Results on long-term performances and laboratory tests of the L3 RPC system at LEP

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The RPC detectors in the L3 experiment at LEP work as a trigger system for the Forward–Backward Muon Spectrometer. It consists of 192 bi–gap RPCs working in streamer mode. We monitored the behaviour of the system over seven years of data taking at LEP. To investigate the aging of the RPCs after this long–term operation, we report the main results obtained from 1994 to 2000, together with the results of tests performed on some RPC chambers in our test site in Napoli with cosmic rays after the dismantling of L3.

1. Introduction

The detection of muons and the measurement of their momenta is achieved in the L3 experiment by the Muon Spectrometer. It consists of a barrel (installed from the beginning of the L3 operation) and of an end–cap component: the Forward-Backward (F/B) Muon Spectrometer [1] (installed in two phases during the winter shut–downs of the LEP machine in 1994 and 1995). This spectrometer extends the polar angle coverage for muon detection from 44° to 22° as required by the higher energies of LEP2.

The Resistive Plate Counters (RPCs) are the Level 1 trigger detectors of the F/B Spectrometer.

The spectrometer is divided into two (forward and backward) octagonal rings made of 16 half–octants, each consisting of three drift chamber layers (FI, FM and FO), the magnet door (magnetized with a toroidal field of 1.2 T) and two RPC layers placed between the external drift chamber layers FM and FO.

Each RPC layer is segmented into three chambers of trapezoidal shape and different sizes, which overlap to avoid dead areas. A cross section of the spectrometer is shown in Fig. 1.

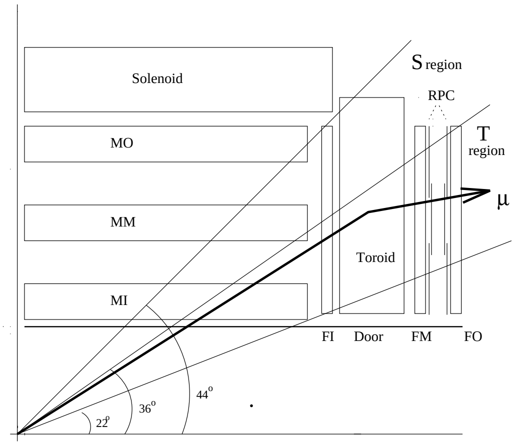

Figure 1. Cross section of the Forward–Backward Muon Spectrometer of L3. The MI, MM and MO are the drift chambers of the Barrel Spectrometer. The RPCs are the trigger detectors in the T (Toroidal) region.

2. The RPC system

The RPC system of the L3 experiment consists of 192 bi–gap chambers working in streamer mode covering a total area of more than 300 m^2.

A bi–gap RPC is made of two separate gas vo-

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lumes (gaps), with independent high voltage and a unique read-out plane for each (Fig. 2). The gas gap is formed by two bakelite plates (2 mm thick, $\rho \simeq 2 \times 10^{11} \Omega$ cm) kept at 2 mm distance by means of a grid of round PVC spacers with 10 cm pitch. The external surfaces of the bakelite plates are painted with a graphite solution in order to apply high voltage. The internal surfaces are varnished with linseed oil with the technique adopted until 1996.

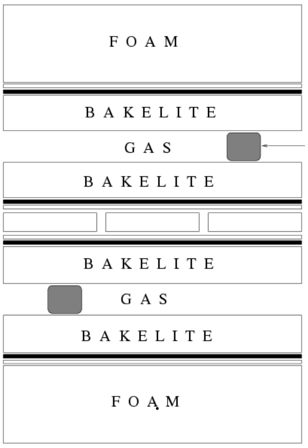

Figure 2. Internal structure of a bi–gap RPC (drawing not in scale).

The gap is filled with an argon, isobutane and freon gas mixture (58:38:4). In 1996 the gas mixture was modified by replacing freon with $C_2H_2F_4$, resulting in an $Ar/iC_4H_{10}/C_2H_2F_4$ (57:37:6) mixture. The HV working point, determined in a long series of tests performed both in Napoli and at CERN before the installation of the detectors, was 7600 V before 1996 and about 7200 V afterwards with the new gas mixture.

The read–out plane is placed between the two gas gaps and is segmented into 32 strips with a pitch of 3.1 cm. The total number of RPC channels is 6144.

Both sides of the read–out electrodes are equipped with front–end electronic boards. Signals are amplified, discriminated ($\simeq$60 mV), and converted to shaped (200 ns) TTL differential outputs. A fast signal formed on each board from the OR of 16 strips is also generated for time measurement.

The RPC trigger system provides a fast identification of muons coming from the interaction vertex of L3. The 96 (FM) + 96 (FO) strip signals of each octant are sent to a Zero Suppressor module strobed by the coincidence of the FM and FO RPC planes. The output is a list of the addresses of the fired strips which is sent as input to the Track Finder module. It searches for a coincidence within roads compatible with muons coming from the vertex in a 96×96 programmable trigger matrix. The pattern of the roads, depending on the muon polar angle and momentum as well as on the magnetic deflection and on the multiple scattering in the iron magnet door, was simulated using Monte Carlo techniques.

The typical trigger time (for 2 + 2 strips fired) is about 1.5 μs. When such a coincidence is found, a trigger signal is generated and together with the information from other detectors gives a level–1 muon trigger for the Forward–Backward Spectrometer.

3. The RPC performances at LEP

During the 7 years of L3 operation after the installation of the F/B Spectrometer, the behaviour of the RPC was continously monitored in terms of “singles” rates and currents drawn by each of the 32 high voltage channels. The singles rate is periodically read during data taking. Fig. 3 (upper plot) shows the mean value per square meter over the 192 bi–gap chambers from 1994 to 2000. An increase in 1996 due to the change of the gas and a constant, slow, reduction of the rate in the following years is evident. The mean value of the currents shows (Fig. 3 lower plot), after the large rise in 1996, the same decreasing trend.

The RPC performances have been analysed as well during the same years. We used dimuon samples from Z decays during LEP1 for which good track reconstruction is provided both in the L3 central tracking detector and in the muon spectrometer. In the LEP2 run, due to higher LEP energies, the dimuon cross section reduced drastically and we used a sample of inclusive single

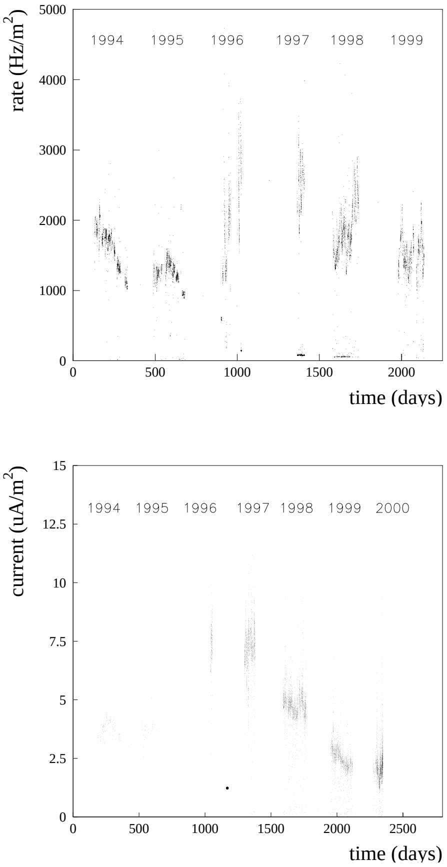

Figure 3. Single Rate distribution (upper) and current distribution from 1994 to 2000 (lower).

muons with lower momenta.

The RPCs provide both position and time information, so we measured each year the space and time resolutions together with the detector efficiency in order to determine the behaviour of our detector. For more details on the RPC performances and the event selection cf. Refs. [2]

First, we determine the cluster multiplicity. Charged particles crossing a single RPC gap produce a discharge in the gas that is a few mm wide. Large track slopes could broaden the discharge and the presence of two discharges in the two gas gaps could induce the signal on more than one strip (cluster). The cluster multiplicity is given by the number of adjacent strips belonging to it. Fig. 4 shows the multiplicity year by year. The increase of the mean multiplicity from about 2 to about 3 is due to the change of the gas in 1996.

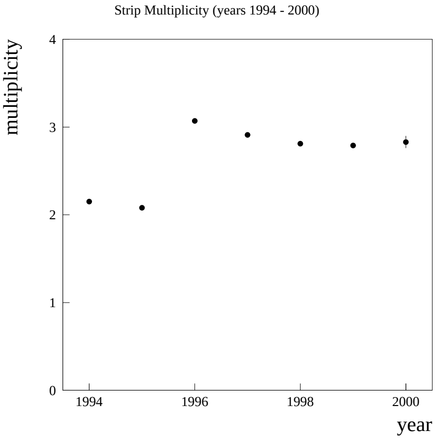

Figure 4. Cluster Multiplicity from 1994 to 2000.

The centre of gravity of the strip cluster gives the RPC position measurement. The resolution of such a measurement is given by comparing it with the position measurement given by the spectrometer. This is just the impact point on the RPC strip plane of the muon track. The difference of the two measurements is a Gaussian curve from which we extract the resolution. The RPC space resolution over the seven years is shown in the upper plot in Fig. 5, and it is quite stable around a value slightly greater than 10 mm, which must be compared with the strip pitch of 31 mm.

The time measurement is provided by the Fast-OR signal of groups of 16 strips. In order to obtain the resolution of our measurement we have to correct the measured time for three main effects: (a) different cable lengths and electronic response among channels, (b) time of flight of the muon and (c) time of propagation of the signal along the strip (about 5 ns/m). Our results, after having taken into account these effects, are shown in the lower plot in Fig. 5. After seven years of running, the RPC time resolution is about 3.5 ns.

Another important parameter from which the status of a detector after many years of running can be deduced is the detector efficiency. We define a detector as efficient if, when a muon crosses the detector, a response from a strip near by the

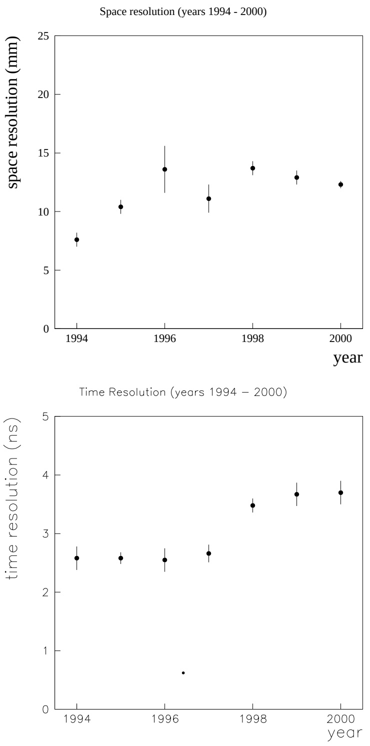

Figure 5. RPC space resolution (upper) and RPC time resolution from 1994 to 2000 (lower).

track impact point on the strip plane is found. The global efficiency of the system is reported in Fig. 6.

A small loss of efficiency is observed from 1994 to 1999 (from 99.5% to 97.0%). A larger loss is found in 2000.

Possible causes of the inefficiency are: (a) electronic failures, (b) change of the gas, (c) gas leaks.

(a) The electronic failures are due to LEP beam lost in the L3 detector hitting the RPC chambers. Because of the high particle rate, large currents are generated in some of the front–end chips causing them to break. They can be replaced, but not immediately.

(b) The change of the gas in 1996 caused an increase of current on the HV channels. We had to lower the HV and since many gaps are powered by the same HV channel, this caused some chambers to move into an unstable region around the knee of the efficiency plateau.

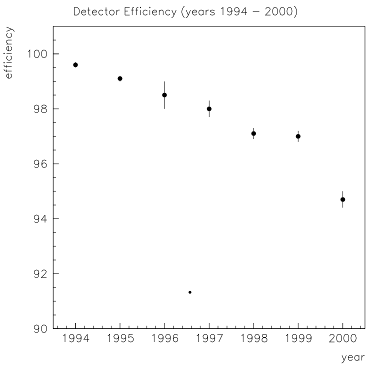

Figure 6. RPC global detector efficiency from 1994 to 2000.

(c) The gas leaks that appeared on some chambers could be fixed only by glueing the gas volumes. This operation was possible, unfortunately, only during the winter shutdowns. Consequently, these chambers operated with lower efficiency for the remaining part of the year.

The inefficiencies of the RPC system have been investigated in more details by analyzing independently each octant. We compared the octant efficiencies over the seven years and found that the decrease of efficiency averaged over all the octants is quite small even if some octants showed larger inefficiency. This is particulary true for the year 2000 where 6 octants with large inefficiencies each showed one of the problems (a) - (c) reported above. From this analysis we conclude that the large drop of efficiency in 2000 is due especially to inefficiencies localised in specific octants and only in small part to the decrease of the average efficiency.

To go into more details, we studied also the efficiency of single chambers. In the first year of operation all the RPC chambers presented an efficiency close to 100% and in the following years this quantity moved slowly towards lower efficiency values. In the year 2000 the region of low efficiencies is more populated than in 1994, but 75% of the chambers still have an efficiency greater than 90%.

This could be considered as good behaviour for such a large system after many years of operation. Unfortunately, these results are limited by the very low statistics of the selected muon tracks hitting a single RPC chambers. The error on the efficiency is in the range from 1% to 10%. To confirm our findings it was decided that more detailed studies with cosmic rays were necessary. So, thanks to the dismantling of the L3 experiment in winter 2001, we had the opportunity to bring some RPC chambers to Napoli.

4. The RPC Tests in Napoli

Ten RPC chambers, corresponding to 20 single gap, were shipped to the test site in Napoli to be analysed in detail under cosmic rays.

The advantage of the tests performed in Napoli is the large statistics of cosmic muon tracks that can be acquired allowing us to measure the efficiency with a precision of the order of 0.1% and the possibility to carry out a scan of the RPC surface with the same precision in order to find regions of local inefficiency.

Another difference with respect to the analysis of the L3 data is the measurement of the single gap efficiency by switching off the other gap of the RPC.

The tests have been performed using the test site designed to analyse the ATLAS RPCs. The set-up is composed of a trigger and a tracking system. The trigger system comprises eight scintillators; four of them, covering a surface of 1 m^2, are mounted in a module on the upper side of the station and the other four in a module on the lower side.

The tracking system is composed of two drift chambers, each mounted on one module and containing 4 layers of 12 single wire cells. The layers are rotated with respect to each other in order to measure the position in two dimensions. The single wire resolution is of the order of 1 mm.

The RPC chambers to be analysed are placed between the two modules. They can move along one direction to completely cover the surface of the RPC over separate data runs.

The first kind of test performed was the determination of the single gap efficiency. In Fig. 7 the efficiencies for the 20 gaps are shown. Four gaps belonging to two RPCs with well known efficiency problems from the L3 analysis show very low efficiency, the remaining gaps show instead a good behaviour; 15 of them have efficiencies greater than 90%.

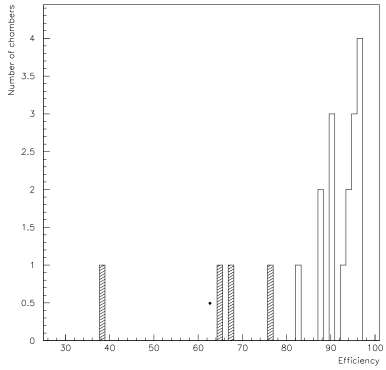

Figure 7. Single-gap efficiency distribution.

The two inefficient RPCs were investigated in more detail. Both were analysed by scanning their surfaces in order to find, on each single gap, the presence of a localised region of inefficiency. The results obtained are similar for all the four gaps. The inefficiencies are distributed in an uniform way all over the gap and no evidence of local inefficiency is found. The same is true also for the other three gaps.

These gaps also showed small problems with gas leaks in L3. To study in more detail the possible causes of the inefficiency, we decided to disassemble the RPC by removing the hard mechanical structure keeping together the two gaps and opening one of the two gas volume in order to verify the status of the inner bakelite surfaces after seven years of operation.

RPC chambers used in other experiments and built with similar, if not identical techniques, show sometimes inefficiencies due to the non-polymerisation of the linseed oil [3].

At a first glance the internal surfaces of the bakelite plates appeared to be in good status without any oil drops due to unpolymerised linseed oil.

We sent a sample of the surface to a chemical laboratory at Turin University. They first analysed the surface with an optical microscope finding some small dark regions randomly distributed. Then they studied the bakelite with FTIR spectroscopy (Fourier Transform Infrared Spectroscopy) through micro–ATR (Attenuated Total Reflectance), which allows a direct analysis of the surface with a depth between 1 and 4 microns [4]. The infrared spectrum of the surface has all the structural characteristics of polymerised linseed oil without any degradation.

The infrared spectrum of the dark regions is typical of bakelite no longer covered by the oil. No other substances were found on the surface. The results of this chemical analysis proved a great stability of the internal bakelite surfaces.

However, the bakelite plates of the gap under observation showed signs of very large mechanical stress that could have changed the thickness of the gas volume. We do not know how much this stress could contribute to such a large inefficiency.

We compared this non-efficient RPC with a good one having efficiency greater than 95% uniformly distributed. The status of the gas volume was similar to the other RPC. The only difference was the absence of any mechanical stress. More studies are necessary to get to a conclusion about the real causes of the inefficiency.

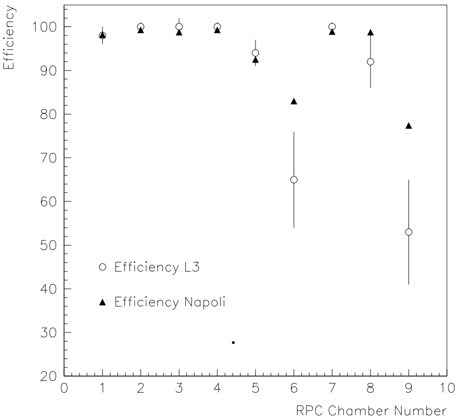

Figure 8. Bi–gap efficiency for the RPC chambers under test.

In order to compare the results obtained with L3 and Napoli data, we took a sample of data with both gaps switched on for each RPC, the same gas mixture and the same HV working points. Fig. 8 shows the L3 and Napoli efficiencies for the 9 chambers under observation. One of the ten chambers has been excluded because of the low statistics of L3 data. There is good agreement between the results especially when the efficiencies are greater than 90%. Only for the two known bad RPCs there is a disagreement of about two sigma and the L3 results seem to be underestimated with respect to the Napoli ones.

5. Conclusions

The conclusion we can draw from the test performed in Napoli on a small sample of the RPC that have been used on the L3 experiment for 7 years are the following:

(a) The single gap efficiency distribution shows that 15 out of 20 gaps have efficiencies greater than 90%. Four gaps with very low efficiencies belong to RPCs that used to show the same problems in the L3 analysis.

(b) The results of the analysis performed with the L3 physics data, even if limited by a very low statistics, are in good agreement with the high-statistics results obtained in Napoli with the possibility of tuning the parameters of each chamber. We can conclude that the analysis performed in Napoli confirms the results obtained in L3 and claim that 75% of the chambers have efficiencies greater than 90% after seven years of running.

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