Studies of Front-End Electronics for High-Precision Timing Measurements with LGADs

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FEE Simulation Background

In time-of-arrival (ToA) measurements, simulations can be used to optimize precision detection and implementation methods in front-end electronics (FEE – Figure 1). Here, the detector, an LGAD (Low-Gain Avalanche Diode), is modeled via charge generation, amplification, and collection by way of particles traversing the detector. The resulting current pulse is prepared and sent to the FEE simulation (Figure 2).

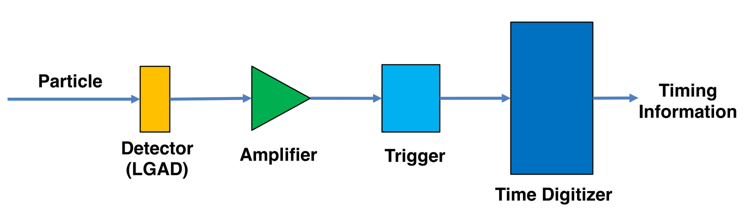

Figure 1. In this project, the above timing Network/FEE model is used [3].

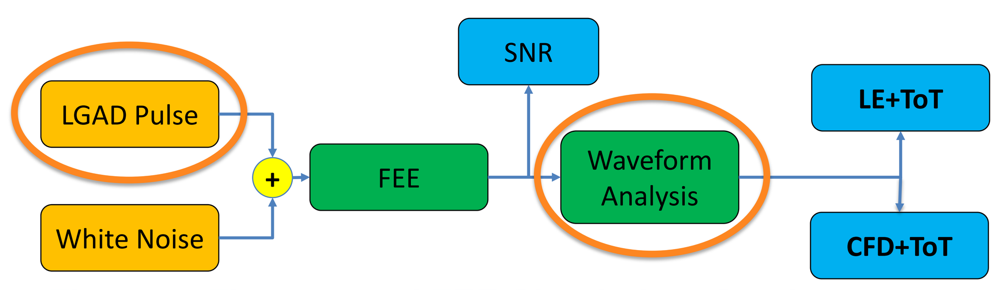

Figure 2. Flowchart of FEE Simulation. Sections developed in this project are circled [2].

Gaussian white noise is then added (mimicking circuit noise), and the signal is sent through a filter and amplifier. This process is repeated for N LGAD 'events', and the ToA values are computed for each event. Theoretically, all events should have the same ToA value. Thus, the spread of the measured results is used to determine the timing precision from the FEE setup [1]. The **goal** of this project is to optimize algorithms within the simulation while maintaining or improving timing precision. All simulations were done in *Mathematica.*

Preparation of LGAD Pulse

To obtain the response of the filter, an input LGAD event ($f[t]$) first needs to be converted to the s-domain. To optimize the Laplace transform, a piecewise linear (**PWL**) approximation of $f[t]$ can be used. However, as a typical simulated event contains $\sim 17{,}000$ points, the Laplace transform can take an excessive amount of time. To accelerate the process, n points can be selected to model $f[t]$, such that the main trends in the signal are captured using a minimal number of points. From previous tests, a balance was found when $n \approx 25$ [1].

$$X[s] = \frac{1}{\sqrt{N}} \sum_{t=1}^{N} f_t \cos\left(\frac{\pi}{N}\left(t - \frac{1}{2}\right)(s-1)\right)$$

Equation 1. Fourier Discrete Cosine Transform (Fourier DCT) (Source: Mathematica).

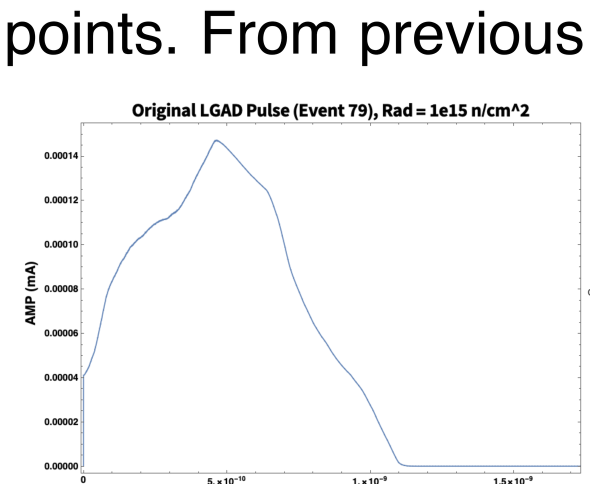

Figure 3. Example of a typical LGAD signal.

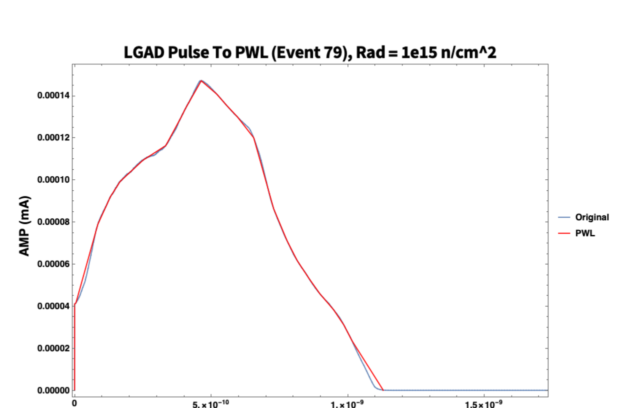

Figure 5. Original LGAD event and PWL approximation from new algorithm.

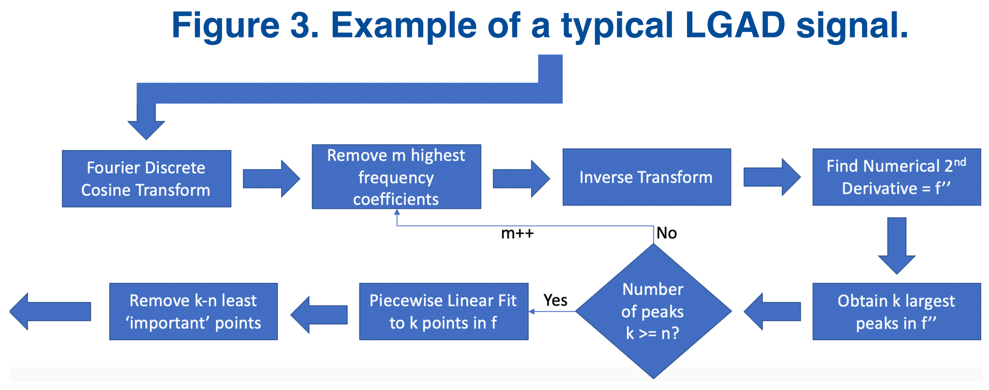

Figure 4. Flowchart of new algorithm.

The old PWL approximation algorithm has some drawbacks. For one, it is time-intensive, taking upwards of 5 hours to run on the primary workstation. Furthermore, the algorithm lacks a formal conceptual structure, as it relies on smoothing the data, and detecting peaks in $\frac{d^2 f[t]}{dt^2}$. Thus, a new algorithm was developed that utilizes the Discrete Fourier Cosine Transform to capture trends in the signal (Figure 4). The robustness and efficiency of the algorithm were tested to validate the new PWL method.

Simulation and Waveform Analysis

Results for the old and new algorithms for one event (Figures 6 and 7) show that the new algorithm's PWL fits the signal better than the old method. Analysis of multiple events indicate that the new algorithm is qualitatively successful in creating PWL approximations of the LGAD events, as well as choosing the best points to keep (Figure 8). Testing also showed that the new algorithm is ~8x faster than the old one, reducing computing resources significantly.

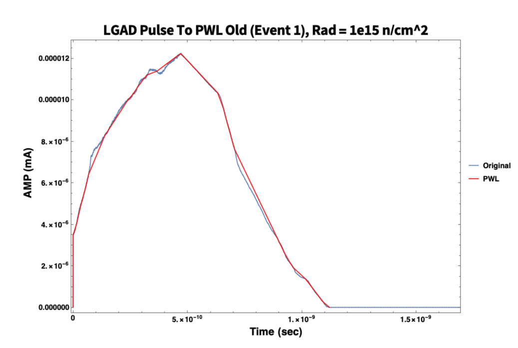

Figure 6. Old algorithm PWL approximation of LGAD Pulse.

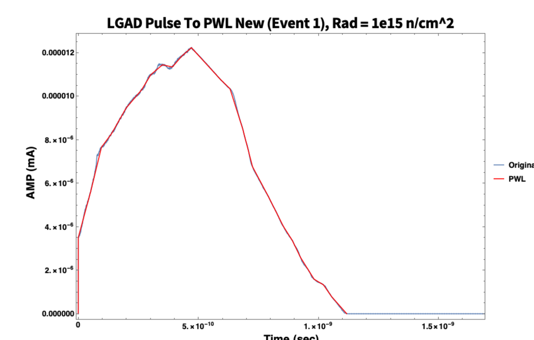

Figure 7. New algorithm PWL approximation of LGAD Pulse.

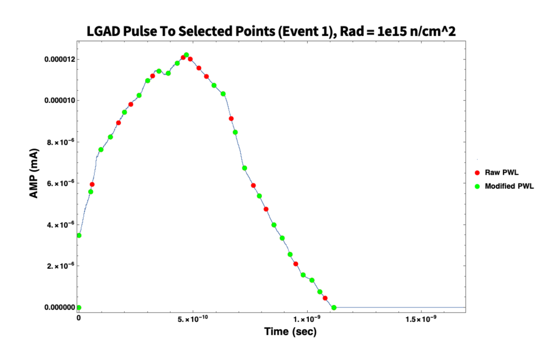

Figure 8. Points selected and removed by new algorithm for PWL approximation.

For each event, once $X[s]$ is found (Equation 1), the response to the (CR-RC^3 in this case) filter is computed and the ToA is calculated as shown in Figure 9. The results are corrected by the response's time over threshold (ToT) or amplitude (Amp).

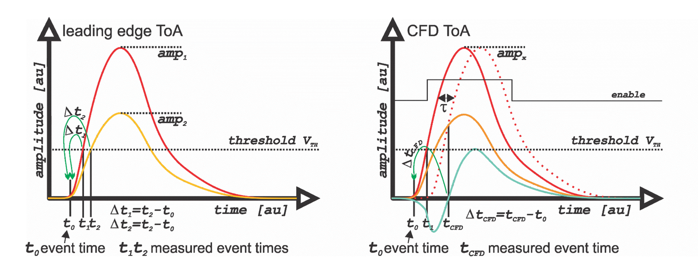

Figure 9. The ToA is computed by referring to a leading-edge (LE) threshold (left) or a constant fraction discriminator (CFD), which searches for the ratio of ToT and Amp that crosses a relative threshold (right) [1].

Tables 1 and 2 display the results of a full simulation with the original and new PWL approximation algorithms for specific signal-to-noise ratios (SNR) and LGAD radiation damage. As can be seen, the precision is nearly identical for all analyses. The discrepancies can be accounted for by a margin of error (due to finite sample size), which is 1.2-3.3% for a sample of 250 events.

	5fC, 1e15 n_{1MeV}/cm^2		
SNR	*21.5*	*43.0*	*71.5*
LE-ToT	**69.2ps**	**39.2ps**	**32.7ps**
LE-TOT δ(t)	65.9ps	27.6ps	19.4ps
LE-AMP	**59.7ps**	**37.1ps**	**32.6ps**
LE-AMP δ(t)	55.0ps	28.8ps	20.6ps
CFD	**45.7ps**	**30.6ps**	**28.2ps**
CFD-TOT δ(t)	45.3ps	20.9ps	12.9ps
psCFD	**63.9ps**	**36.6ps**	**30.6ps**
psCFD-TOT δ(t)	74.4ps	33.3ps	19.8ps

Table 1. Old algorithm, 250 Samples

	5fC, 1e15 n_{1MeV}/cm^2		
SNR	*21.5*	*43.0*	*71.5*
LE-ToT	**72.0ps**	**38.3ps**	**29.0ps**
LE-TOT δ(t)	61.2ps	29.2ps	20.2ps
LE-AMP	**59.0ps**	**37.3ps**	**31.2ps**
LE-AMP δ(t)	51.4ps	28.8ps	19.7ps
CFD	**45.6ps**	**30.8ps**	**26.9ps**
CFD-TOT δ(t)	43.0ps	21.0ps	12.4ps
psCFD	**64.6ps**	**36.5ps**	**27.9ps**
psCFD-TOT δ(t)	67.1ps	32.7ps	19.4ps

Table 2. New algorithm, 250 Samples

	5fC, 1e15 n_{1MeV}/cm^2
SNR	*21.5*
LE-ToT	**75.7ps**
LE-TOT δ(t)	68.6ps
LE-AMP	**62.2ps**
LE-AMP δ(t)	54.3ps
CFD	**46.1ps**
CFD-TOT δ(t)	44.6ps
psCFD	**67.5ps**
psCFD-TOT δ(t)	73.8ps

Table 3. Old algorithm, 1000 Samples

	5fC, 1e15 n_{1MeV}/cm^2
SNR	*21.5*
LE-ToT	**66.7ps**
LE-TOT δ(t)	60.0ps
LE-AMP	**56.7ps**
LE-AMP δ(t)	49.4ps
CFD	**41.6ps**
CFD-TOT δ(t)	40.6ps
psCFD	**58.5ps**
psCFD-TOT δ(t)	66.3ps

Table 4. New algorithm, 1000 Samples

Tables 1-4. Timing precision results with algorithms for different SNR ratios and sample sizes. Errors are computed as root-mean-square values (error of measurement method) from reference/mean ToA.

From Tables 3 and 4, one can see that discrepancies in timing precision remain generally minor, and the consistency of the timing precision indicates that the new algorithm is functional. However, more testing is required on full sample sets and on the changes in timing behavior for subsets of events.

Conclusion

A new algorithm to model LGAD events with modified piecewise linear fits successfully retains the timing precisions from previous methods, while creating a more formal framework around the procedure and running more efficiently. This will allow for simpler modifications and adaptations in the future, and a more seamless transition from simulated to real detector events.

References

[1] G. Deptuch, "Time of Arrival (ToA) measurements in the High Luminosity Large Hadron Collider Experiments (HL-LHC) and synergetic opportunities,". *Internal Fermilab report: unpublished*, February 2019.

[2] C. Peña, G. Deptuch, et al, "A simulation model of front-end electronics for high-precision timing measurements with low-gain avalanche detectors," *Nucl. Instrum. Meth. A [Preprint]*, June 2019.

[3] H. Spieler, "Fast Timing Methods for Semiconductor Devices," *IEEE Transactions on Nuclear Science*, vol. NS-29, no. 3, June 1982.

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