Study of ToA Measurement with CFD Using Switched Capacitor Sampling or Bucket-Brigade Analog Time Delay Line

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Introduction

Studies of ToA measurements:

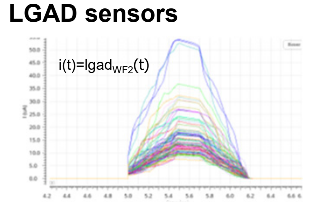
Motivation

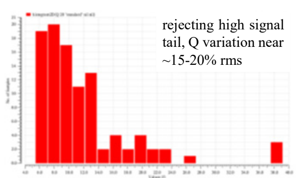
4D (position and time) – tracking in the HL-LHC experiments.

Intended Sensor

Low-Gain Avalanche Diodes segmented into a pixelated structure with the proposed pixels sizes ranging from about 1mm^2 to about 3mm^2; typical capacitance of the sensor segment on the order from a few pF up to about a dozen pF (for the largest pixels sizes considered), while the thickness (volume producing charge signal) typically less or equal to 50μm thick; charge produced by ionization drifts to the zone of high electric field, where multiplication with a typical gain of 10 increases the signal; ToA measurement precision constrained by variation of the total charge (Landau-like distribution with MPV of less than 10fC) and i(t) waveform fluctuation.

Current signal and variation of generated charge in LGAD sensors





Courtesy of Nicolo Cartiglio (INFN, Torino) WeightField2: a simulation program to optimize UFSD; http://personalpages.to.infn.it/~cartigli/weightfield2

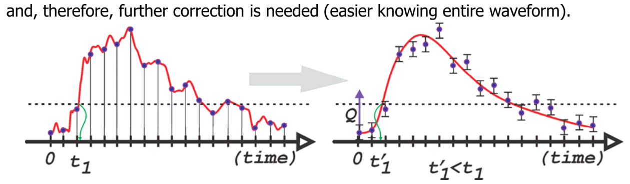
Courtesy of Quan Sun (SMU, Dallas TX).

Finite duration of development of charge signal, event-to-event varried magnitude of the total produced charge, and jittering of the current waveform certainly contribute to the measurement error with each arrival time of particles can be estimated.

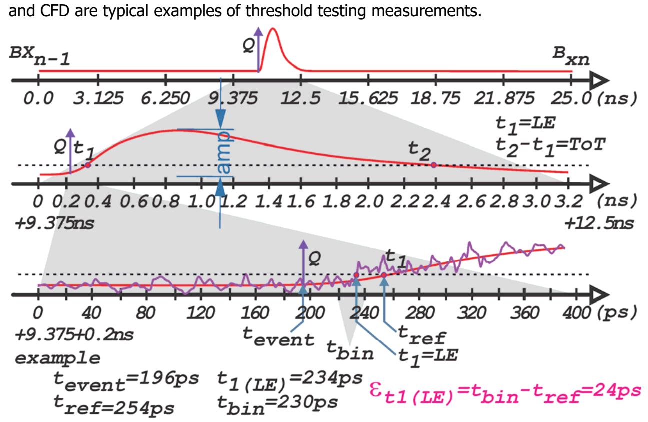
Time of Arrival (ToA) measurements

ToA measurement circuits are typically based on:
- waveform sampling and deriving of ToA from some sort of fitting, or
- finding time pointers when a waveform meets directly some criteria (level crossing)

Waveform sampling: knowing the theoretical form of signal, 'fitting' can yield t'$_1$ that is a more precise estimator of threshold crossing than t$_1$ - resulting from comparing raw signal with threshold - (regardless of LE, CFD or other method used). The difference between time '0' and t'$_1$ is deterministic unless, e.g. timewalk is present and, therefore, further correction is needed (easier knowing entire waveform).



Thresholds testing: finding pointers when a raw waveform meets some criteria (level crossing) produce small quantity of data (e.g. 10 bits every event occurence) and is practical for integrated multichannels systems due to conserving silicon area and power consumption, however, it is sensitive to stochastical errors (time walk and imperfection of circuitry: threshold offsets, time-to-flip overdrive dependence, etc. LE and CFD are typical examples of threshold testing measurements.



t$_1$ is an estimator of t$_{ref}$; instead of t$_{event}$, estimator of t$_{ref}$ is measured; if t$_{ref}$-t$_{event}$ is deterministic, there is no error, binning adds quantization noise on t$_1$

ToA simulation package

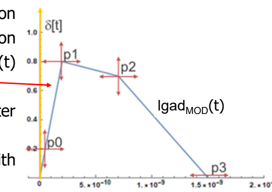
symbolic-numerical calculation in Mathematica:

Motivation for Mathematica script

Learn what method should be chosen for the design of a readout integrated circuit and what ToA measurement error could be expected under the constraints of LGAD sensor properties, implementability in IC, power budget and resulting SNR.

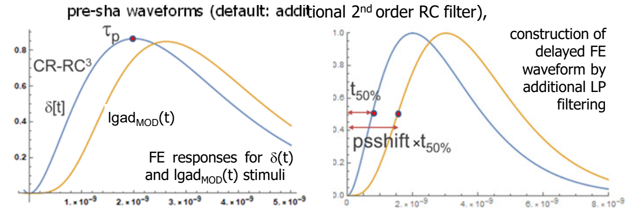
Script developed to study:

- LE based on single threshold and averaged result of multiple thresholds,
- CFD using real signal and pseudo delay by additional low pass filtering (psCFD),
  - both methods without and with correction based on amplitude measurements using ToT and using peak detection.
- Dependence of LE, CFD and psCFD on input signal form, i.e. δ(t) or Igad$_{MOD}$(t) approximated (piece-wise-linear PCW) charge pulse (worst case variation),
- Dependence of LE, CFD and psCFD on variation of charge magnitude for δ(t) or Igad$_{MOD}$(t) and on timing properties of Igad$_{MOD}$(t)-approximated i(t) (points p0,p1,p2,p3 are allowed to move),
- Dependence of LE, CFD and psCFD on FE filter pulse response time properties,
- Dependence of LE, CFD psCFD on noise with waveforms of filtered white noise (transient),

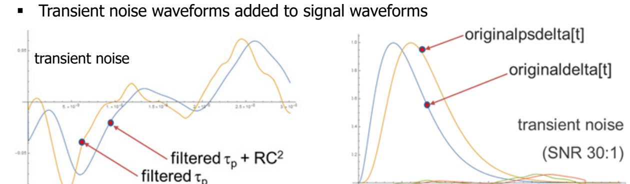


Features to approach IC implementation:

- Transfer function of FE preamplifier-shaper can be any function that possesses *s*-domain expression and analytical inverse Laplace transform (default: 2nd order CR-RC filter, τ_p=1, 2, 4, 6 ns),
- Bipolar signal for CFD created by:
  - subtraction of scaled down pre-sha and delayed pre-sha waveforms,
  - subtraction of scaled down pre-sha and additionally low-pass filtered pre-sha waveforms (default: additional 2nd order RC filter),

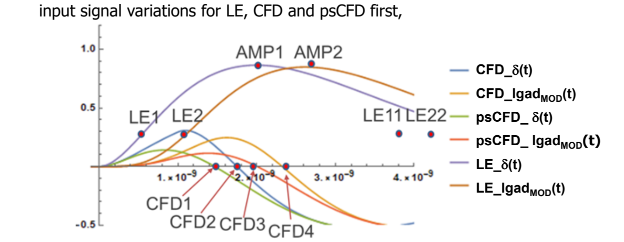


- Transient noise produced as a superposition of impulse responses to a sequence of δ(t) stimuli (white noise with sampling period = τ_p/100) scaled to the tested SNR and interpolated for continuity
- Transient noise waveforms added to signal waveforms



Results of simulations:

- "Time domain" simulations are carried out taking into account transient noise and input signal variations for LE, CFD and psCFD first,



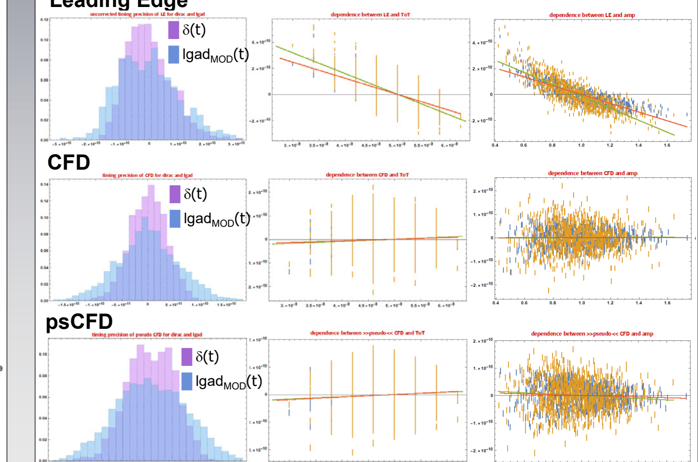
- Results LE1, AMP1, LE11, LE2, AMP2, LE22, CFD1, CFD2, CFD3, CFD4 are stored,
- „Time domain" simulations are followed by quantization studies, where each "time domain" event is randomly placed in the BX time window and time (toaquant) and amplitude (ampquant) measurements are quantized, ToT results are additionally binned (totquant).

Simulation results

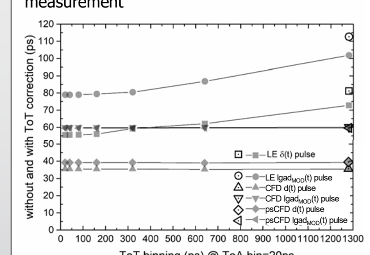
Example ToA measurements simulation results

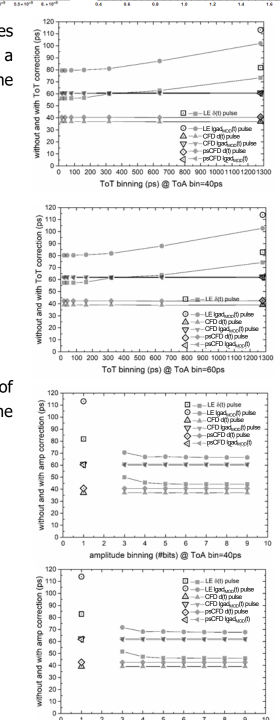
τ_p=2ns **SNR=30** and

input charge pulse variation: Q±20%, (p0, p1, p2, p3) ±10% - not fitted to Igad$_{WF2}$(t) yet, quantization binning: toa=20ps, tot=400ps, amplitude=10bits

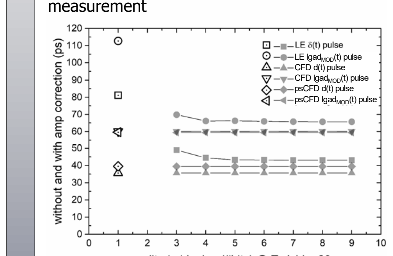


dependence of ToA measurements on properties of the signals with correction using ToT as a function of ToT quantization and binning of time measurement





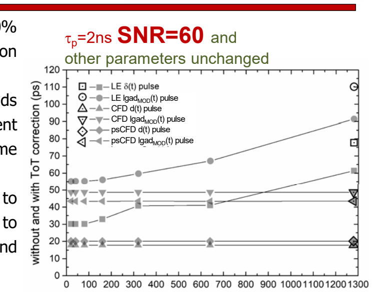
and correction using amplitude as a function of amplitude quantization and binning of time measurement



Conclusions

- CFD performs generally 20%-30% better than LE with correction using ToT or amplitude,
- Finite duration of Igad$_{MOD}$(t) yields less good ToA measurement precision than δ(t) for the same total charge variation,
- ToT or amplitude do not have to be measured with high precision to allow LE correction (250ps and 5bits are satisfactory),
- CFD and psCFD yield close results, difference can result from nonequivalence of 'delay' and 'ratio' parameter

τ_p=2ns **SNR=60** and other parameters unchanged



Circuit concepts

Extrapolating on expected SNR

50μm thick LGAD with gain=10 produces Mean[Q]=Range[30-40ke-]

What ENC to expect? ENC= ∝ Sqrt[τ_p] => for X-ray pixel detector τ_p=100ns yields ENC=~100e-, so is it realistic to assume ENC$_{LGAD}$>1,000e-

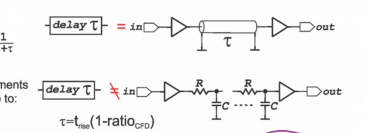
max SNR is worth any price

Directions for circuit:

- CFD method yields better ToA precision,
- psCFD and CFD operate with similar results but psCFD requires implementation of continuous LP filer (passive components),
- Discriminator needs to yield response free of overdrive dependency

practical issue with CFD in IC:

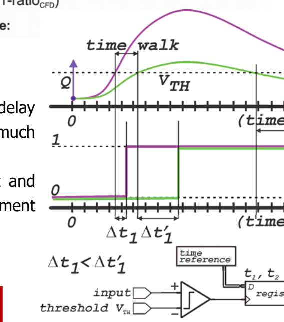
- needed delay $H(s)=e^{-\tau s}$ but practically achievable is $H(s)\propto\frac{1}{s+\tau}$
- lack of actual dealy causes errors in „zero-crossing" position measurements when waveform shape changes due to:
  - amplitude dependence
  - varied charge collection timing

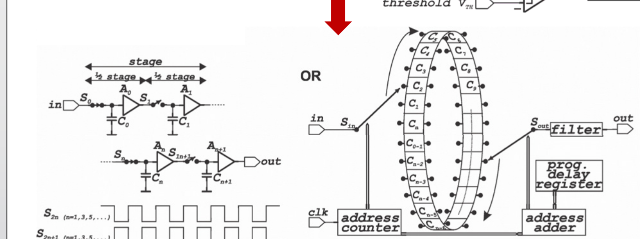


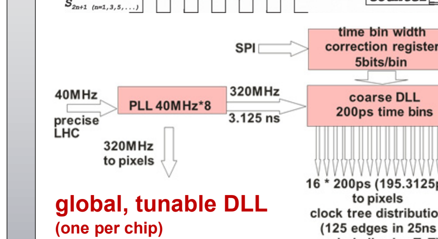
solution could be discrete time analog delay line:

Typical discriminator

- additionally to time walk, introduces delay with which it reacts depending on how much its input is overdriven,
- this delay is threshold level dependent and may introduce additional ToA measurement error and may falsify ToT
- should feature equalization of delay

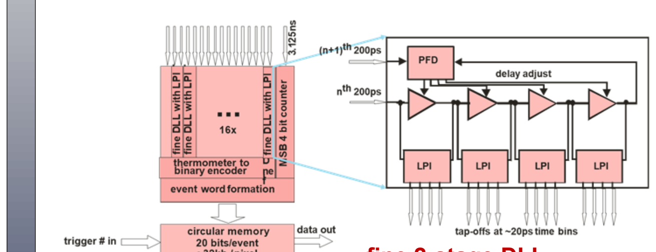






global, tunable DLL
(one per chip)

- Delay line clocked with locally generated, fine clocks used for time bins
- Structure based on division of ToA measurement between global coarse DLL and local fine DLL



fine 2-stage DLL
(one per ToA measurement channel)

References

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