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Nuclear Instruments and Methods in Physics Research A 583 (2007) 264–269
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Gas mixture studies for streamer operation of Resistive Plate Chambers at low rate

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Received 31 August 2007; accepted 17 September 2007
Available online 29 September 2007

Abstract

Gas mixtures have been studied in order to be used in the Resistive Plate Chambers (RPCs) of the OPERA spectrometers. We are interested in mixtures with a low R-134a concentration in order to reduce the streamer charge and the operating voltage without spoiling the usual RPC performances.

PACS: 29.40.Cs

Keywords: RPC; Gas mixture; Streamer

1. Introduction

Typical gas mixtures for streamer-operated Resistive Plate Chambers (RPCs) are composed of argon (Ar), tetrafluoroethane ($C_2H_2F_4$, also known as R-134a) and isobutane ($isoC_4H_{10}$). Argon provides high charge multiplication. Isobutane acts as a UV photon quencher. Tetrafluoroethane is an electronegative gas, whose addition increases the primary ionization and the quenching power of the mixture. It also produces HF [1–3], which damages the electrode surface. Since few years, sulfur hexafluoride (SF_6) in concentrations lower than 1% has been added to usual gas mixtures [4–7], in order to decrease the streamer charge and the cluster size. OPERA is an experiment dedicated to the observation of ν_μ into ν_τ oscillations in the 730 km baseline CNGS (CERN Neutrino to Gran Sasso) beam. A detailed description of the detector together with its physics potential can be found in Ref. [8]. The experiment is endowed with two magnetic spectrometers for the identification and the reconstruction of muons, mainly to reject the charm background. In each spectrometer, precise deflection measurements are performed by means of drift tubes, while RPCs are used as inner trackers inside the iron magnets and as trigger detectors for the drift tubes.

OPERA RPCs are operated in streamer mode with large and easy-to-discriminate signals. Given the low counting rate inside the Gran Sasso underground Laboratories, with a 3 km water equivalent rock overburden, bakelite electrodes with resistivity greater than $5 \times 10^{11}\,\Omega\,\text{cm}$ are utilized. Preliminary measurements on the installed RPCs have shown counting rate values around $20\,\text{Hz/m}^2$ [9].

The OPERA RPC system is made of about 1000 chambers for a total volume of $7\,\text{m}^3$, to be flushed at five refills/day. Since we decided to employ an open flow gas system, the estimated gas consumption is $35\,\text{m}^3/\text{day}$. In order to reduce the cost of the gas, we have investigated the possibility of lowering as much as possible the R-134a concentration, without increasing the operating current. We have therefore exploited the strong electro-negativity of SF_6 to compensate for the multi-streamer increase due to the decrement of R-134a. The results of the performed tests are shown in Section 3.

We have also verified (see Section 4) that mixtures with low R-134a concentration match all of the OPERA RPCs requirements, which are:

- large signal amplitudes (50–100 mV), as Front-End electronics is connected to the read-out strips through twisted flat cables as long as 13 m;

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0168-9002/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2007.09.030

- good time resolution (1–2 ns), not to spoil the good space resolution (300 μm) of the drift tubes;
- long aging time as expected for typical gas mixtures.

2. Experimental set-up

Most of the measurements described in this paper have been performed with a set-up composed by a tower of three RPCs as wide as $(50 \times 50)\,cm^2$, used for triggering cosmic rays, and by one $(60 \times 70)\,cm^2$ RPC under test.

All the RPCs are read-out by means of pads covering the entire detector surface. Because of the big capacitance, the read-out electrode acts like an integrator circuit [6]. Signals from the pad are discriminated at 45 mV.

The current of the RPC under test is measured with a digital scope on a 1 MΩ resistor placed in series to the detector in the HV circuit. The charge/count is estimated dividing the current by the measured counting rate. Ohmic contributions to the current are negligible.

The trigger chambers have been operated with the gas mixture $Ar/C_2H_2F_4/isoC_4H_{10} = 48/48/4$.

3. Charge/count studies

3.1. Ternary mixtures without SF_6

At first we tried to decrease the tetrafuoroethane content with the isobutane fixed at 4%.

In Fig. 1 the efficiency vs the operating voltage is shown for three different R-134a concentrations. Reducing the R-134a amount from 48% to 20% the operating voltage is reduced from 8 kV down to 6 kV.

In Fig. 2 the charge/count is compared as a function of the efficiency, even if mixtures with a low R-134a concentration are expected to reach lower plateau efficiency values because of the reduced primary ionization. Lowering the R-134a concentration, the charge/count increases.

3.2. Quaternary mixtures with SF_6 addition

Using as a baseline gas the mixture $Ar/C_2H_2F_4/iso\,C_4H_{10} = 76/20/4$, we tried to add different SF_6 quantities in concentrations ranging from 0.25% to 1%.

SF_6 is a strongly electronegative gas. Its addition raises the operating voltage by about 50 V/0.1%, as shown in Fig. 3.

The charge/count is strongly reduced, as suggested by Fig. 4. Its value is approximately independent of the SF_6 quantity, once added.

3.3. Quaternary mixtures with fixed SF_6 concentration

Finally we moved the R-134a concentration with 4% isobutane and 1% SF_6 fixed. This final test has been performed in order to investigate the optimal R-134a concentration value at which the SF_6 addition, lowering the streamer charge, compensates for the loss of quenching power at low R-134a concentrations.

In Fig. 5 the charge/count as a function of the efficiency is shown for different R-134a concentrations, from 10% to 32%. Only for the lowest value, the loss of quenching power causes a significant increase of the charge/count. For

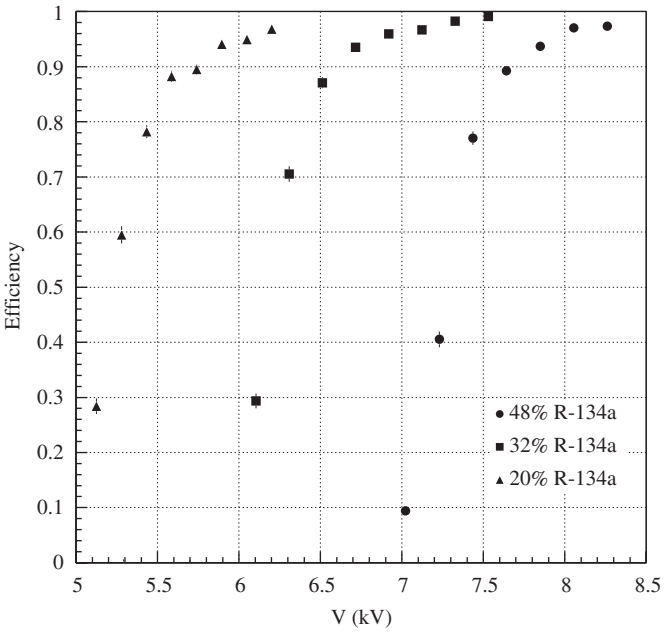

Fig. 1. Efficiency vs operating voltage for three ternary gas mixtures with different R-134a and argon concentrations. Isobutane is fixed at 4%.

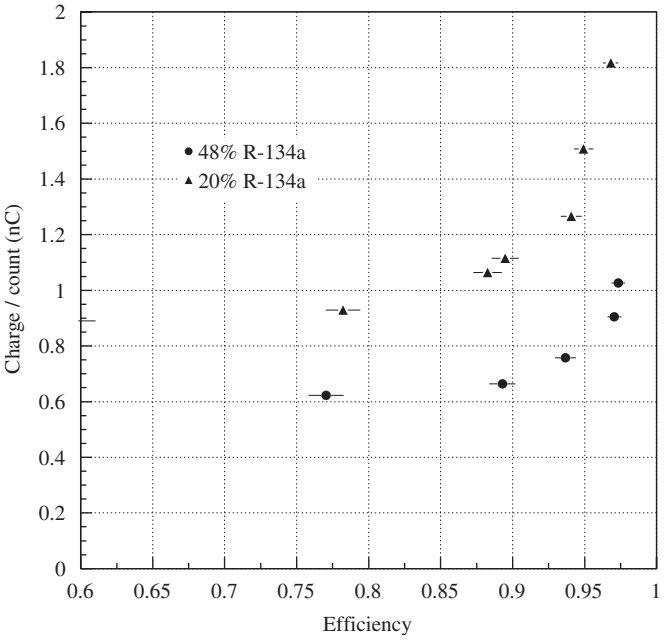

Fig. 2. Charge/count vs efficiency for ternary gas mixtures with different R-134a and argon concentrations. Isobutane is fixed at 4%.

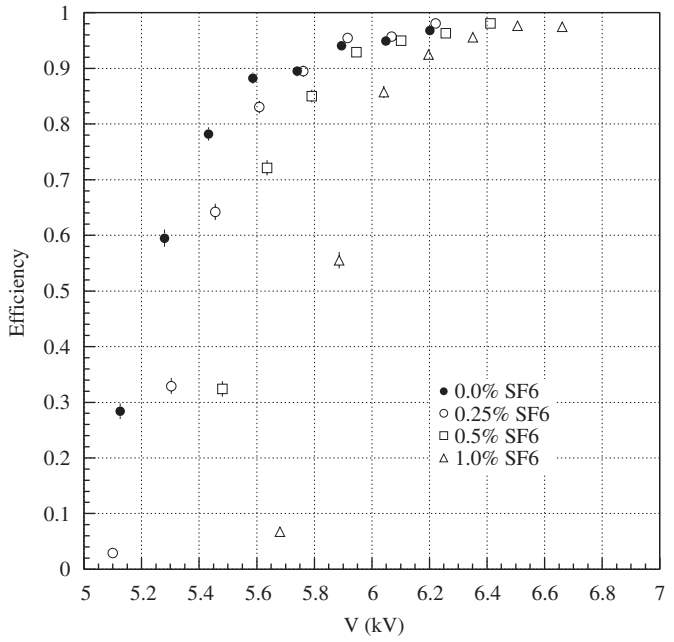

Fig. 3. Efficiency vs operating voltage with different SF_6 additions to the baseline gas mixture $Ar/C_2H_2F_4/isoC_4H_{10} = 76/20/4$.

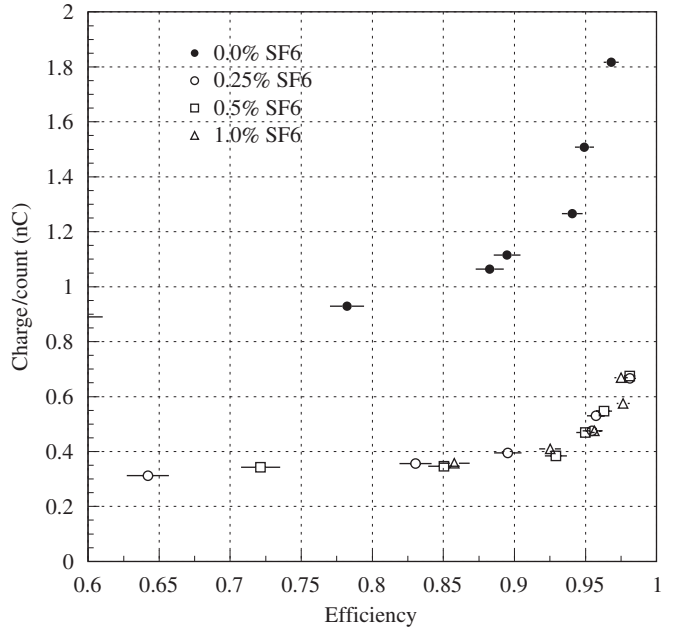

Fig. 4. Charge/count vs efficiency with different SF_6 additions to the baseline gas mixture $Ar/C_2H_2F_4/isoC_4H_{10} = 76/20/4$.

the other values, the loss of quenching power looks well compensated by the charge lowering due to SF_6 addition, and the charge/count is almost independent of the tetrafluoroethane quantity. Fig. 5 also shows that quaternary mixtures with SF_6 have charge/count values which are about one half of the ones observed with the gas mixture $Ar/C_2H_2F_4/isoC_4H_{10} = 48/48/4$, also reported in the plot.

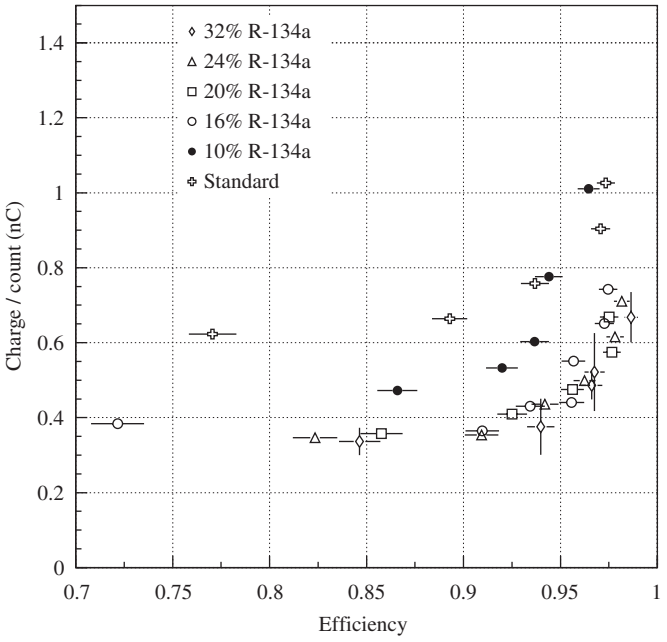

Fig. 5. Charge/count vs efficiency for different tetrafluoroethane (R-134a) quantities. Isobutane and SF_6 are fixed at 4% and 1%, respectively. As a reference the charge/count vs efficiency is reported also for the ternary gas mixture $Ar/C_2H_2F_4/isoC_4H_{10} = 48/48/4$ ("Standard").

4. Tests on low R-134a concentration gas mixtures

According to the plot shown in Fig. 5 it is not convenient to reduce the R-134a concentration to values lower than 20%. We have therefore further investigated the properties of the mixture $Ar/C_2H_2F_4/isoC_4H_{10} = 76/20/4$ with 0.5% SF_6 addition, compared to a typical ternary mixture, in order to verify that the requirements exposed in Section 1 are fulfilled. The difference between 1% and 0.5% SF_6 addition is affecting mainly the operating voltage (see Figs. 3 and 4). The streamer properties have been studied using ADCs for measuring the prompt charge induced on the read-out electrode of the test chambers and of the trigger RPCs. Single particles in cosmic rays are selected by cuts applied on the charge of trigger RPCs. In Fig. 6 the charge spectrum of one RPC is shown as an example. From the charge spectra it is possible to measure the single streamer charge and the multi-streamers probability, in addition to the average prompt charge.

In Fig. 7 the average prompt charge (i.e. the charge induced on the read-out electrode) is shown, together with the single streamer charge. The multi-streamers probability is instead shown in Fig. 8. It is evident that the number of multiple streamers is almost as twice as using the reference ternary gas mixture, but with a much lower charge for single streamers.

In order to measure the time resolution, the test chamber in the set-up has been replaced by two RPCs read-out by means of 3.5 cm pitch strips. To fully simulate the OPERA set-up, the strips are terminated on one side on their characteristic impedance and on the other side on

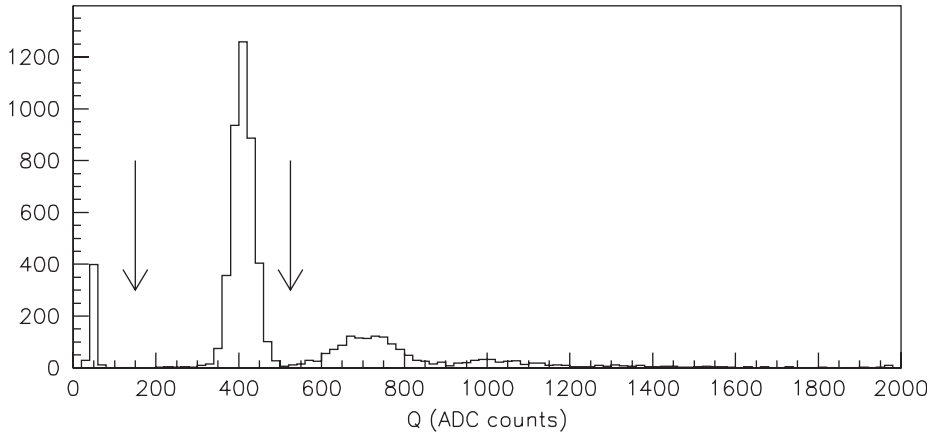

Fig. 6. Induced charge for the gas mixture $Ar/C_2H_2F_4/isoC_4H_{10} = 56/40/4$ at $V = 7.6\,kV$. One ADC count is 0.83 pC. The cuts for selecting single streamers are also shown.

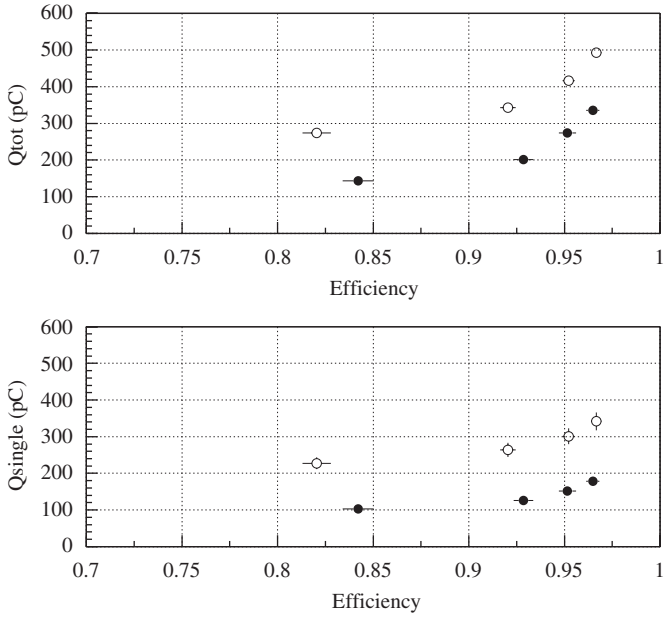

Fig. 7. Total prompt charge (upper plot) and single streamer prompt charge (lower plot) for the gas mixtures $Ar/C_2H_2F_4/isoC_4H_{10} = 48/48/4$ (blank marks) and $Ar/C_2H_2F_4/isoC_4H_{10} = 76/20/4$ with 0.5% SF_6 addition (full marks).

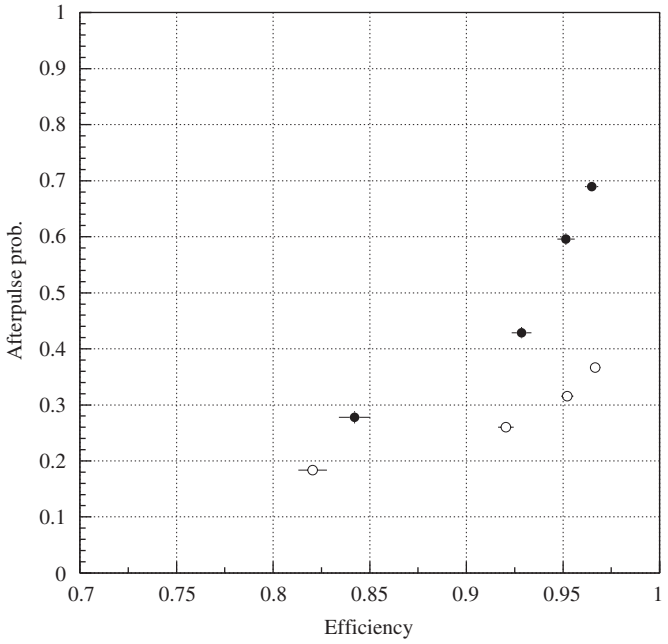

Fig. 8. Multiple streamers probability for the gas mixtures $Ar/C_2H_2F_4/isoC_4H_{10} = 48/48/4$ (blank marks) and $Ar/C_2H_2F_4/isoC_4H_{10} = 76/20/4$ with 0.5% SF_6 addition (full marks).

110 Ω. On this side, the 16 strip panels covering the test RPCs are read-out by means of two OPERA timing boards [10]. These circuits discriminate the signals on each strip providing at the same time a digital OR and the analog sum.

In Fig. 9 the time resolution is shown for $Ar/C_2H_2F_4/isoC_4H_{10} = 76/20/4$ with 0.5% SF_6 addition and for $Ar/C_2H_2F_4/isoC_4H_{10} = 48/48/4$ gas mixtures. A threshold value of 4 mV has been applied to strip signals. The timing properties of the two gas mixtures are similar.

With the previous set-up we measured also the amplitude and the width of single streamers by acquiring waveforms on a digital scope. The results are reported in Fig. 10: the widths look similar while the amplitude is about one half with the considered quaternary gas mixture.

In order to study possible aging effects, operation tests have been performed on real size OPERA RPCs flushed at five refills/day with the gas mixture $Ar/C_2H_2F_4/iso C_4H_{10} = 76/20/4$ with the addition of 0.7% SF_6. After 1 year of operation in the external Gran Sasso Laboratories, at counting rates $\sim$300 Hz/m^2 (one order of magnitude higher than typical values measured on the experiment inside the underground laboratories), no performance deterioration has been observed. The detailed results of this and other tests can be found in Ref. [11].

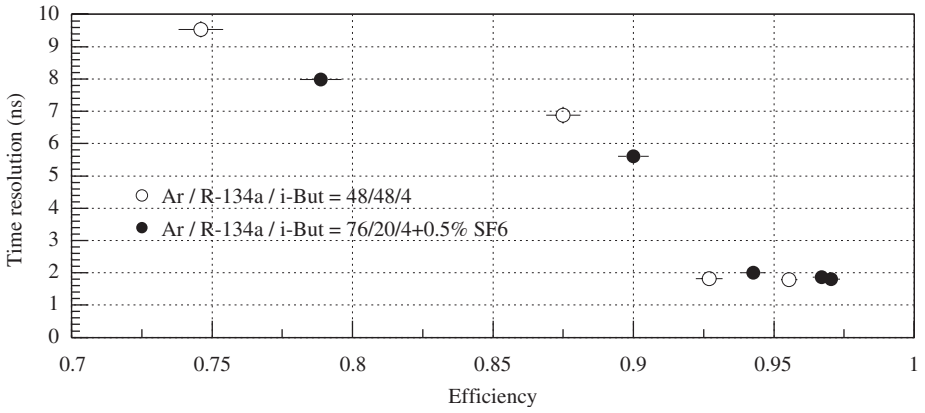

Fig. 9. Time resolution vs efficiency measured for the gas mixtures $Ar/C_2H_2F_4/isoC_4H_{10} = 48/48/4$ and $Ar/C_2H_2F_4/isoC_4H_{10} = 76/20/4$ with the addition of 0.5% SF_6. The time resolution is defined as the sigma of the Gaussian fit to the distribution of the time-of-flight between the two RPCs under test.

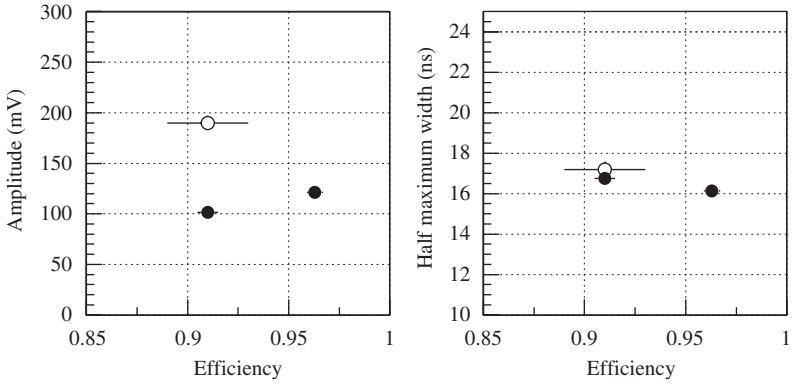

Fig. 10. Single streamer parameters for the gas mixtures $Ar/C_2H_2F_4/isoC_4H_{10} = 48/48/4$ (blank marks) and $Ar/C_2H_2F_4/isoC_4H_{10} = 76/20/4$ with 0.5% SF_6 addition (full marks).

5. Conclusions

The RPCs of the OPERA spectrometers are operated in streamer. The gas system is an open flow system with the detectors flushed at approximately five refills each day. With respect to mixtures employed in other experiments, we have investigated the possibility of decreasing as much as possible the tetrafluoroethane concentration with the addition of a small quantity of SF_6, in order to have low operating voltage and current values, as well as to reduce the cost of the gas.

From our studies it is evident that the R-134a concentration cannot be reduced to values lower than 20%. The charge/count of the studied mixtures does not depend on the SF_6 concentration, once added. We have further investigated the properties of the gas mixture $Ar/C_2H_2F_4/isoC_4H_{10} = 76/20/4$ with 0.5% SF_6 addition, in order to verify that it matches all of the requirements for the OPERA RPCs. With this gas mixture the operating voltage is around 6 kV, 2 kV lower with respect to the typical gas mixture $Ar/C_2H_2F_4/isoC_4H_{10} = 48/48/4$. This operating voltage is lower than the discharge threshold in RPCs filled with nitrogen or air. Nitrogen flushing before the start of data-taking can therefore be used to prevent damaging of chambers with a low gas flux, as nitrogen contamination raises the discharge voltage. The operating voltage decrease is useful also for improving the insulation of the HV system.

Though the measured counting rate for OPERA RPCs is very low, detector imperfections could cause high local counting rates with enhanced local aging effects. We are confident that the reduction of the total charge released in the gas in each detector count should slow the aging of the chambers. Long term operation tests have been carried out at cosmic ray fluxes on real size OPERA RPCs, without observing anomalous aging effects. Together with the R-134a concentration, also the number of primary ionizations inside the gas gap is reduced. Nevertheless the time resolution is not spoiled by the low tetrafluoroethane quantity. The increase of the number of multiple streamers is not a problem at low counting rates, since a short shaping time of digital signals is not needed.

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