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# HIGH RATE RESISTIVE PLATE CHAMBERS

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## Abstract

In this paper we consider some factors that could improve the high rate performance of the RPC; we consider the role of freon in the operation of RPCs and present results with an asymmetric RPC with one glass and one melamine resistive plate.

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section A

## 1. INTRODUCTION

The Resistive Plate Chamber is a simple gaseous detector; it has been the object of extensive studies during the last years. Essentially it is a gas volume enclosed by two resistive plates. High voltage is applied to electrodes on the outer surfaces of these resistive plates, producing a high electric field across the gas gap. Electrons liberated in the gas by through-going ionising particles avalanche in the high electric field, thus producing signals on the external electrodes. If the electric field is even stronger, the avalanche can initiate a spark breakdown. Due to its ease of construction and operation, the low cost and the good time resolution, it has been proposed as a suitable detector for the muon trigger for the LHC experiments[1-2], where thousands of square metres will be needed. The estimated flux due to background radiation is up to thousands of Hz/cm$^2$; therefore the device considered must be able to operate efficiently at such high rates. In our effort to develop RPCs operating with maximum efficiency at high rates, we have undertaken systematic R & D in order to find the most suitable plate material, gas mixture, width of the gas gap and mode of operation. As described in our publications we have opted for the "avalanche" mode of operation (low gas gain); also we have chosen a wide gas gap, since this suppresses sparks [6]. The RPCs with which we performed the majority of the studies described here have an 8 mm gas gap and resistive plates of melamine-phenolic laminate 0.8 mm thick. More details regarding the construction and operation of our RPCs can be found in our previous publications [3-6].

In this paper we discuss some factors that affect the high rate operation of the RPC. We first discuss, in section 2, the signal formation on pick up strips. In section 3 we discuss the gas gain with freon as part of the gas mixture. In section 4 we discuss the high rate operation of the RPC and show that the flow of charge through a glass plate is different from melamine laminate.

## 2. SIGNAL FORMATION ON PICK UP STRIPS

The current in the pick up electrode is produced by the movement of charge. The magnitude and sign of this current can be calculated from the normalised ‘weighting field’, the concept of which has been described by Radeka [7]. The normalised weighting field is calculated by applying 1 V to the electrode of interest and fixing all others at 0 V. Its form may have little relationship to the electric field needed to operate the device. Current is produced in the external electrodes by the movement of charge; the magnitude and sign can be calculated from : $i = q.\mathbf{E}_W\mathbf{v}$, where $\mathbf{E}_W$ is the normalised weighting field and $\mathbf{v}$ is the velocity of the charge q. Thus the expected shape of the current pulse is shown in figure 1 for an avalanche starting with one electron at the cathode, producing 4.4 $10^7$ electrons. This is the fast signal; by integration we find a charge of 460 fC on the pick up strip (1/15 of the total 7 pC charge of the electrons in the avalanche). Our detection threshold of ~100 fC is similar to the threshold mentioned by other researchers in the field of RPCs [8]. The average charge on the strip is 1 pC, thus on average we have avalanches producing 15 pC of electron charge ($10^8$ electrons).

## 3. GAS GAIN WITH FREON GAS MIXTURES

In the first studies of RPCs operated in spark mode, it was found necessary to add freon to the gas mixture. Otherwise the efficiency decreased with increasing voltage and it was difficult to obtain high efficiencies, even at very low rates.

During the avalanche process an electron can either multiply through an ionising collision or be captured by a freon molecule to form a negative ion. The cross section for electron capture by a freon molecule is strongly peaked towards low energies. At low electric fields, where the kinetic energy gained by the electron between collisions is low, the attachment coefficient $\eta$ is high and the Townsend coefficient $\alpha$ low [9]. The number of electrons produced in an avalanche is $N = N_0 e^{\alpha x}$, where $N_0$ is the initial number of electrons, x is the distance and $\alpha$ is the Townsend coefficient. For freon we replace $\alpha$ in the above with the effective $\alpha$, $\bar{\alpha} = \alpha - \eta$, and this increases linearly with E [9] (rather than the exponential rise observed in gas mixtures not containing freon [10]). So, for a gas mixture containing freon, we would expect a) faster drop in efficiency on reducing the voltage, b) longer efficiency plateau (since there is a slower rise in gas gain). In figure 2 we show the efficiency curves for 10% isobutane with 90% Argon with and without the addition of 0.5% of $C_4F_{10}$. The change is remarkable and as expected.

Since wide gap RPCs have a smaller dynamic range in avalanche size [6], they are less likely to produce sparks; we have therefore chosen to work with wide gas gaps. However, it may be possible for chambers with narrow gaps (~2 mm) to be operated in a 'pure avalanche' mode. Duerdoth et al.[11] have measured the transition between 'proportional' and 'streamer' mode (their nomenclature) with freon mixtures varying between 4 and 40%. They worked with a gas gap of 1.6 mm. They find that there is a threshold of avalanche size above which a streamer is initiated. This threshold slightly increases with higher freon concentrations. With increasing freon concentration they measured a) a smaller rise in the magnitude of the streamer signal with increasing voltage, b) a smaller step between the proportional and the streamer signal. In figure 3 we plot the ratio of charge of the proportional / streamer signal as a function of the freon percentage, at the knee of the plateau (lower curve) and at 1000 V above the knee of the plateau (upper curve). A linear extrapolation predicts that if one works with a very high fraction of freon (~80%), the streamer signal becomes equal in magnitude to the proportional signal.

However one should not overlook that the above measurement is of the ‘fast’ signal. There is an increasing amount of charge carried by positive and negative ions; although this charge does not generate a fast signal, it does exist and has to be neutralised by current flow through the resistive plates. Thus at high rates there will be a much larger voltage drop across the resistive plate. However this can be compensated by increasing the high voltage applied to the chamber (this will increase the noise/dark current - at present we are aware of no published results on such measurements).

The avalanche process is terminated by the arrival of the electrons at the anode. The fast signal is generated by the movement of the electrons. However with freon a large fraction of the electrons are captured and become immobile. In figure 4 we show the charge on the cathode observed from a 4 mm gap RPC using 3 different gas mixtures. In the upper plot, the gas contained no freon; a clear step is observed due to the arrival of the electrons. The slow ramp is due to the drift of the positive ion cloud towards the cathode. This ramp flattens out when the positive ions arrive at the cathode. The middle plot is with a gas containing $CF_4$, which is not so electronegative as other freons. The fast step due to the electrons is smaller in comparison with the ramp caused by the positive ions. The lower plot is for a gas containing 10% freon ($CCl_2F_2$). The fast step can no longer be observed. Thus one sees that the ratio of ‘fast signal’ compared to slow deposition of charge is many orders different if freon is part of the gas mixture.

We have tested a chamber with freon $C_4F_{10}$. It is a heavy gas and thus the number of primary ionisation clusters/mm should be high (~15 clusters/mm). This would have allowed us to consider constructing RPCs with smaller gas gaps; however we found that it had poor dielectric strength. If we used a percentage higher than 3%, the chamber would draw continuous current at a voltage below normal avalanche operating mode. However, like other freons, it is very electronegative. We have discussed above that the total amount of generated charge in the avalanche process is much higher if freon is used. At high particle flux the efficiency is reduced by the voltage drop across the resistive plate. Thus, we would expect with increasing rate, a faster fall in efficiency for gases containing freon than those gases not containing freon. We show in figure 5 the efficiency versus voltage for various rates. The curves refer to 10% isobutane, 89.5% Argon and 0.5% $C_4F_{10}$. We also show the dark current drawn by the chamber. In figure 6 we plot the efficiency versus rate. The lower curve is keeping the voltage constant (at 12.2 kV), while the upper curve is with an increasing voltage for the higher rate points. We also plot the data for 40% DME 60% Argon for a fixed high voltage. This falls on the upper curve. Thus the rate capability of a chamber operated with freon can be boosted by increasing the high voltage to mimic a chamber operated without freon. The price one has to pay is an increased dark current (thus increased noise).

## 4. HIGH RATE BEHAVIOUR AND THE ASYMMETRIC RPC

At the CERN PS the spill is 400 ms in length (however the majority of the particles arrive during 250 ms). Depending on the structure of the 'super-cycle' we can have either one or two spills every 15 to 20 s. The results quoted from test beams are biased by the finite length of the spill. In our first studies of RPCs operated in spark mode we found a large drop in efficiency during the spill [4]. In our later studies with avalanche mode operation we found that the majority of the change occurred during the first 50 ms of the spill. Recently we have made a measurement with an asymmetric RPC and studied the change of efficiency during the spill.

Our asymmetric RPC has the two resistive plates made from different materials: one plate is Schott A4 glass*, 1.8 mm thick and the other plate is melamine-phenolic laminate, 0.8 mm thick; the gas gap is 8 mm. The cross section is shown in figure 7. The resistivities are $10^{11}$ Ω cm for the melamine laminate (with 1% water vapour) and $10^{12}$ Ω cm for the glass (independent of water vapour). Assuming a relative dielectric constant $\varepsilon=2$ for the melamine laminate and $\varepsilon=4$ for the glass, the capacitance per square centimetre is 2 pF/cm$^2$.

When high voltage is applied on the RPC, initially the resistive plates are in an electric field. The resistive plate is a dielectric, the electric field causes electric dipoles within the material to be aligned such that the voltage at the surface is reduced. Since there is an electric field inside the resistive sheet, any free charge carriers inside the plate will migrate so that this field is neutralised. Thus, eventually, the anode surface will have an excess of holes, while the cathode surface an excess of electrons; the field inside the plate will be very weak, tending towards zero.

In figure 8 we show the efficiency plateau for the asymmetric RPC; we see that a different voltage is required depending on whether the glass plate is the anode or the cathode electrode. An extra 1000 V is needed if glass is used as the anode electrode. A symmetric RPC constructed with both plates of melamine laminate operated at a similar voltage to that of the asymmetric chamber with glass cathode electrode.

Fixing the voltage and varying the rate gives similar results for both the glass anode and cathode to previously measured chambers [6]. A notable exception is that it is easier to reach 100% efficiency at low rates when the glass is the cathode; also the plateau is longer. We have measured the variation of efficiency during the spill for the case of the glass

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* Schott produces dark glasses for various purposes, such as the fabrication of welding goggles. The darkness is obtained by adding iron oxide to the glass, which also decreases the resistivity. This glass is available with values of A1 through to A14; higher A values correspond to darker, lower resistivity glass.

cathode (the case of the glass anode was not measured mainly for technical reasons related to the strip readout). We show the results in figure 9a for three rates. The rates we have quoted in previous papers are obtained by integrating the number of particles triggering the scintillators over a full spill and assuming a spill is 1/3 s. The particle flux during the spill is shown in figure 9b. It is clear that the spill is shorter than we previously estimated.

For the 2 kHz/cm$^2$ data there is a drop in efficiency to ~80% and then it stabilises. From figure 8 we see that the voltage has to be reduced by 600 V to give this efficiency. Since the resistance per cm$^2$ is 20 times higher for the glass as compared to the melamine laminate, we assume the cathode is responsible for this voltage drop; thus with a resistance of 2 $10^{11}$ Ω/cm$^2$, 3 nA/cm$^2$ produces the 600 V drop. This is equivalent to an average charge of 1.5 pC/avalanche at a rate of 2 kHz/cm$^2$. We now consider an element of the plate as a capacitor (2 pF/cm$^2$) and find that 1200 pC/cm$^2$ gives a 600 V drop. This happens in 100 ms, i.e. 200 avalanches. Thus one has on average 6 pC/avalanche. Thus the average charge per avalanche drops from ~10 pC to ~2 pC when the voltage is reduced by 600 V across the gas gap. This reduction is consistent with our expectations from the first Townsend coefficient.

## 5. SUMMARY AND CONCLUSIONS

The resistance per unit area (rather the resistivity) is important as this dictates the voltage drop across the resistive plate for a given current flow. Thus for a given plate material, thinner sheets should give a higher rate cut-off. The capacitance per unit area is also important; a deposit of charge on the surface of the plate will cause a smaller disturbance to the electric field if the capacitance is high; thus again thinnest possible plate materials should be employed.

A wide gas gap allows operation of the RPC with low spark probability utilising gas mixtures with low (or zero) freon contents. Narrow gap RPCs need a high fraction of freon to suppress sparks. We have seen that there is an increase of ionic current when freon is part of the mixture; however this needs to be measured for gases with high freon content as the avalanche process could be different.

The rate limit of the asymmetric chamber presented here is ~ 100 Hz/cm$^2$ (efficiency > 95%). As discussed above, this is dominated by the resistance of the glass plate. Glass with one order lower resistivity is available commercially in large sizes. We also believe that we can increase the sensitivity of our preamplifiers by a factor 5. This should increase the rate limit to 5 kHz/cm$^2$. Higher rates can be obtained by using specially prepared materials. It should be noted that the rate limit we quote is the most pessimistic (i.e. for flood illumination with the voltage set for low rate, low noise operation).

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# FIGURE CAPTIONS

1. Expected shape of current pulse on pick up strip for a gas avalanche producing 4.4 $10^7$ electrons.
2. Efficiency versus voltage for Argon-isobutane, with and without the addition of 0.5% $C_4F_{10}$.
3. Ratio of charge of proportional /streamer signals versus freon percentage in gas mixture (data from ref. [11]).
4. The signal from an RPC (4 mm gas gap) observed with a charge amplifier attached to the cathode. The upper plot is for a gas not containing freon, the middle plot is for a gas containing $CF_4$; the lower plot is for a gas containing freon ($CCl_2F_2$).
5. Efficiency versus voltage for various particle fluxes. The gas mixture is 89.5% Argon, 10% isobutane and 0.5% $C_4F_{10}$.
6. Efficiency versus particle flux. The upper curve is for 40% DME 60% Argon and keeping the voltage fixed and also for 89.5% Argon 10% isobutane and 0.5% $C_4F_{10}$ but with an increased voltage for higher rates. The lower curve corresponds to 89.5% Argon 10% isobutane and 0.5% $C_4F_{10}$ with a fixed voltage.
7. Cross section of the asymmetric RPC.
8. Efficiency versus voltage for asymmetric glass/melamine RPC at (upper) 1 Hz/cm$^2$, and (lower) 1 kHz/cm$^2$. The gas mixture was 42% Argon, 19% DME, 39% $CO_2$ .
9. (a) Efficiency during the spill for 3 particle fluxes. The gas mixture was 42% Argon, 19% DME, 39% $CO_2$. (b) Measurement of incident particle flux during spill in 4 x 4 cm$^2$ scintillator.

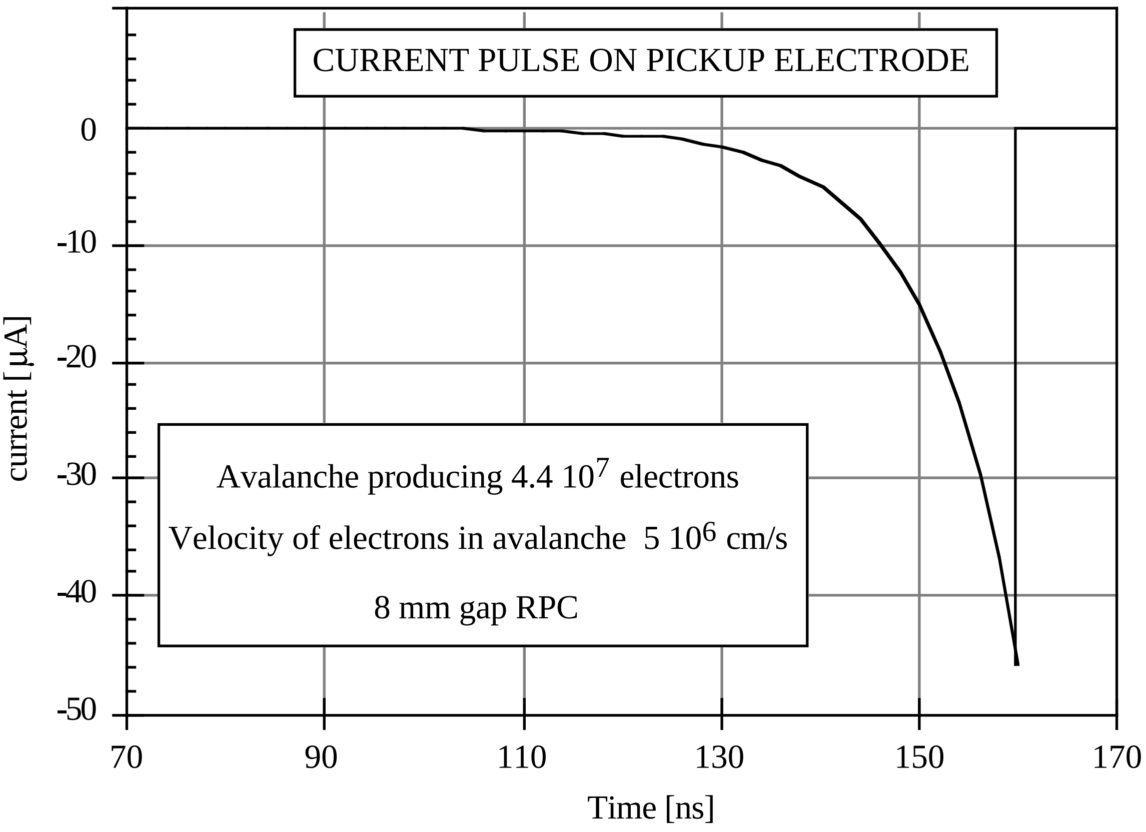
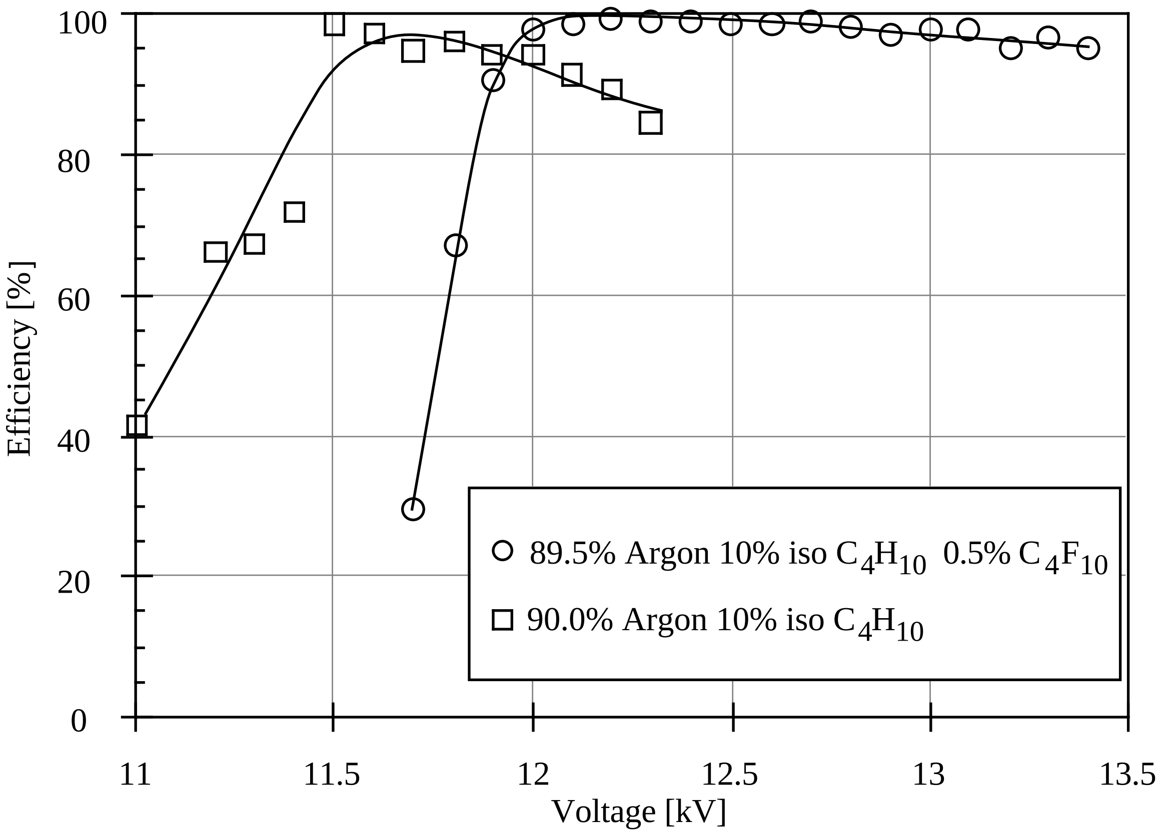

CURRENT PULSE ON PICKUP ELECTRODE
Avalanche producing 4.4 10^7 electrons
Velocity of electrons in avalanche 5 10^6 cm/s
8 mm gap RPC
current [ μA]
0
-10
-20
-30
-40
-50
70
90
110
130
150
170
Time [ns]

*Figure 1*



Efficiency [%]
0
20
40
60
80
100
11
11.5
12
12.5
13
13.5
Voltage [kV]
○ 89.5% Argon 10% iso $C_4H_{10}$ 0.5% $C_4F_{10}$
□ 90.0% Argon 10% iso $C_4H_{10}$

*Figure 2*

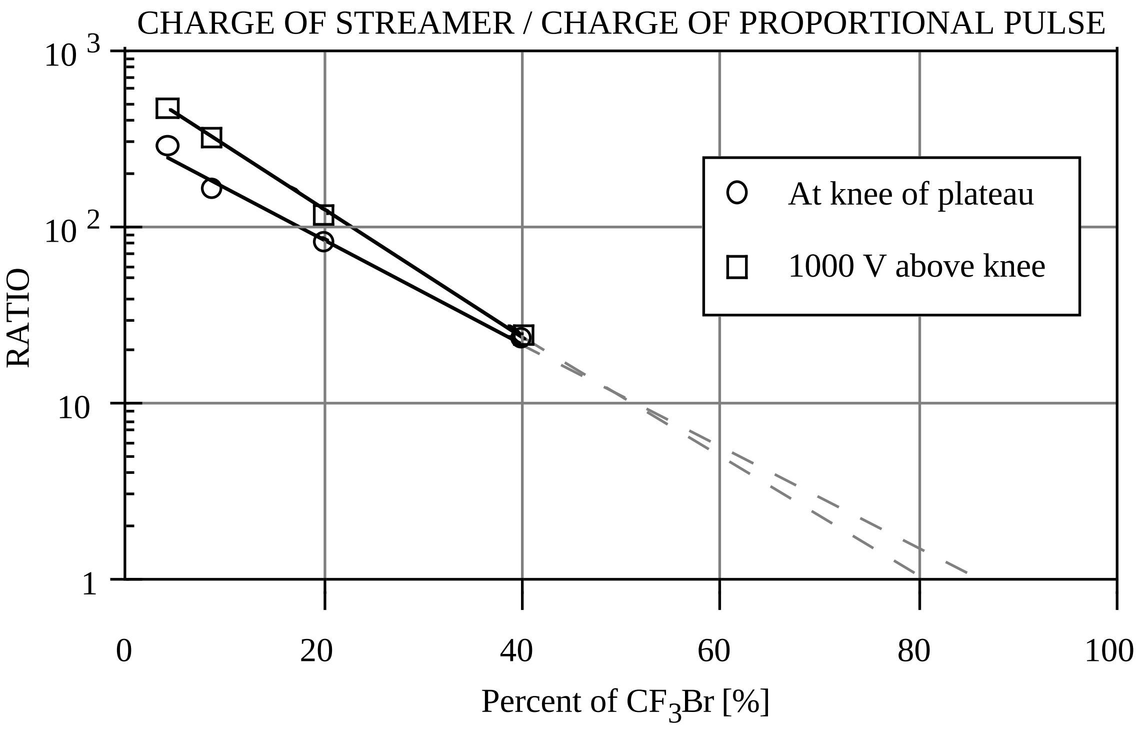

CHARGE OF STREAMER / CHARGE OF PROPORTIONAL PULSE
RATIO
10 3
10 2
10
1
0
20
40
60
80
100
Percent of CF3Br [%]
At knee of plateau
1000 V above knee

*Figure 3*

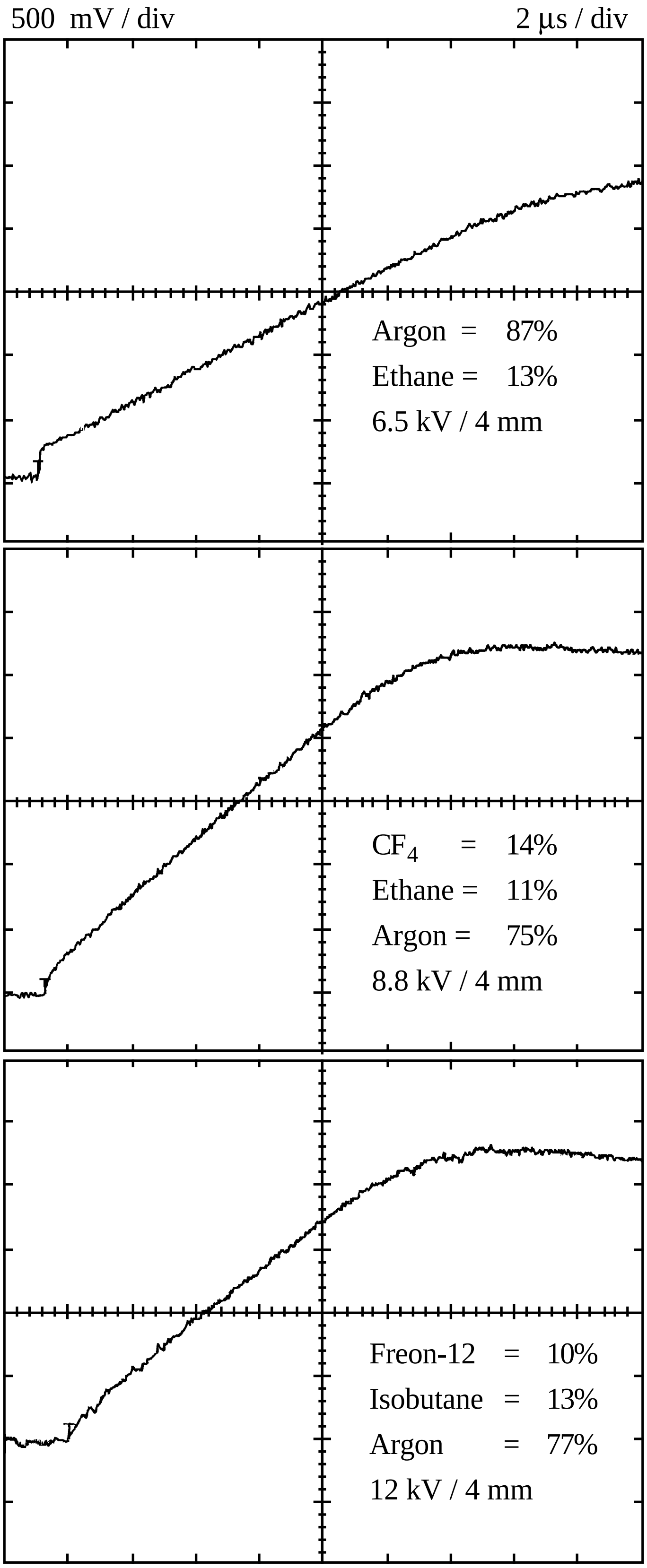

500 mV / div
2 µs / div
Argon = 87%
Ethane = 13%
6.5 kV / 4 mm
CF$_4$ = 14%
Ethane = 11%
Argon = 75%
8.8 kV / 4 mm
Freon-12 = 10%
Isobutane = 13%
Argon = 77%
12 kV / 4 mm

*Figure 4*

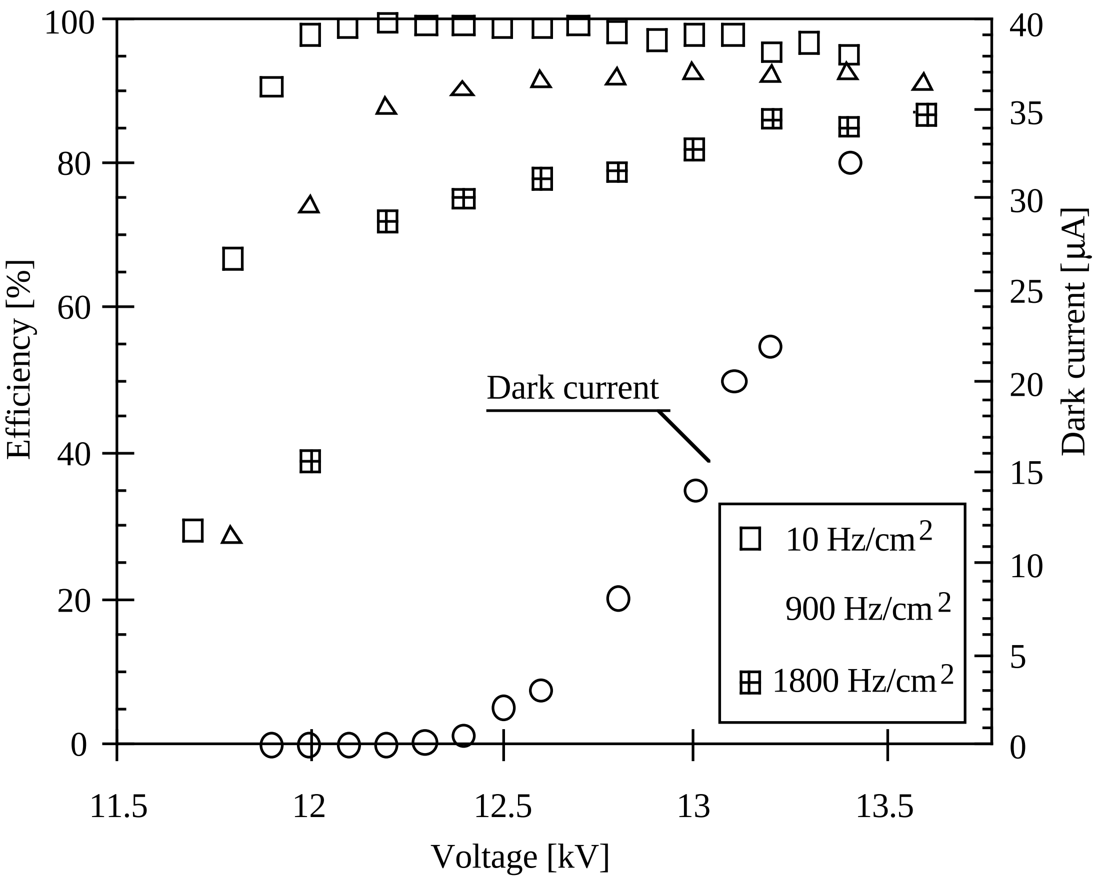

100
80
60
40
20
0
Efficiency [%]
40
35
30
25
20
15
10
5
0
Dark current [μA]
11.5
12
12.5
13
13.5
Voltage [kV]
Dark current
□ 10 Hz/cm²
△ 900 Hz/cm²
⊞ 1800 Hz/cm²

*Figure 5*

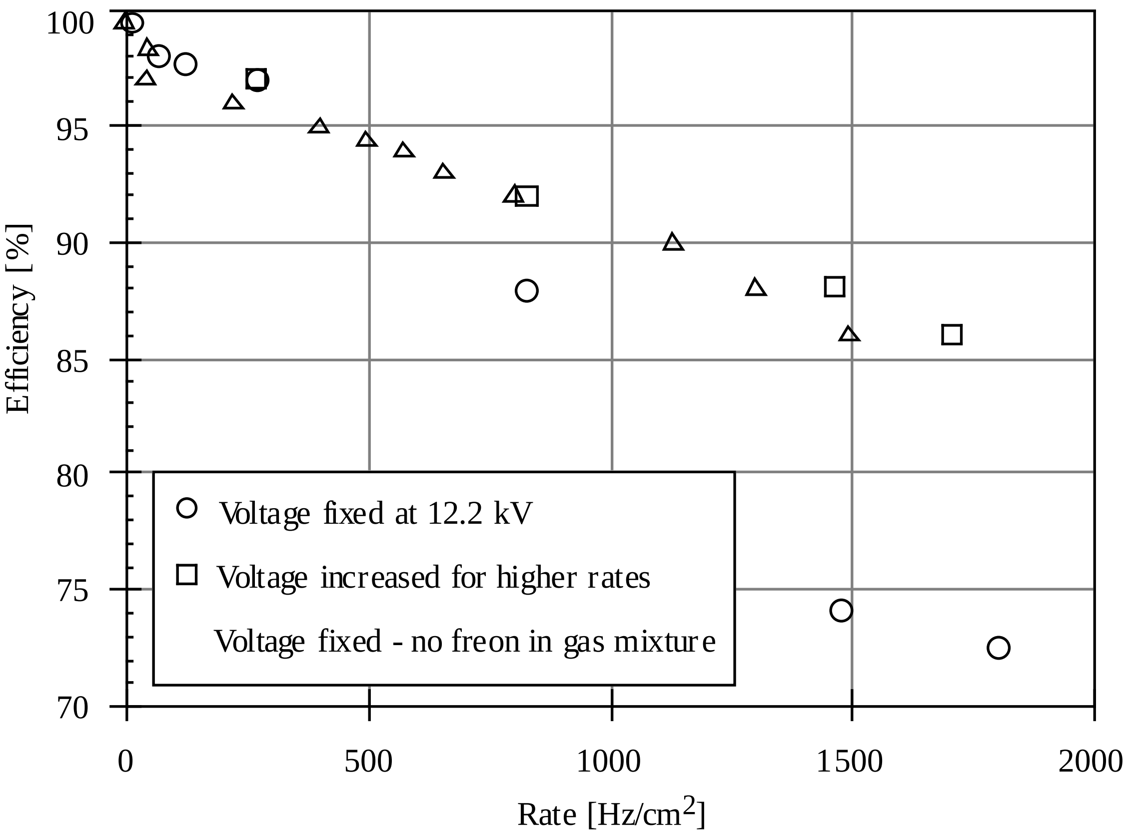

Efficiency [%]
100
95
90
85
80
75
70
0
500
1000
1500
2000
Rate [Hz/cm²]
○ Voltage fixed at 12.2 kV
□ Voltage increased for higher rates
Voltage fixed - no freon in gas mixture

*Figure 6*

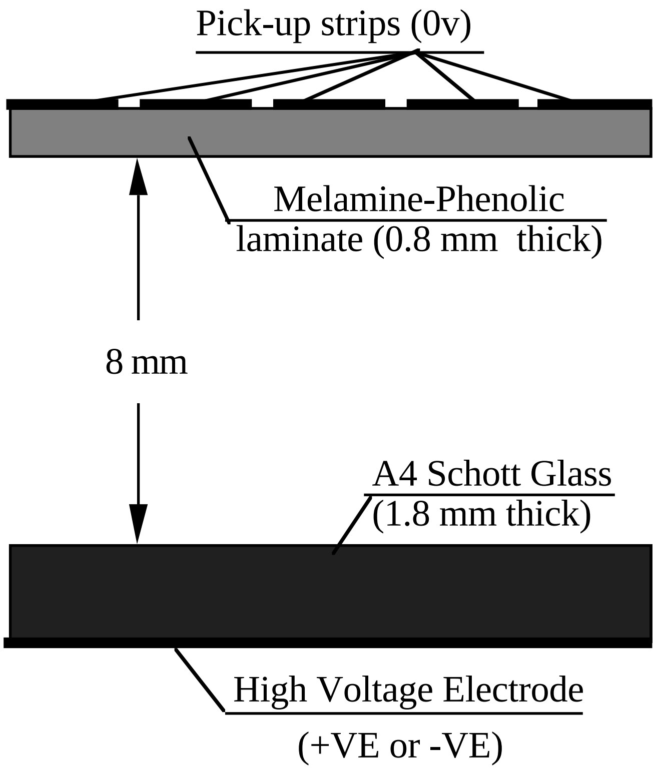

Pick-up strips (0v)
Melamine-Phenolic laminate (0.8 mm thick)
8 mm
A4 Schott Glass (1.8 mm thick)
High Voltage Electrode
(+VE or -VE)

*Figure 7*

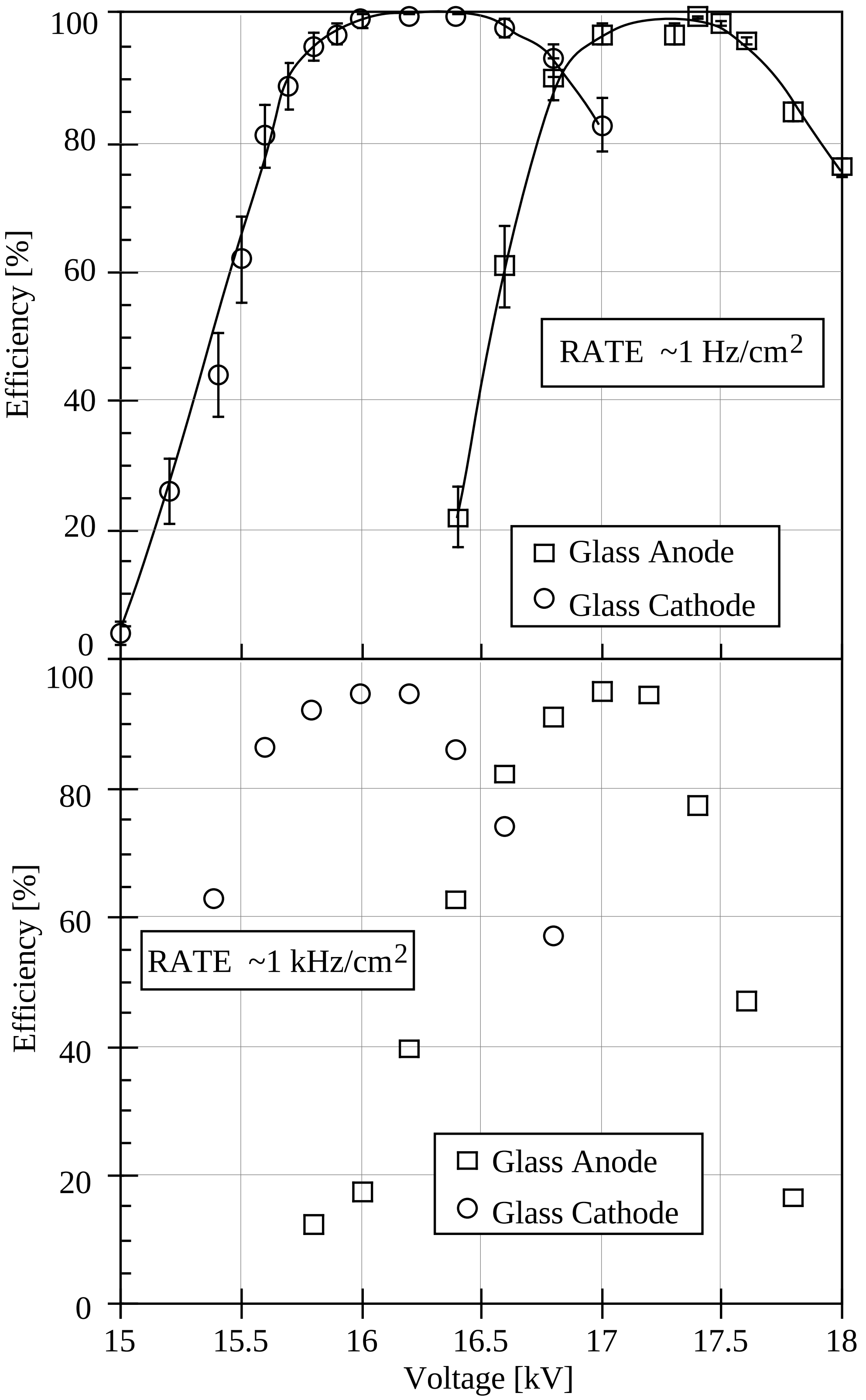

RATE ~1 Hz/cm2
Glass Anode
Glass Cathode
RATE ~1 kHz/cm2
Glass Anode
Glass Cathode
Efficiency [%]
Efficiency [%]
0
20
40
60
80
100
0
20
40
60
80
100
15
15.5
16
16.5
17
17.5
18
Voltage [kV]

*Figure 8*

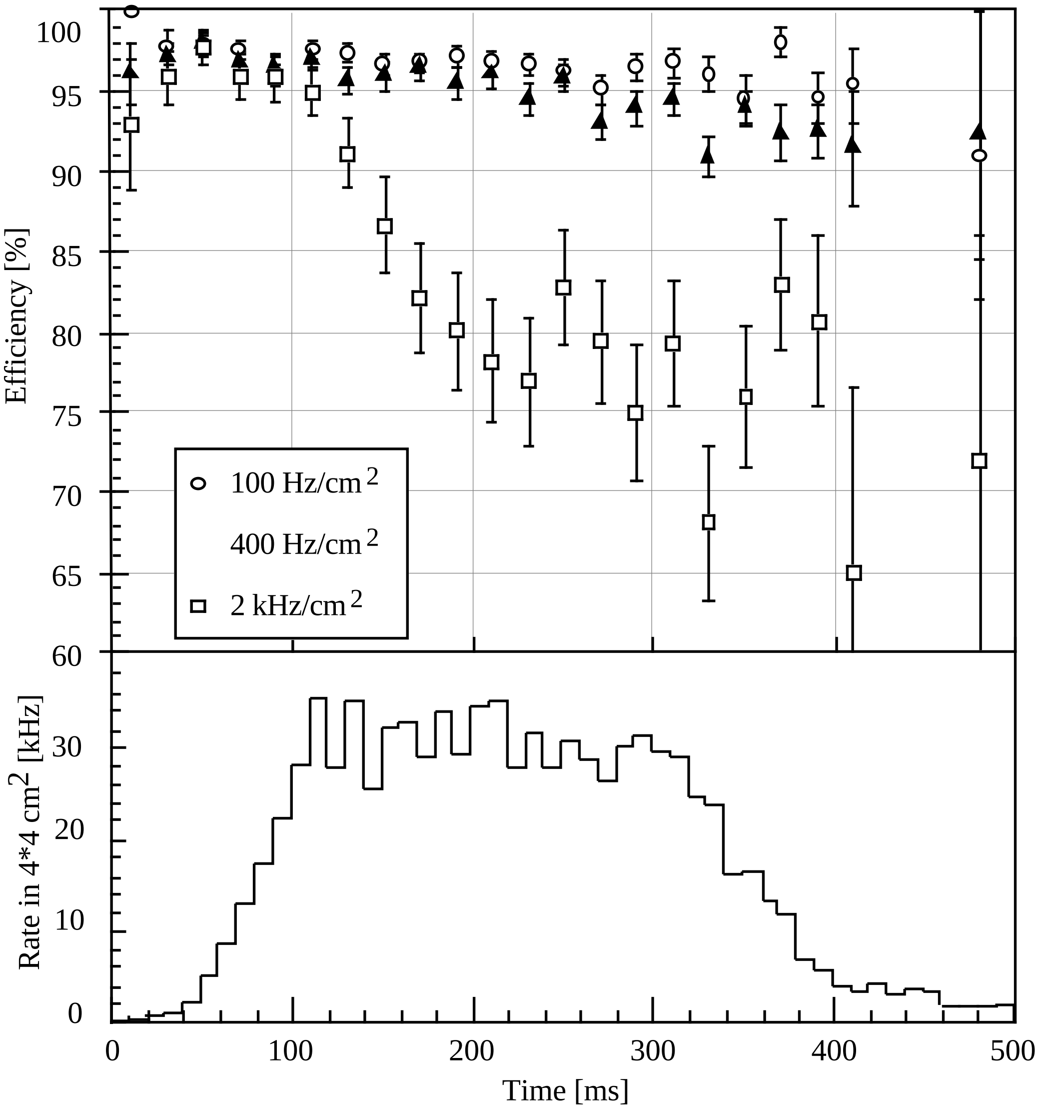

100
95
90
85
80
75
70
65
60
Efficiency [%]
100 Hz/cm$^2$
400 Hz/cm$^2$
2 kHz/cm$^2$
30
20
10
0
Rate in 4*4 cm$^2$ [kHz]
0
100
200
300
400
500
Time [ms]

*Figure 9*