RPC based 5D tracking concept for high multiplicity tracking trigger

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RPC based 5D tracking concept for high multiplicity tracking trigger

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ABSTRACT: The recently approved High Luminosity LHC project (HL-LHC) and the future colliders proposals present a challenging experimental scenario, dominated by high pileup, radiation background and a bunch crossing time possibly shorter than 5 ns. This holds as well for muon systems, where RPCs can play a fundamental role in the design of the future experiments. The RPCs, thanks to their high space-time granularity, allows a sparse representation of the particle hits, in a very large parametric space containing, in addition to 3D spatial localization, also the pulse time and width associated to the avalanche charge. This 5D representation of the hits can be exploited to improve the performance of complex detectors such as muon systems and increase the discovery potential of a future experiment, by allowing a better track pileup rejection and sharper momentum resolution, an effective measurement of the particle velocity, to tag and trigger the non-ultrarelativistic particles, and the detection local multiple track events in close proximity without ambiguities. Moreover, due to the fast response, typically for RPCs of the order of a few ns, this information can be provided promptly to the lowest level trigger. We will discuss theoretically and experimentally the principles and performance of this original method.

KEYWORDS: Electronic detector readout concepts (solid-state); Resistive-plate chambers; Calorimeter methods; Particle tracking detectors

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Contents

1	The track pileup problem in future experiments	1
2	The RPC hit to hit resolution power	1
2.1	1D meantimer	2
3	The 2D meantimer concept	3
3.1	The 2D meantimer basic definitions	4
4	Beam test performance of the 2D meantimer concept	5
5	The fifth dimension: the charge	6
6	Wrap-up, applications and conclusions	8

1 The track pileup problem in future experiments

The present outlook of future collider experiments, including the HL-LHC program, highlights a sensible increase of luminosity, which is obtained both by increasing the proton bunches collision multiplicity μ and by decreasing the bunch to bunch separation time. With reference to LHC, μ will increase from the present value of 30 up to 200, while in the ultimate Future Circular Collider (FCC) scenario the bunch separation is expected to decrease from the present 25 ns to 5 ns only [1]. This scenario is even more challenging for the new generation of sampling calorimeters based on the particle flow concept, for which it is essential an excellent track to track separation to be able to reconstruct the shower profile, and a fast timing to reject pileup clusters simulating an high energy primary particle. As a template scenario, the FCC will produce p-p collisions of 100 TeV center of mass energy, reaching a peak luminosity of $10^{36} \text{ cm}^{-2} \text{ s}^{-1}$ [2].

These premises represent a strong motivation for future experiment to favour fast detectors, capable to manage an high instantaneous local track multiplicity. Among these RPCs have been used extensively in LHC experiments [3, 4] as detectors for the muon trigger systems due to the high time resolution and simple and economic construction.

2 The RPC hit to hit resolution power

A typical detector system has a sensitive surface of a single gap module of a few m^2 , in principle capable of a space-time resolution up to $\sim 0.4 \text{ ns} \times 100 \mu\text{m}$ according to the most recent developments [5]. Recently single gap RPCs has recently found an application in tracking calorimetry [6]. Making reference to figure 1 one can estimate the typical RPC hit volume occupancy in phase-space (x,y,z,t) which has a direct impact on the hit rate occupancy, or in other words the amount of

Figure 1. Representation of RPC phase space hit occupancy. one hit typically occupies (FWHM) $2 \text{ ns} \times 4 \text{ mm}^2$. This numbers are dependent on the detector layout.

distinguishable states. As we can see RPC hits are extremely localized occupying a tiny amount of phase space volume. Taking as a reference a 1mm gas gap inducing the signal on a set of strips, one hit occupies $2 \text{ ns} \times 4 \text{ mm}^2$ being these numbers the FWHM duration and induction footprint [5]. In this conditions a phase-space volume of $1 \text{ s} \times 1 \text{ cm}^2$ can contain up to 5×10^9 separable states or equivalently, a 1 GHz/cm^2 instantaneous rate would produce just $\sim 10\%$ occupancy. Of course this concept must be not confused with the rate capability which is measure on the average and not on the instantaneous rate. Of course these are theoretical values based on the physical space-time occupancy of a hit which can be limited by the space-time limits of the readout (TDC time resolution and pickup element dimension) and by ambiguities generated by the pileup of multiple simultaneous hits. In facts a 2D strip line based readout (one hit is simultaneously read by orthogonal strip sets) generates in general $N^2 - N$ fake hits (being N the number of physical hits) corresponding to all the hit strips crossings, so it is unambiguous only in case of single physical hit. The classic solution to this problem, is replacing the strip sets with a matrix of pads, resolving completely the x-y ambiguity. This solution is the classic one adopted in high pileup environments such as pixel systems and tracking calorimeters. The cost in terms of channels scales with N^2 while the strip cost scales with N . Another problem with this solution is that the front end (FE) electronics must be installed all across the detector sensitive area with non negligible problems of design, and has drawbacks on the detector thickness, radiation hardness, construction complexity and maintenance.

2.1 1D meantimer

An alternative solution is the so called meantimer readout (already applied to RPCs [7]), based on the concept of a single strip set equipped with a precise TDC at both strip ends reading independently t_1 and t_2 , the signal time of arrival to the front end measured with respect to an arbitrary common

reference. By exploiting this double readout of the very same avalanche one can compute the real hit time $t_0 = (t_1 + t_2)/2$ (hence the name meantimer), and the second coordinate: $t_1 - t_2$, the uncertainty being driven only by the time digitization precision. For example, assuming a propagation speed $V = 15 \text{ cm/ns}$ and a time binning of 200 ps the spacial resolution would be of $3/\sqrt{12} \text{ cm}$. With reference to figure 2 and considering $(x_1; t_1)$, $(x_2; t_2)$ as two simultaneous hits, the following relations hold:

$$\begin{cases} x_1 &= V(t_1 - t_0) \\ x_2 &= V(t_2 - t_0) \\ L &= x_1 + x_2 = V(t_1 + t_2 - 2t_0) \\ t_0 &= (t_1 + t_2 - L/v) \end{cases} \quad (2.1)$$

where L (the strip line length) and V (the propagation speed) are constants of the system. These relations allow not only to extract additional information but also to avoid hit ambiguities unless the hits interest the same strip. This readout scheme which is robust if we except the last case, has two problems, though: an asymmetric resolution on the second coordinate and the necessity of installing two amplifiers on the same strip which is tricky when operating with fast and sensitive amplifiers.

Figure 2. Sketch of the 1D meantimer readout concept.

3 The 2D meantimer concept

We propose here a simple and original readout scheme for RPCs combining the advantages of independent X-Y strips and the 1D meantimer, which is in principle already usable ex post on a detector layout as the one implemented in the ATLAS RPCs. In substance a physical hit being read out by two independent strip sets can be exactly reconstructed without ambiguities by imposing the respect of the space-time relations basing on the X and Y arrival times. Differently from the meantimer the spacial resolution is homogeneous on the two coordinates and can be much higher than the one allowed by the time of arrival measurement, which is instead used to determine the resolution power of simultaneous hits. In this scheme the FE electronics play a fundamental role since the performance is driven by the sharpness of the RPC signal and by the time digitization precision, on typical detectors of a few m^2 .

3.1 The 2D meantimer basic definitions

Figure 3 sketches a 2D readout strips set, hit by two particles in positions α and β . An hit is associated to a cluster of strips on each of the two orthogonal views, four clusters in total, characterized by position of the center of the cluster (x_i, x_j, y_l, y_k) , time of detection t , and total charge of the cluster q^{clus} . The real hits are given by the correct association of clusters: $\alpha(x_i, y_l)$; $\beta(x_j, y_k)$ while the opposite combination generates two fake hits $\gamma(x_i, y_k)$ and $\delta(x_j, y_l)$ at the other strip crossings.

Figure 3. Basic definitions of simultaneous hits clusters read by a 2D orthogonal strips set.

The gaussian shaped symbols in correspondence of α and β recalls the shape of the physical signal distribution on the strips which depends on the detector layout [5]. We summarize in table 1 the most relevant physical quantities being used in the subsequent calculations: The definitions

Table 1. We prefer to have borders around the tables.

t_0	real time of the physical signal
v	signal propagation velocity (~ 0.15 m/ns)
2δ	avalanche signal distribution width (FWHM)
d	strip pitch
t_n	lowest time of a given cluster
x_n	x strip id with the lowest time of a given cluster
y_n	y strip id with the lowest time of a given cluster
q_y^{clus}	$\sum q_{y_l}$ estimated charge of the cluster

above are used in equation (3.1), containing the fundamental relations of this technique:

- the position of a signal on a given projection is measured by the time difference with respect to t_0 on the orthogonal projection
- The total charge collected for a given cluster on one projection is equivalent to the one on the orthogonal projection

$$\begin{cases} x_i d = v(t_{yl} - t_0) \\ y_l d = v(t_{xi} - t_0) \\ q_{xi}^{\text{clus}} = q_{yl}^{\text{clus}} \end{cases} \rightarrow \begin{cases} t_0 = \frac{x_i t_{xi} - y_l t_{yl}}{x_i - y_l} \\ \frac{v}{d} = \frac{(x_i - y_l)}{(t_{yl} - t_{xi})} = v \\ (x_i - y_l) = v(t_{yl} - t_{xi}) \end{cases} \quad (3.1)$$

We can remove the ambiguity introduced by a 2D strip system, by imposing that the rightly associated cluster projections conserve the validity of these relations. In equation (3.1), we derive from the left member some observable: t_0 and v , respectively the impact time and the characteristic propagation speed in the strip lines. This values can be used either for calibration purposes or to perform the cluster crossing discrimination as it will shown later.

4 Beam test performance of the 2D meantimer concept

To test the 2D Meantimer concept we used two identical RPC prototypes, built for the ATLAS Phase-1 upgrade (scheduled by 2019) and installed in the GIF++¹ of CERN in a completely overlapped configuration, as shown in figure 4. The gas gap is 1 mm thick, defined by 1.2 mm thick HPL electrodes, having a total area of $50 \times 100 \text{ cm}^2$. The chambers is read out though two sets of 25 mm pitch orthogonal strip panels, having 40 and 20 strips on the horizontal and the vertical coordinates respectively. The strips are equipped with a newly developed amplifier [8], which waveforms were acquired by 8 channels per each view of CAEN DT5742 digitizer operated at 2.5 G samples/s, after $(16 \pm 0.03) \text{ m}$ of Lemo cables. The non precise cable length will therefore introduce a systematic uncertainty in the time measurement which can be eliminated via calibration. The test was performed using a 100 GeV muon beam triggered by a set of scintillators having an

Figure 4. The test setup at the GIF++ of CERN. The 2D readout connections are highlighted.

acceptance projected on the test chamber of $12 \times 12 \text{ cm}^2$. Moreover one of the two chambers was used as a beam tracker to select muons having the correct space-time correlation with respect to the tested chamber.

Applying eq. (3.1) to the beam data, we can calculate the hit matrix from the list of x and y clusters as:

$$v_{xi}^{y_k} |_{i,j,k,n}^{1 \dots N} = \frac{(x_i - y_k)}{(t_{yk} - t_{xi})} \quad (4.1)$$

¹The new Gamma Irradiation Facility of CERN.

being N the total number of hits counted on each view. These elements correspond to real hits only if they are compatible within errors to d/v . In figure 5 are shown the $1/v$ distribution and the space time correlation from $(t_{yk} - t_{xi}) = d/v(x_i - y_k)$, providing an estimate of the average propagation speed of (15.6 ± 0.2) cm/ns. The standard deviation of about 15% in the $1/v$ distribution is a

Figure 5. Distribution of $1/v$ (top) and space time correlation of the hits along the y coordinate.

combination of several factors: time binning, difference in cable length, amplifier response and saturation, charge distribution width, wide strip pitch, local defects, etc. Since this parameter is used to discriminate the fake hits a calibration matrix is important to achieve the maximum discriminating power. In the very good approximation of a single muon track per event and taking a sufficient statistics, one can calculate both the calibration and the error matrix, defined as its variance, at any given strip crossing:

$$\bar{v}_{x_1}^{y_1} = \frac{(x_1 - y_1)}{(t_{y1} - t_{x1})};, \quad \sigma \bar{v}_{x_1}^{y_1}. \quad (4.2)$$

Then the acceptance criterion for coupling two hits on orthogonal views is:

$$|\bar{v}_{x_1}^{y_1} - (t_{y1} - t_{x1}) - (x_i - y_l)| \leq \sigma \quad (4.3)$$

In figure 6 we test this framework with real data, using single muon tracks to produce a calibration distribution derived from eq. (4.2) (top plot). On the other side we obtained multiple hits events, used to measure the bottom plot observable, derived from eq. (4.3), by piling up offline random event hits, relative to two particular strips on both views, so to compare to a specific matrix element of eq. (4.2). It is important to observe that this last distribution does not peak at zero due to coupling wrong hits x, y hits on fixed strips, and its width is broadened by taking signals coming from different avalanches, thus carrying with it the intrinsic avalanche time fluctuations, which would have been automatically cancelled when taking a single signal. It worth here to stress that the real hit timing is not affected by the RPC time resolution (which paradoxically helps to reject fake hits) but only on the readout jitter and on the digitization binning. The $\pm 3\sigma$ calibration reference is reported with the vertical dashed lines, on the bottom plot, showing that it is possible to suppress 62% of the fake hits conserving most of the signal.

5 The fifth dimension: the charge

In the previous section we have established that a 2D meantimer method can certainly help to disambiguate track which are at a minimum distance (see figure 7) which depends on the width of

Figure 6. Calibration distribution derived from eq. (4.2) and test distribution of derived from 4.3 (bottom), obtained by random pileup of single track muon events on selected strips.

Figure 7. Schematic representation of the 2D meantimer method track to track resolution depending on the readout time resolution.

the calibration distribution driven ultimately by the time measurement precision (e.g. 3 cm radius with 200 ps resolution). A great help in increasing the discrimination power comes from the natural wide spread of the RPC avalanche charge distribution, feature which normally is considered as a drawback of the RPC technology limiting the detector performance. This spread is mostly due to the fluctuation of primary ionization and avalanche multiplication, amplified by the intense electric field of the RPC and only partially moderated by the avalanche saturation. Recalling the charge conservation relation in 3.1, i.e. the the clusters projecting the same avalanche on x and y , must have the same total charge within errors, it is immediate to note that a wide charge distribution makes very unlikely that by chance two simultaneous avalanches produce the same charge on the two projected clusters, thus offering further discriminating power. This additional parameter is very complementary to the 2D meantimer since it works even with hits falling in neighboring strips on one view.

Similarly to the 2D meantimer method we define a charge calibration matrix $\sigma \bar{q}_{y_1 x_1}^{\text{clus}}$ as the charge distribution variance calculated on single hits and a condition of compatibility with a real hit:

$$|\Delta q_{x_i y_k}^{\text{clus}}| = q_{x_i}^{\text{clus}} - q_{y_k}^{\text{clus}} \leq \sigma \bar{q}_{y_1 x_1}^{\text{clus}} \quad (5.1)$$

Figure 8. x vs. y cluster charge scatter plot. The black points correspond to the single hit muons of the calibration matrix, the red points are the purposely mismatched clusters obtained through pileup of two random events.

This relation has been applied to the single muon tracks and the result is shown in figure 8 by the black points, while the red points are the negative test sample generated by purposely mismatched clusters obtained through pileup of two random events. The result is a 68% of rejection power with a 95% cut efficiency.

6 Wrap-up, applications and conclusions

In this paper we presented a new and original technique the RPC 5D tracking to exploit the vast parametric space and peculiar features of the RPCs for high multiplicity tracking performance. The results experimentally demonstrated in sections 4 and 5 are based on completely independent aspects of our technique exploiting space time correlation and charge correlation of the RPC hits respectively. Their combination provides an overall rejection power of 89% and an overall cut efficiency of 95%. We remark that the experimental setup was not purposely built or optimized for this purpose but conversely is affected by several layout and performance limitations. This notwithstanding, the 5D tracking technique provide an excellent result which encourage to push the research in the direction of designing a optimized setup to test the limits of the technique.

Several concept detectors can benefit from this technique, such as particle flow based calorimeters, reaching pad like performance with a much easier and compact layout; large area cosmic rays detectors where is desirable to add shower tracking at affordable costs. A demonstration of the simplicity of this idea is the fact that the ATLAS RPC system it is already compatible with the 5D tracking concept, as it was designed in 1997, by simply replacing the readout electronics, which is anyway scheduled for the LHC Phase-2 upgrade [9]. Adding this feature would consist just in better exploiting the data already present in the detector to achieve local multiple track reconstruction capability, even in real time, to extend the ATLAS discovery potential.

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