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Streamer studies in Resistive Plate Chambers

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ABSTRACT

Resistive Plate Chambers (RPCs) are widely used in high energy physics. While avalanche mode operation is mandatory in high rate environments (ATLAS and CMS experiments at LHC), streamer mode operation is often preferred in low rate applications because of the high signal amplitude. Typical mixtures for streamer operation are composed of Argon, Tetrafluoroethane and Isobutane, with additions of SF_6 below 1% to reduce the charge delivered in the gas. In this paper, results about the streamer properties observed with different mixtures are presented.

1. Introduction

Streamer operated RPCs have been employed in different experiments [1], covering a wide range of interest from B factories to QGP studies at LHC and from high energy cosmic rays to neutrino physics.

Typical gas mixtures are composed of Argon, Tetrafluoroethane, Isobutane and Sulfur Hexafluoride. Argon is a noble gas, with a high charge multiplication (Townsend coefficient), used only in streamer mode operation. Isobutane is an UV-quencher gas, but its concentration is typically limited by flammability requirements. Tetrafluoroethane is an electronegative gas with a high primary ionization. It is the baseline gas for avalanche operation, while in streamer mode it is used also for its UV-quenching power. Sulfur Hexafluoride is a strongly electronegative gas, used in avalanche mode to suppress the streamer fraction, catching slow electrons before their recombination with positive ions [2]. In streamer mode it is used to strongly reduce the operating charge [3], allowing to operate RPCs using gas mixtures with low Isobutane and Tetrafluoroethane concentrations, resulting in a high after-pulse probability [4]. Adding SF_6 to mixtures with a high Tetra-fluoroethane concentration ($>36\%$), an improvement of the time resolution is also observed [5].

In this paper, we show the detector performance measured while changing the concentration of each gas (see Section 3). A waveform study of streamer characteristics has also been performed and the results are reported in Section 4.

2. Experimental set-up

The set-up, whose sketch is shown in Fig. 1, is composed of three trigger RPCs and another three chambers under test, all with a gas gap of 2 mm. The trigger RPCs have an area of $50\times50\,cm^2$ and are read-out by means of a pad covering the whole detector surface. The signals from the pads are discriminated at 15 mV and are fed to an ADC with 600 ns gate. The trigger is given by the coincidence of the discriminated signals and isolated tracks are selected requiring that single streamer charges are recorded on the ADCs.

The three chambers under test are one $50\times50\,cm^2$ RPC, similar to the trigger detectors, read-out with a single pad acquired by the ADC and two $60\times70\,cm^2$ RPCs read out by means of 16 copper strips, with 3.5 cm pitch, connected to a Timing Board. The Timing Boards are circuits designed by the

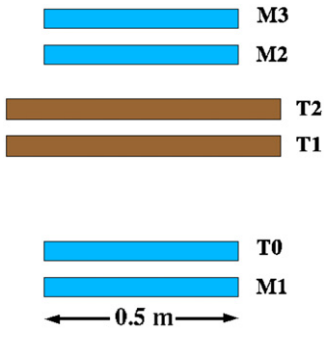

Fig. 1. Sketch of the experimental set-up, with the trigger chambers (M1, M2, M3) and the three chambers under test (T0, T1, T2).

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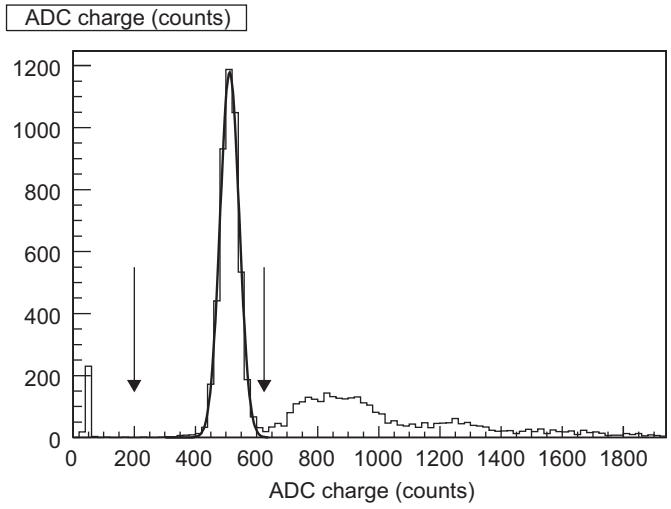

Fig. 2. Induced charge for the gas mixture $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$ at $V=7.6$ kV. One ADC count is 0.83 pC. The cuts for measuring the efficiency and the multi-streamer probability have been also drawn. Note that the ADC pedestal has not been subtracted.

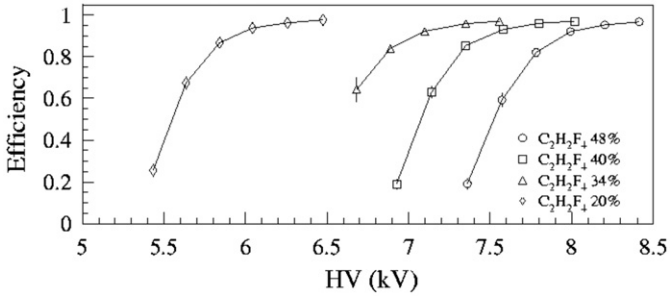

Fig. 3. Efficiencies for different R134a concentrations in ternary mixtures $Ar/C_2H_2F_4/isoC_4H_{10}=96-\alpha/\alpha/4$, with $\alpha=20\%$, 34%, 40%, 48%.

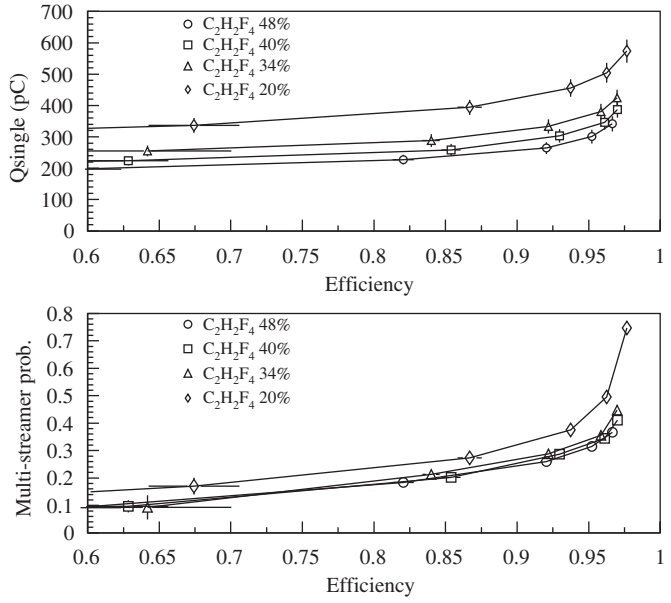

Fig. 4. Streamer induced charge (upper plot) and multi-streamer probability (lower plot) as a function of the efficiency for ternary mixtures $Ar/C_2H_2F_4/isoC_4H_{10}=96-\alpha/\alpha/4$, with $\alpha=20\%$, 34%, 40%, 48%.

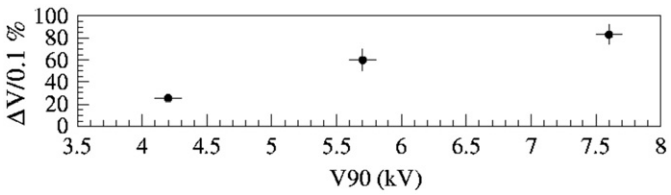

Fig. 5. Efficiency shift per unit of SF_6 addition as a function of the knee voltage (90% efficiency) of the baseline gas mixture without SF_6. The three considered mixtures are, in order of increasing knee voltage, $Ar/C_2H_2F_4/isoC_4H_{10}=83/10/7$, $Ar/C_2H_2F_4/isoC_4H_{10}=76/20/4$ and $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$.

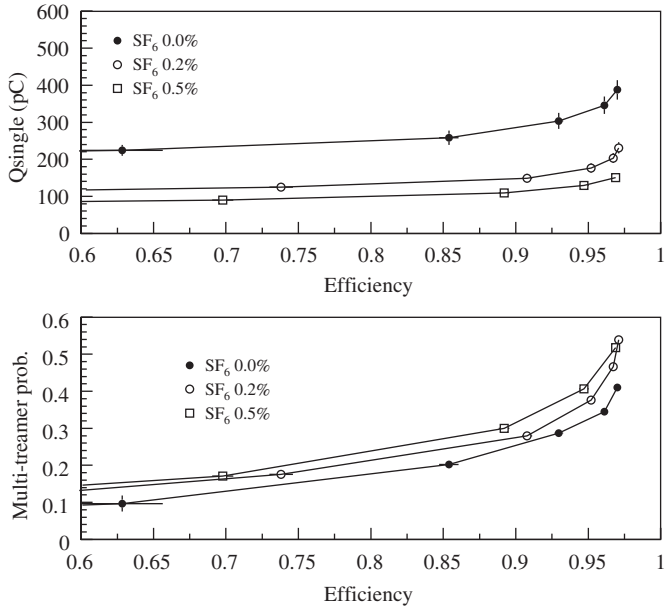

Fig. 6. Streamer induced charge (upper plot) and multi-streamer probability (lower plot) as a function of the efficiency for different SF_6 additions to the baseline gas mixture $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$.

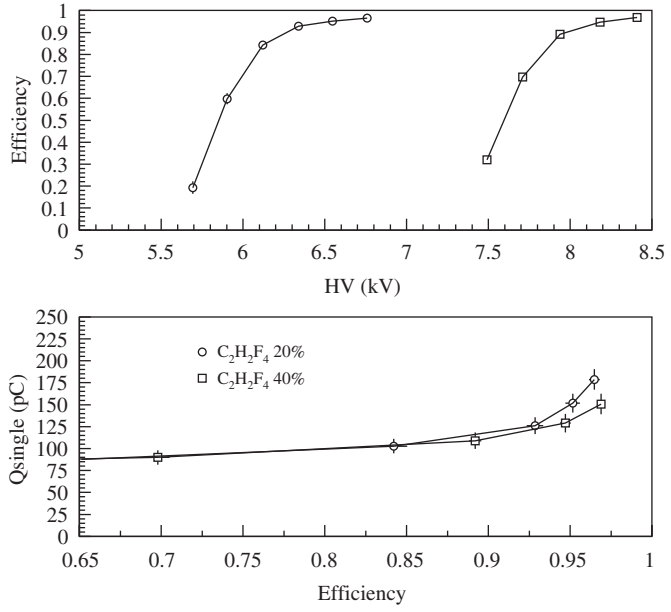

Fig. 7. Efficiency as a function of the operating voltage (upper plot) and streamer induced charge as a function of the efficiency (lower plot) for different R134a volume concentrations in mixtures $Ar/C_2H_2F_4/isoC_4H_{10}=96-\alpha/\alpha/4$ with 0.5% SF_6 added, for $\alpha=20\%$ and 40%.

electronics workshop of the Frascati INFN laboratories for the Drift Tubes trigger of the OPERA experiment. In addition to a digital OR, these perform the analog sum of the strip signals, which is acquired in our set-up by a digital scope with 1 ns sampling. A description of the OPERA Timing Boards can be found in Ref. [6]. The set-up was originally designed to test Timing Board prototypes. Therefore, in order to simulate the OPERA experiment read-out, the strips are terminated on 110 Ω on the Timing Boards side and on the characteristic impedance of 25 Ω on the opposite side.

3. ADC test results

The measurements described in this section have been performed on the chamber T0, with the read-out pad acquired by an ADC.

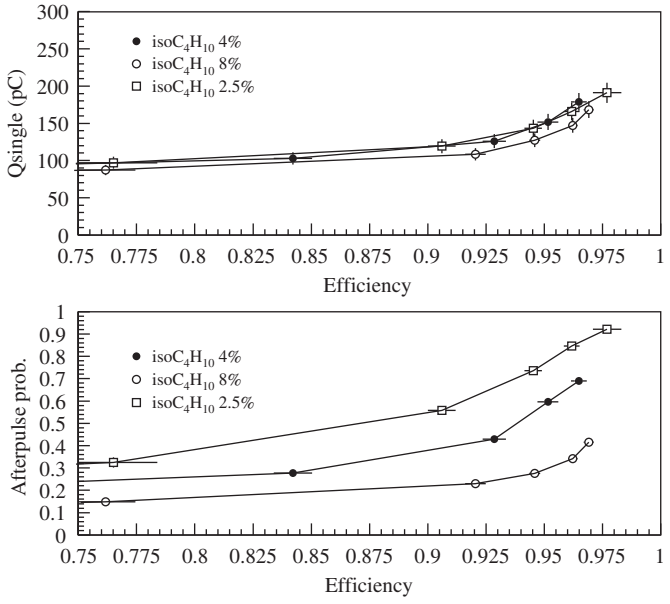

Fig. 8. Streamer induced charge (upper plot) and multi-streamer probability (lower plot) as a function of the efficiency for different Isobutane volume concentrations in mixtures $Ar/C_2H_2F_4/isoC_4H_{10} = 76/24-\alpha/\alpha$ with 0.5% SF_6 added ($\alpha = 2.5\%$, 4%, 8%).

The efficiency, the single streamer charge and the multi-streamer probability are obtained by means of cuts on the induced charge distribution, as suggested in Fig. 2. Efficient events, presenting one or more streamers, are selected by means of the lower cut. Since the streamer charge is high and well separated from both the pedestal and the avalanche charge, the measured efficiency is independent of the applied threshold in a wide range of values. The single streamer charge is evaluated by a Gaussian fit around the corresponding peak in the distribution, correcting for the ADC pedestal measured independently. The multi-streamer probability is estimated by counting the events above the upper cut. Different cuts on the induced charge have been applied, depending on the mixture and the operating voltage.

Given typical detector single counting rates around 100 Hz, accidental coincidences within the ADC gate should occur with probabilities lower than 0.01%, and are therefore negligible.

In order to take into account the different environmental conditions during data-taking, the operating voltages have been rescaled [2,7] to standard temperature and pressure values $T_0 = 293$ K and $P_0 = 1010$ mbar, according to the relationship $V = V_a \times (T/T_0) \times (P_0/P)$, where V_a and V are the applied and the rescaled voltages, respectively.

Ternary mixtures without SF_6 have been considered first: $Ar/C_2H_2F_4/isoC_4H_{10} = 96-\alpha/\alpha/4$, with $\alpha = 20\%$, 34%, 40%, 48%. In Fig. 3, the efficiencies are shown as a function of the operating voltage. The efficiency curves displace toward higher HV values, from 6 kV to more than 8 kV, as R134a concentration increases from 20% to 48%. These mixtures also show increasing streamer charge and multi-streamer probability for lower R134a (higher Argon) concentrations, as shown in Fig. 4. The charge dependence on the Tetrafluoroethane fraction can be explained by its electronegativity (electron attachment) and also by its UV quenching power (limiting the streamer development).

Secondly, we added different SF_6 quantities to the baseline gas mixture $Ar/C_2H_2F_4/isoC_4H_{10} = 56/40/4$. We observed that efficiency curves move toward higher voltages proportionally to the SF_6 concentration (roughly 100 V every 0.1% for the considered baseline mixture). As an exercise, this shift has been compared with similar measurements performed with different baseline mixtures, $Ar/C_2H_2F_4/isoC_4H_{10} = 83/10/7$ [8] and $Ar/C_2H_2F_4/isoC_4H_{10} = 76/20/4$ [4]. As shown in Fig. 5, the shift seems to scale with the operating voltage. From the plots shown in Fig. 6, it is evident that the streamer charge is halved by the SF_6 addition, and is further reduced as the concentration increases.

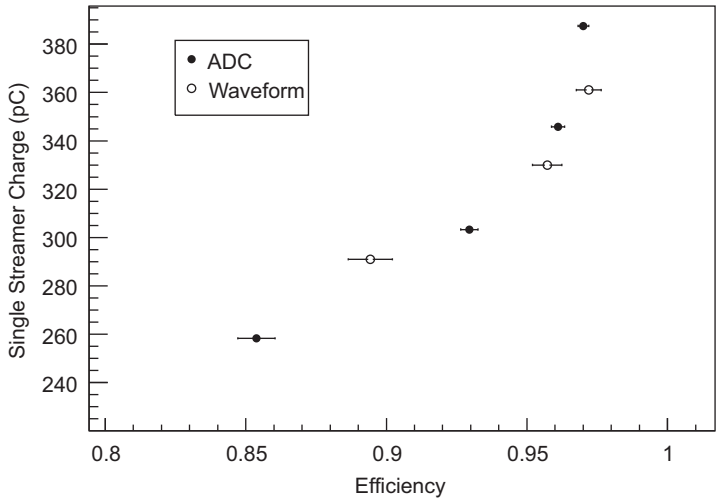

Fig. 9. Single streamer charge as a function of the efficiency for the gas mixture $Ar/C_2H_2F_4/isoC_4H_{10} = 56/40/4$ measured with an ADC on chamber T0 and with the waveform analysis on chamber T2.

It is worth noticing that the multi-streamer probability increases slightly with the SF_6 concentration, as seen in Fig. 6. Since SF_6 is known to suppress the streamer fraction in avalanche mode, we would have expected an additional "quenching" with its addition, but this is apparently not in agreement with the data, which show instead a higher multi-streamer probability. A possible explanation is that the shrinkage of the streamer reduces the lateral size of the zone with a low electric field, increasing the possibility to start a second streamer.

Another interesting property of SF_6 added mixtures is that the streamer charge is almost independent of the other three components. As an example, in Fig. 7, the streamer charge is shown as a function of the efficiency for two baseline gas mixtures, $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$ and $Ar/C_2H_2F_4/isoC_4H_{10}=76/20/4$, with the same 0.5% addition of SF_6: the efficiencies reported in the plot for the two gas mixtures correspond to operating voltages different by about 2 kV.

Finally, we tested three mixtures with different Isobutane quantities in mixtures with a fixed quencher (Isobutane+Tetrafluoroethane) concentration: $Ar/C_2H_2F_4/isoC_4H_{10}=76/24-\alpha/\alpha$ with 0.5% SF_6 added, for $\alpha=2.5\%,4\%,8\%$. The three gas mixtures have similar operating voltages (increasing with the R134a concentration, but

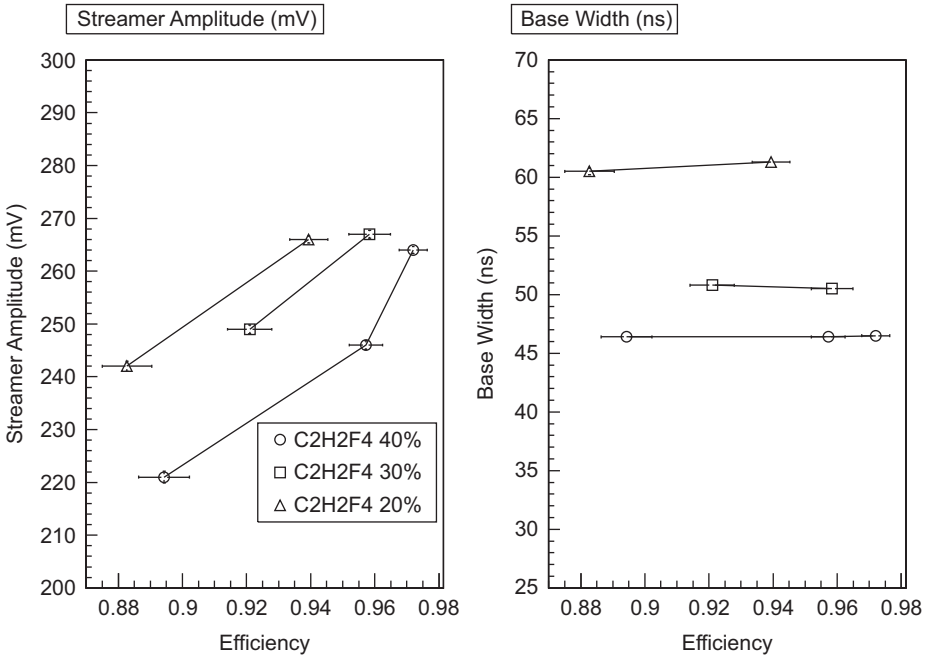

Fig. 10. Single streamer properties as a function of the efficiency for different R134a concentrations in ternary mixtures $Ar/C_2H_2F_4/isoC_4H_{10}=96-\alpha/\alpha/4$, with $\alpha=20\%$, 30%, 40%.

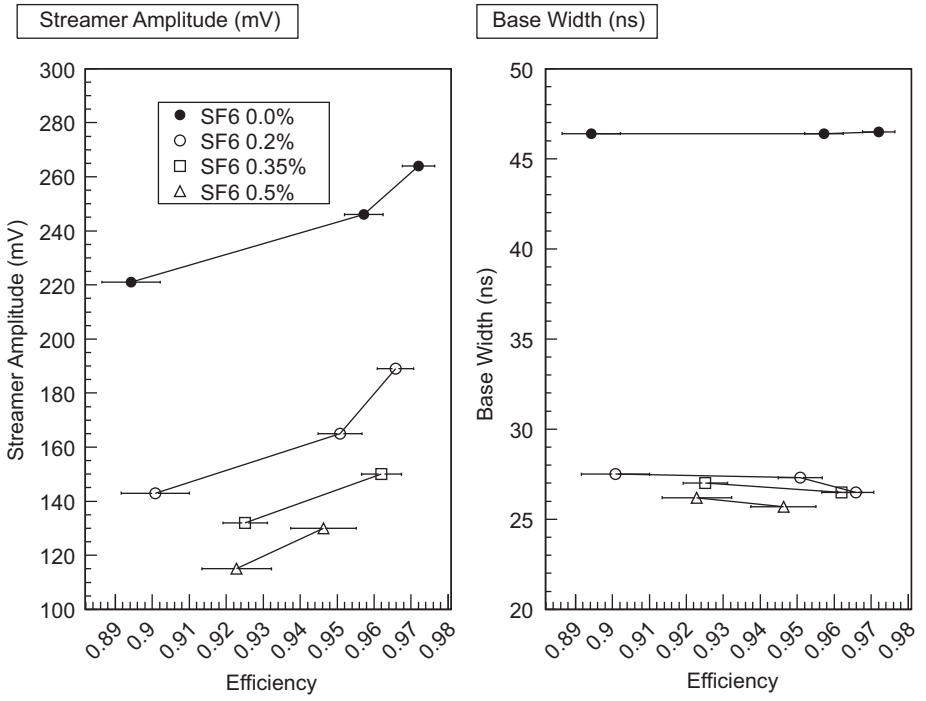

Fig. 11. Single streamer properties as a function of the efficiency for different SF_6 additions to the baseline gas mixture $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$.

within 400 V) and identical streamer charges, as shown in Fig. 8. The multi-streamer probability increases considerably with decreasing Isobutane concentrations, demonstrating that Isobutane is the most efficient UV photon quencher among the considered gases.

4. Waveform analysis

For a better understanding of the streamer phenomena a waveform analysis has also been performed. As in the case of the ADC analysis, only events with single streamers in the trigger chambers have been considered. The points represented in the plots of this section are based on samples of about 1000 events each; two samples of about 10 000 events at fixed operating voltage have also been acquired for systematics studies using two gas mixtures, with and without SF_6.

By comparing the signals acquired on a single strip with the corresponding ones processed through the Timing Board, we have observed that the acquisition system shows an integrating time of about 10 ns due to the presence of long delay cables used in the

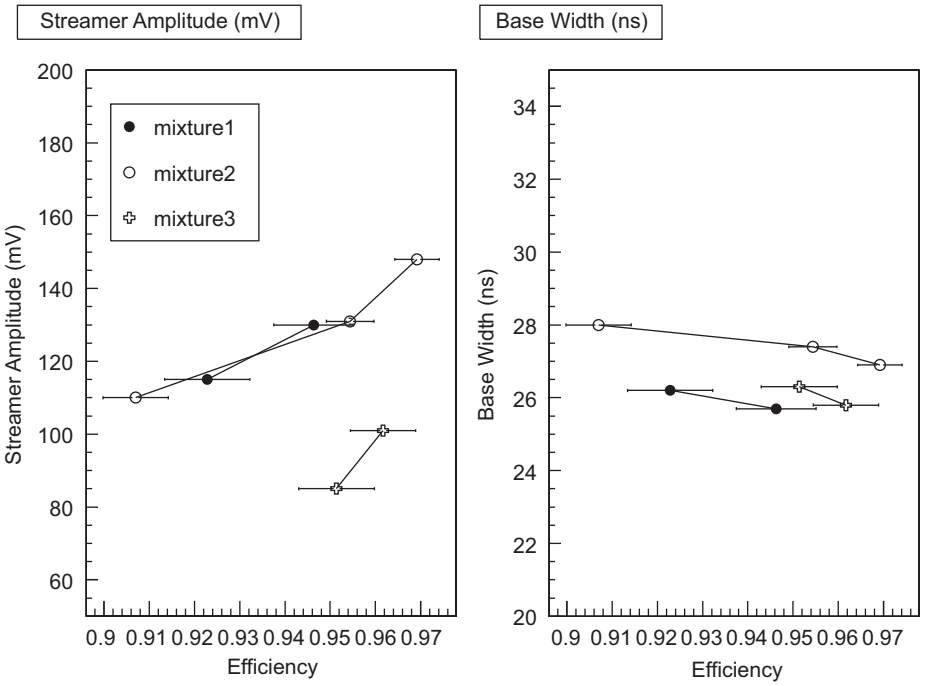

Fig. 12. Single streamer properties as a function of the efficiency for three mixtures: $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4 + 0.5\%\ SF_6$ (1), $Ar/C_2H_2F_4/isoC_4H_{10}=76/20/4 + 0.5\%\ SF_6$ (2) and $Ar/C_2H_2F_4/isoC_4H_{10}/SF_6=74/20/4/2$ (3).

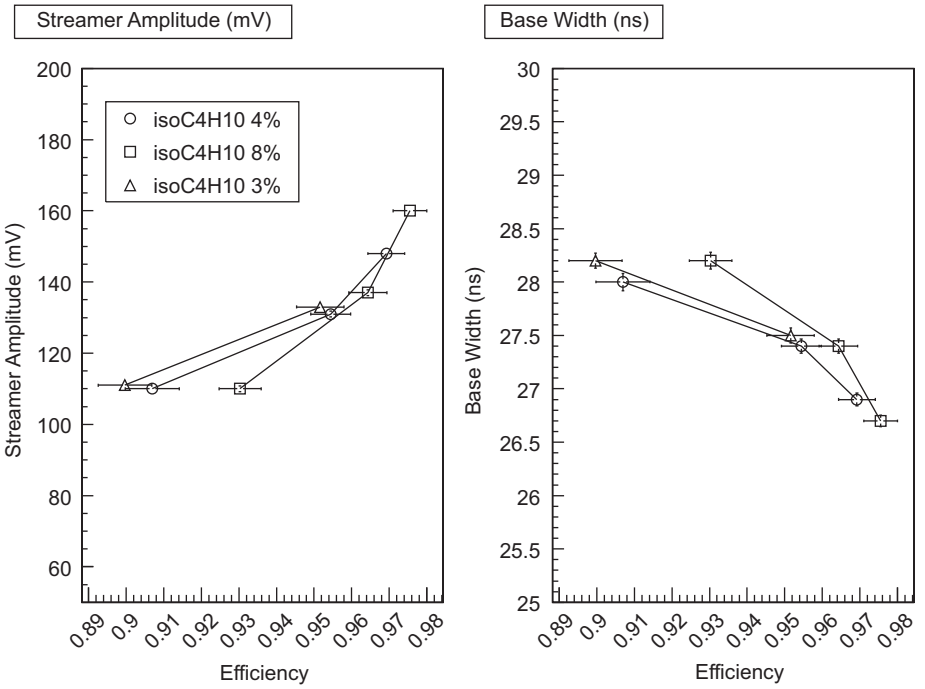

Fig. 13. Single streamer properties as a function of the efficiency for different Isobutane concentrations in mixtures $Ar/C_2H_2F_4/isoC_4H_{10}=76/24-\alpha/\alpha$ with 0.5% SF_6 added ($\alpha=3\%$, 4%, 8%).

set-up to simulate the OPERA experiment read-out for which the Timing Boards have been designed. The following analysis of streamer parameters, unless stated otherwise, is based on the Timing Board analog sum of chamber T2 signals, but it must be considered that:

- real rise-times are a few ns if measured directly from the read-out strips;
- real streamer widths are $\sim$10 ns narrower;
- real streamer amplitudes are higher, depending on the different streamer width (the product between the streamer amplitude and width after the propagation in the delay cable being equal to that of the input signal).

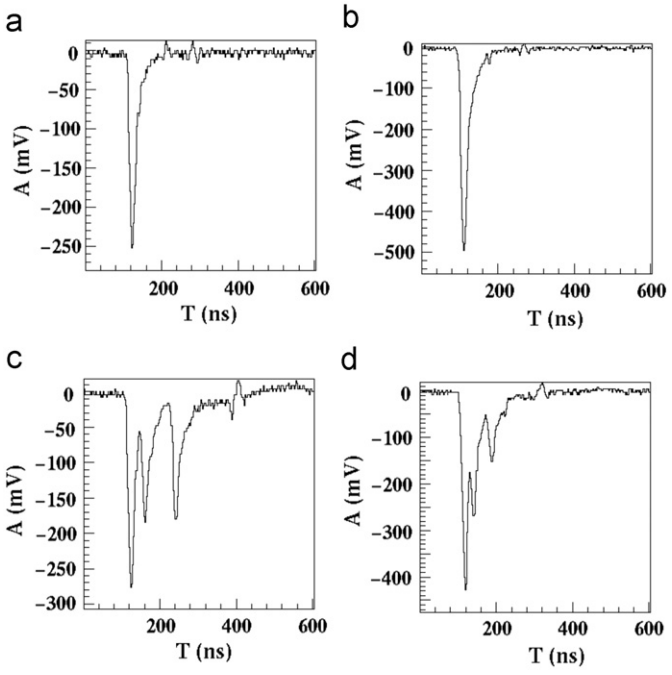

Fig. 14. Typical signal waveforms acquired with the gas mixture $Ar/C_2H_2F_4/i\text{-}C_4H_{10}=62/34/4$ at 7.7 kV: single streamer (a), double amplitude streamer (b), single streamer followed by after-pulsing (c), double amplitude streamer followed by after-pulsing (d).

Single streamer charges measured with the ADC on chamber T0 and with the waveform acquisition on chamber T2 are in good agreement, as shown in Fig. 9.

4.1. Single streamers

For the analysis of single streamers we have considered the signal amplitude and the base width from 15% of the amplitude on the rising edge to the same level on the falling edge.

In Fig. 10, the single streamer properties measured for different R134a concentrations in ternary mixtures $Ar/C_2H_2F_4/isoC_4H_{10}=96-\alpha/\alpha/4$, with $\alpha=20\%$, 30%, 40%, are shown. It is interesting to note that streamers grow in amplitude and width for decreasing R134a concentrations. While moving the R134a concentration from 40% to 20%, the increase in amplitude is around 10%; that of the base width is more consistent (25–30%).

Then we tested different SF_6 additions to the baseline gas mixture $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$. As shown in Fig. 11, a strong reduction of the streamer amplitude and width is observed with the addition of SF_6 to the mixture. For mixtures containing SF_6, the amplitude and the width decrease slightly with increasing SF_6 concentration.

As already noticed, the streamer charge with the addition of SF_6 is almost independent of the ternary base mixture, in a wide range of operating voltages. This is confirmed in Fig. 12, which shows the single streamer properties for three mixtures: $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$ + 0.5% SF_6, $Ar/C_2H_2F_4/isoC_4H_{10}=76/20/4$ + 0.5% SF_6 and $Ar/C_2H_2F_4/isoC_4H_{10}/SF_6=74/20/4/2$. Indeed the two mixtures with a similar SF_6 concentration show the same streamer amplitude. The streamer widths are similar, though a small difference is observed for the first mixture with 20% R134a.

Similar streamer properties are observed varying the Isobutane concentration from 3% to 8% in mixtures $Ar/C_2H_2F_4/isoC_4H_{10}=76/24-\alpha/\alpha$ with 0.5% SF_6 added (see Fig. 13).

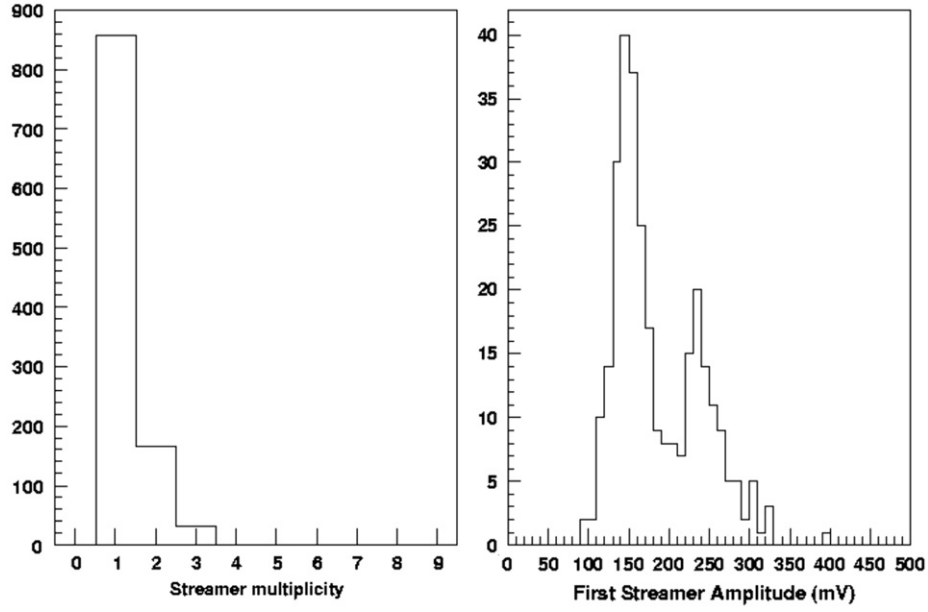

Fig. 15. Example of streamer multiplicity and first streamer amplitude distributions for the gas mixture $Ar/C_2H_2F_4/i\text{-}C_4H_{10}=56/40/4$ at 8.2 kV with 0.35% SF_6 addition. The events in the distribution of the first streamer amplitude have been selected requiring a charge greater than that of single streamers. The first peak corresponds to normal after-pulsing, while the second peak is due to events with prompt simultaneous streamers.

4.2. Multi-streamer studies

The multi-streamer probability has been estimated in the previous sections by the induced charge. In this subsection, a waveform based analysis is presented. At first sight, the acquired waveforms can be divided into three classes: single streamers, streamers with double amplitude, and streamers followed by one or more after-pulses. There are also signals belonging to both of the last two classes. Typical waveforms are shown in Fig. 14.

High amplitude streamers in the data are interpreted as the simultaneous presence of more streamers. We think that this effect is not due to fluctuations in the primary ionization, on which the streamer charge seems to be weakly dependent (see Ref. [9]). In addition, the passage of high-ionizing particles would have been noticed first by the charge induced on the read-out pads of the trigger chambers. Given the distance between the chambers, the angle between the triggered particle direction and the vertical axis does not exceed 45°; therefore the projection on the electrodes of the path inside the gas gap is less than 2 mm and the development of multiple parallel streamers by a single track can be excluded.

Exploiting the acquired waveforms, we attempted to evaluate separately the probabilities of simultaneous streamers and of

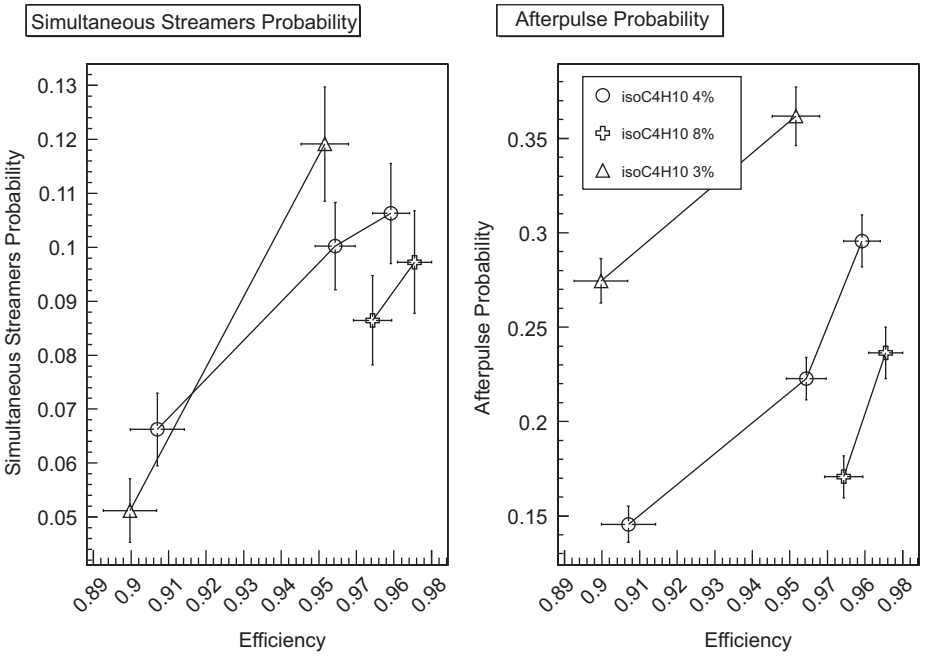

Fig. 16. Simultaneous streamers (left plot) and after-pulsing (right plot) probabilities as a function of the efficiency for different Isobutane volume concentrations in mixtures $Ar/C_2H_2F_4/isoC_4H_{10} = 76/24-\alpha/\alpha$ with 0.5% SF_6 added, for $\alpha = 3\%$, 4%, 8%.

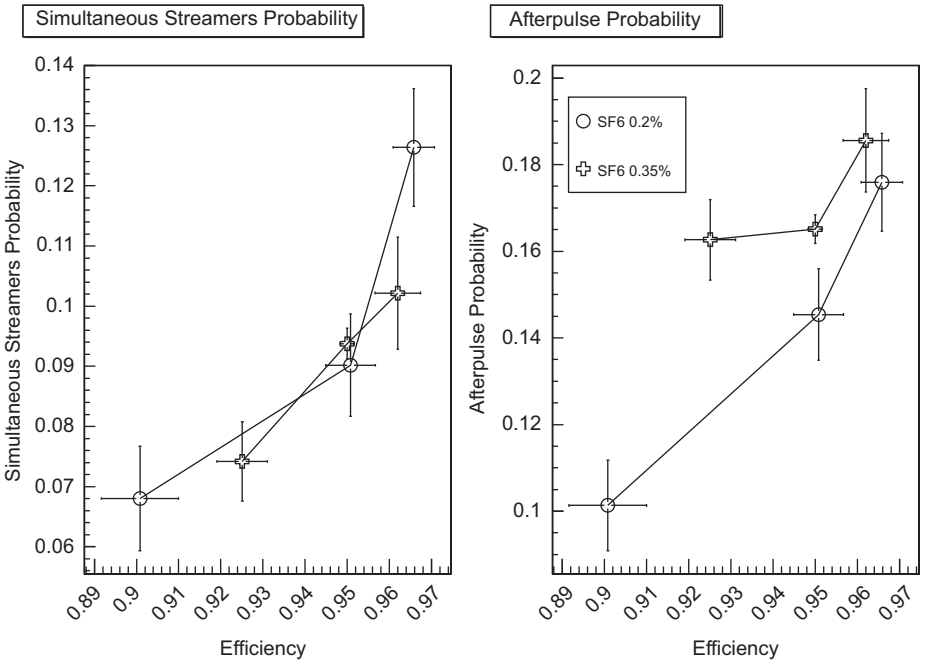

Fig. 17. Simultaneous streamers (left plot) and after-pulsing (right plot) probabilities as a function of the efficiency for different SF_6 additions to the baseline gas mixture $Ar/C_2H_2F_4/isoC_4H_{10} = 56/40/4$.

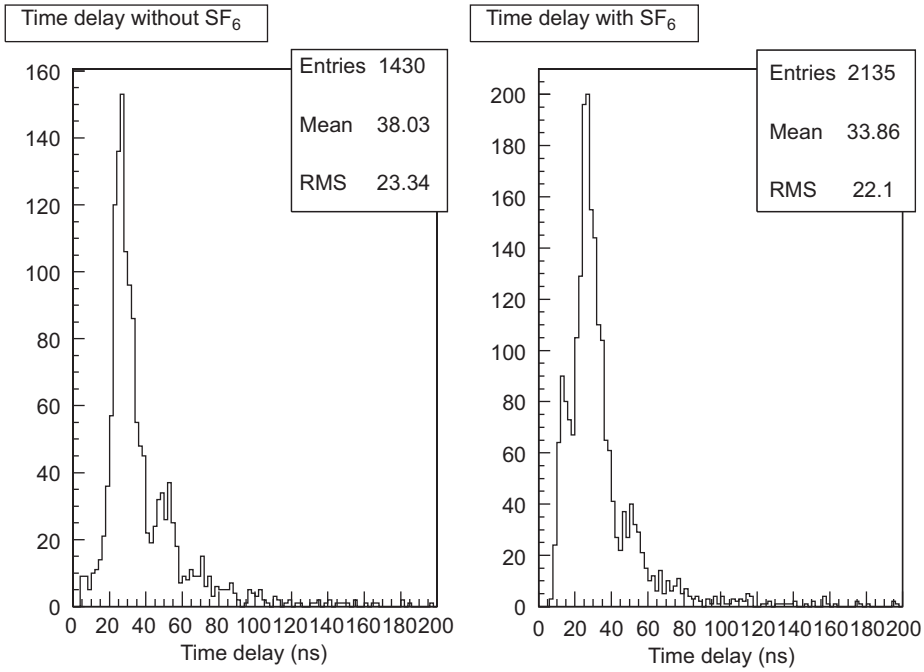

Fig. 18. Distribution of the time delay between the maximum amplitude of the first two streamers in after-pulsing events. Two mixtures have been considered: $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$ ($V=7.40$ kV, $\varepsilon=92.5\pm0.2\%$) in the left plot; $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$ with the addition of 0.35% SF_6 ($V=8.09$ kV, $\varepsilon=95.0\pm0.2\%$) in the right plot.

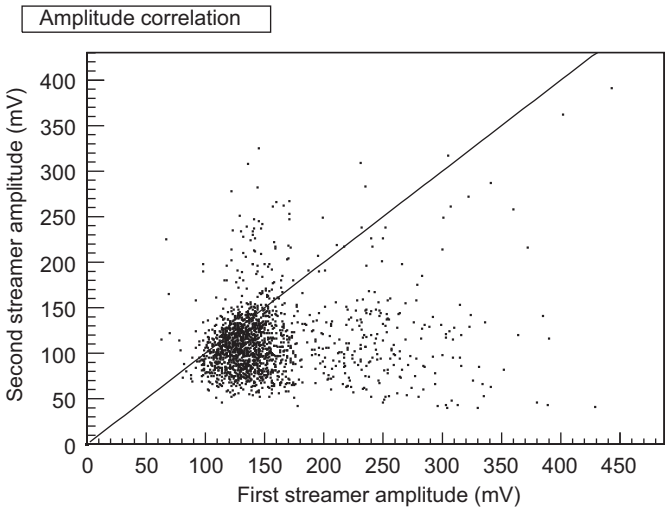

Fig. 19. Correlation between the amplitudes of the first two streamers in after-pulsing events for the gas mixture $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$ with 0.35% SF_6 addition ($V=8.09$ kV, $\varepsilon=95.0\pm0.2\%$).

after-pulsing. The streamers are counted on the basis of the waveform zero-derivative points and the sign of the derivative around these points, using a cut on the corresponding signal amplitude to avoid counting avalanches and electrical noise. The cut value is 100 mV for SF_6-free mixtures; while for mixtures with SF_6, a cut of 50 mV is applied to the first streamer and 40 mV to the following ones. Simultaneous streamers are selected using the amplitude of the first streamer. An example of the resulting distributions is given in Fig. 15.

Since it is difficult to distinguish simultaneous from close-in-time streamers in mixtures without SF_6, due to the high streamer width, results on simultaneous streamers are displayed only for the following mixtures:

- different Isobutane concentrations in $Ar/C_2H_2F_4/isoC_4H_{10}=76/24-\alpha/\alpha$ with 0.5% SF_6 addition, for $\alpha=3\%$, 4%, 8%;
- different SF_6 additions (0.2%, 0.35%) to the baseline gas mixture $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$.

Decreasing the Isobutane concentration we observe an increase of both simultaneous streamers and after-pulsing, with the latter more pronounced (Fig. 16). For different SF_6 additions, the small increase of the multi-streamer probability is due mostly to after-pulsing (see Fig. 17). After-pulsing is a consequence of UV photons escaping the first streamer, while simultaneous streamers can be originated by δ-rays or UV photons produced in the precursor avalanche growth. According to Fig. 16, the simultaneous streamer probability is lower than the afterpulse probability and has the same qualitative dependence with respect to the Isobutane concentration (which is related to the UV-quenching power). In addition, the range of δ-rays in gases hardly exceeds 1 mm (see for instance Ref. [10]), while the diameter of streamers according to Ref. [11] is greater than 5 mm. These two considerations suggest a probable UV origin of simultaneous streamers, as for after-pulsing.

In Fig. 18, the distribution of the time delay between the first two streamers in after-pulsing events is shown for two gas mixtures: $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$ with and without 0.35% addition of SF_6. The two distributions show the existence of characteristic peaks, the main being around 25 ns. The lack of events at small time delays (<20 ns) in the absence of SF_6 is an instrumental effect due to the higher signal width.

In Fig. 19, the correlation between the amplitudes of the first two streamers in after-pulsing events is shown for the gas mixture $Ar/C_2H_2F_4/isoC_4H_{10}=56/40/4$ with the addition of 0.35% SF_6. A time delay greater than 20 ns is required in order to avoid the summing-up of the two streamer signals. In many cases, the

second streamer has a lower amplitude with respect to the first one; this is probably a consequence of the null electric field in the "discharge cell" of the first streamer. The same effect is observed with the other mixtures and for simultaneous streamers; for example, in Fig. 15, the second peak is at 250 mV, while the first one is at 150 mV.

5. Conclusions

Typical gas mixtures for streamer operation of Resistive Plate Chambers are composed of Argon, Tetrafluoroethane and Isobutane, with small additions (below 1%) of SF_6. In this paper, we have reported the studies on streamer properties performed with different quaternary gas mixtures, exploiting also a waveform analysis.

We have shown that the quenching capability of the mixtures relies mostly on the Isobutane concentration, even if some quenching is also due to the presence of Tetrafluoroethane.

SF_6 addition strongly reduces the streamer charge at the price of a small increase of multiple streamers, supposedly a consequence of the primary streamer dimension shrinking. According to a waveform study, separating simultaneous streamers production from after-pulsing, this increase is due to mainly after-pulsing.

Another interesting result concerning mixtures containing SF_6 is that streamer properties are independent of the concentrations of the other three considered gases in the tested operating voltage range (6–8 kV).

The observed presence of simultaneous streamers, having the same qualitative dependence on the quenching components of the gas mixture that after-pulsing has, is probably due to UV emission in the precursor avalanche development.

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