PROGRESS IN PARTICLE IDENTIFICATION BY IONIZATION SAMPLING

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The present generation of large scale dE/dx detectors was conceived in the mid-seventies. In fixed target physics applications (EPI, ISIS) the achieved particle identification efficiency allows for π/K separation in the relativistic rise region. In the family of compact colliding beam detectors (e.g. AFS, ARGUS, CLEO, JADE, TPC, UA1), only the LBL TPC performance was so far sufficient for operation beyond the minimum of ionization. New central detectors foreseen for experiments in near future (LEP) should be more performing and will require resolutions which are at the limits imposed by systematic higher order effects. Influence of various design parameters on the optimization of the dE/dx sampling performance is discussed, supported by recent result from measurements of full-scale detector segments and including tests using ionized tracks generated by pulsed UV lasers. Merits of longitudinal drift and fine sampling are compared to results obtained by classical charge integration.

1. Introduction

Particle identification by ionization sampling represents an attractive method for applications in compact colliding beam detectors, where it is easily combined with the track reconstruction task of the vertex chambers. The progress in the development of this method can be illustrated by examples of the history of several large scale devices, fully or at least partially dedicated to dE/dx sampling. First detectors designed for hybrid bubble chamber experiments at fixed target accelerators were of a “box” geometry with 2-coordinate readout. Particle momenta were measured “outside”, and the tracks inside the detector were straight (neglecting the influence of weak stray magnetic fields). Due to short beam spill and small duty cycle requirements of bubble chambers, the background level and corresponding space-charge problems were not too severe. The EPI detector for BEBC at CERN was proposed in 1973 [1], the construction started in 1974 [2] and the first data were taken with the fully operational set-up in 1978–1979 [3,4]. The EPI consists of a fixed matrix of rectangular proportional cells. Large drift volumes were introduced into the design of ISIS [5], proposed in 1974 for EHS at CERN. Full scale operation and data taking using ISIS started in 1980–1981 [6,7]. A reduced version of ISIS (CRISIS [8]) was proposed for FNAL hybrid experiment in 1978. Both EPI and ISIS are large volume atmospheric pressure detectors aiming at dE/dx resolution near 6% fwhm, which is necessary for efficient particle identification up to about 100 GeV/c.

Colliding beam detectors operate in magnetic fields and must be more compact than the above mentioned devices. If the required resolution cannot be reached at atmospheric pressure in a given volume, the gas pressure

must be correspondingly increased. The most ambitious design of a 3-dimensional pictorial chamber containing large drift space – TPC – was proposed in 1976 for PEP at SLAC [9]. This high pressure chamber took first data in 1982 [10,11] and resolution comparable to EPI and ISIS performance was attained. Due to increased pressure the TPC cannot compete with the atmospheric pressure devices at very high particle momenta. The jet chamber for the JADE [12] experiment at PETRA was proposed in 1976 and the data taking started in 1980 [13]. In this detector the “bicycle wheel” geometry having moderate drift distances was adopted for the first time. A similar geometry was used for the AFS vertex detector at ISR (proposal in 1979 [14], completed in 1981–1982 [15]). The dE/dx segments in the CLEO detector for CESR [16] were fully equipped in 1981–1982 [17]. Planar chambers with relatively long drift path were used in the design of the UA1 central detector (dipole magnet) proposed in 1978 for the CERN $\bar{p}p$ collider [18], first data were taken in 1982 [19].

Basically, from the quoted examples we see that the presently operational generation of large scale detectors using dE/dx sampling for particle identification was conceived in the mid- or late-seventies and that it took on the average about 4 to 5 years from prototype tests to full operation. A new generation of central detectors with improved performance will be needed in near future for experiments planned for LEP, SLC and TRI-STAN. In this perspective, the possibilities and limits of the present state of the ionization sampling method will be examined in the following paragraphs, with emphasis put on the prospects of the π/K separation at highest attainable momenta. More detailed knowledge about developments over the last few years may be obtained by comparing the relevant contributions to the 1980

Uppsala Conference on *Experimentation at LEP* [20], to the 1982 SLAC Conference on *Instrumentation for colliding beam physics* [21] and to the 1982 *Nuclear science Symposium* [22].

2. High resolution ionization sampling

Fluctuations of the ionization energy loss in thin absorbers and their influence on the detector design were extensively treated theoretically and experimentally [6,23–29]. Results obtained in large detectors under very clean conditions (selected tracks, no background, etc.) are in reasonable agreement with predicted performance. Nevertheless, there are still persistent discrepancies between the predicted relativistic rise including density effect corrections [30] and results of measurements which show systematically smaller values [26,29,31]. Also, the predicted increase of the relativistic rise with reduced sample size [6,24,26,32] was not confirmed experimentally. This subject will be discussed in more detail in connection with “longitudinal drift”.

The dependence of the shape of the ionization loss distribution on the sample size is generally determined by changing the gas pressure, which inevitably means change of the gas amplification factor. This difficulty could be avoided by using sums of several “simultaneous” particles (in terms of the time response of the detector and electronics) at the same pressure. Single 4 cm sample distributions of 1, 2, 3 and 4 “simultaneous” 70 GeV/c pions in Ar + 5% CH₄ at 1 and 4 atm are shown in fig. 1 [31]. The most probable values are at channel 45 (42), 98 (92), 154 (144) and 214 (194) for 1, 2, 3 and 4 particles respectively, at 1 (4) atm. The gas gain at 4 atm was reduced by a factor of 4 with respect to the gain at 1 atm, so that the product of ionization loss and gas gain is roughly the same in both cases. If normalized to the peak value for single particles, the double particle peak is at 2.18 (2.19), for triple particle the ratio is 3.42 (3.43), the quadruple particle shows onset of slight saturation at higher pressure (ratio 4.76 at 1 atm but only 4.62 at 4 atm). This is in agreement with a factor of about 2.15 for a twofold increase in the sample size, which could be derived from the formula for the most probable ionization loss and which is caused by the logarithmic term containing the sample thickness.

Fig. 2. shows the truncated mean distributions of lowest 40% values of 64 samples of 4 cm at 1 and 4 atm [31,33] corresponding to single sample distributions from fig. 1. Now the peak positions normalized to the single particle distributions are, at 1 and 4 atm, about 2.3, 3.6 and 5.0 for double, triple and quadruple particles respectively. This effect is caused by the sensitivity of the truncated mean to the changes in shape of the ionization loss distribution. It is more evident in fig. 3 [33]

Fig. 1. Single 4 cm sample pulse height distributions for 1, 2, 3 and 4 particles in 1 and 4 atm of Ar+5% CH₄.

where the retention percentage for the truncated mean is taken as a parameter.

Practically it means that the relativistic rise measured using the truncated mean method for processing of data from this kind of detector will be somewhat improved if a lower percentage is used (100% retention corresponds to overall mean and shows obviously a linear behaviour). This effect should be taken into consideration when comparing data obtained under different retention percentages. Lower percentages are clearly advantageous, but there is evidently a practical limit imposed already at about 20% by greater statistical fluctuations and by increased sensitivity to noise. The final resolution attainable by the truncated mean method is rather insensitive to the choice of the retention percentage in the range from 40 to 70% [31], but the above mentioned arguments are in favour of the lower percentages close to 40%. It should be noted that in all considerations concerning the dE/dx resolution we assume that the detector output signal (including electronics) is really proportional to the energy loss deposit. This means especially that there are no problems with saturation, space charge and dynamic range. It is generally accepted that the gas gain should be kept below 10^4 to avoid difficulties connected to angle dependent corrections for saturation.

Fig. 2. Truncated mean distributions of 64×4 cm samples for single, double, triple and quadruple particles. 70 GeV/c pions in 1 atm (top) and 4 atm (bottom) of Ar + 5% CH₄.

3. Choice of the gas mixture

In order to attain the best particle identification in a given depth of the detector, we need a gas which has narrow distribution of ionization loss, high relativistic rise and low electron attachment (sensitivity to impurities), especially if the detector contains a large drift space. This will also influence the choice and percentage of the quenching agent, with additional demands for saturated drift velocity and small diffusion dictated by the track reconstruction requirements. In big volume

detectors, the choice of gas is also influenced by the economic aspects (cost of gas, open or closed gas system with purification). Concentrating first on the resolution aspects only, we see from fig. 4 [34] where the relative width of the ionization loss distribution of 15 GeV/c pions in a 4 cm sample at 1 atm is plotted as a function of the average molecular weight, that heavy hydrocarbons are considerably better than noble gases. Surprisingly, for neon, argon, krypton and xenon the performance is about the same in spite of large differences in density and in the ionization potentials (21.6

Fig. 3. Truncated mean response for multiple particles with retention percentage as a parameter.

eV for Ne; 12.1 eV for Xe). To compare the particle identification efficiency in various gas mixtures, we need to incorporate the corresponding relativistic rise

Fig. 4. Single 4 cm sample resolution as a function of average molecular weight.

Fig. 5. Identification efficiency at 15 GeV/c for π/p and e/π for various gases as a function of pressure.

for each gas. Fig. 5 [34] shows the resolving power for π/p and e/π at 15 GeV/c, where the distance between various particle peaks is expressed in number of standard deviations as a function of the gas pressure. Truncated mean of 40% smallest values was used for data from a detector containing 64 samples of 4 cm. At 1 atm neon, krypton and xenon have practically the same merits for π/p separation, followed by neon/argon mixtures and by argon. For the interpretation of the gain in the resolving power with increased pressure it should be remembered that this dependence will be different at different particle momenta (15 GeV/c in fig. 5). Pure hydrocarbons are at atmospheric pressure comparable to argon; the advantage of narrow distributions is offset by small relativistic rise. This is clearly visible in the e/π data where the obtained separation is too small to be of any practical use. Comparison of e/π and π/p data for neon and argon indicate steeper slope of the relativistic rise in neon but higher plateau level in argon, so that argon is more efficient for e/π separation. Xenon has the highest relativistic rise, thereby giving the best e/π separation.

Fig. 6. Signal attenuation over 41 cm of drift distance for various gases as a function of pressure.

In case of a long drift path in the detector the influence of the attenuation of the ionization signal by attachment must be taken into account. In fig. 6 [34] the level of signal after 41 cm of drift is plotted as a function of pressure for Ar/CH₄, Ar/Ne/CH₄, Ne/C₂H₆, Xe/C₃H₈, CH₄, C₂H₄, C₂H₆, C₃H₈ and iC₄H₁₀. The gas purity was in the 5–10 ppm O₂ range for noble gases and about 15–20 ppm O₂ for the hydrocarbons. Argon, neon and methane are remarkably insensitive to attachment, pure hydrocarbons may be acceptable in special cases, for relatively short drift distances. Unfortunately, heavy hydrocarbons are detrimental to the lifetime of the detector (deposit on the electrodes). Results of similar measurements concerning various quenchers in argon [31] show problems with CO₂ as a quenching agent. The rate of electron attachment is obviously dependent on the drift velocity, i.e. on the E/p value used.

Drift velocity measurements for a wide variety of gas mixtures are available (see e.g. refs. 29 and 34 and refs. given therein). Certain neon mixtures show saturated drift velocities already at low E/p values which is making them attractive for applications in imaging detectors, if the saturated level of about 3.5 cm/ μ s is

Fig. 7. Drift velocities in mixtures of Ne/iC₄H₁₀ and in 3-component mixtures of Ne/Ar/C_nH_m.

acceptable. Examples of drift velocities in Ne/iC₄H₁₀ and Ne/Ar/(C₂H₄, C₂H₆, C₃H₈) are shown in fig. 7 [29].

The better performance of neon with respect to argon in 64 samples of 4 cm was also found for 128 × 2 cm samples [29]. The resolution was improved by better control of systematic effects (working without drift) which allowed for gain of one standard deviation in the resolving power. The relativistic rise in neon was measured at several pressures; examples for 1 and 2 atm are shown in fig. 8 together with data for argon from [31]. The higher plateau level in argon and steeper slope in neon were confirmed.

4. Performance required for relativistic π/K separation

Neglecting for the moment possible conflicts with demands for optimized track reconstruction performance (geometry, gas gain, sample size, drift distance, response of electronics chain and pulse shaping, etc.) we could try to evaluate a set of minimum requirements which will make a “most compact” detector adequate for π/K identification in the relativistic rise region. To

Fig. 8. Relativistic rise at 1 atm (top) and 2 atm (bottom) in Ne and Ar.

illustrate the difficulties encountered there, fig. 9 [4] shows the ionization measured on fast forward secondaries from 70 GeV/c K^+p interactions. Due to background tracks and related pattern recognition problems causing loss of useful samples, the performance of the detector (EPI, 128×6 cm samples, 1 atm Ar + 5% CH_4 , 6.6% fwhm overall resolution attained during

Fig. 9. Ionization measurements for positively charged secondaries from 70 GeV/c K^+p interactions in the EPI detector with > 80 clean samples.

calibration) was reduced to about 8% fwhm. The bands of pions and kaons are clearly visible, but it will be desirable to have resolution better than the quoted 8% fwhm ($\sigma/E \sim 3.4\%$). In the example of 15 GeV/c protons, pions and electrons measured in 128×2 cm samples in Ne/ C_2H_6 at 2 atm shown in fig. 10 [29], the width of the distributions is about 7.5% fwhm.

In large scale devices the final performance is more dependent on the combination of various systematic effects than on the number of samples or sample size, so we could simplify the optimization procedure by concentrating on the required detector depth. A compila-

Fig. 10. Truncated mean distribution for 15 GeV/c protons, pions and electrons in Ne/ C_2H_6 at 2 atm, using 128×2 cm samples.

Fig. 11. Resolutions achieved in large detectors as a function of the total detector depth.

tion of resolutions achieved so far in big operational detectors, and in some full scale tests is shown in fig. 11. The covered range in depth extends above 10 m · atm equivalent. The plot in fig. 11 contains data from: (a) EPI, 1/2 EPI [3,4] and EPI test [23]; (b) high pressure results for Ar/CH₄ [29]; (c) low pressure Xe/C₃H₈, assuming rough equivalence with Ar [34]; (d) LBL TPC [11]; (e) ISIS 1 and ISIS 2 [6,7]; (f) CRISIS test [8]; (g) JADE jet chamber [35]; (h) CLEO dE/dx detector [17]; (i) AFS vertex chamber [15]; (j) ARGUS test [36]; (k) pure C₃H₈ [29] showing the record performance obtained to date (the arguments against the use of pure hydrocarbons were already discussed). With the exceptions mentioned above, the gas mixture used was in the majority of cases Ar/CH₄ (Ar/CO₂ in ISIS and CRISIS, Ar/C₂H₆ in AFS). The plotted results represent always the best performance attained under ideal conditions, i.e. for selected events with limited background. Some of the "error bars" indicate degradation of resolution under severe background conditions. The depth dependence could be expressed with reasonable precision by $13.5L^{-0.37}$ (drawn on the graph). If the 8% fwhm limit in resolution is to be attained, depth of at least 4 m · atm will be needed. Estimations based on semi-empirical formulas [23,26,28] give comparable results. The atmospheric pressure version of such a detector will not fit into the space available in colliding beam applications. Increasing the pressure will improve the situation, providing that the inevitable pressure vessel could be tolerated and, furthermore, that the gain in resolution is not offset by considerable decrease in the relativistic rise. Fortunately, the influence of the pressure on the slope of the relativistic rise is not very strong, so that in the first approximation only the maximum momenta will be affected. An operational pressure near 2 atm is clearly the best for practical reasons. The pressure vessel walls can be kept reasonably thin and the pump-down option offers great ad-

Fig. 12. Expected particle separation in Ne and Ar at 2 atm. Truncated mean of 128 × 2 cm samples.

vantages in control of the gas purity. Fig. 12 [29] shows as an example the particle identification efficiency for a detector of 5.12 m · atm (2.56 m at 2 atm) equivalent depth, with resolution close to 7.5% fwhm. The full curves are for neon and the dashed ones for argon. The sample size is 2 cm, the resolving power (D/σ) scale on the right is for a scaled-down version of 128 × 1 cm samples at 2 atm. The differences in favour of neon (with the exception of e/π separation) were found to be more pronounced for large sample size, which indicates that (4 cm · atm) is already well below the optimum value in neon. For argon the optimum sample size is about 5 cm · atm. In our previously proposed limit case of 4 m · atm detector depth, we could expect the π/K separation at a level of $\geq 4\sigma$ from ~ 3 to ≥ 20 GeV/c. Use of neon will allow for operation at lower pressure, if a certain loss in the e/π separation efficiency with respect to argon is acceptable.

It is difficult to discuss in sufficient detail all the aspects of the influence of the electronics design (ac coupling, baseline shifts, pulse shaping response, pile-up, etc.) on the detector performance. We shall concentrate only on problems related to the shape of the ionization loss distributions with respect to the available dynamic range of the electronics chain. This is especially im-

Fig. 13. Relative width of single sample ionization loss distributions as function of sample size.

portant for relatively small samples below 1 cm·atm where only a limited number of reliable distribution measurements is available. Those measurements were realized at reduced pressure in samples of depth of several cm. The dependence of the width of single sample ionization loss distribution on the sample size is shown in fig. 13. The data in the plot are from: (a) EPI [3,4] for Ar/CH₄ at 1 atm; (b) high pressure result in Ar/CH₄ [29]; (c) low pressure in Xe/C₃H₈, assuming similar behaviour for all noble gases as illustrated in fig. 4 [34]; (d) pure C₃H₈ results for comparison [29,34]. The distribution width follows reasonably well a $(85t)^{-0.26}$ dependence (full line in the graph). The discrepancy with the $(96t)^{-0.32}$ dependence proposed in ref. 27 (dashed line) is within acceptable limits. Results

for argon from ref. 26 are comparable. The distributions measured at low pressures could therefore be used for sample depth ≤ 0.5 cm·atm. Fig. 14 shows examples of such distributions, derived from [34]. It corresponds to about $0.4 \div 0.5$ cm of argon at 1 atm. The first distribution is for a particle at the minimum of ionization (~ 40 ion pairs, ~ 600 eV energy loss). The second distribution is for the plateau of the relativistic rise ($\sim 1.6I_0$). The relative width is about 130% in the first and $\sim 115\%$ fwhm in the second case. The arrows on the top indicate shifts of the peaks which will be typically caused by ± 20 mb (maximum encountered) variations in the atmospheric pressure. Introducing realistic angular corrections for track length in both planes with respect to the signal wire will produce (with some reserve) the last distribution at about $4I_0$. Note that the plotted distributions are not normalised. The position of the I_0 peak could be shifted towards the low values, if the signal to noise ratio will remain at acceptable level. This is important, because the truncated mean method “prefers” the low ionization values. At the upper end we see the limit of the dynamic range of the 8-bit linear ADC. Fig. 15 shows the distributions from fig. 14 “processed” in an ADC with logarithmic response. The dashed distribution represents the mentioned reserve if the noise level is tolerable. A linear 9-bit ADC will have adequate dynamic range. In principle, the dynamic range of a “logarithmic” ADC could be expanded or compressed within certain limits [37], but it seems that 6-bit log ADC will be just sufficient. If such wide dynamic range will be not needed, the actual ADC resolution of

Fig. 14. Examples of single 0.4 cm sample distributions at 1 atm. Particles at minimum ionization, on the plateau, and with maximum correction for angular effects.

Fig. 15. Distributions from fig. 14 processed in a logarithmic response ADC.

only 4 bits will be sufficient (the errors are dominated by the fluctuations in the ionization loss).

5. Longitudinal drift and fine sampling

As already mentioned in sect. 2, a potential improvement in the efficiency of the particle identification will be in using many very fine sampling intervals [38]. Recently, several experiments were realized in order to investigate the performance of detectors where the ionization deposited in the detector drifted along the particle trajectory and the fine sampling was obtained by flash ADCs at 10–40 ns intervals. With fast shaping amplifier response and at moderate drift velocity the corresponding sample “size” was below 1 mm. Improvements of resolving power by about a factor of two were quoted from prototype measurements [39,40], when selected part of the data was extrapolated to 1 m of total track length.

To illustrate the method fig. 16 shows (top) an example of a single 15 GeV/c pion detected in 1 stage (4.7 cm of drift) of a 16-stage detector [41] in Ar/CO₂ and with 25 ns sampling interval, corresponding to about 0.3 mm sample “size”. Most of the large individual ionization clusters are visible, the small clusters were smeared by diffusion and not resolved. The bottom part of fig. 16 depicts the result of accumulation of many such events under the same conditions. The peak at the beginning is caused by the addition of ionization from both sides of the signal wire inside the proportional cell. Due to limitations imposed by the response of the shaping circuits, only 133 samples per stage (“flat part” in fig. 16) could be used in this case, so that from the total detector length of 88 cm only 64 cm were “active” for particle identification. A similar example is shown for Ne/C₃H₈ in fig. 17 (top). The sample “size” corresponding to 25 ns sampling rate was about 0.9 mm, 35 samples per stage were used. In the bottom part of fig. 17 are shown the final distributions of a truncated mean of 40% smallest values for 15 GeV/c protons, pions and

Fig. 16. Example of a flash ADC response over 4.7 cm of longitudinal drift (25 ns/bin) for one 15 GeV/c pion passing through one stage of the detector filled with Ar/CO₂ at 1 atm (top). Summed response for many particles in all 16 stages of the detector (bottom).

Fig. 17. The FADC response (25 ns/bin) summed over 16 stages and many particles for Ne/C₃H₈ (top) and distributions of truncated means (40% smallest values) for protons, pions and positrons at 15 GeV/c in Ne/C₃H₈, using 560 samples per track (bottom).

electrons, in Ne/C₃H₈. The resolution for pions is in the range of $15 \div 20\%$ fwhm, which is consistent with the predicted value for about 50 cm detector length in fig. 11. Also, the $e/\pi/p$ ratios are comparable to results obtained by classical charge integration over large samples [29,34]. Similar behaviour has been found for several different gas mixtures for a variety of drift velocities. So it seems that apart from technical difficulties which will arise in construction of large volume detectors of this type, there is virtually no improvement in performance which will allow for reduction of the detector size. Measured widths of the single “fine” sample distributions were added for comparison into fig. 13: (e) Ar/CO₂ (0.3 mm) and Ar/C₃H₈ (0.9 mm) [41]; (f) Ar/CO₂ [40]; (g) Ar/CH₄ [39]. Compared to values expected by extrapolation from “large” samples, the “fine” samples distributions appear narrower. This may be an indication that the content of “fine” sample is not correctly defined by the drift distance between two FADC samples. Indeed, the average distance between the primary ionization clusters, electron diffusion during the drift,

sampling interval and the shaping time constants are of the same order, which may introduce correlation effects.

6. Amplitude calibration using laser beams

Recently, use of laser induced ionization for simulation of charged particle tracks was introduced and is now widely used [42–49]. In spite of the fact that the exact mechanism of (double) excitation is not yet fully understood, pulsed UV lasers are currently used for generation of long straight tracks in big detectors, for position calibration, drift velocity and diffusion measurements, measurements of space charge effects, etc. Compared to pulsed X-ray sources used previously [19], present two-stage N₂ lasers are compact and easy to operate. The required UV transparent windows could be incorporated into the detector without great difficulties. Another attractive features of the use of laser beams is the possibility of beam splitting for studies of two-track resolution. We will concentrate here on the applications aimed at amplitude measurements ($\approx dE/dx$) over long tracks, without any photo-ionizing additives in the gas.

Using pulse length of ~ 300 ps fwhm, energy density $\geq 10 \mu\text{J}/\text{mm}^2$ at 337 nm (photon energy 3.7 eV) is required to produce ~ 100 electrons/cm in Ar at 1 atm, which corresponds to the energy loss of relativistic particles. The number of electrons was found to depend quadratically on the energy density up to about $20 \mu\text{J}/\text{mm}^2$, with a transition to linear dependence at higher energy densities. This transition was reproduced in several experiments, which is somewhat surprising, because it indicates presence of a common photo-ionizing impurity in similar concentrations (the 3.7 eV photons from the N₂ laser cannot ionize directly the argon

Fig. 18. Pulse amplitudes measured simultaneously using N₂ laser tracks through 2.56 m long detector. Beam enters at cell 0. Uncorrected data in Ar/CH₄ at 2 atm, no focusing.

Fig. 19. Amplitude distributions from groups of adjacent cells from fig. 18 at the detector entry (a), near centre (b) and at the exit (c). Laser intensity fluctuations (14% fwhm) not removed.

atoms with ionization potential of 15.7 eV). The dimensions of the laser beam spot could be made sufficiently small by adequate collimation, with beam divergency limited essentially by diffraction (at least in one plane). If the available energy density is high enough to work in the linear range, track lengths above 2 m could be used for amplitude calibration. Single lens focusing cannot be applied, but the use of an afocal system [48] may produce even more uniform beam over the same distance. Pulse-to-pulse intensity variations could be to great extent corrected for by using a reference photodiode. Almost symmetric pulse height distributions were obtained, with relative width $< 20\%$ fwhm. In a two-track resolution study [49] onset of saturation at gas amplification factor $\sim 5 \times 10^3$ has been found, which is consistent with the generally accepted value in argon.

In principle, lasers cannot be used for absolute calibration for dE/dx purposes, due to long-term stability problems (beam area, halo, unknown photosensitive impurities in the gas, etc.). Reliable relative calibration (mapping of local non-uniformities) will depend on the level of control over the beam area and energy density. As an example, fig. 18 shows uncorrected data from amplitude measurements realized in our group at CERN. The track length is 2.56 m in 2 atm of Ar/CH₄ mixture. A two-stage 300 ps pulse length N₂ laser was used, with the halo removed by collimation, without focusing. The laser output was 240 μ J and the measured pulse amplitude at the detector entry was

about 3 times higher than ionization signal from relativistic particle tracks. The fluctuations of the laser intensity (14% fwhm on a reference photodiode) were not removed. Uncorrected distributions from groups of channels at the detector entry, near the centre and at the exit are shown in fig. 19. The relative widths are 20, 24 and 26% fwhm respectively. The amplitude ratio from entry to exit is about 4:1 and the dependence on distance along the track is roughly exponential (the amplitude scale is arbitrary). More sophisticated (YAG) lasers working at different wavelength and with beam of better quality will make the amplitude measurements more reliable.

7. Conclusions

Particle identification by ionization sampling could be easily combined with the trajectory determination in the central vertex chambers of large colliding beam detectors. If a compromise solution to conflicting demands for optimized track reconstruction (diffusion, drift velocity, gas gain) could be found (separate functions?), at least 4 m · atm equivalent path will be needed for reliable π/K separation in the relativistic rise region. Ar/CH₄ is the best gas mixture for application in large drift volumes, because of its low sensitivity to impurities. Use of neon will allow for reduction in the gas pressure with respect to argon. K/p separation is marginal in any case, e/ π separation will be better in argon.

Optimum dE/dx performance extending to higher momenta will be obtained at atmospheric pressure. Use of (moderate) pressure will open the attractive option of pump-down of the pressure vessel (less problems with the gas purity).

The dE/dx sampling will be most efficient in a detector geometry with classical (small) drift cells of the ARGUS type, which could work with single hit electronics without problems related to space charge (no gating required). A bicycle wheel geometry similar to the jet chamber one for JADE with moderate drift distances will suffer less from the systematic effects than a TPC detector with much longer drift. There the space charge problems already affect the track reconstruction precision and a perfect gating system is required [50]. The TPC is also very sensitive to impurities in the gas.

In general, the dE/dx sampling efficiency will be better if a sample size $> 1 \text{ cm} \cdot \text{atm}$ is used. There is no hard experimental evidence for certain predictions of improved performance for smaller sample size.

In order to reach the desired particle identification efficiency, all systematic effects must be fully under control. Detailed analysis of parameters affecting the detector performance is not possible here, so I will simply make a list of the most important ones, together with some potential problems:

- Mechanical tolerances and stability (temperature, pressure, electrostatic forces).
- Uniformity of electric and magnetic field in the drift space.
- Absolute amplitude response calibration, control and monitoring (gas pressure and temperature, mixture stability, gas purity, stability of the power supplies and of electronics gain, etc., long-term monitoring precision, especially if operating at atmospheric pressure – see example in ref. 4).
- Background problems (space charge, gating efficiency for long drift distance, saturation effects).
- Large corrections for inclined and curved tracks.
- Response of the electronics chain (noise, stability, pulse shaping, baseline shifts, crosstalk, dynamic range, etc.).

Some of the important design features could be easily tested using laser generated tracks; the final performance of a big detector could be assessed only in particle beam tests.

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