Development of Transition Radiation Detectors for hadron identification at TeV energy scale

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Abstract. Many modern and future accelerator and cosmic ray experiments require identification of particles with Lorentz γ-factor up to 10^4 and above. The only technique which reaches this range of Lorentz factors is based on the transition radiation detectors (TRD). This paper describes the development of a TRD based on straw proportional tubes. A prototype of such kind of detector was built and tested at the CERN SPS accelerator. Monte Carlo simulation model of the detector which matches well the experimental data was developed. This program was used for the simulation of a full-scale TRD for hadron identification at TeV energy scale.

1. Introduction

The separation of hadrons at very high energies is an important and difficult task of particle identification. Already now, there are tasks at modern accelerators, where such separation is a key element for the planned experiments. With an increase of the energy of colliding particles, a need for a technique that would allow the separation of protons, kaons, and pions of high energies will increase. The planned study of the charged hadrons production at small angles

at the Large Hadron Collider (LHC) [1] is a good example of such an experiment. In this experiment the energy of secondary hadrons almost reaches the maximum energy available at LHC of 6.5 TeV and covers the pseudo-rapidity region $\sim 5 < |\ \eta\ | < 9$ which is not available to other experiments at the LHC. In addition to studying the fundamental QCD processes the measurement of the composition of hadrons in these experiments is extremely important for the physics of ultrahigh-energy cosmic particles.

The only particle identification technique able to effectively separate hadrons with this energy range is based on the properties of the X-ray transition radiation (TR) production. Most of transition radiation detectors are designed to separate electrons and pions and they use the threshold effect of the TR production. In these detectors the TR yield starts to be significant at γ-factor of $\sim 5 \times 10^2$ and saturates already at $\sim 2 \times 10^3$. This TRD operation range is defined by the radiator and the detector properties: material, thickness and number of radiator foils, the gap between the foils, detector material and its thickness. The probability density of TR photons exiting from the radiators is a complex function of the particle's γ-factor, the radiator parameters, photon emission angle and photon energy. Integrating over the angle, one obtains the TR spectrum with many maxima. TR production at each maximum has its own γ-factor dependence. This feature can be used to develop a single detector with responses to a few γ-factor regions, which could significantly enhance its performance.

We have built and tested a TRD prototype with different radiators and several types of beam particles covering Lorenz factor range from ~ 140 to $\sim 3.6 \times 10^4$. Monte Carlo (MC) model was developed and simulations were performed and compared with the data. Finally, this fine-tuned MC model was used to simulate the possibility of hadron separation with full-scale TRD for the planned Very Forward Hadron Spectrometer [1].

2. Test beam measurements

Set-up based on proportional tube arrays was built and tested at the CERN SPS accelerator (Figure 1). Beam particles cross 22 layers of thin-walled proportional chambers (straws) which detect particle ionization losses and TR photons. The straws of 4 mm diameter are filled with gas mixture of 71.8% Xe, 25.6% CO_2 and 2.6% O_2. Similar straw chambers are used in the Transition Radiation Tracker [2] of the ATLAS experiment [3] at the LHC. Several particle beams were used: 20 GeV pions and electrons, and muons with energies 120, 180 and 290 GeV. Four different types of radiators were tested – table 1.
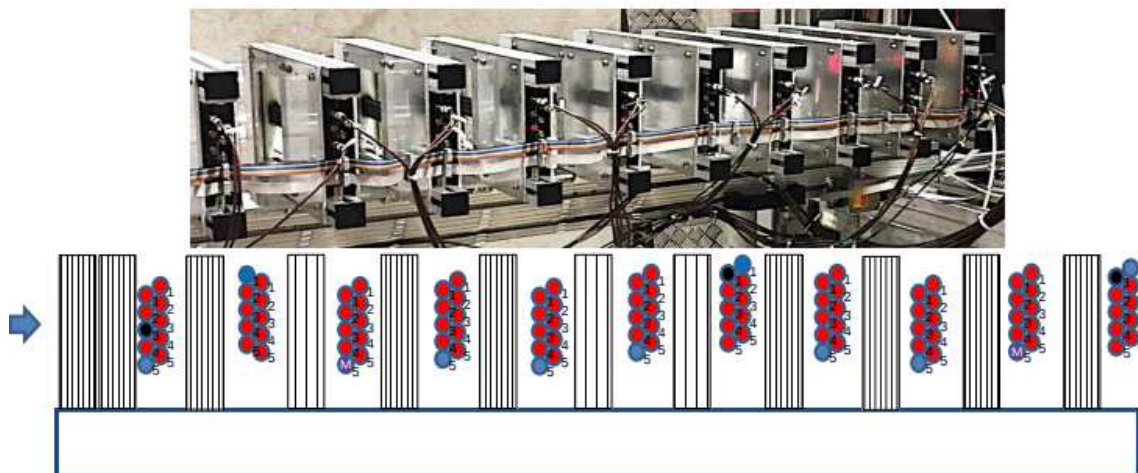
**Figure 1.** Photo and schematic view of the TRD straw prototype.

Table 1. Radiator parameters.

	Foil material	Density, g/cm^3	Foil thickness, μm	Gap between foils, mm	Number of foils
1	Mylar	1.39	50	3	15
2	Polyethylene	0.95	67	2	15
3	Polyethylene	0.95	67	3	15
4	Polyethylene	0.95	91	2.3	15

3. Monte Carlo simulation and comparison with test beam results

In order to carefully describe the measured spectra, dedicated Monte Carlo simulations were performed. The MC software includes detailed description of the detector geometry and the materials and the physics processes: dE/dx ionization in straw gas and TR photons generation and absorption. More detailed description of the MC program can be found in [4, 5].

A comparison of the simulation results and data was done for all particle energies and different radiators. Figures 2 and 3 show some examples. A very good agreement between data and MC is observed.
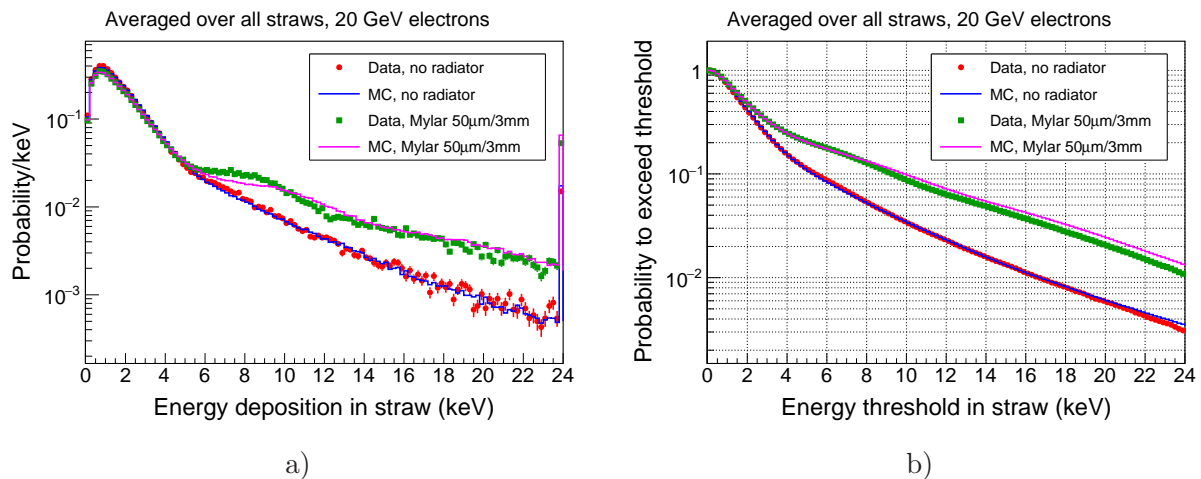
Figure 2. Comparison of experimental and simulated spectra of energy registered in the straws with Mylar radiators and 20 GeV electron beam. a) differential spectra, b) integral spectra (probability to exceed energy threshold). The rightmost bins in the differential spectra include the overflows.

4. Expected hadron identification with LargeTRD

Using the fine-tuned MC program one of the possible variants of the full-scale TRD for the charged hadron production study in very forward direction has been evaluated. In order to cover full range of γ-factors it is proposed to build it as two physically separate detectors with different properties. For small γ-factors one of the detectors has double straw layers interleaved with radiator consisting of 20 foils with 40 μm thickness separated by 1 mm. The probability to have a hit above 6 keV as a function of γ-factor is shown in figure 4 a). The other detector has similar structure but the radiator with 15 85 μm foils separated by 2 mm is used. This detector is supposed to operate at the gas pressure of 2 bar in order to increase the detection
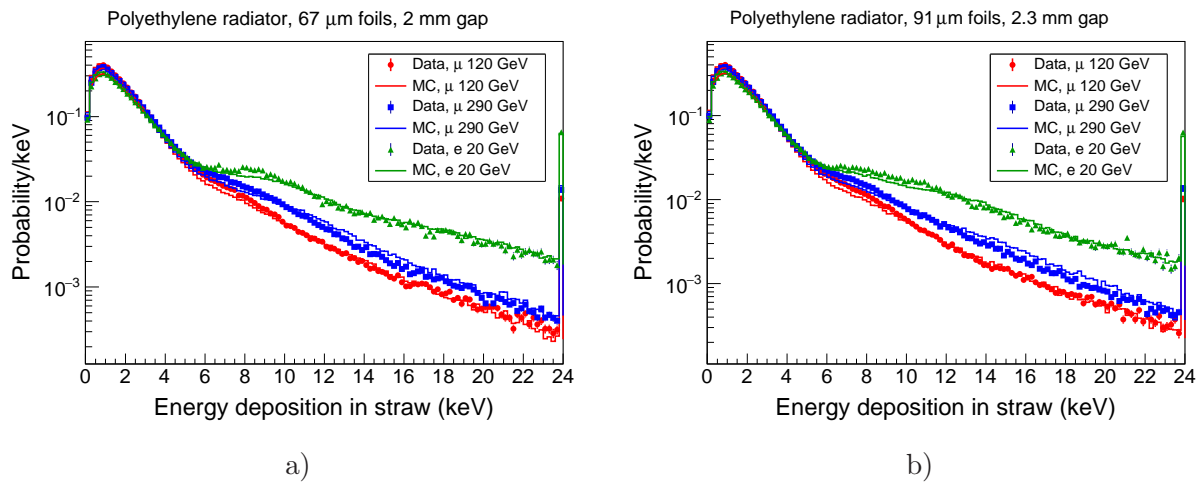
Figure 3. Comparison of experimental and simulated spectra of energy registered in the straws for different beam particles and polyethylene radiators: a) 67μm foils, 2 mm gap, b) 91μm foils, 2.3 mm gap. The rightmost bins include the overflows.

efficiency since TR photons are produced at higher energies in such radiator. Two different registration energy ranges which have different Lorentz factor behaviour will be used: 9–18 keV, and above 18 keV. γ-dependencies for these TR energy ranges are shown in figure 4 b) and c) correspondingly.
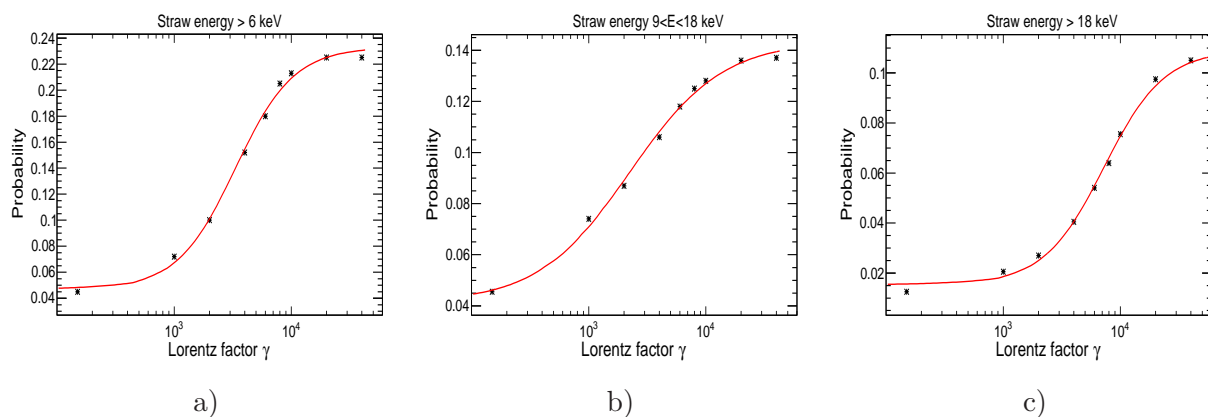
Figure 4. Simulated dependencies of energy deposition probability on Lorentz factor for two detectors and different straw energy deposition. a) first detector, E > 6 keV, b) second detector, 9 keV < E < 18 keV, c) second detector, E > 18 keV.

In order to reconstruct particle composition in the planned study of charged hadron production in very forward direction at the LHC a special method based on the Bayesian approach [6] was implemented. According to Bayes' theorem one can write

$$P(H_i|\vec{S}) = \frac{P(\vec{S}|H_i)C(H_i)}{\sum_{k=\pi,K,p} P(\vec{S}|H_k)C(H_k)}$$

The probability estimate $P(\vec{S}|H_i)$ can be interpreted as the conditional probability that the set of detector signals $\vec{S}$ will be seen for a given particle sort H_i. However, the variable of interest

is the conditional probability that the particle is of sort H_i, for measured detector signal $\vec{S}$ (i.e. $P(H_i|\vec{S})$). The priors $C(H_i)$ serve as a 'best guess' of the true particle yields per event and can be determined from the iterative procedure:

$$C_{n+1}(H_i, E) = \sum_{\vec{S}} P_n(H_i|\vec{S})$$

This method was applied for reconstruction of particle and antiparticle compositions expected in the planned experiment on charged hadron production in the forward direction. The TRD with responses shown in figure 4 was taken as an example. Detector 1 consists of 22 sets of radiator + double straw layers (44 straw layers in total). The other detector consists of 50 sets of radiator + double straw layers (100 straw layers in total). The total length of the proposed set-up with these two detectors will be 3 meters. The result of hadron composition reconstruction is shown in figure 5. One sees that the described approach allows to reconstruct the particle spectra with an accuracy less than two percent.

a)   b)
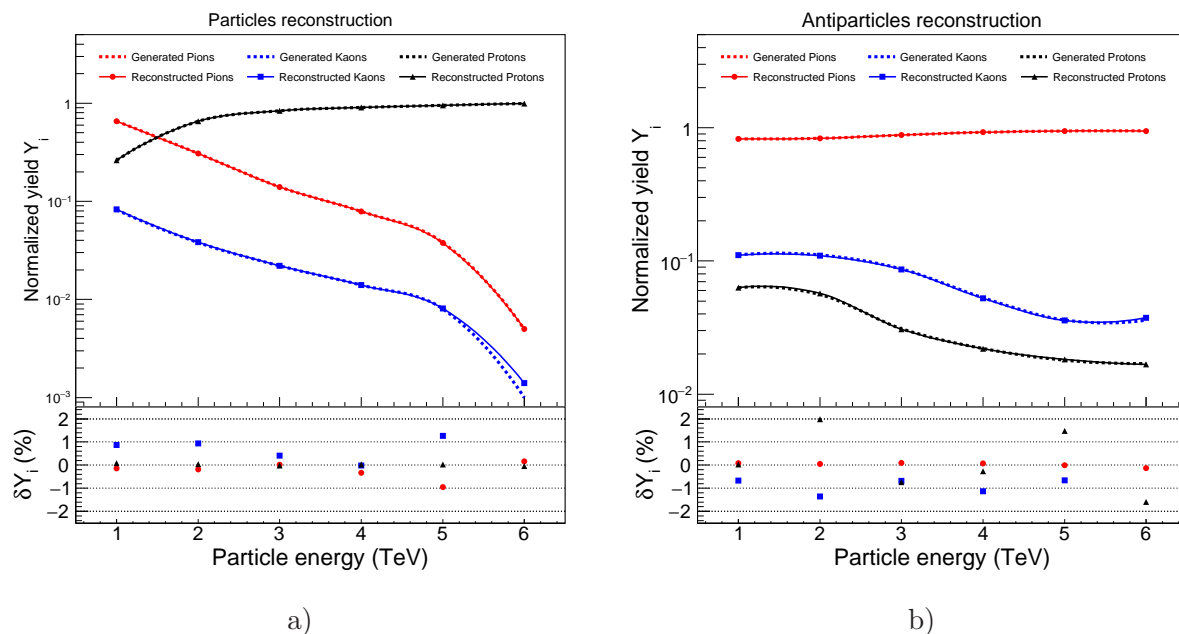
Figure 5. Particle composition reconstruction with the Bayesian method. The dotted lines indicate the fraction of particles generated in p-p collisions in the planned study of charged hadron production (MC), the solid ones – reconstructed particle composition. a) for positively charged particles, b) for negatively charged particles. In the lower parts of the graphs, the relative errors of reconstruction are plotted.

5. Conclusions

A transition radiation detector prototype based on straw proportional tubes was built and successfully tested at the CERN SPS using different types of beam particles and radiator configurations. The developed and carefully tuned Monte Carlo model describing the detector prototype set-up has shown a good agreement with the experimental data. The MC model was used for simulation of a full-scale TRD for hadron identification at TeV energy scale which can be used for the planned study of charged hadron production in very forward direction at the LHC. A dedicated technique based on Bayesian probability approach was developed for

the reconstruction of hadron spectra and implemented in the software package. This technique was used to reconstruct the expected composition of particles and antiparticles produced in forward direction at the LHC. It was shown that hadron spectra can be reconstructed with a percent level of precision over the entire range of considered hadron energies from 1 to 6 TeV.

References
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