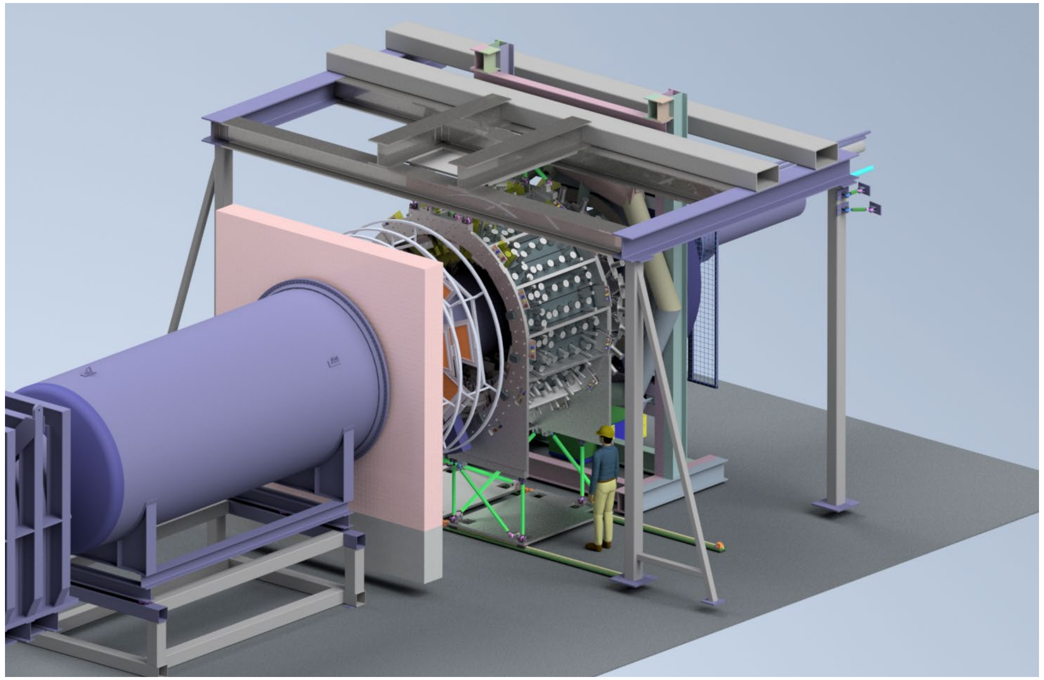
Integrating Detector Overview

MOLLER Collaboration Meeting
June 2022

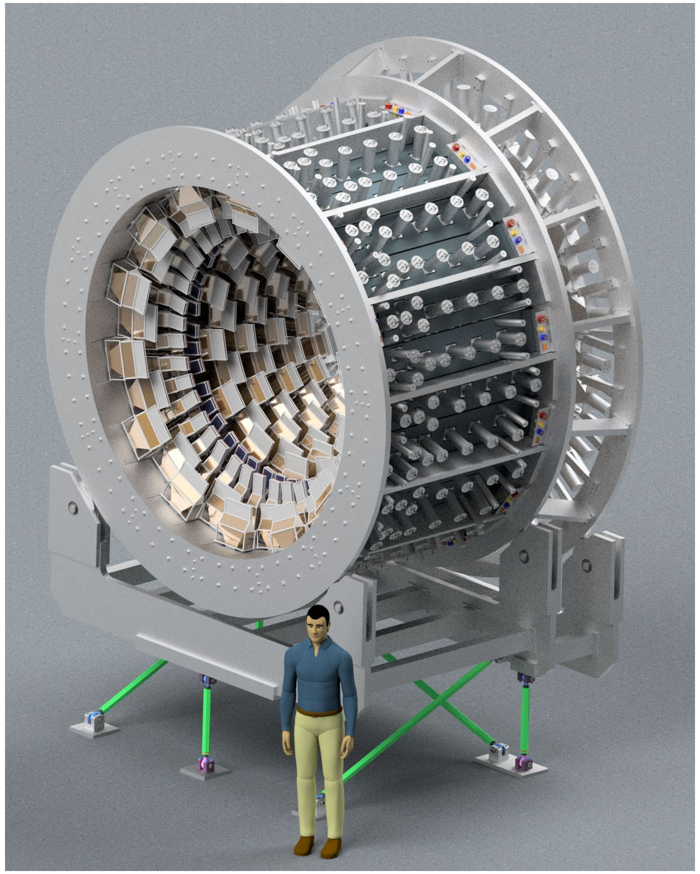
Michael Gericke

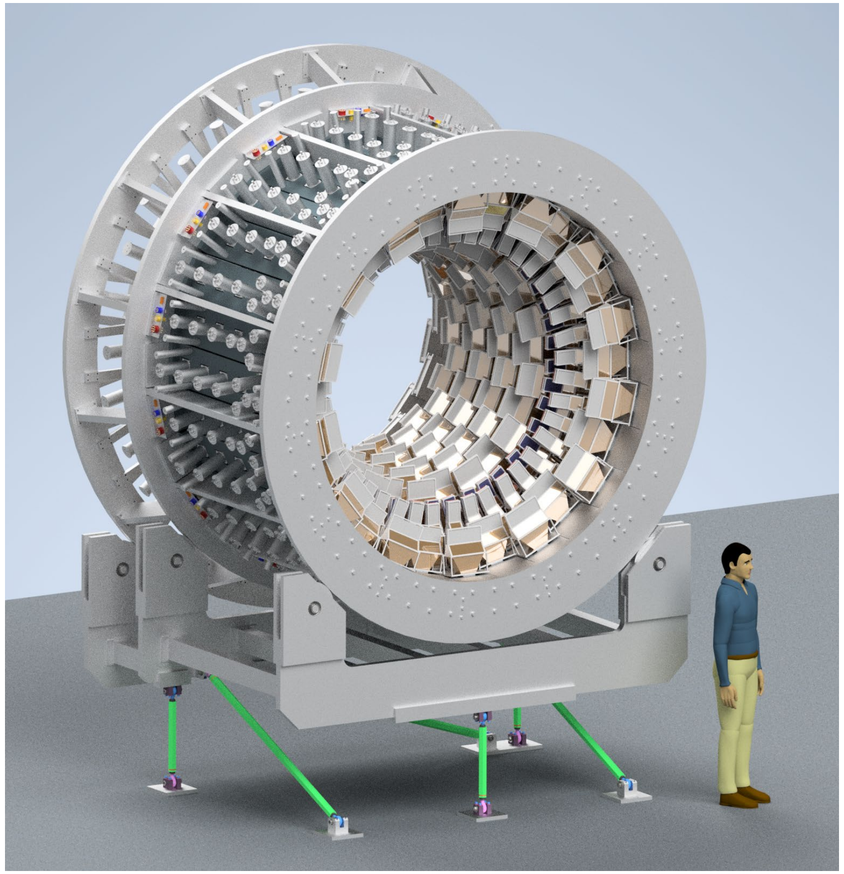
- WBS 1.04.02/03 and partial 1.07.02 Overview/Status
  - Detector layout (tiling), R1-5 module design, and beam test update
  - R6 module design and beam test update (Krishna's talk)
  - Shower Max design (Dustin's talk)
  - Cable Management (Dustin's talk)
  - Radiation hardness (Dustin's talk)
  - Overall detector mounting structure (Larry's talk)
  - Front-end Electronics (Jie's talk)
  - SBM and Scanner (Devi's talk)
- Organization of Work
- Schedule



In this talk:

- Thin module design progress and process
  - Detector nomenclature/numbering
  - Detector tiling
  - Module design
  - Simulations
- May beam time update
- Ring 5 profile pixel detectors
  - Brief update
- Schedule and work to completion
  - Time-line





Proposed detector nomenclature and numbering:

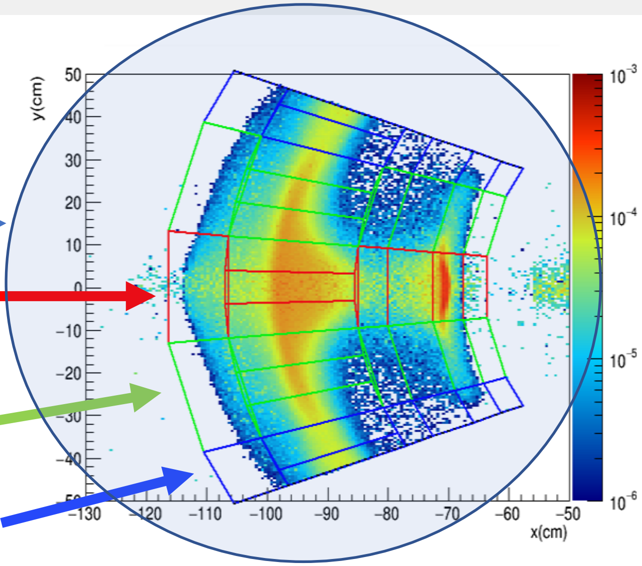
(Discussed in Feb. 16/17 email exchange)

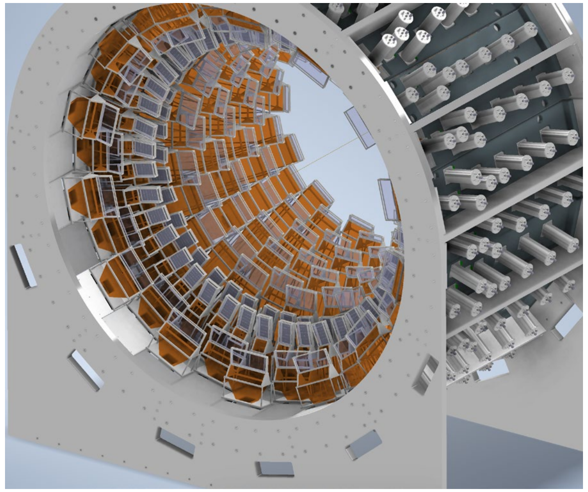
- Septant
- Sector (open, transition, closed)
- Segment (one of 28)
- Module

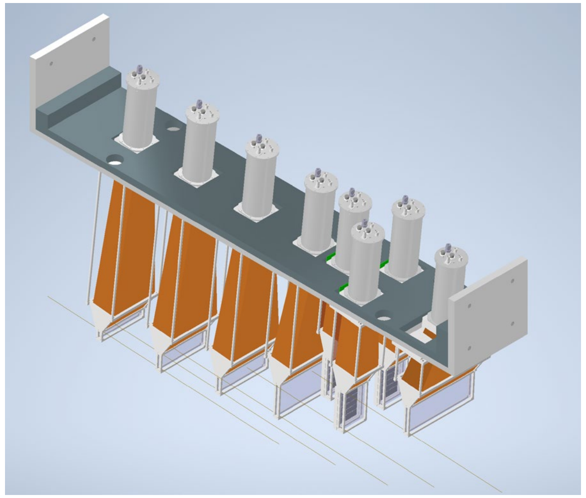
Open

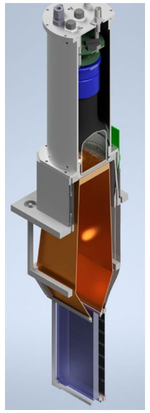
Transition

Closed









Proposed detector nomenclature and numbering:
(Discussed in Feb. 16/17 email exchange)

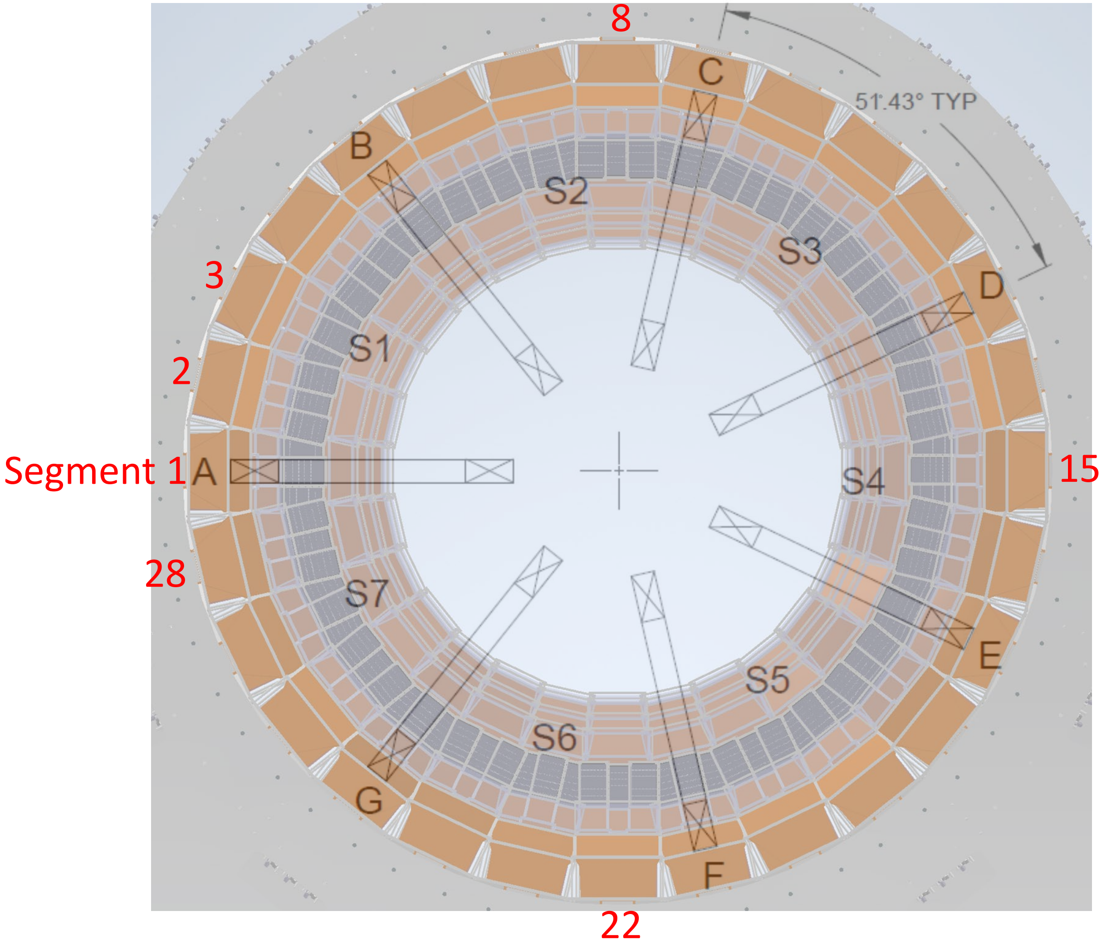
- Numbering:

  Sg[1,28]R[1,6][L,C,R,X]

  The [L,C,R] only apply to R5

- Examples:
  - Segment 8 ring 5 center name: Sg8R5C
  - Segment 11 ring 3 name: Sg11R3X

- Implement a lookup table to relate detector module to a particular septant and sector, e.g:
  - All even segments are transition sectors
  - Sg = 4(n-1) + 1 are closed sectors (n = [1,7] septants)
  - Sg = 4(n-1) + 2 are left transition sectors
  - Sg = 4(n-1) + 3 are open sectors
  - Sg = 4(n-1) + 4 are right transition sector



Detector Tiling:

- The thin detector array consist of 6 rings and 224 detectors
  - 28 segments around the annulus
  - Each segment has a total of 8 detector modules (3 ring 5 detectors + others)
  - 84 detectors in ring 5 and 28 in each of the other rings
  - Each detector module consists of a quartz, tile, an air-core light guide, and a PMT

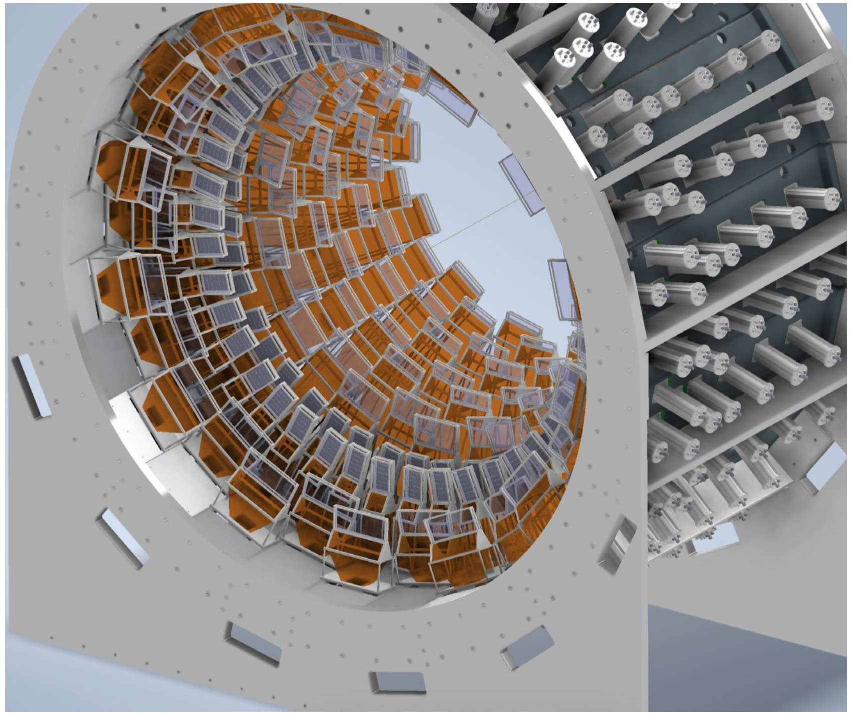
- Detector quartz tile sizes and positions were optimized (signal deconvolution) for a plane detector located 22 m from the Hall center (configuration 22) – Ciprian, Zuhal and Sakib

- The modules must overlap slightly, to cover the azimuth so that the rings need to be staggered along the beam direction. They also need to be spaced such that assembly and access to quartz tiles is possible.

- The process of designing the final physical detectors includes propagating the positions and sizes from the simulation plane to the corresponding physical location.

- The cathode location is fixed by the detector mounting structure and shielding simulations.

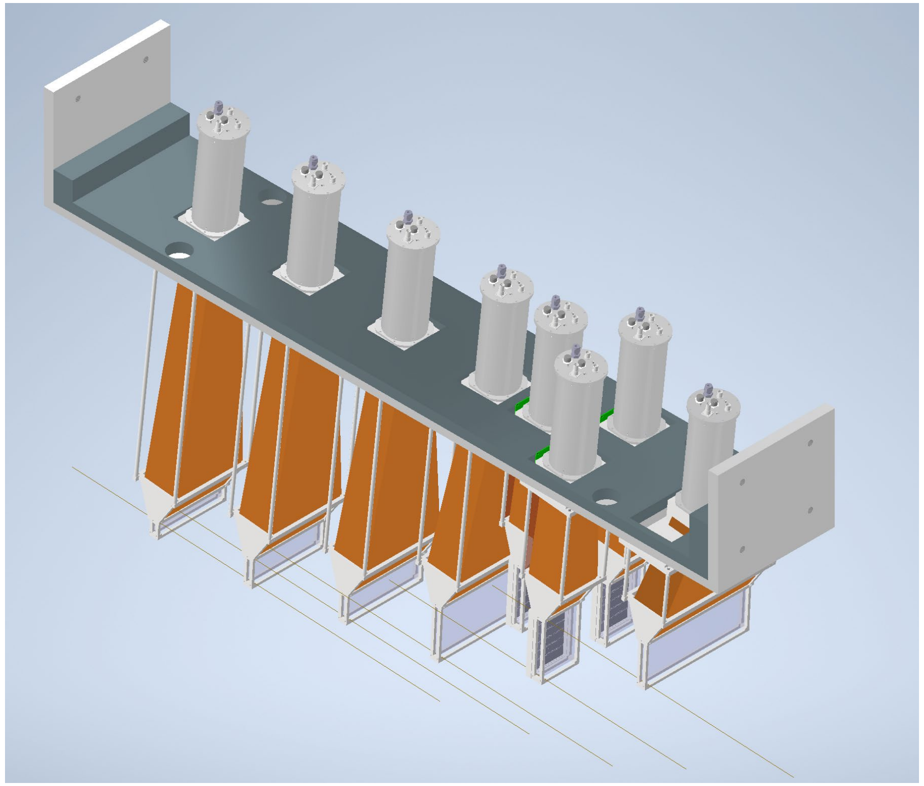
- The quartz tile location and cathode location then constrains the rest of the module design.



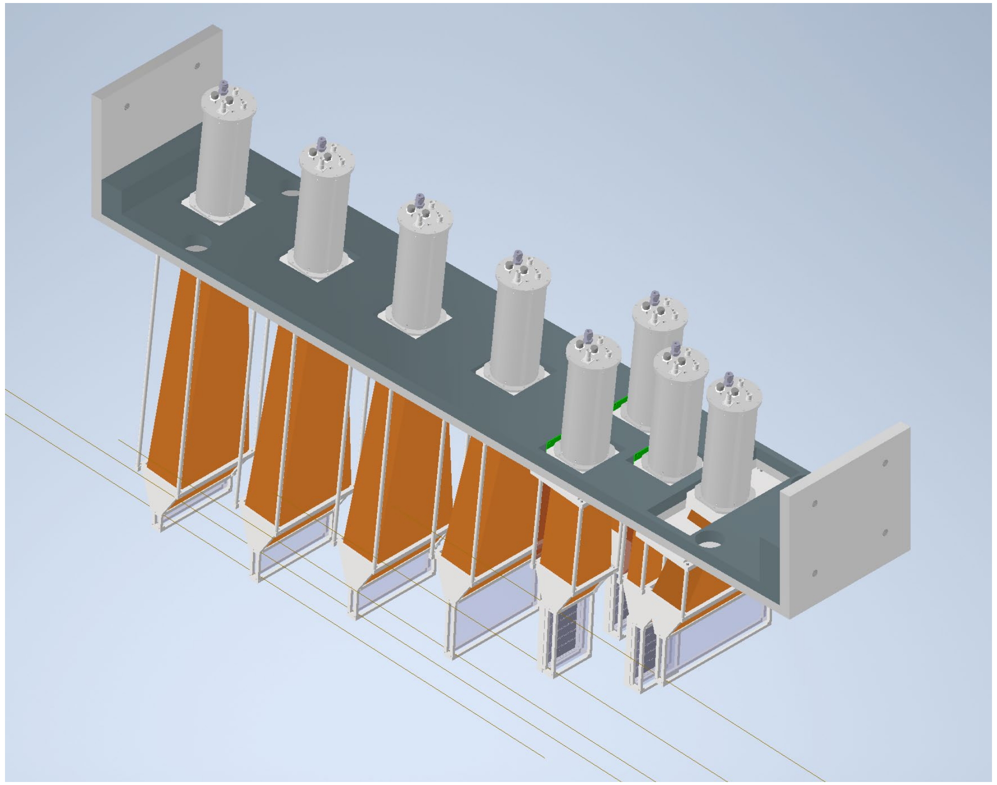
Detector Tiling:

- Two different segment assemblies to allow for overlap in the azimuth which give different module designs.
  - Front-flush: detectors are arranged toward the front of the array
  - Back-flush: detector are arranged toward the back of the array

Front-flush Segment



Back-flush Segment



Detector Tiling:

- Two different segment assemblies to allow for overlap in the azimuth which give different module designs.
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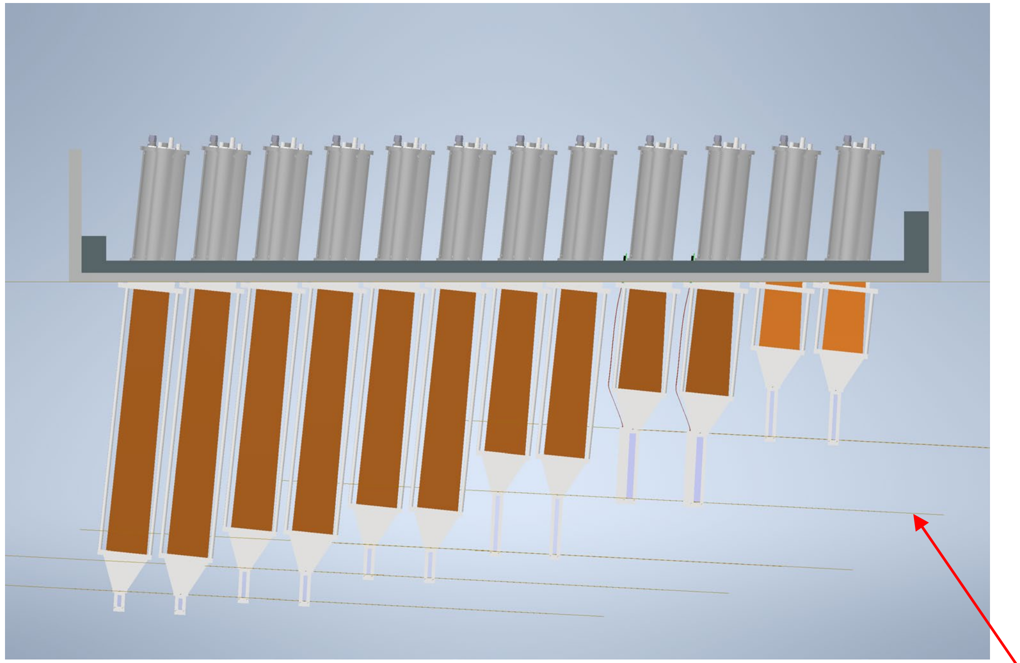
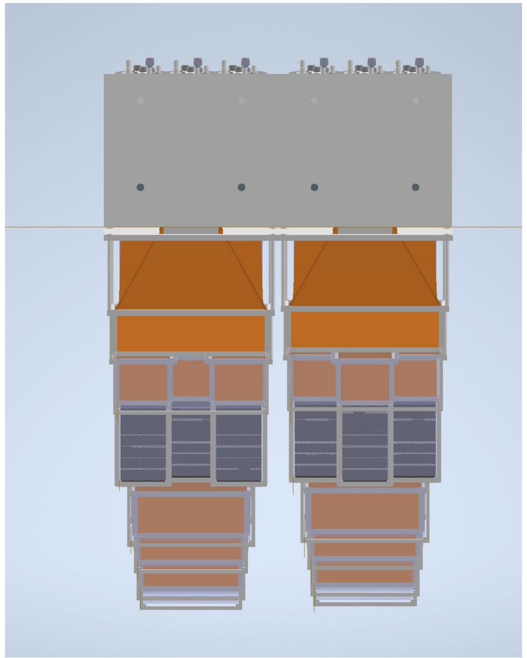
Beam left view



Alignment check

Front view (test)



$\theta = 3°$ line

Detector Tiling:

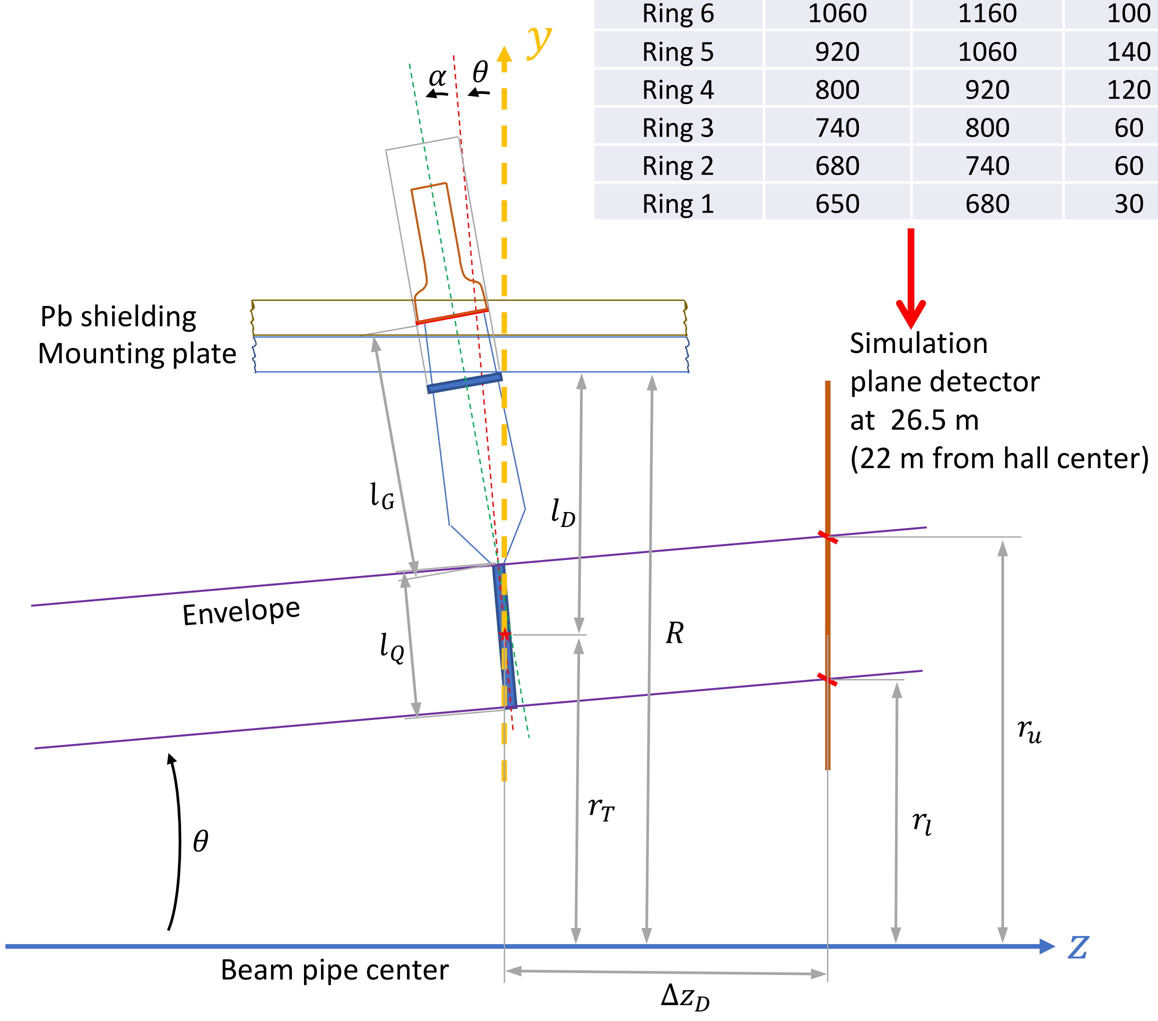
- Major parameters of the detector mechanical design
  - Detector bore: R
  - Detector location: Δz_D
  - Cathode location wrt. quartz: l_G
  - Quartz angle: $\theta = 3°$
  - Light guide to quartz angle: $\alpha = 3°$

- Reference point in z wrt. Hall center (22.198 m) is located midway between the two ring 5 tiles

- Procedure
  - Choose z-location of quartz within structure limits wrt. simulation plane
  - Calculate required light guide length
  - Determine the bounding volume
  - Simulate possible light guide geometries
  - Design the module for the simulated geometry
  - Iterate …

Simulation Positions: Config 22

	r_l [mm]	r_u	dr
Ring 6	1060	1160	100
Ring 5	920	1060	140
Ring 4	800	920	120
Ring 3	740	800	60
Ring 2	680	740	60
Ring 1	650	680	30



Detector Tiling:

- Steps to locate the module mounting cut-outs in the segment plate for each module and module length

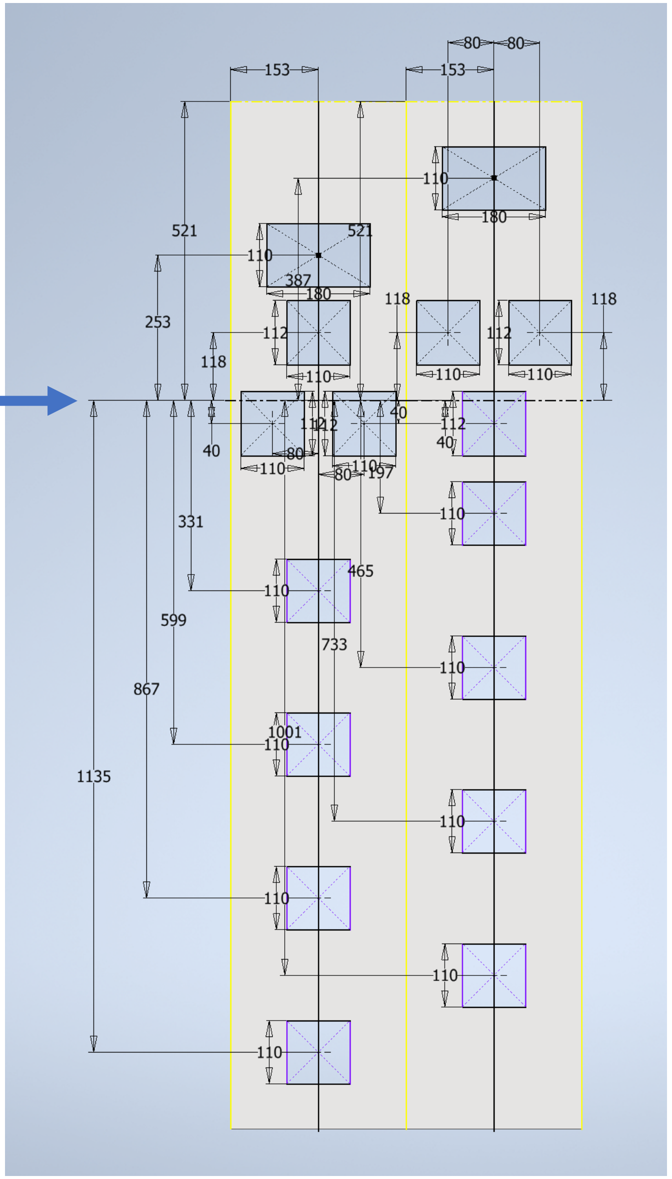
  1. Locate a line on the segment mounting plate, such that the mid-plane between the two R5 tile azimuthal planes is located at the 22.198 meters from the hall center

  2. Distribute the module cut-outs in the two segment plates for all rings, taking into account:

     a. Ring overlap
     b. Interference during insertion
     c. Module structure sizing, spacing, and access
     d. PMT housing size
     e. Module tilt

  3. Adjust the light guide length according to the z-location of the module

$22.1983\ m$



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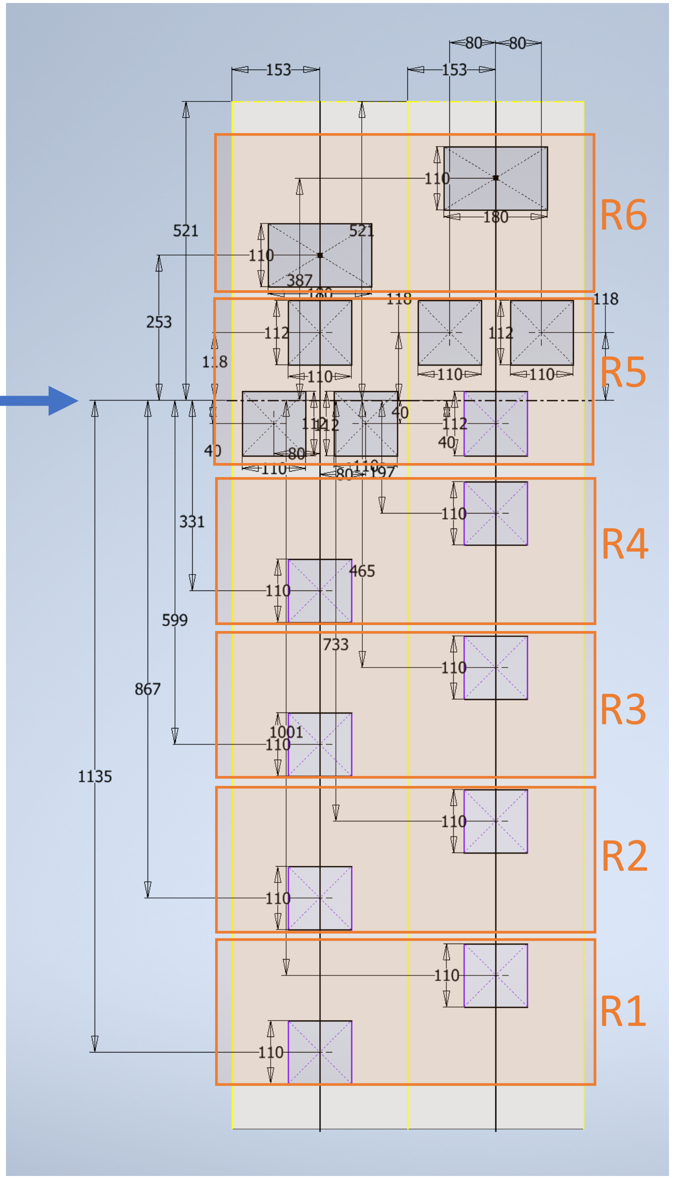
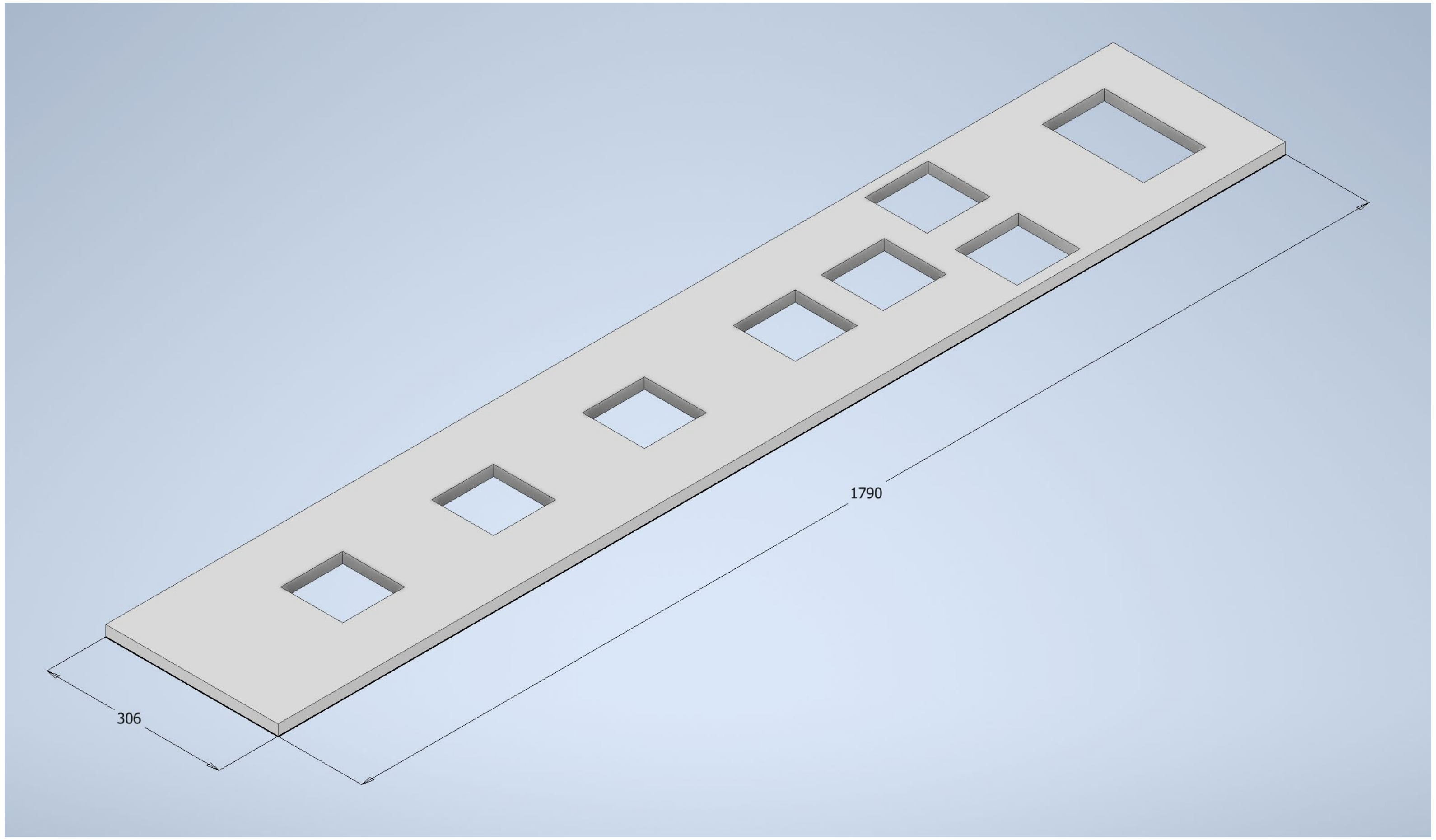


Detector Tiling:

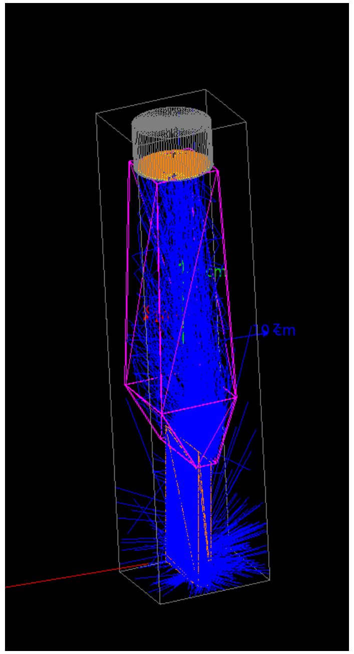
Note: Segment plate is now $1790\ mm$ long (original length was $1764\ mm$)



Detector module design:

- Within the geometric limits, optimize the light yield, background minimization, by varying light guide design in simulation
- Export optimized LG design to STL format and import into CAD,
- Then design the module mounting structure around the LG-Quartz assembly
- Module mounting plate mates to existing overall mounting structure (Larry's talk)
- Take care of auxiliary design issues and properties: Air flushing of LG, radiation damage effects mitigation, electronics accessibility …

Simulation → Simulation writes STL file → Import STL into CAD → Design module structure around LG



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-------- Ranecu engine status ---------
 Initial seed (index) = 0
 Current couple of seeds = 1449865798, 864960622
----------------------------------------
Graphics systems deleted.
Visualization Manager deleting...
mgericke@gericke-basement:~/MOLLER/Simulations/DetectorOptical/build$ ls -la
total 19356
drwxrwxr-x  4 mgericke mgericke    4096 Jun 15 16:43 .
drwxr-xr-x 12 mgericke mgericke    4096 Jun 14 01:27 ..
-rw-rw-r--  1 mgericke mgericke   35417 Jun 14 01:24 CMakeCache.txt
drwxrwxr-x  7 mgericke mgericke    4096 Jun 15 16:41 CMakeFiles
-rw-rw-r--  1 mgericke mgericke    1557 Jun 14 01:24 cmake_install.cmake
-rw-rw-r--  1 mgericke mgericke   75666 Jun 15 16:50 gmon.out
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-rw-rw-r--  1 mgericke mgericke     227 Jun 14 01:27 libMOLLEROptDict.rootmap
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mgericke@gericke-basement:~/MOLLER/Simulations/DetectorOptical/build$
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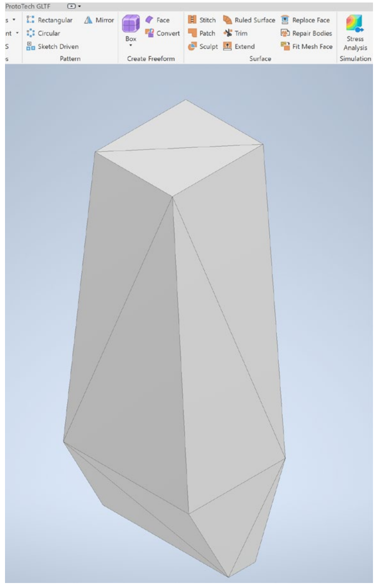
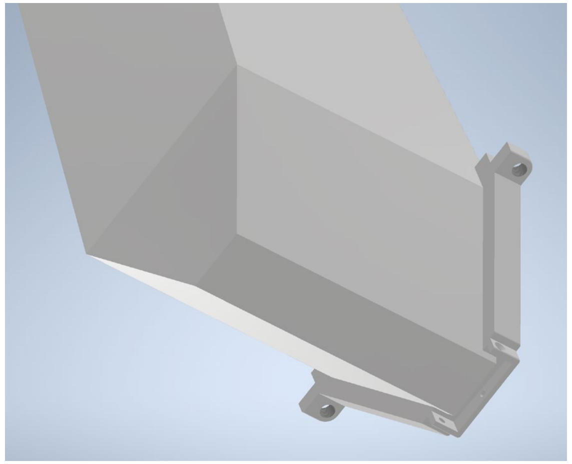
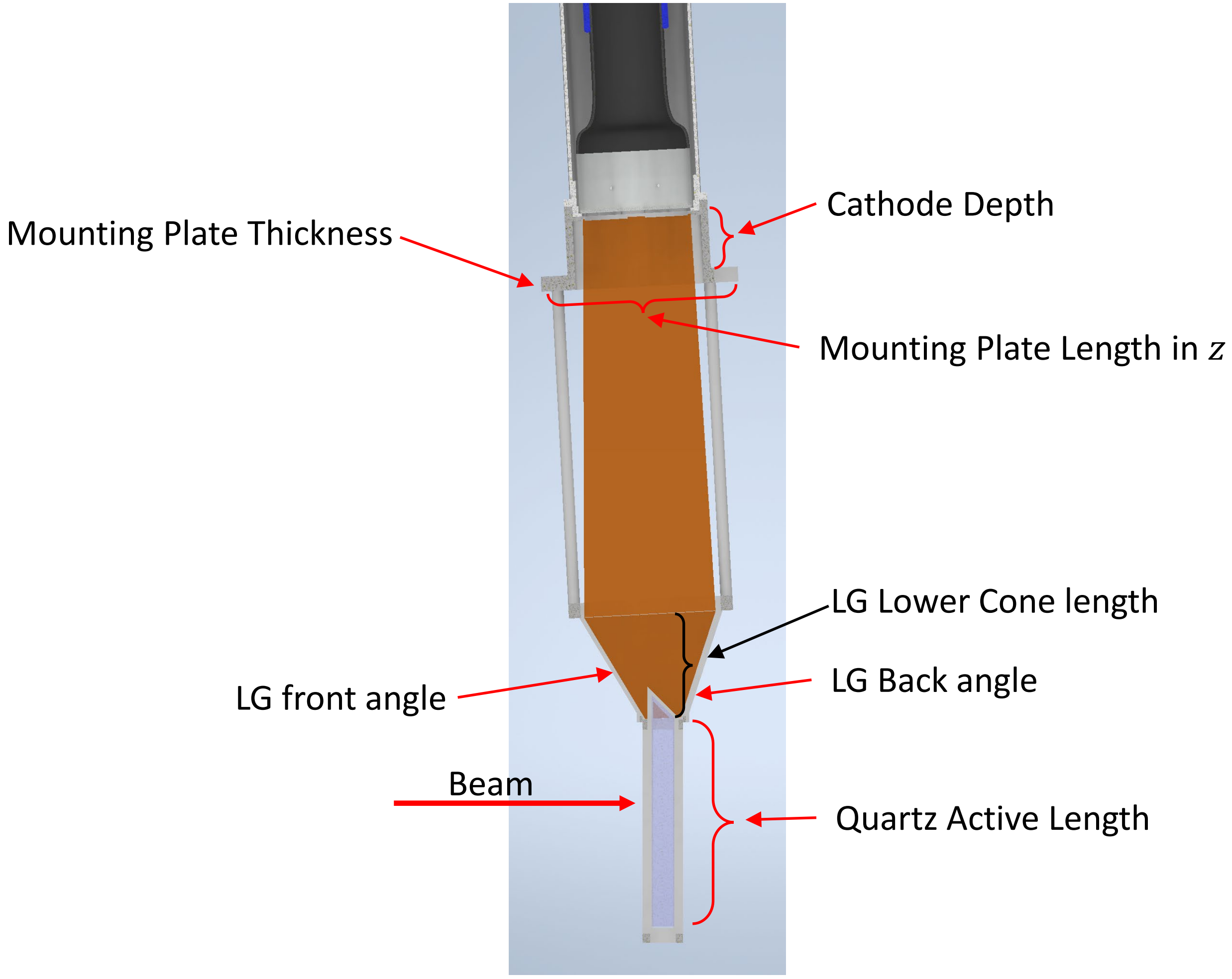


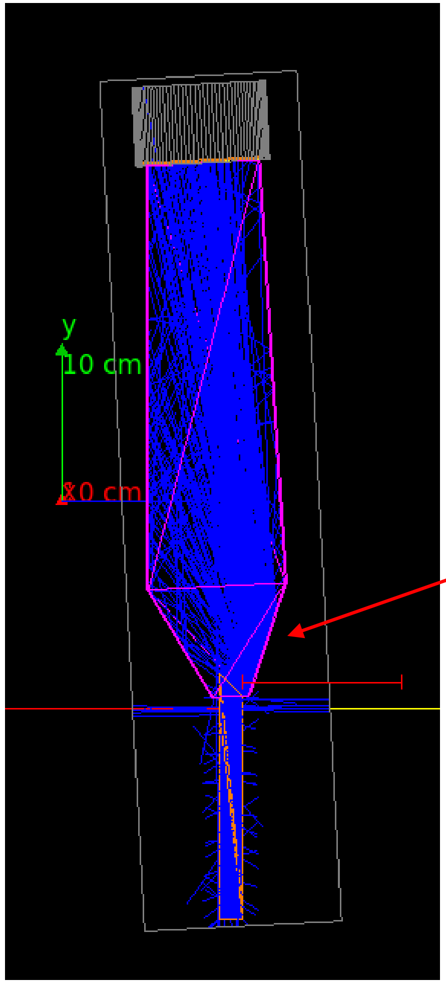


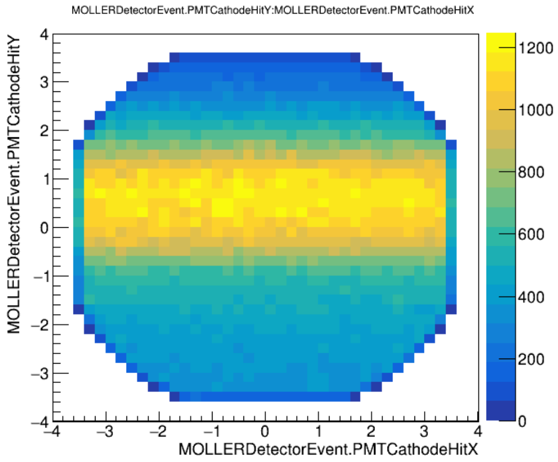
Detector module design:

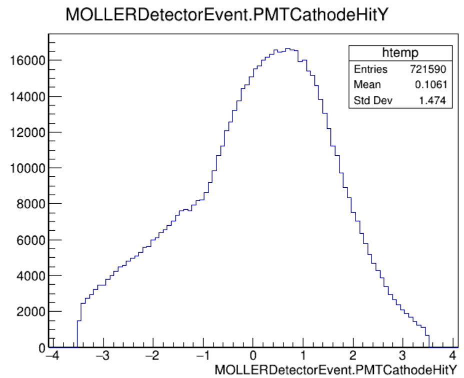
Light guide geometry can be tweaked to optimize quartz light readout and suppress light guide background



Ring 5



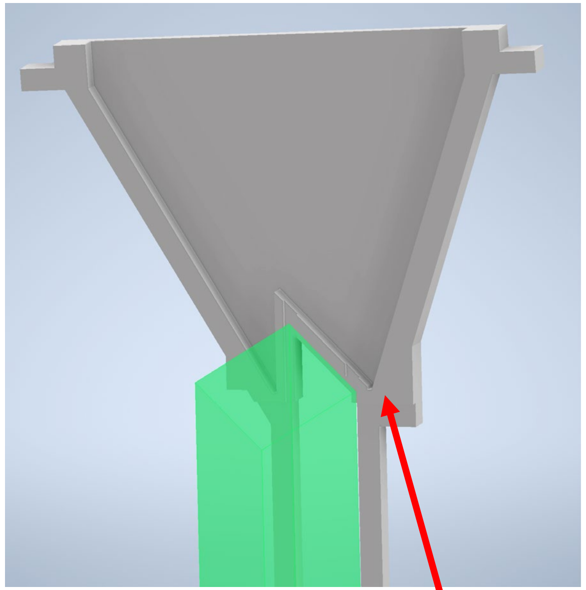




Detector module design:

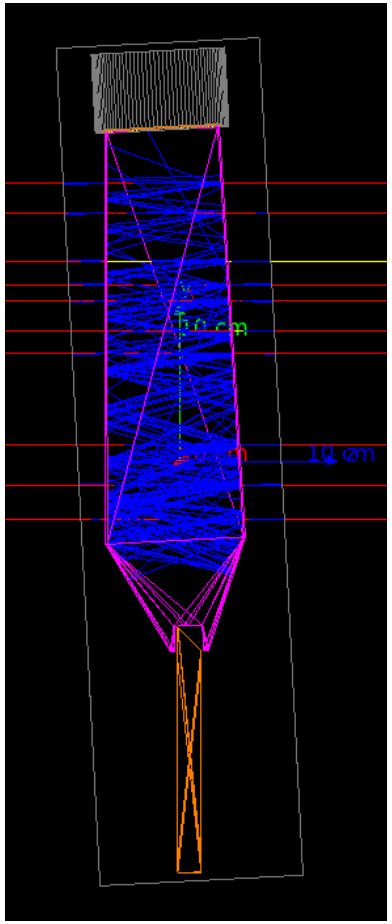
Ring 5

Light guide geometry can be tweaked to optimize quartz light readout and suppress light guide background

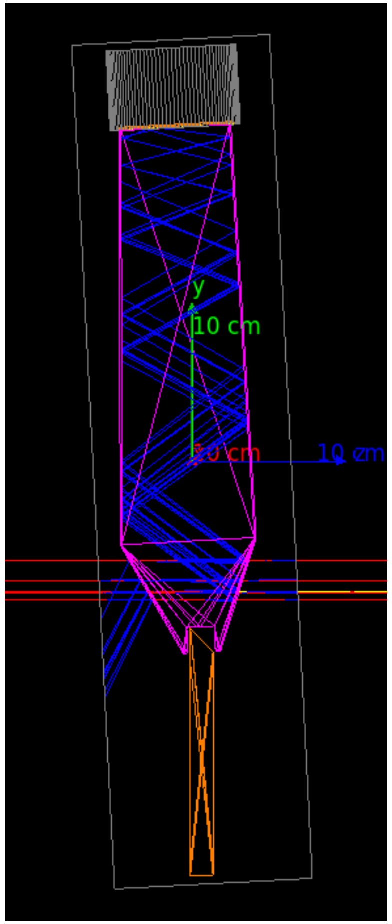


Design a monolithic tray for quartz and light guide that fixes the angle relationship.

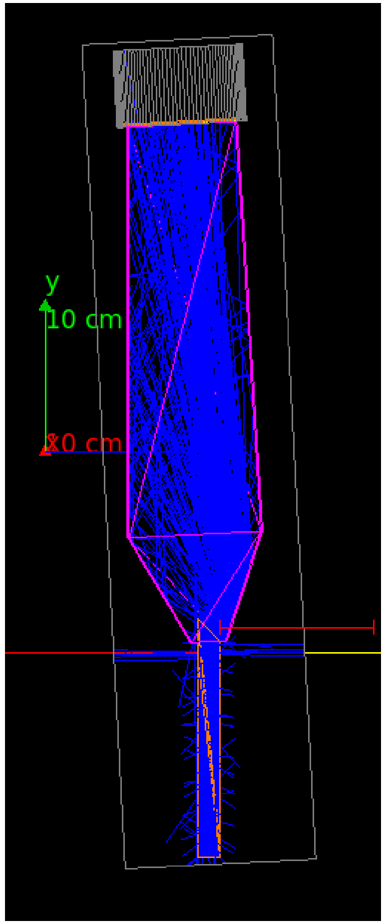
Hard to machine, but easy to 3D print.



Upper guide events



Lower guide events

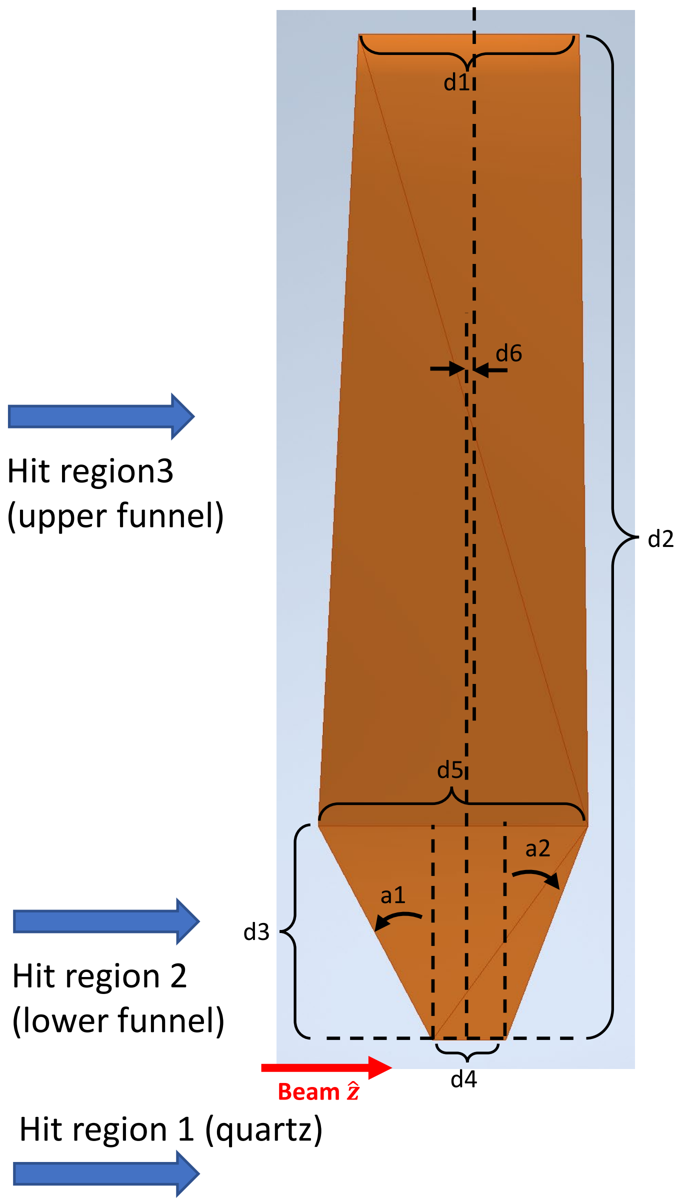


Quartz events

Detector module design:

Ring 5 Simulations:

- Output from many separate simulations while varying
  - Hit region (1,2,3)
  - Lower funnel upstream angle (a1) (14 to 22 deg in 1 degree steps)
  - Lower funnel downstream angle (a2) (16 to 24 deg in 1 degree steps)
  - PMT to quartz offset (d6) (-6 to 6 mm in 2 mm steps)
  - Quartz thickness (d4) (10 to 20 mm in 1 mm steps)
- Fixed parameters:
  - Lower funnel height (d3) = 75 mm
  - Light overall length (d2) = 329 mm
  - Guide PMT interface opening (d1) = 70 mm
  - LG rotation angle (wrt. quartz) = 3 degrees
  - Electrons at normal incidence to quartz
  - Quartz width (azimuth)
  - Quartz length (radial)
  - Quartz bevels = 0.5 mm



Detector module tiling/design:

Ring 5 simulations results for 17 mm thickness:

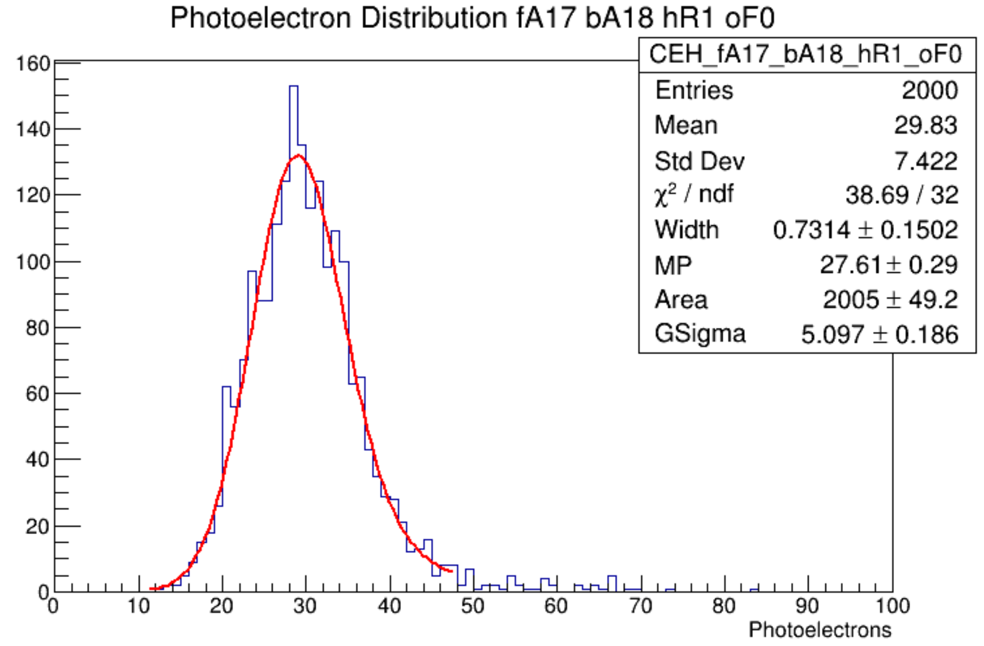
- The photo-electron distribution for hit region 1 (quartz) was fitted with a Landau-Gauss convolution
- The "most probable value" (MP) and the fit sigma were extracted to record the mean photo-electron yield $\langle n_{pe} \rangle$ and calculate the detector resolution or excess noise:

$$\alpha^2 = \frac{\sigma^2}{\langle n_{pe} \rangle^2}$$

Note that the experimental goal is to have $\alpha^2 \leq 0.04$ and that the overall experimental grows with the excess noise factor

$$\frac{1}{\sqrt{N}}\sqrt{1+\alpha^2}$$

- For the other two hit regions a straight up mean was taken from the histograms, without fitting.



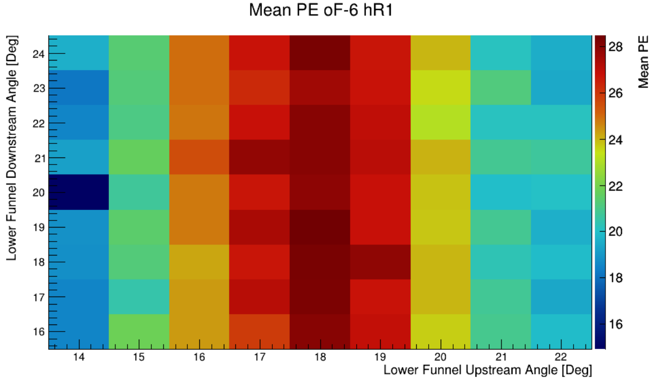
Detector module tiling/design:

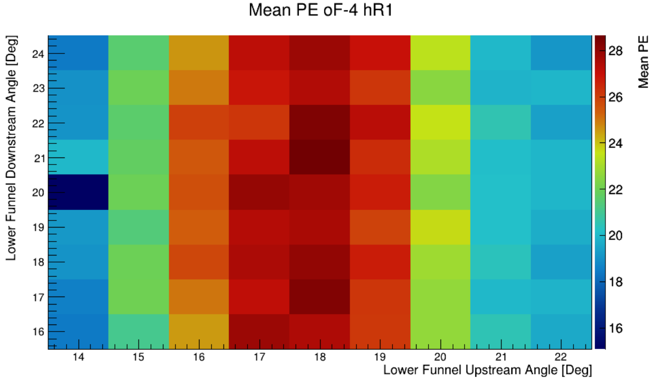
Ring 5 simulations results for 17 mm thickness:

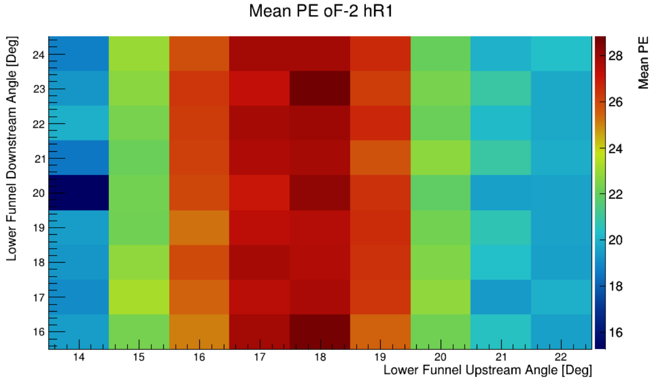
Hit region 1 (quartz) mean PE yield:

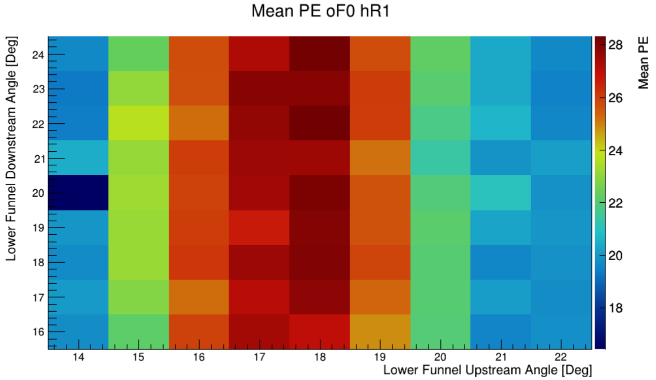
- Since so many runs were taking for various angles, the first step in extracting the best parameter values was, to plot all angles dependence versus z-offset between the PMT and the quartz.

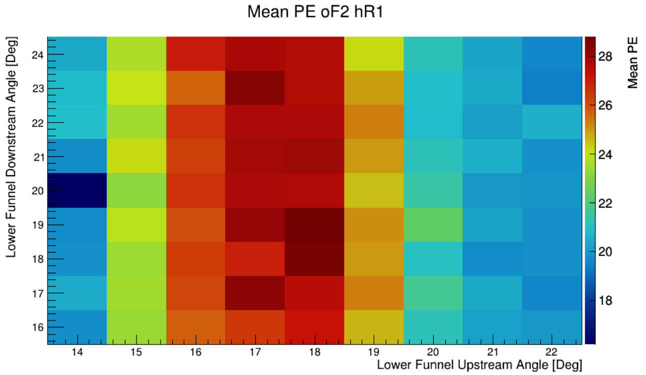
- The plot nomenclature:
  - oF = PMT to quartz offset -6 to 6 mm
  - hR = hit region

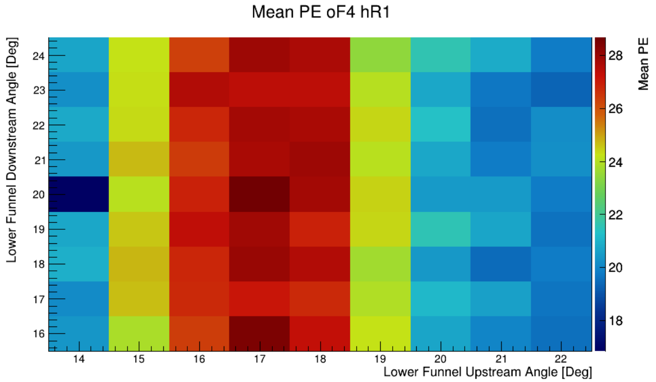


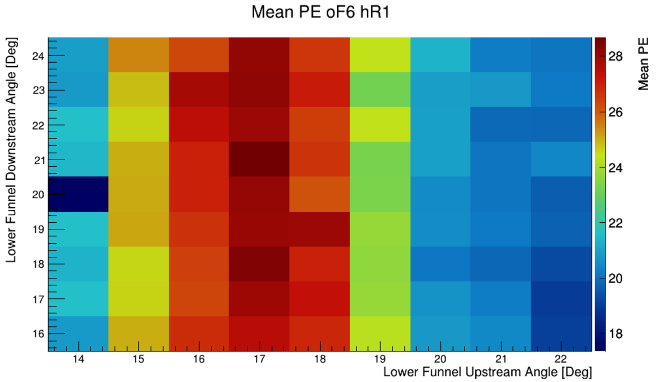










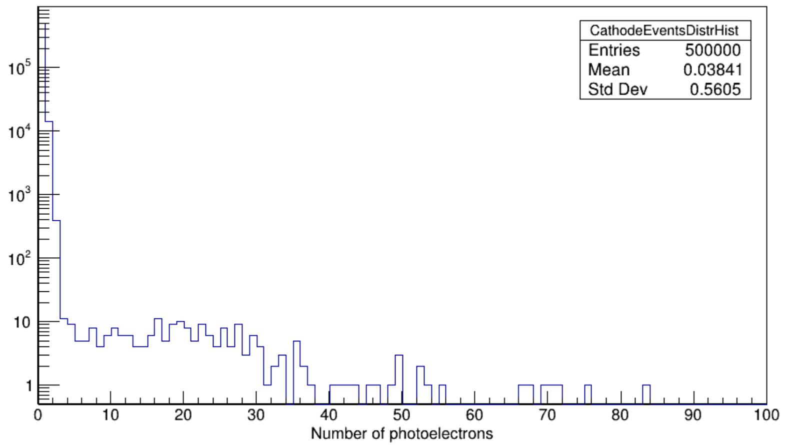


Detector module tiling/design:

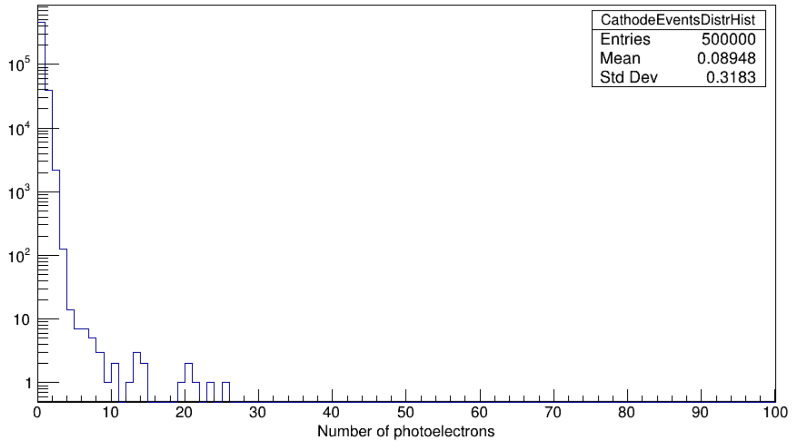
Light guide geometry can be tweaked to optimize quartz light readout and suppress light guide background

Ring 5 “best” geometry results:

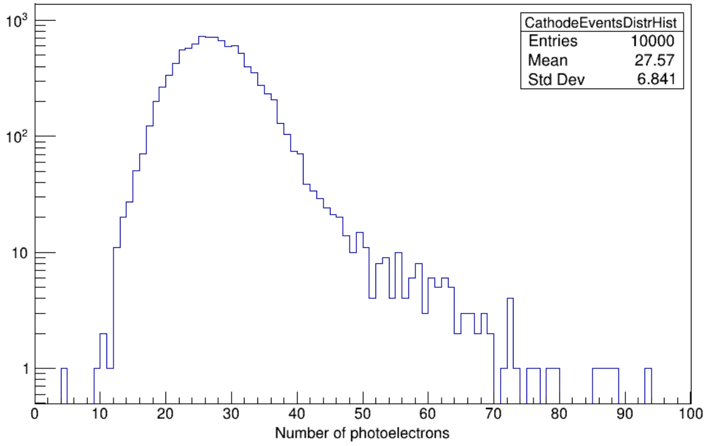
Upper guide events



Lower guide events



Quartz events



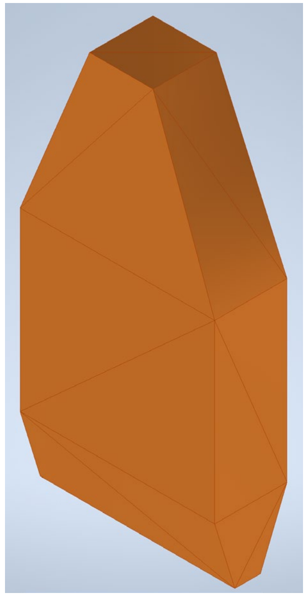
See appendix for more simulation results.

Detector module design:

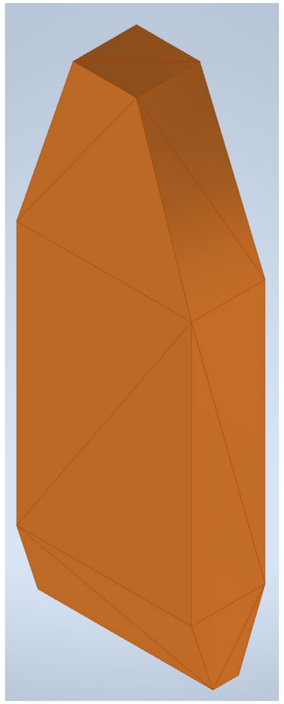
Status:

- Rings 1 – 4 have now also been fully simulated and the light design is optimized
- All of them used 20 mm quartz thickness
- The average light yield and excess noise is pretty much the same for all rings
    - Ring 4: 22 pe, 10%
    - Ring 3: 22 pe, 10%
    - Ring 2: 22 pe, 10%
    - Ring 1: 22 pe, 10%
- These results need to be further verified with some more simulations and then another beam test

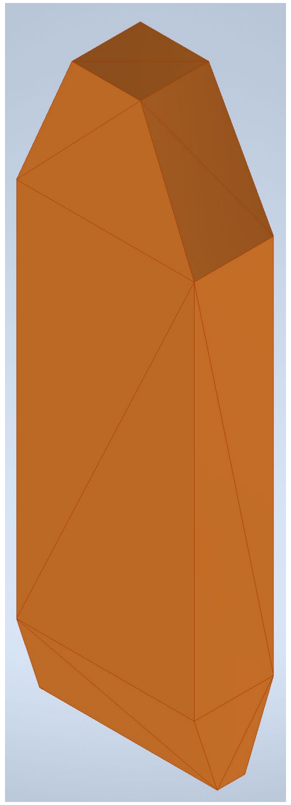
Work by Sakib Rahman



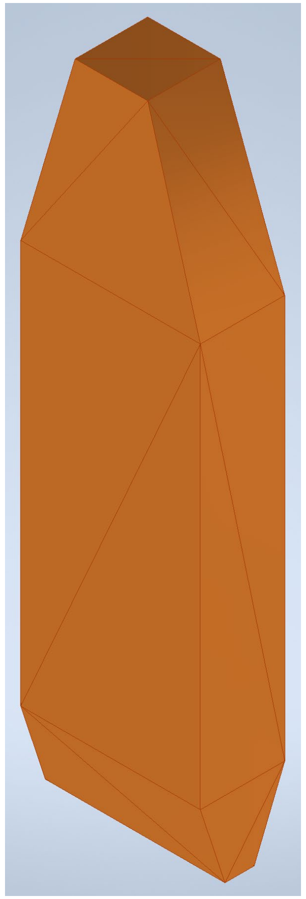
Ring 4



Ring 3



Ring 2



Ring 1

Detector module design:

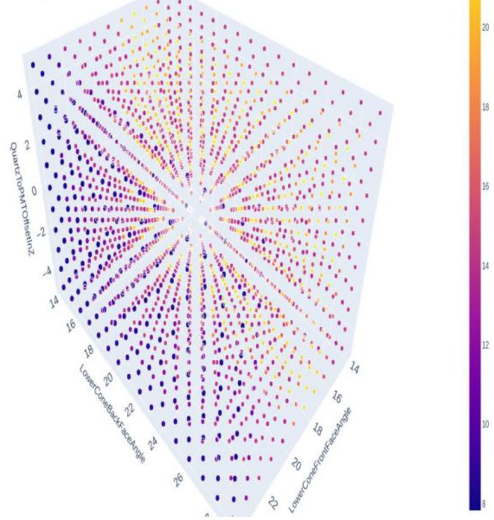
Status:

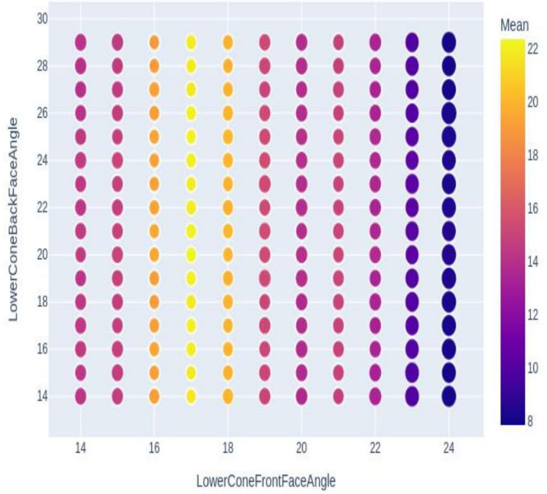
- Rings 1 – 4 have now also been fully simulated and the light design is optimized

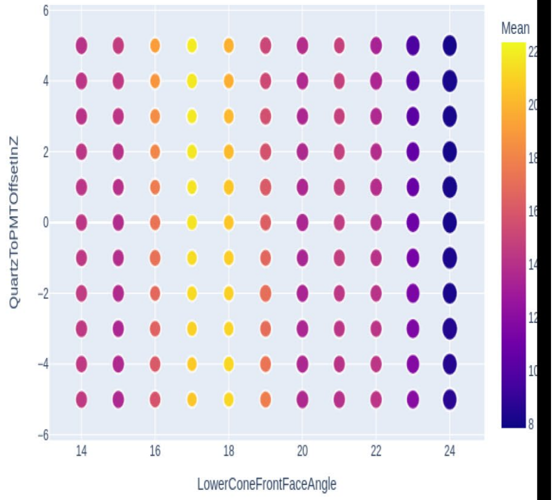
- Apologies for bad quality images – just copied from a pdf

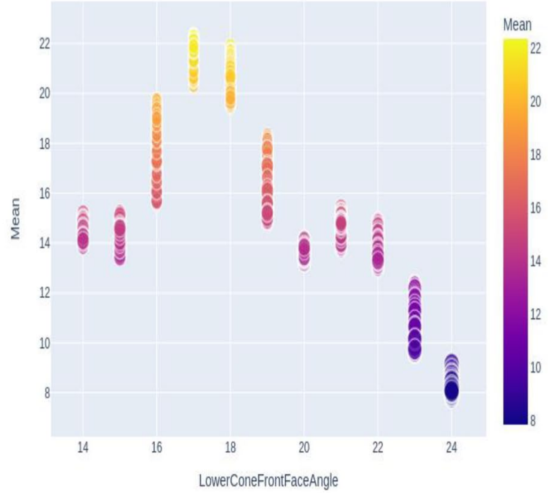
- There will be a detector technote soon that will provide the details for all rings.

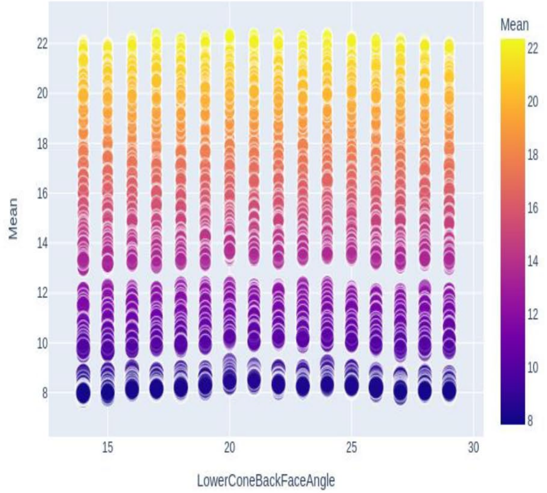
Size represents excess noise
Color represents mean

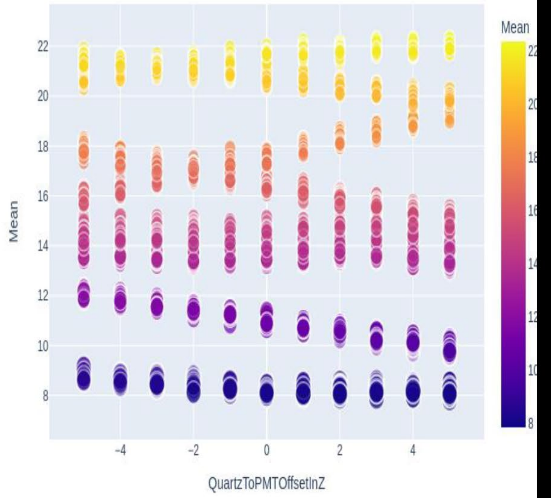












Detector module design:

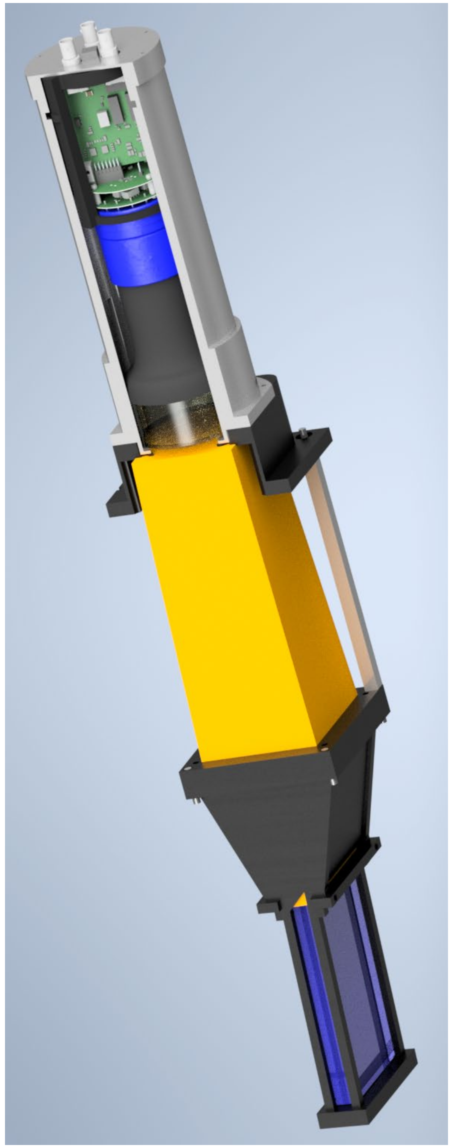
Mounting Structure Design (Brynne, Nafis, and Myself)

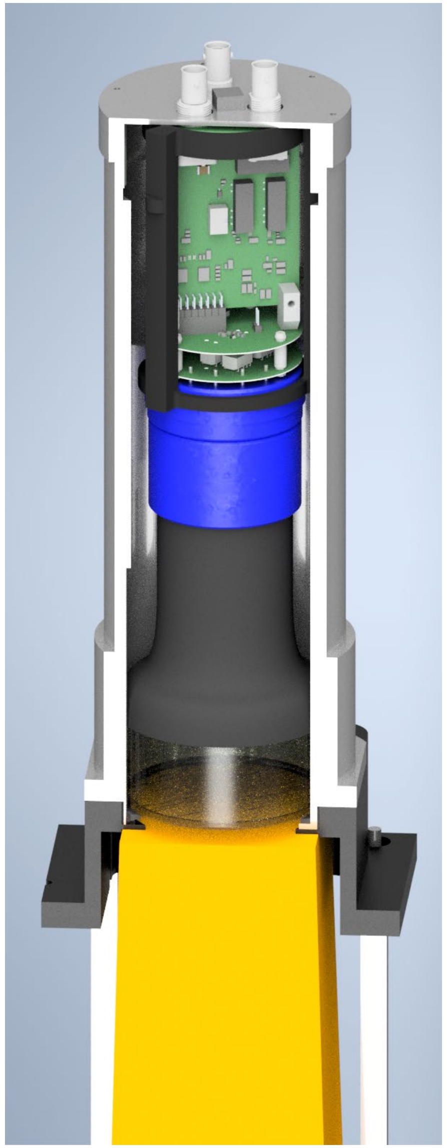
- For ring 5 the module mounting structure has been implemented in CAD and was constructed
- The CAD design is parameterized so that adoption to the other rings should be reasonably straight forward.
- Open tasks:
  - Now in a position to finally revisit R1-4 module design and strengthen the structure – then Larry can do FEM
  - Make convenience changes to the quartz tray and lower cone assembly
  - Finalize the module interface plate with the segment plate
  - Verify and complete PMT housing design (Brynne)

Detector module design:

PMT Housing Design (Brynne, Nafis, and Jie)

- We are nearing the end stages of front-end electronics design (base + preamp) – see Jie's talk
- Besides the PMT and base, the module is also supposed to house the integration mode and event mode preamps
- Brynne designed the new PMT/electronics housing that is monolithic with respect to being detachable as a unit from the rest of the module
- A beta version of this module was made by Brynne and Nafis for the May beam test



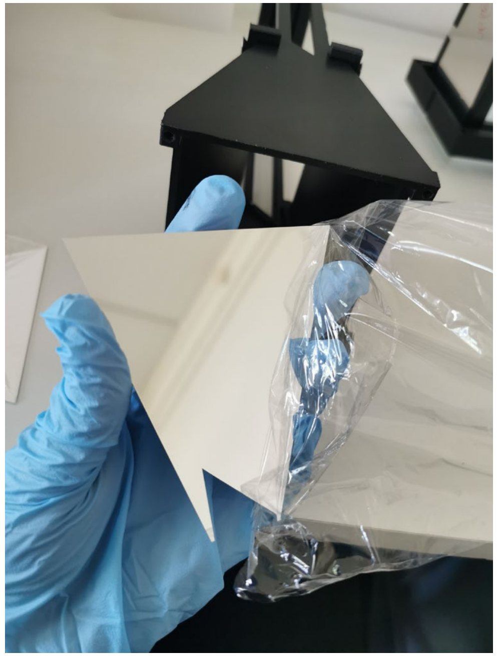
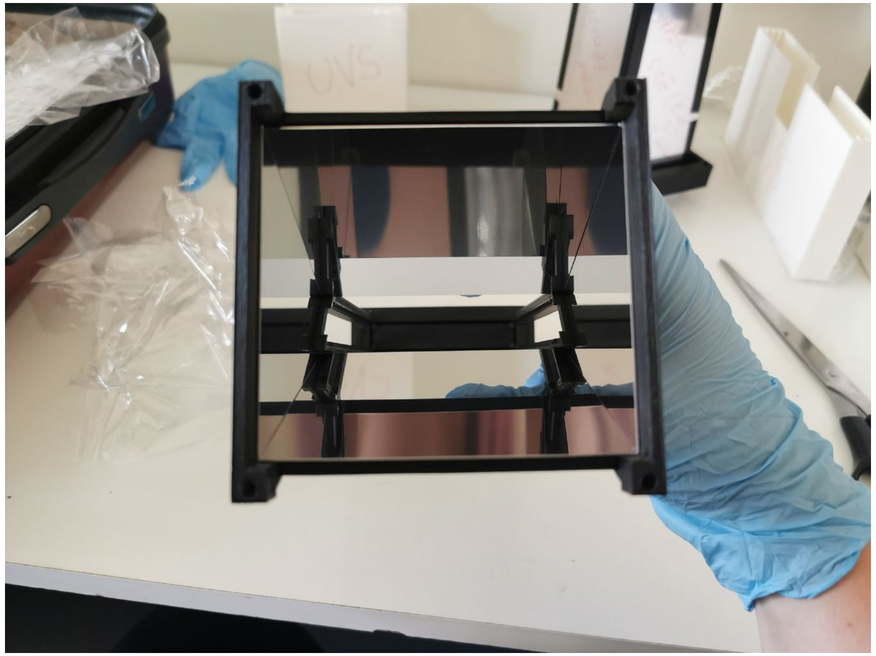


Detector module design:

PMT Housing Design (Brynne, Nafis, and Jie)

- The ring 5 module structure was 3D printed
- Laser-cut light guide sheets individually installed in the lower funnel



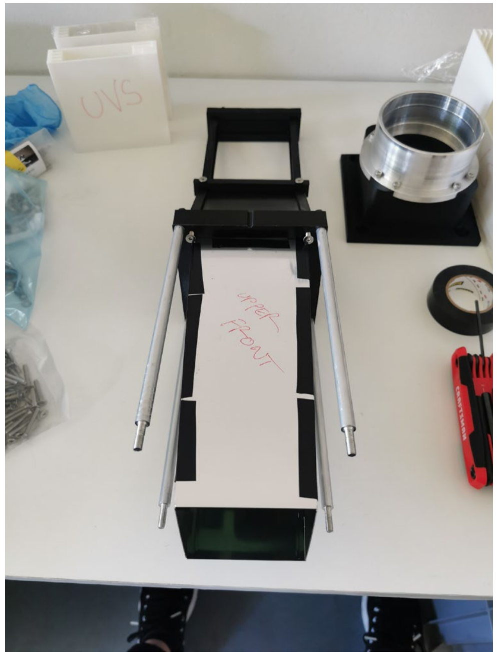



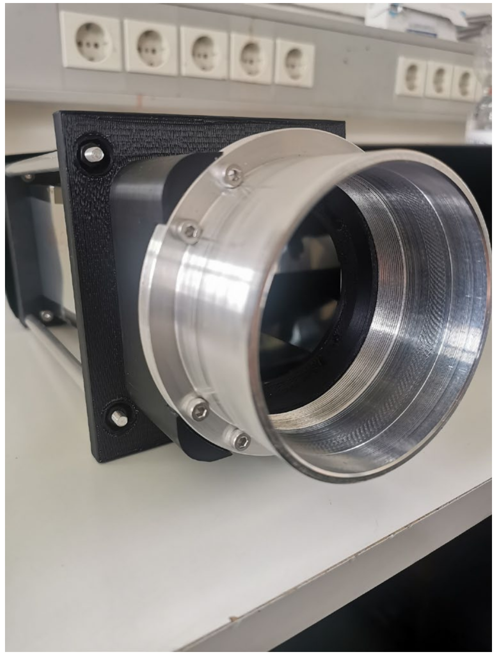
Detector module design:

PMT Housing Design (Brynne, Nafis, and Jie)

- The PMT housing unit is threaded into flange that attaches to the part that attaches to the segment plate and positions the PMT cathode regressed into the lead shielding.

- A light-sealing bag slides over the module.

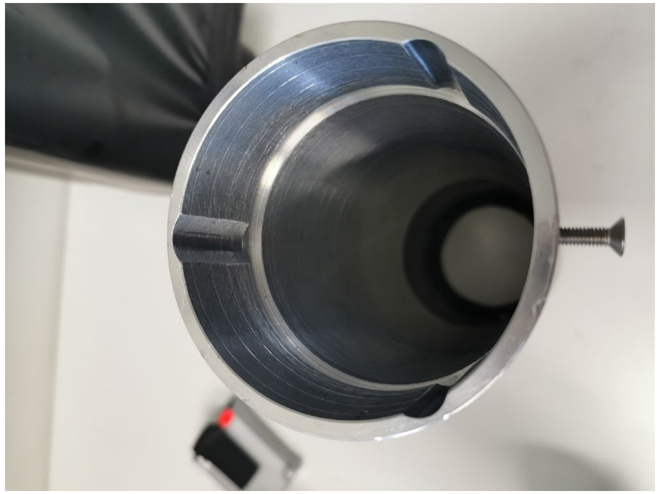


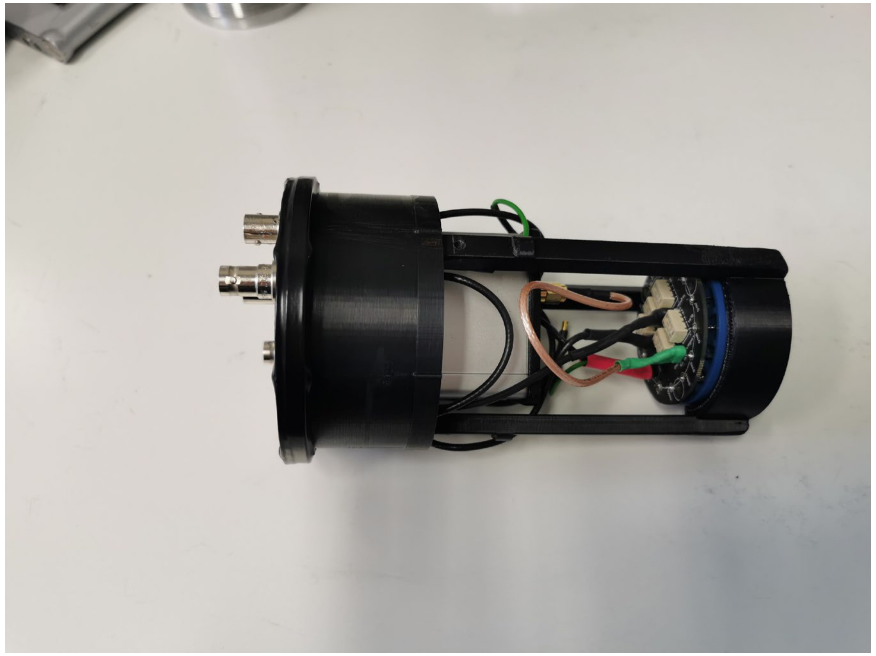



Detector module design:

PMT Housing Design (design and machining by Brynne Blakie)

- The PMT/electronics housing is a combination of 3D printed holder and aluminum housing (the top part would be metal as well in the final design)
- The PMT/electronics holder inserts into housing and is held by bayonet twist



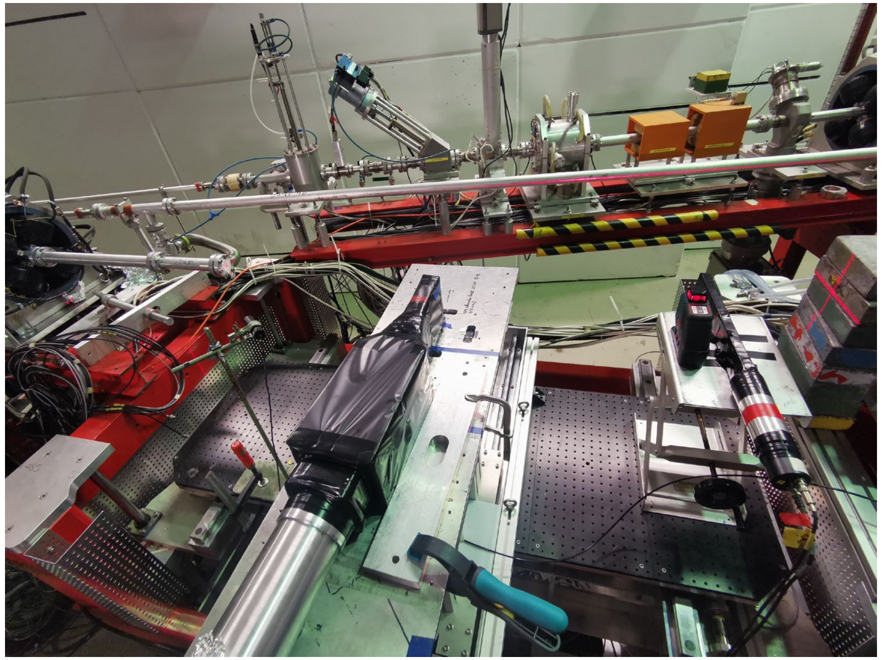


Detector module design:

PMT Housing Design (design and machining by Brynne Blakie)

- Very little additional light sealing at the PMT housing required
- Complete unit very rigid and all components well protected

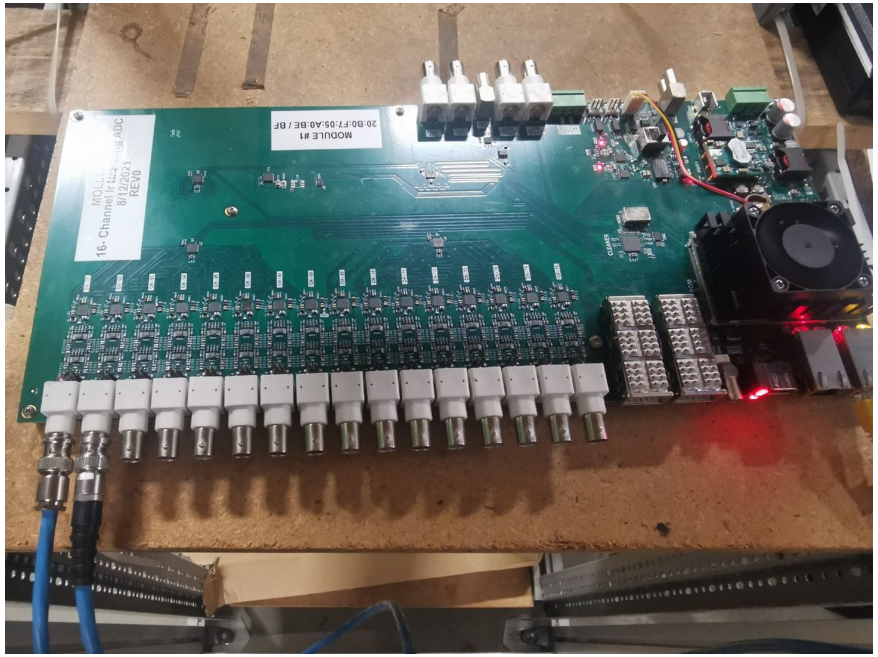


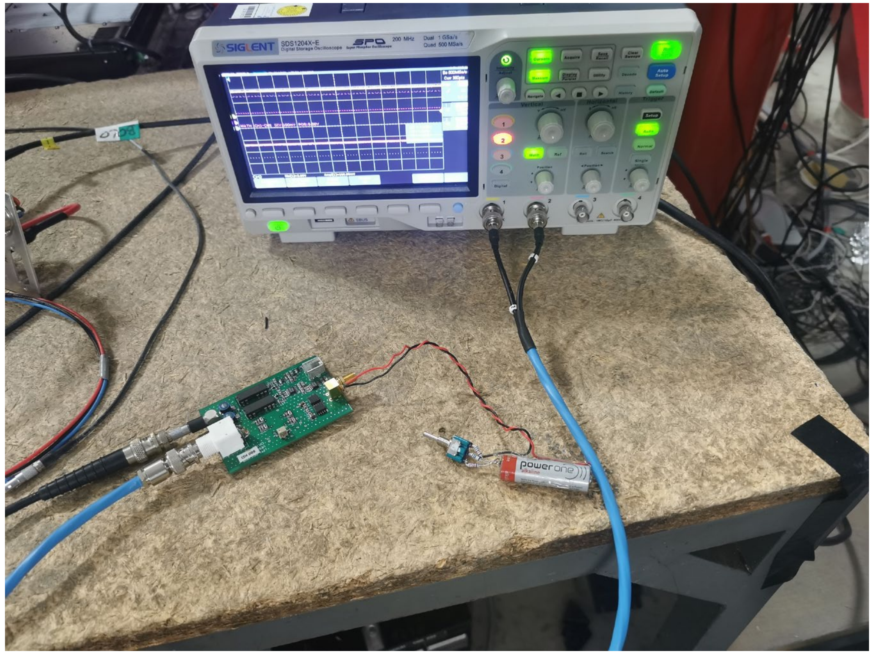



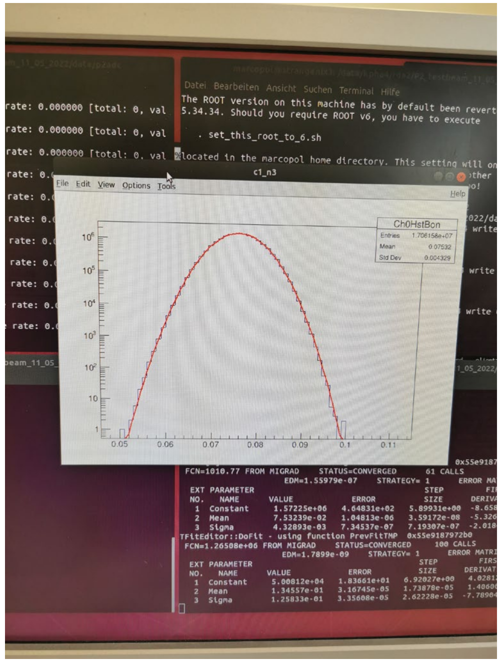
May beam time:

Detector performance

- Beam test was conducted with full integrating electronics chain including first full 16 channel ADC board
- Still faced noise issues with the preamp, due to DC/DC converter and offset pot, but eventually got one of the preamps behaving very well (noise issues – see Jie's talk)

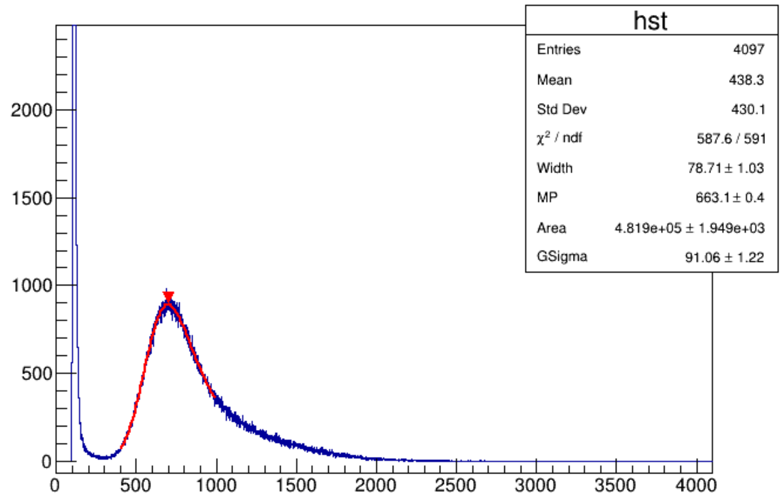






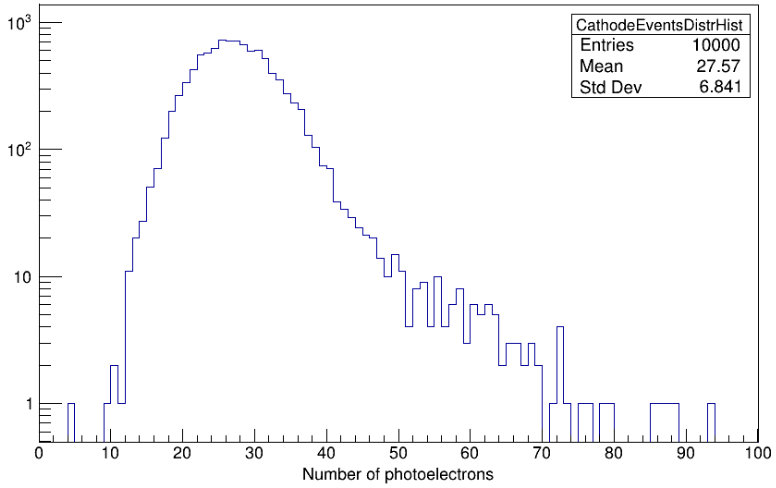
May beam time:

Very brief (and preliminary) look at a few detector results (at the very beginning of looking at the data)



Event mode with Myro Silver: $n_{pe} \simeq 25$

Event mode with UVS: $n_{pe} \simeq 36$

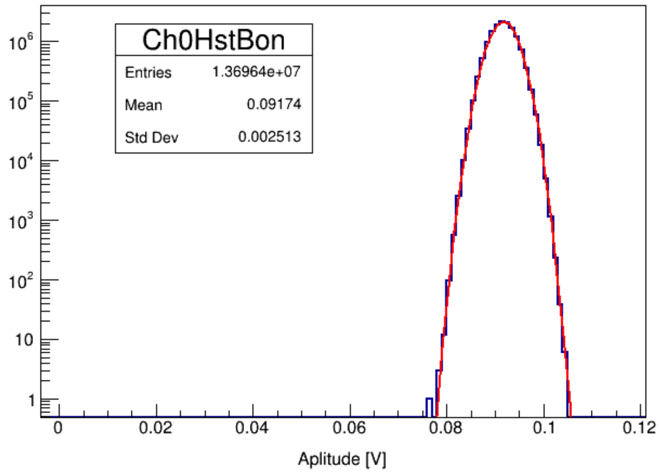


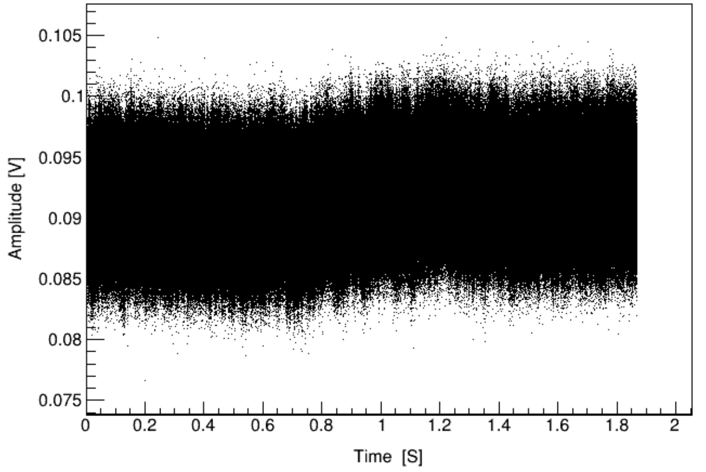
Simulations (MS reflective data)

May beam time:

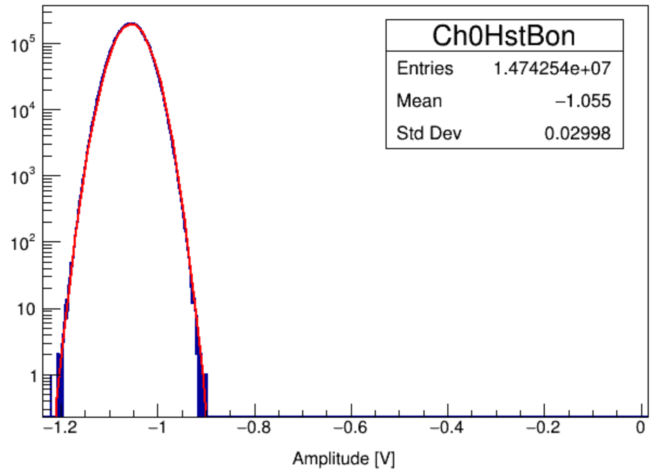
Very brief look at a few detector results (at the very beginning of looking at the data)

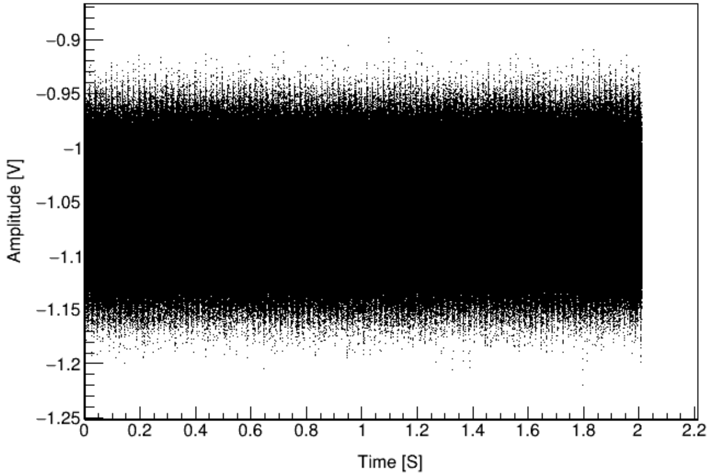
Beam off, HV off data: $\sigma \simeq 2.5\ mV$





Beam on, 2 GHz rate: $\sigma \simeq 30\ mV$



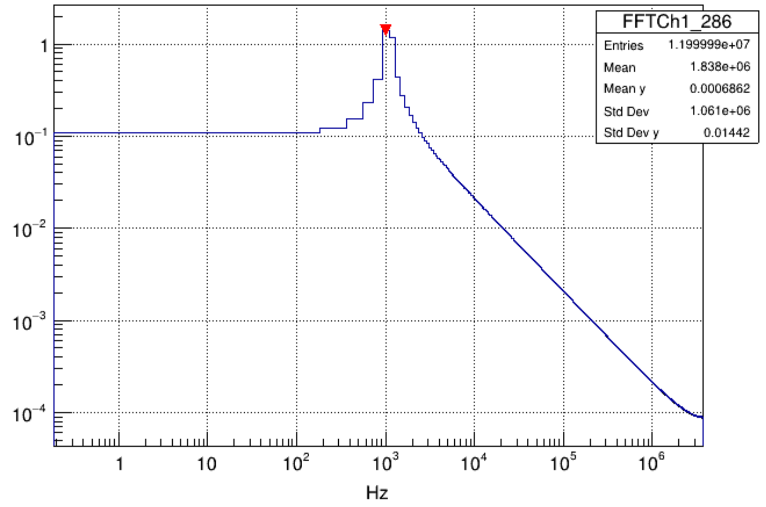


May beam time:

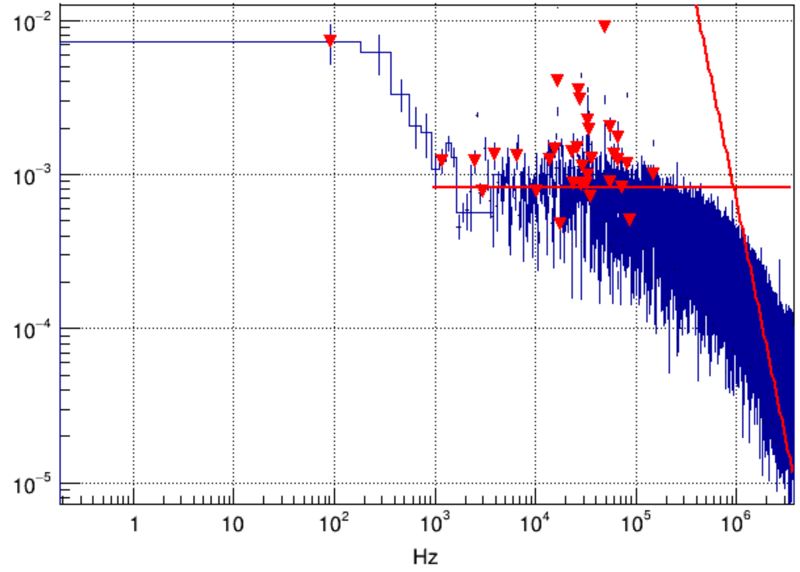
Very brief look at a few detector results (at the very beginning of looking at the data)

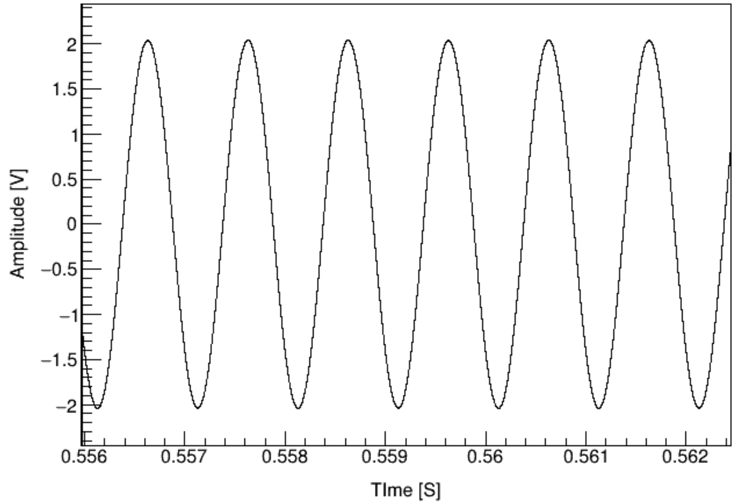
ADC board filter performance is not great, because we currently don't have the proper amplifiers installed in the front-end filter.

They should arrive sometime in August to be switched out on all 5 prototype boards.



1 kHz reference signal into channel 1





Detector tasks:

Subsystem	Parameter	Description	Owner
Integrating Detectors	Tiling (geometry optimization)	Simulations and deconvolution	Ciprian / Zuhal
	Radiation Exposure/Hardness	Simulations/Calculations	Ciprian (sim) & Dustin (meas)
	Cabling / Patch Panel	Planning and integration	Dustin (Michael)
	Air Flush/Electronics Cooling	Simulation/Design	Michael & Dustin
Thin Integrating Detectors	Mounting Structure Design	CAD and integration	UMass / Larry Bartoszek
	Ring 1 Modules	Simulation & Design	Sakib / Michael
	Ring 2 Modules	Simulation & Design	Sakib /Michael
	Ring 3 Modules	Simulation & Design	Sakib / Michael
	Ring 4 Modules	Simulation & Design	Sakib / Michael
	Ring 5 Modules	Simulation & Design	Michael / Brynne (prod.) / Nafis (prod.)
	Ring 6 Modules	Simulation & Design	Chandan / Jonathan / KK
Shower Max Detectors	Mounting Structure Design	CAD and integration	Dustin
	Modules	Simulation & Design	Dustin
Front-end Electronics	PMT base	Design/Testing/Fabrication	Jie, Michael, Brynne
	Base switching control unit	Design/Testing/Fabrication	Mainz (& Jie, Michael, Brynne)
	Preamplifier	Design/Testing/Fabrication	Jie, Michael, Brynne (TRIUMF)
	Preamp control unit	Design/Testing/Fabrication	Open (Manitoba – maybe Mainz)
	PMT/Base linearity	Design/Testing	Dustin & Michael

Detector tasks:

Subsystem	Parameter	Description	Owner
Scanner	Mounting Design	CAD and integration	VaTech (Mark Pitt)
	Detector design	Simulation and Design	VaTech (Mark Pitt)
	Cabling / Patch Panel	Planning and integration	VaTech (Mark Pitt)

Detector tasks:

	Task	Description	Status	Progress	Responsible
1	Design detector mounting structure	Overall mounting scheme	in progress	60% ?	KK
2	Study shower-max splashback	Thin detector background	In progress	60% ?	KK
3	Determine detector cross-talk	Study resulting syst. Effects (after tiling)	In progress	0%	KK/Michael/Ciprian
4	Optimize detector quartz dimensions/positions	Minimize syst. effects and backgrounds	Nearly done	80% ?	Ciprian/Michael
5	Evaluate robustness of quartz	Irradiate quartz and measure transmission loss	In Progress	60% ?	Dustin
6	Scintillation and Cherenkov in the LG.	Study light guide background	Closed		KK
7	Radiation testing of detector components	Test all detector materials and parts	In progress	60% ?	Dustin
8	Quartz photon sensitivity	Investigate quarts efficiency to photons	Closed		Michael
9	Design thin detector module	Design module mounting structure	In progress	80%	Michael
10	Shower max detector module design	Determine structure, size, and mounting structure	In progress	80% ?	Dustin
11	Estimate of backgrounds at the PMTs	Simulation of all possible background levels	In progress	80% ?	Chandan +
12	Establish shielding needs around PMTs	Find needed combination of light and heavy materials	In progress	80% ?	Chandan +
13	Optimize ring 1-4	Optimize optical properties (LG) of the ring 1 module	In progress	80%	Sakib
16	Optimize ring 5	Optimize optical properties (LG) of the ring 4,5 module	In progress	90%	Michael
17	Optimize ring 6	Optimize optical properties (LG) of the ring 6 module	In progress	70% ?	KK

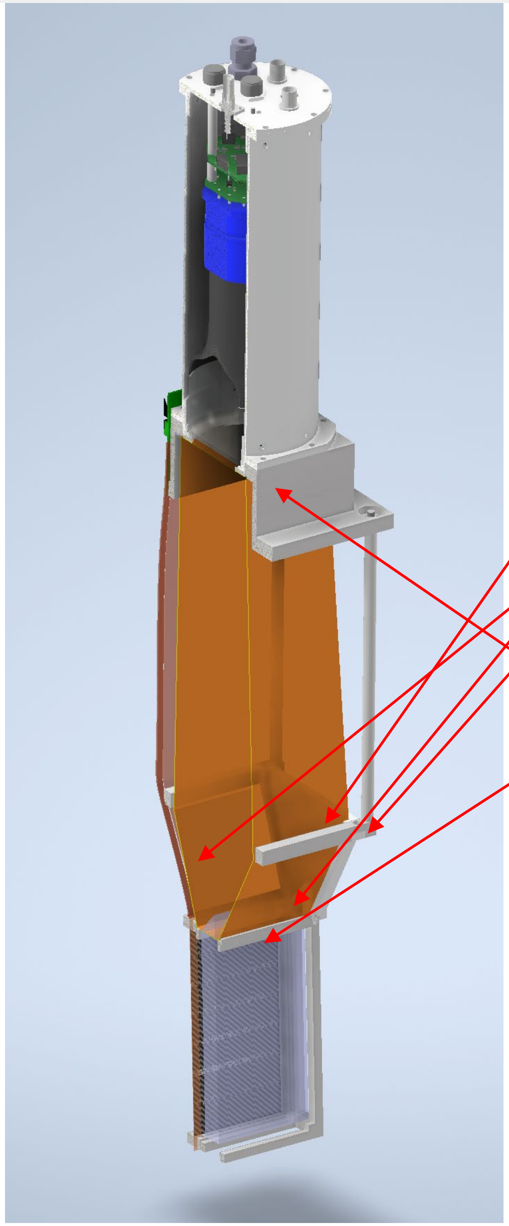
Detector tasks:

	Task	Description	Status	Complete Before	Responsible
18	Develop PMT base design	Design PMT base with switching mechanism	In Progress	80%	Jie / Michael
19	Develop preamp design	Design and build the preamplifier	In Progress	80%	TRIUMF/ Jie / Michael
20	Develop Integrating ADC	Design and build the ADC boards	Nearly done	80%	TRIUMF / Jie / Michael
21	Verify detector linearity	Establish that the detectors are linear at the 0.1% level	In progress	60% ?	Dustin / Michael
22	Verify radiation hardness of electronics	Establish that the electronics can survive the radiation	In progress	60% ?	Dustin / Michael

Backup

Detector module tiling/design:

- Overall size of the geometry is limited by the space within the detector mounting structure and
  - need for assembly space (getting hands in there)
  - additional space for light sealing
  - additional space for R5 for HVMAPS structure
- We can vary the size of the light guide geometry within $\approx \pm\ 1\ cm$ depending on the location (not at the top)
- Parameters we can play with:
  - Lower cone angles (drives the upper cone angles)
    - Front angle
    - Back angle
    - Side angles
  - Lower cone size (drives the upper cone size)
  - Quartz thickness
  - Quartz-LG interface size
  - Relative location of PMT to quartz in beam direction
  - Light guide surfaces (straight versus bent – within limits)
- We cannot change the upper end of the LG / PMT interface by much, without making changes to the overall detector mounting structure

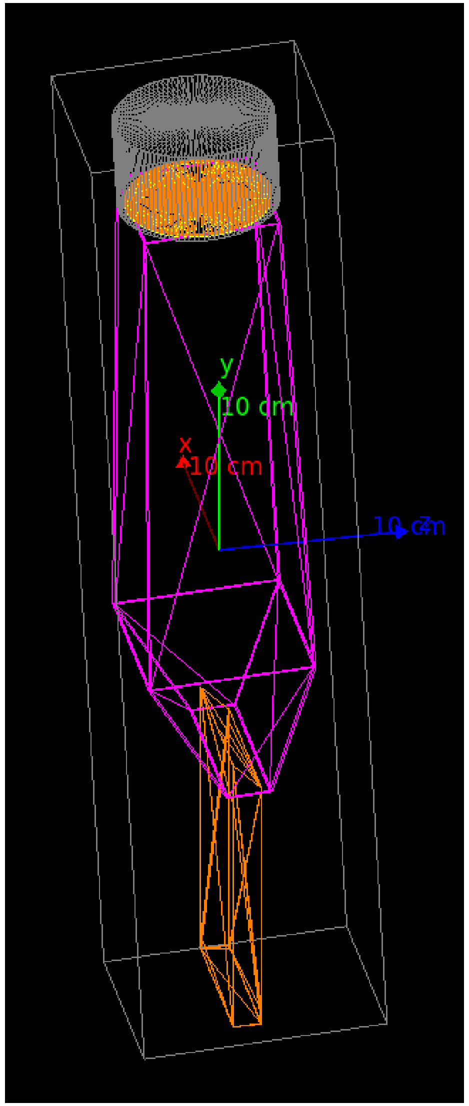


```
#  Geometry help:
#
#              | PMT|
#              ------         ________ Upper Interface
#             /      \
#            / Upper  \
#           /  Guide   \
#          /   Cone     \     ________ Lower Interface
#          \            /
#           \  Lower   /
#            \ Guide  /
#             \Cone  /        ________ Quartz-LG interface plane
#              |    |
#              |    | Quartz
#              |    |
#    --->      |    |
#   Beam (Z) |_ __|
#
#                ^
#               / \  (y)
#                |
#  (x) into screen


#/Det/LightGuideLowerConeSideAngle 21 deg        #These are normally straight, unless

/Det/LightGuideLowerConeBackAngle 21 deg         #Angle between positive y axis (leng
/Det/LightGuideLowerConeFrontAngle 28 deg        #Angle between positive y axis (leng

/Det/LightGuideLowerInterface 7.0 cm             #Distance between quartz-LG interfac
/Det/LightGuideUpperInterface 329 mm             #Distance between quartz-LG interfac

/Det/LightGuidePMTInterfaceOpeningX 7.0 cm       #These should stay fixed - set by th
/Det/LightGuidePMTInterfaceOpeningZ 7.0 cm

/Det/LightGuideQuartzInterfaceOpeningX 9.2 cm   #These should be set according to the
/Det/LightGuideQuartzInterfaceOpeningZ 2.2 cm    #But larger, according to the CAD mo

/Det/QuartzSizeZ 15 mm
/Det/QuartzSizeX 84 mm
/Det/QuartzSizeY 140 mm                           #Without the 45 degree cut
/Det/QuartzBevelSize 0.1 mm                      #Should not normally have a bevel. S

/Det/QuartzRotX -3 deg                           #rotate the quartz w.r.t. the light
/Det/PolarRotation 3 deg                         #counter rotate the detector as a wh

/Det/LightGuideQuartzToPMTOffset 0 mm            #offset of PMT along Z w.r.t quartz

#/Det/SetSegmentedRadDamageFlag                  #Uncomment to include quartz radiati
#/MOLLEROpt/QuartzRadDamage 70                   #Set peak quartz radaiation damage t
/Det/UpdateGeometry

/Generator/EventHitRegion 1                      #1 = quartz, 2 = lower LG cone, 3 =
 = 2x2 mm^2 spot on upper guide
```

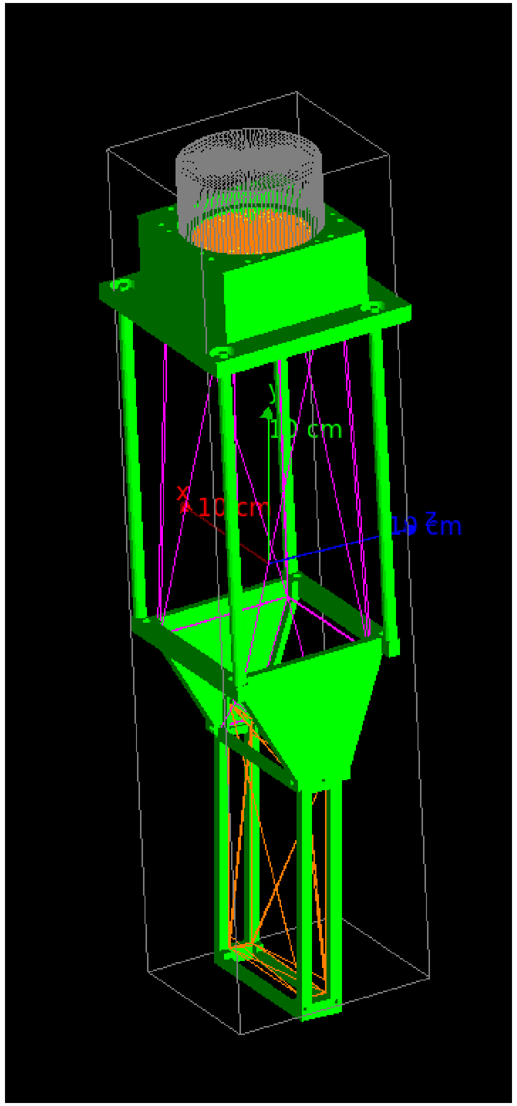
Detector module tiling/design:

- Simulate the quartz and light guide geometry (vary the aforementioned parameters in simulation)
- Simulation automatically exports the current LG design in the simulation as in stl file format
- Import the light guide stl file into CAD and design the mounting structure around it, to satisfy all other criteria (other than light yield, etc.)
- Export the designed mounting structure as in stl file format and convert that to GDML format
- Import the GDML structure into the simulation
- Check for overlap and interference
- Run simulation again

Without mounting structure



With mounting structure

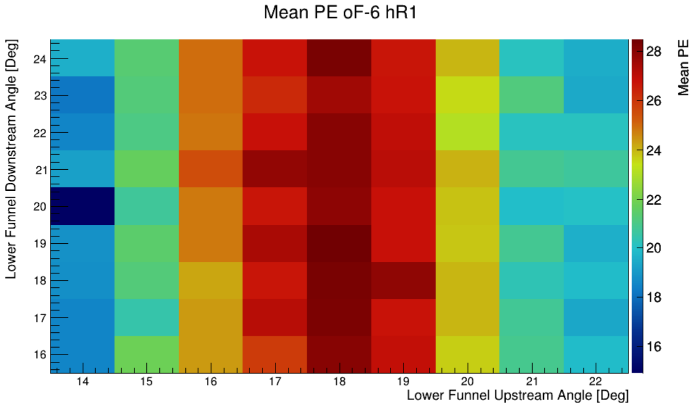


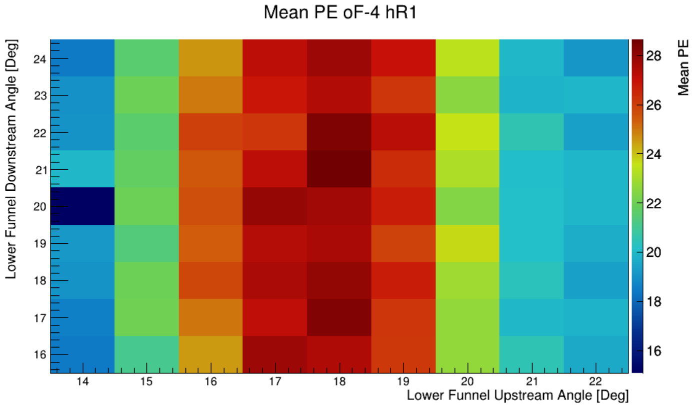
Integrating Detector Module Design

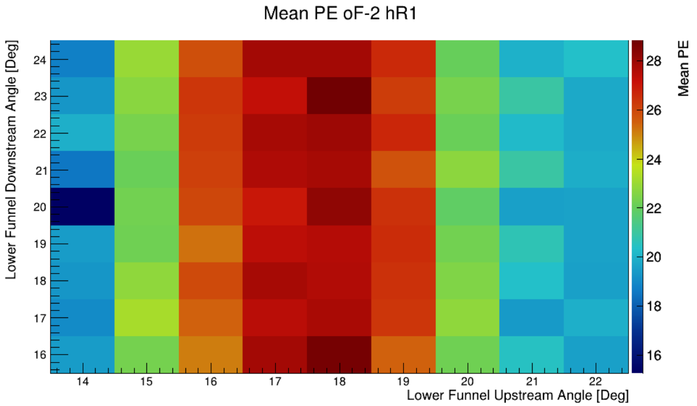
Ring 5 simulations results for 17 mm thickness:

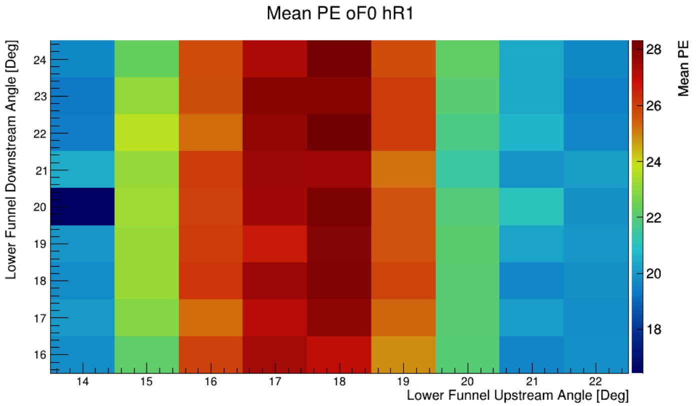
Hit region 1 (quartz) mean PE yield:

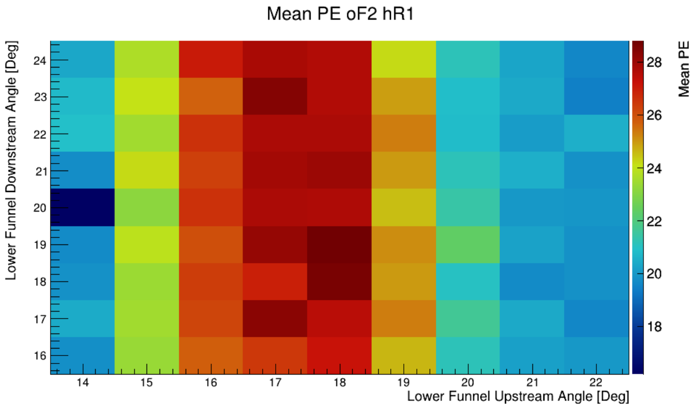
- It is clear from these plots that there is very little dependence on the lower cone back face (or downstream) angle.
- It is also clear that only the $[17,19]\ deg.$ angle range is viable
- The highest reached PE number is fairly independent of the PMT LG offset, but $\pm\ 2\ mm$ compete for the highest PE yield (see also later slides)

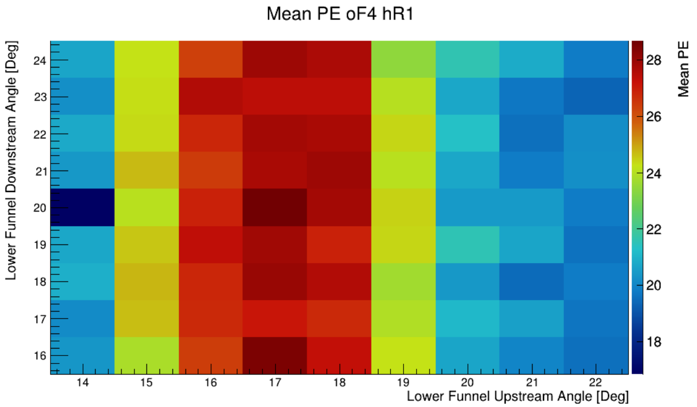


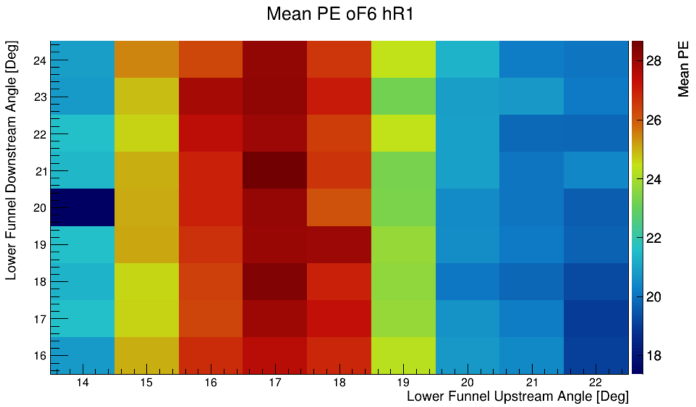










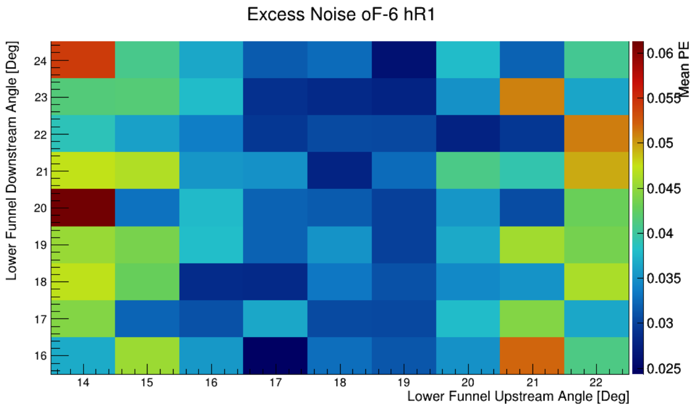


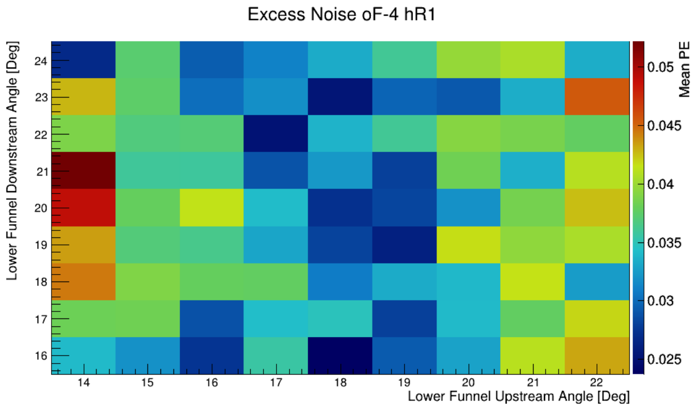
Integrating Detector Module Design

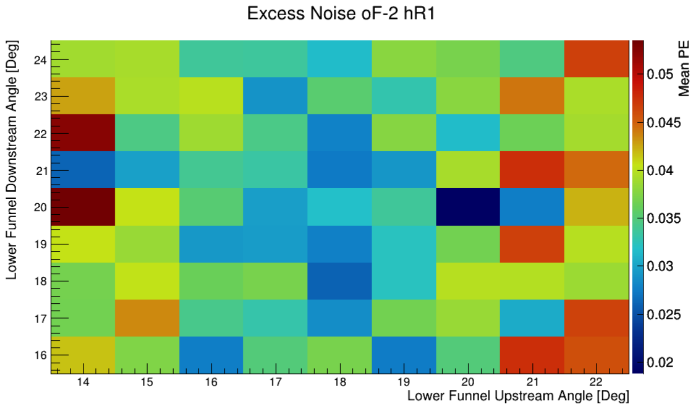
Ring 5 simulations results for 17 mm thickness:

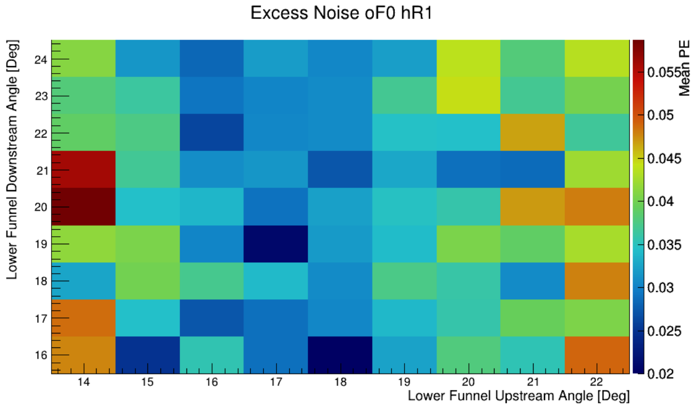
Hit region 1 (quartz) excess noise:

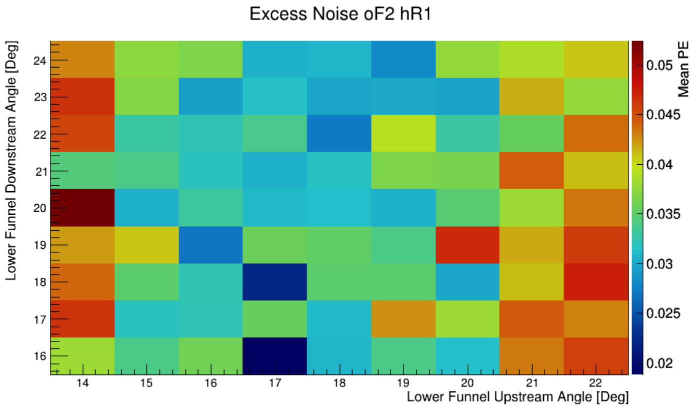
- Excess noise is generally smaller for the same angle range as the yield is largest: $[17,19]\ deg$.
- Generally, the blue and green parameter combinations are acceptable from pov. of the experiment excess noise requirement.
- There is no clear dependence on the PMT to quartz offset.

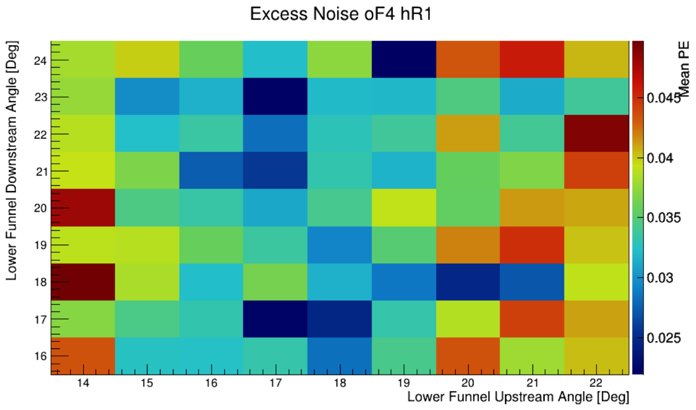


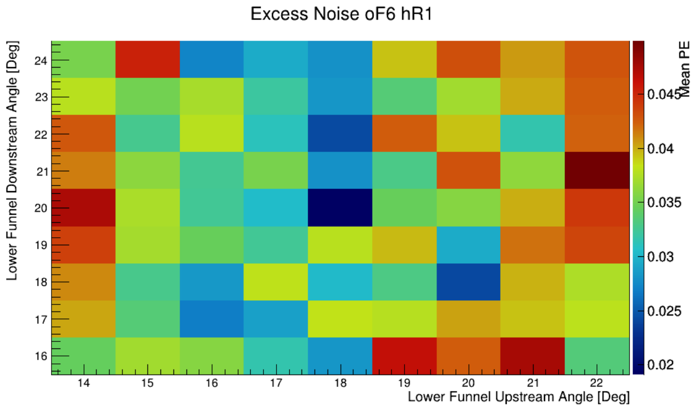










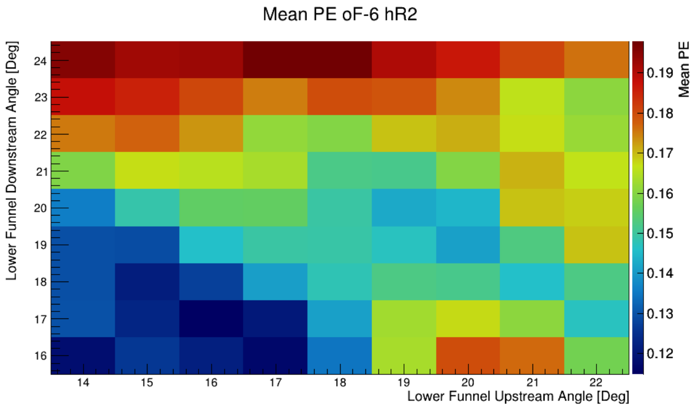


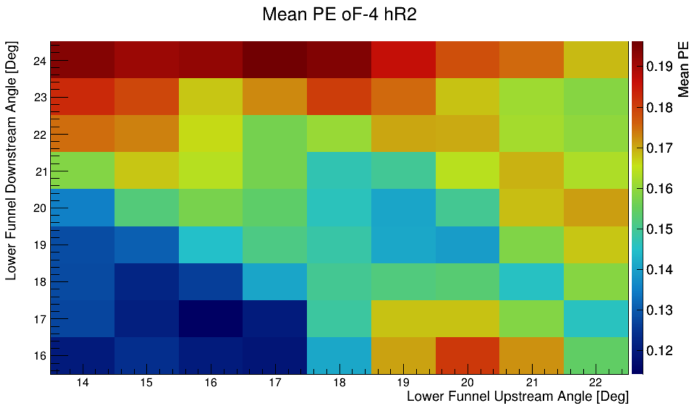
Integrating Detector Module Design

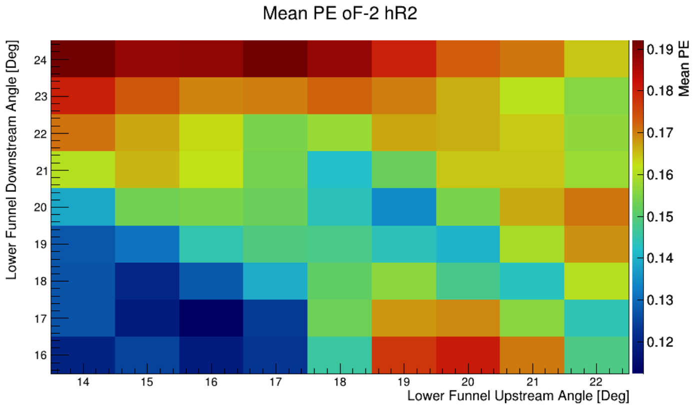
Ring 5 simulations results for 17 mm thickness:

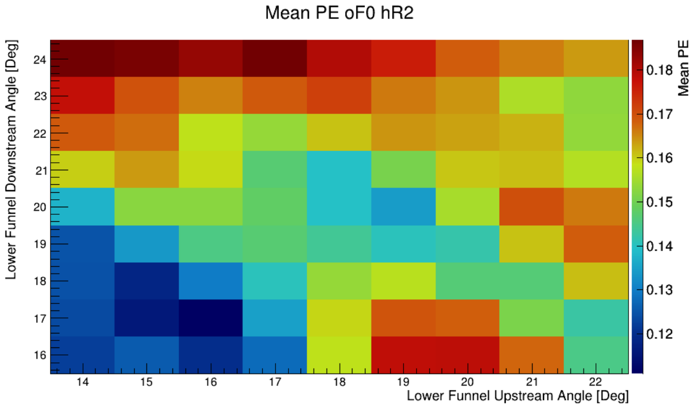
Hit region 2 (lower funnel) mean PE yield:

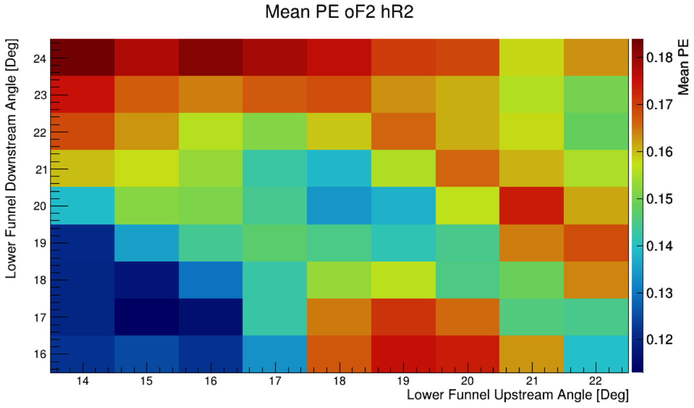
- Here we want to minimize the PE yield
- Lower angles are better, both for the upstream and downstream angles.

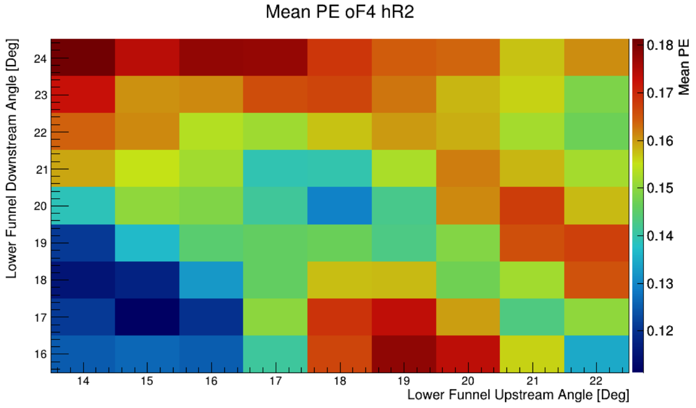


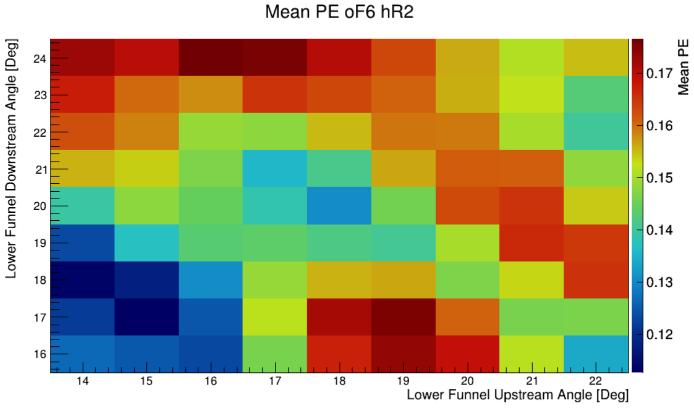










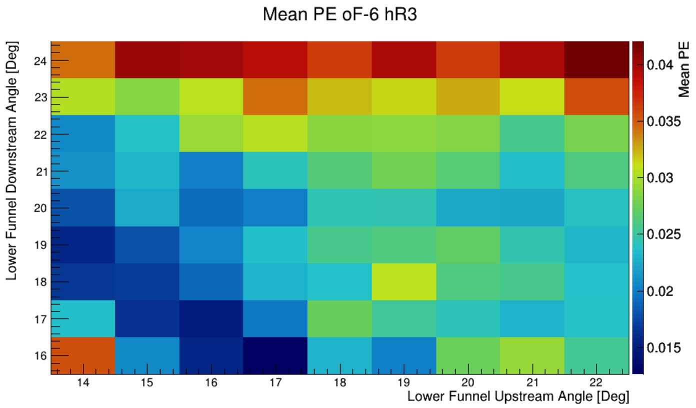


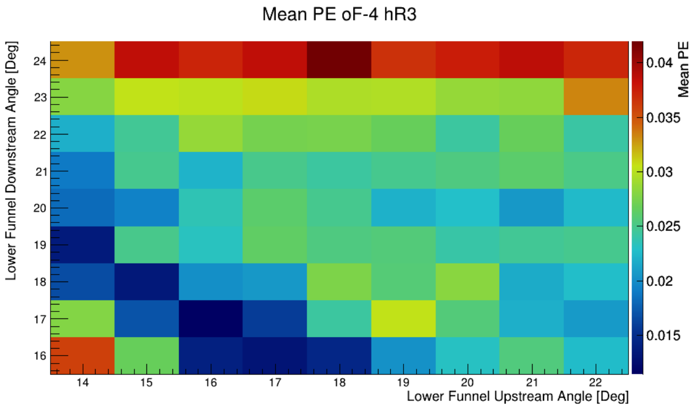
Integrating Detector Module Design

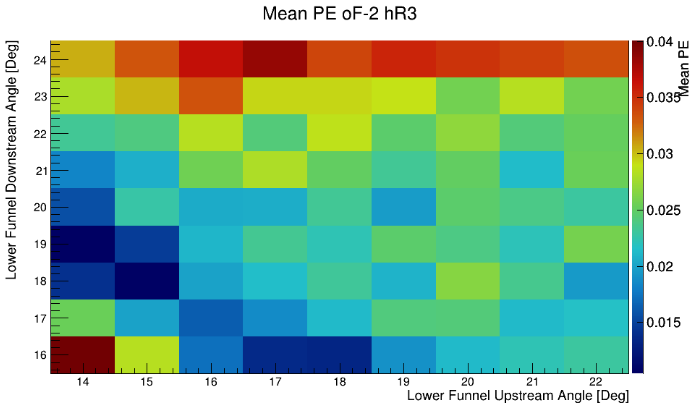
Ring 5 simulations results for 17 mm thickness:

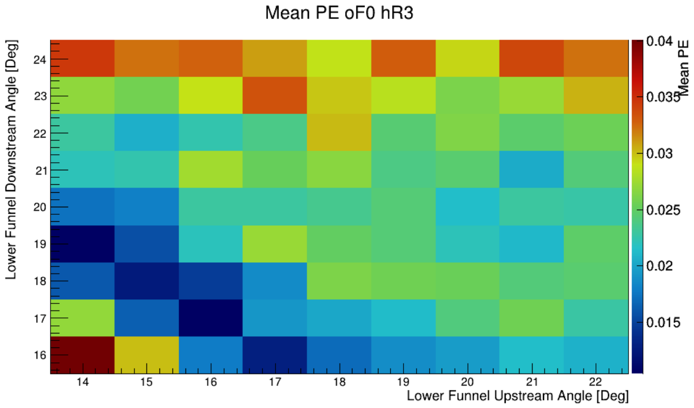
Hit region 3 (upper funnel) mean PE yield:

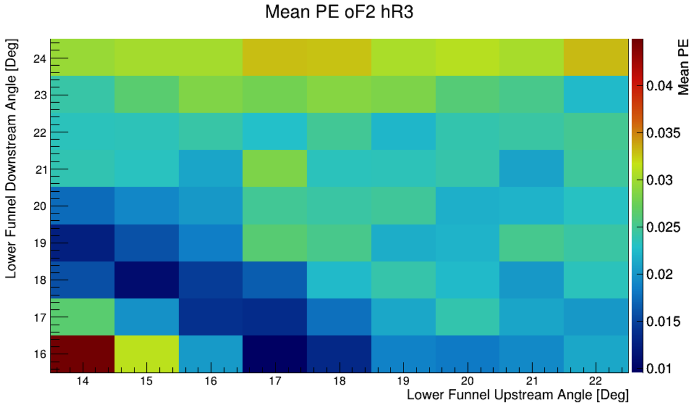
- Here we want to minimize the PE yield
- Generally, lower angles are better, both for the upstream and downstream angles. Except for the lowest angle combination.

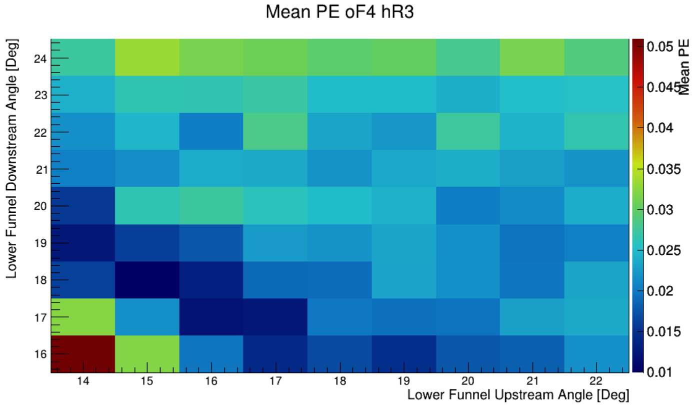


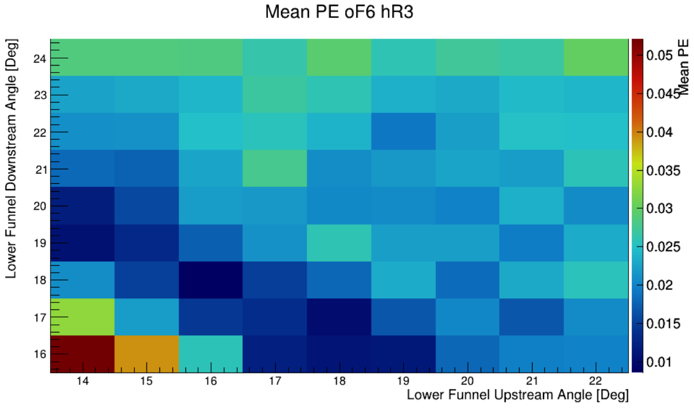








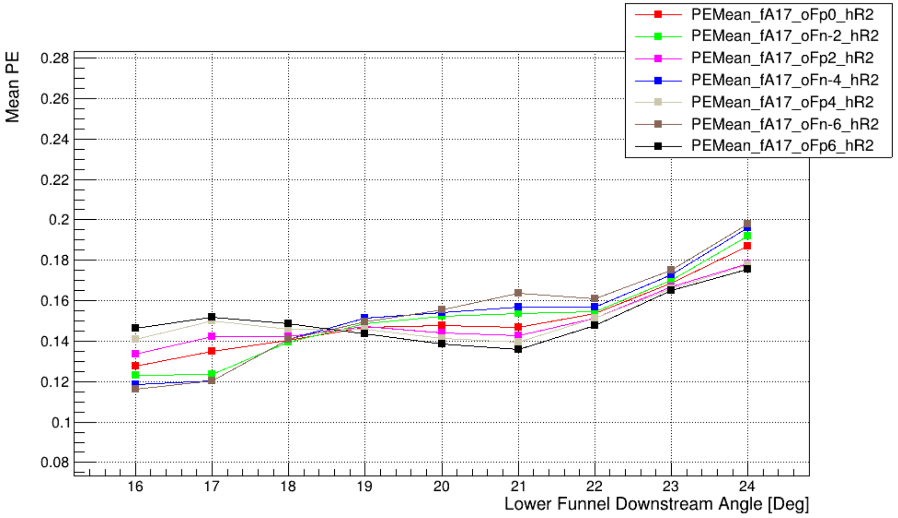


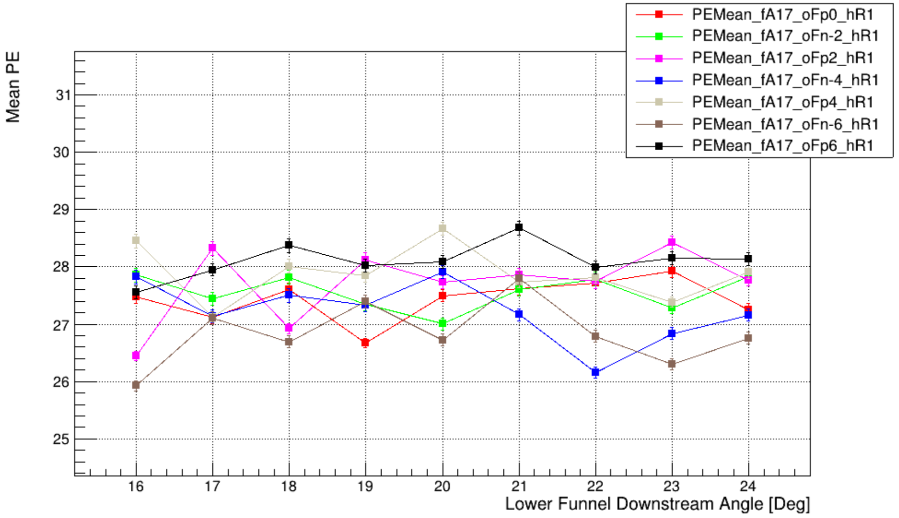


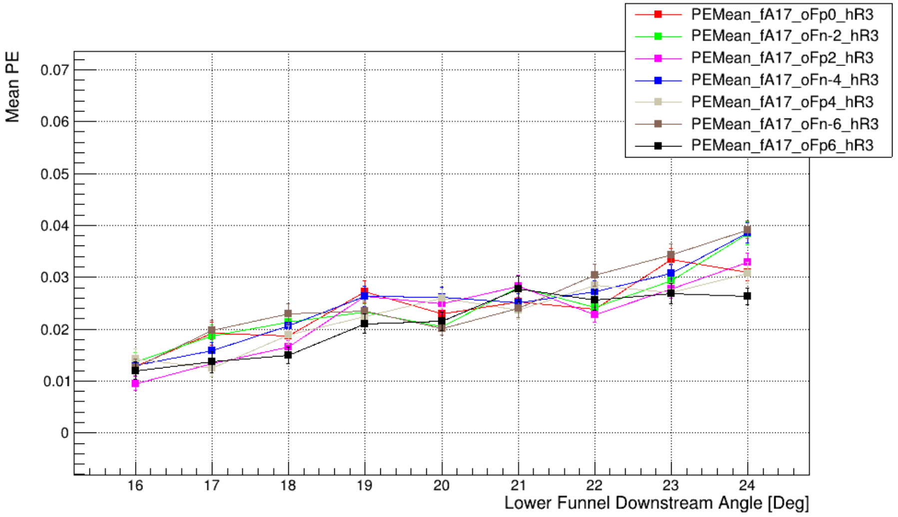
Integrating Detector Module Design

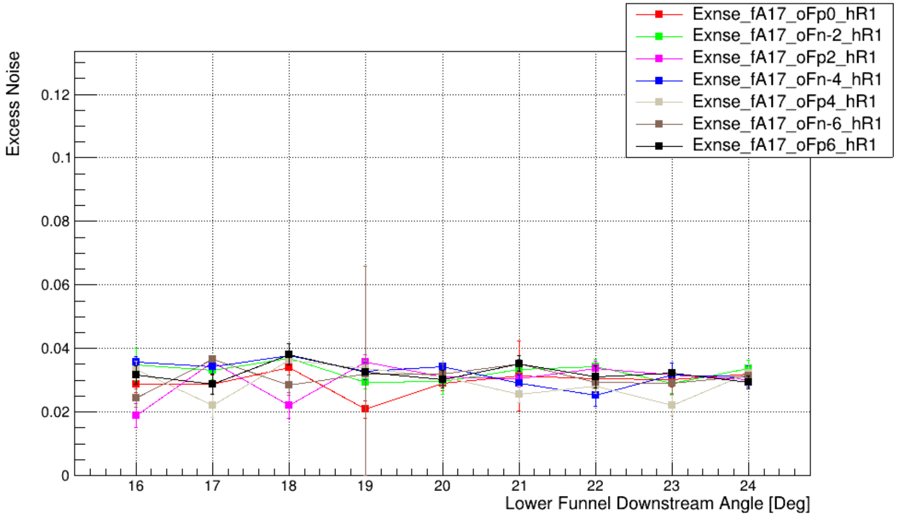
Ring 5 simulations results for 17 mm thickness:

Focus on upstream angle $= 17\ deg$:









Integrating Detector Module Design

Ring 5 simulations results for 17 mm thickness:

Focus on upstream angle $= 18\ deg$: