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THE PARALLEL PLATE CHAMBER AS A DETECTOR FOR FAST, RADIATION RESISTIVE CALORIMETRY

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Abstract

The Parallel Plate Chamber (PPC) is a single-gap, gaseous detector with planar electrodes, working in the avalanche mode. It consists of sixteen 1 mm gap cells, each 126.5 by 126.5 mm². The gas filling is pure isobutane at NTP. The chamber operates without breakdown up to the electric field of 60 kV/cm. The PPC has a very fast response, and a time resolution of a few nanoseconds. The detection efficiency is close to unity. No saturation effects were observed for collected charges up to 1 pC. Results of the scanning of the electron and hadron shower development, using the prototype detector plane, are presented.

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1. Introduction

The traditional gaseous wire detectors are reliable, relatively cheap, easy to build and operate. The readout for these detectors is well developed. However, there might be certain difficulties when using them for the detection of charged particles in the new high-luminosity collider experiments, because of rate limitation and lack of radiation hardness. When considering the operating conditions at the LHC or SSC, the following are the requirements for gaseous detectors:

- Counting rate capability up to $10^7 \text{ cm}^{-2} \text{ s}^{-1}$.
- Radiation resistance of at least a factor 100 higher than that of the conventional wire chambers.
- Very fast response and good time resolution of a few nanoseconds.
- Good position resolution.
- Low cost per surface unit.

A possible answer to these requirements is a Parallel Plate Chamber (PPC). The PPC¹⁾ is a single-gap gaseous detector with planar metal electrodes. The gap between the electrodes is narrow, and the electric field—which is uniform in the gap—is large enough to give rise to the avalanche multiplication of primary ionization at any point of the gas volume. A moderate gas gain of 1000 to 10 000 can easily be obtained without spark discharges.

The detected signal in a PPC depends on the length of the avalanche, i.e. on how far the initial ionization is from the anode. Therefore, there is no proportionality between the energy deposit and the collected charge.

The number of ion pairs in the avalanche is:

$$N(x) = N_0 \exp \left[\int_0^x \alpha(x) dx \right] = N_0 \exp (\alpha x) ,$$

where N_0 is the number of primary ion pairs, α the first Townsend coefficient, and x is the distance from the ionization point to the anode.

The average gas gain for the primary ionization over x is:

$$\int_0^D \frac{N(x) dx}{N_0 D} = \frac{1}{D} \int_0^D \exp (\alpha x) dx = \frac{\exp (\alpha D)}{\alpha D} ,$$

where D is the gas gap size.

Because of the position fluctuations for a small number of primary ionization clusters, randomly distributed along the path of a minimum ionizing particle, the pulse-height spectrum of such particles has an approximately $1/A$ -like dependence, where A is the pulse height (see Appendix).

There is a finite probability for a minimum ionizing particle to pass through the chamber gap without any interaction in the gas medium. For example, in isobutane this kind of inefficiency is about 1% for a 1 mm thick detector [4]. Furthermore, if the initial ion pairs are created near the collecting electrode, the avalanche length is small, and the charge collected at the anode may be below the level of detection.

The gas used in the PPC should not be transparent to its own UV light in order to avoid the photoabsorption on the cathode, and the generation of secondary avalanches spreading over the gas volume. Pure isobutane has been chosen as the working gas because of its high absorptive power for light quanta. The other advantage of isobutane is its large dE/dx value resulting in high efficiency for relativistic particles in a small chamber gap.

1) Pioneering studies of a similar device are known (see, for instance, Refs. [1–3]).

As the PPC has a uniform electric field and operates at atmospheric pressure, a gas pressure stabilization is needed to keep the E/ρ value constant.

The development of the signal in the PPC is easily predictable, because of the simplicity of the PPC geometry; the pulse shape is determined by the motion of both electrons and ions. During the avalanche multiplication, which lasts less than a few nanoseconds after the passage of a particle, the electrons are collected at the anode, and the cloud of positive ions drifts toward the cathode. The electron component of the signal is very fast, because of the high electron-drift velocity in the strong electric field and the narrow gap. The time resolution for detectors with parallel electrodes is well known and similar to that of a spark counter [5].

The PPC can operate in intense particle beams since, at moderate gas gain, the local reduction of the electric field at the place of the avalanche is very small because of the large lateral extension of the avalanche in the chamber [3]. The global space-charge influence in a PPC is rather weak when compared with conventional wire chambers, where the gas multiplication takes place in the vicinity of the anode wire. The rate capability of a similar detector has been studied quantitatively [6]. The detector was operated at a flux of 10^5 Hz/mm² without any particular problems.

As the large surface of the PPC electrodes is a few orders of magnitude greater than that for the anode wire, the ageing effects in a PPC are negligible.

2. Chamber construction

The design principle of the PPC is shown in Fig. 1. A PPC consists of thin metal electrodes affixed to flat glass plates. The electrodes are separated by spacers.

Extensive studies were required to construct chambers which could operate at a very strong electric field over a long period of time. The R&D work involved three main items:

- mechanical accuracy and stability;
- electrode surface conditions;
- chamber cleanliness.

The details of the cell design are presented in Fig. 2. The PPC components include two optical glass plates, eight metal electrodes, and four glass fibre epoxy spacers. We used optically-flat glass plates 126.5×126.5 mm² and 2.5 mm thick. They are inexpensive and readily available from industry. Two sets of low carbon steel electrodes, 60×60 mm² and 2.35 mm thick, were cut from a solid bar on a lathe. They were milled to their final shape and all four edges were rounded on one side. The grooves were then milled on their outer faces to release all remaining mechanical tensions. The inner surfaces of the electrodes were carefully polished until a mirror surface was obtained. In order to maintain a precision flatness of about 10 μ m, each set of four electrodes was machined in one go. Four spacers were machined in the same way to an absolute accuracy of 5 μ m.

First, the electrodes were glued to the glass plates using precision guides. All components were cleaned with alcohol and assembled in a dust-free room in a stream of twice-distilled water. The Plexiglas frame was then sprung around the outside of the cell. The cell was put under a bell jar and pumped to remove all traces of water. Finally, the frame was glued to the glass plates to make the cell gas-tight.

The high voltage was applied to each of the four electrodes through the holes in the glass support. The preamplifiers were connected in the same way to the opposite electrodes, the gas inlet and outlet plugs were fixed at two diagonal corners of the cell.

The cells were flushed with pure isobutane (0.9996). In order to keep dust out, the gas passed through several filters, including an electrostatic one (Fig. 3).

The cells, which successfully passed the test with radioactive sources, were used to assemble the full-size PPC. The chamber consists of sixteen $126.5 \times 126.5 \text{ mm}^2$ cells covering the surface of $508 \times 508 \text{ mm}^2$. The design of the multicell chamber is presented in Fig. 4.

3. Results

Different radioactive sources (^{239}Pu , ^{55}Fe , ^{109}Cd , ^{106}Ru), as well as a charged beam (3 GeV/c), were used to study the PPC properties. The collecting electrode was connected to a fast, low-impedance, current preamplifier [7] which has the following characteristics:

- noise: 3500 electrons with a loading capacitance of 30 pF;
- amplification: 60 mV/1 μA ;
- rise time: 2.5 ns.

For the tests with the radioactive sources the low-noise ‘slow’ charge sensitive amplifier has also been used, with moderate gains:

- noise: 500 electrons;
- integration time: 500 ns.

During tests the gas conditions were monitored with an ^{55}Fe source.

The current pulse shape is shown in Fig. 5. The pulse has a very sharp peak which reflects the avalanche development, and a long flat tail corresponding to the positive ion collection on the cathode. Figure 6 shows the electron component of the signal. The full width at the base is 7 ns.

A typical pulse-height spectrum for relativistic particles is shown in Fig. 7. The 1/A-like shape of this spectrum can be seen. Pulse-height spectra of the ^{55}Fe and ^{109}Cd signals are shown in Figs. 8 and 9, respectively. The spectrum of ^{55}Fe signals represents the X-rays interactions with working gas, which are distributed randomly over the PPC gap (sharply falling part of the spectrum) and with the metal of the cathode (Gaussian-like peak). In the latter case, the photoelectrons, which have a rather small range, are located near the cathode surface, and therefore have practically the same avalanche length. The pulse-height spectrum for X-rays from ^{109}Cd is different. It has the same sharply falling part, which corresponds to interactions of 22 keV photons with the gas, but the peak is shifted to the left (Fig. 9), and has a shape which is not Gaussian. This is because the photoelectrons emitted from a cathode have energy greater than in the ^{55}Fe case and larger ranges, but the stopping power of these photoelectrons is significantly less. The difference of the peak shape can be explained by the fact that the X-rays of ^{109}Cd are sometimes scattered from the surface of the cathode.

The dependence of the collected charge on the high voltage for different radioactive sources is shown in Fig. 10. The 5.15 MeV α -particles flux from ^{239}Pu was typically $1.5 \times 10^4 \text{ mm}^{-2} \text{ s}^{-1}$. There is no saturation up to at least a charge value as high as 1 pC. For comparison, in a conventional gas proportional counter filled with isobutane, the saturation effect is clearly seen at a collected charge of about 1 pC [8].

The efficiency for minimum ionizing particles was measured in a beam of muons and charged π -mesons (3 GeV/c). A telescope of scintillator counters was used for the trigger, with a gate width of 50 ns, and the detection threshold was set to twice the r.m.s. noise value. In Fig. 11 the pulse-height spectrum is shown. The efficiency for minimum ionizing particles as a function of the applied high voltage is presented in Fig. 12. It flattens out at

the 90% level, as expected from Monte Carlo calculations. The pulse height for relativistic particles depends on high voltage, as shown in Fig. 13.

The individual cells were calibrated using 3 GeV/c electrons. The beam was directed into the centre of each cell placed behind four radiation lengths of an absorber. The r.m.s. value of the gas-gain distribution equals 29%. This corresponds to a 6 μm accuracy of gap sizes.

In order to measure the electron and hadron shower development, a scan with one chamber was performed. A stack of depleted uranium sheets, each of 5 mm thickness, with lateral dimensions of approximately $500 \times 500 \text{ mm}^2$, was used (Fig. 14). The PPC was put in consecutive positions between uranium plates in the stack and, through the measurements of the mean value of the chamber response in each position, the total responses of the corresponding calorimeter to hadrons, electrons, and muons were obtained. The shower curves for electrons and hadrons are shown in Figs. 15 and 16. In order to find the integral response the data were fitted using the standard shower shape function:

$$A \times x^B \times \exp(-x \times C) .$$

For the electron data, all three parameters were found from the fit. For the hadronic shower the only scale factor A was allowed to vary, the two remaining parameters were calculated using our data from the uranium scan with the wire chamber working with pure isobutane [9].

The hadron response (i.e. the integral of the longitudinal shower profile) for the isobutane filling is equal to:

$$44.4 \pm 6.7 \text{ MIP/GeV}$$

and higher than the electron response, which is:

$$37.1 \pm 0.6 \text{ MIP/GeV},$$

where MIP is the chamber response for minimum ionizing particles.

The electron/hadron ratio is:

$$0.84 \pm 0.13 .$$

It is well known [9] that the hydrogen contained in the detector gas affects the hadronic response significantly. Therefore, by choosing a proper gas mixture (for instance, isobutane with a noble gas), one can tune the electron/hadron ratio to 1 for a hadron calorimeter, with uranium plates as the absorber, and PPCs as the active detector.

4. Conclusions

The PPCs we have built have shown the following features in tests with radioactive sources and in a charged particle beam:

- the full pulse-width for the electron component is 7 ns;
- the average gas gain is as high as 5×10^4 ($E = 5900 \text{ V/mm}$);
- no saturation effects were observed;
- the efficiency for minimum ionizing particles is 90% for a 1 mm gap;
- the chambers operated successfully without breakdowns up to the field value 60 kV/cm for 1 mm gap.

The technology used for the PPC production is rather simple, which facilitates the production of similar chambers in large quantities for calorimetry and other applications.

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APPENDIX

Let us assume that the primary ionization clusters, with N_0 pairs, are distributed randomly over the distance to the anode, then the number of electrons collected is:

$$N = N_0 \times \exp (\alpha \times x) ,$$

where x is a random value $\in [0, D]$, α the first Townsend coefficient, and D the gas gap size.

The probability function to collect N avalanche electrons is:

$$F(N) = \frac{\ln(N) - \ln(N_0)}{\alpha \times D} ,$$

where $N \in [N_0, N_0 \times \exp (\alpha \times D)]$.

The probability density function (p.d.f.) is:

$$P(N) = \frac{dF(N)}{dN} = \frac{1}{\alpha \times D} \times \frac{1}{N} .$$

Finally, including the fluctuations in the number of primary electrons,

$$P^*(N) = \sum_{k=0}^{N-1} P(N - k) \times P_0(k),$$

where $P_0(N)$ is the p.d.f. for the number of initial electrons.

If the gas gain $(\alpha \times D)$ is high enough, and therefore the contribution of N_0 fluctuations is small in comparison with the position fluctuations, $P^*(N)$ is approximately proportional to $1/N$.

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Figure captions

Fig. 1 Artist's view of a PPC cell.

Fig. 2 The design of a PPC cell.

Fig. 3 PPC test set-up scheme.

Fig. 4 The design of the multicell PPC.

Fig. 5 Current pulse from the PPC with an ^{55}Fe source.

Fig. 6 The electron component of the PPC current pulse.

Fig. 7 PPC cosmic muon pulse-height distribution. The 'slow' readout is used (see text).

Fig. 8 The PPC ^{55}Fe pulse-height distribution.

Fig. 9 The PPC ^{109}Cd pulse-height distribution.

Fig. 10 High-voltage dependence of the PPC pulse height for ^{239}Pu , ^{55}Fe , ^{109}Cd and cosmics. Most probable values for ^{55}Fe and ^{109}Cd correspond to photo-peak.

Fig. 11 Pulse height spectrum for relativistic particles and for pedestal (dashed). The 'fast' readout is used (see text).

Fig. 12 Detection efficiency for relativistic particles as a function of high voltage.

Fig. 13 Pulse height for relativistic particles vs high voltage.

Fig. 14 Test beam layout.

Fig. 15 Longitudinal development of the electron shower.

Fig. 16 Longitudinal development of the hadron shower.

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