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Development of gaseous particle detectors based on semi-conductive electrode plates

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Summary. — A new kind of particle detector based on RPC-like structure was developed. Semi-conductive electrodes with resistivity ρ up to $10^8\,\Omega\cdot$cm have been used to improve the RPC rate capability. The aim is to obtain a detector with sub-nanosecond time resolution capable of working in a high-rate environment (rate capability of the order of MHz/cm^2). In this paper the results on two different detector structures are presented: one with 1 mm gas gap and both SI(Semi-Insulating)-GaAs electrodes ($\rho \sim 10^8\,\Omega\cdot$cm), and the other characterized by 1.5 mm gas gap, one SI-GaAs electrode and one intrinsic silicon electrode ($\rho \sim 10^4\,\Omega\cdot$cm).

1. – Introduction

The increasing luminosity in future colliders requires the development of new detectors capable of working with higher rate and higher time resolution for bunch crossing identification. At present, the rate capability of RPCs (Resistive Palte Chambers) exceeds 1 kHz/cm^2 [1]. Due to the detector ageing, the initial rate capability drops off as the integrated luminosity increases. The RPC detectors developed for the experiments at LHC (designed luminosity $L = 10^{14}\,\text{cm}^{-2}\,\text{s}^{-1}$) can work for ten years at a rate of 100 Hz/cm^2 [1]. At future colliders such as HL-LHC and FCC (Future Circular Collider) the luminosity will increase by a factor of 5 to 30 [2]. In this scenario it would be extremely useful to develop a detector similar to the RPC as far as time resolution and radiation hardness are concerned, but with a rate capability of the order of MHz/cm^2.

2. – Increasing the rate capability

An RPC [3,4] detector can be described as a set of unit cells interconnected according to the diagram in fig. 1. A unit cell is characterized by the gas capacitance C_G, the electrodes capacitances C and by R_T and R_L resistances, which represent respectively

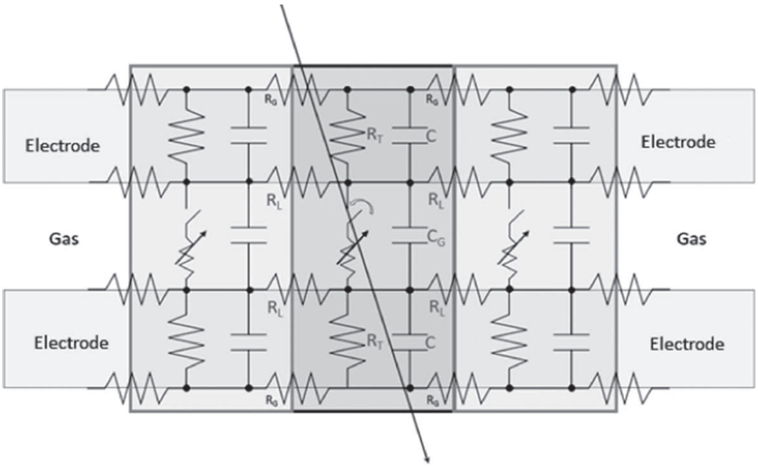

Fig. 1. – Semplified equivalent circuit superimposed on an RPC detector sketch.

the electrode resistance in the normal and parallel directions with respect to the electrode surface. R_G is the resistance of the graphite layer which distributes the high voltage V on the electrode surface.

If the high voltage across the gas gap V_{gas} is high enough (applied electic field E greater than 5 kV/mm for 95%/4.5%/0.5% of $C_2H_2F_4$-iC_4H_{10}-SF_6 gas mixture), a ionizing particle crossing a unit cell triggers an avalanche multiplication. This process can be seen as the closure of the switch in the equivalent circuit of the unit cell involved in the discharge. The resistance R_T dumps the voltage across the gas gap proportionally to the current generated in the avalanche discharge. The resistance $R_L \gg R_G$ restricts the transfer of energy from adjacent cells, and this is the reason for the RPC rate capability.

When a charged-particle flux Φ crosses an RPC detector, the simultaneous ignition of many unit cells occurs and the cumulative effect causes a voltage drop on the electrodes. Expressing the electrode resistance as a function of the electrode resistivity ρ and the thickness d, as shown in fig. 2, the effective voltage on the gas gap can be written as in eq. (1) with $\langle Q \rangle$ representing the mean charge involved in a single process and Φ_{eff} the number of processes occurring in the detector per unit time and surface.

$$V_{gas} = V - 2\rho d \langle Q \rangle \Phi_{eff}. \tag{1}$$

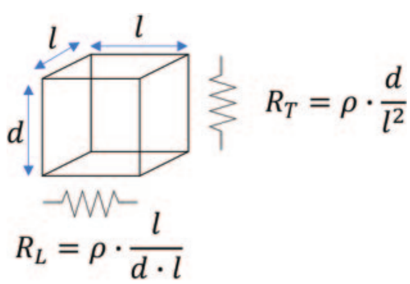

Fig. 2. – Representation of a three-dimensional electrode unit cell.

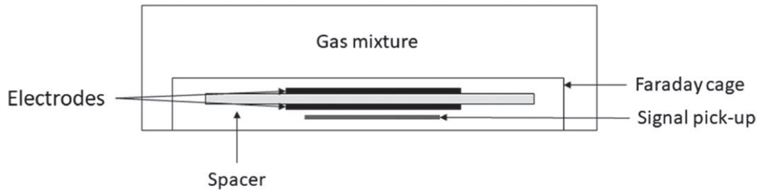

Fig. 3. – Prototype sketch.

The effective flux Φ_{eff} contains the contribution of both the spontaneous noise and the ionizing-particles events, the latter being a fraction $\epsilon\Phi$ of the particle flux, where ϵ is the efficiency and it depends on the voltage across the gas gap V_{gas}. For $\epsilon \sim 1$ and Φ much greater then the noise flux, then $\Phi_{eff} \sim \Phi$. To prevent the detector from losing efficiency as Φ rises, it is necessary to minimize the voltage drop on the electrodes in such a way to fix the V_{gas} value. For this purpose two strategies have been combined during the test:

- reduction of the average charge $\langle Q \rangle$ using a charge amplifier with high signal-to-noise ratio [5];
- replacement of the standard insulating electrodes with Semi-Insulating electrodes with lower resistivity ρ and thickness d.

3. – Prototypes

The first tested prototype was made of two SI-GaAs electrodes spaced with a 1 mm thick PET circular crown. Both electrodes were 400 μm thick and had a resistivity of the order of $10^8\,\Omega\cdot$cm. The gas gap was filled with a gas mixture of $C_2H_2F_4$-iC_4H_{10}-SF_6 (95%/4.5%/0.5%). The signal was read with a pad placed under the low-voltage electrode (see fig. 3).

The second prototype had 1.5 mm gas gap, one silicon electrode and one SI-GaAs electrode. In this case the gas gap was filled with a gas mixture of iC_4H_{10}-Ar (60%/40%).

Both detectors were placed in series with a 100 MΩ resistance in order to avoid that the power dissipated in the electrode due to any anomalous electric discharge may damage the crystal. The operational parameters of the charge amplifier used for the FE electronic are listed in table I.

TABLE I. – *Front End electronics features.*

Voltage supply	3–5 V
Sensitivity	2–4 mV/fC
Noise (up to 20 pF input capacitance)	1000 e^- RMS
Input impedance	100–50 Ohm
B.W.	10–100 MHz
Power consumption	10 mW/ch
Radiation hardness	1 Mrad, 10^{13} n $\cdot$ cm^{-2}

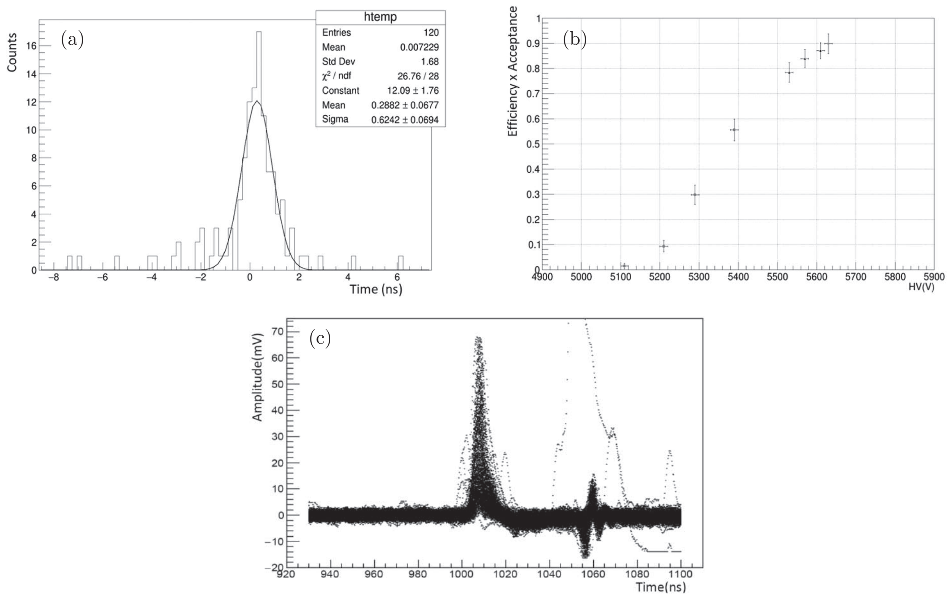

Fig. 4. – (a) Time difference with respect to the trigger detector [6] corrected for the time-walk effect ($HV = 5630\,\mathrm{V}$, prototype 1); (b) "efficiency times acceptance" (1 mm gas gap, prototype 1); (c) Pulse samples, prototype 1.

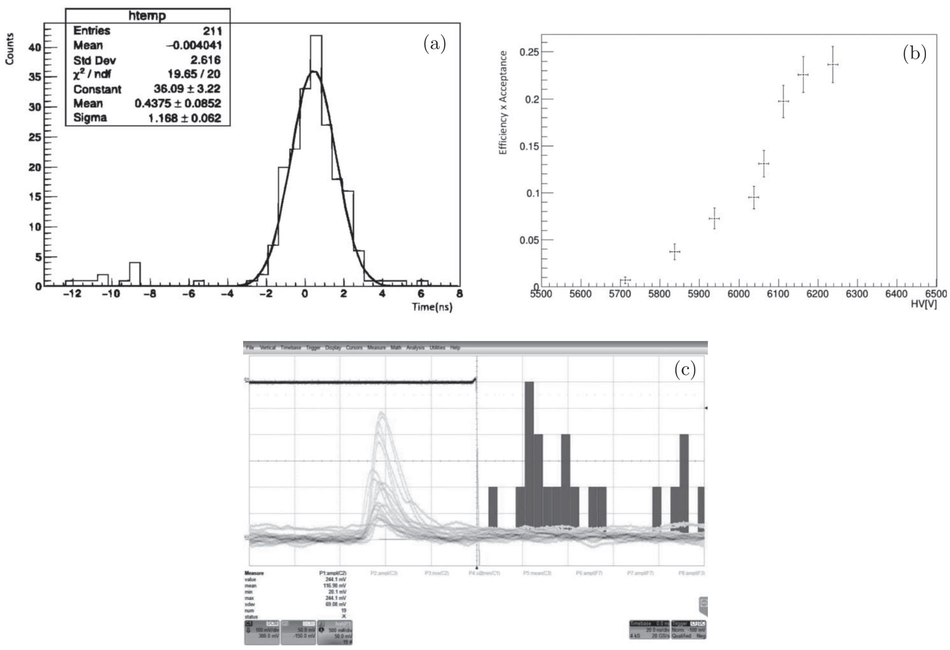

Fig. 5. – (a) Time difference with respect to the trigger detector corrected for the time-walk effect (prototipe 2); (b) "efficiency times acceptance" (1.5 mm gas gap, prototype 2); (c) Pulse samples, prototype 2.

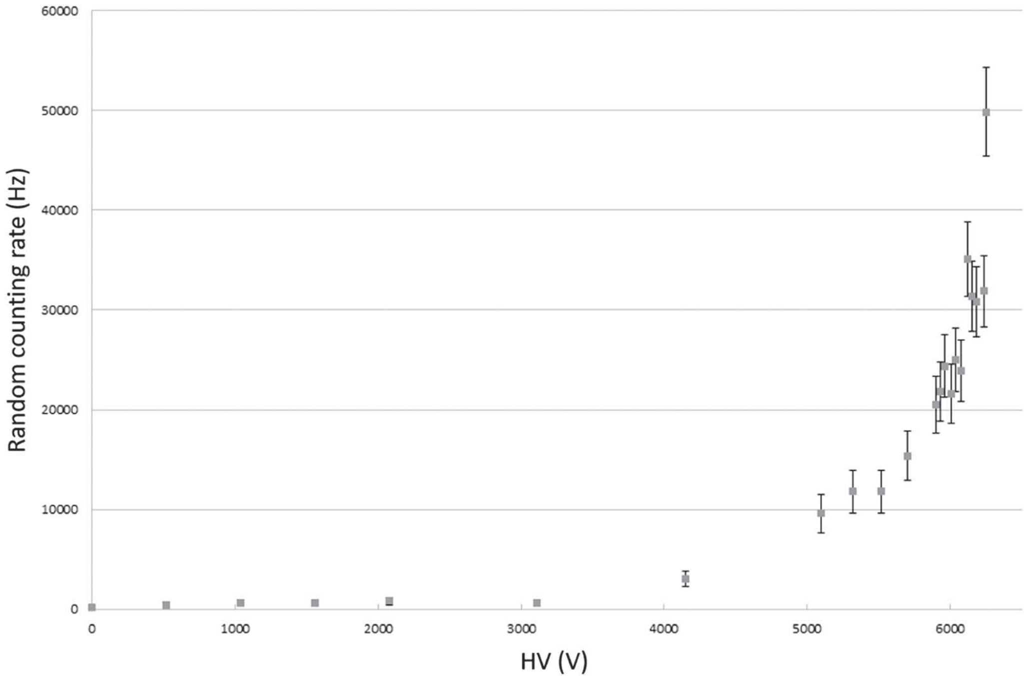

Fig. 6. – Random counting rate as a function of high voltage.

4. – Experimental test

The characterization of the first prototype was carried out at the Beam Test Facility (BTF) of the National Laboratories of Frascati with a beam of 450 MeV electrons. The average multiplicity of particles per bunch was fixed at 0.3 for the whole duration of the test. Two silicon detectors optimized for time-of-flight measurements have been used as the trigger reference. The trigger-time resolution has been measured during the test, resulting in (180 ± 4) ps. A summary of the results is shown in fig. 4. The time resolution has been evaluated by measuring the jitter of the electron time of flight with respect to one silicon detector, corrected for the time-walk effect. A jitter of (590 ± 90) ps was measured. The "efficiency times acceptance" curve shows a knee at about 5600 V.

The characterization of the second prototype was carried out at INFN laboratories of Rome Tor Vergata using atmospheric muons. Two scintillators have been used as the trigger reference. The trigger-time resolution has been measured during the test, resulting in (456 ± 14) ps. The final results are shown in fig. 5. The time resolution has been evaluated as described above: a jitter of (1.10 ± 0.09) ns has been measured. The "efficiency times acceptance" curve shows a knee point at about 6200 V.

Random counting rate has been measured by acquiring waveforms in a 10 μs time window. The results are shown in fig. 6. The high random counting rate is ascribed to the roughness and the imperfection of the spacers.

5. – Conclusions

The results obtained in these preliminary tests provide a solid foundation for the development of a new type of RPC detector. The efficiency knee as well as the time resolution are consistent with the standard RPC performances in spite of the extremely high random counting rate. For an experimental confirmation of the rate capability increase a test has been planned. Further studies are needed to investigate the detector stability and the interactions between the gas mixture components and the electrode surface.

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