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Mechanisms affecting performance of the BaBar Resistive Plate Chambers and searches for remediation

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Abstract

The BaBar experiment at PEPII relies on the Instrumentation of the Flux Return (IFR) for both muon identification and K_L detection. The active detector is composed of Resistive Plate Chambers (RPC's) operated in streamer mode. Since the start of operation the RPC's have suffered persistent efficiency deterioration and dark current increase problems. The "autopsy" of bad BaBar RPC's revealed that in many cases uncured Linseed oil droplets had formed on the inner surface of the Bakelite plates, leading to current paths from oil "stalagmites" bridging the 2 mm gap. In this paper a possible model of this "stalagmite" formation and its effect on the dark current and efficiency of RPC chambers is presented. Laboratory test results strongly support this model.

Based upon this model we are searching for solutions to eliminate the unfavorable effect of the oil stalagmites. The lab tests show that the stalagmite resistivity increases dramatically if exposed to the air, an observation that points to a

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possible way to remedy the damage and increase the efficiency. We have seen that flowing an oxygen gas mixture into the chamber helps to polymerize the uncured linseed oil. Consequently the resistivity of the bridged oil stalagmites increases, as does that of the oil coating on the frame edges and spacers, significantly reducing the RPC dark currents and low-efficiency regions. We have tested this idea on two chambers removed from BaBar because of their low efficiency and high dark current. These test results are reported in the paper, and two other remediation methods also mentioned. We continue to study this problem, and try to find new treatments with permanent improvement.

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1. Brief review of BaBar Instrumented Flux Return system (IFR) and its efficiency history

The active detectors of the BaBar IFR system are RPC's between iron slabs. The total area of the RPC's is about 2000 m^2, including 774 planar RPC's and 32 cylindrical modules. The BaBar RPC consists of two high resistivity Bakelite electrodes (10^{11} to 10^{12} $\Omega\cdot$cm in volume resistivity). The gap between the electrodes is 2mm, and every 10cm in x and y direction there is a 2mm-thick lipped cylindrical spacer to maintain gap uniformity. G-10 bars are glued to the edges of electrodes along the perimeter to form a gas tight volume for each chamber. The inner surface of the chamber is coated with a linseed oil/n-pentane (70/30) mixture. The initial gas mixture used was Ar/R134A/Iso-butane (48/48/4), which was later changed to the mixture currently used: 59/37/4. A detailed description of the RPC chambers can be found elsewhere [1].

The initial performance of RPC's was checked carefully before the installation. The average dark current was less than 10μA/m^2, single's rate ~ 1kHz/m^2, efficiency > 95%. They appeared to be excellent. At the end of 1998 the whole system started to collect the cosmic ray data.

During the summer of 1999 the temperature in the iron slots was rising up to 29 ~ 33 °C, which caused dramatic increases in dark current, to the extent that some chambers drew currents surpassing the upper limit of the high voltage supply, and had to be disconnected. Efficiencies dropped more than 10% in that period. A cooling system was installed by October 1999, stabilizing the temperature at 19-21°C. This arrested the rapid decrease in efficiency, but since then the efficiency has continued to decrease at a much slower pace [1].

At SLAC a test stand was set up to look into the temperature effect. Test results reproduced the disastrous effect: after raising the temperature to 36°C for 10 days, and then returning to room temperature, the dark current increased by fact of 5-9 and the efficiency dropped by 9-17%. Latter another test showed that even a moderate temperature rise to 28°C resulted in unrecoverable damage.

An “autopsy” of some damaged chambers revealed a shocking fact: many linseed oil droplets were spread over the inner surfaces of the bakelite electrodes, some bridging the gap and forming electric-short spots. Around the lipped spacers and frame edges more uncured linseed oil was found. The surfaces were sticky, further indicating the linseed oil coating was not completely cured. Chemical analysis (FTIR) of the linseed oil on the surface found extraneous pthalates, which were not existing in original oil. Pthalates are used in industry to make plastic material flexible, and might prevent the linseed oil from polymerization [2]. More detailed information and photos on the autopsy can be found elsewhere [3,4].

2. Linseed oil stalagmites: formation and effect on the efficiency

We realized that three basic conditions have to be met to form oil stalagmites: enough linseed oil existing on the surface; elevated temperature to soften the uncured oil film and make the oil molecules movable; high electric field on the surface to help pull the softened oil film away from the electrode and reach the opposite electrode. Unfortunately all three conditions were met during the summer of 1999.

The following resistor network model can quantitatively describe the effect of a bridged oil stalagmite on the dark current and efficiency.

Because of the symmetrical structure, we can simply consider the top half of the model. Assume the oil stalagmite sits at origin of the coordinate system. We divide the surrounding area with series of concentric rings with same width, as the dashed-line circles shown in figure 1. The solid-line circles are drawn at the middle of the dashed-line rings. We can then calculate the volume resistance for the dashed-line Bakelite cylinders, and the surface resistance between two adjacent solid-line rings. The resulting resistor network is readily calculable. R_{s0} represents the resistance of the oil stalagmite, and the matrix form of the linear equation system can be written as

$$MI = V$$

where I and V are one-column matrices to represent the loop currents (as shown in the figure 1) and source voltages. M is an n×n matrix, $M_{i,i}$ is the sum of all resistors through which mesh current I_i passes, $M_{i,i+1}$ are the sums of all resistors through which mesh current I_i and I_{i+1} pass. If I_i and I_{i+1} are in the same direction, $M_{i,i+1} > 0$; otherwise <0. The rest of the $M_{i,i}$ are zeros. Assume for example a 3mm diameter stalagmite, 2mm thick Bakelite electrode, volume resistivity $\rho \sim 2.9\times10^{12}\ \Omega$cm, surface resistivity $\sigma \sim 5.3 \times 10^{11}\Omega/$. In figure 2 two scenarios are shown: first, an uncured oil stalagmite $R_{stalagmite} << R_{bakelite}/20$, therefore assume $R_{stalagmite} \approx 0$; and second, a cured oil stalagmite with $R_{stalagmite} = R_{bakelite}/20$. If we define the active voltage criteria at 95% of the nominal value 8000V, e.g. 7600V and then compare the two scenarios, we find the inefficient region is reduced from r = 22mm (uncured) to 8mm (cured), and the dark current drops from 22.3 nA to 4 nA. For a $1m^2$ area in which there are 100 stalagmites, the inefficient area would be 15% for $R_{stalagmite} \approx 0$, and 2% for $R_{stalagmite} = R_{bakelite}/20$.

3. Polymerization and resistivity of linseed oil stalagmites

The resistance of an oil stalagmite has very strong dependence on its polymerization. If we expose an oil stalagmite to air and monitor its leakage current, we can find a remarkable increase of its resistivity, as shown in figure 3. The first test (#1) was ended on the 6-th day, by which time the resistivity had increased by a factor of 126, and a second test (#2) showed that by the 25-th day the resistivity had climbed more than 300 times.

For comparison the lower curve (#3) in the figure represents measurements with the oil stalagmite in the RPC gas. After 34 days the resistivity only climbed 3.7 times higher. There are two possible reasons for this latter increase: ionic current depletion as J. Va'vra suggested [5], and residual oxygen left in the sealed container that was used for holding the oil stalagmite.

4. Remediation of the deteriorated BaBar RPC's.

There is no conceivable way to remove the oil stalagmites inside the chamber, so based upon our present understanding, we tried the opposite route: curing the stalagmites and making them less harmful. The procedure was to flow N_2/O_2 (40/60) into the test chamber, let the oxygen polymerize the uncured linseed oil, thus reducing the dark current and inefficient area. The test results are shown in figure 4. At first the dark current dropped from 86μA to 32μA, then stabilized at ~35μA. The efficiency increased from 83% to 96%, but after two months of operation it dropped back to 82%. A second test chamber gave similar results: good initial improvement for both dark current and efficiency, then although the dark current remained low, the efficiency deteriorated back to its value before the test.

We also tried to flow dry air to cure the oil, but the flow rate was limited and the results from different institutions showed no improvement in either dark current or efficiency.

The third experiment in remediation was to put the chambers in a dry metal box maintained at 10% of relative humidity by flowing dry nitrogen gas into it, and flowing pure Ar gas through the chambers. The dark current shows a slow decrease: -0.5% ~ -1.5%/day, and the initial efficiencies increased significantly: for example, for chamber #6 from 5% to 82%. However, the increase was not sustained and dropped very fast, as we can see from figure 5 [6].

A brief summary of these remediation efforts is presented in Table 1.

5. Conclusions

- BaBar IFR RPC chambers are suffering persistent efficiency deterioration since the start of operation. An unexpected temperature rise in the summer of 1999 led to a dismal start of BaBar RPC life and left serious permanent damage to their performance.
- Intensive investigation reveals: for those chambers with high dark current and lower efficiency the major culprit could be the bridged uncured linseed oil stalagmites and excess linseed oil around the spacers and edges. Curing the linseed oil can rejuvenate those sick chambers. Oxygen treatment is along this direction.
- In a dry box flowing Ar through the chambers shows: good initial efficiency improvement and fast deterioration afterwards. It suggests that the surface resistivity of linseed-oil-coated Bakelite might be changing in the procedure.
- The BaBar RPCs appear to suffer from several different problems, and we are searching for other routes to the final remediation recipes. The remediation saga of BaBar RPC chambers continues…

References

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Table 1. Summary of various remediation efforts.

Method	Initial status	Dark current	Efficiency
O_2/N_2(60/40) with high flow rate (50sccm)	Large dark current, moderate efficiency	Good improvement, no deterioration	Good initial improvement, but deteriorates afterwards
Dry air, low flow rate	Large dark current and low efficiency	No improvement	No improvement
In dry box, flow Ar with large flow rate	Large dark current and low efficiency	Improving with time	Good initial improvement, but deteriorates fast

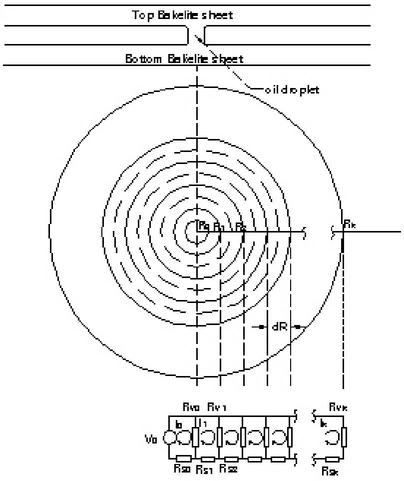

Figure 1. Resistor network model of the bridged oil stalagmite

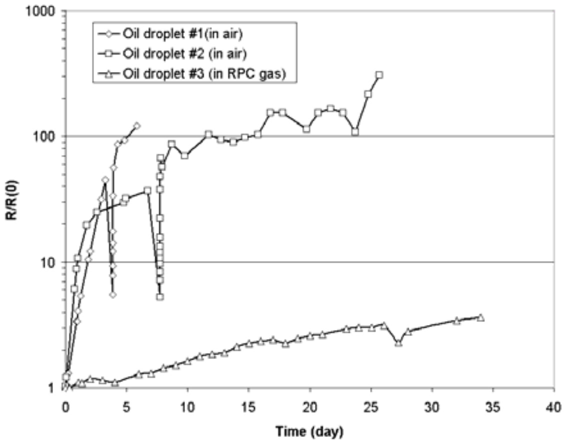

Figure 3. Effect of polymerization of a linseed oil stalagmite on its resistance.

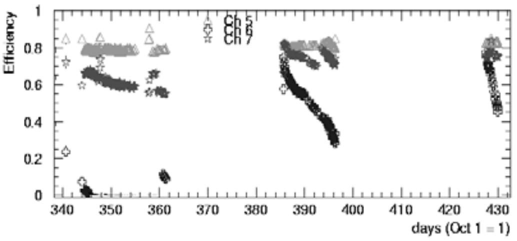

Figure 5. . Efficiency versus time for a test chamber enclosed in a dry box, with pure Ar gas flowing to treat the chamber

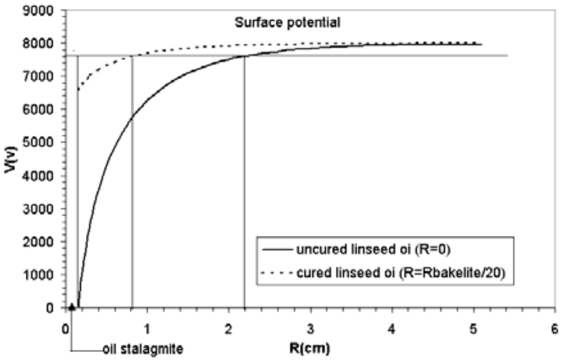

Figure 2. Potential distribution on the Bakelite electrode inner surface.

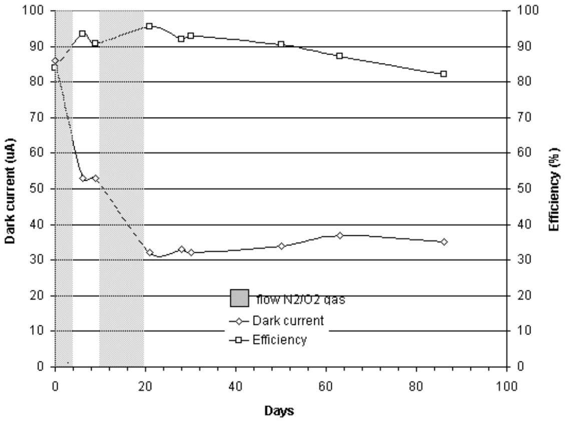

Figure 4. Oxygen treatment for test chamber #1: dark current and efficiency.