Simulation of the time resolution of a 50 μm low-gain avalanche detector.

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Abstract

In this paper we report simulation results on the timing resolution of a 50 μm low-gain avalanche detector (LGAD). The simulation includes: sensor fluctuations, front-end electronics, and quantization. Comparisons on the performance for different front-end electonics (FEE) bandwidths (BWs) are presented, as well as the dependance on singal-to-noise ratio (SNR). Two approaches to measure the timestamp are presented: leading edge (LE) and constant-fraction-discrimination (CFD). Aditionally, the time resolution is studied as function of the irradiation of the sensor. Simulated LGAD pulses before irradiation, and after neutron fluences of 5×10^{14} n/cm^2 and 1×10^{15} n/cm^2, are studied. The time resolution a 50 μm LGADs was found to be 30 ps for FE electronics BWs larger than 350 MHz and SNRs larger than 30. The time resolution at a SNR of 30 for fluences of 5×10^{14} n/cm^2 and 1×10^{15} n/cm^2 were found to be 30 ps and 40 ps, respectively.

Key words:
Silicon, Timing, LGAD

Contents

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1. Introduction

Future colliders, including the high luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN, will operate with an order of magnitude higher instantaneous luminosity compared to what has been achieved at the large hadron collider (LHC) so far. With the increased instantaneous luminosity, the rate of simultaneous interactions per bunch crossing (pileup) is projected to reach an average of 140 to 200. Pileup increases the difficulties in separating particles from the hard scattering interaction with those produced in different pileup interactions. In particular, the ability to discriminate between jets produced in the events of interests, especially those associated with vector boson fusion processes, and jets produced by pileup interactions will be degraded. Additionally, the efficiency to identify high p_{T} isolated electrons and muons will be severely reduced due to the high density of pileup particles in their vicinity. The missing transverse energy resolution will also deteriorate, and several other physics objects performance metrics will suffer the detrimental effects of pileup.

One way to mitigate the pileup effects mentioned above, complementary to precision tracking methods, is to perform a time of arrival measurement associated with each particle. Such a measurement with a precision of about 30-40 ps, will reduce the effective amount of pileup by a factor of 10, given that the spread in collision time of the pileup interactions at HL-LHC is foreseen to be approximately 200 ps. It has been previously shown that a precision of better than 20 ps can be achieved for electromagnetic showers measured with silicon sampling calorimeters [1–3] using traditional planar silicon detectors while precision of 30 ps can be achived for minimum ionizing particles (MIPs) measured with low-gain avalanches detectors (LGADs) [4–6].

LGADs are envisioned to be used in the CMS and ATLAS experiment upgrades for HL-LHC in order to overcome the event reconstruction challenges posed by the high rate of concurrent collisions per beam crossing. The implemented regions of pseudorapidity (η) are: $|\eta| > 1.5$, and $2.4 < |\eta| < 4.2$ for CMS and ATLAS, respectively. In order to achieve the desired timing precision across a large area of the detectors, the sensors will need to provide high uniformity of signal response and timing resolution. Beam test measurements have provided encouraging results towards achieving such detectors [4].

In this paper, we report simulation results on the timing resolution of a 50 μm low-gain avalanche detector (LGAD) which includes the effects of the sensor fluctuations, front-end electronics (FEE), and quantization. Our results indicate that for FEE analog bandwidths (BWs) larger than 350 MHz and signal-to-noise ratios (SNRs) larger than 30, measured at the output of the FFE, time resolutions of 30 ps and 40 ps are obtained when using time-walk corrections based on time-over-therhold (ToT) measurements to both timestamping techniques: constand-fraction-dricrimination (CFD) and leading-edge (LE), respectively. These results are compatible with previous measurements on LGAD timing resolutions carried out in laboratory and beam test conditions [4–6]. We study the time resolution for four different FEE shaping times: 0.5 ps, 1.0 ps, 2.0 ps, and 4.0 ps; three SNR: 20, 30, 100; and three irradiation levels: pre-radiation, 5×10^{14} n/cm^2, and 1×10^{15} n/cm^2. For every point in this scan we evaluate the time resolution for LE and CFD.

The paper is organized as follows: the simulation is described in Sec. 2; algorithms used in the timing reconstruction and analysis are described in Sec. 3; simulation results are presented in Sec. 4, followed by the conclusion in Sec. 5.

2. Simulation Framework

The simulation framework is based on c++ programing language. The LGAD pulses are obtained from Weightfield2 (WF2), a 2-dimensional silicon simulator [**?**]. WF2 provides sets of 1000 LGAD pulses which models the response of the sensor to minimum ionizing particles (MIPs). We generated 3 sets of LGAD pulses for a 50 μm LGAD: pre-irradiation, and after neutron fluences of 5×10^{14} n/cm^2 and 1×10^{15} n/cm^2. The simulation framework takes the LGAD pulses (from WF2) and adds gaussian white noise (hereafter white noise). At this point the LGAD pulses with the added white noise are fed into the simulation of the FEE (see Fig. 1). The output of the FEE simulation is the convolution of the impulse response function and the input signal at the FEE. We consider four shaping constants for the impulse response of the FEE: 0.5, 1.0, 2.0, and 4.0 ns (the FEE simulation will be described in detail in Sec. 2.2). At the output of the FEE block we have a "realistic" LGAD pulse which includes the effects of sensor fluctuations, shaping of the FEE, and noise. A waveform analysis is performed with the pulses obtained at the output of the FEE block. We assign timestamps to each pulse by using algorithms that emulate an ideal LE discriminator and an ideal CFD. For each threhold we obtain a LE and CFD timestamps as well as the corresponding time-over-theshold (ToT) of the pulse. The SNR is defined as the ratio of the most probable value (MPV) of the amplitude distribution to the width of the amplitude distribution at a fixed sample (where only noise is present). We study 3 SNR scenarios: 20, 30, and 100. A schematic diagram of the simulation is shown in Fig. 1.

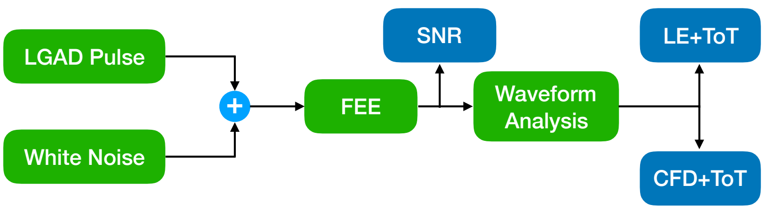

Figure 1: A schematic diagram of the simulation. Each simulation configurable block is shown in green. The most relevant outputs of the simulation are shown in blue.

2.1. LGAD pulse library and simulation

We need to ask Nicolo to send us a paragrah for the Weightfield2 (WF2)

2.2. Fron-end Electronics simulation and noise injection

The front-end simulation is implemented in c++ programing language. It combines analytical calculations when possible but it mostly relies numerical methods. We implement most calculations in the time domain, while the frequency domain is mostly used to cross-check noise and the FEE expected response.

2.2.1. front-end implementation

We use a second order low-pass filter which transfer function and impulse response are given by equations 1 and 2, respectively.

$$H(S) = \frac{\frac{1}{\tau_s^2}}{(S + 1/\tau_s)^2} \quad (1)$$

$$h(t) = \frac{t}{\tau_s^2} e^{-t/\tau_s} \quad (2)$$

The output pulse of the FEE is the convolution (in time domain) of the pulse coming from the LGAD library and the FEE impulse response. The time base for the pulses and the convolution is 1 ps – this is the sampling time that we use for the whole signal simulation, noise is treated differently and cover in **??**.

2.2.2. noise injection

blah blah blah

3. Timing Reconstruction and Analysis

3.1. Leading edge and constant fraction discriminators

3.2. Time-walk correction and time over threshold

4. LGAD Front-end Electronics Performance

We present a number of different studies of the LGAD sensors. such that they are above the noise levels listed for each board in Sec. **??**. All measurements other than those described in Sec. **??** and 4.3 were performed at room temperature.

4.1. Front-end electronics shaping time studies

4.2. Timing Performace as a function of signal-to-noise ratio

4.3. Timing Performace as a function of irradiation

5. Conclusion

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