University Linear Collider Detector R&D
FY2009

Aging Study for SiD Hcal and Muon System RPCs

Personnel and Institution(s) requesting funding

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Project Overview

Resistive Plate Chambers (RPCs) are the present SiD baseline detector choices for both the muon system and hadron calorimeter. Several types of RPCs have been successfully constructed and tested in the worldwide HEP community. RPCs with Bakelite electrodes were invented and developed by Santonico *et a.l* and used in L3, BaBar, CMS, ATLAS, STAR, ALICE ToF, and a variety of cosmic ray and neutrino experiments, such as ARGO-YBJ, OPERA.

The BESIII Muon group of IHEP (Beijing) and Gaonengkedi, Inc. (Beijing) have developed a new type of Bakelite for use in the BES III and Daya Bay Muon Systems that does not require linseed-oil treatment, and RPCs using this material have achieved acceptable dark noise rates.[1] These RPCs are operated in streamer mode in their present applications. So far, the aging effects of the BESIII RPC have not been thoroughly tested, and there is no published report available on this topic. At Princeton, a preliminary study of IHEP RPCs to be used in the Daya Bay Muon System has indicated a significant aging effect that must be understood and mitigated prior to use of this technology in the SiD.

The present proposal is to continue and extend our RPC aging studies using 5 so-far-untested, bare BESIII RPCs (50 x 50 cm^2) that are on hand. Our machine shop will add readout strip planes, HV cables and gas tubing to these 5 RPCs, which will then be subjected to a new round of aging studies. To monitor the efficiency of these RPCs, we also need to expand our cosmic-ray-trigger counter array and related electronics.

A longer-term goal of the study is to collaborate with IHEP and Gaonengkedi to develop new variants of Bakelite that are more resistant to aging.

This study would be a continuation of ILC R&D on RPCs at Princeton.[2,3] A summary report of our previous work on RPC electrodes was presented in RPC2007 workshop, and will soon be published in a special issue of Nuclear Instruments and Methods in Physics Research, Section A.[4] See also:[5,6,7]

RPC Aging Overview

As is well known,[8] the major cause of aging in RPCs is HF vapor, which is a byproduct of gas avalanche in the Freon-based gas mixture. There must also be sufficient water vapor present to activate the HF vapor as a weak acid, according to $HF + H_2O \rightarrow H_3O^+ + F^-$.

Glass RPCs with metal tubing for the gas supply permit operation at very low levels of water vapor, therefore dramatically reducing the destructive effect of HF vapor, as shown in the Belle experiment. However, operation of Bakelite RPCs at their nominal volume resistivity depends on a controlled level of water vapor in the RPC gas mixture (≈ 0.4 %), which implies that a significant level of $H_3O^+F^-$ is inevitable in these chambers.

The following preliminary observations from the Daya Bay RPC aging test at Princeton deserve further study:

(1) After the equivalent of 5 years of streamer operation at cosmic-ray background levels, a BESIII Bakelite RPC already shows some profound aging affects.

(2) The map of the aged areas suggests that details of the distribution of the gas throughout an RPC system may have a significant effect on RPC aging..

These preliminary observations are consistent with our generic R&D results, in which we found that without a linseed-oil coating on the inner surface for the BESIII RPC its resistance to attack by HF vapor is much worse than linseed-oil-coated Italian Bakelite.

To repeat these tests in more systematic way and get more reliable results will be the first goal of the proposed ILC R&D project.

A second and more important goal for this ILC R&D project is the search an oil-free surface treatment of Bakelite that is resistant to effects of HF vapor.[†]

Results of Prior Research

The proposed work continues and extends studies of the BESIII (IHEP) RPC aging performance. Following are brief summaries of previous Princeton ILC R&D results on the HF production, adsorption and attack to the RPC electrode surface.

(1) HF production in RPCs

The concentration of HF in the exhaust gas from an RPC was monitored by bubbling the exhaust gas through a water-based mixture known as Total Ionic Strength Adjusting Buffer (TISAB). The latter was chosen to permit accurate measurements of F^- ion concentration by a special-purpose probe..

[†] The historical use of linseed oil on Bakelite electrodes has mitigated the issue of HF vapor at the expense of other aging effects.

Our test apparatus is shown in Fig. 1. The F^- ions contained in the exhaust gas were trapped by the TISAB and the resulting concentration of F- ions is measured by an electrode probe immersed in the TISAB, which was connected to a data-acquisition system that monitored the probe output voltage. Figure 2 shows the amount of F^- ions trapped by the TISAB *vs*. time. At the same time the current drawn by the RPC chamber was also recorded.

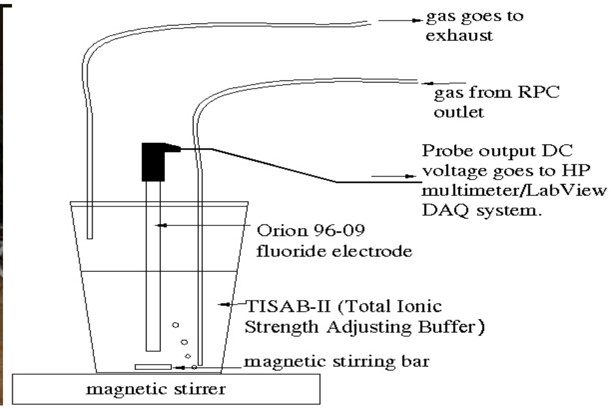


Figure 1. Fluoride probe set-up to test the production of fluoride in RPC gas mixture.

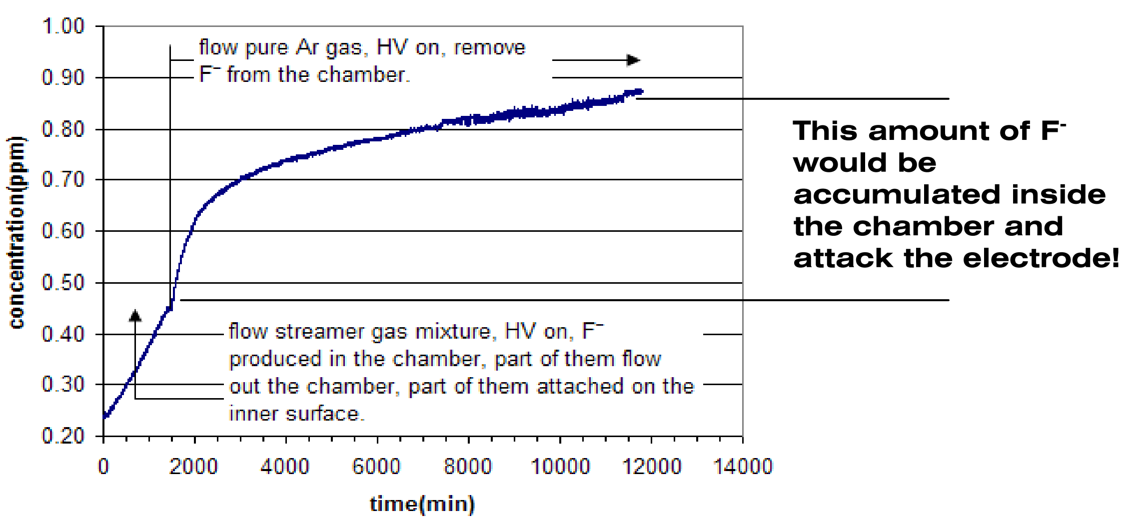


Figure 2. Concentration of fluoride ions in the sampling solution *vs.* time.

For the first 1500 min the RPC was operated with the nominal gas mixture and HV on. During this time HF is produced in the chamber. Some HF is flushed out of the chamber and accumulates in the TISAB, but a significant amount remained in the chamber, adsorbed on the Bakelite electrodes. The first straight line section shows linear dependency of fluoride concentration on the time, which indicates the steady production of fluoride in RPC gas discharges. This section corresponds to the un-adsorbed F^- production rate. The accumulating charge Q is calculated to be 22.5mC during streamer operation, therefore the rate is about 1.19×10^{19} F^-/C.

The second section of the curve is recorded for pure Ar gas operation. In pure Ar the UV light created in the gas discharge can release the adsorbed fluoride from the surface, therefore we can see the fluoride concentration is continuing increase. Eventually the fluoride concentration reaches saturation, from which we can estimate the total amount of fluoride produced. It is 0.45ppm F^- in 40CC solution after accumulating 22.5mC of charge. Therefore we derive the fluoride adsorption rate is $\sim 2.67\times10^{19}$ F^-/C.

(2) Effect of hydrofluoric acid on the resistive plate surface

We exposed various materials to a HF vapor environment in controlled ways. We measured the surface resistivity before and after the exposure to indicate what type of electrode is most robust against attack by HF.

The test device is shown in figure 3.

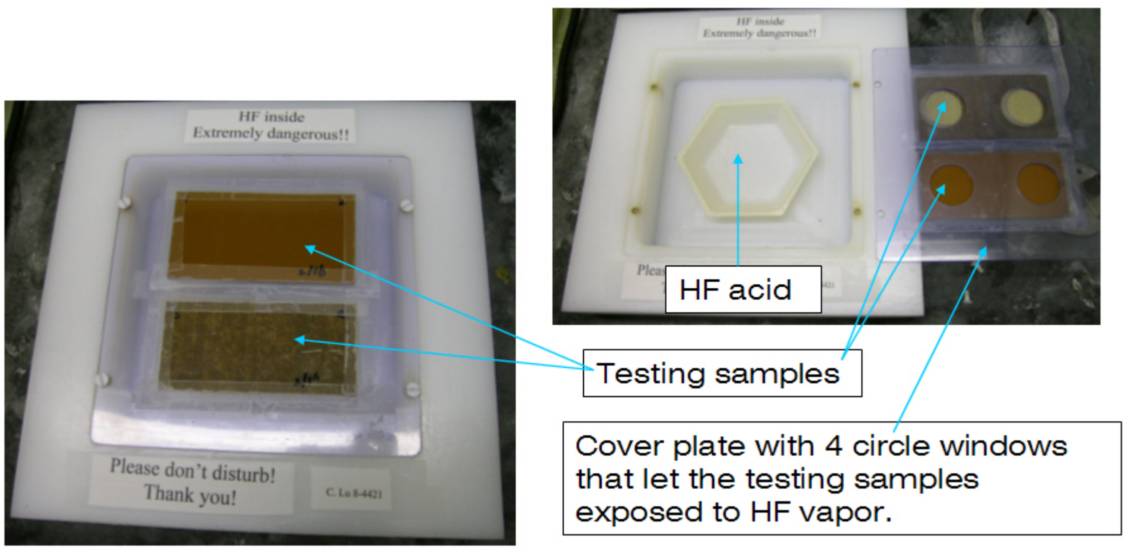


Figure 3. Test device to study effects of HF on surefaces.

The BaBar (Italian) Bakelite plate has two different surfaces: one side with a "marble" pattern, and the other side with a uniform brown color. The "marble" surface is smoother than brown surface, and is normally used as the surface in contact with the RPC gas. But its resistance to HF vapor corrosion appears worse according to the test results shown in Fig. 4. After 24 hours of exposure to HF vapor the "marble" pattern was completely destroyed, and the surface looked very rough. The brown surface showed slight discoloration, much less severe than on the "marble" surface.

Another test showed that a Linseed-oil coating on the Bakelite surface effectively protected the surface from HF vapor attack. After 24 hours of exposure no discolored region could be seen on Linseed-oil coated surfaces.

The BES III Bakelite surface was badly attacked by HF vapor, as seen in Fig. 5.

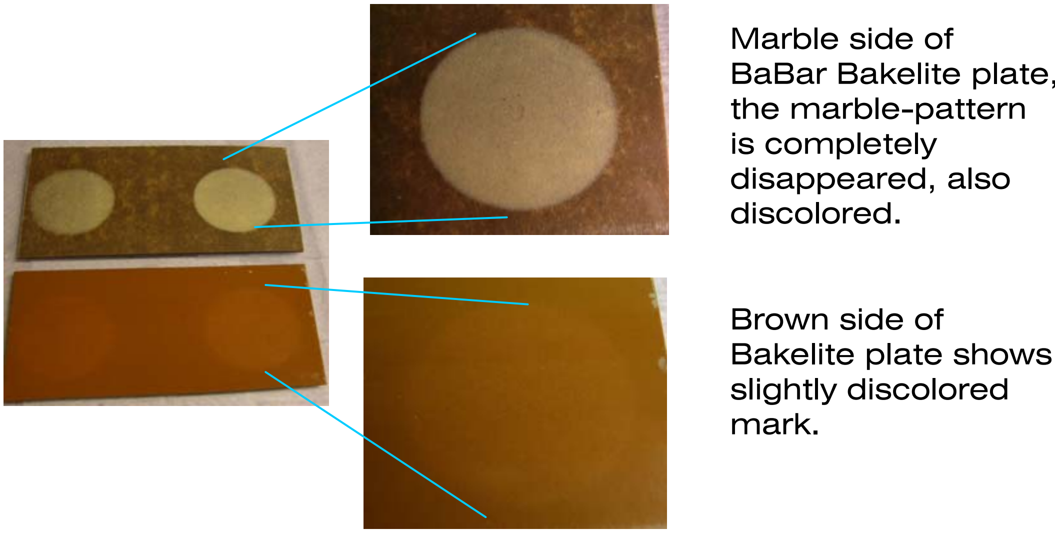


Figure4. HF vapor corrosive action on BaBar Bakelite surface.

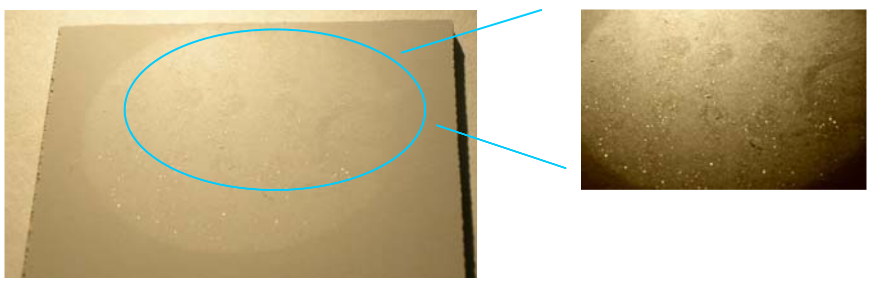


Figure 5. HF corrosive action on BES III bakelite surface.

The time dependence of the Bakelite surface resistivity during exposure to HF vapor is shown in Fig. 6. In first hour of exposure the surface resistivity dropped very quickly.

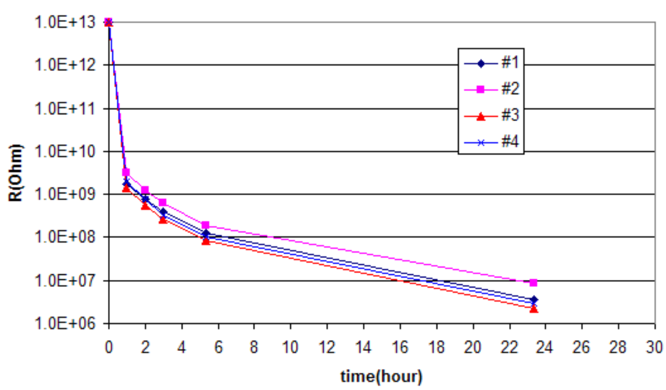


Figure 6. Surface resistivity variation of BESIII Bakelite upon the exposure to HF vapor.

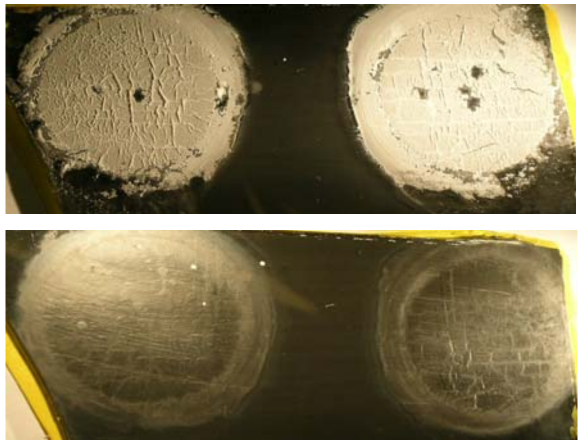


Figure 7 HF vapor effect on Belle RPC glass surface, (top) before water rinse; (bottom) after water rinse.

Belle's RPC glass surface, after exposure to HF vapor for ~24 hours, looked powdery, as seen in Fig. 7. The powdery "skin" could be easily removed by water rinses, and the glass surface looked chapped.

We summarize the HF corrosive effect on the surface resistivity for various RPC electrodes in Fig. 8. The linseed-oil-coated BaBar (Italian) Bakelite was the most resistive to the HF vapor. The IHEP Bakelite was not as good as Italian Bakelite, especially the linseed-oil-coated Italian Bakelite; it was slightly better than the Belle glass electrode.

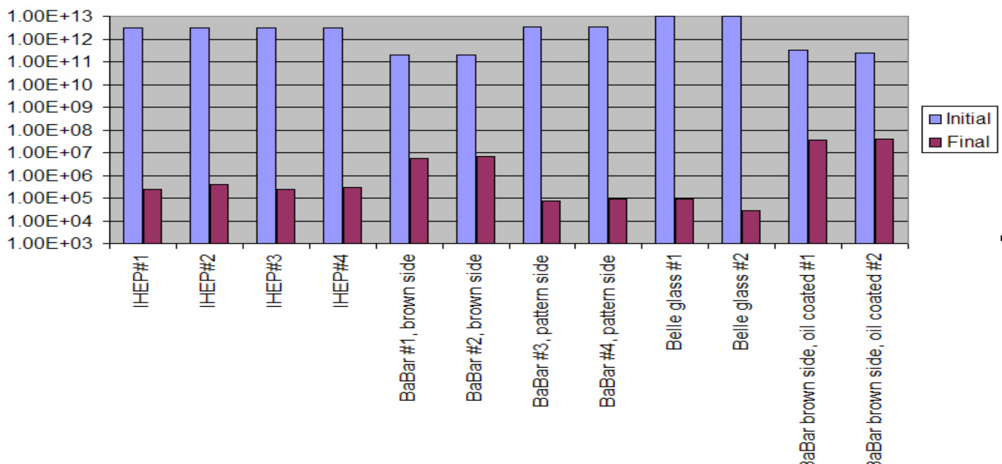


Figure 8. Surface resistivity of Bakelite before and after exposure to HF vapor.

Based on above results we can further test the damage inflicted on the electrode by HF due to operation of RPC chamber quantitatively in following steps:

1) Pipette 90µL of 48% concentration HF acid into our test container. After the HF drop vaporized, it will produce ~ 1.3×10^{21} HF molecules inside the container. The total inner area of the container is 10^3 cm^2, $1.3\times10^{21}/10^3$ cm^2 = $1.3\times10^{18}/cm^2$, that is equivalent to a $2m^2$ RPC operated at 5µA for 12.4 years assuming the previous derived HF adsorption rate = 2.67×10^{19} F^-/C.
2) Test the surface resistivity. The ratio of surface resistivity change (before/after) is ~ 500 to 900 for IHEP Bakelite. The glass surface shows similar resistivity change.

Such a big surface resistivity reduction certainly will affect the normal RPC operation. We didn’t test this ratio for different amount of vaporized HF, it may not be linear.

(3) Preliminary aging observation on BESIII RPCs

The Daya Bay muon system is using BESIII RPCs as one of its muon veto detector systems.

Our aging-test setup for the BESIII RPCs is shown in figure 9. A small (50 x 50 cm^{2}) BESIII-type RPC is placed above a full-size (2 x 1 m^2) BESIII RPC. A Co-60 source (~0.1mCi) was placed at two locations on top of the small RPC. Since the full size RPC was ~ 10 cm farther from the source, the gamma-ray intensity was much lower that at the small RPC; however, the total rate of gamma-ray interactions was essentially the same in both chambers..

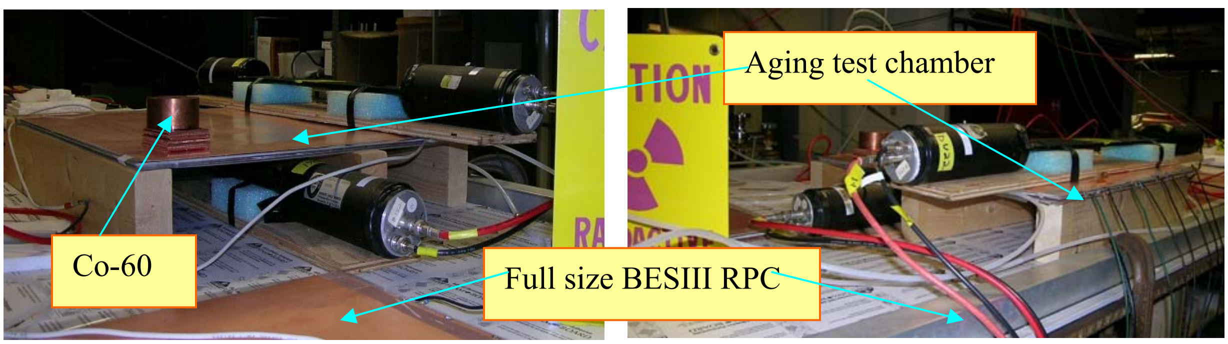
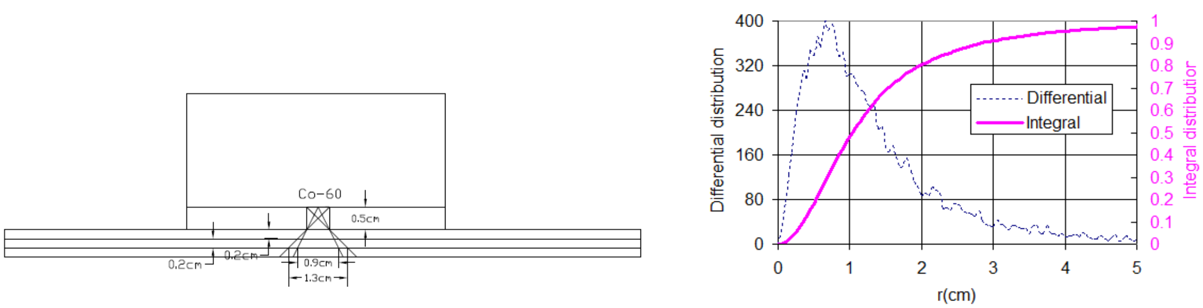


Fig. 9. Aging test chamber and a full size BESIII RPC with the Co-60 source and trigger counters (when source is on, the trigger counters are turned off, they are not aligned for cosmic ray trigger.

The Co-60 source was enclosed in a copper collimator, shown in Fig. 10. Monte Carlo calculation indicated that 80% of the gamma-rays were concentrated in a circle of radius ~ 2cm on the small RPC,as shown in Fig. 10(b).



(a) (b)

Fig. 10. The geometry of Co-60 collimator (a) and the gamma-ray distribution based on the geometry and Gamma ray absorption (b).

The measured streamer-rate distribution among 8 strips (6cm wide each) was surprisingly broad, as seen in Fig. 11(a), and did not resemble the gamma-ray distribution. This is due to the limitation of the streamer-mode RPC rate capability. We use the measured rate distribution among the strips to simulate the streamer distribution in the RPC, finding that the distribution shown in Fig. 11(b) resembles the distribution of 11(a). We then use this distribution to estimate the aging dose for the RPC.

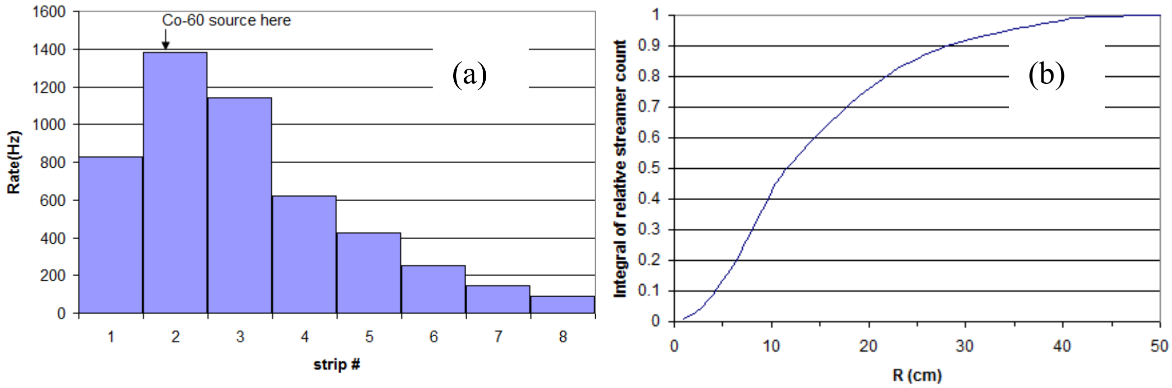


Fig. 11. Measured streamer rate distribution among 8 strips (a) and the simulated integral streamer distribution in the aging test (b).

The currents in the RPCs are recorded all the time with two Agilent 34401A digital multimeters via LabView.

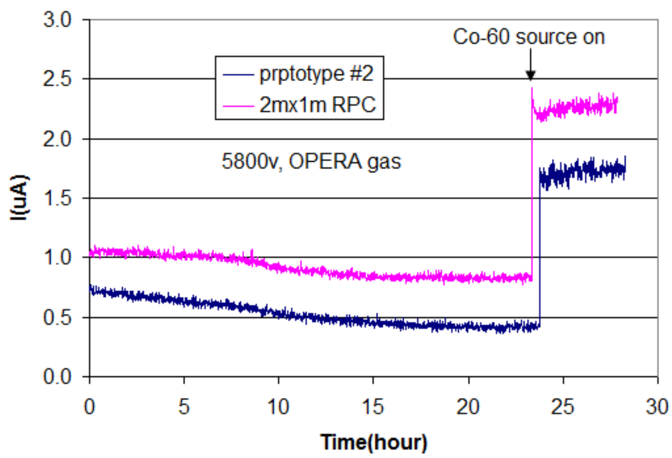


Fig. 12. The chamber currents, before aging, showed a jump of about *dI* ~ 1.3 µA when the Co-60 source was applied at hour 24.

Before the aging started we measured the change *dI* in chamber current due to placement of Co-60 source near the chamber, is shown in Fig. 12. The two RPCs had similar current jumps at 5800V and with OPERA gas mixture, the current jump *dI* was around 1.2 ~ 1.3 µA. From Fig. 11(b) we know ~ 40% of the streamers were concentrated in a circular region of radius R = 10cm. Then, the current dose/area can be calculated: $0.5\mu A \cdot 3600 \cdot 24/\pi R^2 \sim 140\ \mu C/cm^2/day \sim 4.1\ mC/cm^2/month$. If we assume 500 pC/streamer, the noise rate of RPC was $\sim 2kHz/2m^2 \sim 0.13 mC/cm^2/month$. Thus the aging-test dose was ~ 30 times the background dose. Roughly speaking, one month of of the aging test was equivalent to 30 months of normal background operation..

The aging test started on 4/30/2008. The Co-60 source was placed above region #1 of Fig. 13. The numbers in the 9 rectangles represent the region # mentioned in the following text. The locations of the gas inlet and outlet are also shown in the figure. The OPERA gas mixture, Ar/R134A/Isobutane/SF6 (75.5/20/4/0.5%), was used at a flow rate of ~10 sccm. After two months of irradiation, the current jump, *dI*, in the small RPC due to the Co-60 source has not shown noticeable change, see Fig. 14 (50x50, before aging and 50x50, after aging). *dI* represents the DC -current-subtracted dark current, which attributes solely to the streamers.

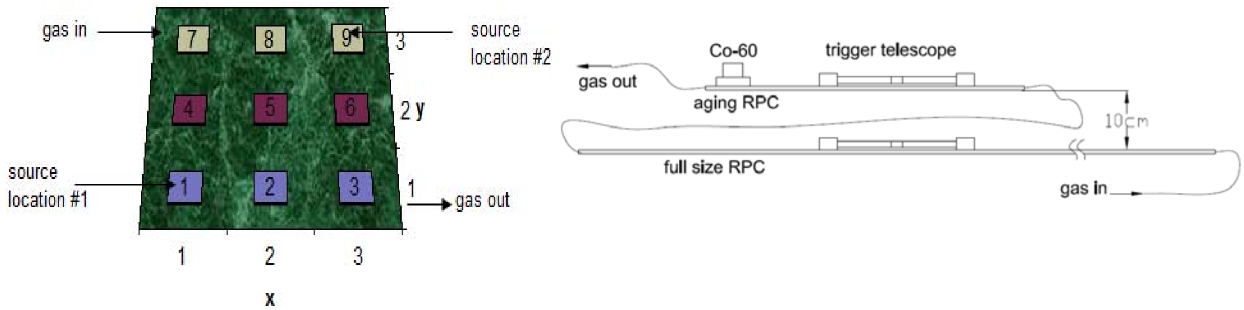


Fig. 13. Aging test chamber and the full size chamber.

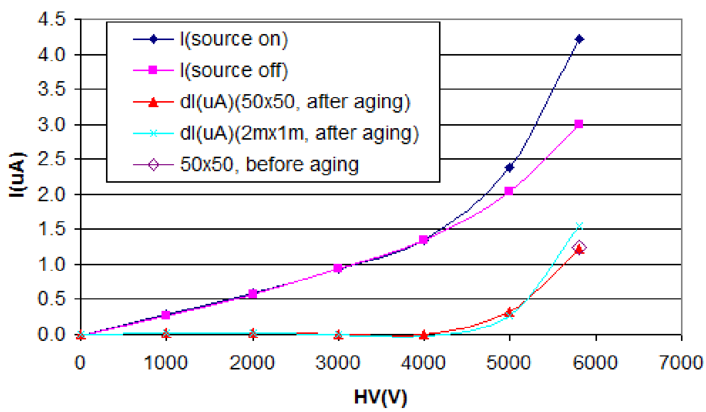


Fig. 14. Aging chamber dark current at 5800V, w/ and w/o source.

After the first round of aging, we surveyed the efficiency in the 9 regions, with results shown in Fig. 15. Although the efficiency plateau curves have quite different starting HV, all of them have more than 90% efficiency above 6000V.

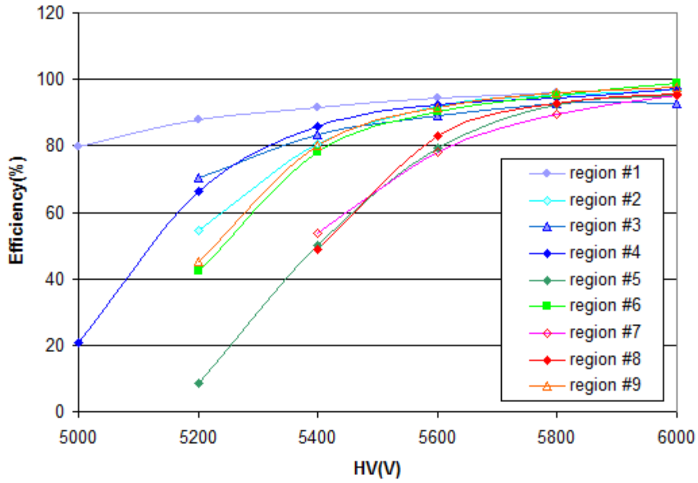


Fig. 15. Efficiency plateau curves of 9 regions.

We also measured the peak spectrum for 9 regions. A noticeable spectrum distortion can be seen for the aged region #1, as shown in Fig. 16. The spectrum on radiated region shows a very broad distribution, although the efficiency is still high, but the distorted spectrum may reflect the aging damage to the internal electrode. The other two spectra, triggered on the unradiated regions, show a narrow distribution, which is a typical streamer distribution. Unfortunately we didn't record the peak spectrum before the aging, so we are not sure if this is solely due to the aging, or may be just due to the bad region originally. To make sure if the aging effect is real, we started a second round of aging test on 8/18/2008, this time placing the Co-60 source on region #9.

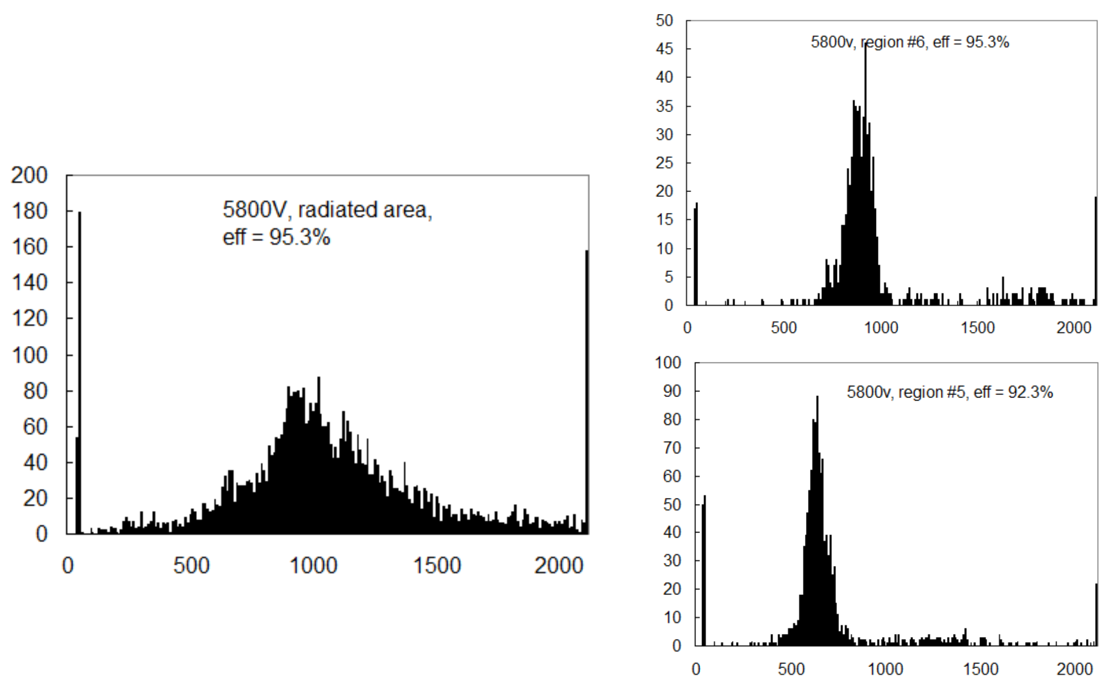


Fig. 16. Streamer peak spectrum from different regions.

The second round of aging lasted for ~ 30 days. The HV was set at 6000V.

After only 16 days another aging effect appeared: the dark currents on two RPCs became different, as shown in Fig. 17. For the full-size RPC, some distance away from the source, the dark current (source off) at 6000V was ~1.5μA, but in the small RPC it was now ~3.6μA! In addition, the current jump due to the source was now smaller for the small RPC. On 9/3/2008, the 16th day in the second round of aging, the current in the small chamber jumped from 5.89μA to 7.25μA, so *dI* ~ 1.36μA, but the current in full-size RPC jumped from 4.26μA to 6.74μA,for *dI* ~ 2.48μA. On 9/22/2008, the 34th day, the current jumps were from 5.13μA to 6.25μA, *dI* ~ 1.12μA, and 3.42μA to 5.69μA, *dI* ~ 2.27μA, respectively, see Fig. 18. Apparently the aging RPC had higher background current, which very much likely was due to the damaged Bakelite inner surface.

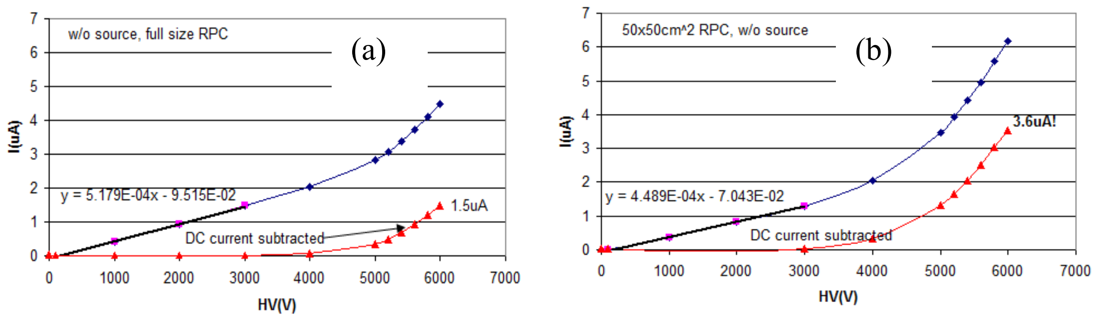


Fig. 17. Chamber dark currents: (a) Full-size RPC; (b) Small RPC.

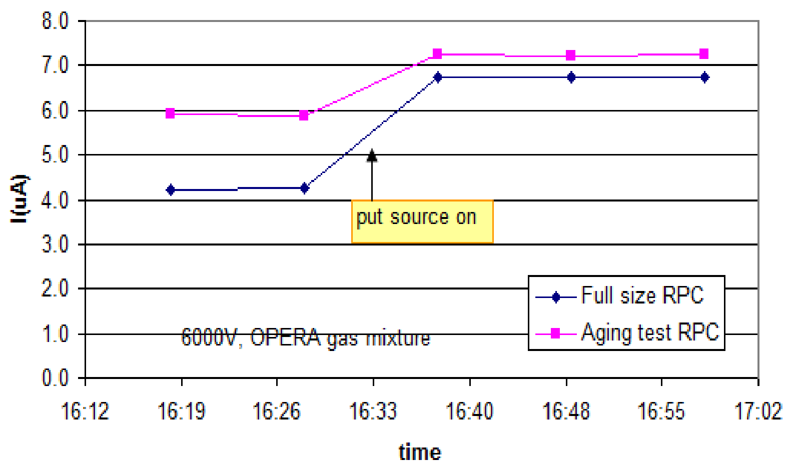
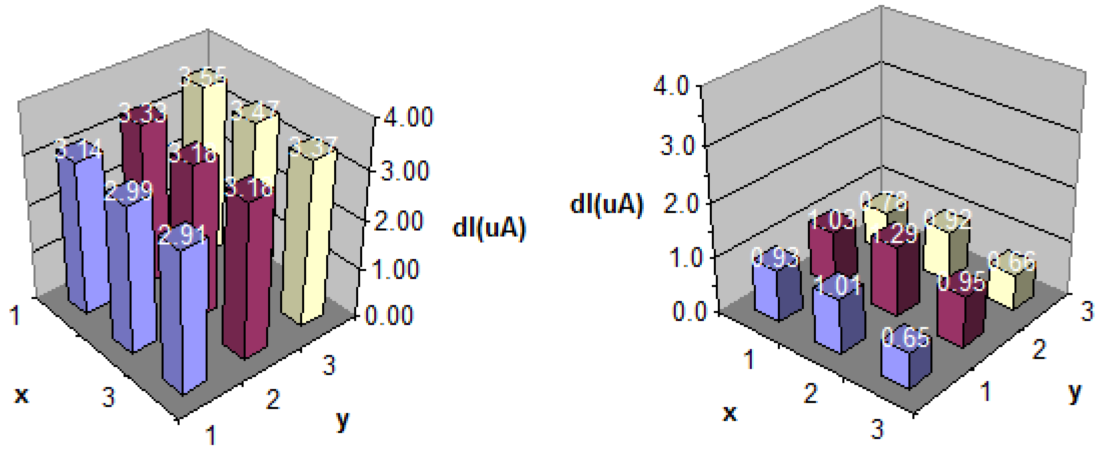


Fig. 18. Chamber current jump due to Co-60 source.

At the end of the second round of aging we surveyed the dark current response in 9 regions. By placing the source on each region and measuring the dark-current jump, *dI*, there, we mapped the chamber. The response is shown in Fig. 19(b). Figure 19(a) is the response of the full size RPC. Figure 20 shows the efficiency survey results. The most surprising feature is that the lowest efficiency was in region #3, near the gas outlet fitting, not in the two irradiated regions. The efficiency in region #7, by the gas inlet, was also surprisingly lower than that in the central region #5; this region is farthest one from two irradiated regions. The scatter plot of efficiency *vs.* dark current jump is shown in Fig. 21. Two lowest-efficiency points show a correlation: lower efficiency related to lower current jump, but the other regions did not follow this trend.



(a) (b)

Fig. 19. Current jump, *d*I, due to a Co-60 source placed over 9 regions, (a) full size RPC; (b) aging RPC.

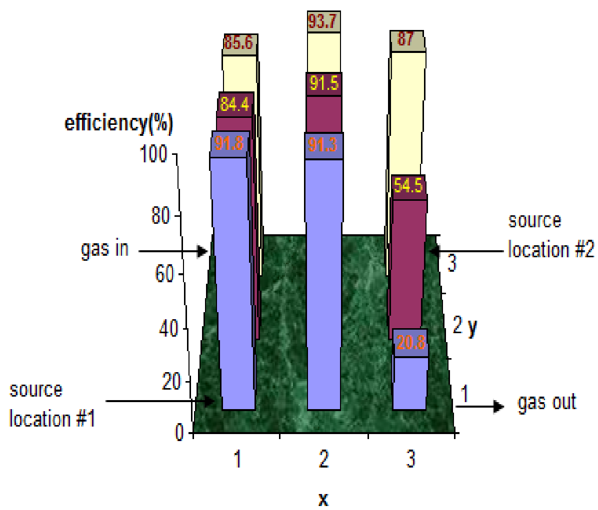


Fig. 20. Efficiency survey results at the end of second round of aging tests.

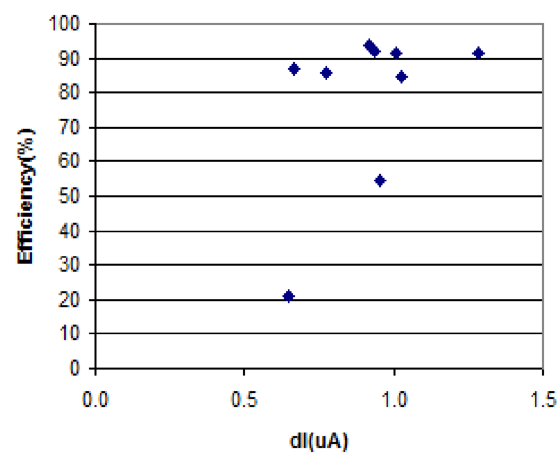


Fig. 21. Scatter plot of efficiency *vs.* current jump, *dI*, for 9 regions.

(4) Summary of the aging test results

As we mentioned above one month of aging test is equivalent to 30 months of cosmic-ray background operation. After two months of aging, some aging effect had already appeared. An additional one month aging at a different location caused serious aging; in some regions the efficiency dropped dramatically.

We propose a working model based on the three observed aging phenomena: 1) The gas outlet region suffered aging the most; 2) For the downstream RPC in a daisy chain of RPCs gas inlet region also suffers badly; 3) The radiated region was not the most damaged region. These facts point to a picture that the HF generated in the streamers stays in the gas volume, pollutes the entire RPC, and the aging is the greatest where the chance to adsorb the pollutant is the highest. This could be the reason why the regions near the gas outlet and inlet damaged most. Because the gas flow has to go through the small diameter fittings there, inevitably the pollutant will be forced to converge in the nearby regions.

Proposal for Further R&D on RPC Aging

The preliminary aging test had many uncertainties. Some small detailed differences may have caused hugely different results. The result presented above is from only one setup, and has not been repeated. In this first try to do a systematic aging study for BESIII RPC, the test procedure was not well organized, making the reliable comparison difficult. Also the cosmic-ray-trigger system was too small (5x5cm^2) to collect sufficient data in short time. A survey of 9 5x5cm^2 required 7-10 days. Due to lack of a decent optical microscope we haven't opened the aged chamber to check the inner surface.

Now that the BESIII-type Bakelite (with its advantageous oil-free operation) is known to be more vulnerable to the HF attack, we should make further improvement in surface treatment of this material.. The chief engineer, Mingfa Su, of the Bakelite manufacturer is willing to be involved in the R&D, but only in the second half of calendar 2009, after completing his present commitments to the Daya Bay project. He has the resources (material, facility, manpower, etc.) to put various ideas into action. We have discussed several new techniques for producing more robust Bakelite before. If this ILC R&D project can be approved, we can start the work by the last quarter of 2009.

Facilities, Equipment and Other Resources

Princeton has most of the test equipment, facilities and expertise for doing this research. The new pieces of equipment we are seeking for funding are the following:

(1) Specialist Inspection Stereo Microscope (Lynx VS8), Vision Engineering

This advanced stereo zoom microscope can be in the range of x7 to x40 magnification. Equipped with additional lenses, the magnification can be increased to x160. The best feature of this device is the patented eyepieceless stereo microscope. Using its rotatable stage, we can survey the surface morphology of various RPC electrodes in detail. Because it is optical, we'll be able to tell the color change after the aging. The basic unit costs ~ $7,500, additional lenses, stage, digital camera, etc. cost ~ $4,500.

(2) Cosmic-ray-trigger counter array

We already have 10 100x7.5cm scintillation counters, which were made during BaBar LST project. We only equipped two of them with PMTs. We need to purchase 8 R1306 Hamamatsu tubes with the socket assemblies to finish the whole trigger array. Total hardware cost is estimated at ~$6,000.

FY2009 Project Activities and Deliverables

We have several untested bare BESIII RPCs (50 x 50 cm^2) on hand. Our machine shop will put on the readout strip planes, HV cables and gas tubing. We plan to make 5 such test prototypes and put them through HV training. Finish the cosmic ray trigger counter array and related electronics.

FY2009 Milestones:
1. Purchase the optical microscope, open the previously aged RPC and survey the inner surface;
2. Set up expanded cosmic-ray-trigger counter array;
3. Prepare 5 new BESIII-type test RPCs;
4. Start a new round of aging tests.

Project Activities and Deliverables Beyond FY2009

In the following years we will collaborate with IHEP and Gaonengkedi to try out various new Bakelite electrodes:
1. Bench top test to make sure the robustness to HF;
2. General performance test for the RPC made out of the new Bakelite electrode;
3. Real aging test for the new RPC.

FY2010 & FY2011 Milestones:
1. Deliver new Bakelite sheets;
2. Deliver small test RPCs made with new Bakelite electrodes;
3. Test the general performance of the new RPCs;
4. Bench top test of the new Bakelite electrodes in HF vapor;
5. Start new aging test for these new RPCs.

Total Project Budget

Item	**FY2009**
Machine shop (inc. benefits)	7000
Undergraduate Students (2 months)	2600
Total Salaries, Wages and Fringe Benefits	9600
Equipment	12000
Travel	2000
Materials and Supplies	9000
Other direct costs	0
Total direct costs	32600
Indirect costs (58% of non-equipment costs)	5220
Total direct and indirect costs	37820

Budget Justification

The fringe rate for machine shop personnel is 32.5% and for students it is 21.5%. The indirect cost rate is 58%. Included in the travel budget are trips from Princeton to Beijing for the new Bakelite study and discussion with Chinese collaborators. We plan to hire a summer student to work on the data taking and analysis for about 1.5 months. The machine shop lab charge will be used for making cosmic-ray-trigger counter array and test stand, and to assemble bare RPCs into working chambers. The materials and supplies include payment to Gaonengkedi (or other Bakelite manufactures).

Broader Impact

To speed up the test process we are proposing to build an expanded cosmic-ray-trigger array. This array will be a useful general purpose device, which can benefit Princeton HEP groups for their future detector R&D work. It is also an ideal device to train the graduate/ undergraduate students in detector hardware and analysis.

If we can achieve the second goal of our R&D, oil-free Bakelite surfaces with improved resistance to HF, it will have big impact on the HEP community. Since large-area, inexpensive muon detector systems are needed for almost every HEP experiment nowadays, RPC systems are common at these detectors. Better performing, longer-lived RPCs will be most welcome.

References

[1] J. Zhang *et al*., Nucl. Instr. and Meth. A 540 (2005) 102

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