Resistive Plate Chambers for the ALICE muon arm

R. Arnaldi[a], A. Baldit[b], V. Barret[b], N. Bastid[b], G. Blanchard[b], E. Chiavassa[a], A. Colla[a*], P. Cortese[c], P. Crochet[b], G. Dellacasa[c], N. De Marco[a], A. Devaux[b], P. Dupieux[b], A. Ferretti[a], B. Forestier[b], M. Gagliardi[a†], M. Gallio[a], R. Gemme[a], S. Grygorian[b], F. Guerin[b], R. Guernane[b], C. Insa[b], F. Jouve[b], F. Manso[b], P. Mereu[a], A. Musso[a], C. Oppedisano[a], A. Piccotti[a], F. Poggio[a], P. Rosnet[b], L. Royer[b], P. Saturnini[b], E. Scomparin[a], G. Travaglia[a], E. Vercellin[a] and F. Yermia[a].

[a]Università di Torino-Dip. di Fisica Sperimentale and INFN-Sez. di Torino, Via P. Giuria 1, 10125 Torino, Italy

[b]LPC Clermont-Ferrand, IN2P3/CNRS et Université B. Pascal, 63177 Aubière Cedex, France

[c]Università del Piemonte Orientale-Dip. di Scienze e Tecnologie Avanzate, Corso Borsalino 54, 15100 Alessandria, Italy

The muon arm of the ALICE experiment at the LHC will study heavy flavour production in heavy-ion, p-A and p-p collisions, through their muonic decays, within the frame of the expected Quark Gluon Plasma formation.

The trigger system of the muon arm consists of four plans of 18 single gap Resistive Plate Chambers (RPC), arranged in two stations covering an area of about 5.5 × 6.5 m^2 each.

The choice of the trigger detectors is the result of an intense R&D program. Beam tests have shown that low resistivity ($\simeq 10^9 \Omega$ cm) RPCs meet the ALICE requirements in terms of efficiency, rate capability, position and time resolution. Two different gas mixtures have been studied: a streamer mixture for heavy ion collisions and a highly saturated avalanche one for p-p collisions. Ageing effects on the detector have been investigated at the CERN Gamma Irradiation Facility for both the streamer and highly saturated avalanche modes.

RPCs have been assembled in Torino; all chambers have been tested with cosmic rays to select the 72 final detectors (plus a number of spares). All RPCs have been characterised and results stored in a database: these include efficiency, cluster size, noise, dark and leakage current.

An overview on the tests of the final RPCs is given together with the preliminary results of the ageing test performed on two small prototypes operated in highly saturated avalanche mode.

1. INTRODUCTION

The muon spectrometer[1] of the ALICE[2] experiment at LHC has as its primary goal the detection and analysis of heavy quarkonia (J/ψ, Υ and excited states) in heavy ion collisions (mainly Pb-Pb, $\sqrt{s}$= 5.5 TeV per nucleon pair), through their muonic decays, in the frame of the expected Quark Gluon Plasma formation: according to theoretical predictions[3], the production of such resonances should be strongly affected by a deconfined medium such as QGP. Data will also be taken in p-p collisions at 14 TeV and in p-A collisions, which will provide a baseline for the analysis.

The ALICE muon spectrometer is composed of a dipole magnet, three absorbers, a tracking system composed of 5 stations of Multiwire Proportional Chambers with pad readout, and a trigger system composed of four planes of Resistive Plate Chambers arranged in two stations.

The Pb-Pb collision rate is expected to be about 8 kHz. Since the maximum trigger rate that can be tolerated by the acquisition system is 1kHz, a cut on the transverse momentum (p_T) of the tracks must be applied to eliminate low p_T background from light hadron decays (Fig. 1). This is done by means of two trigger stations that

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[*] Presently at CERN

[†] Corresponding author, e-mail: gagliard@to.infn.it

provide an estimate for the transverse momentum of muons from their deviation in magnetic field.

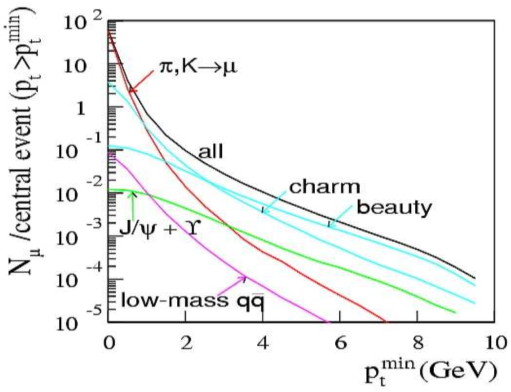

Figure 1. Number of muons within the spectrometer acceptance with $p_T > p_T^{min}$ in a central Pb-Pb collision at 5.5 TeV per nucleon pair, as a function of p_T^{min} (figure from Ref. [1]).

The p_T cut applied on muons will be 1 GeV/c (optimised for charmonium states) and 2 GeV/c (for bottomonium), thus reducing the trigger rate in Pb-Pb collisions to about 500 (90) Hz for opposite sign dimuons from charmonium (bottomonium), while keeping an efficiency of about 70% (90%).

The trigger stations are located at 16.1 m and 17.1 m from the interaction point; they are composed of two parallel detection planes each. Each plane is composed of 18 Resistive Plate Chambers[4], that come in three different shapes. The size of the detectors ranges from 72 × 210 cm^2 to 76 × 276 cm^2. The detectors will be read on both sides with orthogonal strips. The pitch of the strips ranges from 10.6 mm to 45.6 mm, depending on both the position of the RPC in the plane and the distance of the plane from the interaction point.

2. RPCs for the ALICE muon arm

After extensive research devoted to the optimisation of spatial resolution[5] ($\sigma \simeq 5$ mm with 2 cm wide strips in streamer mode), rate capability[6] (up to 100 $\mathrm{Hz/cm}^2$) and detector lifetime[7,8], the design of the detector has been defined: the ALICE RPCs are single gap (2 mm) detectors, with low-resistivity bakelite electrodes ($\rho = 3 \div 9 \cdot 10^9 \Omega\mathrm{cm}$) internally coated with a double layer of linseed oil. For A-A collisions, a wet streamer gas mixture will be used, made of 50.5% Ar, 41.3% $C_2H_2F_4$, 7.2% i-C_4H_{10} and 1% SF_6. For p-p collisions, a highly saturated avalanche mixture will be used: it will be described in detail in Sec. 4.

The streamer signal will be discriminated by means of the ADULT[9] Front End Electronics, using a dual threshold method that provides the timing information from the avalanche precursor of the streamer, thus improving the time resolution (which is of the order of 1÷2 ns).

3. Testing of the final detectors

The gas gaps for the ALICE RPCs have been produced by General Tecnica (Colli, Italy); quality assurance[10] on the gas gaps has been performed at the INFN Laboratori Nazionali Gran Sasso. Strip planes, stiffening planes and mechanical supports have been realised and assembled at the INFN laboratories in Torino. Over 120 gas gaps have been produced.

The final detectors (72), plus spares, have been chosen and characterised by means of extensive tests in Torino. Such tests include:

- the detection of possible gas leaks;
- the electrodes resistivity under working conditions, measured with the argon method[10];
- the current-HV curve, and the detection of possible (ohmic) leakage currents;
- the mean noise rate and the noise map of the detector, with the auto-trigger method;
- the efficiency-HV curve in cells ≃ 20 × 20 cm^2;

- the efficiency map at working HV, with a granularity of $\simeq 2 \times 2$ cm^2;
- the cluster size, i.e. the number of adjacent strips fired per event, roughly proportional to the spatial resolution;
- the dark current absorbed at working HV.

3.1. Efficiency measurements

The measurement of efficiency is performed after flushing the gas gap with the streamer mixture described in Sec. 2.

The detector efficiency is measured with cosmic rays (muons) by means of a dedicated test bench (Fig. 2): it is composed of an hodoscope (three planes of nine scintillators each, covering an area of 90 × 150 cm^2), two reference RPCs (172 × 87 cm^2 each) and four test slots. The two reference RPCs are read on both sides with orthogonal 2 cm wide strips; with the spatial information provided by these tracking RPCs, the cosmics rays can be tracked to obtain information on the impact point on the test slot planes and to perform a local measurement of the efficiency. Given the surface of the tracking RPCs and the available electronics channels, two half-chambers at a time can be tested.

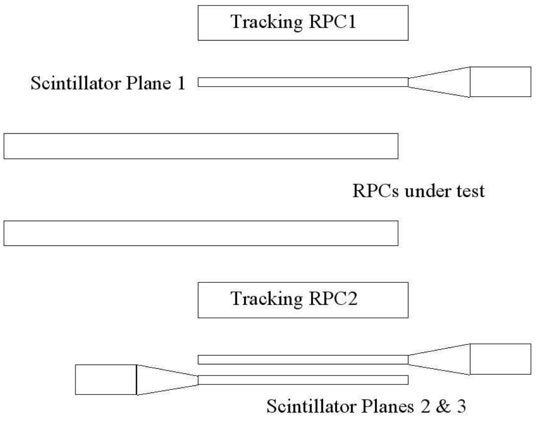

Figure 2. The Turin test bench for the RPCs of the ALICE muon arm.

Events with only one cluster per plane in the tracking RPCs are selected (to avoid ambiguities); cluster size is required to be no larger than 2 (to improve resolution and cut off cosmic ray showers). The distribution of the offset between the expected impact coordinates and those measured by the RPCs under test can be used for alignment and to evaluate the resolution of the method, which is of the order of the cm. The event is considered detected if, on both planes, the offset is less than a tolerance value depending on the strip pitch of the RPC under test.

Such a method implies some systematics on the measurement of efficiency, due to possible false triggers of the tracking RPCs, or to scattering of the muons off the structures of the test bench. Such an error has been estimated to be about 3÷4%. The efficiency measurements presented here are not meant to evaluate the absolute RPC efficiency, but the uniformity of the efficiency throughout the whole surface of the detector.

The efficiency as a function of high voltage is measured in 21 different cells for each half-chamber: the surface of the cells is about 20 × 20 cm^2. The efficiency curve can be different from cell to cell (Fig. 3); each curve is fitted and 4 parameters are extracted:

- maximum efficiency;
- the voltage value at which the efficiency is 50%;
- the voltage value at which the efficiency is 90%;
- the slope of the curve in the linear region.

The spread of such parameters is related to the uniformity of the detector; the most sensitive among these is the voltage value at which the efficiency is 50%: for most of the chambers such spread is less than 1%(Fig. 4).

To evaluate even better the uniformity of the chambers, and to detect any imperfection, though small, efficiency maps (Fig. 5) are measured at two voltage values, 8200 V and 8100 V: such values are right above the working voltage for most chambers. The aim of the test is also to decide

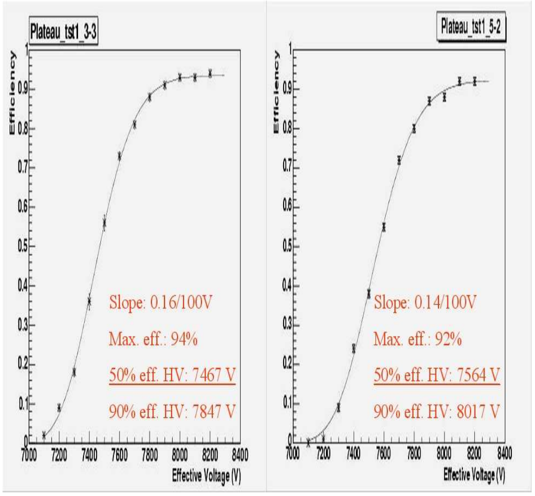

Figure 3. Efficiency curves for two 20 × 20 cm^2 cells of a same RPC.

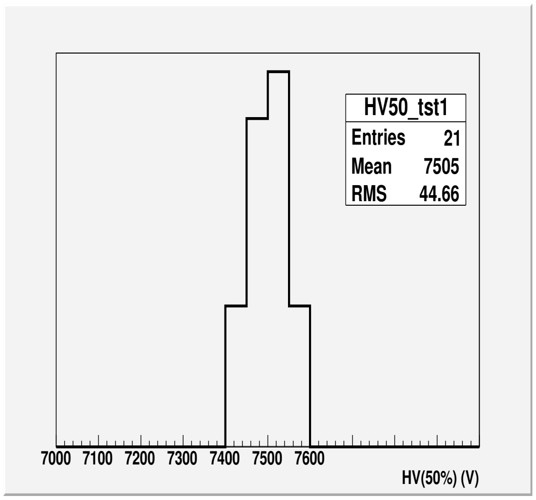

Figure 4. Distribution of the voltage at wich the detector reaches 50% efficiency for cosmic rays, over 21 20 × 20 cm^2 cells of a half-chamber.

how many Volts above the working point the detector should be operated in order to have it fully efficient over all its surface: lower efficiency zones at working voltage can be recovered at higher voltages, especially those which originate from a locally wider gas gap.

The cells for efficiency maps are about 2 × 2 cm^2 large. With 10^6 events per run ($\simeq$ 10 h acquisition time), the statistics is of about 500 events in central cells, 100 in peripheral cells, 50 in the very side cells. The statistical error on the measurements of efficiency at working voltage ranges from 1% to 4% according to the position of the cell. The position resolution is such that even the spacers ($\o$ =1 cm) that keep the distance between electrodes constant can be resolved in the map (Fig. 5).

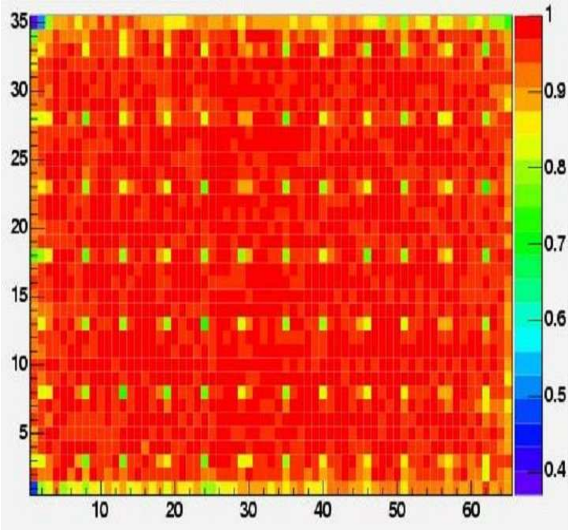

Figure 5. Efficiency map of a half chamber operated at 8200 V. The x and y coordinates define the position of the 2 × 2 cm^2 cells. The low efficiency cells that appear every 10 cm correspond to spacers.

Very few detectors have shown major efficiency disuniformities, thus it was possible to apply a strict selection on the uniformity of the efficiency; the selection criteria will be discussed more in detail in Sec. 3.4.

3.2. Noise measurements

The noise of the detectors is quantified with the dark counting rate, i.e. the counting rate of the detectors with no beam or irradiation, when the hits are only due to cosmic rays and intrinsic noise. The measurement of noise is performed as a function of high voltage.

The counting rate is measured locally with the auto-trigger method: the trigger is given by the detector itself, selecting events with at least one hit on both strip planes. The detector surface can be divided in cells defined by the crossing of the strips in the two directions. The rate (Hz/cm^2) in a cell is calculated from the number of hits in the cell, divided by the area and the elapsed time (corrected for the dead time of the acquisition system). Such a method provides the noise map of the detectors (Fig. 6), on which noisy spots can be detected.

For most of the produced detectors the rate at 8200 V in streamer mode is less than 5 Hz/cm^2 over the whole surface. A few detectors have shown hot spots up to several tens of Hz/cm^2: these have been discarded. The distribution of the mean noise rate over all tested chambers is peaked around 0.1 Hz/cm^2 (Fig. 7).

3.3. Dark current

The dark current absorbed by the detector is an important parameter because ageing effects are roughly proportional to the current drawn during long-term operation (see Sec. 4). The main source of dark current is of course the dark rate, but other effects such as ohmic parasitic currents may be present. The correlation with dark rate is clearly seen from the distribution of the dark current at 8200 V (Fig. 8), which has a similar shape as the one of the rate (Fig. 7). The peak value is about 0.1 nA/cm^2, corresponding to a total current of about 2 μA for the biggest chambers.

3.4. Selection criteria and database

After collecting a vast amount of data and characterising all detectors, criteria have been defined

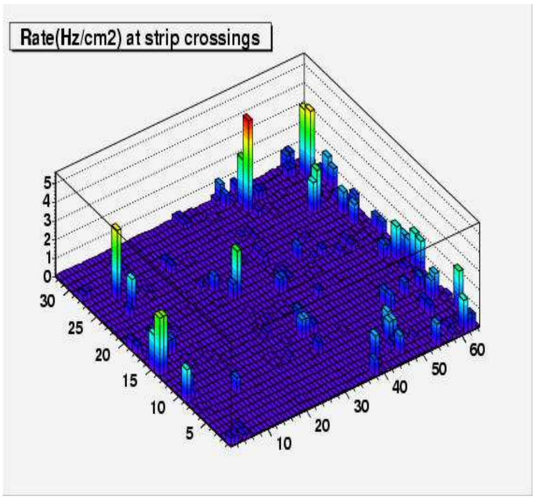

Figure 6. Noise map at 8200 V of a detector showing good performance and low dark current ($\simeq$ 2 μA). The noise rate is plotted as a function of the strip number in the x and y directions.

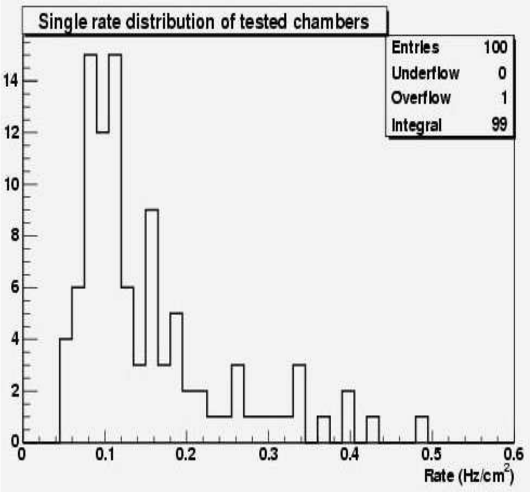

Figure 7. Distribution of the mean noise rate at 8200 V over 100 tested detectors.

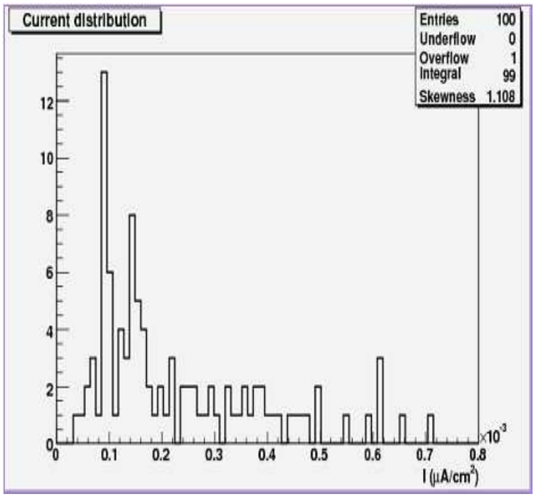

Figure 8. Distribution of the dark current at 8200 V over 100 tested detectors.

to select the final detectors and the spares. The following features are common to all the selected detectors:

- the efficiency at working voltage (evaluated by taking into account systematic errors described in Sec. 3.1) is higher than 95% in all 2 × 2 cm^2 cells;
- the voltages at which the efficiency curves in different 20 × 20 cm^2 cells reach 50% efficiency lie all in a 400 V range;
- the mean noise rate at 8200 V is lower than 0.4 Hz/cm^2.

Those chambers were discarded that, though matching the above criteria, show:

- excess of hot spots (i.e. cells with noise rate larger than 20 Hz/cm^2 at 8200 V);
- high dark current ($> 8\ \mu$A at 8200 V);
- parasitic currents at low voltage (I $> 0.5\ \mu$A at 5000 V).

At present, 116 detectors have been tested:

- 95 have been selected, 21 discarded;
- the 72 final detectors have been chosen and installed in their final position in ALICE[11];
- 23 detectors have been selected as spares;
- more detectors will be produced and tested, to increase the number of available spares.

The commissioning of the whole trigger system is expected to start in spring 2007. All detectors have been fully characterised; the results of the tests have been stored in a database that will be made available for reference to the collaboration.

4. Ageing tests with a highly saturated avalanche gas mixture

4.1. Ageing and p-p collisions

The long-term operation of a RPC can lead to alterations of its characteristics. Such alterations include the increase of the bakelite resistivity due to flushing the gap with dry gas: it has been experimentally shown[7] that this can be avoided by using a wet mixture, i.e. adding about 1% water vapour to the gas. Other ageing effects may arise from surface damaging due to the streamer discharge: this problem can be overcome by coating the electrodes with a double linseed oil layer. Still, ageing effects cannot be fully neutralised: they are assumed to be proportional to the current drawn by the detector throughout its life, i.e. to the number of integrated hits (usually measured in Mhits/cm^2) it has counted. The conversion factor from hits to current is the charge deposited on the electrodes at each signal: at fixed HV, this quantity depends on the gas mixture, namely on the amount of quenching gases it contains. Ageing tests on RPCs operated in streamer mode have been carried out at the CERN Gamma Irradiation Facility. The detector lifetime was proven to be compatible with the ALICE heavy ion program[8].

The ALICE data taking scenario in proton-proton collisions is rather different than in A-A collisions. There are two main reasons that lead to the choice of a different gas mixture for p-p collisions:

- the expected high p_T muon rate is much lower, and so is the occupancy of the detector: the momentum resolution requirements can be relaxed, and thus a larger cluster size (i.e. a slightly worse spatial resolution) can be accepted;

- the hit rate on the chambers will be higher, mainly due to the interaction of the higher intensity beam with residual gas in the beam pipe[12]; moreover, the data-taking time per year in p-p collisions will be 10 times higher: to limit ageing effects, the charge deposited on the electrodes must be reduced.

The two above facts, i.e. the possibility to accept a larger cluster size and the need to reduce the charge, lead the collaboration to study the possibility of operating the detectors in avalanche mode in p-p collisions. Since the minimum threshold that can be set on the Front End Electronics is 10 mV[9], the avalanche mixture must be highly saturated, in order to provide signals large enough to be read with the FEE designed for streamer operation.

After an intense R&D program[13], a mixture was selected, made of 89.5% $C_2H_2F_4$, 10% i-C_4H_{10} and 0.5% SF_6. Preliminary test with cosmic rays and beam tests at the CERN SPS X5 have shown that such a mixture satisfies the ALICE requirements for p-p running, even under high irradiation rate.

4.2. Ageing tests at the Gamma Irradiation Facility

Ageing tests have been performed at the CERN Gamma Irradiation Facility on two 50 × 50 cm^2 prototypes. The setup of the test is shown in Fig. 9: the detectors have been operated under high photon-induced counting rate (around 50 Hz/cm^2). The efficiency for cosmic rays has been monitored as a function of the integrated hits. Periodical data-taking at GIF off has also been performed to measure dark current, rate and efficiency without irradiation.

The two prototypes, which in the following will be labelled as RAV3 and RAV4, have been operated at a voltage of 10050 V and 10100 V respectively. The detectors have integrated 570 Mhits/cm^2 (RAV3, Fig. 10) and 540 Mhits/cm^2 (RAV4, Fig. 11). In both cases, a sudden increase of the absorbed current occurred at some point, but it was found to be due to bad insulation (RAV4) and to a problem with the water vapour cooling system (RAV3).

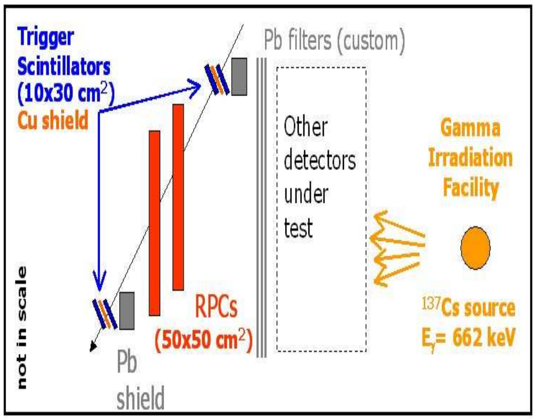

Figure 9. The setup for the ageing tests at the Gamma Irradiation Facility.

The efficiency of both prototypes is fairly constant at a high value ($\simeq$ 98%) when measured at GIF off, while a slight decrease occurs under irradiation: the efficiency, however, never decreases below 95%. The dark rate of RAV4 shows a slight increase as a function of the integrated hits; this is not observed for RAV3. The rate does not exceed 2 Hz/cm^2. The behaviour of the dark current reflects the behaviour of the dark rate, the maximum value reached being 3 μA. If one assumes a mean rate on the RPCs of 10 Hz/cm^2 in p-p collisions[14], the detector lifetime is compatible with at least five years of operation in the ALICE p-p program.

The efficiency curve of RAV3 (RAV4) has been measured at the beginning of the test and after 255 (310) Mhits/cm^2: no modification of the curve has been observed.

The two prototypes are now being tested at the Turin test facility described in Sec. 3, with

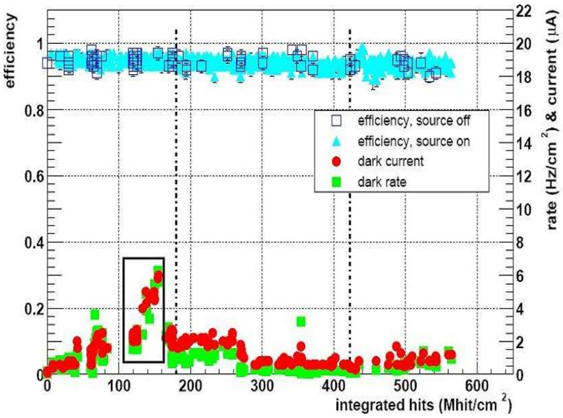

Figure 10. Evolution of efficiency, dark current and dark rate as a function of the integrated hits, for the 50 × 50 cm^2 prototype labelled as RAV 3 in the text, operated at 10050 V, 970 mbar and 20°; the region in the black frame corresponds to a period of high current and rate due to a problem with the water vapour cooling system.

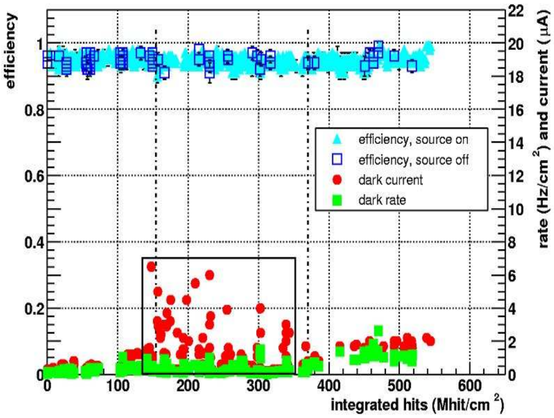

Figure 11. Evolution of efficiency, dark current and dark rate as a function of the integrated hits, for the 50 × 50 cm^2 prototype labelled as RAV 4 in the text, operated at 10100 V, 970 mbar and 20°; the region in the black frame corresponds to a period of unstable current due to bad insulation.

the aim of obtaining a high granularity efficiency map like the one shown in Fig. 5, so that effects of ageing can be evaluated on a very local scale.

5. CONCLUSIONS

The tests on the final detectors of the ALICE muon arm trigger system allowed the collaboration to fully characterise all of them, and to select detectors with uniform efficiency and reasonable noise and dark current levels. The ALICE RPCs are presently installed in their final positions. A good number of spare detectors is also available; more spares are to be produced and tested.

Ageing tests have been carried out at the Gamma Irradiation Facility on two prototypes operated with the highly saturated avalanche mixture chosen by the collaboration for the ALICE p-p program. Preliminary results show that the detector lifetime is compatible with such a program. The test will be completed with a high-granularity measurement of the efficiency of the aged prototypes.

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