Laser-TCT with Allpix^2

Overview of the allpix::DepositionLaserModule and some comparisons with experimental data.

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5th Allpix Squared User Workshop
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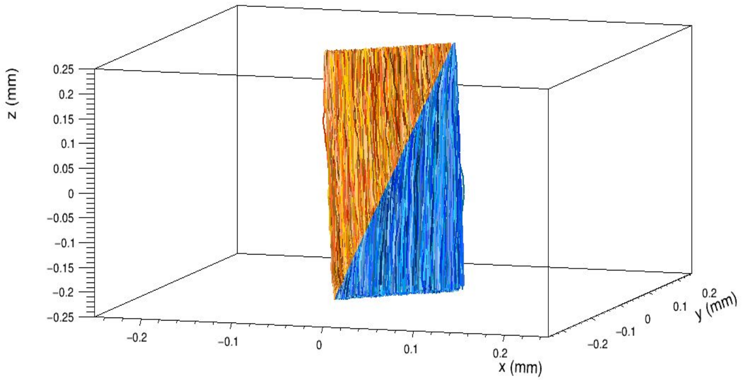
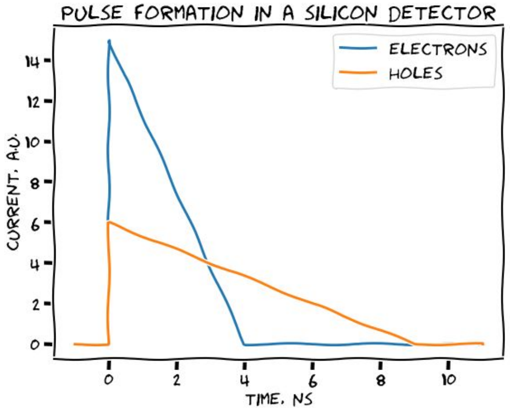
HELMHOLTZ

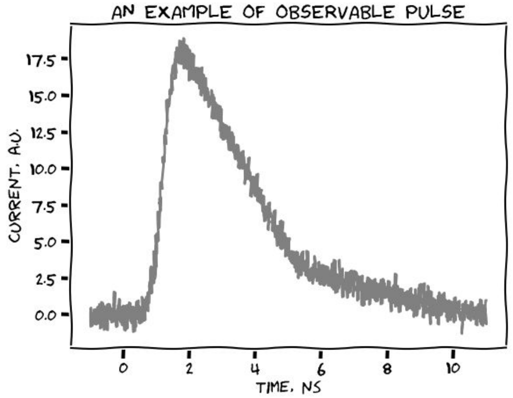
Transient Current Technique (TCT) basics

Signal formation principles and sensor features



$$I(t) = q\vec{v}(t) \cdot \vec{E_W}(\vec{r}(t))$$





Bulk spatial features that are *encoded* in the pulse shape:

- Electric field
- Weighting potential
- Depletion region

The experiment:

- inject charge in a *controlled* way
- study transient pulses

E.g., with a pulsed laser

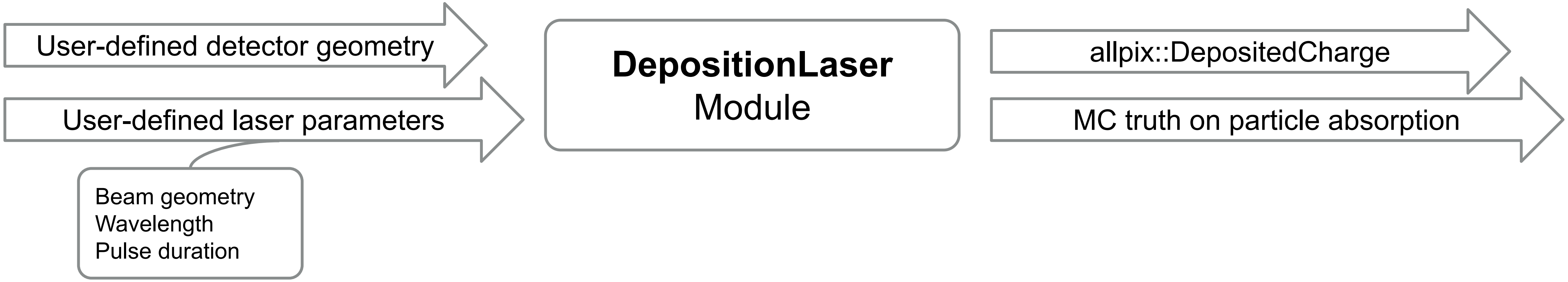
Application domains:

- Radiation-damaged sensors
- Sensors with complex structure

How to simulate laser charge injection with Allpix^2?

allpix::DepositionLaserModule

A dedicated event generator for energy deposition with pulsed lasers



→ *The module is available in Allpix^2 since v2.4.0!*
https://gitlab.cern.ch/allpix-squared/allpix-squared/-/tree/master/src/modules/DepositionLaser

Features:

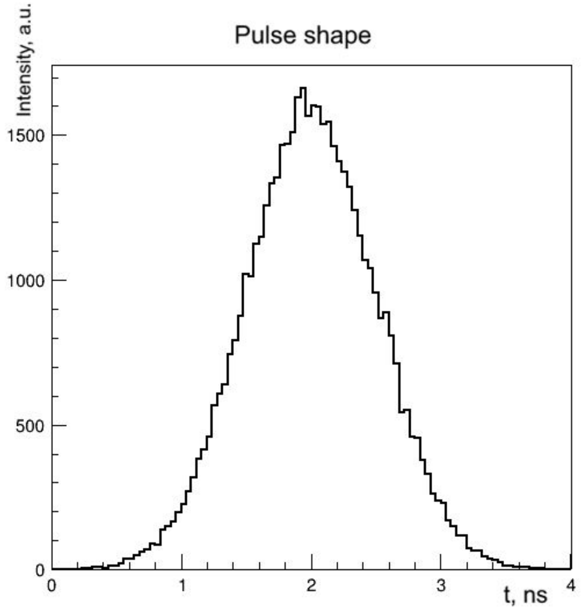
- No dependency on Geant4
- Follows modular approach of Allpix^2
- Full compatibility with Allpix^2 geometry (passive objects, multi-detector setups)
- Follows sustainable development philosophy of Allpix^2

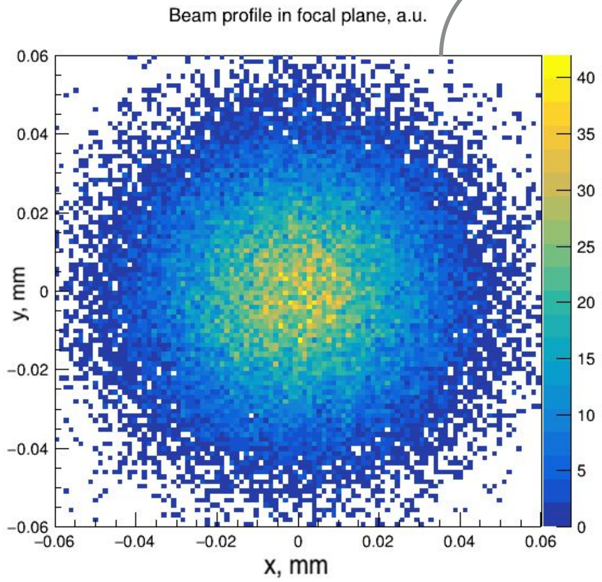
allpix::DepositionLaserModule

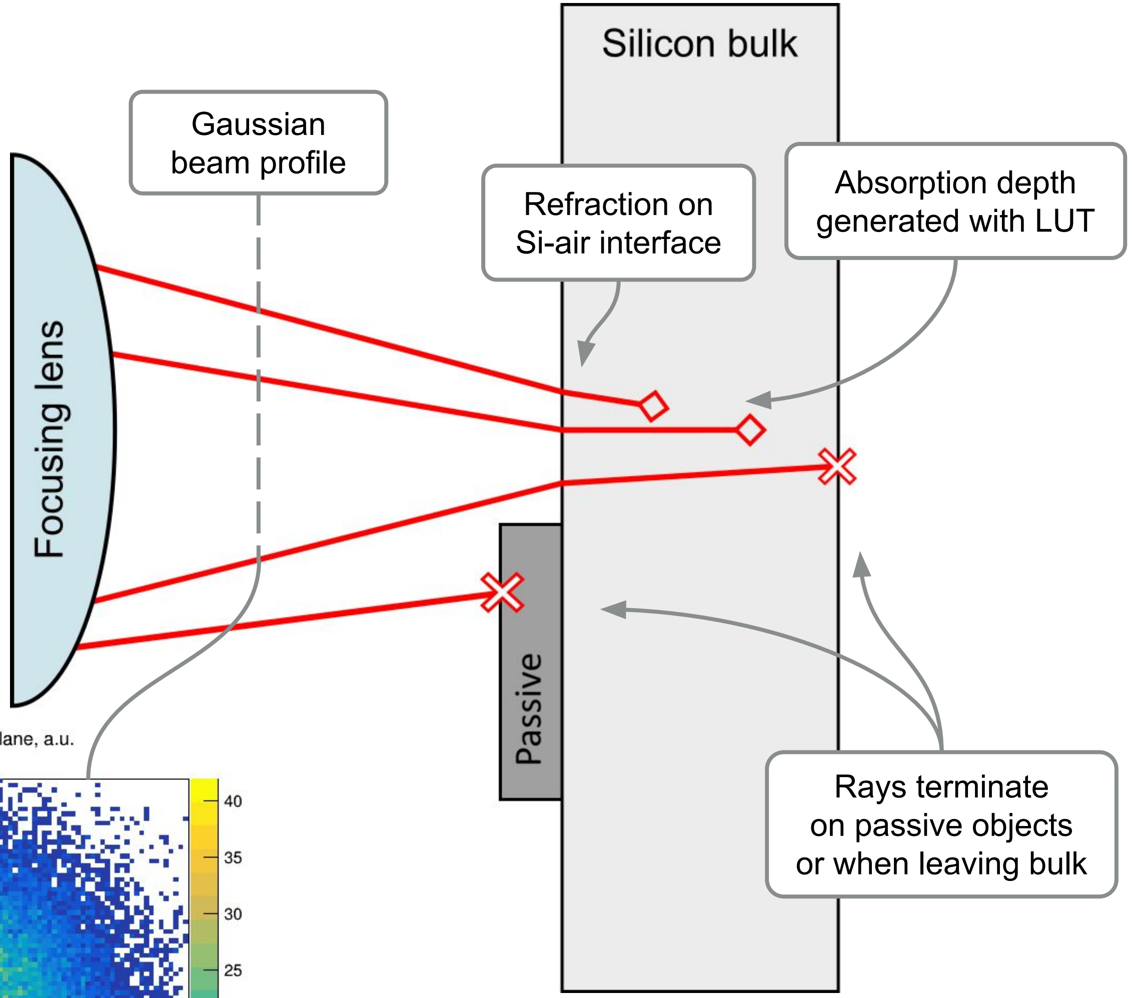
Simulation principle

Simulation features:

- Laser pulse is modelled as a set of **individual photons**, each considered a *straight ray*
- Intensity distribution reproduces a **gaussian beam**
- Adjustable **pulse duration**
- Experiment-based **lookup table** [1] with absorption and refraction coefficients for different wavelengths







[1] https://doi.org/10.1002/pip.4670030303

Module usage and features

```
[Allpix]
number_of_events = 1
```

A few events (or one) is usually enough

Each event is compute-heavy! Consider using `group_photons`

Module usage and features

```
[Allpix]
number_of_events = 1

[DepositionLaser]

# Specify beam geometry
source_position = 0mm 0mm -5mm
beam_direction = 0 0 1
beam_geometry = "converging"
beam_waist = 10um
focal_distance = 5mm
beam_convergence_angle = 20deg
```

A few events (or one) is usually enough

Each event is compute-heavy! Consider using `group_photons`

No need to call `[GeometryBuilderGeant4]`

Module usage and features

```
[Allpix]
number_of_events = 1

[DepositionLaser]

# Specify beam geometry
source_position = 0mm 0mm -5mm
beam_direction = 0 0 1
beam_geometry = "converging"
beam_waist = 10um
focal_distance = 5mm
beam_convergence_angle = 20deg

# Specify parameters of the pulse
wavelength = 1064nm
number_of_photons = 10000
pulse_duration = 1ns
```

A few events (or one) is usually enough

Each event is compute-heavy! Consider using `group_photons`

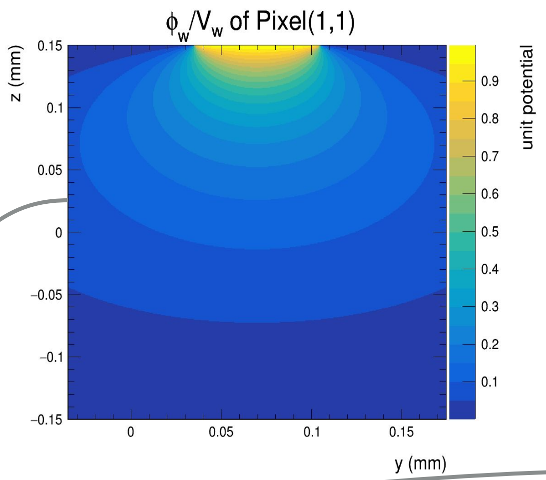
No need to call `[GeometryBuilderGeant4]`

Or explicitly define `absorption_length` and `refractive_index`

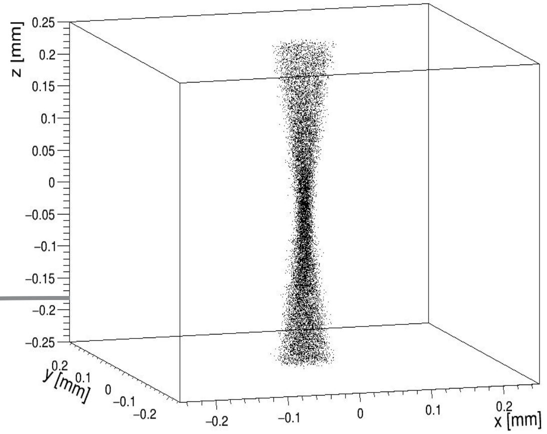
One cannot usually know these a priori

Example simulation pipeline

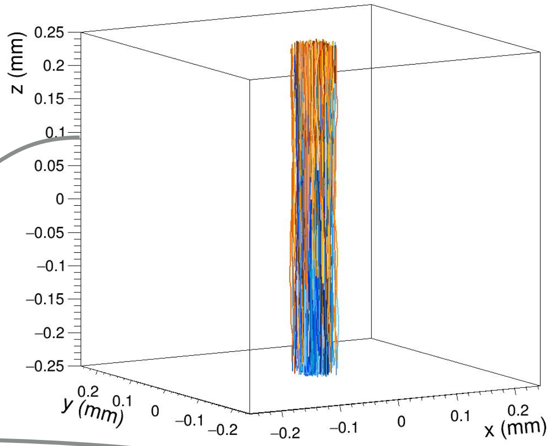
ElectricFieldReader & **WeightingPotentialReader**
define e.field and w.potential distributions



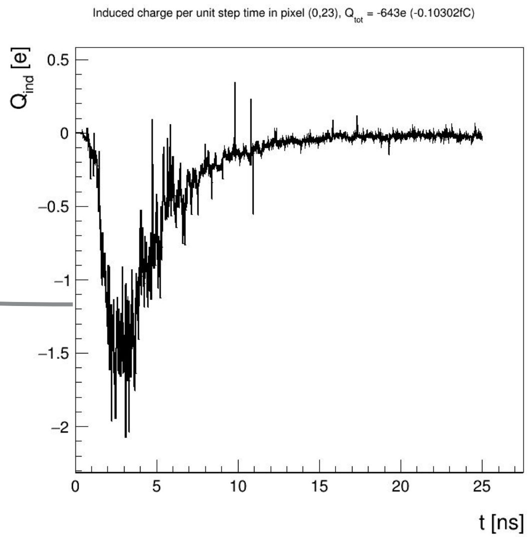
DepositionLaser
generate charge carriers, deposited in the bulk



TransientPropagation
track individual carriers through the bulk and
calculate induced currents (Shockley-Ramo)



PulseTransfer
accumulate induced currents and store data



Pulse post-processing (external)
account for the amplifier effects

TCT experiments:
Data/MC comparisons

Laser-TCT experiments

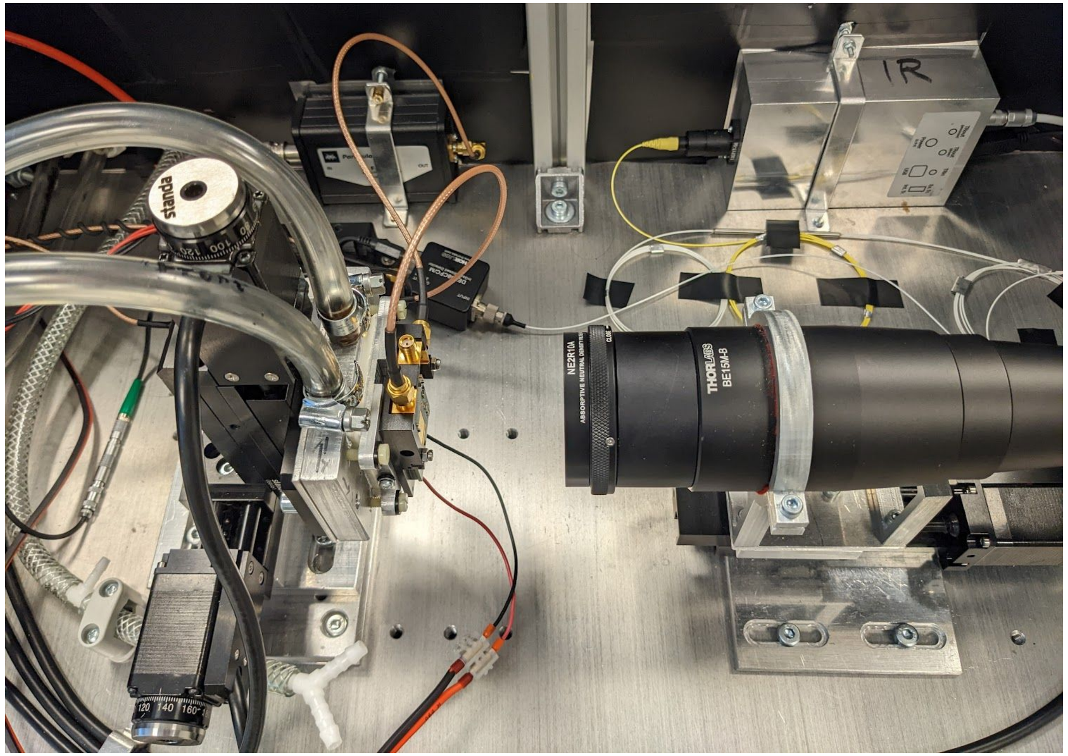
A flexible testbench for sensor R&D

Pulsed lasers are a common tool for charge injection:

- micrometer aim precision
- high repeatability
- tunable intensity

Red
pen.depth O(μm)
= *heavy particle absorption*

Near infrared
pen.depth O(mm)
= *m.i.p passage*



Experimental setup at DESY

Red (672 nm) and IR (1064 nm) lasers:

- beam can be focused to a spot up to **~10 μm**
- pulse duration of approx. **50 ps**
  → ~negligible w.r.t. signal collection time, thus does not significantly affect waveforms

A few more components to make a complete setup:

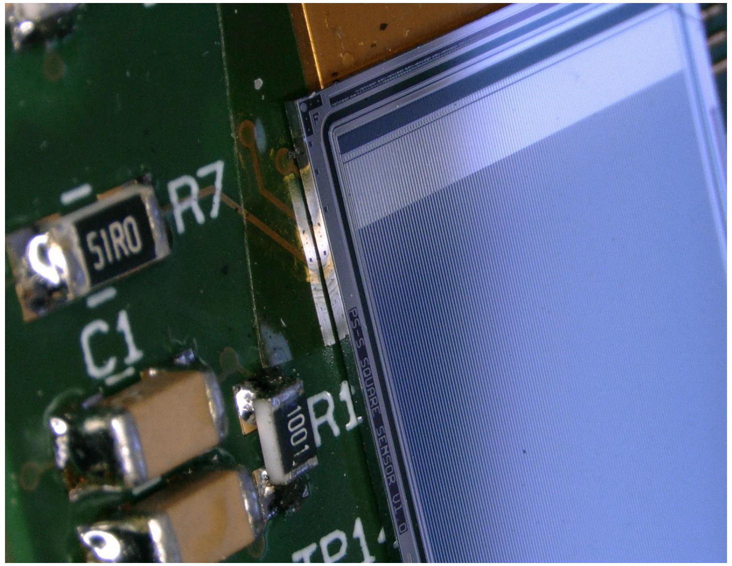
- Focusing optics
- Positioners
- High-bandwidth (2 GHz) amplification and readout
  → BW not infinite thus has to be accounted for

The sensor

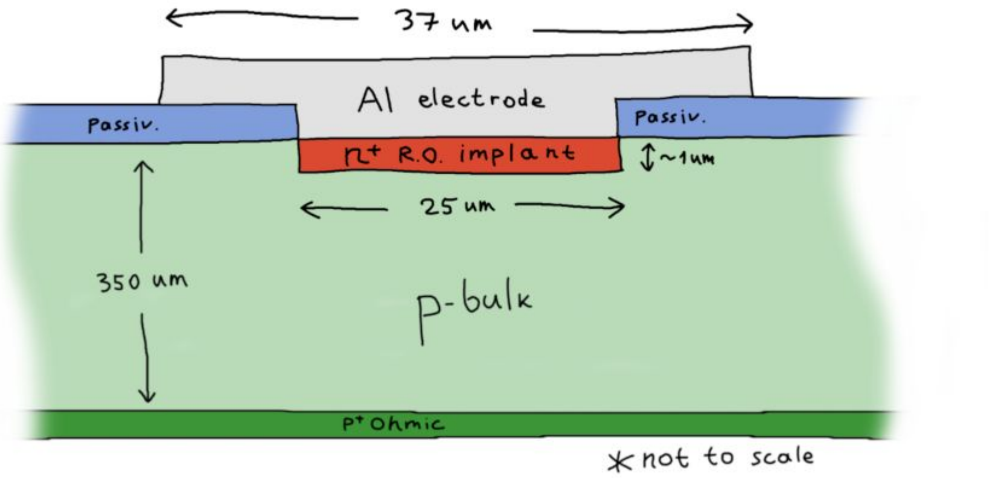
Strips and strips

“Baby PS-s”: a strip sensor demonstrator for CMS Phase-2 Outer Tracker

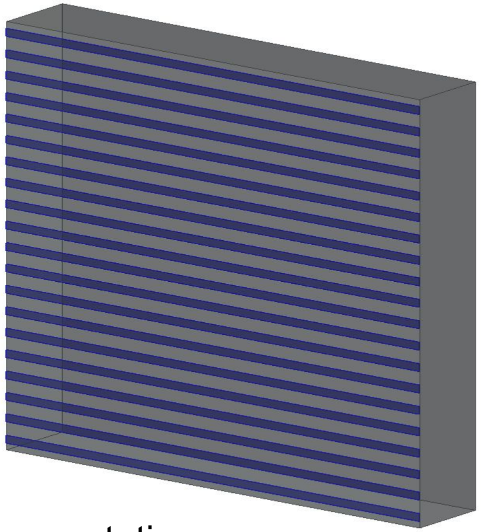
- 350 um thickness
- 100 um pitch
- n-in-p (electron-collecting)
- depletion at ~280V



The Real Thing on a PCB



Alu electrodes block light!
needs to be accounted for



The Allpix Squared Representation

Sensor model for APSQ + TCAD

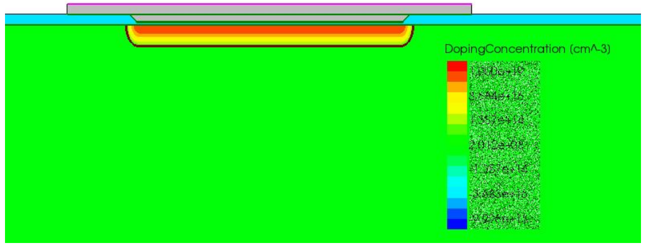
Precise models for precise simulations

For modelling of charge propagation in transition regions (e.g., next to implants), precise field models are **crucial**
→ especially for **red-TCT**

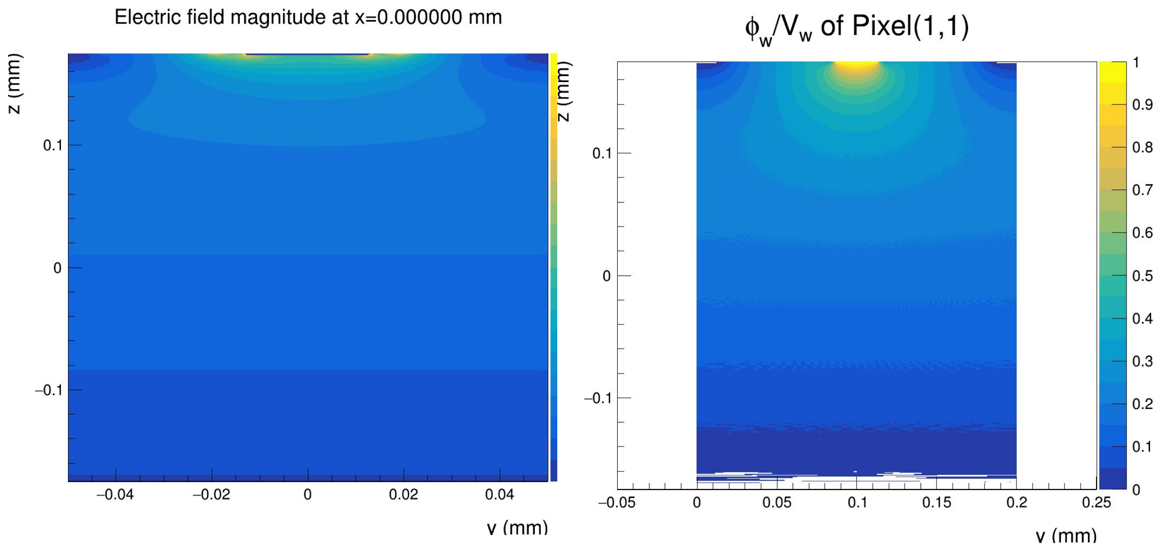
Solution: use TCAD

- 2D field model is sufficient for a *strip sensor*
- Exact bulk doping is not known of course
  → set it in TCAD such that V_{depl} matches the real sensor
- TCAD model accounts for non-zero depth of readout implants
  → use 3D implants in Allpix to ensure proper collection

Also: performance benefit in [TranisentPropagation]
"**`mesh`**" WP model is much faster than "**`pad`**"



Doping profile



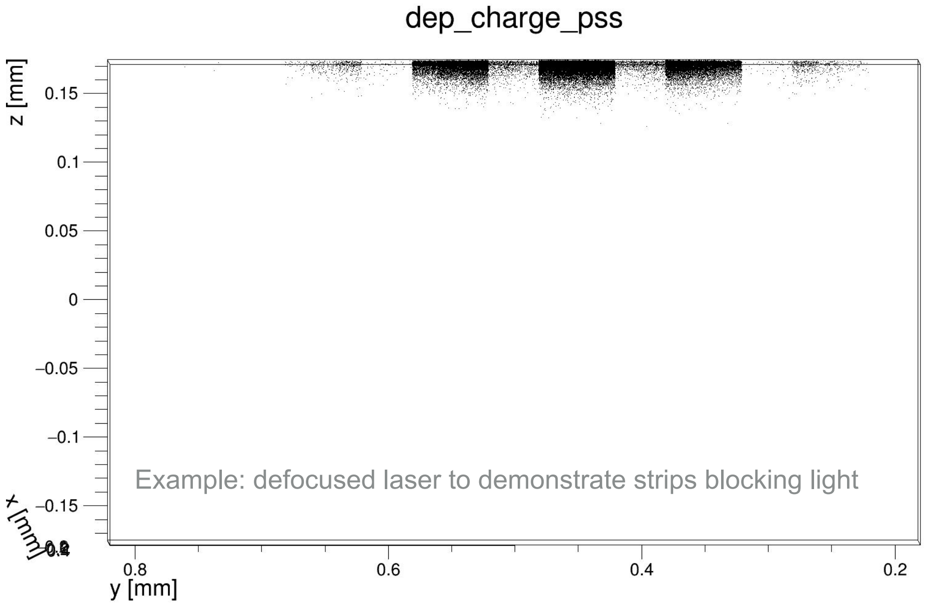
Electric field magnitude

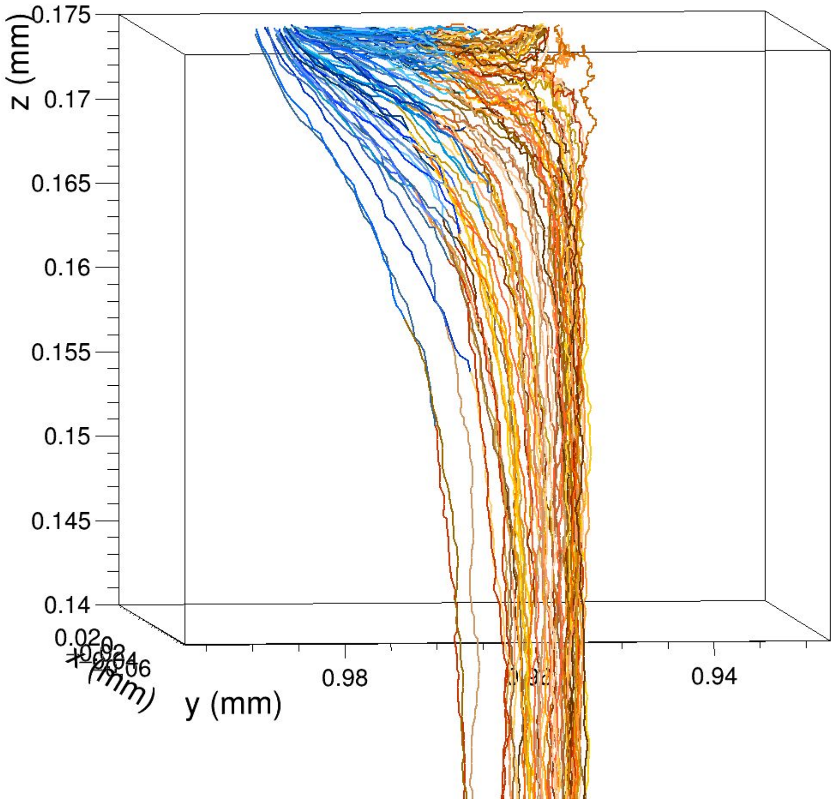
Weighting potential

Thanks to A. Velyka for providing TCAD!

Red laser injection

Signal formation





All the deposition is happening in a thin layer close to collection implant:

- Prompt pulse from electrons
- The hole cloud drifts through the whole bulk, *profiling the electric field*

Red laser injection

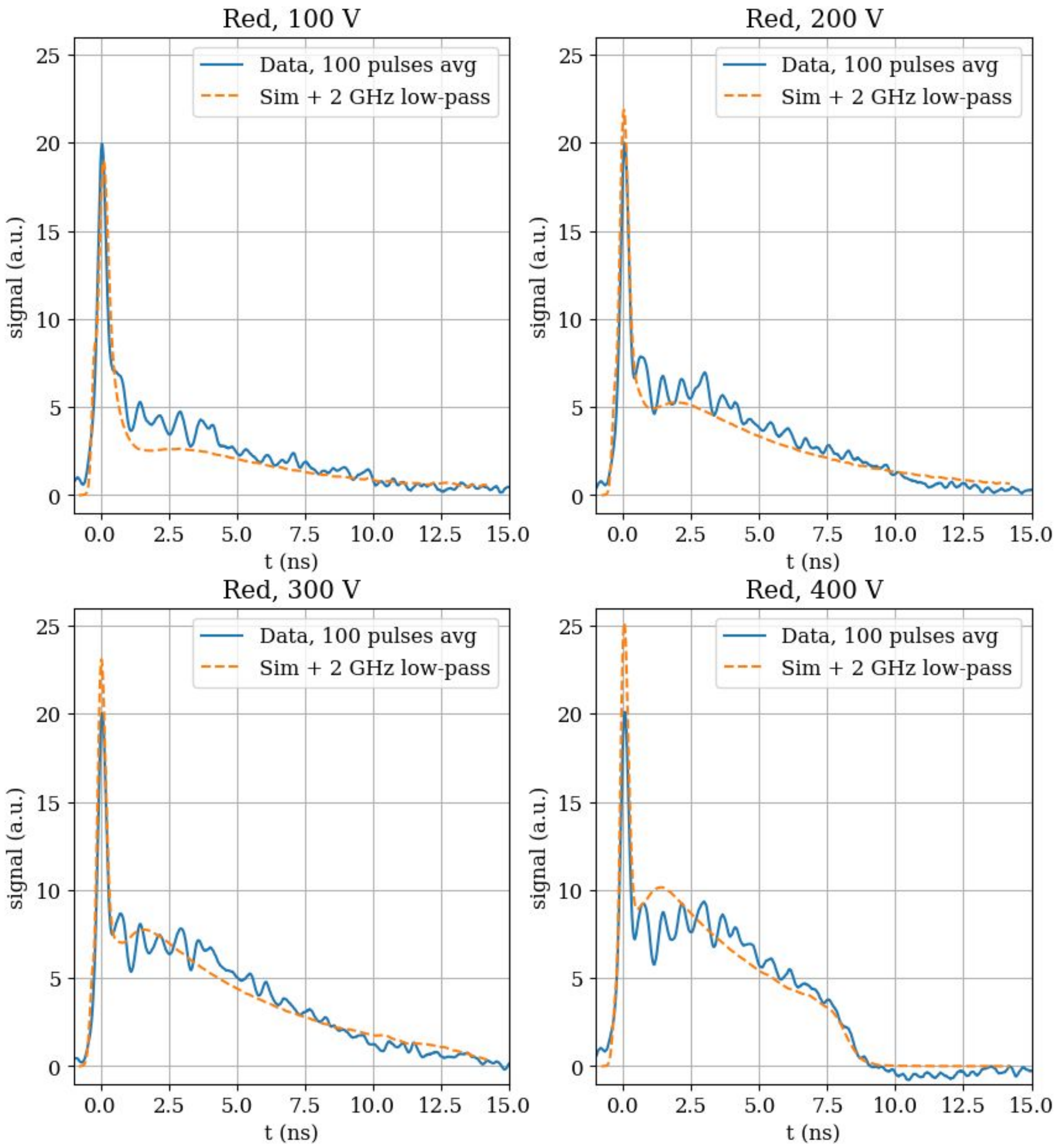
Data/MC comparison

Comparison:

- Electron peak: integral should be unaffected by the bias V
  - Data: the amp is insensitive to small width changes
  - Sim: the peak becomes sharper with V increase
- Hole component: roughly reflects E-field z-profile
  - Increases with V
  - Sharper cut-off if V_{depl} is exceeded
  - Good data/sim match!

Challenges:

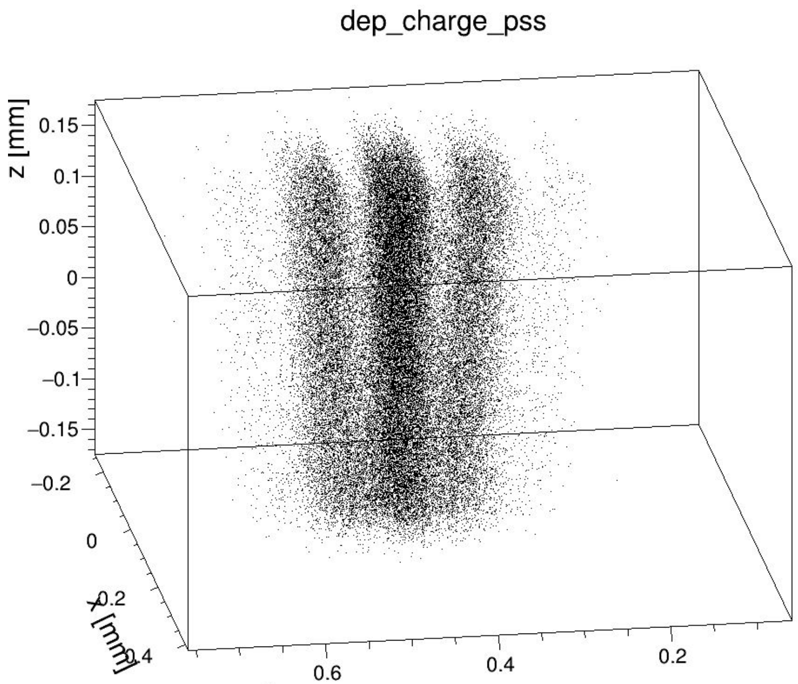
- Signal shape (both data and sim) is highly affected by the exact injection location
- Simulated shape of hole component is highly affected by the mobility model → here: **“`arora`”**
- Oscillation in the measured signal: interference from the laser → partially dealt with by moving the laser head further from amps



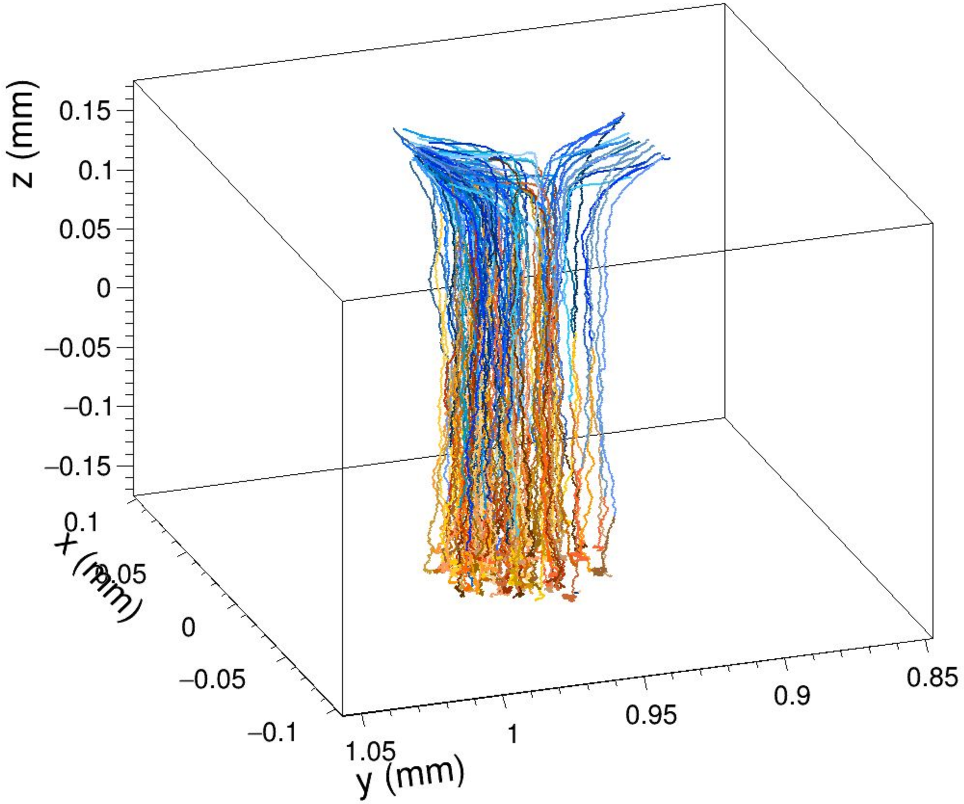
work in progress

Infrared laser injection

Signal formation



Example: defocused laser
to demonstrate strips blocking light



Deposition is ~uniform along the bulk

- Decaying component from electrons (*relatively fast*)
- Decaying component from holes (*relatively slow*)

Infrared laser injection

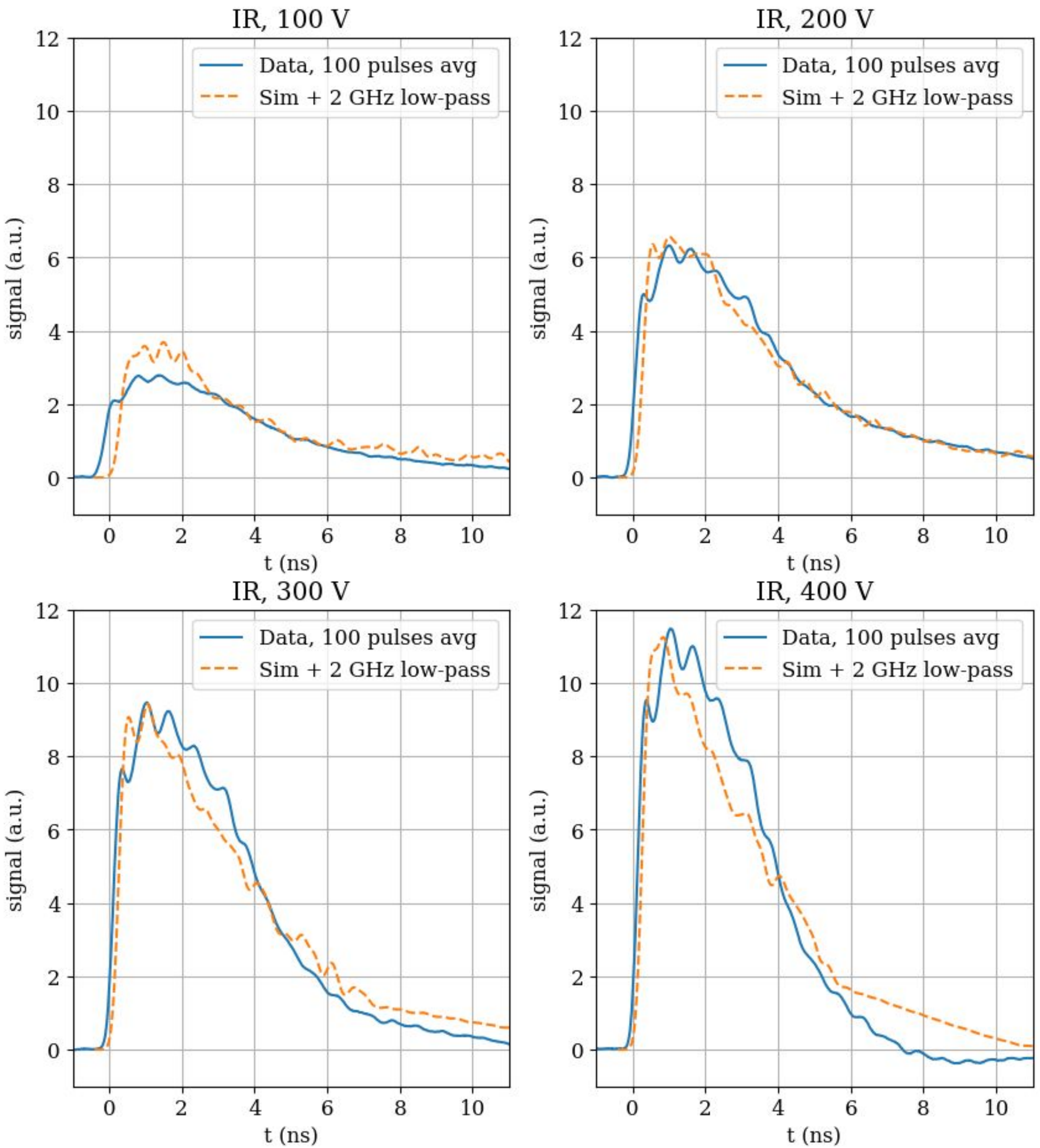
Data/MC comparison

Comparison:

- Total induced charge:
  - Increases with V, as active sensor thickness increases
  - As V_{depl} is reached, the pulse integral is unchanged
- The slowest part at under-depleted sensors: diffusion from the no-field region
  - Overestimated by simulation

Challenges:

- Simulated shape of both components is highly affected by the mobility model → here: **“`jacoboni`”**
- Proper mobility estimate requires knowledge of doping concentration!
- More accurate estimate of diffusion needed
- Oscillation in the measured signal: interference from the laser → partially dealt with by moving the laser head further from amps



work in progress

Conclusions

- The **deposition generator** for laser-TCT simulations is complete and functional
- With it, Allpix^2 is capable of reproducing sensor response in different scenarios of **TCT experiments**
    - Certain scenarios show **good match** to experimental data
    - However, **further tuning** of simulation is required for better precision and to cover wider range of use cases

That's it!

Thank you for attention!