High-rate characterisation of large-size RPC prototypes

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DELIVERABLE REPORT

HIGH-RATE CHARACTERISATION OF LARGE-SIZE RPC PROTOTYPES

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Abstract:
Large RPC detectors operating efficiently at high particle rates have been developed. The excellent fast timing capabilities of these detectors are exploited by using low-jitters readout electronics. Good spatial precision is obtained by developing a new 2D readout scheme.
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Executive summary

Large RPC detectors operating efficiently at high particle rates have been developed. The excellent fast timing capabilities of these detectors are exploited by using low-jitters readout electronics. Good spatial precision is obtained by developing a new 2D readout scheme.

1 INTRODUCTION

Large RPCs with high rate and excellent timing capabilities have been developed as well as a dedicated readout system providing excellent time measurement. Detectors with size exceeding 1m² have been built and tested with the new electronics. Tests at GIF++ and on CERN SPS beam lines show the new system to achieve an efficiency better than 95% and an absolute time resolution of 377 ps at particle rates exceeding 2 kHz/cm².

In its simple version a RPC is made of two resistive plates whose outer face is covered by a resistive coating. The two plates play the role of two electrodes. The distance between the two electrodes is maintained constant using insulating spacers. A gas mixture usually made of C₂H₂F₄, iso-C₄H₁₀ and SF₆, circulates in between the two plates. Applying high voltage to the two electrodes creates an electric field inside the gas gap. When a charged particle crosses the detector, it ionizes the gas molecules. Primary electron-ion pairs are produced initiating an avalanche of charges under the electric field. After the passage of the charged particle the avalanche charges are absorbed through the resistive electrodes. The higher the resistivity of the electrodes the longer is the time needed to evacuate the charge. During this process the electric field is locally diminished and passage of other charged particles may go undetected. Once the charges are absorbed the local electric field is then restored to its initial value.

2 HIGH RATE RPC

To increase the RPC rate capabilities the time needed to evacuate the charge needs to be shortened. One possibility to achieve this is to reduce the electrode plate resistivity with respect to the resistivity of the HPL material currently used to fabricate the RPC electrodes. This requires the development of new materials whose electric bulk resistivity should be in the range of 10⁸ to 10⁹ Ω.cm. Another possibility is to reduce the gas gap that limits the avalanche development and thus its charge. This reduction of the gas gap could be accompanied by the reduction of the electrodes thickness to reduce the time needed to cross it.

The two possibilities were studied. First large detectors were built using a new low resistivity glass developed by Tsinghua University [1]. Large RPCs made of HPL but with small gas gap and thinner plate with respect to the ones currently used (2-3 mm) were built. In parallel a new readout electronics system was developed to read out the large HPL RPC detectors operating in high flux conditions.

2.1 LARGE RPC MADE OF LOW-RESISTIVITY GLASS

The Tsinghua group has developed a new kind of stable low resistivity glass (10⁹-10¹⁰ Ω.cm) by introducing special metallic components in the fabrication of the glass. Unfortunately the new technique has a limitation on the size of the plates that can be made with the new glass. The maximum size of thin plates one can produce with this new glass could not exceed 32 cm x 30 cm. Several beam tests were conducted with detectors made of such small glass plates in the past [2][3]. The results of those tests demonstrated the high rate capability of the detectors made with the new glass.

To build large detectors using these relatively small plates, two methods are used:
The first one consists in assembling the glass plates of the same thickness with a special glue. Cylindrical spacers of 6 mm diameters are used to keep the gas gap at 1.2 mm. The coating is then applied on the assembled plates. This allows obtaining gas tight single gap detectors of large size similar to the small ones with limited dead zones as can be seen in Fig. 1. Using this method, a detector including two single-gap glass RPCs has been built and cast into an aluminium cassette. A PCB with strips of about 1 cm pitch is inserted between the two single gaps. The strips are connected using coaxial cables to a test board hosting one HARDROC ASIC[4].

![Fig. 1 Picture of the large 2-gap RPC built by assembling small glass plates by gluing them.](image)

The second method was proposed to avoid the usage of glue that is likely to be sensitive to hard radiation. Small plates with different shapes are gathered to form several small RPC gaps with no frame. Spacers made of hollow cylindrical tubes of 1 cm long and 1.2 mm external diameter are used as spacers. A fishing line of small diameter (slightly smaller than the internal diameter of the hollow tubes) crossing these short tubes is used to fix the spacers without preventing the gas from circulating freely in the gaps. The small RPCs being separated in this construction, their connection to high voltage is performed through very thin copper tape linking every two adjacent small RPCs.

Two large gaps are built following this approach and then set one above the other after inserting in between a PCB with pick-up strips identical to the one described above.

The two gaps as well as the PCB are cast in a cassette that is gas tight. A plate the same size of the detectors is equipped with few springs and put into contact with the detectors in the cassette. It ensures that no place could be left between the two detectors and the PCB. Figure 2 shows a picture of the RPC chamber built in this way.

Both cassettes were placed in a cosmic test bench to measure their efficiency as function of the HV. Figure 3 shows the efficiency of the two large detectors as a function of the applied high voltage. One can see that an efficiency plateau around 96% is reached at 7 kV for both chambers and that the current-HV dependence is the same for both chambers. The mechanical design features a smaller leakage current. This is probably due to the absence of the frame that ensures the gas tightness in that case.
The cassette made using the mechanical assembly was also found to be more robust and it was transported to be tested at the GIF++ facility where a very intense gamma source of 662 keV photons is available. The intensity of the source is adjustable thanks to a system of Lead walls allowing the study of the detectors response under the irradiation of different gamma rates. A fraction of the gammas interacted in the RPC chambers producing avalanches. This represents a particle rate that can reach a few thousands of Hz/cm$^2$.

In addition, the GIF++ facility is conceived to allow the passage of the H4 beam line particles. Our large RPC was exposed to a muon beam of 120 GeV at different source intensity values. Figure 4 shows the efficiency of the detector as a function of the applied high voltage for different particle rates. An efficiency higher than 85% can be reached at particle rates exceeding 2 kHz/cm$^2$. It is worth noticing here that an increase of up to 1 kV is observed to reach the efficiency plateau when going from source off to a 3kHz/cm$^2$ for this detector made of low resistivity glass.
2.2 LARGE RPC MADE OF HPL

Although the feasibility of large detectors made of small glass plates was confirmed, it presents however several technical difficulties and requires more effort in order to build robust detectors. To avoid these constraints and have large RPCs with high rate capability the possibility to use thin HPL plates and thin gas gap has been studied.

Several large gaps were built with different HPL plate thicknesses: 1, 1.2, 1.4 and 1.6 mm. For each of them, a gas gap was chosen to have the same plate thickness. A preliminary study of these detectors by our Korean partners of the CMS collaboration led to choose the 1.4 mm plate thickness as the best solution. This solution provides high rate capability by reducing the mean avalanche charge by a factor of 3 with respect to the CMS and ATLAS current RPCs for which 2mm HPL plates with a gas gap of the same size was used. It ensures also a good stiffness when compared with the 1 and 1.2 mm solutions. The stiffness is indeed important to keep the gas gap thickness stable over the large detector size.

Several 2-gap RPC detectors as the one described in Fig. 5 (left) were built. A new readout electronics system was used to test them as will be described in the next section.

**Fig. 4 Efficiency of the mechanically assembled 2-gap glass RPC as a function of the effective applied high voltage for different particle rates using the CMS gas mixture at the GIF++**

**Fig. 5 Scheme of the HPL-electrode 2-gap RPC proposed to equip two of the high η CMS muon stations.**
3 READOUT ELECTRONICS SYSTEM

To read out the large RPC detectors and to exploit their fast timing capability and their spatial resolution while keeping a reasonably low number of electronic channels a dedicated system was developed. The system uses a radial pick-up strips Printed Circuit Board (PCB) inserted between the two gaps of a large RPC as shown in Fig. 5(right). The induced signal on the strips following the avalanche produced by the passage of a charged particle is read out from the two ends of each of the strips thanks to two channels of an ASIC called PETIROC [5]. This ASIC has 32 channels. Each channel has a preamplifier with an overall bandwidth of 1 GHz and a gain of 25. Each channel provides a charge measurement and a trigger output that can be used to measure the signal arrival time. It was originally developed by the OMEGA group to read out SiPM devices, but its dynamic range (60 fC-160 pC) qualifies it for the readout of RPC detectors as well. The low jitters of the preamplifier provide an excellent tool to measure the time arrival of the RPC signal with a great precision. For this a delay-line TDC on FPGA is used. The difference of the time arrival of the signal from the two ends of a strip is then used to deduce the position of the charged particle passage on the strip.

Hereafter a detailed description of the different components of the readout electronics system.

3.1 PRINTED CIRCUIT BOARD (PCB)

The best way of reading efficiently the two ends of the strips and to keep the electromagnetic perturbations at a low level is to have a PCB that hosts both the strips and the readout electronics. A small trapezoidal PCB (Fig. 6), 50 cm long was conceived and produced. It hosts strips with 4 mm pitch in the central part, namely that to be inserted between two gaps. This part of the PCB is made of copper strips covered by a dielectric layer on both sides of the PCB. The two ends of the strips are routed on the lateral sides of the PCB to be located outside the detector and they are protected from external perturbations by grounding layers on both sides. Finally, the readout electronics is placed on the top part of the PCB. This includes two PETIROC ASICs as well as two mezzanines hosting each a cyclone II Altera FPGA where the TDC firmware is coded. The PCB has a 6-layer structure.

To test the principle of this 2D readout system a 5 pC charge was injected on one point of the strip. The time arrival of the signal detected at the two ends of the strip was used to estimate the time resolution. A resolution of 30 ps was found for the T2-T1 measurement, leading to an individual time resolution better than 25 ps for each channel.
The lateral return strips characteristics were indeed chosen so to have the same impedance as those of the strips with respect to the gaps anode in order to reduce the loss of signal by reflection. Unfortunately, it was found that the high coating resistivity of the gaps anode does not allow the use of the anodes as grounding reference of the transmission line. Nevertheless, the electronics board was tested on several HPL small detectors in a beam test at the H4 SPS beam line at CERN. Figure 7 shows the position precision one obtained by using the formula:

\[ Y = \frac{L}{2} - V(T_2 - T_1) \]  

(1)

Where \( V \) is the signal velocity and \( L \) is the total length of the strip including the return part.

![Fig. 7 Time difference of the signal arrival as a function of the beam position with respect to the PCB edge.](image)

To equip large RPC detectors such as the ones proposed for the RE3/1 and RE4/1 of the high eta CMS muon stations, one needs to have a PCB as long as 1.7 m. It was not possible to find a company capable of producing a 6-layer PCB of this length. To overcome this difficulty two solutions were proposed:

### 3.1.1 Coaxial cable connected PCB

A simple but longer (1.65 m) trapezoidal PCB (58 and 32 cm for the bases) with 48 cooper strips 35 μm thick and a pitch of 0.9 cm on average placed in the center of a 600 μm FR4 insulating material was conceived and fabricated by the ELVIA Company (Fig. 8 (left)). The PCB was inserted between two HPL gaps with the same length (but twice as wide as the PCB). The impedance of the strips was measured by several methods and found to be 43 Ω. To reduce the cost, commercial coaxial cables of 50 Ω were used to connect the two ends of the strips to a Front Electronics Board (FEB).

### 3.1.2 Embedded return strips PCB

The success of the first version of long and thin PCB encouraged us to go further and work with the ELVIA Company to include the return strips on the same PCB. To limit the zone reserved to the return strips that extends the PCB beyond the detector surface, the pitch of these return strips should be as small as possible and, at the same time, their impedance should be the same as that of the strips (43 Ω). The best compromise was found by extending the dielectric layer on the lateral edges and choosing return strips 200 μm wide and 300 μm pitch placed at the same level of the strips within the
dielectric layer but with two grounding planes placed on the two sides of the extended part of the PCB (Fig. 8 (right)). With this design, the return strips have the same impedance as the strips and no reflection is then expected. In addition, the two ends of the strips are routed to the wide basis of the trapezoidal plate where a connector is soldered. The connector is used to plug the FEB directly on the PCB.

![Fig. 8 Left: Long PCB (1.65 m) for coaxial cables. Right: Long PCB with embedded return strips.](image)

### 3.2 FRONT ELECTRONICS BOARD (FEB)

In order to read out the strips, a new board is used hosting, in addition to an impedance matching circuit, one 32-ch PETIROC ASIC and a mezzanine equipped with a Cyclone II Altera FPGA (Fig. 9). A TDC firmware that was developed for medical applications by the University of Tsinghua [6] was adapted to our use. The new FPGA TDC firmware could manage in principle the 32 preamplifiers output of the PETIROC channels. Unfortunately, due to the limited capability of this FPGA, the number of TDC channels was reduced to 25 to avoid possible instabilities during operation; the 25th one is used to record the arrival time of the external trigger.

To read out the 48 strips four FEBs were used. They were fixed on an aluminum cassette that contains the two gaps as well as the PCB. They were wrapped in an envelope made of a 1 mm copper sheet to ensure a controlled reference grounding of the strips. The connection between the PCB strips and the FEBs was made through apertures in the copper envelope and the aluminum cassette.
3.3 DATA ACQUISITION SYSTEM

A dedicated data acquisition system was developed to control the readout electronics, to read the data and ensure their consistency. It allows the configurations of the different ASICs to guarantee uniform response to a given signal. Indeed, in order to equalize the 32 channels response, the ASIC has two adjustment systems. A common 10-bit Digital Analogue Converter (DAC) system ensures the triggering level adjustment in the dynamic range of the ASIC. An individual 6-bit DAC is used in each channel to achieve a similar response of the ASIC's channels. When a signal with an amplitude exceeding a value (threshold) determined by the configuration parameters is detected the preamplifier output signal is conveyed to one of the FPGA TDC channels to measure its time arrival and record it temporarily in the FPGA memory before sending it to the computer.

It is important to mention that, when a low threshold (close to the limit of 60 pC) is set to operate the PETIROC channels, a phenomenon of retriggering in some cases is observed, and as a consequence this results in spurious signals. To solve this problem the system was required to pause the acquisition for a very short time (10 ns duration) after a time interval of 30 ns following the arrival of the first signal on one of the channels. The time interval of 30 ns allows the signal on the other channels and, in particular, that associated to the other end of the fired strip to be detected.

4 BEAM TESTS RESULTS

Two large cassettes, each including a 2-gap RPC, were built. One cassette was equipped with a PCB with the coaxial cables connection to the FEB and the second with integrated return-strip PCB. The two were placed in the GIF++ and exposed to a muon beam with different irradiation rates. To estimate the efficiency of these two detectors an external trigger system made of two large (20 cm) PM-Scintillator systems placed outside the GIF++ bunker (to avoid to be fired by the source photons) and two small PM-Scintillator systems (4 cm large) placed close to the two RPC cassettes was used. When a signal is seen in coincidence in the four systems it is sent to the 25th channel of each FEB FPGA TDC and its time arrival is measured as for the strips signals. The efficiency of each of the two chambers is then estimated as follows.
\[
\epsilon = \frac{N}{N_{\text{trig}}} - \frac{N_{bkg}}{N_{\text{trig}}} \\
1 - \frac{N_{bkg}}{N_{\text{trig}}}
\]

Where \(\epsilon\) is the muon efficiency, \(N_{\text{trig}}\) is the number of triggers, \(N\) the number of events for which the two ends of at least one strip are fired during a time interval of a few ns and \(N_{bkg}\) is estimated by counting events for which at least a strip is fired (both ends) in a time interval of the same length but uncorrelated with the trigger. This formula takes thus into account the spurious contribution to the efficiency due to the source photons.

Figure 10 shows the efficiency of the two cassettes at different particle rates as a function of the effective high voltage applied on each gap after correcting for the effect of the temperature and pressure. These results show that efficiencies higher than 95\% are reached for particle rates up to \(2\) kHz/cm\(^2\). The rate is estimated by counting the number of clusters of fired strips in a given time interval normalized to the instrumented surface and to the efficiency. To achieve the clustering efficiency first the different TDC offsets are estimated and corrected by using muon signals for which more than one strip is fired at source-off. The channels associated to the same side of the PCB are clustered if the signal arrival time difference is within \(5\) ns (corresponding to three standard deviations of the time arrival difference of these channels with respect to the trigger one). A cluster is then built by associating the fired channels of the two sides of the PCB if they share at least a common strip.

To validate the impact of such a good time resolution on the determination of the \(Y\) coordinate of the muon impacting the detector along the strips, a chamber equipped with an embedded return strips PCB was put on a micron-precision movable table and the time difference of the two ends of a fired strip associated to a muon event was measured (Fig. 11(left)). Formula (1) was then applied to determine \(Y\). The average value of \(Y\) was plotted against the one given by the table position as shown in Fig.11 (right). A maximal deviation of less than \(1.5\) cm with respect to a perfect linear behavior is observed. This, combined with the resolution of determining the associated \(Y\) measurement, allows to determine the absolute \(Y\) position with \(2\) cm of uncertainty all along the chamber.

To determine the absolute time resolution of these RPC detectors using the fact that the muon beam is more or less perpendicular to the RPC planes, the time difference of the signal of the left side of the strips fired in the same muon trigger event of the two RPC detectors was estimated and added to that obtained with the other side as can be shown in Fig.12. One can estimate that the absolute time resolution of these large chambers is better than \(533/\sqrt{2}=377\) ps. This time resolution is even better if one takes only the central strip in case several strips are fired. This is indeed explained by the fact that the higher the charge the better the time resolution and smaller is the impact of the time walk.
Fig. 10: Efficiency of two large HPL 2-gap RPC (one using coaxial cables and one with the embedded return strips) as a function of the converted gamma rates.

Fig. 11 Left: Time difference of signal arrival on one of the strips. Right: Average time difference of the signal arrival as a function the beam position with respect to the edge of a mobile table for all the strips.
Fig. 12 Time difference of two detectors. The mean value divided by square of 2 provides the 2-gap HPL RPC absolute time resolution.

5 CONCLUSIONS

Large 2-gap RPC detectors made with two different materials (low resistivity glass and HPL) were built and successfully tested. Both show that high efficiency is achieved at particle rates exceeding 1 kHz/cm². In addition, a new readout electronics system using excellent timing electronics was conceived and used to study these detectors. This results in a very good spatial precision by using the time information read-out at both ends of a strip. The same readout electronics system exploits the excellent fast timing capability of the RPC detectors. This work will continue in the coming months. A new version of the PETIROC with a lower threshold (20 fC) is being produced. This will allow to obtain a high efficiency at lower applied high voltages and thus with less avalanche charge. Reducing the avalanche charge will then increase the rate capability and will also limit the detector aging.
REFERENCES


## ANNEX: GLOSSARY

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<td>HPL</td>
<td>High Pressure Laminate</td>
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<td>ASIC</td>
<td>Application-Specific Integrated Circuit</td>
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<td>Printed Circuit Board</td>
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<td>Time Digital Converter</td>
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