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DEVELOPMENT AND PERFORMANCE OF A
LARGE-SCALE MULTILAYER PROPORTIONAL COUNTER SYSTEM
USED IN THE EXTERNAL PARTICLE IDENTIFIER (EPI) AT CERN

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Abstract

A matrix of 4096 gas proportional counters of $6 \times 6 \text{ cm}^2$ cross section and 1 m height arranged in 128 layers of 32 cells each is used for identification of fast pions, kaons and protons emerging from hadron interactions in the 3.7 m bubble chamber (BEBC). Particle separation in the momentum range up to at least 70 GeV/c is achieved by ionization sampling in the region of the relativistic rise. Resolution in dE/dx of 6% FWHM (2.5% RMS) was reached and maintained over extended running periods. The relativistic rise was measured in the momentum range of 20-110 GeV/c. The results of the EPI tests are used in analysis of certain practical application limits of the dE/dx sampling method.

Introduction

Identification of relativistic particles by ionization sampling in thin gas layers is used in a number of detectors being designed for colliding beam machines (e.g. "bicycle wheel" detector for PETRA at DESY; TPC for PEP at SLAC; "image chamber" for $\bar{p}p$ collider at CERN) and for hybrid

bubble chamber systems (CRISIS for FNAL; ISIS for EHS at CERN). The External Particle Identifier (EPI) was constructed at CERN with the aim of helping to resolve ambiguities in identification of fast forward secondaries emerging from hadron interactions in the Big European Bubble Chamber (BEBC). The ionization sampling detectors have the advantage of good granularity and are more suitable for applications in restricted space conditions than multicell threshold Cherenkov counters.

Particle identification by ionization measurements

As shown in fig. 1, a single layer atmospheric pressure gas proportional counter has typically a resolution of about 60% FWHM and the distribution of ionization losses is asymmetric. Between pions and kaons at 70 GeV/c the difference of most probable value of ionization is only about 8%. Increasing the single detector thickness does not help because even at 5 m depth the resolution is still about 20% and the asymmetry remains (fig. 2, data from [1]). However, under certain conditions it

is possible to improve the resolution of a single counter and reach for example 8% FWHM in dE/dx resolution by method shown in fig. 3. The detector that was used to study this was 120 cm long and of a small diameter (0,5 cm); particles traversed along the detector axis [2]. A large part of the energetic δ -rays responsible for big fluctuations in ionization losses left the sensitive volume and the asymmetry of the ionization loss distribution was thus removed by a "geometrical cut". Fig. 4 shows the results obtained at 8.25 GeV/c for Ar + 3% C₃H₈ at 20 atm. Due to its small acceptance, the applications of such a detector are of course rather limited.

Statistical treatment of ionization loss samples from many layers of detectors traversed by the same particle allows greater flexibility in reaching an adequate dE/dx resolution. Maximum likelihood fitting or simply a truncated mean method (e.g. mean of lower half of the measured values) produces a distribution which is almost gaussian in shape, the width being reduced proportionally to the square root of the number of samples.

Optimization criteria for design of a multilayer detector, valid also for dE/dx sampling in large drift volumes, are summarized in fig. 5 for argon at atmospheric pressure. Total detector length is shown as a function of number of layers of a given thickness, needed for a required resolution in dE/dx . Below 10% FWHM the particle separation is only marginal. The performances (achieved or expected) of TPC, EPI, ISIS and IC are also

indicated in fig. 5. For devices working at higher pressures the sample thickness must be scaled correspondingly. The resolution curves are valid for the ideal case of a detector with all layers identical in response and using an ideal maximum likelihood method for data analysis. Truncated mean methods degrade the resolution generally by about 0.5 to 1% (e.g. instead of 5.5% FWHM only 6% is reached). The same is true for disturbances in the maximum likelihood fitting caused by cut-offs and crossing tracks. Further possible degradation by the influence of a long distance drift in certain detectors now under construction is not yet properly understood. In this respect the EPI represents a very conservative approach to the design of an ionization sampling detector.

The EPI detector

The EPI was constructed to work in conditions specific to bubble chamber operation [3]. The RF separated beam allows for full $\pi/K/p$ separation up to 70 GeV/c; partial separation is possible up to about 120 GeV/c with the help of a tagging system consisting of threshold Cherenkov counters and two scintillation counter hodoscopes. Due to the RF cavities the beam spill time is limited to 3-4 μ s, the flux being typically about 5 particles per accelerator burst. Under those conditions all particles from a given burst are treated as

simultaneous and no time resolution inside this burst has to be envisaged. The 3.7 m bubble chamber was not designed for hybridization, so the access and therefore the acceptance at the chamber exit are limited. The beam axis is at 4 m above ground level. Any equipment installed in the bubble chamber hall is subject to very strict hydrogen safety regulations, requiring pressurization, complicated interlocks, alarms and excluding use of certain gas mixtures for the external detectors. As shown in fig. 6 the EPI is a matrix of 4096 individual 1 m high proportional counters (cross sections of $6 \times 6 \text{ cm}^2$) arranged in 128 layers of 32 cells each. 64 double-layer modules create a stack of about 8.5 m in total length. The module frames are epoxy glued sandwiches of printed circuits and glass. The partitions between adjacent counters are formed by single field wires as shown in fig. 6. The electrostatic field map is presented in fig. 7 for inside cells. The field map in fig. 8 indicates the influence of the module frame and the detector edge on the corner cells. In order to minimize this effect, each layer has additional cells at the edges, which are not used in the data analysis.

At 2.2 kV the drift time difference between electrons produced by a particle traversing near the central wire and by one that passes near the cell boundary is $1.02 \mu\text{s}$ (fig. 9, measured using a collimated ^{106}Ru source). The spread of the distribution is $0.43 \mu\text{s}$ FWHM for the source aligned on the signal wire and nearly $1 \mu\text{s}$ when aligned on the cell boundary^(*).

To reduce losses of information due to multiple tracks in the forward cone of the emerging secondaries the non-interacting primary beam particles pass through an insensitive region near the EPI edge as marked in fig. 6. This region is produced by fixing thin glass sleeves on the first six signal wires of each layer. Fig. 10 shows several drift time spectra measured at different vertical positions along the edge of one of these glass sleeves. The transition between zero and full efficiency extends to about 1 cm from the edge of the glass tube.

$\text{Ar} + 5\% \text{CH}_4$ at atmospheric pressure flows slowly through the detector at a rate of about 5 l/min. Inside the detector box an overpressure of 2 g/cm^2 is maintained by a special exhaust flap valve. The total sensitive volume is about 17 m^3 . The gas amplification factor in a cell is 4×10^3 , a single minimum ionizing particle produces on the average 0.15 pC of charge at the amplifier input (for an energy deposit of 9 keV/6 cm). The electronics, consisting of an amplifier, shaper, track and hold, ramp comparison 8-bit ADC and readout circuits for each of the 4096 channels, are mounted directly on the detector modules.

The ionization deposited by the particle traversing the detector is sampled in up to 128 independent measurements on each track. The digitized pulse amplitudes are transferred to the on-line computer (NORD-10) formatted and written onto magnetic tape. The ionization information is processed off-line

(*) Note that the accumulation time for the latter spectrum was four times longer. From this it follows that on the average the drift velocity is about $3 \text{ cm}/\mu\text{s}$.

together with the bubble chamber and tagging data for each event. The particle momentum is determined from the bubble chamber measurements. After filtering out the background and crossing tracks the corresponding string of the ionization samples is reconstructed and processed. The obtained ionization estimator is then compared to a previously measured reference curve.

Two typical EPI events are shown in fig. 11, where the detector is "seen" from the top and the particles are coming from the left. Fig. 12 shows the EPI assembly in place behind BEBC. The detector is mounted in a pressurized steel box on a support allowing for alignment to various primary beam momenta. The precision of rotation, horizontal and vertical movements is within 1-2 mm. The total weight of the assembly is about 52 t. More technical details could be found in [4].

The EPI performance

In order to push the dE/dx detector performance to higher momenta, an excellent linearity and absence of saturation effects is essential. Fig. 13 shows an example of an energy response calibration, using ^{241}Am X-rays superimposed on a ^{90}Sr spectrum. The measurements were performed using a single $6 \times 6 \text{ cm}^2$ EPI cell. The full line in fig. 14 shows the linearity of the energy response (correct within 1%) as measured by various X-ray sources. No saturation effects were detected up to 60 keV of energy deposit. Space charge effects impose

an upper limit on the gas amplification factor, in our case $A < (5 \times 10^3)$. The dashed area on fig. 14 indicates the single cell resolution as a function of energy deposit. The range of dE/dx sampling is also indicated.

The dE/dx detectors working at NTP are sensitive to atmospheric pressure variations. Fig. 15 shows the recording of the EPI performance, monitored by radioactive sources over a period of several days. An increase of 1% (10 mb) in the atmospheric pressure was causing about 7% drop in the measured ionization values. This effect could be reduced to some extent by an automatic gain control acting upon the H.T. on the detector. Regular checking of the "absolute" calibration of the dE/dx scale is performed using particles of well-known momenta (primary beam).

When the corrections for differences of response of the individual cells and the above mentioned pressure corrections were applied, the resolution of the complete EPI detector was 6% FWHM for particles traversing the full detector length. This is shown in fig. 16 for 50 GeV/c momentum and an unseparated mixture of pions and protons. For each event the mean of 40% smallest values of a sample of 128 traversed cells is plotted.

Finally, the relativistic rise of ionization was measured in the 20-110 GeV/c momentum range as presented in fig. 17, together with some previous EPI prototype results. The dotted curve represents the theoretical

predictions for the relativistic rise including Sternheimer's density effect corrections. The measured ratio of ionization on the Fermi plateau to minimum ionization was established to be near $I/I_0 = 1.55$. This value should be valid for currently used gas mixtures at NTP. It should be remembered that the ionization plateau level is considerably lower at higher gas pressures which must be taken into account in design of high-pressure dE/dx sampling detectors.

Summary

The EPI characteristic features could be summarized as follows:

Identification efficiency:

flux and experiment dependent;
 $\pi/K/p$ up to 70 GeV/c.

Resolution in dE/dx:

6% FWHM (2.5% RMS) achieved.

Detector:

1 m (V) x 1.92 m (H),
4096 cells in matrix 32 x 128,
each cell 6 x 6 x 100 cm³.

Length:

~ 8 m + box + MWPC's.

Beam hole:

36(H) x 6(V) cm², full length of the detector.

Gas:

Ar + 5% CH₄ at NTP, flow 5 l/min.,
detector volume 17 m³.

Amplification factor:

4×10^3 , non-linearities below 1% over the full dynamic range,
9 keV/6 cm deposited by minimum ionizing particle, 0.15 pC of charge produced.

Time resolution:

slow, corresponding to the beam spill time (~ 5 μ s).

Data acquisition:

8-bit ADC per channel, 300 μ s conversion time (could be reduced to 80 μ s), double event buffer per channel.

Readout time:

< 10 ms for 4096 channels in the hardware, under 100 ms via parallel data link and CAMAC DMA interface into a NORD-10 computer.

Movements:

± 10 cm vertically, $\pm 5^\circ$ rotation,
 ± 3 m (+ 5 m extension) laterally,
precision ~ 1 mm.

Weight:

52 t including supports.

Determination of entry and exit point:

3 chambers from the External Muon Identifier; additional 2 x 3 MWPC planes of 0° , $\pm 30^\circ$, 4 mm wire spacing, total of 3000 wires, 16 time slot buffers per wire.

25 000 BEBC pictures of 110 GeV/c K^- were taken with EPI, the development of the off-line programs and data analysis follows the processing of the bubble chamber data. Another SPS run fully dedicated to hadrons in BEBC with EPI is being prepared.

Conclusions

From the experience gained during the EPI tests it is possible to indicate and discuss several factors influencing the application limits and the maximum attainable resolution.

Those considerations are valid also for other dE/dx sampling detectors. Even the most important of such effects appear only at the 1% "absolute" level (compared to 6% FWHM). They were therefore not yet noticed during some reduced scale prototype tests of the new detectors. It seems that the practical limit in resolution, which could be reached in large-scale detectors, is about 5% FWHM.

It has been pointed out already, that the "brute force" simple method of truncated mean is slightly less efficient than an ideal full maximum likelihood method, where more information contained in the shape of the ionization loss distribution is used. Theoretically the net gain there is about 0.5% on the level of 6% FWHM. This potential improvement of resolution is unfortunately mostly cancelled out by the strong dependence of the fitting on the position of the high-energy cut-off relative to the peak and by the increased sensitivity to crossing tracks. Further causes of loss in resolution are residuals from inevitable lack of precision in the individual channel response corrections and in the long-term monitoring of the energy loss calibration (see e.g. the difference between the X-ray and ^{90}Sr sources and the last beam particle data point on fig. 15). Precise corrections of the influence of the edges of the detector and of the beam hole boundary are difficult. Wrong decisions in filtering and pattern recognition programs are obviously also reducing the resolution which deteriorates rapidly for higher particle fluxes and multiplicities.

From fig. 1 it is clear that the signal to noise ratio and consecutively the value of ionization chosen for the lower cut in useful data is also important, especially in connection with the truncated mean method, where the influence of small ionization values is artificially exaggerated. In the same context the position chosen for the most probable value of ionization inside the ADC dynamic range will slightly modify the detector performance, as well as the related problem of handling the contents of the overflow ADC bin.

When using the truncated mean method it should be kept in mind that the behaviour of a truncated mean as a function of the deposited ionization is different from that of the overall mean. This could be demonstrated with the help of a simple model. Let the ionization deposited in a cell follow a rectangular distribution with width 2α and overall mean $\bar{a}$. Then the mean of e.g. the smallest 50% of all values from a large set of samples is $[\bar{a} - \frac{1}{2}\alpha]$. Now let the particles traverse two successive cells. The folded distribution is then a triangle with base-line 4α and overall mean value $2\bar{a}$, as expected. The truncated (50%) mean is by contrast more than doubled:

$$\bar{X}_t = 2\bar{a} - \frac{1}{3}(2\alpha) = 2\bar{a} - \frac{2}{3}\alpha.$$

To quantify this increase for the experimental situation the EPI measurements for pions and protons at 50 GeV/c were used. For each track the values of adjacent cells were added to form 64 12 cm samples

from the original 128 of 6 cm. While the overall mean doubles, the mean of 40% smallest values increases almost 2.2 fold. Since this is just a reflection of the narrowing of the distribution with increased ionization, it in effect follows that the relative rise in ionization rises more steeply with momentum for a truncated mean method than the overall mean. In correcting for increased track length for strongly slanted tracks the same remark holds. For the EPI experiments the latter effect is typically on the level of less than 0.1% with few values above 0.5% and could be ignored in most cases.

It is interesting to note that the ADC resolution could be reduced without excessive loss in the performance of the detector. This is shown in the following table where the original 50 GeV/c π/p EPI data were correspondingly "spoiled" by successive divisions of all ionization values by 2 with full rounding (the electronics implications resulting in possible non-linearity were not taken into account):

ADC bits	8,7,6	5	4	3	2
FWHM [%]	6.0	6.3	6.9	8.1	9.7

In the extreme case of yes/no (1 bit) decisions the loss of resolution could be compensated for by increasing the number of samples to 1000-2000 as indicated by an asterisk on fig. 5. This is already a method very similar to measurements of the primary specific ionization by a set of low-efficiency counters or by gap counting in a streamer chamber, where the distributions are more gaussian in shape. Another asterisk on fig. 5

indicates the other extreme case of a small number (16) of thick samples, which is interesting economically, but which will probably suffer from space charge effects.

Finally, a few general remarks about the resolution limits could be made concerning the new generation of dE/dx sampling devices using large-volume drift space and where the main effort in prototype studies were oriented mostly towards the precise track reconstruction. At present there is not yet enough convincing evidence available, that in addition to some problems discussed above, there will not appear further difficulties for inclined and crossing tracks, "old" and "new" tracks drifting across the same volume, influence of positive ion clouds from background tracks, influence of the drift field non-uniformities on the amplification factors of the charge collecting wires, etc. Also, the gas mixtures which are more suitable (small diffusion) for the track reconstruction might turn out to be less suitable for the dE/dx sampling. The spatial resolution for several simultaneous tracks running very closely together in jets might be considerably reduced if reliable ionization information would have to be collected.

In spite of certain inherent limitations of the dE/dx sampling detectors, these devices are very promising and will in the future profit even more from the new developments in electronics

components (CCD's). The high pressure detectors of this type are probably the only available compact equipment for colliding beam machine applications. On the other hand, improvements on the higher momentum side are possible by using heavier gas under reduced pressure and perhaps a combination with transition radiation detectors.

References

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Fig. 1 Typical distribution of ionization losses in a single 4 cm thick layer of argon at NTP.

Fig. 2 Single layer resolution as a function of layer thickness.

Fig. 3 Principle of reduction of the asymmetric tail of the distribution of the ionization losses by a "geometrical cut" in a long, small diameter single counter.

Fig. 4 Resolution of 8% FWHM achieved with the single counter of fig. 3.

Fig. 5 Optimum number of layers and layer thickness for a given resolution and total detector length.

Fig. 6 Schematic layout of the EPI.

Fig. 7 Field map of a single 6 x 6 cm² detector cell. Note the difference in the boundary between two adjacent double layer modules and two inside cells.

Fig. 8 Field map of a corner cell.

Fig. 9 Drift time spectra of a collimated ^{106}Ru source aligned on the single cell axis (left) and on the boundary between adjacent cells (right).

Fig. 10 Drift time spectra for several positions of the ^{106}Ru source along a glass sleeve in the "beam hole" region.

Fig. 11 Typical EPI events. Top view of the 32 x 128 counters matrix.

Fig. 12 EPI assembly behind BEBC. The beam axis is at 4 m above the floor.

Fig. 13 Spectrum of ^{241}Am superimposed on ^{90}Sr as measured in a single $6 \times 6 \text{ cm}^2$ cell.

Fig. 14 Linearity of a single cell response measured by X-ray sources.

Fig. 16 Protons and pions in unseparated beam at 50 GeV/c. Corrected data, mean of 40% smallest values per event from slice 2 of the EPI.

Fig. 17 Relativistic rise of the ionization measured during the EPI tests in the 20-110 GeV/c momentum range.