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Limited streamer chambers for the Large Volume Detector

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LIMITED STREAMER CHAMBERS FOR THE LARGE VOLUME DETECTOR

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The tracking system of the Large Volume Detector, an underground experiment to study muons and neutrino astronomy, will use ~15000 limited streamer chambers. We describe a comparison between the standard binary mixture (30% argon + 70% isobutane) and a low-hydrocarbon ternary mixture (2% argon + 10% isobutane + 88% carbon dioxide). The ternary composition results in a 400-volt-shorter single count-rate plateau, a 20% smaller primary streamer pulse-height, and a much higher streamer multiplicity. The count-rate plateaux have also been studied over a wide composition range of isobutane, argon, and carbon dioxide mixtures. We also discuss the streamer chamber quality control procedures and the results obtained from a sample of 2900 devices operated with the binary mixture.

1. Introduction

The Large Volume Detector¹ is an underground experiment being developed at the Gran Sasso laboratory². The experiment is mainly aimed at studying neutrino bursts from stellar collapses, solar neutrino emission, astrophysical point-like sources of gammas and neutrinos, neutrino oscillations, monopoles, and proton decay. The tracking system of LVD uses ~15000 limited streamer chambers, which divide its volume in eight horizontal and five vertical planes. The tracking readout originates from external pickup strips. The LVD chambers are Frascati-standard³, coverless devices, with a length of 6.3 m. The chambers are made of PVC profiles containing eight 1-cm² rectangular troughs internally coated with graphite paint. Silver-plated, 100- μ m, Cu-Be wires are extended through the center of each cell and connected to a printed circuit board at two ends. Plastic bridges support the wires at 50-cm intervals. The profiles are enclosed by a PVC jacket, and plastic caps, welded at the two ends, provide electrical and gas connections.

The operating principles of streamer chambers have been well studied⁴⁻⁶. When a large number of chambers are to be used, the

choice of the filling gas and the selection of high-quality chambers are two of the major issues. In this paper we address these two questions in the particular context of the LVD experiment. The studies performed to investigate the operational characteristics of carbon dioxide, isobutane, and argon mixtures are described. We also discuss the procedures to select reliable and high-quality chambers and report the results.

2. Performance of a low-hydrocarbon ternary mixture

A large number of plastic streamer chambers with graphite-coated cathode are being used in accelerator and underground experiments of high energy and nuclear physics. The chamber operation strongly depends upon the filling gas. The gases usually employed for this purpose are mixtures of a noble gas (argon or neon) and a hydrocarbon component (ethane, isobutane, or n-pentane). The binary⁷ (30% argon + 70% isobutane or 25% argon + 75% isobutane) and the ternary⁸ mixtures (15% argon + 25% n-pentane + 60% carbon dioxide) are largely used and considered as standard mixtures due to their satisfactory performances. All three are flammable in air because of their high percentage of hydrocarbon components. Operating with a large

volume of flammable mixture, as in LVD which requires 75 m³ of filling gas, implies strong safety constraints. Consequently, many low-hydrocarbon mixtures have been proposed and investigated by different groups⁹⁻¹⁴. We have made detailed investigations of an already suggested low-hydrocarbon *ternary* mixture¹⁵ (2% argon + 10% isobutane + 88% carbon dioxide) and have compared its performance with that of the standard *binary* composition (30% argon + 70% isobutane).

For all the measurements reported in this paper, the gas mixture was formed by using Hi-Tech mass flow transducers (F200 series) and the compositions obtained were within 1% of accuracy. Four chambers with their lengths between 85 and 105 cm were selected out of a batch of 100 devices with their count rate plateau-length greater than 800 volts, using the binary mixture. The chamber wire signal was discriminated by a threshold of -8mV/50 Ω , which is suitable to make the plateau knee voltage a true representation of transition between the proportional and the limited streamer regimes³. The comparison between single count-rate curves of these chambers with the two mixtures under study, are reported in Fig.1. All four chambers showed very similar results and typical data are reported in this paper. Both the mixtures have a plateau knee at 4500 volts. For dead times longer than 600 ns, the binary mixture exhibits a plateau length greater than 800 volts, and with 200 ns the plateau length is still greater than 550 volts. On the other hand the ternary mixture has practically no plateau with 200 ns dead time, and with longer than 1 μ s, the plateau length reaches a maximum of 500 volts. In Fig.2 we show 100 superimposed wire signals for both the mixtures at 300 volts above the count-rate plateau knee, as observed by hp54111D digital oscilloscope. The scope was triggered internally with a threshold of -20 mV. The data are characterized by very high pulse-multiplicity in the case of the ternary mixture, compared to the binary composition. Pulse trains wider than 500 ns are abundant with the ternary mixture, which originate the breakaway observed in the plateau curves of Fig.1b when dead times of less than 1 μ s are used.

Different phenomena exist that can cause pulse multiplicity in a streamer chamber. The trivial case, originated by rear-end reflection, did not interfere in our measurements because of the short length of the wires, with the maximum possible delay much less than the pulse duration.

A second source of pulse multiplicity is caused by particles crossing the chambers, making a smaller angle with the wire plane.

(a) 30% argon + 70% isobutane

(b) 2% argon + 10% isobutane + 88% carbon dioxide

Fig.1 Single count-rate curves with different dead times.

(a) 30% argon + 70% isobutane

(b) 2% argon + 10% isobutane + 88% carbon dioxide

Fig.2 One hundred superimposed wire signals at 4800 volts. (50ns/div, 20mV/div)

These tracks originate more than one streamer along their path, which we call geometrical multistreamers. All the corresponding pulses arrive within an interval from 0 to the drift time value for the electrons to travel along half of the chamber cell.

Finally, streamers can regenerate themselves if the mixture does not have a sufficient quenching ability. Photons from the primary streamer, if not absorbed by the quenching gas, travel to the cathode where they can cause emission of electrons. These electrons can originate secondary streamers called "afterpulses". The process can reiterate itself with two or more afterpulses arriving with an intervening delay equal to the drift time across half of the cell dimensions.

To further investigate the performance of the two mixtures, we set up a three-scintillator counter telescope. The telescope, with the appropriate electronics¹⁶⁻¹⁷, was used to furnish a trigger for the hard component of cosmic rays within a selection angle of $\pm 3^\circ$ with the wire plane. It strongly reduced the possibility of geometrical multistreamers, and the simulations showed that with this configuration the probability for geometrical multistreamers is less than two percent.

Fig.3 Chamber efficiency as a function of voltage above plateau knee.

The experimental setup, as described above, also allowed us to measure the chamber efficiency and drift time spectra for the electrons. As shown in Fig.3, both the mixtures have almost the same efficiency curves. The drift time spectra with the two mixtures, measured at 4600 volts, reflect an unsaturated drift velocity of the electrons in the ternary mixture and a nearly constant drift velocity in the binary composition. (Fig.4). We found that the maximum drift time for electrons, corresponding to the half cell dimensions, is about 100 ns for the binary mixture and 92 ns for the ternary composition.

(a) 30% argon + 70% isobutane

(b) 2% argon + 10% isobutane + 88% carbon dioxide

Fig.4 Electron drift time spectra at 100 volts above the plateau knee.

A comparison of afterpulse generation is usually based on single count-rate plateau measurements performed with different dead times or on pulse charge spectra. However, these methods are not significant enough to yield precise results. For a more resolved comparison, we observed individual streamer events using the digital oscilloscope triggered by the telescopic coincidence. We printed a total of 15000 individual signals, with the two mixtures at different applied voltages. Some typical signals with the binary mixture are shown in Fig.5.

The analysis of the recorded pulses allowed us to study the average primary streamer pulse-height and afterpulse probability. The ternary mixture exhibited a ~20% smaller average primary streamer pulse-height, compared with the binary composition (Fig.6). The poor quenching ability of the ternary mixture is shown by the average streamer-multiplicity curve of Fig.7. Figure 8 shows the distribution of overall streamer multiplicity for the two

Fig.5 Typical wire signals. (a) Single streamer (b) Photon generated afterpulse. (c) Cascaded photon generated afterpulses (d) Geometrical multistreamer (100ns/div, 50mV/div)

mixtures. Considering these curves for the ternary composition (Fig.8b), we see that a significant contribution to pulse multiplication is made by events with two to five afterpulses. The trains of two to five afterpulses are so frequent that even the probability of one-afterpulse-event starts decreasing from more than 200 volts above the plateau knee.

In general, afterpulses can be ignored when a dead time of the order of microseconds is acceptable for chamber operation, and the readout is originated by wire signal. However, when pickup strip readout is used, the multi-strip induction is determined by streamer multiplicity, and afterpulse generation becomes an important parameter. For strips lying perpendicular to chamber wires, the average cluster size reaches a value of 1.75 strips at 200 volts above the plateau knee with the well quenched binary mixture (Fig.9). Whereas, at the same voltage for the ternary mixture, the percentage of afterpulses is already three times higher than that of the binary mixture (Fig.7).

Fig.6 Primary streamer pulse-height as a function of applied voltage.

Fig.7 Average streamer multiplicity caused by afterpulses as a function of applied voltage.

(a) 30% argon + 70% isobutane

(b) 2% argon + 10% isobutane + 88% carbon dioxide

Fig.8 The percentage of events with the given number of afterpulses.

Fig.9 Average number of strips fired by one crossing particle (binary mixture).

Fig.10 Single count-rate plateau knee/length for different compositions of argon, isobutane, and carbon dioxide mixture.

3. Alternative ternary mixtures

The studied low-hydrocarbon ternary mixture (2% argon + 10% isobutane + 88% carbon dioxide) is at the limit of the flammability region¹⁸. Other combinations of the three gases can be tested with the intent to find a useful mixture with a smaller isobutane percentage, compared with 70% of the standard binary mixture. We explored a wide domain of various ternary compositions by measuring the corresponding single count-rate plateaux of the chambers with 1 μ s dead time and a discriminator threshold of -8mV/50 Ω . In Fig.10 we report the values obtained for the knee voltage and the length of the plateaux. As expected, the knee position moves to higher voltages, and the length of the plateau increases when the quenching gas percentage (isobutane or carbon dioxide) is increased. The poor quenching ability of carbon dioxide is demonstrated by the increase in knee voltage and reduction in plateau length when the carbon dioxide to isobutane ratio increases for a given argon percentage. For a better understanding of possible alternatives to the standard binary composition, a detailed investigation is needed concerning afterpulse formation, electron drift time, and streamer charge. The results on the plateau knee and its length suggest that possible alternative mixtures to be considered are (13% argon + 29% isobutane + 58% carbon dioxide) and (8% argon + 20.4% isobutane + 71.6% carbon dioxide). These two have a reduced isobutane

percentage compared with the standard binary mixture (by a factor of 2.4 and 3.4 respectively) and at the same time exhibit a sufficiently long plateau with an acceptable knee-voltage.

4. Chamber quality control

One of the major concerns in the use of plastic streamer chambers for LVD is their reliability in time, especially in view of the fact that the operating period of the experiment is planned to cover a few decades and the replacement of malfunctioning chambers is practically impossible after their installation. Hence, the testing procedures and the acceptance criteria to guarantee a specified operation and a long lifetime for the devices are primary factors. The necessity of selecting good-quality chambers has been faced by many experimental groups. However, the testing methods and the selection criteria differ largely and there are no well-established standards¹⁹⁻²⁴.

To face the problem of LVD streamer chamber quality-control we decided to make an intensive study of the aspects of chamber performance that could affect their successful operation. The Astra laboratory²⁵ was set up at Frascati for this purpose and it was equipped with the instruments necessary for R&D investigations on related aspects of chamber operation. Quality

control procedures were developed that observed each chamber for more than a month. During these procedures, the chambers were filled with standard binary mixture (30% argon + 70% isobutane) prepared by using Hi-Tech mass flow transducers (F200 series). A continuous and parallel mixture flow of 1 volume/24 hr was used with gas leakage kept at less than 1% volume per day. The mixture overpressure was maintained at 5–6 mbars with controlled ambient temperature (22–24°C) and humidity (<60%). Carlo Erba's Vega series gas chromatograph (GC600) was used to monitor mixture impurities. Thus water and nitrogen concentrations were kept within 0.4–0.7% and 0.3–0.5% respectively. Each chamber had an independent voltage channel provided by a CAEN SY127 power supply. A current limiting resistor of 10 M Ω was used in series with each voltage channel. The quality control procedures carried out in Astra can be divided in two stages: conditioning and long-duration quality selection test.

4.1 Conditioning.

During conditioning the voltage was applied to the chambers starting from 2000 volts. Every 30 minutes the chamber voltage was increased by 100 volts, maintained at 4700 volts for five hours, and then pulled up from 4700 to 5100 volts in 30-minute-steps of 50 volts. The data acquisition system read the chamber current and its voltage every 30 seconds. Chambers were not allowed to draw more than 5 μ A of current. When a chamber started to draw this maximum value of current, the channel voltage was reduced in such a way that the supply acted as a constant current source. A "trip" condition was recognized if a chamber continuously drew the maximum current for more than the "trip time" of 10 seconds. If a trip occurred, the chamber voltage was switched off for 2.5 minutes (rest time) and then brought up to one voltage step lower than the step at which it had shown the trip condition. All voltage transitions were made with a ramp up of +50 volts/s and a ramp down of -500 volts/s. Conditioning was continued for two days and if a chamber could not reach 4900 volts, it was considered as a conditioning failure and removed from the test. Out of 2912 chambers, 4.4% failed during the conditioning phase.

4.2 Long-duration quality selection test.

The chambers passing the conditioning phase were kept at 4900 volts for more than four weeks. The same monitoring and control logic was used as during conditioning, with the exception that after a trip and subsequent switching off, the chamber was again switched on at 4900 volts.

The basic quality evaluation for selecting reliable chambers was based on average current and current bursts. The current expected to be drawn by a chamber, under a cosmic and local radioactivity environment, is of the order of a few tens of nA. However, many causes, such as surface current leakage, dust particles inside chambers, and anode wire instabilities, can originate higher or instable currents. Current "spikes" (sporadic bursts of current) were observed for almost all the chambers, even for those which otherwise had a low and stable average current. If the voltage generator is not current limited, the current spikes can have a magnitude of hundreds of μ A and can last up to a few minutes, as we observed in a dedicated test. If uncontrolled, they can cause permanent damage to the device. Spike protection was realized by limiting the voltage source to a maximum current value. As a chamber starts to draw a high current, its anode voltage is reduced by the ohmic drop across the current limiting resistor. The voltage is further reduced as the current reaches the maximum allowed value and the supply begins to act as a constant current source. Finally, if the overcurrent state persists longer than the trip time, the chamber is rescued by being switched off for the set rest time. During all these phases, the anode voltage decreases largely from the preset working point and the chamber loses its ability to serve as an efficient detector. The efficiency of a chamber is determined by measuring the time for which its voltage could be kept on, without any current limiting action by the power supply. This time, expressed as a percentage of the total time of observation, is defined as service time efficiency.

The choice of maximum current limit, trip time, and rest time is a compromise between various considerations. The set value of the maximum current limit determines the ohmic drop of the voltage before a current limiting action is undertaken by the supply. The trip and rest times have a significant effect on the safety protection of the chambers at the cost of their service time efficiency. The trip time and the maximum current limit have to be small enough for long-lasting and high magnitude spikes not to cause permanent damage to the chamber. They should also be small enough to prevent the chamber from working with an anode voltage that is too low compared to the preset working point without any intervention by the current limiting action of the supply. At the same time, the values have to be large enough to tolerate the small variations in average current and not to invoke any unnecessary current limiting action of the supply. The maximum current limit was set at 5 μ A, taking into account that in the actual LVD apparatus a group of 10–20 chambers will be

Fig.11 Probability density graphs for the first week of long-duration quality selection test.

connected to the same voltage channel. The set maximum current limit allows a 50-volt drop ($5 \mu\text{A}$ through $10 \text{ M}\Omega$) to be ignored by the voltage monitoring system. Our experience shows that the spikes that last for more than 5 seconds have little chance of extinguishing themselves. Correspondingly, we used a trip time of 10 seconds. The subsequent rest time was set to 2.5 minutes, which is a reasonable estimate for the interval during which the voltage control system of LVD apparatus will be able to scan all the voltage channels.

5. Quality selection of chambers.

In Fig.11 we show the probability density graph for average current and service time efficiency for the first week of observations. The average current distribution is peaked at $\sim 120 \text{ nA}$, and 86% of the chambers fall below 300 nA (Fig.11a). Figure 11b shows that 82% of the devices have more than 98% service time efficiency. Each of the probability density graphs has two different slopes, suggesting that their populations can be divided in two groups, that begin to overlap at points that roughly correspond to 97% service time efficiency and 750 nA average current.

Figure 12 establishes the correlation between the weekly average currents and service time efficiency. We observe that many chambers have a decreasing current and an increasing service time efficiency from the first to the second week, while for the following three weeks the majority shows an almost stable behavior. The same evolution trend is observed if we consider the average current and service time efficiency averaged over all the

chambers for different weeks (Table 1). In order to further confirm the improvement trends, the chambers with service time efficiency greater than 97% are divided from those with service time efficiency less than 90% on the basis of the first week, and we follow their subsequent evolution. The occupancy probability tree (Fig.13a) shows that 26.7% of the chambers with service time efficiency less than 90% in the first week transit to the region better than 97% in the second week, and then most of them maintain this improved quality. Similarly we divide chambers with their average current less than 750 nA from those which show an average current greater than 1500 nA . The resultant occupancy probability tree (Fig.13b) shows that the improvement in chamber current, during the first week, is even higher compared with service time efficiency.

Table 1

Weekly average current and service time efficiency averaged over all the chambers.

Week No	Av. current	Service time efficiency
1	363 nA	92.5%
2	281 nA	96.8%
3	275 nA	96.9%
4	272 nA	96.9%

Fig.12 Evolution trend in average current and service time efficiency. Each quadrant compares respective quantity for the given two weeks and each chamber is shown by a dot. In Fig.12b the quantity (service time efficiency - 0.015) is plotted.

(a) On the basis of first week's data the chambers are divided into class A (efficiency > 97%) and class B (efficiency < 90%). In the following weeks, a chamber transits from B to A if it reaches an efficiency > 97% and from A to B if its efficiency becomes < 97%.

(b) The first week's divisions are < 750 nA (for class A) and > 1500 nA (for class B). In the following weeks, transition from B to A is recognized if a chamber reaches a current < 750 nA and from A to B if its current becomes > 750 nA.

Fig.13 Occupancy probability tree for service time efficiency (a) and average current (b). Only those chambers are considered which fall either in class A or in B for the first week's data. The percentages written in italics have greater than 30% statistical error.

Considering the general improvement trend observed at the beginning of the acceptance test, it was decided to apply the quality selection cuts from the second week onwards. A chamber was selected only if it exhibited a service time efficiency greater than 97% and an average current less than 750 nA for each of the last three weeks. An excursion across the selection cuts compatible with the repeatability of the measurement, 0.5% for service time efficiency and 15% for average current, was tolerated. Using the above-mentioned selection criteria, the resultant percentage of the chambers in various quality categories is shown in Table 2. It is to be remarked that, although the current selection cut is placed at 750 nA, 92% of the selected chambers have an average current less than 300 nA. We classify these as very high-quality chambers. In Fig. 14 we show typical correlation plots for average current, service time efficiency and standard deviation of current for these chambers during the last week. The distributions for these devices are peaked at 70 nA for standard deviation of current, 99.97% for service time efficiency, and 105 nA for average current.

The major aim of our selection criteria was to identify reliable, stable, and long-life chambers. The stability and lifetime of the selected chambers can be estimated from the trend shown by the rejection rate for each week of the long-duration quality selection test (Table 3). The percentage of rejected chambers is reduced roughly by a factor of six as we go from one week to the next. This numerical trend can be extrapolated to estimate that the percentage of chambers that transit across the boundaries of the selection criteria during the following one year should be a decimal fraction. It is to be noticed that the selection limits are applied for identifying high-quality chambers, and the limits at which chambers cannot function as detectors are more tolerant, especially with regard to current. Therefore, we have to distinguish between the chambers that lose their high-quality and those which give an operational failure. This makes the expected mortality rate even smaller than the rate at which chambers lose their high-quality.

However, the predicted mortality rate has to be confirmed experimentally because of the relative validity of the numerical extrapolation. In fact, a lifetime test performed with a large number of chambers observed for a few weeks can only provide indications of early chamber failure and it is less significant than a test performed with a comparatively small number of chambers for a long period. For this reason, we are performing a lifetime test using 100 selected chambers, which have been under observation

Table 2

Distribution of chambers in various quality categories. Based on one week's data, a chamber is considered to be of high quality only if it shows a service time efficiency greater than 97% and an average current less than 750 nA.

Chamber quality (last three weeks)	Percentage
1. Always high	81.5%
2. Always low	11.4%
3. Single transition	
high $\longrightarrow$ low	1.4%
low $\longrightarrow$ high	4.1%
4. Multiple transition	1.6%

Table 3

Weekly rejection rate.

Week No	Rejection percentage
2	15.9%
3	2.6%
4	0.4%

for seven months in the Astra laboratory. During this test, the chambers are being maintained at 4900 volts and have been switched off occasionally in the case of a power failure or hardware maintenance. When switched off, they undergo a small conditioning process of two hours before being turned on. During the seven months, only two chambers have transited across the average current boundary up to 1.5 μ A, while still maintaining the high service time efficiency. None of the chambers has shown any deterioration that makes it useless as an efficient detector.

Confirmation of the long lifetime of our selected chambers has also come from their experimental use. Roughly 1500 of these were mounted on LVD tracking segments and used for different measurements, which were spread over one year. Another batch of 500 chambers was transported to Gran Sasso, installed in a mechanical structure, and left in an uncontrolled humidity and temperature environment for more than eight months before being used again (Fig. 15). The behavior of both these groups of chambers agrees with a mortality rate of less than 1% per year.

(a) Average current vs service time efficiency

(b) Standard deviation of current vs service time efficiency

(c) Standard deviation of current vs average current

Fig.14 Typical correlation plots for very high-quality chambers during fourth week of the long-duration test. In (a) and (b) service time efficiency - 0.015 is plotted.

Fig.15 Distribution of plateau knee and length for 500 chambers at Gran Sasso. The plateau knee voltage is reduced because of the lower ambient pressure.

6. Conclusions

The comparison between the low-hydrocarbon ternary mixture (2% argon + 10% isobutane + 88% carbon dioxide) and the standard binary composition (30% argon + 70% isobutane) shows the definite superiority of the latter, both in the saturated electron drift velocity and in a smaller afterpulse probability. Furthermore, the expected lifetime of chambers operated with a low-quenching mixture has never been demonstrated and it is questionable whether it could be comparable with the score reached by the standard binary mixture. However, we believe that a more resolved study has to be performed for other carbon dioxide based low-hydrocarbon ternary mixtures. The mixtures (13% argon + 29% isobutane + 58% carbon dioxide) and (8% argon + 20.4% isobutane + 71.6% carbon dioxide) are more suitable candidates for further investigations.

The procedures and the criteria applied to select high-quality

limited streamer chambers for the Large Volume Detector have been described. Experimental results, from the lifetime test and from practical use of the selected chambers, show that their mortality rate is less than 1% per year.

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