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Toward a new generation of RPCs

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This paper reviews the RPC applications to the experiments of next generation supercolliders such as the High Luminosity LHC. The optimization required for this purpose includes the rate capability as well as the timing and tracking accuracy. Finally some consideration are presented in view of the RPC applications to future Cosmic Ray experiments.

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1. Introduction

RPC2012 falls after more than 3 years of LHC operation, which is a substantial time period to evaluate the RPC behaviour in the middle-long term. All the experiments equipped with RPCs both for trigger and time of flight purposes, Alice, Atlas and CMS, have experienced a very smooth and efficient running of this detector. In particular it was observed that a long running time under well controlled working conditions produced a very good detector conditioning with systematic decrease of the dark currents down to values as low as 60 pA/m^2 for the 2 mm single gap RPCs. This made the simple current measurement an efficient method to map the machine background [1] and even to evaluate the machine luminosity [2]. This long term performance test will be concluded when LHC will operate at its maximum luminosity and full energy of 14 TeV, in 2014. However, the upgrade of LHC to the High Luminosity LHC (HL-LHC), in the next future, requires a substantial upgrade of the currently operating RPCs as well. This paper has the purpose to study how each working parameter can be improved to meet the requirements of the future colliders.

The situation of the RPCs dedicated to Cosmic Ray shower detection is in some sense similar. The Argo-YBJ detector has been running very smoothly during the last 4 years [3] at a duty cycle close to unity and with very little maintenance needs. It produced relevant physics results mainly in the study of CR anisotropy and variable intensity gamma sources at the TeV energy [4]. Also in this case a substantial upgrade is needed in order to improve the sensitivity of RPC-based detectors to low energy cosmic ray showers in the energy range down to 100 GeV. Some upgrade ideas are discussed in section 5.

2. RPC operation at the High Luminosity LHC

The RPC proved to be an excellent detector for muon triggering at LHC. Its extension to the HL- LHC requires however a substantial improvement of its performance. Some ideas are discussed in this section.

2.1 Operation at high rate

The rate capability of the RPCs is limited by the modest current that can flow through their high resistivity electrodes. The RPCs presently working at LHC in Atlas and CMS can achieve a maximum rate of about 0.5 kHz/cm^2 and a gain of more than one order of magnitude is needed to cope with future applications. This can be obtained in principle either by reducing the electrode resistivity in order to get larger working current or by reducing the delivered charge per count in order to get larger rate at fixed current. These two ways are by no means equivalent. Indeed the rate problem is ineludibly connected to the ageing problem which is also relevant for a detector conceived to operate for 10 years in inaccessible positions. The ageing rate, for fixed working conditions of gas flow, temperature, humidity etc, is proportional (or more than proportional) to the instantaneous operating current. The rate increase at fixed current has therefore the crucial advantage to leave the ageing rate unchanged with respect to the present RPCs whose features are now very well known thanks to the full time operation of about 15 thousand m^2 of detector at LHC. The price to be paid for this approach to the rate problem is the development of a new front end electronics with a substantially improved sensitivity to very small signals and an excellent signal to noise ratio. This is not new in RPC history. The same procedure was followed when switching from the streamer to the avalanche working mode [5], which made the LHC world accessible to the RPCs thanks to the development of new front end circuits. Recent tests at the Cern GIF show that the goal of a rate capability > 10 kHz/cm^2 is well achievable [6]. Some results are shown in section 3.

2.2 Timing and background rejection

The RPC "golden parameter" is well known to be its outstanding time resolution. The importance of a very accurate timing for the background rejection, particularly in the end cap regions, is strongly supported by recent MC results showing that the muon arrival time is peaked in a window of a few ns after the bunch crossing time, whereas most of the background is uniformly distributed in the interbunch crossing time or peaked elsewhere [6]. The improvement of the time resolution at the level of a few hundred picoseconds is therefore of crucial importance for the RPCs to be used as trigger detectors at HL-LHC. The key point to improve the timing is to use very thin gas gaps, possibly in a multigap structure, to compensate the reduced primary ionization in the gas. Results presented at several RPC workshops [7; 8; 9¸10] show that resolutions much below 100 ps are achievable with gaps of 200-300 µm in multigap chambers. A relevant goal to be pursued for the muon detectors at the HL-LHC is to create a new generation of RPCs keeping the same lay out simplicity as those operating in Atlas and CMS, with self-supporting gas volumes, thinner gas gaps (i.e. << 2 mm) and read out through strips up to a few meters long. This would allow to cover the very large areas required for muon detection, and to get very high timing capability at relatively low cost, which is also a relevant point in a world where the available funds for basic research are clearly diminishing.

2.3 Tracking accuracy for a sharp Pt threshold

An efficient muon trigger at LHC and even more at HL-LHC must have a transverse momentum threshold as sharp as possible in order to reduce the trigger rate at acceptable values. This requires a drastic improvement of the RPC tracking capability well above the present value of about 7 mm, based mainly on the read out strip width. An extensive study of the RPC space resolution based on the measurement of the charge centroid is shown in section 4.

2.4 RPC performance vs gap size

Finally, it must be stressed that the gap size, in addition to determining the time resolution also has a substantial impact on the charge delivered by a single avalanche developing in the gas. The charge indeed decreases with the gap size [11] and for very narrow gaps it becomes extremely small. As a consequence narrow gaps are also particularly suitable for increasing the rate capability. However, the detection of very small signals from narrow gaps requires a very sensitive front end electronics which remains anyway a key element to increase the rate capability.

3.. Multigap understanding

This section analyzes the most important aspects of the multigap RPC working mode with the purpose of deepening the understanding of a device that has had relevant time of flight applications [7; 8; 9;10]. This analysis concerns the signal pick up as well as the field equalization in the different gaps.

In the multigap RPC there are many gaps developing simultaneous avalanches which induce signals in the same read out electrodes. This may suggest that in a n-gap structure the induced signal is n times the one of the single gap, which would be very helpful for a low gas gain working mode. We examine two different cases below.

3.1 The serial multigap

The "serial" multigap, shown in fig 2 (right side), is characterized by a number of floating electrodes whose potentials, in principle, scale in such a way as to equalize the field in all gaps. Indicating with X_e , X_i the average drift distances of the electrons and the ions respectively, with g the gas gap size and Q_{tot} the total charge delivered in the gas (i.e. the number of electron-ion pairs), the prompt and ionic charge of a monogap are given by $Q_{prompt} = Q_{tot} X_e/g$ and $Q_{ion}=Q_{tot}X_i/g$, for a negligible electrode thickness.

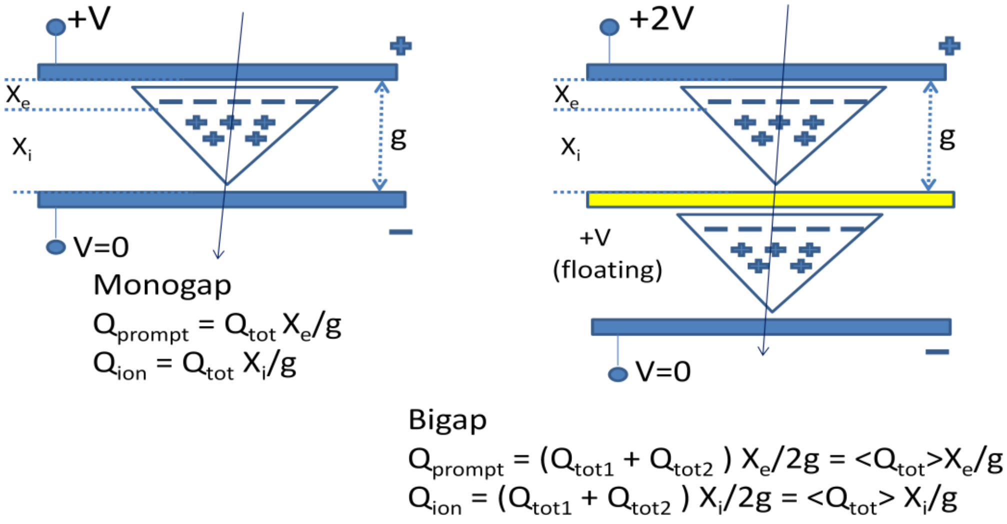
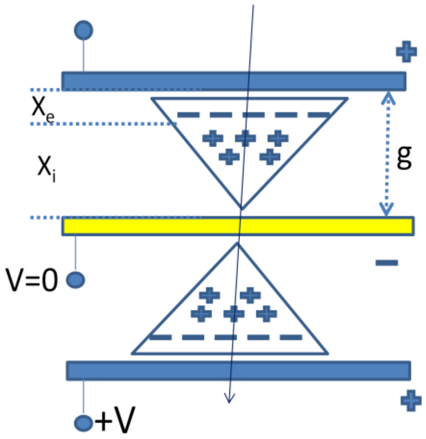


Fig 1. The bigap in serial configuration (right) and comparison with the monogap (left). The multigap structure gives in average the same prompt and ionic charge as the single gap. The charge distribution however is $\sqrt{2}$ ($\sqrt{n}$ in the general case) times narrower than the one of the single gap ($\sigma_{average} = \sigma/\sqrt{n}$).

In the case of two gaps in series: $Q_{prompt} = (Q_{tot1} + Q_{tot2}) X_e/2g = <Q_{tot}> X_e/g$ and $Q_{ion} = (Q_{tot1} + Q_{tot2}) X_i/2g = <Q_{tot}> X_i/g$. The increased amount of charge drifting in the gas is therefore compensated by the reduced ratio of the drift distance to the overall gap 2g. In conclusion, the serial multigap compared to the monogap does not change, in average, the amount of charge induced on the pick up electrodes but gives a narrower charge distribution as expected for the average of n (the general case) independent terms: $\sigma(<Q_{tot}>) = \sigma_{averag} = \sigma/\sqrt{n}$. This gives a substantial advantage in the discrimination of the signal from the noise by the front end electronics and reduces therefore the detection inefficiency, occurring when $Q_{prompt} < Q_{threshold}$.

3.2 The parallel bigap

In the “parallel” bigap, shown in fig 2, the two gaps are connected in parallel to the voltage supply and the central electrode collects the charge induced by both gaps, the drift distance being identical to the single gap size. The total induced charge is therefore two times that of each monogap: a parallel bigap gives an extra bonus of a factor of 2 in the prompt charge which should allow to work at lower gas gain. This advantage however cannot be scaled to an arbitrary number of gaps $n > 2$. Moreover it is not compatible with the two-dimensional readout, the pick-up strips in the central electrode being transmission lines surrounded by ground reference electrodes on both external sides of the chamber.



Parallel bigap

$Q_{prompt} = (Q_{tot1} + Q_{tot2})\, X_e/g = 2 \langle Q_{tot}\rangle X_e/g$

$Q_{ion} = (Q_{tot1} + Q_{tot2})\, X_i/g = 2 \langle Q_{tot}\rangle X_i/g$

Fig 2. The parallel bigap. In this configuration the induced signal is two times that of a single gap. This is a relevant advantage for a low gas gain operation.

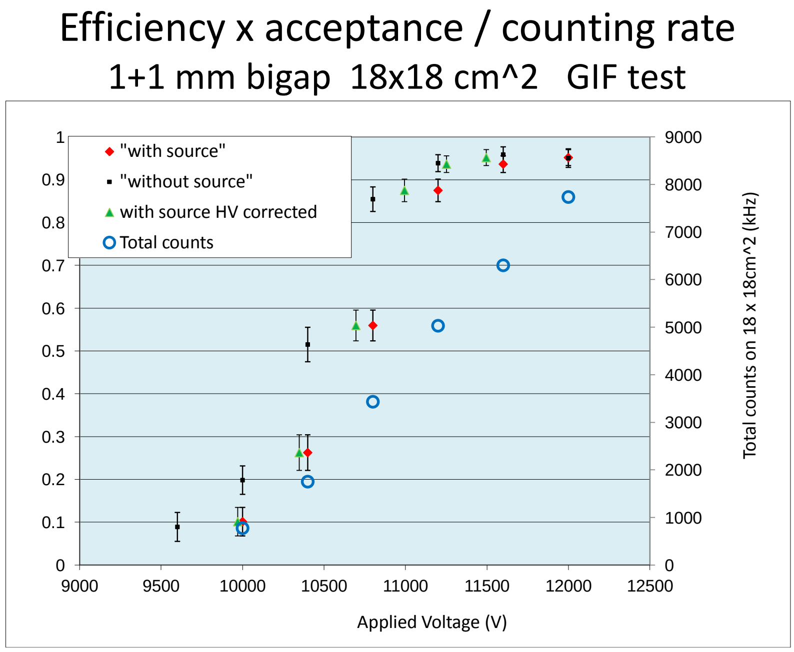
3.3 The “self equalizing field” principle

The working of a serial multigap RPC is based on the principle that for identical gaps the intermediate floating electrodes take the potential that equalizes the field in all gaps. Indeed the current through all gaps being the same, the voltage drop of all gaps is also the same under the assumption of uniform gas ionization. This principle however assumes a negligible dark current. At very low voltage however the current is dominated by the ohmic term, due to the non perfect mutual isolation of the electrodes, which is not necessarily the same for all gaps. In this case the field may be different from gap to gap and the detection efficiency would be dominated by the gap of maximum field which should be also that of maximum resistance between the electrodes. This effect should disappear under intense irradiation by an external source. In this case the operating current would be dominated by the gas ionization and the dark current effect should be negligible.

A perfect gas volume construction and conditioning should reduce to acceptable values this effect, which limits the validity of the self equalizing field. This should require a dedicated R&D.

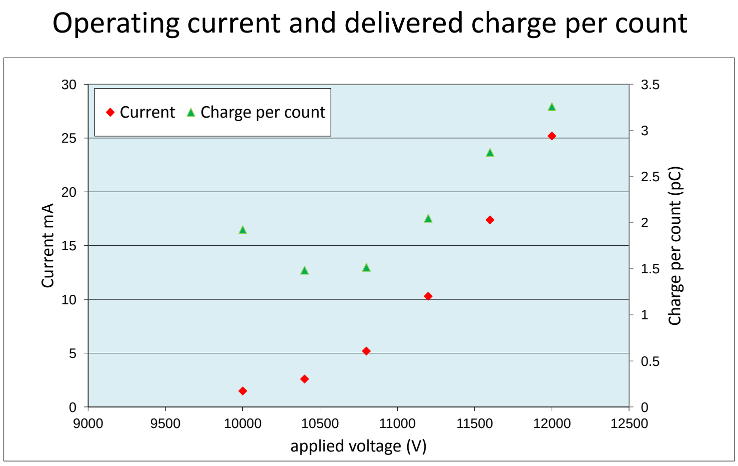
The performance of a 1+1 mm bigap RPC in serial configuration equipped with a new front end electronics circuit [12], is shown in fig 3 and 4. The chamber, of sensitive area is 18x18 cm^2, was heavily irradiated with gamma photons from the ^{137}Cs source of the Cern GIF [9]. The efficiency was measured with cosmic muons selected by a set of plastic scintillators. The gas mixture is the Atlas and CMS standard one ($C_2H_2F_4/iC_4H_{10}/SF_6$=94.7/5.0/0.3).

Fig 3 shows that full efficiency is reached at 11.5 kV, with a total counting rate of 6.3 MHz corresponding to 19 kHz/cm2, which is a relevant improvement wrt the RPCs operating in Atlas. The points at source OFF are displaced to a lower voltage with respect to the points at source ON corrected for the voltage drop across the resistive electrodes. This indicates a somewhat different field between the two gaps with an over-efficiency given by the gap at higher field. Fig 4 shows that at source ON and full efficiency the total delivered charge per count is about 2.7 pC. The corresponding value for the present Atlas chambers is 20 pC. This represents a major achievement of the new front end circuit coupled to a 1+1 mm bigap instead of the 2 mm monogap.



Efficiency x acceptance / counting rate
1+1 mm bigap 18x18 cm^2 GIF test

Fig 3. Efficiency x acceptance (left scale) and counting rate (right scale) of a 1+1 mm bigap in serial configuration. Test carried out at the Cern GIF. Sensitive area 18x18 cm^2. The plot at source OFF (black squares) should coincide with the one at full source including the correction for the voltage drop across the resistive electrodes (green triangles). The observed difference indicates an unbalance between the fields in the two gaps.



Operating current and delivered charge per count

Fig 4 Operating current (left scale) and delivered charge per count (right scale) vs operating voltage. The delivered charge at source ON and full efficiency is as low as 2.7 pC with a gain of allmost one order of magnitude wrt the present Atlas chambers.

4. Precision tracking with RPCs

The method of the charge centroid, based on the charge distribution measurement of a few contiguous strips around the muon track, allows in principle to obtain a space resolution of the order of 100 µm with RPCs as for other gaseous detectors. It should be stressed that RPCs equipped with orthogonal strips on opposite sides of the gas volume, allow to measure the charge centroid position in the plane, with full symmetry between the two coordinates.

This makes the RPCs an excellent tracker. Preliminary beam tests have shown a spatial resolution better than 0.3 mm. Further work has to be invested to optimize the precision tracking.

It has been also shown, in the framework of the muon detection at LHC, that the tracking accuracy is important not only for momentum measurements but also for triggering purposes, when a sharp threshold in transverse momentum is needed, in particular in the end cap regions. In this case the position measurement must be achieved in a very short time which may be not compatible with the computation time of the charge centroid. Therefore it has been proposed , as an alternative method, to use RPCs with narrow strips, typically 2 mm, equipped with a fast maximum selector circuit which can select, within 10 ns, the strip where the induced charge is maximum [12]. Preliminary beam test results have shown that a position accuracy 0.3 mm is achievable with this method.

5. Astrophysics application: RPC optimization for Extensive Air Showers detection

In addition to the applications in collider physics, the RPC gave also a relevant contribution to the Cosmic-Ray physics and Astrophysics. Particularly important are the results of the Argo-YBJ experiment (Tibet, 4300 m asl) concerning the Cosmic Ray anisotropy in the few degrees range and the monitoring of variable intensity gamma sources in the TeV energy scale. The main RPC challenge in this field is to lower to about 100 GeV the energy threshold for the detection of cosmic showers, in particular gamma showers, with ground based detectors. The importance of detector arrays with duty cycle close to unity, particularly in the detection of variable intensity sources, is strongly confirmed according to the recent Argo-YBJ experience. The sensitivity of Argo to low energy showers however is limited by its oversimplified layout of a single layer detector without any lead converter on top of it. Its sensitivity would be greatly enhanced by a “calorimetric” approach to the cosmic shower detection. This would require the following changes with respect to the present Argo layout:

1) Avalanche working mode instead of the present streamer mode. This would allow to discriminate single hits from e+ e- pairs produced by the conversion of a gamma photon
2) Analog read out over squared pads of area around 60x60 cm^2. Presently the same area is covered by 8 strips with digital read out. The analog read out requires a ADC channel per pad but the number of pads would be drastically reduced
3) 3 layer structure with a 5 mm lead converter on top of each layer instead of the present single layer without converter.

The calorimetric approach would greatly enhance the Argo sensitivity and would make it very competitive in the range of energy 100 GeV- 1TeV with respect to water Cerenkov detectors. A relevant investment of simulation is crucial to test different ideas of optimization.

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