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# Performances of RPCs in the BaBar experiment

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The BaBar experiment uses a big system based on RPC detectors to discriminate muons from pions and to identify neutral hadrons. About 2000 m$^2$ of RPC chambers have been working at SLAC since the end of 1998. We report on the performances of the RPC chambers focusing on new problems discovered in the RPC behaviour. These problems started very soon after the installation of the chambers on the detector when the high ambient temperature triggered an increase of dark currents inside the chambers and a reduction of the efficiency. Careful analysis of the BaBar data and dedicated R&D efforts in the laboratory have helped to identify the main source of the trouble in the linseed oil varnish on the bakelite electrodes.

## 1. Introduction

RPCs have been used in the BaBar [1] experiment as active detectors for muon identification and neutral hadron detection inside the Instrumented Flux Return (IFR) [2]. RPC chambers are inserted into the gap between iron plates used to return the magnetic flux of the experiment.

The area covered by the RPC system is about 2000 m$^2$ for a total number of 774 planar RPCs and 32 cylindrical modules.

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The IFR is composed of six sextants with 19 layers in the barrel and two endcaps with 18 layers each. The total iron thickness is 65 cm in the barrel region and 60 cm in the endcaps.

A schematic view of the RPC used in BaBar is shown in Fig. 1. They are single-gap chambers with a 2 mm wide sensitive volume and two bakelite electrodes of the same thickness. The bakelite has been selected to have a bulk resistivity between $10^{11}$ and $10^{12}$ $\Omega\cdot$cm. The voltage is applied to a graphite layer with a surface resistivity of 100 k$\Omega$/square produced by coating the external side of the bakelite electrodes. Polycarbonate spacers are glued on a grid every 10 cm to maintain the correct thickness of the sensitive volume. Nine millimeter wide G-10 bars are glued along the chamber perimeter to guarantee the gas tightness.

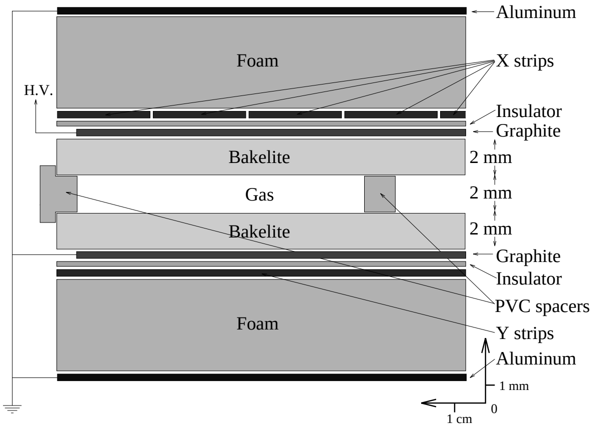

Figure 1. Cross section of a planar RPC.

The inner surface of the bakelite is varnished three times with a mixture of 70% linseed oil and 30% n-penthane to make it smoother and to reduce accidental streamers from discharge points along the electrode.

The sensitive volume of the RPC is filled with a mixture of Argon, Isobutane and $C_2H_2F_4$ with ratios that have been changed over time, but started with a mixture in the following ratios 48%, 4%, 48%.

The present paper is organized as follows: in section 2 the initial performances of the RPCs just after production are reported; section 3 will concentrate on the problems found very soon after the full detector was installed and on the tests carried out with the detector to try to investigate these problems; section 4 will show the role of the linseed oil in the RPC problems as reproduced in dedicated test stations, and by analysing BaBar chambers removed from the apparatus; in section 5 an overview of the results obtained from studying materials used for RPC construction will be reported; in section 6 first results of RPCs from a new production will be given before going to the final conclusions.

## 2. Initial RPC performances

RPCs were produced at General Tecnica factory between 1996 and 1997. All the chambers were sent to Frascati, where their performances were carefully tested, before delivery to SLAC. A dedicated test station was set up in Frascati to test the RPCs with cosmic rays.

Each chamber was tested for gas tightness and for mechanical integrity (no popped spacers). Dark current, single rate and efficiencies as a function of the cosmic impact point were monitored for about one week. After the test the RPCs were sent to SLAC and tested again in the same way before insertion into the iron gaps.

For each chamber the dark current, single rate and total efficiency were measured as a function of the applied voltage to establish the working point. At the working voltage, high-statistics runs allow to measure the efficiency vs. the local impact point coordinates in order to check the uniformity.

The results [3] can be summarised in the following way: average dark current below 10 $\mu$A/m$^2$, single rate about 1 kHz/m$^2$, excellent detection efficiency (greater than 95%), and no correlation between RPC performances and bakelite resistivity at this level. Chambers showing problems, such as no gas tightness or broken spacers were discarded. Similar results were found at SLAC.

## 3. RPC performances at the BaBar experiment

The RPCs were inserted into the iron gaps of the IFR in 1997. At the end of '98, the electronics and the ancillary services were installed and the IFR group was ready to collect cosmic rays to test the system. At the beginning of summer '99, the ambient temperature was greater than expected (about 28-31°C in the experimental hall and 29-33°C inside the iron slots). The dark currents of the chambers started to increase in such a way that the high voltage power supply limits were exceeded and chambers with dark current greater than about 100 $\mu$A/m$^2$ were disconnected.

A cooling system was installed in October 1999 and completed in the endcaps by January 2000.

After the cooling was installed the temperature was stabilised at 19-21°C inside the detector, which reduced the dark currents and premitted to reconnect disconnected chambers. Unfortunately, the dark current did not return back to the initial low values at the reduced temperature, and also the detection efficiency started to decrease as a function of time. Fig. 2 shows the average detection efficiency of all the RPCs as a function of time. The dark markers show the average efficiencies of all the RPCs as a function of time including disconnected chambers. The big reduction is mainly due to the increasing number of disconnected chambers during the initial period. A partial recovery of the average efficiency is evident in October 2000, when the cooling system permitted to reconnect most of the chambers. The main problem is represented by the constant reduction of the connected chambers (empty markers in the plot) that did not recover their performances when the temperature was back to low values.

Fig. 3 shows the efficiency as a function of the local position on the chamber for different IFR layers. Complicated inefficiency patterns are present in bad chambers, very often starting around a region of spacers and along the frame.

In order to investigate the problems and to try to recover the chamber efficiency, we performed several tests on the RPCs in the detector: gas flow was increased in selected chambers, the front-end electronic threshold was reduced, weights were put over inefficient regions. No effects were found. The gas composition was regularly tested and showed good stability.

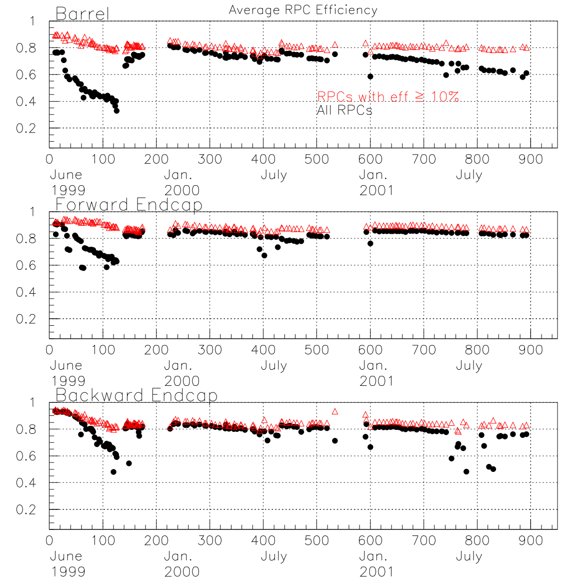

Figure 2. Efficiency history of RPCs. The dark markers represent the average efficiency of all BaBar RPCs including disconnected chambers. Empty markers represent the average efficiency of RPCs with efficiency greater than 10%.

To correlate the RPC performances with the production time, we classified the chambers into good chambers (efficiency greater than 90 %) and bad chambers. If we order them as a function of the production time, we see that most of the good chambers are concentrated at the beginning and at the end of the production period. This could be a hint at problems during the RPC production.

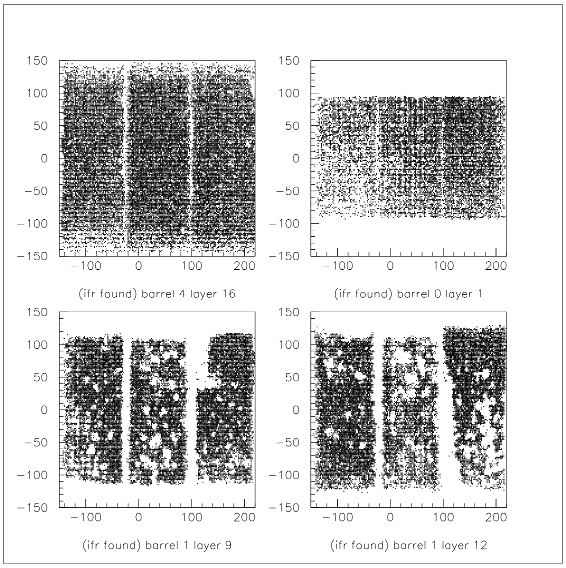

Figure 3. RPC efficiency map: the first histogram shows the efficiency map of a layer (composed of three RPCs) with high efficiency, in the other histograms inefficiency patterns seem to start around the spacers and along the frame.

## 4. The role of the linseed oil

In order to investigate the peculiar effects seen in the BaBar RPCs, we started systematic R&D in various laboratories to try to reproduce the anomalies seen in BaBar and to try to recover the performances in some way.

In the SLAC test station nine RPCs built at the end of the BaBar production were tested inside an oven and subjected to heating cycles up to 36°C. Is well known that the bakelite resistivity decreases as a function of temperature. When the RPCs operated at 28°C and then at 32°C, an increase of the dark current was clearly observed. On the average, each RPC started at 7 $\mu$A/m$^2$ at ambient temperature, reached 13 $\mu$A/m$^2$ at 28°C and 20 $\mu$A/m$^2$ at 32°C. As soon as the oven temperature reached 36°C, the dark current started to increase without reaching any apparent stable value. When the temperature was reduced to the initial value, the dark current was about 40 $\mu$A/m$^2$. We conclude that some irreversible effect damaged the RPCs in a permanent way. At the same time, the efficiencies of the RPCs started to decrease as was also seen in the BaBar chambers.

A couple of these damaged chambers were opened in order to look inside. Several drops of oil were found all over the bakelite surface; most of these drops span the two millimiter gap and short out the electrodes locally. The oil was not polymerised and was very sticky. The same effects were seen on BaBar chambers at the end of 2000 when 24 chambers of the forward endcap were replaced with RPCs from the new production and were opened to check the oil coating. Similar drops were found on the inner bakelite surface, and a big amount of oil was found around the spacers and along the frame.

The main conclusion of this analysis seems to relate the RPC problems to the missing polymerisation of the linseed oil and the formation of oil droplets under the action of an electric field. The idea that oil stalagmites could be created under the action of an electric field was confirmed in laboratory tests with bakelite plates varnished with fresh linseed oil. The application of 4-5 kV triggered the formation of oil stalagmites within a few hours. The more viscous BaBar linseed oil might need more time to generate such droplets.

## 5. Material tests and recovery procedures

Several tests were carried out with any single material component of the RPC in order to study the behaviour under temperature cycling. Bakelite, fresh linseed oil, G-10 (used for RPC frame), and polycarbonate (used for RPC buttons) were heated and the volume and surface resistivity were measured. Apart from the fresh linseed oil, no permanent effects were found.

Analyses of linseed oil samples taken from a BaBar chamber show lower resistivity of $2.1 \cdot 10^8$ $\Omega$·cm vs. $76.7 \cdot 10^8 \Omega$·cm of fresh linseed oil. We conclude that some permanent effect changed the basic composition of fresh linseed oil. Jerry Va'vra suggested [4] that the basic linseed oil molecules R-COOH could dissociate into H$^+$ and R-COO$^-$. These ions could increase the conductivity of the linseed oil. Water coming from outside or from the bakelite could enhance such process providing new ions to the system.

A chemical analysis [5] of the BaBar linseed oil was performed with the Fourier Transform Infrared Analysis (FTIR). In the analysed BaBar chambers, some extraneous components were found: phtalates and free fatty acids. Phtalates inhibit the polymerisation process, and free fatty acids are a signature of decomposition of the linseed oil.

Based on these results, a simple model could be used to try to explain the inefficiency of the RPCs. For some reason, still not completly understood, the linseed oil used to varnish the bakelite surfaces was not polymerised during the production. Under the action of the electric field, oil drops were created that shorted the two electrodes (see Fig. 4) and provided a physical channel with low resistivity for electric current. Excess of oil along the spacers and along the frame define additional channels for the current. According to this model the observed high dark currents are due to the flow of ions along these channels, and the drop of the efficiency is due to the local reduction of the electric field around these regions.

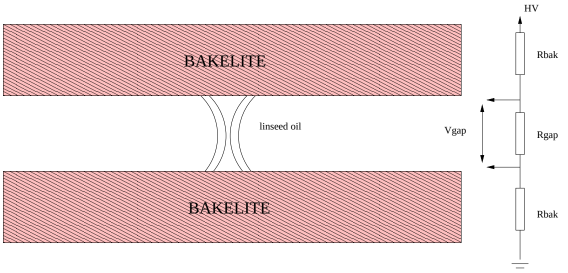

Figure 4. Schematic model of the inefficiency mechanism: linseed oil droplets short the electrodes and the system could be represented by a network of resistors. The voltage between RPC gaps is reduced.

Following these ideas, a test to try to recover the performances was carried out by flowing oxygen inside of low-efficiency chambers. The $O_2$ should help to polymerise the linseed oil increasing the resistivity of the droplets and reducing the current and the inefficiency region. Unfortunately, the benefits found in the laboratory seem to be temporary. After an initial increase of efficiency, the performances deteriorate again over time. Adding a small amount of $O_2$ directly to the gas mixture appears to reduce the rate of deterioration, but is not able to stop it.

## 6. Performances of new RPCs

At the end of 2000, 24 chambers of the forward endcap were replaced with chambers from new production. The new RPCs have a smoother bakelite surface and have been varnished just once with a mixture of 40% linseed oil and 60% epthane (vs. 70% linseed oil and 30% n-penthane varnished three times). As a result the oil layer on the bakelite surface is at least a factor 2-3 less than before and perfectly polymerised, without excess of oil around spacers and frame.

The new RPCs have been under test for about 1 year showing very low dark current (below 2 $\mu$A/m$^2$) and high detection efficiency (greater than 95%) that is stable over time.

A special analysis has to be done for the outermost layers affected by very high machine background of $\sim$ 70 kHz/m$^2$. These RPCs start to show a decrease of the efficiency, which is still under investigation, but is probably due to the impossibility to work in streamer mode at such high rates. It is yet to be understood why the single rate of the RPCs is about 35 kHz/m$^2$ when the beam is off.

## 7. Conclusions

The RPCs of the BaBar experiment showed new aging effects probably due to the only partial curing of the linseed oil coating the electrode surface. After a first period when the performances of the chambers were very good, under the influence of high ambient temperature in the experimental hall of BaBar, the RPCs started to show a reduction of efficiency and an increase of dark current. From tests carried out in the laboratory that reproduced this behaviour it is clear that, under the action of an electric field, the unpolymerised linseed oil generates droplets shorting the electrodes and reducing the electric field locally. In some cases it has been possible to improve the RPCs performances by flowing $O_2$ into the damaged chambers. This helps to polymerise linseed oil, reduce dark currents and recover efficiency. However, these benefits are not stable, and over time the efficiency of the chamber goes back to lower values. RPCs from new production (less linseed oil inside) have been tested on the detector and show good performances. Some yet to be understood problem appears on chambers exposed to high background from the machine.

## 8. Acknowledgements

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