LZ System Test Simulations: Cross Checks and Steps Forward

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Overview

1. Overarching Questions/Motivation

2. Simulation tools: BACCARAT and LightGuide

3. Detector geometry construction

4. Cross-checks between BACCARAT and LightGuide

5. Informing the multi-PMT array design

Overarching Questions

How do we better understand the optical properties of the System Test detector?

What kinds of simulations will help us achieve this understanding?

What can we learn about light collection in the multi-PMT array?

How do we motivate design for the multi-PMT array?

BACCARAT

- "Basically A Component-Centric Analog Response to Anything"

- Framework in Geant4 for simulations of LZ and related detectors

- C++-based

- Can construct arbitrary detector geometries

BACCARAT

- "Basically A Component-Centric Analog Response to Anything"

- Framework in Geant4 for simulations of LZ and related detectors

- C++-based

- Can construct arbitrary detector geometries

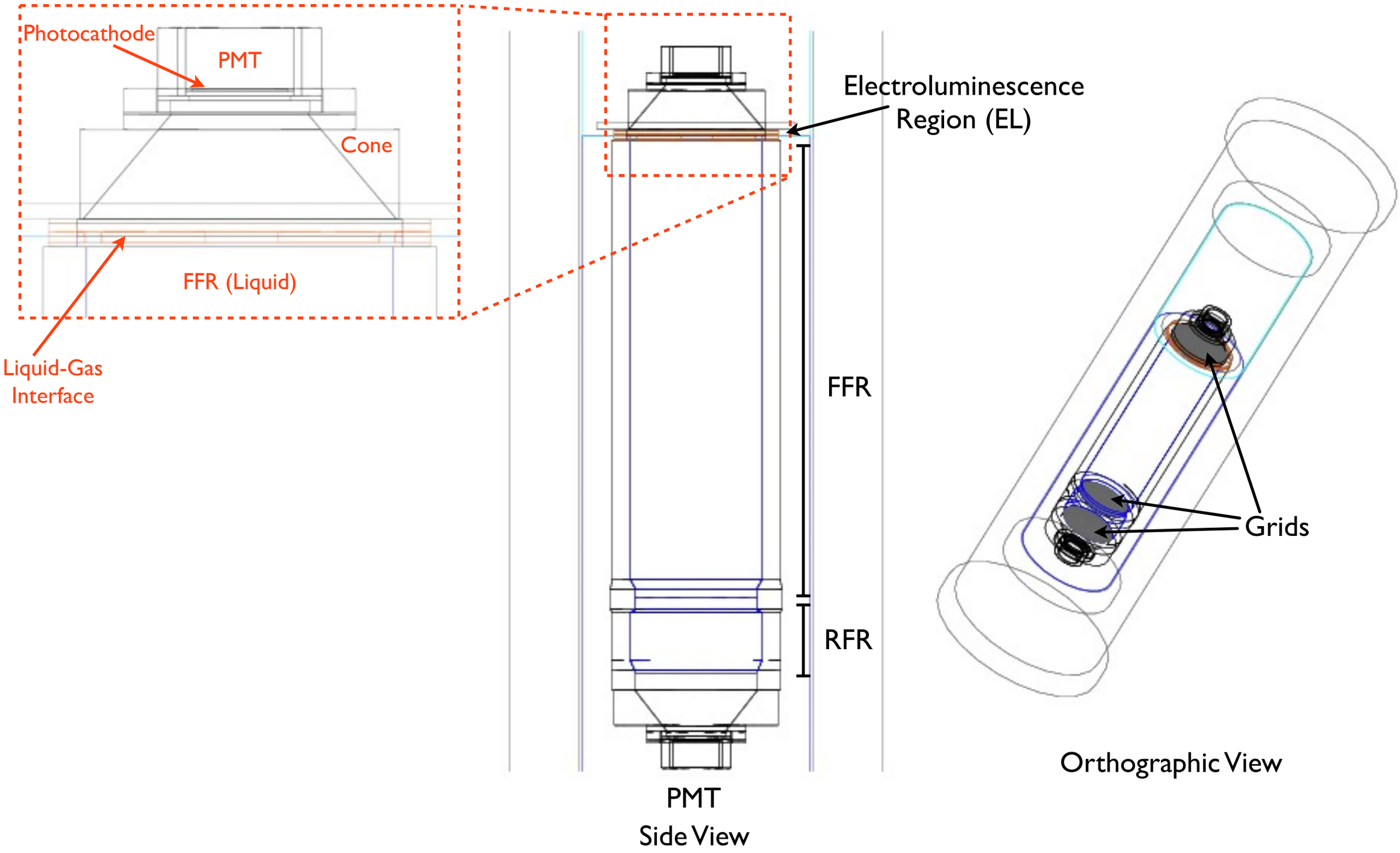
LightGuide

- Photon propagation/tracking software built by Tom

- Matlab-based

- Detector geometries are somewhat constrained

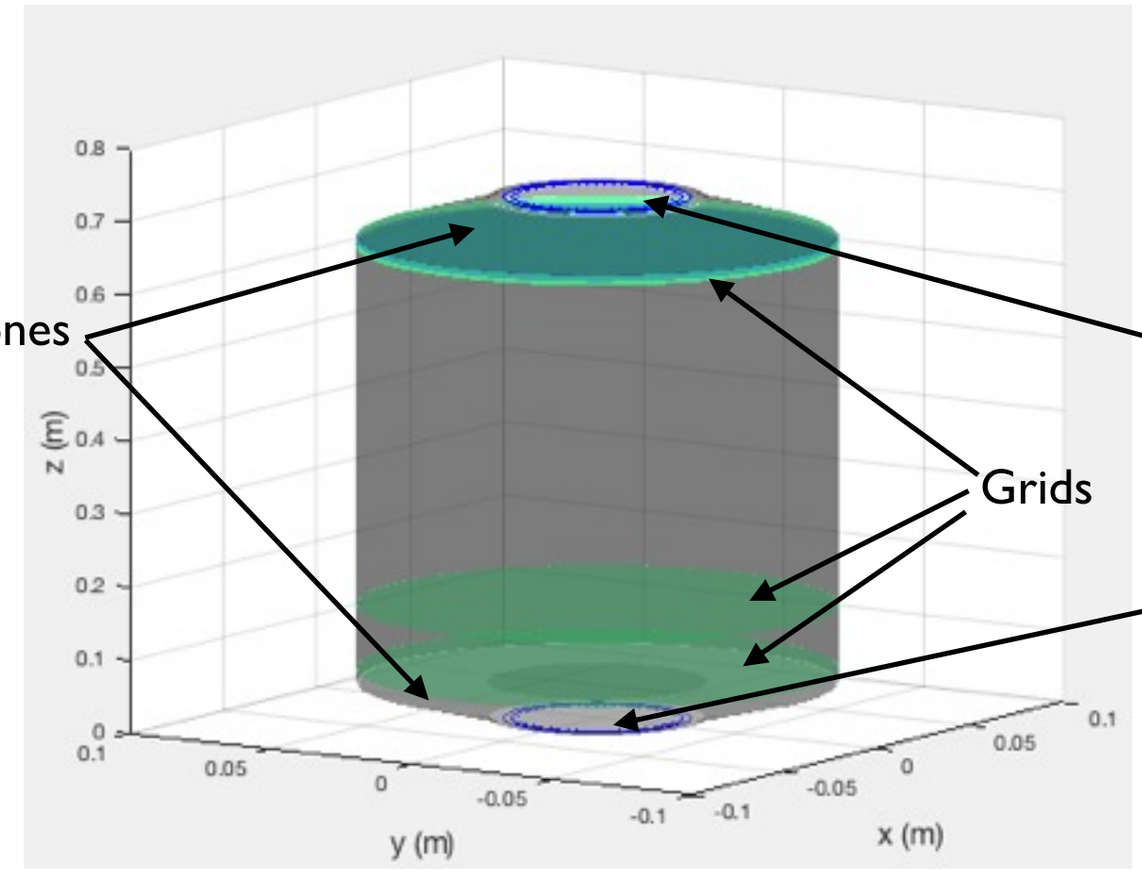
Building the System Test Detector Geometry in BACCARAT



Building the System Test Detector Geometry in LightGuide

- Geometry courtesy of TJ

- Set of cones and cylinders with correct optical properties stacked on top of each other



LightGuide Geometry Visualization

What's the Goal?

Photon Detection Efficiency (PDE):

noun. 1. (*Physics*) The average fraction of photons emitted during an interaction that are absorbed by a photocathode

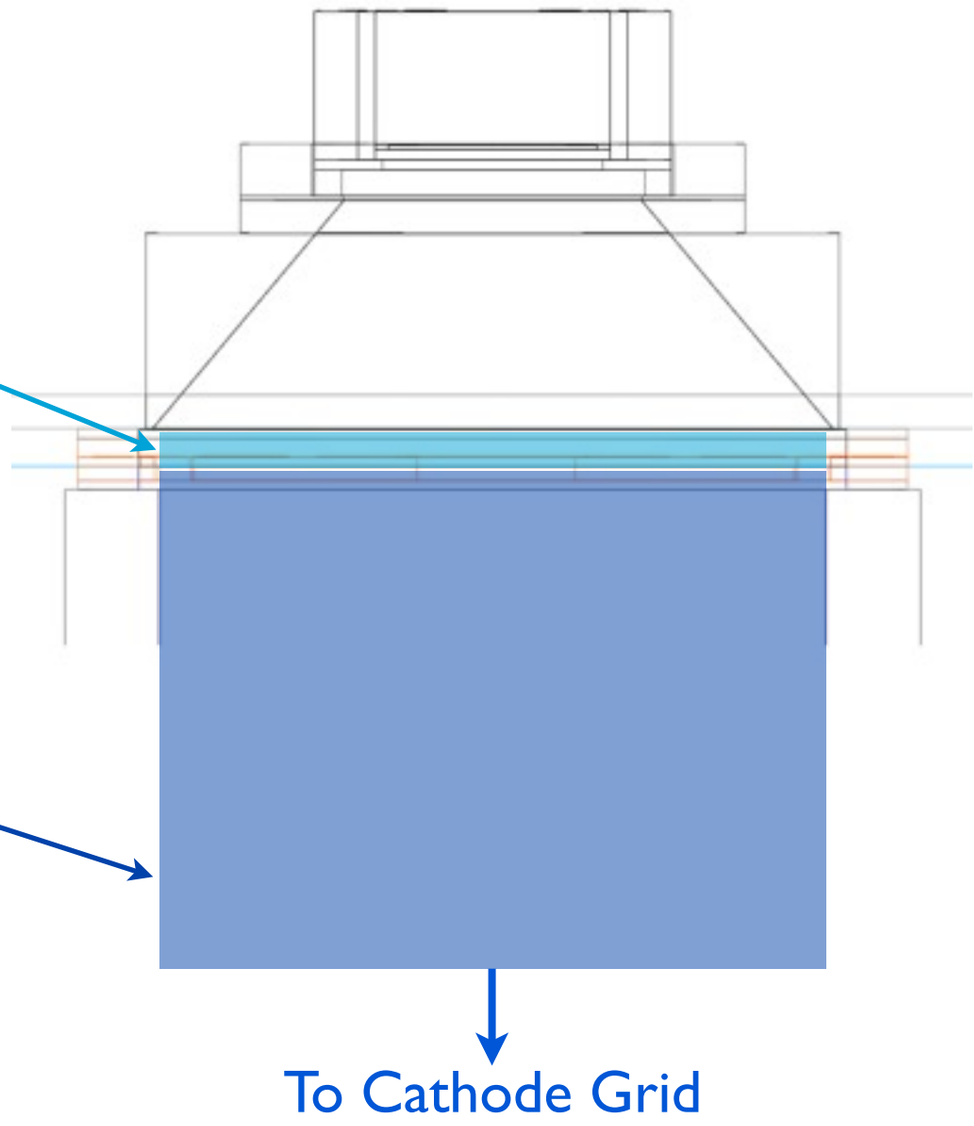
Simulating in BACCARAT:

S2 PDE: Gas Photon Bomb in disk in EL region

- 2M photons, isotropic

S1 PDE: Liquid Photon Bomb in cylinder in FFR.

- 10M photons, isotropic



What's the Goal?

Photon Detection Efficiency (PDE):

noun. 1. (*Physics*) The average fraction of photons emitted during an interaction that are absorbed by a photocathode

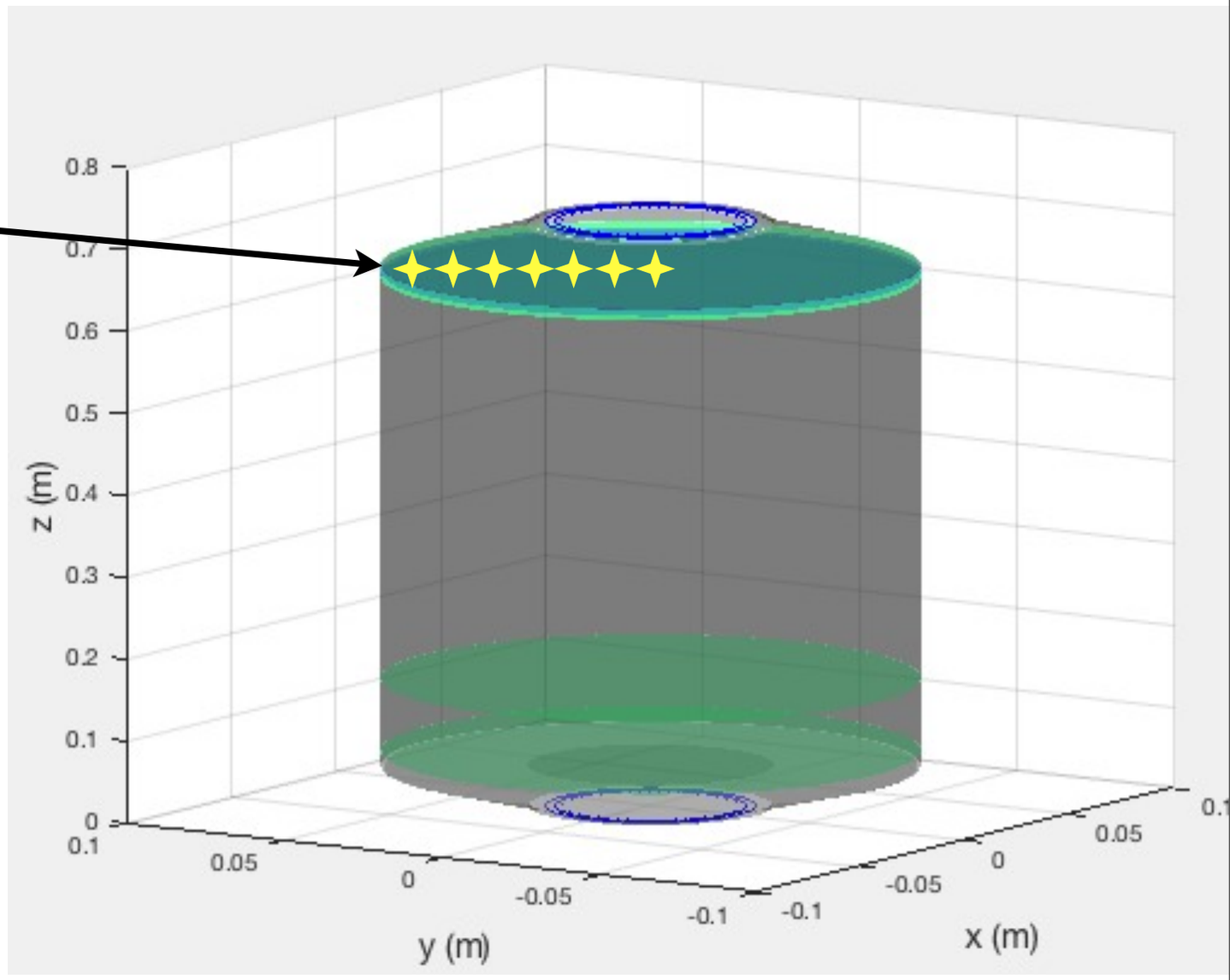
Simulating in LightGuide

S2 PDE: Isotropic photons from points spaced equally in R

- 7 R points, 100K photons/point

S1 PDE: Isotropic photons from points spaced equally in R and Z

- (3 Z points) X (5 R points) = 15 points, 100K photons/point

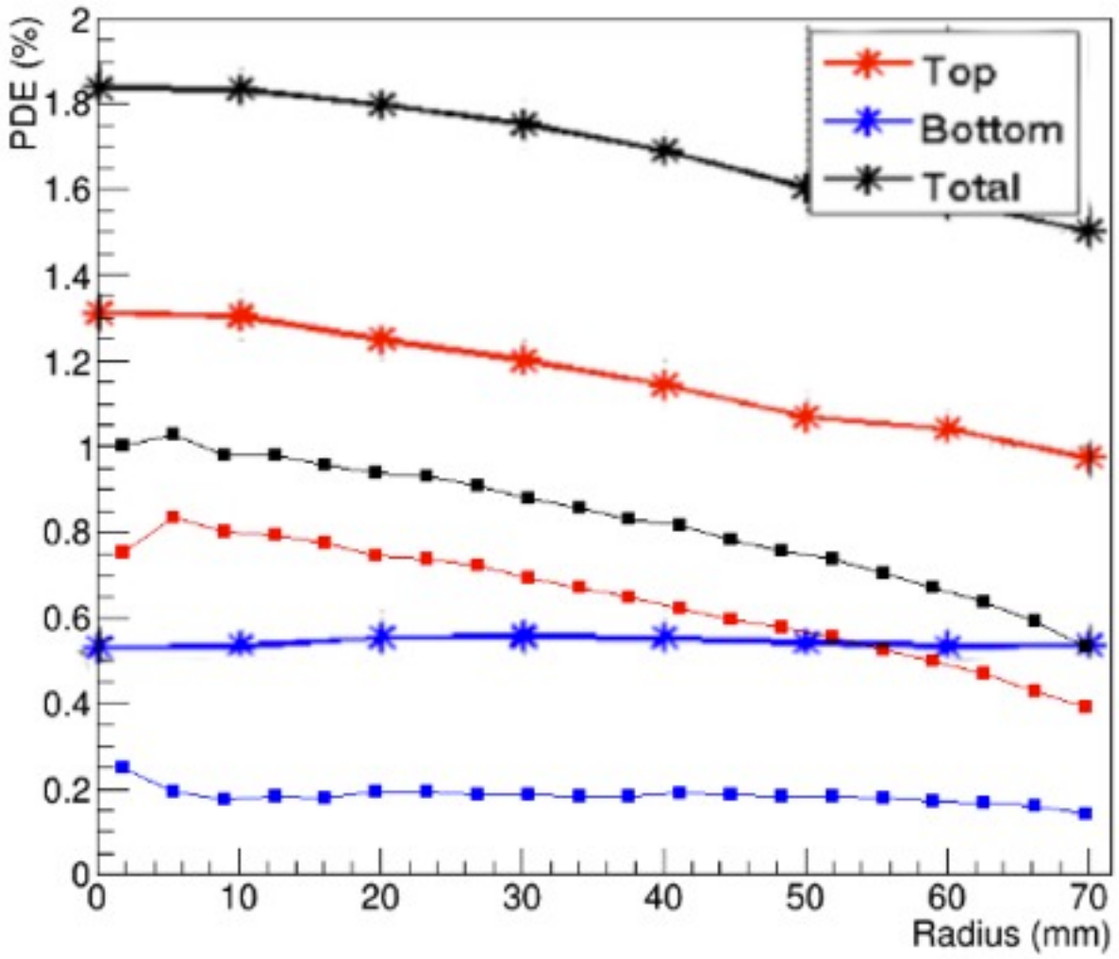


Out-of-the-Box Comparison

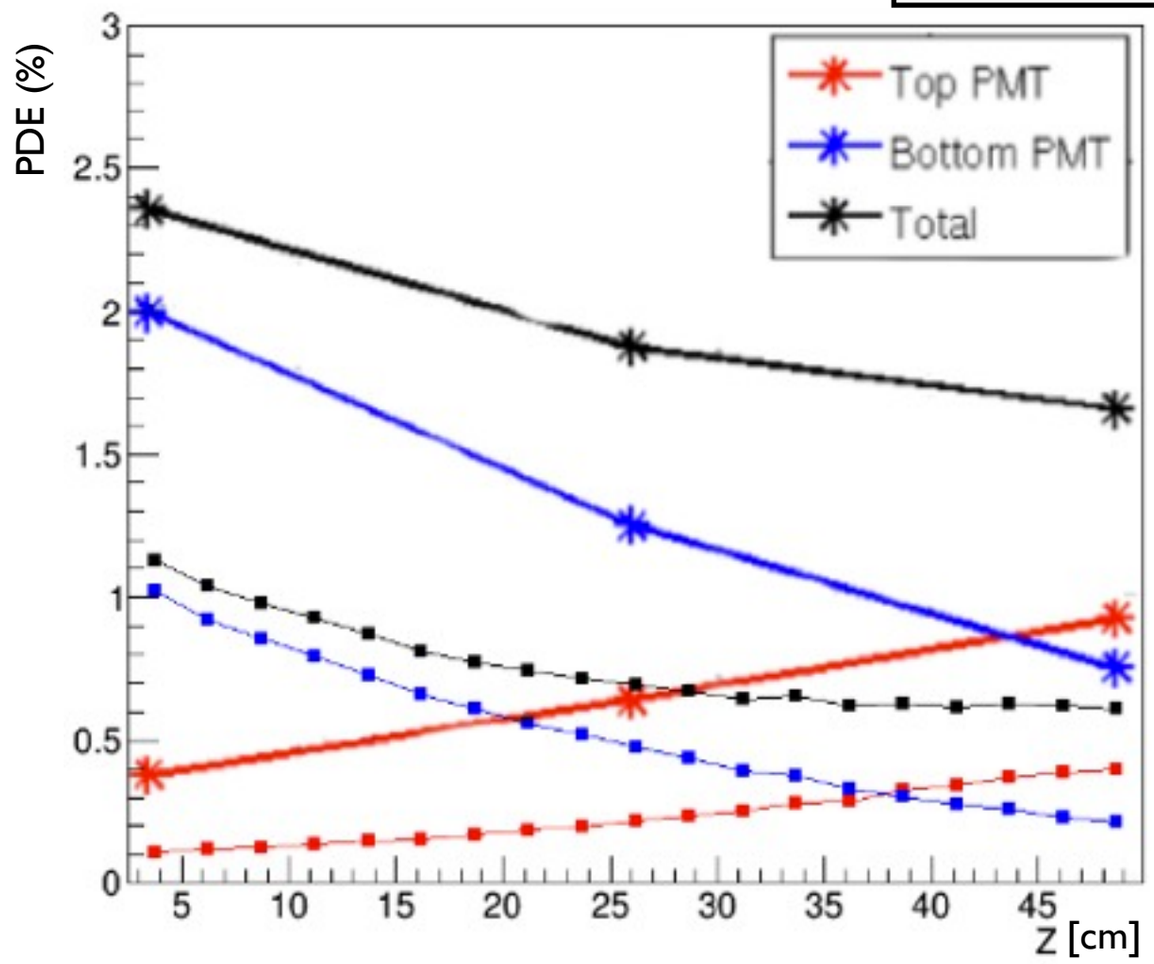
Legend
* LightGuide
■ BACCARAT

Total PDE
Bottom PDE
Top PDE

S2 PDE vs. R



S1 PDE vs Z



Initial estimates: LightGuide PDE is 2-3 times that of BACCARAT

- LG plots are from TJ's September 2016 presentation

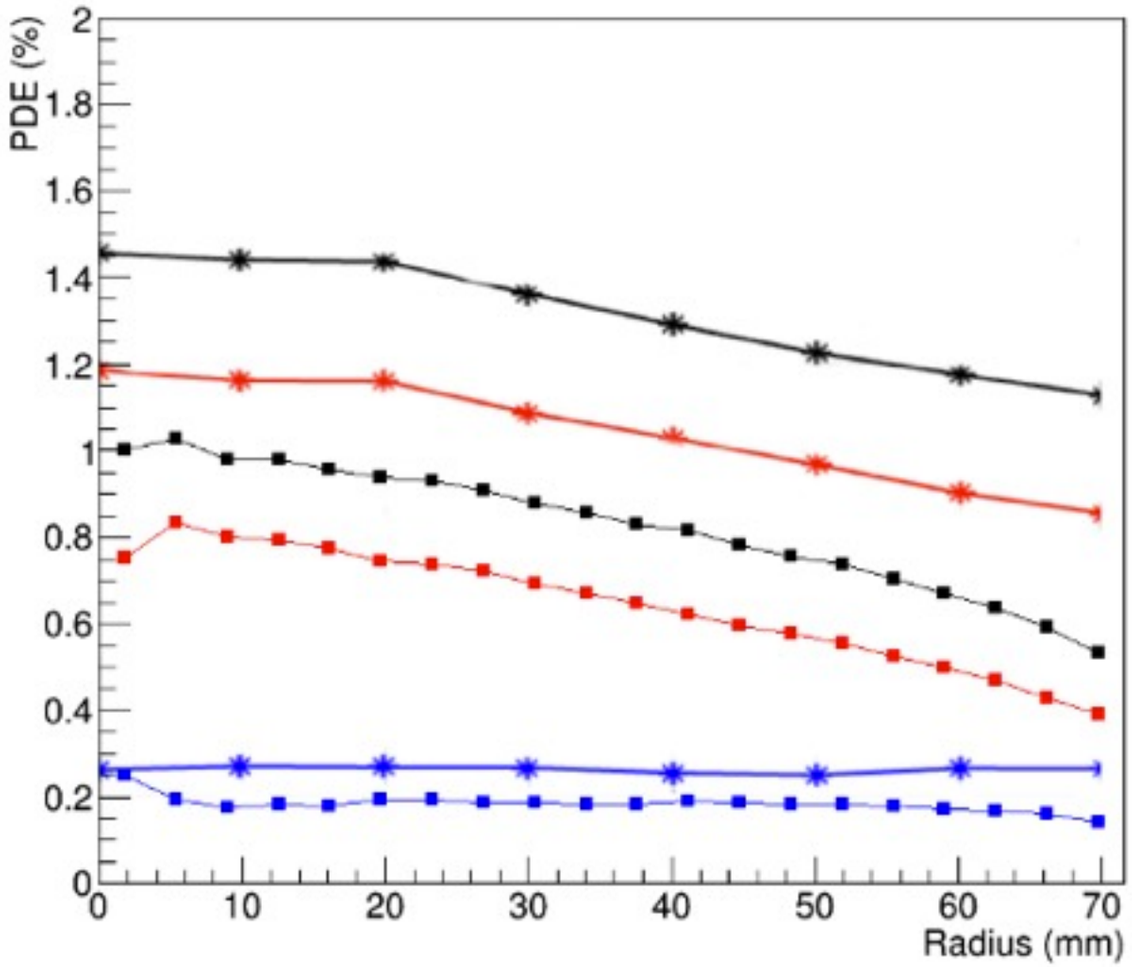
- Not good. We want to know what's causing this discrepancy.

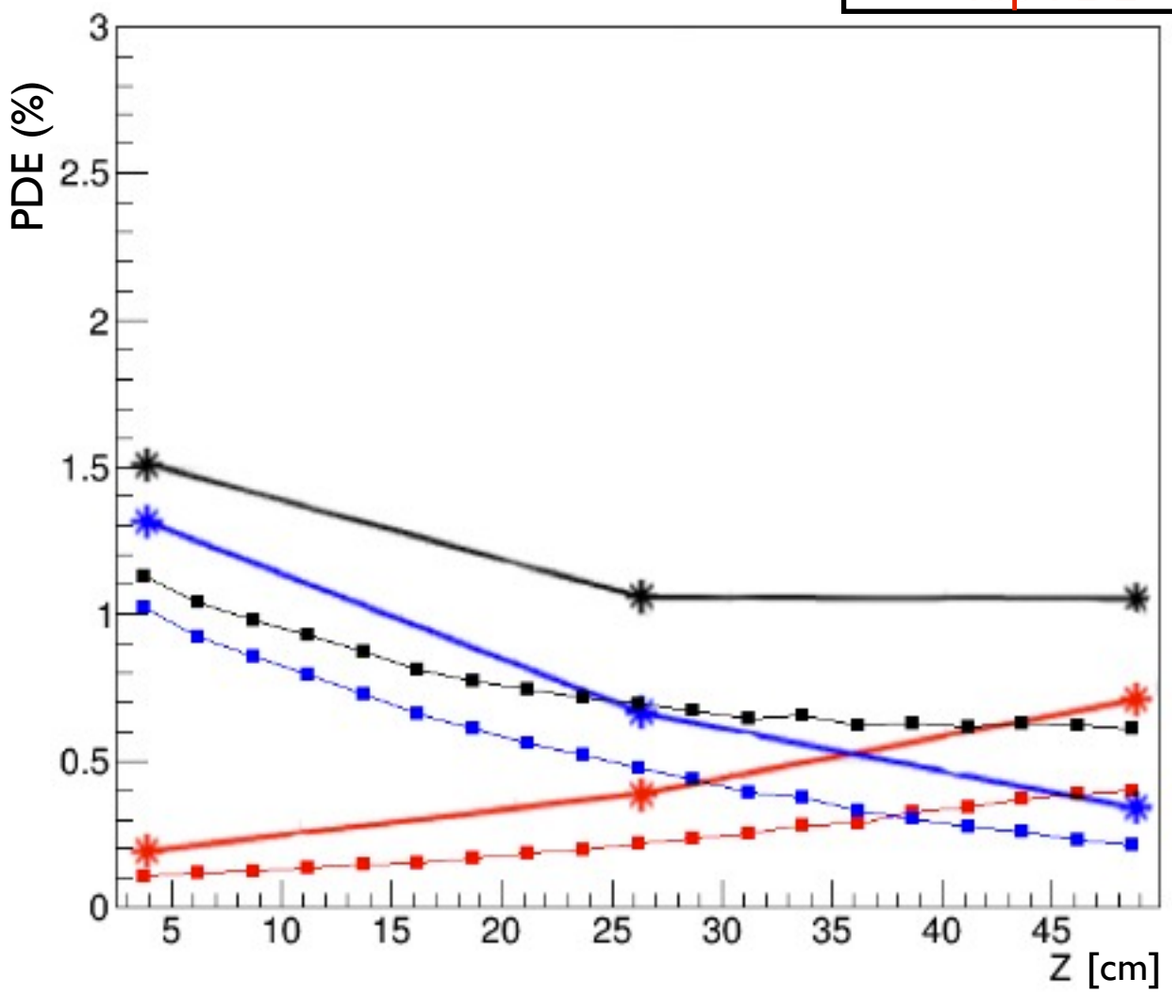
PDEs don’t agree, but upon closer inspection, neither do the simulations...

Let’s make sure our simulation packages are doing the same thing:

Iteration	Change
1	None - Out-of-Box
2	Updated Optical Params (LG)
3	Corrected A-G Region Surfaces (LG)
4	Lambertian Reflection (LG)
5	Adjusting Geometries (LG/BACC)

Iteration 2





Legend
- LightGuide
- BACCARAT

Total PDE
Bottom PDE
Top PDE

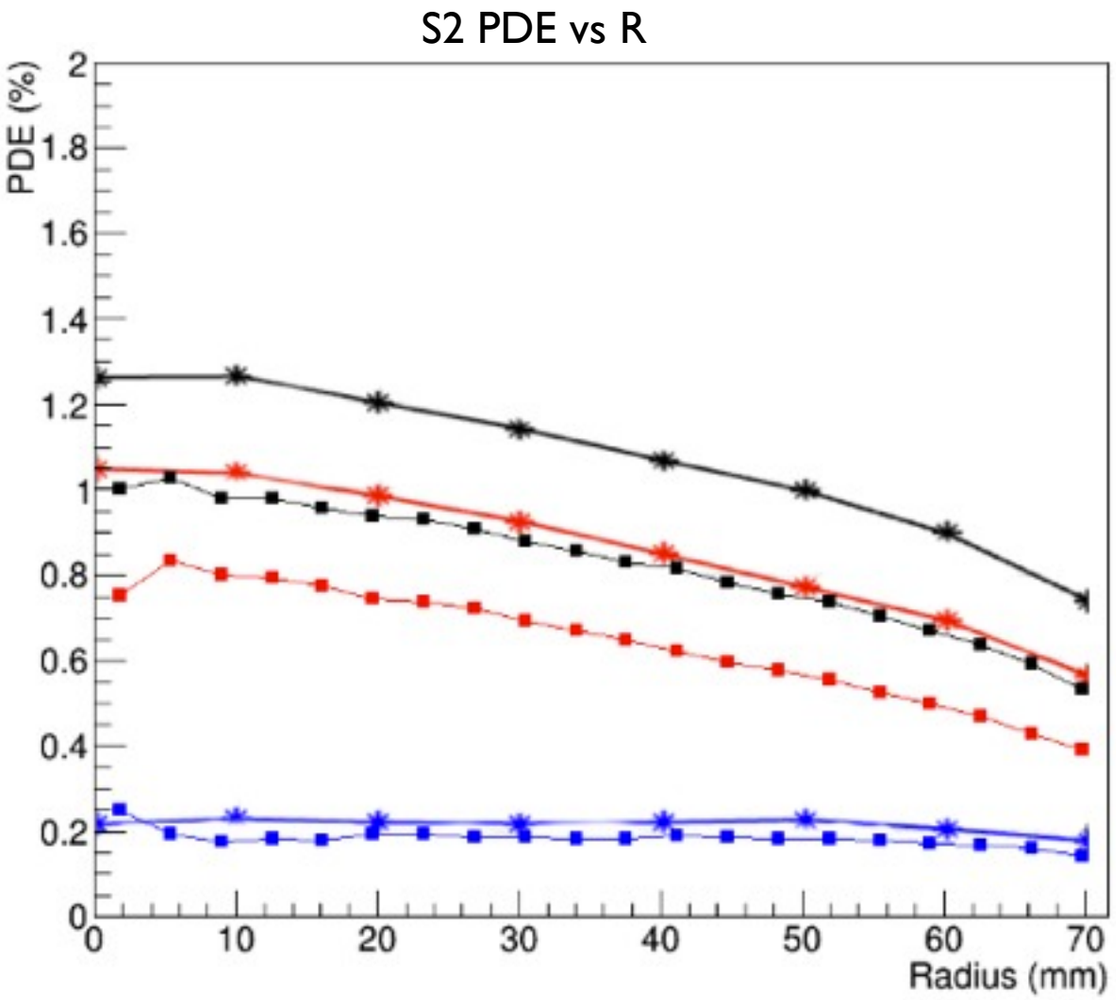
Software changed: LightGuide
Change made: Updated Optical Parameters

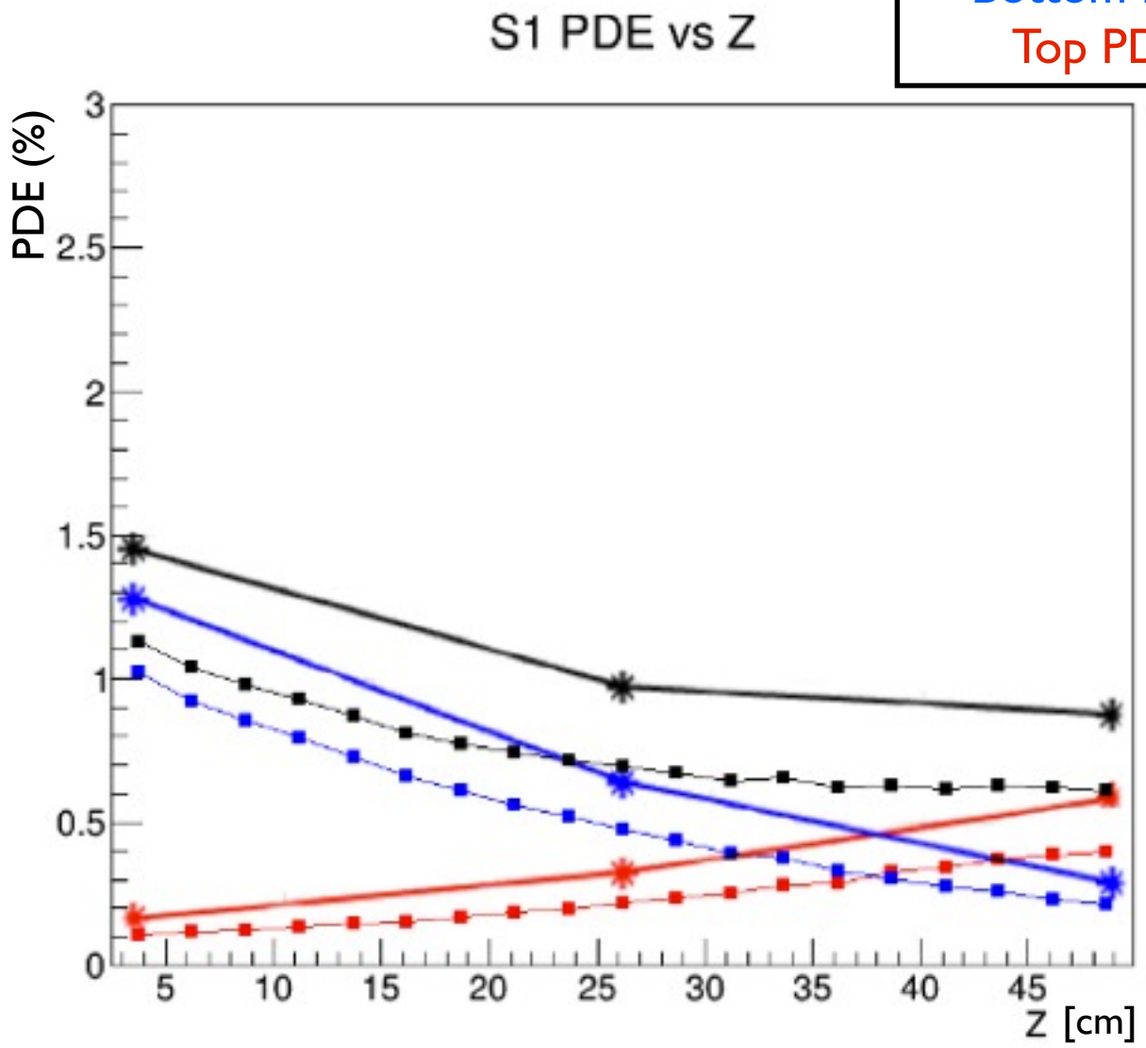
- LXe-Teflon Refl: 98% → 95%
- L/GXe-Steel Refl: 10% → 20%
- LXe Absorption Length: 100m → 30m
- GXe Absorption Length: 17523m → 500m
- GXe Reyleigh Scat. Length: 52.57m → 500m

New Discrepancy S2: LG PDE is ~150% of BACC PDE
New Discrepancy S1: LG PDE is ~140-200% of BACC PDE

Iteration 3

Legend
* LightGuide
■ BACCARAT
Total PDE
Bottom PDE
Top PDE





Software changed: LightGuide
Change made: Changed G-A region surfaces from Teflon to Stainless Steel
Details:

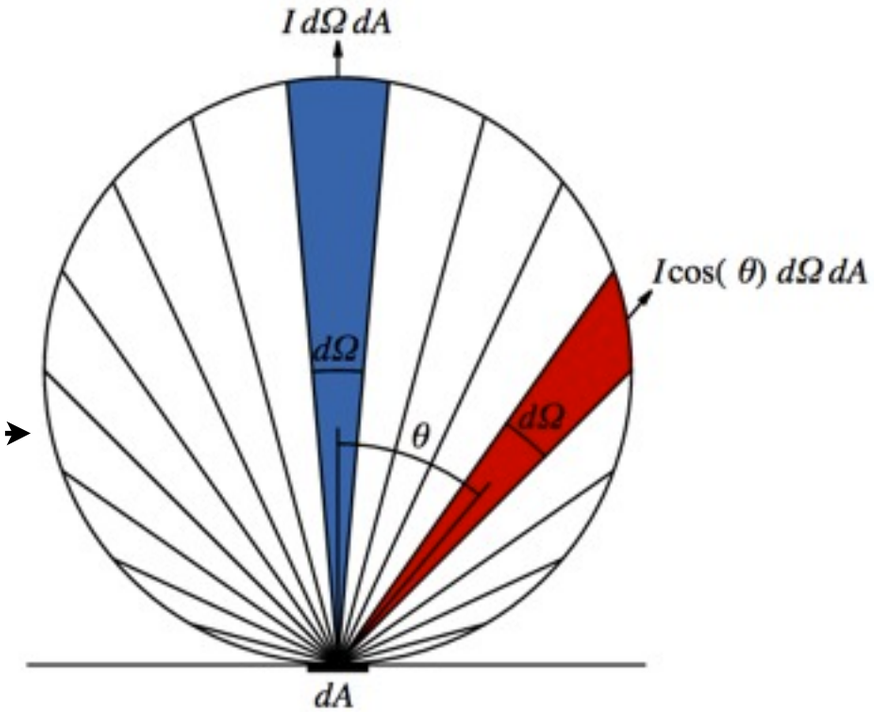
Teflon Reflectivity: 0.8 in gas, 0.95 in liquid
SS Reflectivity: 0.2 in both

New Discrepancy S2: LG PDE is ~130% of BACC PDE
New Discrepancy S1: LG PDE is ~140% of BACC PDE

Lambertian Reflection (Theory)

For a "perfect" diffuse reflector:

- Radiant intensity of reflected light is proportional to cos(θ), where θ is the angle between the surface normal and the emitted ray.



- Angular pdf: $2sin(\theta)cos(\theta)$

Then sample θ, φ (defined from the normal to the reflecting surface) from:

$$\phi = 2\pi x$$
$$\theta = arcsin(\sqrt{y})$$

where x, y are uniformly random between 0 and 1.

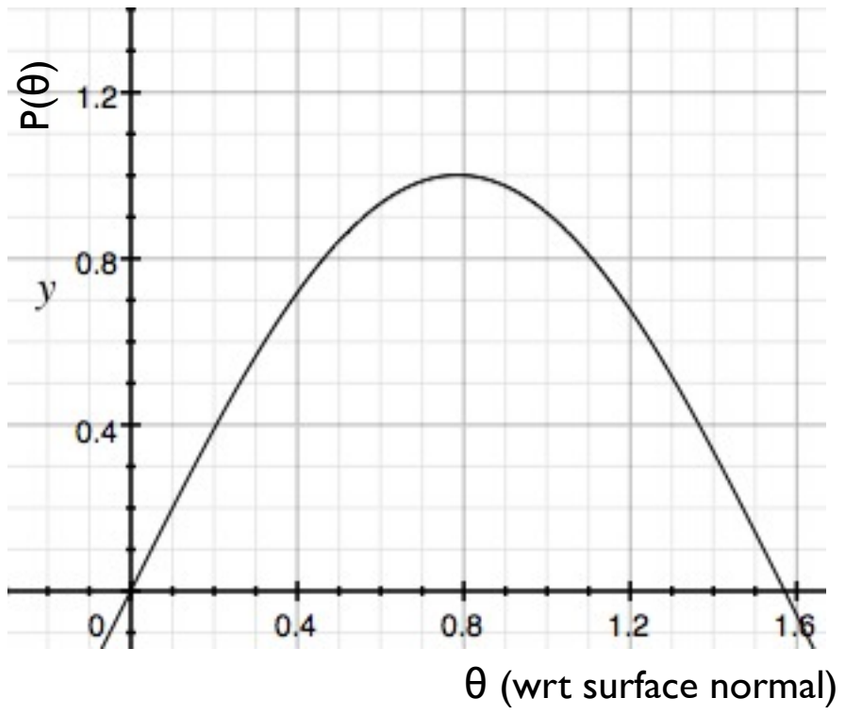
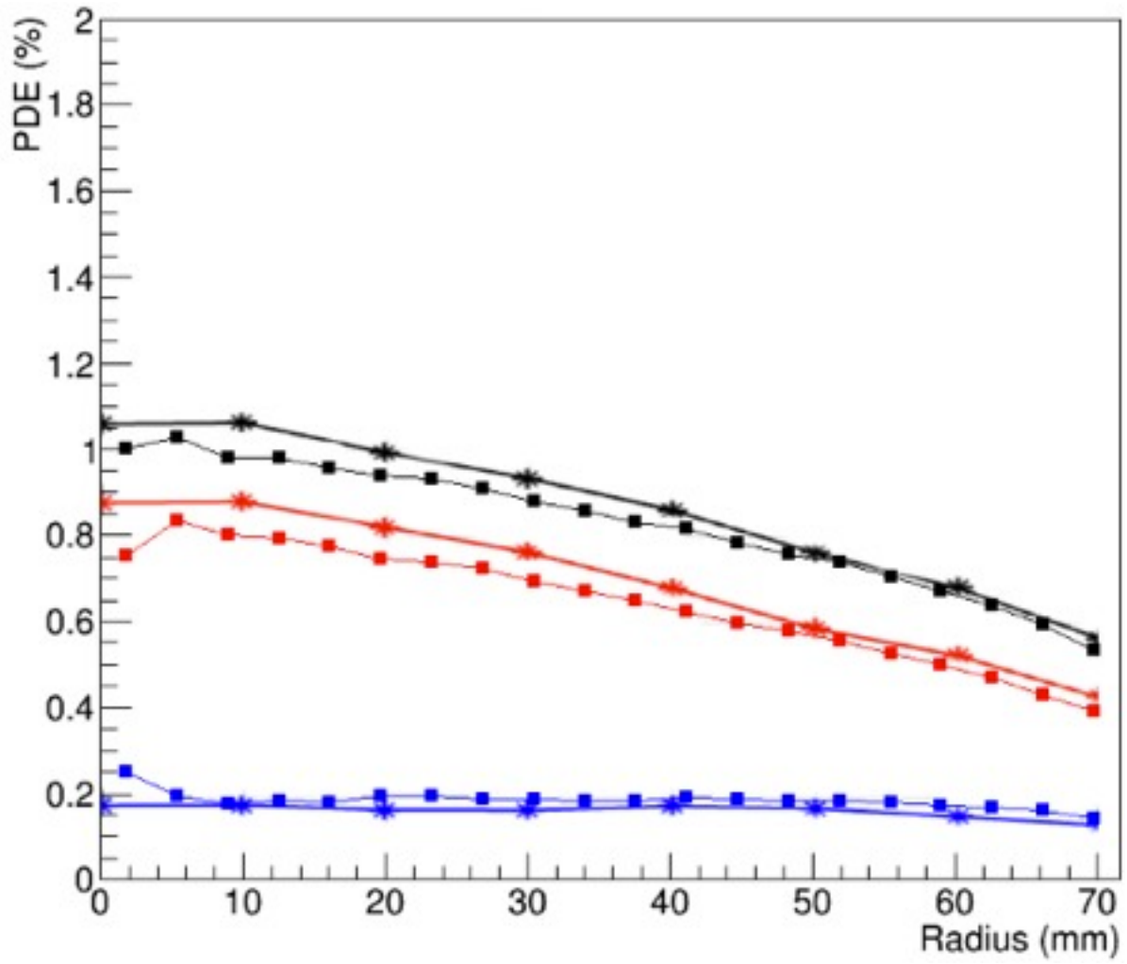


Image Credit: https://en.wikipedia.org/wiki/Lambert's_cosine_law

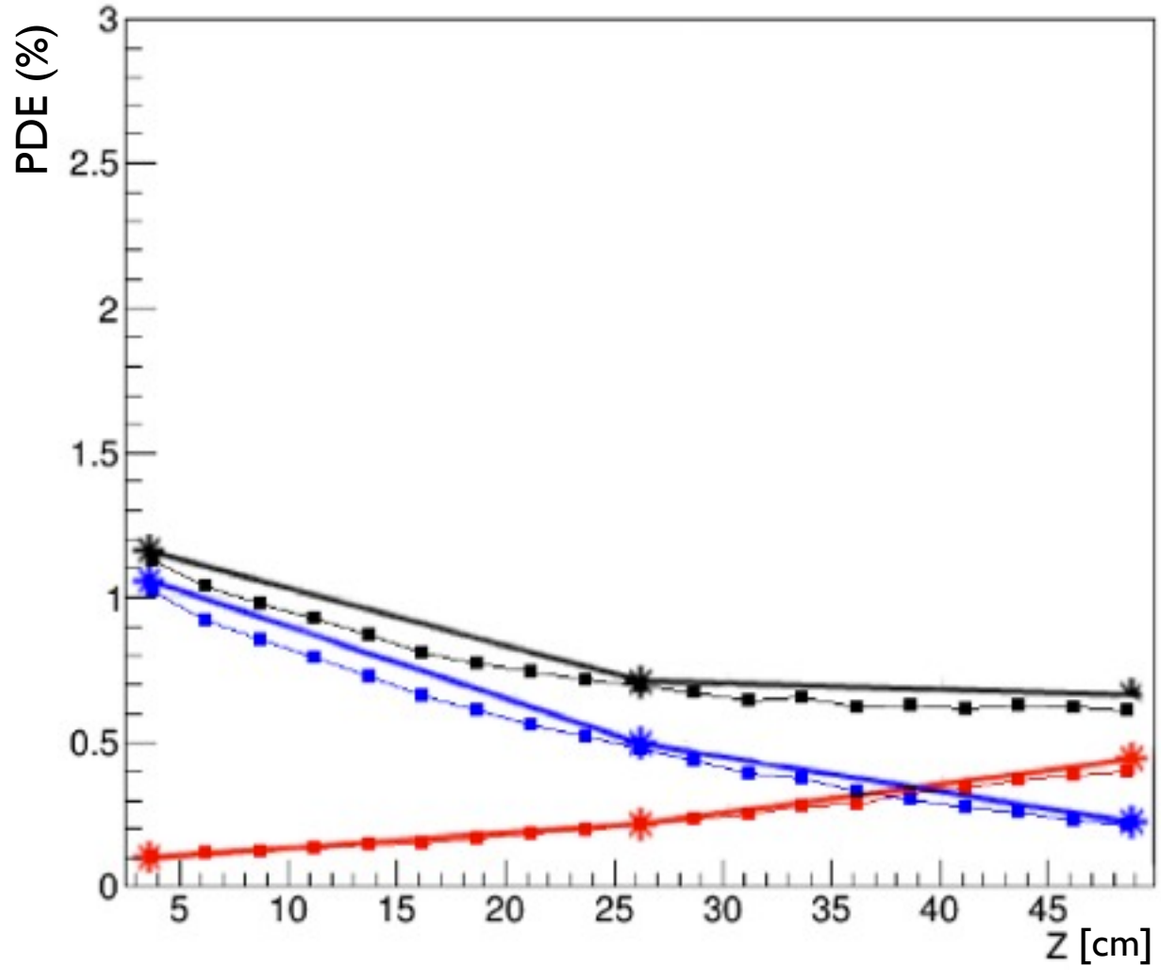
Iteration 4

Legend
* LightGuide
■ BACCARAT
Total PDE
Bottom PDE
Top PDE

S2 PDE vs R



S1 PDE vs Z

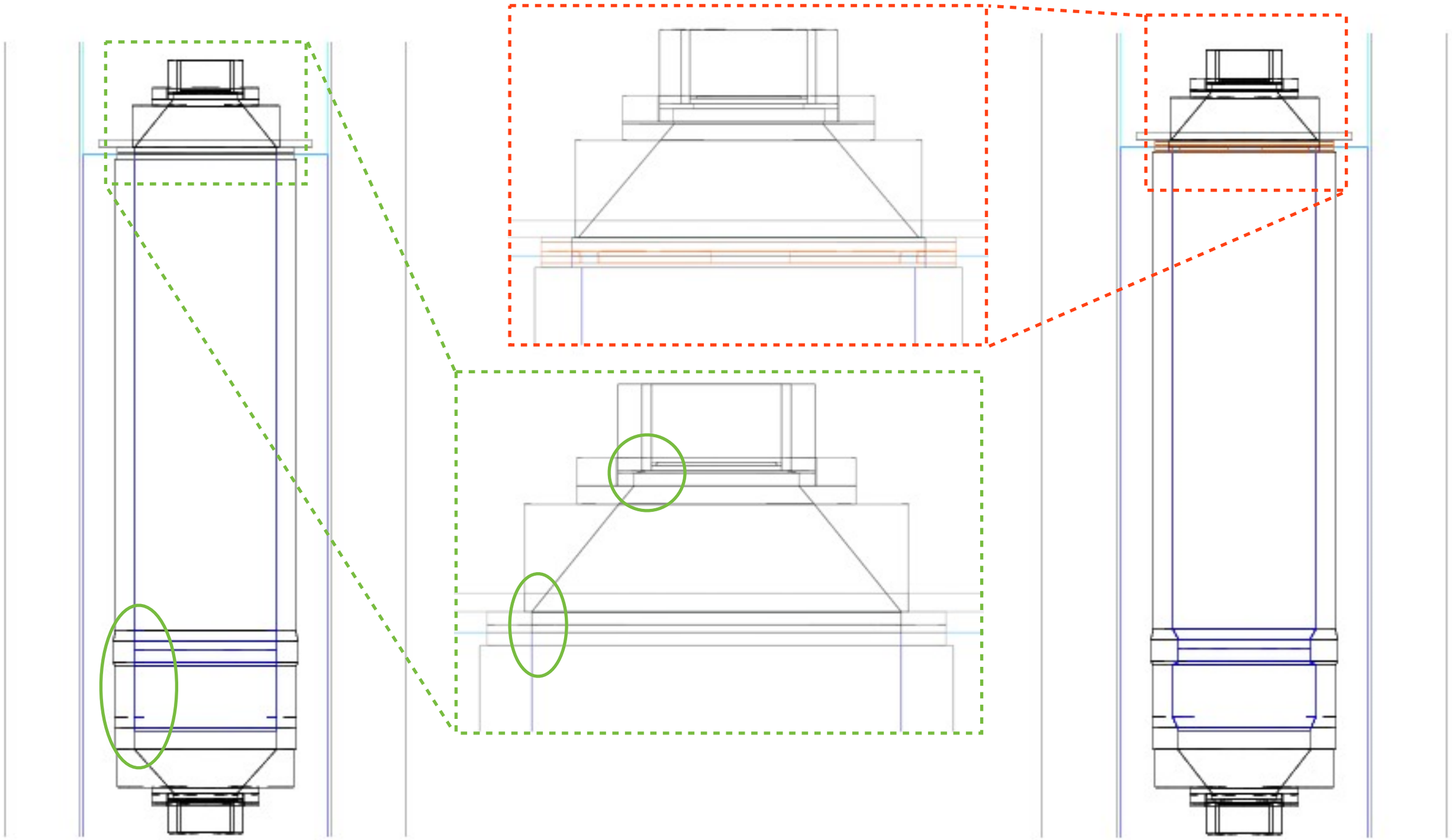


Software changed: LightGuide
Change made: Implemented Corrected Lambertian Reflection
Details:

Previous implementation in LG gave isotropic reflection.

New Discrepancy S2: <10%
New Discrepancy S1: <10%

BACC and LG don't have identical geometries...
Let's fix that!



Modified Geometry

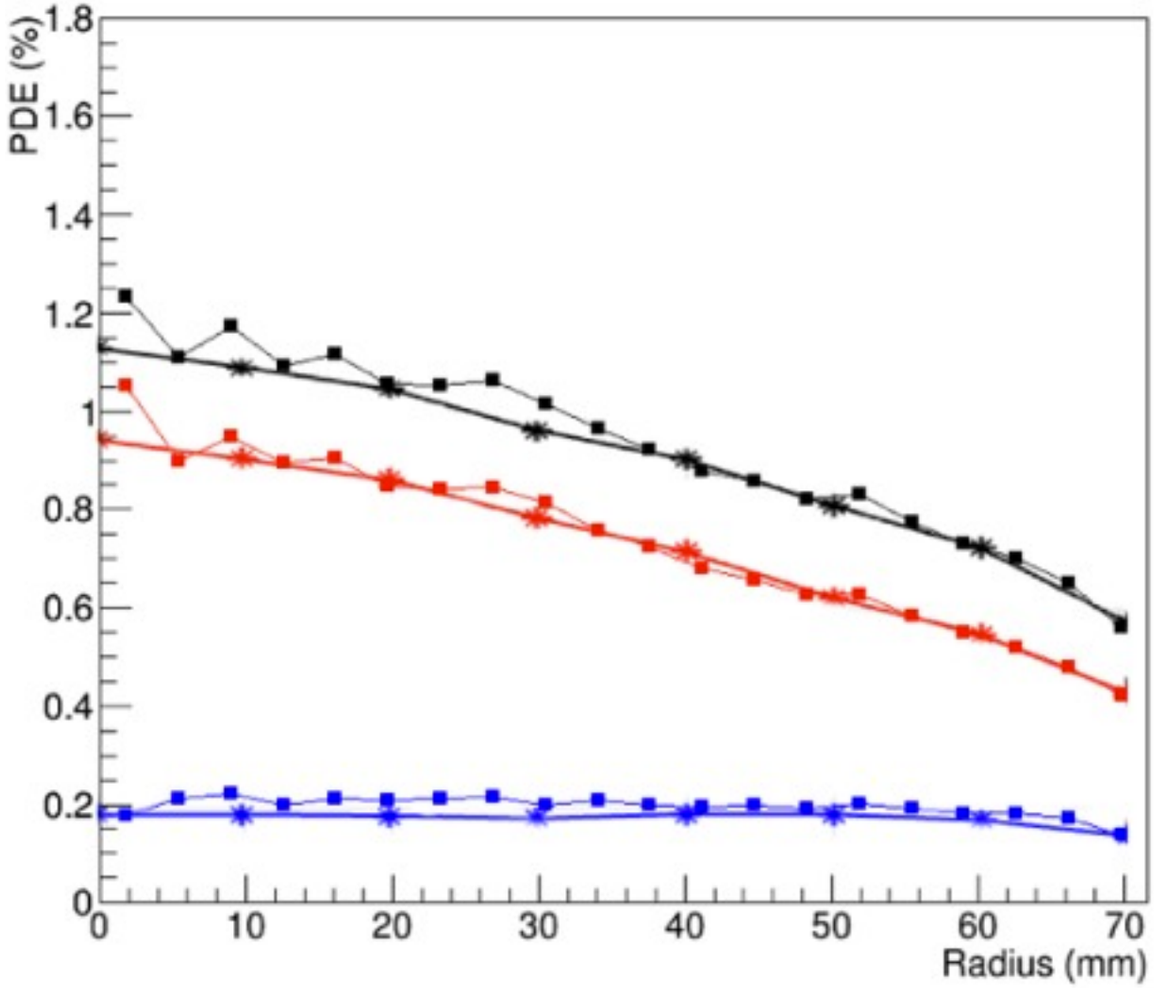
Old Geometry

Iteration 5

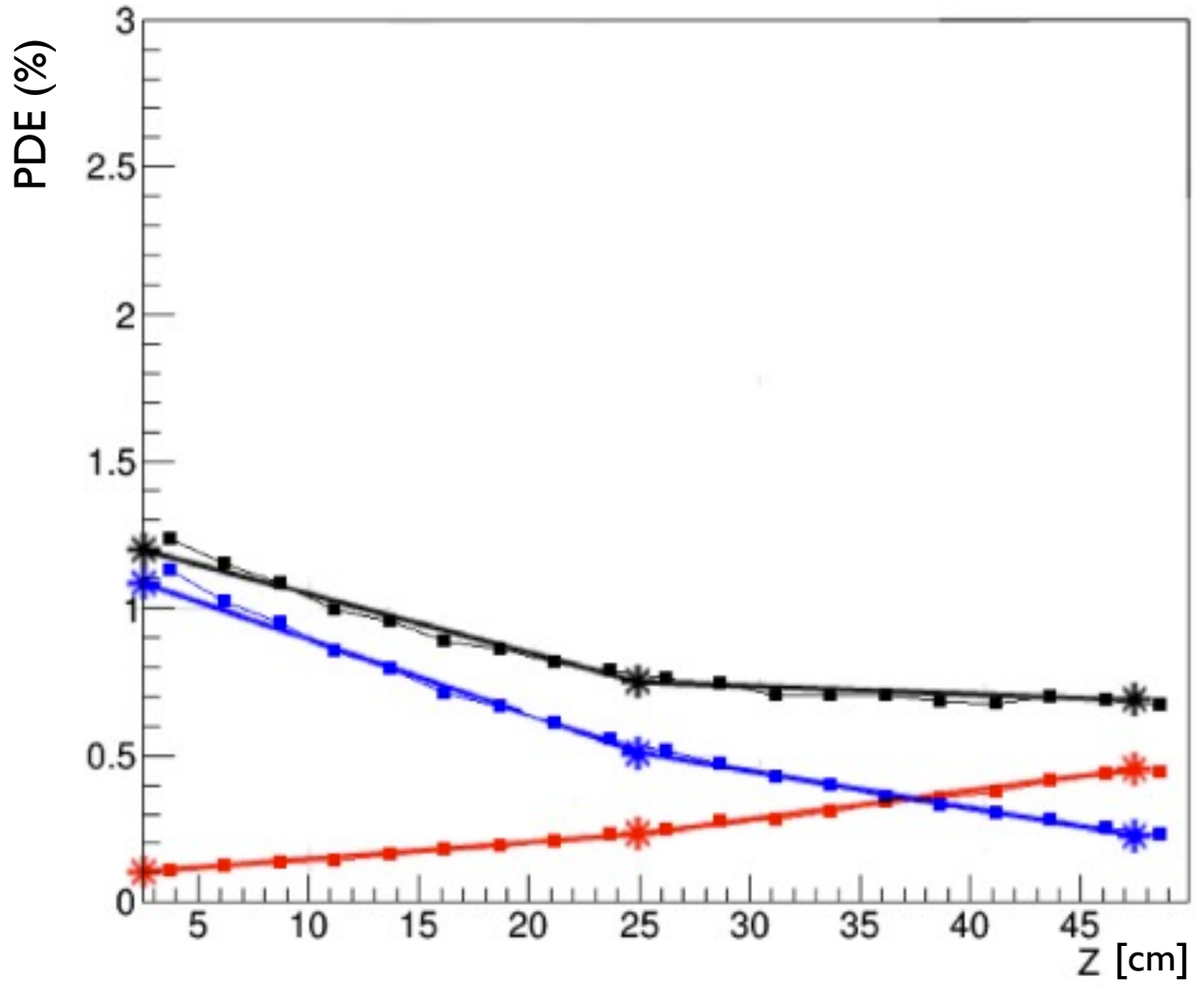
Legend
* LightGuide
■ BACCARAT

Total PDE
Bottom PDE
Top PDE

S2 PDE vs R



S1 PDE vs Z



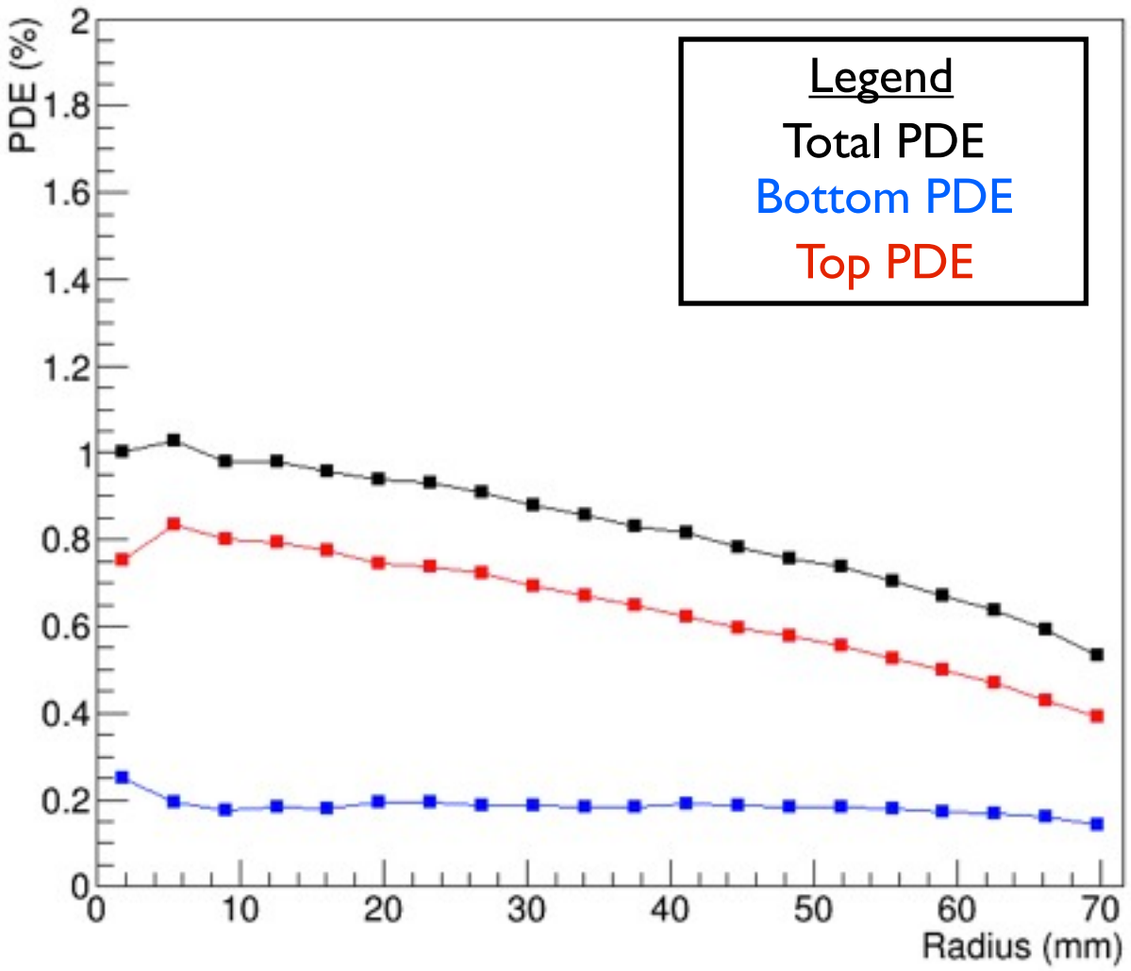
Software changed: BACCARAT and LightGuide
Change made: Tweaked geometries to make them more coincident

New Discrepancy S2: few %
New Discrepancy S1: few %

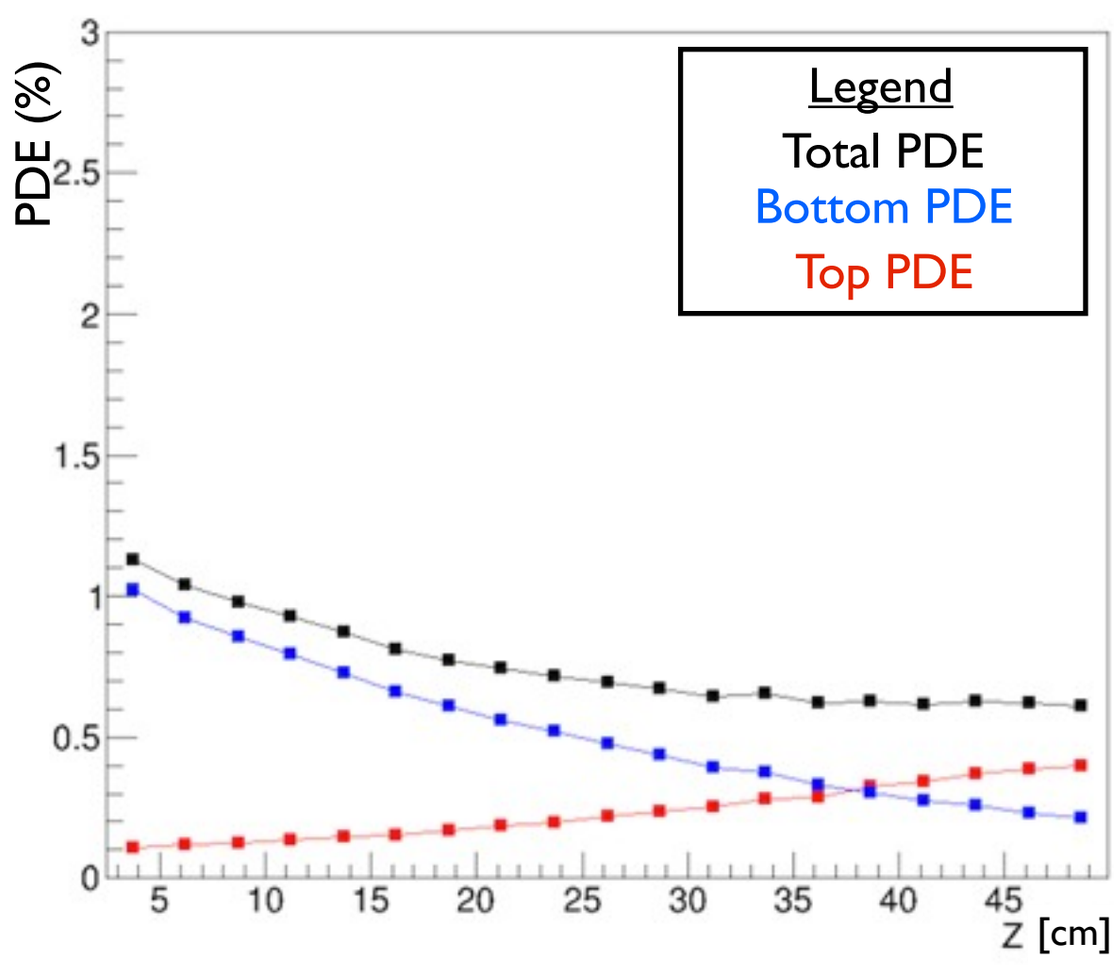
Now that we've cross-checked our PDE, what does the System Test PDE tell us?

Back to simulating within fully detailed BACCARAT geometry.

S2 PDE vs R



S1 PDE vs Z

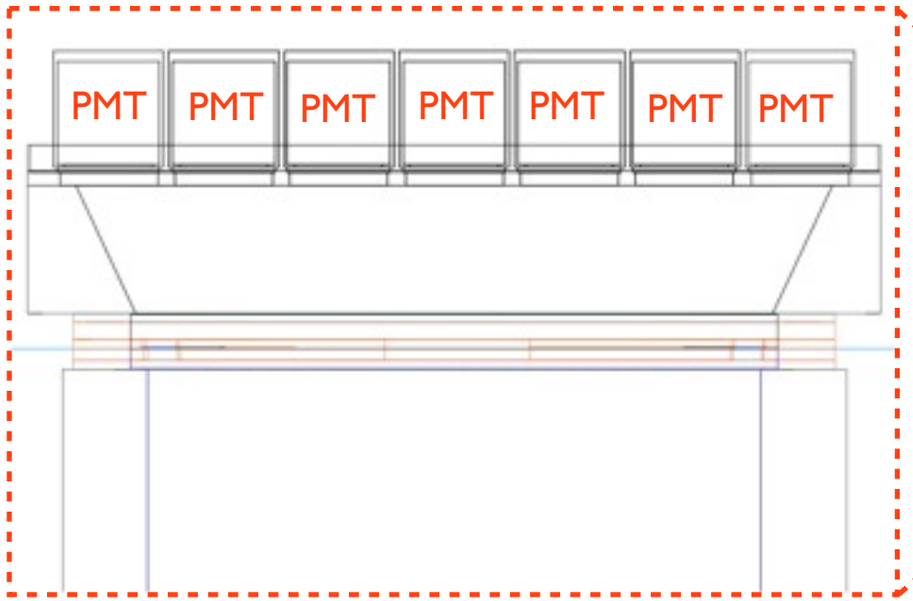


A single extraction electron will produce ~900 photons for nominal field values.

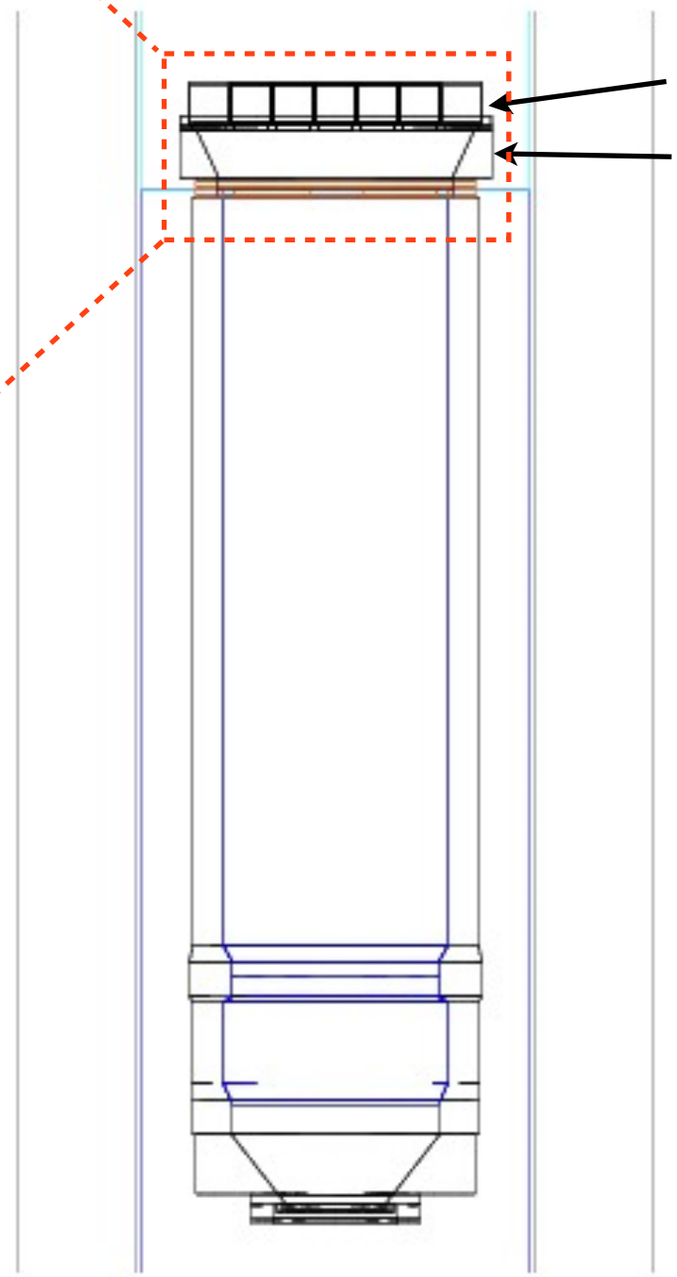
- From our simulated PDE, we expect to see ~8 photons per extraction electron.

- We can check this against calibration data to better understand light collection within the System Test.

Multi-PMT Array Light Collection Study

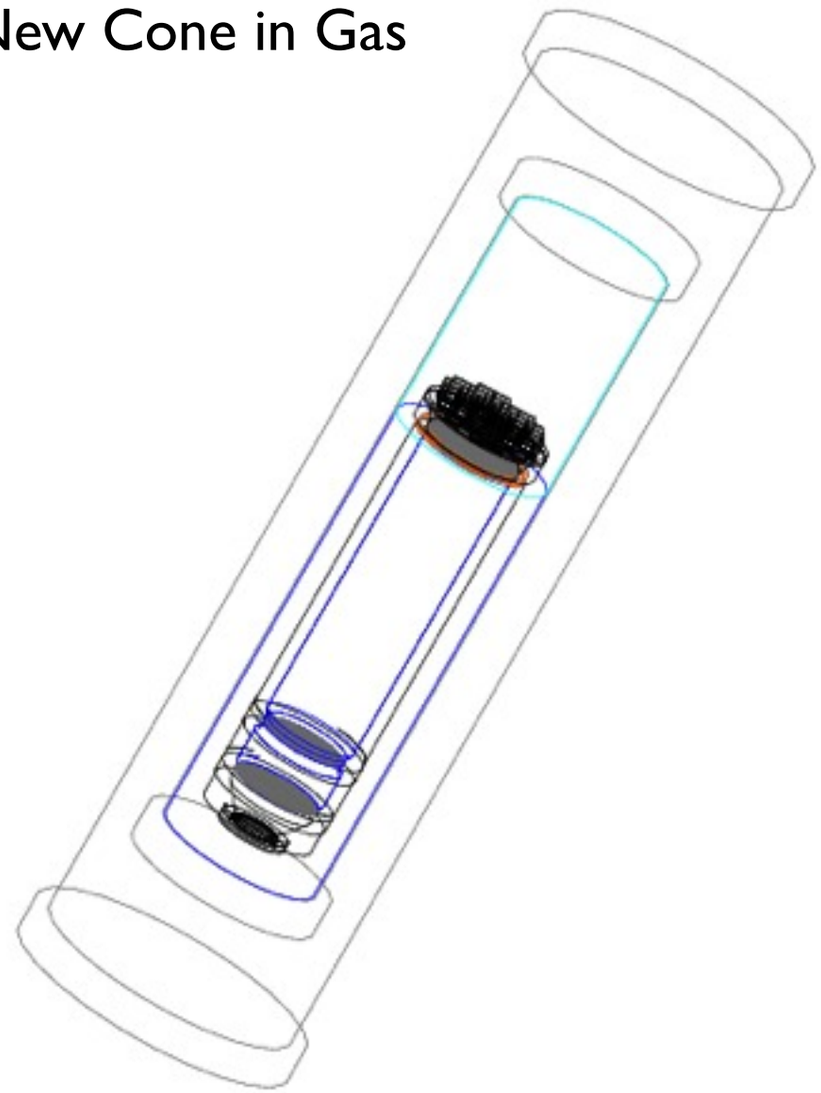


Array Profile View



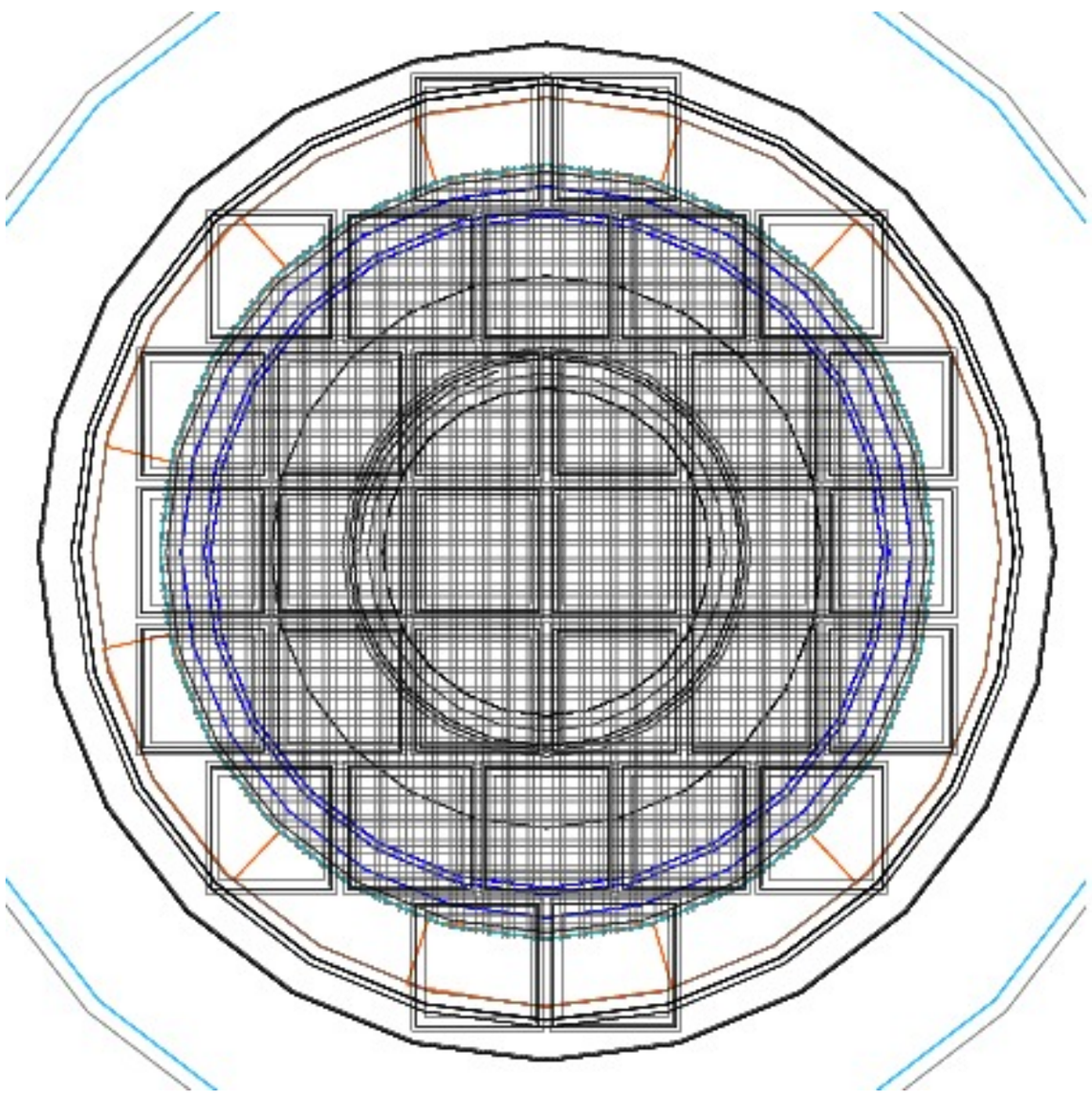
Multi-PMT Array

New Cone in Gas

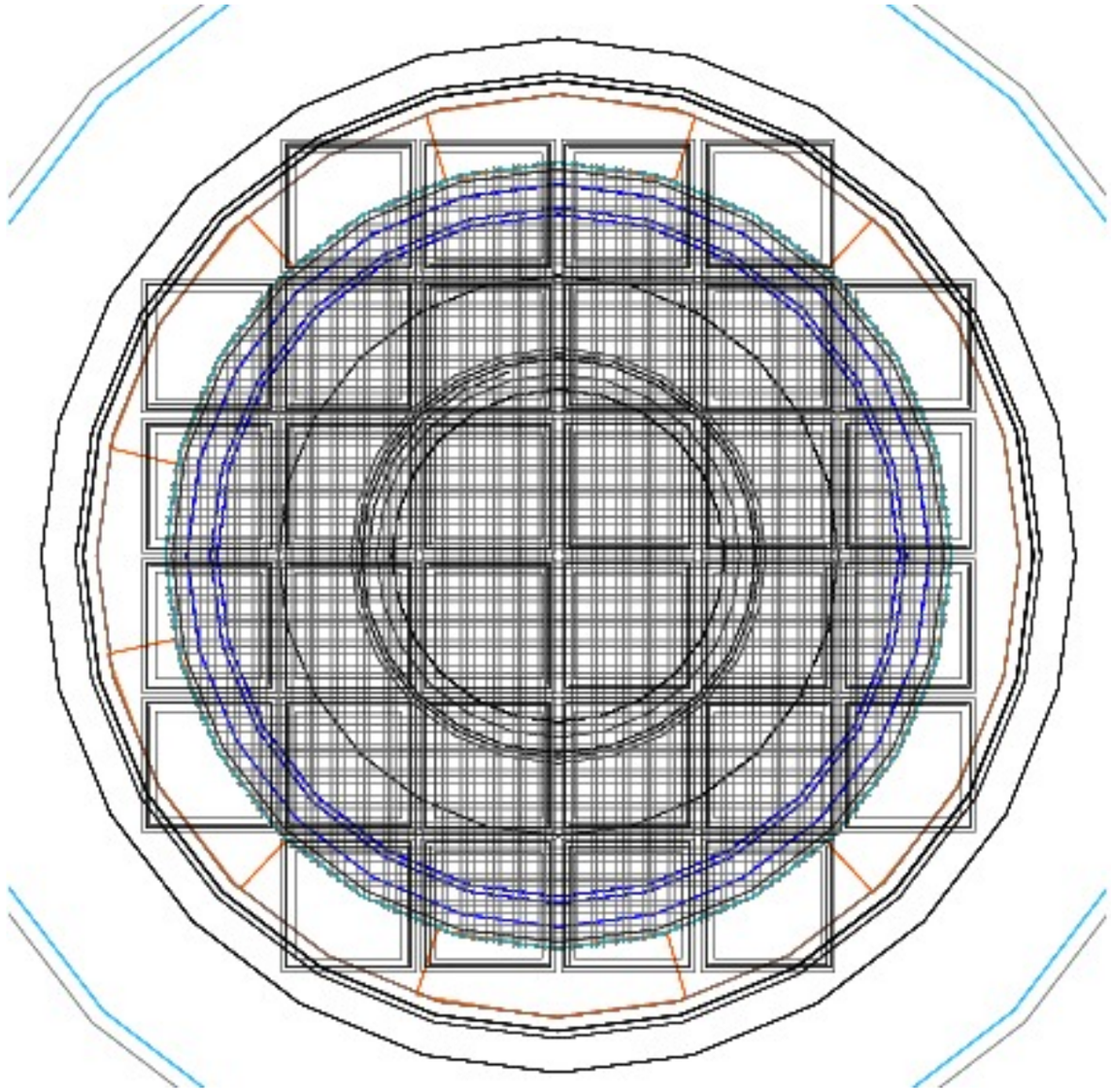


Top Array Designs (by Alden)

(Each square is a 1” R8520 PMT)



Hybrid Array Top-Down View

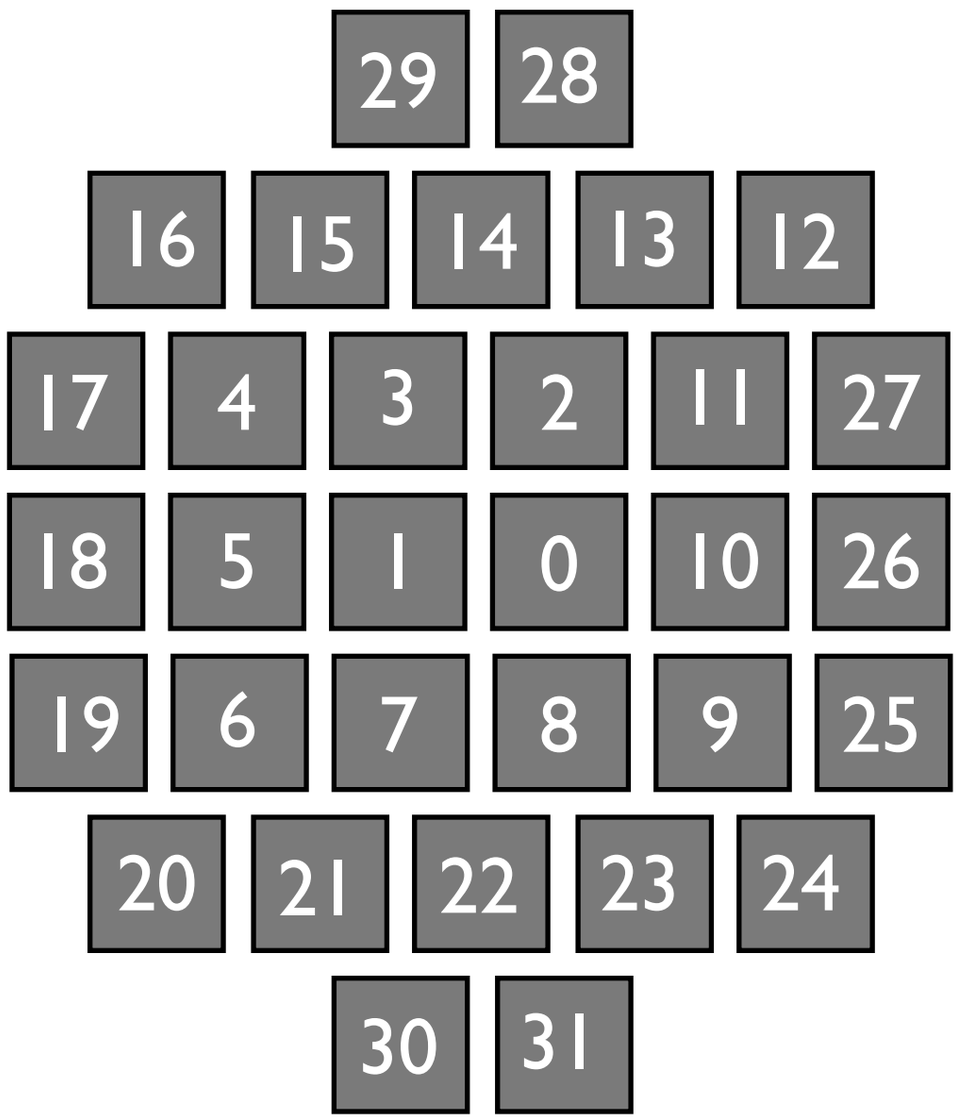


Square Array Top-Down View

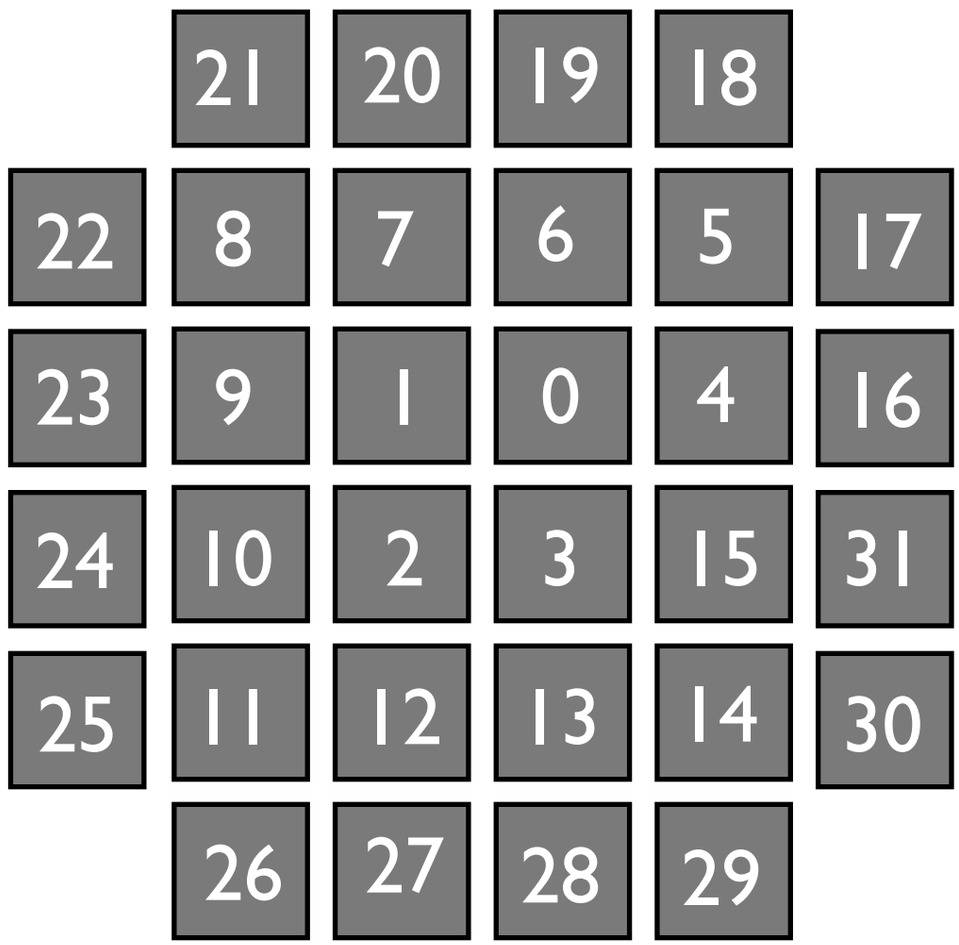
Establishing a PMT Numbering Convention

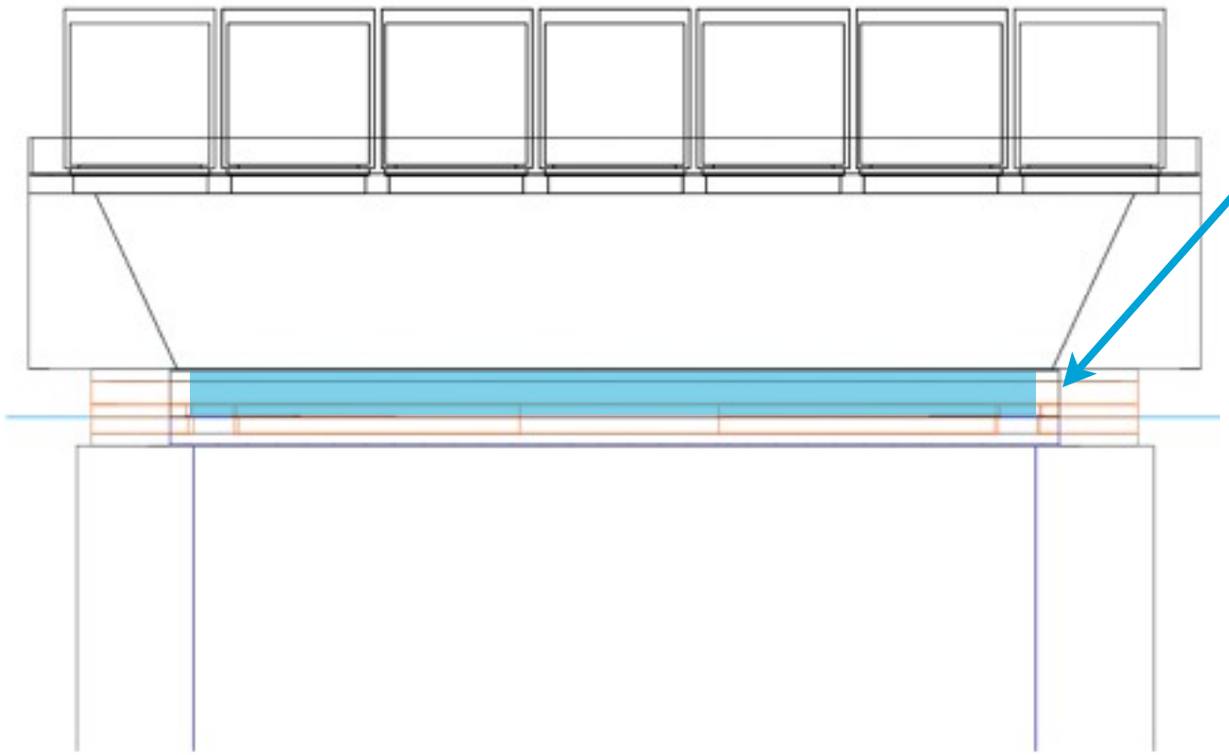
Mostly follows a rule of "smaller index ⟷ smaller R,"
progressing counterclockwise.

Hybrid (top-down view)



Square (top-down view)





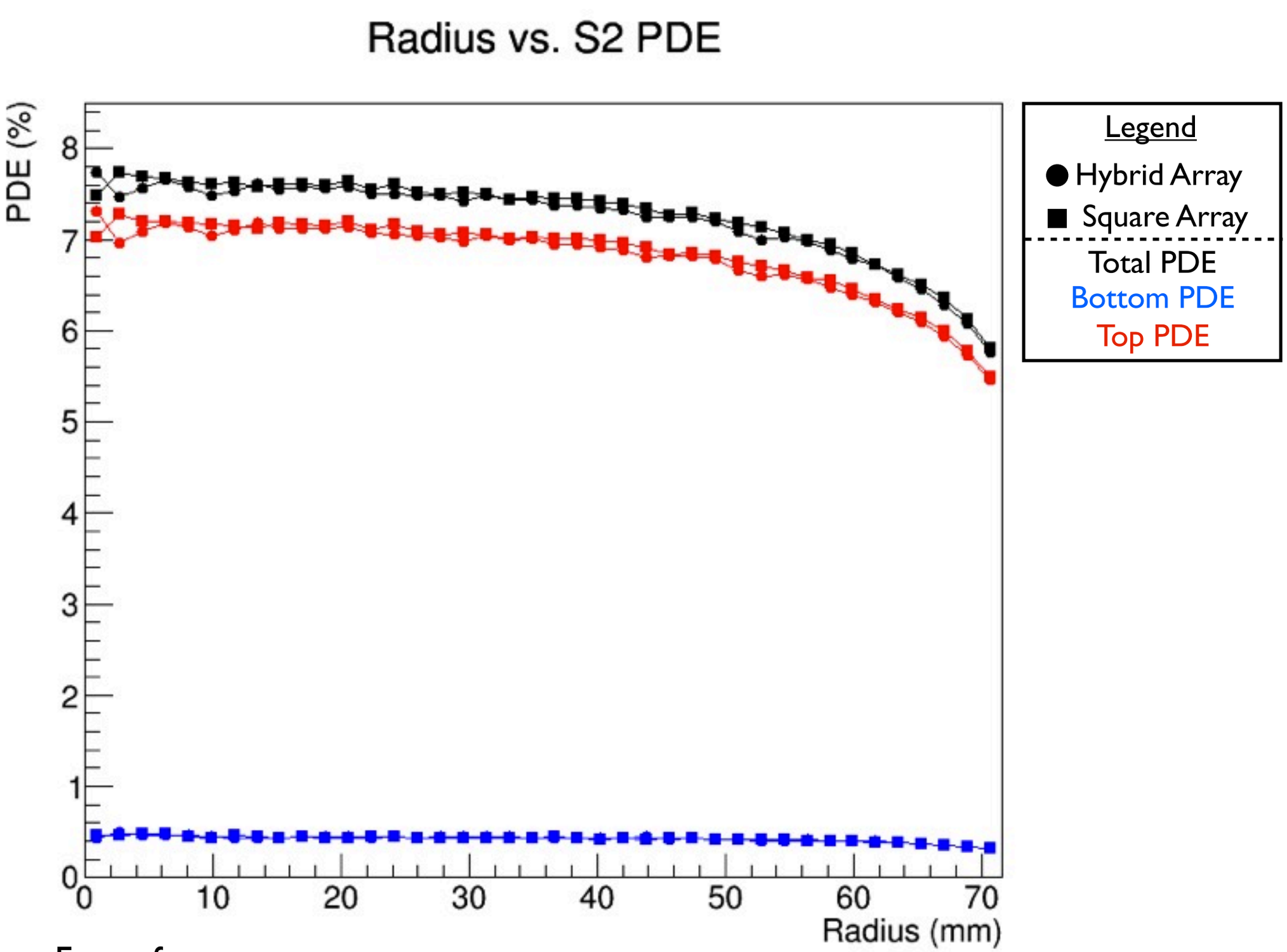
What did we simulate?

S2 PDE: Gas photon bomb in disk in electroluminescence region

- 1D plots: 10M photons, isotropic

- 2D heat map (to be presented at a later date): 500M photons, isotropic - IN PROGRESS

Sims done for both square and hybrid arrays



For reference:

- Scale of total S2 PDE for the 2-PMT array: 1%-level
- Scale of total S2 PDE for LZ (from TDR): 9%-level

Hit Occupancies

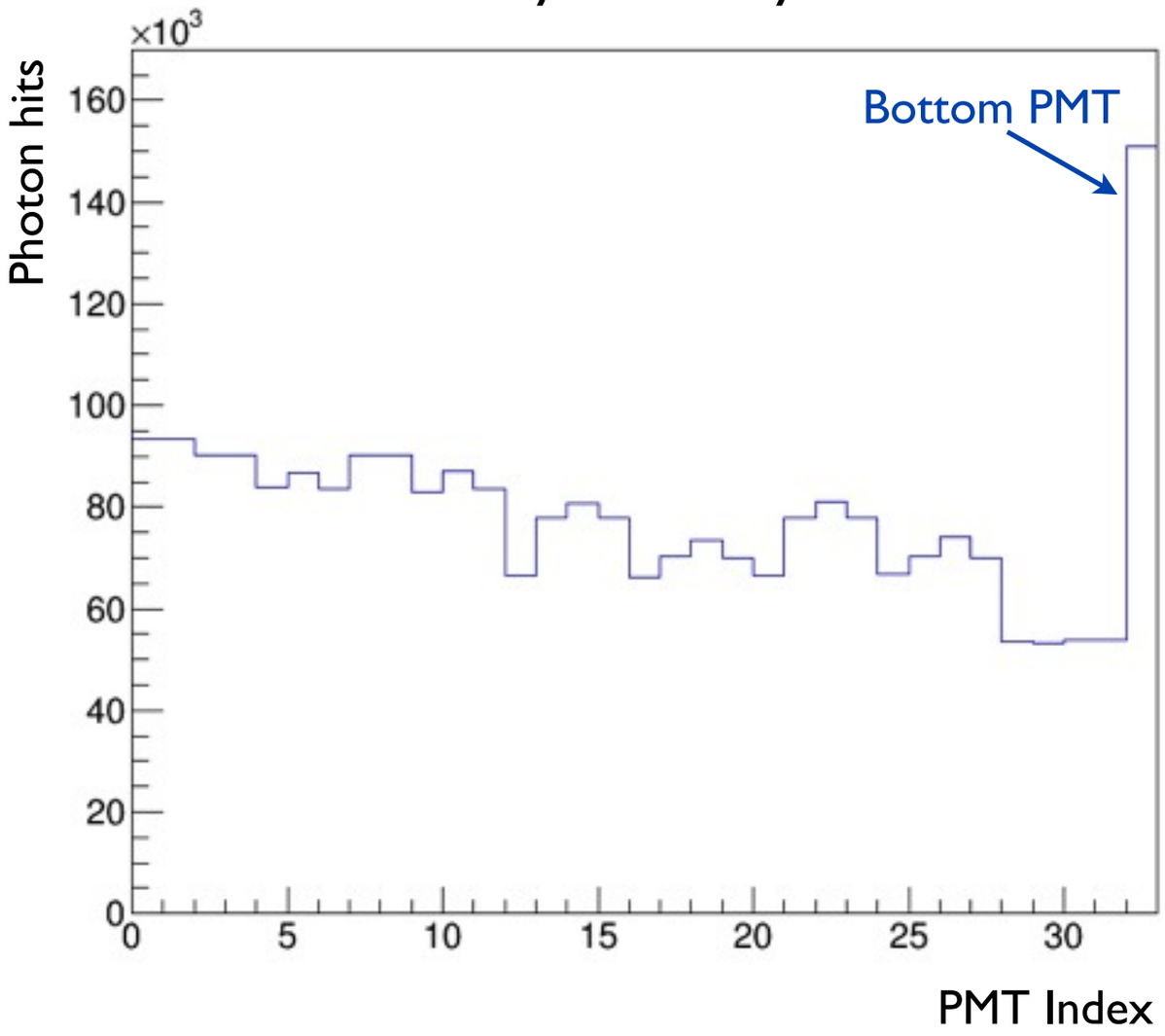
Another measurable in the System Test:

- Given uniformly distributed extraction electron sample, how many hits should the PMTs see?

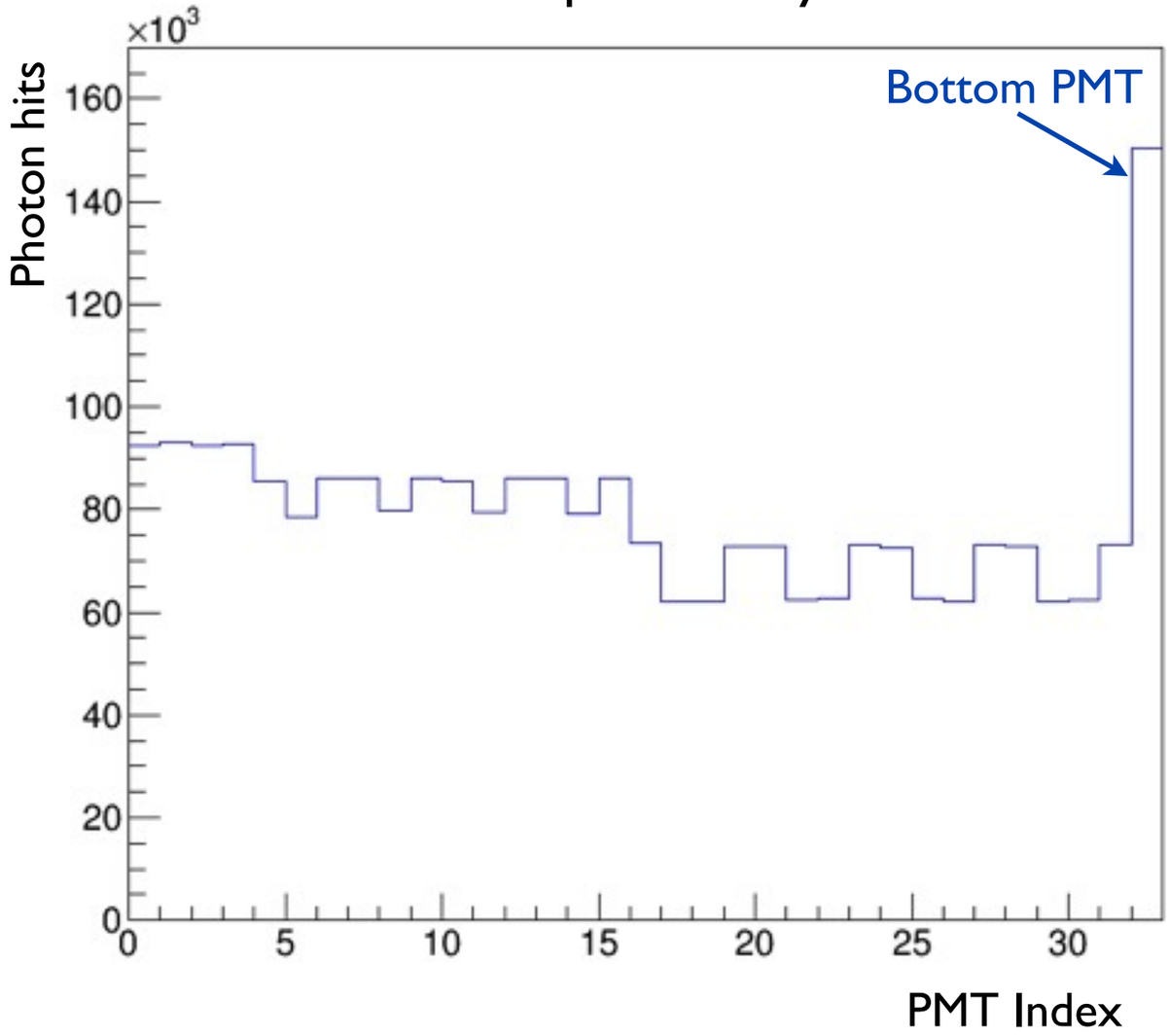
- Is another test to see if light collection is as expected

Provides another metric for evaluating light collection uniformity

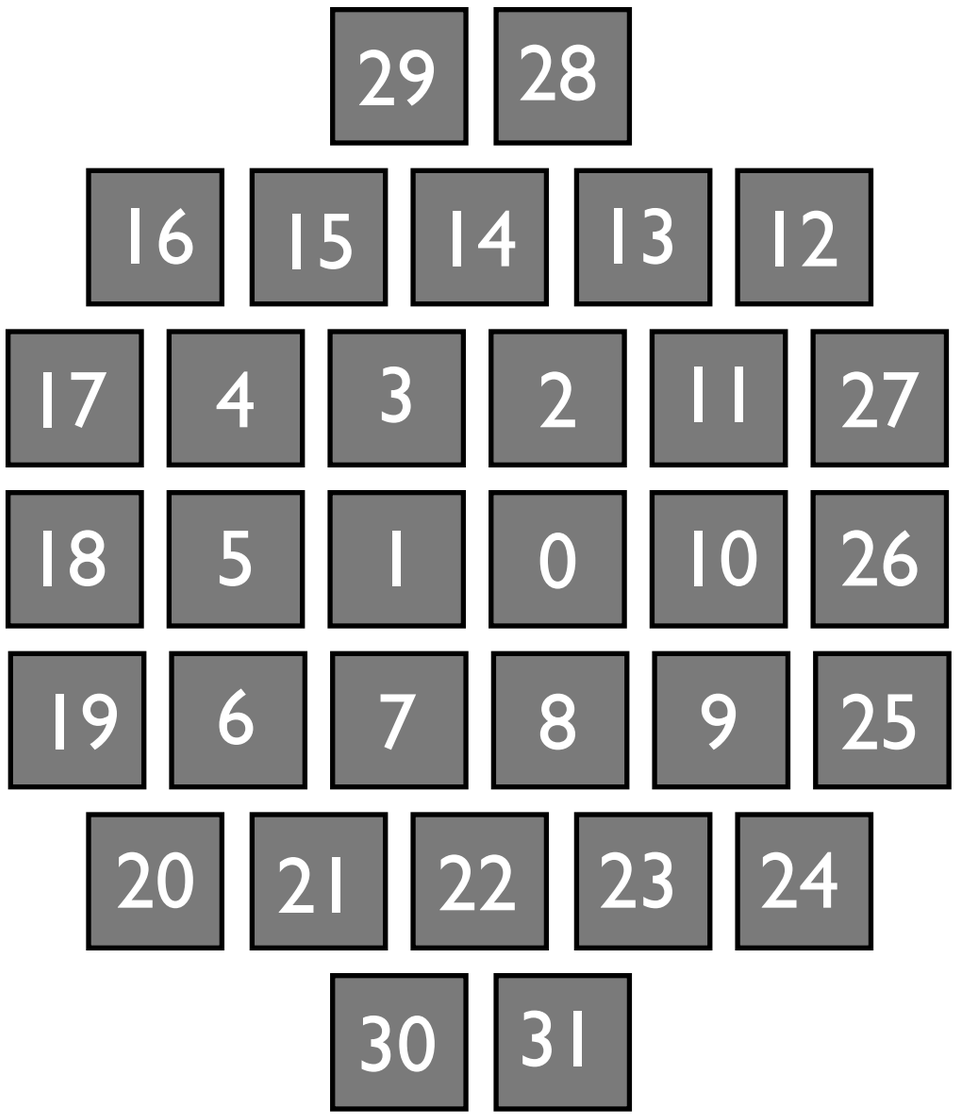
Hybrid Array

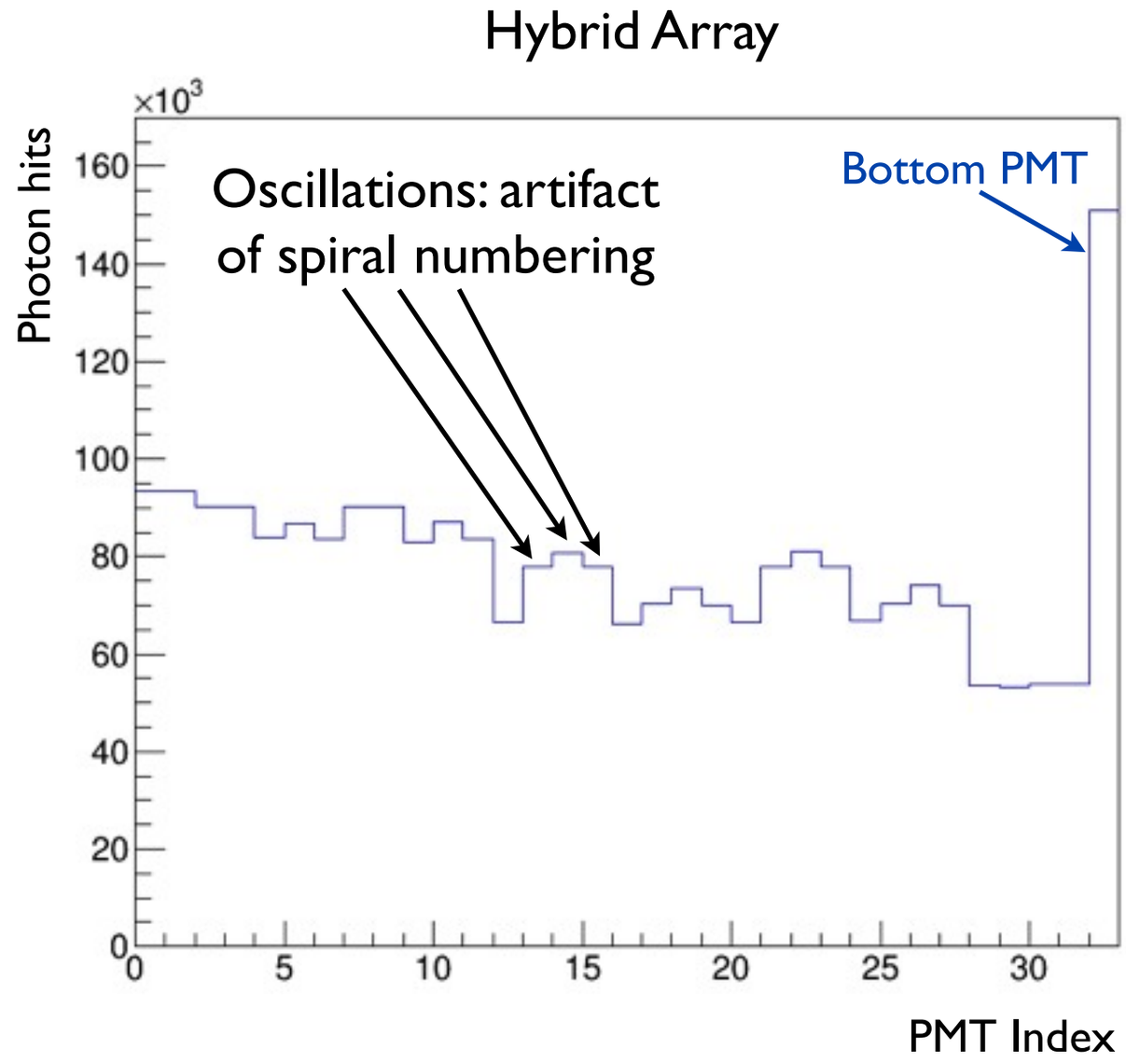


Square Array



Do these occupancies make sense?





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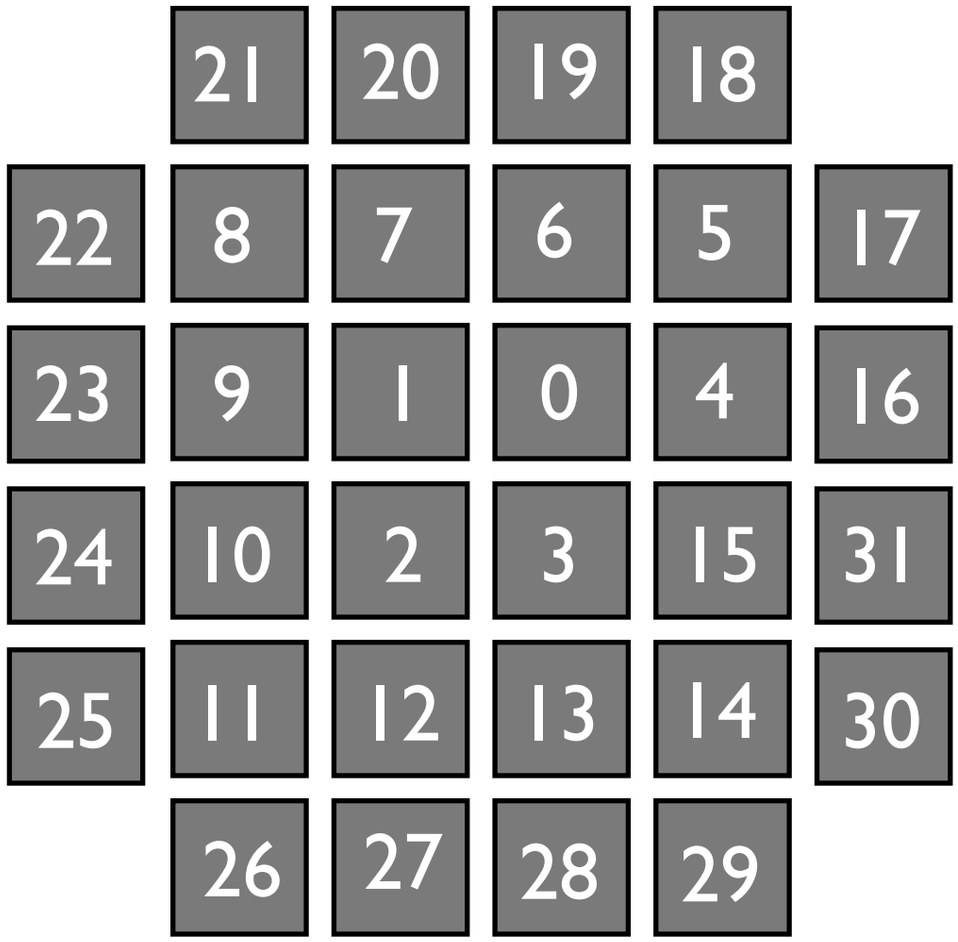
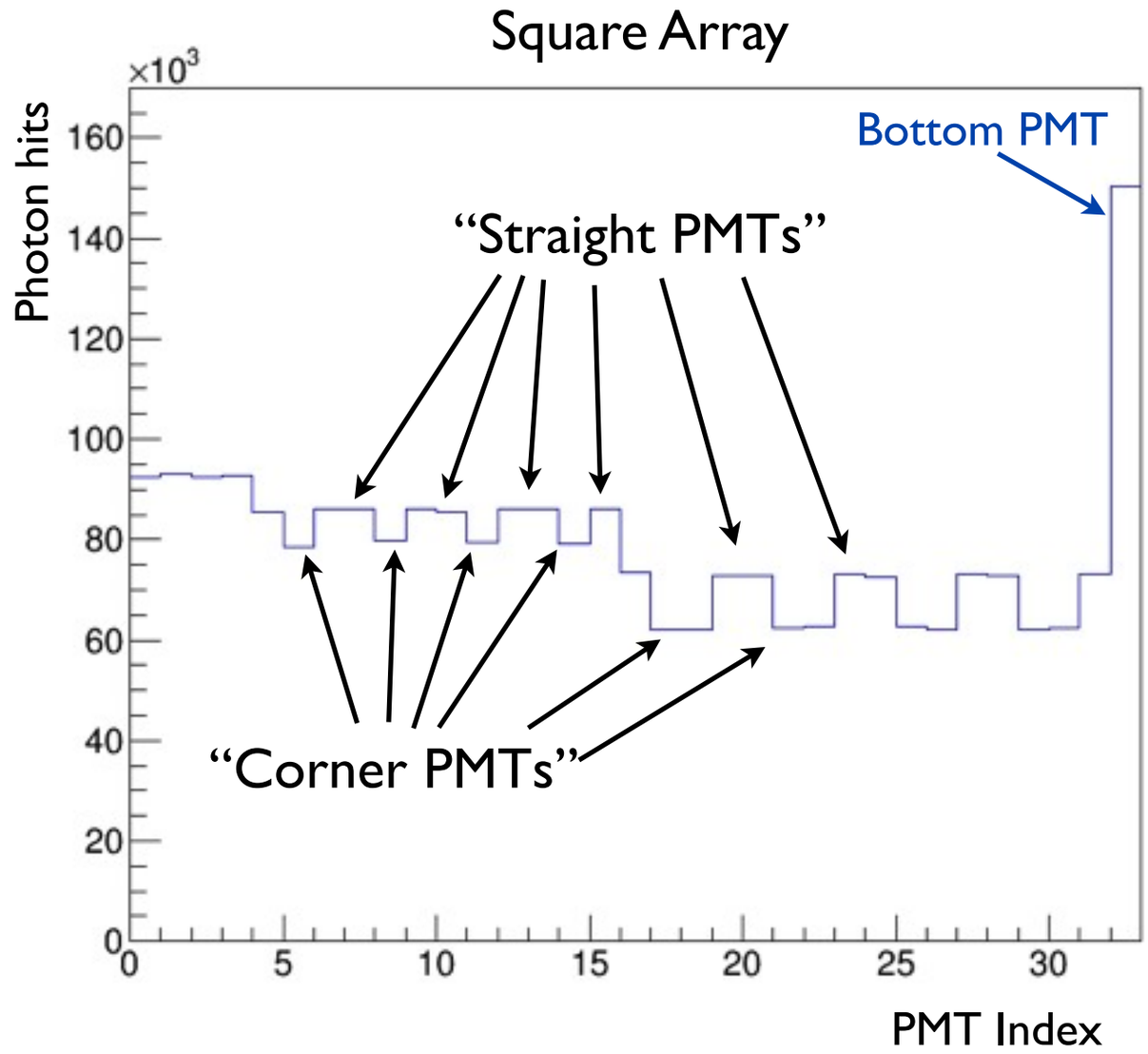


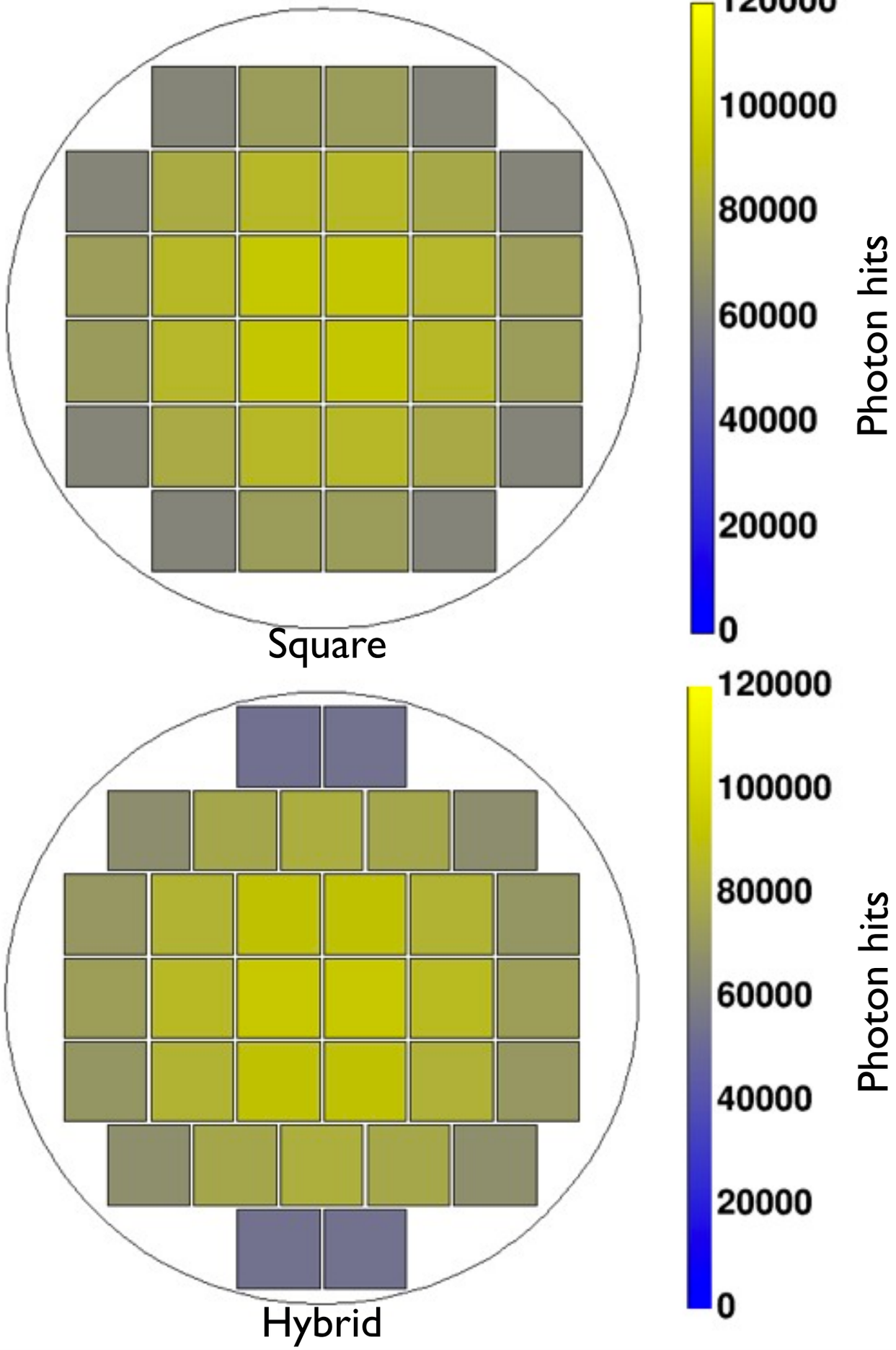


Hit Maps

Hit Map
= Hit Occupancy + Spatial Visualization

Code is from modifications to a rudimentary event display I coded up in ROOT for the multi-PMT array

Reminder: 10M photons in photon bomb



Summary

- BACCARAT and LightGuide simulation tools agree on the 2 PMT System Test PDE, to %-level for simplified BACC geometry.

- We now have expected S1 and S2 PDEs for comparison with 2-PMT System Test data.

- Implemented multi-PMT array geometries in BACCARAT as well

- Ran LC comparisons of the two multi-PMT arrays

  + Some simulations are still ongoing

  + Mostly, the array geometry change didn't affect metrics like PDE