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THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

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ABSTRACT

It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

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1. INTRODUCTION

Neutrino experiments have divided themselves naturally into two broad classes, i.e. high resolution bubble chambers with a relatively small sensitive mass, and electron detectors in which only few of the global features of events are observed in a much more massive target volume. There has been a growing need for a novel device which combines the large amount of specific information on the topology of events of a bubble chamber with the much larger mass, timing, and geometrical flexibility of a counter experiment. The physics justifications for such an instrument are discussed elsewhere¹⁾.

Recently (1974), Nygren²⁾ has revised an old (1969) idea of Charpak³⁾ by introducing what he has called the Time Projection Chamber (TPC). Briefly, the idea consists of drifting the whole electron image of an event occurring in a noble gas towards a collecting multielectrode array which is then capable of reconstructing the three-dimensional image (x,y,z) of the event from the (x,y) information and the drift time t. We propose to extend this very same concept to a liquefied noble gas -- more specifically, liquid argon -- leading to what we would like to call a Liquid-Argon Projection Chamber (LAPC). The basic features of such a new instrument are worked out in this paper, almost entirely on the basis of what is already known about liquid-argon counters. Tests on a small LAPC prototype are being pursued at the present time⁴⁾.

2. LIQUID ARGON AS A NEUTRINO TARGET

There are several reasons why pure liquid argon can be considered as an almost ideal target material for the LAPC:

- i) it is dense (1.4 g/cm³);
- ii) it does not attach electrons and hence it permits long drift-times;
- iii) it has a high electron mobility;
- iv) it is cheap, 140-500 dollars/ton, depending on source and quality;
- v) it is easy to obtain and to purify -- many of the organic impurities are frozen out from its liquid form;
- vi) it is inert and it can be liquefied with liquid nitrogen.

A possible drawback is that some modest cryogenic equipment is required in order to maintain it.

From the physical point of view, liquid argon has properties which make it very similar to the freon CF₃Br of the celebrated Gargamelle experiments:

	Argon	CF ₃ Br
Nuclear collision length	53.2	49.5 cm
Absorption length	80.9	73.5 cm
dE/dx, minimum	2.11	2.3 MeV/cm
Radiation length	14	11 cm
Density	1.40	1.50 g/cm ³

3. IONIZATION PROCESS

The energy loss required to produce an ion pair in liquid argon is 23.6 ± 0.5 eV⁵⁾. In the high-density liquid, a certain number of these electrons recombine with the positive ions, unless an appropriate electric field separates them quickly. The column recombination process is well studied⁶⁾ and illustrated in Fig. 1. For minimum counting tracks the recombination is almost entirely suppressed at field strengths $E \geq 10$ kV/cm. For strongly ionizing tracks, such as α -particles, the effect persists up to very large field strengths. For instance, at $E = 40$ kV/cm, still only 25% of the initial charges are actually liberated. The saturation plateau for minimum tracks gives a measured⁶⁾ electron yield of $(1.21 \pm 0.04) \times 10^{-14}$ coulomb/cm, corresponding to (0.95 ± 0.04) of the theoretically expected value. Note that since the saturation effect can be calibrated, the loss of charges at high specific ionization density can be corrected for at the analysis stage.

4. DRIFT PROCESS

The drift velocity of electrons in pure liquid argon has been extensively studied⁷⁾. The results are shown in Fig. 2a. This drift velocity v shows a linear dependence with respect to the electric field for voltages less than 200 V/cm and it saturates at high fields. In the range 1 to 50 kV/cm, which is the range of interest, v can be approximated by

$$v = 2.1 \times 10^5 E^{1/3} \text{ cm/sec ,}$$

where E is the applied field expressed in kV/cm. Note that the drift velocity for the solid phase is substantially faster (Fig. 2b), and that the drift velocity in the liquid phase as a function of the temperature varies about as $T^{3/2}$ (Fig. 3).

Oxygen, and to a lesser extent nitrogen, impurities can easily capture free electrons. The attachment coefficient for oxygen is a rapidly decreasing function of the electron energy, and "hot" electrons are less easily captured (Fig. 4).

Therefore attachment can be effectively reduced by increasing the electric field. In Fig. 5a and Fig. 5b we show the mean free path length for absorption by oxygen impurities as a function of the applied electric field. In a first approximation, results can be parametrized as

$$s = 0.12 E/p \text{ cm},$$

where s is the mean free path, E is the field in kV/cm, and p is the O_2 concentration in ppm in volume. A similar formula has been found for N_2 with about two orders of magnitude smaller effect (Fig. 6). Miller and colleagues⁷⁾ have demonstrated that liquid argon prepared from gas that is further purified with a simple activated charcoal trap to remove O_2 , led to electron lifetimes corresponding to a residual oxygen impurity content of about 4×10^{-2} ppm. We can use this indicative value for the purity in our estimates of the expected performance of the LAPC. The mean free path is then $\lambda = 3.0 E$ (cm), with E in kV/cm. A mean free path of 30 cm is then achieved with $E \cong 10$ kV/cm. Clearly, oxygen-free argon is the central problem for the LAPC.

We note at this point that commercial amplifiers^{*)} can give for the present application an equivalent input noise of about 2×10^{-16} coulomb r.m.s. An appreciable attenuation during the drift process can be tolerated since signals are generally much larger than noise. Note, however, that large attenuation may lead to non-linearities in the drift-time calibration because "hot" electrons are less attenuated.

5. DIFFUSION OF ELECTRONS

The transverse diffusion of electrons in liquid argon has been measured by Derenzo et al.⁶⁾ at $E = 2.7$ kV/cm. Their result is based on a 2 mm gap chamber (Fig. 7). They define a diffusion factor \tilde{D} , $\sigma_x = \tilde{D} \cdot Z$, where σ_x is the r.m.s. of the electron diffusion orthogonal to the electric field, and Z is the electron shift distance parallel to the electric field. The results give $\tilde{D} = 28 \mu\text{m}/\text{mm}^{1/2}$, corresponding to only $\sigma_x = 0.48$ mm after $Z = 30$ cm of drift length. Clearly the drift occurs with a remarkably small lateral spread.

The intrinsic longitudinal diffusion is expected to be comparable to the transverse area. Unless care is taken, the time resolution of the amplifier may become the determining factor since, for instance, at 10 kV/cm, a 0.5 mm drift length corresponds to a 110 nsec time interval. However, since signals are generally large, an amplifier with a response of about 200 nsec seems possible at the present level of the technology, giving a longitudinal resolution of ~ 1 mm.

*) LeCroy Research Systems Model QV100.

6. BASIC LAYOUT OF THE CHAMBER

The conceptual layout of the chamber is shown in Fig. 8. Electrons produced by the ionizing tracks are drifted toward a plane of strips, which for clarity are oriented in only one direction. The image moved in this way into the charge-coupled devices is equivalent to the image seen when looking with a television camera from infinity along the line of the strip. In other words, the drifting into the read-out plane is entirely equivalent to the grid scanning that a TV camera performs over the cathode carrying the image. The extension to a multi-view device is obvious, and it is shown in Fig. 9. The read-out of charges on several directions can be realized either by sharing the charges with strips or using grids which detect the charge images.

7. CONCLUSIONS

It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques.

REFERENCES

- 1) See, for example, NAL Summer Study 1968, Vol. 3; NAL Summer Study 1969, Vol. 2, etc.
- 2) D. Nygren, 1974 PEP Summer Study (PEP-137).
- 3) G. Charpak et al., Nuclear Instrum. Methods 80, 13 (1970).
- 4) J. Losecco and A. Sessions, Harvard Univ., private communications.
- 5) M. Miyajima et al., Phys. Rev. A9, 1439 (1974), and reference 6 therein.
- 6) W. Hofmann et al., Nuclear Instrum. Methods 135, 151 (1976).
- 7) L. Miller et al., Phys. Rev. 166, 871 (1968).
- 8) S. Derenzo et al., Nuclear Instrum. Methods 122, 319 (1974).

Figure captions

- Fig. 1 : Charge collected Q as a function of the electric field E between the number of gaps for a β -source (curve a) and an α -source (curve b). The full curves are theoretical predictions. The concentration of oxygen was $\lesssim 1$ ppm.
- Fig. 2 : a) The field dependence of the electron drift velocity in liquid Ar at 85 K.
b) The field dependence of the electron drift velocity in solid Ar at 82 K.
- Fig. 3 : The temperature dependence of the low field mobility in Ar. T_r denotes the triple point.
- Fig. 4 : Attachment coefficients for oxygen in liquid argon.
- Fig. 5 : a) The product of the electron capture distance $v \cdot \tau$ and the oxygen impurity content P_0 (in v.p.m.) plotted against the applied field E .
b) Mean free path length for absorption λ_{O_2} by oxygen impurities as a function of the electric field.
- Fig. 6 : Oxygen and nitrogen attachment coefficient versus electric field.
- Fig. 7 : Schematic of chamber construction. Gold anode pattern (light) on sapphire substrate (dark). (a) Overview showing fan-out to circular ring of bonding pads (18 μm diameter). (b) Enlargement of central region showing 24 strips between two broad electrodes used to make the field more uniform. (c) Further enlargement showing 15 μm wide strips on 20 μm centres.
- Fig. 8 : Schematic of a single-view LAPC. The "image" stored in the CCDs is equivalent to the image seen looking parallel to strips.
- Fig. 9 : Extension of the LAPC to a multi-view device.

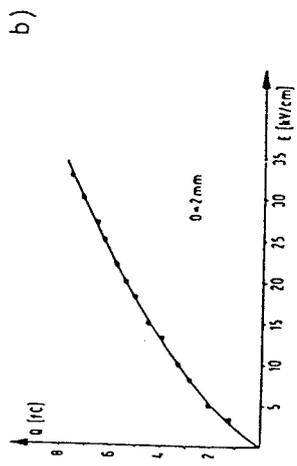
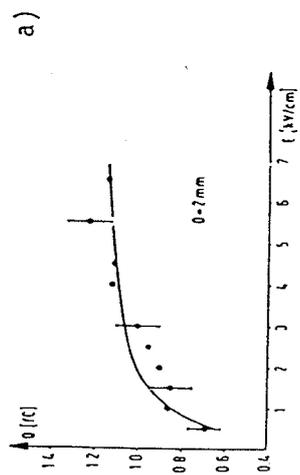
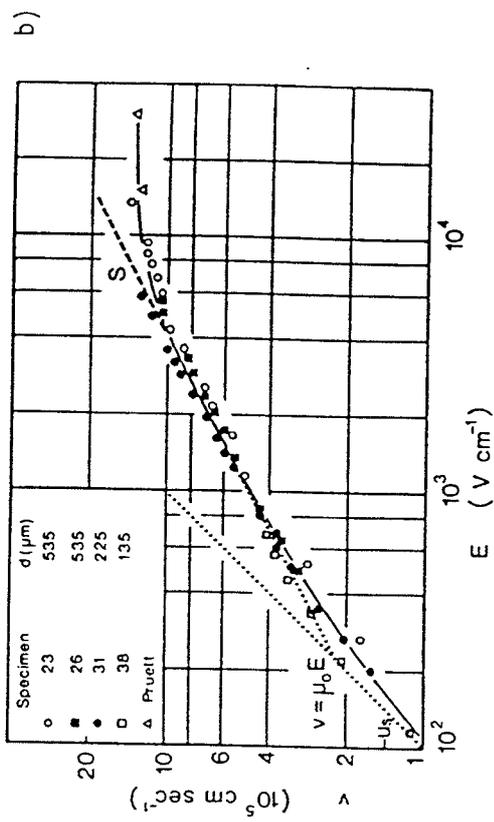
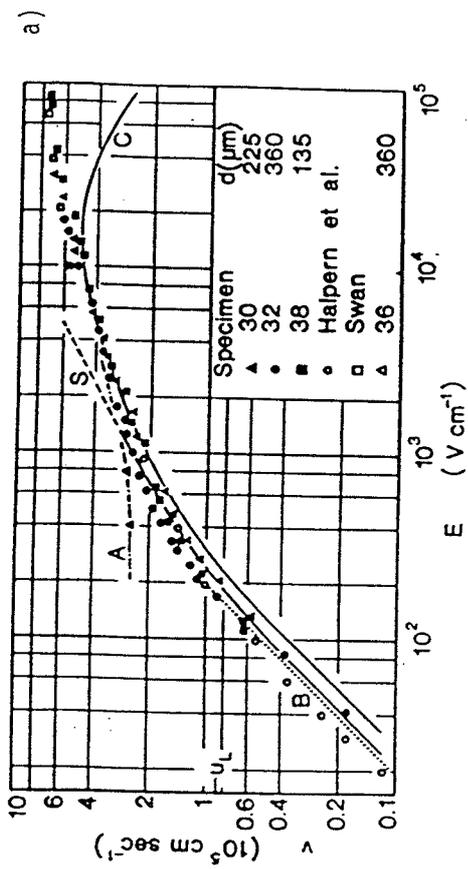


Fig. 1

Fig. 2

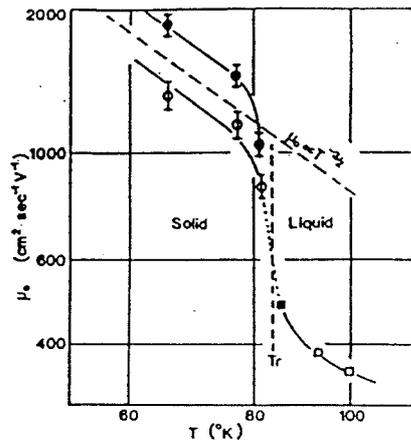
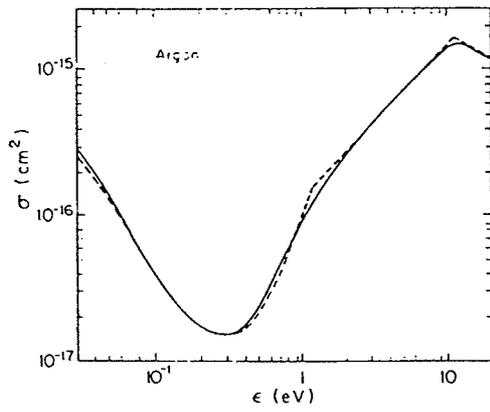
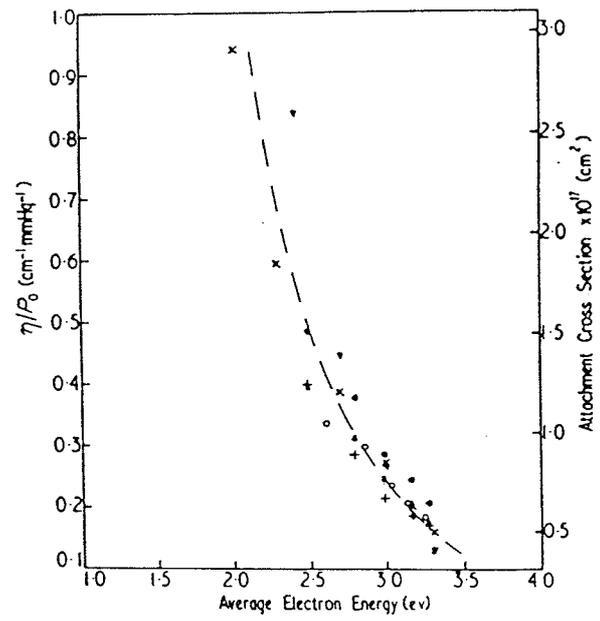


Fig. 3

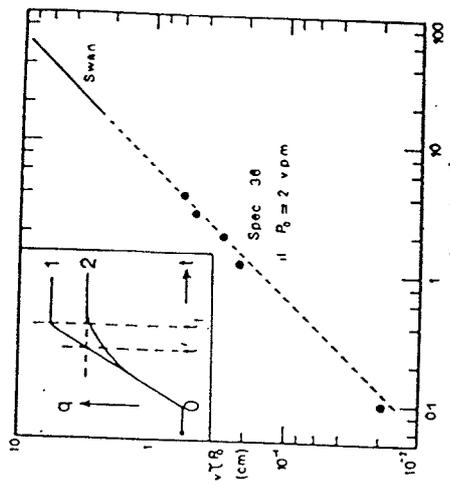


a)

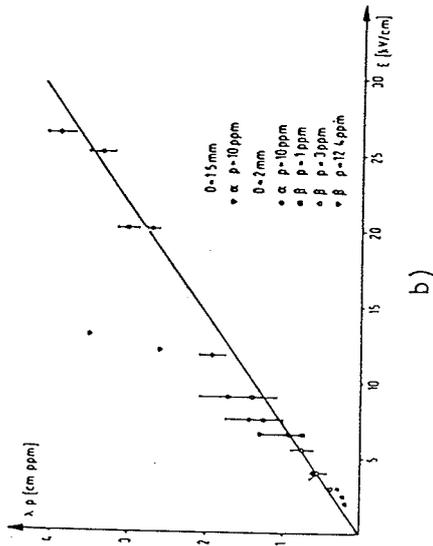


b)

Fig. 4



a)



b)

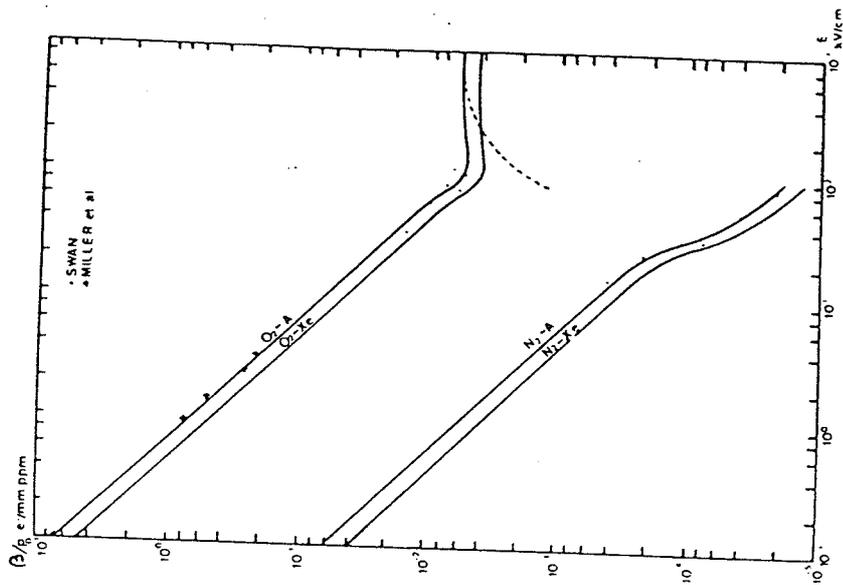


Fig. 6

Fig. 5

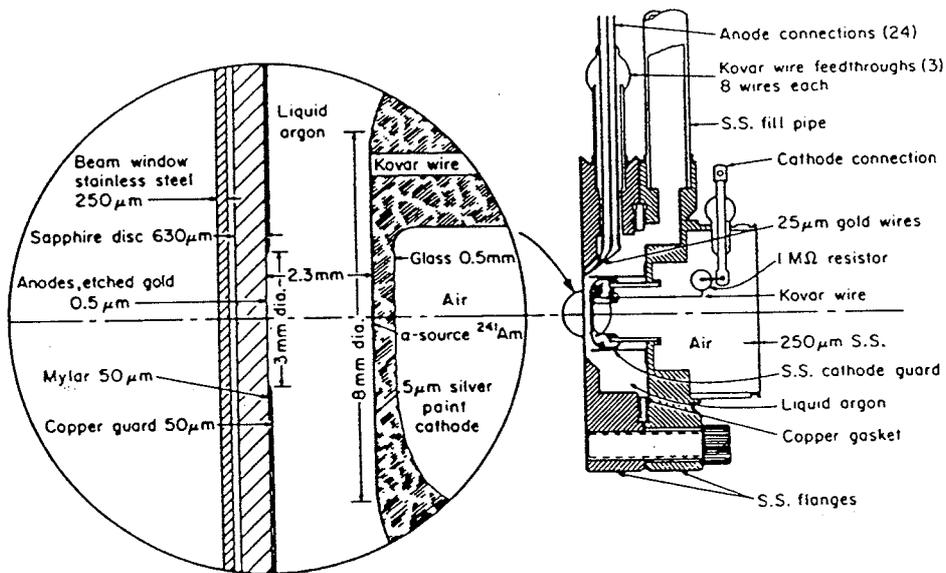
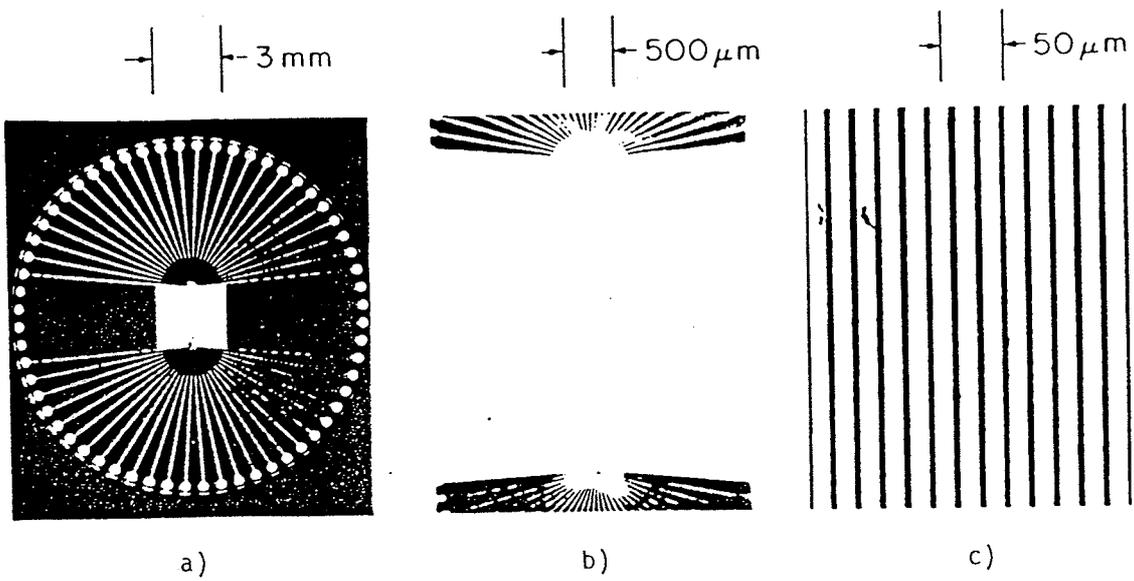


Fig. 7

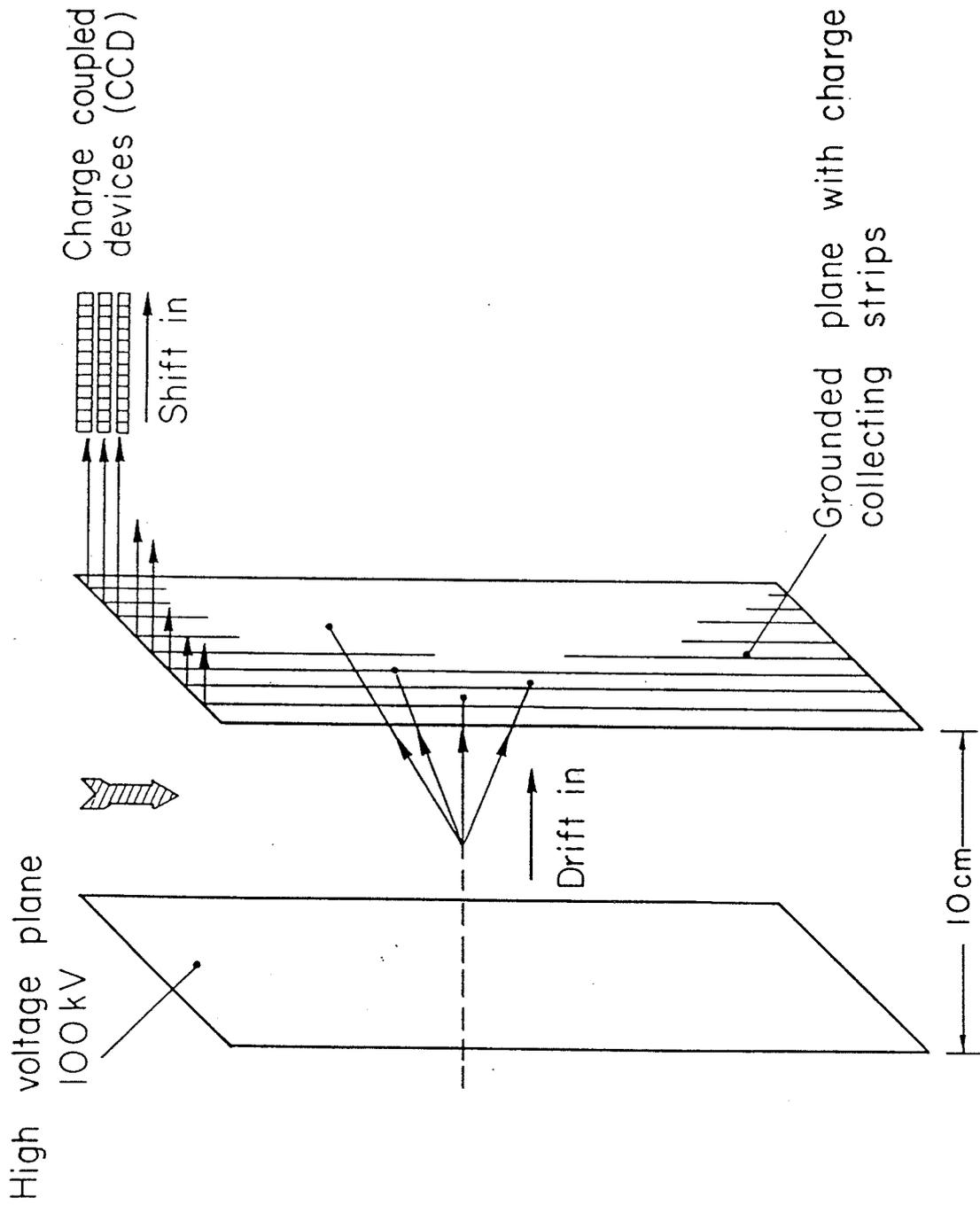


Fig. 8

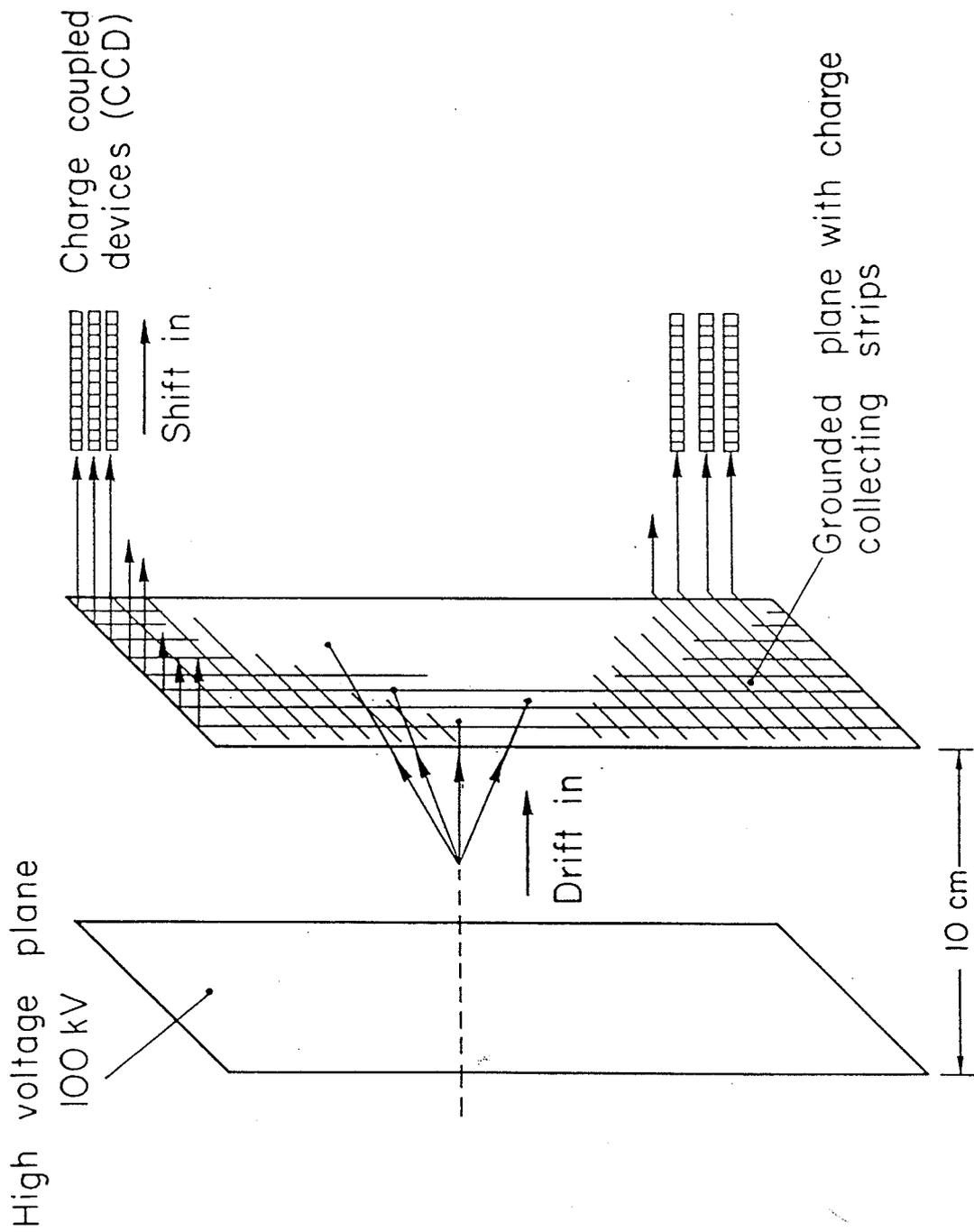


Fig. 9