Hyper-K Outer Detector Light Injector Calibration Documentation

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Contents

1 Introduction

This document is intended to serve primarily as a handover document for the next person to take over this work. Accordingly it will be written more as a guide than a formal document, so that whoever you may be, you can get things up and running in the first instance, while then gaining greater insight into the work and how to move it forward. Sections 3, 4, and 5 are the ones that you could choose to skip to just to get the ball rolling, but I would *strongly* suggest reading everything in order to get a good understanding of the work. I know this isn't a short document but there are many elements involved in the OD calibration and one could easily get lost.

For a more formal and thorough overview of the light injection (LI) calibration strategy for the the outer detector (OD), I would suggest reading the calibration section of the OD technical report. I will attach a copy as Appendix C to this document. Something to be aware of with the OD TR though is that some of the results presented there are for configurations in WCSim that are not current (due to changes in the OD design since the report was written, and an issue with how quantum efficiency (QE) is implemented in WCSim). I will expand on those points below, and in the subsequent sections of this document I will include more current results with the right QE settings (where available).

For actual guidance on installing, setting up, and running WCSim, if you're not familiar, I would direct you to the computing documentation (Hyper-K edition) written by Tom Dealtry and Matt Lawe, as well as the tutorials in the WCSim GitHub `https://github.com/WCSim/WCSim/wiki`.

1.1 General calibration strategy

The LI calibration system will study PMT properties using an array of diffuse sources across the whole detector (21 per end cap, 80 in the barrel), and water properties using collimators directed across the diameters of the end caps (4 per cap) and up the height of the barrel (4 in barrel) in order to produce long path lengths of light. More details are given in Appendix C, but to briefly describe the concepts involved:

(a) Using low intensities of light delivered through the diffuse array, the PMTs can be illuminated to approximately the single pe level, which will help measure drift in the gain over time. Higher intensities of light can be used to saturate the response of the PMT/electronics system, and so within this range of intensities the linearity of the charge response will also be able to be studied (see Appendix section C.1).

(b) Injecting high intensities of light via the collimators will allow us to detect changes in the absorption and Rayleigh scattering of the water, as well as changes to the Tyvek reflectivity over time. Changes in these properties will result in changes to the charge deposition across the detector (see Appendix section C.2).

1.2 Things to be aware of

1.2.1 Angles!

Everywhere in this document when I talk about the opening angle of the LIs I will be talking about the **half angle**. I will endeavour to consistently say half angle, but I am fallible, so if I forget the half please know it is implied. As a general note, the nominal diffuser half angle used in these studies is 40 degrees, and the nominal collimator half angle is 2 degrees.

1.2.2 WCSim is being replaced... eventually

Something will be replacing WCSim. It does not exist yet. I don't know when it will (that is something to pay attention to software group meetings about). But because of this planned change, development of WCSim (at the higher level) is winding down/done. So if you're reading the rest of this section wondering if something will be fixed/improved upon, the answer is (in WCSim) no. At the moment we do the best with what we've got.

1.2.3 Quantum Efficiency (QE) in WCSim

Short version: for optical photons it is bad and wrong. Especially so for OD simulations. Always use SensitiveDetector_Only, lest you overestimate the QE by more than a factor of 2.

Longer version: see Appendix B.

Still always use the QE method SensitiveDetector_Only. Any other method will vastly overestimate the QE. SensitiveDetector_Only will give you the closest to expected QE (and perhaps a slight underestimate). The numbers behind this assertion are shown in the appendix, in Figure 12. But basically if you have a PMT with a QE of 28% at 400nm, SensitiveDetector_Only will give you an effective efficiency of 24.6%, as opposed to 63-67% with other methods.

1.2.4 The simplicity of the detector geometry

If you're not familiar with WCSim, then one thing to know is that the detector geometry is very simplistic. It is (for the most part) not based on CAD models, simply the basic measurements of the detector. There are no objects like electronics boxes, water pipes, etc. The PMT placement is uniformly generated by the software when given a percentage photocoverage (or a number of PMTs per cell).

Similarly, when placing the light injectors into the model, as there currently aren't any landmarks/specific objects to avoid (other than the PMTs themselves), the injectors are just reasonably evenly spaced around the detector (positions as calculated are given in Appendix A.1, for reference). One day there will hopefully be a more realistic geometry, into which you more intelligently place the LIs. Today is not that day.

1.2.5 The simplicity of the light injector profiles

At the moment the light sources are just simulated as isotropic cones of light. Some measurements of potential LI profiles have been made, and some measurements are yet to be done. But once those profiles exist, they should replace the simplistic cones.

1.2.6 The top cap support structure

This warrants its own full section later in the document, but I will raise the point now. There will be a support structure in the top cap of the OD that introduces a lot of material that obviously can obstruct the light. The metal struts will (hopefully) be wrapped in Tyvek, to improve light collection a bit. But it has an effect, as will be discussed in Section 6.

1.2.7 The number of PMTs in the simulation

In my simulations thus far, I have used a photocoverage of 0.22%, which results in 9500 PMTs. The design for the OD has changed, and the number of PMTs will likely be 7500-8000 (but pay attention in OD meetings in case this changes). The reason I haven't switched to this number yet myself is because between the QE kerfuffle, and two different top structure designs, I've been trying to quantify those particular changes in the last few months, and so I needed to keep the number of PMTs constant. But this work should move to the correct level of photocoverage.

1.3 Things that need studying sooner rather than later

There are many things to do, but these I feel are some of the most important (in order of importance):

1. **Completing the collimator studies in the top cap with the support structure in place** - As you'll see later, there is a need to look again at the absorption sensitivity, and to look for the first time at the tyvek reflectivity, for the collimator studies in the top cap. This is important because it informs whether we want collimators in the top of the OD.

2. **Switching to 7.5-8k PMTs** - Obviously we want to actually determine the performance of the calibration system with the expected number of PMTs.

3. **Implementing the more realistic LI profiles** - This depends on when you get them, but using a more realistic light profile will obviously be beneficial.

4. **Repeating saturation and single pe coverage studies with the newer top support structure design** - The new design only became available a few weeks ago, so I haven't been able to repeat these. However, given that the structure was not a huge problem with the old design, which had more material in it, I expect things to still be okay. But that should be confirmed.

2 Code base

In this section I'll describe the calibration settings in WCSim, and go into a little more detail about what is being done by the code. It isn't necessary

Calibration source	Description
fullInjectors	The full array of 122 LI.
colBarrel	A single LI positioned at the bottom of the barrel pointing up.
colTop	A single LI pointing across the diameter of the end cap.
colBottom	A single LI pointing across the diameter of the end cap.
satBarrel	A single LI mid-height in the barrel.
satTop	One of the inner three LI in the end cap.
satBottom	One of the inner three LI in the end cap.
timeTop	Old setting; a top cap source that was used for some timing tests.
IWCDfullInjectors	An array of LI for the IWCD geometry, no longer used.

Table 1: Calibration source types in WCSim

to understand the latter to initially start turning the handle on the studies, but it will be important as you start development (or come across bugs that I've missed).

2.1 Github

The relevant repo is here: `https://github.com/CPidcott/WCSim/tree/OD_calib_devel`

2.2 Calibration macro settings

There are a number of calibration settings used in the macros at run time, defining the type of calibration to be run, the number of photons to simulate, their wavelength, and the half angle of the LI. While these can be queried within WCSim, I'll explain them here.

2.2.1 /mygen/generator calibration

This sets the the generator, shockingly enough, to calibration.

2.2.2 /mygen/calibrationsource

Defines what kind of calibration to run. Default setting is fullInjectors. Full list of settings is in Table 1.

2.2.3 /WCSim/calibrationsource/NumCalibParticles

Sets the number of photons to generate per LI per WCSim event. Default value is 5000. So for example, if the calibration source is satBarrel, this will result in that single LI producing 5000 photons per event. If the calibration source is fullInjectors, per event you will produce 5000 photons from each of the 122 LI per event, so 610000 photons per event.

2.2.4 /WCSim/calibrationsource/CalibSourceHalfAngle

Sets the half angle to be simulated (in degrees). Default value is 40.

2.2.5 /WCSim/calibrationsource/CalibSourceWavelength

Sets the wavelength of light to simulate (in nm). Default value is 400nm.

2.3 Source simulation

The code that produces the LI simulations is in $WCSimRootDir/src/WCSimPrimaryGeneratorAction.cc, starting at line 512. As described previously, the light sources used are simple isotropic cones of light, with the photons being generated over 20ns with a random flat profile (to approximate a 20ns pulse from an LED).

If you're familiar with Geant4, you might wonder why I've essentially reinvented the wheel (or rather GPS class) by implementing these using particle gun commands rather than the GPS settings. Basically I didn't 100% trust what the GPS class was outputting, so I explicitly defined my sources with code I knew worked.

If you're not familiar with Geant4, the previous paragraph need not concern you. Especially since, as previously mentioned, soon these light settings will need to be replaced with the actual light profiles from diffuser measurements.

2.4 Detector simulation

As mentioned previously, in the studies I have performed thus far, the detector has 0.22% PMT coverage. The OD wall Tyvek reflectivity is set at 90%. When the top cap support structure is included (I suggest commenting it out for barrel/bottom cap only studies, as it drastically slows down the simulation by a factor of 4 or 5) I simulate it skinned with 80% reflectivity tyvek (to somewhat imitate poorly wrapped 90% reflectivity tyvek). The wall Tyvek reflectivity is set in $WCSimRootDir/src/WCSimConstructMaterials.cc using WCODTyvekReflectivity (which can be set in tuning_parameters.mac, a file that you'll get more familiar with in Section 5), while the support structure strut tyvek reflectivity is hard coded to 80% using StrutTyREFLECTIVITY set at line 914 in WCSimConstructMaterials.cc.

In terms of the settings used at run time to define the detector, there are a number of OD specific settings used in the .mac file, these can be seen in $WCSimRootDir/macros/calibrations_macro.mac, lines 10-26. These are all obviously also set in the various mac files described in the later sections on running the studies, but it is worth noting what these settings are so that you're familiar.

2.5 Arrangement of main studies

Within the OD calibration development repo, I've arranged the single pe, saturation, and collimator studies into their own directories (named single_pe_studies, saturation_studies, and collimator_studies respectively). Within these directories are the scripts and macros required to perform the simulations and analyses. The corresponding sections of this document are also arranged accordingly.

(I think) all of these would need to be run from your top level WCSim working directory, so scripts and .mac files would need to be moved, however for the sake of organisation this is how I've arranged them in the repo.

One common feature you'll notice is a root macro to reduce the WCSim output, imaginatively named ReduceODOutput.C. It reduces the size of the output files by approximately a factor of 300, pulling from the WCSim output files the key variables used in the OD studies (e.g. hit charge, time, and PMT information). This is particularly important for the collimator studies, which given the statistics used would otherwise result in terabytes of data.

ReduceODOutput.C includes a nearestInjDist variable, which calculates the distance between a PMT and it's nearest LI *in the diffuse source array*, which means two important things; (1) that the variable is not applicable for collimator studies, and (2) that if you change the positions of the LIs in WCSimPrimaryGeneratorAction, you will need to apply the same change at line 120 of ReduceODOutput.C.

The following sections will describe the files, scripts and tools used to perform this analysis. I'll include job submission scripts, as these are important (particularly for the more resource intensive saturation and collimator studies) to parallelise the work. The Sheffield cluster uses condor, so these scripts do too, and you might need to adjust the scripts accordingly for any other systems. I've also tried to strip out the more specific directory paths, so you'll need to alter those to fit your needs.

2.6 General and miscellaneous scripts

There are some scripts that I have used over the last few years for various smaller tasks. I'll include them in a miscellaneous_scripts directory in case they are ever useful, but I make no promises as to quality, functionality, comments, etc. Nor will I document them here. They'll just be there, do with them as you will.

3 Diffuse single pe studies

While in practice individual LIs will be pulsed, in simulation I run all of them at once (rather than run 122 separate jobs). With these studies we're looking to confirm that we can achieve single pe coverage of the detector. These simulations use 10000 photons per LI per event, and we look at the mean digitised charge collected across the detector, as well as the efficiency of delivering charge to the PMTs (how many events result in charge detected), which will change as a function of distance between the PMTs and their nearest LI.

3.1 Simulation methods/tools

Within the single_pe_studies directory there are three relevant files:

- full_diffuse_fibres.mac: defines the WCSim run settings.
- submitWCSim.sh: can be submitted to your job/batch submission system, setting the directories to save the output to, runs WCSim, produces the reduced output file, and removes the full sized WCSim output file.

- ReduceODOutput.C: creates the reduced output file, resulting in much smaller file sizes.

Then, in a condor based system, you would submit the job with:

```
$ condor_qsub /path/to/submitWCSim.sh -e /scratch/user/default_diffuse.err
-o /scratch/user/default_diffuse.out
```

3.2 Analysis methods/tools

The analysis of your reduced output file is performed using OD_Analysis_reduced.C. You use it as such:

```
$ root -l -x 'OD_Analysis_reduced.C("/path/to/reduced_output_file.root")'
```

This will produce plots of the efficiency of delivering light to the PMTs as a function of distance from their nearest LI and just by PMT ID, the (poisson) mean charge collected by the PMTs as a function of distance from their nearest LI and just by PMT ID, and a full view of the sum of the charge collection across the detector for all events.

3.3 Current results

Figures 1-3 show some of the results for the HK OD *in the absence of the top cap support structure* for 10000 photons per LI per event.

In Figure 1, we can see that the mean digitised charge is close to the single pe level we want, except in the PMTs that are closest to the LIs. This is particularly prominent in the barrel region, where we see peaks corresponding to the 5 vertical rings of LIs. For these PMTs, to make a single pe measurement, we would want to illuminate them with a more distant LI.

In Figure 2 we can see this effect again, instead now we're looking at the sum of the charge across the detector for all 1000 events. The positions of the "hot spots" show where our LIs are placed, with far cooler regions in between.

In Figure 3 we see the efficiency with which we're detecting charge in the PMTs as a function of the distance of the PMT from its closest LI. This information is also contained in the colour scale in Figure 1, but is more clear here. We see clearly that the efficiency drops as we move further from the LI, and we also see two features to the curve between 0 and 300cm; the higher curve corresponds to the barrel region where the effect of being closer to the LIs is more pronounced due to the 1m OD (as opposed to 2m in the caps),

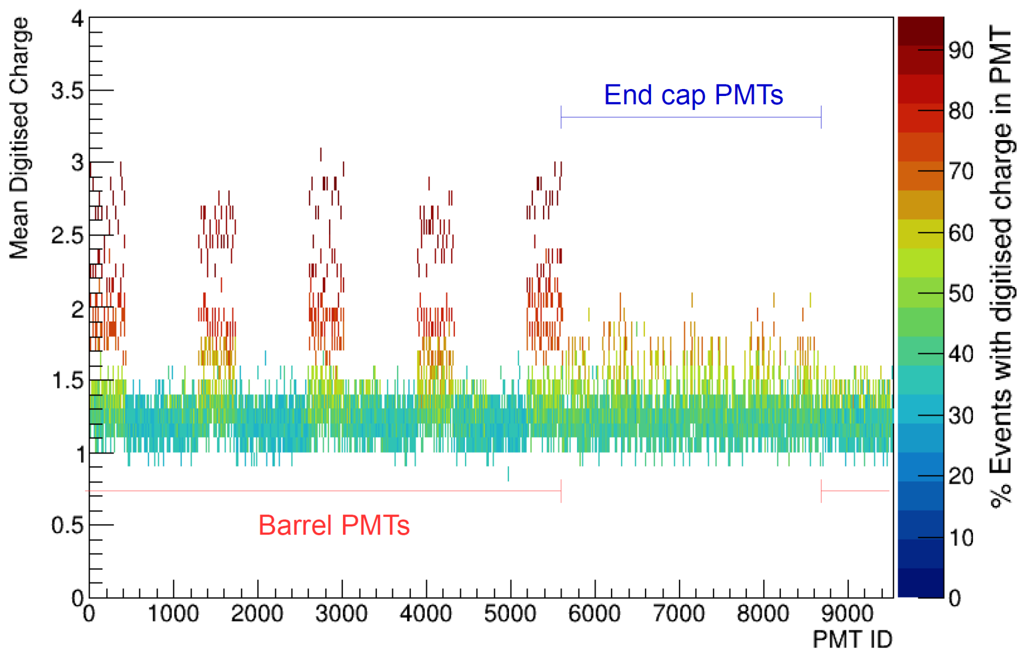


Figure 1: Mean charge collected per PMT per event that resulted in charge being collected, at low light levels injected through the diffuser array. The colour axis represents the number of events for which charge was collected by the PMT, out of 1000 simulated events (so effectively efficiency).

so the light has diffused less and as such is more intense after the first initial reflection from the outer wall back onto the PMTs.

4 Diffuse saturation studies

For these studies I have been simulating a single source in the centre of the barrel, and single sources in the central rings of the end caps, as outlined in Figure 4. In future studies, sources closer to the edges of the caps and top/bottom of the barrel should also be studied. But it would be worth confirming whether or not there will be a skirt between the caps and the barrel (there isn't currently in WCSim) as that will impact the results.

In the current design, the limiting factor of the operating range for the PMT response is actually the electronics response, which is expected to saturate around 200 pe. As such, this has been used as the threshold for sat-

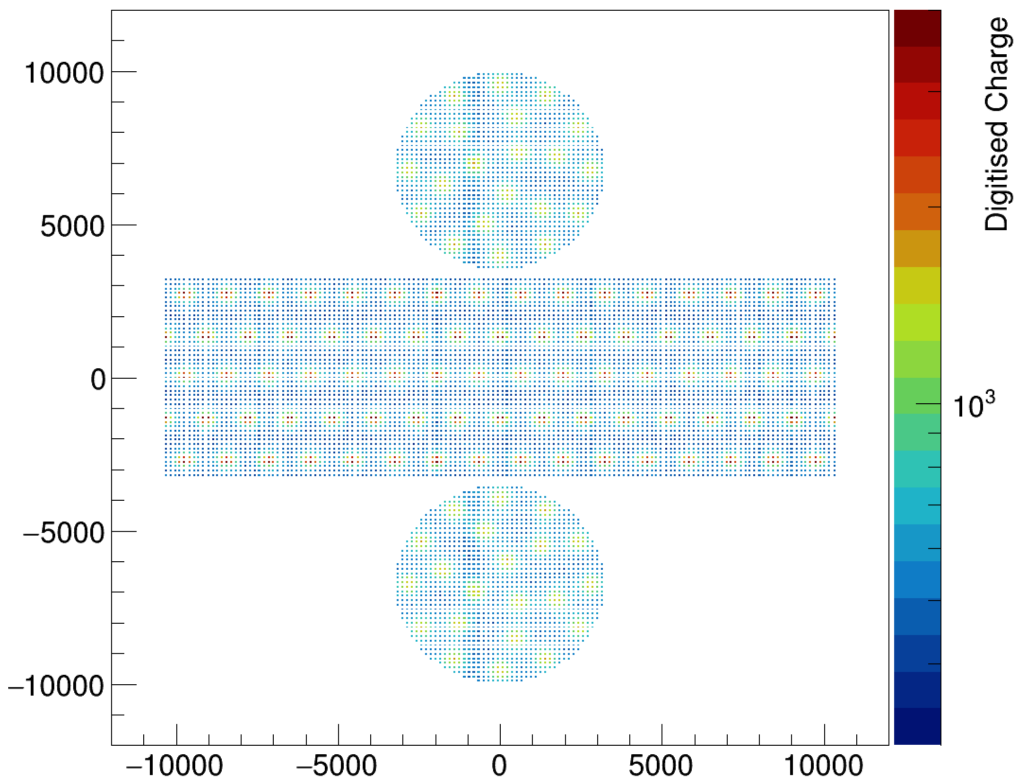


Figure 2: Charge collected over 1000 events. Each cell represents one PMT+WLS plate (but plate drawn to 60cm for visibility in plot, as opposed to the 30cm in the simulation).

uration studies, to determine what proportion of PMTs we can expect to saturate with the diffuser system.

Simulating the number of photons required to saturate the PMT response is computationally intensive, and it was not possible to simulate sufficient light levels to saturate 100% of PMTs in the radius of interest. These studies used photon numbers of 9×10^6 per event, simply because that is how many photons I could simulate with 8GB of RAM. The actual number of photons we're likely to be able to get from the LED system is something it would be good to get from a real measurement, to inform the future light levels used

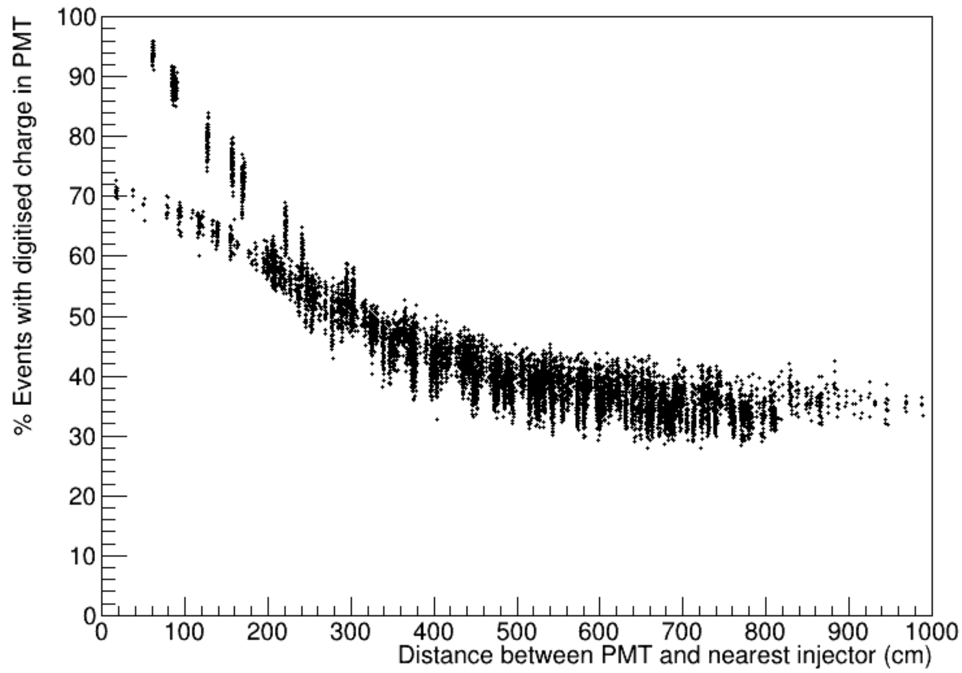


Figure 3: Efficiency of detecting charge in the PMTs, as a function of the distance between the PMTs and their nearest LI.

in saturation studies.

4.1 Simulation methods/tools

Within the saturation_studies directory there are four relevant files:

- one_diffuse_fibre.mac: defines the WCSim run settings. This is set up to run a single event.
- submitWCSim.sh: sets the directories to save the output to, runs WCSim, produces the reduced output file, and removes the full sized WCSim output file. This is called by subMultiDiffuse.sh
- subMultiDiffuse.sh: Will submit 1000 WCSim jobs, incrementing the random seed each time, so that you can generate 1000 saturation events

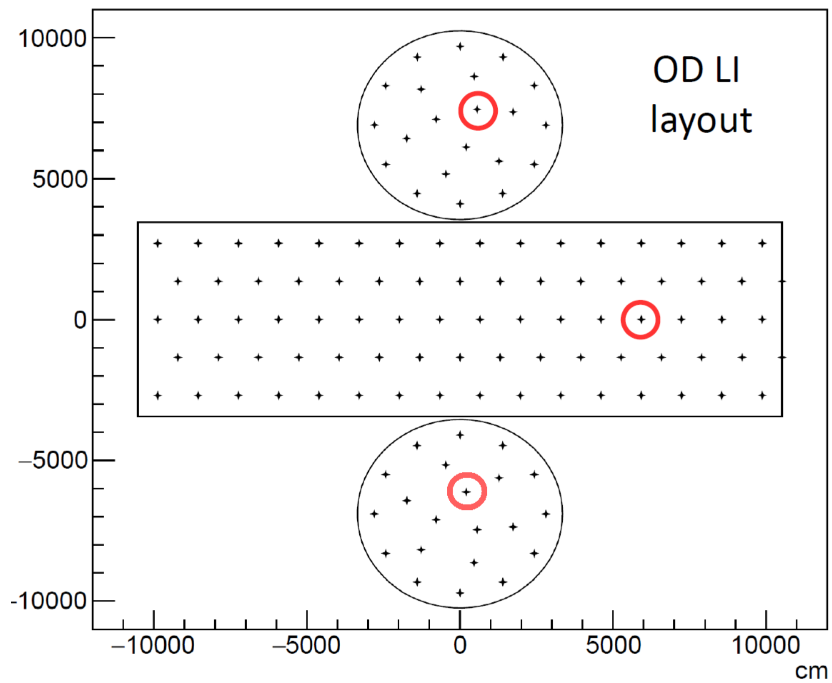


Figure 4: Sources used in saturation studies, outlined in red.

in a parallelised and less painful (to you, not your cluster) manner. Currently set up to use a condor system.

- ReduceODOutput.C: same as previously described.

Currently one_diffuse_fibre.mac, submitWCSim.sh, and subMultiDiffuse.sh are set up for running the barrel saturation (calibrationsource = satBarrel) studies. To run for the top or bottom caps, all instances of ”barrel” need to be changed accordingly. You might choose to edit these scripts to make top/bottom/barrel an argument that sets this up at the command line. But that is not currently how the scripts work.

So you need to make sure that your paths are all pointing to the right place, and make sure that across those three files you've been consistent in whether you're running for the barrel, top, or bottom cap.

You then very simply run everything using

```
$ ./subMultiDiffuse.sh
```

This will run your 1000 single event jobs, and every output WCSim file will have the reducer applied to it. If any jobs fail/disappear, you can re-run that script; there is a line that will check which reduced output files exist, and for the ones missing it will resubmit the job.

You will then need to hadd the 1000 reduced files into a single file to pass to the analysis.

4.2 Analysis methods/tools

The mean PMT charge response per light injection event within an 8.5 metre radius of the diffusers was studied. This radius was used as it is the maximum distance between any PMT and its nearest injector (in these central areas of the caps/barrels - closer to the edges it can be up to 10m).

The analysis of your hadded reduced output file is performed using OD_Saturation_Analysis_reduced.C You use it as such:

```
$ root -l -x 'OD_Saturation_Analysis_reduced.C(
      "/path/to/hadded_reduced_output_file.root")'
```

This will produce plots of the mean charge per PMT per event as a function of distance from the LI, as well as plots showing the charge collected within 8.5 metres of the LI.

Actually, there is an additional root macro, mean_plot_threshold.C, that will make a much better version of that first plot (with errors from the poisson fit for the mean). You use that script as such:

```
$ root -l -x 'mean_plot_threshold.C(
      "/path/to/hadded_reduced_output_file.root")'
```

4.3 Current results

Figures 5 and 6 show some of the results for the HK OD *in the absence of the top cap support structure* for 9 million photons per LI per event, for the bottom and barrel LIs (I'll address the top cap in the support structure section).

In the left hand plots, the overlaid circles represent the outer edges of incident light, as would be expected (from basic trig, not rigorous study) for a 40 degree cone of light originating on the inner wall, and then being reflected back from the inner wall towards the faces of the PMTs. The inner circle represents one such reflection. The second circle represents the second wave of incident light, the first wave having been then reflected from the inner wall, back towards the outer wall, and then incident on the inner wall once more. And so on for subsequent circles.

The purpose of these circles is to demonstrate the different levels of intensity each region of PMTs is exposed to, as with each reflection the light has had more opportunity to diffuse out, and so the intensity drops between reflections. This can help us understand what we then see in the charge vs distance plots.

In Figure 5, the first wave of incident light (after the first reflection) is intense enough to saturate the PMTs, and so the 11 PMTs contained by the inner circle in the left hand figure correspond to the 11 points above the threshold in the right hand plot.

In Figure 6 we instead see that PMTs beyond the second circle see greater or equal to threshold charge, as the barrel region is half the depth of the end caps, and as such the light has diffused less between reflections, and it takes more reflections for the intensity to reduce too low to generate above threshold charge collection. Hence the difference in the percentage of PMTs saturated in the bottom cap vs the barrel: 11% vs 25%.

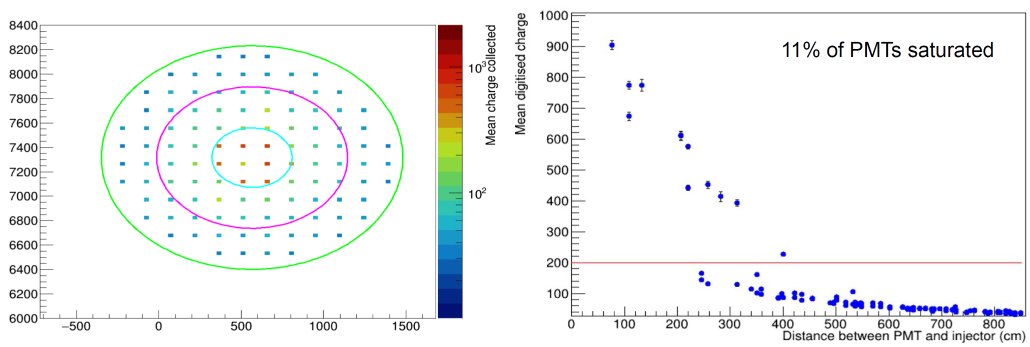


Figure 5: Left hand plot shows the mean charge collected in the PMTs within 8.5m of the LI in the bottom cap. The rings drawn on represent the outer edge of the incident light from reflections with the outer wall of the OD. The right hand plot shows the mean charge collected by each PMT in this region, as a function of the distance from the LI. The red line denotes the saturation threshold of 200 pe.

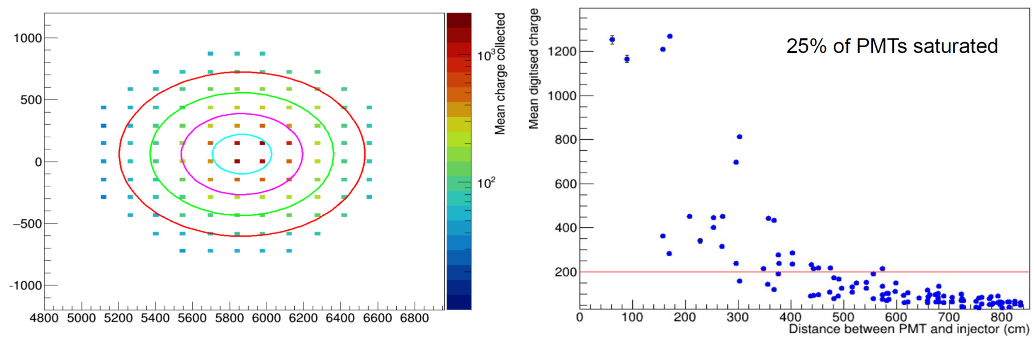


Figure 6: Left hand plot shows the mean charge collected in the PMTs within 8.5m of the LI in the barrel. The rings drawn on represent the outer edge of the incident light from reflections with the outer wall of the OD. The right hand plot shows the mean charge collected by each PMT in this region, as a function of the distance from the LI. The red line denotes the saturation threshold of 200 pe.

5 Collimator studies

While there will be 12 collimators in total, I currently simulate a single source in each of the top, bottom, and barrel, because each region is symmetrical so it makes no difference. At this point, if you haven't already, I very strongly suggest you read Appendix C.2, so that you understand the approach here.

The strategy at the moment is simply to see how sensitive we are to changes in the the absorption and Rayleigh scattering in the water, and changes to the reflectivity of the Tyvek. This is done by varying these properties (independently of one another, keeping the others constant), and comparing the difference in the charge collected across the relevant regions of the detector for these varied cases versus the charge distribution for the default parameters case, using a Pearson's Chi Squared test statistic. Then I generate a plot of the chi squared as a function of the percentage change in the parameter in question. For absorption and scattering, the parameters are varied by $\pm 30\%$, in steps of 5, with then 1% steps between $\pm 5\%$. For reflectivity, since that will only possibly get worse, the parameter is reduced by up to 30%, in 5% steps above 10%, 1% steps between 10 and 5%, and 0.5% steps below that.

Appendix C contains results for both the bottom cap and the barrel, but this is with the incorrect QE method. I've rerun the bottom cap simulations with the SensitiveDetector_Only QE method, and will show those in this section, but I haven't had time to repeat the barrel. I will address the top cap in Section 6. As a note, the bottom cap simulation uses 100,000 events, 10,000 photons per event, whereas the barrel requires greater statistics, so the simulation uses 1,000,000 events, 10,000 photons per event.

None of this runs quickly, even with the jobs parallelised as they are (I'm talking days for the bottom cap simulations, weeks for the barrel, and weeks for the top cap if the support structure is in place). So have fun with that.

5.1 Simulation methods/tools

This is the most involved set of simulations, and there are a lot of steps involved. Accordingly, be more careful at each stage.

As a point of reference, in WCSim the absorption parameter is referred to as abwff, Rayleigh scattering as rayff, and I refer to reflectivity in my scripts as refl, so those three words are going to pop up a lot.

Within the collimator_studies directory there are eight relevant files:

- water_properties_testing.mac: defines the WCSim run settings. This is set up to run a 1000 events.
- local_water_params.mac: this is a copy of the tuning_parameters.mac that WCSim normally uses; for different parameter settings a copy of this will be produced and passed to WCSim at run time so that it runs with the modified parameter setting.
- submitWaterParams.sh: sets the directories to save the output to, runs WCSim, produces the reduced output file, and removes the full sized WCSim output file. This is called by the subMulti<X>.sh scripts.
- subMultiDefault.sh: Will submit 100/1000 WCSim jobs, incrementing the random seed each time, so that you can generate your collimator events in a parallelised and less painful (to you, not your cluster) manner. Currently set up to use a condor system.
- subMulti<X>.sh: Where X = Abwff/Rayff/Refl. Will submit 100/1000 WCSim jobs, incrementing the random seed each time, so that you can generate your collimator events in a parallelised and less painful (to

you, not your cluster) manner. Currently set up to use a condor system.

- ReduceODOutput.C: same as previously described.
- hadd_reduced_files.sh: exactly what it sounds like, you'll generate multiple files for dozens of parameter settings, so you don't want to hadd those manually.

Currently water_properties_testing.mac, submitWaterParams.sh, and subMulti<X>.sh are set up for running the barrel collimator (calibrationsource = colBarrel) studies. To run for the top or bottom caps, all instances of "barrel" need to be changed accordingly. Also, the for loop in subMulti<X>.sh will need to have the upper limit reduced to 100. You might choose to edit these scripts to make top/bottom/barrel an argument that sets this up at the command line. But that is not currently how the scripts work.

5.1.1 subMultiDefault.sh

The simplest step, generating your default water parameters simulation. This is run using

```
$ ./subMultiDiffuse.sh
```

This will run your 1000 barrel (100 end cap) jobs, and every output WCSim file will have the reducer applied to it. If any jobs fail/disappear, you can re-run that script; there is a line that will check which reduced output files exist, and for the ones missing it will resubmit the job.

You will then need to hadd these files together, for instance with a filename like default_barrel.root.

5.1.2 subMulti<X>.sh

The process will be the same whether using Abwff, Rayff, or Refl. For instance, for absorption, you will run using

```
$ ./subMultiAbwff.sh
```

This will run your 1000 barrel (100 end cap) jobs for multiple values of abwff, and every output WCSim file will have the reducer applied to it. If any jobs fail/disappear, you can re-run that script; there is a line that will check which reduced output files exist, and for the ones missing it will resubmit the job.

5.1.3 hadd_reduced_files.sh

Once you've run your absorption, scattering, and reflectivity simulations, you will then need to use hadd_reduced_files.sh to hadd together the constituent files for each parameter setting. The paths to the files are hard coded in this file, so you'll need to set them accordingly.

5.2 Analysis methods/tools

To process the output of the collimator studies there are two relevant files:

- reduced_chi_squared_errors.C
- args_write_chi2_errors_to_file.sh

The chi squared calculations are performed using reduced_chi_squared_errors.C, which calculates the chi squared for the full sample per setting, while also splitting the sample into 10 sub samples, and using the standard deviation of the chi squareds of the sub samples to give the error/uncertainty for the full sample.

An important note about this script: In order to get the degrees of freedom, one needs to know the number of PMTs involved in the region of interest. At one point I was having an issue getting this directly from the output files, and so I hard coded the numbers in. If you change the number of PMTs in the OD, *these hard coded values will need to be updated.* Or better yet, make it so the code actually finds the correct number properly. I just didn't have time and then forgot to change it.

reduced_chi_squared_errors.C is then called by args_write_chi2_errors_to_file.sh, which runs it for every parameter setting and writes these out to text files; one file for the chi squared values and one for the errors, per parameter. So for just the barrel (which in WCSim is cylLoc 4, top is 5, bottom 3), you will end up with six text files (<X>_cylLoc4_reduced_chi_sq.txt and cylLoc4_<X>_chi2_errors.txt [X = abwff/rayff/refl]). Yes, my naming conventions suck. You are free to change them!

You run args_write_chi2_errors_to_file.sh by using

```
$ ./args_write_chi2_errors_to_file.sh <region> <parameter>
```

So for instance, for absorption in the barrel, you would enter at the command line:

```
$ ./args_write_chi2_errors_to_file.sh barrel abwff
```

This is quite a lengthy process, it will take hours to run as it is analysing multiple files, each from simulations that used millions of photon generations, so I usually use nohup when running it.

The numbers in these text files can then be placed in the plotting macros Barrel_Water_Params_chi2_plot.C (or Bottom, or Top) and refl_chi2_plot.C.

5.3 Current results

As can be seen in Figure 7, we are sensitive to changes in the absorption at around the 10% level, and in scattering from just a couple of percent. We are also highly sensitive to changes in the Tyvek reflectivity, even at the sub-percent level.

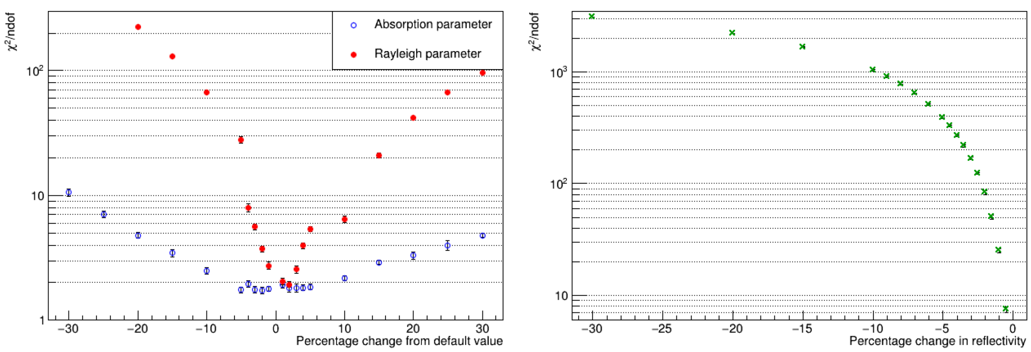


Figure 7: Left hand plot shows the chi squared distribution as a function of the percentage change in the water parameters away from the default. Right hand plot shows the chi squared distribution as a function of the percentage change in the Tyvek reflectivity away from the default.

6 Top structure studies

As I've mentioned throughout this document, there will be a support structure in the top cap that introduces a lot of material that can obstruct light. The plan (to my knowledge) is to try and at least wrap the struts in the support structure in Tyvek, to try and regain some of the light collection.

The current design for the support structure is shown in Figure 8. As you can see, it could pose quite the impediment to light. The internal stucture of the structure is slightly less obstructed than it might otherwise appear, looking from the outside of the model though. Within the structure there are many diagonal crossbars, such as those I've highlighted yellow in the image. But there are fewer vertical bars inside than the image implies, as many only exist in the outer layer/wrap around on the edge of the structure. So for instance, the bar I've highlighted in red is only on the outside.

I draw attention to this for the sake of the collimators; we could attach the collimator unit to the inner face of these outer bars, and they would have a reasonably clear path through the triangle created by the yellow highlighted crossbars.

The top cap support structure is added to the simulation in $WCSim-RootDir/src/WCSimConstructCylinder.cc, starting at line 177. For guidance on using the CAD model in the simulation (especially if new ones arise) I'm going to direct you to Ewan Miller.

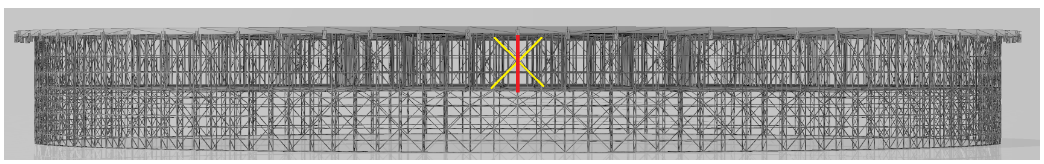


Figure 8: Top support structure CAD model.

All of the following studies use the same tools as those used in the single pe, saturation, and collimator studies. The comparisons in Figures 9 and 10 were (I think) done using OD_Top_Strut_Comparison_Plots.C, which I'll place in the miscellaneous_macros directory.

6.1 Impact on single pe studies

This was studied with the old model. It is more fully discussed in Appendix C.3, and this study was done with the correct QE method. As can be seen in that section, the mean charge collected per PMT *for events where charge was collected* is not negatively impacted by the presence of the support structure. Where we do see an effect is in our efficiency of delivering light to PMTs further from the LIs, which is not unexpected.

This can be compensated for by tuning the intensity of the light that we inject through the LI. I haven't looked into this too much, but I have compared the case where we inject 15000 photons through the diffusers in the presence of the top cap, to the case where we inject the nominal 10000 photons in the absence of a top cap. This is shown in Figure 9. I've also done the same for 13000 photons, Figure 10.

While I haven't determined the precise intensity tuning for different PMT-LI distances, it is clear that we can compensate for the efficiency losses caused by the support structure by increasing the light injected appropriately.

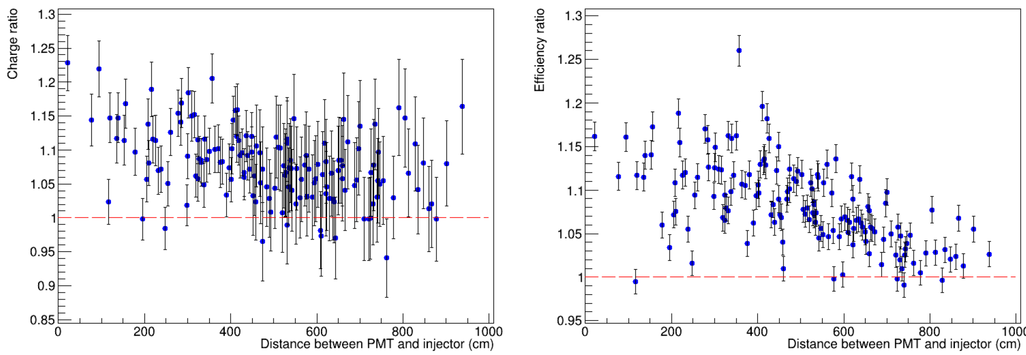


Figure 9: Mean charge (left) and efficiency (right) comparison between the case for 10k photons with no support structure, and 15k photons with a support structure.

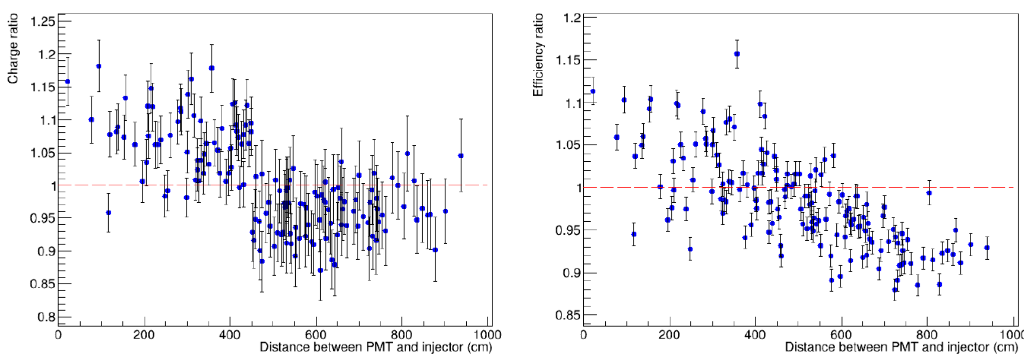


Figure 10: Mean charge (left) and efficiency (right) comparison between the case for 10k photons with no support structure, and 13k photons with a support structure.

		No Struts	Struts
Diffuser (40deg HA)	**% PMTs saturated**	**11.3**	**13.2**
	Mean Q in 8.5m radius	12473	13638
	# hits across whole OD	2866194	1808374
Scratched fibre (26deg HA)	**% PMTs saturated**	**11.3**	**13.2**
	Mean Q in 8.5m radius	14174	16104
	# hits across whole OD	2845696	1799107
Bare fibre (12deg HA)	**% PMTs saturated**	**15.1**	**18.9**
	Mean Q in 8.5m radius	18532	18839
	# hits across whole OD	2834238	1791858

Table 2: Impact of top support structure on saturation on PMTs.

6.2 Impact on saturation studies

This, again, was studied with the old model. But it comes with some good news; the top support structure is actually mildly beneficial in terms of saturating the PMTs near the LI. For brevity, I'll represent this in a Table 2. This was studied for a range of possible diffuser/non-diffuser types, but now we're pretty set on using diffusers. What appears to be happening, based on the increase in charge collection within the region of the LI, but overall reduction in hits across the detector, is that in this region the struts are actually causing additional reflections of light back in towards the PMTs in the region.

6.3 Impact on collimator studies

This I have looked at with the new model. But due to the time constraints before I left, I didn't have time to study reflectivity, and I had to use a reduced number of parameter settings. The results of thses studies are shown in Figure 11. As can be seen, we have very promising results for the scattering, but something is askew with the absorption.

It looks as though the centre of the distribution is offset. This would maybe point to something going amiss when I changed the water parameter settings, though the way the simulations are set up to run I can't see how that would happen. The other possibility (though the small error bars would indicate otherwise) is that we simply need more statistics. Or it could be simply that studying changes in absorption is a no go for the collimators in the top cap.

This warrants further study. The absorption studies should be repeated, and the missing data points for scattering should also be filled in. And of course, the study for the Tyvek reflectivity (though you would then need to account for the Tyvek on the support structure struts as well).

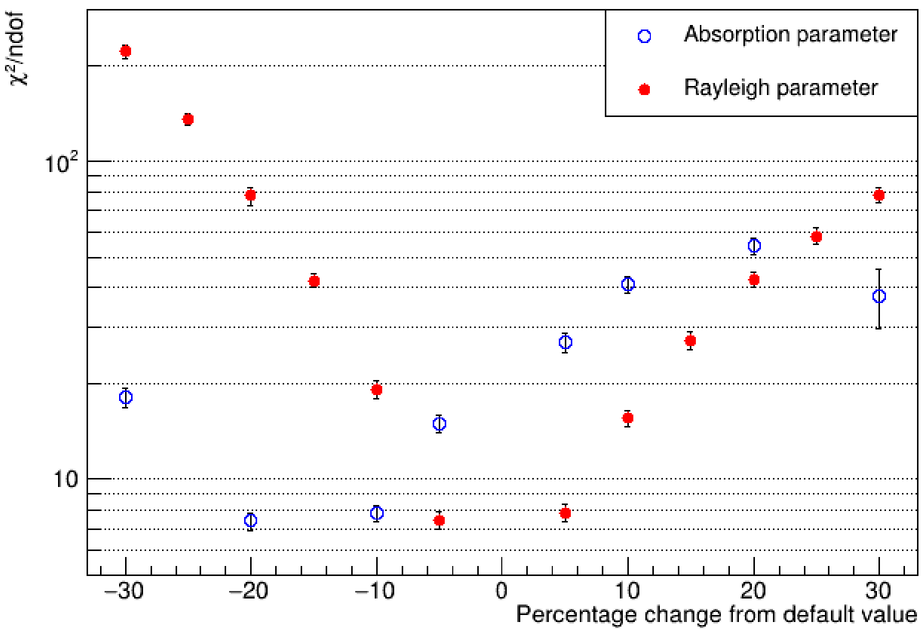


Figure 11: Chi squared distribution as a function of the change in the absorption and scattering parameters for the top cap collimator with the new top cap support structure in place.

7 Wavelength tests

All the studies performed thus far have been at 400nm, but the question was raised as to whether this is an optimal setting. I've briefly studied wavelengths between 360-400nm to see if there is any real difference. The short answer is that (on the basis of simulations for single pe coverage and saturation - I didn't have time to repeat the collimator studies) there isn't.

But there might be a physics/engineering reason down the line, so keep that in mind.

More details on the studies done so far can be found in a presentation I gave in the October 2022 FD6 pre-meeting here: `https://hkdbweb.in2p3.fr/doc/meetingfiles/A00004583/HK_OD_Calib_201022.pdf` (you will need to have an HK account and hope the meeting planning website smiles on you in order to make that link work).

A Diffuse source layout/positions

A.1 5 layer barrel default

As seen in Figure 13.

A.1.1 End Caps

The same positions are simulated in both end caps; top cap sources have z position 3362.01cm, bottom cap -3362.01cm (in current geometry). This is for placement on the inner walls facing outwards, with a 7cm clearance of the faces of the PMTs (I allowed for an LI/mounting assembly of up to 10cm, but this could obvously be adjusted when numbers are known). The sources are arranged in rings of 3, 6, and 12 sources, with radii of 800cm, 1810cm, 2800cm. The list of positions for either cap is shown in Table 3.

A.1.2 Barrel

For the five layers of sources in the barrel, the second and fourth layers are offset from the first, third, and fifth. But within those two groups the positions of the PMTs are the same. Once again, the sources are placed with the light originating 10cm away from the structure of the wall (radius 3317.01cm in current geometry). The list of barrel positions is shown in Table 4. The reason for the ring at z = 60cm (rather than at 0) is because at 0 the light injectors intersected with PMT positions.

x (cm)	y (cm)
565.6854	565.6854
-772.741	207.0552
207.0552	-772.741
1748.326	468.4625
468.4625	1748.326
-1279.86	1279.863
-1748.33	-468.462
-468.462	-1748.33
1279.863	-1279.86
2800	0
2424.871	1400
1400	2424.871
1.72E-13	2800
-1400	2424.871
-2424.87	1400
-2800	3.43E-13
-2424.87	-1400
-1400	-2424.87
-5.1E-13	-2800
1400	-2424.87
2424.871	-1400

Table 3: End cap LI x and y positions.

z (cm)	x (cm)	y(cm)
2700/60/-2700	3253.27	647.12
	2757.99	1842.83
	1842.83	2757.99
	647.12	3253.27
	-647.12	3253.27
	-1842.83	2757.99
	-2757.99	1842.83
	-3253.27	647.12
	-3253.27	-647.12
	-2757.99	-1842.83
	-1842.83	-2757.99
	-647.12	-3253.27
	647.12	-3253.27
	1842.83	-2757.99
	2757.99	-1842.83
	3253.27	-647.12
1350/-1350	3317.01	0.00
	3064.52	1269.36
	2345.48	2345.48
	1269.36	3064.52
	0.00	3317.01
	-1269.36	3064.52
	-2345.48	2345.48
	-3064.52	1269.36
	-3317.01	0.00
	-3064.52	-1269.36
	-2345.48	-2345.48
	-1269.36	-3064.52
	0.00	-3317.01
	1269.36	-3064.52
	2345.48	-2345.48
	3064.52	-1269.36

Table 4: Barrel LI positions.

B QE in WCSim

Welcome to hell. I'm going to start out by explaining how this is designed to work with Cherenkov photons, to help you then understand what has gone wrong with laser/primary generated optical photons.

It should also be noted that there are other aspects of the calculation of QE in WCSim that are not immediately clear as to why they exist (but the gist seems to be that they are that way to make the implementation of PMT QE consistent with SK PMTs, while supposedly working for HK PMTs. If you want to know more about that though, I would suggest talking to Federico Nova or someone in the HK software group, because that is more a conversation, rather than something easily written/read).

(a) There are four methods of implementing QE in WCSim that can be selected at runtime, and this is how they *should* work:

    (i) Stacking_Only - This reduces the the number of photons generated at run time (e.g. if you aim to simulate 100 photons, but the highest QE of your PMTs is 30%, then 30 photons will be generated and then absorbed).

    (ii) SensitiveDetector_Only - QE is applied at the detector (e.g. if you aim to simulate 100 photons, 100 will be generated, and QE effects will be applied at the detector level).

    (iii) Stacking_And_SensitiveDetector - In the stacking part, the maximum QE is applied to reduce the total number of photons. On the detector side, the rest of QE are applied according to a QE/QE_{max} distribution (e.g. if you aim to simulate 100 photons, and you have a mix of PMTs with different QEs, then the number of generated photons will be reduced by a factor equivalent to the highest QE, and then at the detector level any difference between QE_{max} and the QE of the PMT in question *should* be accounted for).

    (iv) DoNotApplyQE - The name says it all (e.g. you tell WCSim you want 100 photons, you are going to generate 100 photons, and absorb 100 photons).

(b) However the implementation of QE for Cherenkov photons and for laser/primary generated photons (such as the optical photons used in LI studies) is different. More on that below.

(c) There is also a ”fudge factor” in WCSim of 4/3, and some correction and collection efficiency factors kicking around (the OD group has looked into this, and Patrick Spradlin especially has spent a lot of time looking into this and has presented on it in software meetings). The net result though is that if you think you have an OD PMT with QE 28%, entered into WCSim as 28%, you're *not* going to get 28% out of WCSim. More on that below. Such fun.

(d) With regards to the QE_{max} discussed above, WCSim will also take into accout the QE of the *ID* PMTs in determining that maximum, which (in conjunction with the messed up implementation of QE for primary photons) will further mess up QE in OD studies.

So in summary, this means that QE in WCSim does not behave as expected for optical photons in the OD. This is why the results in the OD TR had to be reproduced, and even then the QE being used is not ideal, it is simply the least wrong, and at least not a vast overestimate. The full logic here is explained in some slides, which in the interests of (my, sorry) time I'm just going to include the salient parts of in Figure 12. But basically if you have a PMT with a QE of 28% at 400nm, SensitiveDetector_Only will give you an effective efficiency of 24.6%, as opposed to 63-67% with other methods.

Cherenkov photons/default	Emission	Absorption	Net
Stacking_Only	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$	1	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$
Stacking_And_SensitiveDetector	$\frac{4}{3}\epsilon_{\rm PM,max}$	$\frac{\epsilon_{\rm PM}(\lambda_{\rm SD})}{\epsilon_{\rm PM,max}}$	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_{\rm SD})$
SensitiveDetector_Only	1	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_{\rm SD})$	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_{\rm SD})$
DoNotApplyQE	1	1	1
Laser/primaries (NULL)			
Stacking_Only	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$	1	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$
Stacking_And_SensitiveDetector	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$	$\frac{\epsilon_{\rm PM}(\lambda_{\rm SD})}{\epsilon_{\rm PM,max}}$	$\frac{4}{3}\frac{\epsilon_{\rm PM}(\lambda_0)\epsilon_{\rm PM}(\lambda_{\rm SD})}{\epsilon_{\rm PM,max}}$
SensitiveDetector_Only	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_{\rm SD})$	$\left(\frac{4}{3}\right)^2\epsilon_{\rm PM}(\lambda_0)\epsilon_{\rm PM}(\lambda_{\rm SD})$
DoNotApplyQE	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$	1	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$

Patrick Spradlin, HK Software Pre-Meeting, 17/02/22

This ε_{PM} considers all PMTs in the system, **including** the ID PMTs, which have a far higher ε than the OD PMTs

Laser/primaries (NULL)	Emission	Absorption	Net
Stacking_Only	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$	1	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$
Stacking_And_SensitiveDetector	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$	$\frac{\epsilon_{\rm PM}(\lambda_{\rm SD})}{\epsilon_{\rm PM,max}}$	$\frac{4}{3}\frac{\epsilon_{\rm PM}(\lambda_0)\epsilon_{\rm PM}(\lambda_{\rm SD})}{\epsilon_{\rm PM,max}}$
SensitiveDetector_Only	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_{\rm SD})$	$\left(\frac{4}{3}\right)^2\epsilon_{\rm PM}(\lambda_0)\epsilon_{\rm PM}(\lambda_{\rm SD})$
DoNotApplyQE	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$	1	$\frac{4}{3}\epsilon_{\rm PM}(\lambda_0)$

This should be 1

Net result is that first two QE methods overestimate QE, and SensitiveDetector_Only slightly underestimates it.

- In the OD group we've tested the effective efficiency returned by WCSim for the different QE methods, using 1000 single photon events fired into the centre of an OD PMT.
- These were 400nm photons so QE should be 28%, though WCSim also applies a factor of 4/3 for ~reasons~, so 4/3*28 = 37.3%

PMT QE Method	QE Expected from previous table	Efficiency measured (raw hits)
Stacking_Only	0.571689 * 1. = **0.571689**	**0.673**
Stacking_And_SensitiveDetector	0.571689 * 0.93333 = **0.533577**	**0.634**
SensitiveDetector_Only	0.571689 * 0.37333 = **0.213431**	**0.246**
DoNotApplyQE	0.571689 * 1. = **0.571689**	**0.673**

Figure 12: A tale of QE based woe.

C HK OD TR Calibration section - REMEMBER! Outdated results!

A light injection system in the OD will be used for calibration of the PMTs and measurements of the optical properties of the water and any degradation of the Tyvek reflectivity over time. For these purposes both diffuse and collimated inputs will be used. The following sections briefly describe the outcomes of studies in WCSim to determine the number of light injectors required and their general position within the outer detector, as well as assess their calibration potential. The detector model in WCSim used for these studies is as described in section [references other section of OD TR], unless otherwise stated.

C.1 OD PMT charge calibration

The PMT calibrations will be performed by an array of diffuse sources that can deliver light to all of the PMTs in the OD. This is a similar concept to that employed in SK, although the reduced width of the barrel region in the HK OD presents a greater challenge for full illumination of the PMTs. The diffuse sources will be mounted on the inner wall support structure, facing out towards the outer wall Tyvek which will reflect the light back towards the PMTs on the inner wall, and will use LED inputs delivered by optical fibres.

The diffuse source used in the simulation is an isotropic cone of light with half angle 40°, modelled after the half angle of the diffuser design for inner detector calibrations. However the final design for the OD diffusers, and as such the actual light profile that will be used, has yet to be decided upon.

C.1.1 Single p.e. calibration

As was done in SK, low levels of light injected via the diffusers will be used to measure the charge response around the single photoelectron level. The single p.e. requirement across all PMTs was used to determine the number of injectors required for the calibration system. Through simulations in WCSim it was determined that full coverage of the detector at the single p.e. level (with some redundancy should there be injector/fibre failures) can be achieved with 21 sources per end cap and 80 sources in the barrel region (122 sources total). The positions of these sources in the simulation is shown in

Figure 13, while Figure 14 shows the mean charge collected per PMT per light injection event, which is close to one for the majority of PMTs. The areas of higher mean charge collection correspond to PMTs closest to the injectors; this is particularly pronounced in the barrel region, where the reduced width provides less distance for the light to travel and diffuse over, resulting in more intense light collected in neighbouring PMTs. During operation calibration of these PMTs can be performed using a more distant light injector, so that the single pe level exposure can still be achieved.

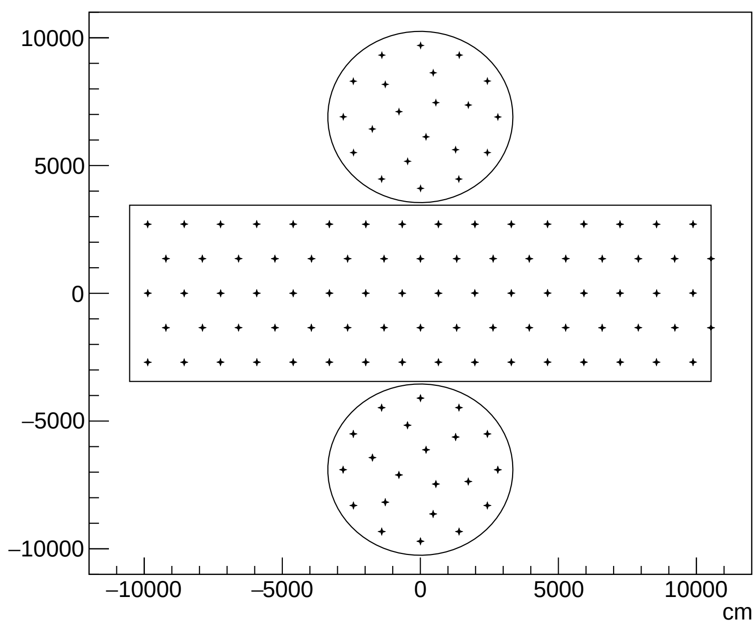


Figure 13: Positions of diffuse light injection points used in calibration simulations.

C.1.2 PMT saturation studies

To calibrate the PMT response across the whole operating range, it is necessary to illuminate the PMTs with enough light to saturate their response. In the current design, the limiting factor of the operating range is the electronics response, which is expected to saturate around 200 pe. As such, this

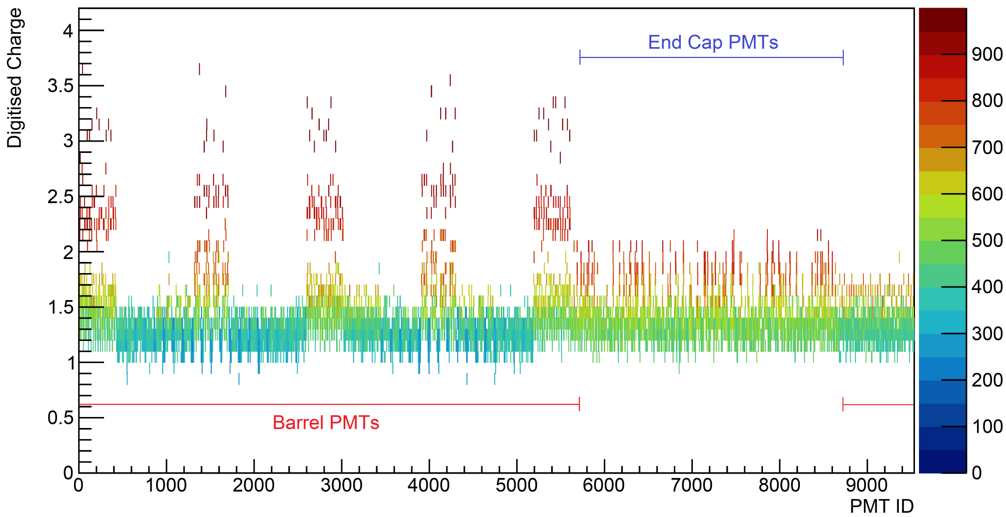


Figure 14: Mean charge collected per PMT per event at low light levels injected through the diffuser array. The colour axis represents the number of events for which charge was collected by the PMT, out of 1000 simulated events.

has been used as the threshold for saturation studies, to determine what proportion of PMTs we can expect to saturate with the diffuser system.

Saturation of PMTs in the barrel and end caps has been considered, using two positions within the diffuser array. The mean PMT charge response per light injection event within an 8.5 metre radius of the diffusers was studied. This radius was used as it is the maximum distance between any PMT and its nearest injector.

Simulating the number of photons required to saturate the PMT response is computationally intensive, and it was not possible to simulate sufficient light levels to saturate 100% of PMTs in the radius of interest. It should be noted that in these studies photon numbers above 9×10^6 are in fact approximations of such yields, generated by increasing the quantum efficiency of the PMTs in the simulation (once again required due to computing constraints), but as demonstrated in Figure 15 multiplying the quantum efficiency by a factor is a reasonable approximation of multiplying the number of photons by that same factor e.g. 3×10^6 photons generated in a simulation with tripled quantum efficiency appears to be an effective approximation for 9×10^6 photons generated in a simulation with the nominal quantum efficiency.

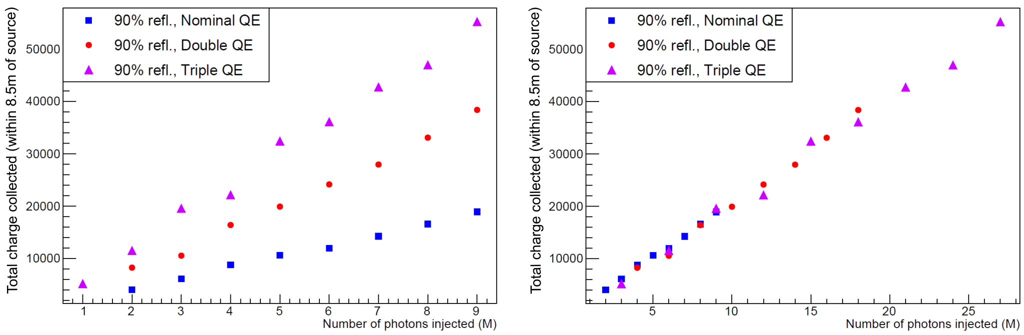


Figure 15: Total charge collected within 8.5 metres for a barrel source as a function of the number of photons injected, comparing the charge collected for PMT quantum efficiency multiplied by a factor (left), and with these points redrawn as though the number of photons has been multiplied by the same factor (right).

Studies of the charge collected and percentage of PMTs saturated as a function of the number of photons injected do demonstrate a generally linear relationship, as shown in the right hand plot in Figure 15 for charge and Figure 16 for the percentage of PMTs saturated, indicating that with sufficient light input it would be possible to saturate all PMTs, although the ability of the LED system to be driven at high enough power to reach that level is yet to be determined. It should be noted that these studies of increased quantum efficiency and charge collection as a function of light input were performed with a marginally different geometry featuring ~5% more PMTs and a more coarsely defined absorption profile for the WLS plates, which were also simulated at 1 cm thickness rather than the 6 mm standard used in the rest of these studies.[1] From these plots we can also see that with the same number of input photons we achieve greater saturation levels in the barrel than in the end caps. This difference is due to the difference in the width of the OD in those regions; in the end caps the cone of light produced by the diffuser has twice the distance over which to propagate, resulting in the incident light covering a much larger area of PMTs.

Using an effective light input of 2.7×10^7 photons, generated with a 20 ns top hat distribution in time to approximate the width of an LED light pulse, the mean charge collected by each PMT within the radius of interest was

[1]While the geometry is slightly different, the behaviour of the PMTs and as such the physics outcomes should be the same.

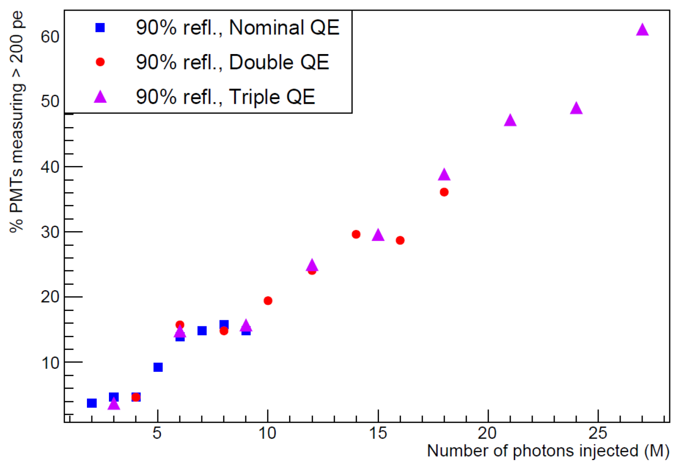


Figure 16: Percentage of PMTs saturated within 8.5 metres for a barrel source as a function of the (effective, generated by increasing the quantum efficiency) number of photons injected.

measured, and this is shown as a function of the distance of the PMT from the light injector for the barrel in Figure 17 and end cap Figure 18. With this number of photons we could expect to saturate the response of 83.0% of PMTs in the barrel region, and 47.2% in the end caps.

It is possible that for those PMTs that are not saturated by light input from a single injector that operating multiple nearby injectors could provide sufficient illumination to saturate their response, and this is be further investigated.

C.2 Measurement of additional OD properties

Collimated beams of light, using input from the inner detector laser, will be used to measure additional properties of the OD, extending the HK calibration regime beyond what was done for SK. These collimated sources are expected to have a half angle of 2 degrees. 12 collimators will be installed into the OD, 6 in the barrel and 3 in each end cap. Their light will be directed parallel to the surface of the PMTs to maximise the distance that the light can travel, thus maximising the impact of absorption and scattering on the OD response. In the end caps the light will be directed across the diameter of the detector, from one side to the other, while in the barrel the collimators will be installed at the bottom of the barrel region and direct their light up-

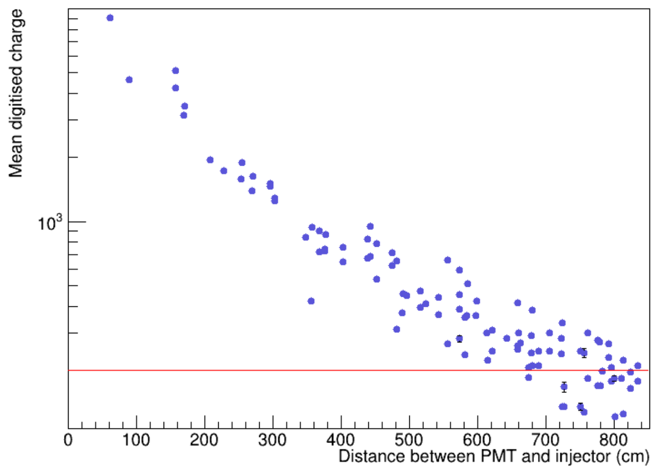


Figure 17: Mean charge collected per PMT as a function of distance from the light injector in the barrel. The saturation charge threshold of 200 pe is represented by the red line.

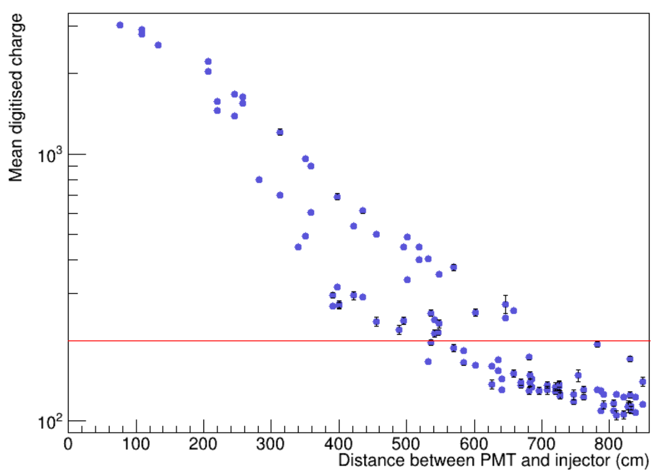


Figure 18: Mean charge collected per PMT as a function of distance from the light injector in the end cap. The saturation charge threshold of 200 pe is represented by the red line.

wards along the height of the detector. The distribution of charge collected for a single collimated beam in the end cap is shown in Figure 19. As the laser system is to be used, a range of wavelengths can be studied, which will also allow for further studies of the response of the PMTs and wavelength shifting plates to different wavelengths to be made in situ.

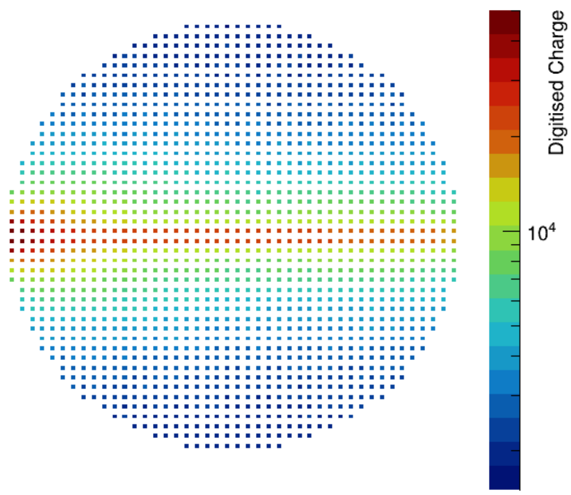


Figure 19: Distribution of charge collected in end cap PMTs for a collimated beam of light injected from the right hand side, travelling across the diameter of the detector region to the left hand side.

C.2.1 Water properties

The water properties studied so far in WCSim are absorption and Rayleigh scattering. Within WCSim, absorption and scattering are scaled by tunable parameters whose current values are set to match those determined for SK. For these studies these parameters were varied (independently) in increments away from their default. An increase in the absorption parameter results in light traveling further before absorption, and an increase in the Rayleigh parameter results in light traveling further before scattering.

The distribution of charge collected in the PMTs was compared between the default case (using the SK parameter values) and the varied cases. These were compared using a Pearson's chi-squared test,

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}. \tag{1}$$

where the default parameter charge distribution over n PMTs was used as the expected values, E, and the varied parameter charge distribution was treated as the observed values, O. The distribution of chi-squared values as a function of the percentage change in the parameter value demonstrates the sensitivity of the collimator system to changes in these water properties. This is shown for a single collimated input to the end cap in Figure 20. It can be seen that we are sensitive to changes greater than 10% in the absorption parameter, and greater than 4% for Rayleigh scattering. For a single collimated input to the barrel, it can be seen from the distribution of chi-squared values in Figure 21 that we are sensitive to changes greater than 10% in the absorption parameter, and greater than 5% for Rayleigh scattering.

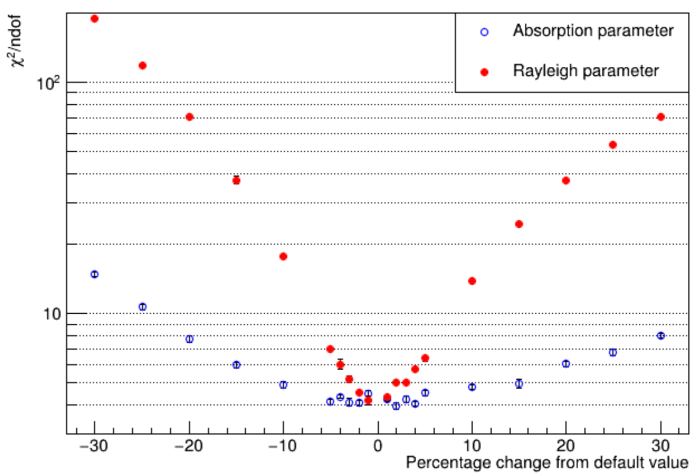


Figure 20: Distribution of chi-squared values as a function of the percentage change from the default values in WCSim for the absorption and Rayleigh scattering parameters, for charge collection in the end cap.

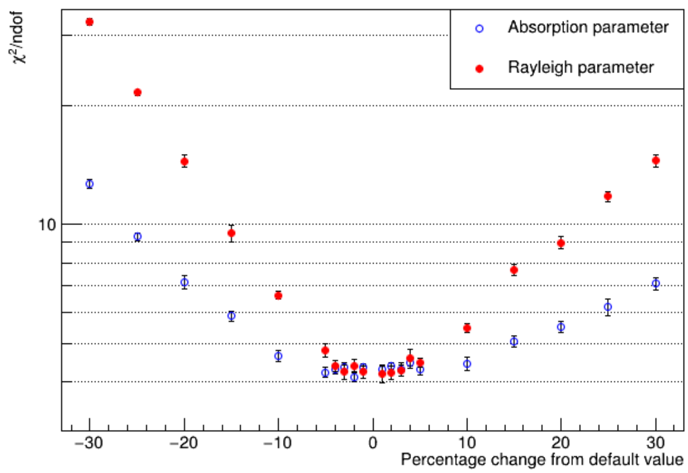


Figure 21: Distribution of chi-squared values as a function of the percentage change from the default values in WCSim for the absorption and Rayleigh scattering parameters, for charge collection in the barrel.

C.2.2 Tyvek reflectivity

A similar scheme can be employed for the Tyvek reflectivity. In this case the reflectivity is reduced from the default of 90% to represent degradation over time. Once again the charge distribution in the default case is compared to the varied cases using a Pearson's chi-squared test. From the distributions shown in Figure 22 for an end cap collimator and Figure 23 for a barrel collimator, it can be seen that in both cases we are sensitive to changes in the reflectivity of less than a percent.

C.3 Impact of top support structure

The presence of the support structure in the top end cap, as detailed in section [references other section of OD TR] presents an obvious obstacle to the transport of light in the end cap, and as such has the potential to impact the efficacy of the light injection calibration system. The impact on the single p.e., charge saturation, and collimator water properties studies needs to be investigated. Both steel support struts and Tyvek coated struts will be considered.

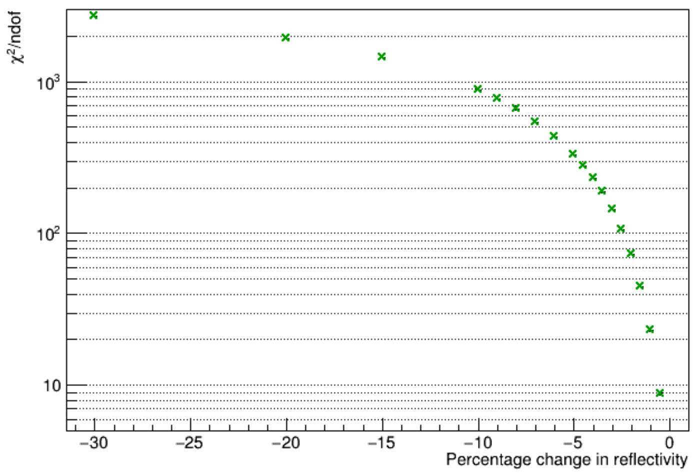


Figure 22: Distribution of chi-squared values as a function of the percentage change from the default Tyvek reflectivity of 90% in WCSim, for the end cap.

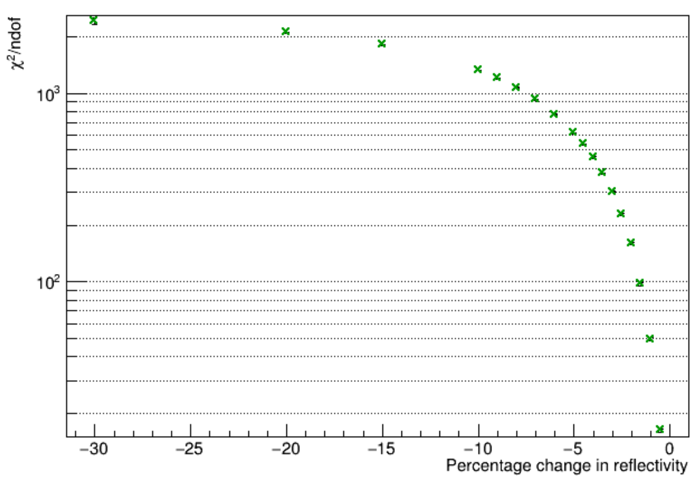


Figure 23: Distribution of chi-squared values as a function of the percentage change from the default Tyvek reflectivity of 90% in WCSim, for the barrel.

C.3.1 Single p.e. calibration

As discussed in section C.1.1, we need to deliver light to all of the top cap PMTs, with a desired mean charge of 1 p.e. being delivered to the PMT. To study this, 1000 events were simulated with 5000 photons per light injector per event, for geometries without a support structure, with steel support struts, and with Tyvek coated support struts. The total charge collected in each top cap PMT for each case is shown in Figure 24. A clear reduction in the charge collected in regions further from the light injectors can be seen, especially for the steel strut case.

The mean charge collected per PMT per light injection event that resulted in charge collected by the PMT, as a function of the PMT distance from the nearest light injector, is shown in Figure 25 for the case where there is no support structure, a steel structure, and a Tyvek coated structure. It can be seen in all cases that for PMTs not in the immediate vicinity of the injector that the mean charge does sit around one, as desired. However looking at the colour axis, which shows how many events of the 1000 simulated resulted in charge being delivered to the PMT, that for the steel and Tyvek cases there is a worse efficiency of delivering light to the more distant PMTs than when there is no support structure, as we would expect.

To better demonstrate this, Figure 26 shows the ratios of the mean charge collected, for events where charge was collected, as a function of distance from the light injector, comparing the no support strut case to the steel strut and Tyvek strut cases. From this we see that that ratio is consistent with what we see in Figure 25, as the ratio is close to one in both cases.

Where we see a real difference between having and not having support struts is when we look at the efficiency of delivering light to the PMTs, meaning the percentage of events for which the PMT collects a charge, as a function of the distance of the PMTs from the light injectors. This is shown in Figure 27. It is clear that there is a significant reduction in the efficiency when steel struts are introduced, which is greatly improved when the struts are covered in Tyvek, although the efficiency isn't totally recovered.

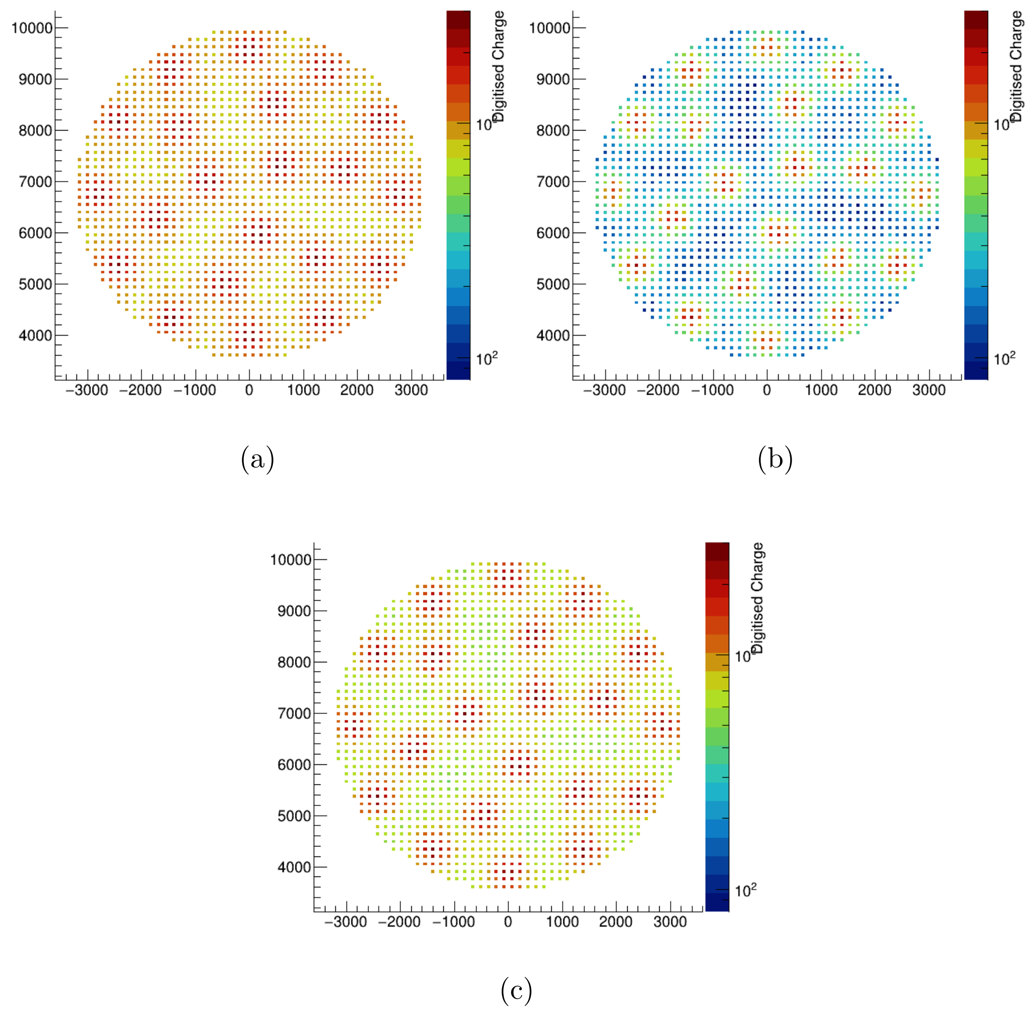
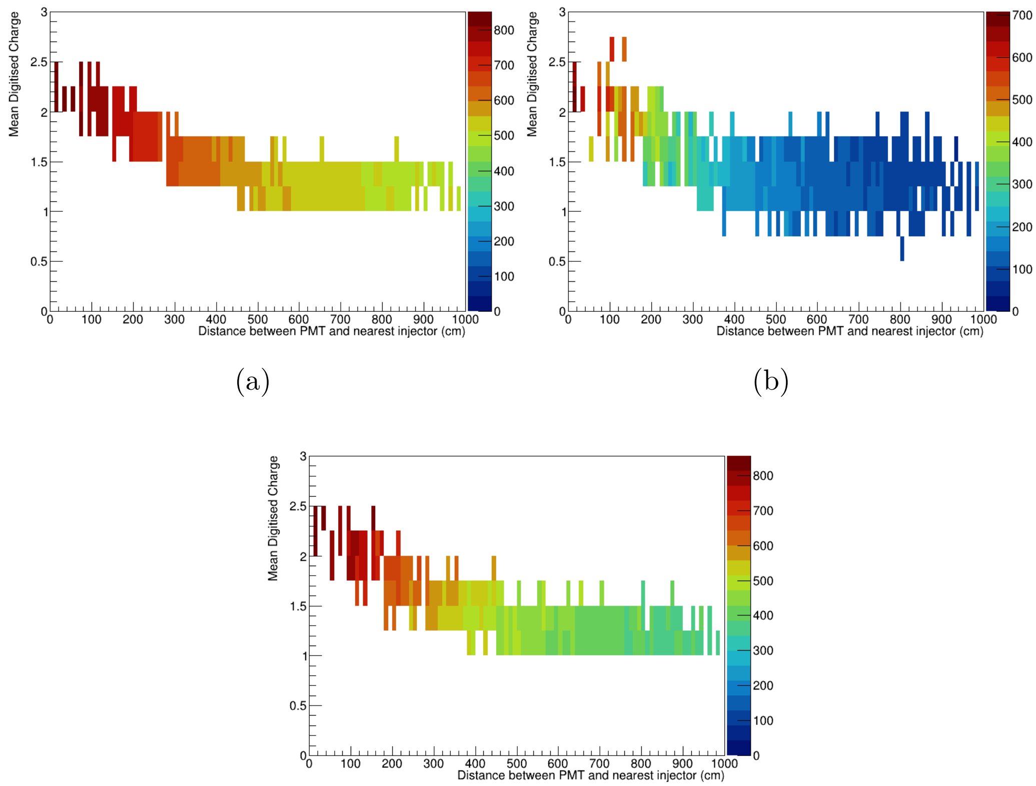


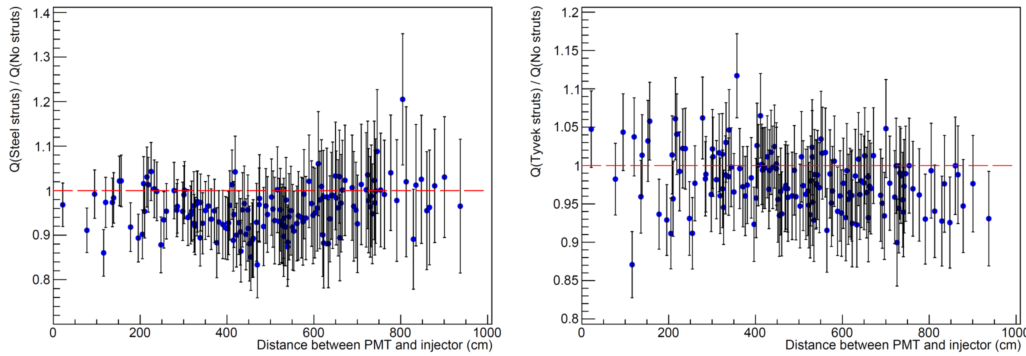
Figure 24: Distribution of charge collected in top end cap PMTs for (a) no struts, (b) steel struts, and (c) Tyvek coated struts.



(a) (b)

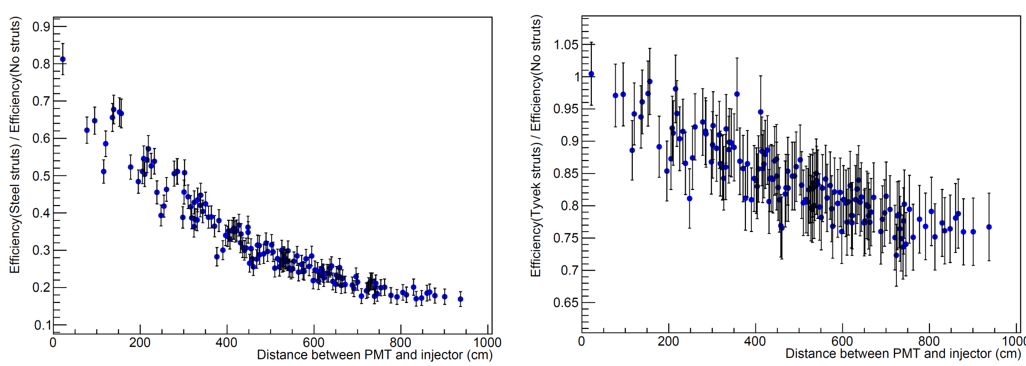
(c)

Figure 25: Mean charge collected per PMT per event at low light levels injected through the diffuser array as a function of distance from the injector, for (a) no struts, (b) steel struts, and (c) Tyvek coated struts. The colour axis represents the number of events for which charge was collected by the PMT, out of 1000 simulated events.



(a) (b)

Figure 26: Ratio of mean charge collected as a function of distance from the nearest light injector, comparing the case where there is no support structure with (a) steel support struts and (b) Tyvek coated support struts.



(a) (b)

Figure 27: Ratio of efficiency of charge collection as a function of distance from the nearest light injector, comparing the case where there is no support structure with (a) steel support struts and (b) Tyvek coated support struts.