Resistive Plate Chamber as an Active Medium for a Digital Hadron Calorimeter

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We report on the development of Resistive Plate Chambers (RPCs) as an active medium of a digital hadron calorimeter for the future International Linear Collider (ILC). RPCs are simple and inexpensive detectors that can detect charged particles with high efficiency and low noise. RPC can provide good position resolution to accommodate fine readout segmentation which is required by Particle Flow Algorithm (PFA) for ILC calorimeters. We present the design, construction and testing of various prototype chambers, with both analog and digital readout. We measured cross-talk of RPC signals on highly segmented readout pads, and developed different designs to control the cross-talk level. We measured the signal rate capability of RPCs to be better than 50Hz/cm^2. RPCs proved to be an excellent choice for the active medium of a digital hadron calorimeter. We completed the R&D on RPC, and now prepare the construction of a 1 m^3 prototype hadron calorimeter section. The prototype section will undergo testing in various particle beams.

1. INTRODUCTION

The future International Linear Collider (ILC) will address exciting new physics and precision measurement. It requires unprecedented jet energy resolution to unambiguously determine hadronic final states, which will be achieved by using Particle Flowing Algorithms (PFA). PFAs require clear separation of signals from individual particles of a jet in each detector subsystem, so that one can choose the best measured energy/momentum to represent the particle energy, and thus achieve better jet energy resolution. The ILC detector is going to be fully optimized for PFA performance.

To separate particle showers within a jet, a specially designed calorimeter system with very fine segmentation is the key. In particular, the hadron calorimeter needs to have a lateral readout cell size of the order of 1×1 cm^2, which means around 10^7 readout channels for the ILC hadron calorimeter alone. With the large number of channels, a traditional analog readout scheme may not be affordable. Monte Carlo studies showed[1] that a digitally readout (i.e., 1 ADC bit/channel) hadron calorimeter can provide comparable single particle energy resolution at this segmentation level, while the much simplified readout scheme can significantly reduce the cost. In addition, since a digital hadron calorimeter gives up the detailed energy deposition information for each cell, newly developped and inexpensive detectors, such as Resistive Plate Chambers (RPC), become excellent candidates for the active medium.

Resistive Plate Chambers (RPC)[2] are particle detectors based on a simple, inexpensive and reliable technology. They have been successfully used in a number of particle physics experiments. RPCs have nearly 100% detection efficiency of charged particles with very low noise rate, and provide good position information. RPC can be made very thin, and can easily be built to cover a large detection area.

A typical RPC configuration is shown in Figure 1. The chamber shown has a thin gas volume enclosed by two glass plates. The gas volume is filled with an appropriate gas mixture. In our case, a gas mixture consisting of R134A : Isobutane : SF_6 = 94.5 : 5.0 : 0.5 is used. High voltage is applied to the gas volume through resistive paint layers on the outer surface of the glass plates. When a charged particle passes through the gas volume, depending on the high voltage applied, the initial ionization will develop into an avalanche or a streamer. The induced signal from the avalanche/streamer can be easily picked up by a readout pad located on the outside of the glass plates.

In case of a digital calorimeter, an RPC needs an array of readout pads of desired size (typically 1×1 cm^2). An avalanche or a streamer, in general, will induce a signal on more than one readout pad and cause signal cross-talk.

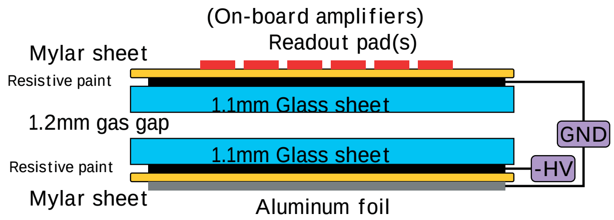

Figure 1: Schematic view of a typical RPC

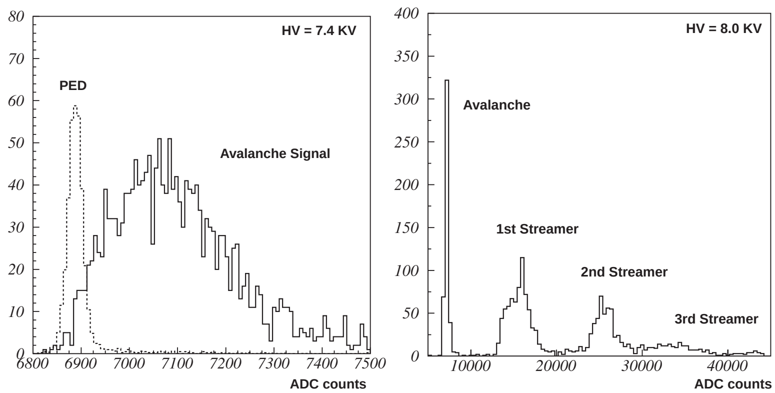

Figure 2: RPC signal charge distribution. a) avalanche signal, b) streamer signal

The levels of cross-talk has been extensively studied for a variety of different RPC designs.

2. RPC SIGNAL AND EFFICIENCY

We have built and tested over 10 RPCs with different design parameters. Each RPC was first tested with cosmic muons, using one large signal readout pad that covers most of the sensitive region of the RPC. The signal from the readout pad was send to a charge integration amplifier that gave the total charge of a signal with 1.1 fC sensitivity. Four layers of scintillator counters, two on top of the RPC and two below with an overlapping region of $\sim 10 \times 10$ cm^2 centered on the RPC readout pad, provided a reliable trigger signal for the charge integration amplifier. System noise, from both the RPC and the readout electronics, was estimated by reading out the amplifier output at random times.

For a given gas mixture, the RPC will not produce any signals below a threshold voltage. Above but not far from that threshold, the RPC will give pure avalanche signal for charged particles. At even higher operating voltage, some avalanches will develop into streamers, and the observed signals will be a mixture of avalanches and streamers. The streamer component becomes larger at higher operating voltage.

For the gas mixture we use, depending on the gap size of the RPC gas volume and operating voltage, avalanche signals give an average charge of 0.2 - 10.0 pC. Figure 2a shows a typical charge distribution of avalanche signals (solid line, average $\sim$0.2 pC), which has a Landau-like shape with a long tail. The dashed line shows a distribution of the amplifier output with random triggers, from which, we estimated the system noise (RPC + readout) to be smaller than 50 fC.

For our gas mixture, depending on the gap size and operating voltage, streamer signals give an average charge $>$ $\sim$30 pC. Figure 2b shows a typical charge distribution of streamer signals. The first narrow peak on the left is the residual avalanche signal at this operating voltage. The broader peaks on the right are from streamer signals. The peak structure is coming from the fact that one streamer can emit photons which may introduce new streamer(s) in the nearby region. Since the amplifier we use has an integration time much longer than the time interval between

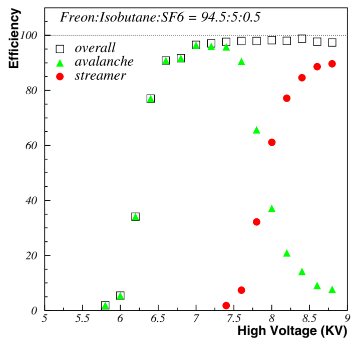

Figure 3: Cosmic muon detection efficiency of RPC (Threshold: 100 fc)

the initial streamer and the photon induced ones, the charge of all streamers is added up. The first peak represents events with only one (initial) streamer, the second peak are events with two (one initial + one photon induced) streamers and thus twice the charge, etc.

Using a threshold of 100 fC, we can remove most of the system noise. Figure 3 shows the cosmic muon detection efficiency for one of our RPCs. The open square dots show the total efficiency which is above 98% for any operating voltage $>$ 7.0 kV. The triangle and round dots show the avalanche and streamer component, respectively, as a function of operating voltage. In the voltage region between 6.8 kV and 7.4 kV, the RPC gives almost pure avalanche signals with an efficiency $>$ 95%. This voltage region is called the "avalanche plateau". For voltages $>$ 8.5 kV, this RPC gives $>$ 90% streamer signal with high efficiency, which is called streamer mode. For a digital hadron calorimeter, our preferred running mode is the avalanche mode.

3. SIGNAL CROSS-TALK AND HIT MULTIPLICITY

To be used as an active medium of a digital calorimeter with very fine segmentation, our RPCs have been tested with multiple small readout pads and a digital readout system. We built a readout board that contains an 8×8 array of signal pads of 1×1 cm^2 size. Signals taken from the pads were amplified by UPC1663 amplifiers mounted on the back of the pads and then sent to a VME board through a 10-feet cable. The VME board was designed and built at Argonne to handle 64-channel signals from the 8×8 array of signal pads. Each channel of the board receives amplified signal from a readout pad and compare the signal to a pre-programmed threshold to convert the signal to a digital bit, i.e., 1 (or "hit") if the signal amplitude is greater than threshold, 0 (or "no hit") otherwise. The digital hit pattern of all channels were readout and recorded into an on-board buffer every 100 ns.

We used cosmic muons to test RPCs with multiple signal pads and digital readout. To distinguish hits from real cosmic muon and noise, we used four layers of scintillator counters, two above the RPC and two below with $\sim 3 \times 3$ cm^2 overlapping area centered on the 8×8 array, to provide a trigger signal.

When a charged particle passes through an RPC, it produces hits on one or more pads, due to the signal cross-talk. The number of hits per particle passing, or hit multiplicity, is a good measure of the cross-talk level. We measured the hit multiplicity of different RPC designs. Figure 1 shows our baseline design. We measured the hit multiplicity of the baseline design as a function of threshold. Since the threshold is directly related to the RPC signal efficiency, instead of plotting the hit multiplicity as a function of threshold, we show in figure 4 the relation between hit multiplicity and RPC efficiency when the chamber was operated at 6.8 kV. At lower thresholds, the RPC is more efficient, but the hit multiplicity, or cross-talk level, is also higher. One can suppress the cross-talk level by raising the threshold, but this also reduces the signal efficiency. Overall, the cross-talk level of the baseline design is reasonably low:

- Hit Multiplicity M = 1.6 - 1.7, at ϵ = 95%

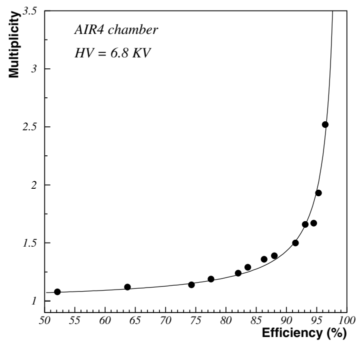

Figure 4: RPC hit multiplicity as a function of detection efficiency, for baseline design

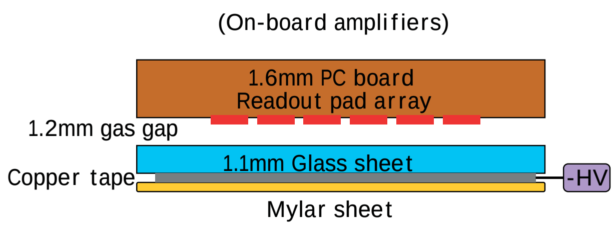

Figure 5: Schematic view of a new RPC configuration with only one glass plate

- Hit Multiplicity M = 1.4 - 1.5, at $\epsilon = 90\%$

The total noise rate for this RPC design is below 10Hz, corresponds to <0.2Hz/cm^2. We also repeated the measurements at different operating voltages on the avalanche plateau, and found that the hit multiplicity - efficiency relation is not sensitive to the operating voltage.

In addition to the baseline design, we tested various other RPC designs to understand the origin of the signal cross-talk and to study the impact of different designs. We tested chambers with the following changes:

- 2-gap chamber. The overall gap size was the same as in the baseline design.
- RPCs with different surface resistivity for the resistive paint layer.
- RPCs with a reduced amount of material between the signal pads and the gas volume, including the use of thinner glass, the removal of the paint layer, or even the removal of the glass plate between the signal pads and the gas volume.

From these tests, we learned that the following factors affect the signal cross-talk level of an RPC:

- 1-gap RPCs have smaller cross-talk than 2-gap RPCs, if the total gap sizes are the same.
- Resistive layer with higher surface resistivity reduces the cross-talk
- Reducing the amount of material between signal pads and gas volume lowers the cross-talk level.

As an example, Figure 5 shows a new design we tested. In this design, we use only one glass plate, and the gas volume in enclosed by the glass plate and a printed circuit board that has the 8×8 pad array on one side and the amplifiers on the other side. The signal pads face the gas volume directly. Figure 6 shows the hit multiplicity measured with this chamber (AIR9) as a function of signal efficiency (square dots and triangle dots), compared with the baseline design (AIR4, round dots). The measured hit multiplicity remains below 1.1, and does not depend on the signal efficiency. The noise rate for this chamber is <0.5Hz/cm^2.

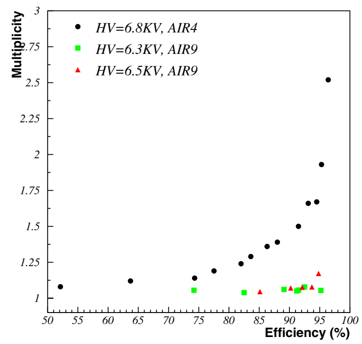

Figure 6: RPC hit multiplicity as a function of detection efficiency, for new design (air9), compared with baseline design (air4)

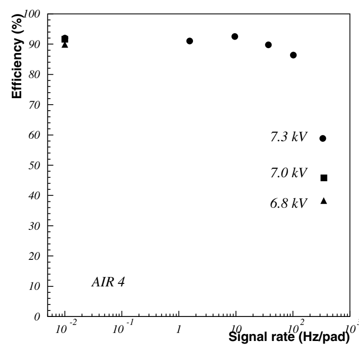

Figure 7: RPC efficiency as a function of signal rate, at different operating voltages

4. RPC RATE CAPABILITY

RPCs can handle a limited signal rate. The charge from signal passes through the glass plate as a tiny current (due to the high resistivity of the glass) and returns to the high voltage supply. When the signal rate is high, the current through the RPC becomes large enough leading to a significant voltage drop on the glass plates. As a result, the voltage across the gas volume and therefore the average signal charge and chamber efficiency decrease.

To measure the rate capability, we used a 0.1 mCi Sr-90 source to illuminate the chamber at different distances, giving rates from $\sim$1Hz/cm^2 up to $\sim$300Hz/cm^2. The smallest distance between the source and the RPC was $\sim$33cm, which is relatively large compare to the active area of the RPC (18×18 cm^2), giving a relatively uniform signal rate across the whole RPC.

Since only part of the electrons from the source reach the RPC gas volume, it is difficult to calculate the signal rate from the source strength and the geometrical information. Instead, we used the RPC itself to measure the signal rate, assuming a negligible rate from noise and cosmic muons. The measured rate was corrected for the measured signal inefficiency. We used cosmic muons to perform the efficiency measurement.

Figure 7 shows the measured signal efficiency for the baseline design as a function of signal rate. The efficiency remains constant at signal rates below $\sim$50Hz/cm^2, but drop rapidly above that. This rate capability is good enough to be used as an active medium for the hadron calorimeter of an ILC detector.

5. OTHER RPC STUDIES

Besides the tests discussed above, we also performed a number of other studies on RPCs. Among them are:

- Glass resistivity measurement: the glass plates have a resistivity of 4.7×10^{10} Ωm at room temperature, and 1.0×10^{10} Ωm after being heated up by the amplifiers.
- Glass bending due to pressure from the gas or electrostatic force: we performed both calculations and measurements which agree very well. The bending is within an acceptable range.
- RPC aging studies: We operated one RPC at a low rate for $\sim$ 2 years, and two RPCs at a high rate ($\sim$100Hz/cm^2) for a few month. No changes in their signal property or any aging effects were observed.
- Large RPC: We built one large size RPC (30.5 $\times$ 91.5 cm^2). Its properties were measured to be identical to smaller RPCs.

All tests on prototype chambers are complete. Based on these measurements, we have developed a base design to be used in a prototype section of a digital hadron calorimeter[3]. This 1 m^3 test section will contain of the order of 4×10^5 channels.

6. CONCLUSION

A digital hadron calorimeter with very fine segmentation is a practical way to achieve excellent jet energy resolution for the ILC. Our R&D efforts shows that RPCs are an excellent choice for the active medium of such a calorimeter. RPCs give big enough signal and nearly 100% detection efficiency for charged particles at very low noise rates. RPCs can be readout with very fine segmentation and the signal cross-talk can be controlled with specific chamber configurations. RPCs can operate with signal rates up to 50Hz/cm^2, which is sufficient for ILC calorimeter.

Acknowledgments

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References

[1] For example, see talks in Calor2002, jet measurement session, http://3w.hep.caltech.edu/calor02/abstract/Presentation/jet/Zutshi.ppt, Videau.ppt, magill.ppt
[2] For more information on RPCs, see e.g. http://mars.fis.uc.pt/ rpc2001/talks.html.
[3] See talk by J. Repond, this proceeding.