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**A Proposal for a Hadron-blind Fast TRD Based on
Secondary Electron Emission**

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A proposal for a hadron-blind fast TRD based on secondary electron emission

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A novel, fast, hadron-blind imaging TRD is proposed. Traditional radiators are followed by novel, particle-blind photon imaging detectors, combining thin CsI photon converters and fast gaseous electron multipliers. The expected performance of the TRD, based on multiple radiator/detector elements, is simulated, using experimental and theoretical data of the photon detector characteristics. Such TRDs can provide 100 GeV electron detection efficiency above 90% with hadronic background rejection factors of $10^2 - 10^4$.

The nanosecond timing, very low occupancy and the high rate capability make these devices very competitive tools for ultrarelativistic electron identification under critical conditions expected in future particle physics experiments.

1. INTRODUCTION

The identification of ultrarelativistic particles with Transition Radiation Detectors (TRD) [1] poses serious problems at high luminosity accelerators. The high occupancy of traditional TRDs, due to particle ionization of the photon detector gas, and their limited time resolution, resulting from relatively long charge collection times (tens to hundreds of ns), put serious physical limits to their applicability at very high repetition rates and large particle multiplicities. Best results are achieved so far with TRDs, based on thin “straw tubes”, having time resolutions of the order of 20 ns [2]. Large detectors of this type are presently developed for the ATLAS experiment at LHC.

Following an initial idea of Margarian [3] we recently proposed a new approach to ultrarelativistic electron identification at high luminosities [4–6]. It is based on a very fast hadron-blind TRD. Traditional radiators are followed by particle-blind TR photon detectors. The photon detectors combine thin, highly emissive, solid photon converters and fast, low-pressure, gaseous electron multipliers [7,6]. The converters consist of thin CsI films which efficiently convert soft X-rays to multiple low-energy (eV) secondary electrons. These are emitted from the converter surface and initiate a multiplication process close to

their emission location.

Figure 1. A schematic representation of the proposed TRD, composed of a sequence of radiators, each followed by several fast, hadron-blind photon imaging detectors.

The surface conversion, followed by the instantaneous multiple-electron emission, eliminates the large time jitter and localization inaccuracies associated with a photoelectric process in conventional gaseous detectors. It leads to excellent localization properties, independent of the photon angle of incidence [8]. The very low efficiency of

the convertor foil and the detector gas to charged particles [9] dramatically reduces the occupancy of the detector, when operated at high particle flux.

In the present article we discuss the expected performance of a hadron-blind TRD based on multiple radiator/detector elements. The results follow an extensive simulation work, based on our Secondary Electron Emission (SEE) models [10–13] and experimental data [6,8,9]. The efficiency for electron detection and e/π separation in the 100 GeV/c range are provided for TRD detectors based on Li and CH_2 radiators.

2. THE PROPOSED TRD

The proposed TRD combines several radiator elements followed by TR-photon detectors, as shown in fig. 1.

Particles are identified according to the number of TR-photon detector hits. The accurate localization of the photon-induced avalanches permits the tracking of the identified particles.

The number of radiator/detector modules and the number of detectors following each radiator element in one module, is derived from the experimental needs. The aim of this work is to provide a calculational means for the optimization of TRD detectors based on the SEE principle. The optimization concerns the type and number of radiator foils per element, the TR CsI convertor thickness, the number of TR-photon detectors per module and the total number of radiator/detector modules in the TRD.

The radiators considered here consist of stacks of thin Li or CH_2 (polypropylene) foils. The number of particle-induced TR-photons and their energy distribution were calculated using formulae provided by ref.15. Typical energy distributions of the TR-photons emitted from Li and CH_2 foils and their conversion efficiency in CsI are shown in fig. 2.

Note the “harder” and broader distribution for CH_2 . Figs. 3 and 4 show the average number and the average energy of the TR photons, induced by electrons and pions, as function of the particle energy. We assumed a 150 μm thick He-filled (1 atm) gap between adjacent foils. It should be

Figure 2. Typical energy distributions of TR-photons, emitted by 100 GeV electrons, from Li- and CH_2 -based radiators with different numbers of foils. Also shown is the absorption probability of the photons in a CsI convertor (200 nm and 400 nm thick for Li and CH_2 respectively).

noted that the number of emitted TR-photons presented in figs. 2,3 already includes empirical correction factors (0.65 for Li and 0.88 for CH_2), based on experimental data from ref. 1.

The SEE photon detector principle is shown in fig. 5. TR-photons are converted in a thin foil of CsI, inducing the emission of several tens of low-energy (eV) electrons into a low-pressure gas. The emitted electrons are multiplied at their emission point in the high electric field set across

Figure 3. The mean number of TR-photons emitted from Li- and CH₂-based radiators, as function of the particle energy.

the first parallel gap. The preamplified avalanche is further multiplied and detected in a second multiplication element. The fact that the photon-induced avalanche is starting at the CsI surface, very near to the photon conversion point [12] leads to a high localization accuracy and to a sub-nanosecond time resolution, as discussed above.

Figure 4. The mean energy of TR photons emitted from Li- and CH₂-based radiators, as function of the particle energy.

The low-pressure multistep avalanche electron multiplier [14] is characterized by a high gain and therefore by a high sensitivity to single or a few electrons. As the pulse-height decreases exponentially with the distance of gas ionization electrons from the converter foil, the detector has a very low sensitivity to charged particles. Due to very

Figure 5. A schematic view of the fast, hadron blind, imaging TR photon detector. TR photons are converted in a CsI layer deposited on a thin metalized Mylar support. The secondary electrons emitted from the conversion point are immediately multiplied in a low-pressure multi-stage electron multiplier, providing subnanosecond timing and sub-millimeter localization. The thin convertor and the low-pressure gas are practically “blind” to relativistic particles. P and M denote the preamplification stage and the MWPC amplification stage, respectively.

low space-charge effects in this operation mode the detector can operate in a stable way at very high counting rates.

In the last 5 years an extensive experimental study of the performance of SEE X-ray detectors was carried out, the main features are summarized below:

- a) The time resolution is 0.6 nsec (FWHM) when 10 or more simultaneous low-energy electrons are emitted from the CsI layer and initiate the avalanche. It deteriorates with decreasing the number of electrons, down to 4 nsec (FWHM) for a single electron [7].
- b) The localization resolution is typically 200-500 μm (FWHM), for X-rays of 6-60 keV respectively [8].
- c) The counting rate capability is of the order of MHz/mm^2 [6].

d) The detection efficiency varies with the X-ray energy. For CsI thickness optimized to given energies, typical detection efficiencies vary from 6% at 6 keV, with 200 nm CsI down to 0.6% at 60 keV, with 2000 nm CsI [8].

e) The pulse-height spectra induced by X-rays in a SEE detector, in the energy range of 6-60 keV, indicate that over the entire range the X-ray photons induce the emission of a large number of secondary electrons per absorbed photon [8].

f) Minimum ionizing particles (MIPs) crossing the detector induce pulse-height spectrum similar to that induced by single UV-photons. Namely, principally single electrons are emitted from the CsI by the interaction of MIPs. The absolute MIPs detection efficiency is of 6-7%, for CsI thickness between 200-800 nm, with 18 Torr of isobutane. About a third of the efficiency is due to the interaction with the CsI convertor, the rest is due to direct gas ionization by the MIPs [9].

These observations lead to the following important conclusions:

- Detector events initiated by the TR-photons can be efficiently discriminated from those induced by the ionizing particles, by setting a threshold on the pulse-height. Fig. 6 shows, on a logarithmic scale, the detection efficiency for MIPs and for 6 and 17.5 keV photons, indicating the discrimination power as function of the detector threshold.
- The sensitivity of the detector to ionizing particles could in principle be further reduced to about 3% by minimizing the gas ionization contribution. This can be achieved by choosing a gas with low primary ionization density such as CH_4 or C_2H_6 , by reducing the pressure down to a few Torr and by reducing the first preamplification gap size. It should be stressed that a low-pressure hydrocarbon gas has a considerably inferior specific primary ionization than He-based

mixtures at atmospheric pressure, and is thus more suitable for the TRD application [9].

In parallel to the experimental work a physical model was developed [10–13] which describes the SEE process and reproduces the experimental performance of the SEE detectors. The model is based on a classical approach and uses microscopic cross-sections for the electron interactions in the converter. Monte Carlo simulations based on the model were developed as a tool for detector optimization.

Figure 6. The detection efficiency of the TR-photon detector for 6 and 17.5 keV photons (relevant to Li and CH₂ radiators, respectively) and for MIPs, indicating the improved particle discrimination with an increasing detector threshold.

3. TRD SIMULATIONS

A simulation code was developed, which permits one to estimate the performance of the proposed TRD system. It provides detection effi-

Figure 7. Detector-hit distributions in events induced by electrons (1 and 100 GeV) and pions (5 GeV) in a 2 m long Li- and CH₂-based TRD. The system comprises 27 modules of 1 radiator (200 foils) and 2 photon detectors each. Other system parameters are: 15 μ m thick, 150 μ m spaced radiator foils; 200 and 400 nm thick CsI converters, for Li and CH₂ respectively; threshold=60 (see fig. 6); detector gas: 10 Torr of C₂H₆. The system threshold (ST) is defined as the minimum number of hits (detectors providing signals above a pulse-height threshold in the event).

ciencies and hit distributions for various incident particles. The simulations include several steps:

- a) Calculation of TR photon yield and spectrum from one radiator with a given number of foils is carried out, including the self-

absorption of photons in the radiator material. An empirical correction factor of the yield (0.65 and 0.88 for Li and CH₂ respectively) is included, based on the data of ref. 1. The variable parameters in this step are the radiator foil material, thickness and number.

- b) Calculation of the photon detection probability by a single SEE detector. The detection probability of TR photons as function of the photon energy and CsI thickness is taken from our experimental data and from the SEE model. Since experimental data exist only for 4 energies (6,8,17.5 and 60 keV) the model simulations are used for the proper interpolation over the entire energy range (particularly important near the CsI shell energies and in the energy range below 6 keV). The variable parameters in this step are the CsI thickness and the detector threshold (defined in Fig. 6).
- c) Photons which are not absorbed in the CsI layer are transmitted, with a given efficiency, to the following photon detector and their detection probability is calculated in a similar way. The process is repeated according to the number of detectors assumed in each module.
- d) The detection probability of the incident particles (electrons, pions) by their direct gas ionization or induced SEE, was taken from our experimental data for MIPs [9]. Our measurements, carried out at 18 Torr of i-C₄H₁₀, yield 6-7% total MIPs detection efficiency with detectors equipped with 200-800 nm thick CsI convertors. However, as discussed in Ref. 9, the particle detection probability can be reduced by a factor of 2-3 when operating at 5-10 Torr of C₂H₆. We therefore use the data of Fig. 6 as our input for the particle detection probability. The detector threshold is assumed to be the same as in the previous step. The relativistic-rise effect does not increase the particle detection probability as compared to that of MIPs, since there is no increase in

the δ -electron production yield. The effect was studied using the code GEANT3 [16].

- e) The TRD simulation program follows the particles and the photons throughout the entire structure, yielding, for each event the number of detector hits (above threshold). Examples of hit distributions are given in Fig. 7 for Li- and CH₂-based TRDs.

The simulation of the TRD performance requires the optimization of many parameters, among them are: radiator foil number and thickness, CsI convertor thickness, module geometry (namely the number of photon detectors following each radiator) and photon detector operation threshold. The optimization in this multiparameter space is a complex task. For example, increasing the number of radiator foils increases the number of TR-photons, but does not necessarily lead to an improved detection; the reason being the self-absorption in the radiator, which shifts the photon spectrum to higher energies, to a range where the photon detector is less efficient. Varying the module geometry and increasing the total number of photon detectors improves the TR-photon detection but also increases the sensitivity to hadrons, which is dominated by the direct interaction process (δ -electron production) in CsI [9]. An increase of the total number of photon detectors is therefore improving the electron detection efficiency, but is degrading the hadron rejection.

We present here some results from a first optimization step: For a given number of radiator foils we optimized their thickness, and the CsI thickness in one TRD module. Then we calculated the distribution of the number of detectors hit in a full, 2 meter long, TRD system for electrons and pions, as function of their energy for a given value of detector threshold. The process was repeated with different threshold values for various geometrical arrangements, within the restriction of 2 m total length. A few examples are shown here.

Fig. 7 shows the hit distribution expected from pions (5 GeV) and electrons (1 and 100 GeV) in a 200 cm long TRD made of 27 modules, each comprising a radiator followed by 2 photon detectors.

Table 1
Electron detection efficiency and background rejection of a 2 m long TRD

27 modules of 1 radiator/2 detectors						
ST :	Li			CH ₂		
	2	3	4	2	3	4
e^- , 100 GeV	0.99	0.94	0.88	0.96	0.88	0.75
e^- , 100 GeV/ π , 100 GeV	7	35	280	20	150	1500
e^- , 100 GeV/ π , 5 GeV	50	940	7000	60	700	18000
e^- , 100 GeV/ e^- , 1 GeV	1.5	2.8	6.1	3	8	22
Mean number of hits (e^- , 100 GeV)	6.3	6.4	6.7	5.1	5.4	5.5

8 Modules of 1 radiator/4 detectors						
ST :	Li			CH ₂		
	2	3	4	2	3	4
e^- , 100 GeV	0.98	0.91	0.77	0.86	0.67	0.44
e^- , 100 GeV/ π , 100 GeV	13	95	1200	55	680	7000
e^- , 100 GeV/ π , 5 GeV	140	2900	140000	120	2500	30000
e^- , 100 GeV/ e^- , 1 GeV	1.9	4	11	5	19	75
Mean number of hits (e^- , 100 GeV)	5.3	5.6	6.0	3.7	4.2	4.9

The radiator is made of 200 foils, 15 μm thick, spaced by 150 μm . The CsI thickness is 200 and 400 nm for Li- and CH₂-based radiators, respectively. The detector threshold is fixed at 60 (see fig. 6), yielding on the average 6 hits for 100 GeV electrons. A lower detector threshold leads to an increased number of hits and allows high resolution tracking of the identified electrons, but degrades the hadron rejection. Therefore, a double-threshold system could be considered to maintain both an accurate tracking and good rejection capability. The efficiency of this TRD to electrons and pions of 1-100 GeV is summarized in Fig. 8 and in Table 1. The system threshold (ST) is defined as the minimum number of hits in an event.

Fig. 9 presents the performance of a 2 meter long TRD comprising 8 modules of 1 radiator + 4 photon detectors each; the radiator comprises 1000 Li or CH₂ foils, 15 μm thick and spaced by 150 μm . The CsI thickness is 200 nm and 600 nm for the corresponding Li and CH₂ radiators. In this configuration the hardening of the TR spectrum from a thicker radiator causes a deterioration of the performance, in terms of electron efficiency and tracking, but the pion rejection factors are improved due to a smaller number of photon

detectors in the system. The efficiency of this TRD system to electrons and pions of 1-100 GeV is summarized in Fig. 9 and in Table 1.

It should be noted that previously published results, of TRDs incorporating larger numbers of radiator foils [6], somewhat overestimate the electron identification efficiency and underestimate the pion rejection. This is due to the use of inexact photon and particle detection efficiencies in the simulations.

4. SUMMARY

A novel TRD is presented, based on fast, hadron-blind, photon detectors. A Monte Carlo simulation of the TRD was developed based on our experimental and theoretical data of the performance of the photon detectors. It allows the optimization of various system parameters and was used to provide the detection efficiencies and rejection factors for electrons and pions in the energy range of 1-100 GeV.

We presented a few examples of possible TRD systems, comprising a large number of photon detectors (32-54). The total detector length was restricted to 2 m, corresponding, for example, to

Figure 8. Pion detection efficiency of the 2 m long TRD having parameters described in fig. 7, as function of energy, for various system threshold values. The efficiency for 1 and 100 GeV electrons (ϵ_1 and ϵ_{100}) are also indicated on the curves.

Figure 9. Pion and electron detection efficiency of 2 m long Li- and CH_2 -based TRDs with 1000 foil radiators. The system comprises 8 modules of 1 radiator and 4 detectors each. Other system parameters are: 15 μm thick, 150 μm spaced foils; 200 and 600 nm thick CsI converter for Li and CH_2 respectively; 10 Torr C_2H_6 gas; threshold 60 (see fig. 6).

a typical available space within the inner tracking detector of an LHC experiment. We demonstrated a possible detection efficiency of 90% for 100 GeV electrons with 100 GeV pion rejection factor (e/π) of 280 (with Li foils) or 150 (with CH₂ foils). 5 GeV pion rejection factors are 7000 and 700 respectively.

It should be stressed that the present results are only preliminary, as the optimization has not yet been completed. More work is needed in order to introduce the tracking performance into the simulation, and to include it in the optimization process. The present results are, however, very encouraging, indicating the feasibility of a fast (nanosecond timing) TRD which can operate with low occupancy at high interaction rates, under very large particle flux.

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