Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Allpix^2 : Un logiciel générique de simulation Monte-Carlo des détecteur pixels semi-conducteurs

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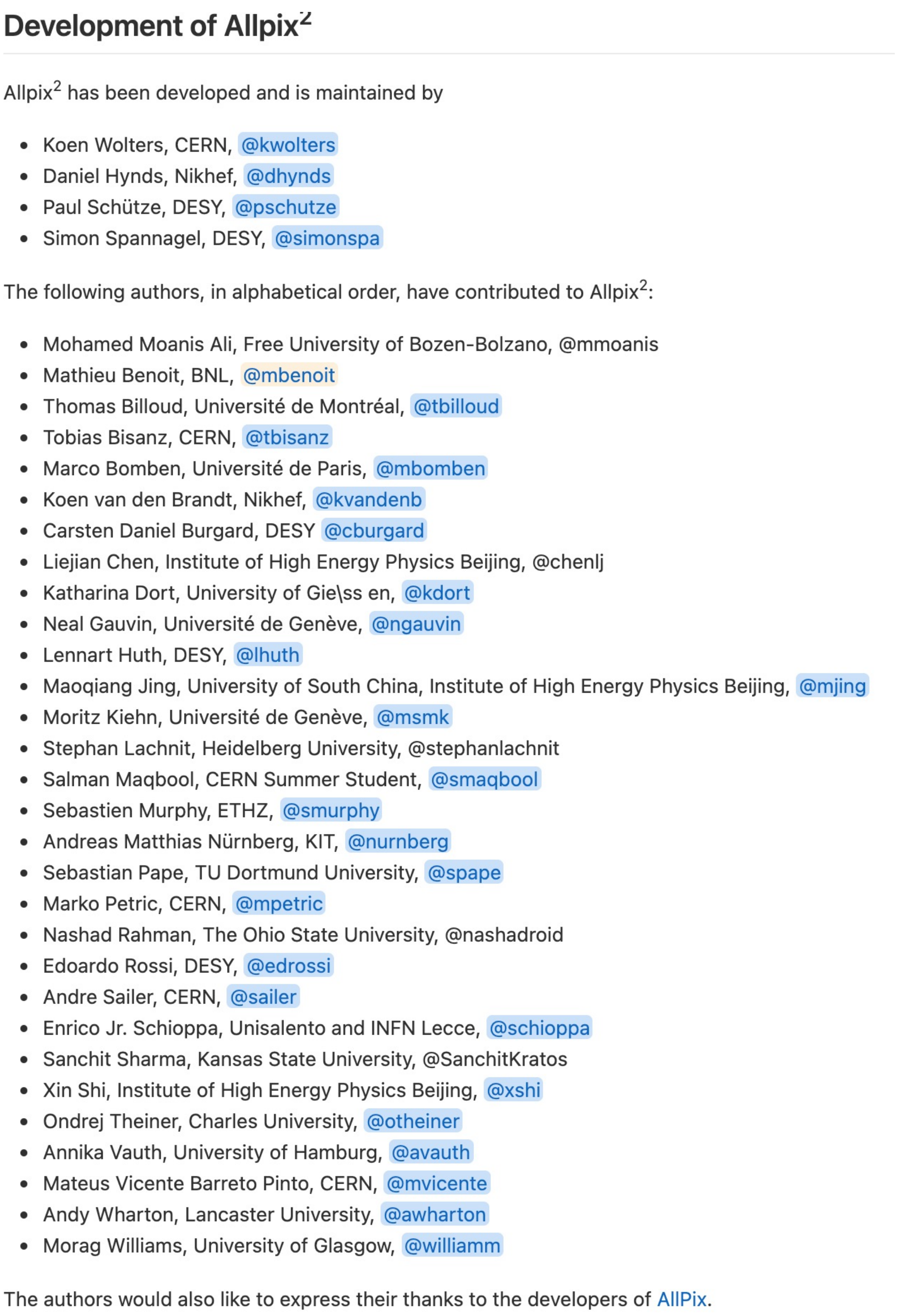
@BrookhavenLab

Outline

- Introduction to the Allpix^2 Framework
- Simulation flow
- Description of modules
    - Energy deposition
    - Charge Transport
    - Transfer
    - Digitization
    - IO and analysis
- Examples
- Ressources

The Allpix^2 team

ap^2
allpix squared



Development of Allpix^2

Allpix^2 has been developed and is maintained by

- Koen Wolters, CERN, @kwolters
- Daniel Hynds, Nikhef, @dhynds
- Paul Schütze, DESY, @pschutze
- Simon Spannagel, DESY, @simonspa

The following authors, in alphabetical order, have contributed to Allpix^2:

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The authors would also like to express their thanks to the developers of AllPix.

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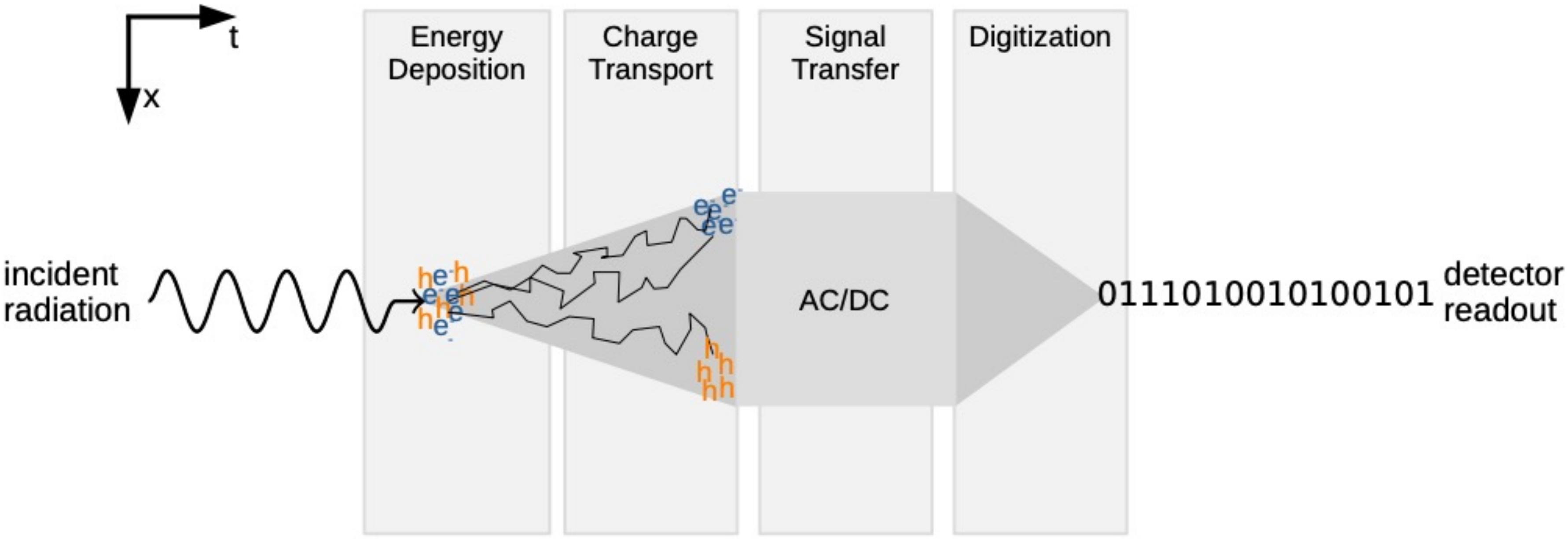
The Allpix^2 Framework

A **Modular, Generic** Simulation Framework for pixel Detectors

- The framework aims at facilitating the different steps of the simulation of semiconductor detectors
  - **Energy deposition in the detector material** (GEANT4 etc.)
  - **Charge Transport in the semiconductor**
  - **Transfer, Digitization and Analysis**

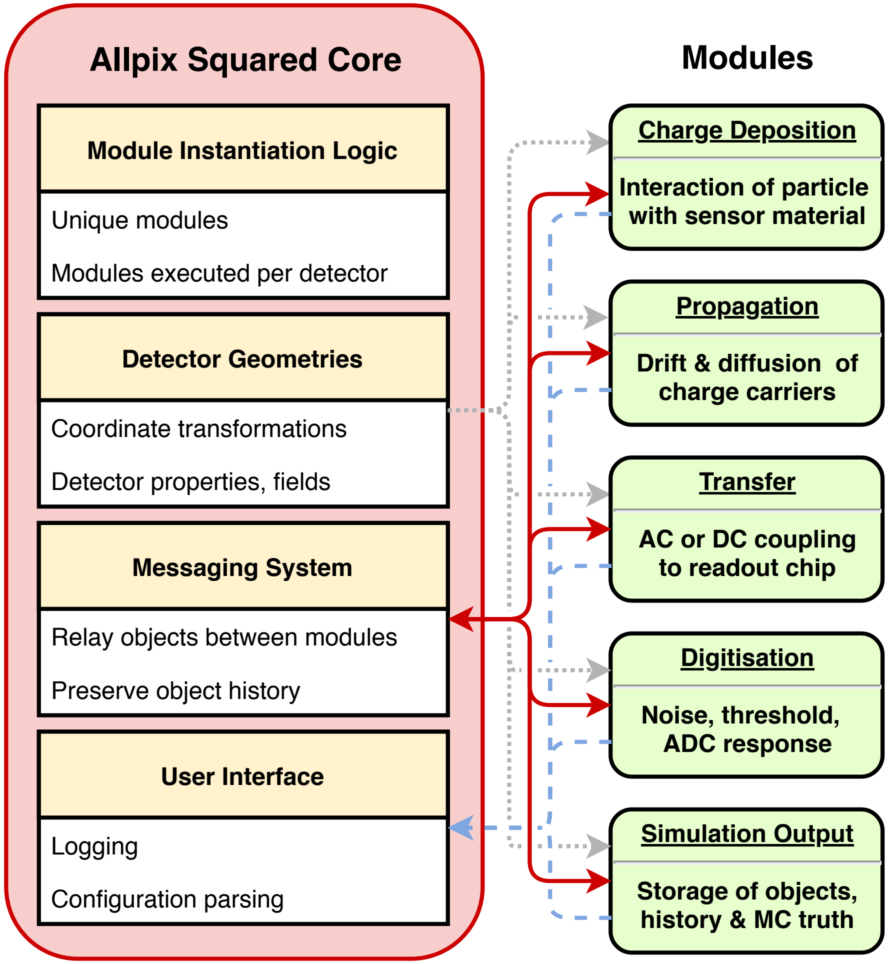
- The developpers aim at implementing the best practices in semiconductor detector simulation in a generic way to provide to the community verified and standardardized methods and a developement environment for further improvement to simulation methods
  - Framework infrastructure
  - Documentation, examples and code demonstration

The simulation flow



The Allpix^2 Framework

The allpix Framework offer a modular way to build a simulation flow and provide the infrastructure (core) to easily transfer information between modules, configure them and log their actions



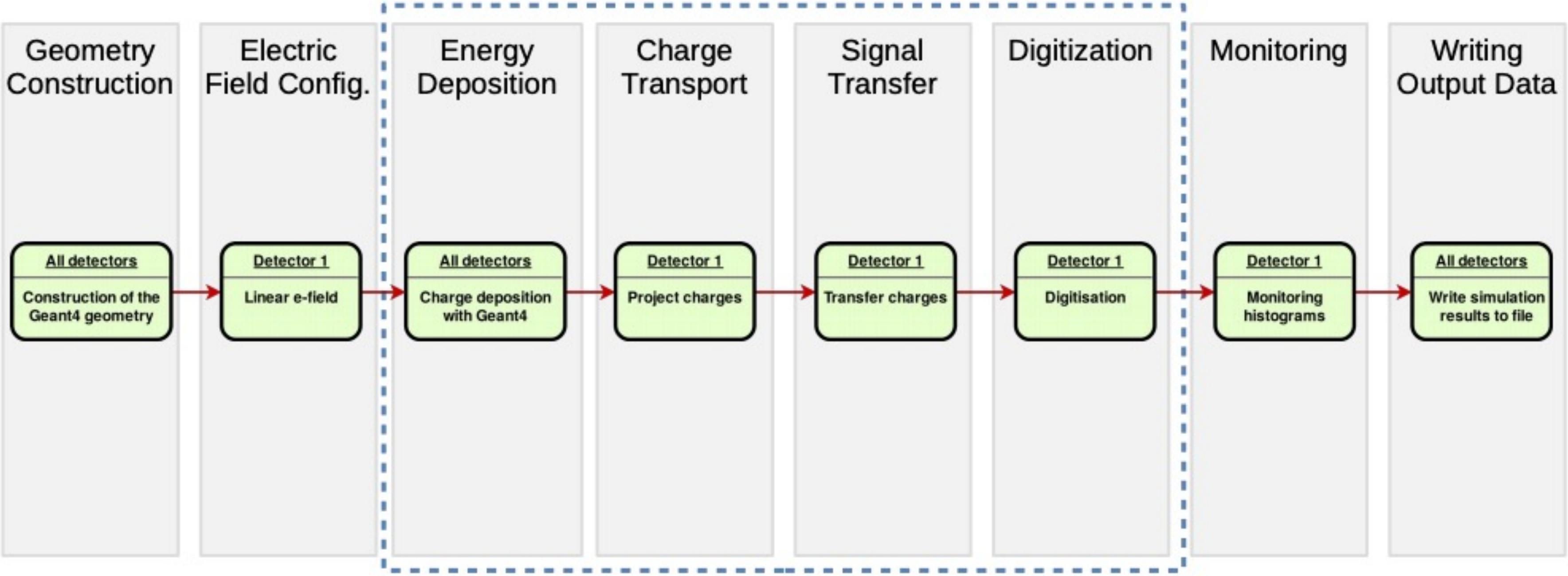
Framework Configuration

- Framework configured by one file
    - All desired modules listed in order of execution
    - Key-value pairs in TOML-style (extended)
    - Human readable
    - Little overhead (e.g. compared to XML)

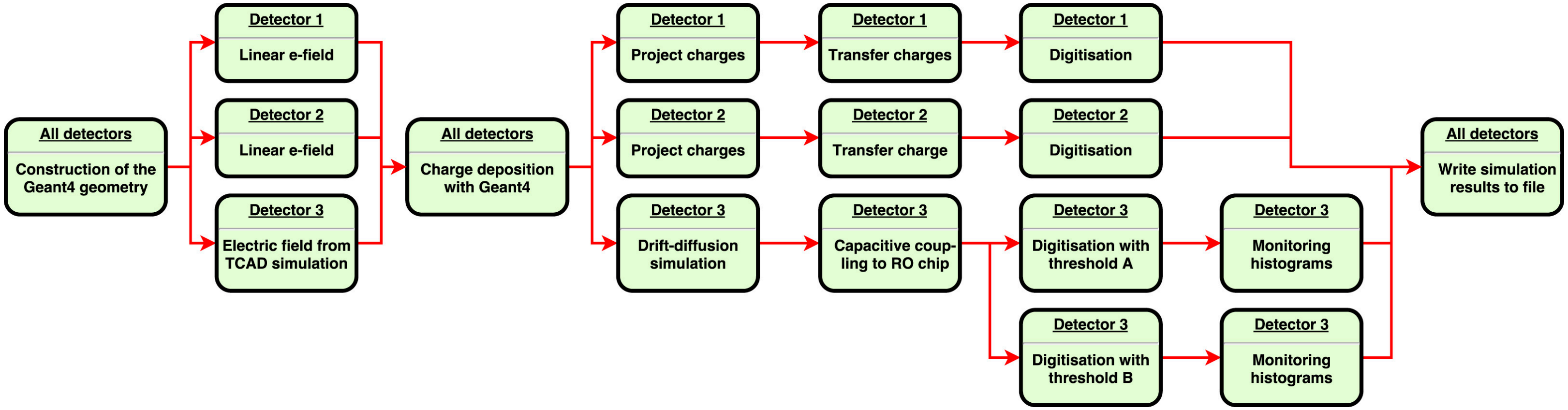
- Support for physical units
    - Never ask what units are used – type them out!
    - Automatic conversion to internal units
    - No need for manual conversions in C++

```
[AllPix]
log_level = "INFO"
number_of_events = 500000
detectors_file = "telescope.conf"

[GeometryBuilderGeant4]
world_material = "air"

[DepositionGeant4]
physics_list = FTFP_BERT_LIV
particle_type = "Pi+"
number_of_particles = 1
beam_energy = 120GeV
# ...

[ElectricFieldReader]
model="linear"
bias_voltage=150V
depletion_voltage=50V

[GenericPropagation]
temperature = 293K
charge_per_step = 10
spatial_precision = 0.0025um
timestep_max = 0.5ns

[SimpleTransfer]
```

Simulation Flow in Allpix^2 (simple)



Simulation Flow in Allpix^2 (Complex)



All detectors
Construction of the Geant4 geometry

Detector 1
Linear e-field

Detector 2
Linear e-field

Detector 3
Electric field from TCAD simulation

All detectors
Charge deposition with Geant4

Detector 1
Project charges

Detector 2
Project charges

Detector 3
Drift-diffusion simulation

Detector 1
Transfer charges

Detector 2
Transfer charge

Detector 3
Capacitive coupling to RO chip

Detector 1
Digitisation

Detector 2
Digitisation

Detector 3
Digitisation with threshold A

Detector 3
Digitisation with threshold B

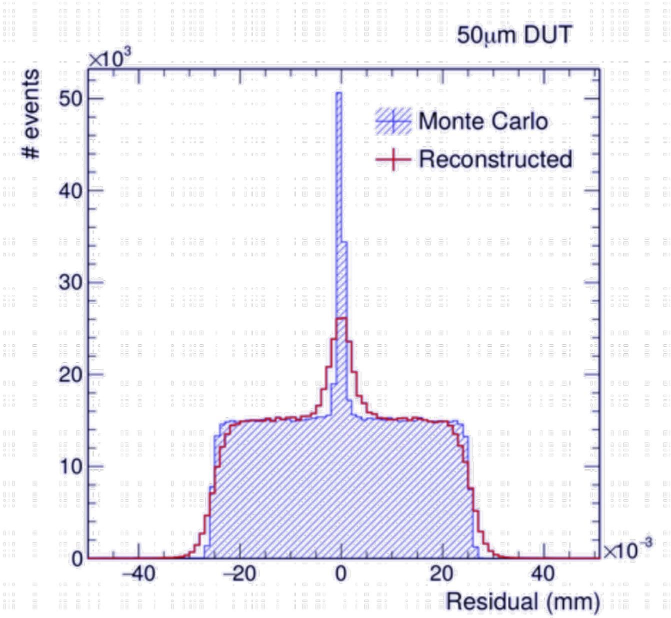
Detector 3
Monitoring histograms

Detector 3
Monitoring histograms

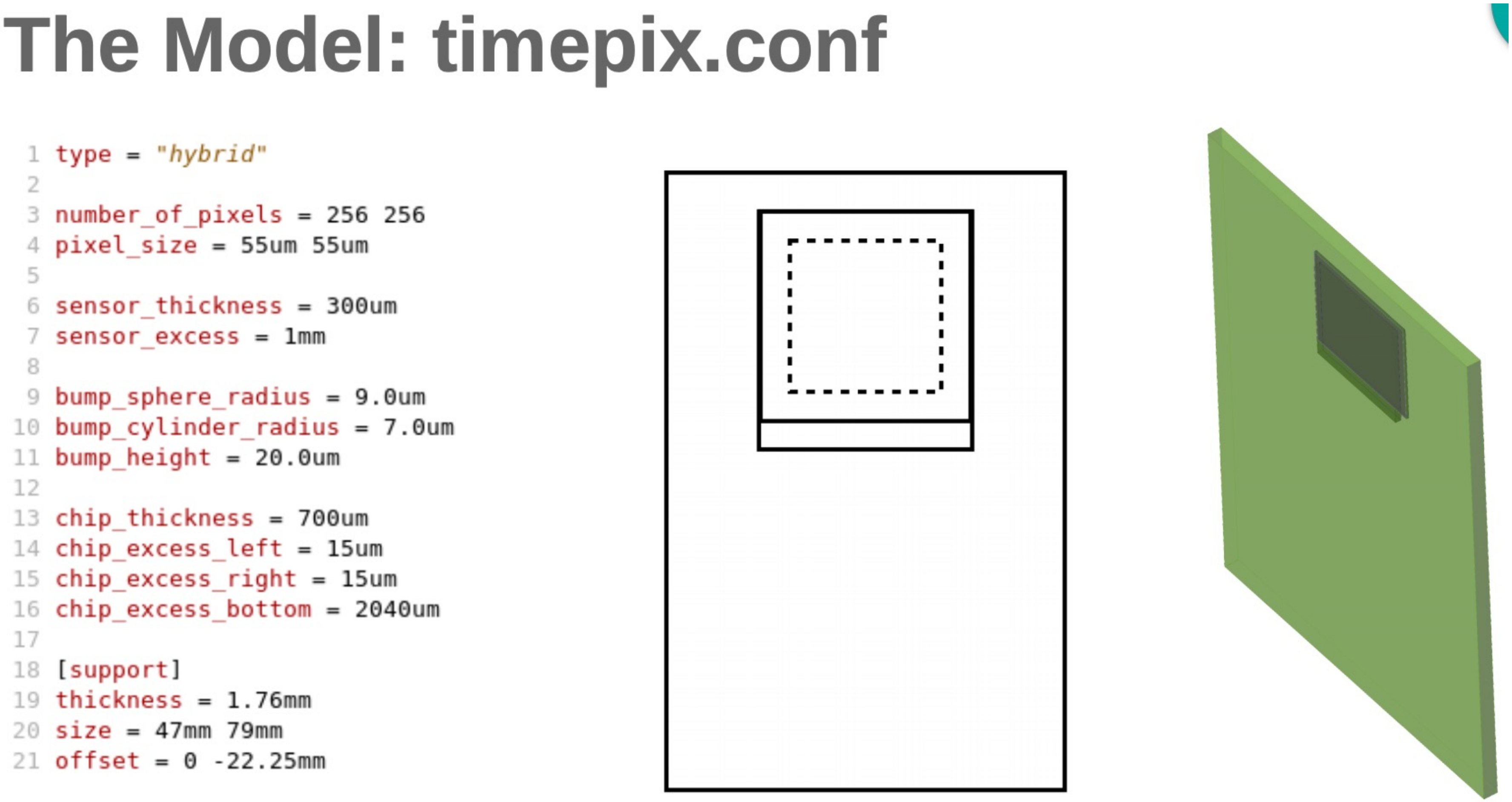
All detectors
Write simulation results to file

Messages & Object History

- Data exchanged between modules by means of messages
  - Message holds specific data type and has an origin (detector name, stream name…)
  - Modules bind to specific message (or message type) via central messenger
- Object history
  - For each object the full provenance is recorded using TRef objects
    - PixelHit ← PixelCharge ← PropagatedCharge(s) ← DepositedCharge(s) ← MCParticle(s) ← MCTrack
  - Allows direct relation of each pixel hit from front-end to initial particle(s)
  - Relation between MCParticles enables sorting between primaries (entered sensor from outside) and secondaries (produced within sensor)
  - Answers questions like “where in the detector did the charge carriers of this hit originate from?”



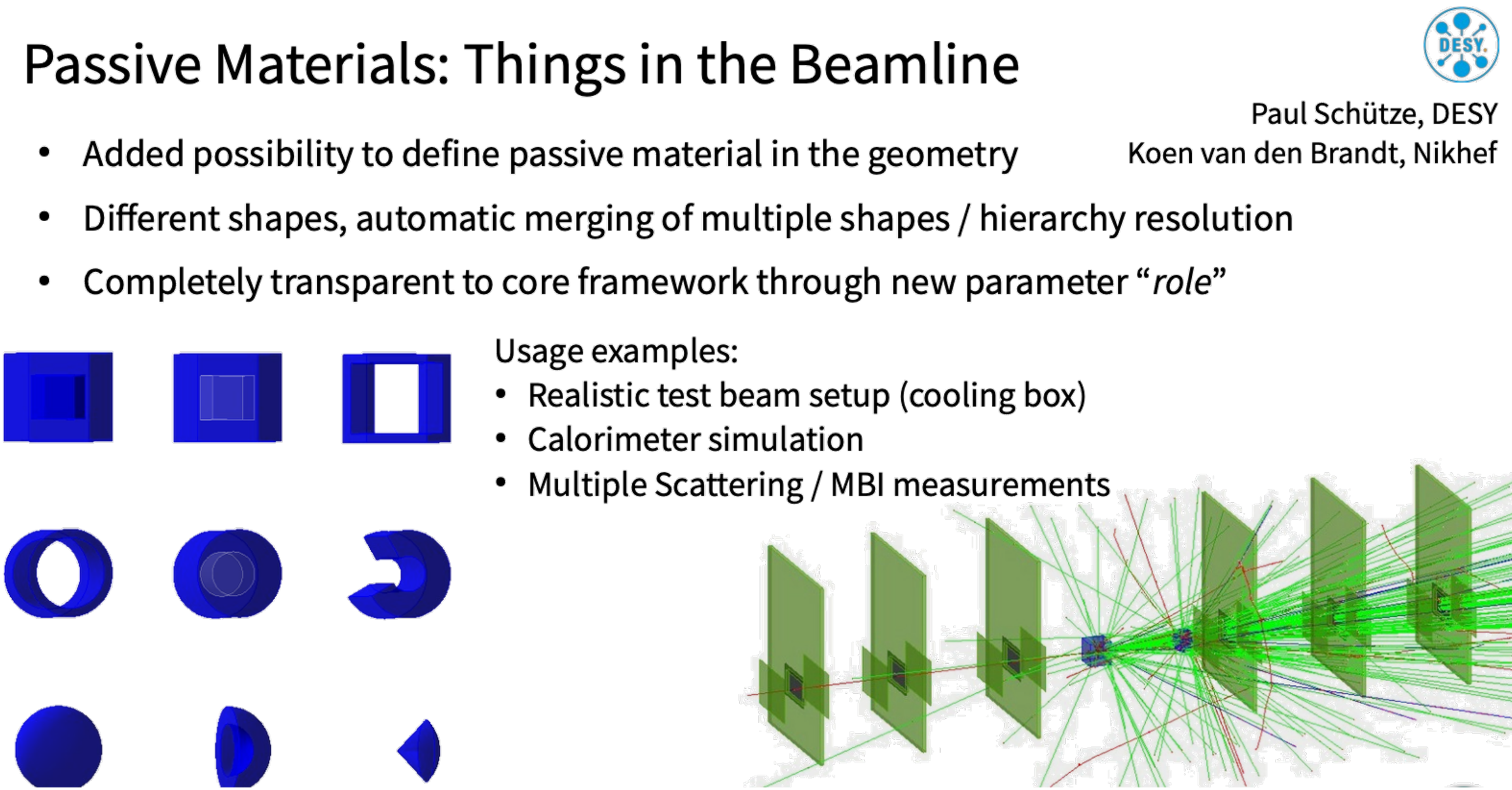
Defining the geometry



The Model: timepix.conf

```
type = "hybrid"

number_of_pixels = 256 256
pixel_size = 55um 55um

sensor_thickness = 300um
sensor_excess = 1mm

bump_sphere_radius = 9.0um
bump_cylinder_radius = 7.0um
bump_height = 20.0um

chip_thickness = 700um
chip_excess_left = 15um
chip_excess_right = 15um
chip_excess_bottom = 2040um

[support]
thickness = 1.76mm
size = 47mm 79mm
offset = 0 -22.25mm
```

Defining the geometry



Passive Materials: Things in the Beamline

Paul Schütze, DESY
Koen van den Brandt, Nikhef

- Added possibility to define passive material in the geometry
- Different shapes, automatic merging of multiple shapes / hierarchy resolution
- Completely transparent to core framework through new parameter "*role*"

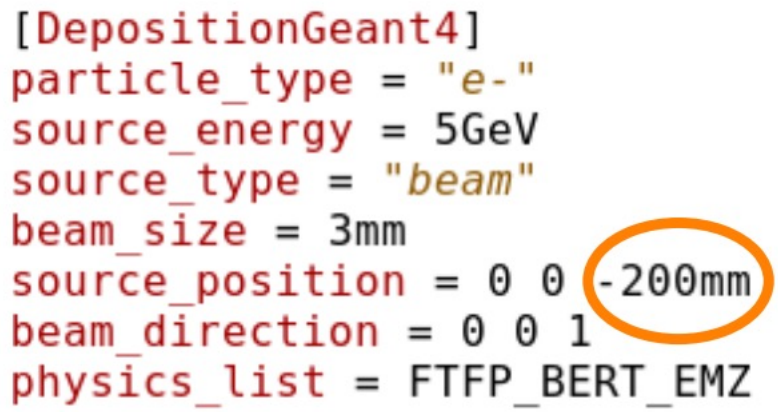
Usage examples:

- Realistic test beam setup (cooling box)
- Calorimeter simulation
- Multiple Scattering / MBI measurements

Defining particle sources and energy deposition model

DepositionGeant4

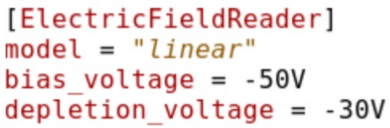
- Interface to Geant4
- Definition of particles and tracking through the setup
- Energy deposition in sensitive material
- Pick …
  - the type of particles (or radioactive sources)
  - the particle energy
  - the origin and direction of the beam
  - the shape and size of the beam
  - a suitable physics list



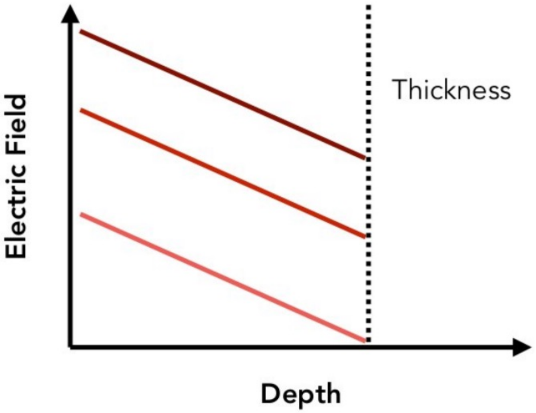
```
[DepositionGeant4]
particle_type = "e-"
source_energy = 5GeV
source_type = "beam"
beam_size = 3mm
source_position = 0 0 -200mm
beam_direction = 0 0 1
physics_list = FTFP_BERT_EMZ
```

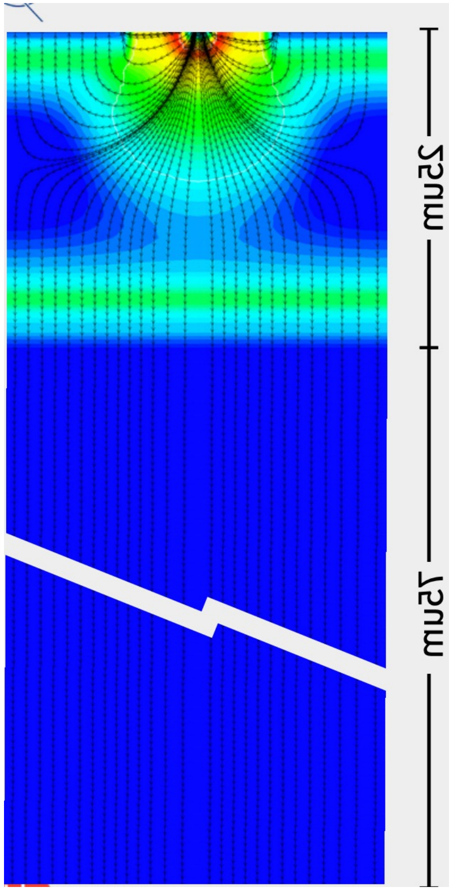
Defining the electric field

- Modules are provided to model detector with common analytical models for simple simulation
- Tools for converting more complex electric field distribution from TCAD (Sentaurus) are provided to import more complex electric field distribution in the Framework



```
[ElectricFieldReader]
model = "linear"
bias_voltage = -50V
depletion_voltage = -30V
```

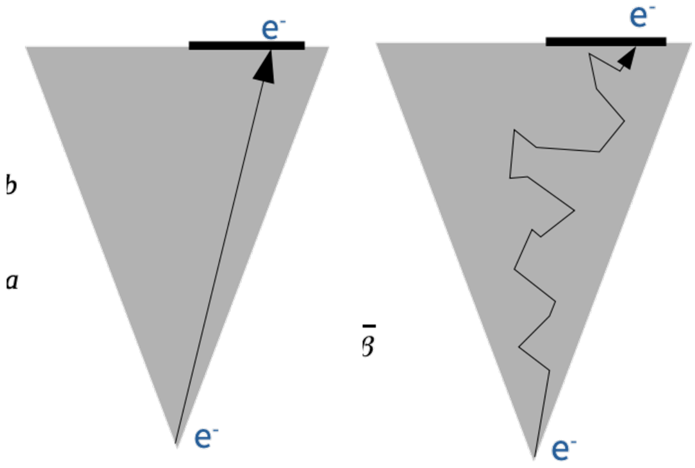


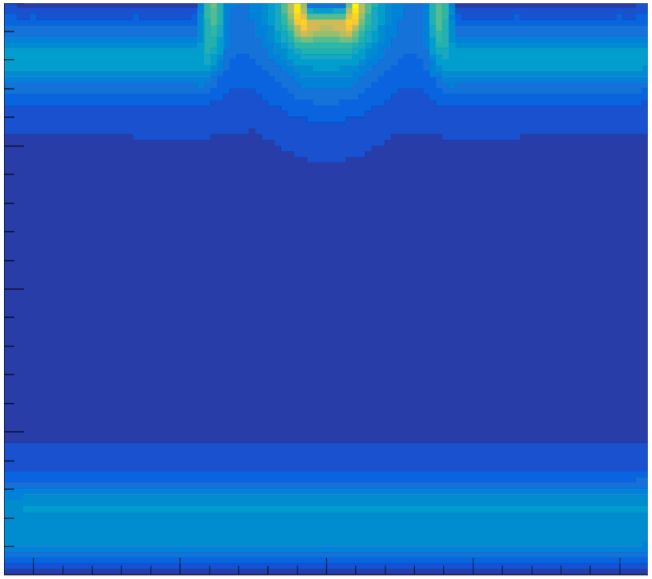


Propagating deposited charge

The framework provide multiple methods to transport the charge in the defined electric field, from simple to complex

- **Projection Propagation**
  - Simple approximation of transport, good for linear electric field and thick sensors, transport to surface then smear charge to account for diffusion
- **Integration of charge motion**
  - Full numerical integration of charge or fragments trajectory via a RKF45 method, in the electric field, taking into account :
    - Mobility
    - Magnetic and electric field

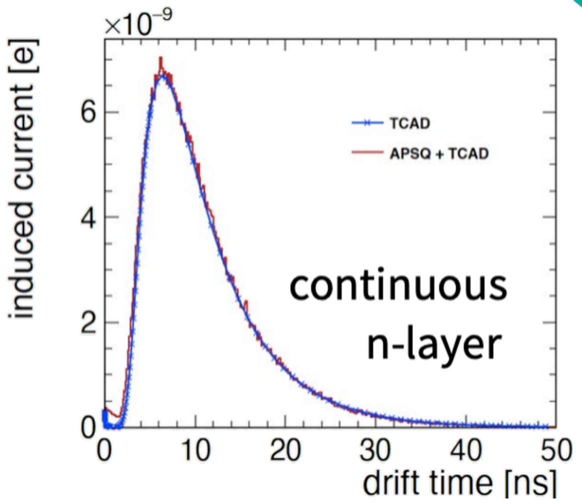


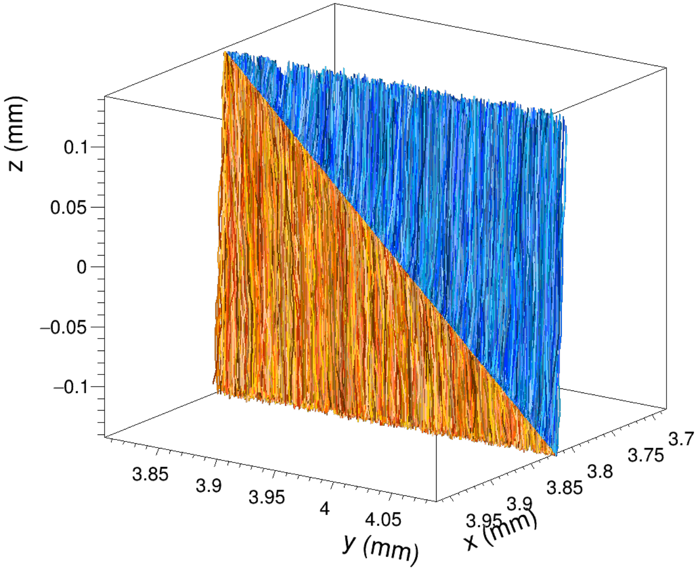


Transfer charge to signal

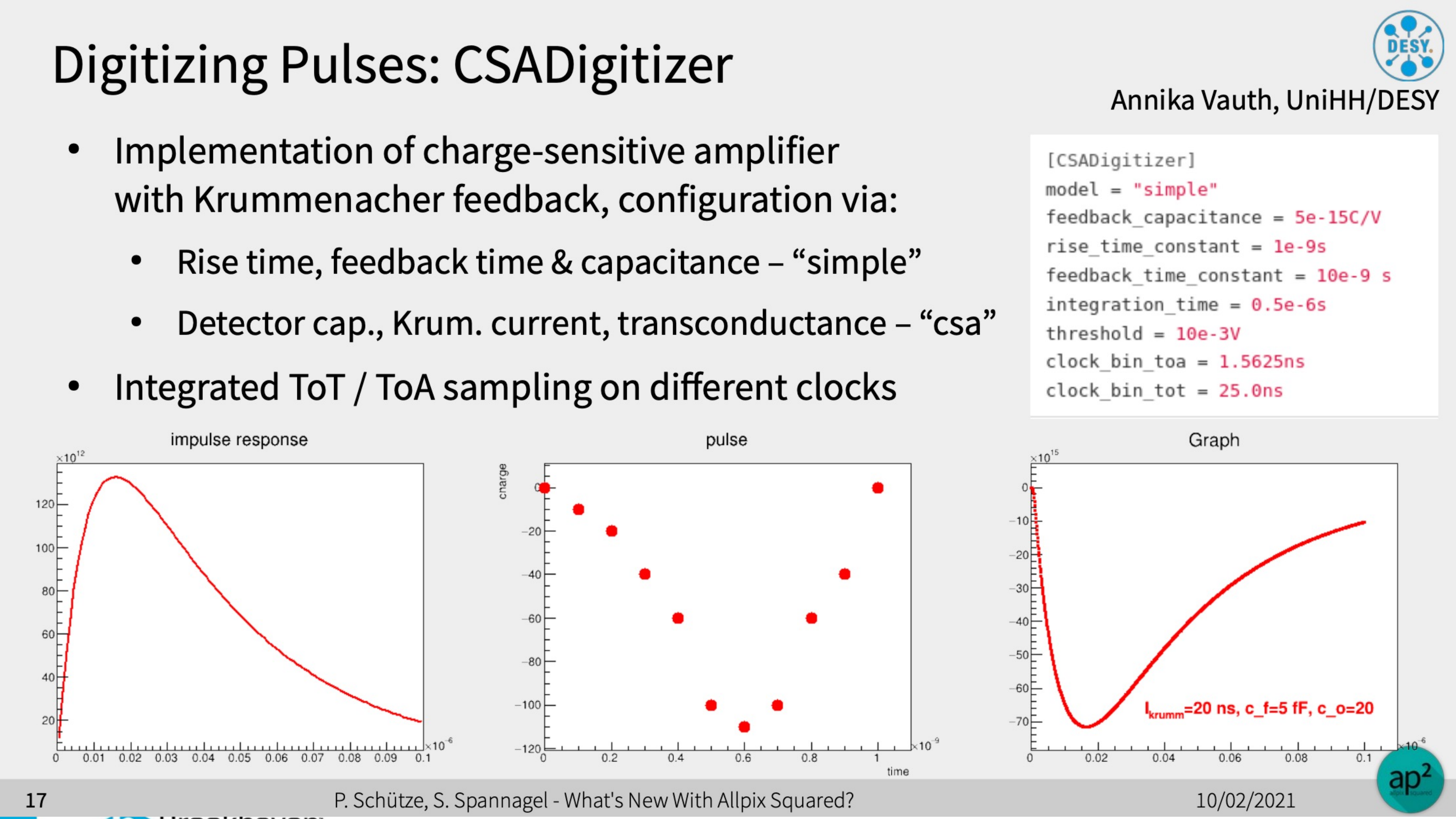
The framework provide multiple transfer method from simple to complex to transform the information from charge trajectory to registered signal in the electrode

- **Simple Transfer**
  - Assign charge to closest electrode at the end of trajectory
- **Simple Ramo**
  - Assign charge to each electrode following start and end point and Ramo Potential model or Ramo potential provided via TCAD
- **Full Ramo**
  - Calculate induced pulse from charge trajectory for each electrode using provided Ramo potential





Digitization



Digitizing Pulses: CSADigitizer

Annika Vauth, UniHH/DESY

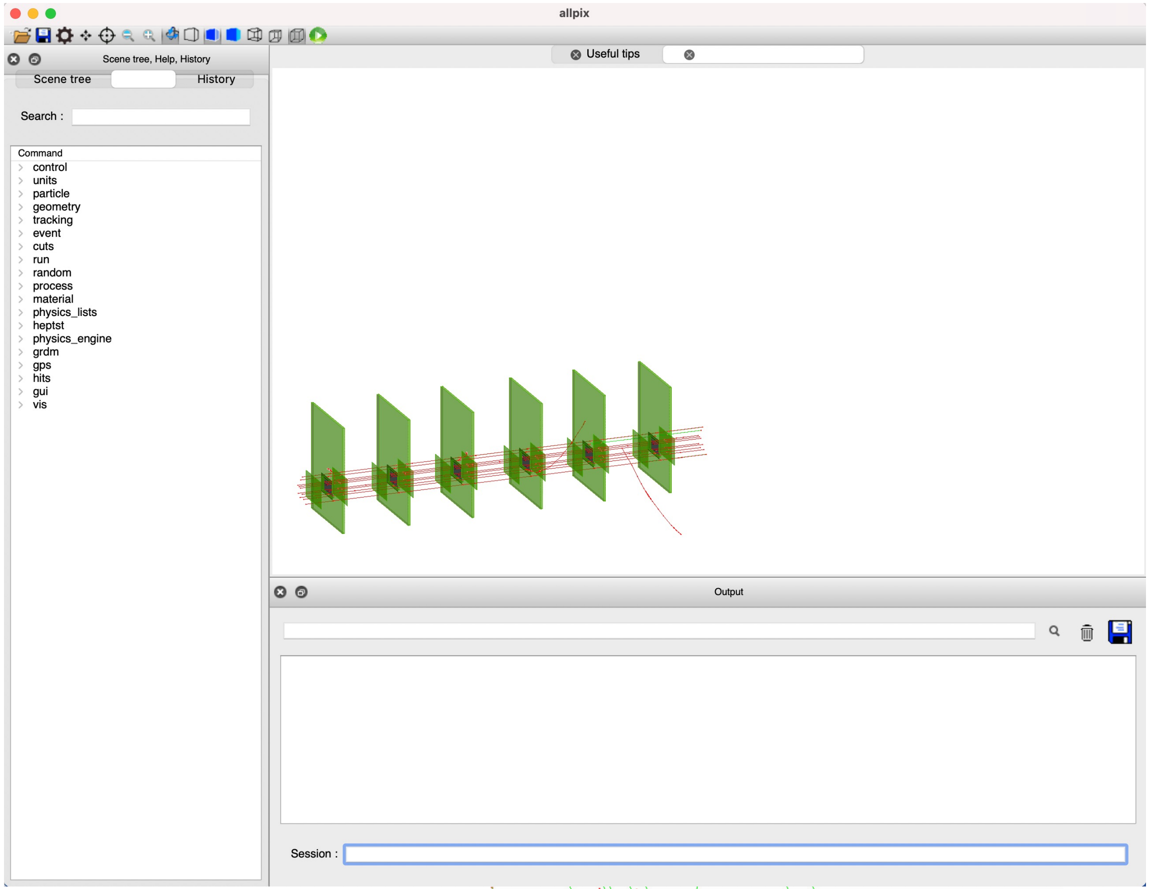
- Implementation of charge-sensitive amplifier with Krummenacher feedback, configuration via:
    - Rise time, feedback time & capacitance – "simple"
    - Detector cap., Krum. current, transconductance – "csa"
- Integrated ToT / ToA sampling on different clocks

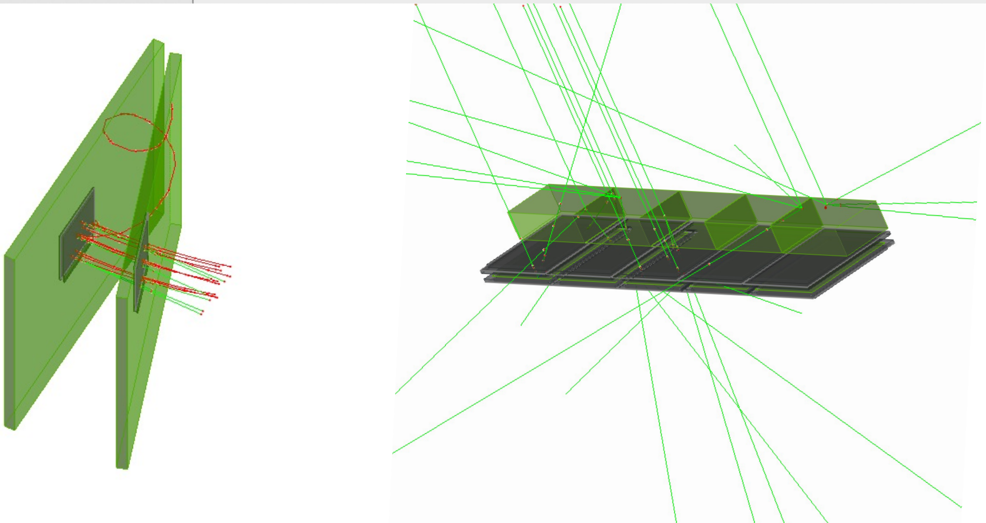
```
[CSADigitizer]
model = "simple"
feedback_capacitance = 5e-15C/V
rise_time_constant = 1e-9s
feedback_time_constant = 10e-9 s
integration_time = 0.5e-6s
threshold = 10e-3V
clock_bin_toa = 1.5625ns
clock_bin_tot = 25.0ns
```

Visualization

The framework comes with an easy to use visualization Module using the GEANT4 capabilities to illustrate the simulation

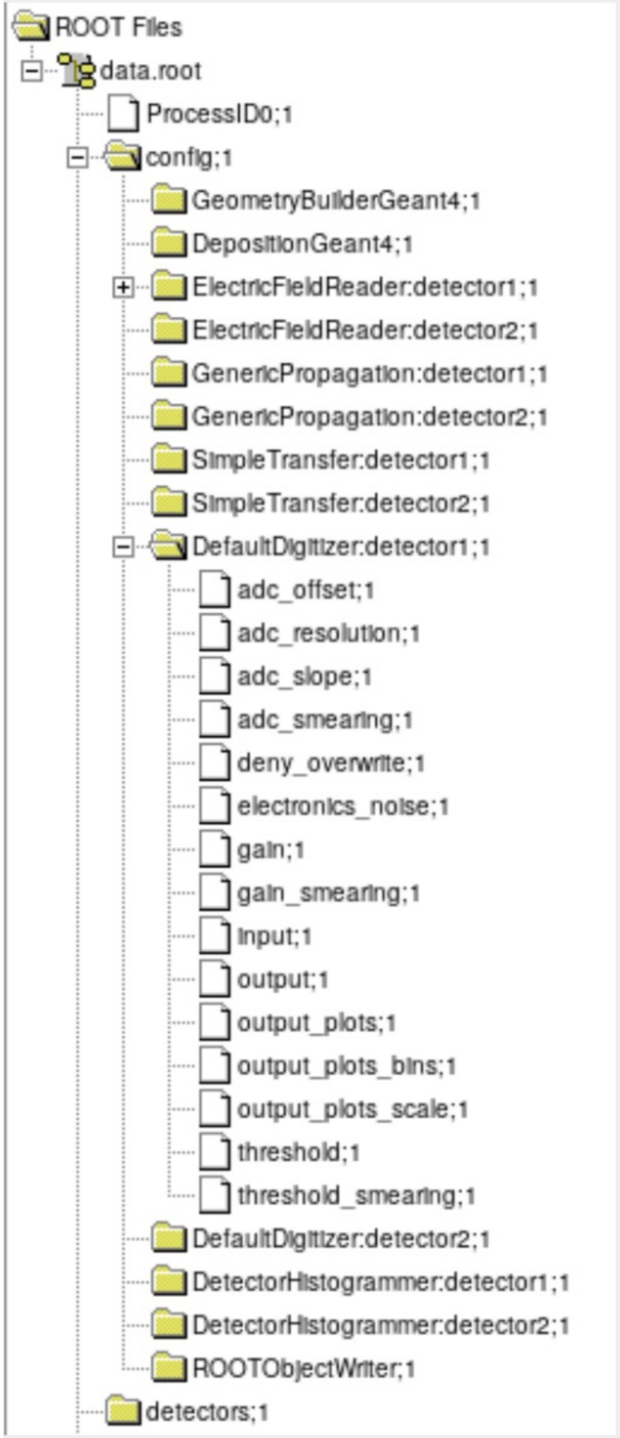
- Particle trajectories, charge, secondaries production
- Volumes, passive and active
- Hit pixels, energy deposition





Output of results

- Different output writers available
  - Eutelescope, RCE, Corryvekran and more
  - Can be use for reconstruction with Telescope software
- Native format: ROOT files with all objects
  - Also contains detectors & sim. parameters
  - Full framework configuration can be reconstructed from single data file
- ROOTObject reader replays data from file
  - Simulate deposition & propagation once
  - Read data from file and quickly repeat final digitization step with different parameters
- Each module reports a set of plots and histogram for rapid analysis of results

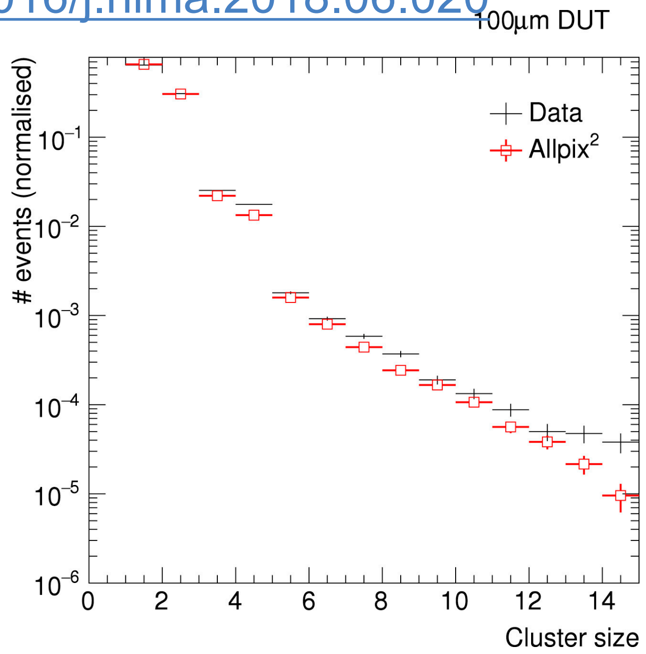


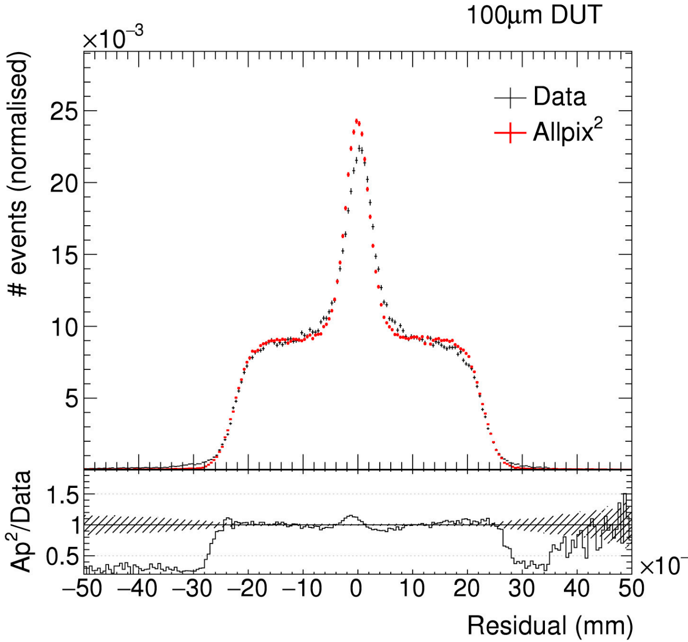
```
ROOT Files
  data.root
    ProcessID0;1
    config;1
      GeometryBuilderGeant4;1
      DepositionGeant4;1
      ElectricFieldReader:detector1;1
      ElectricFieldReader:detector2;1
      GenericPropagation:detector1;1
      GenericPropagation:detector2;1
      SimpleTransfer:detector1;1
      SimpleTransfer:detector2;1
      DefaultDigitizer:detector1;1
        adc_offset;1
        adc_resolution;1
        adc_slope;1
        adc_smearing;1
        deny_overwrite;1
        electronics_noise;1
        gain;1
        gain_smearing;1
        input;1
        output;1
        output_plots;1
        output_plots_bins;1
        output_plots_scale;1
        threshold;1
        threshold_smearing;1
      DefaultDigitizer:detector2;1
      DetectorHistogrammer:detector1;1
      DetectorHistogrammer:detector2;1
      ROOTObjectWriter;1
    detectors;1
```

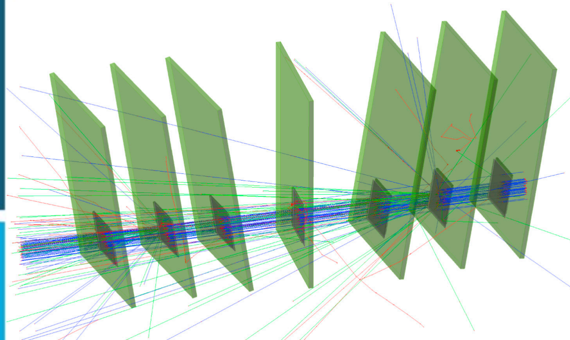
Example Application

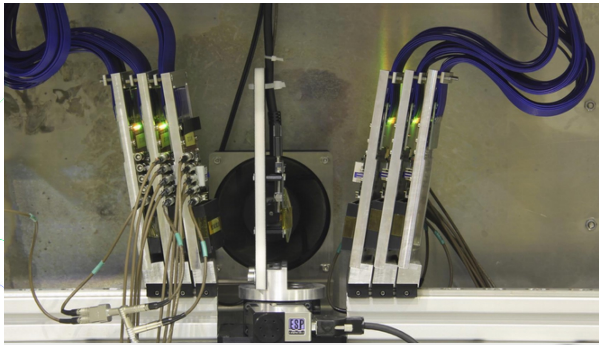
NIMA 901 (2018) 164 – 172
doi:10.1016/j.nima.2018.06.020

- Simulation of a beam telescope setup: CLICdp Timepix3 telescope @ SPS H6
  - Telescope: 6x Timepix3 w/ 300 µm sensors
  - DUT: 1x Timepix3 w/ 50 µm sensor
- Validation of reconstruction
- Different algorithms used:
  - Telescope: projection
  - DUT: successive integration
- Linear electric field approximation
- Very good agreement between data and simulation observed (total charge: Geant4; cluster size: both; residual shape: Allpix^2)



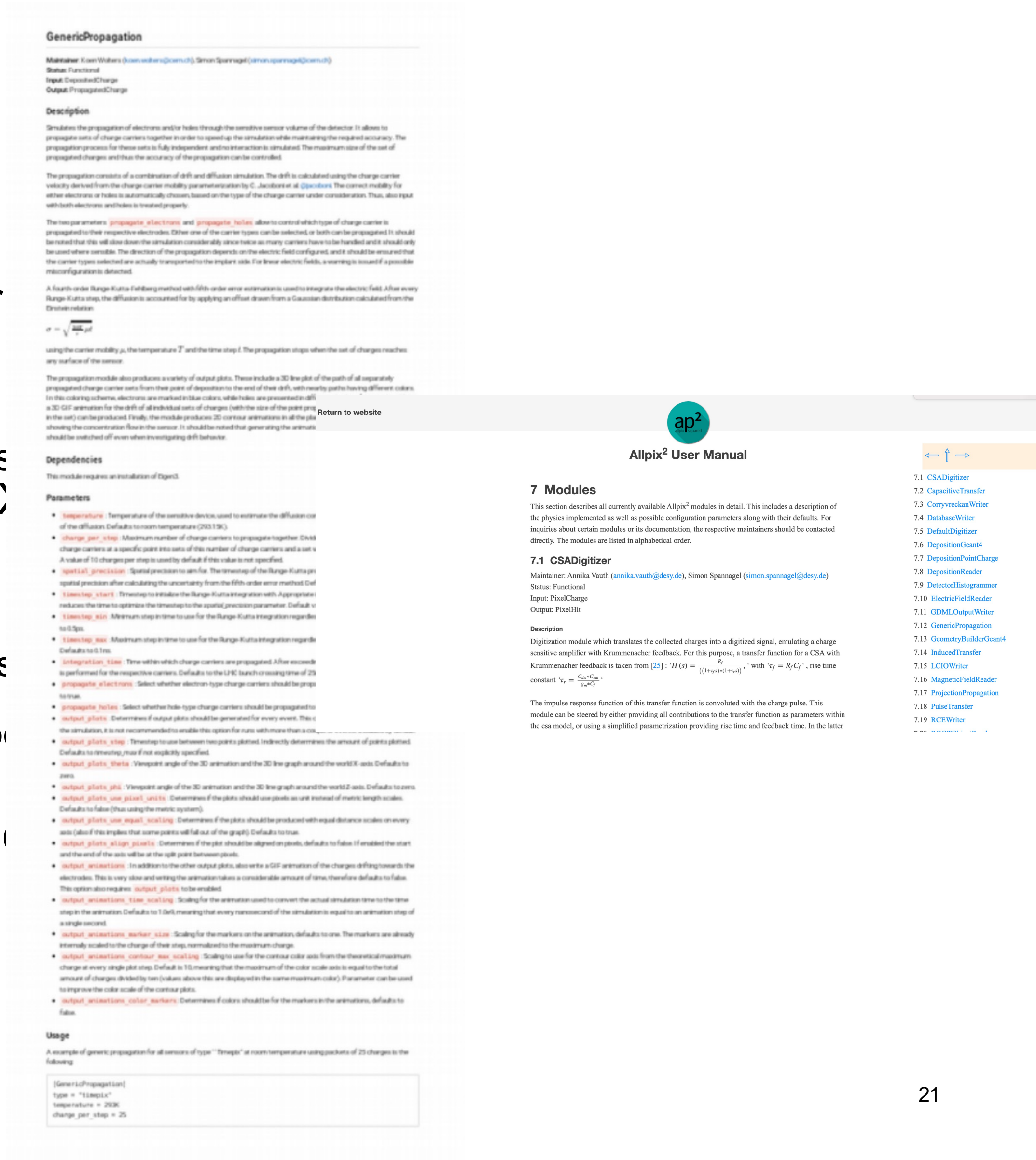






Documentation, coding guidelines, peer review

- Focus from the very beginning on well-documented framework
  - Source code documentation for every class, method
    - Doxygen markup for code reference
    - Deployed to the website for tags
  - Extensive User Manual in LaTe
    - Automatically compiled by CI
    - Module documentation as Markdown
      - Document module parameters algorithms
      - Included in manual via Pando
- Peer review of code for inclusion help maintains cod readability and preserve the usability



GenericPropagation

Status: Functional
Input: DepositedCharge
Output: PropagatedCharge

Description

Return to website

Allpix^2 User Manual

7 Modules

This section describes all currently available Allpix^2 modules in detail. This includes a description of the physics implemented as well as possible configuration parameters along with their defaults. For inquiries about certain modules or its documentation, the respective maintainers should be contacted directly. The modules are listed in alphabetical order.

7.1 CSADigitizer

Maintainer: Annika Vauth (annika.vauth@desy.de), Simon Spannagel (simon.spannagel@desy.de)
Status: Functional
Input: PixelCharge
Output: PixelHit

Description

Digitization module which translates the collected charges into a digitized signal, emulating a charge sensitive amplifier with Krummenacher feedback. For this purpose, a transfer function for a CSA with Krummenacher feedback is taken from [25] : ‘$H(s) = \frac{R_f}{((1+\tau_f s)*(1+\tau_r s))}$, ‘ with ‘$\tau_f = R_f C_f$ ‘, rise time constant ‘$\tau_r = \frac{C_{det}*C_{out}}{g_m*C_f}$ ‘

The impulse response function of this transfer function is convoluted with the charge pulse. This module can be steered by either providing all contributions to the transfer function as parameters within the csa model, or using a simplified parametrization providing rise time and feedback time. In the latter

Conclusion

The Allpix^2 Framework, a generic tool for simulation of semiconductor detectors combine the power of GEANT4 with state of the art algorithms for the simulation of transport, transfer and digitization

- Easy to use , no coding required in most case
- Validated widly by the community
- In constant evolution, each version gets better !
- Well documented, including examples

We hope to have convinced you to have a look at the framework !

All the good links !!!

Website https://cern.ch/allpix-squared

Repository https://gitlab.cern.ch/allpix-squared/allpix-squared

Docker https://gitlab.cern.ch/allpix-squared/allpixsquared/container_registry User

Forum: https://cern.ch/allpix-squared-forum/

Mailing Lists:

- allpix-squared-users https://e-groups.cern.ch/e-groups/Egroup.do?egroupId=10262858
- allpix-squared-developers https://e-groups.cern.ch/e-groups/Egroup.do?egroupId=10273730
-

User Manual:

https://cern.ch/allpix-squared/usermanual/allpix-manual.pdf

Tutorials

For multiple hands-on tutorials and in-depth presentation on allpix

https://project-allpix-squared.web.cern.ch/project-allpix-squared/page/publications/

Users who published so far :

https://www.scopus.com/results/citedbyresults.uri?sort=plf-f&cite=2-s2.0-85048755761&src=s&imp=t&sid=e2843363bb8a407e98425a734fed7a9e&sot=cite&sdt=a&sl=0&origin=inward&editSaveSearch=&txGid=7bb166821b2dc64286a13edfe8973e2b