current, high singles counting rate and breakdowns. It has been shown that a thin layer of linseed oil coated on the inner surfaces of a RPC gas gap can significantly improve the bakelite surface smoothness and, therefore, greatly enhance the performance of the RPCs [5]. In order to treat the inner surfaces, the RPC gas gaps are filled with a liquid containing linseed oil and the liquid is then drained slowly. The thin layer of linseed oil left on all surfaces inside the gap, including the surfaces of the spacers, is cured by flowing dry air through the gaps of RPCs for tens of hours. In some cases, this treating process repeats up to three times in order to obtain the best results [6].

In late 1990s, serious operational problems were observed by the BaBar experiment in their RPC system [6,7]. A systematic R&D program was set up to investigate and the incompletely cured linseed oil layer inside the gas gaps was identified as the main source of the problem. The resistivity of uncured linseed oil is much lower than the same cured oil. If it accumulates around the spacers, incompletely cured linseed oil can shorten an RPC gap. Also, whiskers can grow from regions of incompletely cured linseed oil under high electric field in the gas gaps and cause discharges. In addition, evidence was found that fluorocarbon chemistry in the presence of water and plasma can accelerate the aging of the RPCs. For example, the HF molecules formed in the avalanches can transform the linseed oil into acidic greases with resistivity ~100 times lower. The fluorocarbon gas is an essential component of RPC gas mixtures and almost all the RPC systems use different types of fluorocarbon gas. Changes in volume and surface resistivity of the linseed oil layer due to changes in the ionic electric conduction after radiation exposure may also contribute to the aging process of the RPCs. Problems associated with linseed oil coating mentioned above are discussed extensively in Ref. [8].

As observed by the Belle collaboration [2], the HF molecules can also damage the electrode surfaces of glass RPCs. A more recent study showed serious damage to the glass RPC running in streamer mode when the water vapor content was kept at 200–300 ppm in the gas mixture [9].

Even before the incident of the BaBar RPC system, there was a considerable effort to develop RPCs that do not require the bakelite surfaces be treated by linseed oil. The main focus of this effort was to develop RPCs that can work in the high-rate environment expected for LHC experiments. Methods to improve the surface quality of the bakelite plates by using fine paper and melamine resin as the surface layer were developed. However, it was shown that the linseed oil surface treatment could still reduce the dark current and noise counts of the RPCs by up to an order of magnitude compared to the RPCs made by using the improved bakelite without the oil treatment [5]. In an effort led by Korean physicists, extensive tests showed that the dark current and noise counts of RPCs made by using the bakelite electrodes developed in Korea without the oil treatment were much higher than chambers made by using oil-treated electrodes [10]. The high-energy physic group of Peking University that worked on RPC R&D for CMS muon system tested a resistive electrode material made in China without the oil treatment [11]. The Chinese material was not acceptable for CMS mainly because the bulk resistivity was too high and the rate capability was insufficient for the CMS muon detector.

Experiments that are constructing bakelite-based RPCs such as ALICE, CMS, ATLAS, ARGO and OPERA have decided to continue the practice of treating the inner surfaces of RPC gas gaps with linseed oil [12]. In particular, the author of Ref. [12] noted that CMS, fearing aging effects related to the presence of oil, had initially decided to adopt non-oiled bakelite. However, the noise level of several tens of Hz/cm^2 observed in non-oiled RPC prototypes and the improvements made in the oiling procedure have persuaded the collaboration to go for the oil treatment. Experiments such as BaBar and LHCb, on the other hand, have decided to abandon the RPCs. In the case of BaBar, operational problems occurred in some of their 200 new RPCs installed in their end caps in a period between 2000 and 2002. These new chambers were manufactured by using the improved construction procedure and with only a single coat of linseed oil instead of three coats for their original RPCs. The BaBar collaboration has decided to replace their RPC system in the barrel region by a detector system based on limited streamer tubes rather than new RPCs [13]. In the case of LHCb, the significant increase in the bulk resistivity of bakelite plates observed during a 3-year study was the main reason for abandoning the RPCs originally planned for their muon triggering [14]. The authors of Ref. [14] concluded that although the radiation may contribute, the effect is mainly due to the drying up of bakelite.

Based on the operational experiences of the BaBar RPC systems and the problems associated with linseed oil coating, we decided to investigate new approaches for constructing RPCs when we started to consider the design of the muon identifier for the BESIII spectrometer [15]. We have made some key advances since we started this project several years ago. The most important innovation is a method to improve the surface smoothness and control the surface resistivity during the high-pressure lamination process when the resistive plates are produced in the factory. We have also developed a method for modifying the phenolic polymer so that we can tune the bulk resistivity of the phenolic sheets to the desired values required for RPCs in different applications. A special graphite paint that we co-developed with the industry is used to make high-voltage electrode layers on the outside surfaces of our resistive plates. The adhesion of this graphite paint to the surfaces of our resistive electrodes is excellent.

A number of prototype chambers were manufactured and tested since we started the RPC development. We have studied the performance of the prototype chambers with various gas mixtures. Effects of bulk resistivity of our resistive plates on the performance of the RPCs were investigated.

Radiation tolerances and long-term stability of our RPCs were also studied. Some of our early results can be found in Ref. [16]. In this paper, we report the performance of prototype RPCs that have been monitored from June 2003 to July 2004.

Based on favorable results of the prototype tests, we have started the production of the RPCs that will be used to build the muon detection system of the BESIII spectrometer. Approximately 2000 m^2 RPCs of different sizes and shapes will be constructed at Beijing Gaonengkedi Co. Ltd., a detector R&D and manufacturing company affiliated with the IHEP, Beijing. The recent RPCs made for the muon identifier of BESIII spectrometer by using the technology developed by us have shown good behavior in Q/A tests. We will report the construction and performance of the chambers for the BESIII spectrometer in another paper.

We have been concentrating on streamer mode operation in our prototype studies because our main purpose was to develop RPCs suitable as muon detectors for the BESIII instrumented flux return where the particle rates are expected to be low. However, we expect that RPCs made by using our technology can also work in a high-rate environment as long as the bulk and surface resistivety of the electrodes are adjusted properly and the RPCs are operated in the avalanche mode.

2. Design and construction of prototype RPCs

The basic structure of our prototype RPCs, as shown in Fig. 1, follows the conventional design of single-gap RPCs. Unlike the standard bakelite surface that is made of a layer of fine paper impregnated with melamine or phenolic resin, the surface of our resistive plates is covered by a layer of specially formulated plastic film. The prefabricated film laminated onto the surface of the phenolic paper plate during the high-pressure lamination process can reduce the surface defects caused by the steel plates used in the lamination process. The thickness of the film is 50 μm and the resistivity of the film can be adjusted to optimize the performance of RPCs. We have also developed a process for adjusting the resistivity of the finished plates within a range of 10^8–10^{14} Ω cm that covers the full resistivity range of 10^9 and 10^{13} Ω cm required for RPC electrode plates in different applications.

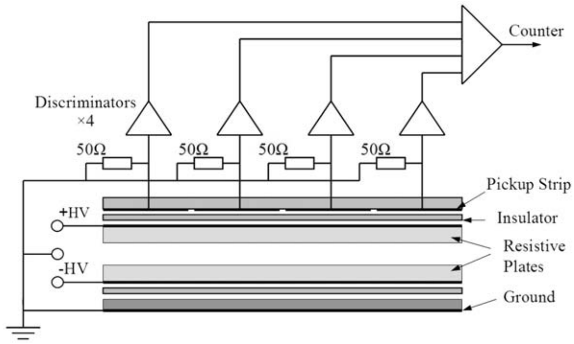

Fig. 1. The design of prototype RPCs for the BESIII spectrometer.

Several RPC prototypes were made in April of 2003. The performances of these prototype chambers were similar. The results reported in this paper are mostly from a prototype chamber that has been monitored for about a year. The bulk resistivity of the resistive plates used for constructing this prototype RPC was about 5×10^{11} Ω cm measured at 20°C.

The resistive plates produced by a local lamination plant were assembled into RPCs without further surface treatment other than regular cleaning. The thickness of the two resistive plates was 2 mm and the gap size was also 2 mm. Spacers and edge frames were glued between the two electrode surfaces. Round spacers made of polycarbonate were spaced by 10 cm in the gas gaps. Graphite paint that we co-developed with industry was applied on the outer surfaces of the resistive plates and the surface resistivity of the graphite electrodes was chosen to be 300 kΩ/□. A layer of 100 μm thick mylar film was glued on top of a graphite layer for electric insulation purpose. The size of the prototype RPCs was 60 cm × 100 cm. A layer of signal pickup strips that are 5 cm wide and 1 m long made from copper clad G10 was placed next to the positive high-voltage electrode insulated by the mylar film.

3. Cosmic ray test setup

Fig. 2 shows our cosmic ray test setup. During the cosmic ray tests, four signal strips were connected to NIM discriminators by coaxial cables and the four outputs of the discriminators were ORed together. The width of the instrumented section of the prototype RPC was 20 cm. We used three scintillation counters in coincidence to trigger the RPCs. The counters were 90 cm in length and 15 cm wide, slightly shorter than a 1 m long RPC and narrower than the four signal strips that were readout. Two of the scintillation counters were placed below and one above the RPC under testing. The trigger rate was about 1 Hz. The test system was controlled by a PC with a Linux operating system. The software for CAMAC interface, data collection and graphic display was based on CERN ROOT software development platform [17] and written by using C^{++} language. The high-voltage ramping and data recording were automated.

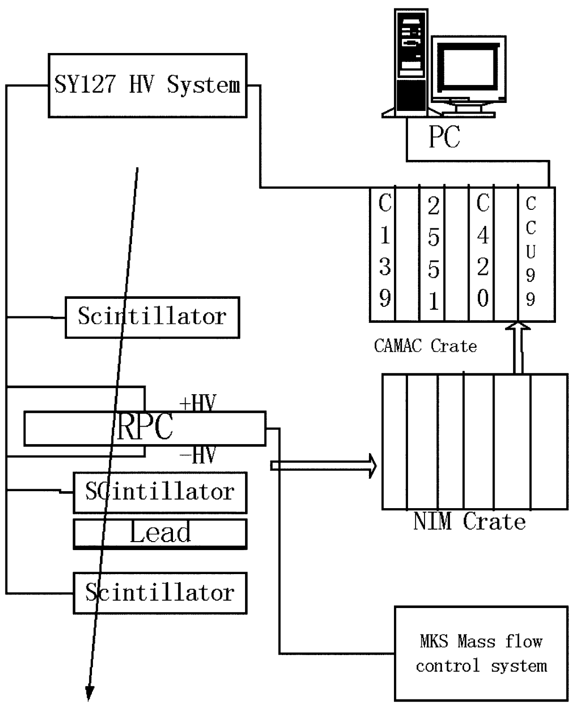

Fig. 2. RPC test system.

Different $Ar/C_2F_4H_2/C_4H_{10}$ gas mixtures were used in our tests. The gas mixing was made by a MKS 247/1259B mass flow control system. The gas flow rate was in a range between 10 and 25 cm^3/min, corresponding to about one volume exchange in every 1–2 h. Part of the reason for the relatively high flow rate was because of the limitation of our gas mixing system. We have observed no significant changes in RPC short-term behaviour due to gas flow rate changes. We used nylon and soft PVC tubing to flow gas in our prototype studies. The coefficients of water vapor diffusion through the walls of these tubing materials are known to be high. The relative humidity in our laboratory was not controlled. We expected the gas mixture in our RPC to contain a significant amount of water vapor that was diffused into the gas stream through the tubing walls. The exact amount of the water vapor in the chamber gas was not analyzed due to lack of equipment. We have not observed any performance degradation caused by water vapor in our RPC gas. The temperature of our laboratory could change from about 16°C in winter and early spring to about 28°C in the summer. We have observed that the temperature changes have negligible effect on the RPC efficiencies. But the temperature changes affect measured values of dark currents and singles counting rates of RPCs because the resistivity of the electrodes depend on temperature.

The high voltages were provided by a CAEN SY127 high-voltage system. We applied a positive and a negative high voltage to the two electrodes of a RPC gas gap in order to reduce the maximum voltage required for each high-voltage power supply. The high-voltage values mentioned in this paper were the total high voltage applied to a gas gap.

An automated program was set to constantly cycle the high voltages applied on the RPC prototypes in 100 V steps. The starting high voltage was 5.5 or 6 kV and the maximum high voltage was 9 or 9.5 kV depending on the gas mixtures used. We normally fix the positive high voltage and vary the negative high voltage during the voltage cycling. The efficiency, singles counting rate, dark current and temperature data were recorded. At each voltage point, we typically collected cosmic ray data for 1000 s and recorded approximately 1000 triggers.

4. Long-term behavior of prototype RPCs

The prototype RPCs were monitored from June 2003 to July 2004. The chamber gas mixture was an $Ar/C_2F_4H_2/C_4H_{10}$ 64.5:22:13.5 during the first part of the study. In April of 2004, the gas mixture was changed to $Ar/C_2F_4H_2/C_4H_{10}$ 50:42:8, which is the gas mixture we intend to use for the BESIII RPC system. The long-term performance of a RPC prototype is shown in Figs. 3–5. The data in these figures were extracted for the 8 kV high-voltage setting. The prototype RPCs were placed near a target in the electron test beam at IHEP from October 2003 to March 2004 and were exposed to scattered electrons. Dark currents and counting rates were monitored during this radiation test. The efficiency was not measured because of the unsuitable beam bunch structure. The data collected during the electron exposure were not included in Figs. 3–5.

As shown in Fig. 3, the efficiencies of the RPC prototype reached 96–98% at 8 kV from the beginning of the test and remained high thereafter. The dark current shown in Fig. 4 was less than $10\,\mu A/m^2$ at the start of the test and dropped to less than $1\,\mu A/m^2$ in about 4 weeks. Please note that the precision for the current monitoring of the CAEN high-voltage power supplies was $1\,\mu A$ and the active area of our prototype RPC was $0.55\,m^2$. As shown in Fig. 5, the singles counting rates at 100 mV threshold reduced from approximately $0.2\,Hz/cm^2$ to $0.05–0.06\,Hz/cm^2$ after the initial training period.

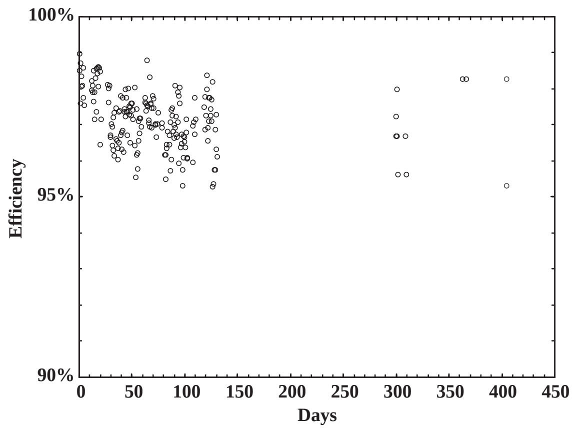

Fig. 3. Efficiencies of a RPC prototype measured over about a year. Data were not included for a 5-month period when the RPC prototype was subject to radiation exposures in the IHEP electron test beam.

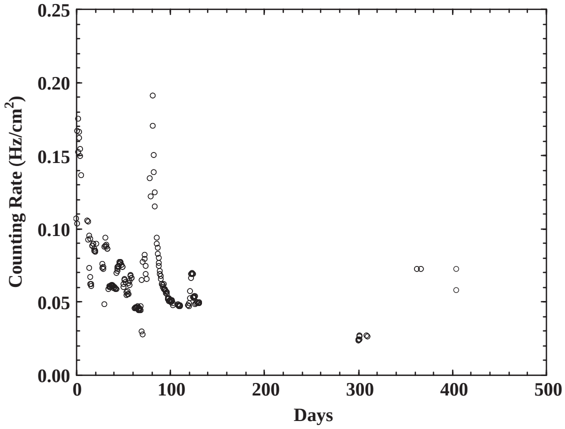

Fig. 4. Dark currents of the RPC prototype at 8 kV measured over a year. Note that the current measurement resolution was about $2\,\mu A$.

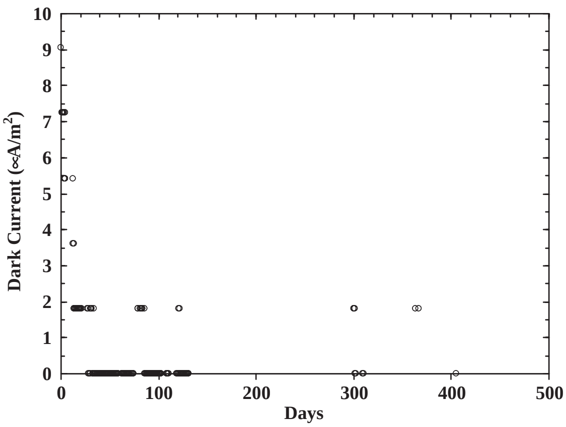

Fig. 5. Singles counting rates of the RPC prototype at 8 kV with a100 mV threshold measured over a year.

As we can see in Figs. 4 and 5, the dark current and singles counting rate for a freshly made RPC chamber decreased consistently over time except during a brief period of time starting around day 80. This was because in late August of 2003, the RPC prototypes were placed near an intense neutron source and a neutron radiation test was performed. The total neutron radiation dose was 100,000 rad and the radiation exposure lasted for about 2 weeks. The dark currents and counting rates of the prototype RPCs increased during the neutron radiation test and recovered to the level before the neutron radiation in about 10 days after the radiation exposure. The efficiency of the chambers, however, was little affected. Also, as can be seen in Figs. 3–5, the behavior of the prototype RPC was not significantly changed after the electron radiation exposure.

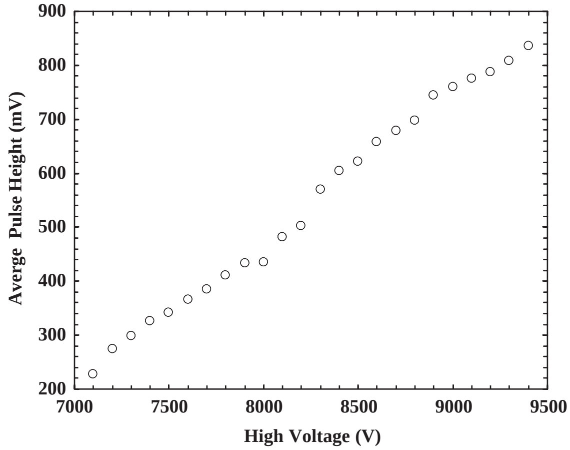

Fig. 6. Average signal amplitudes versus the high voltage.

5. Performance of prototype RPCs

The test results described in this section lasted several days from the end of May to the beginning of June 2004. The temperature of our lab was 20–28 °C. As mentioned above, the RPC efficiency is not significantly affected by the temperature. But changes in lab temperature can cause some minor irregularities in our dark current and singles rate data. The gas mixture used in the measurements reported in this section was $Ar/C_2F_4H_2/C_4H_{10}$ 50:42:8 and the flow rate was 15 cm^3/min.

The pulse heights versus the high voltages are shown in Fig. 6. The pulse heights shown in this figure were the averages of a number of pulses measured by a digital scope that was connected to a signal pickup electrode with a 50 Ω termination. As Fig. 6 shows, the signals amplitudes increased almost linearly with the high voltage from about 200 mV at 7 kV to about 840 mV at 9.4 V.

For RPCs working in a low counting rate environment, the efficiency level on the efficiency plateau, the length of the efficiency plateau, the dark current and the noise rate are the most important parameters to judge their performance. In Fig. 7, we show the measured efficiencies versus the applied high voltages for different discrimination threshold values at 50, 100, 150, 200 and 250 mV. In this study, we cycled the RPC high voltages from 6 kV up to 9.5 kV in 100 V steps. For the three lower thresholds (50, 100 and 150 mV),

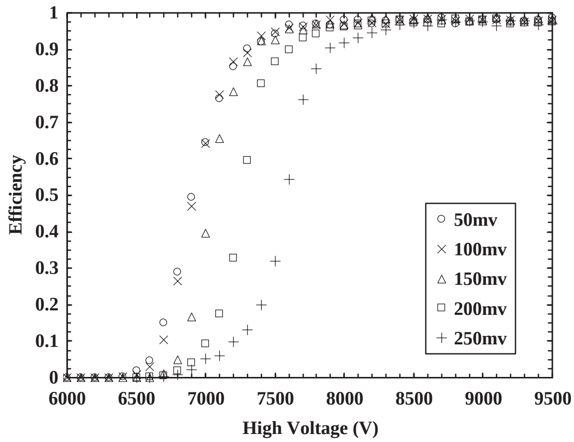

Fig. 7. Efficiencies versus high voltage for different discrimination thresholds.

the efficiency plateaus started from approximately 7.5 kV. The measured efficiencies on the plateaus for all threshold values were in the range between 96% and 98%. The efficiency measurements excluded the dead band around the detector edges because the trigger scintillators were smaller than the area of the RPCs under testing. Part of the measured inefficiencies, however, could be attributed to the round spacers in our single-gap prototypes. We estimate that the inefficiency caused by the spacers was about 1.3%.

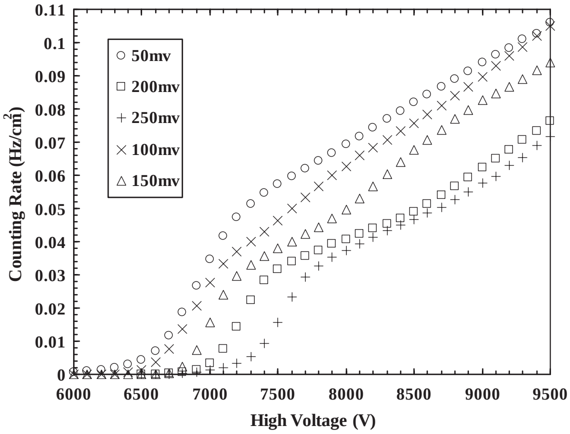

Fig. 8. Singles counting rates versus high voltage for different discrimination thresholds.

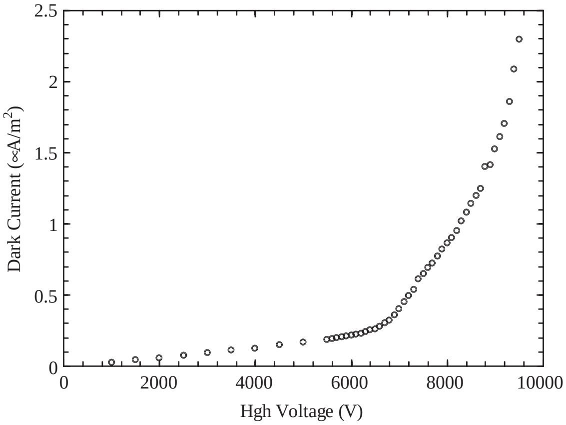

Fig. 9. Dark current versus high voltage.

Fig. 8 shows the singles counting rates versus the high voltage for different threshold values. The singles counting rate at 8 kV, 500 V above the knee of the plateau, was approximately $0.05\,\mathrm{Hz/cm^2}$ when the threshold was set at 150 mV. The counting rates on the efficiency plateau vary among different pickup strips by up to 15%. Counting rates that we report here were averages of four signal strips scale to $1\,\mathrm{m^2}$. Fig. 9 shows the measured dark current versus the applied high voltage. The dark current was approximately $0.9\,\mu\mathrm{A/m^2}$ at 8 kV.

The efficiencies of our prototype RPCs on the plateau are similar to the efficiencies of the BaBar RPCs that have a similar design and are also operated in the streamer mode. The original BaBar RPCs were fabricated by the Italian company General Tecnica using their standard bakelite electrodes with three layers of linseed oil coating. The reported average efficiency of the mass-produced BaBar RPCs measured in a cosmic ray test station was about 97% [18]. The dark current of BaBar RPCs varied from chamber to chamber and was generally less than $9\,\mu\mathrm{A/m^2}$ at 90% efficiency. The singles counting rate was in the order of $0.1\,\mathrm{Hz/cm^2}$ also at 90% efficiency. The resistivity of the electrodes in the BaBar RPCs was in the range of 10^{11}–$10^{12}\,\Omega\,\mathrm{cm}$. As stated in Ref. [18], the BaBar tests did not show clear correlations between the bulk resistivity and the RPC performance. The design and operation parameters of RPCs in ARGO and OPERA are similar to that of BaBar RPCs. The performance of these RPCs, also fabricated by General Tecnica using bakelite electrodes with a single layer of linseed oil coating, is similar to the performance of the BaBar RPCs. The dark currents of the ARGO and OPERA RPCs are in the range of one to a few $\mu\mathrm{A/m^2}$ and singles rates are about $0.1\,\mathrm{Hz/m^2}$ [19].

As mentioned earlier, the resistivity of electrodes in our prototype RPCs was about $5\times10^{11}\,\Omega\,\mathrm{cm}$ at 20 °C and they were tested using an $Ar/C_2F_4H_2/C_4H_{10}$ 50:42:8 gas mixture. The resistivity of the BaBar RPCs was similar to ours and the gas mixture was $Ar/C_2F_4H_2/C_4H_{10}$ 60.5:35:4.5 that has more argon and less isobutene than the gas mixture we used in our tests. Despite minor differences in test conditions, we can conclude that the performance of our prototype RPCs is as good as the initial performance of the BaBar RPCs and the RPCs in ARGO and OPERA experiments.

RPCs used in Belle experiment were made from regular window glass plates. The resistivity of the glass electrodes is typically in the range of 5×10^{12}–$10^{13}\,\Omega\,\mathrm{cm}$. Unlike the resistivity of bakelite electrodes, the resistivity of the glass plates cannot be easily adjusted. Due to the higher resistively of the electrodes, the streamer sizes are generally smaller than that in RPCs made of bakelite electrodes with lower resistivity. This may explain why the efficiencies of RPCs made from glass electrodes with a single 2 mm gas gap operating in the streamer mode are typically below 95%. A small fraction of signals may not have fully developed into streamers that are large enough to be detected in RPCs with high-resistivity glass electrodes. The RPCs made of floating glass electrodes usually have lower singles counting rates and lower dark currents compared to the bakelite RPCs due to the superior surface quality and higher resistivity of the glass plates. Based on our prototype studies described above, we believe the overall performance of our prototype RPCs made by using our resistive plate material is comparable to that of RPCs with glass electrodes. The performance of RPCs made of glass electrodes reported in published literature can be found in Ref. [20].

6. Behavior at extreme high voltages

Fig. 10 shows the oscilloscope traces of 100 triggered cosmic muon signals registered in a RPC prototype at 8 kV. The oscilloscope input termination was 50 Ω. The amplitude of most signals was around 400 mV and some pulses were much larger. No delayed secondary streamers were recorded for these 100 triggers. At higher voltage, the situation was quite different. Fig. 11 shows 20 triggered cosmic ray muon signals at 12 kV. The signal pulse shapes were much more irregular at 12 kV and the largest primary streamer size could be as large as a few volts. Some muon pulses could last up to several microseconds with multiple secondary streamers. Nonetheless, the RPC prototype operation was still stable at 12 kV.

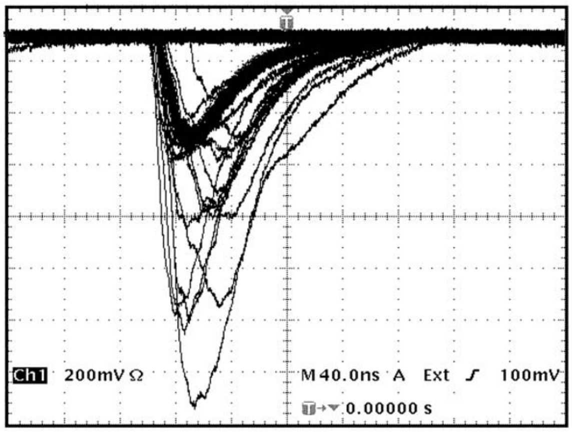

Fig. 10. Oscilloscope traces of 100 triggered cosmic ray muons registered in a RPC prototype at 8 kV. The horizontal scale is 40 ns/div. and the vertical scale is 200 mV/div. The average signal size from a pickup electrode is about 400 mV with a 50 Ω termination. No secondary streamers were recorded.

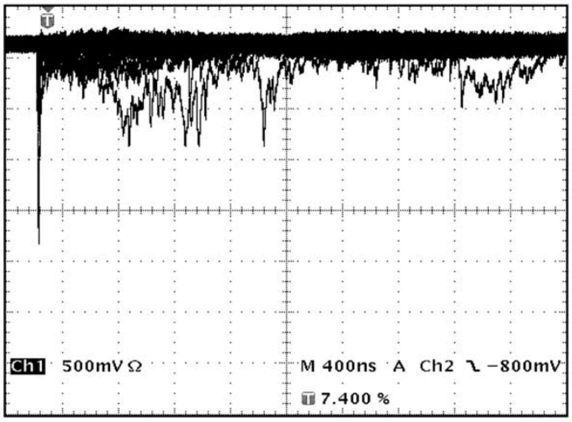

Fig. 11. Oscilloscope traces of 20 triggered cosmic ray muon signals recorded in RPC at 12 kV. The horizontal scale is 400 ns/div. and the vertical scale is 500 mV/div. Some pulses can be as large as a few volts and can last several microseconds with multiple secondary streamers.

In the regular high-voltage cycling tests described in the previous sections, the maximum high voltage that we applied to the RPC prototypes was 9.5 kV. Our RPC prototypes can be operated much beyond the 9.5 kV limit. In Fig. 12, the efficiencies and singles counting rates of the prototype RPC were measured up to 12 kV. The gas mixture used was $Ar/C_2F_4H_2/C_4H_{10}$ 50:42:8. The efficiency plateau remained quite flat and started to drop slightly above 9.5 kV, almost 3 kV beyond the knee of the efficiency plateau. The counting rates shown in this figure were obtained by setting the discrimination threshold to 100 mV. The counting rates increased roughly linearly as the high voltage increased and, even at 12 kV, the counting rate remained quite low at $\sim$0.4 Hz/cm^2.

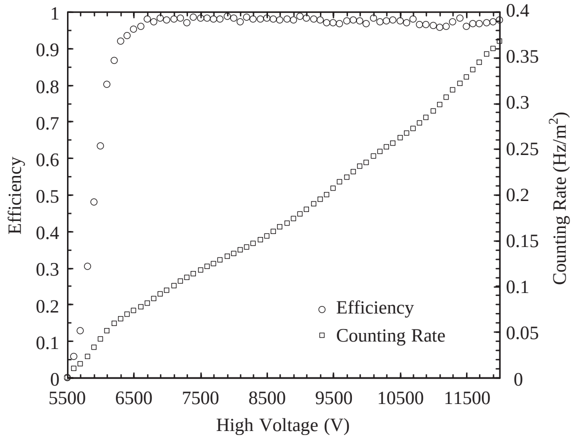

Fig. 12. Efficiencies and singles counting rates versus the high voltage up to 12 kV. This plot shows the behavior of the prototype RPC under extreme high voltages. The gas mixture used was $Ar/C_2F_4H_2/C_4H_{10}$ 50:42:8.

7. Conclusion

The prototype RPCs for the BESIII spectrometer manufactured by using a new type of resistive electrodes that we developed showed very promising performance without the conventional linseed oil treatment. The BESIII RPC prototypes had high efficiency, long plateau, low singles counting rate and dark current. The measured efficiency of a single 2 mm gap RPC was in the range of 96–98% and the plateau length could exceed several thousand volts. After a fairly long training period, the dark current dropped to the level of less than 1 $\mu A/m^2$ with our operating gas in the streamer mode and the singles counting rate reached the level below 0.1 Hz/cm^2. The performance of the RPC prototypes has been quite stable over a period of 1 year. The performance achieved by our prototype RPCs is comparable to the RPCs with linseed-oil-treated bakelite or glass electrodes.

The prototype RPCs reported in this paper were made from electrodes with relatively high bulk resistivity and were intended for low-rate operation in streamer mode. However, we expect that RPCs made by using our technology can also work well in a high-rate environment if the bulk resistivity of the electrodes is properly chosen and the chambers are operated in the avalanche mode. Further studies are needed in order to verify this.

The technology that we developed is well suited for large industrial-scale production of RPCs at low cost. We are currently fabricating RPCs for the BESIII spectrometer at the Beijing Gaonengkedi Science and Technology Co. Ltd. A total of approximately 2000 m^2 RPCs will be used to identify muons and to measure their momenta. We are also investigating the possibility of using our technology to build RPCs for future large particle physics experiments such as the Fermilab off-axis electron neutrino appearance experiment NOνA that may eventually require several hundred thousand square meters of RPCs. Also, we are considering the possibility of using RPCs made by using our technology as readout detectors for digital hadron calorimeters and muon identifiers in future linear collider detectors.

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