Timing in Silicon Sensors
Reflexions on W. Riegler's presentation

Vincent Boudry

Institut Polytechnique de Paris

Timing in PFA

TNA support + WP14

Context

Very nice CERN detector seminar Werner Riegler on

Time resolution of silicon sensors

Werner Riegler, CERN, werner.riegler@cern.ch

October 15, 2021

https://indico.cern.ch/event/1083146/ and references inside:

- [1] W. Riegler and G. A. Rinella, ‘Time resolution of silicon pixel sensors’, J. Inst., vol. 12, no. 11, pp. P11017–P11017, Nov. 2017, doi: 10.1088/1748-0221/12/11/P11017.

A very quick and imperfect skimming...

Interest for Silicon Calorimeters

Long presentation (60+ pages)

- Time resolution of 'standard' planar silicon detectors
- Signal processing and center of gravity (c.o.g.) time of a signal
- Contribution from noise, optimum filters
- Contributions from 'weighting fields' = non parallel fields

Planar sensors

– Shaping of signal

– Time resolution by Center-of-Gravity

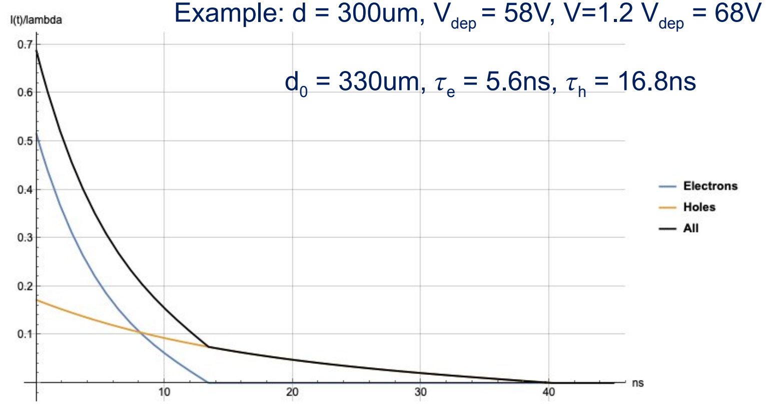
In silicon sensors the signal edge is instantaneous (i.e. sub ps level)

- acceleration of electrons to 10^7cm/s in vacuum is 0.14ps
- passage of the particle through a 50um sensor takes 0.16ps

Other examples and speed vs HV given

Example: d = 300um, V_{dep} = 58V, V=1.2 V_{dep} = 68V

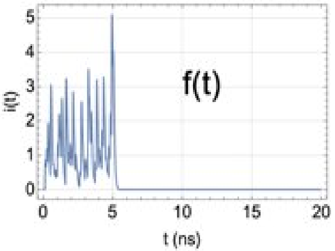
d_0 = 330um, τ_e = 5.6ns, τ_h = 16.8ns

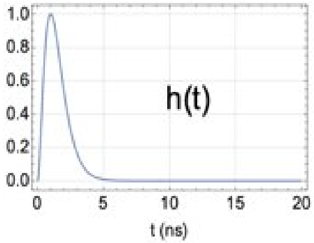


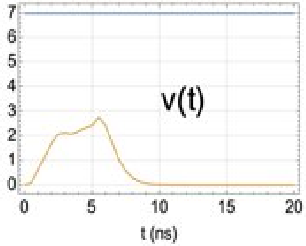
Signal speed
vs Filter BW

➡ **formulas for t_{COG}**

Electronics processing of a detector signal







Frontend delta response:

$$h(t) = \left(\frac{t}{t_p}\right)^n e^{n(1-t/t_p)}\,\Theta(t)$$

Filter Order

$$\Theta(t) = \begin{cases} 0 & x < 0 \\ 1 & x > 0 \end{cases}$$

Corresponding transfer function:

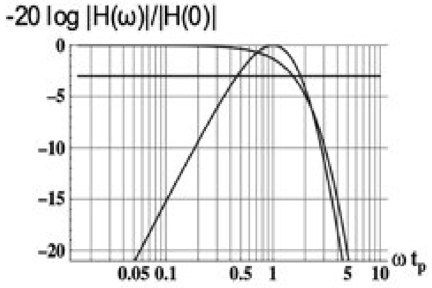
$$H(\omega) = \frac{t_p e^n n!}{(n + i\omega t_p)^{n+1}}$$

$$\omega_{bw} = n\sqrt{2^{1/(n+1)} - 1}/t_p$$

$$\approx 1.54/t_p \text{ for } n = 4$$

t_p=1ns f_{bw} ~250MHz

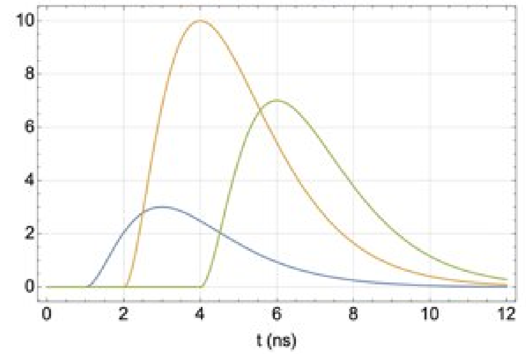
$$v(t) = \int_0^t h(t - t')f(t')dt'$$



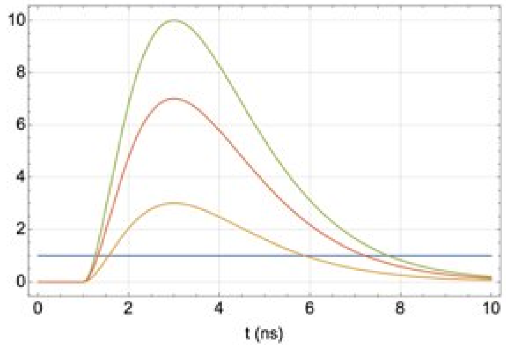
Time Slew

Electronics 'slower' than the detector signal, time slewing

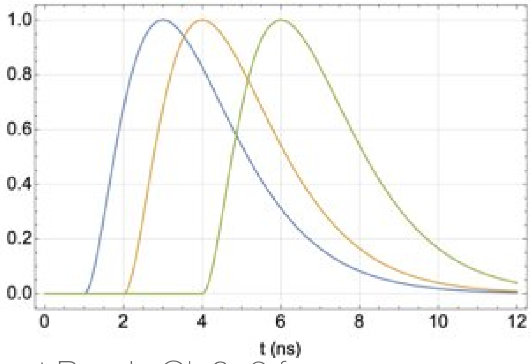
Delta response shifted by t_{cog} and scaled by Q



'time slewing'



Signal normalized to same amplitude → time



There are many different ways to correct for this slewing effect

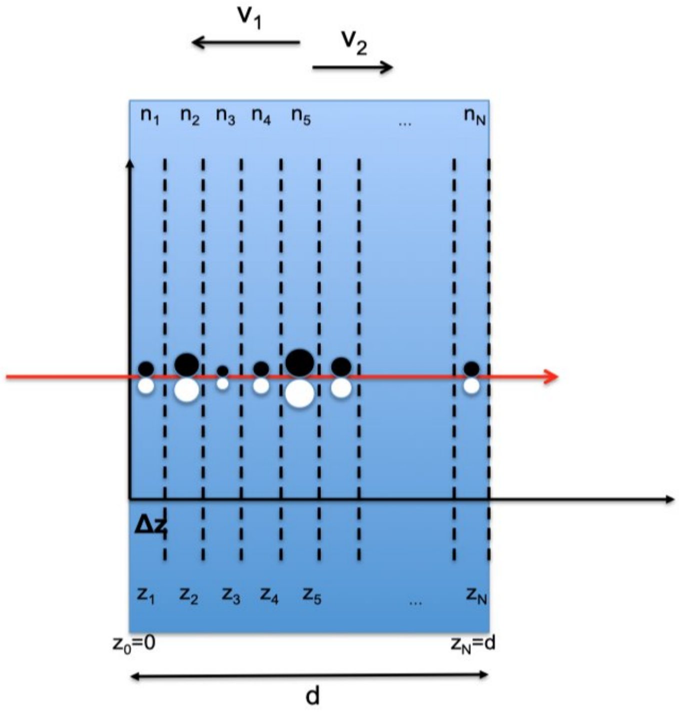
- Constant Fraction discrimination
- Standard discrimination using time over threshold to correct for pulse-height
- Standard discrimination + pulseheight to correct for pulse-height
- Standard discrimination + total charge to correct for pulse-height
- Multiple sampling and 'fitting' the know signal shape
- ….

→ What is the c.o.g. time resolution of a silicon sensor ?

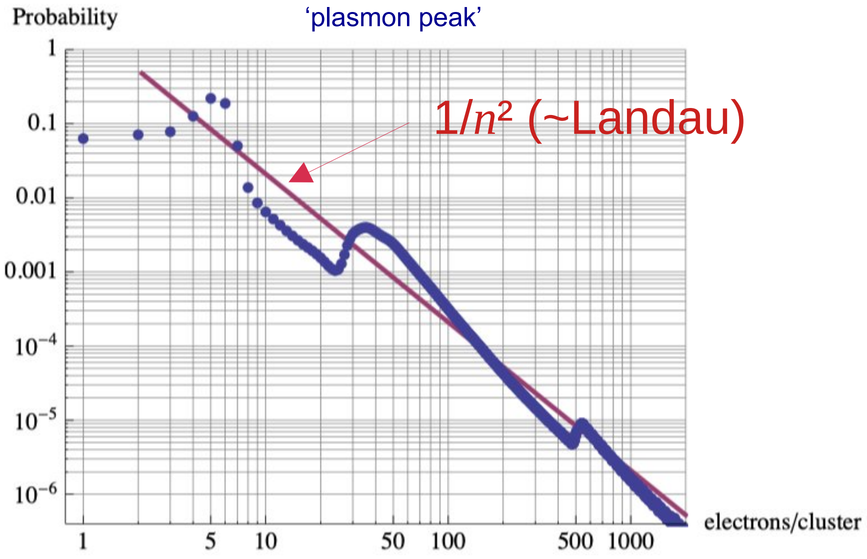
Energy fluctuations → Time fluctuations

Landau fluctuations

– Primary interaction: λ=0.21μm.



PhotoAbsorption Ionization (PAI)



Landau vs PAI

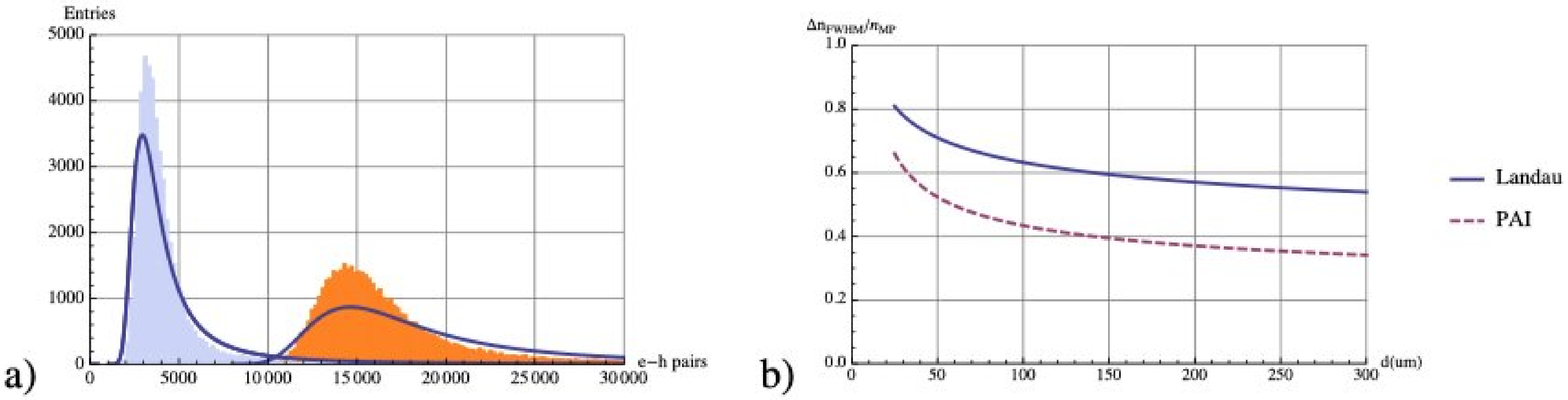
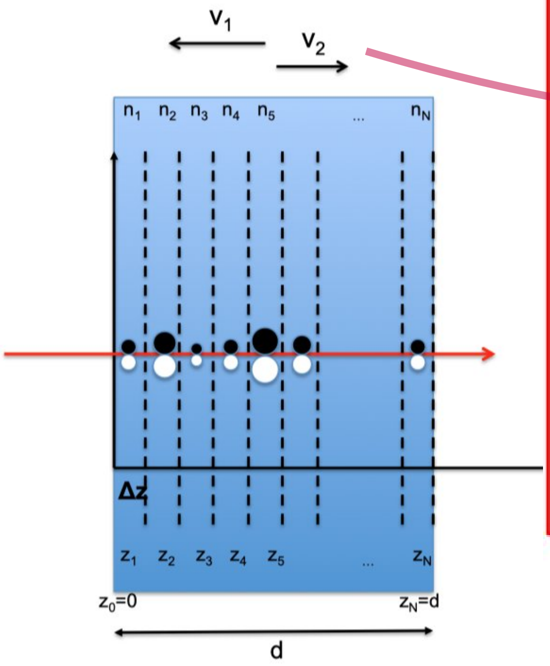


Figure 2. a) Distribution of the number of e-h pairs in 50 μm (blue) and 200 μm (orange) of silicon. The histograms show the PAI model, the solid lines show the Landau theory. b) Ratio of full width half maximum and most probable values for the Landau and PAI model for different values of silicon thickness. The Landau theory overestimates the fluctuations by 25–35%.

Theroritical Time resolution on planar Si sensor



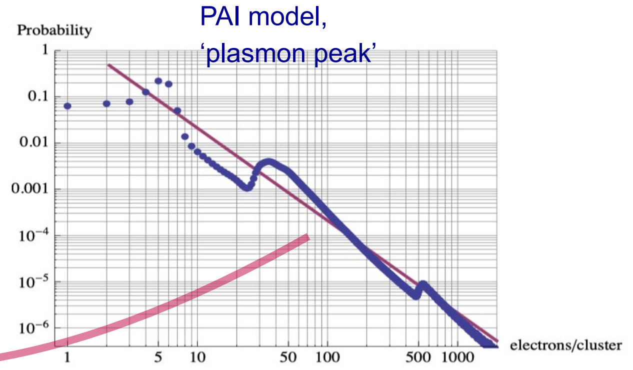
$$\Delta_\tau = w(d)\sqrt{\frac{4}{180}\frac{d^2}{v_1^2} - \frac{7}{180}\frac{d^2}{v_1 v_2} + \frac{4}{180}\frac{d^2}{v_2^2}}$$

$$w(d)^2 = \frac{d}{\lambda}\int_0^\infty \left[\int_0^\infty \frac{n_1^2\, p_{\text{clu}}(n_1)}{(n_1+n)^2}dn_1\right] p(n,d)\,dn$$

For v_1=v_2

$$\Delta_t = w(d)\frac{1}{\sqrt{180}}\frac{d}{v} \approx 0.075\, w(d)\, T$$

50um sensor: 0.075 x 0.2 x 650ps = 10ps

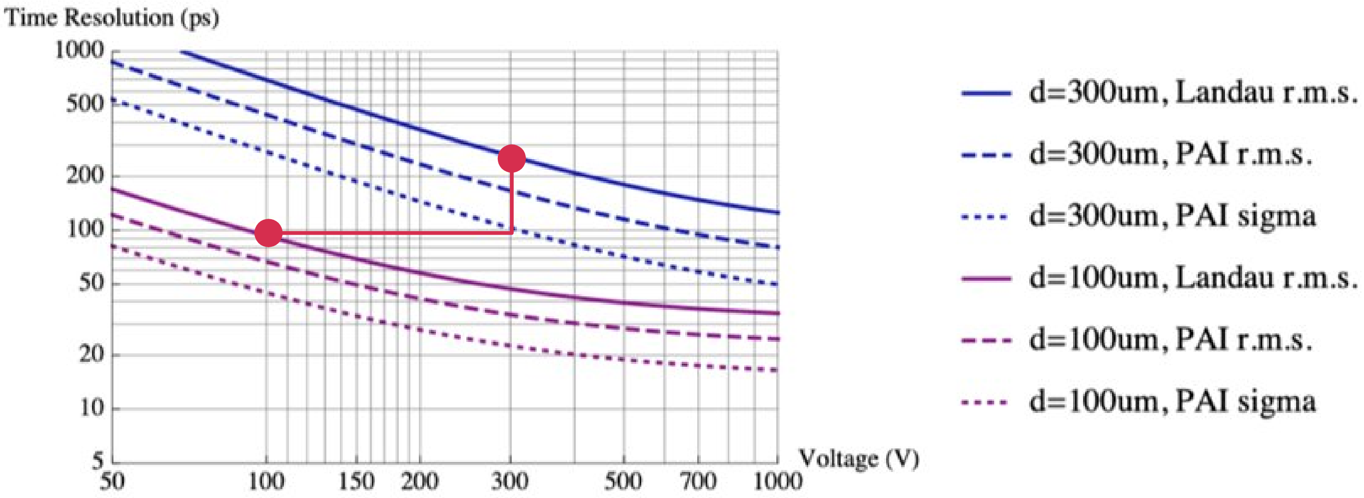


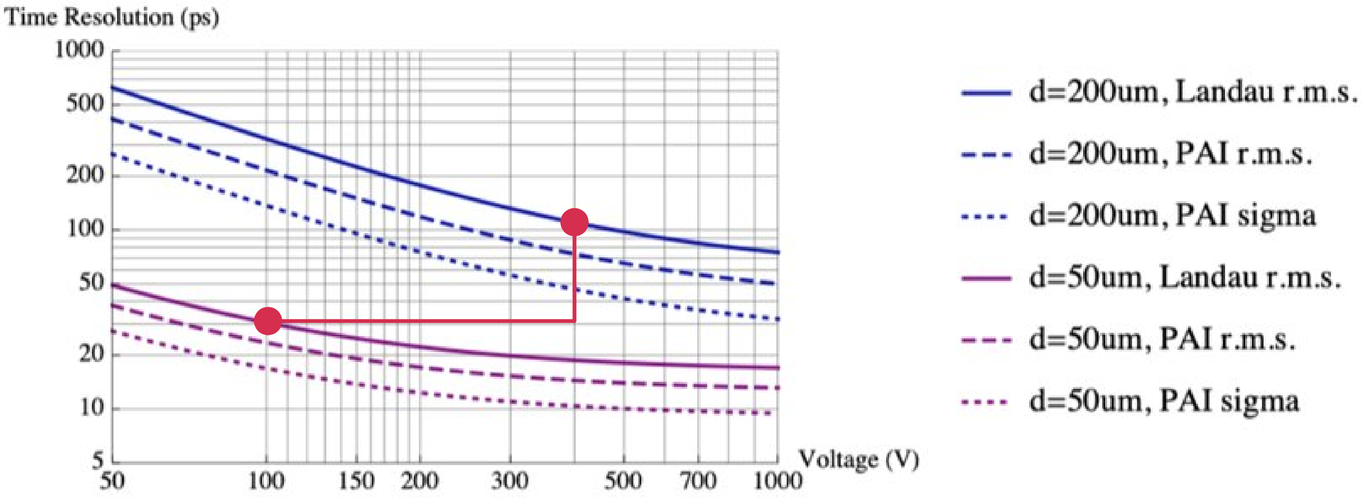
T= total e- drift time = total h drift time
= total width of the 'triangle'

For Laudau distrib :

$$w(d)^2 = \frac{1}{\ln(d/\lambda)} \qquad d/\lambda \to \infty$$

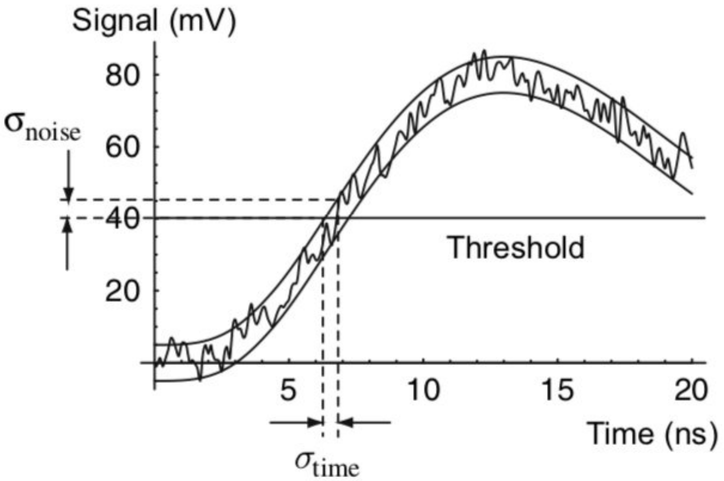
Center of gravity time resolution for silicon sensors





50um sensor, 10ps

Noise



Noise ➡ Optimal filters…

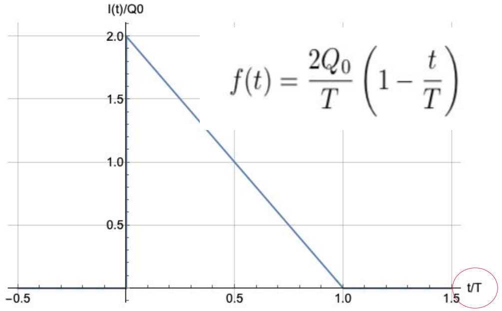
– max the "slope to noise" ratio = d/dt of max(S/N) ratio.

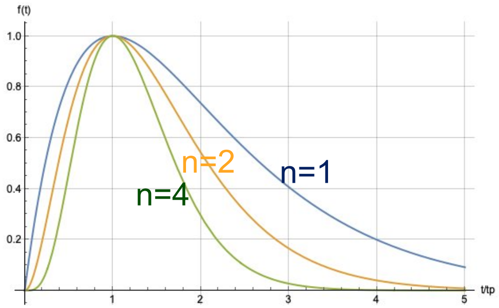
Neglecting parallel noise (which is a good approximation in most practical applications) the optimum electronics peaking time t_p is between T and 1.5T.

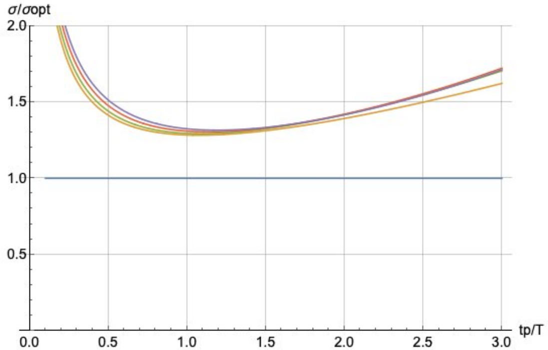
T = Transit Time

The achieved time resolution is only about 30% worse than the best achievable one with the optimum filter !

This will give the smallest noise contribution to the time resolution.

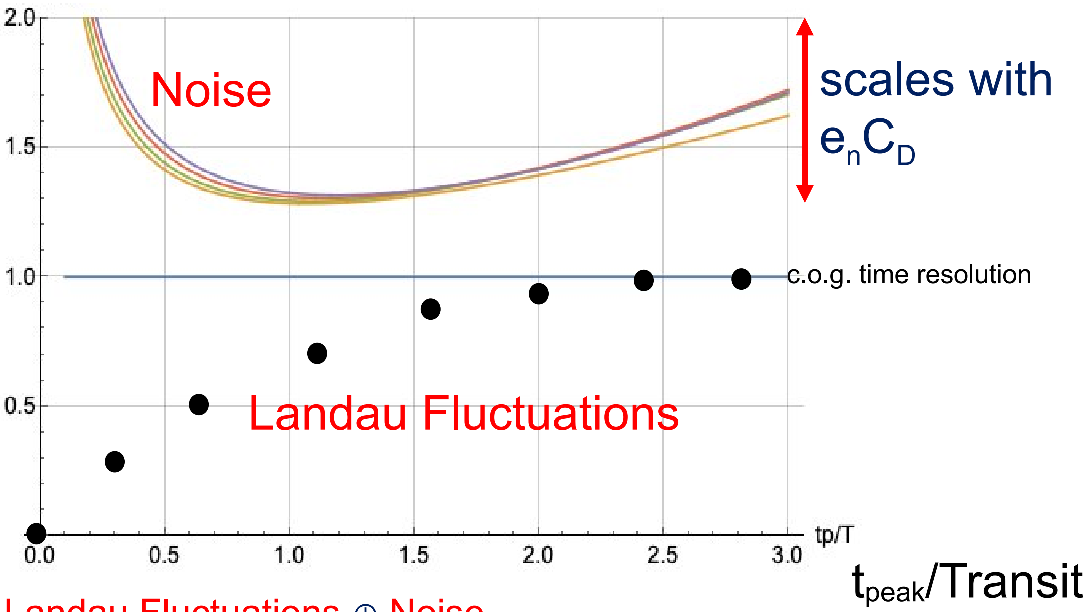






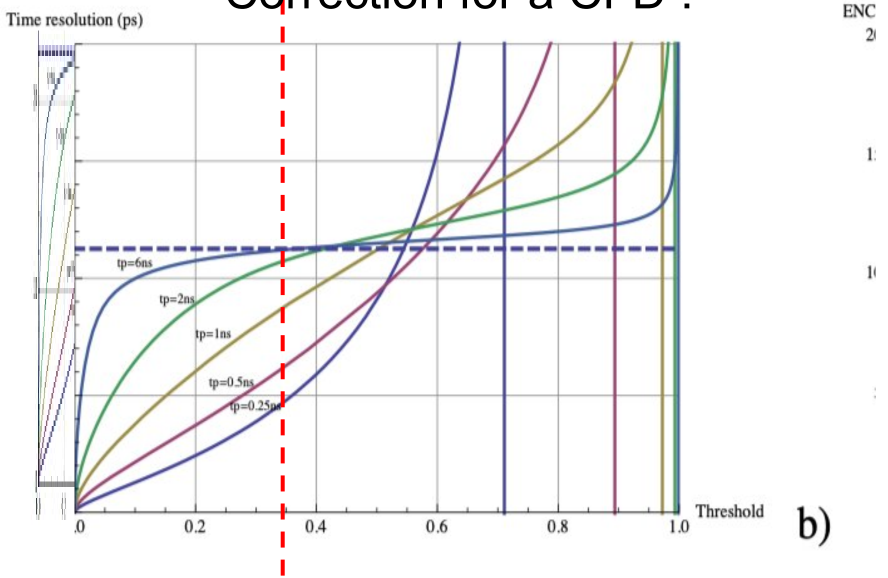
t_{peak}/Transit

Noise + Landau



Landau Fluctuations ⊕ Noise

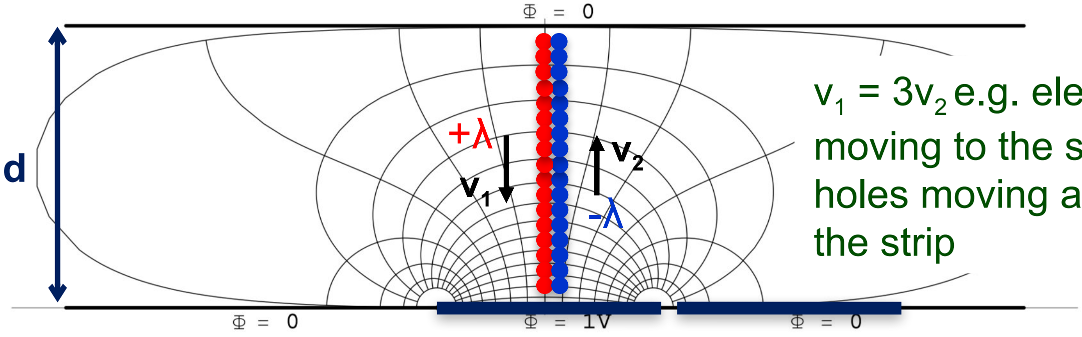
Correction for a CFD :



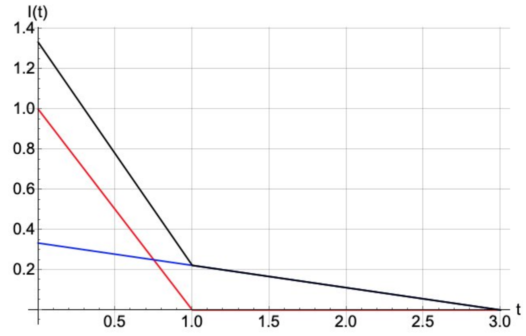
➡ **optimal thickness of sensors (T ↔ thickness)**

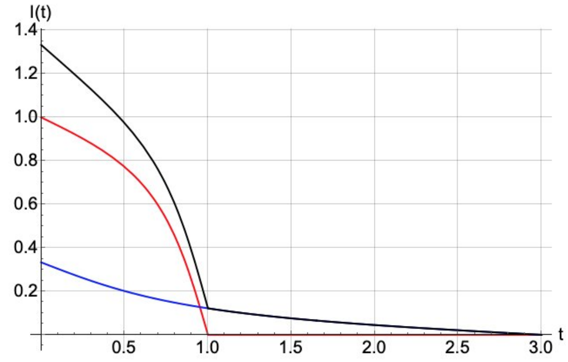
Some slide son pixel sizes (for pix detectors)

- ➡ Non uniformities (“weighting field”)
  - ➡ distorded signals



v_1 = 3v_2 e.g. electrons moving to the strip and holes moving away from the strip





W. Riegler conclusions

Good time resolution demands thin sensors.

Thin sensors give small charge and large capacitance i.e. unfavorable S/N and k/N.

Capacitance can be reduced by making the pixels small.

If the pixel size is in the same order as the sensor thickness, the weighting field fluctuations start to dominate … and there will be many channels …

… between a rock and a hard place …

→ Sensors with internal gain to overcome the noise limit (like gas detectors !)

→ Turn the by sensor 90 degrees and realise a parallel plate geometry in 3D ! (see slide 62, 63)

This seems to apply mostly to thin pixel detectors

- needs to be re-evaluated for calorimeters.

Garfield and Garfield++

CERN | Consult | Writeups | Garfield

Garfield - simulation of gaseous detectors

Responsible at CERN: Rob Veenhof
Manual Type: User Guide
Version: 9
Author: Rob Veenhof
Reference: W5050

Created: 1 Sep 1984
Last Update: 7 Sep 2010
Verified: 7 Sep 2010
Valid until: further notice
Support Level: High

What Garfield does

Garfield is a computer program for the detailed simulation of two- and three-dimensional drift chambers.

Fields

Originally, the program was written for two-dimensional chambers made of wires and planes, such as drift chambers, TPCs and multiwire counters. For many of these configurations, exact fields are known. This is not the case for three dimensional configurations, not even for seemingly simple arrangements like two crossing wires. Furthermore, dielectric media and complex electrode shapes are difficult to handle with analytic techniques. To handle such increasingly popular detectors, Garfield is interfaced with the neBEM program. Garfield also accepts two and three dimensional field maps computed by finite element programs such as Ansys, Maxwell, Tosca, QuickField and FEMLAB as basis for its calculations. The finite element technique can handle nearly arbitrary electrode shapes as well as dielectrics.

Transport and ionisation in gas mixtures

An interface to the Magboltz program is provided for the computation of electron transport properties in nearly arbitrary gas mixtures. Garfield also has an interface with the Heed program to simulate ionisation of gas molecules by particles traversing the chamber.

Transport of particles, including diffusion, avalanches and current induction is treated in three dimensions irrespective of the technique used to compute the fields.

Applications

The program can calculate for instance the following:

- field maps, contour plots and 3-dimensional impressions;
- the wire sag that results from electrostatic and gravitational forces;
- optimum potential settings to achieve various conditions;
- plots of electron and ion drift lines;
- x(t)-relations, drift time tables and arrival time distributions;
- signals induced by charged particles traversing a chamber, taking both electron pulse and ion tail into account.

Related information

- help facility with examples for nearly every command, which can be consulted from within the program and via WWW
- technical notes on specific areas of the program and on related topics
- bug reports
- examples that illustrate the use of the program
- CNL articles (up to 2000)
- news (from March 2005)
- running the program at CERN
- source files of the program

Last updated on 8/2/11.

TU WIEN

CERN-THESIS-2012-208
13/12/2012

DISSERTATION

Microscopic Simulation of Particle Detectors

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines
Doktors der technischen Wissenschaften unter der Leitung von

Univ. Prof. Dipl.-Ing. Dr. Christian Fabjan
E 141
Atominstitut der österreichischen Universitäten

eingereicht an der Technischen Universität Wien
Fakultät für Physik

von

Dipl.-Ing. Heinrich Schindler
Matrikel-Nr. 0225800
Mechtlerstr. 17, 2100 Korneuburg

Diese Arbeit wurde unterstützt vom
Österreichischen Bundesministerium für Wissenschaft und Forschung.

Wien, im Oktober 2012

Garfield++ User Guide

Version 2020.5

H. Schindler

July 2020

https://garfield.web.cern.ch/garfield/ https://cds.cern.ch/record/1500583 https://garfieldpp.web.cern.ch/garfieldpp/

Magboltz and Heed

Magboltz - transport of electrons in gas mixtures

Responsible at CERN: Rob Veenhof
Manual Type: Source files, cross sections
Versions: 11.10
Author: Stephen Biagi
Reference: none

Created: 20 May 1995
Last Update: 3 Nov 2020
Verified: 3 Nov 2020
Valid until: further notice
Support Level: Normal

Magboltz

Magboltz solves the Boltzmann transport equations for electrons in gas mixtures under the influence of electric and magnetic fields.

Further information:

- LXCAT cross section compilation;
- The cross sections used by Magboltz 7.1, interfaced with Garfield 9 (current default)
- How to use Magboltz

Magboltz source files:

- Source file for version 7.1 (default since 13/4/2005);
- Source file for version 8.9.1 (edition of 27 Sep 2010, reinstoring GeH_4 and SiH_4 and improving $C_2H_2F_4$);
- Source file for version 8.9.2 (edition of 14 Nov 2010, hydrogen update);
- Source file for version 8.9.3 (edition of 24 Feb 2011, xenon ionisation cross section corrected);
- Source file for version 8.9.4 (edition of 25 May 2011, xenon ionisation cross section changed at threshold);
- Source file for version 8.9.5 (edition of 12 Jun 2011, TMA);
- Source file for version 8.9.6 (edition of 27 Aug 2011, update of low energy argon excitation cross sections);
- Source file for version 8.9.7 (edition of 25 Sep 2011, krypton update);
- The source file for version 9.0.1 (edition of 12 May 2012) was corrected with version 9.0.3;
- Source file for version 9.0.3 (edition of 28 Aug 2013);
- The source file for version 10.0.1 (edition of 24 Apr 2013) was corrected with version 10.0.2;
- Source file for version 10.0.2 (edition of 28 Aug 2013);
- Source file for version 10.0.4 (edition of 17 Jun 2014);
- Source file for version 10.6 (edition of 3 Dec 2014);
- Source file for version 10.13 (edition of 5 Oct 2015);
- Source file for version 10.14 (edition of 12 Jan 2016);
- Source file for version 11.1 (edition of 14 Dec 2016);
- Source file for version 11.2 (edition of 19 Oct 2017);
- Source file for version 11.3 (edition of 29 Nov 2017);
- Source file for version 11.4 (edition of 29 Apr 2018);
- Source file for version 11.5 (edition of 23 Oct 2018);
- Source file for version 11.6 (edition of 13 Nov 2018);
- Source file for version 11.7 (edition of 26 Feb 2019);
- Source file for version 11.9 (edition of 30 Aug 2019);
- Source file for version 11.10 (edition of 3 Nov 2020).

https://magboltz.web.cern.ch/magboltz/

ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 554, Issues 1–3, 1 December 2005, Pages 474-493

Modeling of ionization produced by fast charged particles in gases

I.B. Smirnov

Show more

Share Cite

https://doi.org/10.1016/j.nima.2005.08.064 Get rights and content

https://doi.org/10.1016/j.nima.2005.08.064

Timing simulations for silicon with GARFIELD++

Jan Hasenbichler (CERN TU-Vienna): monolithic silicon detectors (ALIPIDE), cluster size, efficiency, time resolution

Ann Wang (Harvard University): time resolution of silicon detectors, LGADs, frontend electronics, noise

Francesca Carnesiecchi (Bologna): time resolution of LGADs

Marius Maehlum Halvorse: time resolution of silicon sensors

H. Schindler & EPFL group of E. Charbon: time resolution and efficiency of SPADs

D. Janssens & INFN Torino group of N. Cartiglia: time resolution and efficiency of AC-LGADs

Interfacing to GEANT:

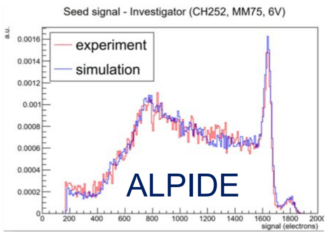

Contents lists available at ScienceDirect

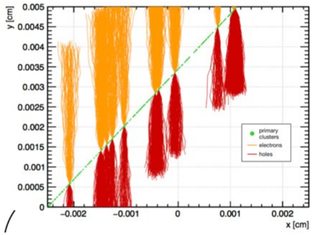
Nuclear Inst. and Methods in Physics Research, A

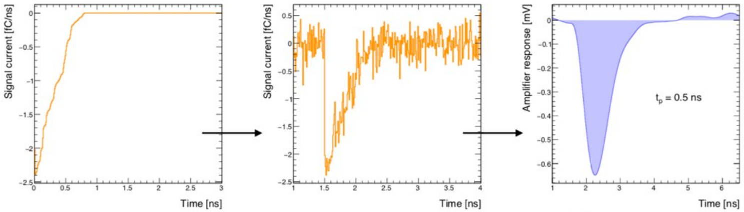
journal homepage: www.elsevier.com/locate/nima

Interfacing Geant4, Garfield++ and Degrad for the simulation of gaseous detectors

Dorothea Pfeiffer[a,b,*], Lennert De Keukeleere[c,**], Carlos Azevedo[d], Francesca Belloni[e], Stephen Biagi[f], Vladimir Grichine[g], Leendert Hayen[c], Andrei R. Hanu[h], Ivana Hřivnáčová[i], Vladimir Ivanchenko[b,j], Vladyslav Krylov[k,l], Heinrich Schindler[b], Rob Veenhof[b,m]



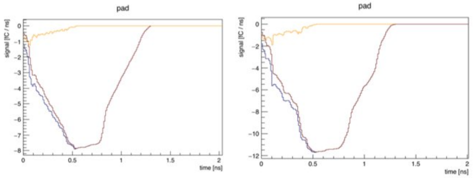





```
void Sensor::AddWhiteNoise(const
double enc, const bool poisson,
const double q0)
```

```
double
UnipolarShaper(const
double t) const;
```

LGAD



- orange = primary electron signal (no primary hole signal)
- brown = avalanche hole signal
- blue = total