Light and Charge simulation

Version 0.1

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Installation

The install process should be very straight forward. It just requires a `root` install. I tested it with `root 6.26/06`, but anything above root5 should work. After cloning the directory, make sure that root is active (`root-config --version` should tell you if not). If not, source your favourite root build. Then, in the main folder just run `make`.

Sometimes this process can fail. The most common cause for this is the existence of older object files (`*.o`), that where compiled with a different root install/compiler/weather condition... In this case, remove all library files (`yes | rm *.o`) and run `make` again.

- **TL:DR** : Run `make`.

Usage

```
./analyze_light <G4_input_file> <SiPM_Placement_File> <Size of PD (cm)> <OutputFile>
```

- `G4_input_file`: Result from the Geant4 simulation (`qpixg4`)
- `SiPM_Placement_File`: Discussed below. Center of each detection element
- `Size of PD`: The full width of a single detection element
- `OutputFile`: Name of the output file
- Optional arguments are:
  - `--number <int>` Run over a subset of events (first n) instead of all in the file
  - `--charge <PathToPlacementFile>` Enables the charge simulation including diffusion using the placment file given
  - `--diffusion` Disables the diffusion during the drift
  - `--pixSize <double>` Using a specified size for the charge detector pixels. Otherwise the size of the SiPMs are assumed
  - `--exclOut` Disables the saving of the G4 input data to the output file

Output File

The output of the charge and light simulations are stored in the `ScintSim_tree`. The charge and light objects are of type `vector<vector<double>>`. The first axis corresponds to the id-number of the detector, just as in the placement files (see below). The second axis runs along the number of detected photons/electrons in this detector , and stores the times. These are not sorted in time! To access the number of photons detected in PD 17, one needs to run

```
total_time_vuv->at(17).size()
```

If one wants to get the hit times of all photons detected on PD 17, you have to

```
for(int photonIt = 0; photonIt < total_time_vuv->at(17).size(); photonIt++){
    time = total_time_vuv->at(17).at(photonIt);
}
```

Same holds for the charge output. See the section about the Analysis File below for more examples.

If the option `--charge` is not enabled, it will still produce an output element for it, which will be empty.

There are two TH2Poly's stored in the output file. These store the locations of the SiPM/Pixels. Again, if not run with the `charge` option, this is just an empty TH2Poly for the charge.

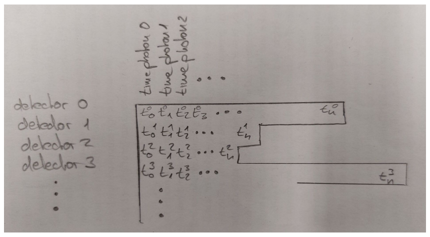


Figure 1: The setup of the vector `total_time_...`

- **TL:DR** : Returns `vector<vector<double>>` of PD-IDs and hit time for each photon/electron and TH2Poly for placement.
- **A note on the numbering: TH2Poly bin n corresponds to detector ID n-1!**
- Example in `Docs/ExampleMacro`

Placement Files

The goal of the code is to be able to run light simulations with arbitrarily placed detectors. For this, a so called placement file is required. These placement files give the center coordinates of each detector. The size of the detectors are determined in a later stage using command line arguments. Below you can find an example of such a placement file.

```
0 5.0 5.0 0 1 3
1 5.0 15.0 0 1 3
2 5.0 25.0 0 1 3
3 5.0 35.0 0 1 3
4 5.0 45.0 0 1 3
5 5.0 55.0 0 1 3
6 5.0 65.0 0 1 3
7 5.0 75.0 0 1 3
8 5.0 85.0 0 1 3
9 5.0 95.0 0 1 3
10 10.0 5.0 0 1 3
11 10.0 15.0 0 1 3
12 10.0 25.0 0 1 3
13 10.0 35.0 0 1 3
14 10.0 45.0 0 1 3
15 10.0 55.0 0 1 3
16 10.0 65.0 0 1 3
17 10.0 75.0 0 1 3
18 10.0 85.0 0 1 3
19 10.0 95.0 0 1 3
```

The first column gives the ID of each detector. These have to be unique. Next, the `x`, `y` and `z` coordinates are given. In the case above, we place 20 detectors on the `z=0` plane. The first ten are all placed with the same `x` coordinates and distanced 10 cm in the y-direction. The last ten are moved 5 cm along the x-axis. See the example in figure 1. The units are understood to be in cm.

The 5th variable is the detector type. This variable is currently not used. Its intension is to be able to implement different types of photo detector, meaning non-rectangular ones, i.e. circular PMTs, or any other difference between them. The last variable is the direction in which the active surface is pointing. If the detector sits on the `z=0` plane, it probably faces along the z-axis. This is noted with the value `3`. For detectors facing along the `y` axis, this value should be `2`, and for detectors facing along the `x` axis, `1`.

Generate for grid layout To generate these files, a helper script is supplied in `PlacementFiles/generate_detpos.py`. It generates a grid placement of a given distancing. Currently the same distancing is assumed for the `x`, `y` and `z` coordinates.

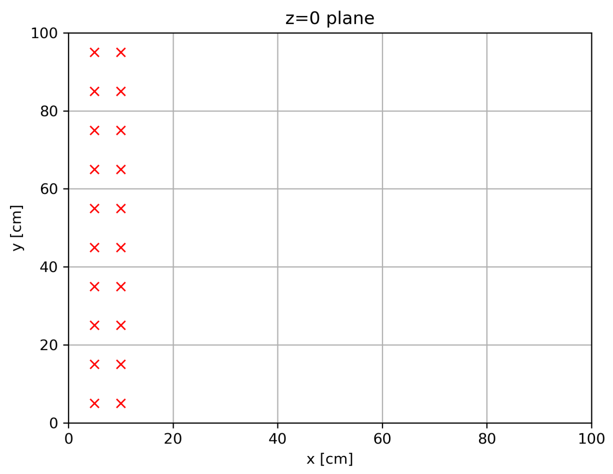


Figure 2: Placements for the example placement file above

But this can be adjusted easily, when required. The way to do that would be to implement different distances for each direction. Currently you comment out the corresponding parts that you don't want any PD placed at.

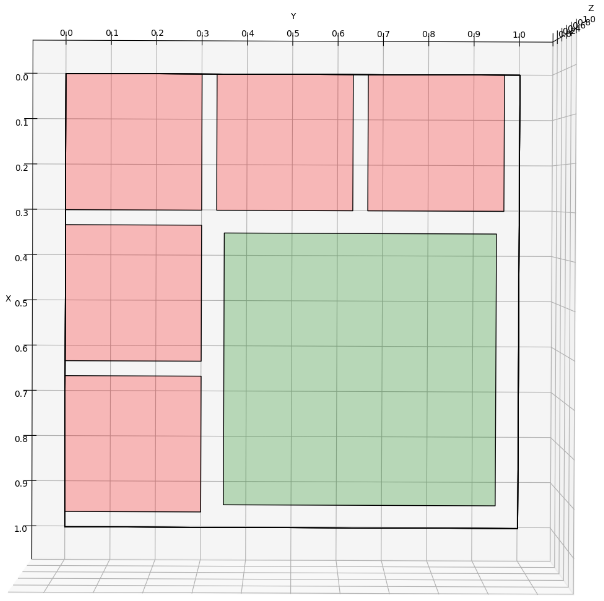
To get the placement file you run `python generate_detpos.py > placmenFileName`. To verify if this placement file you can adjust `1_plot_detector_locations.py` to plot the detectors in a 3D plot. Things to adjust here are the read in placement file in

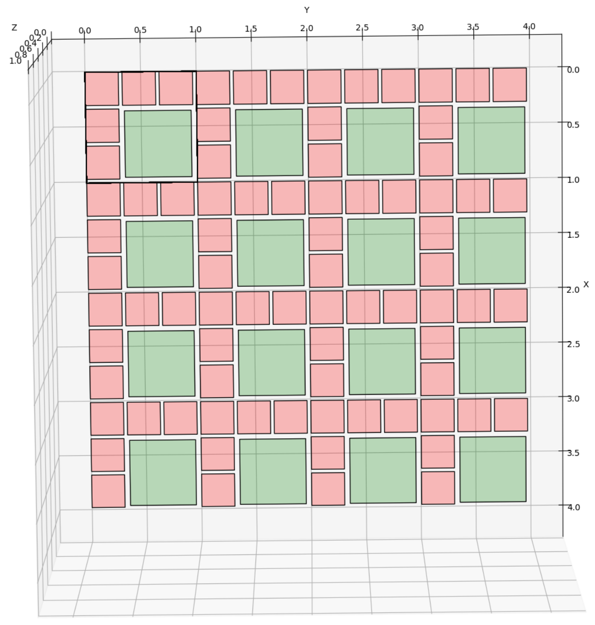
```
with open('../SoLAr_10cm_FieldCage.txt', 'r') as csvfile:
```

and then a little bit below the sizes of the detectors you want to plot. In the case we want to have $2 \cdot 2cm^2$ pixels, the placement file above would produce the example in figure 2. Then run `python 1_plot_detector_locations.py` and you will see a 3D plot of the placements and sizes of the detector you created.

Generate for SoLAr Tiles Also here we have a helper script, `PlacementFiles/generate_detpos_SoLAr.py`. At the top, you determine the size of the Anode/Readout plane and the distance between single tiles. A tile here is understood to be a 1×1 cm^2 assembly of 5 charge pixels and 1 SiPM (see below).

The code returns two files, `SiPM` and `Pixel`. They store the positions of the SiPM's and Pixel's…





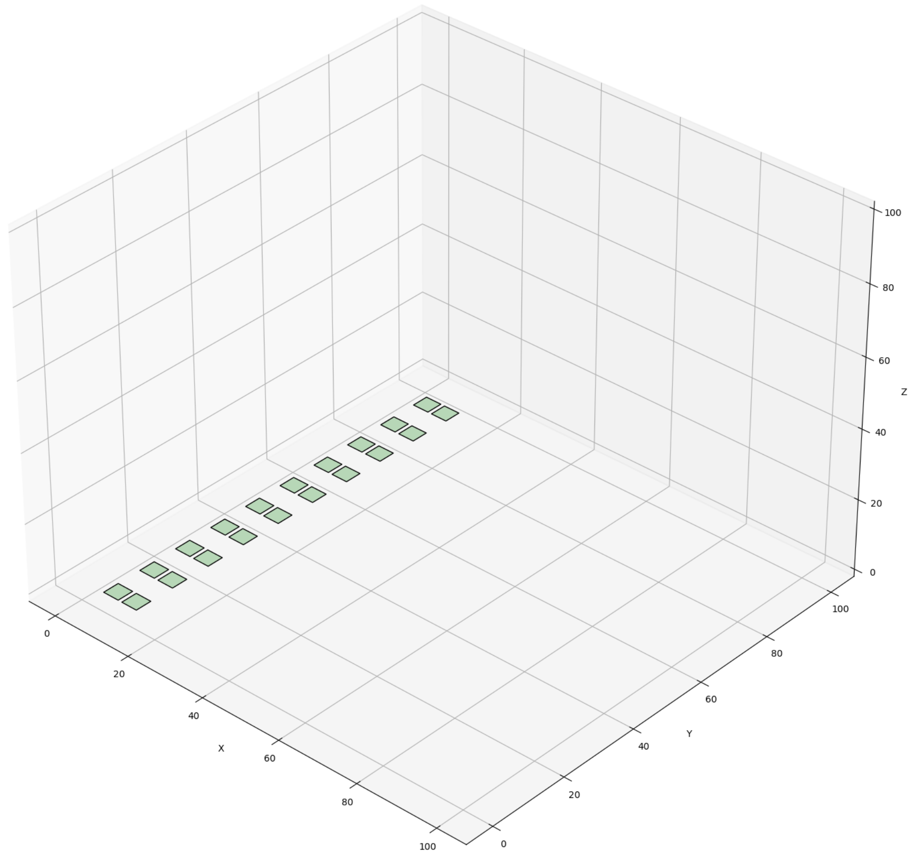


Figure 3: Example of the placement file on the X-Y plane with $2 \times 2cm^2$ pixels

There is a known problem to occour, if the spacing and sizes are incompatible. Some of the detectors actually lie outside of the actual detection plane in this case. Again, see below.

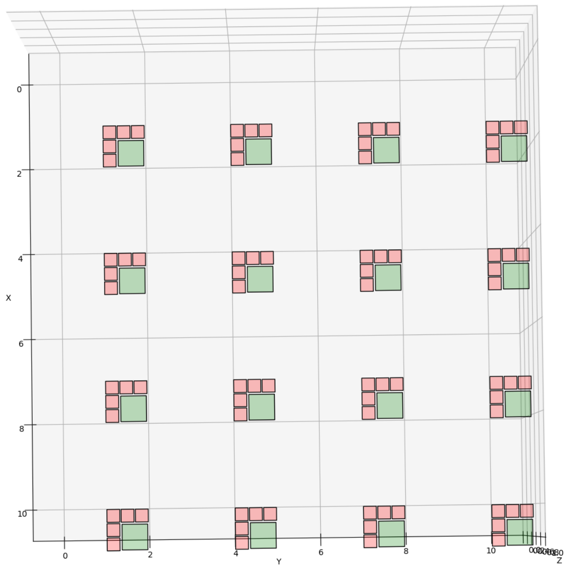


Figure 4: A problematic placement

It's the users obligation to verify that there are no strange placements.

For smaller files we have the `plot_SoLAr_locations.py` to return a 3D plot to verify. For larger ones, this is code is to slow - at least on my machine. A 2D version could speed things up - but not implemented yet. (Or move to a proper GUI/C++ version at some point).

Simulation procedure

Light

- Based on this Paper
- Removed the visible light and enabled placement of PD on all planes, implemented LArQL model
- Split the total amount of photons produced in an event by the fractional solid angle of each photo-detector element

The idea of the light simulation is to first approximate the photons that arrive in each Photo Detector by its relative solid angle and then correct this approximation for effects like rayleigh scattering. The geometrical approximation for detector i is then just

$$N_{\gamma}^{Det} = \Delta E \times S_{\gamma}(dE, dx, \epsilon) \times \Omega_i/4\pi \times exp(-d/\lambda) \qquad (1)$$

- ΔE energy deposit
- S_{γ} the light yield function, in our case LArQL
- $\Omega/4\pi$ fractional solid angle of the detector i
- λ the absorption length (here 20m)

Then a Gaisser-Hillas function is used to correct for the effect of Rayleigh scattering and positional dependences. The time is finally constructed using a exponential plus landau function which is randomly sampled. For the details about the Gaiser Hillas and the time sampling, the paper and source code are a good combination as explaination.

- Drawbacks: Scales linearly with the number of PD. Results dependend on the parametrisation. This was build for DuNE and SBND, including the wires etc. This means that events which are placed in a smaller Volume (like SoLAr) are affected, if they are not in the center of the detector. Moving them to one side, we accumulate different effects due to asymmetry. For DuNE/SBND these are corrected for, but for SoLAr they wont. Its hard to tell how significant they are. We could rebuild a parametrisation for SoLAr using Danieles G4SOLAr.

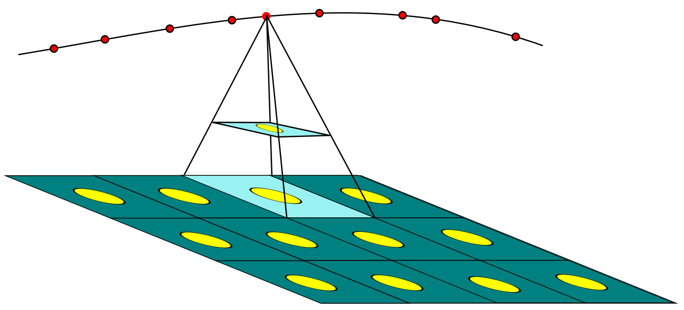


Figure 5: Conceptual Drawing of the Semi Analytical Model

Charge

Similar approach, where the number of electrons are calculated from the hits using LArQQ. These electrons are assumed to be produced at the hit-point. Then their starting position is smeared in the x-y plane according to the D_T drift constant, with the drift-time calculated as $t_{drift} = z/v_{drift}$. Along the z-axis the electrons are smeared with the D_L drift constant in the same manor. These starting positions are then stored in a vector. Here we assume that the drift-direction is along the z-axis, and the charge-readout sits on the z=0 plane. In the main event loop we loop through all the produced starting points, figure out if a PD/CD sits below this point. For this a TH2Poly is used as a way to determine the CD-ID. The time is then produced according to $t = z/v_{drift}$ and stored in the output object.

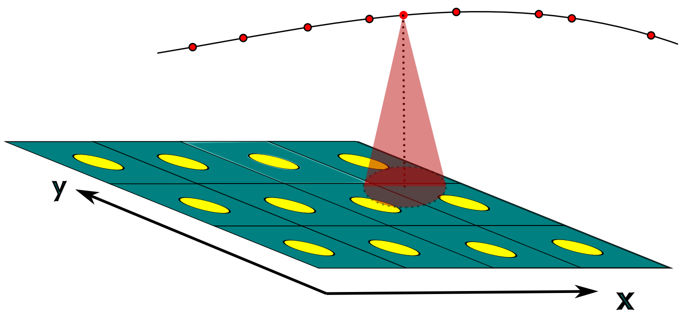


Figure 6: Conceptual Drawing of the Charge Simulation

- Drawbacks: Currently we need to assume a super-non-optimized electric field, which means most of the charge is lost, as it is not sitting perfectly above a pixel.

Analysis of the files

I included an analysis example script. It is just a simple ROOT macro, which can be run by `./Run.sh`. Most of it is heavily commented, so you should be able to understand everything. If not, feel free to contact me.

The code shows how to access the time vectors, how to get the pulse shape and the position of each detector. It builds an event display. Non the less, lets summarise the most common steps:

- **Building a pulse shape for the jth detection element** For this we need to access the `j` subvector of `total_time_vuv` and then loop through its contents, which are the arrival times.

  ```
  vector<double> jth_subdetector = total_time_vuv->at(j);
  TH1F *h_pulseShape = new TH1F("PS", "PS", 100,0, 4);
  for(int photonIt = 0; photonIt < jth_subdetector.size(); photonIt++){
      double time = jth_subdetector.at(photonIt);
      h_pulseShape->Fill(time);
  }
  ```

  Its noteworthy that the times inside the vector are in units of microseconds. This means above pulse shape spans up to 4 μs

- **Building the accumulated pulse shape** Here we do the same as above, just with an extra `for` loop over the subdetectors.

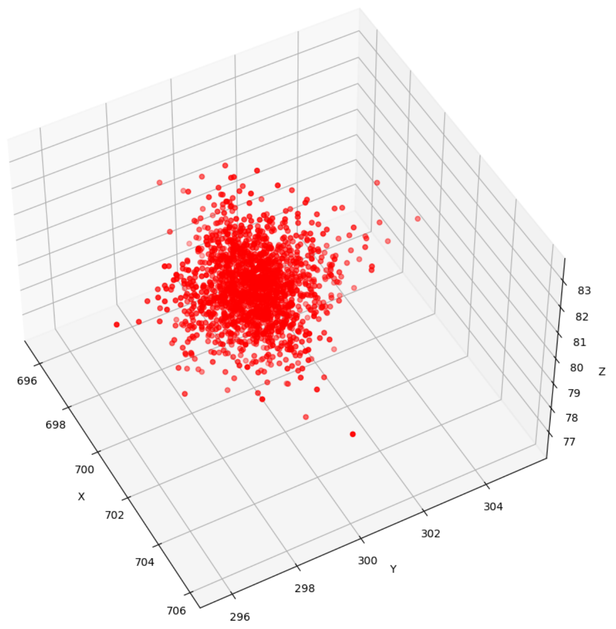


Figure 7: Starting Positions of electrons of a single energy deposit after smearing

```
TH1F *h_pulseShape = new TH1F("PS", "PS", 100,0, 4);
for(int detectorIt = 0; detectorIt < total_time_vuv->size(); detectorIt++){
    for(int photonIt = 0; photonIt < total_time_vuv->at(detectorIt).size(); photonIt++){
        double time = total_time_vuv->at(detectorIt).at(photonIt);
        h_pulseShape->Fill(time);
    }
}
```

- **Get the bin center of a detector** As `TH2Poly` seems to not have `GetBinCenter` for a single bin number implemented, we need to do this ourselfs... This is done building dictionaries of bin numbers and bin centers.

```
CLTree->GetEntry(0);
map<int, double> CDbinsX;
map<int, double> CDbinsY;
TList * list = (TList*)ChargeReadout->GetBins();
TIter next(list);
TH2PolyBin *bin;
while((bin = (TH2PolyBin*)next())){
  CDbinsX.insert(pair<int, double>(bin->GetBinNumber(), (bin->GetXMax()+bin->GetXMin())/2));
  CDbinsY.insert(pair<int, double>(bin->GetBinNumber(), (bin->GetYMax()+bin->GetYMin())/2));
}
```

Here `CLTree` is the tree from the simulation and `ChargeReadout` is the `TH2Poly` stored in the root file, named `charge_placement_map`. We retrieve a list, which is filled with so called `TH2PolyBin` objects. These bins can give us their bin-number and their locations. We store this connection between bin number and the center point of our bins in a dictionary. To then get the center coordinates of bin `i` we do

```
double x_center = CDbinsX(i);
double y_center = CDbinsY(i);
```

This should be part of any analysis script we write. Therefore it is worth building these dictionaries in the simulation itself and storing them in the root file directly. To do this, copy the construction code above in to the simulation code, just behind the building of these TH2Poly-objects. Then you need to define a new `data_output` functon, that stores these dictionaries in to the root file. The same dicitonaries is build for the light detectors inside the example script.

- **Conecting a single detection element to a coordinate**. As the numbering scheme in TH2Poly is strange, the i'th subvector corresponds to the bin $i + 1$ inside the TH2Poly. Meaning, to get its center coordinates, we need to run `CDbinsX(i+1)` and `CDbinsY(i+1)`. This could be circumvented when building the dictionary differently. But I prefer to have the direct bin numbering in the dictionary, instead of the shifted one. Feel free to change to your liking.

ToDo's

- Current Status: The runtime is an issue
  1. Light
     - No straight forward to multi thread this, as ROOT objects are called in the loop which are not thread safe!
     - If code should be used long term, a refactoring in its own class would be necessary
  2. Charge
     - An earlier version of the code was already MTed, this should also be possible with the new version. Here it is important to make sure that not more time is used passing the final vector between cores, but actually calculating things.
- A better initial distribution of the starting electrons could also be useful. Similar, most of the electrons currently fall in the big space where the SiPM sits and are not detected. But in a real detector one could probably tweak the electric field to circumvent this. Not entirly sure how this should be implemented. Maybe a simple approach would be to take the electrons that hit nothing (in the TH2Poly this should be bin -5), and then take a 80% (or whatever efficiency you have) of them and distribute them in to the neighbouring pixels. For this a rounding using the relative could be efficient?
- The TH2Poly for the light output assumes that the orientation is 3 (on the x-y plane). This should be fixed for possible light-field-cage studies. Meaning, that 6 TH2Polys should be created and stored, corresponding to the 6 sides of the detector. For this a bin-shift would be necessry. The light simulation still works with other placements, but the identification between detector-id and placement would need to happen through the read in of the original placement file.
- Implement the center dictionaries directly in to the root files (see above)
- Validate / Build parametrisation for SoLAr