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High altitude test of RPCs for the Argo YBJ experiment

The ARGO-YBJ Collaboration

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Abstract

A 50 m^2 RPC carpet was operated at the YanBaJin Cosmic Ray Laboratory (Tibet) located 4300 m a.s.l. The performance of RPCs in detecting Extensive Air Showers was studied. Efficiency and time-resolution measurements at

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the pressure and temperature conditions typical of high mountain laboratories, are reported.

Keywords: Gamma-ray astronomy; Extensive air shower; ARGO-YBJ; RPCs

1. Introduction

The aim of the ARGO-YBJ experiment is the study of cosmic rays, mainly γ-radiation, in an energy range down to about 100 GeV, by detecting small size air showers with a ground detector. This very low-energy threshold, which is below the upper limit of the next generation satellite experiments, is achieved in two ways:

(1) By operating the experiment at very high altitude to better approach the level where low-energy air showers reach their maximum development. The choice of the YangBaJing (YBJ) Cosmic Ray Laboratory (Tibet, China, 30.11° N, 90.53° E.), 4300 m a.s.l, was found to be very appropriate.

(2) By utilizing a full coverage detector to maximize the number of detected particles for a small-size shower.

The choice of the detector is subject to the following requirements. The search for point sources requires the accurate reconstruction of the shower parameters, mainly the direction of the primary particle, in order to suppress the isotropic background. This can be obtained by a diffuse sampling on the arrival times of the shower front particles with nanosecond accuracy. Moreover, the full coverage concept requires an extremely large active detector area which is only achievable with a very reliable and low-cost detector. Robustness is a further important requirement for a detector to be operated far away from the facilities available in ordinary laboratories. The use of Resistive Plate Chambers (RPCs) has been envisaged to meet these requirements. Indeed, RPCs offer noticeable advantages owing to low-cost, large active area, excellent time resolution and possibility of an easy integration in large systems.

The ARGO-YBJ detector consists of a single RPC layer of $\sim 5000\,\mathrm{m}^2$ and about 92% coverage, surrounded by a ring of sampling stations which recover edge effects and increase the sampling area for showers initiated by > 5 TeV primaries.

The trigger and the DAQ systems are built following a two-level architecture. The signals of a set of 12 contiguous RPCs, referred to as CLUSTER in the following, are managed by a Local Station. The information from each Local Station is collected and elaborated in the Central Station. According to this logic a CLUSTER represents the basic detection unit.

A CLUSTER prototype of 15 RPCs, shown in Fig. 1, has been put in operation in the YBJ Laboratory in order to check both the performance of RPCs operated in a high-altitude laboratory and their capability of imaging a small portion of the shower front.

In this paper the results concerning the performance of 2 mm gap, bakelite RPC detectors operated in streamer mode at an atmospheric depth of $606\,\mathrm{g/cm^2}$ are described. Data collected by the carpet and results from their analysis will be presented elsewhere.

2. The experimental set up

The detector, consisting of a single-gap RPC layer, is installed inside a dedicated building at the YBJ laboratory. The set up, shown in Fig. 1, is an array of 3×5 chambers of area $280 \times 112\,\mathrm{cm}^2$ each, lying on the building floor and covering a total area of $8.5 \times 6.0\,\mathrm{m}^2$. The active area of $46.2\,\mathrm{m}^2$, accounting for a dead area due to a 7 mm frame closing the chamber edge, corresponds to a 90.6% coverage. The RPCs, of 2 mm gas gap, are built with bakelite electrode plates of volume resistivity in the range (0.5–1) $10^{12}\ \Omega\,\mathrm{cm}$, according to the standard scheme reported in Ref. [1]. The RPC signals are picked up by means of aluminum strips 3.3 cm wide and 56 cm long which are glued on

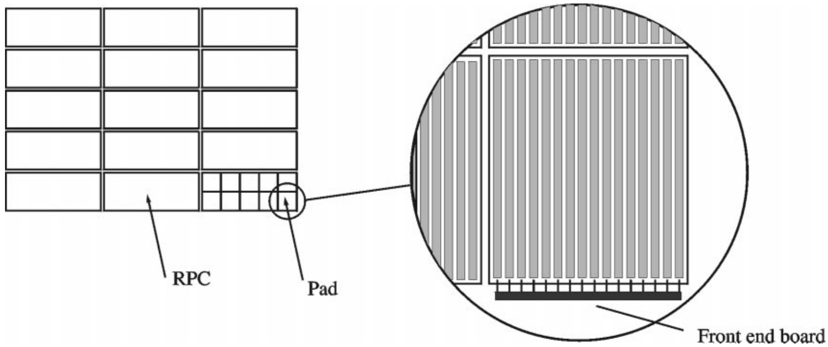

Fig. 1. Layout of the CLUSTER prototype which has been tested. Each RPC is subdivided into 10 Pads. The details of the Pad are also shown.

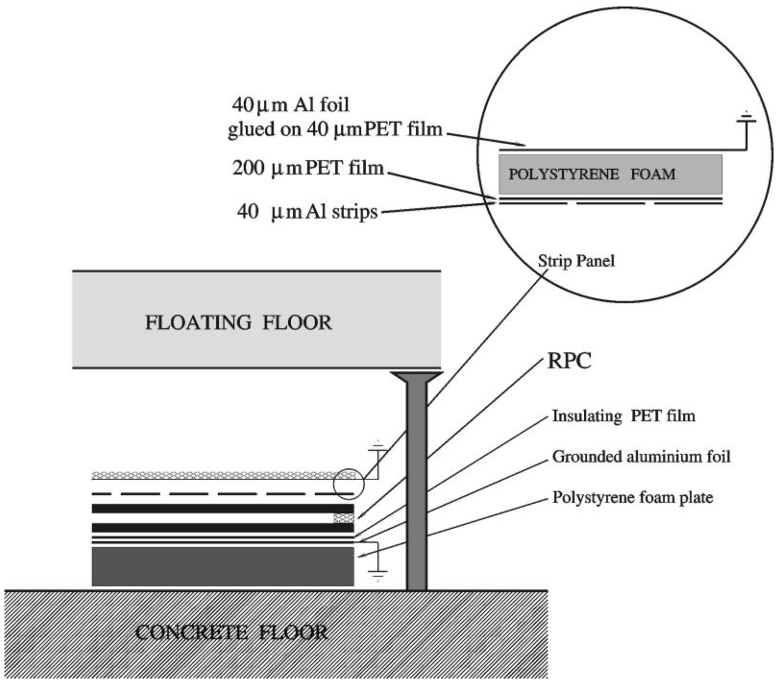

Fig. 2. Cross-section of the detector with details of the strip panel.

a 0.2 mm thick film of plastic material (PET[1]) used as a robust support which allows one to work out the strips by milling a full aluminum layer. The strips are embodied in a panel, consisting of a 4 mm thick polystyrene foam sheet sandwiched between the PET film and an aluminum foil used as a ground reference electrode. The detector cross-section is given in Fig. 2.

A rigid polystyrene foam plate is used to avoid the direct contact of the RPCs with the concrete floor. The strip panel lies on top of the detector with the strips oriented in the direction of the detector short side as shown in Fig. 1. At the edge of

[1] Poly-ethylene-tereftalate.

the detector the strips are connected to the front end electronics and terminated with 50 Ω resistors. The opposite end of the strips, at the center of the detector, is not terminated. The RPC bottom electrode plate is connected to a negative high voltage so that the strips, facing the grounded plate, pick up a negative signal. A grounded aluminum foil (see Fig. 2) is used to shield the bottom face of the RPC and an extra PET foil, on top of the aluminum, is used as a further high-voltage insulator.

The front-end electronics that has been used in the present test is not the one envisaged for the final experiment, which will be described elsewere, but is an already-existing 16-channel circuit [2] developed for RPCs working in streamer mode. The circuit contains 16 discriminators with about 50 mV voltage threshold and gives the following output signals:

- The Fast OR of the 16 discriminators with the same input-to-output delay (10 ns) for all the channels, which is used for time measurements and trigger purposes in the present test.
- Serial read out of each channel that could be used for a strip-by-strip read out. This possibility, however, is beyond the purposes of the present test.

The circuit is mounted on a 50×15 cm^2 G10 board which is fixed on top of the strip panel close to the edge of the detector as shown in Fig. 1. The length of the board is approximately tuned with the width of 16 strips so that very short wires (a few cm) can be used for connecting each strip to the corresponding input electrode on the board.

The 16 strips connected to the same front end board are logically organized in a PAD of 56×56 cm^2 area. Each RPC is therefore subdivided into 10 PADs which work like independent functional units. The PADs are the basic elements which define the space–time pattern of the shower; they give indeed the position and the time of each detected hit. The fast OR signals of all 150 pads are sent through coaxial cables of the same length to the carpet central trigger and read out electronics.

The trigger logics allows one to select events with a pad multiplicity in excess of a given threshold. At any trigger occurrence the times of all the pads are read out by means of multihit TDCs of 1 ns time bin, operated in common STOP mode. Each TDC has 32 input channels and can store up to 16 events per channel. The multiple hit operation is particularly important in detecting the core of high-energy showers where several particles can fall on the same pad in a time interval of hundreds of nanoseconds. The trigger signal is used as the common STOP signal. For each event the trigger multiplicity, the set of all pads which produced the trigger and the times of all pads of the carpet are recorded.

As the carpet consists of just a single-layer detector, a direct measurement of the detection efficiency and time resolution requires the use of an auxiliary "telescope" which can clearly define a cosmic-ray impinging on it. The set up was therefore completed with a small telescope consisting of three RPCs of $50 \times 50\,\mathrm{cm}^2$ area with 16 pick-up strips 3 cm wide connected to front-end electronics boards similar to the ones used in the carpet. The three RPCs were overlapped one on the other and the triple coincidence of their fast OR signals was used to define a cosmic ray crossing the telescope.

The gas system consisted of a central mixing station using three mass flowmeters that measured the gas composition with the required accuracy, better than 1% for all the components, and five parallel gas lines each feeding three RPCs in series. The gas sharing among the five input lines was equalized using identical high-impedance capillary pipes in series with each line and the regular gas flow was monitored by bubblers put at the exit of each line. An open gas circuit was used, as only a modest amount of gas, about 15 l/h corresponding to four volume changes per day, was needed during about two months of carpet operation. Three gas components were used: argon, *iso*-butane C_4H_{10} and tetrafluoroethane $C_2H_2F_4$ that will be indicated in the following as Ar, *i*-But and TFE, respectively.

The high-voltage system consisted of five 10 kV supplies each one feeding three RPCs in parallel. The operating voltage was settable to the wanted value within 10 V accuracy and the operating current was monitored with a 1 μA sensitivity instrument. A further two channel HV supply with 10 nA sensitivity current monitor was used to feed the auxiliary telescope.

3. Data taking and experimental results

The peculiar working conditions of the mountain YBJ laboratory are not only a very low average pressure of about 600 mbar, corresponding to an atmospheric vertical depth of 606 g/cm^2, but also a temperature that could be particularly low in winter even inside the laboratory.

The measurements described in this paper were performed in the second-half of February 1998 with an external temperature ranging between -20°C and -5°C and in the first-half of May when the temperature was in the range -5 to 15°C. The internal temperature was kept, by using some heaters, between $+4$°C and $+8$°C in the first run and around 16–18°C in the second. The laboratory temperature and pressure were monitored during all data taking.

The RPCs of the test carpet were operated in streamer mode [3] as foreseen for the final experiment. This mode delivers [4] large amplitude saturated signals, and is less sensitive than the avalanche or proportional mode [5] to electromagnetic noise, to changes in the environmental conditions and to mechanical deformations of the detector. On the other hand the larger rate capability achievable in avalanche mode [6] is not needed in a cosmic-ray experiment.

The first task to be carried out was the optimization of the gas mixture and the search for the detector operating point in the YBJ laboratory conditions. This was accomplished by means of the auxiliary telescope, before the start of the carpet test. The efficiency of the RPC in the central position of the telescope (RPC2 in the following) was measured as the ratio of the number of triple coincidence events to the number of double coincidences of the other two RPCs. Three gas mixtures were tested which used the same components, Ar, *i*-But and TFE, in different proportions: TFE/Ar/*i*-But = 45/45/10; 60/27/13 and 75/15/10. In the three cases the ratio Ar/TFE was changed to a large extent, leaving the *i*-But concentration relatively stable.

TFE is a heavy gas with good quenching properties [5]. An increase of TFE concentration at the expense of the Ar concentration should therefore increase the primary ionization thus compensating for the 40% reduction caused by the lower gas target pressure (600 mbar) and reduce the afterpulse probability. For each of the three gases a voltage scan was made for RPC2, leaving the other two RPCs at a fixed operating voltage, and the following measurements were made: RPC2 counting rate and current, double and triple coincidence rate.

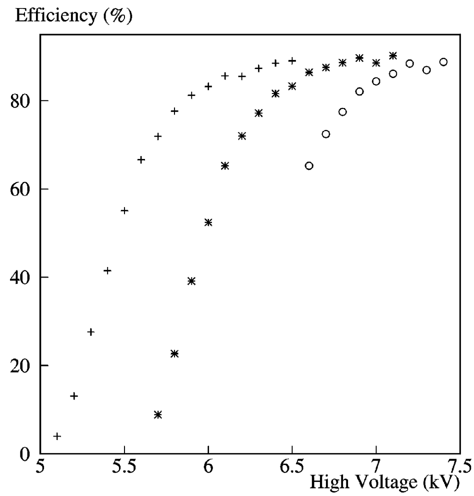

Fig. 3. Detection efficiency of one RPC of the auxiliary telescope vs. operating voltage for three gases: TFE/Ar/*i*-But = 45/45/10 (+); 60/27/13 (∗) and 75/15/10 (○).

The detection efficiency vs. the operating voltage for the three gases is shown in Fig. 3. The reduction of the argon concentration in favor of TFE results in a clear increase of the operating voltage as expected from the large quenching action of TFE. The data shown in Fig. 3 are consistent with an increase of 30–40 V in operating voltage for a 1% reduction of the argon concentration in the mixture. In spite of the different operating voltages all three gases approach the same efficiency of about 90% which includes the inefficiency due to geometrical effects. A more systematic study of the plateau efficiency is presented below, in connection with the carpet test.

Fig. 4 shows the RPC2 current and counting rate vs. the operating voltage for the three gases. A small current linearly increasing with the voltage is measurable well below the point where the RPC starts to show a significant counting rate. We interpret this as a leak current not flowing through the

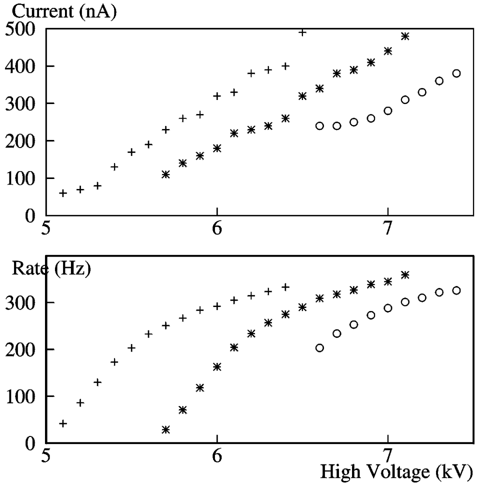

Fig. 4. RPC2 operating current and counting rate vs. voltage for the three gases already mentioned in Fig. 3: TFE/Ar/*i*-But = 45/45/10 (+); 60/27/13 (∗) and 75/15/10 (○).

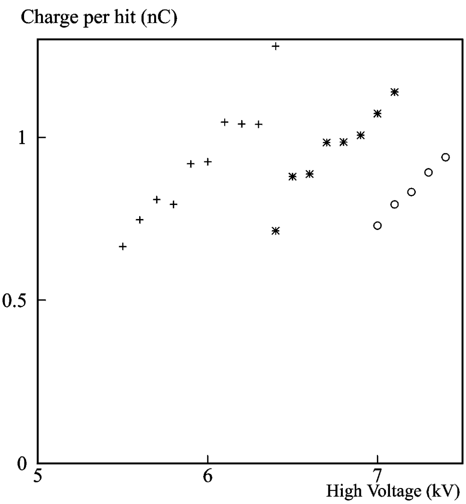

Fig. 5. Charge delivered per count for the three gases vs. operating voltage: TFE/Ar/*i*-But = 45/45/10 (+); 60/27/13 (∗) and 75/15/10 (○).

RPC gas and not taking part in the detector working mechanism.

The ratio of the operating current to the counting rate gives the charge per count delivered in the RPC gas, which is shown in Fig. 5 as a function of the operating voltage for the three gases. Here the small term corresponding to the current leaks, as mentioned above, is subtracted from the total current. The data presented in Fig. 5 show that the higher the TFE fraction, the lower is the charge delivered in the gas by a single streamer. Concerning the optimization of this parameter the following points should be noted.

- The signal charge, in streamer mode operation, is anyway much above the achievable threshold of the front end electronics. This is particularly true for the final front end electronics that will be used for the experiment. Therefore, a larger detector signal is not an advantage in this respect.
- A lower operating current, on the contrary, is an advantage even if in a cosmic-ray experiment the currents are expected to be modest.
- In a cosmic-ray experiment, on the other hand, the analog measurement of the hit density, which is achievable either from amplitude measurements of the strip signals or by sampling the operating current in appropriate time intervals, is an interesting possibility to be exploited for studing the shower core at energies as high as about 100 TeV. Indeed, according to a Monte Carlo simulation of the final experiment, the digital read out of pads near the shower core, is expected to saturate at about 15–20 TeV. In this respect, a lower delivered charge extends the dynamic range achievable for the analog measurement.

We decided, therefore, to operate the test carpet with the gas mixture corresponding to the highest fraction of TFE.

The tests performed on the carpet were essentially the same as for the auxiliary telescope. Fig. 6 shows the operating efficiency for the ORed pads 2-3-7-8 of one RPC of the carpet. The efficiency was measured using cosmic-ray signals defined by the triple coincidence of the RPCs of the auxiliary telescope which was placed on top of the carpet and centered on the corner among four pads. The counting rate of the same pads OR signal, together with the RPC current, are reported in Fig. 7 vs. the operating voltage. The results of the gas with TFE = 45% are also reported for comparison. A rather flat counting rate plateau is observed corresponding to a rate of about 400 Hz for a single pad of area 56×56 cm^2. The residual slope of the

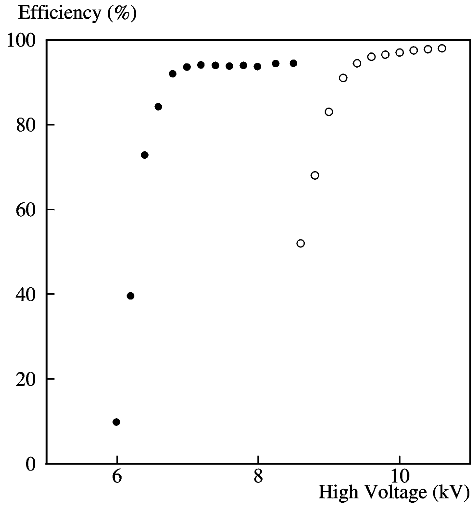

Fig. 6. Detection efficiency vs operating voltage for one of the carpet RPCs (●). The same curve for a 2 mm gap RPC operating at sea level is also reported (○) for comparison.

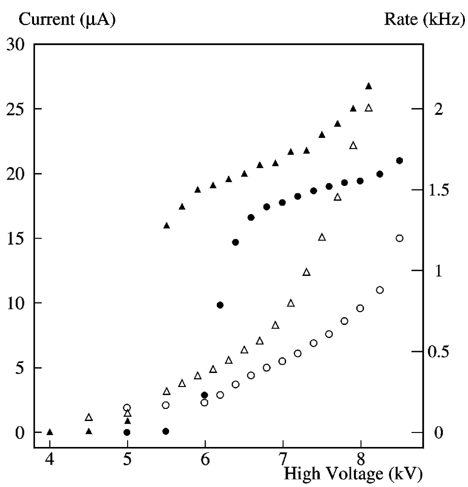

Fig. 7. Counting rate (full triangles and circles) and operating current (open triangles and circles) vs. voltage of one RPC of the carpet. Results are presented for the gas with 45 % (triangles) and 75 % (circles) of TFE, respectively. The rate shown refers to four ORed Pads out of the 10 pads of the RPC.

plateau is mostly due to afterpulses occurring after the end of the 250 ns shaped discriminated signals which produce a double counting of the signal due to the same CR track. The rate and efficiency curves rise in the same voltage interval as expected.

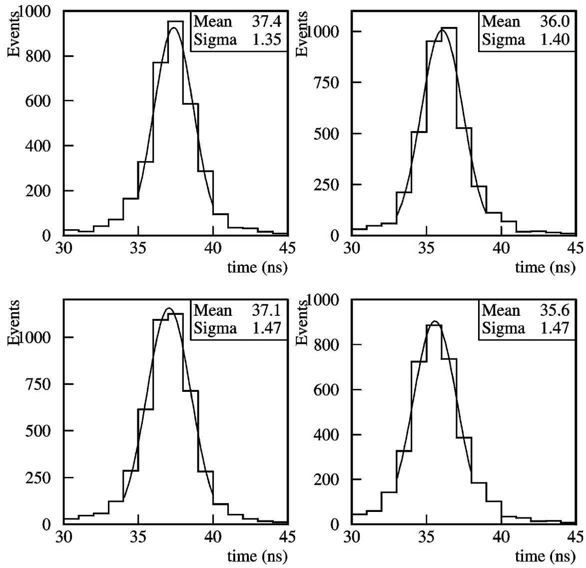

Fig. 8. Time jitter distribution of four pads of the carpet. The telescope RPC2 signal is used as common stop. The operating voltage is 7.4 kV.

The time-jitter distribution of the pad signals was obtained by measuring the delay of the fast OR signal with respect to RPC2 in the trigger telescope. This distribution is shown in Fig. 8 for the four pads. The average of the standard deviations is 1.42 ns corresponding to a resolution of 1.0 ns for the single RPC if we account for the fact that the distributions in Fig. 8 show the combined jitter of two detectors.

In the detection of extensive air showers, however, the primary cosmic-ray direction is measured by comparing the times of hits due to different particles of the shower. The space–time distribution of the shower hits allows one to fit the front of the shower that can be assumed to a good approximation to be a plane. The time-residual distribution of the individual shower particles with respect to the front is reported in Fig. 9. The long tail of delayed hits is due to particles arriving much after the shower front.

4. Discussion of the results

The use of RPCs for the detection of Extensive Air Showers in high-altitude laboratories poses

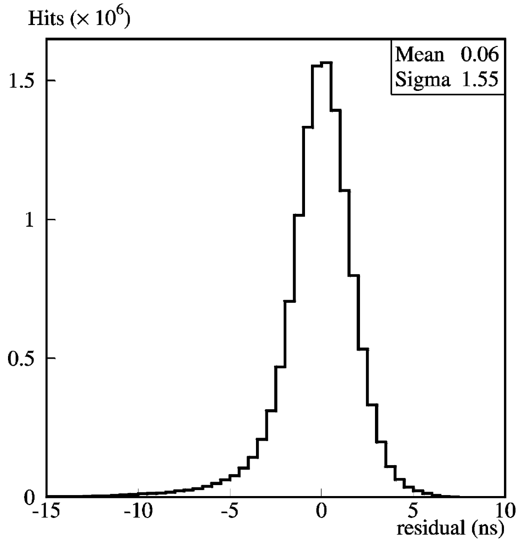

Fig. 9. Time-residual distribution for all 150 Pads. The trigger signal is used as common stop.

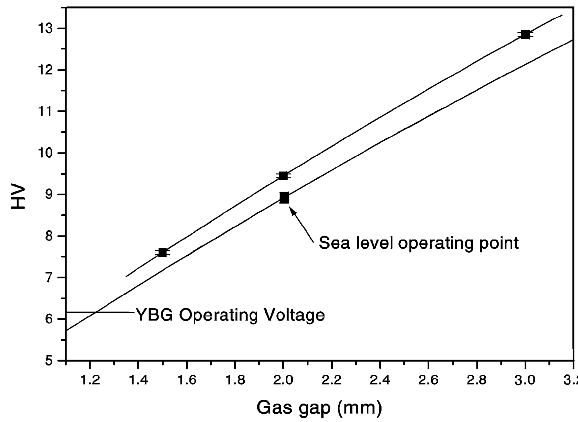

Fig. 10. Operating voltage vs. gas gap for the binary gas TFE/*i*-But = 97/3 (upper curve) and for the YBJ gas TFE/Ar/*i*-But = 75/15/10 (lower curve).

some basic questions that the present test attempts to answer:

- how do the operating voltage and plateau efficiency scale with the pressure for the streamer mode operation?
- how does the detector time resolution compare with the intrinsic jitter of the shower front?

With the purpose of answering the first question a 2 mm gap RPC was operated at sea level with the same gas, TFE/ Ar/*i*-But = 75/15/10, used for the YBJ carpet. The detection efficiency vs. operating voltage in Fig. 6, compared with the operation at 600 mbar pressure in YBJ, shows an increase of about 2.5 kV in operating voltage.

The effect of small changes of temperature T and pressure P on the operating voltage can be accounted for [7] by rescaling the applied voltage V_a according to the relationship

$$V = V_a \frac{P_0}{P} \frac{T}{T_0}$$

where P_0 and T_0 are arbitrary standard values, e.g. 1010 mb and 293 K, respectively, for a sea level laboratory. However, starting from the YBJ data, the above formula predicts an operating voltage at sea level which is considerably larger than the experimental one.

A large change of pressure produces a proportional change in the gaseous target mass per unit surface, like a change of the gas gap size. The operating voltage as a function of the gap is studied in Ref. [8] for 1.5, 2, and 3 mm gap RPCs, in the case of the binary gas mixture TFE/*i*-But = 97/3. The result is shown in Fig. 10 where the operating voltage in streamer mode is defined as that giving 50% streamer probability with respect to the plateau.

The data which refer to the same pressure of 1010 mbar and temperature of 293 K, show that the voltage does not scale proportionally to the gap, the electric field (voltage/gap) being larger for thinner gaps. Indeed the avalanche to streamer transition occurs when the gas amplification, $e^{\alpha g}/\alpha g$, exceeds a given threshold. The larger the gap the smaller is the α value and therefore the electric field that is needed for reaching the streamer threshold. A zero constraint parabolic fit of the three experimental points is also reported in Fig. 10. The fitted curve, which refers to the binary gas, can be scaled to the YBJ gas, TFE/Ar/*i*-But = 75/15/10 at 20°C temperature, using the point at sea level (8.6 kV at 1010 mbar and 32°C, rescaled to 20°C according to the above formula) and assuming that the ratio of the operating voltages for the two gases is the same for all gap sizes. The result is the lower curve in Fig. 10 which represents the operating voltage vs. gap for the YBJ gas and fits well the YBJ operating point, 6.12 kV, if we assume that a 2 mm gap at the YBJ pressure of 603 mbar is equivalent to a 1.2 mm gap at 1010 mbar. The above assumption is based on the fact that, in the ideal gas approximation, the mass per unit surface of the gaseous target, which fixes the operating voltage for each gas, is given by the parameter *gap* · *pressure*/*temperature*.

Fig. 6 also shows that the plateau efficiency measured at YBJ is 3–4% lower than that at sea level. Although a lower efficiency is expected from the smaller number of primary clusters at the YBJ pressure, we attribute most of the difference to the underestimation of the YBJ efficiency. At the YBJ level indeed the ratio of the cosmic radiation electromagnetic to muon component is about 4 times larger than that at sea level. A spatial tracking with redefinition of the track downstream of the carpet would eliminate the contamination from soft particles, giving a more accurate and higher efficiency. On the other hand, the lower efficiency could hardly be explained with the gas lower density. The number of primary clusters in the YBJ test, estimated around 9, is the same as in the case of some gas, e.g. Ar/*i*But/CF3Br = 60/37/3, that was frequently used at sea level with efficiency of 97–98% [9].

The time-residual distribution in Fig. 9 shows a long tail due to delayed particles traveling well behind the shower front. The Gaussian fit, disregarding this tail, gives a standard deviation of 1.6 ns to be compared with the RPC intrinsic time resolution of 1.0 ns. Taking into account the additional uncertainties due to the propagation time of the signal traveling along a strip of 56 cm and to the impact point of the shower particle which can be anywhere inside the PAD we get a total RPC jitter of 1.3 ns. The residual jitter of the shower front can be estimated to be $\sigma_{\text{shower}} = 0.9$ ns.

This is valid for high-energy showers selected by the multiplicity trigger as in the case reported in Fig. 9. At lower energies the shower jitter increases gradually.

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