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SF_6 quenched gas mixtures for streamer mode operation of RPCs at very low voltages

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Abstract

In the present paper we describe a search for gases that allow to reduce the energy of the electrical discharge produced in Resistive Plate Chambers (RPCs) operated in streamer mode, by reducing both the operating voltage and the released charge. This can be achieved, with current gas mixtures of argon, tetrafluoroethane (TFE) and isobutane, by reducing the total amount of quenching components (TFE + isobutane) down to 10–15% and compensating for the lower gas quenching power with the addition of small amounts of SF_6. We show here that SF_6, even for concentrations as low as 1% or less, has a strong effect in reducing the delivered charge in low quenched gases and allows to achieve a proper working mode of the RPC even at voltages as low as 4–5 kV over a 2 mm gas gap.

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Keywords: Gaseous detectors; RPCs; Electrical discharge

1. Introduction

Most of the effort invested in RPC research in the last years was mainly triggered by the need of creating a detector particularly suitable for the requirements of LHC, the CERN Large Hadron Collider, and was therefore focused to the avalanche working mode which has a larger rate capability with respect to the streamer mode. This research resulted in relevant improvements of the RPC performance in addition to a better understanding of the detector physics [1]. However, the streamer mode operation, due to the advantage of producing large, saturated and easy to discriminate signals is still of interest for several experiments [2] where the rate capability requirements are not particularly strong.

The main difference between the avalanche and the streamer mode operation is the amount of delivered charge that, although gas dependent, is usually several tens of times larger in streamer mode [1]. The consequences for the streamer operation are: a lower rate capability, which is limited by the maximum current that can flow

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across the high resistivity electrodes and a higher energy released in the gas.

The latter point is important not only because in case of very high counting rate the total power dissipated in the gas may exceed the acceptable limit for the experiment environment, but also for the effect of the released power on the detector itself. Indeed the RPC electrode plates are usually made with materials whose resistivity is an exponentially decreasing function of the temperature like in the case of usual semiconductors. A large released energy produces an increase of temperature which in turn reduces the resistivity and the dead time. This "positive feedback" mechanism might act as an amplifier of the local noise rate induced by a defect of the electrode surface and bring, in extreme cases, to a self-sustaining discharge.

We investigate in this paper the possibility of reducing the energy released in streamer mode by operating the RPCs with gases requiring much lower working voltages. A further advantage of these gases is also a significant simplification of the high voltage system.

The gas mixtures currently used for RPC operation in streamer mode are composed of argon, TFE ($C_2H_2F_4$) and isobutane, usually with a large amount of TFE (about 50% or more) and a small amount of isobutane (about 3–6%) not to exceed the gas flammability limits [3]. The operating voltage is about 8 kV and can be lowered by reducing the TFE concentration. However, the reduced total amount of quenching components (TFE + isobutane) results in an abnormally large amount of charge delivered in the gas for each detector count.

We study here the quenching properties of small amounts of SF_6 added to the gas mixtures and we show that even for concentrations below 1%, SF_6 has a very strong effect in reducing the delivered charge in low quenched mixtures.

SF_6 is well known as streamer suppressor in highly quenched gases used for avalanche mode operation [4]. Its effect of limiting the charge delivered in streamer mode was also studied [5], in alternative to CF_3Br [6], mainly in view of increasing the rate capability in streamer mode operation. The same effect, as shown in this paper, is particularly strong in low quenched gases and allows to use them for a stable operation of RPCs in streamer mode.

We describe the set-up of the test in Section 2. The experimental results are presented in Section 3. In Section 4 the performance comparison of standard and low voltage gases is also made for a RPC which had been purposely damaged [7] by operating it at high temperature.

2. Experimental set-up

The search for gas mixtures with low operating voltage is carried out using a $50 \times 50\ \mathrm{cm}^2$ RPC with 2 mm gas gap. The electrode plates, 2 mm thick, are made up of a phenolic laminated plastic material, with the superficial layer facing the gas, about 50 μm thick, of melaminic polymer. An overall resistivity of $5 \times 10^{11}\ \Omega\,\mathrm{cm}$ has been measured using two $5 \times 5\ \mathrm{cm}^2$ electrodes applied on the plate faces. The inner surfaces of the plates are coated with a few micron thick polymerised linseed oil layer. The coating procedure is reported in Ref. [8].

The test is performed with cosmic rays triggered by three scintillators. With the purpose of simplifying the data acquisition, RPC signals are picked up by a single pad $50 \times 50\ \mathrm{cm}^2$ covering the detector on the high voltage side. The pad signal is sent via coaxial cable to a CAMAC discriminator with input impedance $R = 50\ \Omega$ and 15 mV threshold. A 1 kΩ resistor connects the read out pad to ground, not to leave it floating when the cable is disconnected.

The chamber is operated in streamer mode. The pad capacitance C is about 1 nF and the time constant RC of 50 ns is much larger than the streamer duration, about 20 ns. In this condition, which is not usual for RPCs [9], the signal is integrated by the pad capacitance. A typical waveform of the pad signal is shown in Fig. 1. The electronics discrimination threshold combined to the large pad capacitance makes the read out insensitive to the avalanche signals, which are much smaller than the streamer ones [1].

The RPC discriminated signals are shaped as 100 ns NIM pulses, as well as the trigger gate given

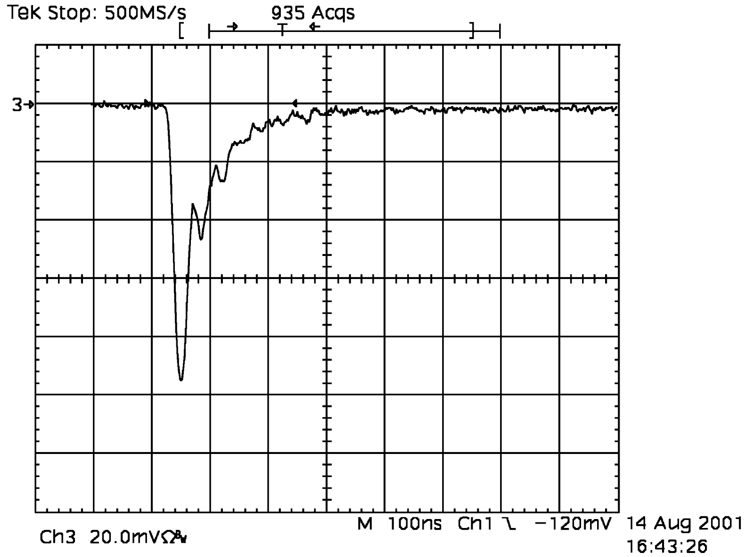

Fig. 1. Typical waveform of the pad signal recorded with a digital scope. The signal is integrated by the large pad capacitance. The risetime of about 20 ns corresponds to the streamer duration: the amplitude is consistent with the total induced charge and the pad capacitance. The exponential tail is due to the 50 ns time constant of the pick up circuit.

by the coincidence of the three scintillators. Efficiencies are measured with a NIM coincidence unit. The charge and time distributions are studied using standard ADC and TDC CAMAC circuits.

The operating current is measured from the voltage drop on a 1 MΩ resistor placed in the ground connection of the high voltage circuit. The charge freed in the gas is extimated from the current to counting rate ratio.

The set-up includes a second RPC of area $120 \times 90\ \mathrm{cm}^2$, damaged by high temperature operation, whose signals are picked up by two pads facing the ground side of the chamber. A test of this chamber flushed with a low operating voltage gas is described in Section 4.

3. Test results

In order to take into account the different environment conditions during data-taking, the operating voltage reported in the following plots is rescaled [4,10] to standard temperature and pressure values $T_0 = 293$ K and $P_0 = 1010$ mbar, according to the relationship $V = V_a(T/T_0)(P_0/P)$, where V_a and V are the applied and the rescaled voltage, respectively.

The detection efficiency vs. operating voltage is plotted in Fig. 2 for the mixture $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 83/10/7$ to which an amount of SF_6 ranging from 0% to 1.6% is added. The addition of SF_6 produces an increase of the operating voltage ranging from 300 V (with 0.8% SF_6) to about 500 V (with 1.6% SF_6) and an increase of the plateau efficiency. The comparison with a “standard” gas mixture, $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 46/48/6$, reported in the same figure, shows that the new gas has an operating voltage about 3 kV lower.

The operating current and counting rate are plotted vs. the operating voltage in Figs. 3 and 4, respectively. The current shows an exponential growth starting from the voltage for which gas multiplication processes become significant. For lower voltages the current is very small and the increase with HV is linear with a slope lower than 1 nA/kV at $T \simeq 24°\mathrm{C}$. The linear current is gas independent and depends only on the resistance of all the elements, like spacers and edge frame, interconnecting the two resistive electrodes.

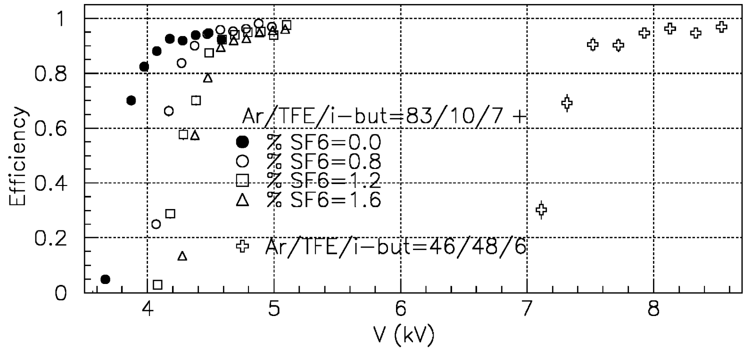

Fig. 2. Efficiency vs. voltage for different SF_6 amounts added to the mixture $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 83/10/7$. The plot of a standard gas mixture, $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 46/48/6$, is also shown for comparison.

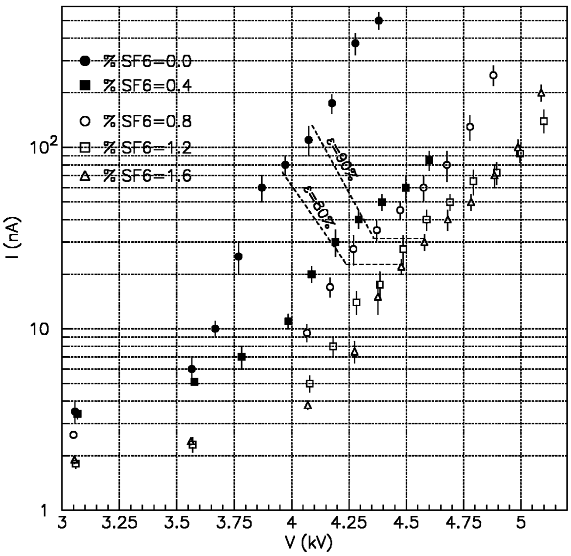

Fig. 3. Operating current at $T \simeq 24°C$ adding different SF_6 amounts to the gas mixture $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 83/10/7$. Below 3 kV the current is linear with a slope of about 1 nA/kV. Approximate constant efficiency lines for $\varepsilon = 80\%$ and 90% are also shown.

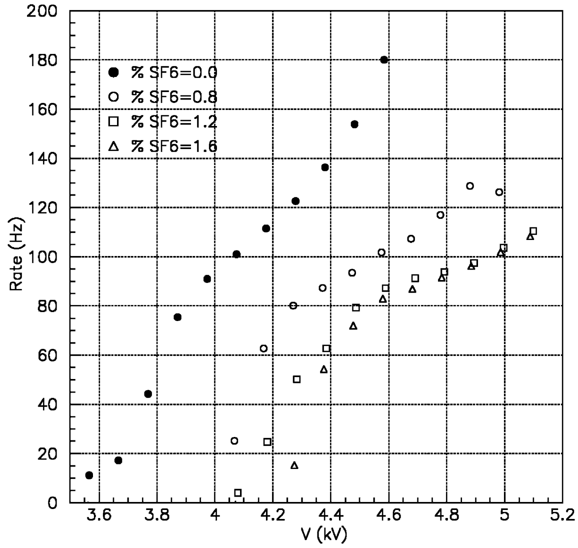

Fig. 4. Counting rate adding different SF_6 amounts to the gas mixture $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 83/10/7$.

Fig. 3 shows that for increasing efficiency the current grows in a dramatic way for the SF_6-less gas, due to insufficient quenching, and in a much weaker way for gases containing SF_6. With the purpose of better focusing this point, we plotted in Fig. 5 the current to counting rate ratio, which represents the total charge delivered in the gas for each produced streamer. The small contribution of the linear term which should be subtracted from the total current, is in this case completely negligible. As shown in the figure, the total charge is much larger for fixed efficiency in the case of SF_6-less gas. On the contrary, when SF_6 is added, it is smaller than for the usual gas mixtures [10,11].

The total charge shown in Fig. 5 gives the energy released in the gas by the combined motion of electrons and ions. It should be distinguished from the prompt charge, mostly due to electron motion only [12,13], which gives the amplitude of the signal available for the front-end electronics.

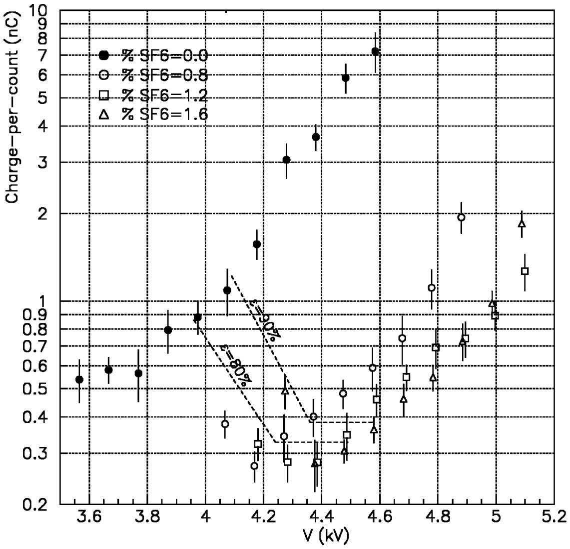

Fig. 5. Total charge per streamer for different SF_6 amounts in the mixture $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 83/10/7$. Constant efficiency lines for $\varepsilon = 80\%$ and 90% are also shown.

The prompt charge distributions of the 0.8% SF_6 gas are shown in Fig. 6 for several values of the operating voltage. The distribution is dominated by the single streamer peak but also shows a long tail due to multiple streamer production which becomes dominant for the highest voltages.

The prompt charge distributions in gases with different amounts of SF_6 are compared in Fig. 7 for a fixed detection efficiency of about 93%. The comparison of the single streamer peaks shows that the relative charge is a factor of 5 larger in the case of the SF_6-less mixture. This suggests that the SF_6 working mechanism is the capture of photoionisation electrons near the first streamer position, which reduces its lateral growth. Moreover, the comparison with the data of Figs. 5–7 shows that the prompt charge is about a factor of 3 smaller than the total charge.

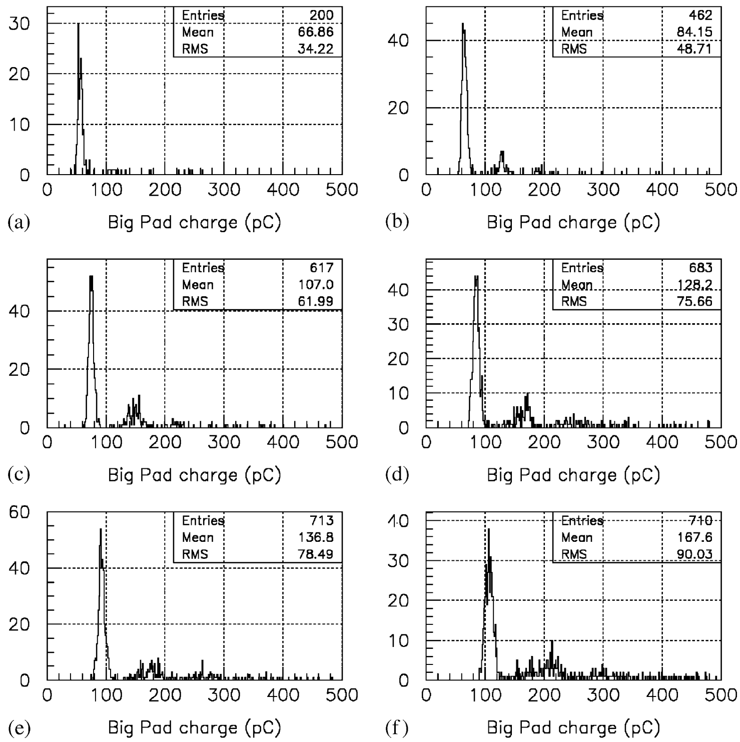

Fig. 6. Prompt charge distributions at different operating voltages for $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 83/10/7$ with the addition of 0.8% SF_6. The voltages and the corresponding detection efficiencies are: (a) $V = 4.07$ kV and $\varepsilon = 25\%$; (b) $V = 4.17$ kV and $\varepsilon = 58\%$; (c) $V = 4.27$ kV and $\varepsilon = 78\%$ (10 events in overflow); (d) $V = 4.38$ kV and $\varepsilon = 87\%$ (10 events in overflow); (e) $V = 4.48$ kV and $\varepsilon = 91\%$ (15 events in overflow); (f) $V = 4.58$ kV and $\varepsilon = 93\%$ (32 events in overflow).

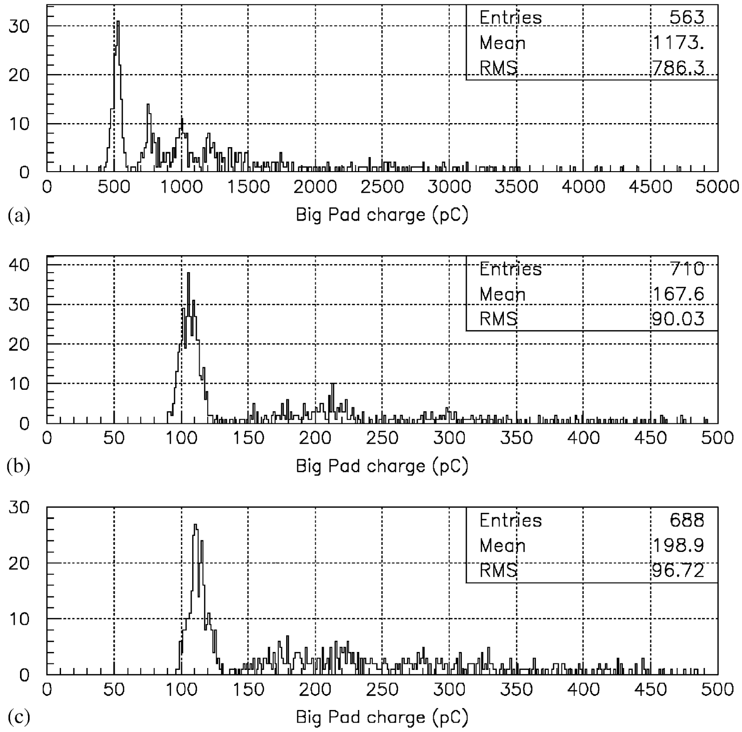

Fig. 7. Prompt charge distributions at 93% efficiency of the mixture $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 83/10/7$ with the addition of: 0% SF_6 (a), 0.8% (b) and 1.6% (c). The events in overflow are 14 (a), 32 (b) and 60 (c). Note the different abscissa scale in (a).

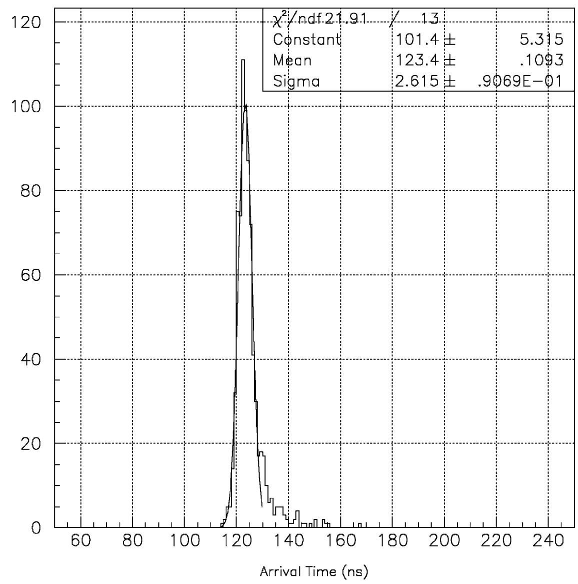

Fig. 8. Arrival time distribution at 4.78 kV with 1.6% SF_6 added to the gas mixture $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 83/10/7$.

In Fig. 8 the arrival time distribution is reported for the gas mixture $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 83/10/7$ with 1.6% SF_6 at an operating voltage of 4.78 kV. Taking into account the signal integration due to the large capacitance of the single pad we conclude that the time resolution obtained with the present gas is not degraded with respect to more usual gases [10].

4. Test of a damaged RPC using a low voltage gas mixture

The performances of standard and low voltage gases were compared using a second RPC, of area 120×90 cm^2, built according to an old procedure, now obsolete, with an inner coating of about 30 μm thick linseed oil layer. This RPC which had been purposely operated at high temperature [7] damaging the inner coating, showed low efficiencies and high operating currents and counting rates.

The gas gap is 2 mm thick, as in the case of the other RPC. The read out is performed with two pads $60 \times 90\ \mathrm{cm}^2$, 3 mm thick, placed on the detector ground side. The voltage polarity is positive, as the signal induced on the read out electrodes, and inverting transformers are used in order to discriminate pad signals at 15 mV with a commercial 16 channel CAMAC discriminator, providing also the OR of the two pads. The operating current was monitored using a voltage to frequency converter and a CAMAC scaler.

In order to avoid gas gap ununiformities due to possible unglued spacers the detector was placed on a horizontal table and pressed by a layer of iron bricks 15 mm thick covering most of the area.

The damaged RPC was tested with two gas mixtures: $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 46/48/6$ and $Ar/C_2H_2F_4/i\text{-}C_4H_{10} = 80/12/8$ with the addition of 0.5% SF_6, that will be referred in the following as the standard and the "low voltage" gas, respectively. In Fig. 9 the efficiencies and the operating currents at the temperature of 20°C are shown for the two mixtures. The dark current exhibits a linear behaviour with the operating voltage, with a slope of about 1 μA/kV at 20°C, almost independent of the gas mixture. The slope of the dark current has a strong dependence on the temperature, as shown in Fig. 10.

In order to study the medium term behaviour the chamber has been operated for 6 days with the low voltage gas, at the temperatures of 20°C (3 days) and 26°C (3 days) and for one day with the standard gas at the temperature of 20°C.

The measured efficiencies and operating currents vs. time are reported in Figs. 11–13 for the two gases. The operating voltages are kept at constant values of 5.3–5.5 kV (depending on the temperature) and 8.52 kV for the low voltage and standard gas, respectively. The standard mixture shows, even on very short time scale, a gradual increase of current and a simultaneous drop of efficiency from 90% to 75%. This is confirmed in Fig. 14 where the efficiency and the current vs. operating voltage at the beginning and at the end of the 24 h operation of the chamber are reported.

A stable operation is instead obtained with the low voltage gas both at 20°C and 26°C. Fluctuations of the operating currents are due to temperature excursions between day and night.

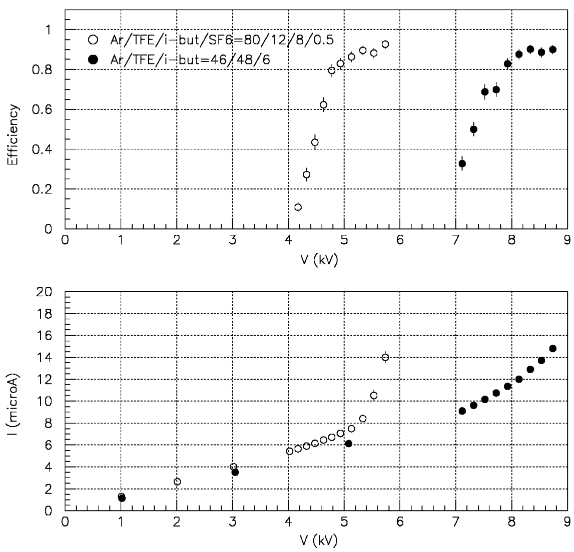

Fig. 9. Efficiency (upper plot) and operating current (lower plot) of the temperature damaged RPC for the standard (full marks) and the low voltage mixture (blank marks).

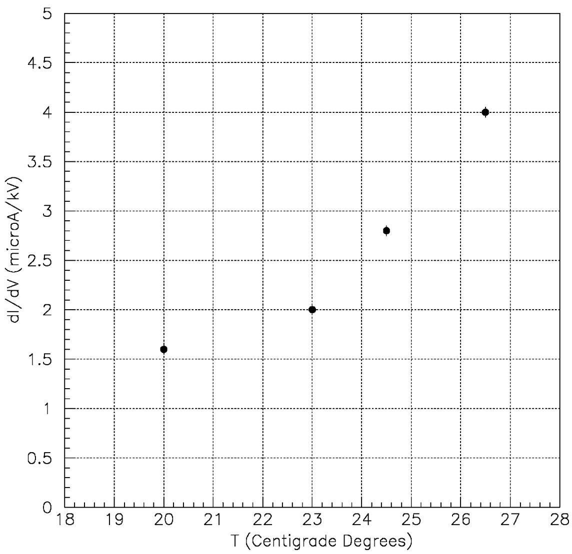

Fig. 10. Slope of the dark current for the temperature damaged RPC as a function of the environment temperature.

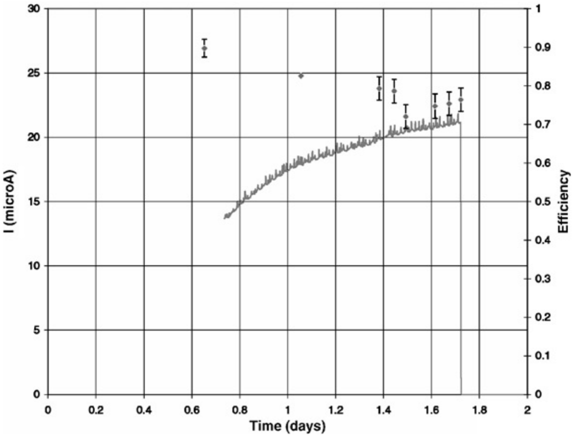

Fig. 11. Efficiency (dots) and operating current (continuous line) vs. operating time for the temperature damaged RPC filled with the standard gas mixture and operated at $T = 20°C$.

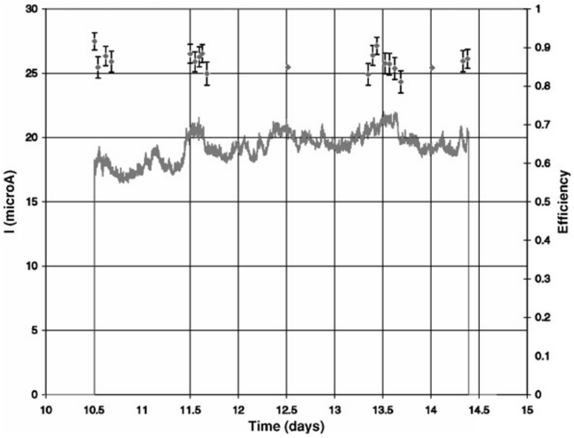

Fig. 13. Efficiency (dots) and operating current (continuous line) vs. operating time for the temperature damaged RPC filled with the low voltage gas mixture and operated at $T = 26°C$.

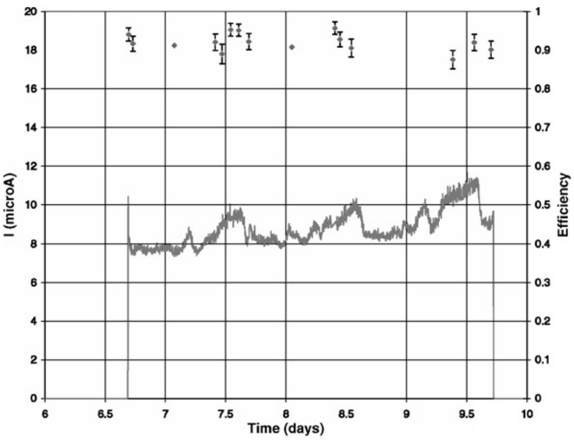

Fig. 12. Efficiency (dots) and operating current (continuous line) vs. operating time for the temperature damaged RPC filled with the low voltage gas mixture and operated at $T = 20°C$.

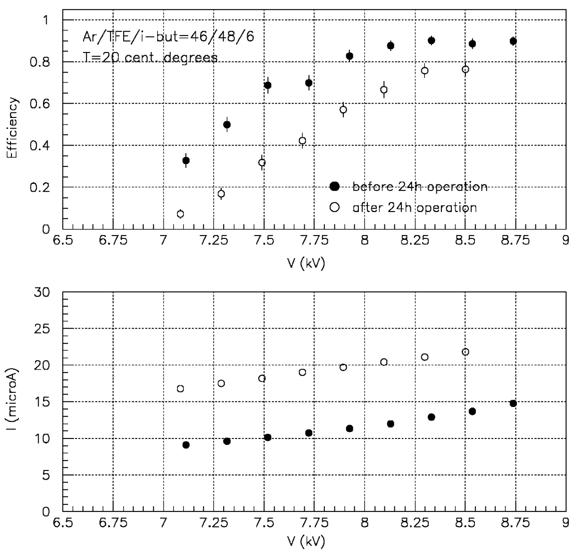

Fig. 14. Efficiency (upper plot) and operating current (lower plot) for the temperature damaged RPC before and after 24 h of operation with the standard gas mixture at a temperature of 20°C.

5. Conclusions

We have shown that RPCs can be stably operated in streamer mode at voltages as low as 4–5 kV over a 2 mm gas gap, using gas mixtures composed of argon with modest amounts of usual quenching components, like isobutane and tetrafluoroethane, and a few permil of SF_6.

We have also proved that the addition of SF_6 for low quenching gases is essential for avoiding very large values of the charge delivered in the gas per single streamer. This charge, for gases containing SF_6, is smaller than for the usual ones. However, a moderate increase of the multiple streamer probability is observed.

The time resolution is not significantly degraded. A test carried out on a damaged RPC has shown that a more stable operation is obtained using the low voltage gas instead of the standard one.

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