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Experience with the BaBar Resistive Plate Chambers

Henry R. Band

***Abstract*—The BaBar detector has operated over 2000 m^2 of Resistive Plates Chambers (RPCs) as muon and neutral hadron detectors since 1999. Most of the original RPC production have lost significant efficiency and many are now completely inefficient. Both the linseed oil used to coat the inner surfaces and the graphite coating on the outer surfaces are implicated as contributors to the efficiency loss which was accelerated by the operation of the RPCs at 29 to 34^{o}C during the first summer. RPCs from 2 more recent production runs have been installed and tested. The most recent RPCs have exhibited stable efficiencies and high voltage plateaus during the first 8 months of service. Some have shown increased dark currents and noise rates.**

I. Introduction

THE BaBar detector[1], operating at the PEPII B factory at the Stanford Linear Accelerator Center (SLAC), utilizes Resistive Plate Chambers (RPCs)[2], installed inside the segmented flux return steel as detectors of muons and neutral hadrons (Instrumented Flux Return or IFR system). The details of the steel design are shown in Fig. 1. The inner steel plates are graded in thickness from the inside to outside to improve detection efficiency for K_L. Over 800 single gap RPCs ranging in size from 1.5 to 3 m^2 are inserted into the gaps. During an upgrade of the forward endcap in the summer of 2002, brass and steel were added to increase the thickness of the muon absorber to greater than 6 nuclear absorption lengths. All of the RPCs in the forward endcap were also replaced.

The RPCs, shown in Fig. 2, consist of two planes of 2 mm thick bakelite (bulk resistivity ~ 5×10^{11} Ωcm) separated by 2 mm polycarbonate buttons and fiberglass frames. The outer surface of the bakelite is coated by graphite paint (100 kΩ/square) and an insulating PET film on both sides. A sandwich of strips, foam, and insulated ground planes is glued to either side. Ionizing tracks traversing the RPC gap produce limited streamers between the bakelite plates. The signals are readout capacitively by strip electrodes oriented along or orthogonal to the long axis of the RPC. BaBar RPCs operate in limited streamer mode, using a gas mixture of 4.5% isobutane, 45 to 60.6% argon and Freon 134a. Operating voltages were 7600 Volts for barrel and backward endcap RPCs and 6700 Volts for the new forward endcap RPCs.

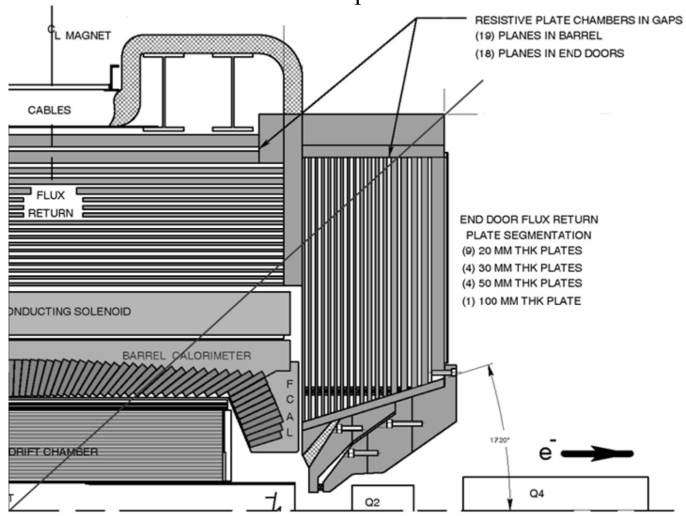

Fig. 1. The BaBar detector showing the details of the flux return steel surrounding the inner detector elements. Single layer RPCs are inserted into the gaps. The barrel chambers(endcap) are made from three(two) RPC high voltage modules connected together to form a single gas volume and share one view of the readout strips.

The original BaBar RPCs were manufactured by General Tecnica [3] in 1996-7.

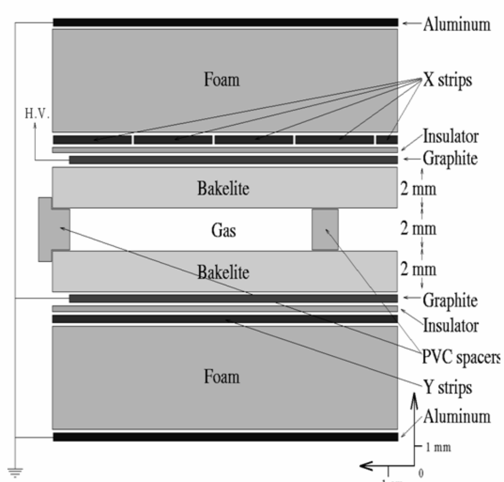

Fig. 2. Cross section of a typical BaBar RPC.

The inner surface of the bakelite was coated three times with a mixture of 70% linseed oil and 30% n-pentane. The

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replacement RPCs produced by General Tecnica in 2000(24 modules) and 2001-2(200modules) were coated only once with a mixture of 40% linseed oil and 60% n-pentane.

II. Original Production RPCs

The RPC modules were tested at Frascati before shipment to SLAC. Two(endcap) or three(barrel) modules were assembled into chambers, sharing one view of the pickup strips and one connection to the gas distribution system. The gas connections within a chamber were serial, downstream modules receiving the output of the upstream module(s). After insertion into the BaBar steel, connection to the data acquisition, high voltage, and gas systems the RPCs were retested with cosmic rays. The average efficiencies were greater than 93%.

The first problems appeared during initial cosmic ray tests of the full detector in early 1999. No provisions for cooling of the RPCs or barrel steel had been made despite the 3.3 kW of power dissipated by the IFR front end electronics mounted inside BaBar . With the end cap doors closed, the temperature inside the barrel rose by ~ 0.5 ^{o} C per day leading to a 14 to 20 %/ per day increase in the RPC dark currents. These sources were sufficient to heat the BaBar steel and chambers to 29-34^{o} C during the initial commissioning run in the summer of 1999. When the current exceeded the capabilities of the HV power supplies, RPCs had to be disconnected. By August 1999 over 50 % of the barrel RPCs had been disconnected. The average efficiency of the RPC chambers is shown in Fig.3 for 1999.

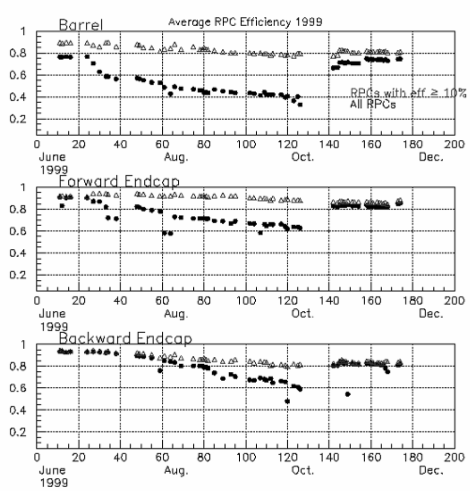

Fig. 3. The average RPC efficiencies determined from cosmic rays during 1999. The solid squares represent the average efficiency of all chambers. The open triangles represent the average of those chambers connected to high voltage.

RPC temperatures were controlled by the installation of water cooled copper loops in the BaBar barrel and endcap steel during the October and December 1999 accesses. To further reduce the heat load, the electronics in the forward endcap were relocated outside the steel during the fall 2000 access. Temperatures are now stable at 19 to 21 ^{o} C in the barrel and 21 to 23^{o} C in the endcaps. A small residual dependence on the experimental hall temperature remains.

The RPC efficiencies did not recover fully when temperatures were stabilized and RPC's were reconnected. Furthermore, the RPC efficiencies have continued to decline in 2000-2003 as seen in Fig. 4. The overall efficiency loss is driven by the nearly constant percentage of RPCs dying and losing all efficiency.

The dips in efficiency in Jan. 2002 and Nov. 2002 were associated with the failure of the IFR front end electronics during abnormal PEP-II background conditions. Efficiencies have been partially restored by changing the gas composition (Jan. 2000 and July 2000) and high voltage operating point and repairing electronics during accesses. During the summer access of 2002 the high voltage and gas distribution systems were upgraded, slowing the loss of chambers and allowed the operation of low efficiency RPCs at higher voltages.

The changes in RPC behavior were initially characterized by non-reversible increases in the dark current(most the current increase with temperature was reversible, however the chambers never returned to the exact initial current), to the appearance of inefficient regions in the RPC area, and to a shift in the RPC high voltage plateau to higher voltages and lower plateau efficiencies. After 1-2 years the dark current of many RPCs declined from its maximum value, sometimes significantly declining in less than 1 month.

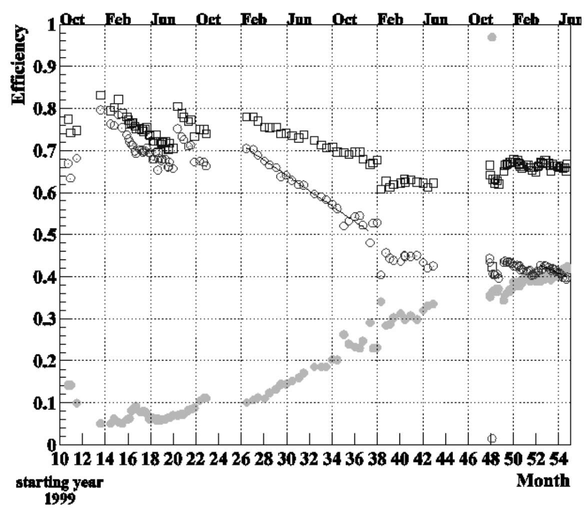

Fig. 4. The average efficiency of the barrel RPCs determined from μ pairs during 1999-2003. The open circles represent the average efficiency of all chambers. The open squares represent the average of those chambers with efficiency > 10%. The grey circles represent the fraction of barrel RPCs with efficiency less than 10%.

III. Test Stand Studies

Since access to the RPCs was severely limited by the factory style operation of PEPII, most of the studies to date have been in dedicated test stands.One study in the fall of 2000 was able to reproduce the increased current and efficiency loss typically observed in BaBar, by heating several test RPCs (produced in 1997) to 36^{o} C for a week. When one of these chambers was opened, it was found that the linseed oil used to coat the bakelite surfaces had collected into drops which in many cases spanned the 2 mm RPC gap, creating high resistance shorts. These current bridges increase the RPC leakage current, locally reduce the electric field within the chamber, and drop the electric field gradient below the value required for streamer production.

When several endcap RPCs were opened later that year, it was found that most showed evidence of improper linseed oil polymerization. As seen in Fig.5, the linseed oil surfaces were tacky to touch and often showed evidence of the linseed oil collecting at the bottom of the RPC or around the button spacers. The overall volume of oil was less than observed in the test RPCs and not always associated with inefficient regions of the RPC.

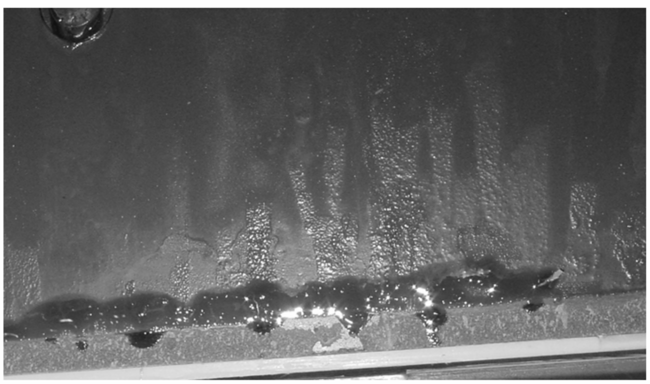

Fig. 5. A photograph of the lower inside edge of an endcap RPC removed from BaBar in 2000. The dark colored linseed oil collected on the botton frame has a significantly lower resistivity than either fresh or cured linseed oil[4].

Oil from damaged RPCs and from spare RPC modules which had never run were analyzed by IR spectroscopy [5]. The spectroscopy saw evidence for fatty acids resulting from the decomposition of the linseed oil as well as phthalates. Phthalates are used as plasticizers in industry for products such as Tygon tubing. Phthalates would inhibit the proper curing of the linseed oil. The presence of the phthalates in the spare RPCs suggests that the linseed oil supply at the factory had become contaminated, inhibiting the proper drying and polymerization of the linseed oil.

The location and abundance of the linseed oil found in autopsies of endcap RPCs was insufficient to be a sole cause of the observed chamber inefficiencies. Recent work by the Atlas RPC group[6] has determined that the resistance of the graphite layer which delivers the high voltage current to the bakelite can change with time, correlated with the integrated current drawn by the chamber.

To test this model, we measured the resistance of the graphite coating in 8 RPC modules removed from the forward endcap and 3 RPC modules still inside the BaBar barrel. All RPCs with efficiencies less than 10% had at least one graphite surface (usually the anode) with a surface resistivity of > 60 mΩ/sq, more than 600 times the nominal expected resistivity. The graphite of these chambers was visually nearly transparent, much lighter than the black surface of a new RPC.

As a further test, the insulating film over a small section of one of the inefficient RPCs was removed. The bakelite surface was cleaned and the graphite paint reapplied. After a high voltage connection was made to the region, the efficiency was re-measured. The efficiency under the new graphite paint was significantly improved, proving that for this chamber the graphite not the linseed oil was the major cause of inefficiency.

IV. Year 2000 RPC production

Twenty four RPCs were produced and installed into the forward endcap in the fall of 2000 to test new procedures for coating the bakelite with linseed oil. No other substantive changes were made. The surface of these chambers was hard and dry to the touch. Two similar RPCs were subjected to a one week heating test. Neither RPC lost efficiency, but one showed a large increase in singles rate and dark current. When opened, this RPC had few linseed oil drops and the bakelite surface was generally dry. However, there were bumps, discolored regions, and droplets clustered near the gas inlets, possibly as a result of the drilling for the gas tubes which are made after the RPC is assembled.

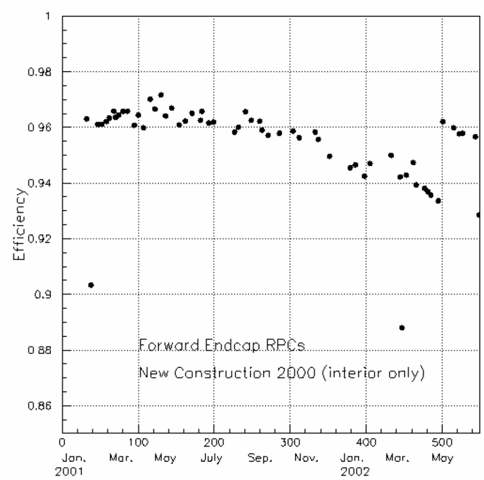

Fig. 6. The average efficiency of RPCs installed in the fall of 2000. The efficiency declined by ~3% before the high voltage was raised in May 2001.

The new style RPCs installed in the outer layers of BaBar suffered from high backgrounds. The rate in Layer 18 was ~12 Hz/cm^2 and Layer 17 was ~3 Hz/cm^2. Layer 18 began to show a loss of efficiency after only 140 days of data taking, corresponding to an integrated charge of 50 mC / cm^2.

The average efficiency of the RPCs in the inner layers (1-12), shown in Fig. 6, was initially stable and then slowly declined. The efficiency loss was recovered by raising the high voltage by 200 Volts, indicating that the knee of the high voltage plateau had shifted. The dark current and noise rates of the RPCs had significantly increased, although remaining small compared to the currents of a typical original production RPC.

V. 2002 FORWARD ENDCAP UPGRADE

With the exception of 4 RPC modules installed in 2000, all of the RPCs in the forward endcap were replaced during the upgrade in 2002. New RPCs were built at the same General Tecnica factory under a stringent quality assurance (QA) program developed by the IFR group. Particular care was made to keep the inner RPC gap as clean as possible and to ensure that the final linseed oil coating was thin and well cured. New molded corner pieces were designed to replace the drilling previously used to make the gas fittings. Multiple filters were added to the linseed oil filling stations and the oil was periodically analyzed for impurities. As part of the QA program about 5% of the RPCs were opened after construction to inspect the surface quality of the RPCs. Many of the QA improvements in RPC production made by the IFR group have been adopted by the LHC detectors.

The average of the RPCs in the inner layers is stable and has shown no decline over the first 8 months of operation as shown in Fig.7.

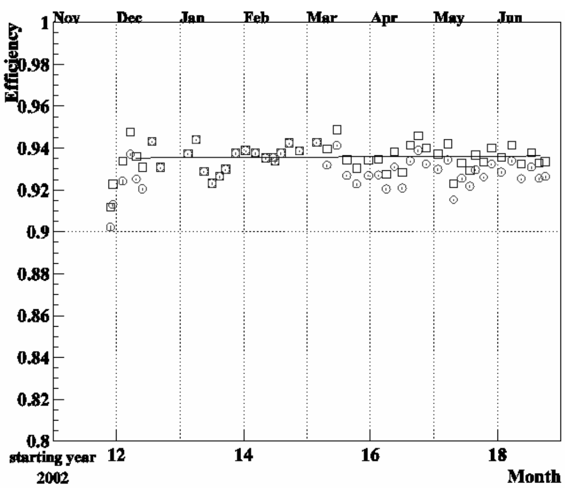

Fig. 7. The average efficiency of RPCs installed in the summer of 2002 in the inner 12 layers of the forward endcap is 93% and is stable in time.

The noise rates in the 2002 RPCs produced by backgrounds from normal BaBar running varied considerably. RPC modules near the bottom of the endcap were dominated by the cosmic ray rate and never drew more than 2 μA. The currents and noise rates of modules closest to the beam line were proportional to the PEPII luminosity and were typically 30 to 50 kHz (1 -3 Hz /cm^2) or 30 to 50 μA. The rates in the outermost layers (15 and 16) were too high to allow normal operation (> 12 Hz / cm^2). The rates in the next outermost layers were lower ~4 Hz / cm^2, but depended on the PEPII backgrounds. A large shielding wall, scheduled for installation in 2004, is planned to eliminate these backgrounds.

The currents drawn by 3 RPCs in layer 1 of the west door are plotted in Fig. 8 for the first 8 months. The 3rd and 4th module from the bottom see the highest background rates. The top plot contains the currents during normal BaBar running. The bottom plot contains the currents during special cosmic ray runs with no PEPII beams. All of the RPCs initially drew < 2 μA without beam backgrounds.

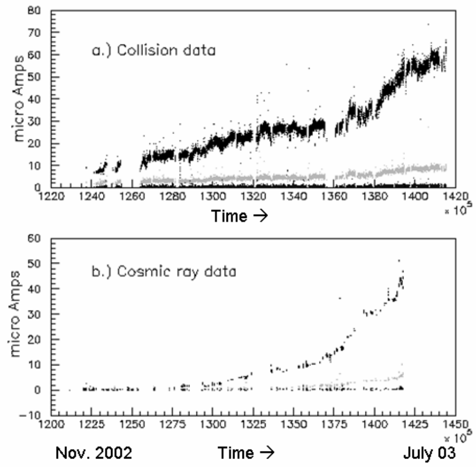

Fig.8. The dark current drawn by 3 RPC modules in layer 1 of the forward west endcap door are plotted versus time. The top plot a is for normal data running. The bottom plot b is for running with cosmic rays only. The three RPCs are all the second chamber in the gas flow string.

All but the bottommost RPC see PEPII induced backgrounds. The charge accumulated by each RPC varied from 1 to 15 mC / cm^2. Several of the RPCs suffered irreversible changes to their dark current and noise rates as evidenced by the cosmic ray values. These were uniformly the second chamber in the gas string. The largest increases were associated by RPCs which accumulated the most charge and were the second chamber in the gas flow string.

The correlation between increased dark currents, background rates, and position in the gas flow string suggest that the downstream RPCs are being exposed to contaminants in the gas produced in the first RPC. The gas flow in the RPCs exposed to higher background rates has been increased from 4 to 8 volume changes per day.

VI. CONCLUSIONS

Resistive Plate Chambers were chosen for the BaBar IFR because they were believed to be robust and well understood. They have proven to be neither in the BaBar experience.

The original production RPCs contained excessive amounts of linseed oil which was never fully polymerized. It is not clear if the cause was a lack of drying time, the filling procedure, or contaminants in the oil. The BaBar RPCs were thermally stressed during the first year of operation thereby accelerating problems associated with the oil.

We have, in addition, found that some RPCs suffer from aging of the graphite layer that distributes the high voltage to the bakelite. This large increase in the graphite surface resistance seems to occur at smaller integrated current than suggested by the present literature.

Our experience with RPCs constructed and installed in 2001,2 has been positive. No loss of efficiency or shift in the high voltage plateau curves have been seen in the first 8 months of operation. Some chambers have shown a worrisome increase in singles rate and dark current correlated with the integrated charge received and the gas flow. More data is needed before final conclusions can be drawn.

VII. ACKNOWLEDGMENT

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