To be submitted to
Nuclear Instr. & Meth.

ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Frascati

LNF-78/60(P)
20 Dicembre 1978

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OPERATION OF LIMITED STREAMER TUBES.

Abstract

We present a study of the basic properties of tubes with thick sense wires (40 ÷ 200 μm) operated in the limited streamer mode. The pulse shape, singles rate, detection efficiency and dead time are discussed, together with the influence of various parameters such as wire diameter, tube shape and dimensions, gas mixtures. Cathode material may be either conductive or resistive for multicoordinate readout. Preliminary results are shown on the possibility to use resistive plastics as cathode.

The results of the study show the possibility to operate limited streamer tubes in a wide range of the geometrical parameters, always maintaining their basic features, i. e. high reliability, easy construction, low cost of both detectors and readout electronics.

1. - INTRODUCTION.

We have started working with thick sense wire tubes in the limited streamer mode, in connection with the development of tube devices with resistive cathode$^{(1)}$. We have shown that in a wide range of resistivity the cathodes are transparent to the pulsed field associated to an avalanche or streamer. These may be localized along one or more tubes by detecting the signals induced on any kind of pick-up electrodes placed outside the tube module (strips, pads, delay lines). It is worthwhile noticing that the pick-up electrodes can be physically disconnected from the tubes.

The use of thick sense wires allows to build relatively unexpensive detectors with high mechanical reliability. The limited streamer mode is characterized by large wire signals ($\gtrsim$ 40 mv/50Ω) and wide high voltage operation range (several hundred volts), so that the readout electronics may be very simple and the operation uncritical. This regime was at first recognized as a limited Geiger one$^{(2)}$. In a succesive study$^{(3)}$ it turned out to be characterized by a streamer discharge mostly on one side of the wire. The streamer propagation toward the cathode is limited due to the electric field decrease.

The use of resistive cathodes, beyond an easy way for multicoordinate readout, can be a further inprovement toward low cost and construction simplicity, by the possibility to use plastics instead of metals. The only limitation in the use of the limited streamer mode is in its relatively long recovery time which sets a limit of the order of 10^2 particles/cm^{2}s.

A system of 330 resistive tubes has been built and operated as a charged particle detector in the $\gamma\gamma$ 2 experiment at the Adone storage ring$^{(4, 5)}$. They are PVC tubes (80 cm long, 18 mm in diameter), with a resistive coating inside with resistivity ranging between 10 and

100 K Ω/cm along the tube. The Cu-Be sense wire is 100 μm in diameter. They are assembled in four layers crossed by 2 cm wide external strips for the longitudinal coordinate readout.

We have extended the work on the limited streamer tubes for a better understanding of the processes involved, and to test the possibility to operate them in a wider range of the geometrical parameters. The aim was to test the operation of tubes with smaller cross section in order to check the feasibility of systems with higher spatial resolution and granularity. We have built square tubes 8 x 8 mm^2 and up to 2. 5 m length, fulfilling the requirements of uncritical operation, high detection efficiency, and low cost.

In conclusion resistive tube devices in the limited streamer mode and with external multicoordinate pick-up electrodes are particularly suited for large detector systems with moderate requirements for spatial resolution and dead time, but where reliability and cost are of primary importance.
By the way, the presence of the separation wall between wires should help in measuring electromagnetic shower energy, by limiting the wire hits due to the very soft component of the electromagnetic cascade, for which the sensitivity of a gas detector is very high. We have prepared a system of tube layers of the $\gamma\gamma$ 2 type interleaved with 1 mm lead absorbers, in order to study its detection properties for low energy (a few hundred MeV) electromagnetic showers.

In paragraph 2 we shall describe the operation features of limited streamer tubes, such as the high voltage plateaux, the wire pulse shapes, the detection efficiency and the dead time. The influence of various parameters will be discussed such as the gas mixture, the tube dimensions and the wire diameter.

Paragraph 3 will be devoted to discussing the influence of the cathode material: metal, resistive varnishes and resistive plastics.

2. - THE LIMITED STREAMER MODE.

The uncritical operation of limited streamer tubes is a consequence of the following basic features:

a) the pulse height distribution exhibits a sharp cut in the small amplitude region (uncritical discrimination threshold);

b) the minimum amplitude is about 40 mV/50Ω (simple amplifiers);

c) there is a wide high voltage range where singles rate is constant (uncritical H. V. supply and gas mixture).

2. 1. - Operation of 18 mm tubes.

For a given geometry of the tube the width of the high voltage operation range increases and its position moves to higher voltages when the relative concentration of the quenching component of the gas mixture is increased. We normally use an argon and isobutane mixture$^{(1)}$, and in fig. 1 typical singles rate curves are shown for different concen-

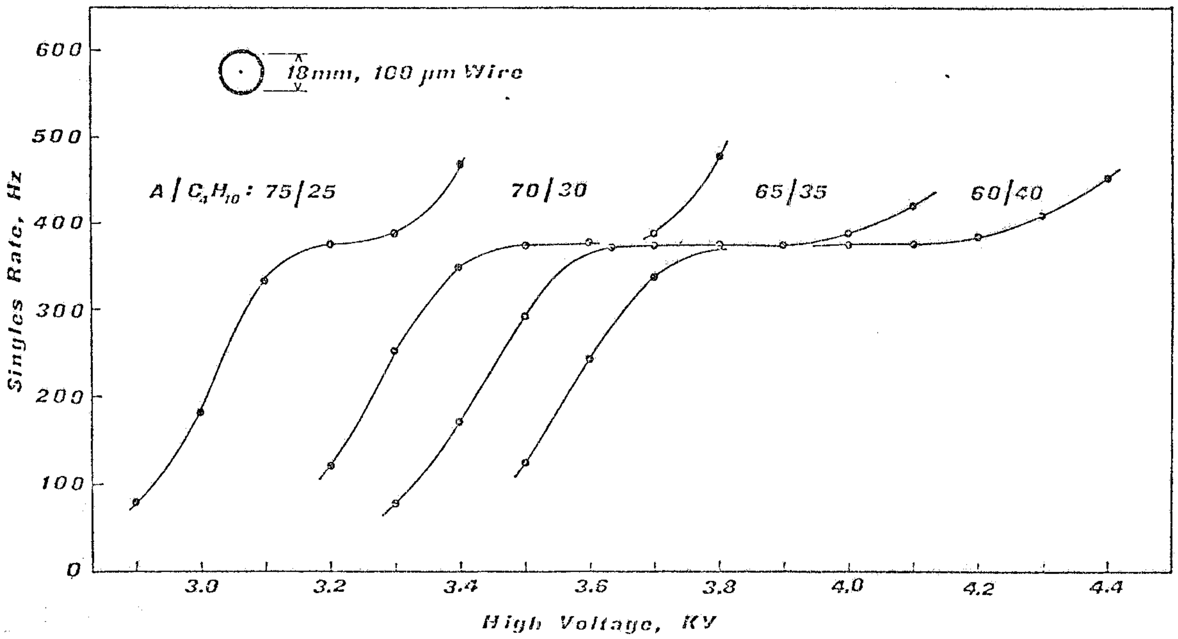

FIG. 1 - Singles rate (Sr^{90} source) vs. H. V. for a tube of the Adone experiment (18 mm diameter, 80 cm length, 100 μm wire) for different concentrations of the argon-isobutane gas mixture. The electronics dead time was 0.5 μs, the threshold 30 mV/50 Ω.

trations of the two gases. They refer to 18 mm resistive tubes, with 100 μm sense wire. The singles rate is generated by a Sr^{90} source. The pulse shaping time is 0. 5 μs and the threshold 30 mV/ 50Ω .

The diameter of the wire is not a critical parameter for the width of the operation voltage range. In fig. 2 the singles rate curves are shown, for 40, 100, 220 μm wire diameters. Pulse height too does not vary dramatically: the minimum is about 20, 40 and 100 mV/ 50Ω for the three wire diameters respectively.

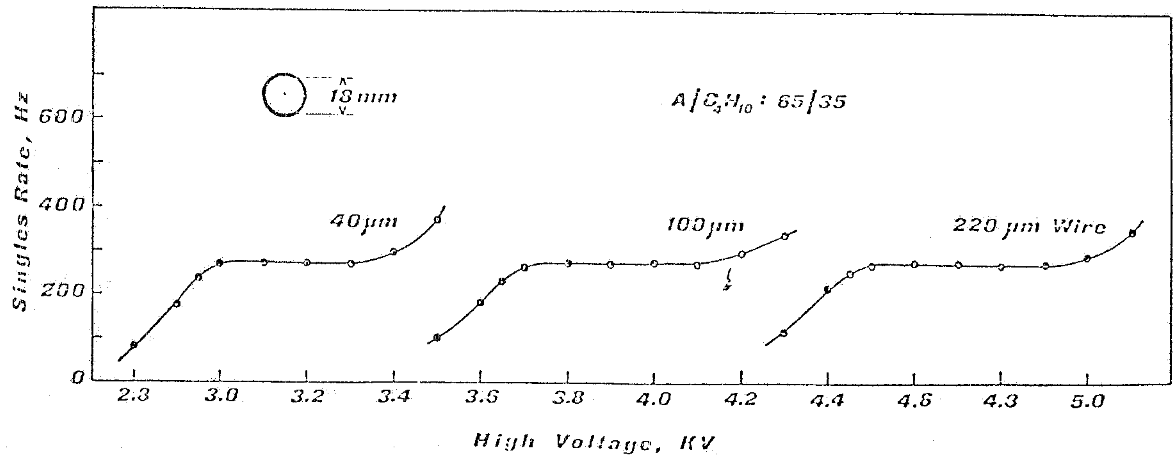

FIG. 2 - Single rate (Sr^{90} source) vs. H. V. for a tube of the Adone experiment for different wire diameters. The electronics dead time was 0.5 μs, the threshold 30 mV/ 50 Ω.

The initial rise of the curves corresponds to the transition between the proportional and the limited streamer pulse generation. At the beginning of the plateaux such transition is completed. Fig. 3 shows the pulses generated in the 18 mm tube with the 100 μm wire, irradiated by an Fe^{55} X ray source. The gas mixture is argon and isobutane (60/40). The pulse height distribution is saturated, corresponding to a single limited streamer process. With a collimated β source (Sr^{90}) the behaviour is substantially similar. With inclined tracks (cosmic rays or uncollimated β source) the pulse height distribution spreads out to higher amplitudes, due to the lengthening of the wire region interested by the multiplication process, and then to multiple limited streamer generation.

At higher voltages afterpulses are generated (see Fig. 3b). The delay time between the primary pulses and the afterpulses is constant for a given tube: it depends only on its diameter and coincides with the drift time of electrons on a radius distance. This fact suggests that afterpulses are generated by the emission of secondary electrons from the cathode, due to ultraviolet photon production in the primary discharge region. Such secondary discharges are contiguous to the primary ones. This is demonstrated by observing the pulses of the primary and secondary discharges on 1 cm wide strips placed orthogonally to the wire. Afterpulses separation in space is ~ 1 cm. Such secondary limited streamer generation is responsible for the rise of the singles rate curves, and for the dependence of the plateau width on the dead time of the wire pulse shaper. The singles rate curves obtained with the X ray source for different dead times are shown in fig. 4. The 150 ns dead time allows to count all of the afterpulses. It must be stressed that the region where afterpulses are produced is stable and reproducible, so that it is a safe region for stable operation. Furthermore since afterpulses are out of time, they will not disturb a strip or pad readout of resistive tubes provided proper timing is established. It will only influence the recovery time of the detector, since the length of the wire interested by the discharge is longer.

As far as pulse heights are concerned, figs. 3a, b show that their variation with high voltage is not large: ~20%/100 V. Figs. 5a, b, c show what happens when the relative concentration of argon and isobutane is changed. They all refer to ~ 100 V above the knee of the corresponding singles rate curves. There is a significant effect only on the pulse duration which decreases when the quenching component concentration of the mixture is increased: from several hundred nanoseconds (25% isobutane) down to ~ 80 ns (55% isobutane).

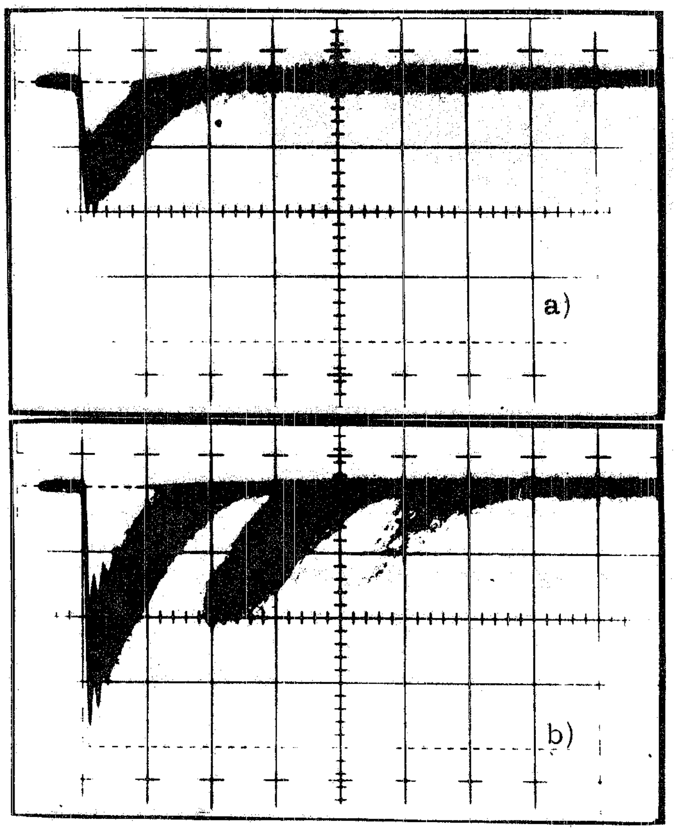

FIG. 3 - Pulse shapes from an Fe^{55} X-ray source for an 18 mm diameter tube, with 100 μm wire, and a gas mixture of argon-isobutane (65/35) :
a) H.V. = 3.7 KV, at the beginning of the single rate plateau ;
b) H.V. = 4.05 KV, showing afterpulse generation
(50 mV/div, 100 ns/div).

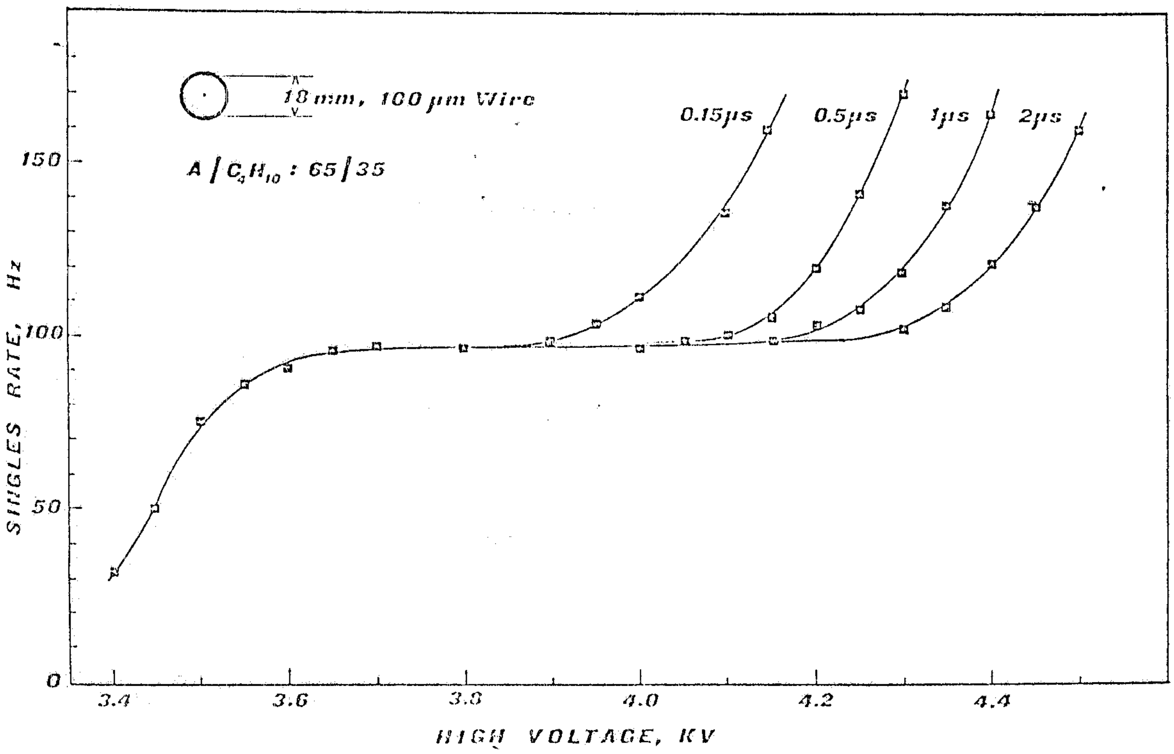

FIG. 4 - Single rate (Fe^{55} source) vs. H.V. for an 18 mm diameter tube with a 100 m wire and an argon-isobutane mixture (65/35); the curves refer to different electronics dead time to show afterpulse generation.

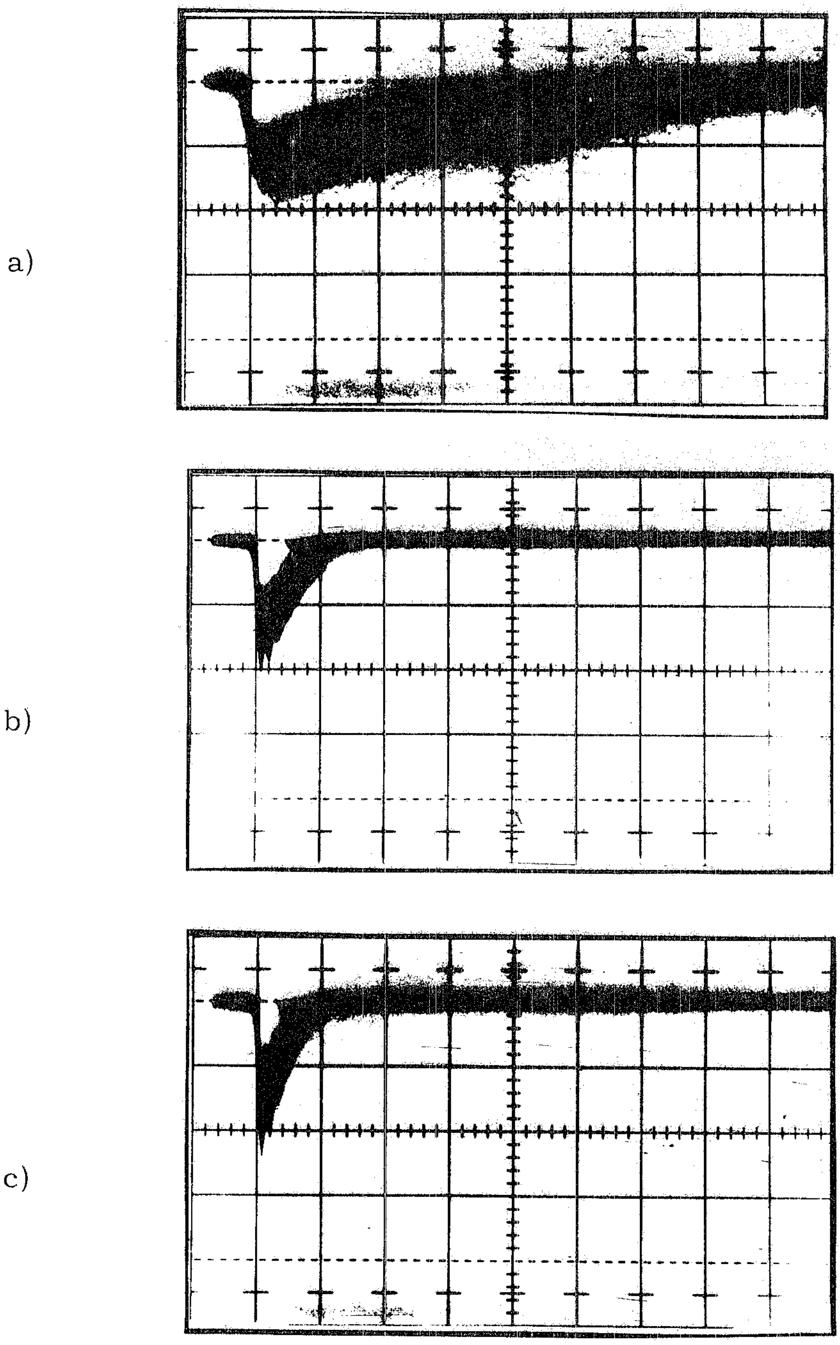

FIG. 5 - Pulse shapes from an Fe^{55} X-ray source for an 18 mm tube with a 100 μm wire: they refer to ~100 V above the knee of the singles rate plateaux for different concentrations of the argon isobutane gas mixture:
a) 75/25 ; b) 55/45 ; c) 45/55 .

The detection efficiency has been measured(4) for the tube layers installed in Adone. The thickness of the separation wall between adjacent tubes is 1 mm. In fig. 6 the efficiency is shown together with the singles rate curve of the layer (32 tubes). In the plateau region the efficiency is 96%. The gas mixture is argon-isobutane (65/35), with an addition of about 1% of 2-propanol.

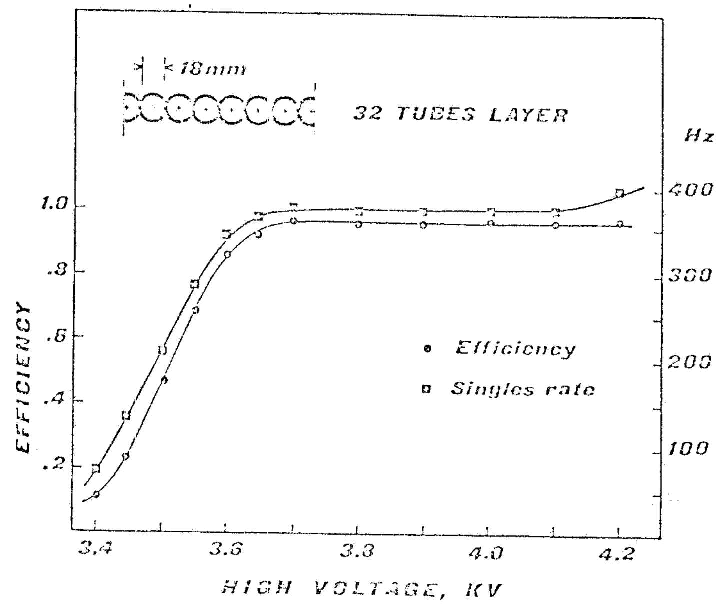

FIG. 6 - Singles rate (cosmic rays) and efficiency vs. H.V. for a tube layer of the Adone experiment: 32 tubes, 18 mm diameter, 100 μm wires, gas mixture: argon-isobutane (65/35) with an addition of 1% 2-Propanol.

2. 2. - Small tube operation.

Up to now the discussion concerned only circular tubes with 18 mm diameter. Square tubes with 18 mm sides show a similar behaviour. Important changes in the plateau width appear if the dimensions of the tube cross section are changed. There is a remarkable difference between the singles rate plateau of the 18 mm tubes compared with a 30 mm tube in the same conditions(1): in order to get the same high voltage plateau width, the smaller tube requires more isobutane. This trend still maintains if even smaller tubes are operated. In fig. 7 the singles rate curves are shown for an alluminium square tube of 8 mm side, with argon-isobutane concentrations of 50/50, 35/65, 25/75. The wire diameter is 100 μm. Heavy isobutane concentrations are needed in order to achieve uncritical operation conditions similar to those quoted for the larger tubes. The curves in fig. 8 are obtained with the 25/75 gas mixture and with different electronics dead time in order to show secondary limited streamer development.

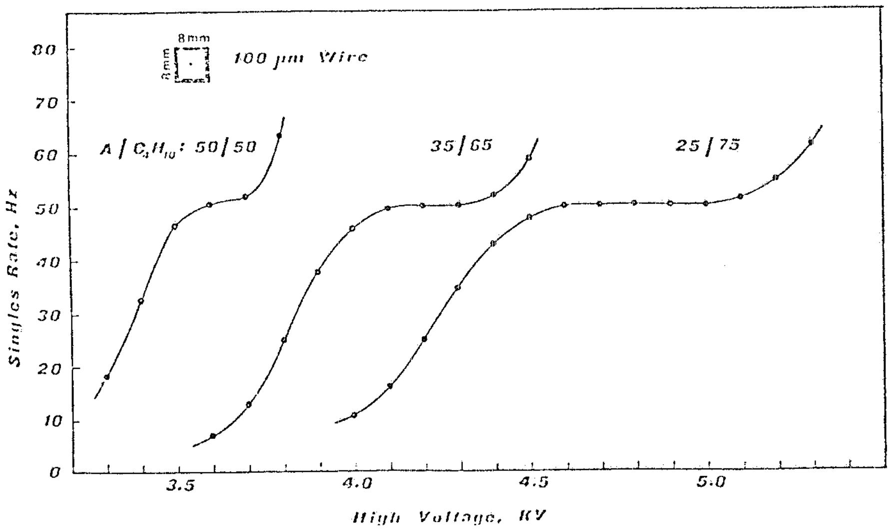

FIG. 7 - Singles rate (Sr^{90} source) vs. H.V. for an 8 x 8 mm^2. Al tube with a 100 μm sense wire for different concentrations of the argon-isobutane gas mixture. The electronics dead time was 0.5 μs, the threshold 30 mV/50 Ω.

The consequences of higher isobutane concentration are:

1) the wire pulses are very short in duration, ∿ 50 ns on a 50Ω load;

2) the high voltage supply must be rather high, ∿4. 8 KV.

The latter may be reduced if thinner wires are used, with a compromise between mechanical and electrical reliability. A 40 μm wire in the same tube exhibits a similar behaviour (Fig. 9). The wider plateaux obtained may not be intrinsic of the thinner wire, but just a consequence of minor criticity in the wire positioning.

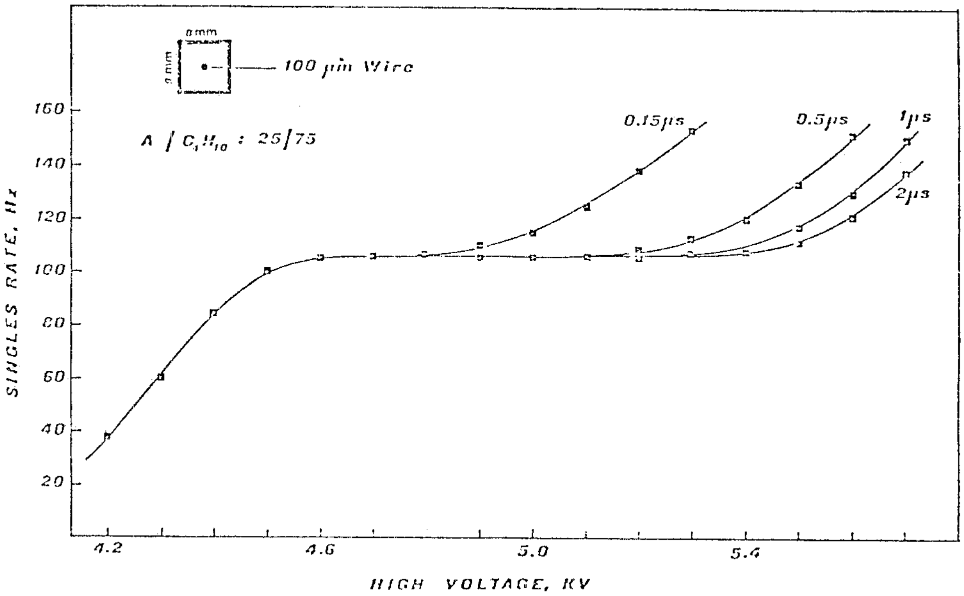

FIG. 8 - Singles rate (Sr^{90} source) vs. H.V. for an 8 x 8 mm^2 with a 100 μm sense wire and a gas mixture argon-isobutane (25/75) with different electronics dead time to show afterpulse generation. The threshold was 30 mV/50 Ω.

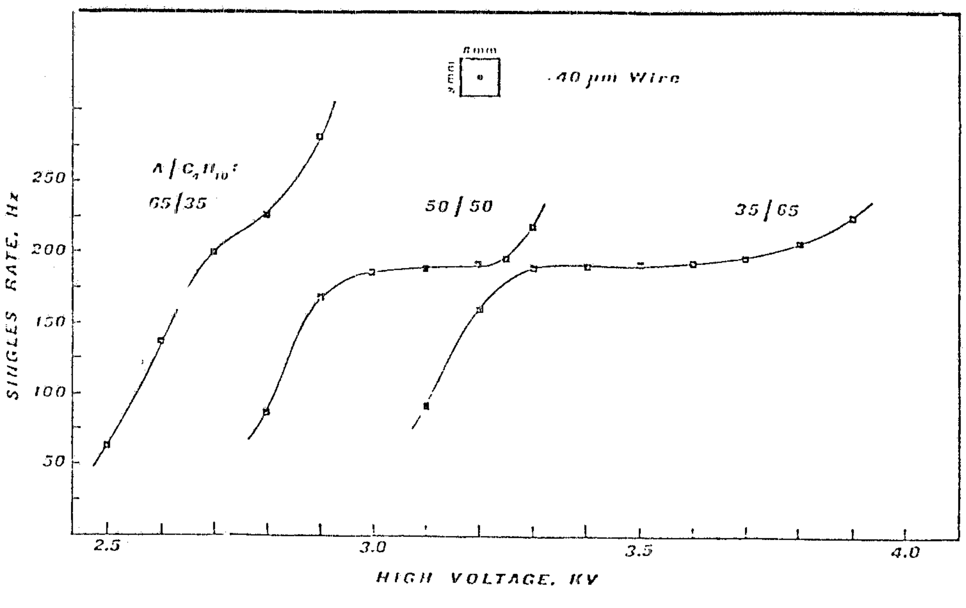

FIG. 9 - Singles rate (Sr^{90} source) vs. H.V. for an 8 x 8 mm^2 Al tube with a 40 μm sense wire for different concentrations of the argon-isobutane gas mixture. The electronics dead time was 0.5 μs, the threshold 30 mV/50 Ω.

This is anyway a serious problem for long tubes, due to planarity requirements and mechanical instabilities. We believe that a reasonable solution is to introduce spacers along the wire. We have tried a very simple arrangement: a PVC cylinder, 5 mm long, with a diameter 0. 3 mm smaller that the square tube side, with a 0. 5 mm hole to hold the wire. We have operated a 2. 5 m long tube with 5 such cylinders equally spaced along the tube. The tube worked similarly to the shorter one, even with a few cm sag. Thinking of large systems, we believe that the cost and work to introduce spacers would be largely compensated by the lack of critical planarity requirements.

For a 32 aluminium tube layer with 1 mm separation between square cells (8×8 mm^2, 100 μm wires) we have measured the efficiency with cosmic rays (see Fig. 10). The plateau level is 96. 7 ± 0. 3%. Assuming that tracks are lost only if they never touch the gas, and taking into account the cosmic ray angular distribution as accepted by the trigger counters, we have computed a detection efficiency of 98. 7%. The geometry defining counters were 10×10 cm^2, and 20 cm apart.

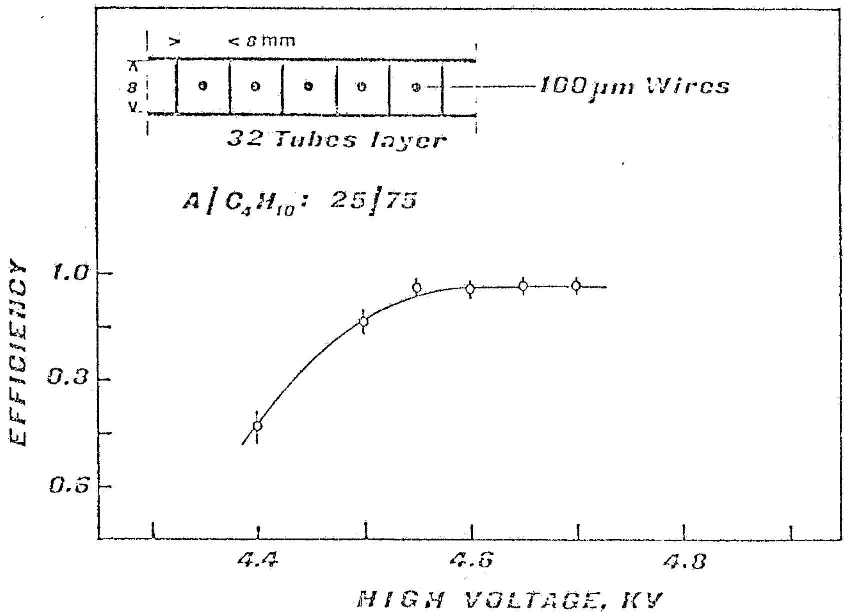

FIG. 10 - Efficiency vs. H.V. for a layer of 32 8×8 mm^2. Al tubes with 100 μm sense wires; gas mixture: argon-isobutane (25/75).

2. 3. - Dead time.

We have measured the dead time τ associated to a limited streamer discharge by the following method. The electrons of two Sr^{90} sources could be independently collimated on the same small region (∼5mm) along the wire of a tube. Let us call s_1, s_2, s_3 the rates measured in a given situation with one, the other, and both sources respectively; let us call S_1, S_2, $S_3 = S_1 + S_2$ the unknown particle rates that enter the sensitive region of the tube from each or both sources. In the hypothesis that each streamer discharge spreads well over the collimation region, the following equations can be written:

$$S_i - \tau S_i s_i = s_i \qquad i = 1,\ 2,\ 3$$

from which

$$\tau = \frac{1 - \sqrt{1 - \frac{s_3}{s_1 s_2}(s_1 + s_2 - s_3)}}{s_3} \quad .$$

The tube for this measurement was built by drilling an 18 mm hole in a brass piece $10 \times 10 \times 10$ cm^3. Three more holes were drilled as sketched in Fig. 11. Two of them were used to collimate the Sr^{90} sour-

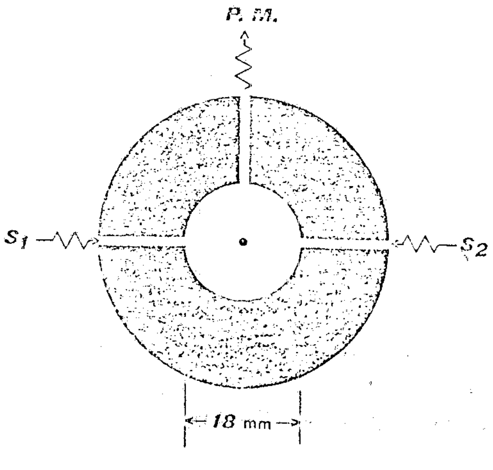

FIG. 11 - Schematic drawing of the dead time measurement set up. S_1 and S_2 are the two Sr^{90} β sources, P. M. a photomultiplier tube.

ces, while the third one was used to detect by a photomultiplier the light emitted by the streamer discharge, in order to check the collimation of the source. Results are shown in Fig. 12 a and b, for two different argon-isobutane mixtures. The wire diameter was 100 μm. The rates s_1 and s_2 were varied between 0.1 and 1 KHz. The quoted errors include systematic uncertainties. A 40 μm wire did not show appreciable differences.

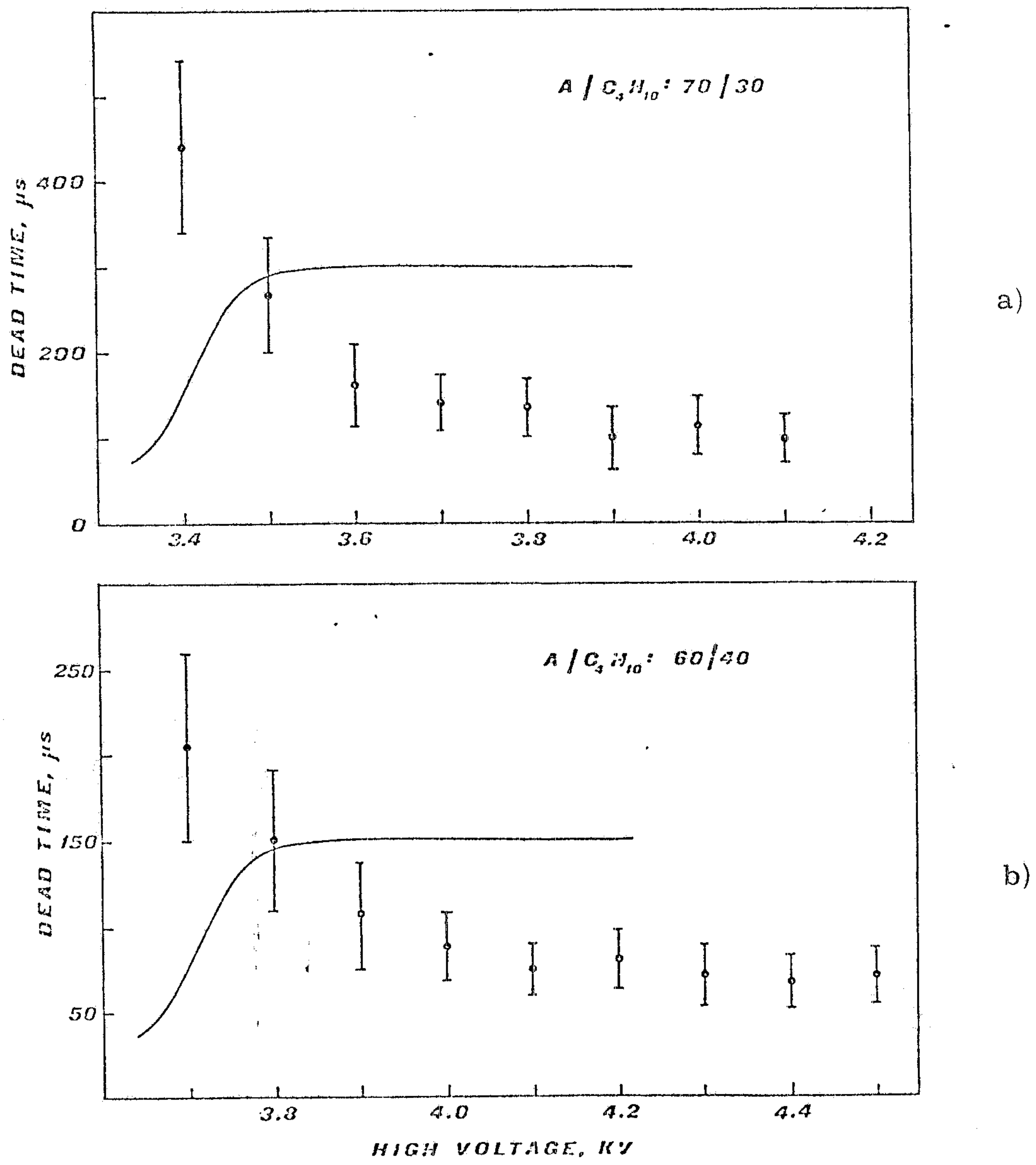

FIG. 12 - Dead time vs. H.V. : 18 mm diameter tube, 100 μm wire (the continuous line shows a typical singles rate plateau) : a) argon-isobutane 70/30 ; b) argon-isobutane 60/40.

3. - METALS, RESISTIVE VARNISHES AND RESISTIVE PLASTICS AS CATHODE MATERIALS.

We have looked for possible differences in tube operation features when different materials are used as cathodes. In order to maintain the test conditions as constant as possible we have used a square tube equivalent device consisting of four plates (10 cm long, 18 mm wide) of a given cathode material, arranged as shown in fig. 13. The plates were inside a PVC box and could be easily replaced without changing the 100 μm sense wire.

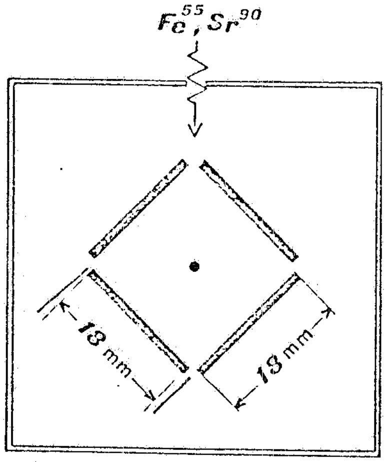

FIG. 13 - Schematic drawing of the square tube equivalent device used to test different cathode materials. The wire was 100 μm in diameter.

For each cathode material we have measured the singles rate as a function of the high voltage. Pulses were generated by a Fe^{55} source, with a rate of ~ 50 Hz. The gas mixture was argon and isobutane (60/40). The electronics dead time was 0.15 μs, in order to count all afterpulses. We have tested nine cathode materials. Four metals: aluminium, copper, stainless steel and brass, with the surface both smooth and sandblasted. Three cathodes were resistive varnishes: colloidal graphite in water$^{(4)}$, graphite in epoxy$^{(5)}$, and the mixture of carbon black and polyacetovinylic glue that we have used for the tubes of the Adone experiment$^{(6)}$. Two cathodes were of resistive plastics: polyethylene doped with carbon black (30 Ωcm resistivity)$^{(7)}$ and Velostat (2 KΩ cm resistivity)$^{(8)}$. The singles rate curve shown in Fig. 14 was obtained with the aluminium cathode. No important differences were observed among all the samples under test. A peculiar feature of aluminium is a high sensitivity to the ultraviolet component of daylight and incandescence lamps. In normal daylight conditions, the light leaking through the gas tubes gave an extra counting rate of a few Hertz.

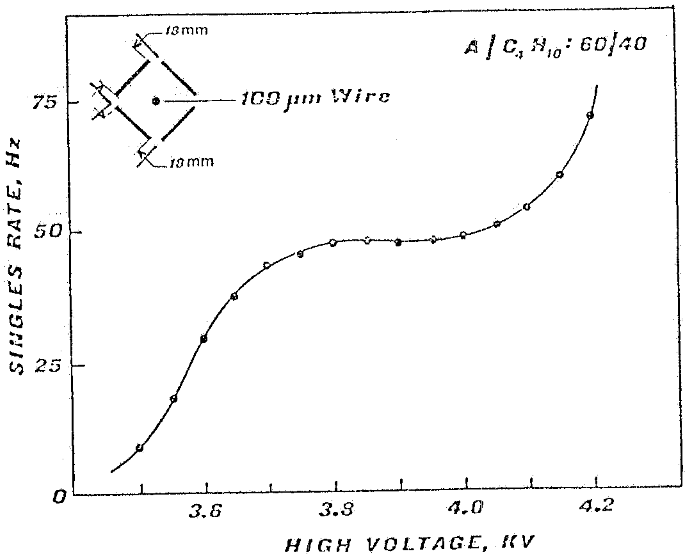

FIG. 14 - Singles rate vs. H.V. for the square tube of Fig. 13 with Al plates as cathode: argon-isobutane (60/40), electronics dead time 150 ns, threshold 30 mV/50 Ω.

If either high local rates are produced on the wire by a radioactive source or if the high voltage is increased enough, without using any particle irradiation, the metal cathodes and some resistive cathodes (our varnish, the graphite-water suspension and the conductive polyethylene) behave similarly without undesired effects. On the other hand the Velostat and the graphite-epoxy cathodes, under the same conditions will go into a steady selfsustaining discharge, which maintains even if either the radioactive source is removed, or the voltage is decreased back to the starting point. This effect is not accidental, since we have observed it in different geometrical conditions, with several other resistive varnishes obtained by mixing carbon black in commercial glues or varnishes. The selfsustaining discharge can show up either as a high rate localized pulse generation of the limited streamer type, or as a very intense dark current. The higher the rate the lower the voltage at which the process will start. Furthermore in the intermediate region between stable and unstable operation, the selfsustaining discharge starts after a rather well defined lapse of time, which can be in the range of tens of seconds. This fact suggests that the quantity responsible for triggering the selfsustaining discharge is the charge developed in the process.

In order to give a more quantitative description, in Fig. 15 we report the singles rate curves obtained with different local rates, for a square tube (8 x 8 mm^2) with a Velostat cathode. Pulses were generated by a Sr^{90} source spreading over ∿ 1 cm of wire. The curves break up at the high voltage value where the selfsustaining discharge takes up within 10 s. A stable operation region exists but it is very narrow: a 200 V high voltage plateau for a local rate not exceeding a few particles/s cm. In order to test quantitatively the hypothesis that the rele

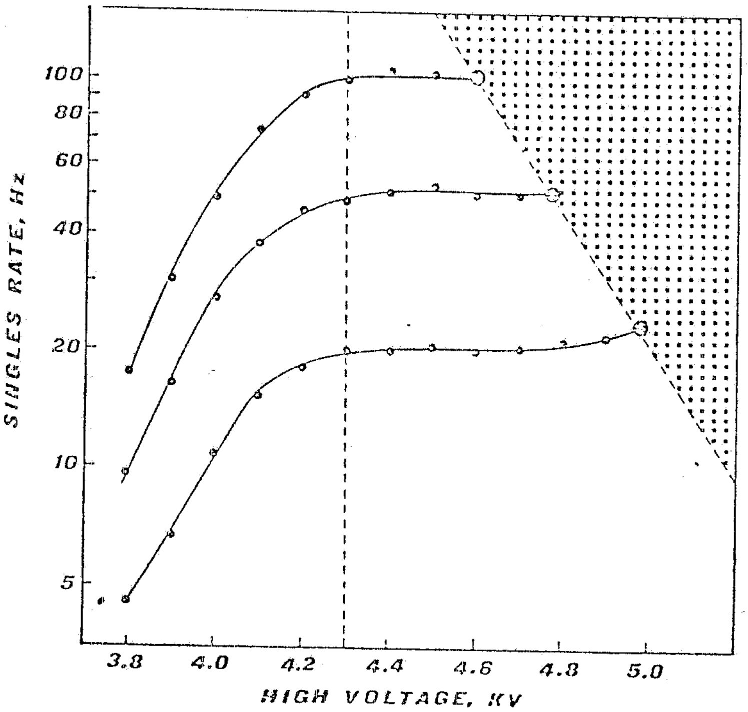

FIG. 15 - Singles rates vs. H.V. for an 8 x 8 mm^2 "Velostat" tube (100 μm wire), showing the points were a self sustaining discharge starts within 10 s for different rates (argon-isobutane : 25/75).

vant parameter is the total charge generated in a given lapse of time, we have measured at a given voltage the average time needed to start the regenerative process for different rates. The results are shown in Fig. 16. The points are fitted reasonably well by a constant charge curve.

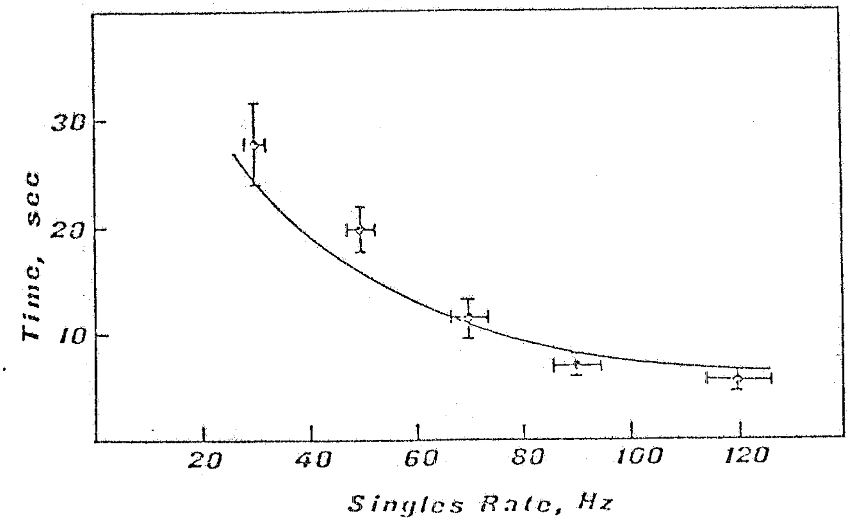

FIG. 16 - Time required to start the selfsustaining discharge in an 8 x 8 mm^2 "Velostat" tube (100 μm wire) as a function of the singles counting rate : (argon-isobutane : 25/75 ; H.V. = = 4.7 KV). The continuous line shows a constant charge hyperbola.

A possible explanation for this effect is the following. The resistive cathode materials we are using, all except the graphite-water varnish, consist of carbon black or graphite particles dispersed in an insulating medium. The charge of the ions produced in the discharge process must then always flow through a thin layer of material with resistivity mostly around 10^{15} Ωcm. If the ion charge flux is too high, there will be a heavy accumulation of ions against the cathode surface, which will increase the electric field inside the insulating layer. As a consequence the current flowing through it will increase too, approaching a steady state where it balances the ion current. But if the equilibrium electric field inside the insulating layer exceeds its breakdown field, discharges will take place, so that electrons may be liberated in the gas together with ultraviolet photons, which will start a regenerative process. In this scheme the maximum sustainable rate for a given cathode material would be proportional to the ratio between dielectric rigidity and resistivity of the insulating dispersing medium.

The long time lapses which can be observed before the process is started, would then have a simple origin. The ion layer, the insulating layer and the carbon black are equivalent to a capacitor, with in parallel the leakage resistance of the dielectric. The product RC of their magnitudes is the time constant of the electric field rise in the insulating layer. The R and C magnitudes are given by

$$R = \varrho \frac{d}{S} , \qquad C = \varepsilon \frac{S}{d}$$

where ϱ is the volume resistivity of the insulating medium, ε its dielectric constant, d its thickness assumed to be uniform, S the cathode surface covered by the ions. The time constant then is

$$RC = \varrho \varepsilon ,$$

which is a function only of the material physical constants. Typical values for $\varrho \varepsilon$ are hundreds of seconds, consistently with the time lapses we observe. From these considerations it turns out that the constant charge fit of Fig. 15 is not fully correct, since the charge flowing through the insulating layer has not been taken into account. This effect causes the time divergence at a rate larger than zero, consistently with the effective trend of the experimental points.

The fact that the resistive polyacetovinylic varnish we use never exhibited the selfsustaining discharge process at any rate or high voltage conditions, and with resistivity between $10^2 \div 10^7$ Ωcm, is consistent with the explanation discussed above, since the dispersing medium has a relatively low volume resistivity ($< 10^{10}$ Ωcm). Furthermore although the polyethylene is a good insulator, the fine behaviour of the resistive polyethylene may also not be inconsistent with it, since the sample we have tested has a very low resistivity ($\sim 30\ \Omega$cm) due to a heavy carbon black concentration (25%). We plan to test polyethylene with higher resistivity values.

Anyway within the scheme where the ratio between dielectric rigidity and volume resistivity is the discriminating factor to obtain a "good" resistive plastic cathode, there is another simple possibility. Such ratio for the most common plastics varies within two orders of magnitude, and the variation is substantially due to the resistivity value. A favourable exception is nylon which gains about four orders of magnitude with respect to the average: it has a dielectric rigidity of 15 KV/mm which is comparable to that of the best insulators, but it has a volume resistivity of only $10^{11}\ \Omega$cm.

We have tested a commercial black nylon tube with 6 mm inner diameter and a 40 μm sense wire. The black colour is due to $\sim 1\%$ carbon black doping, which does not change appreciably the resistivity of the material. The tube was painted outside by a low resistivity varnish in order to minimize the resistance through which the tube current must flow. We could observe the pulses generated by a radioactive β source, without undesired effects. This test is promising but not conclusive: high rates could not be significantly produced due to the strong feedback on the high voltage set by the large series resistance ($\sim 10^9\ \Omega$) cm. We plan to obtain low resistivity nylon samples in order to check the possibility to use it as cathode in wire amplification devices.

Acknowledgements.

We wish to thank U. Denni for his invaluable assistance in the measurements, G. Mazzenga and A. Rutili who built our test modules. We are grateful to V. Valente and B. Borgia for many stimulating discussions.

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(6) - ACQUADAG, by ACHESON ITALIANA S. r. l., Milan, Italy.

(7) - DAG 213, by ACHESON COLLOIDEN, B. V., Scheemda, Holland.

(8) - "MURISAN" stainer by Attiva, Genova, Italy, and VINAVIL NPC, by MONTEDISON, Italy.

(9) - Polyethylene DHD 7704 BLK, by the courtesy of UNION CARBIDE ITALIA S. p. A..

(10) - VELOSTAT, by the courtesy of 3M ITALIA S. p. A..