Comparison of non-commercial detector simulation packages

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Motivation

- One of the conclusions from 1st TCT workshop at DESY – we need to have reliable simulations tools to understand and explain TCT measurements
- Non-commercial tools have been developed within RD50 by different groups: and need to be cross-checked:
  - Weightfield 2 (Torino, UCSC-SCIPP, …)
    https://indico.cern.ch/event/273880/session/4/contribution/59/attachments/493722/682260/cenna_ufsd_simulator.pdf
  - TRACS (CERN, Santander…)
    https://indico.cern.ch/event/334251/session/1/contribution/25
  - KDetSim (JSI)

    https://indico.desy.de/getFile.py/access?contribId=26&sessionId=3&resId=0&materialId=slides&confId=12934
  - Hamburg University

- Aim of this talk is also to point to certain issues which people using TCAD often overlook in large commercial simulation packages.
  - calculation of induced current in the multi-electrode system
  - effect of the boundary conditions to calculated fields which
- To trigger the interest among wider audience…

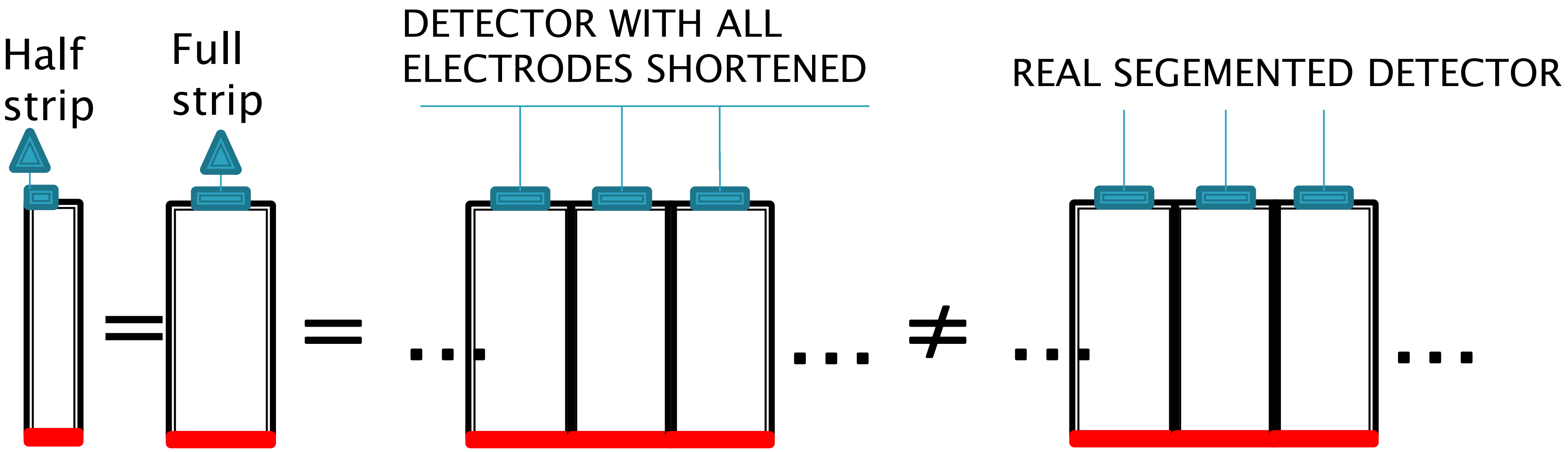
Overview of the basic properties

- What is common to those simulations/simulators:
  - they solve Poisson Equation (or more general Gauss law) for an input N_{eff} rather that calculating N_{eff} from microscopic defects (TCAD approach).
  - charge drift is considered in a static electric field and is done in steps.
  - the induced current in calculated by Ramo's theorem.
- Where do they differ – mostly in technical details:
  - they use different solvers and meshing tools
  - slightly different approach to "stepping".
  - different platforms, GUI/IO tools
- These tools are not meant for replacing the TCAD simulations, but are complementary to them. They:
  - are more suitable for multi-electrode systems by taking weighing field into account.
  - allow simpler carrier generation which can be any distribution – i.e. coupling to other software packages e.g. GEANT4.
  - are well suited for Monte Carlo Studies of detector performance (charge sharing, magnetic field, position resolution …)
  - are available on the level of source code – very high flexibility
  - are fast and therefore allow for modeling and fitting of the field parameters/N_{eff} to the measurements
  - allow in principle TCAD fields to be imported for MC approach studies

Overlook of the basic properties

	WF2	TRACS	KDetSim
Dimensions	2D	2D	3D
E field from	$\Delta U = -\frac{\rho}{\varepsilon\varepsilon_0}$	$\Delta U = -\frac{\rho}{\varepsilon\varepsilon_0}$	$\nabla(\varepsilon\nabla U) = -\frac{\rho}{\varepsilon_0}$
Meshing	Custom (variable, orthogonal semi adaptive)	Open FEM library FENICS (adaptive, advanced), parallel processing	Custom (variable ,not adaptive)
Physics	drift, diffusion, B, trapping,	drift, trapping (not MC wise)	drift, diffusion, B, trapping, impact ionization*
Electronics	More advanced	Basic (RC…)	Basic (preamp,CR,RC), FFT for signal processing
OS/Framework	Mac, Linux (partially ROOT based-compile from scratch)	Mac, Linux	Linux,Mac,Windows, ROOT based
User interface/IO	GUI (batch file)	GUI / CLI	CLI (ROOT GUI)

Choice of boundary conditions



Half strip

Full strip

DETECTOR WITH ALL ELECTRODES SHORTENED

REAL SEGEMENTED DETECTOR

All neighboring electrodes also with $U_w=1$ -> all strips shortened

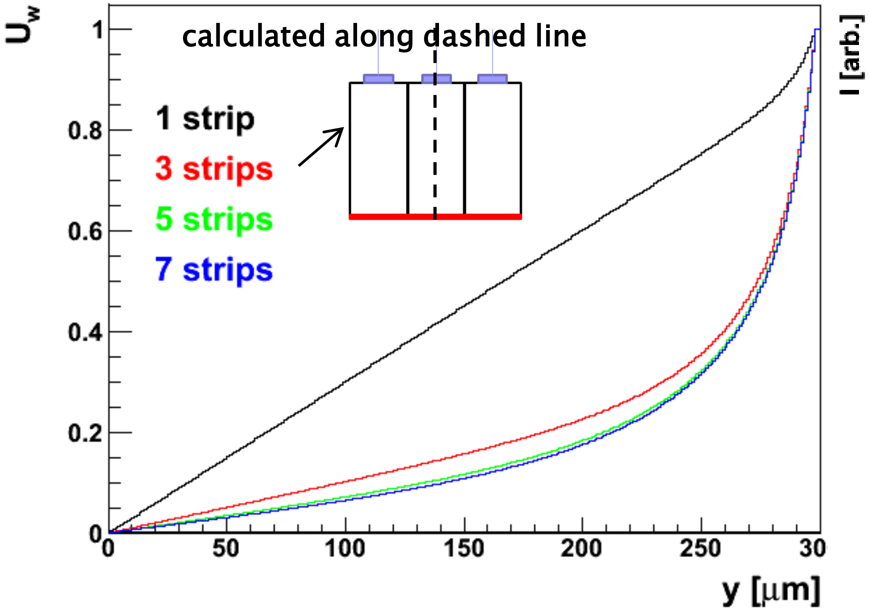
All neighboring electrodes at $U_w=0$ -> individual channels

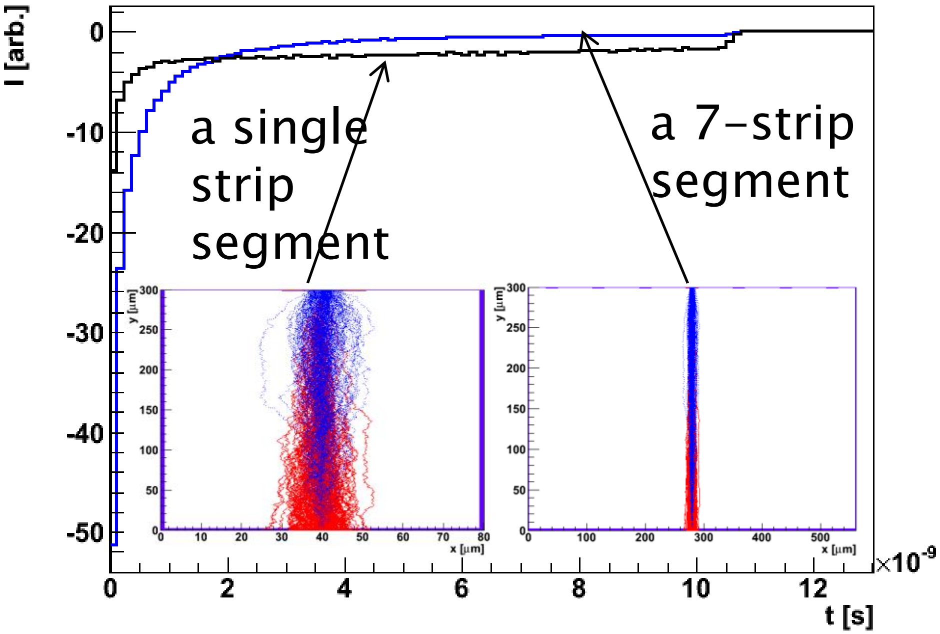
Unlike for electric field where for the symmetry reasons only a half strip can be used to calculate the field one should simulate a much larger section for the weighting field. Often not done in TCAD simulations.

A lot of effects in irradiated silicon detectors – such as e.g. "trapping induced charge sharing" can not be simulated without proper weighting field.

Example of simulated currents

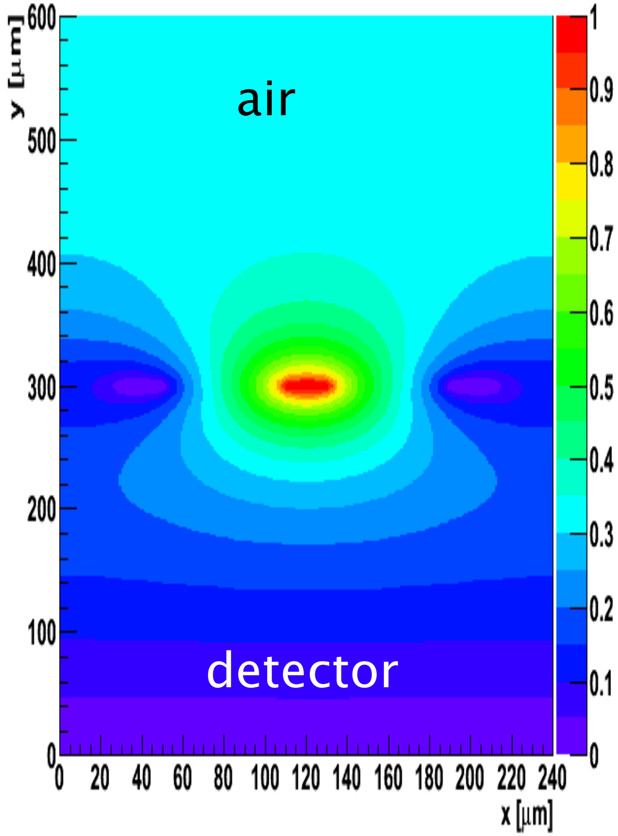
80 μm pitch, 20 μm width, 300 μm thick, $V_{bias}=200$ V, $N_{eff}=10^{12}$ cm^{-3}, n-on-p

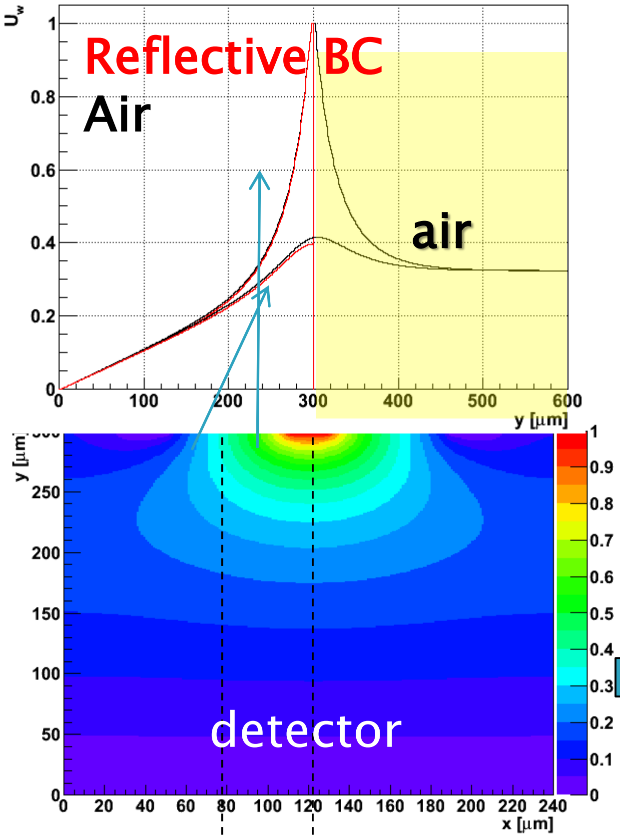




- It is clear that more strips should be taken into account: >3 should be enough
- any simulation tool that calculates the current induced in a sensors should include more strips than simply the minimum defined by symmetry!
  - Separate calculation of U_w and U is a good approach as it saves a lot of time, particularly for iterative approaches (modeling)

Choice of boundary conditions – U_w

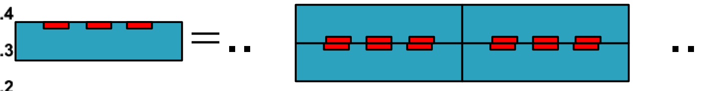




Reflective BC (von Neumann) at non-electrode surfaces

$$\nabla U_w = 0$$

No field lines escape the sensors – hence the structure is fully symmetrical in all directions



- ➢ For ATLAS geometry detectors the effect of reflective boundary conditions on the surface to weighting field is small – few % at most in the interstrip region. Should be looked individually for each structure.
- ➢ Same applys for electric field calculation.

Comparison of simulators

n-p pad/strip detectors at 300 K

TEST

1) Simulation of pad detectors (300 μm thick) with $N_{eff}=0$ at 50 V,200 V and 500 V for electron and hole injection i.e. top and bottom illumination

2) Simulation of pad detector as in 1.) with $N_{eff}=-2 \bullet 10^{12}$ cm^{-3} at 300 V

3) Same as 1.) and 2.) for strip detector (7 segments) of ATLAS geometry
   - 80 μm strip pitch
   - 20 μm strip width (no metal overhang)
   - 300 μm thick

GOAL

Cross check of drift/diffusion/stepping , mobility verification

Calculation of 1D field (simple case)

Verification of weighting and electric field calculation in a segmented device

All the comparison are done with default mobility models!

Mobility models differ

[1] *C. Canali, G. Ottavian, A. Alberigi, “Drift velocity of electrons and holes and associated anisotropic effects in silicon,” J. Phys. Chem. Solids, vol. 32, p. 1707, 1971.*

[2] C. Sharft, R. Klanner, Measurement of the drift velocities of electrons and holes in high-ohmic <100> silicon, NIM A

[3] S. Selberherr, W. Hansch, M. Seavey, and J. Slotboom, “The evolution of MINIMOS mobility model,” Solid-State Electron., vol. 33, no. 11, pp. 1425-1436, 1990.

[4] WF2 - T. Bauer, M. Friedl, and M. Krammer. `A Simple Model of Charge Collection in Silicon Detectors'. 2000.

[5] *Jacoboni, C., C. Canali, G. Ottaviani, and A. A. Quaranta, Solid State Electron.* ***20, 2****(1977) 77-89*

Parameterization:
Usually Caughey-Thomas,
with different β, v_{sat} and μ_0
and their dependencies on *T*:

$$\mu^{CT}(E) = \frac{\mu_0^{CT}}{\left(1 + \left(\frac{\mu_0^{CT} \cdot E}{v_{sat}^{CT}}\right)^{\beta}\right)^{1/\beta}}$$

Klanner Scharf:

$$1/\mu^{KS}(E) = \begin{cases} 1/\mu_0^{KS} & E < E_0 \\ 1/\mu_0^{KS} + 1/v_{sat}^{KS} \cdot (E - E_0) & E \geq E_0 \end{cases}$$

$$1/\mu_h(E) = \begin{cases} 1/\mu_0^h & E < E_0 \\ 1/\mu_0^h + b \cdot (E - E_0) + c \cdot (E - E_0)^2 & E \geq E_0 \end{cases}$$

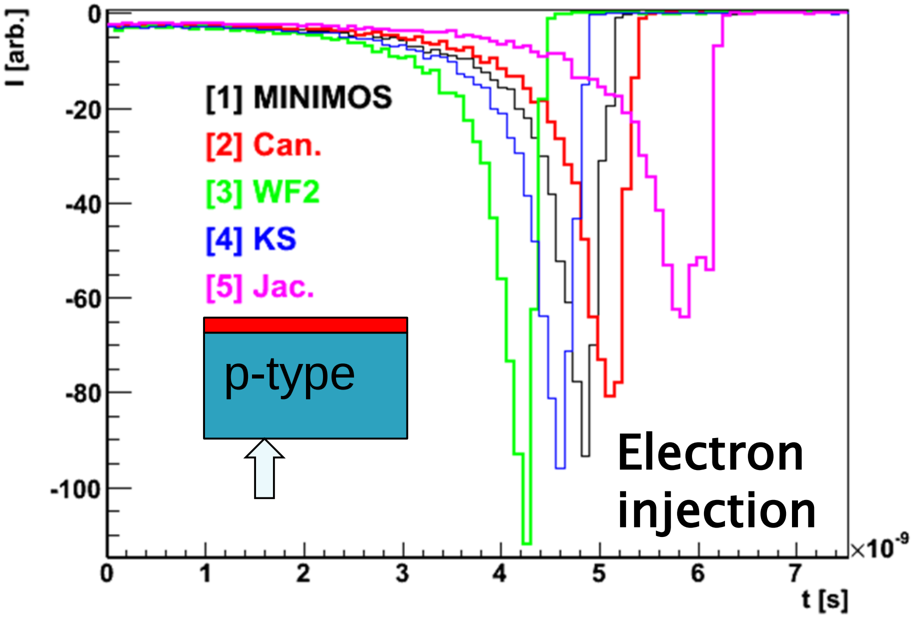
@300 K	[1]	[2]	[3]	[4]	[5]
$\mu_{0,h}$ [cm^2/Vs]	487	486	484	480	474
$\mu_{0,e}$ [cm^2/Vs]	1484	1523	1498	1350	1440
$V_{sat,h}$ [cm/s]	7.4e6	8.18e6 (limited range)	8.03e6	9.5e6	9.4e6
$V_{sat,e}$ [cm/s]	1.06e7	1.055e7	1.01e7	1.1e7	1.054e7

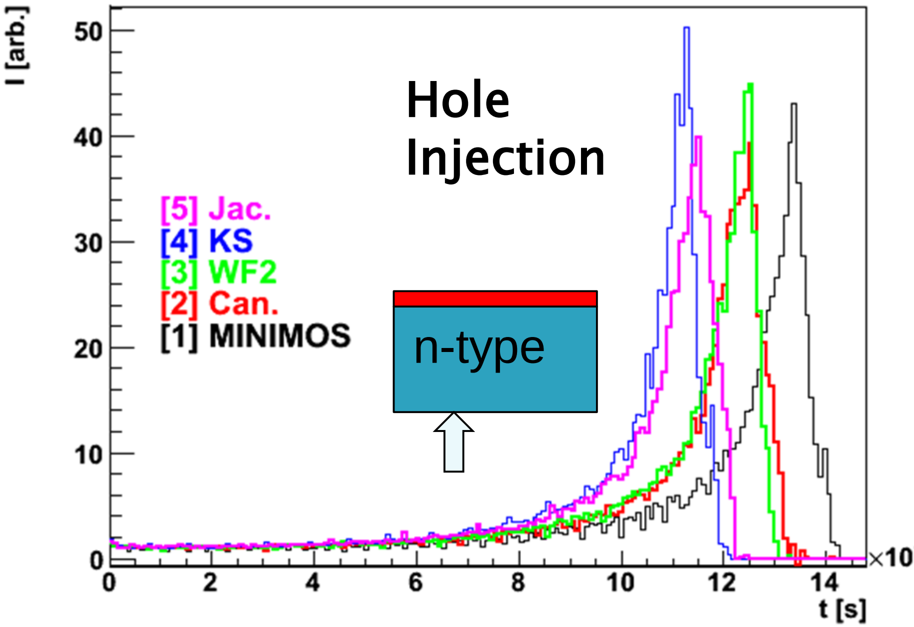
Note that mobility models are different for <111> and <100>! [5]&[2] are <100>.

Mobility models differ

The mobility parametrizations differ quite a lot which results in differences. The difference depends on *E* and *T*.

Strip detector (injection underneath of implant) with N_{eff}=0 at 200 V and 300 K





Different mobility models are included in KDetSim and checked by KDetSim
Differences are reflected also in WF2, TRACS

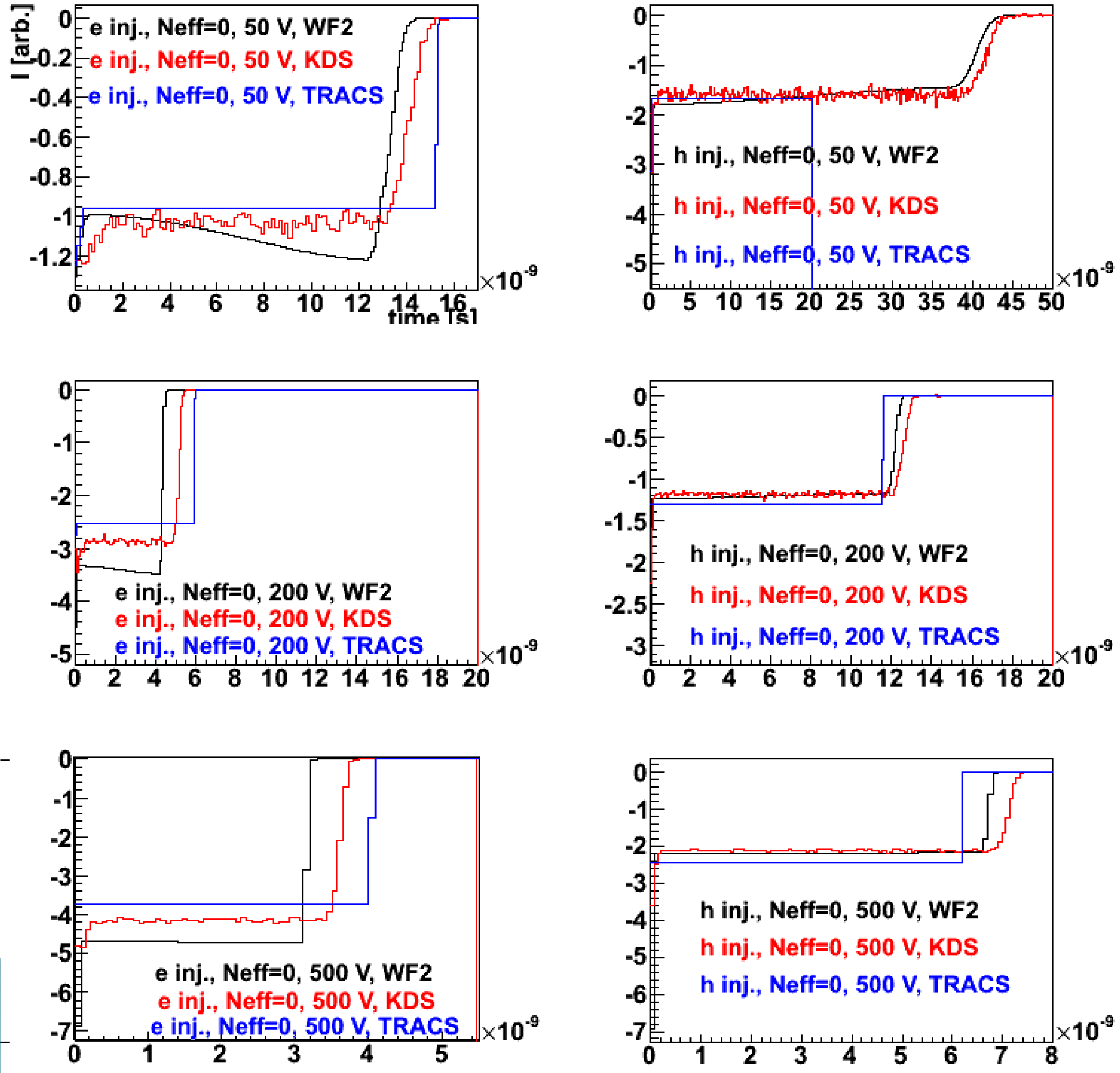
Time of arivals of electrons to the strip is very sensitive to mobility. The time can be calculated as

$$t_{p,e,h} = \frac{W^2}{\mu_{e,h} V_{bias}}$$

Pad detector comparison – no doping

ELECTRON injection

HOLE injection

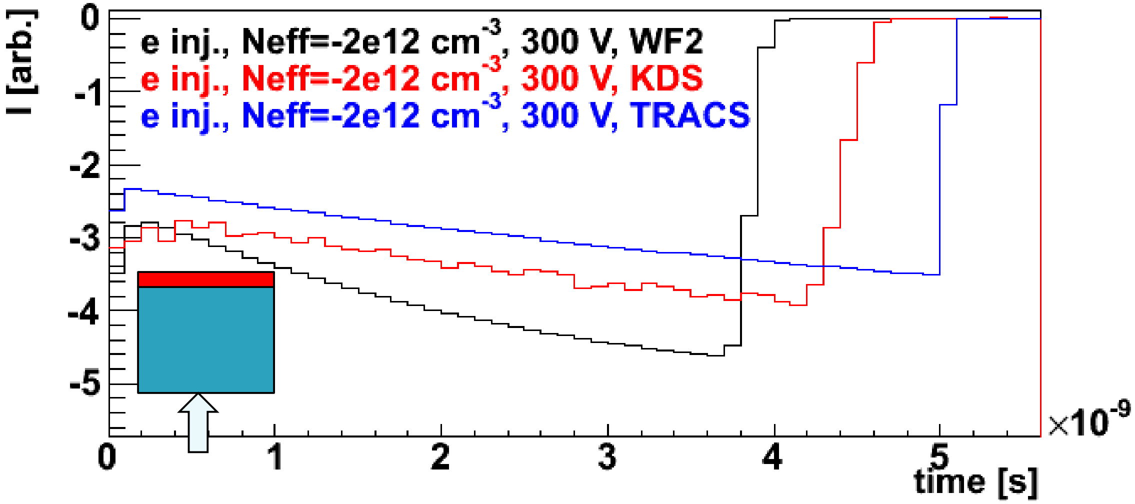


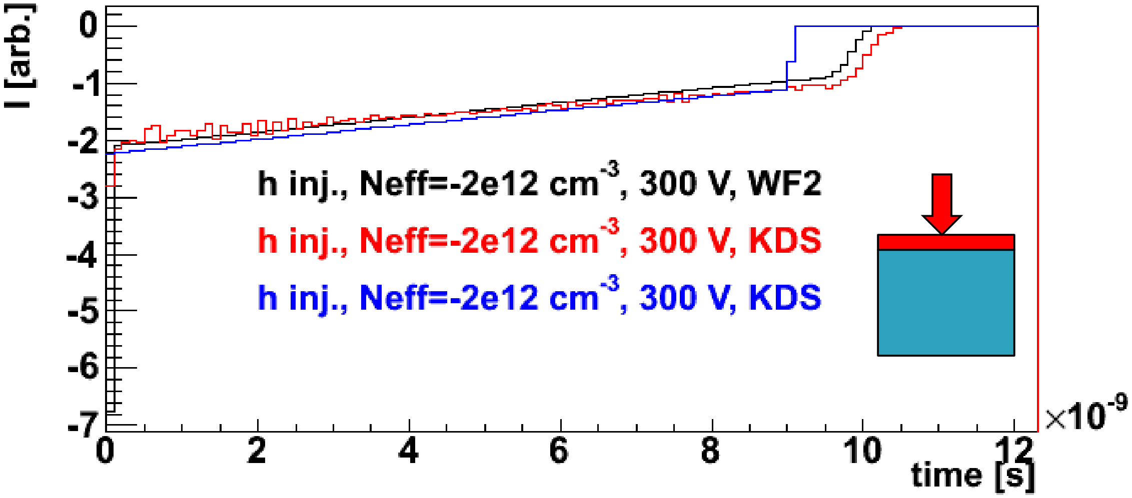
Plots are normalized to the same charge

- At low voltages – slight slope for WF2 due to the weighting field calculation
- Some differences in mobility models – hole models seem to agree better with each other
- Diffusion tails seem to be marginally different for KDS and WF2 (TRACS doesn't have it)

A general statement – simulators agree well – the differences arise from known reasons.

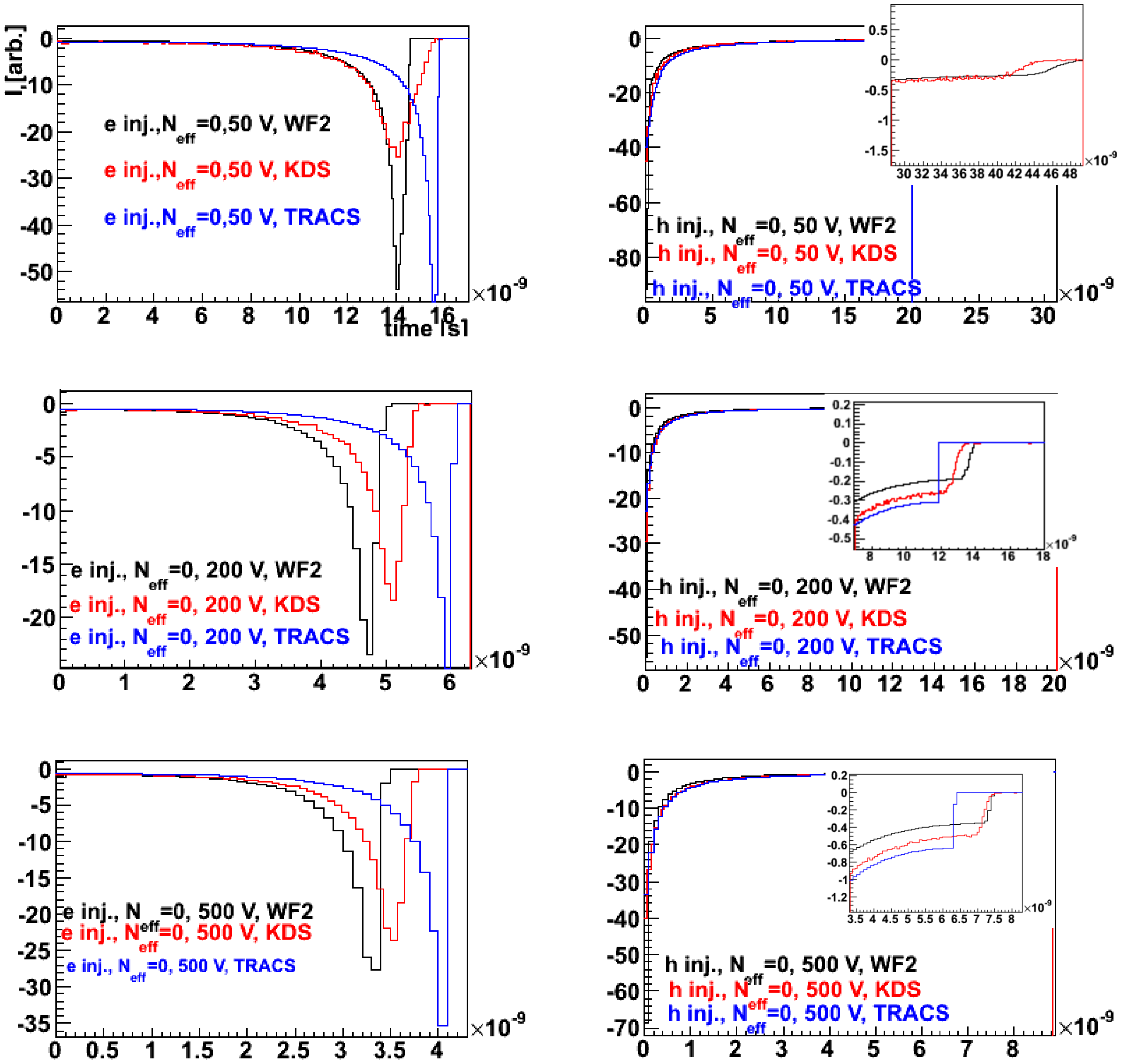
Pad detector comparison – doping





- The slope of the induced current, which is an indication of the N_{eff}, is similar!
- Again larger variation of electron mobilities in that range results in difference simulated currents.
- Smaller difference for holes
- Note these are extremes – so any m.i.p. simulation would give a better agreement.

Strip detector comparison – no doping



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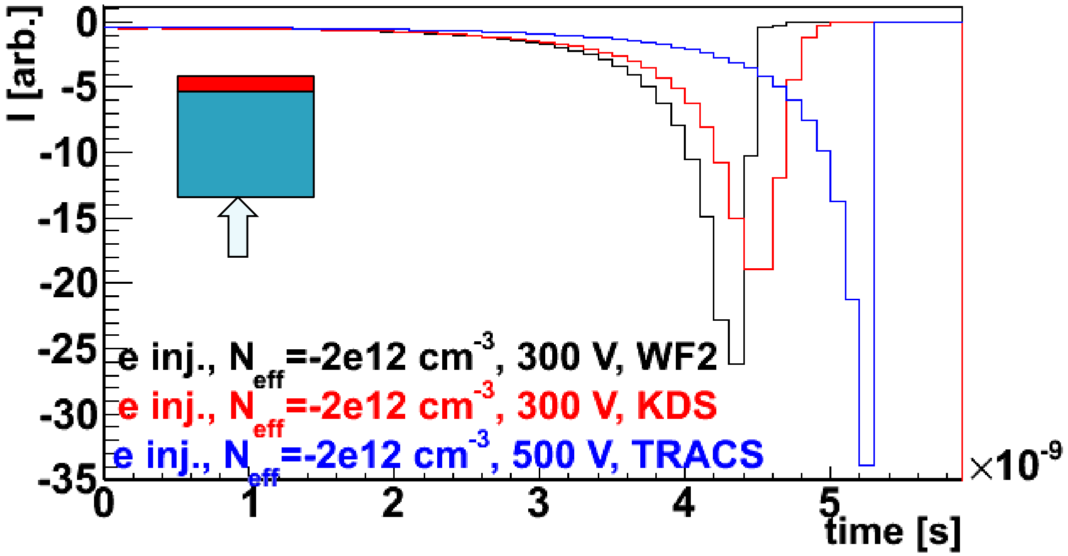

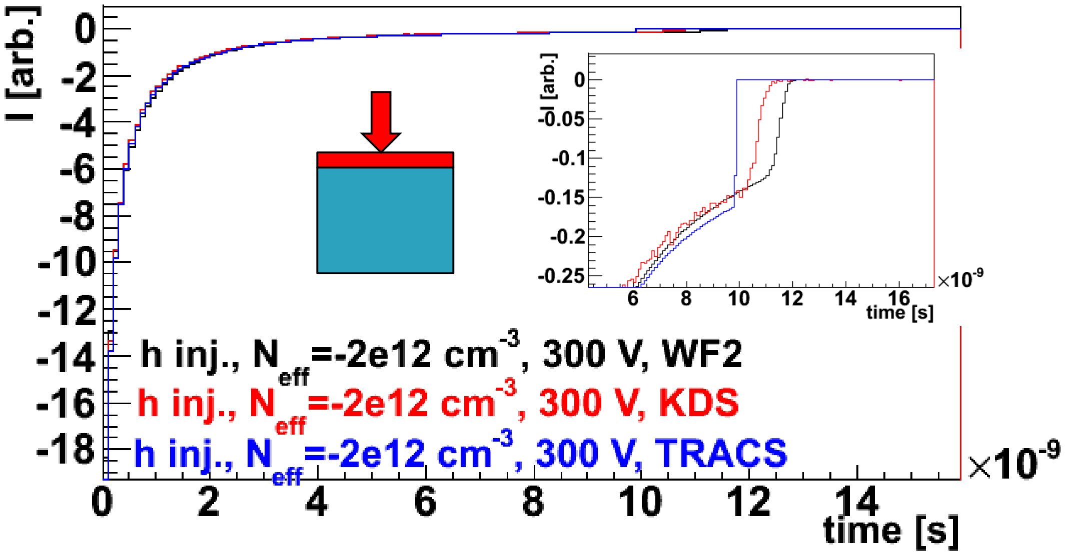

Same observation as for the pads: smaller difference of hole mobilities folded with the weighting field gives a very good agreement for holes and vice versa for electrons

Conclusions

- Custom made simulators are complementary tools for TCAD and offer lots of advantages for: detector operation studies MC, modeling – iterative procedures, CPU time
- It is essential that for all simulations tools (TCAD, custom) one checks the influence of boundary conditions particularly calculation of induced current in TCAD should account for neighboring strips.
- All three tested detector simulators give comparable results – differences mostly due to different mobility models:
  - at the moment there is no clear preference for any mobility model
  - slight difference in diffusion between WF2 and KDetSim

Future work ....

- A common interface from TCAD in any from would be welcome i.e. field map in any form that can be imported to simulators.
- No model includes changes in mobility due to irradiations – needs to be included in the future.