Nuclear Instruments and Methods in Physics Research A 706 (2013) 73–78

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Geant4 simulation of transition radiation detector based on DEPFET silicon pixel matrices

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ARTICLE INFO

Available online 14 May 2012

Keywords:
Transition radiation detector
TRD
DEPFET
Active pixel detector
Silicon detector
Geant4

ABSTRACT

This paper presents new developments in Monte Carlo simulation for test beam measurements of a silicon transition radiation detector based on DEPFET—a silicon active pixel detector. The test of DEPFET with fiber radiator has been carried out at the DESY 5 GeV electron beam. Monte Carlo simulation of the test beam setup is based on Geant4. A comparison of Geant4 simulation with test beam data is presented.

1. Introduction

Transition radiation detectors (TRD) have the attractive feature of being able to separate particles by their gamma factor. In high energy physics, TRDs are typically used for electron identification and hadron background rejection [1]. The main problem in the detection of transition radiation photons is to separate TR from ionization energy losses of charged particles.

The classical TRD is based on gaseous detectors filled with a xenon based gas mixture to efficiently absorb transition radiation photons. The typical absorbed TR energy is about 10–15 keV while the background of dE/dx from a charged particle is about 2–3 keV.

Replacing the xenon-based gaseous detectors by modern silicon detectors is complicated by the large energy losses of charged particles in $300-700\ \mu m$ of silicon which is about 100–300 keV. A DEPFET sensor [2,3] has a good signal to noise ratio which allows to measure ionization from charged particles in a thin layer of silicon (down to $30\ \mu m$) [9]. In this case the ionization from charged particles (10–15 keV) is in order of the TR photon energy. Additionally, due to its high granularity (down to $20 \times 20\ \mu m^2$), the DEPFET allows measuring angular distribution of TR photons. The use of the angular separation between TR photons and particle tracks is discussed in detail in Refs. [1,7,8].

The main features of DEPFET which are used in the new TR detector concept are a fully depleted substrate and low noise energy measurements. Fig. 1 shows a schematic cross-section of a DEPFET sensor with a pixel size of $20 \times 20\ \mu m^2$ and $450\ \mu m$ thickness. Particles crossing the DEPFET sensor with an angle of incidence around 40° have a track length in one pixel of about $30\ \mu m$. In this case the energy deposited in one pixel is a factor of 10 lower (~ 10 keV, than for a particle with an angle of incidence 0° and comparable with ionization from TR photons.

About 10–30 points of dE/dx measurements, depending on the particle angle, could be used for particle separation. However, most of the TR photons are absorbed in the first 3–7 bins (pixels) along a track.

Nowadays the DEPFET substrate can be thinned down to $50\ \mu m$ [15]. Fig. 2 shows an application of a thinned down DEPFET matrix for a TR detection. The drawback of this method is that the efficiency of registering TR will be also lower. The advantage is that the pixel size could be much larger $\sim 50-200\ \mu m$.

2. Test beam setup

The test of DEPFET with a fiber radiator has been carried out in December 2009 at DESY. Detailed description of the setup and results is discussed in the previous article [4]. DESY has a pure electron beam with an energy up to 7 GeV. For these relatively low energy electrons, the multiple scattering in a 15 cm radiator is about 0.2 mrad and comparable with a TR angular distribution. Readout of a DEPFET and data acquisition system is described in Ref. [5]. Tests were done using a standalone DEPFET module (COCG VS H3.0.07 $20 \times 20\ \mu m^2$) with signal to noise ratio ~ 220 for MIP, pixel size $20 \times 20\ \mu m^2$ and $450\ \mu m$ thickness. Fiber radiators with different thicknesses have been used for the tests. The radiator consists of polypropylene (PP) fibers of $20\ \mu m$ diameter, and produced as fleece layers (mats) of about 2.2 mm thickness and density 0.1 g/cm^3. The layers were stacked to give a total radiator thickness of 15.5 cm with an average density of 0.083 g/cm^3 [6].

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http://dx.doi.org/10.1016/j.nima.2012.05.009

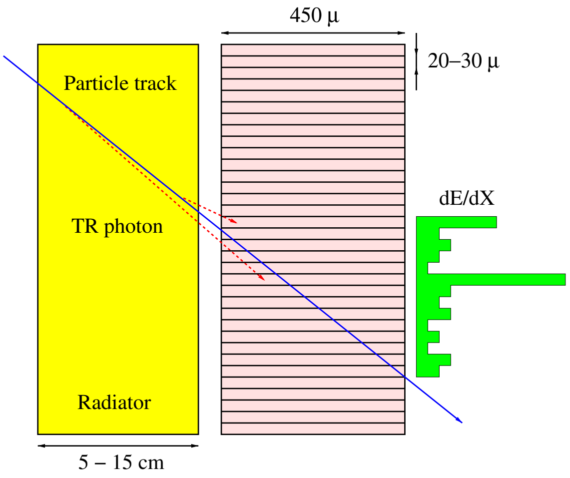

Fig. 1. TRD with 450 µm thick silicon.

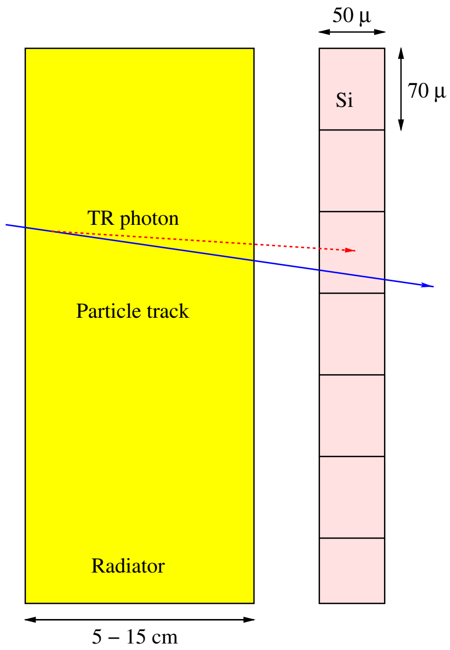

Fig. 2. TRD with 50 µm thick silicon.

3. Monte Carlo simulation

For initial Monte Carlo simulation the ATLSIM package [14] based on GEANT3 is used together with a transition radiation simulation program, which has been developed for the simulation of the ATLAS TRT [16].

The absorbed transition radiation energy in ~500 µm thick silicon detector with 15 cm of radiator, placed at a distance of ~2 cm from the detector surface is in good agreement with a measured spectrum [4]. However, the TR model of this program does not simulate the angular distribution of TR photons, which is very important in this case. For this reason, we had to switch to Geant4 where the TR angular distribution is implemented. The test beam setup was implemented in *Geant4.9.4.p01*. Unfortunately, the default version also does not describe the experimental data in the part of TR angular distribution.

Investigation of this problem shows that the agreement is not good due to lack of experimental data on angular distribution of TR and some theoretical uncertainties [11]. After tuning simulation parameters which are related to the angular distribution of TR photons, a good agreement between Geant4 and experiment is achieved. Using the recent experimental data allows to improve the simulation of TR photon angle. Tuned version of the code will be available in the next release of Geant4.

The simulation of pixel detector response includes the noise of readout electronics, the charge diffusion in pixels and the ADC discretization. Geant4 offers several options for simulation of ionization losses and transition radiation processes. The particle dE/dx in 450 µm silicon is simulated according to the photo absorption ionization (PAI) model [12,13].

The current Geant4 transition radiation model includes several classes. The two most important ones are *G4RegularXTRadiator* for description of radiator with fixed foil and gas gap thickness and *G4GammaXTRadiator* for description of irregular radiator with gamma distributed foil and gas gap thickness [10]. Regular radiator is described in terms of foil and gas gap thickness and density. The number of foils is calculated from the radiator length. For irregular radiators there are two more parameters describing the thickness fluctuation of foils and the gas gap: *AlphaPlate* and *AlphaGas*. *G4GammaXTRadiator* was selected for simulating the fiber radiator which was used in the test beam. A *foil thickness* parameter of 16 µm was chosen for 20 µm fibers as average path in the fiber. The gas gap is a free parameter and could vary from 100 to 1000 µm; the value of 300 µm was found well tuned to describe experimental data. Variation of fluctuation parameters *AlphaPlate* and *AlphaGas* does not show significant sensitivity of the result to these parameters and the default value of 100 was used for both parameters. The Geant4 data processing flow was the same as for the experimental data. The energy calibration in Monte Carlo is done in the same way as for the experimental data simulating the data from a gamma source of 59.5 keV (^{241}Am).

4. Comparison between the experimental data and the Geant4 Monte Carlo

Silicon as detector for TR photons shows a good efficiency. The maximum possible path of TR photons in 450 µm DEPFET rotated at 40° is about 600 µm. In this case, the DEPFET has almost a 100% efficiency for TR up to 12 keV (Fig. 3).

4.1. Cluster reconstruction

Due to charge sharing, a deposited charge in the silicon detector usually spreads over several pixels, typically within a 3 × 3 pixel area. Reconstruction of a cluster in an event is done by

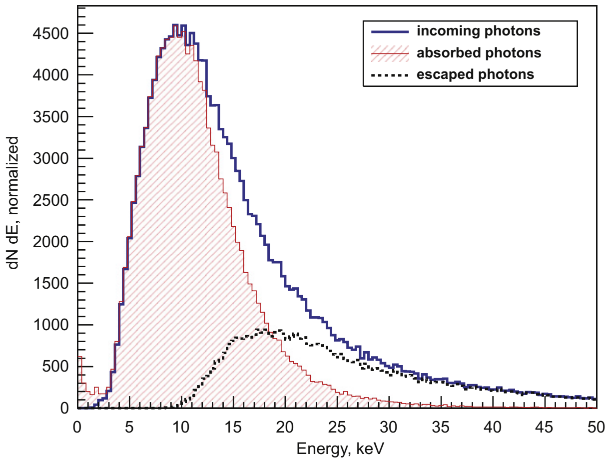

Fig. 3. A Monte Carlo spectrum of generated, absorbed and escaped transition radiation photons for 600 µm thick silicon and 15.5 cm thick radiator.