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Si-pixel Transition Radiation Detector with separation of TR-photons and particle track by B-field. (Proposal for TESLA detector)

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Abstract

This proposal describes a Transition Radiation Detector (TRD) for the detector currently being planned for the TESLA Linear Collider. The principle of measurement is based upon the spacial separation between the trajectories of particles and their associated TR-photons, which is caused by the particle's deflection in the 3T magnetic field of the TESLA detector. Under this proposal the 5 - 30 keV Transition Radiation X-rays will be detected using a Si-pixel detector.

Pion rejection factors of 6 to 100 or greater can be achieved over a wide range of momenta up to 90 GeV/c, for an electron detection efficiency of $\geq 90\%$. Under these conditions a spatial resolution for the track of 15 μm is expected.

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1 Introduction

1.1 Electron ID in TESLA detector: motivation

One of the most essential performance goals of the TESLA detector [1] is very good e/π separation. The motivations behind these goals are:

1. The detection of high p_T inclusive isolated electrons with jet rejection.

   The jet background consists mainly of π^0-mesons, which carry most of the jet energy and are not matched to a high-p_T charged track. Also present, are electron pairs from Dalitz decays of π^0/η mesons, convertion photons from π^0/η decays, and high-p_T charged hadrons which yield an electromagnetic shower in the calorimeter.

   The detection of isolated electrons with $p_T \geq 40GeV/c$ together with a good jet rejection is very important for hadron colliders where the high p_T electron to jet ratio is very low. For existing colliders this ratio is 10^{-3} and is expected to be $\sim 10^{-5}$ for LHC [2]. For the TESLA collider the isolated high p_T electron to jet ratio is much higher compared to hadron colliders, this is because the $e^+e^- -> q\bar{q}$ cross section is much lower and there is a large electron rate from $e^+e^- -> WW$ and $e^+e^- -> ZZ$ reactions. Therefore the moderate jet rejection of $\leq 10^3$ is quite sufficient for TESLA.

2. The detection of electrons in jets, for instance, the tagging of b-jets using relatively soft ($p = 5$ to 40 GeV/c) electrons.

   A considerable amount of "new physics" signals consist of b-jets ($H -> b\bar{b}$, top decays etc.), therefore their selection is extremely important. The most powerful way to tag b-jets will be to look for displaced vertices [1]. However the tagging of soft electrons inside the b-jet will provide a valuable complement to this, giving the additional possibility to separate b-jets from u, d, gluon and even s jets (using electron's transverse momentum relative to the jet axis. In addition the e^+ or e^- tagging of b and c jets allows the measure of vertex charge (b,c separation from $\bar{b}$,$\bar{c}$)

   Soft electron b-jet tagging requires good electron identification inside the hadron jet and is difficult to achieve using information from the calorimeter alone. Monte Carlo simulations for ATLAS [2] have shown that hadron rejection inside gluon jets achievable by calorimetry alone is only approximately 30.

3. The identification of conversion photons and π^0/η Dalitz decays. Which may be very useful for the reconstruction of certain final states.

   The identification of such soft electrons and e^+e^- pairs inside the QCD jet may be considerably improved by the use of a TRD in addition to the calorimeter and Time Projection Chamber (TPC).

1.2 Electron ID in the TESLA detector: performance

The electron ID in the TESLA detector can be achieved using both destructive (electron shower in Calorimeter) or non-destructive techniques (dE/dx measurements in the TPC and/or usage of Transition Radiation).

In the case of calorimetry the information about the spatial shower development, both laterally and longitudinally, must be used. This in turn requires a very fine calorimeter cell granularity to allow a good measurement of the first and second moments of the shower shape. As an example, the H1 liquid-argon calorimeter [3] has a sampling structure very similar to that proposed for the TESLA detector (shashlik calorimeter option). With an electromagnetic cell size of $\sim 30mm$ gives a pion misidentification at 30 GeV of 2 to 5 $\cdot 10^{-3}$ leading to a pion rejection power of 200 to 500, with 95 % of electrons being correctly identified. Further improvement of the calorimeter rejection power, by a factor of 2 to 4, can be achieved using the 1 to 2 X_0 presampler [1]. For lower energies [3] the π-rejection is considerably worse, by a factor of 5 for 10 GeV.

This calorimeter rejection factor is related to isolated particles (π or e). In the case of high energy jets the calorimeter particle ID is expected to be considerably worse [2] due to overlap of jet particles. For instance some estimates based on the simulation of reaction of $t\bar{t}$ final states at $\sqrt{s}$=500GeV [1] give the fraction of overlapping hits inside electromagnetic shower envelop (at least 3×3 towers) of about 10%.

Measurements of dE/dx by the TPC is a powerful tool for electron identification but this is only possible at low energies. For example, at least 3σ separation is possible up to 8 GeV but this reduces to only 1.5σ separation at 20 GeV [4]). Note that the separation, in standard deviations, between particle species in hadronic jets is also heavily influenced by track overlap in the TPC [4].

It is possible to achieve an additional e/π separation (non-destructive), by using the detection of the Transition Radiation X-rays produced by electrons. It is proposed that the TRD be positioned in the radial space between the Si-tracker and the TPC.

2 Transition Radiation Detector for the TESLA experiment.

2.1 Concept

Usually transition radiation detectors in high energy physics experiments [5] detect TR photons, together with dE/dx losses of the particle. These losses form the major contribution to the background in TR measurements, and it is this which limits the hadron rejection capability of TRDs. For instance, the achievable hadron rejection level is only about 5 for the total TRD length, $18cm$, available within the TESLA detector (a radial spacing between Si-tracker and TPC [1]).

Background due to dE/dx seems unavoidable because the TR angle is very small, $\sim 1/\gamma$, where γ is the Lorentz-factor of the particle. However in the case of the TESLA detector with it's high magnetic field, B = 3T, one can make use of the separation in space of the particle trajectory, which is deflected by the B field, and that of the TR photons, which is not.

The deflection distance between the particle track and TR photon detected is given by:

$$\delta \sim \frac{L^2 B}{p};$$

where:
L is the particle path between TR radiator and detector
p is the momentum of the particle.

The typical δ-value for the proposed TRD position is about

$$200\mu m \cdot \frac{30GeV/c}{pGeV/c}$$

for $\theta = 90°$ (See Fig. 3).

So completely separate detection of the TR photons and the associated particle track is possible using a high granularity detector, for example Si-pixel or Si-strip detectors.

In such a case, if the mean number of TR photons is large enough to give a good electron efficiency, the hadron rejection is determined not by background associated with particle dE/dx as usual, but by external backgrounds. This background may consist of γs from beam-beam effects and synchrotron radiation or coincidental particle hits. In this case the e/hadron separation is expected to be sufficient over a wide range of electron energies from the TR threshold, approximately 2 GeV, and above (see below).

2.2 TRD design

It is proposed that the Transition Radiation Detector be located in the intermediate gap between the Si-tracker and the TPC (radial spacing of 12 to 30 cm). It consists of two parts (Fig. 1):

- The TR radiator consists of 300 polypropylene foils each $20\mu m$ thick. The radial thickness of the radiator is Z dependant and varies from 8 cm to 3 cm, in order to have the same radiator thickness over all values of the TRD polar angle θ. The radiator thickness is about 1% of X_0 (independently on the rapidity) and $\Delta Z = \pm 50cm$.

- The particle and TR X-ray detector will use Si-pixels with a pixel size of 50 $\mu m\times$ few mm in Z. The Si-pixel thickness of $400\mu m$ is used in order to obtain a good absorption of TR X-rays, $5 \div 30keV$. The pixel pitch of 50 μm, in B-field bending plane, is needed for separate detection of particle and TR-photons. The pixel length is a compromise between total number of pixels, approx. 10^7, and the requirement of having a small pixel capacitance, in order to obtain acceptable electronics noise at a level of 200-300 e [7], [8]. Each pixel has a very small acceptance, $\Delta\psi \times \Delta\eta(\theta = 90°) = 1.7 \cdot 10^{-4} \cdot 8 \cdot 10^{-3}$.

  The radial thickness of the Si-pixel detector and electronics is about $1\% X_0$, including the mechanical support [1].

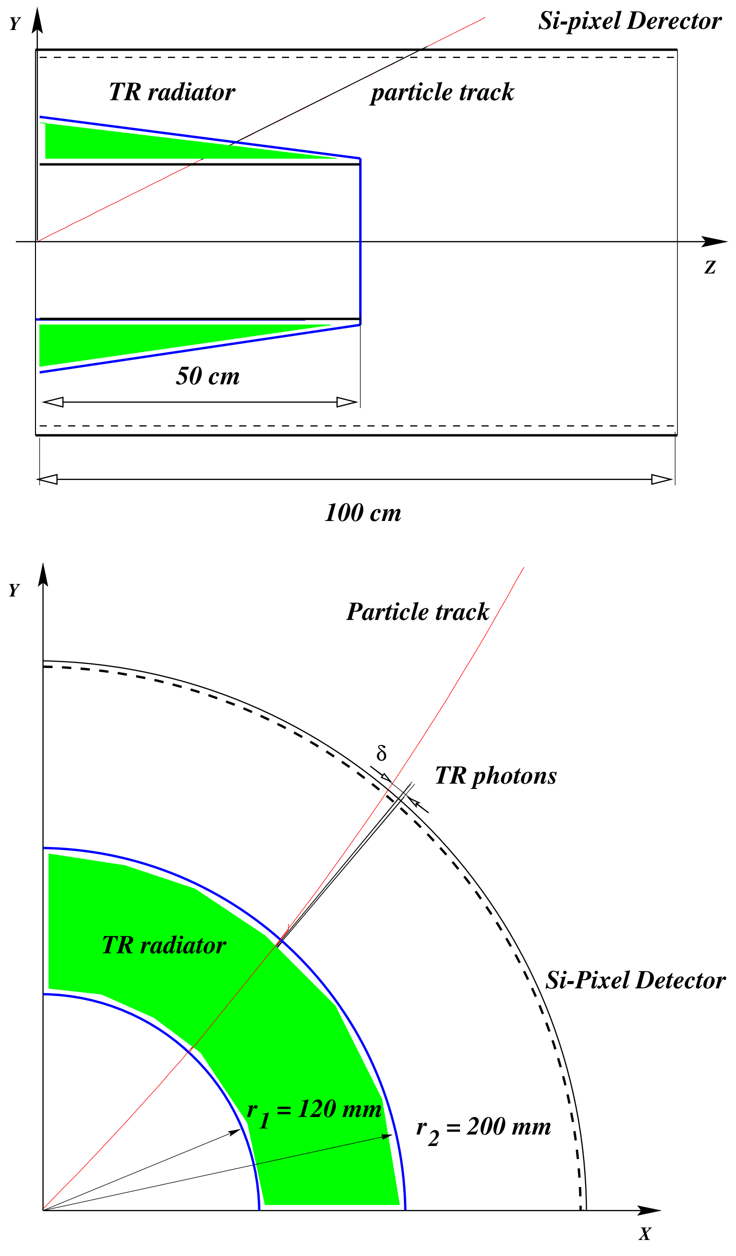

Figure 1: Schematic view of the TR radiator and Si-pixel TRD concept

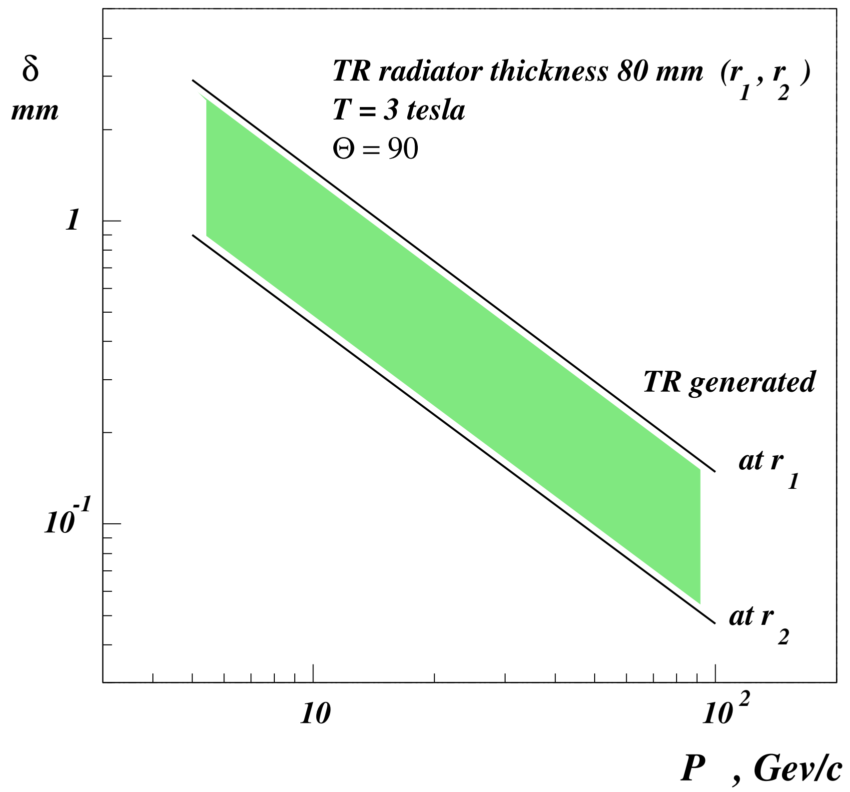

Figure 2: Separation, δ, between particle track and TR photons for proposed Si-pixel TRD geometry. Values of δ - for a radiator thickness of 8 cm at $\theta = 90^o$

2.3 Expected TRD performance

The key parameter which defines the TRD performance is the distance between the track and the TR photons (δ). The δ - value is shown in Fig. 2 for the TRD geometry described in Fig. 1 and for pseudorapidity $\eta = 0$.

Fig. 3 shows the two-dimensional plot of $E_{TR_{photon}}$ vs δ for electrons with a momentum of 30 GeV/c.

One can see that there is a difference between the values of δ for photons radiated at the beginning of the TR radiator, $\delta_{max} = 500\mu m$, and those which are radiated at the end part of the TR radiator, $\delta_{min} = 150\mu m$. The energy spectrum of the TR photons absorbed by a Si detector of thickness $400\mu m$ is shown in Fig. 4 while the distribution of the number of detected TR-photons is shown in Fig. 5 .

Fig 3 - Fig 5 are related to $\eta = 0$ ($\theta = 90°$).

The same distributions for $\eta = 1.3$ ($\theta = 30°$) are shown in Fig 6 - Fig 8.

One can see that:

- the mean number of detected TR photons is about 3 per electron. This shows, that the requirement of detecting at least one photon corresponds to an electron efficiency of $\epsilon = 1 - e^{-3} = 0.95$.
- the mean TR detected photon energy is about 11 keV. To keep an electron efficiency of $\geq 90\%$ it is necessary to detect TR photons above a threshold of 5-6 keV.
- There is no significant difference in TR yield for the two different rapidities.
- There is significant narrowing in the range δ for $\eta = 1.3$ due to smaller radial thickness of the TR radiator (See Fig 1).

In order to misidentify the hadron as an electron there should be at least one hit in a pixel(s), which is positioned in the region of the track location, known from the Si-tracker and TPC (See Fig 3, Fig 6). The total area of such a "TR-expected" pixel(s) is about 1 - 5 mm^2 ($p_\perp$ - dependent).

The probability of the pion misidentification is ϵ_π which is determined by:

- coincidental particle hits in Si-pixels, which are expected to be triggered by TR X-rays. The expected position of such Si-pixels is known from

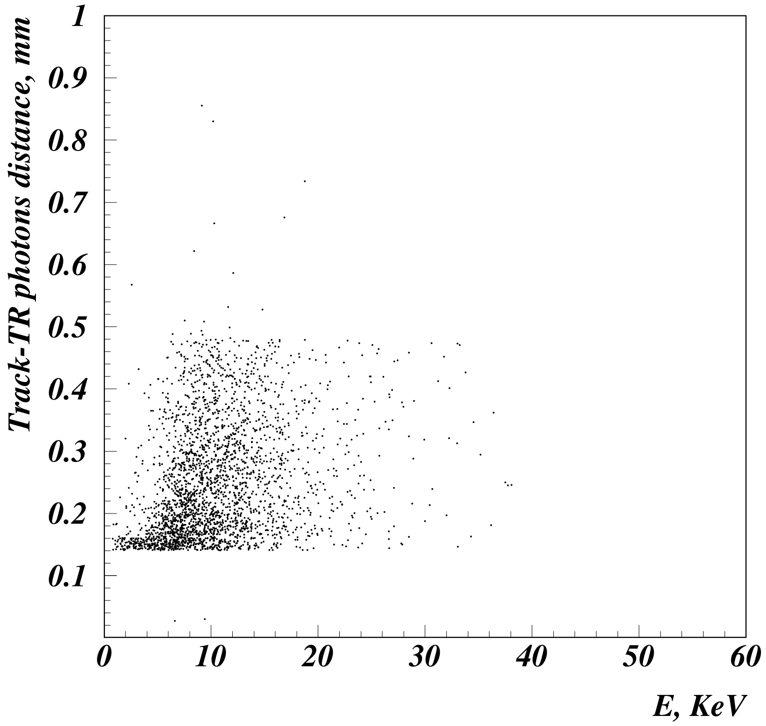

Figure 3: Two dimensional plot of δ vs absorbed TR photons energy ($\theta = 90^o$) for electrons with a momentum of 30 GeV/c

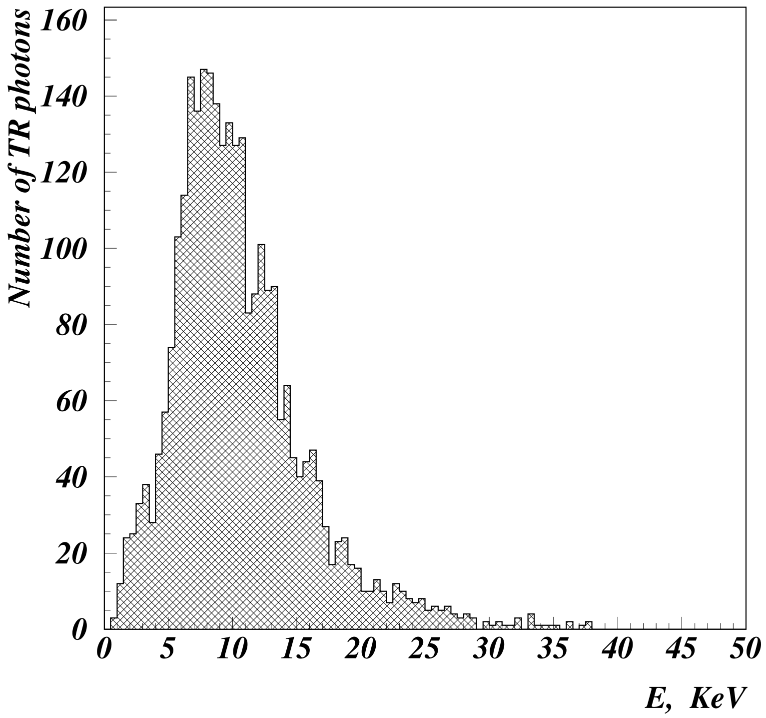

Figure 4: The energy spectrum of the TR-photons absorbed in Si-pixel detector ($p = 30\ GeV/c$, $\theta = 90^o$.)

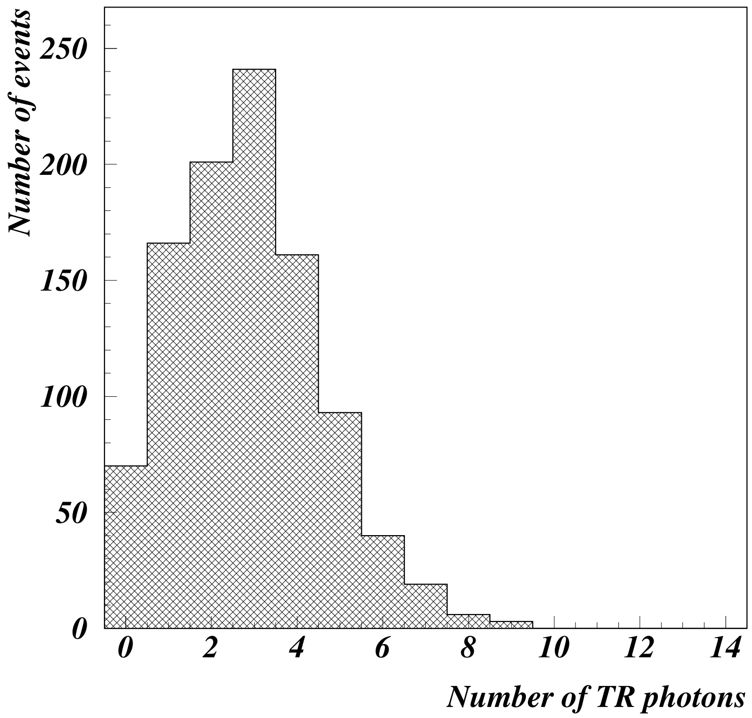

Figure 5: Distribution of the number of detected TR-photons ($p = 30\ GeV/c$, $\theta = 90^o$.)

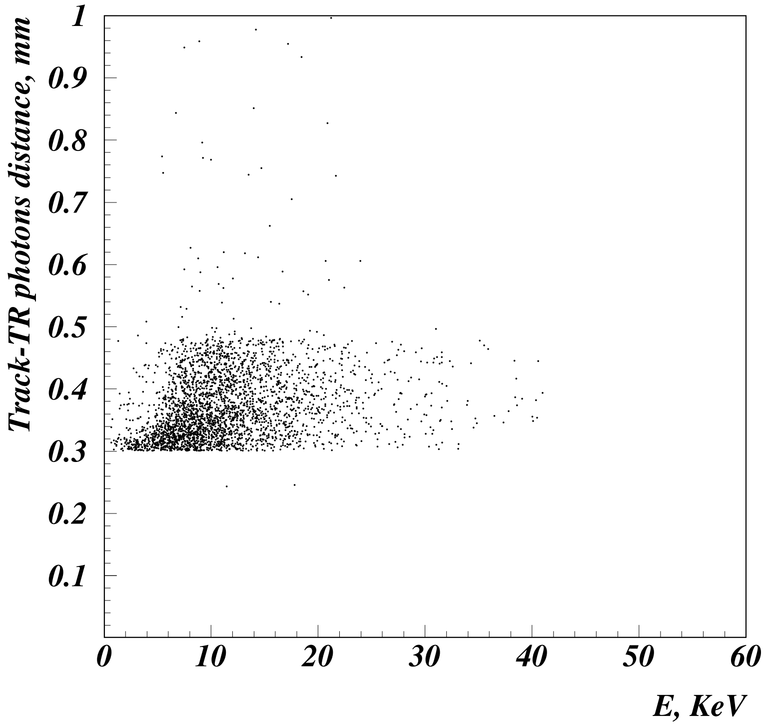

Figure 6: Two dimensional plot of δ vs absorbed TR photons energy ($\theta = 30^o$) for electron momentum of 30 GeV/c.

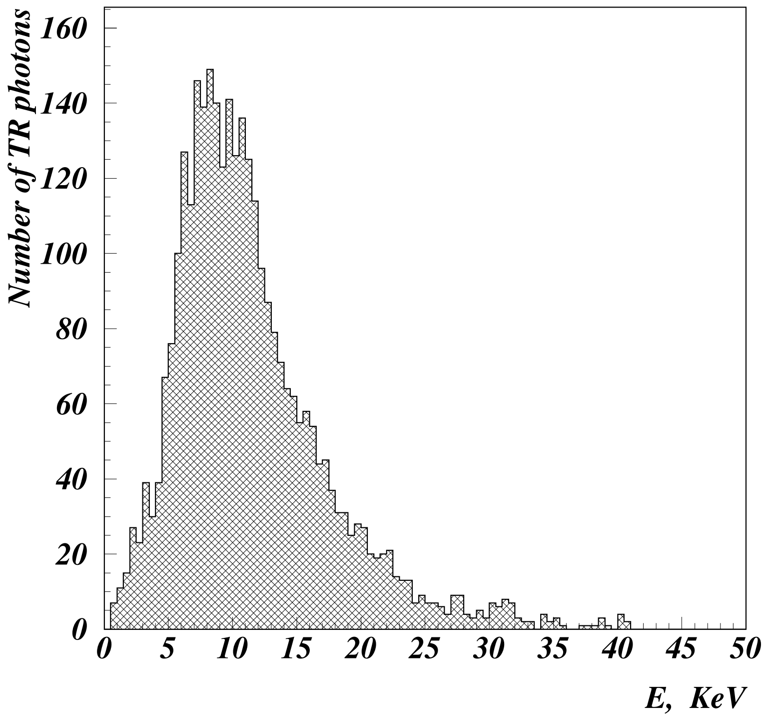

Figure 7: The energy spectrum of the TR-photons absorbed in Si-pixel detector ($p = 30\ GeV/c$, $\theta = 30^o$.)

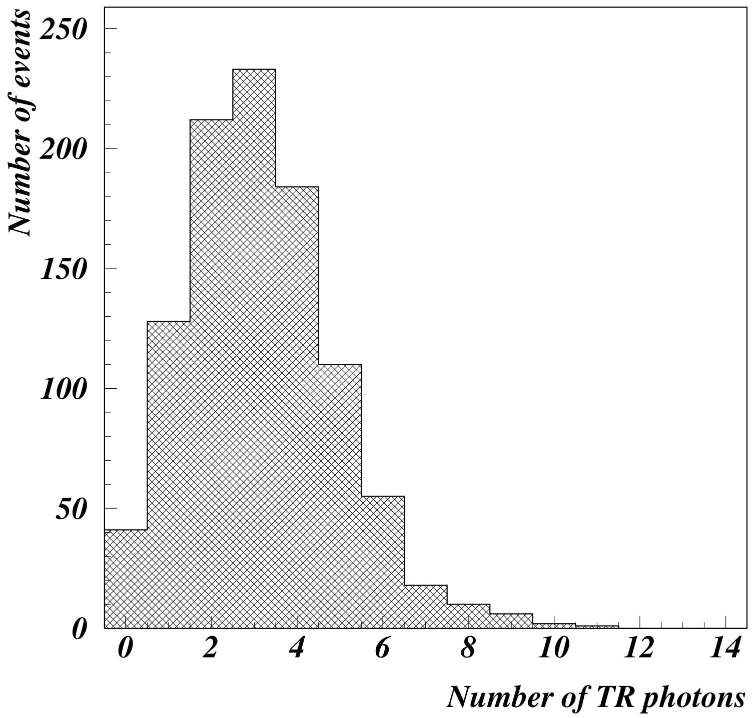

Figure 8: Distribution of the number of detected TR-photons ($p = 30\ GeV/c$, $\theta = 30^o$.)

the track position and particle momentum which can be obtained from Si-tracker and TPC. The expected hit density even inside a high energy jet can be estimated at $\sim 10^{-3} hits/mm^2$ [1] for each bunch crossing and r = $30cm$, where the Si-TRD is located. Moreover, the energy losses of the jet particle will be about 140 keV, compared to 5 - 60 keV for the TR X-ray signal.

- coincidental γ-ray hits originating from beam-beam effects and beam synchrotron radiation. The estimation from background studies [1],[6] for the TPC gives an upper limit of about 100 $hits/bunch$ over the whole Si-TRD, which is less than $2 \cdot 10^{-5} hits/mm^2 bunch$. There is a possibility that this number may increase due to the formation of tightly spiralling slow electrons in the B-field, although this has yet to be studied.

- the contribution of noise from electronics + detector.

  Keeping in mind that a single 6 keV photon produces in silicon a charge of about 1700 electrons, an equivalent noise charge at the level of $\leq 300e$ rms is necessary to obtain a reasonable signal-to-noise ratio [8]. The ATLAS Si-pixel detector [7] with a pixel size of $50\mu m \times 400\mu m$ and fast shaping (LHC bunch crossing is $25ns$) has a typical noise of 150 electrons rms. For the TESLA detector the shaping time of about 100 - 150 ns is acceptable, so the the noise level of $300e$ rms for Si-TRD pixel size of $50\mu m\times$ few mm seems to be achievable.

- two or three neighbouring pixels can be triggered due to charge sharing and high energy δ - rays, giving the imitation of TR-photon hits. For a $50\mu m$ pixel pitch [7] the number of double hits of about 15% and triple or more hits of about 2% have been obtained experimentally for a threshold of 2000 e. Taking into account that the track position in the Si-TRD is well known from the Si-tracker and TPC, real pion misidentification can be estimated as 7.5% for track - TR-photon distance 75 μm -125 μm and $\sim$ 1% for track - TR -photon distance $125\mu m - 175\mu m$.

- charge sharing due to Lorenz angle. The Si-pixel TRD will operate in a magnetic field of 3 TESLA, the magnetic field and electric drift field inside the silicon pixel detector therefore will be orthogonal and the drift velocity will assume a component along the direction of $\vec{E} \times \vec{B}$. The charge carriers will then drift at an angle θ_L with respect to the direction of the electric field, θ_L being the Lorentz angle. Depending on the angle of the incident particle, the charge collected will spread between pixel cells. The spread being minimum where θ equals θ_L. The Lorentz angle θ_L has been measured [7] for $B = 1.4T$ and can be predicted for the TESLA detector as $\sim 20°$. In order to avoid the pixel to pixel spread, the Si-pixel detector has to be tilted at an angle of θ_L. The pixel to pixel spread due to the magnetic bending angle of the particle in the Si-pixel detector is much smaller than the track - TR-photon distance:

$$4\mu m \cdot (\frac{30GeV/c}{p}) \text{ compared to } 200\mu m \cdot (\frac{30GeV/c}{p})$$

and can be neglected.

For the high momentum region, where the pion Lorentz-factor is quite large, there is a principal limitation of e/π separation because pions start to radiate TR-photons.

The pion TR yield becomes comparable with that of electron TR-yield at momenta over $200 - 300$ GeV/c.

Finally Fig. 9 shows the estimated pion misidentification probability vs momentum; two ϵ_π values are presented:

- one is based on double (triple) hit rates in pixels with a pitch of $50\mu m$ [7] from relativistic particle.

- the second is determined by the TR yield from pions.

As one can see from Fig. 9, the main reason which defines the e/π separation for all TRD rapidity coverage is the transition radiation by pions. Nevertheless the expected probability for pions to be misidentified as electrons is quite low ($\leq 10^{-2}$) for pion transverse momentum up to $p_T \simeq 40GeV/c$, and not worse than ~ 6 up to $p \simeq 90GeV/c$.

As far as concerns the tracking capability of Si-pixel TRD, the spatial resolution expected is $\sim 15\mu m$ in the $r - \psi$ plane [7], and $\sim 1mm$ in Z. Because $r - \phi$ and Z resolution of the Si-pixel detector is substantially better than TPC resolution, the additional Si track detector at $r = 30$ cm will be useful [9] for:

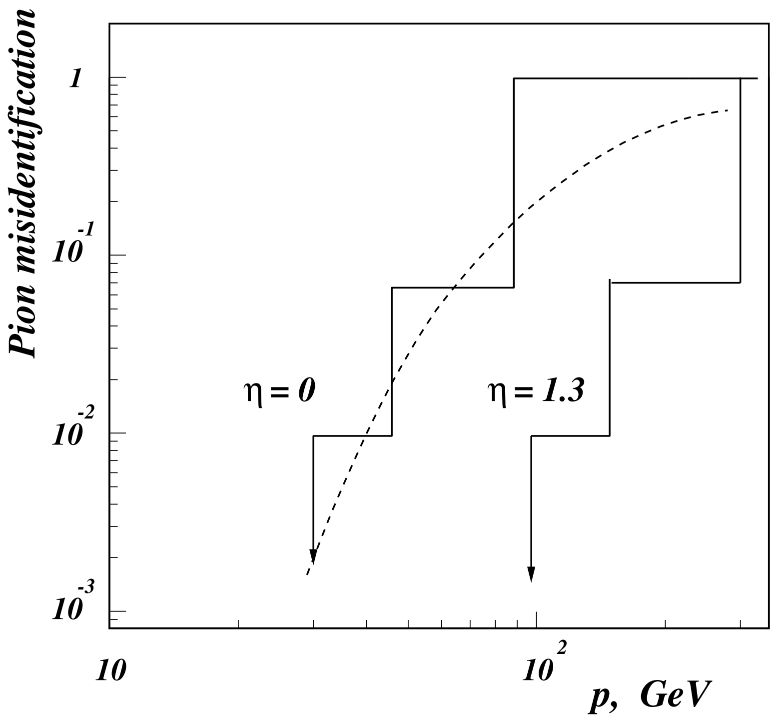

Figure 9: Pion misidentification probability as a function of the momentum for electron efficiency = 90%: solid line - determined by charge sharing between Si-pixels; dashed line - determined by pions TR radiation (does not depend on η).

- improvement of the momentum rasolution;
- improvement of the track merging efficiency for a matching procedure between TPC and VTX detector.

3 Conclusions

The main purpose of the Si-pixel TRD in the TESLA experiment is to provide electron identification inside the hadronic jets, complementary to the calorimeter.

The possibility to predict the TR photon position relative to the electron track, combined with the very small size of the TR-photon envelope $\Delta\psi \times \Delta\eta \simeq 10^{-5}$, makes Si-pixel TRDs practically insensitive to the particle density inside the jet at hadron rejection factors of up to $\geq 10^{-2}$.

This is not the case for the calorimeter, where $\Delta\psi \times \Delta\eta$ of the electromagnetic shower envelope is about 10^{-3}, which is two orders of magnitude more compared to the Si-pixel TRD.

The additional Si-pixel $r - \psi$ space point ($\sigma \simeq 15\mu m$) may prove to be very useful for the TESLA detector momentum resolution and pattern recognition, of course, e/π separation by Si-pixel TRD has to be confirmed in beam test measurements. This is currently being planned.

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