CERN-EP/80-144
11 August 1980

POSSIBLE IMPROVEMENTS IN THE PERFORMANCE OF GASEOUS DETECTORS

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ABSTRACT

Existing gaseous detectors, because of their intrinsic limitations in rate, time and multitrack resolution, appear rather unsuited for the high complexity of the events expected at LEP energies. In the present paper, I will describe several new approaches that may lead to substantial improvements in detector capability: the multistep chamber in various configurations, the use of very high pressure detectors, and the photo-ionization proportional chamber applied, for example, to Čerenkov ring imaging. Also, some speculations on a pressurized air detector for the analysis of low-rate complex events are presented.

Invited talk at the
International Conference on Experimentation at LEP
Uppsala, 16-20 June 1980

1. INTRODUCTION

Multiwire proportional and drift chambers are nowadays largely used in various configurations, in high-energy physics experimentation and in other branches of applied research. For a long time, however, fundamental limits on the performance of multiwire chambers have been identified, mainly in their rate capability, multi-track resolution and localization accuracy; although some improvements may still be possible, some of the above-mentioned limits are intrinsic in the proportional multiplication mechanisms. In this paper I should like to discuss several new approaches to the detection problem that may lead to substantial improvements in the performance of the instruments. Needless to say, most of the detectors that will be presented here are still in a very preliminary phase of development, and extensive work is still required to see if they could ever be implemented as valuable instruments for physics experimentation.

2. THE MULTISTEP CHAMBER APPROACH

A preamplification and transfer process has recently been investigated with the structure illustrated in Fig. 1 [1-3]. Electrodes a, b, and c, made either with thick parallel-wire grids or crossed-wire meshes, delimit a region of high electric field, E_p , followed by a region of lower field E_T . Charges injected into, or produced within, the high field region experience inelastic collisions and multiply in an avalanche process; under suitable conditions, the lateral spread of the avalanche can be increased so as to equal or exceed the pitch of the wires of the electrode b. A fraction of the electrons of the original avalanche, roughly equal to E_T/E_p , transfers then to the lower field region, along the tubes of the field lines connecting the two regions. The quantizing effect of the discrete wire structure is virtually obliterated if the avalanche head is large enough, and a good energy resolution is observed on the transferred charge.

The gain of the amplifying section, a conventional parallel-plate chamber, can be written as $e^{\alpha l}$ (where α is the first Townsend coefficient); the fast -- or electron -- induced charge on electrode b is then expressed by

$$Q_e = \frac{e^{\alpha l}}{\alpha l}, \quad (1)$$

as can be shown with simple electrostatic considerations [4]. If a fraction f of the electrons is transferred, the fast signal induced on electrode c is then given by

$$Q'_e = f e^{\alpha l}. \quad (2)$$

For typical values of $\alpha l \approx 10$ and $f = 0.3$, the signal induced by the transferred fraction of electrons clearly exceeds the original signal on b, see Fig. 2.

Notice also that the transferred signal does not contain any ion component; as we will see later, this may be a considerable advantage in achieving multitrack separation.

The crucial point for a correct transfer is a large lateral spread of the avalanche: in the example, about 1 mm over a 5 mm long avalanche development. Such a spread is very unusual for normal gaseous electronics conditions, being typically an order of magnitude smaller in drift chambers (thus allowing good coordinate localization [5]). A substantial spread has been observed at very low concentrations of organic quencher in a noble gas, and is particularly large in mixtures where the ionization potential of the quencher exceeds the energy of an atomic or molecular excited state of the noble gas itself. This has led to the assumption of a photon-mediated avalanche spread [1], that however will not be discussed here although it may have fundamental relevance to the development of gaseous detectors. Figure 3 shows the measured avalanche spread in a 5 mm thick preamplification gap, as a function of the percentage of acetone in argon, under normal conditions. A convenient value for correct transfer in the geometry of Fig. 1 appears to be about 1.5% acetone, leading to an avalanche with a standard deviation of 250 μm , quite appropriate for proper transfer through a 500 μm pitch wire grid.

Two peculiar properties are observed in the structure described. The first, defined as a "skin effect", is indeed a characteristic of all parallel-plate counters: charges produced close to the upper cathode, or injected into the high field from a drift region above, receive full amplification; charges liberated within the amplifying volume, on the other hand, receive a gain exponentially decreasing with the distance of production from the cathode. This property has been exploited to improve greatly the localization power of gaseous counters in the detection of low-energy electrons emitted at the cathode surface, as is the case in radio-chromatography [6,7] and thermal neutron detection with a thin converter [8]. One can imagine exploiting the skin effect to improve particle counting in shower detectors, where the emission by the converters of large-angle electrons in the gas detector is indeed a serious nuisance: this seems a very tempting subject for future research.

The second peculiarity concerns the gain that can be attained in a parallel-plate chamber before breakdown. This is normally situated between 10^4 and 10^5 , mainly because of the feedback of ions and photons that induces secondary cathode emission. It has been observed that in a double structure, i.e. a preamplification and transfer element followed by a similar parallel-plate amplifier or a conventional multiwire proportional chamber, gains in excess of 10^6 can be safely attained [2]. Since this is possible in gas mixtures having an excellent photo-ionization efficiency, the first application of the multistep chamber has indeed been in the detection of photons emitted by Čerenkov effect [9-11].

Figure 4 shows an example of single photoelectron pulse-height distribution, obtained at very high gain in a two-step chamber operated with argon and 3% of triethylamine (TEA), a vapour having a photo-ionization threshold of 7.5 eV and a peak quantum efficiency at 8 eV of about 40% [10]. Electronic detection of single photoelectrons is already possible at these gains. A further enhancement of the signal can be obtained, however, applying a high-voltage pulse on the second step of the detector at the proper time, thus developing a spark, a very convenient method for visual image analysis. Various techniques for Čerenkov ring imaging

are described elsewhere in these proceedings [11]; let me only mention here that a good level of stability and performance has been achieved in this kind of detector, that will certainly add to our arsenal of particle identifiers. In the spark detection mode, automatic vidicon read-out systems have been implemented for fast image digitization and analysis, see Fig. 5 [12].

The mechanism of induced pulse formation is very different in a multiwire and in an avalanche chamber. In the first case, ions produced in the avalanche around the thin anode wire recede from the wire itself, inducing positive charges in all surrounding electrodes; a measurement of the centre of gravity of the induced pulse distribution on the cathode is a very effective way of obtaining accurate, bidimensional coordinate localization in proportional chambers [13-15]. The lateral extension of the induction is however rather large, around two gap units, thus limiting the multitrack separation power of the device.

In the avalanche chamber instead, although the avalanche itself may be rather large (1 mm or so), the signal induced on the anode wires does not exceed this value and is indeed even narrower because of an electrostatic compensation mechanism (Fig. 6). In these conditions, very close tracks can be correctly separated, as shown in Fig. 7 for two tracks 2.5 mm apart [16]. One would expect to improve even more on these characteristics at pressures exceeding the atmospheric, thus implementing a unique tool for multitrack identification in jet-like events; at atmospheric pressure, a similar improvement may be obtained by the use of thinner electrode structures, as for example micromeshes, that would allow operation with a smaller avalanche spread still keeping the good transfer characteristics.

A natural addition to a two-step chamber is an electronic shutter, or gate, between the amplifying elements to realize a gated gaseous detector. We have done experiments with the structure shown in Fig. 8 [16], where the gate is constituted by a set of parallel wires, 500 μ m apart, alternatively connected to two polarizing potentials. Full blocking of the drifting electron cloud is observed at polarization potentials around ± 100 V, and the transparency can be restored by the

application of a symmetric pair of pulses of the same amplitude. By proper optimization of the symmetry of the pulses and good a.c. grounding of the intermediate electrodes, pick-up of the gating signal on the detection electrode (the last one of the structure) can be minimized as shown in Fig. 9.

The gated multistep chamber solves, in principle, the problem of selective detection of ionization in a very high particle flux environment. Indeed, each of the two elements of amplification operated at a low enough gain as to minimize space-charge effects, and the full amplification is set only for selected events when the gate is pulsed open; for a typical choice of individual gains around 10^3 and at low opening rates, one should gain three orders of magnitude in rate capability compared with a conventional chamber operated continuously at a gain of 10^6 .

A flux-dependent breakdown phenomenon appears, however, that in part frustrates our expectations, for the time being. For a given ionizing particle flux, a well-defined maximum operational voltage is attainable in each of the two elements, even with a closed gate, and the breakdown voltage decreases with the increasing flux. This sets a natural limit to the maximum efficiency that can be obtained at a given rate, as shown in Fig. 10; for a minimum ionizing particle flux of 1.5×10^5 , full efficiency is barely reached before breakdown.

A better understanding of the rate-depending breakdown mechanism is certainly necessary in view of a practical use of the device. Obviously, a lower discrimination threshold would help in attaining full efficiency before breakdown (for the described measurement, threshold was set at around 0.1 pC, which is not particularly low). I should mention here that no permanent damage results to the chamber after a breakdown, since the detector contains no thin wire elements, and the electronics can easily be protected by a pair of fast switching diodes at the input.

The measured time resolution of the gated multistep chamber, 10 ns FWHM, is not particularly attractive for high-flux environments. The possibility however of selectively activating only a section of the chamber, by suitably grouping the

gating wires on individual pulsers, can greatly simplify the pattern recognition problem; the selection can be realized, for example, by a scintillation counter hodoscope geometrically matching the gating structure and operating with much better resolution times.

In large drift volume detectors, as for example the Time Projection Chamber [17], the possibility of gating into the active part, a multiwire chamber, only selected events may solve serious problems of image distortion expected at high event rates and due to positive ion feedback in the drift volume [18,19].

In conclusion, the multistep chamber, in one of the various configurations described, may allow improvements of the rate capability and multiparticle separation with a localization accuracy approaching that of drift chambers and cathode read-out proportional chambers. Another consideration concerns the possibility, still to be better established experimentally, that the parallel-plate chambers are less sensitive in localized space-charge gain modifications of the kind observed in multiwire chambers. Indeed, the surface interested by the avalanche in a wire chamber is normally around $100 \times 10 \mu\text{m}^2$, thus implying large charge densities and a geometry-dependent gain (variation of the effective gain with the detected track orientation and its time structure [19,20]). In an avalanche chamber of the kind described, the interested surface at the anode is around 1 mm^2 , three orders of magnitude larger. Could this solve the geometry-dependent problems encountered in dE/dx ionization measurement devices? This is again a subject for further investigation.

3. OPERATION AT VERY HIGH PRESSURES

A general trend in large-volume electronic gaseous detectors is to operate at pressures higher than atmospheric, to improve their performances. This is mostly done, however, to increase the specific energy loss of fast charged particles in view of obtaining a better identification in the relativistic rise region; detectors working at 4 atm are operational, and the Time Projection

Chamber will soon operate at 10 atm (see for example the review talk of Flügge in these proceedings [21]). Elementary gaseous electronics suggests that, at equal values of the reduced field E/P in the drift region, the electrons diffusion decreases as $P^{-1/2}$, where P is the pressure. A naïve argument assumes then that the localization accuracy improves in the same ratio; this may not be completely true, however, because of the increased production of long-range δ -electrons per unit length as the gas density is increased [22]. Measurements realized in Xe at 20 atm show indeed the appearance of considerable tails in the reconstructed accuracy distribution for fast particles [23]; a multiple sampling technique, with obliteration of measurements exceeding a prefixed value, may be required to achieve an effective accuracy improvement according to the $P^{-1/2}$ scaling law.

Recently, a Russian group has shown the possibility of operating gaseous detectors at very high pressures, up to several hundred atmospheres [24]. In this research, the most valuable parameter is not, however, the localization accuracy of each track (partly spoiled anyhow by multiple Coulomb scattering in the detectors' walls and gas) but instead the multiparticle separation that can reach 100 μm or better. This kind of resolution, that may allow for example the study of charmed particles' decay almost down to the vertex, is made possible both because of the very small diffusion of electrons at such high pressures, and because of a careful choice of gas mixtures with a low saturated drift velocity, less than $1 \text{ cm } \mu\text{s}^{-1}$ as shown in Fig. 11 [24]. Indeed, when the detection is implemented with a conventional multiwire proportional counter, typical signal duration times around 100 ns are obtained (including both the physical avalanche growth and electronics effects) and, with the use of faster gases, this would imply multitrack separations in the mm range.

It is soon realized that the proportional avalanche growth process at detection is indeed the most severe limiting factor for good multitrack resolution at high pressures. It is known indeed that, for a given counter geometry, the operational voltage for a given multiplication factor increases roughly as $P^{1/2}$, P being the counters' gas pressure [25]; if, on the one hand, this is a favourable factor

since it does not result in the necessity of using exceedingly large anodic voltages at high pressures, on the other hand it implies a reduced velocity of the ions in the field around the anodes (the ionic mobility being proportional to E/P). As most of the detected signal in proportional counters is determined by the movement of the positive ions in the avalanche, the pulse decay time is correspondingly slower and quickly erases any improvement in multitrack resolution that would result from the reduced electron diffusion.

This has been well recognized by the authors of reference 24, who in a following work [26] have made the obvious step to implement detection without charge multiplication, exploiting the mechanism of secondary gas scintillation.

The secondary emission of photons in a well-defined wavelength band by electrons experiencing inelastic collisions in noble gases, under the influence of strong electric fields, has been exploited for many years in practical devices mainly because of the very good energy resolutions that can be obtained for soft X-rays; for a review work on the matter see, for example, Policarpo [27]. The mechanism of secondary photon emission has been identified as the result of the decay of excited dimer molecules of the noble gases, produced by inelastic electron-atom impacts. Secondary light emission sets in at values of the electric field well below any charge multiplication, and therefore avoids the fluctuations intrinsic in the avalanche mechanism that tend to spoil resolution.

Detection without charge multiplication was already recognized long ago to be a possible way to overcome the space-charge problems at high-radiation fluxes typical of proportional counters; in a device called a scintillating drift chamber [28] X-ray fluxes in excess of $10^6 \text{ mm}^{-2} \text{ s}^{-1}$ could be properly counted coupling a secondary emission gas volume to a photomultiplier detector. In other works, localization has been obtained over extended areas, using a ring of several photomultipliers to detect the light flash produced in the scintillating device, and implementing a suitable algorithm to find the centre of gravity of the detected signals [29-31]. As we will see in the next section, the problem of detection

lies in the fact that pure noble gases scintillate in the far and vacuum ultraviolet domain, thus requiring a wavelength shifter at the photomultiplier window, which is a seriously limiting factor both to the efficiency and the localization properties. Also, the formation and decay time of the excited dimers has to be properly considered if one wants to achieve good multitrack resolution; the authors of Ref. 26 have shown that the addition of 0.3% N_2 to argon reduces the light emission decay time, at 100 atm, to about 20 ns, which implies a possible two-track resolution well below 100 μm . The same authors have speculated on the use of thin scintillating fibres for the detection and localization of the light flashes in a large surface device; further work is certainly necessary in this very promising direction of research. For other possible applications, see also the work of Policarpo in these proceedings [32].

4. COUPLING THE SCINTILLATING PROPORTIONAL COUNTER TO THE PHOTO-IONIZING CHAMBER

It has been proposed by Policarpo [33] and experimentally demonstrated since [34] that coupling a noble-gas proportional scintillation chamber to a multiwire proportional chamber containing a vapour with good quantum efficiency in the region of photoemission, allows the maintenance of the very good energy resolution of the first device with the localization properties of the second. The structure of the photo-ionizing proportional scintillation chamber is shown in Fig. 12. To better situate the detection problem, I have collected in Fig. 13 the measured secondary emission spectra of argon, krypton, and xenon [35]; and in Fig. 14 the quantum efficiencies of acetone [36], benzene [37], triethylamine (TEA) [10] and Tetrakis-dimethylamino-ethylene (TMAE) [38], the last being only a relative measurement. The average cut-off wavelength of several existing windows is also shown in Fig. 14.

Clearly, photons produced by the scintillation of argon can be detected by the combination LiF-benzene, and those produced in krypton by TEA, with a CaF_2 window: the last combination is the one demonstrated in Ref. 34. There seemed,

however, to be no way of detecting the xenon scintillation light in a photo-ionizing gas chamber, since all products having a sufficiently low ionization potential (6 eV or so) appear to exist only in the solid phase at room temperature. Recently, Anderson [39] has shown the possibility of working with TMAE, a liquid having in the vapour phase the unbelievably low photo-ionization threshold of 5.4 eV. Despite its very low vapour pressure at room temperature, TMAE seems to have a very large photo-ionization cross-section -- around 7 eV (the values given in Fig. 12 are only relative) -- with a photoelectric efficiency estimated at around 25% for the Xe scintillation in a layer about 20 mm thick. If these findings are confirmed, and if the use of the product is not too impractical in multi-wire chambers (it is rather aggressive), considerable improvements on present-day detectors are at hand. Between various possibilities of applications, let me mention only the following:

- In astrophysics, the use of xenon as scintillating gas coupled to a photo-ionizing proportional chamber with localization has of course a great advantage because of the extended detection efficiency of xenon at short X-ray wavelengths, and also because of its secondary emission yield larger than for any other noble gas.
- The Čerenkov ring imaging technique would be considerably simplified by the use of fused silica windows, cheaper and handier than the fluoride crystals. Moreover, the chromatic aberrations and absorption losses in the radiator are greatly reduced at the longer wavelengths, as compared with the use of TEA as photo-ionizing vapour. Preliminary images obtained with the multi-step spark chamber detector described in Refs. 9 and 12 using TMAE as photo-ionizing vapour are shown in Fig. 15, where an overlap of ten events appears. Obviously, quantum efficiency is still not as good as for TEA (cf. Fig. 5, which corresponds to a single event), and moreover there are problems with the beam spark that extends over centimetres, probably as a consequence of secondary photon reconversion.

to improve the drift properties (see Fig. 11) will have a considerable financial impact, in view of the masses involved; 0.5% Xe in a 30 m³, 300 atm detector (such as the one proposed by the authors of Ref. 24) results in almost half a million dollars' expenditure! One may wonder if there is not a cheaper gas around. The answer is obvious: it is air. Unfortunately, air still contains a non-negligible fraction of oxygen, despite serious efforts made by mankind to replace it by carbon dioxide!

A solution to the dilemma has been recently proposed [41]: it consists in the possibility of directly detecting the ions produced in the gas, instead of the electrons, as was done long ago in the so-called slow ion chambers [25]. The problems with ions are obviously their low mobility implying long collection times, and the absence of charge multiplication in the gas; on the other hand, as ion diffusion is extremely small, fantastic space accuracies may be dreamed of.

Figure 16 shows the ion component of the charge collected in a small ionization chamber, having about 2 × 2 cm², operating in air under normal conditions and irradiated with an ²⁴¹Am α -source. For the measurement, we have used a very simple charge amplifier with a long decay constant. The signal clearly appears above the background, and even shows a decent energy resolution. Remarkably enough, the signal is only slightly degraded at low fields, showing perhaps that electron attachment (with the formation of negative ions) is defeating electron-ion recombination, a well-known problem at high ionization densities. Because of the geometry, the 5.4 MeV α particles emitted by the source were losing about 2 MeV in the sensitive volume, which is just about the energy loss per cm of minimum ionizing particles in air at 100 atm! Complex events produced in a pressurized air tank may therefore be sampled, with decent energy resolution, in 1 cm intervals. And, of course, one would get twice the same event pattern, from both positive and negative ions drifting in opposite directions, thus allowing computation of the time of the event. Could this be the ideal large-mass, cheap detector for rare-event physics, as in the study of neutrino interactions or proton lifetime, dreamed of by many physicists nowadays?

- The problems caused by slow positive ions in very high pressure drift chambers, discussed in the previous section, may be solved operating the detector in the scintillating mode, coupled with a photo-ionizing chamber at normal pressure (where the velocity of ions is much faster for a given proportional gain).
- Large-area phototubes or image intensifiers in the visible range may become feasible. Indeed, most conventional photocathode materials are known to survive in a pure noble gas environment (photosensitive gas cells have been on the market for a long time). One can think then of producing an "upwards" wavelength shift detecting the visible photons with a photocathode surface coating the inside of a gas cell containing xenon, generating then secondary scintillation with the primary photoelectron and detecting and localizing the flash in the photo-ionizing chamber as described.

Still, a lot of work is required to learn how to work with TMAE. Apart from its chemical activity (it is a strong reducer), a major problem may appear just in connection with its extended quantum efficiency at low frequencies; photons released in the avalanches can induce secondary phenomena, thus limiting the maximum gain of the counter.

5. USING AIR AS DETECTION MEDIUM

In Section 3 I have discussed the considerable improvements to be expected in particle detection by the use of very high pressure gases. Apart from the technological implication of such an approach, it is maybe worth mentioning a major problem intrinsic to these devices: a very good gas purity is required for proper electron drift. For a typical value of the oxygen attachment coefficient at moderate electric fields ($\sim 10^{-4}$ attachments/collision [40]) the mean free path of electrons in a noble gas containing 1 ppm of O_2 at 100 atm, is about 10 cm. Maintaining such a level of purity over large volumes is certainly not a simple task. Moreover, the addition of even small quantities of xenon in argon,

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Figure captions

- Fig. 1 : The preamplification and transfer mechanism [1,2]. A charge q injected in the high-field region between electrodes a and b produces an avalanche multiplication. In poorly quenched gases, the lateral avalanche spread can exceed the wire spacing of electrode b, and a fraction of the electrons in the avalanche transfer to the lower field region between b and c (the shaded areas). The transfer efficiency is roughly E_T/E_P .
- Fig. 2 : The signal induced by the multiplying and transferring charge in the electrodes b and c of Fig. 1 (upper and lower trace, respectively) at $E_T/E_P \approx 0.2$. The horizontal scale is 500 ns/div [3].
- Fig. 3 : Avalanche size in the preamplification element as a function of the percentage p of acetone in argon. The dashed line represents the estimated real size, deducing a collimated source width of about 300 μm standard deviation. At 1.5% of acetone, the avalanche has a σ of about 250 μm [3].
- Fig. 4 : Single photoelectron pulse-height spectrum, measured in a two-step chamber filled with argon-triethylamine (97-3). The most probable pulse-height is around 1 pC at the chamber [2].
- Fig. 5 : An image of a Čerenkov ring obtained with a multistep spark chamber, operated with triethylamine, and coupled to a television digitizer. The contour of the sparks is recorded and displayed; the event shows six photon points and the central beam spot [12].
- Fig. 6 : Comparison of the real charge distribution (dashed curve) and fast induced charge signal distribution measured on the last electrode of a two-step avalanche chamber. The channel width is 500 μm , corresponding to the wire spacing in the electrode.

- Fig. 7 : Two simultaneous tracks 2.5 mm apart detected on the last electrode of the two-step avalanche chamber. The bin width corresponds to 500 μm [16].
- Fig. 8 : The multistep gated avalanche chamber. Electrons are preamplified in A1 and transferred towards a gating electrode. This is constituted by a grid of parallel wires, closely spaced, and alternatively connected to a pair of polarizing potentials $\pm V_G$. Full blocking of the gate is obtained at a suitable value of V_G (around 100 V), and full transmission can be restored applying a pair of symmetric pulses as shown. Gated tracks are then detected in the second element of amplification A2 [16].
- Fig. 9 : Pulses observed on the preamplification and amplification electrodes (A1 and A2 of Fig. 8) in the gated operation, in the detection of 5.9 keV X-rays. The electrostatic pick-up of the 100 V gating pulse on A2 is negligible (lower track).
- Fig. 10 : Efficiency plateaux of the gated multistep chamber in the detection of minimum ionizing particles, as a function of the gain in the second amplification gap and for various values of the gain in the first. The sparking voltage in A2 as a function of particle flux is also indicated; the corresponding maximum values of V_1 are shown.
- Fig. 11 : Electron drift velocity as a function of electric field, at very high pressure (100 atm [24]) the gas used is argon with 0.5% Xe (1); and the same with addition of methane in the percentages 0.1% (2), 0.2% (3), 0.5% (4) and 1.0% (5).

- Fig. 12 : The photo-ionizing proportional scintillation chamber [34]. The two elements, separated by a LiF window, contain a scintillating pure noble gas and a photo-ionizing vapour in argon, respectively. Charges produced in the absorption region induce secondary scintillation without charge multiplication in the high field between electrodes 2 and 3; some of the emitted photons are reconverted in the lower proportional counter and detected.
- Fig. 13 : Spectral distribution of the photons emitted by secondary scintillation in noble gases [35].
- Fig. 14 : Quantum efficiency versus wavelength for several vapours, and cut-off of typical window materials [36-38]. The quantum efficiency of TMAE is only a relative value.
- Fig. 15 : First evidence of Čerenkov ring imaging using the multistep spark chamber with TMAE as photo-ionizing vapour. Ten events have been overlapped in the picture; the central spark, corresponding to the beam, is very bright in this highly photosensitive gas.
- Fig. 16 : Signal given by ions in a chamber operated in air at atmospheric pressure [41]. The source of ionization is a beam of α particles from ^{241}Am , losing about 2 MeV in the ionization chamber. The horizontal scale is 500 $\mu\text{s}/\text{division}$, and the vertical 10^{-2} pC/division. The drift field is 500 V/cm.

Fig. 1

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