SolidStateDetectors.jl:
Open-Source Simulation of Semiconductor Detectors

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Solid
State
Detectors

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SolidStateDetectors.jl

- Open-source simulation software package, written in julia
- 3D calculation of electric potentials and electric fields
- Can simulate arbitrary geometries, e.g. segmented detectors
- Documentation: https://juliaphysics.github.io/SolidStateDetectors.jl/stable/
- Fast field calculation: SIMD on CPU, also supports GPU calculation
- Calculation of capacitance matrix
- Simulation of fields in undepleted detectors ⇒ C-V curves
- Experimental features: diffusion and self-repulsion of charge clouds
- Recent additions: support for Geant4.jl and charge trapping models

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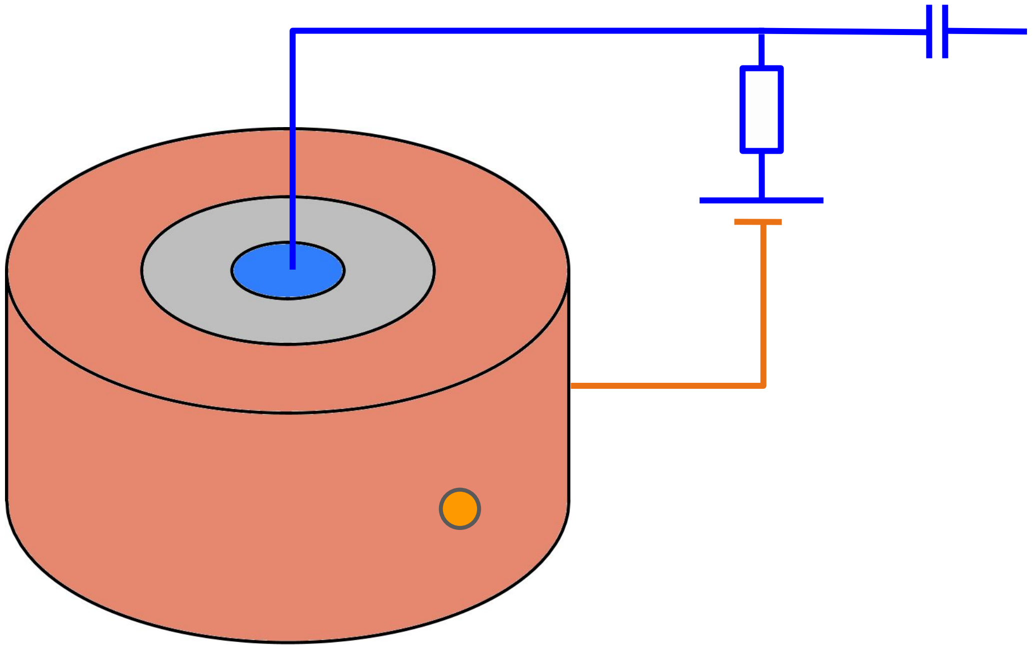
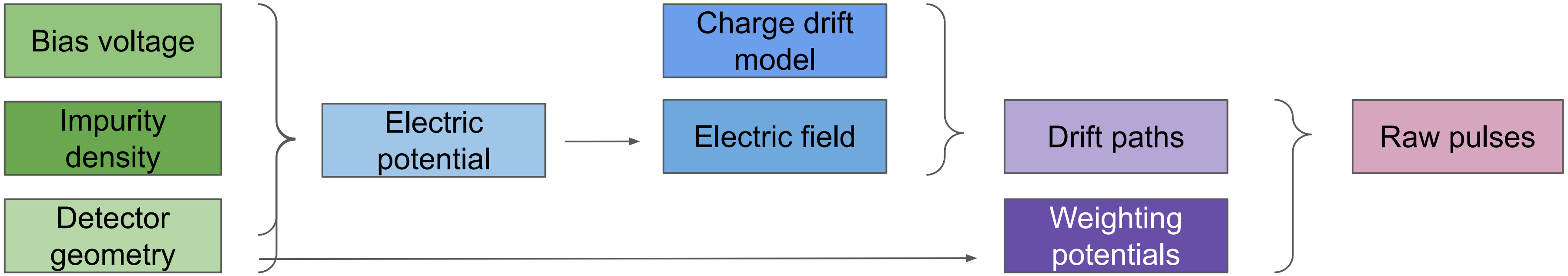
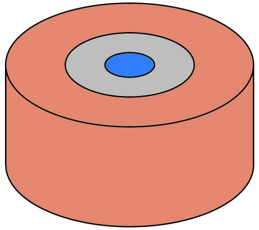
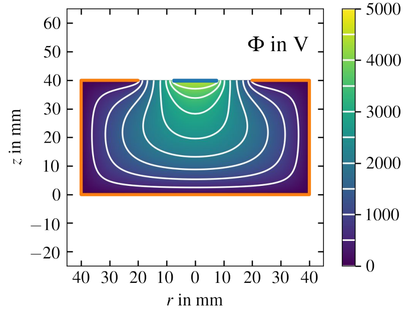
Example Detector Simulation Setup

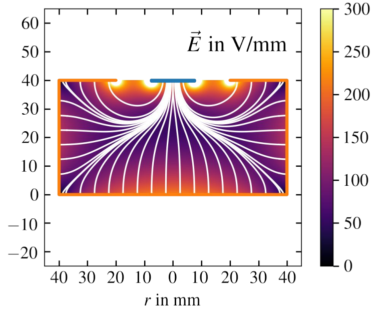


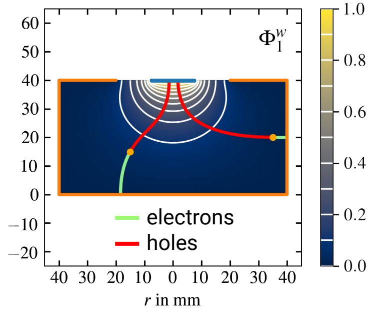
Pulse Shape Simulation Chain

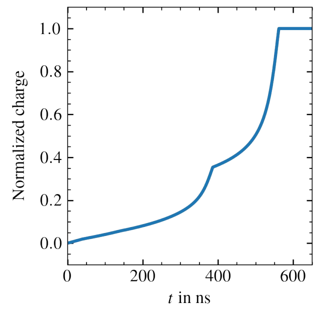




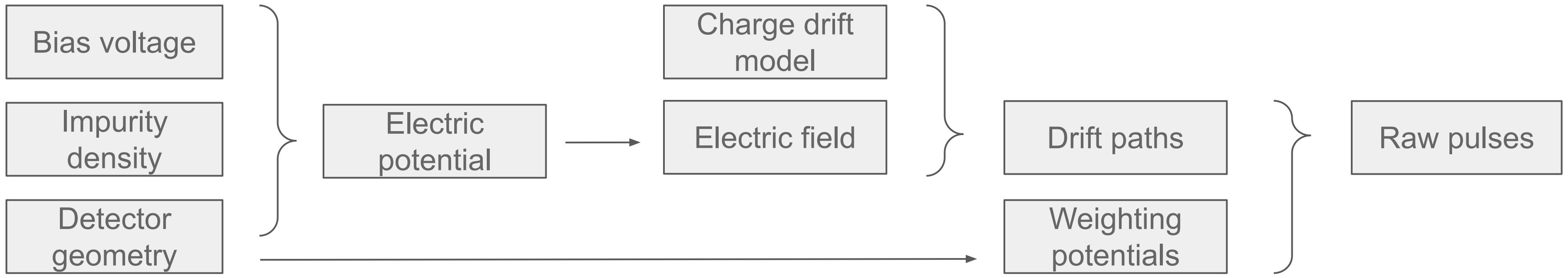


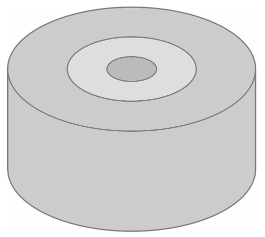


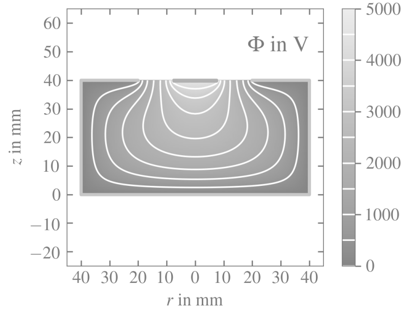


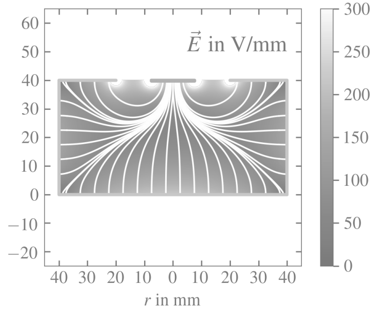


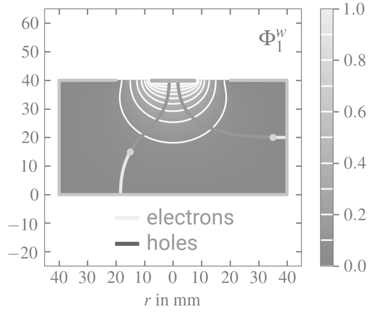
Pulse Shape Simulation Chain

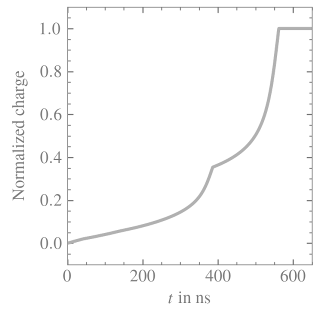












Electric Potential Calculation

1. Maxwell equation:

$$\nabla \cdot (\epsilon_r(\mathbf{r}) \cdot \nabla\Phi(\mathbf{r})) = -\frac{\rho(\mathbf{r})}{\epsilon_0}$$

Electric potential

Required input:

- charge density ,
- dielectric distribution ,
- boundary conditions for

Impurity density

Bias voltage

Detector geometry

SSD solves this numerically

- Successive Over-Relaxation (SOR) algorithm
- Red-Black division of the grid → parallelization (CPU vectorization, GPU support)
- Adaptive grid

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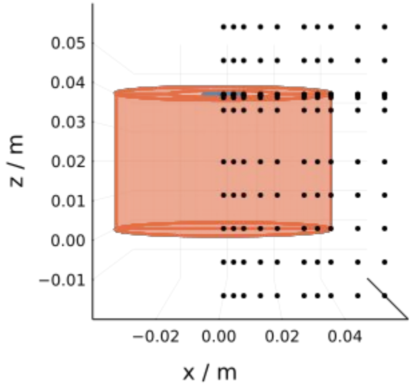
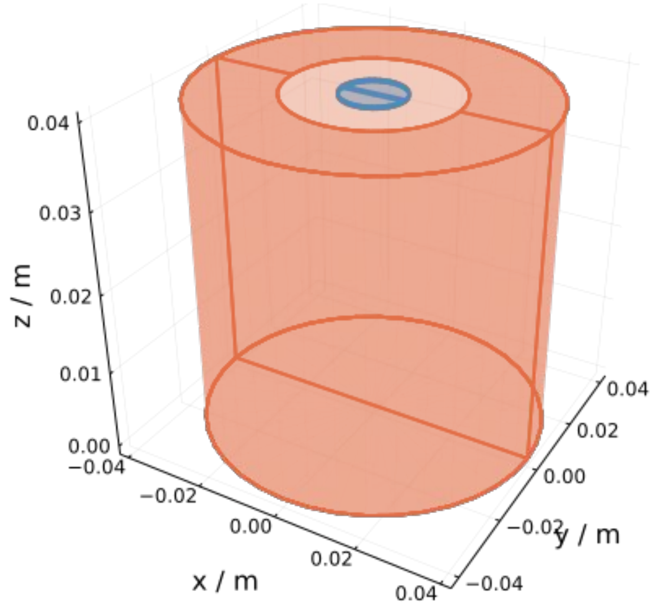
Electric Potential Calculation

Electric potential

Numerical approach: Divide your world (detector + surroundings) into small parts and calculate for each part (grid point) its potential





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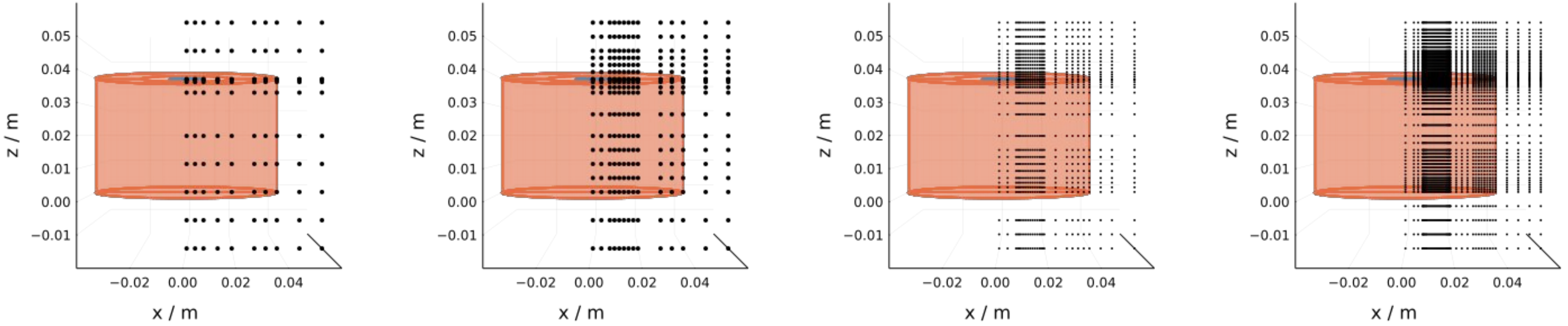
Electric Potential Calculation

Numerical approach: Divide your world (detector + surroundings) into small parts and calculate for each part (grid point) its potential

Adaptive grid: Start with a coarse grid (10 x 10 x 10 points) and become finer (eg. 200 x 200 x 200 points)



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Electric Potential Calculation

How to calculate the potential of a single grid point?

$$\boxed{\nabla \cdot (\epsilon_r(\mathbf{r}) \cdot \nabla\Phi(\mathbf{r})) = -\frac{\rho(\mathbf{r})}{\epsilon_0}}$$

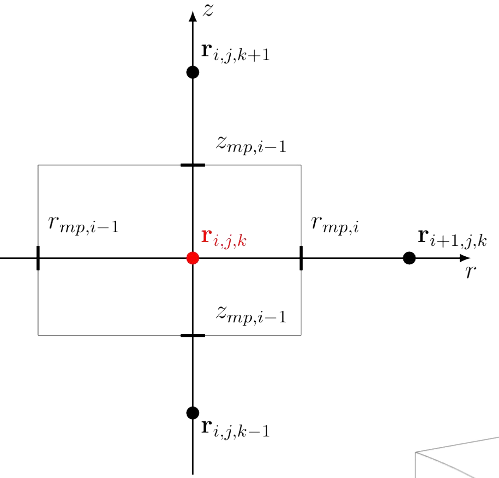
Integral form:

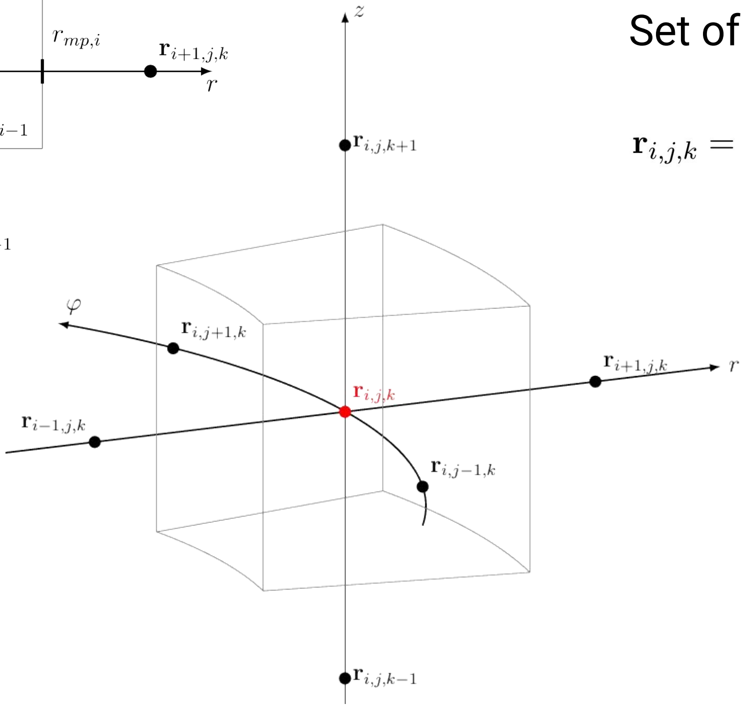
$$\iiint_V \nabla \cdot (\epsilon_r(\mathbf{r}) \cdot \nabla\Phi(\mathbf{r}))\ dV = \iiint_V -\frac{\rho(\mathbf{r})}{\epsilon_0}\ dV$$

Divergence theorem:

$$\oint\!\!\!\oint_S (\epsilon_r(\mathbf{r}) \cdot \nabla\Phi(\mathbf{r})) \cdot d\mathbf{S} = -\iiint_V \frac{\rho(\mathbf{r})}{\epsilon_0}\, dV$$

Electric Potential Calculation





Grid size: = N grid points

Set of grid points:

$$\mathbf{r}_{i,j,k} = \begin{pmatrix} r_i \\ \varphi_j \\ z_k \end{pmatrix} \qquad i \in 1,\ldots,N_r;\; j \in 1,\ldots,N_\varphi;\; k \in 1,\ldots,N_z$$

Mid points :
(points between actual grid points)

$$\begin{aligned} r_{mp,i} &= r_i + 0.5\cdot(r_{i+1} - r_i) \\ \varphi_{mp,j} &= \varphi_j + 0.5\cdot(\varphi_{j+1} - \varphi_j) \\ z_{mp,k} &= z_k + 0.5\cdot(z_{k+1} - z_k) \end{aligned}$$

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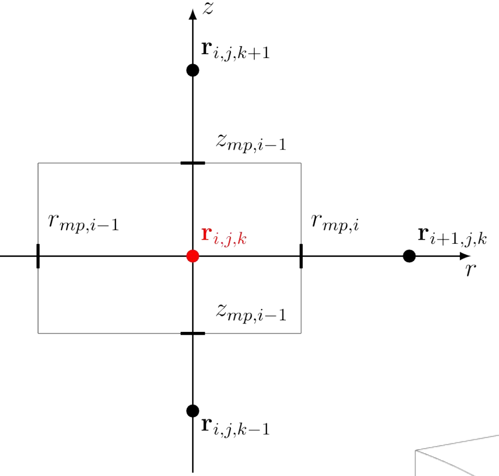
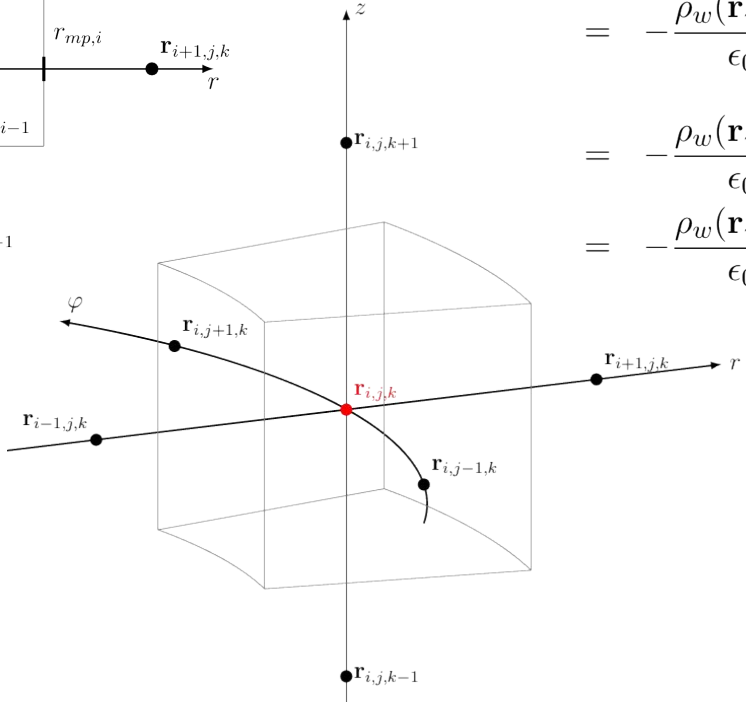
Electric Potential Calculation





$$
\begin{aligned}
-\iiint_V \frac{\rho(\mathbf{r})}{\epsilon_0}\, dV &= -\int_{r_{mp,i-1}}^{r_{mp,i}} \int_{\varphi_{mp,j-1}}^{\varphi_{mp,j}} \int_{z_{mp,k-1}}^{z_{mp,k}} r \cdot \frac{\rho(\mathbf{r})}{\epsilon_0}\, dz\, d\varphi\, dr \\
&= -\frac{\rho_w(\mathbf{r}_{i,j,k})}{\epsilon_0} \int_{r_{mp,i-1}}^{r_{mp,i}} \int_{\varphi_{mp,j-1}}^{\varphi_{mp,j}} \int_{z_{mp,k-1}}^{z_{mp,k}} r\, dz\, d\varphi\, dr \\
&= -\frac{\rho_w(\mathbf{r}_{i,j,k})}{\epsilon_0} \cdot \frac{1}{2}(r_{mp,i}^2 - r_{mp,i-1}^2)(\varphi_{mp,j} - \varphi_{mp,j-1})(z_{mp,k} - z_{mp,k-1}) \\
&= -\frac{\rho_w(\mathbf{r}_{i,j,k})}{\epsilon_0} \cdot V_{i,j,k} = Q_{i,j,k}^{eff}
\end{aligned}
$$

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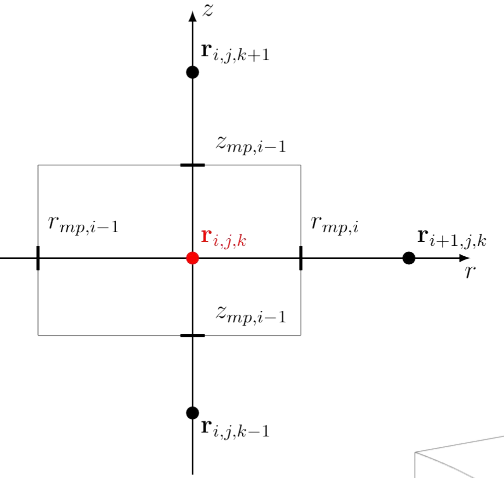
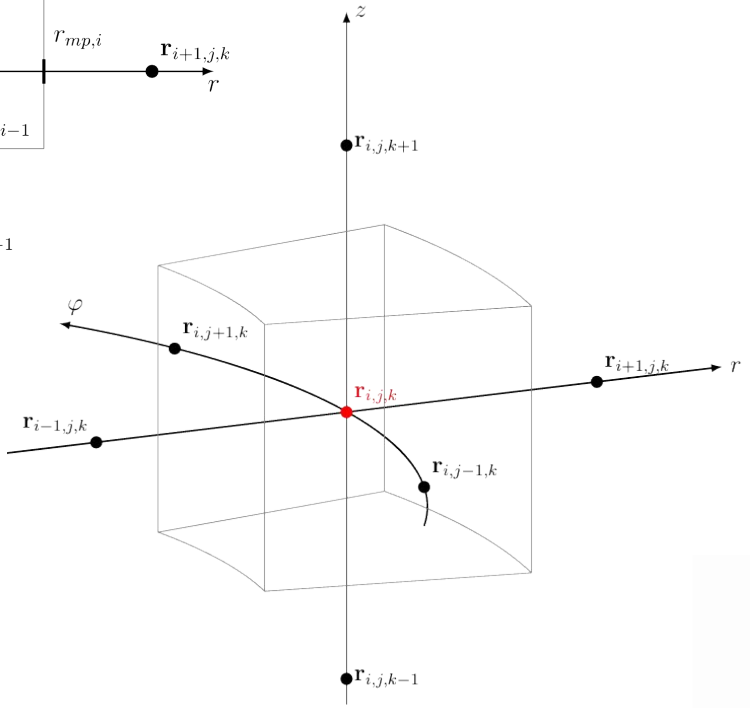
Electric Potential Calculation





$$\oiint_S (\epsilon_r(\mathbf{r})\nabla\Phi(\mathbf{r}))\cdot d\mathbf{S} = \iint_{r^+} + \iint_{r^-} + \iint_{\varphi^+} + \iint_{\varphi^-} + \iint_{z^+} + \iint_{z^-}$$

$$\iint_{r^+} = \int_{z_{mp,k-1}}^{z_{mp,k}} \int_{\varphi_{mp,j-1}}^{\varphi_{mp,j}} -\epsilon_r(\mathbf{r})\left(\nabla\Phi(\mathbf{r})\right) r_{mp,i}\,\mathbf{e}_r\,d\varphi\,dz$$

$$\iint_{r^-} = \int_{z_{mp,k-1}}^{z_{mp,k}} \int_{\varphi_{mp,j-1}}^{\varphi_{mp,j}} +\epsilon_r(\mathbf{r})\left(\nabla\Phi(\mathbf{r})\right) r_{mp,i+1}\,\mathbf{e}_r\,d\varphi\,dz$$

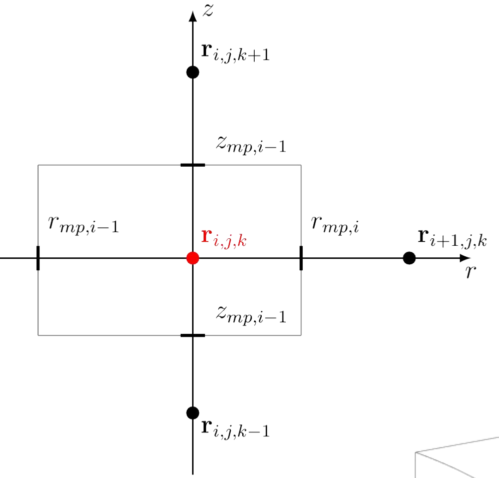
$$\iint_{\varphi^+} = \int_{r_{mp,i-1}}^{r_{mp,i}} \int_{z_{mp,k-1}}^{z_{mp,k}} -\epsilon_r(\mathbf{r})\left(\nabla\Phi(\mathbf{r})\right)\mathbf{e}_\varphi\,dz\,dr$$

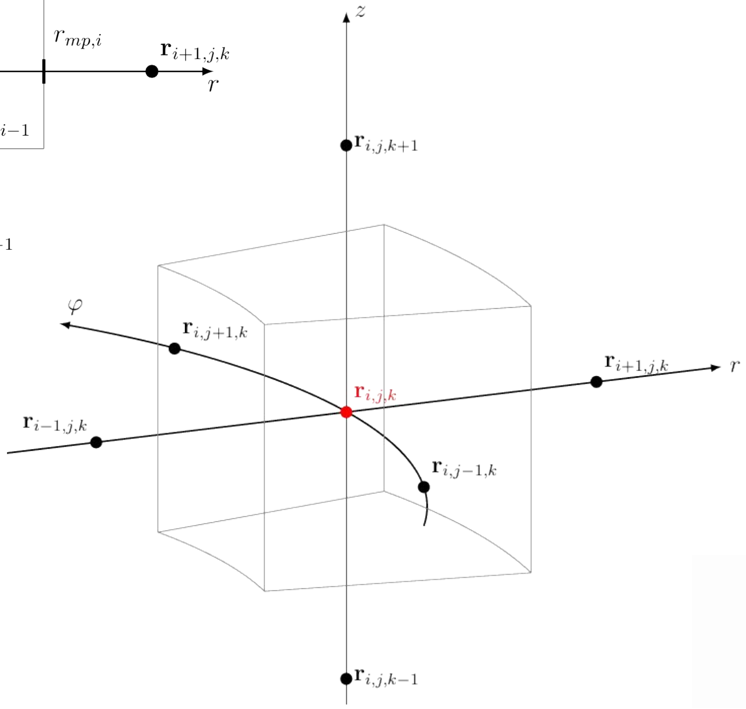
$$\iint_{\varphi^-} = \int_{r_{mp,i-1}}^{r_{mp,i}} \int_{z_{mp,k-1}}^{z_{mp,k}} +\epsilon_r(\mathbf{r})\left(\nabla\Phi(\mathbf{r})\right)\mathbf{e}_\varphi\,dz\,dr$$

$$\iint_{z^+} = \int_{r_{mp,i-1}}^{r_{mp,i}} \int_{\varphi_{mp,j-1}}^{\varphi_{mp,j}} -\epsilon_r(\mathbf{r})\left(\nabla\Phi(\mathbf{r})\right) r\,\mathbf{e}_z\,d\varphi\,dr$$

$$\iint_{z^-} = \int_{r_{mp,i-1}}^{r_{mp,i}} \int_{\varphi_{mp,j-1}}^{\varphi_{mp,j}} +\epsilon_r(\mathbf{r})\left(\nabla\Phi(\mathbf{r})\right) r\,\mathbf{e}_z\,d\varphi\,dr\ .$$

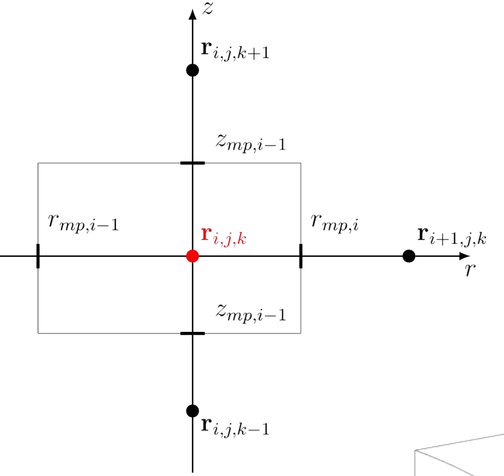
Electric Potential Calculation

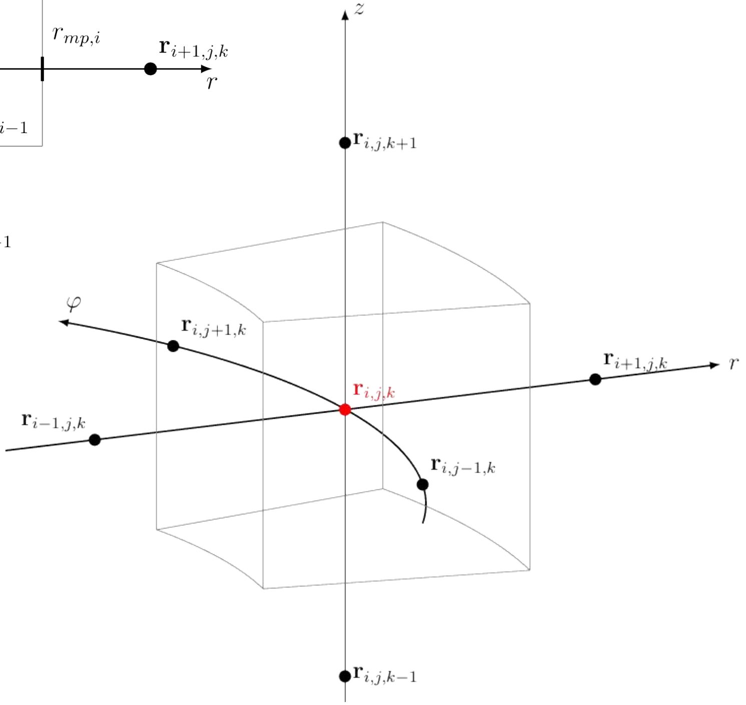




$$
\begin{aligned}
\iint_{\varphi^+} &= \int_{r_{mp,i-1}}^{r_{mp,i}} \int_{z_{mp,k-1}}^{z_{mp,k}} +\epsilon_r(\mathbf{r})\,(\nabla\Phi(\mathbf{r}))\;\mathbf{e}_\varphi\,dz\,dr \\
&= \int_{r_{mp,i-1}}^{r_{mp,i}} \int_{z_{mp,k-1}}^{z_{mp,k}} \epsilon_r(\mathbf{r})\frac{1}{r_i}\frac{\partial}{\partial\varphi}\Phi(\mathbf{r})\,dz\,dr \\
&= \int_{r_{mp,i-1}}^{r_{mp,i}} \int_{z_{mp,k-1}}^{z_{mp,k}} \epsilon_r(\mathbf{r})\frac{\Phi_{i,j+1,k}-\Phi_{i,j,k}}{r_i\cdot(\varphi_{j+1}-\varphi_j)}\,dz\,dr \\
&= \frac{\Phi_{i,j+1,k}-\Phi_{i,j,k}}{r_i\cdot(\varphi_{j+1}-\varphi_j)}\cdot\int_{r_{mp,i-1}}^{r_{mp,i}} \int_{z_{mp,k-1}}^{z_{mp,k}} \epsilon_r(\mathbf{r})\,dz\,dr \\
&= \frac{\Phi_{i,j+1,k}-\Phi_{i,j,k}}{r_i\cdot(\varphi_{j+1}-\varphi_j)}\cdot\epsilon^{w,\varphi^+}_{i,j,k}\cdot\int_{r_{mp,i-1}}^{r_{mp,i}} \int_{z_{mp,k-1}}^{z_{mp,k}} dz\,dr \\
&= \frac{\Phi_{i,j+1,k}-\Phi_{i,j,k}}{r_i\cdot(\varphi_{j+1}-\varphi_j)}\cdot\epsilon^{w,\varphi^+}_{i,j,k}\cdot(r_{mp,i}-r_{mp,i-1})(z_{mp,k}-z_{mp,k-1}) \\
&= \frac{\Phi_{i,j+1,k}-\Phi_{i,j,k}}{r_i\cdot(\varphi_{j+1}-\varphi_j)}\cdot\epsilon^{w,\varphi^+}_{i,j,k}\cdot A^{\varphi^+}_{i,j,k}
\end{aligned}
$$

Electric Potential Calculation





$$
\begin{aligned}
\oiint_S (\epsilon_r(\mathbf{r})\nabla\Phi(\mathbf{r}))\cdot d\mathbf{S} = &+\iint_{r^+} + \iint_{r^-} + \iint_{\varphi^+} + \iint_{\varphi^-} + \iint_{z^+} + \iint_{z^-} \\
= &+ \frac{\Phi_{i+1,j,k}-\Phi_{i,j,k}}{r_{i+1}-r_i}\cdot\epsilon^{w,r^+}_{i,j,k}\cdot A^{r^+}_{i,j,k} \\
&- \frac{\Phi_{i,j,k}-\Phi_{i-1,j,k}}{r_i-r_{i-1}}\cdot\epsilon^{w,r^-}_{i,j,k}\cdot A^{r^-}_{i,j,k} \\
&+ \frac{\Phi_{i,j+1,k}-\Phi_{i,j,k}}{r_i\cdot(\varphi_{j+1}-\varphi_j)}\cdot\epsilon^{w,\varphi^+}_{i,j,k}\cdot A^{\varphi^+}_{i,j,k} \\
&- \frac{\Phi_{i,j,k}-\Phi_{i,j-1,k}}{r_i\cdot(\varphi_j-\varphi_{j-1})}\cdot\epsilon^{w,\varphi^-}_{i,j,k}\cdot A^{\varphi^-}_{i,j,k} \\
&+ \frac{\Phi_{i,j,k+1}-\Phi_{i,j,k}}{z_{k+1}-z_k}\cdot\epsilon^{w,z^+}_{i,j,k}\cdot A^{z^+}_{i,j,k} \\
&- \frac{\Phi_{i,j,k}-\Phi_{i,j,k-1}}{z_k-z_{k-1}}\cdot\epsilon^{w,z^-}_{i,j,k}\cdot A^{z^z}_{i,j,k}
\end{aligned}
$$

Solid State Detectors

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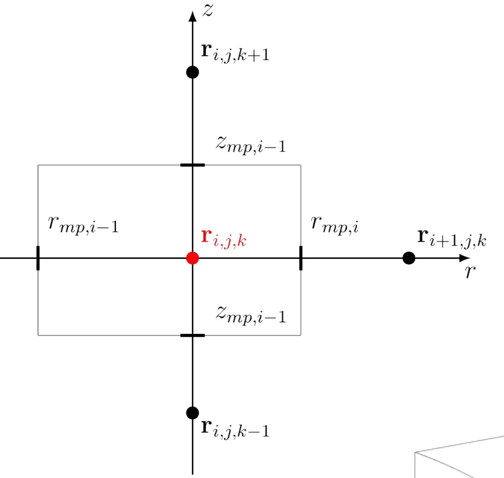
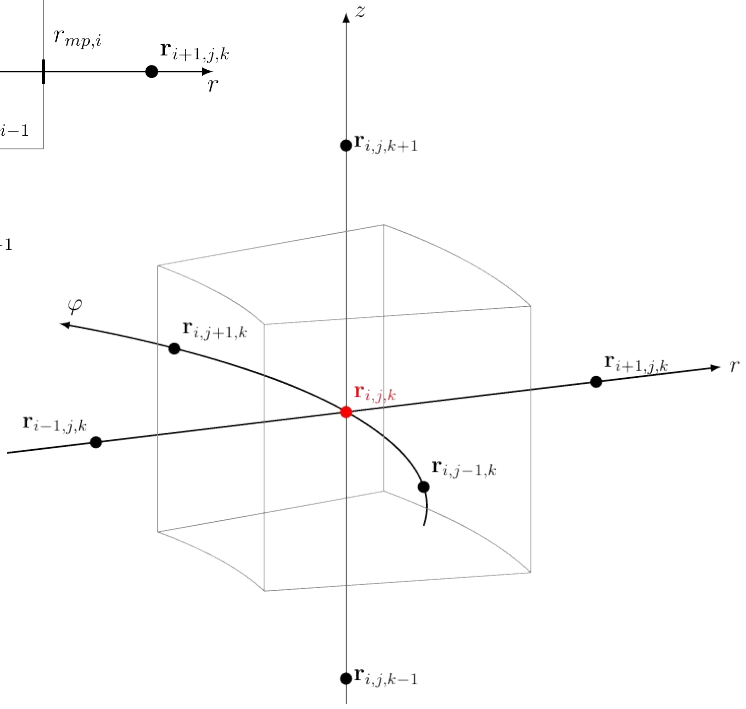
Electric Potential Calculation

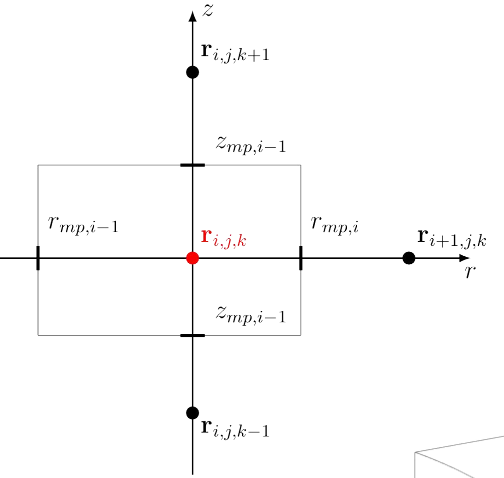
Electric potential

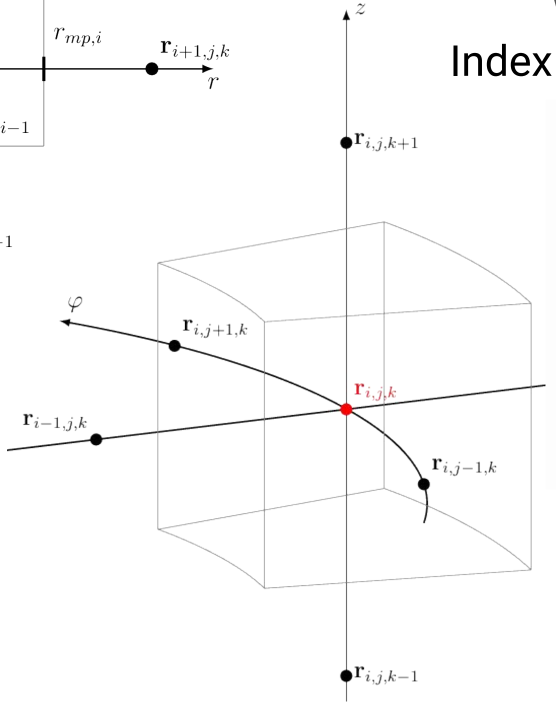




$$
\begin{aligned}
Q^{eff}_{i,j,k} = \; & + \frac{\Phi_{i+1,j,k} - \Phi_{i,j,k}}{r_{i+1} - r_i} \cdot \epsilon^{w,r^+}_{i,j,k} \cdot A^{r^+}_{i,j,k} \\
& - \frac{\Phi_{i,j,k} - \Phi_{i-1,j,k}}{r_i - r_{i-1}} \cdot \epsilon^{w,r^-}_{i,j,k} \cdot A^{r^-}_{i,j,k} \\
& + \frac{\Phi_{i,j+1,k} - \Phi_{i,j,k}}{r_i \cdot (\varphi_{j+1} - \varphi_j)} \cdot \epsilon^{w,\varphi^+}_{i,j,k} \cdot A^{\varphi^+}_{i,j,k} \\
& - \frac{\Phi_{i,j,k} - \Phi_{i,j-1,k}}{r_i \cdot (\varphi_j - \varphi_{j-1})} \cdot \epsilon^{w,\varphi^-}_{i,j,k} \cdot A^{\varphi^-}_{i,j,k} \\
& + \frac{\Phi_{i,j,k+1} - \Phi_{i,j,k}}{z_{k+1} - z_k} \cdot \epsilon^{w,z^+}_{i,j,k} \cdot A^{z^+}_{i,j,k} \\
& - \frac{\Phi_{i,j,k} - \Phi_{i,j,k-1}}{z_k - z_{k-1}} \cdot \epsilon^{w,z^-}_{i,j,k} \cdot A^{z^z}_{i,j,k}
\end{aligned}
$$

Electric Potential Calculation





$$\Phi_{i,j,k} = a^0_{i,j,k}\,\Big[\,Q^{eff}_{i,j,k} + a^{r^+}_{i,j,k}\cdot\Phi_{i+1,j,k} + a^{r^-}_{i,j,k}\cdot\Phi_{i-1,j,k} + a^{\varphi^+}_{i,j,k}\cdot\Phi_{i,j+1,k} + a^{\varphi^-}_{i,j,k}\cdot\Phi_{i,j-1,k} + a^{z^+}_{i,j,k}\cdot\Phi_{i,j,k+1} + a^{z^-}_{i,j,k}\cdot\Phi_{i,j,k-1}\,\Big]$$

Index change

$$\begin{pmatrix}\Phi_1\\ \Phi_2\\ \vdots\\ \Phi_N\end{pmatrix} = \begin{pmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,N}\\ a_{2,1} & \ddots & \ddots & \vdots\\ \vdots & \ddots & \ddots & \vdots\\ a_{N,1} & \cdots & \cdots & a_{N,N}\end{pmatrix}^{N\times N} \cdot \begin{pmatrix}\Phi_1\\ \Phi_2\\ \vdots\\ \Phi_N\end{pmatrix} + \begin{pmatrix} a^0_1\,Q^{eff}_1\\ a^0_2\,Q^{eff}_2\\ \vdots\\ a^0_N\,Q^{eff}_N\end{pmatrix}$$

System of N linear equations

Electric Potential Calculation

System of N linear equations

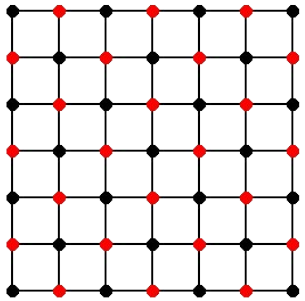
Gauss-Seidel method

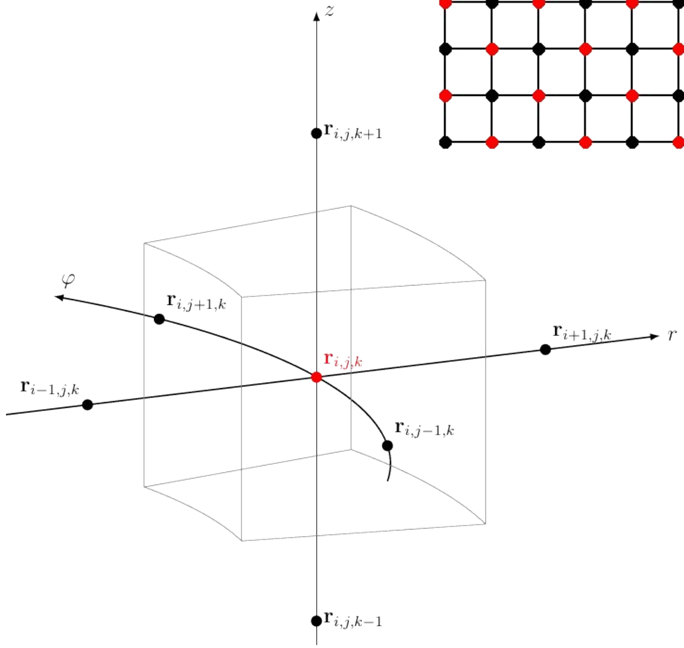
Set initial state: Φ^0

Solve this equation several times, until an equilibrium is reached (until it “converges”, i.e. the potential does not change any more).

The Successive Over-Relaxation (SOR) method is based on the Gauss-Seidel method, but normally converge much faster to its equilibrium.

Red-Black Algorithm





N equations

Red-Black algorithm (Even / Odd)

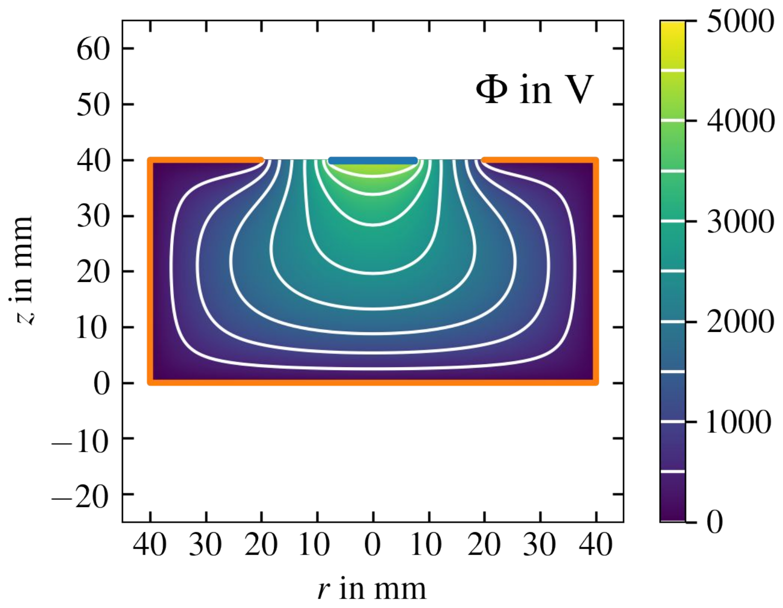
$$\mathbf{\Phi}_R^{k+1} = \mathbf{A}_R \cdot \mathbf{\Phi}_B^k + \mathbf{Q}_R \qquad | \ N/2 \text{ equations}$$

$$\mathbf{\Phi}_B^{k+1} = \mathbf{A}_B \cdot \mathbf{\Phi}_R^k + \mathbf{Q}_B \qquad | \ N/2 \text{ equations}$$

Red (black) points do not depend on values of other red (black) points, so they can be updated simultaneously

Electric Potential Calculation

```
julia > calculate_electric_potential!(sim)
```



Electric Potential Calculation

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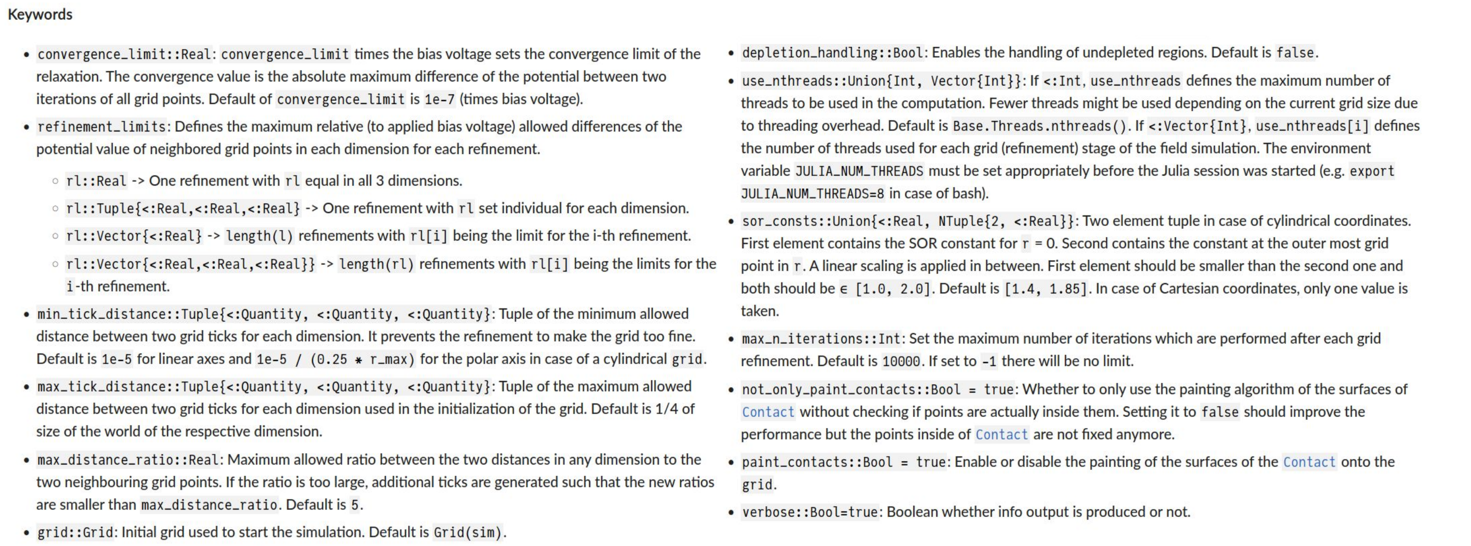


Keywords

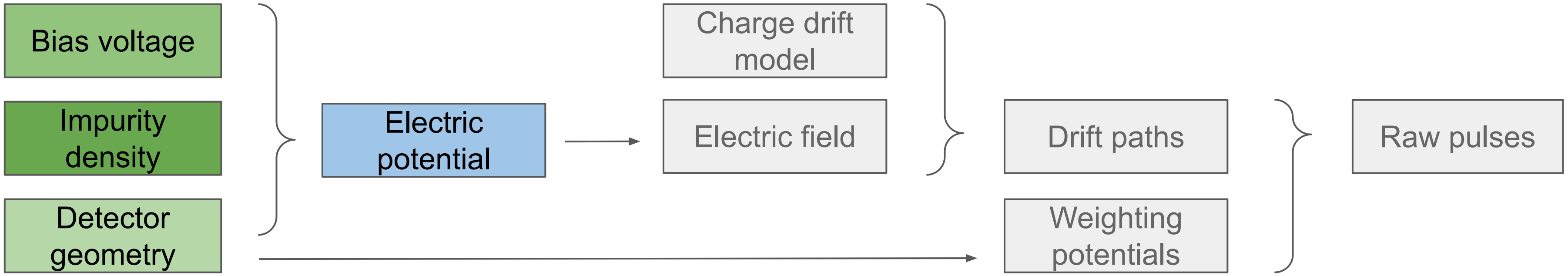
- `convergence_limit::Real`: `convergence_limit` times the bias voltage sets the convergence limit of the relaxation. The convergence value is the absolute maximum difference of the potential between two iterations of all grid points. Default of `convergence_limit` is `1e-7` (times bias voltage).
- `refinement_limits`: Defines the maximum relative (to applied bias voltage) allowed differences of the potential value of neighbored grid points in each dimension for each refinement.
  - `rl::Real` -> One refinement with `rl` equal in all 3 dimensions.
  - `rl::Tuple{<:Real,<:Real,<:Real}` -> One refinement with `rl` set individual for each dimension.
  - `rl::Vector{<:Real}` -> `length(l)` refinements with `rl[i]` being the limit for the i-th refinement.
  - `rl::Vector{<:Real,<:Real,<:Real}}` -> `length(rl)` refinements with `rl[i]` being the limits for the `i`-th refinement.
- `min_tick_distance::Tuple{<:Quantity, <:Quantity, <:Quantity}`: Tuple of the minimum allowed distance between two grid ticks for each dimension. It prevents the refinement to make the grid too fine. Default is `1e-5` for linear axes and `1e-5 / (0.25 * r_max)` for the polar axis in case of a cylindrical `grid`.
- `max_tick_distance::Tuple{<:Quantity, <:Quantity, <:Quantity}`: Tuple of the maximum allowed distance between two grid ticks for each dimension used in the initialization of the grid. Default is 1/4 of size of the world of the respective dimension.
- `max_distance_ratio::Real`: Maximum allowed ratio between the two distances in any dimension to the two neighbouring grid points. If the ratio is too large, additional ticks are generated such that the new ratios are smaller than `max_distance_ratio`. Default is `5`.
- `grid::Grid`: Initial grid used to start the simulation. Default is `Grid(sim)`.
- `depletion_handling::Bool`: Enables the handling of undepleted regions. Default is `false`.
- `use_nthreads::Union{Int, Vector{Int}}`: If `<:Int`, `use_nthreads` defines the maximum number of threads to be used in the computation. Fewer threads might be used depending on the current grid size due to threading overhead. Default is `Base.Threads.nthreads()`. If `<:Vector{Int}`, `use_nthreads[i]` defines the number of threads used for each grid (refinement) stage of the field simulation. The environment variable `JULIA_NUM_THREADS` must be set appropriately before the Julia session was started (e.g. `export JULIA_NUM_THREADS=8` in case of bash).
- `sor_consts::Union{<:Real, NTuple{2, <:Real}}`: Two element tuple in case of cylindrical coordinates. First element contains the SOR constant for `r` = 0. Second contains the constant at the outer most grid point in `r`. A linear scaling is applied in between. First element should be smaller than the second one and both should be `∈ [1.0, 2.0]`. Default is `[1.4, 1.85]`. In case of Cartesian coordinates, only one value is taken.
- `max_n_iterations::Int`: Set the maximum number of iterations which are performed after each grid refinement. Default is `10000`. If set to `-1` there will be no limit.
- `not_only_paint_contacts::Bool = true`: Whether to only use the painting algorithm of the surfaces of `Contact` without checking if points are actually inside them. Setting it to `false` should improve the performance but the points inside of `Contact` are not fixed anymore.
- `paint_contacts::Bool = true`: Enable or disable the painting of the surfaces of the `Contact` onto the `grid`.
- `verbose::Bool=true`: Boolean whether info output is produced or not.

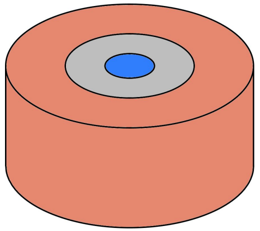
Documentation on GitHub
https://juliaphysics.github.io/SolidStateDetectors.jl/stable/

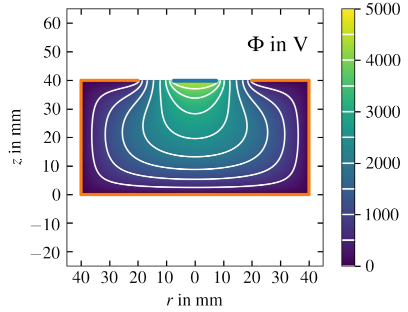
Solid State Detectors

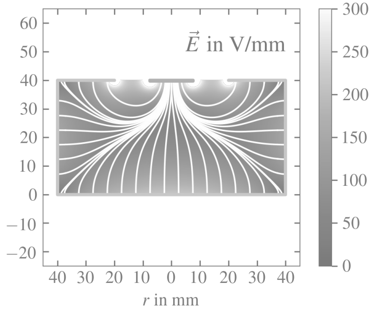
MAX-PLANCK-INSTITUT FÜR PHYSIK

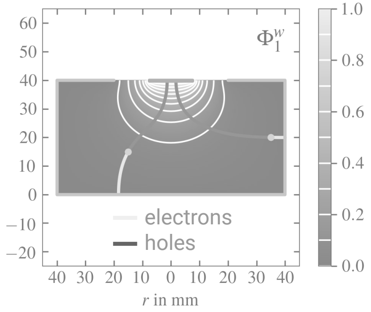
Pulse Shape Simulation Chain

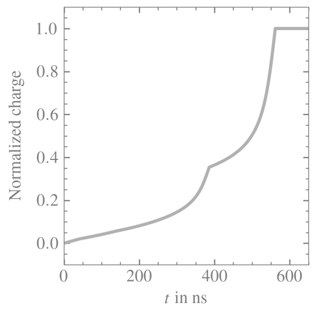












Electric Field Calculation

Electric potential

$$\Phi_{i,j,k}$$

$$\downarrow$$

$$\mathbf{E}_{i,j,k} = \left(E_r^{i,j,k}, E_\varphi^{i,j,k}, E_z^{i,j,k}\right)$$

$$\downarrow$$

Electric field

Mean of finite difference:

$$E_r^{i,j,k} = -\frac{1}{2}\left(\frac{\Phi_{i+1,j,k} - \Phi_{i,j,k}}{r_{i+1} - r_i} + \frac{\Phi_{i,j,k} - \Phi_{i-1,j,k}}{r_i - r_{i-1}}\right)$$

$$E_\varphi^{i,j,k} = -\frac{1}{2}\left(\frac{\Phi_{i,j+1,k} - \Phi_{i,j,k}}{\varphi_{j+1} - \varphi_j} + \frac{\Phi_{i,j,k} - \Phi_{i,j-1,k}}{\varphi_j - \varphi_{j-1}}\right)$$

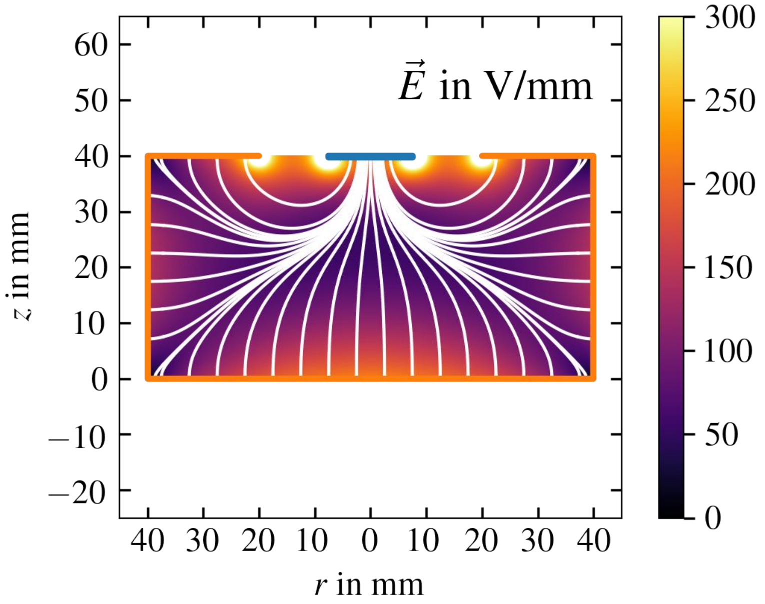
$$E_z^{i,j,k} = -\frac{1}{2}\left(\frac{\Phi_{i,j,k+1} - \Phi_{i,j,k}}{z_{k+1} - z_k} + \frac{\Phi_{i,j,k} - \Phi_{i,j,k-1}}{z_k - z_{k-1}}\right)$$

Electric field at any point **r** (through linear interpolation)

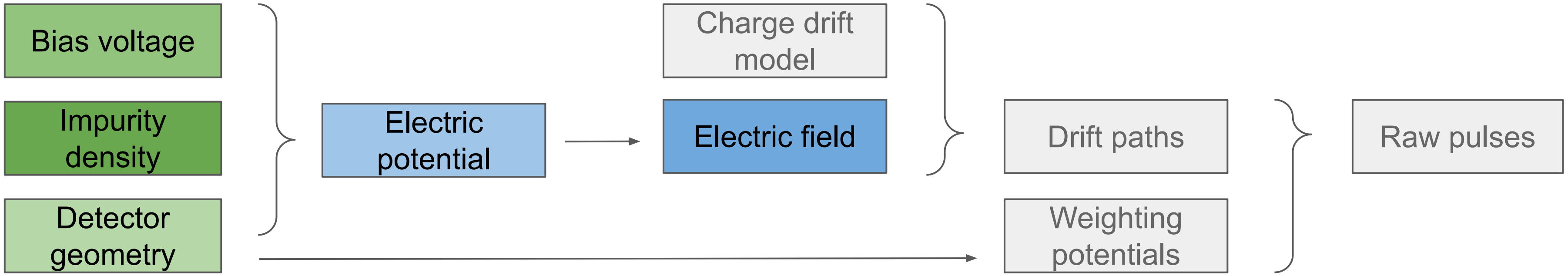
Solid State Detectors MAX-PLANCK-INSTITUT FÜR PHYSIK

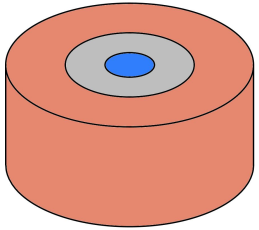
Electric Field Calculation

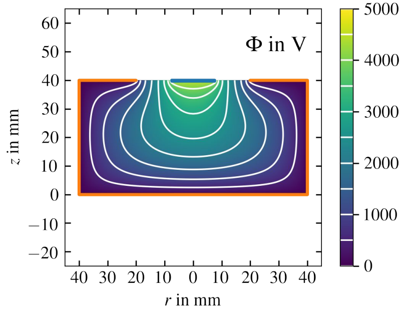
```
julia > calculate_electric_field!(sim)
```

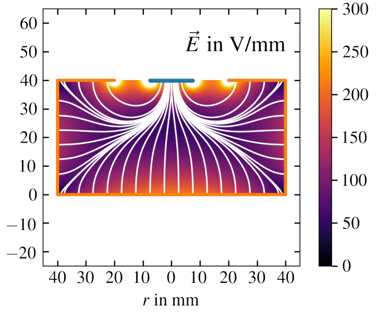


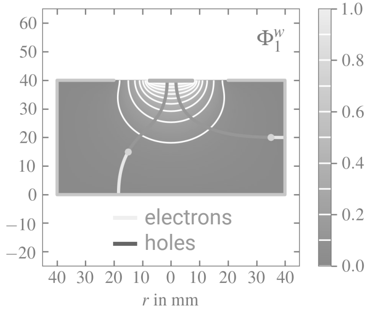
Pulse Shape Simulation Chain

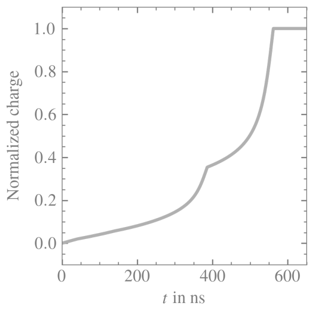




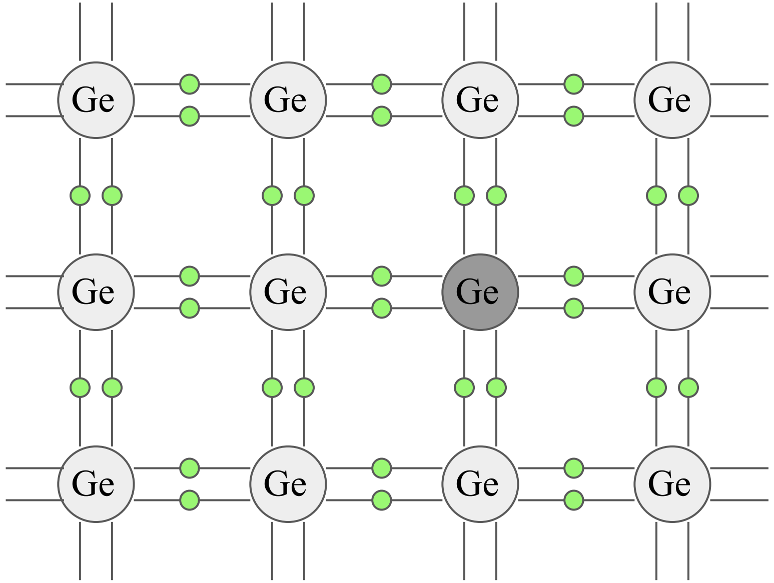




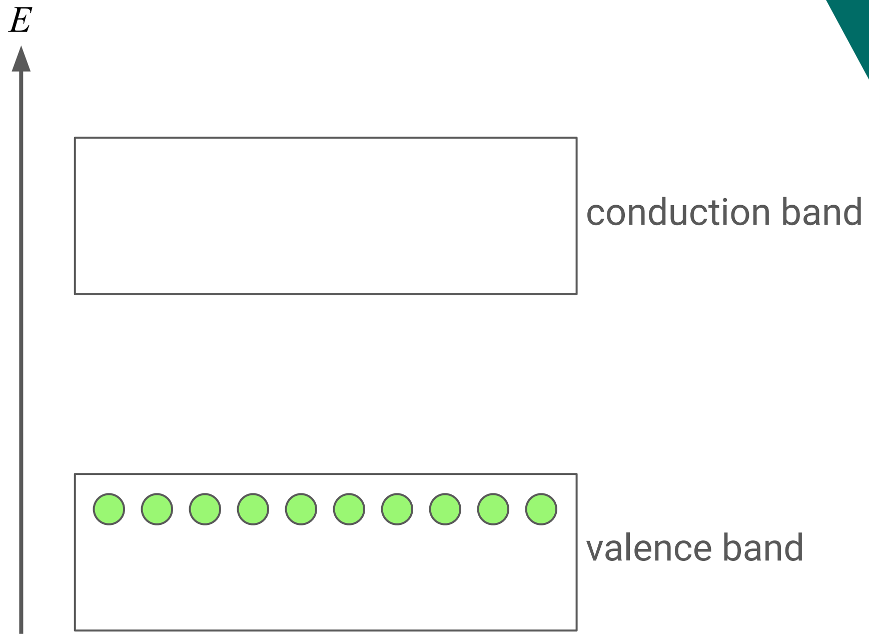




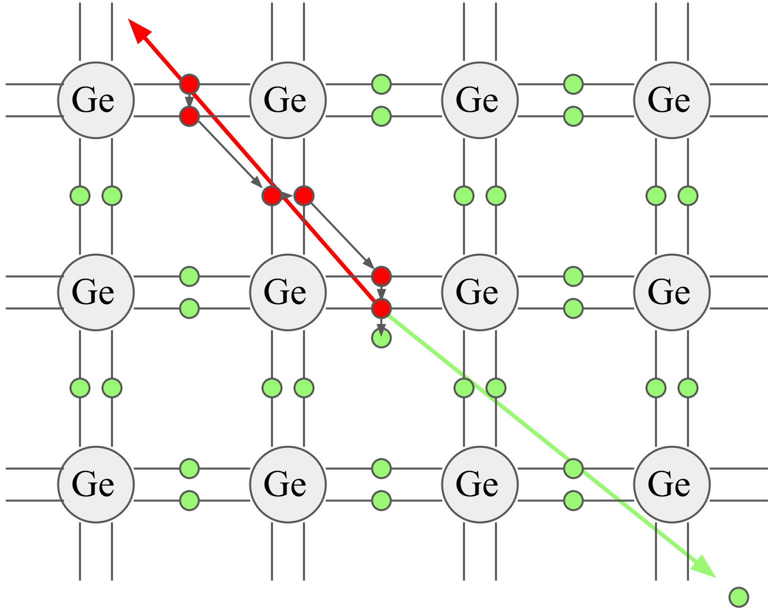
Charge Drift Models



● electrons

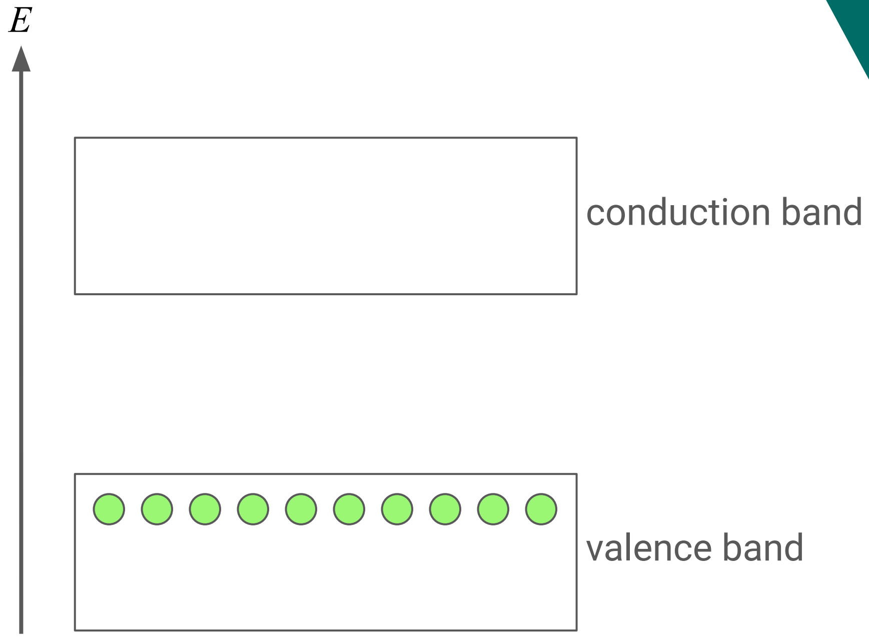


Charge Drift Models

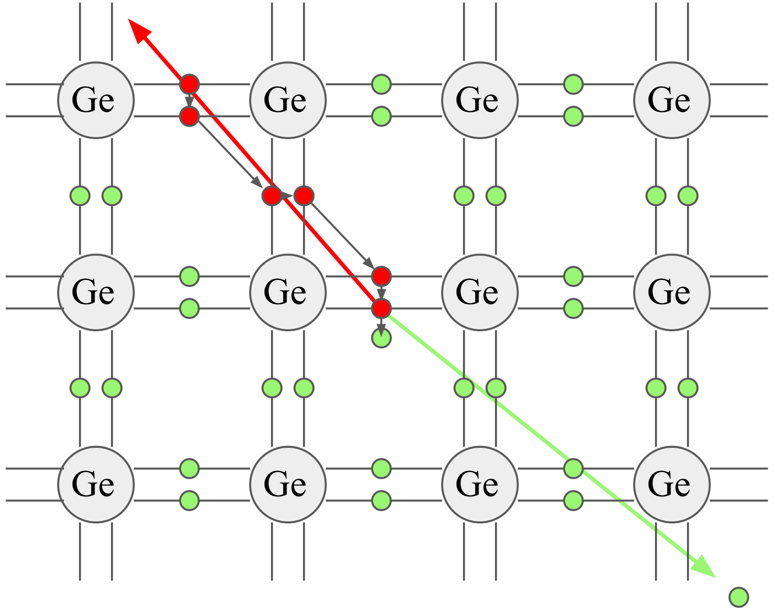


● electrons

● holes

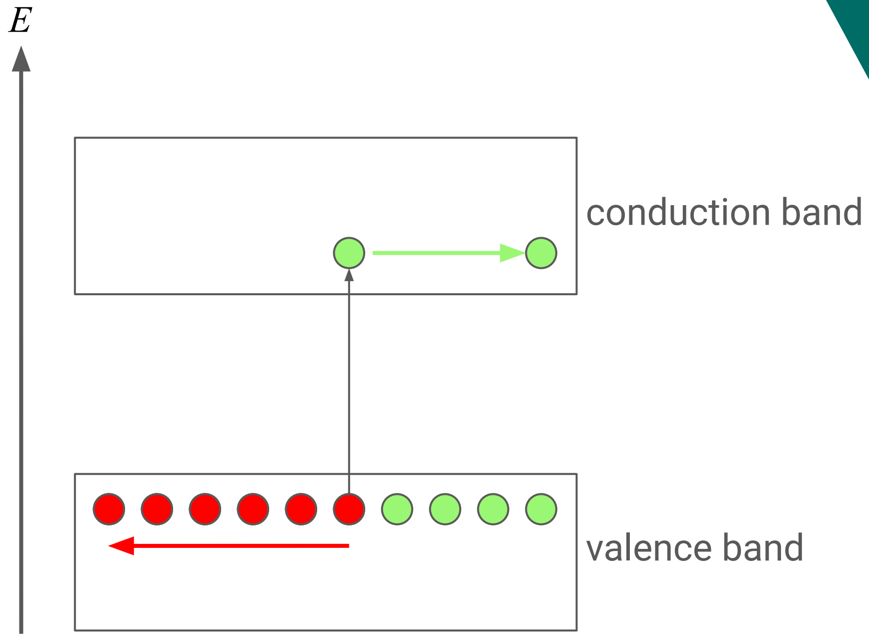


Charge Drift Models



🟢 electrons

🔴 holes



one electron-hole pair per 2.96eV

Solid State Detectors MAX-PLANCK-INSTITUT FÜR PHYSIK

Charge Drift Models

Charge carriers in germanium move in the presence of an electric field

Drift velocity of electrons and holes:

is the mobility tensor:

- saturates for high electric field strengths
- anisotropic in germanium
- temperature dependent

There are models for :

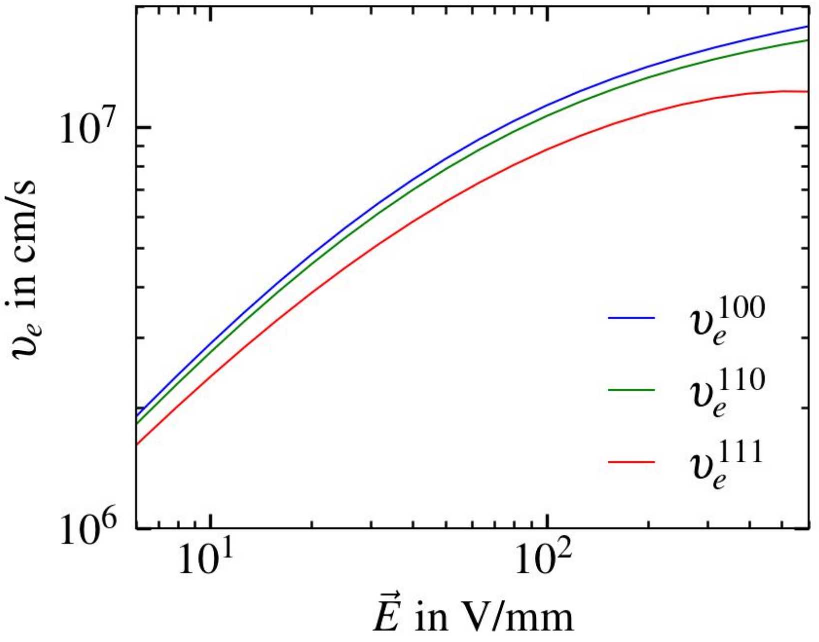
L. Mihailescu *et al.*, Nucl. Instr. and Meth. A **447** (2000) 350, doi: [10.1016/S0168-9002(99)01286-3](https://doi.org/10.1016/S0168-9002(99)01286-3)
B. Bruyneel *et al.*, Nucl. Instr. and Meth. A **569** (2006) 764, doi: [10.1016/j.nima.2006.08.130](https://doi.org/10.1016/j.nima.2006.08.130)

but usually parameters of the models have to be fitted to each individual detector

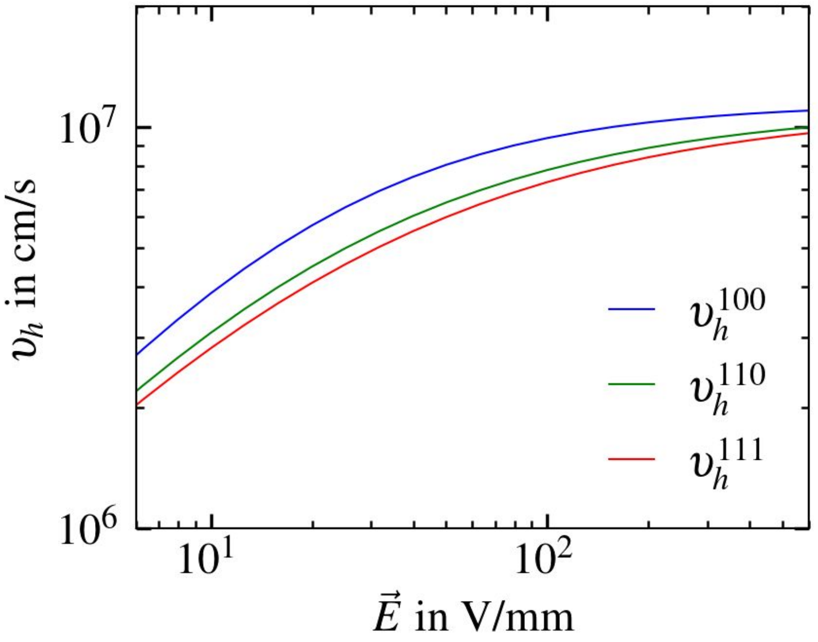
Charge drift model

Charge Drift Models

Electron drift in germanium



Hole drift in germanium

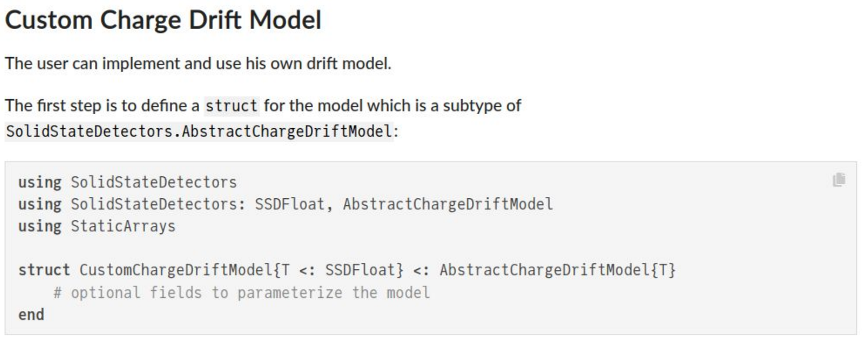


SSD offers a predefined model
doi: 10.1016/j.nima.2006.08.130

Charge Drift Models

Charge drift model

```
julia > cdm = ADLChargeDriftModel( )
julia > sim.detector = SolidStateDetector(sim.detector, cdm)
```



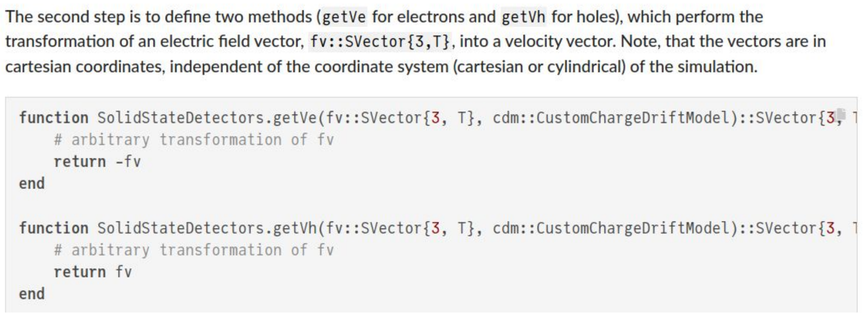
Custom Charge Drift Model

The user can implement and use his own drift model.

The first step is to define a `struct` for the model which is a subtype of `SolidStateDetectors.AbstractChargeDriftModel`:

```
using SolidStateDetectors
using SolidStateDetectors: SSDFloat, AbstractChargeDriftModel
using StaticArrays

struct CustomChargeDriftModel{T <: SSDFloat} <: AbstractChargeDriftModel{T}
    # optional fields to parameterize the model
end
```



The second step is to define two methods (`getVe` for electrons and `getVh` for holes), which perform the transformation of an electric field vector, `fv::SVector{3,T}`, into a velocity vector. Note, that the vectors are in cartesian coordinates, independent of the coordinate system (cartesian or cylindrical) of the simulation.

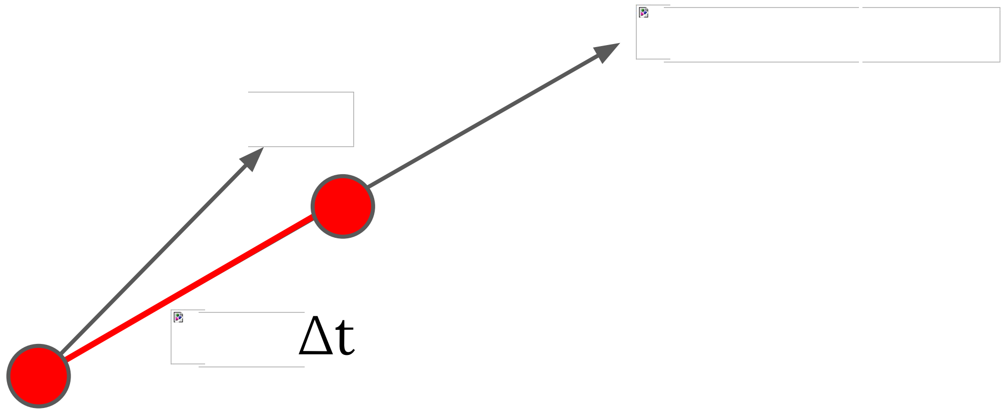
```
function SolidStateDetectors.getVe(fv::SVector{3, T}, cdm::CustomChargeDriftModel)::SVector{3, T
    # arbitrary transformation of fv
    return -fv
end

function SolidStateDetectors.getVh(fv::SVector{3, T}, cdm::CustomChargeDriftModel)::SVector{3, T
    # arbitrary transformation of fv
    return fv
end
```

Documentation on GitHub
https://juliaphysics.github.io/SolidStateDetectors.jl/stable/

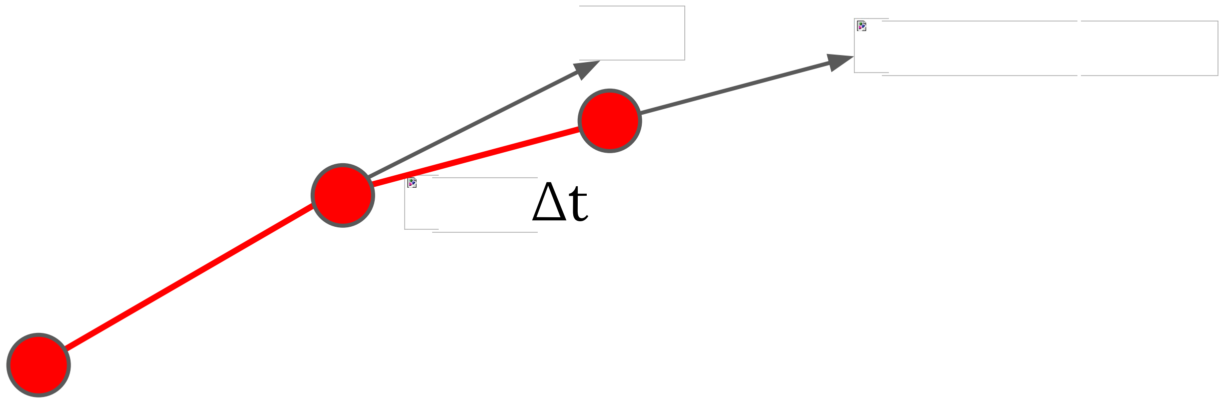
Charge Drift Simulation

Drift velocity for electrons and holes:



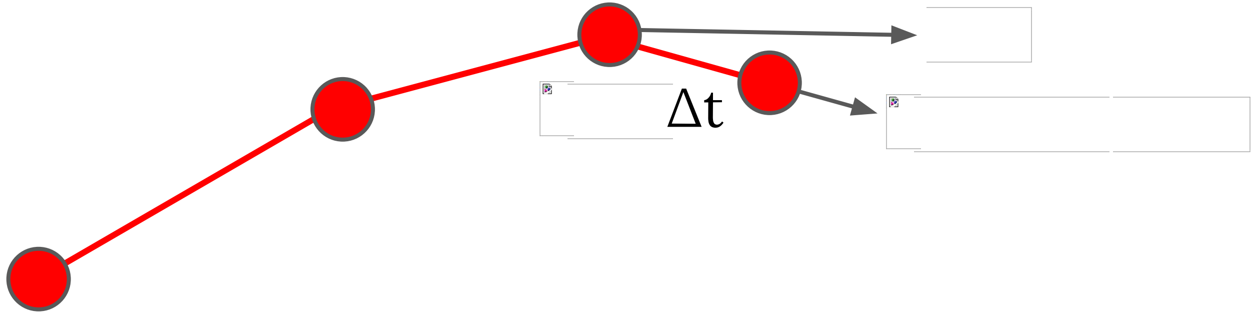
Charge Drift Simulation

Drift velocity for electrons and holes:



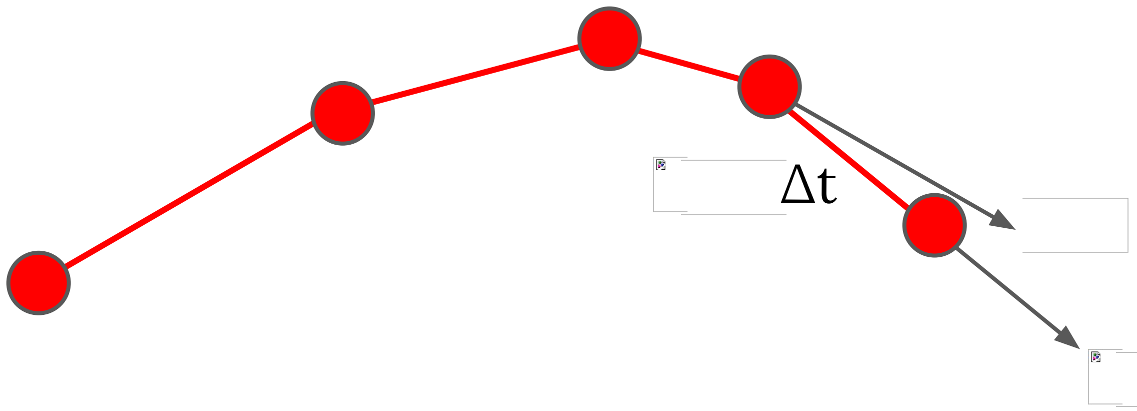
Charge Drift Simulation

Drift velocity for electrons and holes:



Charge Drift Simulation

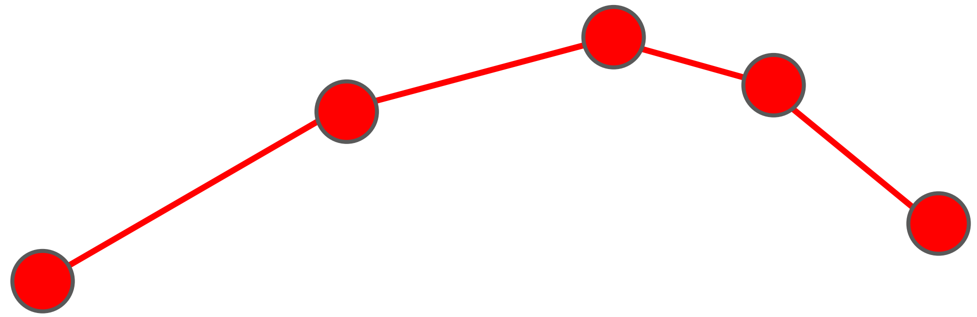
Drift velocity for electrons and holes:



Charge Drift Simulation

Drift paths

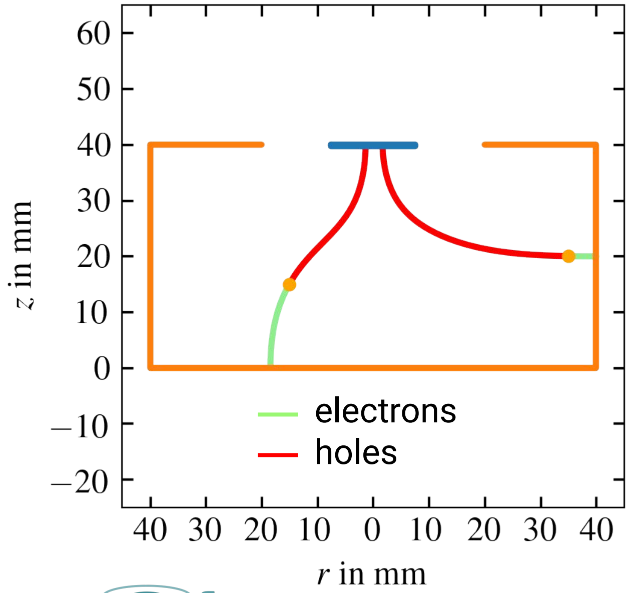
Drift velocity for electrons and holes:



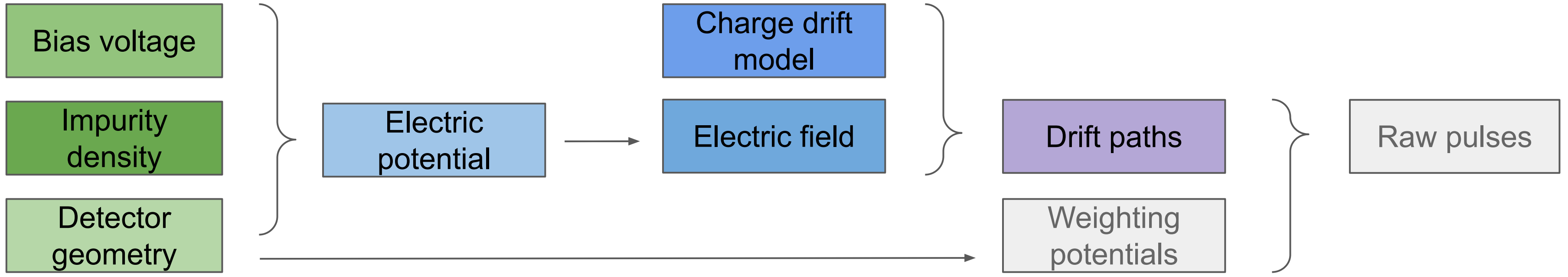
Charge Drift Simulation

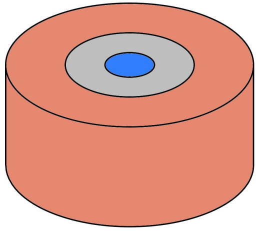
Drift paths

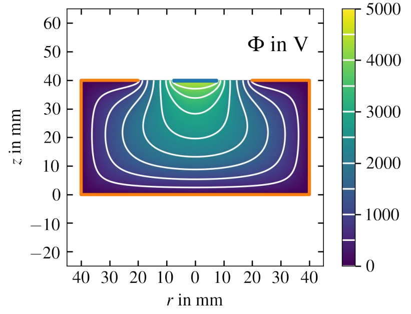
```
julia > locations = [CartesianPoint(0.035,0,0.02), CartesianPoint(-0.015,0,0.015)]
julia > energies = [1000u"keV", 300u"keV"]
julia > evt = Event(locations, energies)
julia > drift_charges!(evt, sim)
```

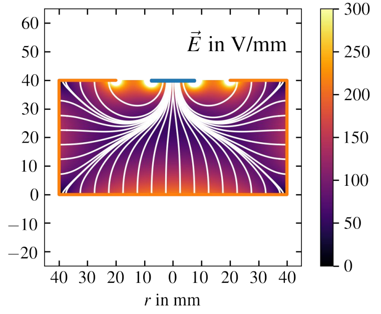


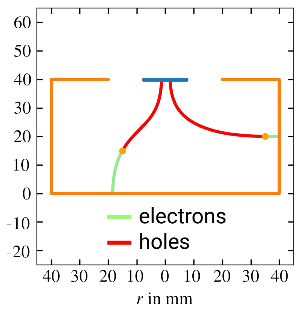
Pulse Shape Simulation Chain

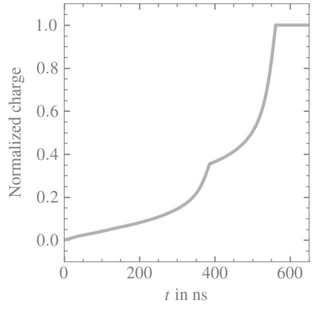












Weighting Potential Calculation

is the so-called weighting potential for electrode i.

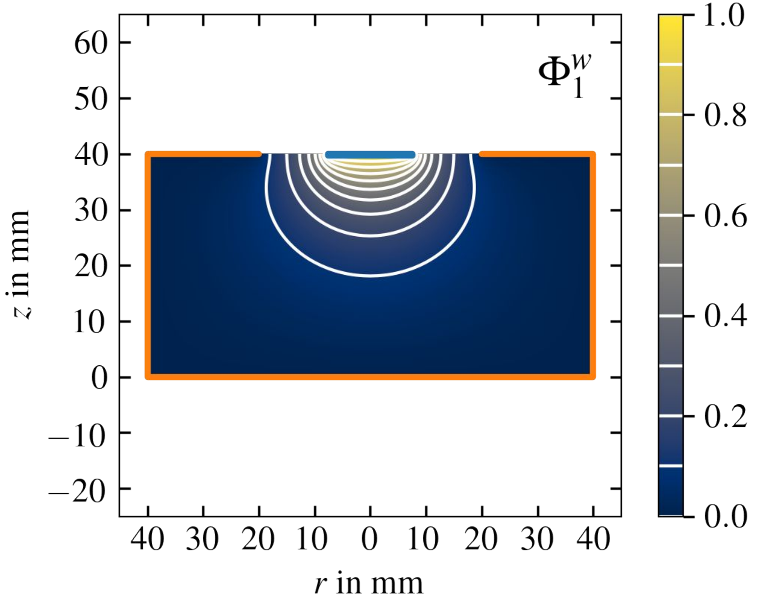
It describes how much charge is induced on the electrode depending of the position **r** of the charge carrier in the crystal.

Same algorithm as for the electric potential but:

- Charge density is set to 0
- The potential values at all contacts are set to 0, but only the potential value of contact i is set to 1.

Weighting Potential Calculation

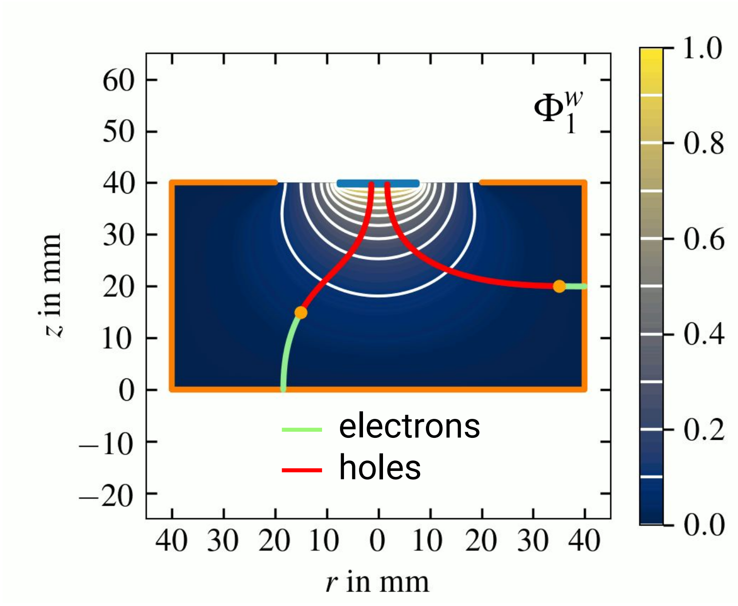
```
julia > calculate_weighting_potential!(sim, 1)
```

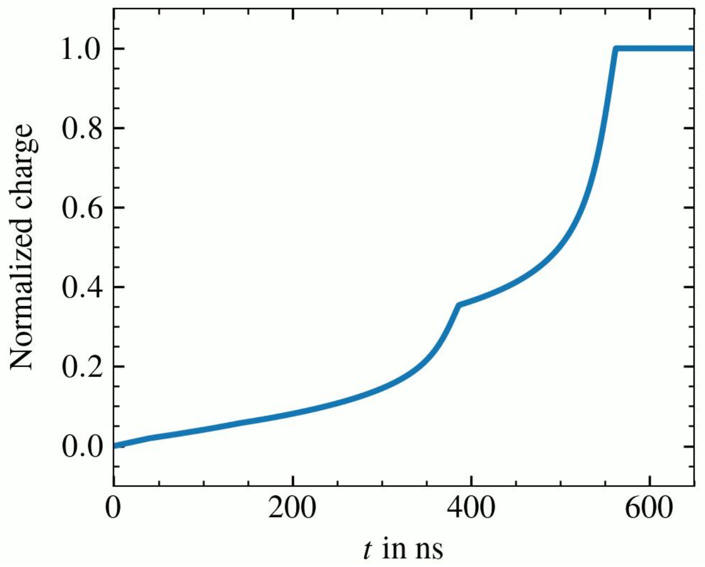


Signal Generation

Raw pulses

Shockley-Ramo Theorem $$Q_i^{ind}(\mathbf{r}_e(t), \mathbf{r}_h(t)) = q \cdot [\Phi_i^w(\mathbf{r}_e(t)) - \Phi_i^w(\mathbf{r}_h(t))]$$

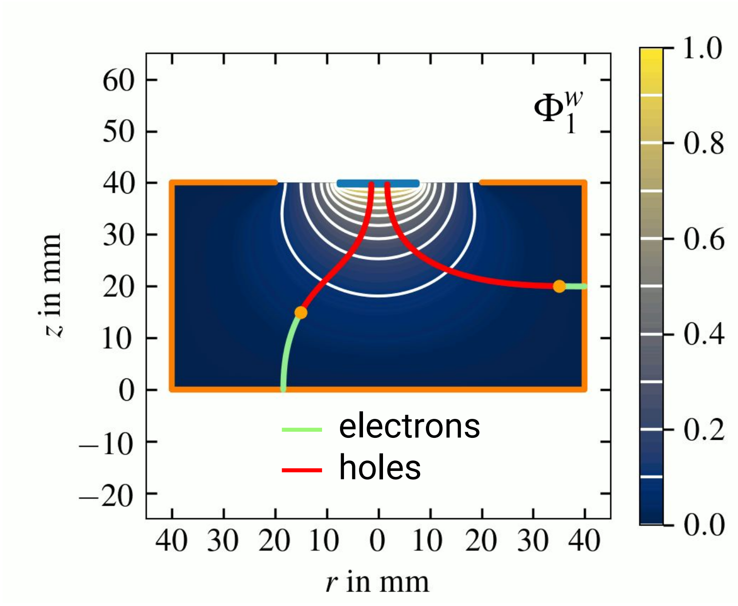


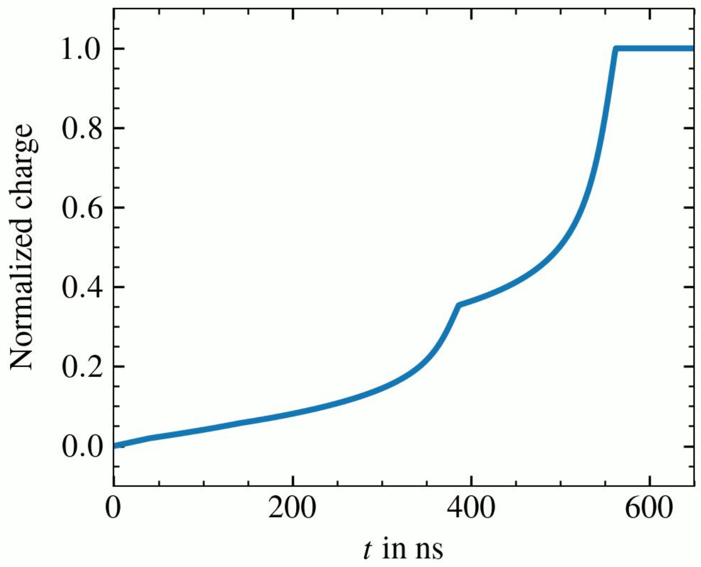


Signal Generation

Raw pulses

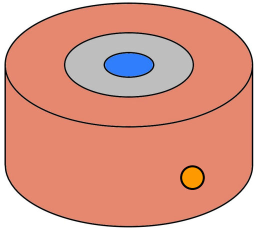
```
julia > simulate!(evt, sim)
```

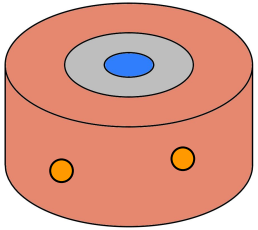


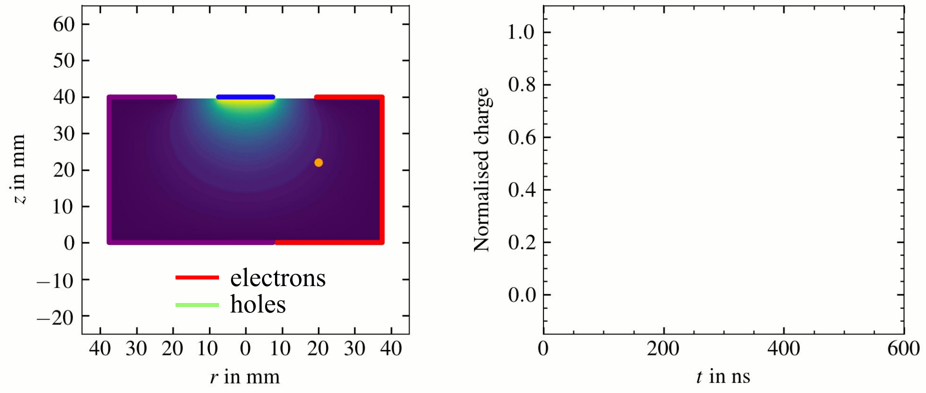


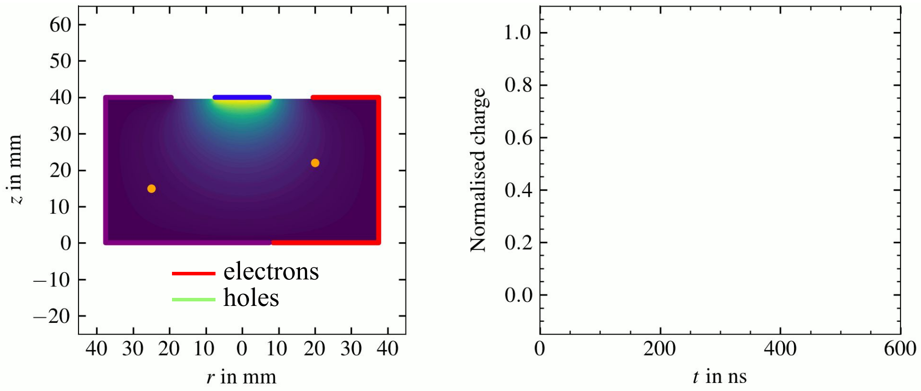
Solid State Detectors MAX-PLANCK-INSTITUT FÜR PHYSIK

Single-site events / multi-site events

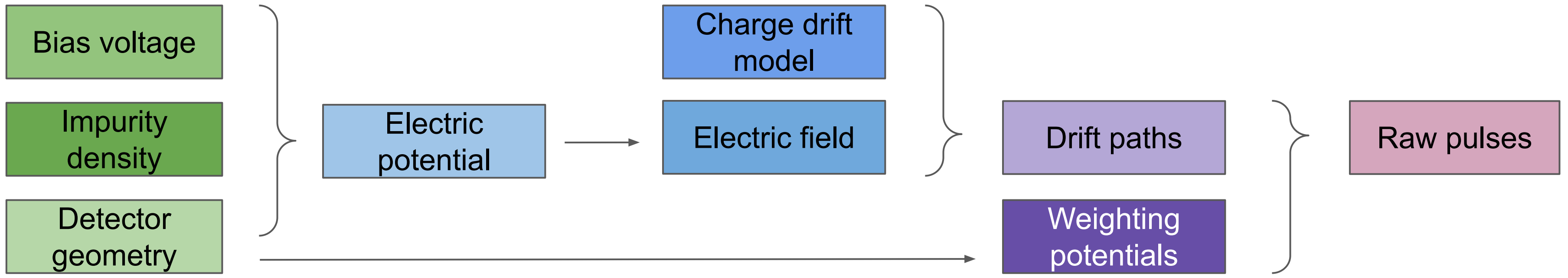


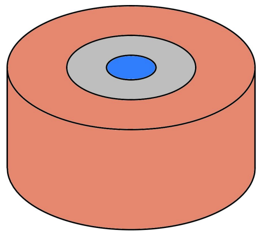


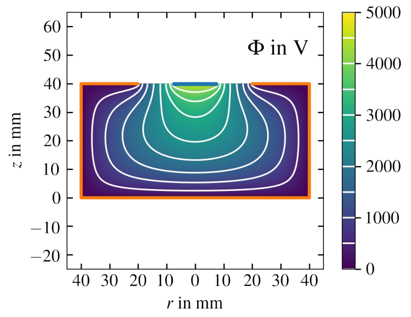


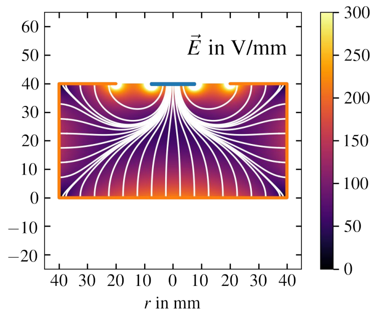


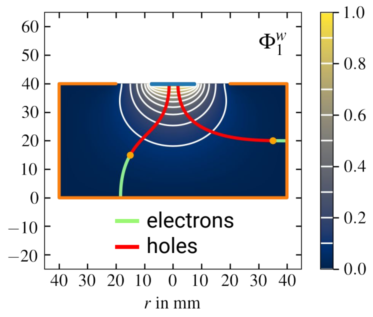
Pulse Shape Simulation Chain

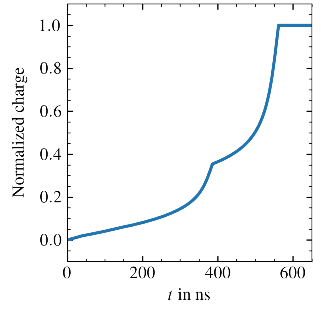








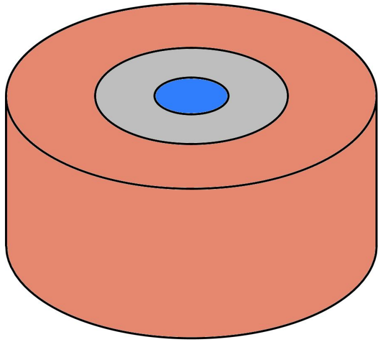




Code examples

Describing the Geometry in a Configuration File

Detector geometry



```
detectors:
- semiconductor:
    material: HPGe
    impurity_density:
      name: constant
      value: -1e10cm^-3
    charge_drift_model:
      include: ADLChargeDriftModel/drift_velocity_config.yaml
    geometry:
      translate:
        tube:
          r: 40
          h: 40
        z: 20
  contacts:
  - name: Core
    material: HPGe
    id: 1
    potential: -4500
    geometry:
      tube:
        r: 7.5
        h: 0.3
        origin:
          z: 39.85
```

```
name: Mantle
material: HPGe
id: 2
potential: 0
geometry:
  union:
  - tube:
      r:
        from: 0
        to: 40
      h: 0
  - tube:
      r:
        from: 40
        to: 40
      h: 40
      origin:
        z: 20
  - tube:
      r:
        from: 20
        to: 40
      h: 0
      origin:
        z: 40
```

Configuration File

Impurity density

Charge drift model

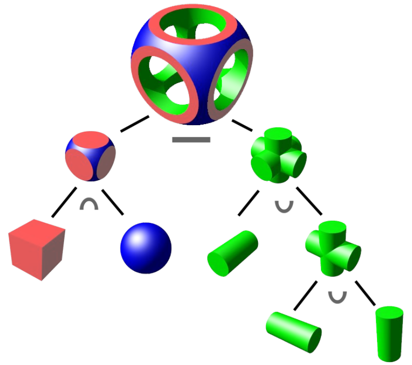
```
name: Point-contact detector
units:
  length: mm
  angle: deg
  potential: V
  temperature: K
grid:
  coordinates: cylindrical
  axes:
    r:
      to: 60
      boundaries: inf
    phi:
      from: 0
      to: 0
      boundaries:
        left: periodic
        right: periodic
    z:
      from: -20
      to: 60
      boundaries:
        left: inf
        right: inf
medium: vacuum
```

```
detectors:
- semiconductor:
    material: HPGe
    impurity_density:
      name: constant
      value: -1e10cm^-3
    charge_drift_model:
      include: ADLChargeDriftModel/drift_velocity_config.yaml
    geometry:
      translate:
        tube:
          r: 40
          h: 40
        z: 20
  contacts:
  - name: Core
    material: HPGe
    id: 1
    potential: -4500
    geometry:
      tube:
        r: 7.5
        h: 0.3
        origin:
          z: 39.85
```

Bias voltage

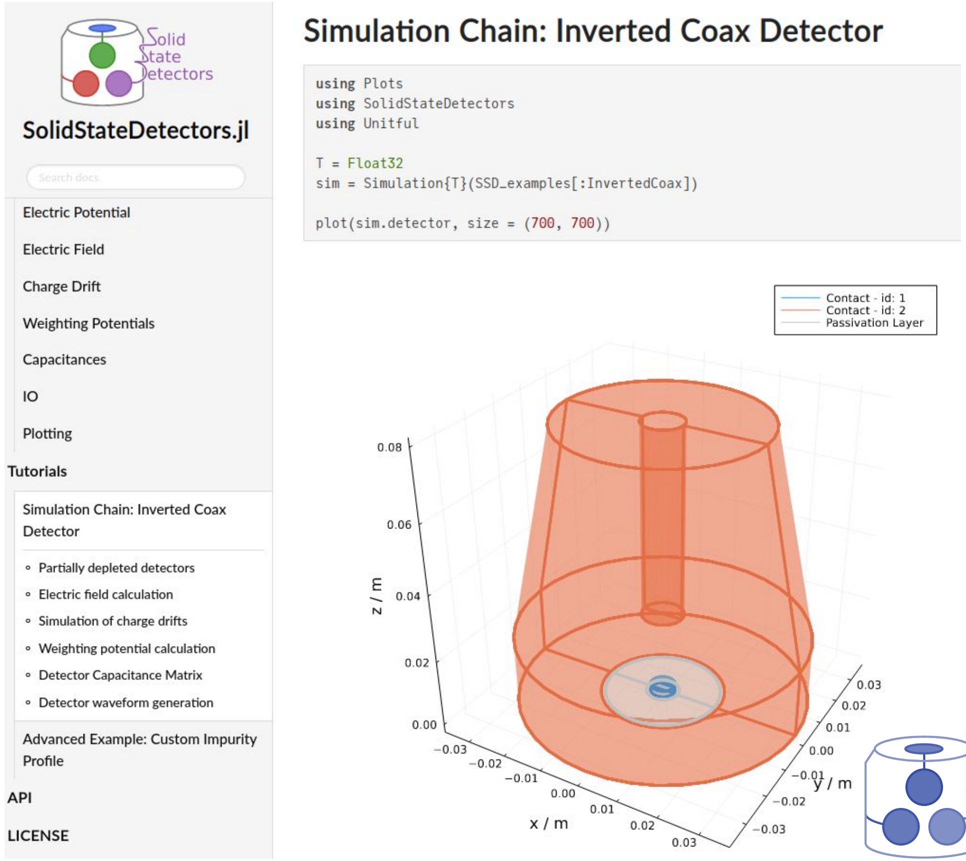
Detector geometry

```
- name: Mantle
  material: HPGe
  id: 2
  potential: 0
  geometry:
    union:
    - tube:
        r:
          from: 0
          to: 40
        h: 0
    - tube:
        r:
          from: 40
          to: 40
        h: 40
        origin:
          z: 20
    - tube:
        r:
          from: 20
          to: 40
        h: 0
        origin:
          z: 40
```



Constructive Solid Geometry
Documentation on GitHub

Documentation on GitHub



SolidStateDetectors.jl

Search docs

- Electric Potential
- Electric Field
- Charge Drift
- Weighting Potentials
- Capacitances
- IO
- Plotting

Tutorials

- Simulation Chain: Inverted Coax Detector
  - Partially depleted detectors
  - Electric field calculation
  - Simulation of charge drifts
  - Weighting potential calculation
  - Detector Capacitance Matrix
  - Detector waveform generation
- Advanced Example: Custom Impurity Profile

API

LICENSE

Simulation Chain: Inverted Coax Detector

```
using Plots
using SolidStateDetectors
using Unitful

T = Float32
sim = Simulation{T}(SSD_examples[:InvertedCoax])

plot(sim.detector, size = (700, 700))
```

Find the latest version of the documentation on GitHub: https://juliaphysics.github.io/SolidStateDetectors.jl/stable/

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Pulse Shape Simulation Chain

```
julia > using SolidStateDetectors, Unitful
```

Pulse Shape Simulation Chain

```
julia > using SolidStateDetectors, Unitful

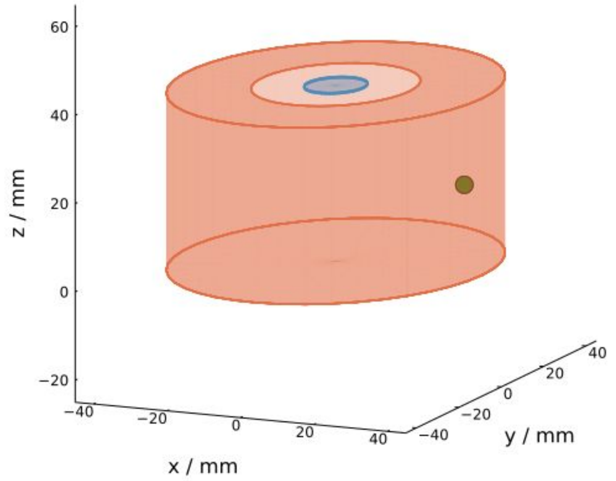
julia > sim = Simulation{Float64}(“BEGe.yaml”)
julia > calculate_electric_potential!(sim)
julia > calculate_electric_field!(sim)
julia > for i in 1:2
                calculate_weighting_potential!(sim, i)
        end
```

Pulse Shape Simulation Chain

```
julia > using SolidStateDetectors, Unitful

julia > sim = Simulation{Float64}(“BEGe.yaml”)
julia > calculate_electric_potential!(sim)
julia > calculate_electric_field!(sim)
julia > for i in 1:2
            calculate_weighting_potential!(sim, i)
        end

julia > locations = [CartesianPoint(0.035,0,0.02)]
julia > energies = [1000u”keV”]
julia > evt = Event(locations, energies)
julia > simulate!(evt, sim)
```



Undepleted detectors – calculating capacitances

```
julia > using SolidStateDetectors, Unitful

julia > sim = Simulation{Float64}("BEGe.yaml")
julia > sim.detector = SolidStateDetector(sim, contact_potential = 500, contact_id = 1)
julia > calculate_electric_potential!(sim, depletion_handling = true)
julia > calculate_electric_field!(sim)
julia > for i in 1:2
            calculate_weighting_potential!(sim, i, depletion_handling = true)
        end

julia > calculate_mutual_capacitance(sim, (1, 2))
```

GPU support

```
julia > using SolidStateDetectors, Unitful
julia > using CUDAKernels, CUDA

julia > sim = Simulation{Float64}("BEGe.yaml")
julia > calculate_electric_potential!(sim, device_array_type = CuArray)
julia > calculate_electric_field!(sim)
julia > for i in 1:2
            calculate_weighting_potential!(sim, i, device_array_type = CuArray)
        end

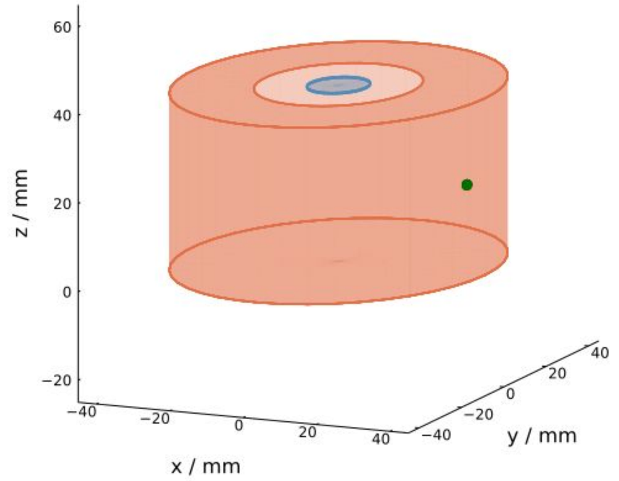
julia > locations = [CartesianPoint(0.035,0,0.02)]
julia > energies = [1000u"keV"]
julia > evt = Event(locations, energies)
julia > simulate!(evt, sim)
```

Simulating Group Effects

```
julia > using SolidStateDetectors, Unitful

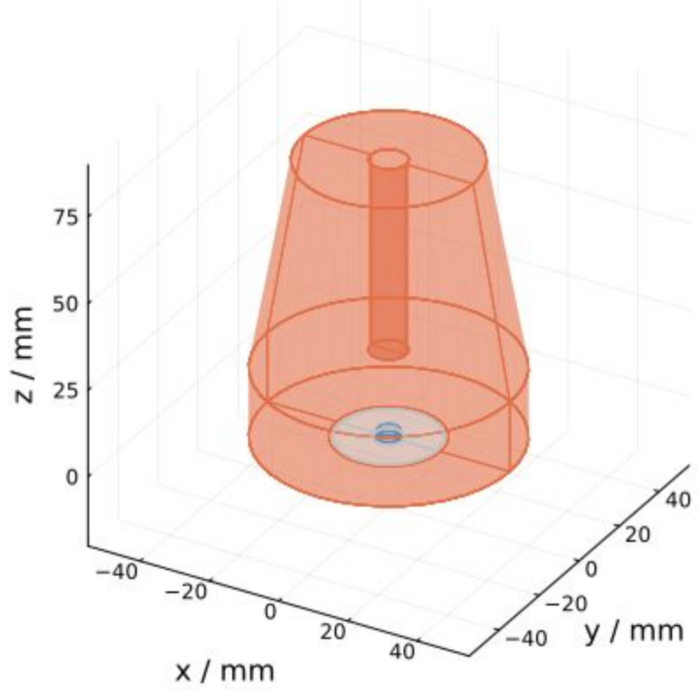
julia > sim = Simulation{Float64}("BEGe.yaml")
julia > calculate_electric_potential!(sim)
julia > calculate_electric_field!(sim)
julia > for i in 1:2
            calculate_weighting_potential!(sim, i)
        end

julia > locations = [CartesianPoint(0.035,0,0.02)]
julia > energies = [1000u"keV"]
julia > evt = Event(NBodyChargeCloud(locations, energies, 100))
julia > simulate!(evt, sim, diffusion = true, self_repulsion = true)
```



Support for Geant4.jl

```
julia > using SolidStateDetectors, Unitful
julia > using Geant4
julia > sim = Simulation{Float64}("ivc.yaml")
julia > simulate!(sim)
```

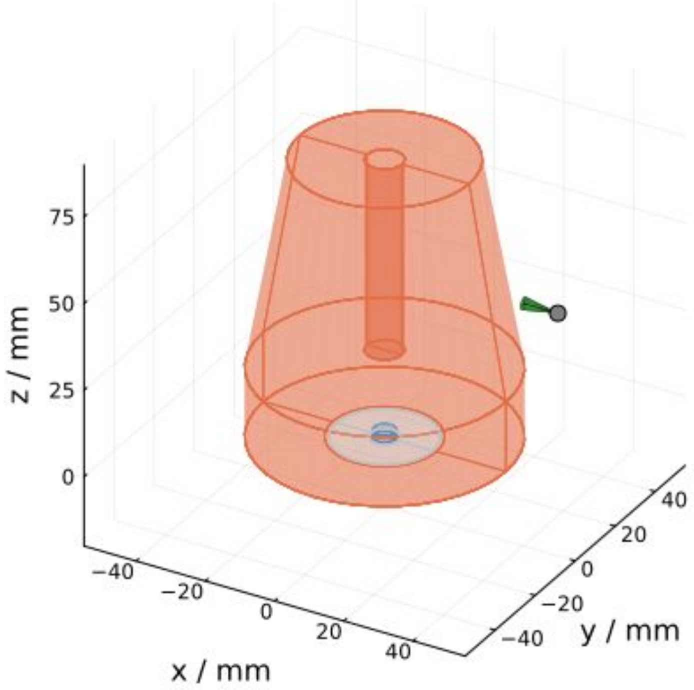


Support for Geant4.jl

```
julia > using SolidStateDetectors, Unitful
julia > using Geant4

julia > sim = Simulation{Float64}("ivc.yaml")
julia > simulate!(sim)

julia > source = MonoenergeticSource(
          "gamma", 2.615u"MeV",
          CartesianPoint(0.05, 0.0, 0.05),
          CartesianVector(-1, 0, 0),
          10u"°"
        )
```



Support for Geant4.jl

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julia > using SolidStateDetectors, Unitful
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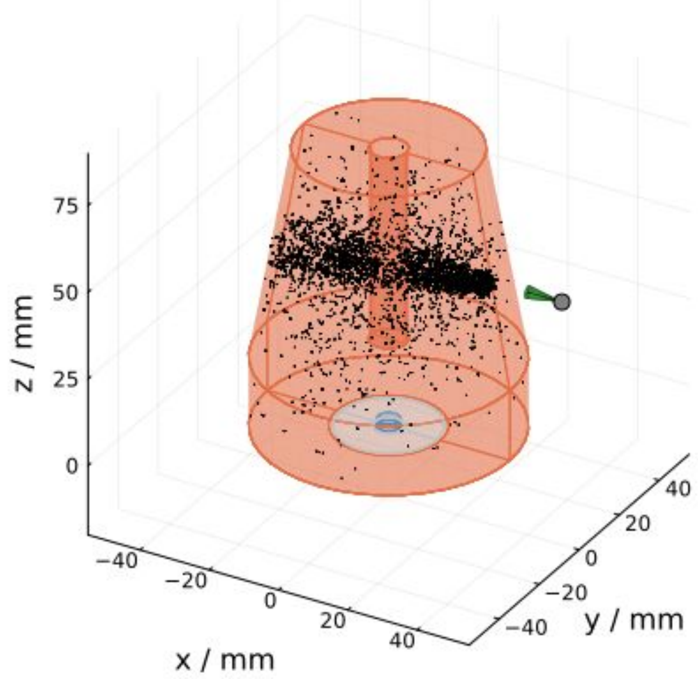
            CartesianPoint(0.05, 0.0, 0.05),
            CartesianVector(-1, 0, 0),
            10u"°"
        )
julia > app = G4JLApplication(sim, source)
julia > evts = run_geant4_simulations(app, 10000)
```



Support for Geant4.jl

```
julia > using SolidStateDetectors, Unitful
julia > using Geant4

julia > sim = Simulation{Float64}("ivc.yaml")
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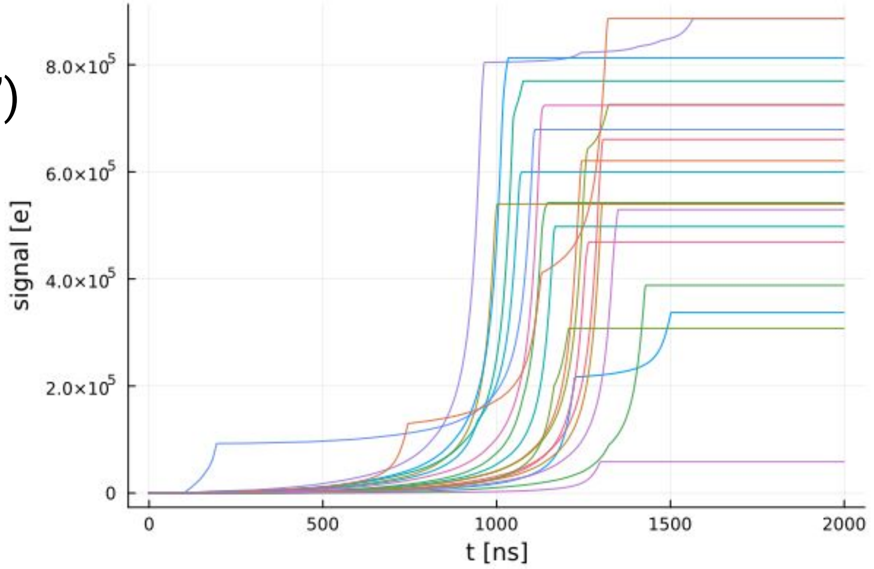
            "gamma", 2.615u"MeV",
            CartesianPoint(0.05, 0.0, 0.05),
            CartesianVector(-1, 0, 0),
            10u"°"
        )
julia > app = G4JLApplication(sim, source)
julia > evts = run_geant4_simulations(app, 10000)

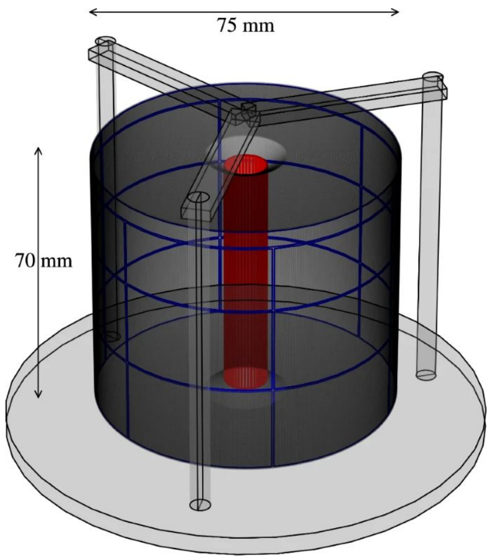
julia > simulate_waveforms(sim, evts)
```

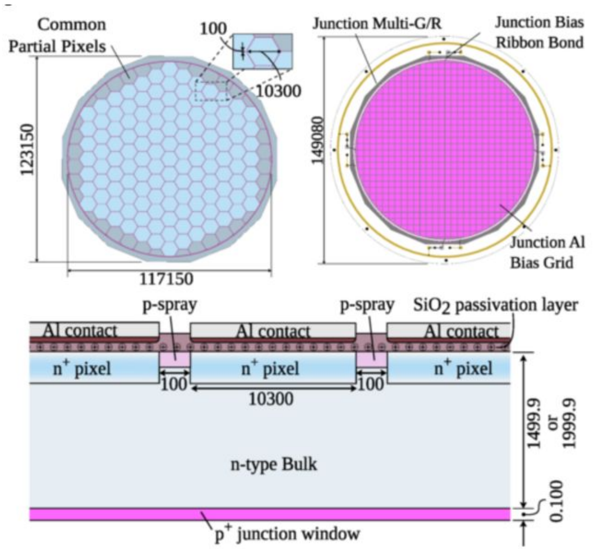


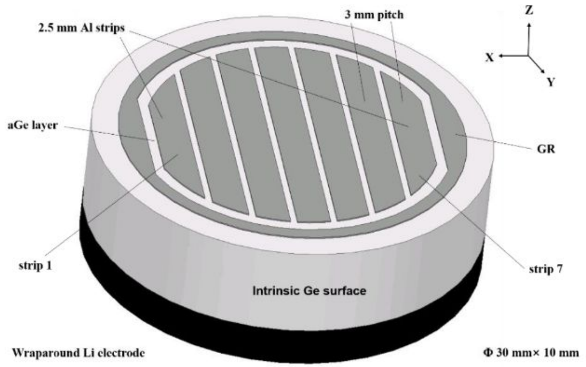
Applications

Publications using SolidStateDetectors.jl

DOI: 10.1088/1748-0221/16/08/P08007







DOI: 10.1140/epjc/s10052-023-11509-8

DOI: 10.1103/PhysRevC.107.065503

DOI: 10.1088/1748-0221/18/05/P05025

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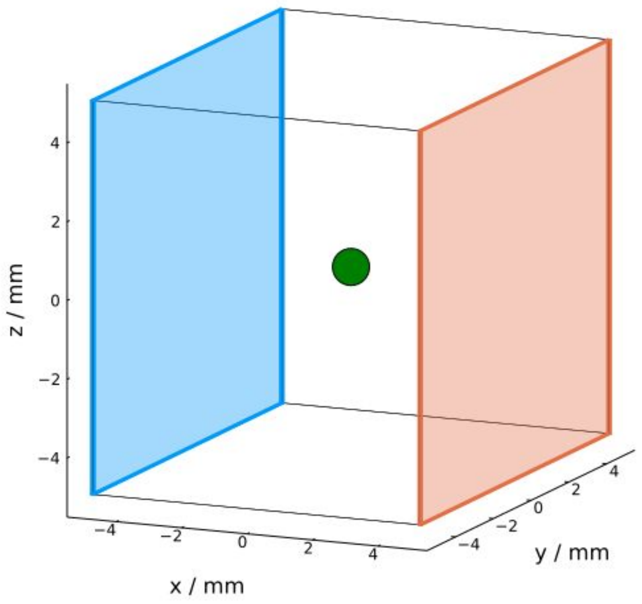
SolidStateDetectors.jl

- Open-source simulation software package, written in julia
- 3D calculation of electric potentials and electric fields
- Can simulate arbitrary geometries, e.g. segmented detectors
- Documentation: https://juliaphysics.github.io/SolidStateDetectors.jl/stable/
- Fast field calculation: SIMD on CPU, also supports GPU calculation
- Calculation of capacitance matrix
- Simulation of fields in undepleted detectors ⇒ C-V curves
- Experimental features: diffusion and self-repulsion of charge clouds
- Recent additions: support for Geant4.jl and charge trapping models

Charge Carrier Drift in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV")
```

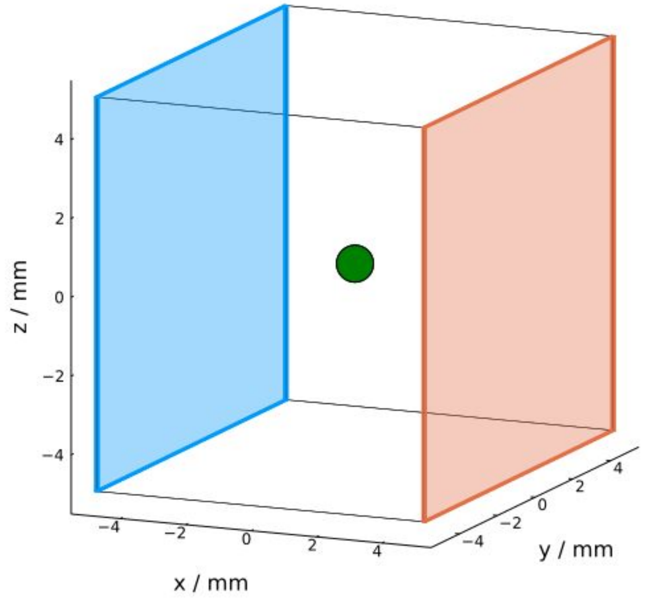


— electrons

— holes

Charge Carrier Drift in Homogeneous Field

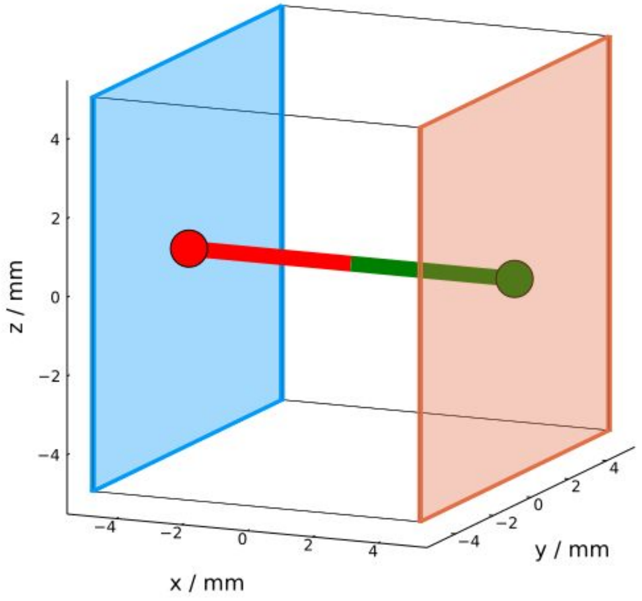
```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV")
julia > simulate!(evt, sim)
```



— electrons
— holes

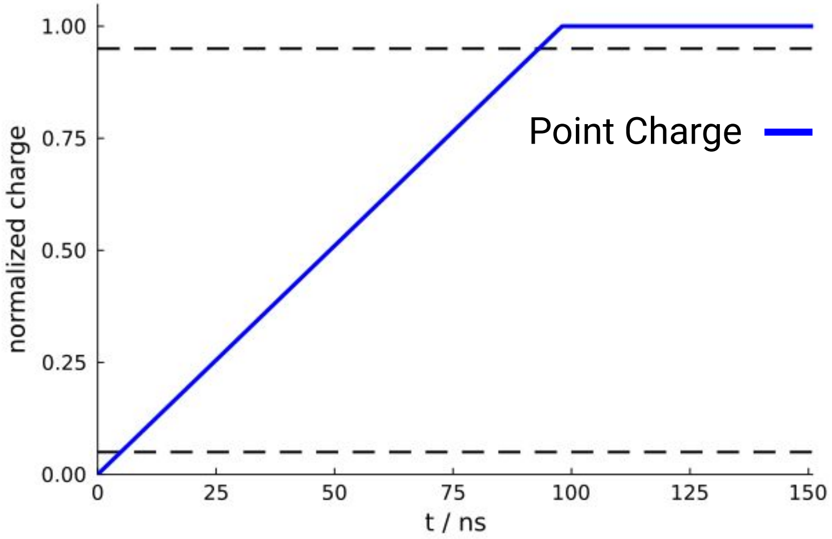
Charge Carrier Drift in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV")
julia > simulate!(evt, sim)
```



🟥 electrons
🟩 holes

```
julia > plot(evt.waveforms[1])
```



Simulating Charge Cloud Motion

☑️ **Drift current:** Charge carrier movement caused by an external electric field $\longrightarrow$ $\vec{v}_e(\vec{r}_e) = \hat{\mu}_e \vec{E}(\vec{r}_e)$ and $\vec{v}_h(\vec{r}_h) = \hat{\mu}_h \vec{E}(\vec{r}_h)$

Simulating Charge Cloud Motion

☑ **Drift current:** Charge carrier movement caused by an external electric field → $\vec{v}_e(\vec{r}_e) = \hat{\mu}_e \vec{E}(\vec{r}_e)$ and $\vec{v}_h(\vec{r}_h) = \hat{\mu}_h \vec{E}(\vec{r}_h)$

☐ **Diffusion current:** Charge carrier movement caused by variations in the charge carrier concentrations → Diffusion equation

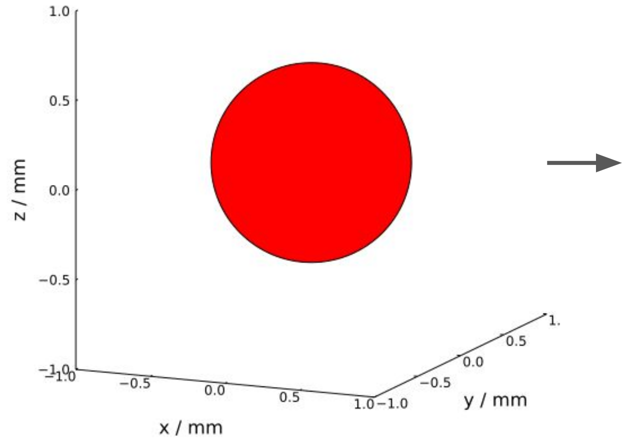
☐ **Self-Repulsion:** Electrostatic repulsion of charge carriers of the same type

→ Coulomb's law: $\vec{E}(\vec{r}) = \frac{Q}{4\pi\epsilon_0\epsilon_r} \cdot \frac{\vec{r}}{|r|^3}$

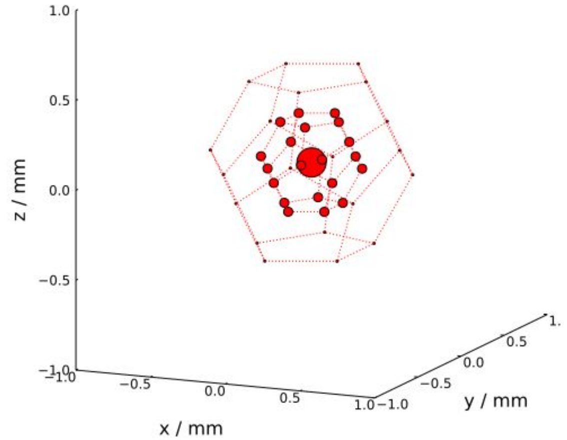
Charge Cloud Models in SolidStateDetectors.jl

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV")
```

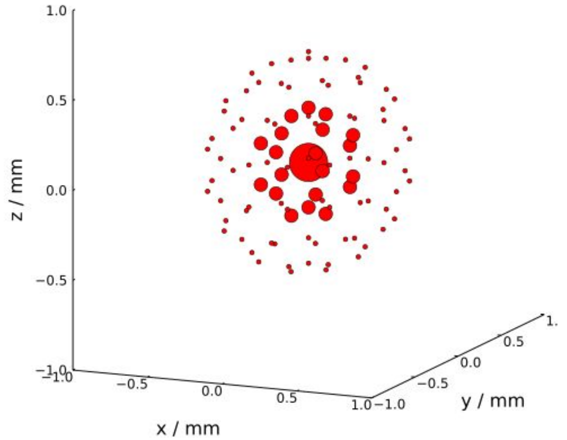
```
julia > evt = Event(NBodyChargeCloud(CartesianPoint{T}(0,0,0), 2u"MeV"))
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 100)
```



Point charge
N = 1

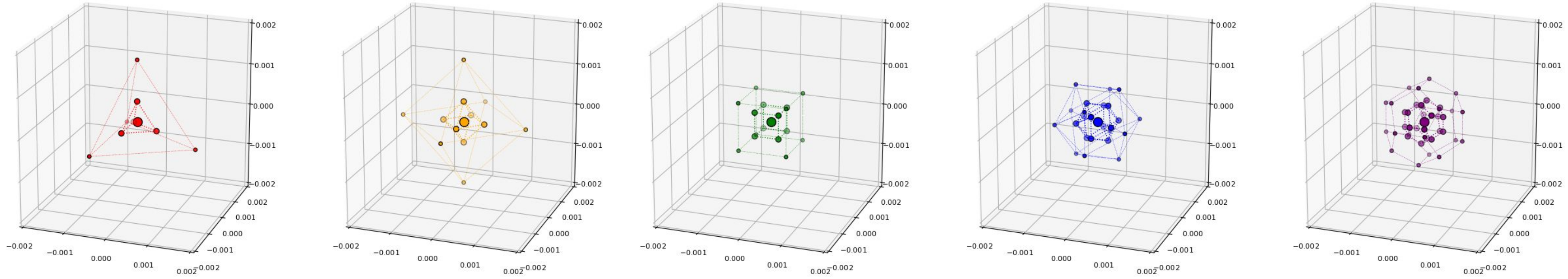


Platonic solid
N < 50



Regular Sphere
N $\gtrsim$ 50

Simulation



Solid State Detectors

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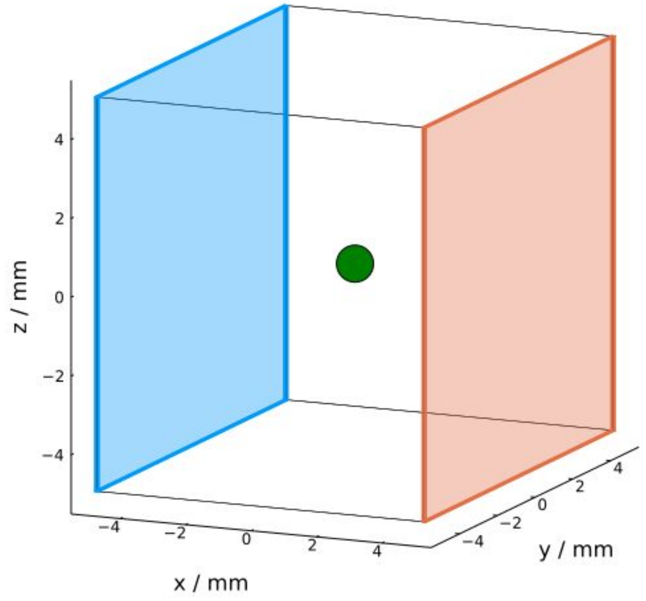
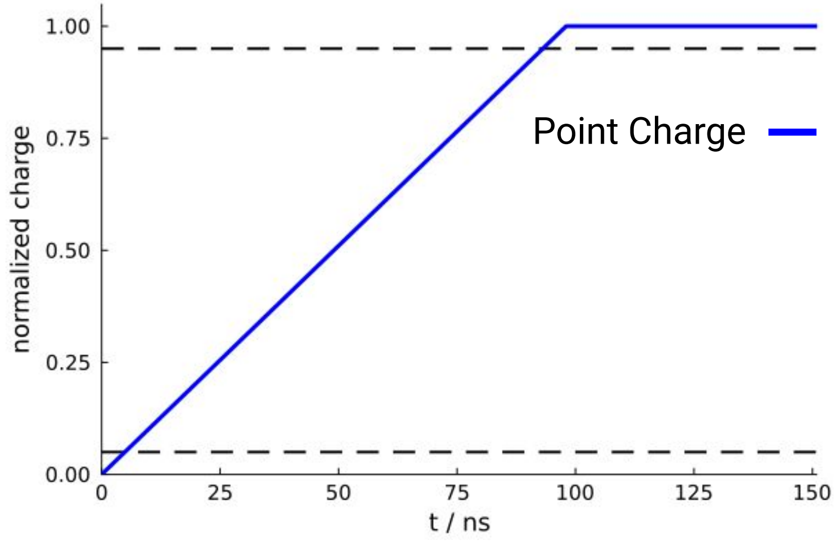
Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV")
```



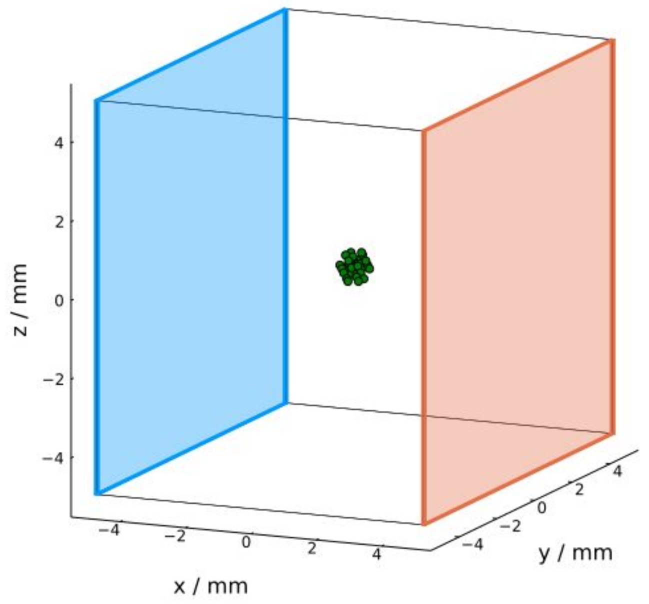
```
julia > plot(evt.waveforms[1])
```



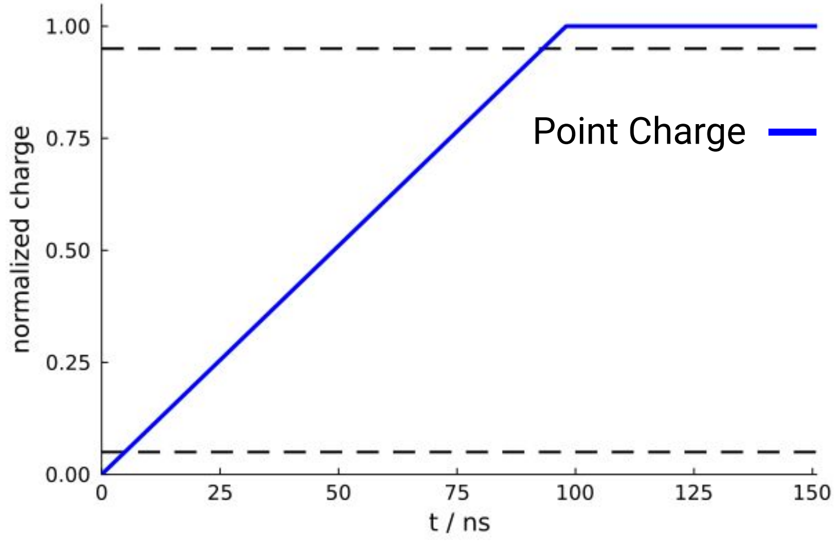
— electrons
— holes

Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 40)
```



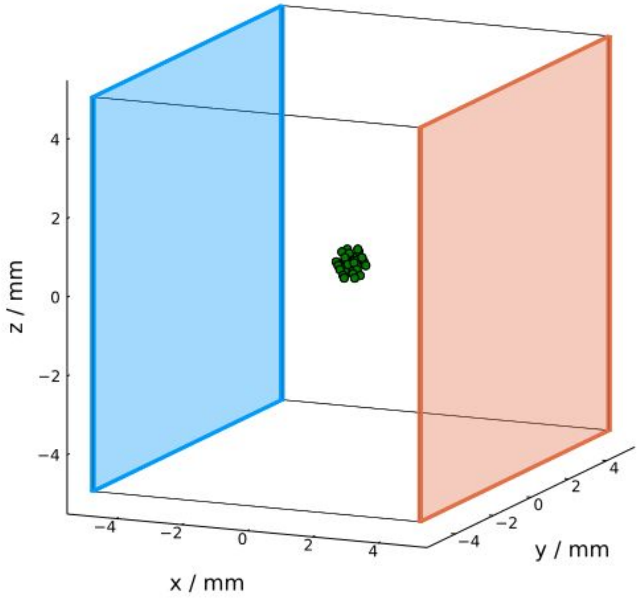
```
julia > plot(evt.waveforms[1])
```



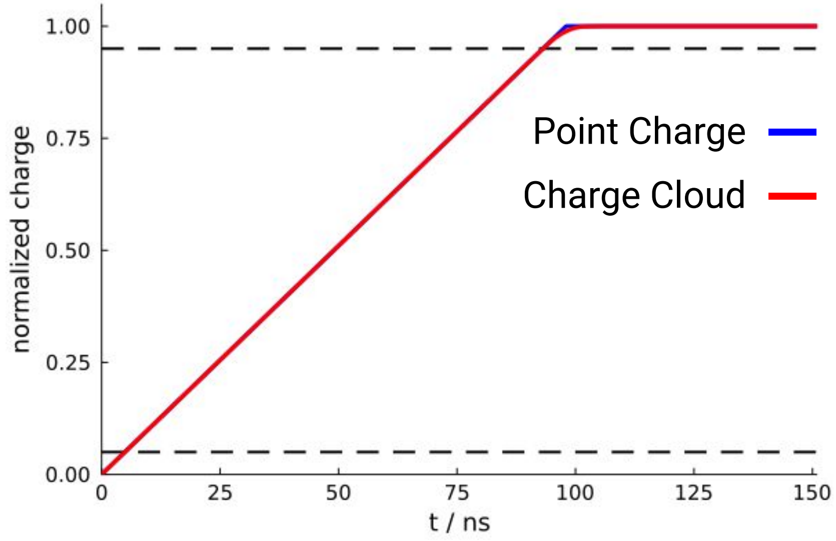
— electrons
— holes

Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 40)
julia > simulate!(evt, sim)
```



```
julia > plot(evt.waveforms[1])
```

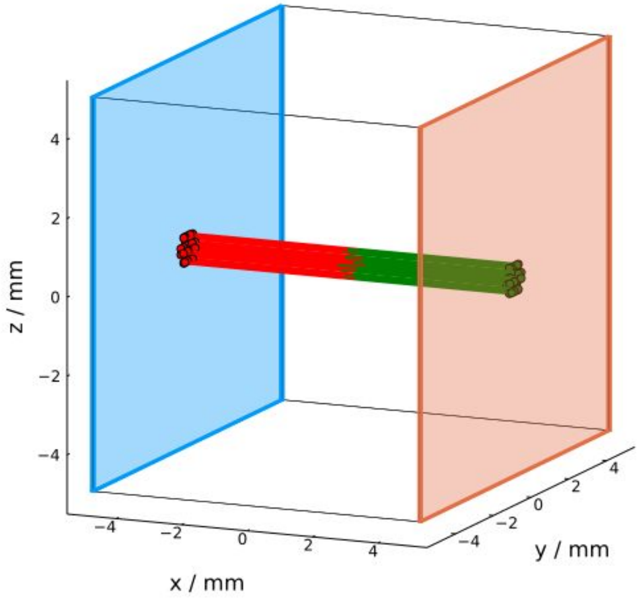


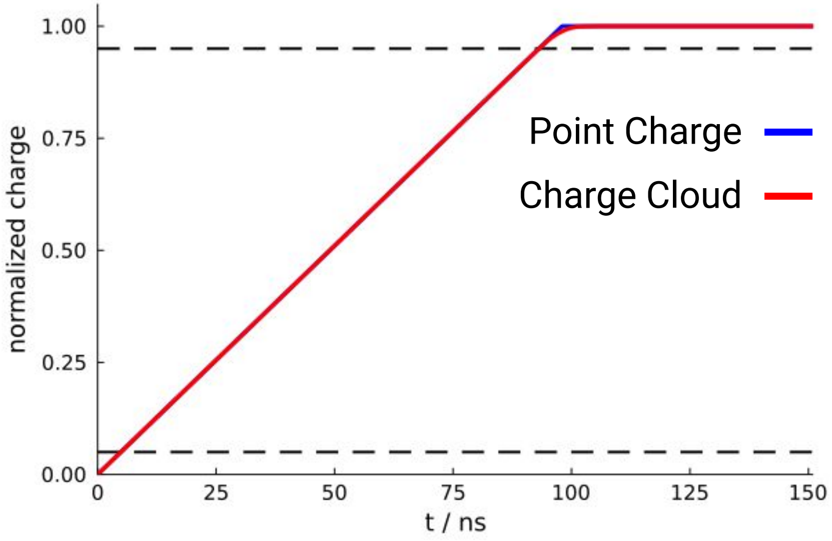
— electrons
— holes

Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 40)
julia > simulate!(evt, sim)
```

```
julia > plot(evt.waveforms[1])
```





🟥 electrons

🟩 holes

Simulating Diffusion

Diffusion equation: $$\frac{\partial n(\vec{r},t)}{\partial t} = -D\,\Delta n(\vec{r},t)$$

n = electron / hole concentration

D = diffusion coefficient

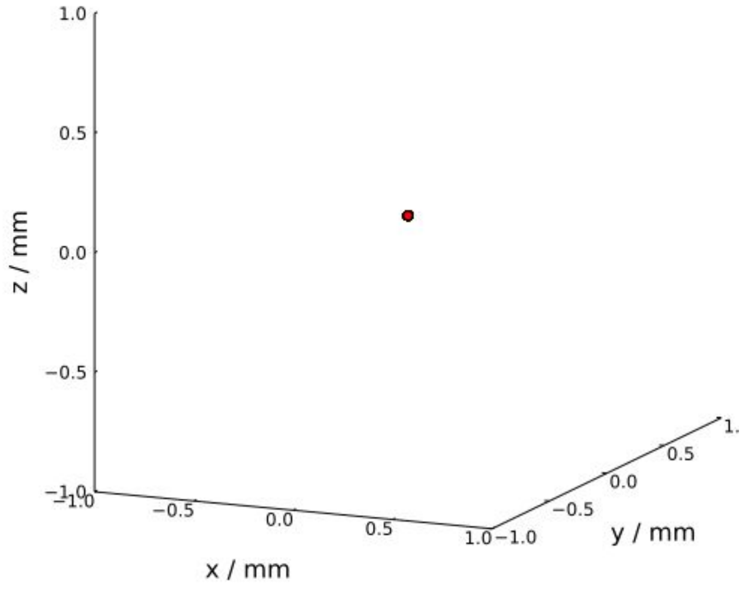
$$n(\vec{r},t) = \frac{n_0}{4\pi D t} \cdot \exp\left(-\frac{r^2}{4Dt}\right)$$

$$\longrightarrow \sigma(t) = \sqrt{2Dt}$$

Solid State Detectors MAX-PLANCK-INSTITUT FÜR PHYSIK

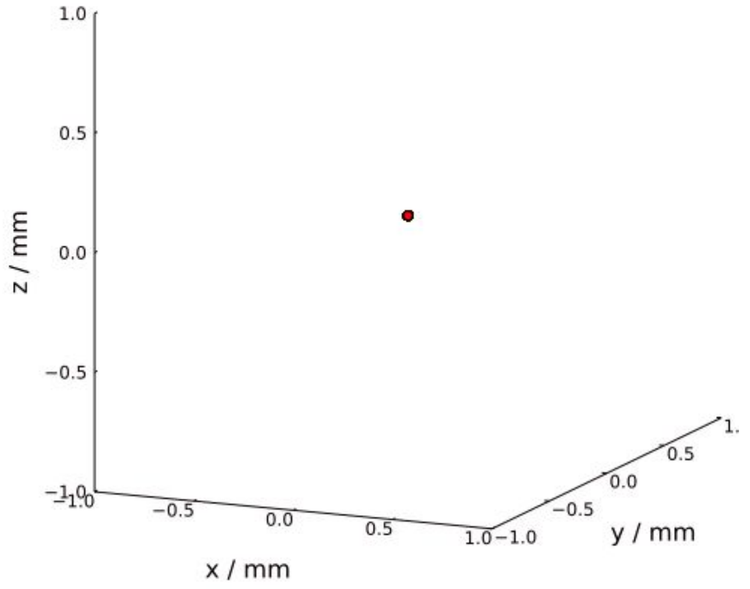
Simulating Diffusion

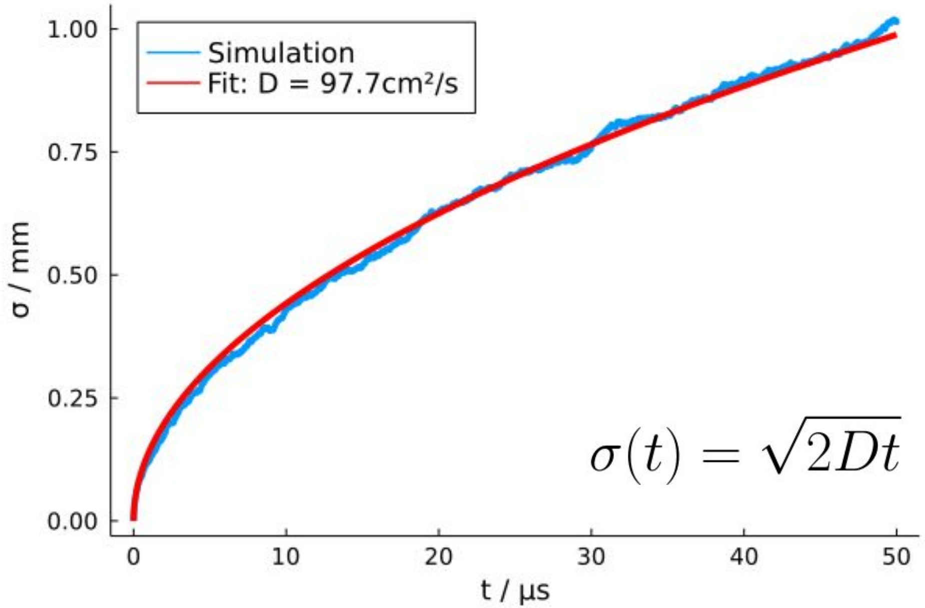
```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 100)
```



Simulating Diffusion

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 100)
julia > simulate!(evt, sim, diffusion = true)
```





$$\sigma(t) = \sqrt{2Dt}$$

Simulating Self-Repulsion

Coulomb's law: $$\vec{E}(\vec{r}) = \frac{Q}{4\pi\epsilon_0\epsilon_r} \cdot \frac{\vec{r}}{|\vec{r}|^3}$$

$\vec{E}$	=	electric field
Q	=	charge
$\vec{r}$	=	distance to charge center

Simulating Self-Repulsion

Coulomb's law:

$$\vec{E}(\vec{r}) = \frac{Q}{4\pi\epsilon_0\epsilon_r} \cdot \frac{\vec{r}}{|\vec{r}|^3}$$

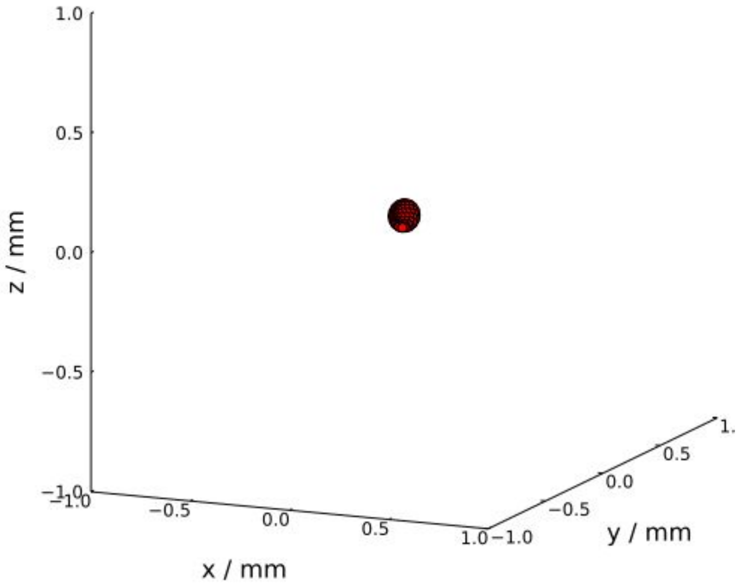
$\vec{E}$	=	electric field
Q	=	charge
$\vec{r}$	=	distance to charge center

$$Q(\vec{r}, t) = \frac{4\pi\epsilon_0\epsilon_r|\vec{r}|^3}{3\mu t}$$

$$\longrightarrow \quad r = \sqrt[3]{\frac{3\mu Q t}{4\pi\epsilon_0\epsilon_r}}$$

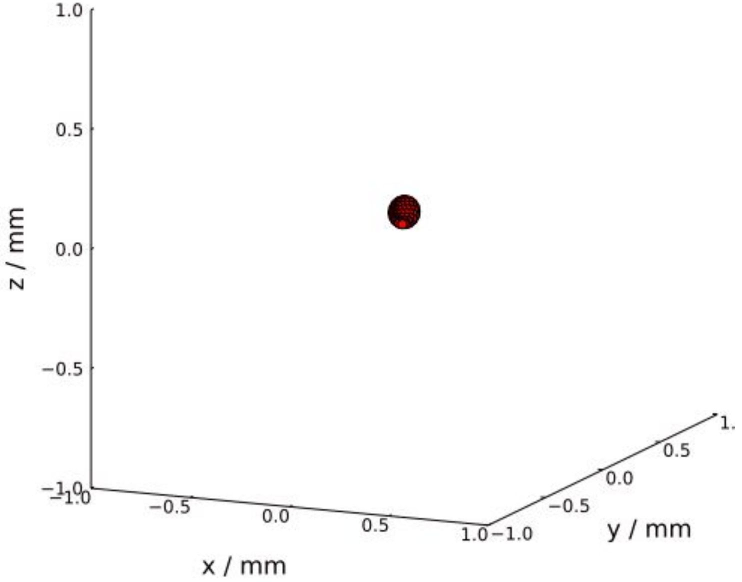
Simulating Self-Repulsion

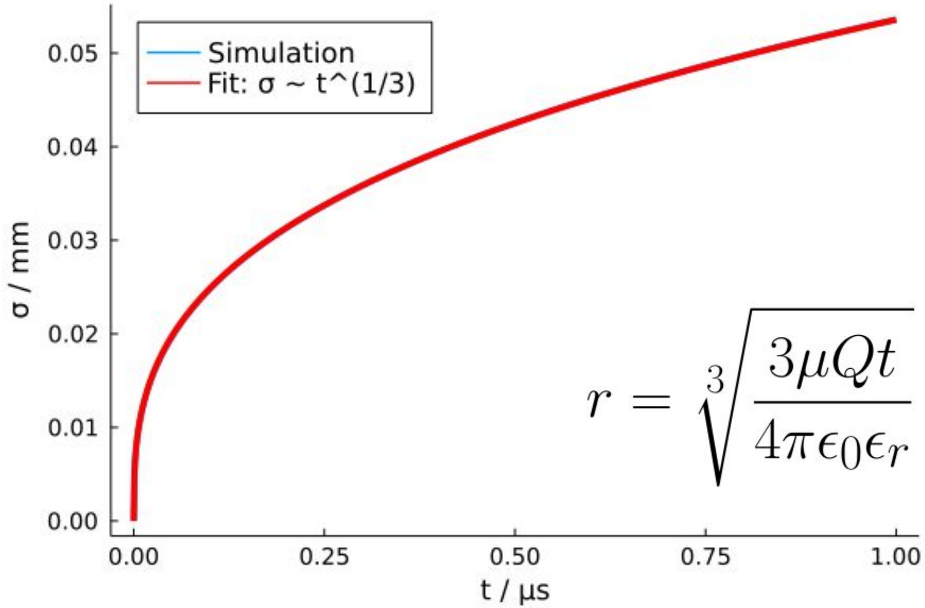
```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 100)
```



Simulating Self-Repulsion

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 100)
julia > simulate!(evt, sim, self_repulsion = true)
```

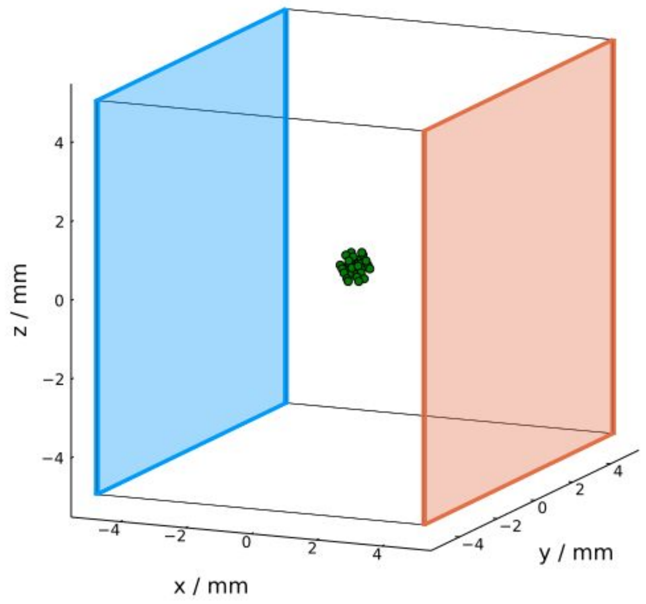




$$r = \sqrt[3]{\frac{3\mu Q t}{4\pi\epsilon_0\epsilon_r}}$$

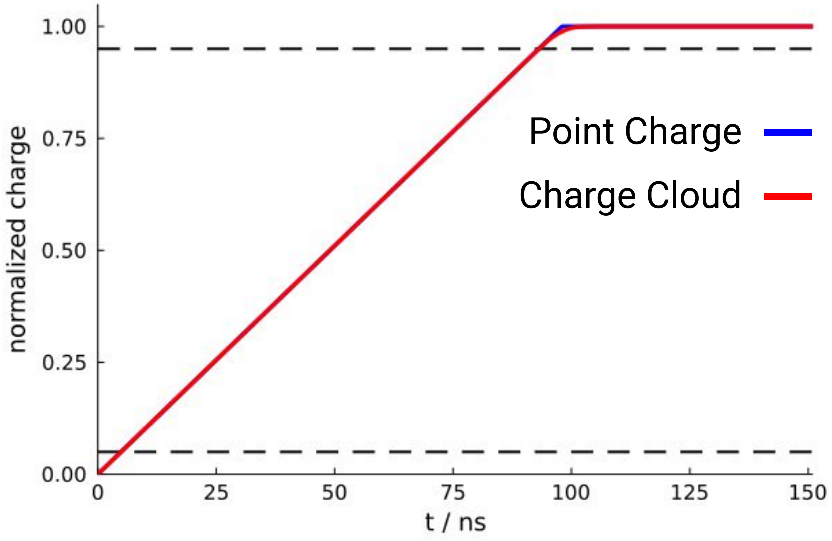
Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 40)
```



→

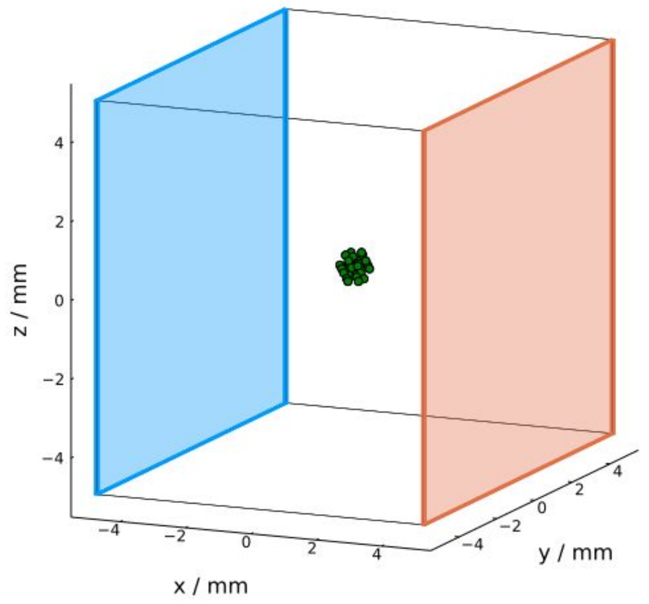
```
julia > plot(evt.waveforms[1])
```



🟥 electrons
🟩 holes

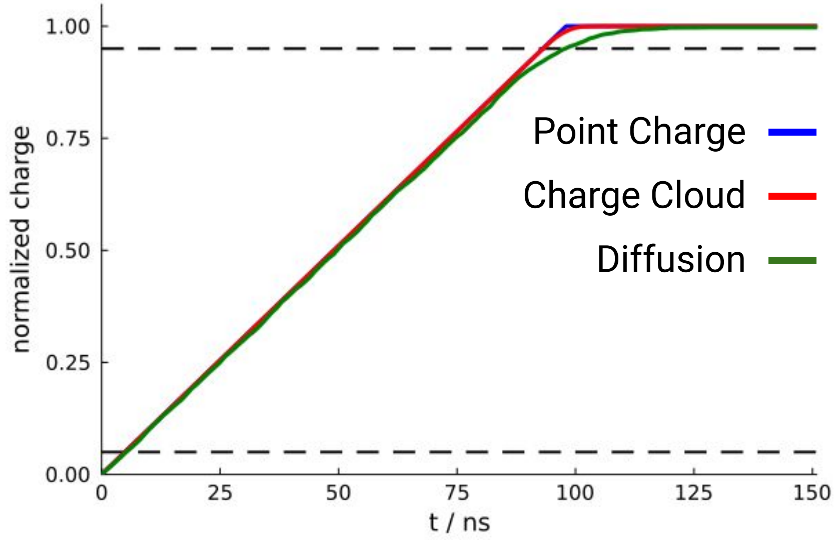
Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 40)
julia > simulate!(evt, sim, diffusion = true)
```



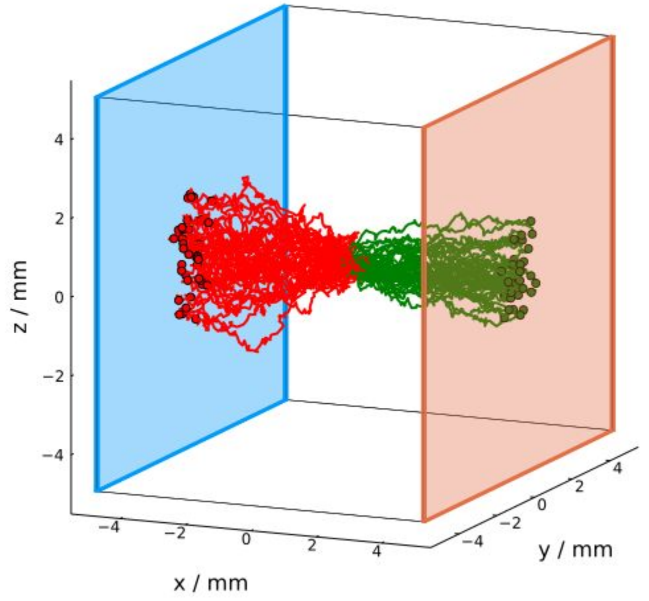
— electrons
— holes

```
julia > plot(evt.waveforms[1])
```



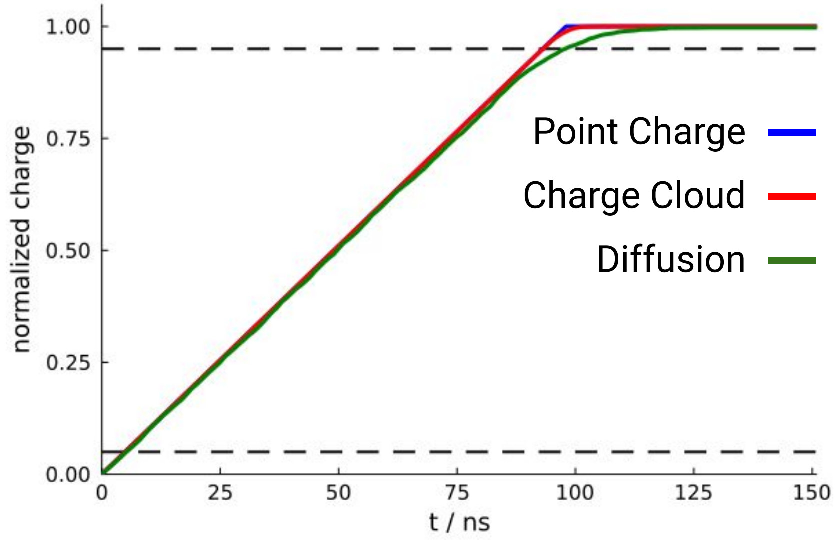
Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 40)
julia > simulate!(evt, sim, diffusion = true)
```



→

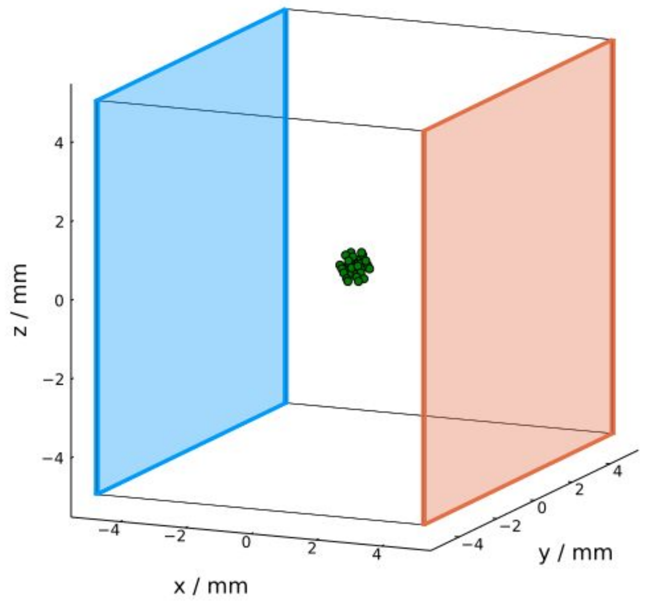
```
julia > plot(evt.waveforms[1])
```



🟥 electrons
🟩 holes

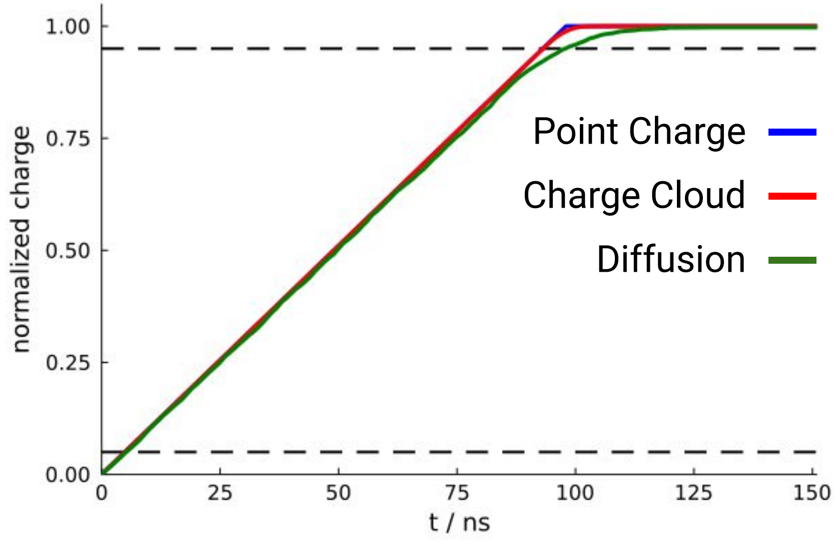
Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 40)
```



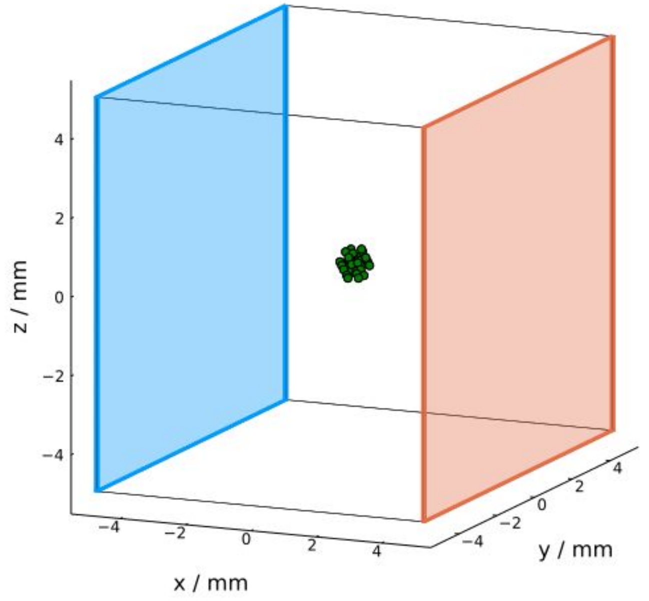
— electrons
— holes

```
julia > plot(evt.waveforms[1])
```

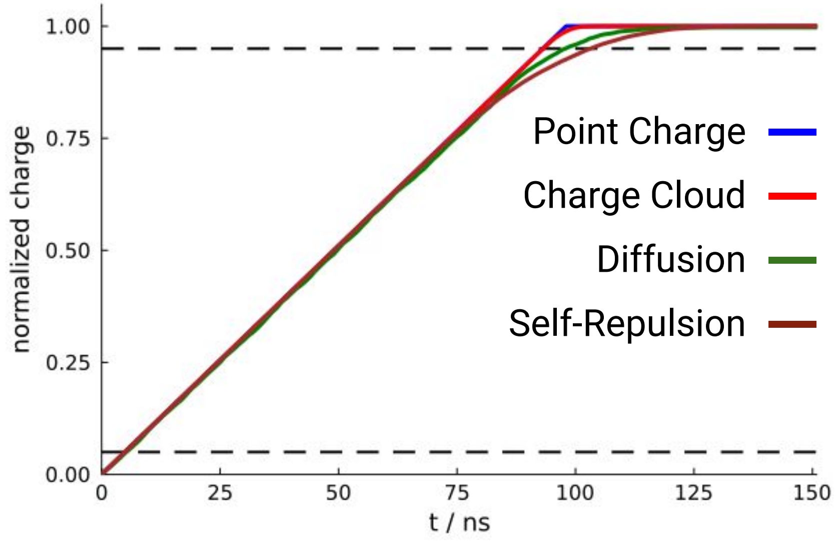


Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 40)
julia > simulate!(evt, sim, self_repulsion = true)
```



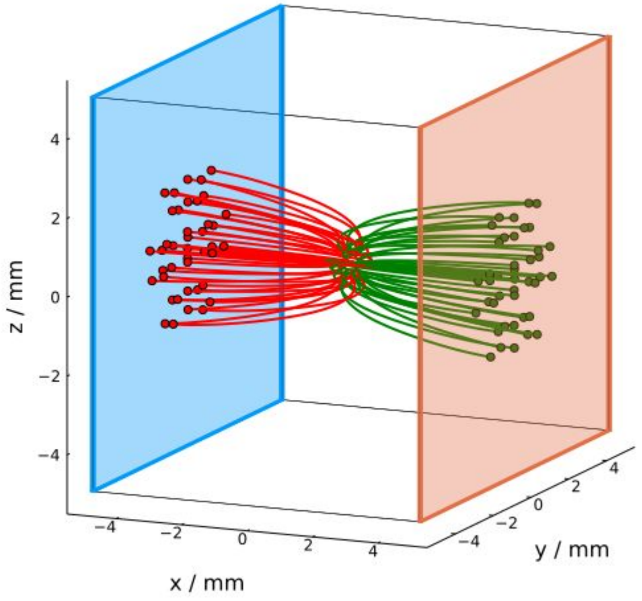
```
julia > plot(evt.waveforms[1])
```



electrons
holes

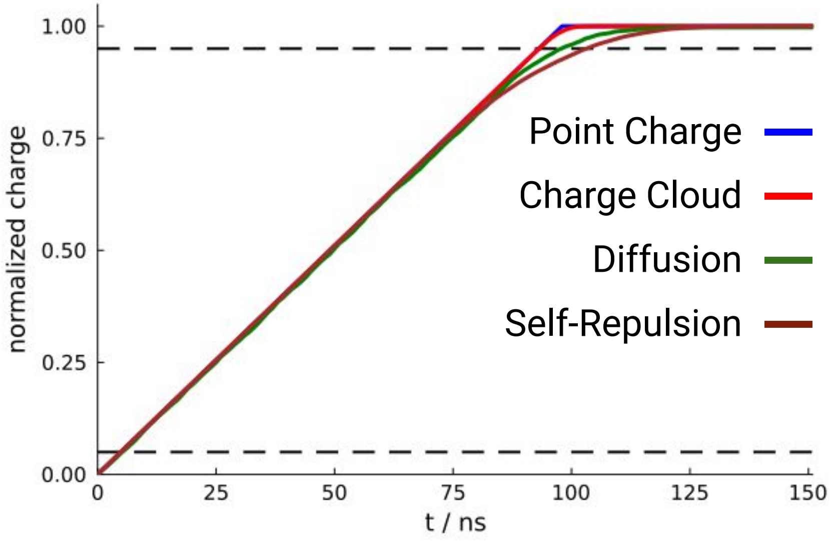
Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 40)
julia > simulate!(evt, sim, self_repulsion = true)
```



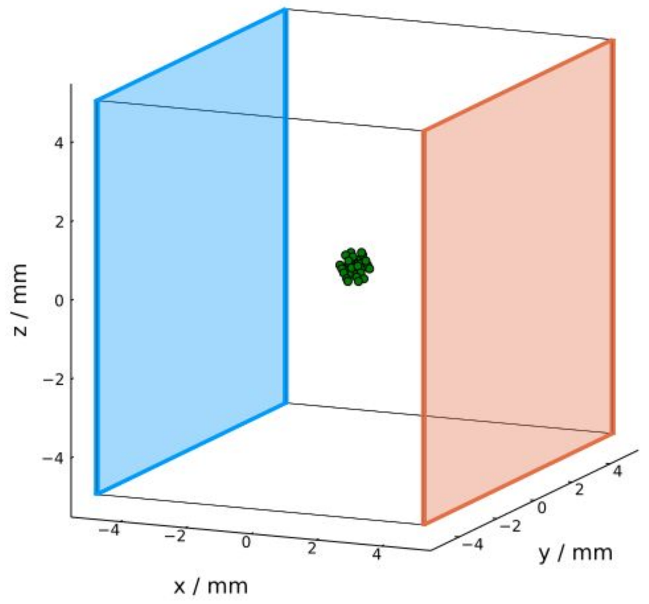
🟥 electrons
🟩 holes

```
julia > plot(evt.waveforms[1])
```

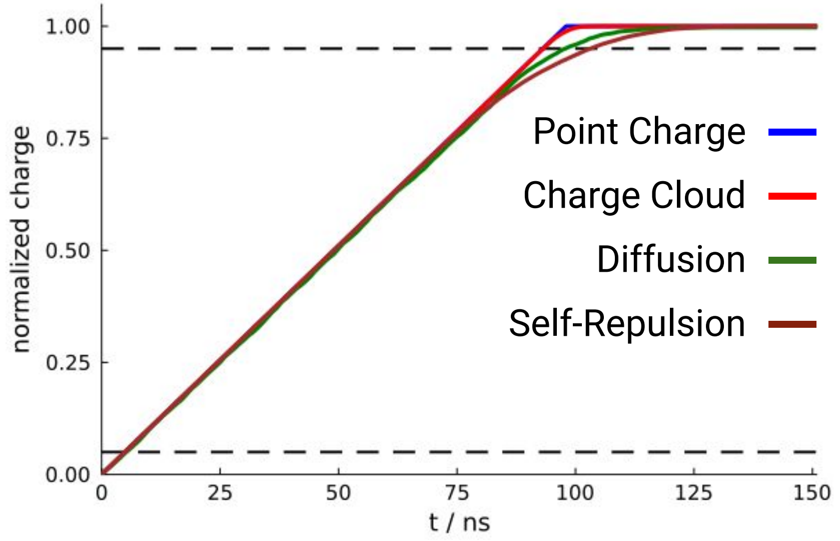


Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 40)
```



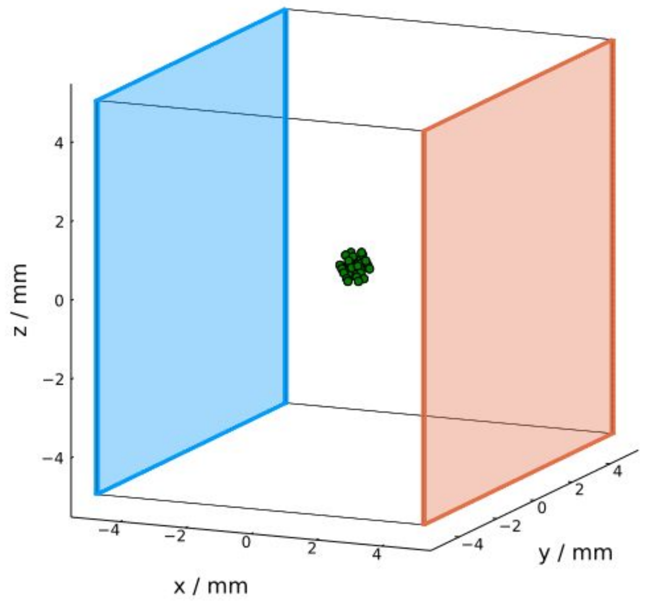
```
julia > plot(evt.waveforms[1])
```



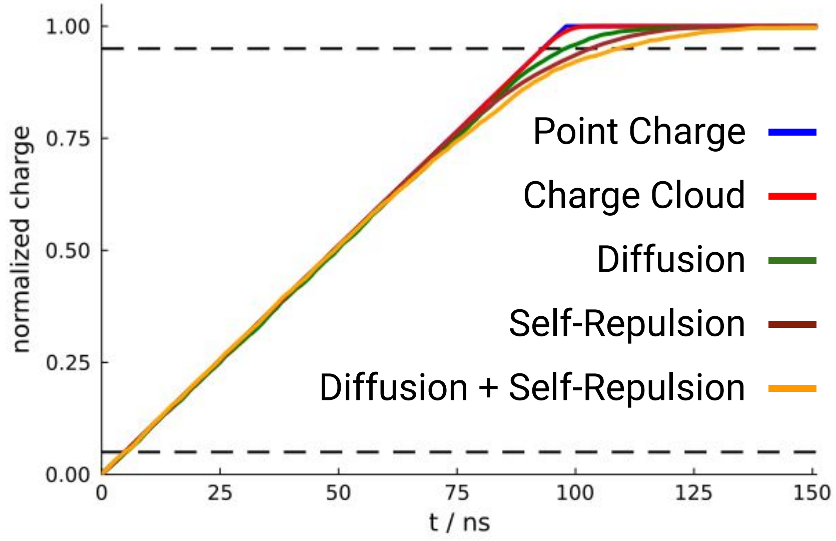
🟥 electrons
🟩 holes

Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 40)
julia > simulate!(evt, sim, diffusion = true, self_repulsion = true)
```



```
julia > plot(evt.waveforms[1])
```

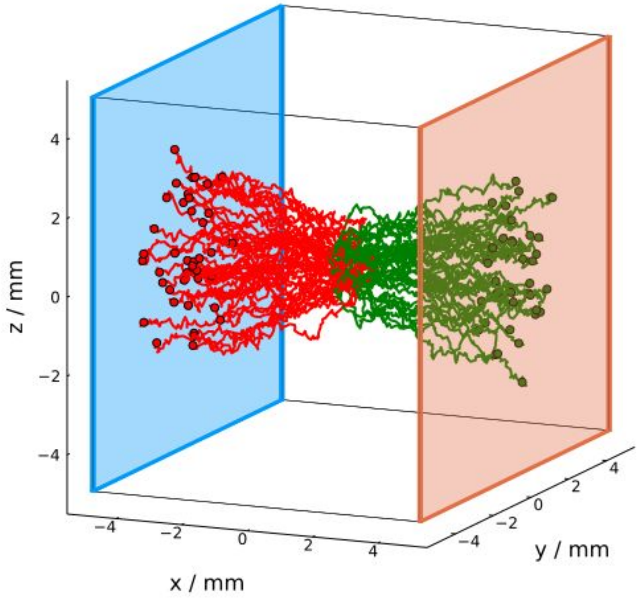


🟥	electrons
🟩	holes

Solid State Detectors MAX-PLANCK-INSTITUT FÜR PHYSIK

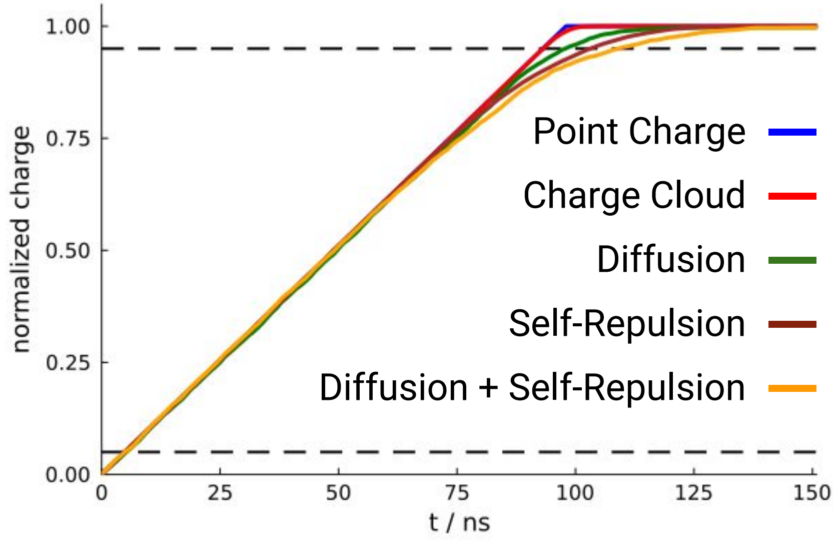
Charge Cloud Motion in Homogeneous Field

```
julia > evt = Event(CartesianPoint{T}(0,0,0), 2u"MeV", 40)
julia > simulate!(evt, sim, diffusion = true, self_repulsion = true)
```

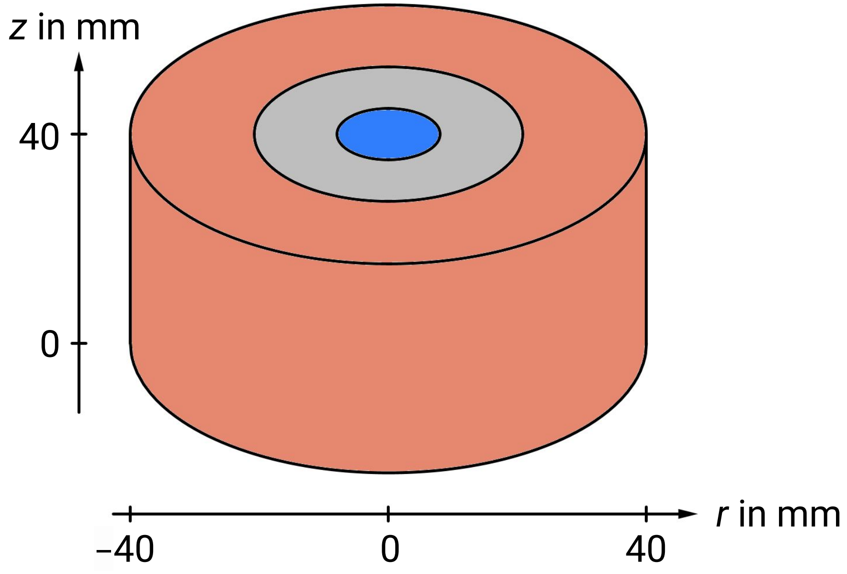


🟥 electrons
🟩 holes

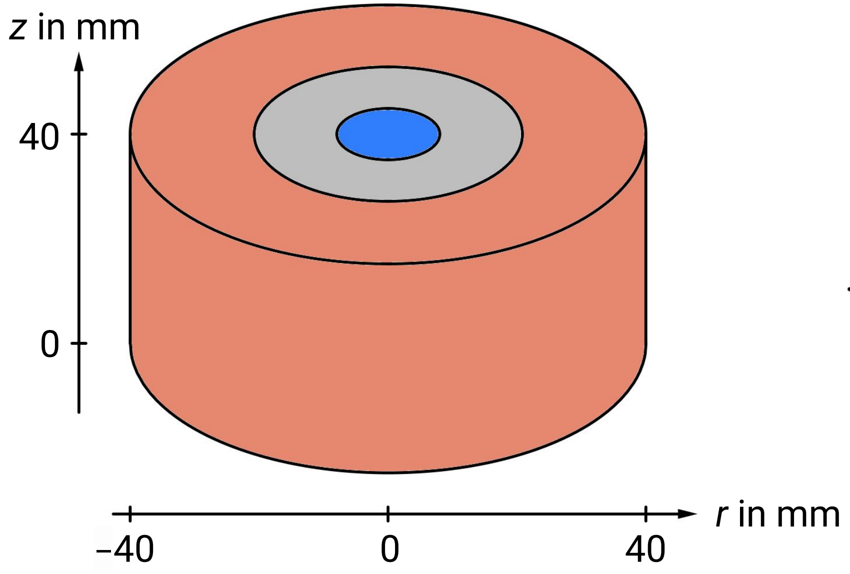
```
julia > plot(evt.waveforms[1])
```

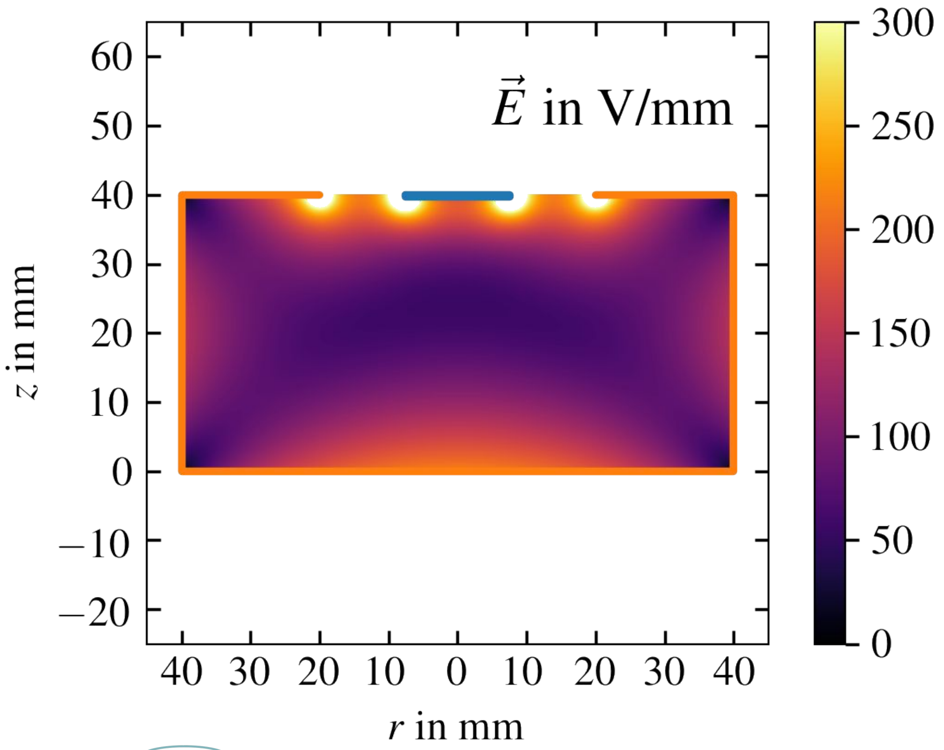


Point Contact Detector



Point Contact Detector

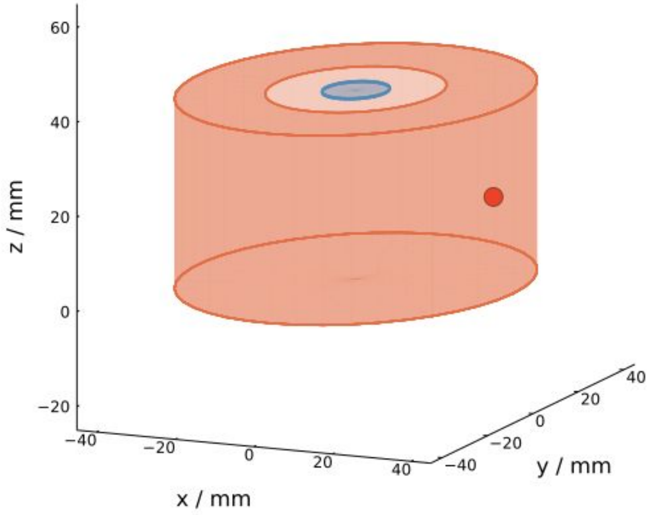




Solid State Detectors MAX-PLANCK-INSTITUT FÜR PHYSIK

Charge Carrier Drift in Point Contact Detector

```
julia > evt = Event(CartesianPoint{T}(0.035,0,0.02), 2u"MeV")
```

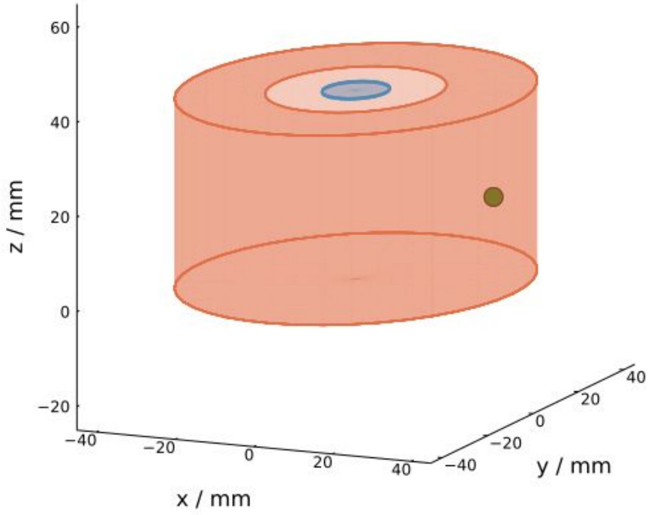


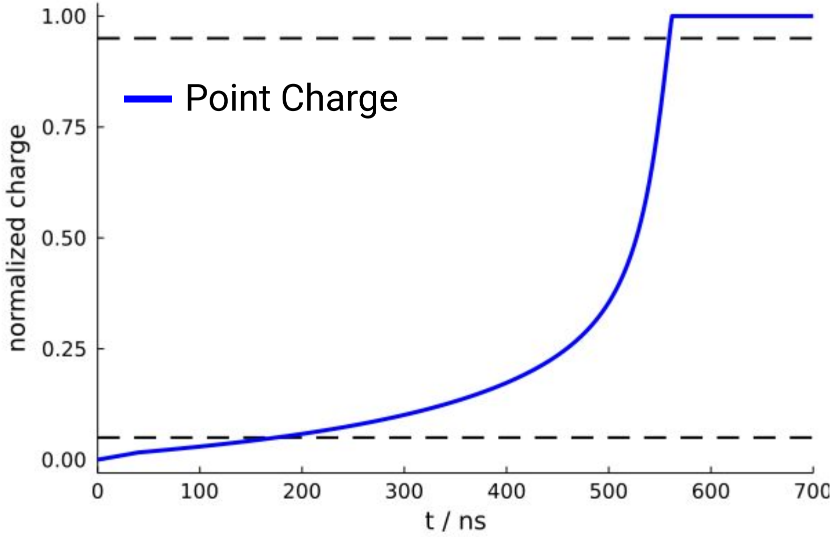
🟥 electrons
🟩 holes

Charge Carrier Drift in Point Contact Detector

```
julia > evt = Event(CartesianPoint{T}(0.035,0,0.02), 2u"MeV")
julia > simulate!(evt, sim)
```

```
julia > plot(evt.waveforms[1])
```





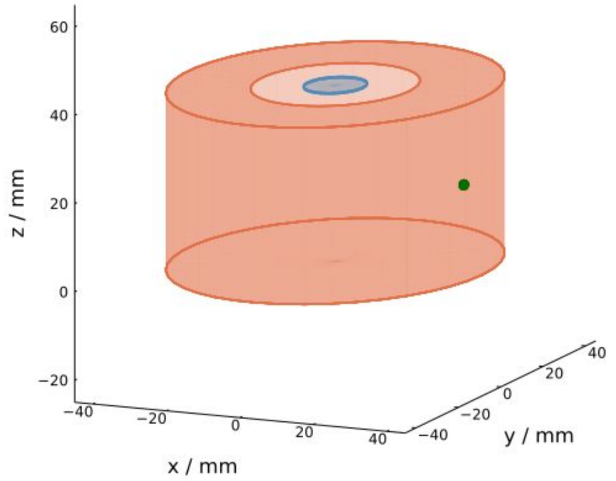
— electrons
— holes

Simulating Group Effects

```
julia > using SolidStateDetectors, Unitful

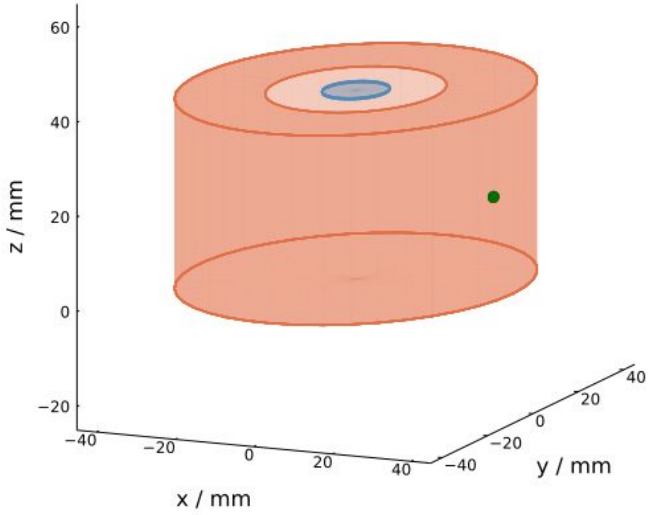
julia > sim = Simulation{Float64}(“BEGe.yaml”)
julia > calculate_electric_potential!(sim)
julia > calculate_electric_field!(sim)
julia > for i in 1:2
            calculate_weighting_potential!(sim, i)
        end

julia > locations = [CartesianPoint(0.035,0,0.02)]
julia > energies = [1000u”keV”]
julia > evt = Event(NBodyChargeCloud(locations, energies, 100))
julia > simulate!(evt, sim, diffusion = true, self_repulsion = true)
```



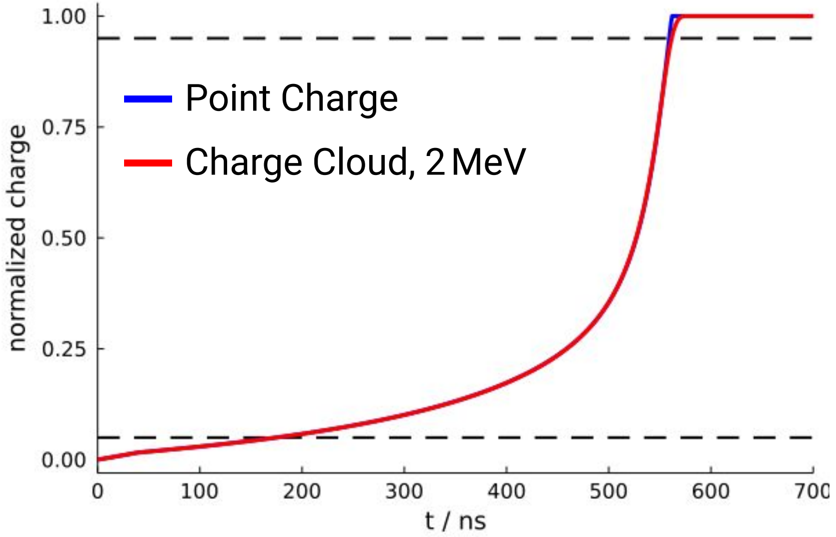
Charge Cloud Motion in Point Contact Detector

```
julia > evt = Event(CartesianPoint{T}(0.035,0,0.02), 2u"MeV", 40)
julia > simulate!(evt, sim, diffusion = true, self_repulsion = true)
```



— electrons
— holes

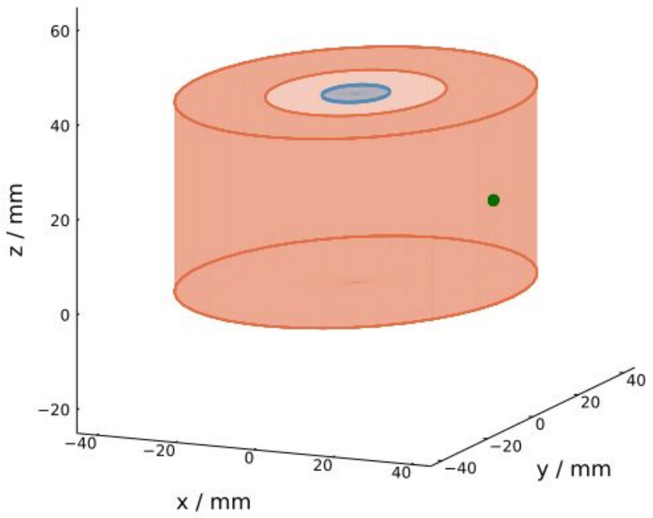
```
julia > plot(evt.waveforms[1])
```

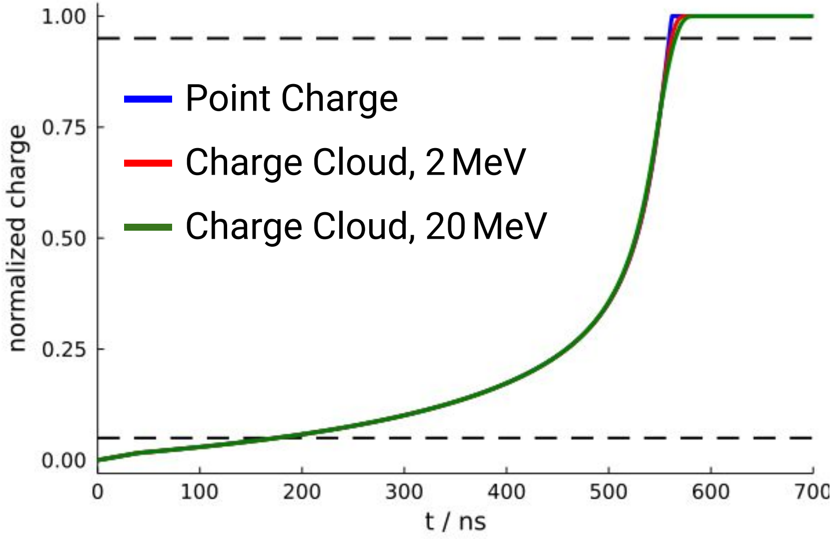


Charge Cloud Motion in Point Contact Detector

```
julia > evt = Event(CartesianPoint{T}(0.035,0,0.02), 20u"MeV", 40)
julia > simulate!(evt, sim, diffusion = true, self_repulsion = true)
```

```
julia > plot(evt.waveforms[1])
```

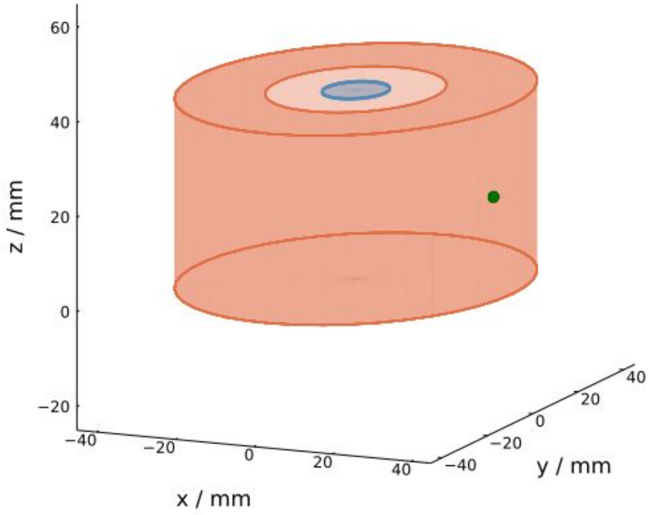




🟥 electrons
🟩 holes

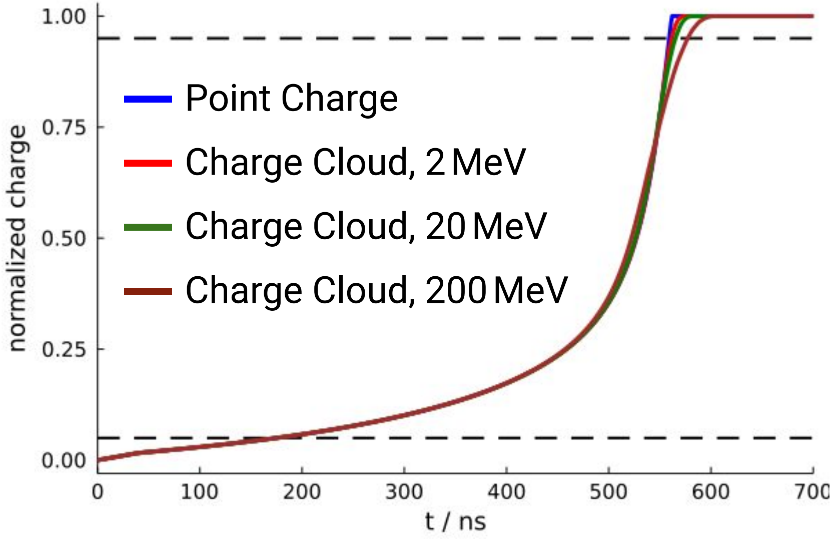
Charge Cloud Motion in Point Contact Detector

```
julia > evt = Event(CartesianPoint{T}(0.035,0,0.02), 200u"MeV", 40)
julia > simulate!(evt, sim, diffusion = true, self_repulsion = true)
```



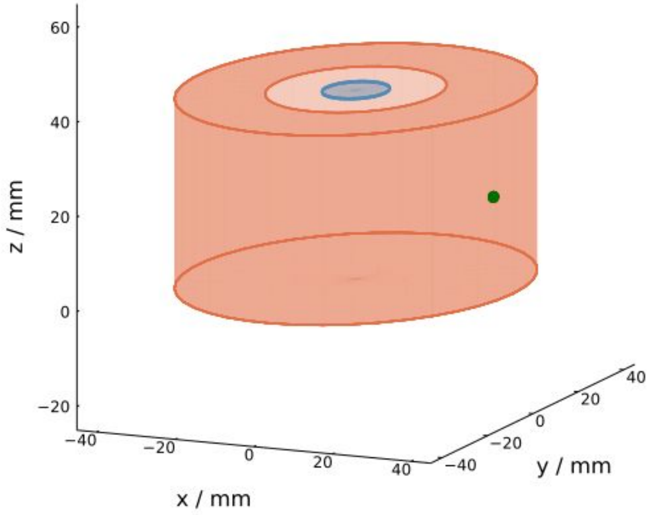
🟥 electrons
🟩 holes

```
julia > plot(evt.waveforms[1])
```

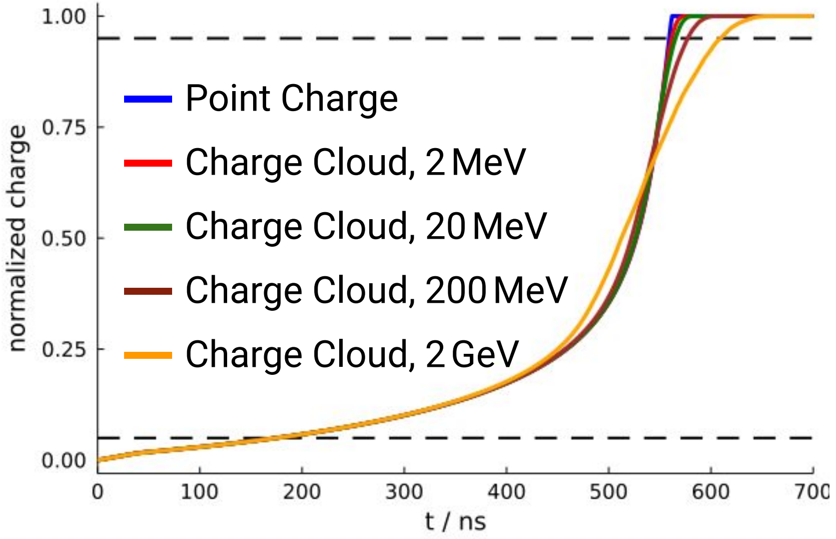


Charge Cloud Motion in Point Contact Detector

```
julia > evt = Event(CartesianPoint{T}(0.035,0,0.02), 2u"GeV", 40)
julia > simulate!(evt, sim, diffusion = true, self_repulsion = true)
```

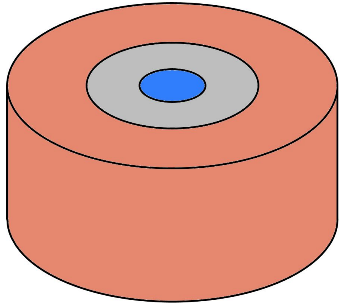


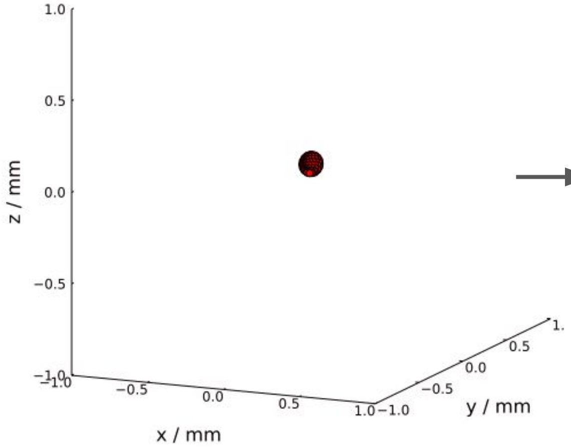
```
julia > plot(evt.waveforms[1])
```

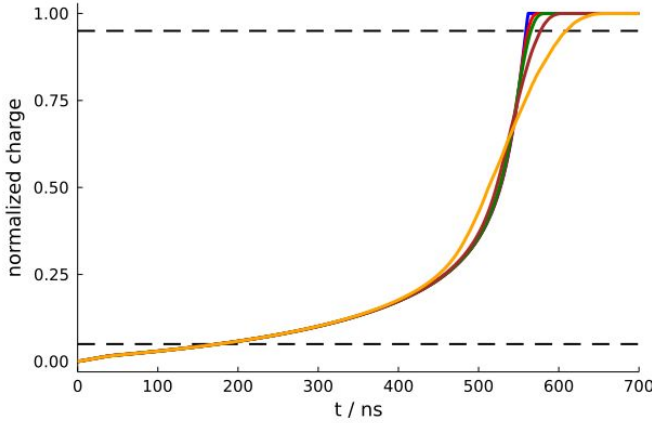


🟥 electrons
🟩 holes

Summary





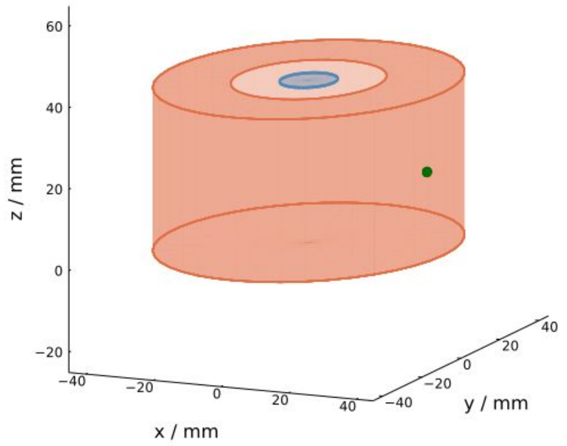


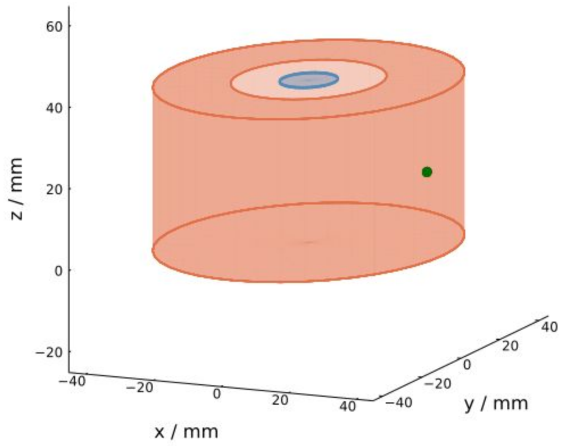
Pulse shape simulation in SolidStateDetectors.jl

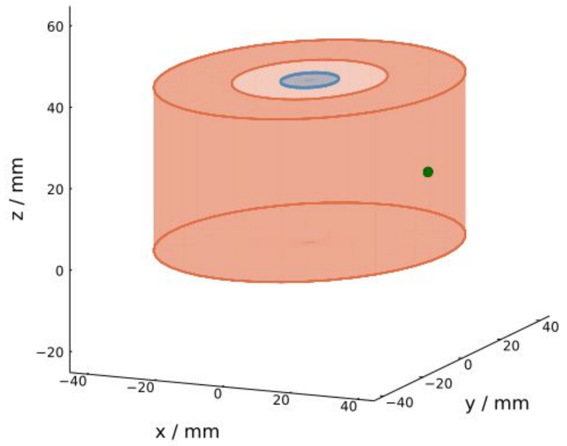
Models to describe diffusion and self-repulsion

Influence on the resulting simulated pulse shapes

Energy dependence







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