A Systematic Study of the Particle Identification Performance in the Transition Radiation Tracker (TRT) of ATLAS

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1 Introduction

The two basic tasks of the TRT in ATLAS are the tracking of charged particles in the inner detector and the identification of electrons [1]. During the last few years, the layout of the TRT was optimised in terms of its tracking capabilities rather than its TR-performance. In order to obtain a reliable prediction for the final detector TR-performance, the simulation of the TRT in the ATLAS software was adjusted to data measured in the testbeam.

The data from the 1991 testbeam setup of the RD6-collaboration were used. The first step was to adjust all parameters of the GEANT simulation of this testbeam setup to the data, for both pions and electrons. This simulation used the complete ATLAS simulation package for the TRT, with the exception of the routines specific to the description of the testbeam setup. After these adjustments, the testbeam setup was replaced by the ATLAS barrel TRT geometry, as it is considered at the moment. This was done in several steps, for each of which the effects on the performance were analysed. One is thus able to make accurate and reliable predictions of the performance for possible changes of the TRT-layout (distance between straws and their geometrical arrangement, choice of radiator etc.).
2 Analysis of testbeam data

Data taken with the detector of the RD6-collaboration during autumn 1991 with the setup shown in fig.1 [2] were studied. The detector consists of 4 blocks of straws embedded in a polypropylene foam radiator of density 0.06 g/cm$^3$. Each block contained 24 planes of straws. The distances between the planes and between the straws in a plane were 8 mm each. In order to achieve a uniform detector response for all incoming particle impact points and directions, the planes were randomly displaced with respect to each other. The straws were 40 cm long and had a diameter of 4 mm. The total number of straws was 864. In order to have an efficient TR-absorption, a short drift-time and stability with respect to discharges, the straws were operated with a 70% $Xe$ / 20% $CF_3$ / 10% $CO_2$ gas mixture at a gas gain of 2.5 $\cdot$ 10$^4$. The angle between the straws and the beam direction was 53$^\circ$ (for more details see [2]). Runs with clean conditions were selected (30 GeV electrons from runs 1101 and 1102, 20 GeV pions from runs 1105, 1107 and 1108). In addition, the straws, which were dead or too noisy (corresponding to about 8% of the total) were discarded from the analysis.

3 Simulation of testbeam data

For the simulation of the testbeam setup, apart from the geometry description, the code from the DICE package [3], which is based on GEANT 3.21 [4] was used. The geometry description was adapted to reproduce the setup of fig.1.

The code, describing the TR-photon production and absorption, the energy loss and the signal processing (digitisation), was extracted from the standard DICE package. In this package, the TR-photon production is simulated using the so-called “field transport” approach [5], described in more detail below. A precise simulation of energy loss fluctuations is done using the PAI (photo-absorption ionisation) model [6].

The signal simulation included the avalanche development, space-charge effects, noise generation, time evolution of the analog signal in the readout electronics and discriminator behaviour [7].

For both the analysis of the testbeam and simulated data, identical routines were used to reconstruct tracks and to measure their characteristics (number of hits, hit distance to the track etc). The energy of the hits, used for track reconstruction, was required to be more than 0.2 keV.

The beam position and its spread were simulated as closely as possible to the position and spread measured from the data.

Software cuts were performed to simulate the trigger selection during data-taking. It was required, that the track line, defined by the first and last GEANT hit, has to enter and leave the detector inside its active fiducial volume. Simulated events with interactions had a small number of hits and were discarded by this trigger.

Inefficient and noisy straws were also accounted for in the Monte-Carlo.
4 Parameter tuning

4.1 Track reconstruction

As shown in several previous RD6 publications, e.g. [2], the TR-performance is rather sensitive to the track reconstruction. It was therefore important to achieve the same track reconstruction quality for the simulation as for the data.

One of the most sensitive distributions studied was the distance of all straw hits (with energy deposition above 0.2 keV) to the reconstructed beam particle track. For pions and electrons respectively, figs.2 and 3 show the probability to observe a hit as a function of the distance to the reconstructed beam particle track to the straw centre. These probabilities are uniform and close to 100% for distances less than the straw radius of about 2mm and fall sharply to values of a few % for larger distances.

4.1.1 Tuning of geometrical parameters

The shape of the falling edge of the distributions in figs.2 and 3 is rather sensitive to the straw radius (position of the edge) and to the individual straw alignment accuracy (slope of the falling edge).

The best agreement between data and simulation was obtained for an inner straw radius of 1.95 cm, as shown in fig.4.

The individual straw misalignment also affects this distribution, as shown in fig.5. The residual alignment accuracy of about 50 μ, determined from the analysis of testbeam data, is consistent with the optimal fit between data and simulation (56 μ).

4.1.2 Background hits

The level of background hits observed in these distributions at distances larger than the straw radius depends on the amount of secondary particles, produced upstream of the prototype, if the event was not rejected by the trigger, and on the amount of electronic noise in the detector.

Hits generated by the material in front of the detector result in a slowly falling background shape for straw hits with large distances from the track. As illustrated in fig.6, variations of the amount of this material in the beam line in front of the detector over a range of 5 – 10% of a radiation length lead to significant distortions of the distribution for electrons.

This material describes the other detectors placed in front of the TRT prototype during the testbeam period, such as beam chambers, trigger counters etc. The best agreement between data and Monte Carlo was found for 9% X₀ of material in front, an amount consistent with the analysis of multiple scattering effects [8].

On the other hand, electronic noise creates a flat background over all distances from the straw hit to the beam track, which is identical for electrons and pions. The level of this noise, measured with the prototype, is consistent with expectations (white noise with an amplitude of σ = 85 eV), as shown in fig.7.

The number of hits per reconstructed track was compared between data and simulation, both for pions (fig.8) and electrons (fig.9). The average numbers of hit straws
$< N_\pi >$ and $< N_e >$ were found to be respectively $41.3 \pm 3.2$ and $41.5 \pm 3.3$, with good agreement between data and simulation.

### 4.2 Simulation of dE/dx

#### 4.2.1 Description of energy loss

The simulation of the energy loss of charged particles in thin gas layers in GEANT versions prior to version 3.21 did not describe perfectly the tails at large energies. This was improved in the GEANT 3.21 version by introducing the PAI model [6] as an option. Due to some inaccuracies in the data tables, GEANT 3.21 still does not describe correctly the fluctuations of the energy loss in a Xe gas.

In addition, in order to have a correct drift-time simulation, the spatial distribution of the deposited energy has to be modelled also. Although this is important for many gas detectors, GEANT does not provide this information. For these reasons, a dedicated code, using the PAI model [6], was developed in the sensitive gas inside the straws to simulate energy loss due to ionisation.

This program calculates the energy deposition of charged particles up to a certain threshold. If an energy deposition above this threshold is simulated, $\delta$-electrons are produced and tracked by GEANT. These cut-off parameters in GEANT are called DCUTE for electrons and DCUTM for hadrons. The tracking of these $\delta$-electrons in GEANT is controlled by the tracking cut-off for electrons (called CUTELE in GEANT). Since $\delta$-electrons are also produced by pions, the choice of this tracking cut-off is important for both initial particle types.

Not all the energy deposited in a straw is measured, due to partial anode screening. This screening (or space-charge effect) was measured separately [5] and introduced in the simulation. In addition, some of the produced $\delta$-electrons escape from the sensitive volume.

The default parameters in DICE are 100 keV for DCUTE and CUTELE and 1 MEV for DCUTM in all materials. The preferred value for DCUTM, from the logical point of view, would be clearly 100 keV as well. The higher value for pions reduces the time consumption of the program fundamentally, since in an average LHC-event pions are the most frequent particles. These values will represent the standard set of parameters for the simulation.

The normalised energy spectra per straw crossed by the reconstructed track, for data and simulation, are compared for 20 GeV pions in fig.10. In addition, the integrated distributions, i.e. the probabilities that a straw has an energy deposition above a certain energy threshold as a function of this threshold, were also compared between data and simulation (with the standard parameter set), as shown in fig.11.

#### 4.2.2 Variation of cut parameters

Using the standard values of the GEANT parameters, as for figs.10 and 11, a good description of the data is obtained, although the simulation slightly underestimates the amount of high-energy hits (about 10% above 4 keV). As shown in fig.12, this effect would be much worse if CUTELE were decreased to 10 keV (some $\delta$-electrons
escape from the sensitive gas volume, since they are tracked down to 10 keV), whereas there is a small increase if CUTELE is increased to 1 MeV (only a small number of \( \delta \)-electrons, which could escape from close to the wall of the straw, have an energy between 100 keV and 1 MeV).

The production of \( \delta \)-electrons in the foam and the walls of the straws, as well as in the gas, was then studied further. By decreasing the \( \delta \)-ray production threshold for pions (DCUTM) and the tracking threshold in the foam and the wall for electrons (CUTELE), more \( \delta \)-electrons from outside the straws reach the gas and produce there more high-energy hits, as illustrated in fig.13 (the parameters in the gas were kept at their standard values). By decreasing, instead, the \( \delta \)-ray production threshold for pions in the gas (DCUTM set to 10 keV instead of 1 MeV), whereby the the tracking threshold for electrons (CUTELE) was kept at 100 keV, most of the produced \( \delta \)-electrons are immediately absorbed in the gas (electrons with energies between 10 keV and 100 keV). In fig.14, where the parameters in the foam and the wall were kept at their standard values, a small increase of high-energy hits due to this is shown. This means that the \( \delta \)-ray production from pions in the gas, as obtained using GEANT, and the subsequent energy deposition of these \( \delta \)-electrons in the gas, as described by the PAI model, leads to almost the same deposited energy spectrum in the straws, as that obtained using the PAI model without producing \( \delta \)-electrons. For a typical TR-threshold of about 5 keV, the size of all the variations described above is small. If a higher \( \delta \)-ray production threshold is preferred, lower values for CUTELE and DCUTM in the wall and the foam give a perfect agreement between data and simulation (see fig.13) and should be used in the ATLAS simulation.

4.2.3 Additional studies

By increasing the foam density, the amount of \( \delta \)-electrons coming from outside the straws into the gas increases, as well as the fraction of high-energy hits. This means that the absorption of \( \delta \)-rays is less important than their production over the foam density range of interest (0.08 to 0.06 g/cm\(^3\)), as shown in fig.15.

No significant difference between GEANT 3.21 and GEANT 3.15 was found in this study, as shown in fig.16.

The complete signal description and dE/dx simulation used in DICE for the TRT were checked as thoroughly as possible. The simulated energy resolution of primary clusters was tuned to be as close as possible to the measured value (11% at 6 keV).

4.3 TR simulation

4.3.1 Theoretical description for regular radiators

The TR-photon production was introduced into the simulation at each tracking step in GEANT. The production algorithm is based on the calculations of [9], using regular foils as radiator. The absorption of these photons is included in the simulation. In the testbeam setup, foam was used as a radiator, a material which should rather be considered as irregular foils, and therefore implies a reduced production of TR-photons. The ratio of TR-photon production between the regular foils used in the
simulation and the irregular foam used in the testbeam setup was determined to be $\epsilon = 1/0.6$. The normalised energy spectra for data and simulation are shown in fig.17 for electrons, where the region used for the normalisation was between 0 and 10 keV. For the dE/dx simulation, the standard parameters described above in section 4.2.1 were used. The probability that a straw, which was hit by the track, has an energy deposition above a certain energy threshold as a function of this threshold, is shown for electrons in fig.18. Although not perfect, the agreement between data and simulation is quite good.

4.3.2 Theoretical description for irregular radiators

The theoretical description of an irregular radiator was also studied, following the calculations described in [10]. The foam used for the TRT prototype can be considered as an irregular foil radiator. By tuning the irregularity factors, $\alpha = \langle l \rangle^2 / \langle \Delta l^2 \rangle$, for the foil thickness as well as for the spacing between the foils (which is filled with gas), a good description of the normalised energy spectrum for the data can be obtained for electrons (the region used for the normalisation was between 0 and 10 keV), as shown in fig.19, for $\alpha = 0.52$. The probability that a straw, which was hit by the track, has an energy deposition above a certain energy threshold as a function of this energy threshold is shown in fig.20, for $\alpha = 0.52$. For $\alpha = \infty$, one obtains the case of a regular radiator. Both the value of $\alpha$ for the foil thickness as well as the value of $\alpha$ for the spacing between the foils, influence the shape of the energy spectrum. In the study presented here, both values of $\alpha$ were kept identical. The simulation was optimised to describe the amount of high-energy hits above a threshold of about 5 keV. By setting the two $\alpha$-parameters to different values, a better agreement over the full energy range between data and simulation should be achieved, a topic to be pursued in the future.

5 Simulation of the ATLAS barrel TRT

The variations of the expected performance over all steps implemented to transfer the simulation from the testbeam to the ATLAS geometry have been carefully studied in the case of the barrel TRT. No material in front of the TRT (from e.g. the pixels and the SCT) was considered in this study.

5.1 Data versus testbeam setup

These variations were monitored in a first step through the probability that a straw hit on the track is above a given energy threshold, as compared between electrons and pions. Fig.21 illustrates this, for analog energy thresholds from 3.0 to 6.5 keV (as well as for a digital discriminator threshold) for the data and the simulation of the testbeam setup (8 mm distance between straws, 1.95 mm inner radius of the straws, no magnetic field). For the simulation of the digital threshold, the time distribution of the electronics signal was taken into account. In a second step, the expected performance was monitored in terms of the electron/pion separation, which is the most relevant figure of merit when studying the expected performance for ATLAS. The electron/pion
separation was estimated in a standard way, by counting the number of transition radiation candidate clusters (i.e. high energy hits with energy $E_{hit} > E_{thr}$). For each possible value of the electron efficiency, the corresponding value of the threshold $E_{thr}$ was determined. By applying the same threshold to the number of TR-clusters expected for pions, the corresponding pion contamination was estimated. Fig. 22 shows the pion efficiency versus the electron efficiency for a TR-threshold of 6 keV, for the data and the simulation of the testbeam setup (8 mm distance between straws, 1.95 mm inner radius of the straws, no magnetic field). For a fixed electron efficiency of 90%, the hadron efficiency versus the TR-threshold is shown in fig. 23. The simulation points differ from low statistics, i.e., below 95% electron efficiency, no pions pass the TR-threshold cuts in fig. 22, and, above 5 keV, there are no entries anymore in fig. 23 (due to technical reasons, no increase of statistics is possible within a small amount of time). In addition, one should note that the points are highly correlated to each other. There is a small difference between the data and the simulation of the testbeam setup, which is mostly due to the small difference between the pion dE/dx spectra obtained for the data and the simulation (see fig. 11). This is confirmed by fig. 21, where the probability for pions to exceed a high-energy threshold is different for the data and the simulation, whereas the probability for electrons is almost identical (in agreement with fig. 18). For a TR-threshold of 6 keV, table 1 shows, for both data and simulation, the probability to observe a TR-hit and the average number of TR-hits for both particle types. Table 1 also shows, wherever the simulation statistics were sufficient, the resulting pion efficiency for an electron efficiency of 90%. The hadron rejection obtained with the data for an energy threshold of 5.5 keV is in perfect agreement with the published result [2].

The next sections are devoted to perform the necessary steps to go from the testbeam simulation to the ATLAS geometry simulation, while controlling the evolution of the expected performance using the plots described in figs. 21 to 23.

### 5.2 Pion energy

The first step was to increase the energy of the pions to the same value of 30 GeV as the electrons, as shown in fig. 24. The larger pion probability at 30 GeV compared to 20 GeV is due to the relativistic rise of energy loss in the Xenon gas, which does not affect so much the high-energy dE/dx Landau-tails, but mainly the average energy loss. The resulting difference in performance is illustrated in fig. 25 and in table 1.

### 5.3 Straw inner radius

The second step towards the ATLAS barrel geometry was to increase the straw inner radius from 1.95 mm to 2 mm. As shown in figs. 26 and 27 and in table 1, both electrons and pions are only slightly affected by this step, since the path-length of the tracks in the gas is only increased by about 3%. The effect is bigger for electrons, however, since more Xenon gas is available to absorb the TR-photons.
5.4 Straw spacing

In order to have a better tracking performance for charged particles, the straw spacing in the ATLAS barrel design is reduced to 6.8 mm. The next step was therefore to reduce the straw spacing in the testbeam setup from 8 mm to 6.8 mm. This implies a reduction of the detector length by 85%. Further all material in front of the TRT prototype during the testbeam, was removed in this step and no bad straws were considered anymore.

As shown in fig.28, the probability that a straw, which was hit by the track, has an energy deposition above a certain energy threshold is quite noticeably decreased for electrons. The performance therefore decreases dramatically, as illustrated in fig.30 and table 1.

The most important reason of the decreased performance is due to the reduced length of the detector. In order to compare the performance of both straw spacings for an equal length of the detector in both setups, the number of TR-hits integrated over the length of the ATLAS barrel TRT (50 cm) was estimated, as shown in fig.29.

For the same energy thresholds the number of TR-clusters from both, electrons and pions, increases for 6.8 mm straw spacing. This is directly correlated to the increase of the number of hits per reconstructed track with an energy deposition above 0.2 keV (e.g. for pions from about 41 to 55). By decreasing the spacing to 6.8 mm, some tracks have now two hits in the two consecutive layers of straws, whose positions are always shifted perpendicular to the beam direction by half of the straw spacing. This, in the case of 8 mm straw spacing, guarantees, that each track crosses exactly one straw in these two consecutive layers of straws (the straw inner radius is 2 mm).

At an energy threshold of about 5 keV the two curves touch each other indicating identical performance. For lower energy thresholds a 6.8 mm straw spacing results in a higher performance, since the low-energy TR-photons are less absorbed in the radiator. For higher energy thresholds, however, a 8 mm straw spacing is preferable, since high-energy TR-photons are more likely produced at 8 mm straw spacing.

In general, one determines a wide plateau for the best energy threshold, with respect to the pion efficiency for an electron efficiency of 90% (5 to 7 keV) (see [2] and fig.23). From the present study, for a threshold below 5 keV the performance for a straw spacing of 6.8 mm is even better than for 8 mm. Due to pileup effects at high luminosity at LHC, on the other hand, a high threshold to define TR-hits, is preferable, although there the performance for a straw spacing of 6.8 mm is worse than for 8 mm.

5.5 Number of straw layers and geometrical arrangements of straws

The limited space for the inner tracker of ATLAS required a reduced number of straw layers (the length of the ATLAS barrel of 51 cm corresponds to 73 straw layers, whereas the length of the testbeam setup with 6.8 mm straw spacing of 65.3 cm corresponds to 96 straw layers). A change with respect to the geometrical arrangement of straws in the testbeam setup was required to obtain a better tracking performance. The setup after these two changes corresponds directly to the present geometrical design of the
ATLAS barrel. For the simulation we used therefore the official code of the simulation of the ATLAS detector [3], where single pions and electrons at 30 GeV were generated with a fixed rapidity of $\eta = 0.49$ (hitting the barrel) corresponding to the same angle between the straws and the beam direction of $63^\circ$ as in the testbeam setup (see fig.1). These single particles covered the ATLAS barrel over the full azimuthal angle. To have clean particle tracks, as was the case in the testbeam setup (simulation of the trigger selection), all tracks with a very low number of hits (lost particles due to interactions) were removed.

These two changes were monitored together in this step through the probability that a straw hit on the track is above a given energy threshold, as compared between electrons and pions. Fig.31 illustrates this, for analog energy thresholds from 3.0 to 6.5 keV (as well as for a digital discriminator threshold) for the two setups. As before, for the simulation of the digital threshold, the time distribution of the electronics signal was taken into account.

The probability for electrons, that a straw hit on the track is above a energy threshold of more than 5 keV is very moderately reduced for the geometrical arrangement of the straws in the ATLAS barrel compared to the other setup, whereas for a lower threshold no difference between the two arrangement is visible for electrons. The same probability for pions shows an opposite behaviour as a function of the energy threshold.

The reduced length should not influence this probability, but the different geometrical arrangement of the straws. This affects namely the distribution of pathlength probabilities for tracks before reaching the next straw, which is important for the TR-yield, as shown in figs.32 and 33. The geometrical arrangement of the straws in the ATLAS barrel produces a more constant pathlength between hits and favours therefore a distance of $2 \cdot 6.8$ mm between the hits, whereas with the testbeam setup a distance of $6.8$ mm between hits is preferred, but distances as large as $4 \cdot 6.8$ mm are quite probable.

Since the probability to have a TR-hit increases slowly with the thickness of the radiator in front of the straw, a pathlength of $6.8$ mm between hits is worse for the TR-yield than a pathlength of $2 \cdot 6.8$ mm, which favours the geometrical arrangement of the straws of the ATLAS barrel. On the other hand, a pathlength between hits of $4 \cdot 6.8$ mm increases the TR-yield compared to pathlengths below $4 \cdot 6.8$ mm, which favours the other arrangement. Both effects compensate each other almost completely.

The small difference for pions between the geometrical arrangement of the straws of testbeam and the ATLAS barrel setup has its origin in different probabilities of hadronic interactions of the pions in the material between the sensitive gas due to the different pathlength probabilities.

The reduced length of the detector explains almost completely the worse hadron rejection expected for the ATLAS barrel setup with respect to the testbeam results, as illustrated in figs.34 and 35 and in table 1.

5.6 Magnetic field

The remaining step to go from the testbeam simulation to the ATLAS barrel simulation was to simulate the nominal magnetic field in the inner detector.
Table 1: TR-performance for a TR-threshold of 6 keV, as measured in testbeam and simulated in successive steps from the testbeam setup to the ATLAS barrel setup. Shown are the probabilities per straw to observe a TR-hit for electrons ($P_e$) and pions ($P_\pi$), the average numbers of TR-hits over the length of the detector for electrons ($<N_e>$) and pions ($<N_\pi>$), and the pion efficiency $\epsilon_\pi$ for a 90% electron efficiency.

As shown in fig.36, there is a small increase of the probability that a straw hit on the track is above a given energy threshold at higher thresholds for both particle types with the magnetic field, but more significant for pions. This is based on the bounding of the $\delta$ electrons inside the straws: without the magnetic field they can escape from the straw.

This affects as well the hadron rejection at energy thresholds above 4.5 keV as illustrated in figs.37 and 38 and in table 1.

6 Conclusion

The simulation of the testbeam setup was adjusted so as to accurately reproduce the data. For this, the dE/dx and the TR-photon production and detection in straws surrounded by radiator were measured and simulated for the setup shown in fig.1. This provides us with a tool to predict realistically the particle identification performance of the ATLAS TRT tracker. In this note, a detailed comparison was carried out between the testbeam results and the expected TR-performance of the barrel TRT, since the TR-performance is expected to be significantly better in the endcap TRT.

The performance of the device was monitored, by moving step by step from the testbeam setup to the conditions of ATLAS. The measured pion rejection factor in the testbeam setup is expected to be degraded by about a factor 13 in the ATLAS barrel TRT, mainly due to the reduced detector length. It is important to note that the barrel TRT geometry was optimised with highest priority for pattern recognition and level-2 track triggering, with, as a consequence, a slightly degraded TR-performance.

The additional material in front of the TRT originating from the precision tracking of ATLAS, a topic to be pursued in the future, should not further degrade the performance. In the present state of the design, foils for the endcap and oriented fibre sheets for the barrel detector are foreseen as radiator, and are expected to give more TR-yield than the foam used in the testbeam setup. Therefore, the hadron rejection should improve compared to the present study.

The Monte Carlo tools provided through this study are essential to optimise the
distance between straws and their geometrical arrangement. Furthermore, they can be used for the selection of the best radiator material, in order to achieve the optimal tracking properties and hadron rejection.

In summary, further work in this field before the final design choices are made should concentrate on:

a. getting a realistic barrel and endcap TR-performance for ATLAS over the full $\eta$ and $p_t$-range.

b. studying the luminosity dependence with the goal to maintain a factor 10 in the rejection for $p_t$ of about 20 GeV at high luminosity.

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8 Appendix

List of the used GEANT data cards:

/*BEGIN TRD1991 DAT RECFM F LRECL 80 */
LIST
TRIG 5000
VIEW 0 0
SETS 0 1
AUTO 0
ANNI 1
BREM 1
COMP 1
DCAY 1
DRAY 1
MULS 2
MNU 1
PAIR 1
PHOT 1
RAYL 0
HADR 4
LOSS 3
PFIS 1
RNDM 12 34
C W.F. CUTELE=2 DCUTE=8, CHANGE AS WELL EMAX
C 0.0001 IS 100KEV
CUTS 1=.0001 2=.0002 3=.0001 4=.0001 5=.0001
CUTS 6=.001 7=.001 8=.0002 9=.001 10=.01
CUTS 11=100.E-9 ( TOF cut, ns )
C 9=PL  3=EL-
C KINE 3 30. 0. 0. 0. 0. -399. 0. 0.4
KINE 9 30. 0. 0. 0. 0.0 -399. 0. 0.4
TIME 2 = 240.
END
References


[3] DICE, a program to simulate the ATLAS detector.

[4] GEANT 3.21 , a system of detector description and simulation tools, Program Library W5013


Figure 1: Testbeam setup in 1991.
Figure 2: Probability to find a straw hit for 20 GeV pions as a function of the distance of the straw hit to the extrapolated beam particle for data and for simulation.
Figure 3: Probability to find a straw hit for 30 GeV electrons as a function of the distance of the straw hit to the extrapolated beam particle for data and for simulation.
Figure 4: Probability to find a straw hit for 20 GeV pions as a function of the distance of the straw hit to the extrapolated beam particle for data and for simulation with different straw inner radii.
Figure 5: Probability to find a straw hit for 20 GeV pions as a function of the distance of the straw hit to the extrapolated beam particle for data and for simulation with different straw alignment accuracies, $\sigma_{\text{al}}$. 

8mm spacing
Figure 6: Probability to find a straw hit for 30 GeV electrons as a function of the distance of the straw hit to the extrapolated beam particle for data and for simulation with different amounts of material in front of the TRT prototype.
Figure 7: Probability to find a straw hit for 20 GeV pions as a function of the distance of the straw hit to the extrapolated beam particle for data and for simulation with different levels of electronic noise, $\sigma_{\text{noise}}$. 
Figure 8: Number of hits with an energy deposition above 0.2 keV on reconstructed 20 GeV pion tracks for data and simulation.
Figure 9: Number of hits with an energy deposition above 0.2 keV on reconstructed 30 GeV electron tracks for data and simulation.
Figure 10: Normalised dE/dx spectra for 20 GeV pions and for data and simulation (the normalisation was performed between 0 and 10 keV).
Figure 11: Probability that a straw, which was hit by the track, has an energy deposition above a certain energy threshold as a function of this threshold for 20 GeV pions and for data and simulation with standard values of the GEANT parameters.
Figure 12: Probability that a straw, which was hit by the track, has an energy deposition above a certain energy threshold as a function of this threshold for 20 GeV pions and for data and simulation with different values of the GEANT parameters CUTELE in the gas.
Figure 13: Probability that a straw, which was hit by the track, has an energy deposition above a certain energy threshold as a function of this threshold for 20 GeV pions and for data and simulation with different values of the GEANT parameters CUTELE and DCUTM in the wall and the foam.
Figure 14: Probability that a straw, which was hit by the track, has an energy deposition above a certain energy threshold as a function of this threshold for 20 GeV pions and for data and simulation with different values of the GEANT parameter DCUTM in the gas.
Figure 15: Probability that a straw, which was hit by the track, has an energy deposition above a certain energy threshold as a function of this threshold for 20 GeV pions and for simulation with different GEANT versions.
Figure 16: Probability that a straw, which was hit by the track, has an energy deposition above a certain energy threshold as a function of this threshold for 20 GeV pions and for simulation with different radiator densities.
Figure 17: Normalised dE/dx+TR spectra for 30 GeV electrons and for data and simulation with the TR-production described using a regular radiator with $\epsilon = 0.6$ (the normalisation was performed between 0 and 10 keV).
Figure 18: Probability that a straw, which was hit by the track, has an energy deposition above a certain energy threshold as a function of this threshold for 30 GeV electrons and for data and simulation with the TR-production described using a regular radiator with $\epsilon = 0.6$. 

10^{-1}

10^{-2}

1

$e$ 30GeV

8mm spacing

Energy threshold [keV]
Figure 19: Normalised dE/dx+TR spectra for 30 GeV electrons and for data and simulation with the TR-production described using an irregular radiator with $\alpha = 0.52$ (the normalisation was performed between 0 and 10 keV).
Figure 20: Probability that a straw, which was hit by the track, has an energy deposition above a certain energy threshold as a function of this threshold for 30 GeV electrons and for data and simulation with the TR-production described using an irregular radiator with $\alpha = 0.52$. 
Figure 21: For 30 GeV electrons versus 20 GeV pions, probability that a straw, which was hit by the track, has an energy deposition above a given energy threshold, for energy thresholds from 3.0 to 6.5 keV and for a digital discriminator threshold, and for data and simulation of the testbeam setup with 8 mm straw spacing, 1.95 mm straw inner radius and no magnetic field.
Figure 22: Pion versus electron efficiency for an energy threshold of 6 keV for data and simulation of the testbeam setup with 8 mm straw spacing, 1.95 mm straw inner radius and no magnetic field.
Figure 23: For an electron efficiency of 90%, pion efficiency versus the TR-threshold for data and simulation of the testbeam setup with 8 mm straw spacing, 1.95 mm straw inner radius and no magnetic field.
Figure 24: Electron versus pion probabilities, that a straw, which was hit by the track, has an energy deposition above a given energy threshold, for energy thresholds from 3.0 to 6.5 keV for simulation with 8 mm straw spacing, 1.95 mm straw inner radius and no magnetic field, and with the pion energy increased from 20 GeV to 30 GeV.
Figure 25: Pion versus electron efficiency for an energy threshold of 6 keV for simulation with 8 mm straw spacing, 1.95 mm straw inner radius and no magnetic field, and with the pion energy increased from 20 GeV to 30 GeV.
Figure 26: Electron versus pion probabilities, that a straw, which was hit by the track, has an energy deposition above a given energy threshold, for energy thresholds from 3.0 to 6.5 keV for simulation with 8 mm straw spacing and no magnetic field, and with the straw inner radius increased from 1.95 mm to 2.00 mm.
Figure 27: Pion versus electron efficiency for an energy threshold of 6 keV for simulation with 8 mm straw spacing, 1.95 mm straw inner radius and no magnetic field, and with the straw inner radius increased from 1.95 mm to 2.00 mm.
Figure 28: Electron versus pion probabilities, that a straw, which was hit by the track, has an energy deposition above a given energy threshold, for energy thresholds from 3.0 to 6.5 keV for simulation with a 2 mm straw inner radius and no magnetic field, and with the straw spacing decreased from 8 mm to 6.8 mm.
Figure 29: Number of electron versus pion TR-clusters in a 50 cm long detector for energy thresholds from 3.0 to 6.5 keV and for simulation with a 2 mm straw inner radius and no magnetic field, and with a straw spacing decreased from 8 mm to 6.8 mm.
Figure 30: Pion versus electron efficiency for an energy threshold of 6 keV for simulation with a 2 mm straw inner radius and no magnetic field, and with a straw spacing decreased from 8 mm to 6.8 mm.
Figure 31: Electron versus pion probabilities, that a straw, which was hit by the track, has an energy deposition above a given energy threshold, for energy thresholds from 3.0 to 6.5 keV and for a digital discriminator threshold for simulation with a 6.8 mm straw spacing and no magnetic field, and for the testbeam setup of 65.3 cm length compared to the ATLAS barrel setup of 51 cm length.
Figure 32: Distribution of distances between successive straw hits with an energy deposition threshold of 0.2 keV for 30 GeV electrons, and for the testbeam setup.
Figure 33: Distribution of distances between successive straw hits with an energy deposition threshold of 0.2 keV for 30 GeV electrons, and for the ATLAS barrel geometry.
Figure 34: Pion versus the electron efficiency for simulation with an energy threshold of 6 keV, a 6.8 mm straw spacing and no magnetic field, and for the testbeam setup of 65.3 cm length compared to the ATLAS barrel setup of 51 cm length.
Figure 35: For an electron efficiency of 90%, pion efficiency versus the TR-threshold for simulation with a 6.8 mm straw spacing and no magnetic field, and for the testbeam setup of 65.3 cm length compared to the ATLAS barrel setup of 51 cm length.
Figure 36: Electron versus pion probabilities, that a straw, which was hit by the track, has an energy deposition above a given energy threshold, for energy thresholds from 3.0 to 6.5 keV and for a digital discriminator threshold for simulation with a 6.8 mm straw spacing and the ATLAS barrel setup, and for no magnetic field and with magnetic field.
Figure 37: Pion versus electron efficiency for simulation with an energy threshold of 6 keV, a 6.8 mm straw spacing and the ATLAS barrel setup, and for no magnetic field and with magnetic field.
Figure 38: For an electron efficiency of 90%, pion efficiency versus the TR-threshold for simulation with a 6.8 mm straw spacing and the ATLAS barrel setup, and for no magnetic field and with magnetic field.