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Study of HF Production in BaBar Resistive Plate Chambers

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Abstract

The BaBar detector has operated over 200 2nd generation Resistive Plate Chambers (RPCs) in the forward endcap since 2002. Many chambers have increased noise rates and high voltage currents. These aging symptoms are correlated with the integrated RPC current as expected, but also depend on the rate and direction of the gas flow, indicating that pollutants produced in the gas can accelerate aging of downstream RPC surfaces. HF produced by decomposition of the Freon 134a component of the BaBar RPC gas in electric discharges has been proposed as the main pollutant. This paper presents measurements of HF production and absorption rates in BaBar RPCs. Since many of the highest rate chambers in the forward endcap were converted to avalanche mode operation, a comparison of HF production in streamer and avalanche mode RPCs is made. Correlations between the HF production rate and other chamber operating conditions were also explored.

Key words: Resistive Plate Chamber, Muon detection, BaBar, Fluorine
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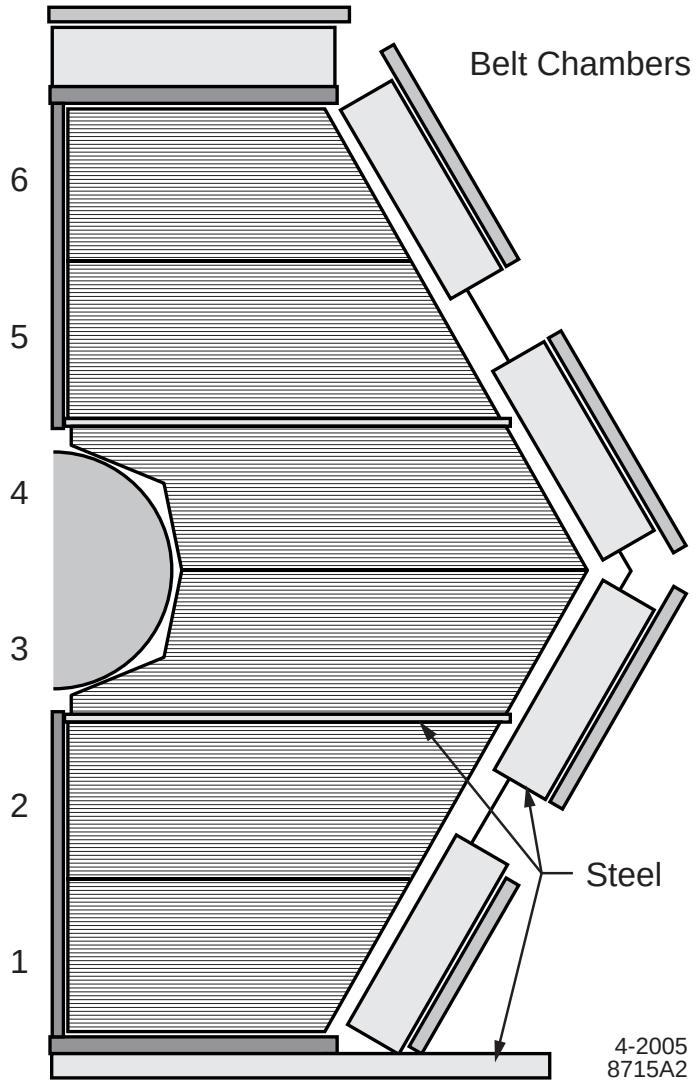

Fig. 1. Typical RPC geometry for a layer in the East door. Each layer contains three chambers. Each chamber is made by two high-voltage modules. The gas lines of the two modules (1-2, 3-4, 5-6) are connected in series.

1 Introduction

The BaBar detector collaboration[1], installed over 200 2nd generation Resistive Plate Chambers [2] (RPCs) as part of an upgrade[3] of the forward endcap muon and neutral hadron detector (IFR) in 2002. BaBar RPCs are constructed from Bakelite treated with linseed oil and operate at 6700 V in limited streamer mode, using a gas mixture of 4.5% isobutane, 60.6% argon and 34.9% Freon-134a ($C_2H_2F_4$).

BaBar endcap chambers are built from two single gap trapezoid shaped high voltage modules joined together by vertical pickup strips and ground planes. The gas output of first module is connected to the gas input of the second

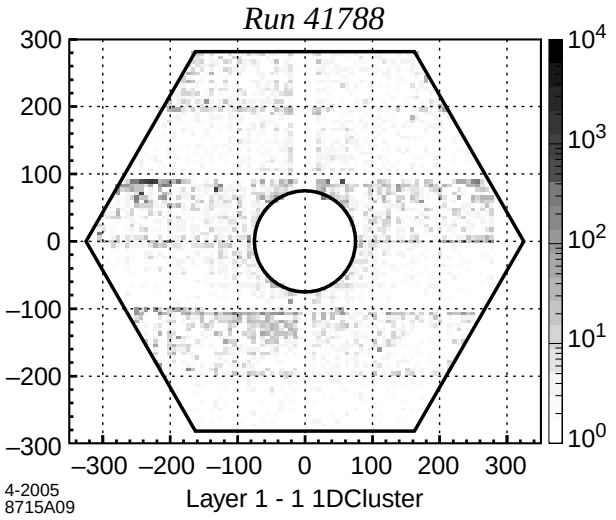

Fig. 2. RPC occupancy in Layer 1 in data collected with no beam and a random trigger.

module. Each endcap door was built from three such pairs as shown in Fig. 1. The HV module area varied from 1.6 m^2 (Modules 1,6), 2.1m^2 (Modules 2,5), to 2.3m^2 (Modules 3,4). During the first two years of operation, fresh gas flowed into the lower HV module and then to the upper HV module. The total gas volume of the chambers varies from 7 to 8 l. Gas flows were about 40 cm^3/minute, corresponding to a gas exchange rate of 0.3 volumes/h. Signal rates, currents, and occupancy were generally proportional to PEPII luminosity with peak rates above 15 Hz/cm^2 in the regions closest to the beam pipe. Rates were much lower (< 2Hz/cm^2) in the top (6) and bottom (1) RPCs.

Early BaBar observations of RPC aging [4] suggested that pollutants produced in the gas in the highest rate areas were being transported to other regions. Although the noise and background rates were symmetric about the beamline, the current and noise rates of the downstream modules increased significantly more than modules which were upstream in the gas flow. Fig. 2 shows the occupancy of layer 1 due to random chamber noise. The upper module of each chamber pair has a higher density of hits than the lower module. In addition, there is a clear increase in number of noise hits in regions of high activity (around the beam-line). The clear pattern of Fig. 2 was diluted when gas flow directions were reversed and gas flows were increased after the second year. After the reversal, currents in most upper modules decreased while the currents in the lower modules (now downstream) increased.

Studies for ATLAS RPCs[5] suggest that both the increased noise rate and the increased ohmic part of the high voltage current could be due to the action of HF on the Bakelite surfaces inside the RPCs. HF can be produced by the breakdown of the $C_2H_2F_4$ gas component during streamer or avalanche discharges. Measurements[6] have shown that the surface conductivity of the

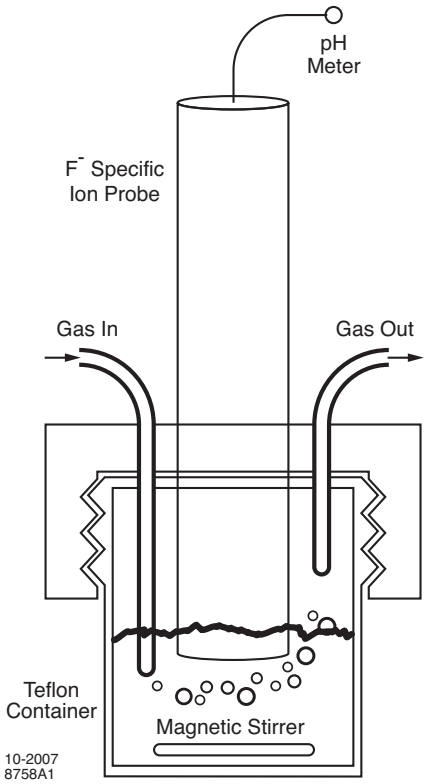

Fig. 3. Schematic view of the experimental setup for the measurement of HF concentration in the RPC exhaust gases.

linseed oil treated Bakelite decreases by $10^3 - 10^4$ after exposure to HF vapor. Lowered internal resistances inside the RPC high voltage structure can easily lead to significant ohmic currents that are not due to gas gain. Autopsies of original production RPCs found bumps in the linseed oil on the inner surface which were associated with regions of increased noise [3]. If HF is associated with the formation of these bumps, the mechanism could be self-sustaining, since the increased field around a bump would generate more discharges, hence more HF,which can further damage the surface. However, this proposed mechanism is not yet supported by any direct measurement of increased HF in or near such bumps or by a detailed understanding of chemistry involved. In this paper we present measurements of the HF concentration in the exhaust gases of full size working RPC chambers.

2 Measurement Technique

The HF in the RPC exhaust gas is measured by bubbling the gas through a solution of distilled water and TISAB (Total Ionic Strength Adjusting Buffer) as shown in Fig. 3. HF contained in the gas dis-associates into H^+ and F^-

ions in the solution and is measured by a fluoride specific ion probe [2]. The probe is continuously immersed in the solution and connected to an acquisition system which monitors the probe output voltage as a function of time. The probe output voltage is proportional to the F^- activity which is in general less than the total ion concentration because the probe is sensitive only to dissociated F^- ions. The TISAB neutralizes the effect of electrode interfering substances such as OH^- or trace metals that could bias the measurement and acts as a buffer, keeping the solution at a constant pH of 5.5. Using the HF acid dissociation constant of $pK_a = 3.45$, the relationship between the fluoride ion concentration ($[F^-]$) and the HF concentration ($[HF]$) can be evaluated using the Henderson-Hasselbach equation [7]at this PH value:

$$pH = pK_a + \log_{10} \frac{[F^-]}{[HF]} \tag{1}$$

which gives a ratio $[HF]/[F^-] = 0.89\%$. Thus nearly all of the HF is measurable as F^- ions.

The probe has a F^- sensitivity of approximately 2μmol/l (0.05 ppm). Several baseline measurements were made to verify that the techniques employed were sensitive to HF produced in the RPCs. A measurement of fresh BaBar gas found no evidence of F^- (concentration of $< 3\mu$mol/l after more than 1 hour of gas flow) showing that any detected F^- must have been produced in the RPC. There was about 20 m of polytetrafluoroethylene (PTFE) gas tubing between the BaBar RPCs under test and the test apparatus. To check if HF was absorbed or emitted by the tubing, fresh gas was sent through tubing which had carried the gas exhaust from a high rate RPC for more than one year of data-taking. After several hours no significant evidence of F^- in the gas was seen. Since the electrode response is sensitive to temperature changes, these measurements were performed in a temperature controlled room $(20.7 \pm 0.3)^\circ$ C.

3 Calibration and Cross-checks

The electrode probes were periodically calibrated with solutions of known concentrations of NaF: 2.6, 5.3, 26.3, 52.6, 263, 526, 2631 μmol/l. Typical calibration curves for two probes are shown in Fig.4. Changes in the calibration response were typically slow with the most sensitive readings at very low F^- concentrations drifting by less than 5% per month.

The fraction of HF captured by the TISAB solution was measured by flowing

[2] Orion 96-09, Thermo Electron Corporation

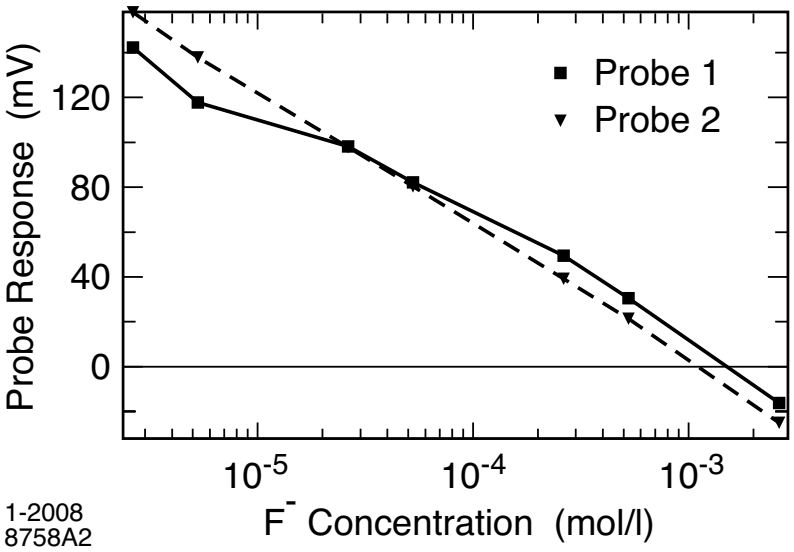

Fig. 4. Typical probe calibration curve with known concentrations of F^- in TISAB solution. Probe 1 and probe 2 are calibrated independently in two separate solutions.

RPC exhaust gas through two separate test setups connected in series. The output gas from the primary solution p was sent to secondary solution s. The F^- concentration was measured in both of solutions at the start (F_p^1, F_s^1) and end of the measurements (F_p^2, F_s^2). Assuming that the capture efficiency was the same for the two solutions we find that:

$$\varepsilon = 1 - \frac{F_s^2 - F_s^1}{F_p^2 - F_p^1}. \tag{2}$$

From these data the HF capture efficiency was approximately 96%.

In the remaining part of this paper we shall assume that the F^- measured in the test solutions originate from HF in the RPC exhaust gases and quote the quantity of HF after correcting for the volume of the test solution(typically 80 ml). The HF values have not been corrected for the capture inefficiency (4%) or the incomplete ionization of the HF (1%).

4 A Typical Measurement

A measurement of the exhaust gas from a layer 16 chamber, shown in Fig. 5, was performed during a period with stable PEPII beams. This chamber, which belongs to the outermost IFR layer, had been off (no high voltage but with gas flowing) for more than one year in the previous BaBar data-taking run due to the large beam backgrounds. The first data show that no significant

105 HF remained in the gas. The high-voltage was ramped to 6700 V 0.8 hr after
106 the start of the measurement. After a short delay the HF concentration began
107 to rise. The HF concentration was measured in a 3 hour period with stable
108 beams (time period a). A linear fit of this period, measured a HF production
109 rate of 4.7×10^{-4} μmol/s. After the high-voltage was turned off, the rate of
110 HF capture decreased. The capture rate was measured after one gas volume
111 change (time period b), and later for a period c equivalent to six gas volume
112 changes. We find that HF appears in the gas even well after the high-voltage
113 had been turned off, with a rate of 3×10^{-6} μmol/s nearly 1% of the peak
114 production rate. Although not shown, the amount of HF in the gas remained
measurable for a week after operation of the chamber.

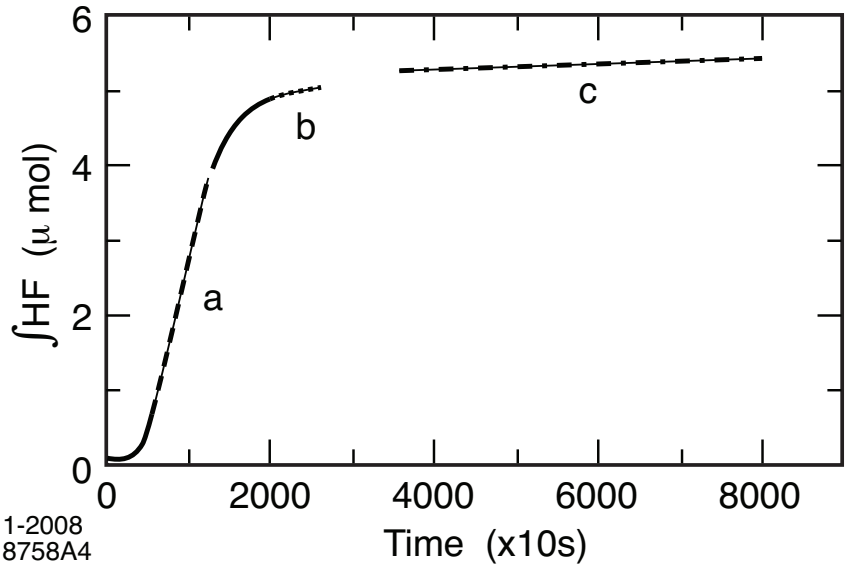

Fig. 5. Measurement of the HF concentration in the test solution as a function of time with the exhaust gas of the bottom chamber in layer 16 of the forward east door bubbling through the solution. Period a corresponds to the time period when the RPC was operating at 6700 Volts. Period b represent the change in concentration measured after the high-voltage was turned off for approximately one volume change. The last period c, represents a measurement of the HF tail after the high-voltage had been off for 6 gas volume changes.

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116 5 Correlation: HF vs current - Streamer RPC

117 A large number of measurements of RPCs with different operating and ambi-
118 ent conditions were made to explore possible correlations with HF production.
119 We studied the dependence of the observed HF rate with the high voltage
120 current. Since only the current that passes through the gas is likely to create
121 HF, we corrected the total current by subtracting off the ohmic contribution

(estimated by scaling the current at voltages below the gas gain turn-on). This study was made for middle chambers (modules 3 and 4 in Fig. 1) which had been operating in streamer mode since installation in 2002. Measurements of the integrated HF production in roughly 24 hour time periods were made over several months and compared to the integrated RPC current. The current was integrated from 3 hours before the start of the HF measurement to 3 hours before the end of the HF measurement. This offset allowed the gas to propagate through the entire chamber before the measurement. The current varied with the PEPII luminosity and operational status. The data is shown in Fig. 6. A clear correlation between the integrated current and the amount of

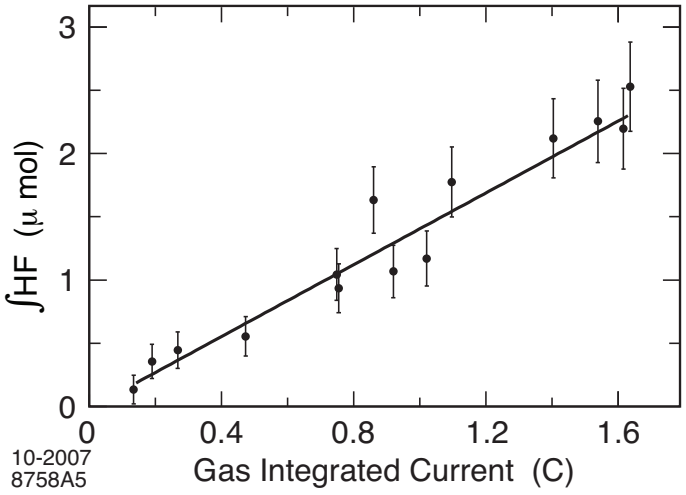

Fig. 6. Daily HF production as a function of the integrated RPC current for a RPC chamber operated in streamer mode.

detected HF is seen. A linear fit to the data in Fig. 6, yields a HF production rate of 1.42 ± 0.11 μmol/C for this RPC. A second streamer mode RPC was also measured and found to have a HF production rate of 2.23 ± 0.23 μmol/C.

6 Correlation: HF vs current - Avalanche RPCs

BaBar has converted several of the highest rate RPCs to avalanche mode operation starting in 2005. Three chambers were tested in saturated avalanche mode in 2005/6. Currently 24 RPCs have been converted to this mode. This situation allows for a comparison of HF production rates in streamer and avalanche mode. The gas mixture used for RPCs in avalanche mode is 19.4% Ar, 4.5% isobutane, 75.5% Freon-134a, 0.6% SF_6. Preamplifiers were inserted between the RPC pick-up strips and the standard front-end electronics to compensate for lower pulse heights in avalanche mode operation. Initial performances have been good with higher efficiencies in the high rate ring around the beamline being demonstrated in all chambers. The average currents in the

RPCs converted to avalanche mode decreased by roughly a factor of four.

We measured the HF concentration in the exhaust gas of a middle chamber which had been operating in avalanche mode for over six months. These measurements were performed simultaneously with the measurements on the neighboring streamer chamber with a second independent probe. In this way the streamer and avalanche RPCs experience nearly identical background and signal conditions.

The avalanche chambers were operated at 9800 Volts. Most of the measurements were made at this voltage, but three measurements were made with high-voltage lowered to 9600 V. The results are shown in Fig. 7. The HF pro-

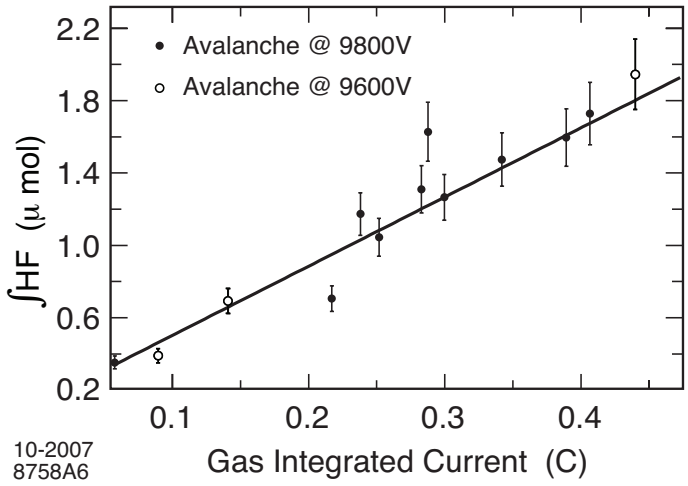

Fig. 7. Daily HF production as a function of the integrated RPC current of a middle RPC chamber operated in saturated avalanche mode. Solid dots represent measurements at the nominal operating voltage of 9800 V. Open dots represent measurements at a voltage of 9600 V. The linear fit is performed only with the nominal voltage data.

duction rate, estimated from the measurements at 9800 V only, is 3.82 ± 0.23 μmol/C. The rate of HF production measured on the avalanche chamber when operated at 9600 V is consistent with the measurements at 9800 V. A second avalanche mode RPC was measured and found to have a lower HF production rate of 1.45 ± 0.14 μmol/C. These values may indicate that avalanche chambers produce more HF per unit charge than the streamer chambers, probably due to the larger Freon-134a fraction, higher voltage, and the presence of SF_6 in the gas mixture. However, since the HF production rate of the avalanche RPCs varies by more than a factor of two, a larger sample of chambers would be needed to draw firm conclusions. We can say that the average amount of HF produced per track in avalanche mode is less than in streamer mode, since the currents drawn by the avalanche RPCs are much less than the streamer mode RPCs.

7 Correlation: HF vs Luminosity

We checked the correlation between HF production and the average PEPII luminosity as shown in Fig. 8. The streamer mode chamber in Fig. 8a has a steeper slope than the avalanche mode chamber shown in Fig. 8b consistent with the conclusions of the previous section, since the RPC currents vary linearly with PEPII luminosity. The streamer mode RPC produces more HF per unit of luminosity than the avalanche mode RPC. To check the consistency of the measurements done with the two electrode probes, a small number of data points were taken with the probes swapped between test solutions. No significant differences were seen.

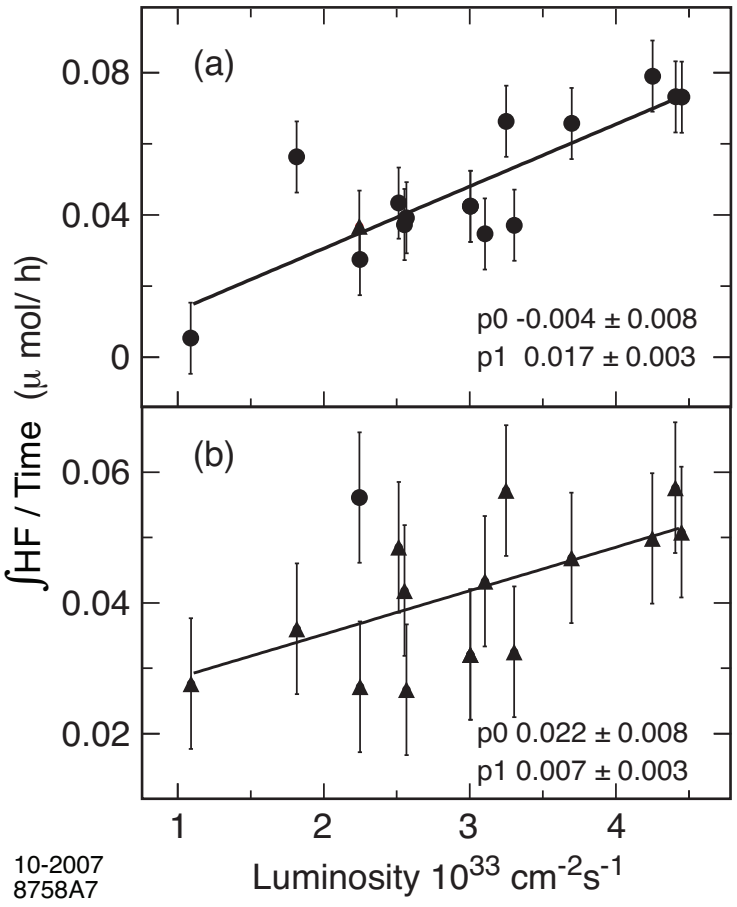

Fig. 8. Integrated HF/h as a function of the instantaneous luminosity of PEPII for streamer chamber (a) and avalanche chamber (b). Circular dots and triangular dots represent measurements with different electrode probes.

8 HF versus Time

The amount of HF in the RPC exhaust gas was measured over a three month period. To compare data with different luminosity and currents, the integrated HF was normalized by the RPC current. These data and the temperatures of the IR hall and endcap steel are plotted in Fig. 9. Different modules produce different amounts of HF. The data show more variability with time than expected from the conservatively estimated errors. No strong correlations were found between the rate of HF production and the temperature, hall humidity, or input gas humidity. These observations are consistent with measurements from the previous year which saw no significant change in the amount of HF when the input gas humidity was changed from 0% to 30% RH.

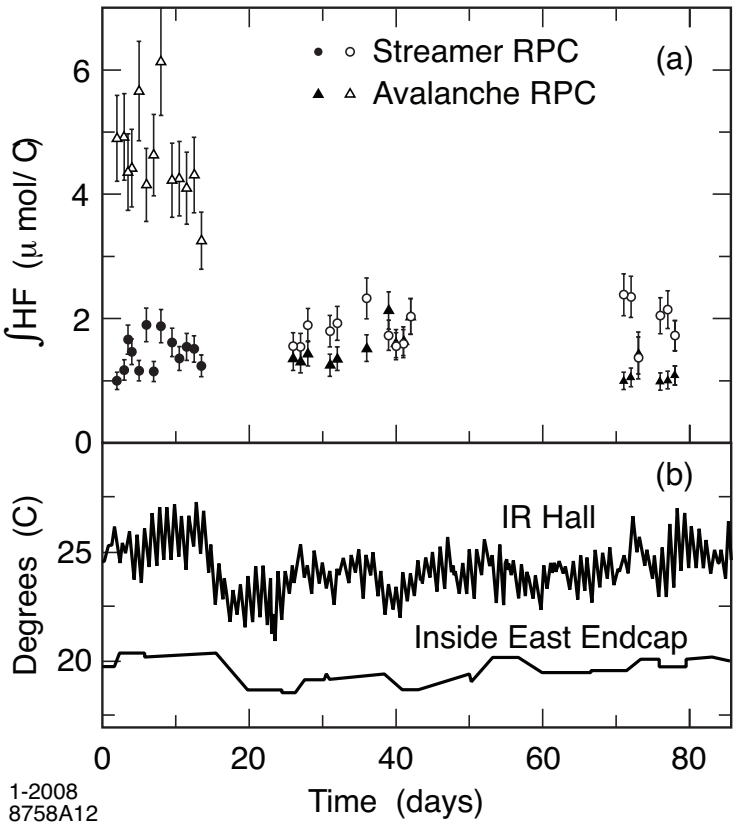

Fig. 9. Integrated HF/C for avalanche and streamer mode chambers plotted versus time in (a): Open triangles - FEM3, Solid circles - FEM2, solid triangles - FEM5, open circles - FEM7. On day 68 the avalanche gas composition was changed to 22.0% Ar, 4.5% isobutane, 73.0% Freon-134a, 0.6% SF_6 and the high voltage was lowered from 9800 V to 9500 V. The IR hall temperature and the temperature inside the forward endcap (layer 10) are plotted in (b).

9 HF Absorption

If HF produces the aging seen in the BaBar chambers, then some fraction of the HF produced in the RPC gas must be absorbed by the inner RPC Bakelite surfaces. To test this hypothesis the HF production rate was measured in a RPC chamber having very different rates in the two high-voltage modules. The RPCs operated in streamer mode with a gas flow of about 70 cm^3/min. The current for the upper module (2 in the numbering scheme of Fig. 1) was $I_{top} \sim 53.2\ \mu A$. The current for the lower module (1) was $I_{bottom} \sim 5.5\ \mu A$. We measured the HF rate with the gas exiting from the bottom module to be $(872 \pm 24) \cdot 10^{-6}$ μmol/s. After reversing the gas flow such that the gas exited the upper (high current module), we measured a HF rate of $(1527 \pm 42) \cdot 10^{-6}$ μmol/s. The measurements are shown in Fig. 10. The observed HF

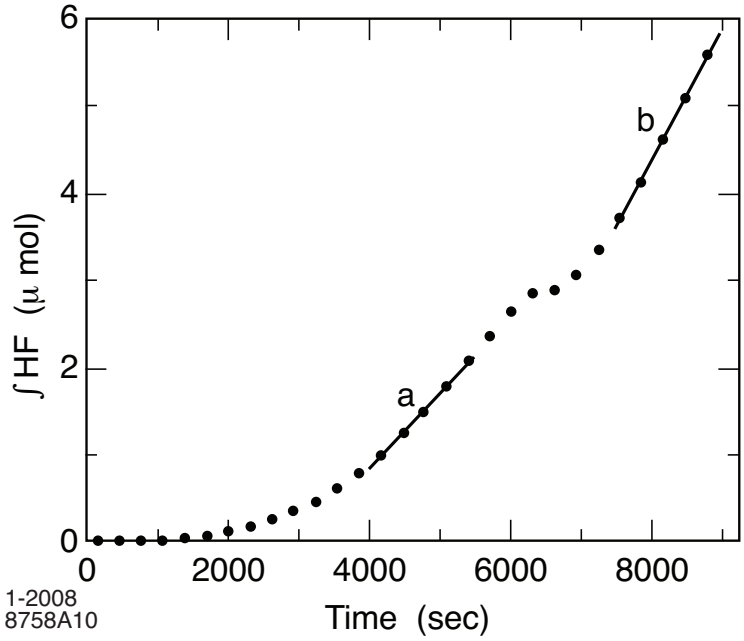

Fig. 10. Measurement of the HF rate in the exhaust gas of a chambers (whose high-voltage modules had very different noise rates) during normal gas flux (0-5500 s) and with reversed gas flux (5500-9000 s). In conditions of reversed gas flux the gas exits from the high-current module.

rate was significantly larger when the gas exhausts directly from the high-current module. This suggests that in the original gas flow configuration part of the HF produced in the high-current module (F_2) was absorbed by the low-current module (F_1). Considering the low-current module as a pure absorber the fraction of HF trapped can be estimated as

$$F_{abs} \simeq \frac{F_2 - F_1}{F_2} = 43 \pm 4\% \qquad (3)$$

A more realistic analysis assumes that the fraction of HF absorbed by the Bakelite surfaces depends only on the Bakelite area. If the backgrounds uniformly illuminate the RPC modules, then on average the HF produced in the gas is exposed to 1/2 the surface area of the chamber in which the HF is produced and 100% of the downstream module. Assuming further that the absorption rates of the two modules are the same leads to the conclusion that 20% of the HF produced in the initial module is absorbed in the initial (upstream) module and 40% is absorbed by the second (downstream) module. Both estimates show that only a fraction of the HF produced in the RPC is flushed from the chamber by the gas flow.

To check if HF was still present in the RPCs after the chambers have been turned off measurements were made on chambers that had been unpowered and flushed for 7 weeks with the nominal gas mixture. After that, the chambers were flushed with pure Ar gas. A residual HF signal was seen in the gas even after 7 weeks. Next, a voltage of 2300 V, producing a total current of about 100 μA was applied. A much higher concentration of HF in the exhaust gas was measured, during and after having switched the high-voltage on. These data are shown in Fig. 11. A significant amount of HF was produced and measured

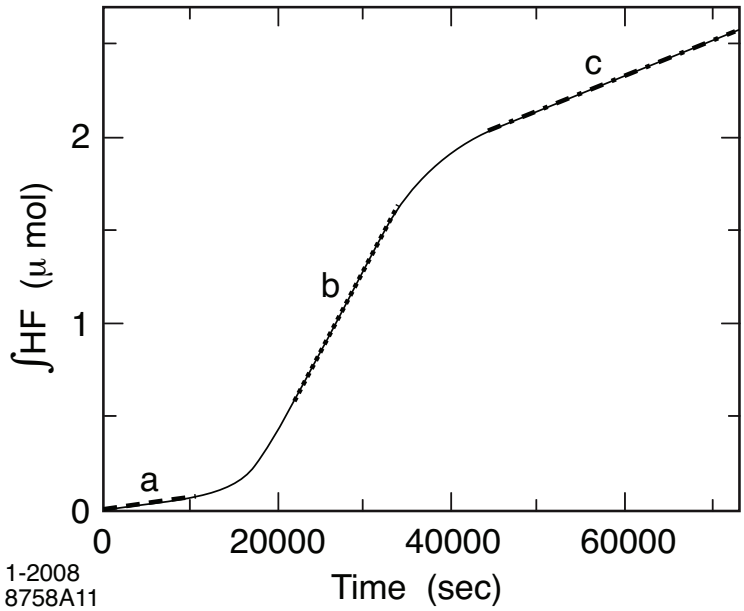

Fig. 11. Measurement of the HF rate in the exhaust gas of a middle chamber when flushed with pure Ar gas. Lines a and c represent linear fits to the intervals with no high-voltage before and after the high voltage was turned on. Line b represents the fit to the interval with 2300 V voltage.

in exhaust gas: $(89.0 \pm 0.1) \cdot 10^{-6}$ μmol/s. Since neither Freon-134a, nor SF_6 is present in the gas mixture, the gathered HF could only be extracted from the inner surface. The extracted HF rate depends on the current drawn by the chamber. HF rate measured in pure Ar with no high-voltage is in-fact significantly reduced, as shown in Fig. 11. These data suggest that a significant

fraction of the HF ions trapped on the chamber surface can be removed by flushing many fresh gas volumes, and/or by applying high-voltage in a pure Ar gas flow.

10 Summary

In conclusion, we have studied the HF production rate in second generation BaBar RPCs operating in streamer or avalanche mode. The amount of HF in the exhaust gas was strongly correlated to the current and to the number of tracks crossing the chamber. Less HF was measured for avalanche chambers than for streamer chambers with similar efficiency and background. This implies that we can expect that aging of the avalanche mode RPCs at the LHC will be slower than that observed in the BaBar RPCs. We have not found any significant correlation of the HF rate with the temperature or with the relative humidity of the input gas.

The amount of HF decreased significantly after the RPC high voltage was removed, but remained measureable for more than 200 gas volume changes. More than 1/2 of the HF produced by an upstream HV module is either self-absorbed or absorbed in the downstream module. When processed with Ar at 2300 V much of the absorbed HF can be removed from the chambers.

These findings are consistent with the following model of RPC aging. HF is produced in the RPC gas at a rate proportional to the number of streamers or avalanches.Most of the HF is absorbed by the linseed oil/Bakelite inner surfaces of either the original RPC or by any RPC downstream in the gas flow. The amount of HF in the HV surfaces builds up over time, reduces the surface conductivity, and causes higher currents and increased noise. Flushing the chambers when off reduces the amount of HF and partially reduces observed current and noise increases. Processing with Ar can further reduce the observed current and noise increases.

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