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Resistive plate chambers in running and future experiments

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Abstract. This document surveys the RPC-based detection systems of running and future collider experiments focusing on the implications of the choice of some basic detector features: number of gaps, electrode material and operating mode. The muon identification systems of the B-factory experiments BaBar and Belle is described and the RPC performance since the first operation of the detectors is briefly reported. The trigger systems of the future LHC experiments ALICE, ATLAS and CMS are discussed and some results obtained in the research and development programs carried out by the Collaborations are reported.

PACS. 29.40.Cs Resistive Plate Chambers; muon; trigger; RPC; ATLAS; ALICE; BaBar; Belle; CMS

1 Introduction

Resistive plate Chambers (RPCs) [1] are parallel plate gaseous detectors that outstand for the excellent time resolution and the relatively low production cost per unit area. These characteristics make them good candidates in any high energy physics experiment demanding large and fast detecting surfaces with space resolutions of the order of cm.

Various RPC configurations exist. A proper choice of the RPC structural parameters allows to tune the detector in terms of time and space resolution, rate capability and intrinsic noise. Single and double gap (~ 2 mm wide) RPCs have a time resolution of a few ns. They can be used for the large muon systems of experiments at colliders. Multi-gap (5 or more gaps $\sim 200\,\mu$m wide) RPCs [2] can achieve a time resolution of less than 100 ps, therefore they are an option for Time-of-Flight (TOF) systems. Operation in proportional mode [3], rather than in the classical streamer mode, causes smaller amounts of charge to be produced in the gas and, therefore, allows the RPC to stand efficiently detecting rates up to $1\,\mathrm{kHz\,cm^{-2}}$. Aging effects related to the accumulated charge are also reduced when the detector is operated in proportional mode. The bulk resistivity (ρ) of the electrodes is also crucial for good rate capability [4]. Bakelite electrodes, which can be produced with ρ down to $10^9\,\Omega\,$cm, allow operation in high rate environments. On the other hand, standard glass electrodes have a ρ not below $10^{12}\,\Omega\,$cm. However, bakelite electrodes, contrary to glass made ones, are normally treated with linseed oil for surface smoothing and UV absorption. The oil treatment allows to reduce intrinsic detector noise and spark occurrence.

The main characteristics of the RPCs chosen for running and future collider experiments are listed in Table 1. Only the RPC-based muon systems are reviewed in the following.

2 B-factories experiments

BaBar [5] and Belle [6] are dedicated B-physics detectors running at the asymmetric electron-positron B-factories PEP-II (SLAC) and KEK-B (KEK), respectively. The common physics goals of the two experiments require the identification of muons and neutral hadrons with high efficiency over a broad momentum spectrum ranging from 600 MeV to some GeV. To this aim both detectors have instrumented the segmented flux return iron of their superconducting solenoid with several RPC detecting layers. Up to 19 (15) layers are present in BaBar (Belle), covering a total area of 2300 (2200) m^2. Pattern recognition [7,8] is based on the matching of the hits in the RPC layers with the tracks measured in the inner detector.

2.1 BaBar RPCs

The history of the BaBar RPC efficiency is shown in Fig. 1. The average efficiency of the barrel (top), forward (middle) and backward (bottom) RPCs is plotted versus time. In each plot full circles refer to all RPCs, while open triangles consider only the RPCs with efficiency greater than 10%. A significant and constant degradation of the efficiency of the detectors is evident.

During initial operation in summer 1999, most chambers showed an increase in dark current and a drop in efficiency following high external temperatures of $30° \div 35°$. After the installation of a cooling system to restore temperature control in the iron gaps containing the RPCs, neither the efficiency nor the original dark current at 20° could be recovered. Extensive tests and inspections done on some of the damaged BaBar RPCs [9] led to the conclusion that the observed behavior could be partly related to excess of uncured linseed oil on the electrode surfaces.

Table 1. RPC characteristics in running and future collider experiments

experiment	operating mode	# gaps	gap width (mm)	electrodes material, $\rho\,(\Omega\,\mathrm{cm})$	gas mixture (%)	readout
BaBar	streamer	1	2	oiled bak., $10^{11} \div 10^{12}$	$60\,Ar + 35\,C_2H_2F_4 + 5\,C_4H_{10}$	strips xy
Belle	streamer	2	2	glass, $10^{12} \div 10^{13}$	$30\,Ar + 62\,C_2H_2F_4 + 8\,C_4H_{10}$	strips xy
ALICE TRI	streamer	1	2	oiled bak., $\approx 3 \times 10^{9}$	$51\,Ar + 41\,C_2H_2F_4 + 7\,C_4H_{10} + 1\,SF_6$	strips xy
ATLAS	prop.	1	2	oiled bak., $\approx 10^{10}$	$96.7\,C_2H_2F_4 + 3\,C_4H_{10} + 0.3\,SF_6$	strips xy
CMS	prop.	2	2	oiled bak., $\approx 10^{10}$	$96\,C_2H_2F_4 + 3.5\,C_4H_{10} + 0.5\,SF_6$	strips x
STAR	prop.	5	0.22	glass, $\approx 10^{13}$	$95\,C_2H_2F_4 + 5\,C_4H_{10}$	pads
ALICE TOF	prop.	10	0.25	glass, $10^{12} \div 10^{13}$	$90\,C_2H_2F_4 + 5\,C_4H_{10} + 5\,SF_6$	pads

At the end of the year 2000 a limited number of chambers of the forward endcap were replaced with new ones produced with a much smaller amount of oil, which was also cured. The new RPCs installed in the outermost layers, which are subject to the highest radiation flux, started showing significant increase in dark current and declining efficiency after 140 days of operation. The average detection rate in these layers was a few $\mathrm{Hz\,cm^{-2}}$. The remaining new RPCs have been losing efficiency at a much lower rate ($< 3\%$ per year).

At the end of 2002 (not shown in Fig. 1) all the old chambers of the forward endcap were replaced. With respect to the chambers installed in 2000, these RPCs were produced with better quality control and less oil. No problem has been reported in the first months of their operation.

The analysis of the replaced BaBar RPCs has put in evidence the role of chemical processes [10], occurring during the operation of the detector, which may alter the physical and chemical properties of both bakelite and linseed oil.

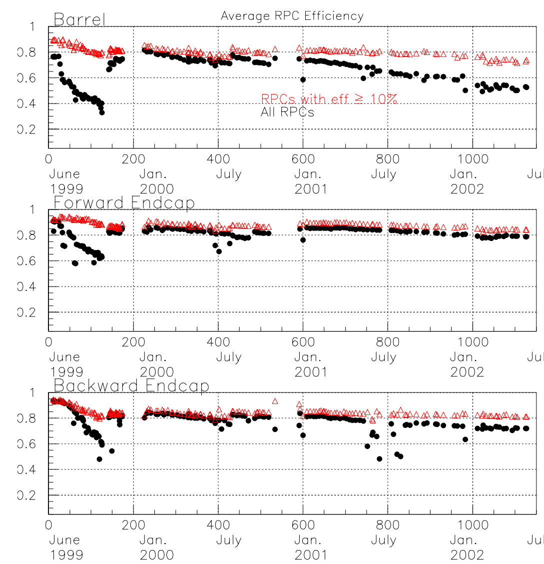

Fig. 1. Average efficiency versus time for the barrel (*top*), forward (*middle*) and backward (*bottom*) BaBar RPCs. Full circles refer to all RPCs, while open triangles consider only the RPCs with efficiency greater than 10%

2.2 Belle RPCs

Two main features differentiate Belle RPCs from BaBar ones: Belle RPCs are double gap and have glass electrodes. Their performance has been stable in time except for a problem which occurred soon after first operation. Some water permeated through the gas system tubing and caused increase in dark current and efficiency drop in several chambers. The water is also believed to have caused formation of HF, which may have partially corroded the glass surface. After drying the detectors and replacing the tubing, efficiency and currents were almost restored. No major aging phenomenon has been observed so far. However, the model that describes conduction in standard glasses [10] predicts that the operation of the detector causes a permanent increase in glass surface resistance, which may lead to observable effects in the long term. Apart from this potential problem, the high resistivity of glass represents a limitation for Belle from the point of view of rate capability. As shown in Fig. 2, a clear correlation exists between the efficiency of the chambers and the detection rate at a luminosity of $5\times10^{33}\,\mathrm{cm^{-2}s^{-1}}$. This is becoming an issue for Belle given the constant progress in luminosity performed by KEKB during the last years and its foreseen upgrade. It is worth noting that semiconductive glass would allow to overcome the limitations described above, but at a price far higher than standard glass.

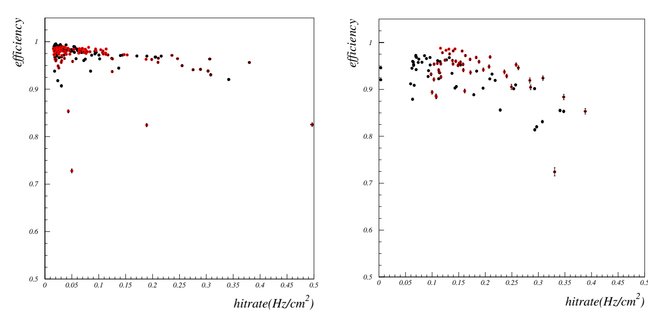

Fig. 2. Efficiency versus rate for the barrel (*left*) and endcap (*right*) Belle RPCs at a luminosity of $5 \times 10^{33}\,\mathrm{cm^{-2}s^{-1}}$

3 LHC experiments

Three of the four LHC experiments, ALICE [11], ATLAS [12] and CMS [13], are equipped with a muon triggering system based on RPCs. The Collaborations have recently started detector mass production.

The ALICE dimuon spectrometer is equipped with an RPC trigger [14] that cover $150\,\mathrm{m}^2$. The RPCs are foreseen to be operated in streamer mode and very low resistivity bakelite (see Table 1) is used in order to cope with the expected maximum rate of $40\,\mathrm{Hz\,cm}^{-2}$.

ATLAS and CMS have much larger RPC systems. The ATLAS Level-1 Muon Trigger [15] is implemented in the barrel region with $7000\,\mathrm{m}^2$ of single gap RPCs arranged in three stations (two RPC layers per station) at increasing radial distances. CMS has an RPC trigger [16] in both barrel and endcap region ($6000\,\mathrm{m}^2$ in total). Up to six double gap RPC layers are foreseen in the barrel and four of them in the two endcaps. The trigger algorithm is based on 4/6 and 3/4 coincidences in both ATLAS and CMS. At the nominal luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ no more than $10\,\mathrm{Hz\,cm}^{-2}$ are expected in the barrel region of both experiments. On the other hand, the forward CMS RPCs may have to stand a rate of up to $200\,\mathrm{Hz\,cm}^{-2}$. Given the quite large uncertainties on the rate estimations, the two experiments have chosen to operate their chambers in proportional mode, which also limits aging effects. Electrodes with oiled bakelite having $\rho \approx 10^{10}\,\Omega\,\mathrm{cm}$ is the choice of ATLAS. CMS has made exactly the same choice in the barrel and in the part of the endcap at pseudorapidity less than 1.6, where the rate is expected not to exceed $20\,\mathrm{Hz\,cm}^{-2}$. The remaining endcap RPCs, which have been recently staged, are non-oiled. It is worth noting that CMS, fearing aging effects related to the presence of oil, had initially decided to adopt non-oiled bakelite everywhere. However, the noise level of several tens of $\mathrm{Hz\,cm}^{-2}$ observed on non-oiled RPC prototypes and the improvements made in the oiling procedure have recently persuaded the Collaboration to go for the oil treatment.

ATLAS and CMS carried out extensive research and development programs with the aim to better understand and improve the proportional mode operation. ALICE worked on developing the streamer mode operation, in particular from the point of view of rate capability. In more recent years, also as a consequence of the problems encountered by BaBar, research focused on tests of aging. The result of one of these tests [17] is shown in Fig. 3, in which the efficiency of an ATLAS prototype RPC is plotted versus the high voltage for different incident rates. The detector had been previously exposed to irradiation for 12 equivalent LHC years. Full efficiency is achieved even at a rate of $300\,\mathrm{Hz\,cm}^{-2}$, though a higher voltage must be applied.

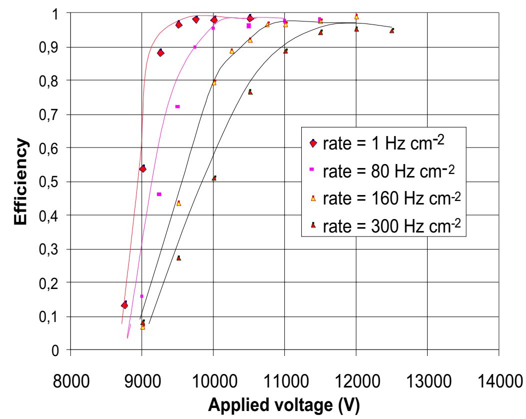

Fig. 3. Efficiency of an ATLAS RPC irradiated for 12 equivalent LHC years [17] vs. applied voltage for different incident rates

4 Conclusions

A survey of the RPC-based muon systems in running and future experiments has been presented in this document. The experience of BaBar evidenced serious aging issues related to oiled bakelite electrodes. A lot of progress has been made in the understanding of these phenomena, which has led to significant improvements in the latest bakelite RPC productions. RPCs with standard glass electrodes have been performing well in Belle, but are only adequate for operation in low rate environments. The LHC experiments have recently started detector mass production after a long phase of R&D and aging studies. The obtained results comply with the LHC requirements.

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