TEST-BEAM PERFORMANCE OF A TRACKING TRD PROTOTYPE

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Abstract

A tracking transition radiation detector prototype has been constructed and tested. It consists of 192 straw tubes, 4 mm in diameter, embedded in a polyethylene block acting as radiator. Its performance has been studied as an electron identifier as well as a tracking device for minimum-ionizing particles.

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1 INTRODUCTION
Lepton identification is expected to play a crucial role in addressing the TeV-scale physics which will become accessible with the commissioning of the Superconducting Super Collider (SSC) or the European Large Hadron Collider (LHC). Transition radiation (TR) is potentially a powerful tool [1] for electron identification at such energies. The radiation process does not significantly affect the particle energy and direction and these measurements are complementary to calorimetry. We present here the results of an R&D program [2, 3] to develop a transition radiation detector (TRD) and integrated tracking device for possible use with an experiment at the SSC or the LHS. This device uses plastic foam as the TR radiator. Thin-walled straw tubes are embedded in the foam as detector for TR quanta and ionization.

2 PROTOTYPE CONSTRUCTION AND TESTING
The prototype consisted of 4 modules (fig. 1). A total of 192 straws were arranged in 64 rows, each containing 3 straw tubes, 4 mm in diameter and 200 mm in length. The position of these three straws in each row was randomly displaced with respect to the preceding one in order to achieve uniform sensitivity of the detector, independently of the impact point of the beam.

The straw tubes were made of 64 μm thick Kapton and were placed in holes drilled in polyethylene foam, the centres of the holes being 8 mm apart. The foam had a density of 59 kg/m³. The pore diameters of the foam (≈ 200 μm) and the wall thickness (≈ 5 μm) between pores were remarkably uniform. Our tests of this foam indicated a TR X-ray yield reaching 85% of that of a regular stack of polyethylene sheets.

The straws were operated with a gas mixture of Xe:CO₂ (50:50). Our previous investigations [4] showed that this mixture combines the advantages of efficient TR absorption and short drift time. This time was measured to be 38 ns for a 4 mm tube diameter and a 50 μm anode-wire diameter. Preliminary results of radiation hardness tests indicated that with this mixture the straws have very long lifetime [5].

Another attractive mixture is Xe/CF₄, for which we measured even shorter drift times with similar energy resolution (fig. 2). This mixture also enhances the robustness of the chamber with regard to breakdowns.

A small lead-glass calorimeter was placed behind the TR modules to provide discrimination between pions and electrons. Additional information for particle identification was obtained from two Cherenkov detectors in the beam line. The purity of the beam (hadron contamination of the electron beam and vice versa) was at the 10⁻⁴ level.

The electronics used for this test consisted of preamplifiers mounted near the ends of the straws connected via approximately 45 m of coaxial cable to fast [12 ns full width at half maximum (FWHM)] shaping amplifiers, whose outputs were digitized by LeCroy 2282 charge-integrating analog-to-digital converters (ADCs). The data were recorded by a Macintosh II using the MacUA1 system software.

The straw tubes were calibrated and monitored using 4 tubes with ⁵⁵Fe sources permanently attached to them. Pedestal and electronic-gain variations were corrected by periodically recording data from a signal pulse injected into each preamplifier. Typically, the 5.9 keV X-ray peak of a ⁵⁵Fe spectrum was measured with a FWHM of 22%. During construction of the modules the uniformity of the gas gain of all the straws was measured. The r.m.s. deviation of the gains was found to be very small (≈ 1%).
The set-up was installed in the X5 test beam of the CERN Super Proton Synchrotron (SPS). Runs were made using the following beams:
- pions at 10, 20, 50, and 75 GeV/c,
- muons at 110 GeV/c,
- electrons at 10 and 30 GeV/c.
The TR modules were rotated so that the beam crossed the straw tubes at angles of 45° and 63°. This is interesting, with a view to possible detector geometries for future collider experiments [2].

3 TEST RESULTS

A typical run consisted of isolated particles passing through the detector in order to determine the rejection power. Figure 3 shows an event display of a single particle crossing the detector. Black circles present ‘hit’ straws, i.e. straws with a deposited energy of more than 0.2 keV. We define a ‘track’ as a band of ±2 mm width with more than 10 hit straws.

Deposited energy spectra for straws crossed by tracks of 10 GeV/c electrons and pions are shown in fig. 4. There is a large excess of energy deposited above 4 keV for electrons, as expected from TR X-rays. The spectrum for double pions, presented in the same figure, was obtained by convolution of the data. Double pions were defined as two pions crossing the detector with less than 4 mm between their tracks.

We have determined the TR photon yield, defined as the number of energy depositions above 5 keV, as a function of the particle γ-factor in the interval 70 < γ < 6 × 10⁴. The experimental results for π and e at 10 and 30 GeV, together with the theoretical predictions, are presented in fig. 5. They contain the contribution both of the relativistic rise in the energy loss, dE/dx (Eπ < 50 GeV, γ < 350), and of the TR photons (γ ≥ 350).

In order to determine the electron/pion discrimination capability, two parameters must be fixed: the energy threshold, E₃, above which a hit is considered as a TR X-ray, and the required number of such hits along the track, N₃. The track is called an electron if it has more than N₃ straws with an energy deposition greater than E₃. Further discrimination of false electrons from various sources can be achieved by utilizing two additional thresholds. The first of these thresholds, E₁, is set at ≈ 0.2 keV and provides > 95% detection efficiency for relativistic particles and is also used for tracking. The second threshold, E₂ ≈ 1.5 keV (located between the one- and two-particle dE/dx distributions), has 50% efficiency for minimum-ionizing particles. All thresholds were implemented in software and were varied.

Figure 6 represents scatter plots of the frequency of high-energy clusters (E > E₃), N₃, against the energy depositions satisfying the condition E₁ < E < E₂, N₁₂, for 30 GeV/c electrons (a), 10 GeV/c pions (b), and convolutions of the data to simulate two pions (c), three pions (d), and two electrons (e). Each point on the plot corresponds to one track. The results are given for a 63° angle between beam and straw axis. The solid lines represent two-dimensional maximum-likelihood cuts for 90% electron efficiency. The importance of the three-threshold algorithm in rejecting overlapping pions or electrons (e.g. from γ-conversions before TRD) is evident.

The performance of the TRD under different conditions is presented in fig. 7. It plots the probability of clusters being produced by electrons above some threshold against the same probability in the case of pions, as a function of the energy threshold for two angles (63° and 48°), between straws and the beam axis. The beam energy was 10 GeV and the gas mixture 50% Xe + 50% CO₂. Equal performance was observed at 63° and 48°.
Having obtained experimental data from our prototype we can simulate events for a detector of any length. Figure 8 shows the isolated pion rejection power as a function of the number of crossed straws or the detector length. This rejection factor corresponds to the electron detection efficiency of 90%. Different curves cover the pion energy range 10–140 GeV (in fact, data for 140 GeV are taken from muons at 110 GeV) for an angle between straws and a beam axis of 63°.

As a reasonable example for future experiments, we considered a detector with 80 layers of straws. The average number of crossed straws will be 40 and the proposed average angle between the particle and the straw axis is 63°. This corresponds to the average detector length of 72 cm. Figure 9 shows the resulting number of ‘clusters’ for this geometry. Each point of the curve corresponds to a certain energy threshold $E_3$. The abscissa of the point is the number of straws hit above this threshold (‘cluster’), produced by 10 GeV electrons, whilst the ordinate is the number of hits produced by pions. As an example, in this geometry, electrons of 10 GeV produce an average of 9 energy deposits above $E_3 = 5.2$ keV for 40 straws crossed, whereas pions at the same energy exceed this threshold only in 2 straws.

4 TRD TRACKING PERFORMANCE
The tracking performance of the detector has been studied with the following procedure: one track was reconstructed using the odd-numbered straws of the original track, whereas the second used the even-numbered straws. Each of these ‘tracks’ was taken as an independent measurement of the same original track.

Straight-line fits were made to each track

\[ y = a_1 x + b_1, \quad y = a_2 x + b_2 \]

and the differences in the slopes and intercepts

\[ \delta_a = (a_1 - a_2)/2, \quad \delta_b = (b_1 - b_2)/2 \]

were calculated, see fig. 11. The errors in track reconstruction amount to 1.5 mrad (fig. 10a) and 0.4 mm (fig. 10b) for 30 crossed straws.

5 TRD SHAPING STUDY
The absorption by a Xe atom of a TR photon produces several primary electrons due to the Auger effect. Their range is much smaller than that of a single $\delta$-electron of the same energy as the TR photon. The ionization cluster produced by a TR photon should therefore be much more localized and one could expect to improve the discrimination between TR photons and ionization clusters by very fast shaping.

5.1 Measurements of the TRD signal time shape
The time shape of the TRD signal was measured during the test with a fast LeCroy oscilloscope, providing about 40 amplitude digitizings with a time step of 2.5 ns. The oscilloscope was connected to one of the straws in the middle of the TRD, which will be referred to as the FAST straw. The shaping with different integration times was simulated by summing neighbouring oscilloscope digitizings; the sum of all digitizings has been taken as an analogue of the QDC signal.

The measurements were done with a 10 GeV beam containing both pions and electrons. The beam axis made an angle of 63° with the straws. A lead-glass calorimeter as well as two Cherenkov counters $C_1$ and $C_2$ were used to select electrons and pions.
5.2 Simulation of the detector for the LHC

In order to imitate the response of the Large Hadron Collider (LHC) detector we simulated straw signals in one tracking channel, defined as a band of 4 mm width and 64 cm length. Forty straws were randomly distributed within this band in such a way that the centre of each straw was not displaced by more than ±2 mm from the band centre. For a single particle the centre of the band coincides with the particle trajectory, whilst for two overlapping particles the band centre line is supposed to be between two trajectories.

For each generated particle and each straw, the distance between the particle trajectory and the centre of the straw was calculated, and the corresponding digitizations from the bank of experimentally measured time shapes were added to the straw signal as a function of time. For each straw the set of signals corresponding to different integration times was produced by summing adjacent time channels.

5.3 Two-pion rejection

A three-threshold cluster-counting algorithm was used to estimate TRD rejection of overlapping particles. For each electron candidate we counted inside the 4 mm band \( N_3 \)—the number of TR clusters, i.e. energy depositions above \( E_3 \approx 5 \text{ keV} \)—as well as \( N_{12} \)—the number of ‘single particle hits’, i.e. straw with deposited energy more than \( E_1 \) but less than \( E_2 \), where \( E_1 \approx 0.2 \text{ keV} \) and \( E_2 \approx 1.5 \text{ keV} \). It is interesting to compare the two-dimensional scatter plots \( N_3 \) with \( N_{12} \) for two very different integration times (fig. 11) in order to understand the nature of the rejection change. It can be seen that a shorter integration time for a TR cluster (upper threshold) does not change the electron distribution (figs. 11d,e) but diminishes the number of clusters from the particle overlap (figs. 11a,b). The shorter integration time for the ‘single particle hits’ changes both pion and electron distributions almost proportionally, thus not improving the double-particle rejection.

For each value of the integration time, energy thresholds \( E_1, E_2, \) and \( E_3 \) were varied to find the minimum of the double-pion rejection factor at the 90% level of electron registration probability.

The dependence of the two-pion rejection on the signal integration time is shown in fig. 12 for two cases:

a) all energy is measured with the same variable integration time;
b) only \( N_3 \) is counted with variable integration time whilst normal electronics with 40 ns shaping time is used to count \( N_{12} \).

A better two-particle rejection can be obtained by counting the TR clusters with an integration time less than 10 ns, whilst the \( N_{12} \) is counted with an integration time of about 40 ns. This rejection improvement can be explained by the difference between a local (\( \approx 300 \mu\text{m} \)) and very fast pulse from TR clusters, and relatively slow \( dE/dx \) pulses from two or more pions. Saturation below 10 ns reflects the finite extent of the pointlike TR clusters due to diffusion.

As the mean distance between overlapping particles is mainly defined by an external tracking device, it is interesting to know the rejection factor dependence on this distance. This dependence is shown in fig. 13 for two values of the integration time at the highest threshold (7.5 ns and 40 ns), and for 40 ns integration time for the ‘single-particle hits’. From this figure we can see that the simulated geometry is the worse case for the two-particle rejection.
Finally, the rejection dependence on the number of crossed straws, in the same conditions of deposited energy measurements and for the average distance of 1.5 mm between two pions, is presented in fig. 14. The general level of the rejection factor for our LHC geometry is better than 1%.

6 CONCLUSIONS

i) We have demonstrated the possibility of developing a combined TRD/tracker with polyethylene foam and thin-walled straw chambers.

ii) This detector has fast response: for example, the drift time in a 4 mm straw diameter can be reduced to 32 ns, while retaining the necessary Xe concentration. Radiation hardness tests of gas mixtures used in these measurements have shown that it is suitable for operation in the high-luminosity LHC environment.

iii) A three-threshold algorithm has been tested that not only allows one to distinguish single electrons from pions, but also effectively discriminates between multiple particles (hadrons in jet events and \( \gamma \) conversions). The rejection power against single pions varies from \( 10^{-3} \) to \( 10^{-2} \) when the pion energy varies from 1 to 10 GeV (the assumed detector length is 64 cm, plus 3 cm of foam preradiator). The TRD can also tag the muons above 100 GeV.

iv) The detector has good tracking capabilities: a simple tracking algorithm can provide an angular accuracy of 1.5 mrad and z-coordinate accuracy (at the entrance point) of 0.4 mm for 30 crossed straws (TRD length 50 cm).

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REFERENCES

[5] V. Bondarenko et al., to be published.
FIGURE CAPTIONS

Fig. 1. Experimental set-up.

Fig. 2. Drift time and energy resolution for 6 keV γ's as a function of the percentage of a CF₄ admixture in a straw chamber with cathode diameter 4 mm and anode diameter 50 μm.

Fig. 3. Event display of a single particle crossing the TRD prototype.

Fig. 4. Deposited energy distributions in one straw for 10 GeV beam energy.

Fig. 5. The predicted γ-dependence (solid line) of the probability of an energy deposition of more than 5 keV per straw, compared with experimental data.

Fig. 6. Scatter plots of the probability for an energy deposition of between $E_1$ and $E_2$ ($N_{12}$) against the probability of exceeding $E_3$ ($N_3$).

Fig. 7. The probability for pions to exceed a given threshold $E_3$ in one straw plotted against the same probability for electrons. The beam energy is 10 GeV.

Fig. 8. Measured pion rejection as a function of the number of crossed straws or the detector length for different pion momenta, for single particles crossing the straws at 63°.

Fig. 9. The number of clusters above a certain threshold $E_3$, produced by 10 GeV electrons and by 3 and 10 GeV pions in a radiator with 40 straws crossed at a 63° angle.

Fig. 10. Angle and position resolution of a 192-straw TRD prototype.

Fig. 11. Two-dimensional distribution (TR clusters plotted against ‘single-particle hits’) for two pions (a)-(c), and at single electron (d)-(e) for different integration times.

Fig. 12. Two-pion rejection as a function of the integration time. In (a) all discriminators have variable shaping time, in (b) only TR clusters are counted with fast shaping.

Fig. 13. Two-pion rejection as a function of the average distance between pions. The two curves correspond to the TR cluster counting with the integration times of 7.5 and 40 ns.

Fig. 14. Two-pion rejection as a function of the number of crossed straws.
Figure 6

Figure 7
Figure 8

Figure 9
Figure 10

Figure 11