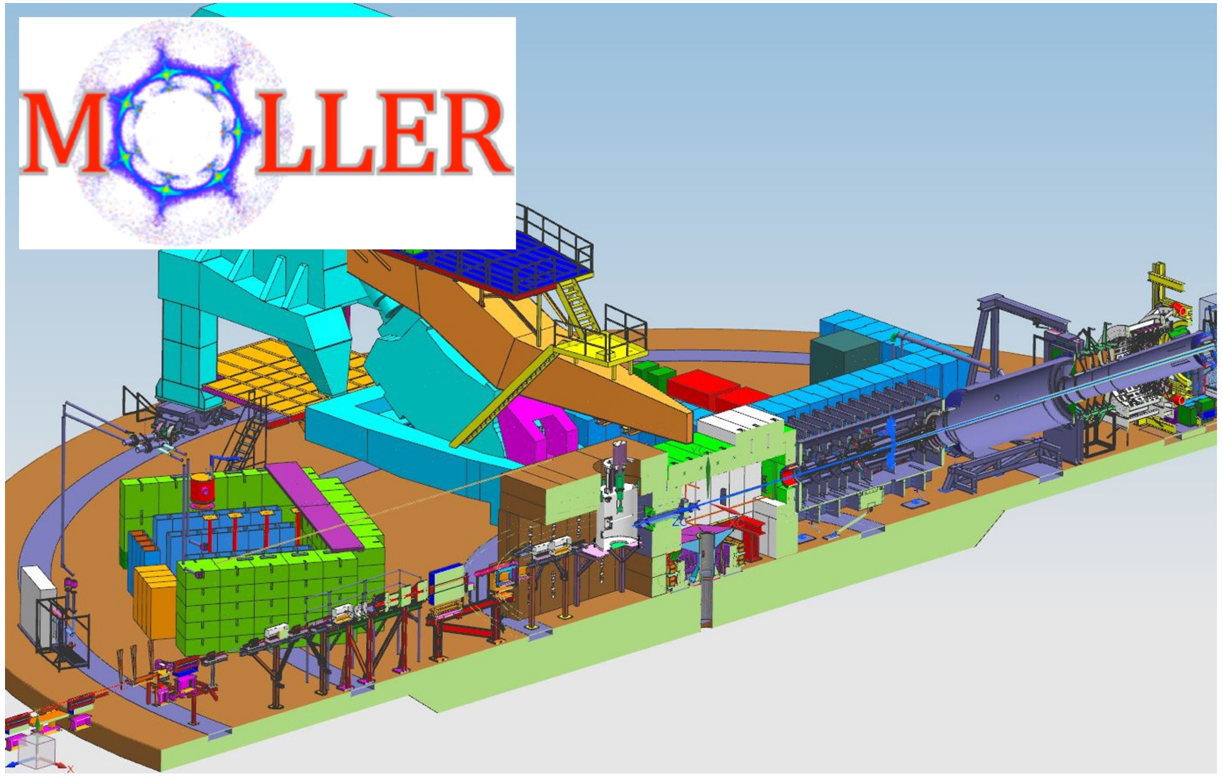
MOLLER CD-2/3 Director’s Review

Shower-max and Radiation Hardness Studies



Dustin McNulty

Idaho State University

August 15, 2023

Outline

- Shower-max Overview
- Design and Engineering
- Risks and Mitigations
- Prototyping, Testbeam and Pre-production Plans
- ES&H and Quality Assurance
- Radiation Hardness Studies: Quartz, Plastic and pmt Base Electronics
- Summary

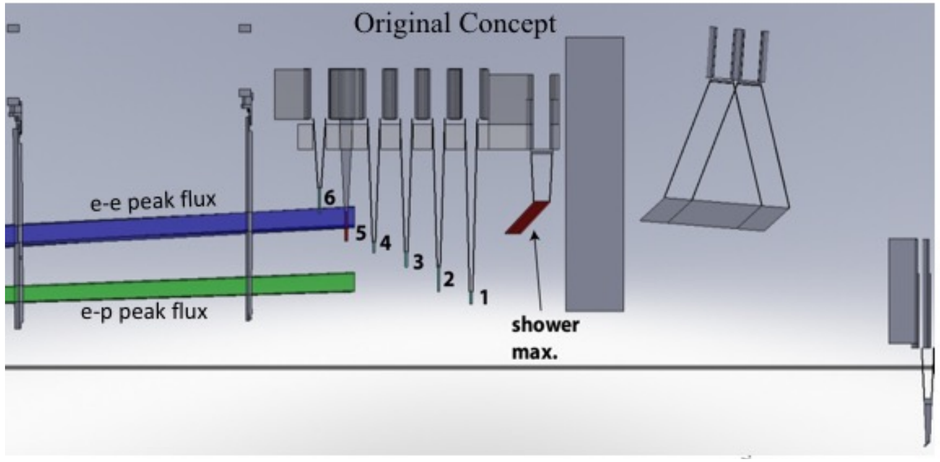
- Team Members:
  - D. McNulty, Idaho State U.
  - Michael Gericke, U. Manitoba
  - Krishna Kumar, U. Massachusetts
  - Larry Bartoszek, Bartoszek Engineering
  - Carl Zorn, Jefferson Lab
  - Justin Gahley, Idaho State U.

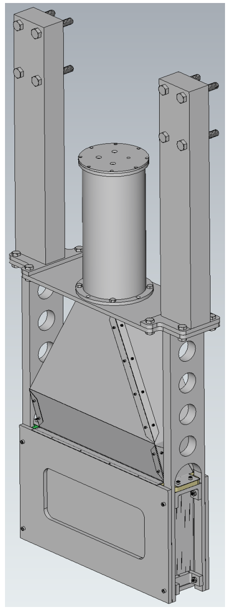
  ISU Graduate students:
  - Sudip Bhattarai
  - Sagar Regmi
  - Jared Insalaco

  ISU Undergraduates:
  - Edwin Sosa
  - Coltyn Fisher
  - Freddy Kouakou
  - Gabriel Ladipo
  - Michael Ladipo

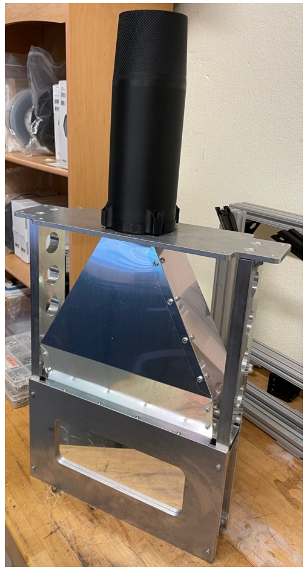
Shower-max Subsystem Overview

2.04.03	Shower Max Detector	Design, Procurement, Assembly, and Test of the Shower-Max detector system. It is composed of an array interleaved layers of quartz radiatiors and thin tungsten sheets making up an EM shower detector system.

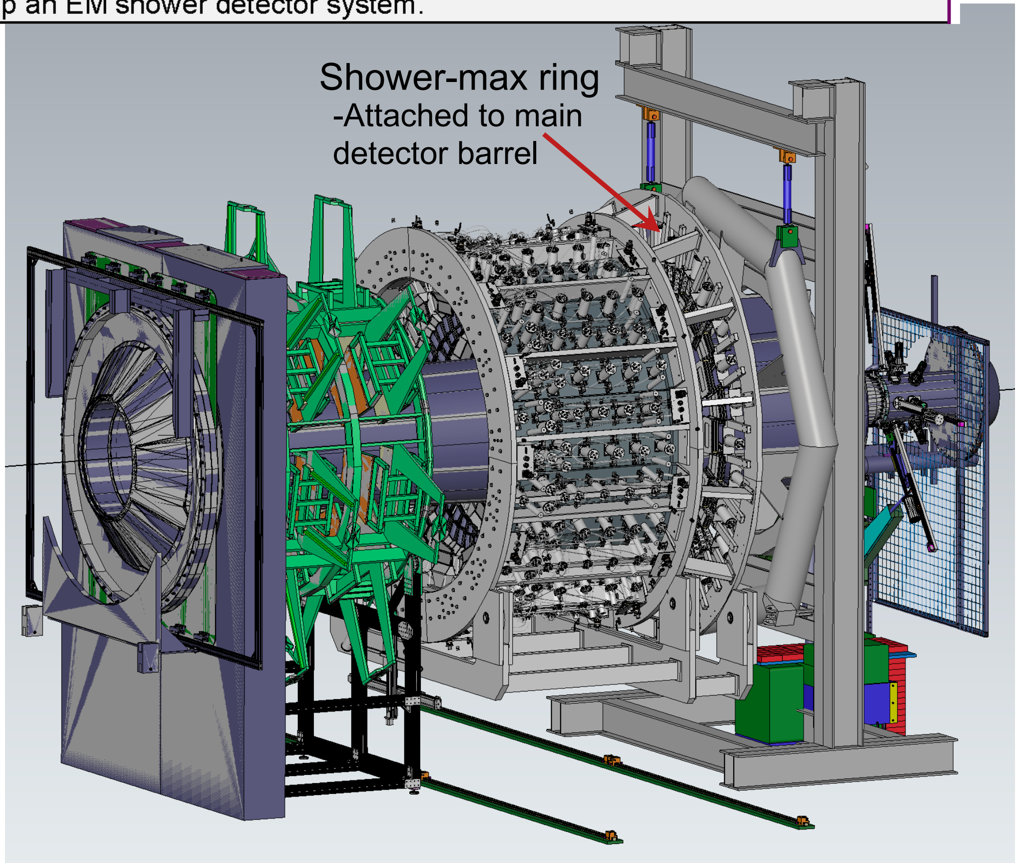




2022 prototype



Shower-max:
An electromagnetic
sampling calorimeter

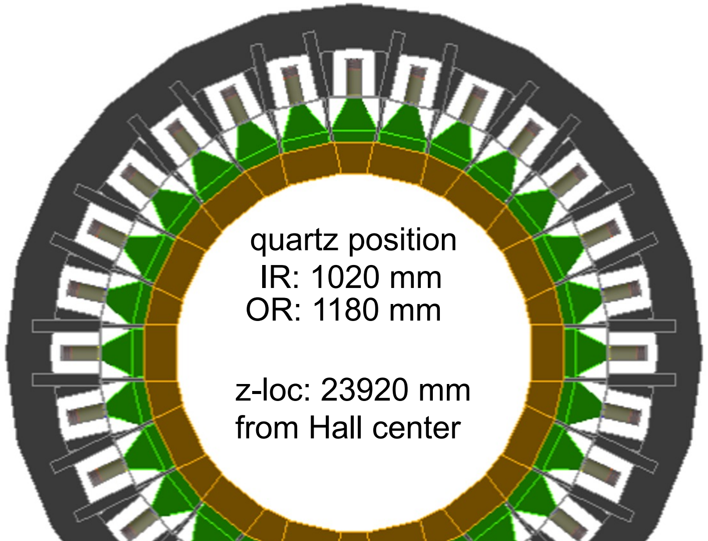


Shower-max ring
-Attached to main
detector barrel

- Designed and positioned to provide additional measurement of Ring-5 integrated flux (MOLLER A_{PV})
- Weights flux by energy $\Longrightarrow$ less sensitive to low energy and hadronic backgrounds
- Also operates in event mode for calibrations and may give additional handle on background pion identification
- Designed to have $\lesssim 25\%$ resolution over full energy range and constructed with rad hard components for long term stability

Shower-max Module and Ring Geometry

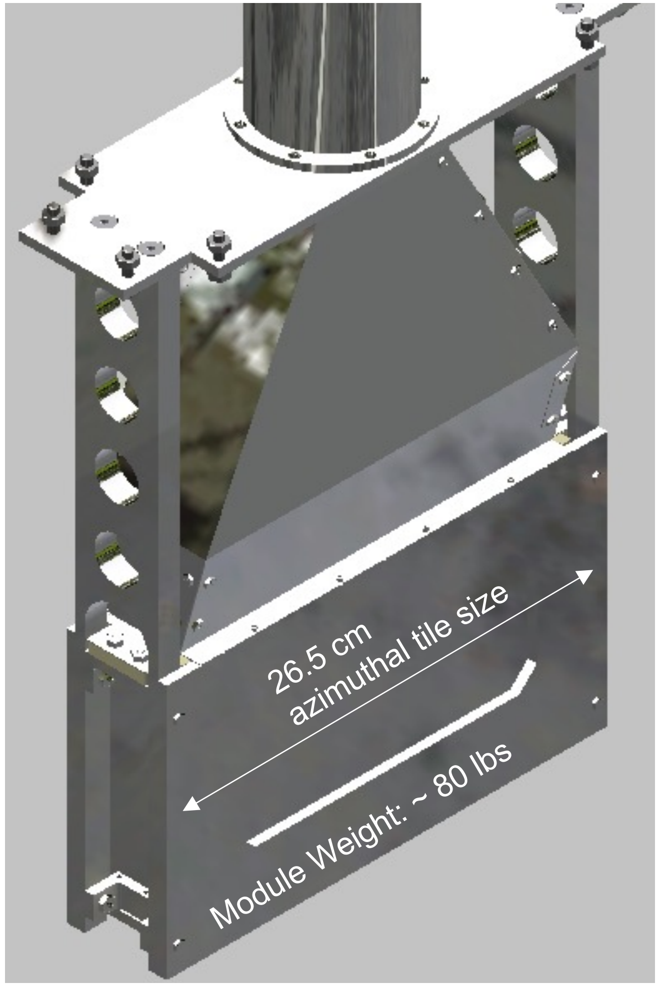
ShowerMax detector: ring of 28 sampling calorimeters intercepting physics signal flux ~1.7 m downstream of ring 5

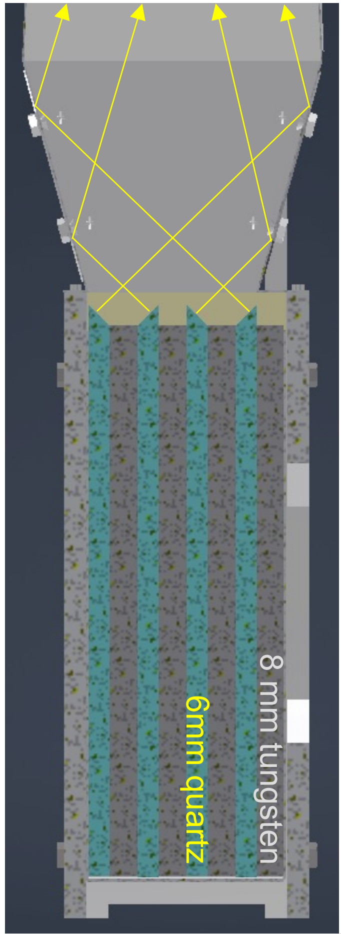


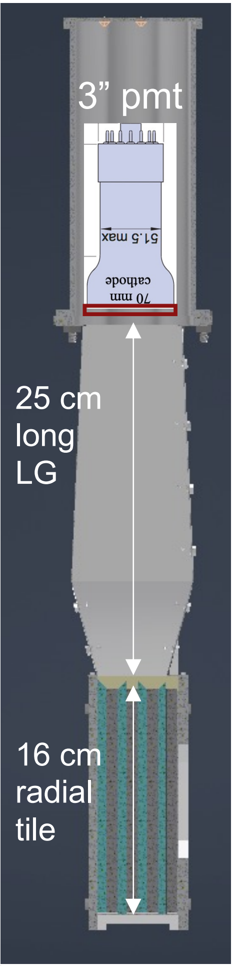
G4 GDML view

- Al. 6061 chassis and al. air-core light guide
- 99.95% pure tungsten and HPFS (quartz) radiators
- Rad. length: ~9.5 X_0
- Molière radius ~ 1.1 cm

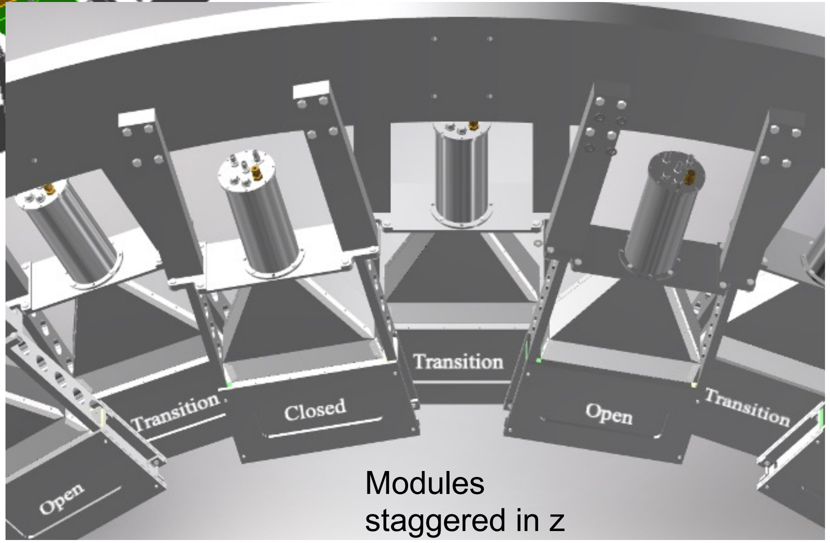
- Using Electron Tubes 9305QKB pmt







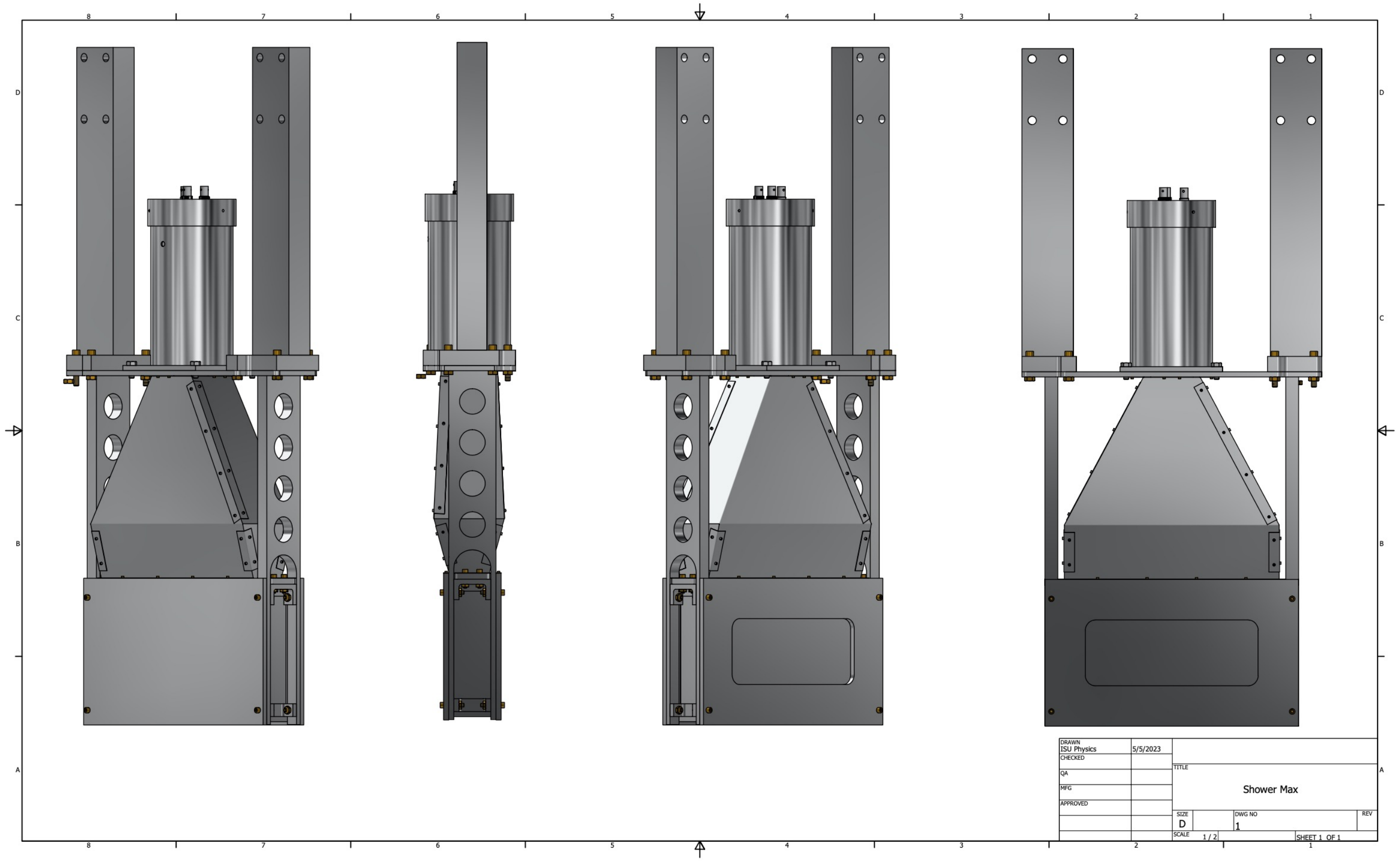
- See L. Bartoszek’s talk for details of the SM and Main detector support structure



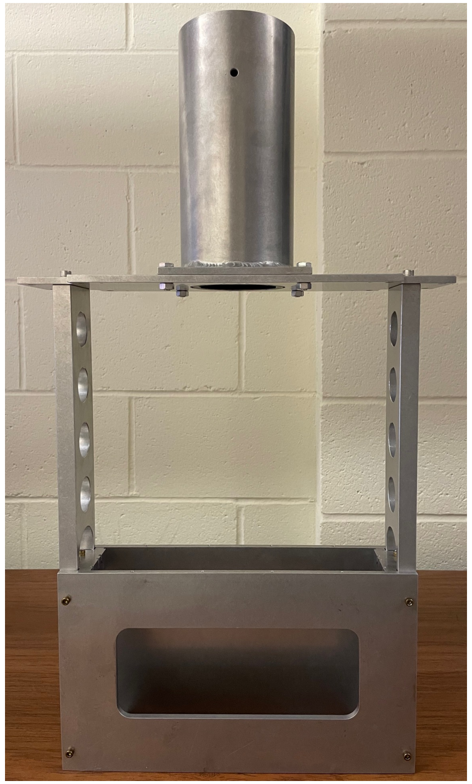
Modules staggered in z

Shower-max: Pre-production – Chassis parts

- Pre-production chassis parts recently received, inspected and assembled
- Only minor changes in chassis parts since last year’s prototype
  - removed all countersink screws and modified support strut base
- Also added the pmt can design



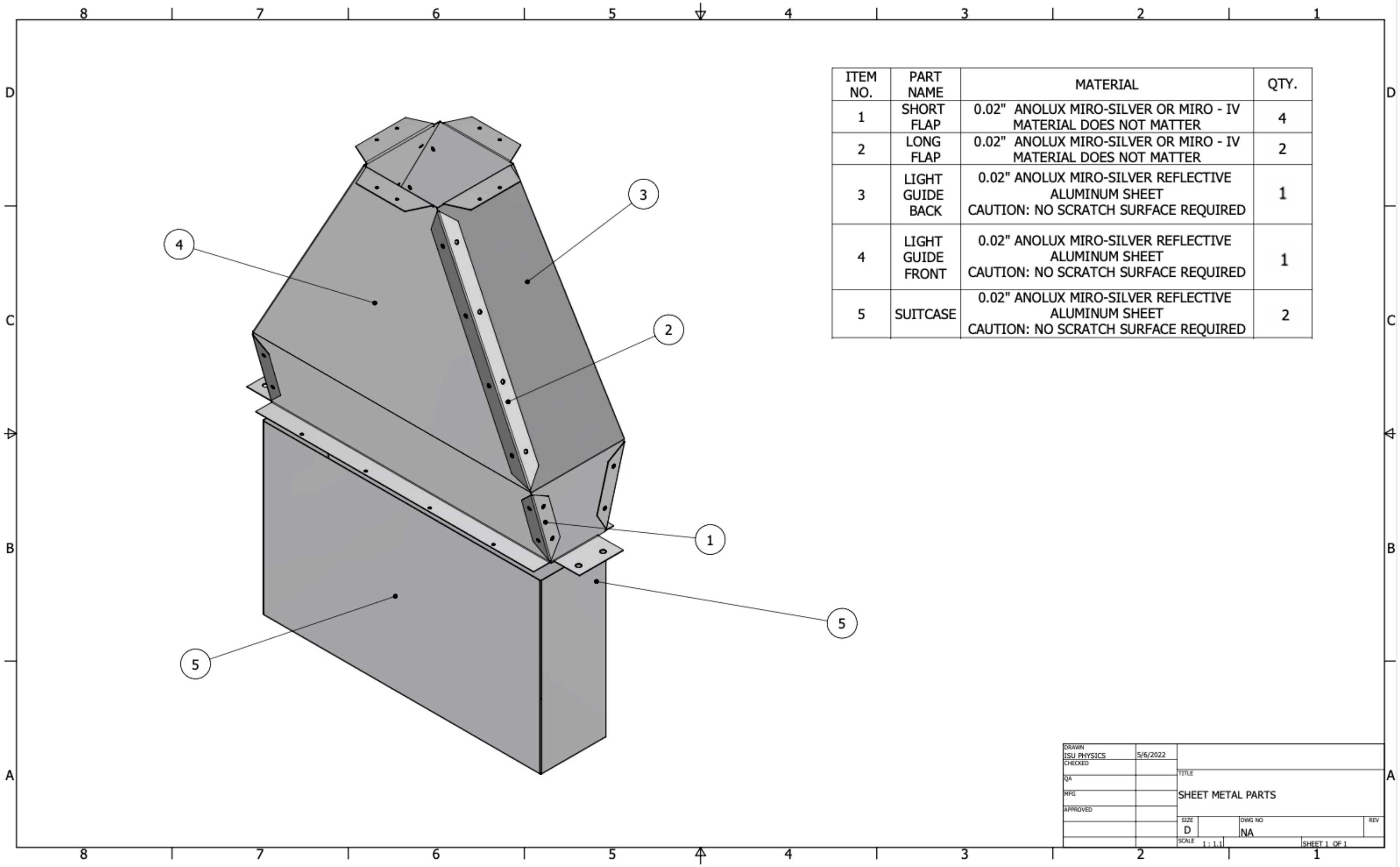
NO.	NAME	MATERIAL	QTY.
1	TOP PLATE	0.25 (1/4)" THICK 6061-T651 ALUMINUM PLATE	1
2	WEB PLATE	0.625 (5/8)" THICK 6061 ALUMINUM	2
3	FACE PLATE	0.25 (1/4)" THICK 6061-T651 ALUMINUM PLATE	1
4	BACK PLATE	0.25 (1/4)" THICK 6061-T651 ALUMINUM PLATE	1
5	RIGHT LEDGE	6061 ALUMINUM	1
6	LEFT LEDGE	6061 ALUMINUM	1
7	UPPER U CHANNEL	0.625 (5/8)" THICK 6061 ALUMINUM	2
8	LOWER U CHANNEL	0.625 (5/8)" THICK 6061 ALUMINUM	2
9	FLOOR	0.25 (1/4)" THICK 6061 ALUMINUM PLATE	2
10	PMT	4" OD. 3.75" (3-3/4)" ID 6061 ALUMINUM	1
11	PMT BASE	0.25 (1/4)" THICK 6061 ALUMINUM PLATE	1



Pre-production module chassis (assembled)

Shower-max Light Guide Parts

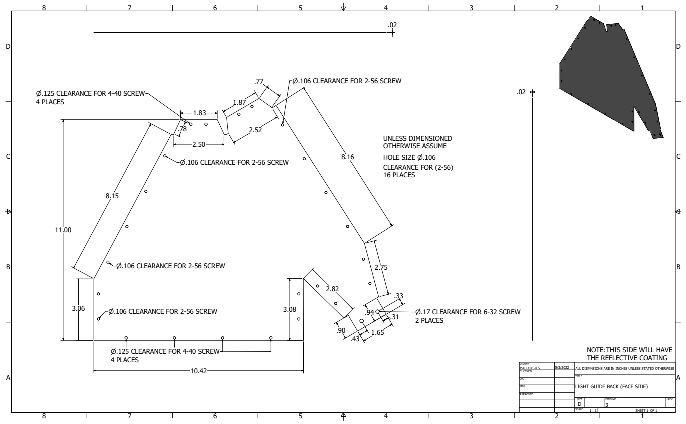
- Light guide parts fabricated using Anolux Miro IV



ITEM NO.	PART NAME	MATERIAL	QTY.
1	SHORT FLAP	0.02" ANOLUX MIRO-SILVER OR MIRO - IV MATERIAL DOES NOT MATTER	4
2	LONG FLAP	0.02" ANOLUX MIRO-SILVER OR MIRO - IV MATERIAL DOES NOT MATTER	2
3	LIGHT GUIDE BACK	0.02" ANOLUX MIRO-SILVER REFLECTIVE ALUMINUM SHEET CAUTION: NO SCRATCH SURFACE REQUIRED	1
4	LIGHT GUIDE FRONT	0.02" ANOLUX MIRO-SILVER REFLECTIVE ALUMINUM SHEET CAUTION: NO SCRATCH SURFACE REQUIRED	1
5	SUITCASE	0.02" ANOLUX MIRO-SILVER REFLECTIVE ALUMINUM SHEET CAUTION: NO SCRATCH SURFACE REQUIRED	2

DRAWN ISU PHYSICS 5/6/2022
CHECKED
QA
MFG
APPROVED
TITLE SHEET METAL PARTS
SIZE D
DWG NO NA
REV
SCALE 1 : 1
SHEET 1 OF 1

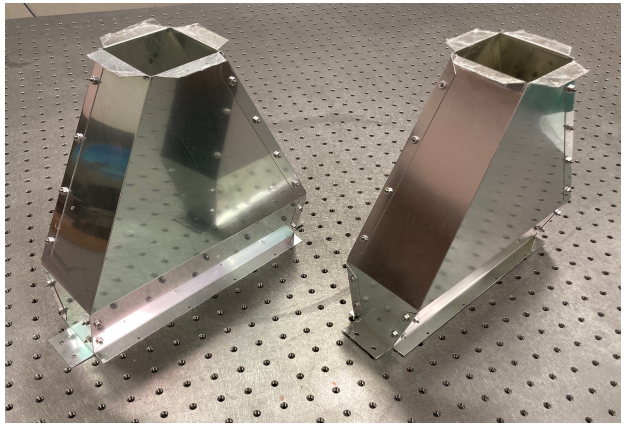
- CNC mirror sheet cut outs; 2 piece design; folded by hand



UNLESS DIMENSIONED OTHERWISE ASSUME
HOLE SIZE Ø.106
CLEARANCE FOR (2-56)
16 PLACES

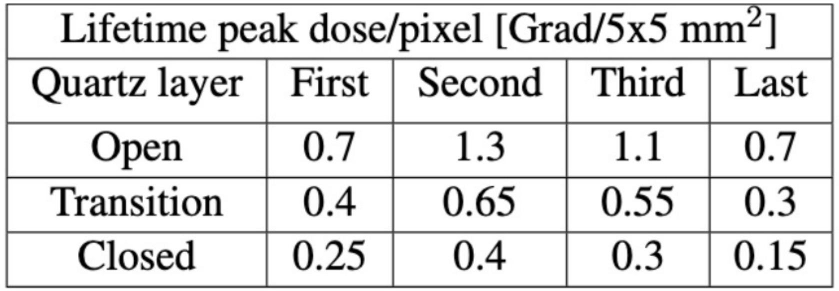
NOTE:THIS SIDE WILL HAVE THE REFLECTIVE COATING

DRAWN ISU PHYSICS 5/3/2022
ALL DIEMNSIONS ARE IN INCHES UNLESS STATED OTHERWISE
CHECKED
QA
MFG
APPROVED
TITLE LIGHT GUIDE BACK (FACE SIDE)
SIZE D
DWG NO 3
REV
SCALE 1 : 1
SHEET 1 OF 1



Risks and Mitigations

- Given the high rates on Shower-max and nature of the calorimeter, lifetime dose densities in the quartz layers are high:
  - ranging from 150 MRad to 1.3 Grad
  - dose accumulation in quartz increases UV light absorption causing progressive signal loss (Risk)



Lifetime peak dose/pixel [Grad/5x5 mm^2]				
Quartz layer	First	Second	Third	Last
Open	0.7	1.3	1.1	0.7
Transition	0.4	0.65	0.55	0.3
Closed	0.25	0.4	0.3	0.15

- The large PE yields of Shower-max combined with high rates leads to very high pmt cathode currents (Risk)

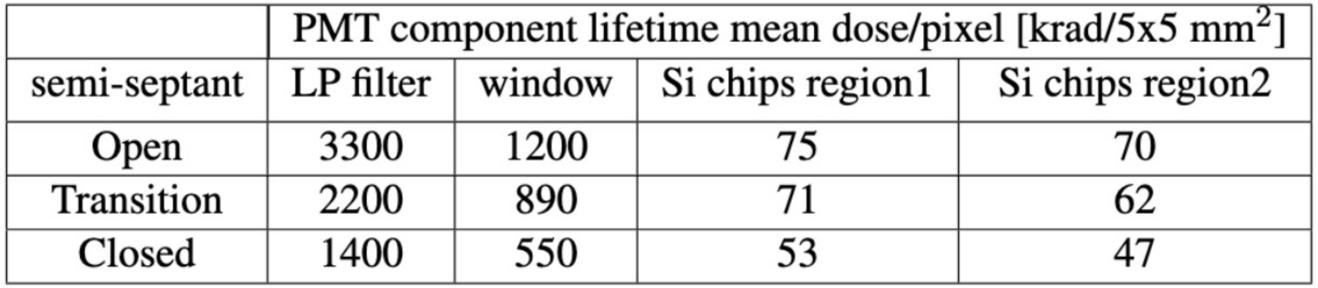
(Mitigation)

- Use longpass (LP) filters in front of pmts to eliminate the UV light contribution to signal thus reducing affects of radiation damage to quartz and lowering pmt cathode currents to reasonable levels

- Lifetime dose estimates in pmt and electronic components (Risk)

(Mitigation)

  - LP filters are corning 7980 HPFS
  - pmt windows are fused silica
  - We are radiation testing electronics for validation



	PMT component lifetime mean dose/pixel [krad/5x5 mm^2]			
semi-septant	LP filter	window	Si chips region1	Si chips region2
Open	3300	1200	75	70
Transition	2200	890	71	62
Closed	1400	550	53	47

2022 Prototyping and Testbeam; Pre-production Module Plans

- Assembled and tested a Shower-max prototype last year at Mainz during November testbeam run
  - Performed radial and azimuthal scans of signal uniformity across the detector face
  - Performed HV scans
  - Performed longpass filter study using a set of 2” diameter filters
  - Also repeated tests with quartz wrapped in aluminized mylar

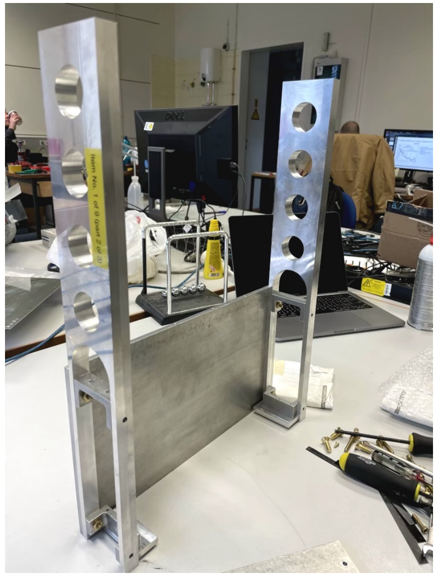
- Constructing a pre-production module and testing with cosmic-rays this month. Cosmic-ray test stand and daq system in place and ready to go. Light guides are last remaining parts to include and are in process

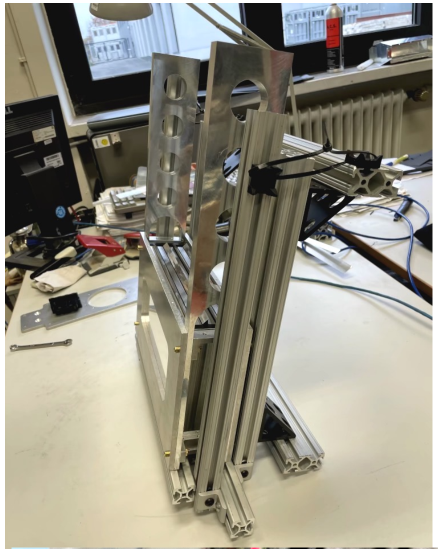
Goals for pre-production module (to be completed by Sept 2023):

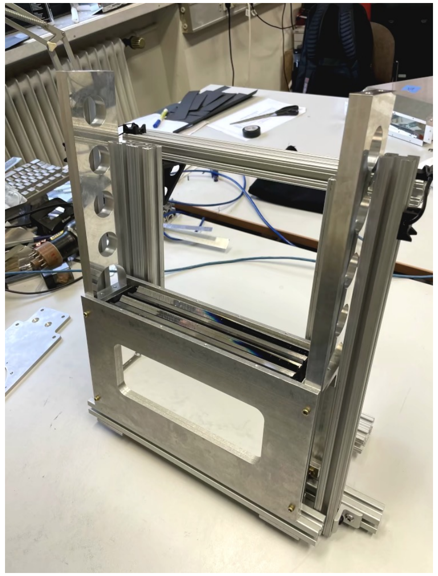
- Test mechanical fitment of final parts and benchmark cosmic-ray signal response
- Validate new quartz and polish from new vendor (Corning 7980 UV grade 5F from HYRDphotonics)
  - We’ve already performed prelim. QA radiation tests on samples from new vendor (and they passed)
- Test new “box” light guide design -- to reduce azimuthal variations seen in 2022 Testbeam results
- Test support bar design (mimic mounting of a horizontal module in the ring; measure deflections)
- Test new pmt can design incorporating 3” diameter longpass filters and gas flow

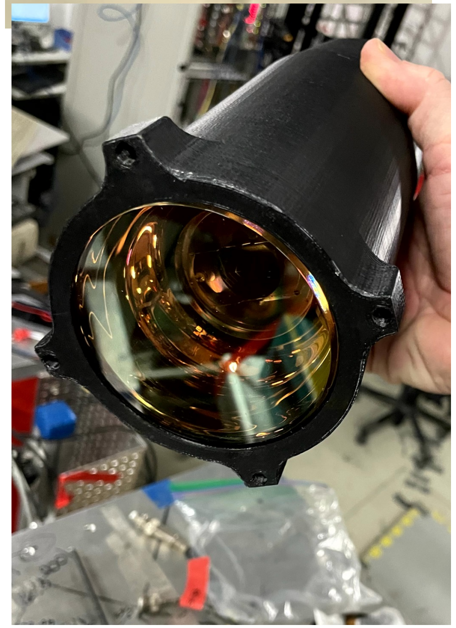
Shower-max: MAMI Testbeam (Nov 21 – 28, 2022)

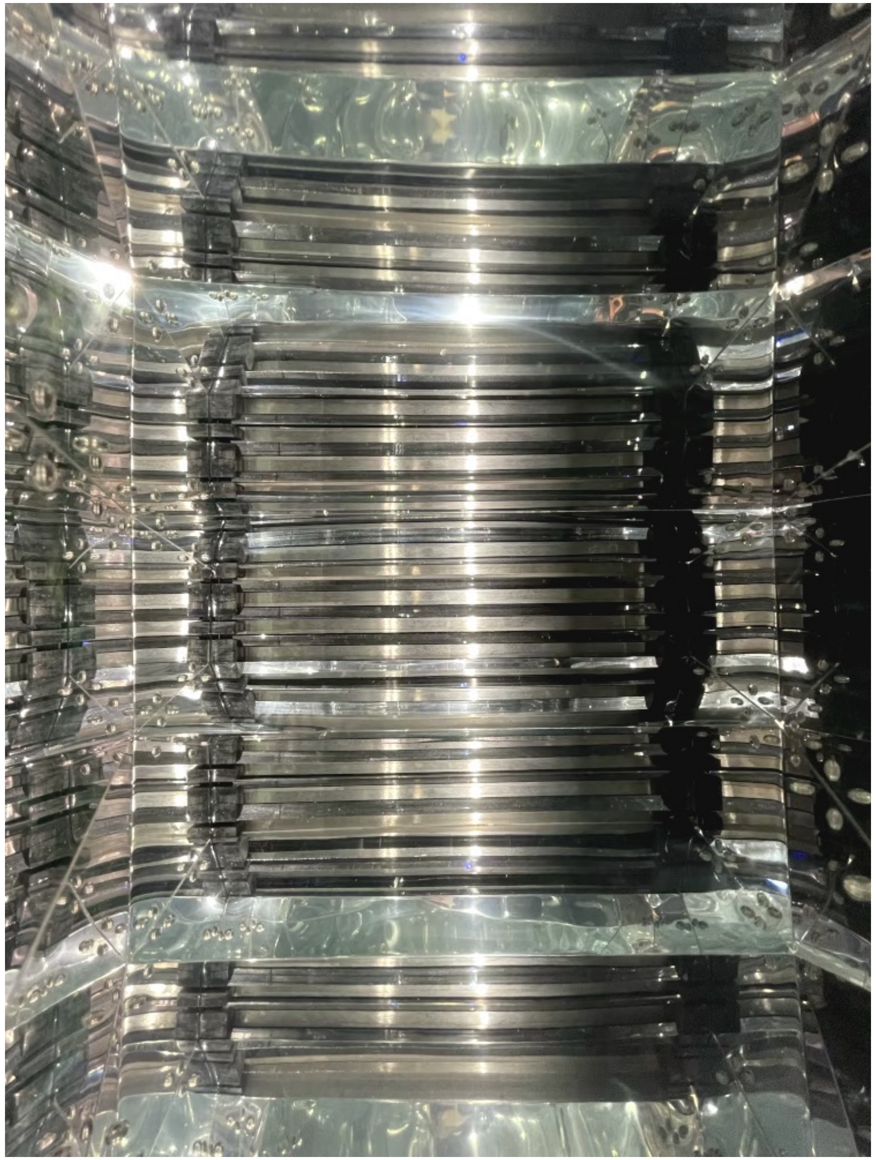
Assembly Photos









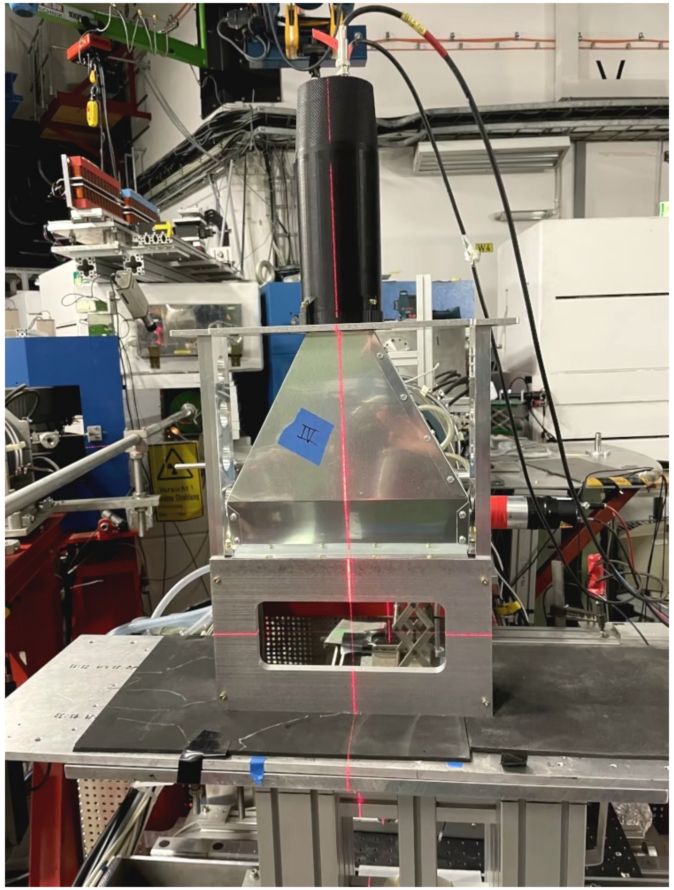


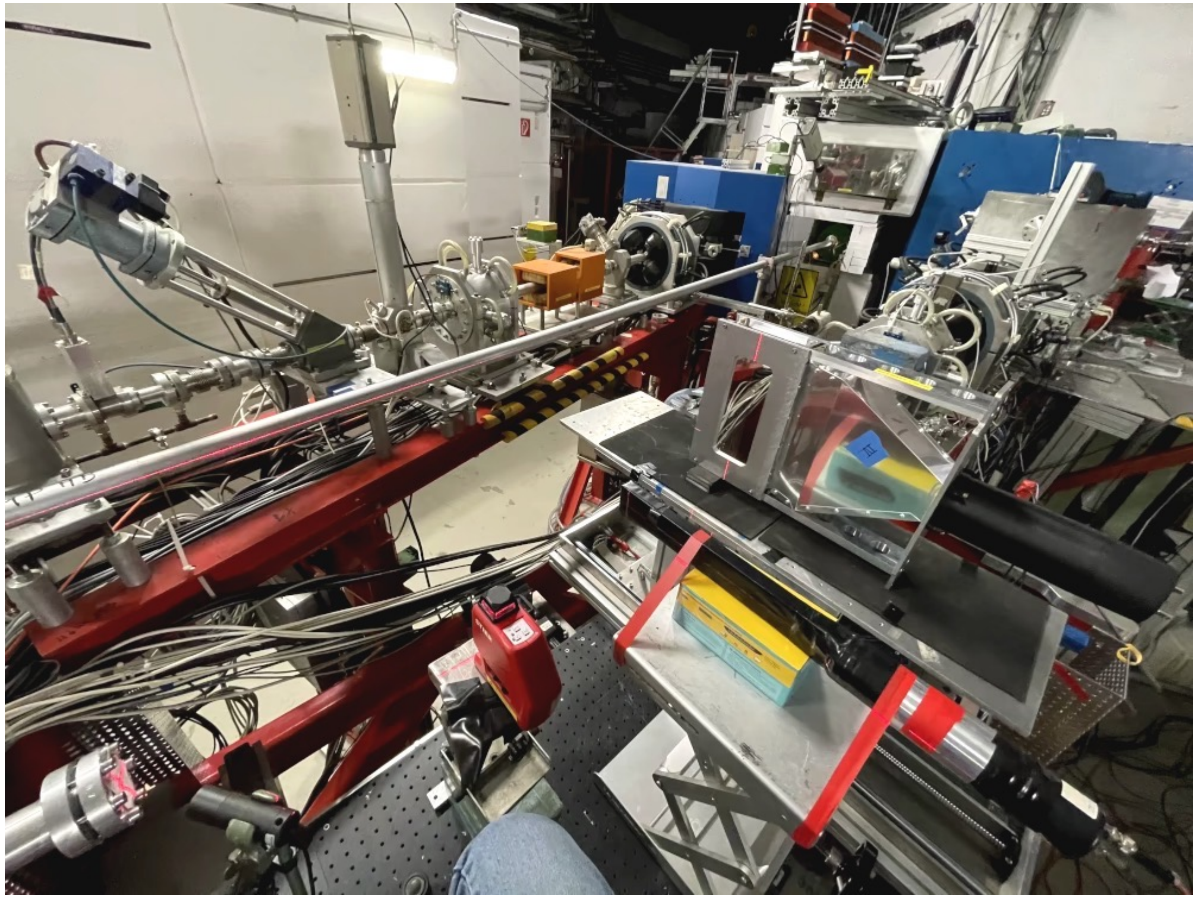
Shower-max: MAMI Testbeam Setup

Studies performed over 3 shifts:

- Azimuthal position scan
- HV scan with beam centered on stack
- Radial position scan, including scan along lightguide
- Longpass filter study – 280, 320, and 400nm
- Above tests were performed for both unwrapped (bare) quartz and aluminized-mylar wrapped quartz configs

Prototype tests performed using 855 MeV electron beam at MAMI

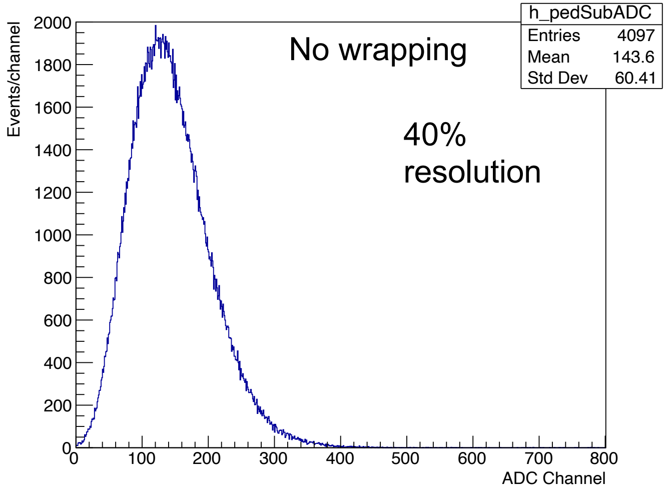




Shower-max Prototype Test Results (855 MeV electrons)

Pulse height Dists

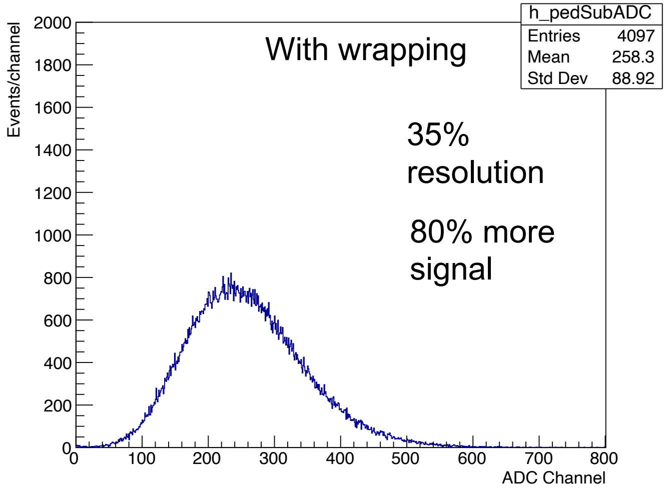
ADC distribution for run 18199



No wrapping

40% resolution

ADC distribution for run 17925



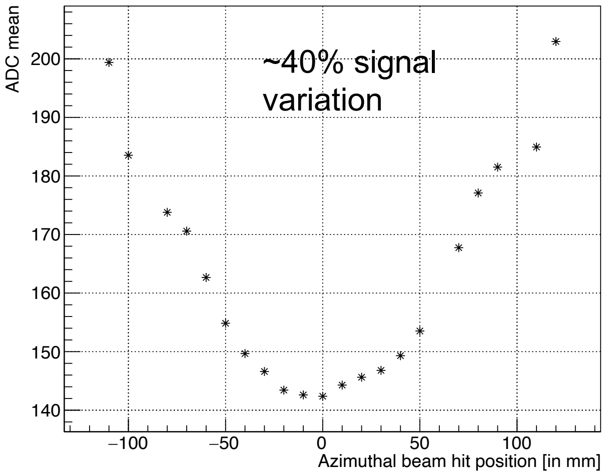
With wrapping

35% resolution

80% more signal

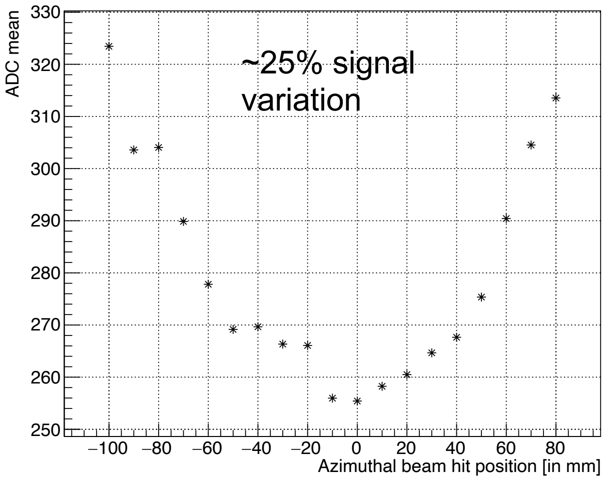
Azimuthal Scans

azimuthal scan in the shower-max



~40% signal variation

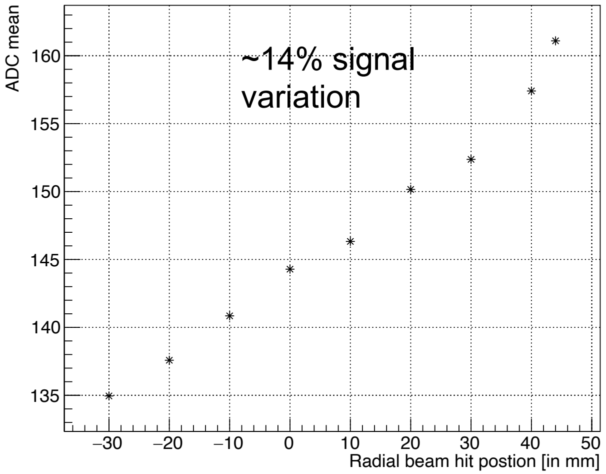
azimuthal scan in the shower-max



~25% signal variation

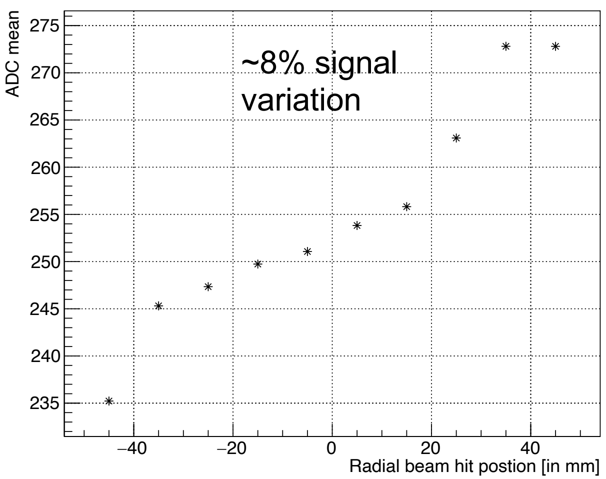
Radial Scans

radial scan in the shower-max



~14% signal variation

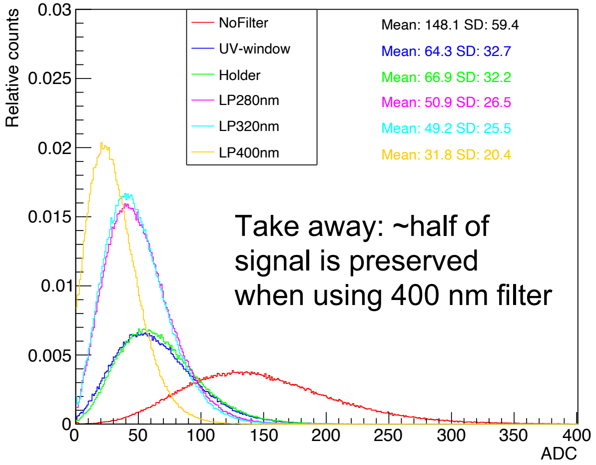
radial scan in the shower-max



~8% signal variation

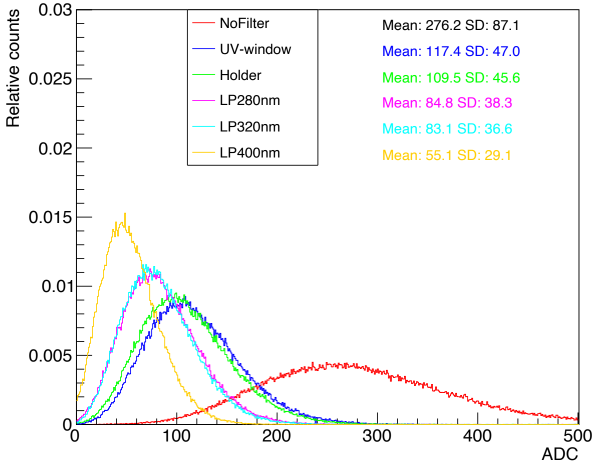
Filter Studies

LP Filter response: bareQuartz



Take away: ~half of signal is preserved when using 400 nm filter

LP Filter response: wrapQuartz



ES&H

- Radioactive material/radiation: – All workers have ISU radiation safety training -- https://www.isu.edu/radiationsafety and several also have JLab rad-worker I training
- Electronics/electrical: – Working with common tools (e.g. potential for cutting) – implement best practices
  – Soldering may be necessary – implement electrical and on the job training for workers
- Hazardous materials (including chemicals, lead): –Lead is not handled or moved around by anyone without training
  –All ISU labs have Chemical Safety Plan with SOPs (we use Isopropyl Alcohol for cleaning)
- Structural (including weldments): – Working with common tools as well as Shop tools; workers must pass Machine Shop Safety course for any tools used; all welding needs are outsourced to qualified vendors
- Pressure systems: – We follow Jlab pressure system safety protocols (for our GEMs in cosmic stand). Gas systems are designed with over-pressure relief valves that limit maximum pressure to 30 psi
- Gas (including flammable gas): – We use non-flammable gases – dry air, nitrogen, and Argon/CO2 standard weld mixes
- Cryogenics (ODH): – No cryogenics are used
- Personnel access (elevated work, confined space): – All ladder use requires training
- Material handling (lifting devices, load testing): – Heavy detector modules require training to handle (possible hoisting and rigging training)

ES&H and Quality Assurance

- All activities and deliverables in accord with Jlab ES&H guidelines and Jlab's Integrated Safety Management System https://www.jlab.org/esh/eshhome
- All institutional EH&S rules are followed (Idaho State University EH&S: https://www.isu.edu/ehs/)

QA/QC considerations:

- Basic metrology will be applied to all received Shower-max parts (aluminum, tungsten, and quartz); assembly fitment is most important test
- Quartz samples for radiation testing will be acquired from manufacturer production ingots or batches
- PMT and electronics quality/function checks (possibly quick gain and/or non-linearity measurement to validate)
- Light guides will be folded and prepared by qualified individual using custom fixtures and following detailed procedures for consistency
- Module assembly procedures and instructions document will be developed and followed
- Module testing and validation procedures document will also be developed

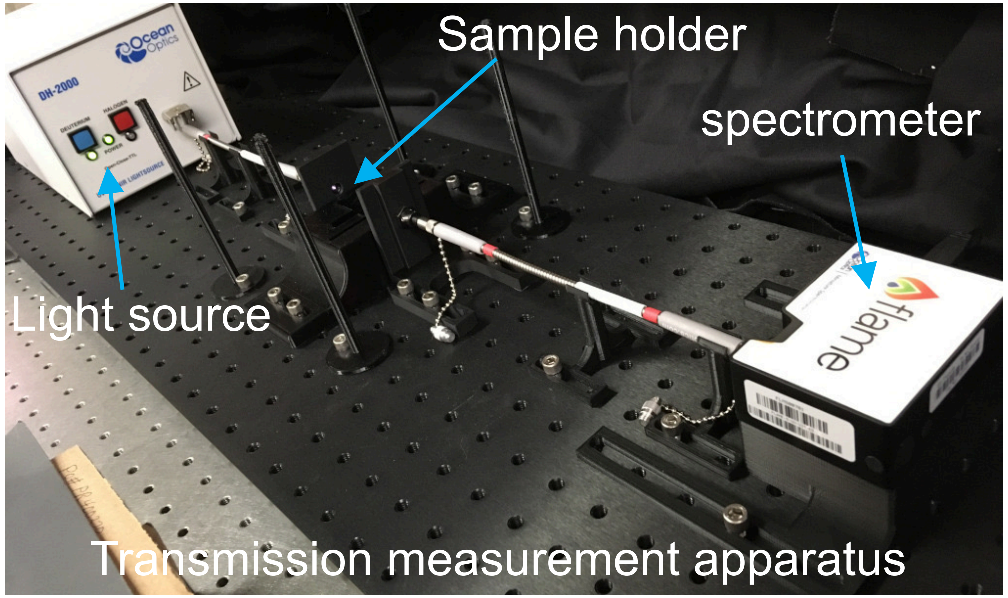
Shower-max Summary

- Shower-max prototype parts fabrication, module assembly and testing went extremely well. MAMI testbeam results validated design, construction, and function
- Testbeam results also validated optical simulation framework; we will use local cosmic-ray testing for validating function and performance of each assembled module
- There have been a few minor tweaks to the chassis and light guide parts based on prototyping experience; these changes are incorporated into final design Shop Drawings
- All pre-production module parts/components have been tested and large order costs updated
- Risks and mitigation strategies have been identified. Using longpass filters eliminates UV light from signal while reducing pmt cathode currents to acceptable levels; the exact filter settings are being determined
- Implementing pmt non-linearity characterization bench tests using full MOLLER readout electronics chain
- **Plan to start parts procurement for construction of all Shower-max modules in late summer/early fall 2023**

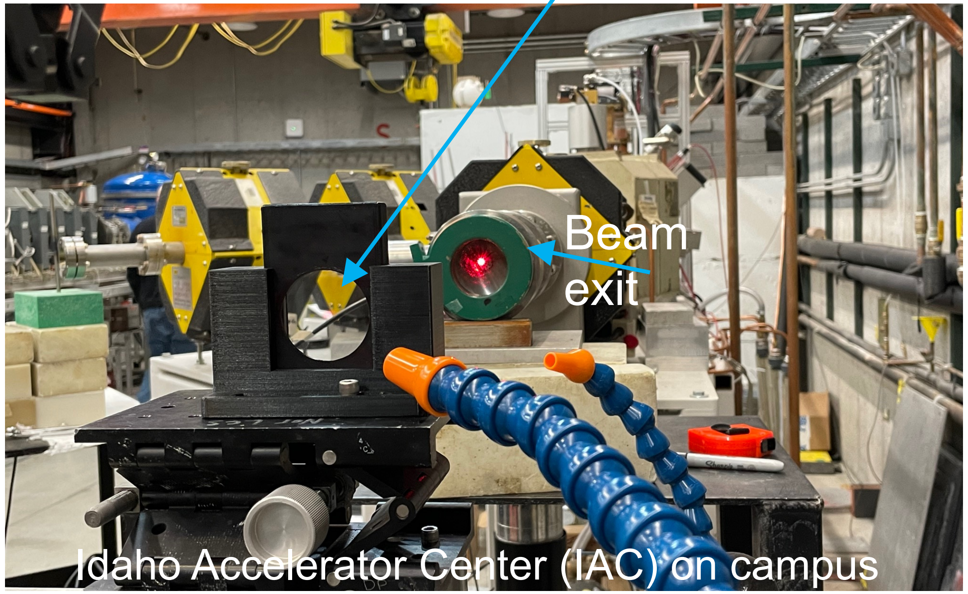
Quartz Radiation Hardness Study (completed)

- Goal: quantify light transmission losses in detector radiators due to damage from anticipated radiation dose (for lifetime of MOLLER) – 45 MRad peak and 120 MRad peak per 5x5 mm^2 for ring 5 and ring 2, respectively
- Five candidate fused silica (quartz) samples chosen for testing: from Corning, Ohara, and Heraeus
- Irradiations conducted at the Idaho Accelerator Center using 8 MeV pulsed electron beam, ~40 mA peak current, ~1 μs pulse width (~40 nC/pulse) at 200 Hz repetition rate; samples are 50 cm from beam exit window
- Dose deposition quantified with G4 simulation benchmarked to beam dose profile and source measurements
- Work by Justin Gahley; report in [docDB #886]

Samples: 5 cm diameter or square, 1 cm thick; polished faces



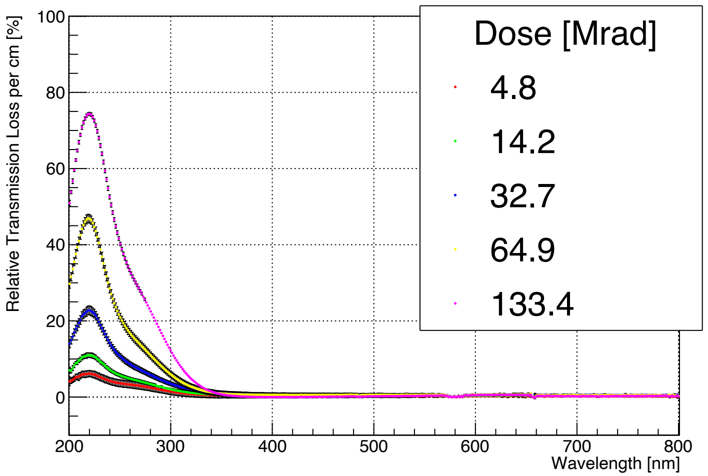
Transmission measurement apparatus



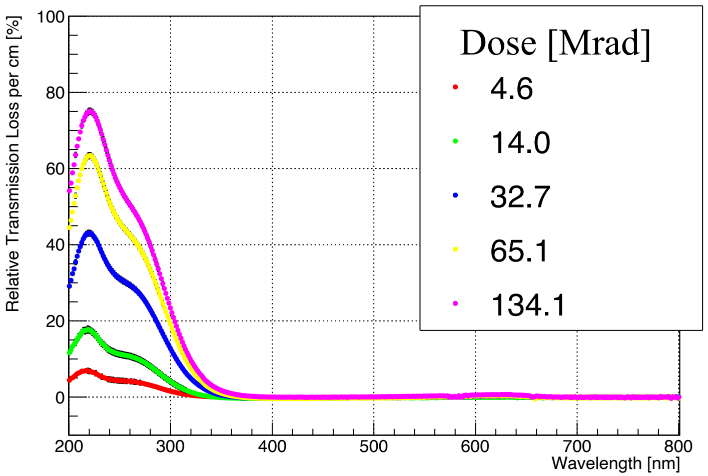
Idaho Accelerator Center (IAC) on campus

Quartz Radiation Hardness Results: Light Loss

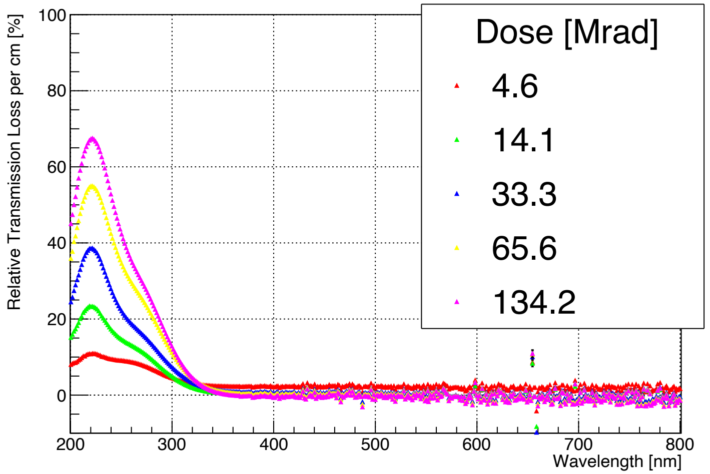
Corning 7980 UV Homogeneity Grade F



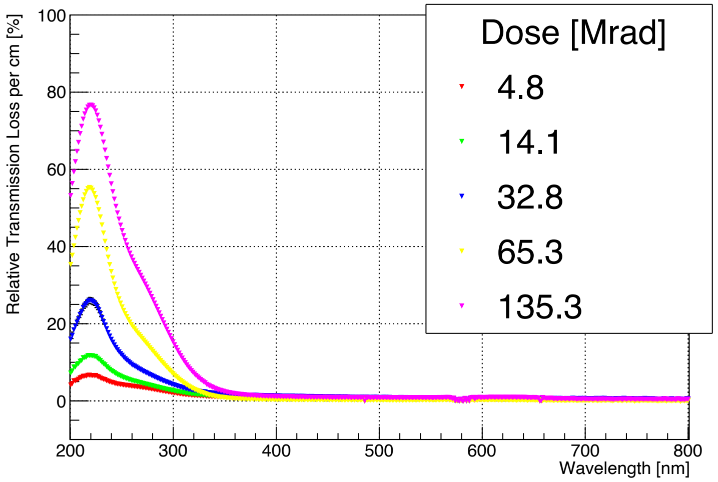
Heraeus Spectrosil 2000 Standard



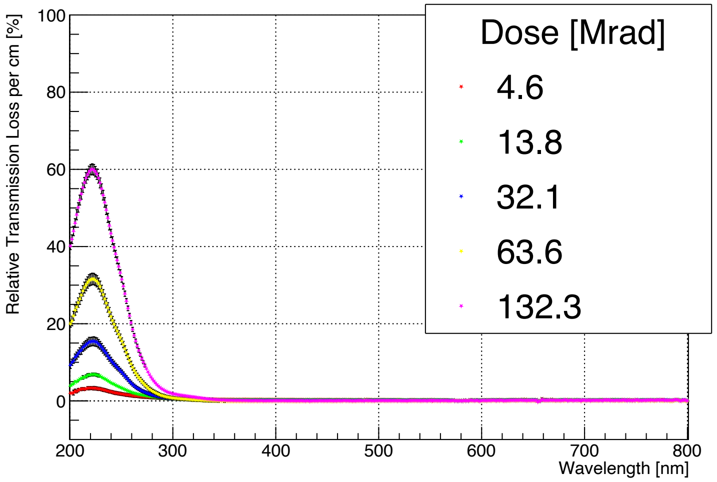
O'Hara SK-1300



Corning 7980 ArF Excimer



Heraeus Spectrosil 2000 High H2



--All samples are wet (> 200 ppm OH content), except SK-1300 which is dry; doped Heraeus has high OH and high H2 content

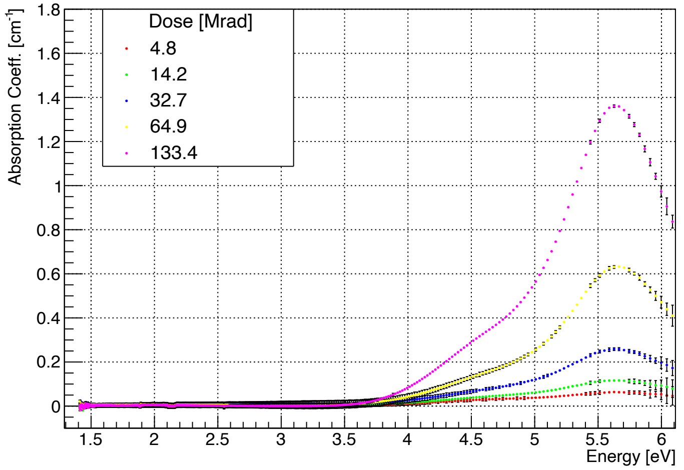
--Main absorption center at 5.6 eV is the E' – unavoidable point-like defects that cause dangling Si atoms which absorb light

--The shoulder structures are from non-binding hydroxide absorption centers around 4.5 – 5 eV

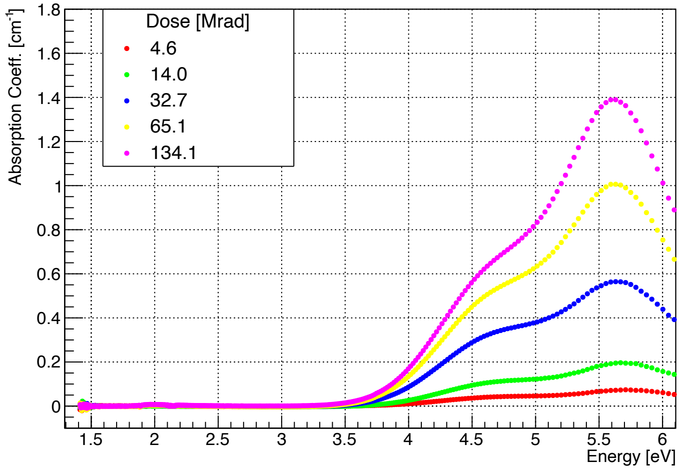
--the high H_2 doped Heraeus shows very little of this damage center at our doses

Quartz Radiation Hardness Results: Absorption Coeff’s

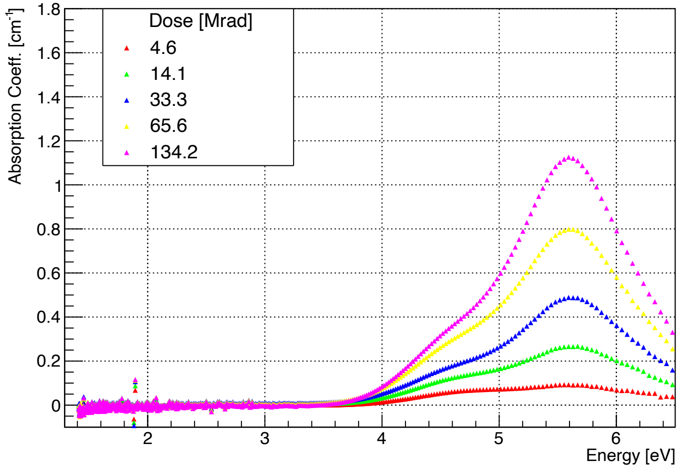
Corning 7980 UV Homogeneity Grade 5F



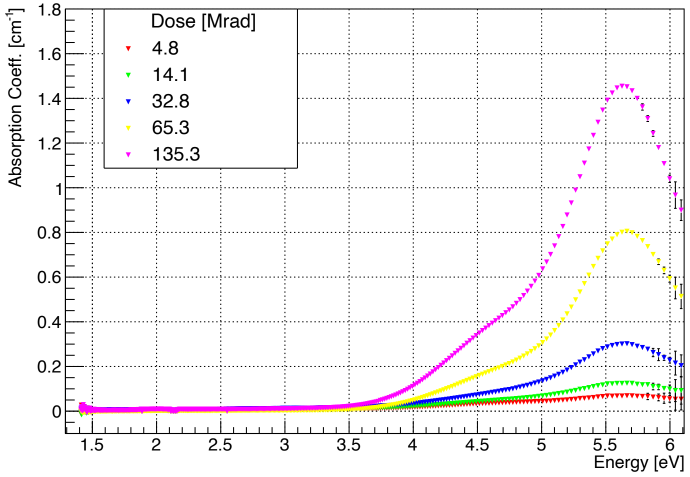
Heraeus Spectrosil 2000 Standard



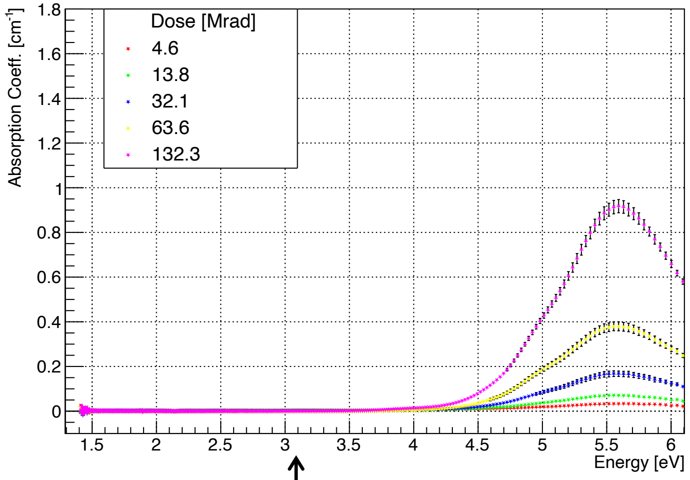
O'Hara SK-1300



Corning 7980 ArF Excimer



Heraeus Spectrosil 2000 High H2



↑
400 nm

--All samples are wet (> 200 ppm OH content), except SK-1300 which is dry; doped Heraeus has high OH and high H2 content

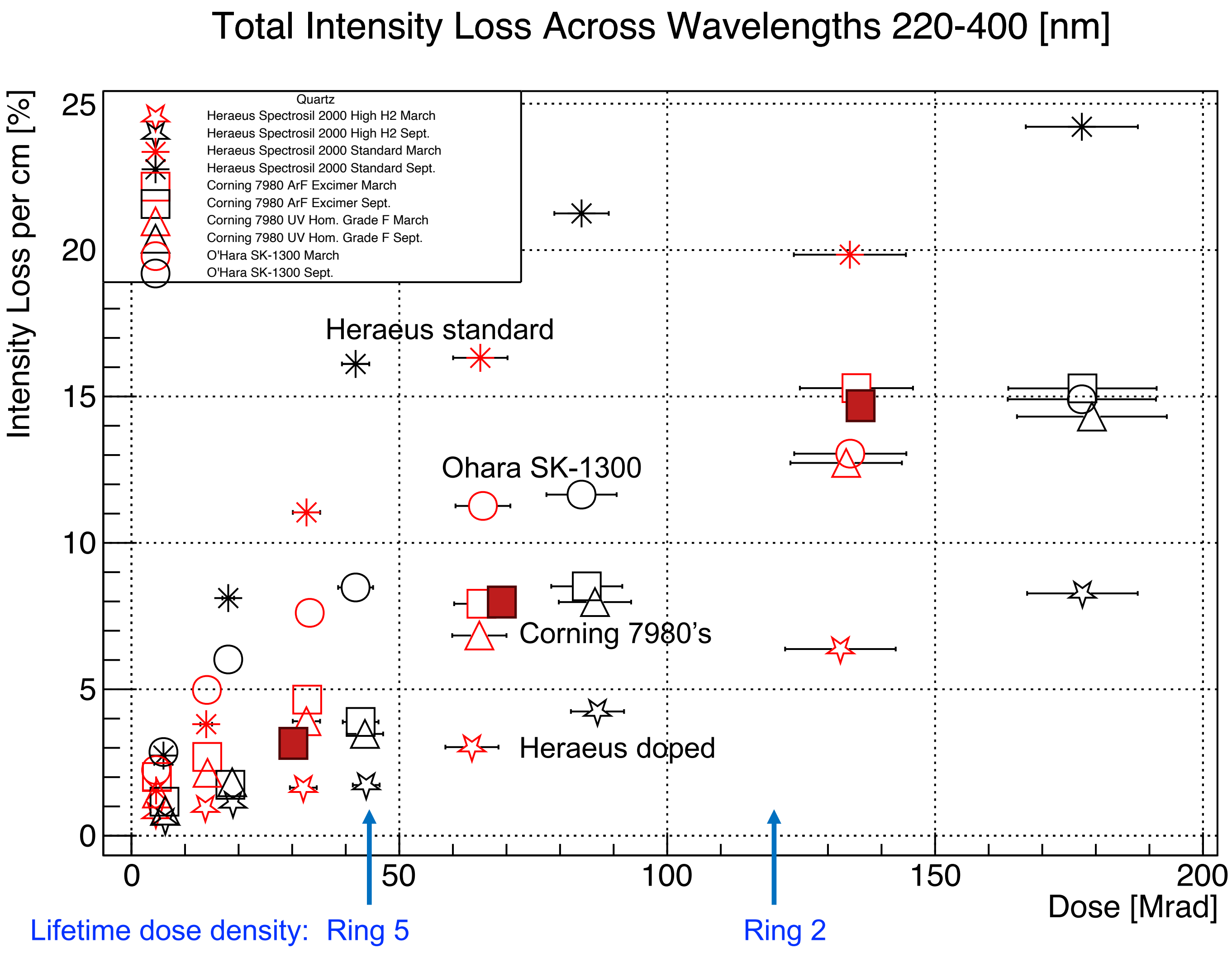
--Main absorption center at 5.6 eV is the E’ – unavoidable point-like defects that cause dangling Si atoms which absorb light

--The shoulder structures are from non-binding hydroxide absorption centers around 4.5 – 5 eV

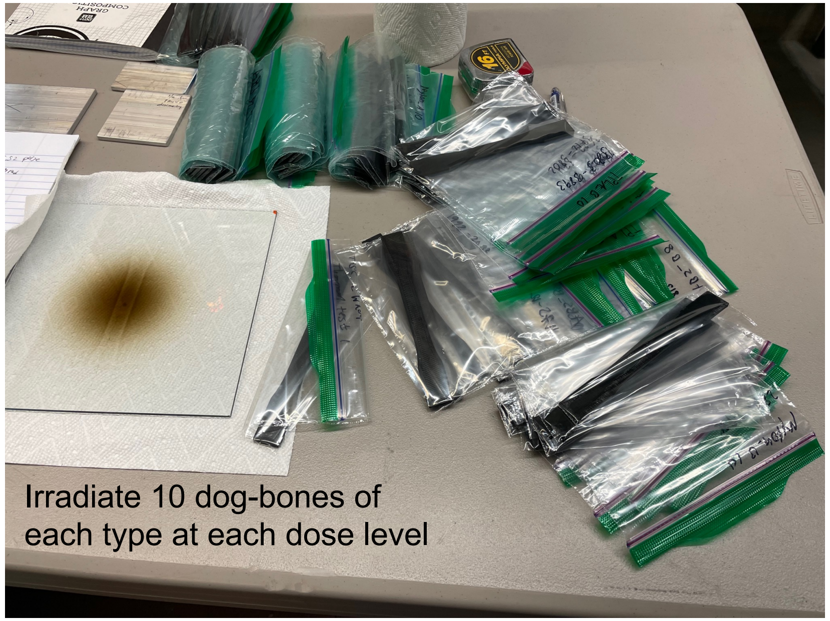
--the high H_2 doped Heraeus shows very little of this damage center at our doses

Quartz Radiation Hardness Summary

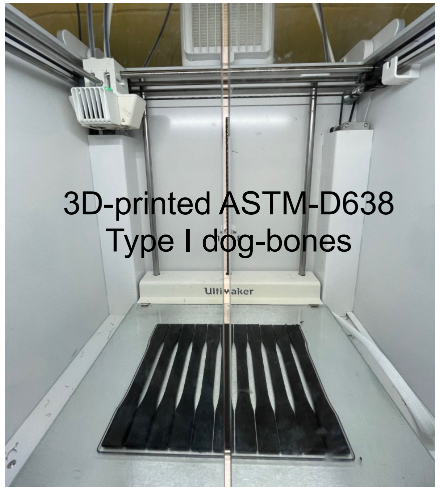
- Quartz radiation damage study completed; the data needed to inform our optical simulations is in hand
- Dose estimates for radiation tests are at 10% precision level
- Heraeus high H_2 doped Spectrosil 2000 is best performing (clearly) – ~no shoulder structure in losses.
- Heraeus standard sample is worst performing – it has greatest light loss above 15 - 20 MRad dose
- We tested 2” LP filters made with Corning 7980 to ~10 MRad; we observed no measurable transmission loss
- Have 3” LP filters, also Corning 7980 (two each: 350 and 400 nm) for Shower-max testing
- Recently QA tested Corning 7980 samples from new vendor (🟥)



3D-printed Plastic Radiation Hardness Study (~completed)

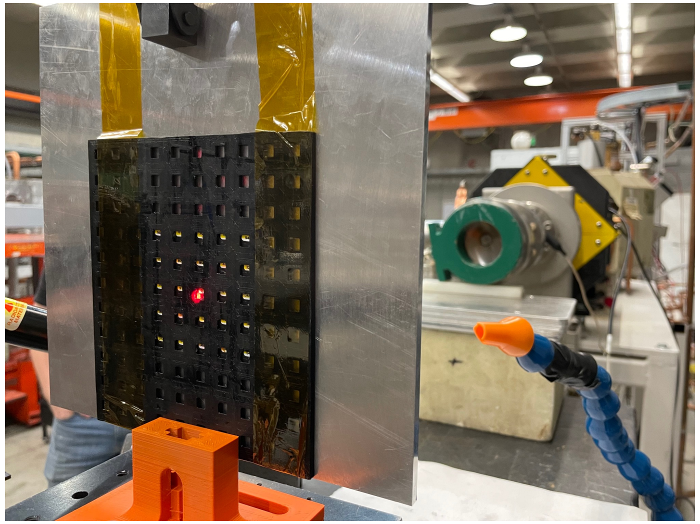


Irradiate 10 dog-bones of each type at each dose level

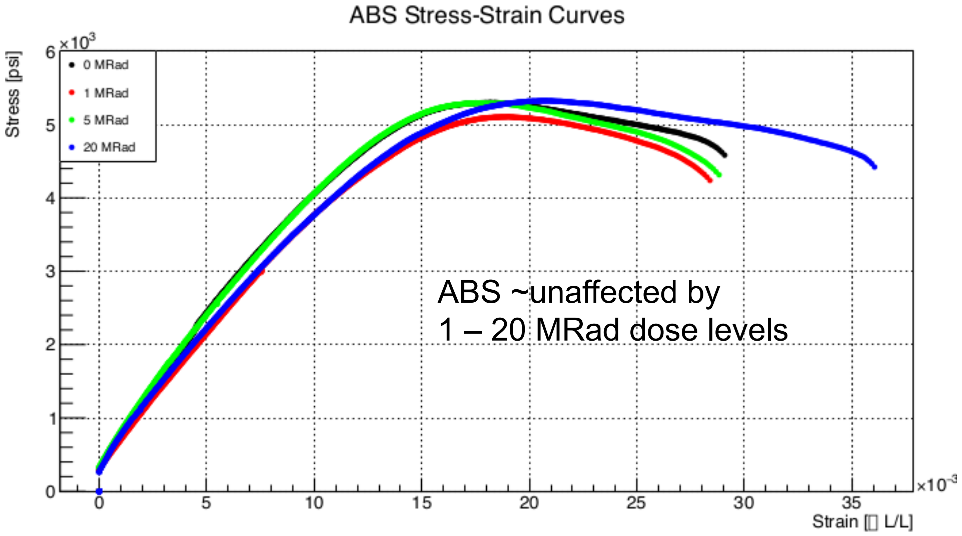


3D-printed ASTM-D638 Type I dog-bones

Nanodot OSL array beam dosimetry

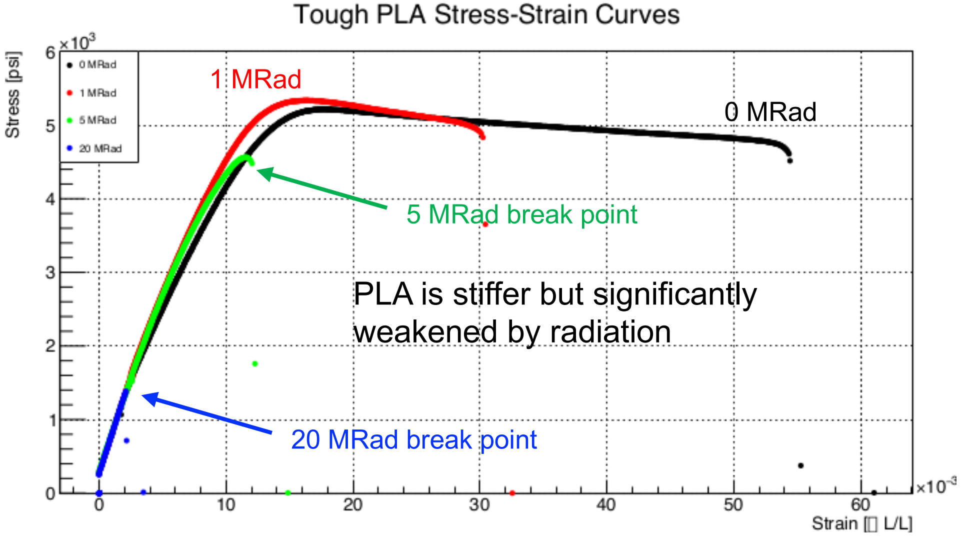


Tensile strength testing apparatus



ABS Stress-Strain Curves

ABS ~unaffected by 1 – 20 MRad dose levels



Tough PLA Stress-Strain Curves

5 MRad break point

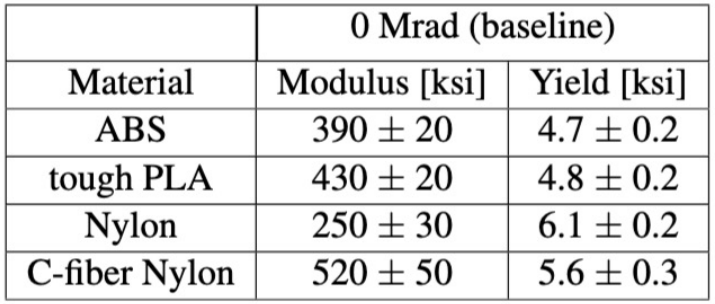
PLA is stiffer but significantly weakened by radiation

20 MRad break point

3D-printed Plastic Radiation Hardness Results

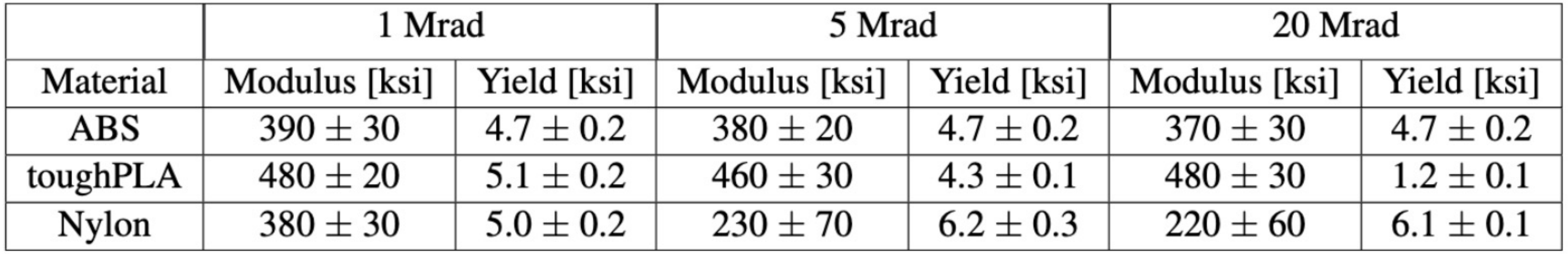
Preliminary results for
3D-printed plastics:

- Tensile strength results for non-irradiated plastic



	0 Mrad (baseline)	
Material	Modulus [ksi]	Yield [ksi]
ABS	390 ± 20	4.7 ± 0.2
tough PLA	430 ± 20	4.8 ± 0.2
Nylon	250 ± 30	6.1 ± 0.2
C-fiber Nylon	520 ± 50	5.6 ± 0.3

- Results following irradiations:
  - PLA has high stiffness but is weakened by radiation
  - Nylon has low stiffness and is not weakened by dose
  - ABS is least affected by radiation



	1 Mrad		5 Mrad		20 Mrad	
Material	Modulus [ksi]	Yield [ksi]	Modulus [ksi]	Yield [ksi]	Modulus [ksi]	Yield [ksi]
ABS	390 ± 30	4.7 ± 0.2	380 ± 20	4.7 ± 0.2	370 ± 30	4.7 ± 0.2
toughPLA	480 ± 20	5.1 ± 0.2	460 ± 30	4.3 ± 0.1	480 ± 30	1.2 ± 0.1
Nylon	380 ± 30	5.0 ± 0.2	230 ± 70	6.2 ± 0.3	220 ± 60	6.1 ± 0.1

- We also recently tested several other plastic materials (analysis is ongoing):
  - Onyx, Ultrasint PA11, Carbon-fiber ABS (dry and wet), and PEEK
  - Radiation dose affects wet samples more than dry, but modulus and yield still sufficient for MOLLER
  - Preliminary result is that Onyx and Ultrasint are rad-hard (up tp 50 MRad), but moduli are lower than other materials tested (we are investigating if this material is still sufficient)

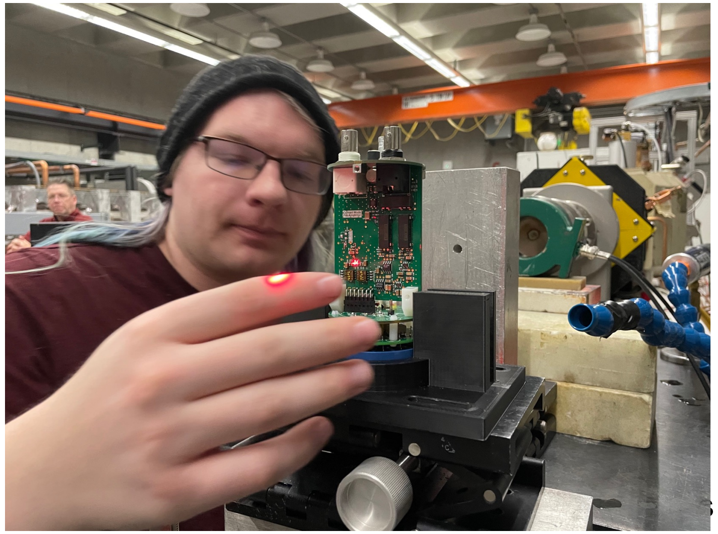
PMT electronics Radiation Hardness Study (ongoing)

➢ Lifetime dose levels on main detector and shower-max pmt electronics is ~60 – 70 kRad

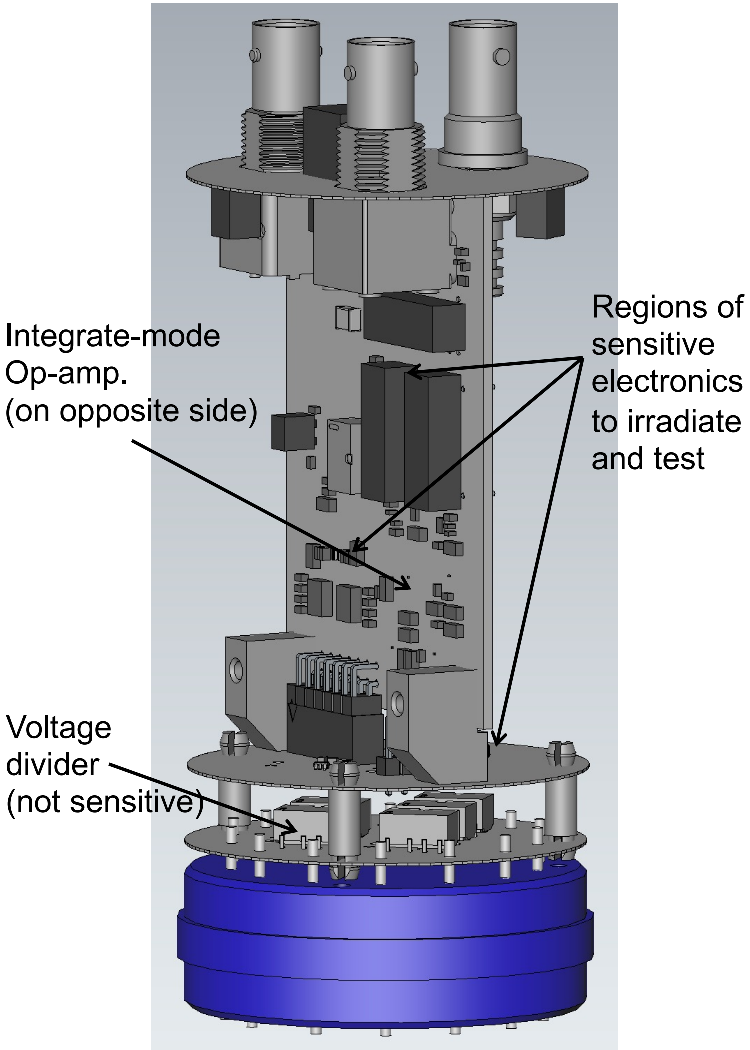
Initial tests took place last December, with follow-up runs this spring and summer

- Beam dose per pulse lower by ~50x compared to plastic and quartz studies
- Irradiated two different regions of the PMT base electronics: both survived to several hundred kRad
  1. the integrate-mode op-amp chip (small aerospace grade chip)
  2. set of three DC-DC converters used for both DAQ modes
- Collimators were used to localize beam dose on specific chips
- Functionality tested in between successive doses

  --Following each dose, we attached base to a PMT and exposed cathode to set of light levels (2, 5, 20, and 27 nC) -- tested gain and signal quality using MOLLER ADC



PMT electronics



Integrate-mode
Op-amp.
(on opposite side)

Regions of
sensitive
electronics
to irradiate
and test

Voltage
divider
(not sensitive)

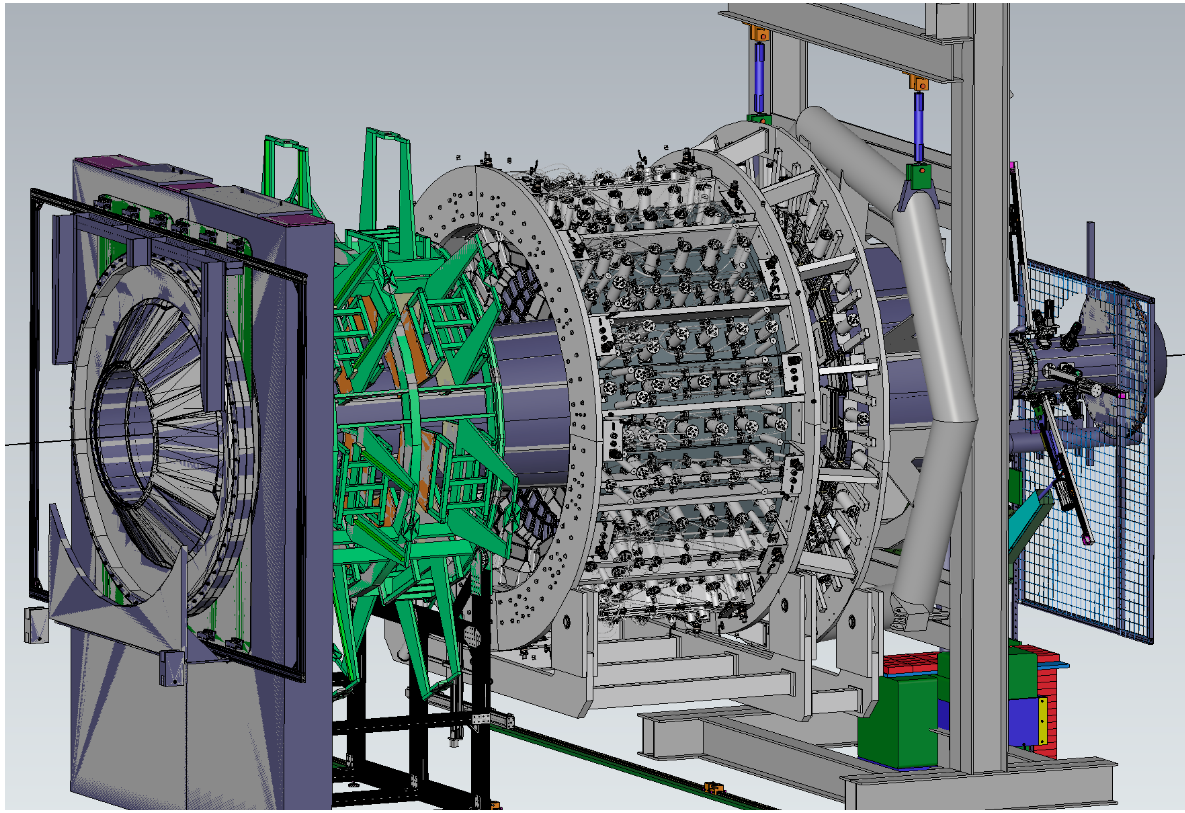
Plastics and Electronics Radiation Hardness Summary

- Plastic irradiation studies nearly complete. We recently tested several filament materials: Onyx® (carbon-nylon), Ultrasint PA11 (castor-oil based laser-sintered material), and carbon fiber (CF) ABS with different moisture content
- Observed trend is that filaments with higher extrusion temperatures are more radiation hard; ABS has not shown any radiation effects up to 50+ MRad dose
- Tensile strength measurements quantify stiffness and strength of the various printed plastics informing deflection analyses of the CAD model and our choice of material
- There are several options for 3D printed plastics that are sufficiently radiation resistant for MOLLER; CF-ABS is the material of choice for the main detector quartz trays
- Electronics radiation testing in progress. So far we have tested main integrating op-amp, original DC-DC converter chip sets, and relay. Preliminary results in general very promising
- Plan to test other sensitive chips later this month: alternative DC-DC converter, voltage regulators, and event-mode amplifier chips (plan to dose very slowly to better mimic experiment)
- Summary documents in progress and will be posted in the Document DB

Shower-max and Radiation Hardness Studies

D. McNulty
mcnulty@jlab.org

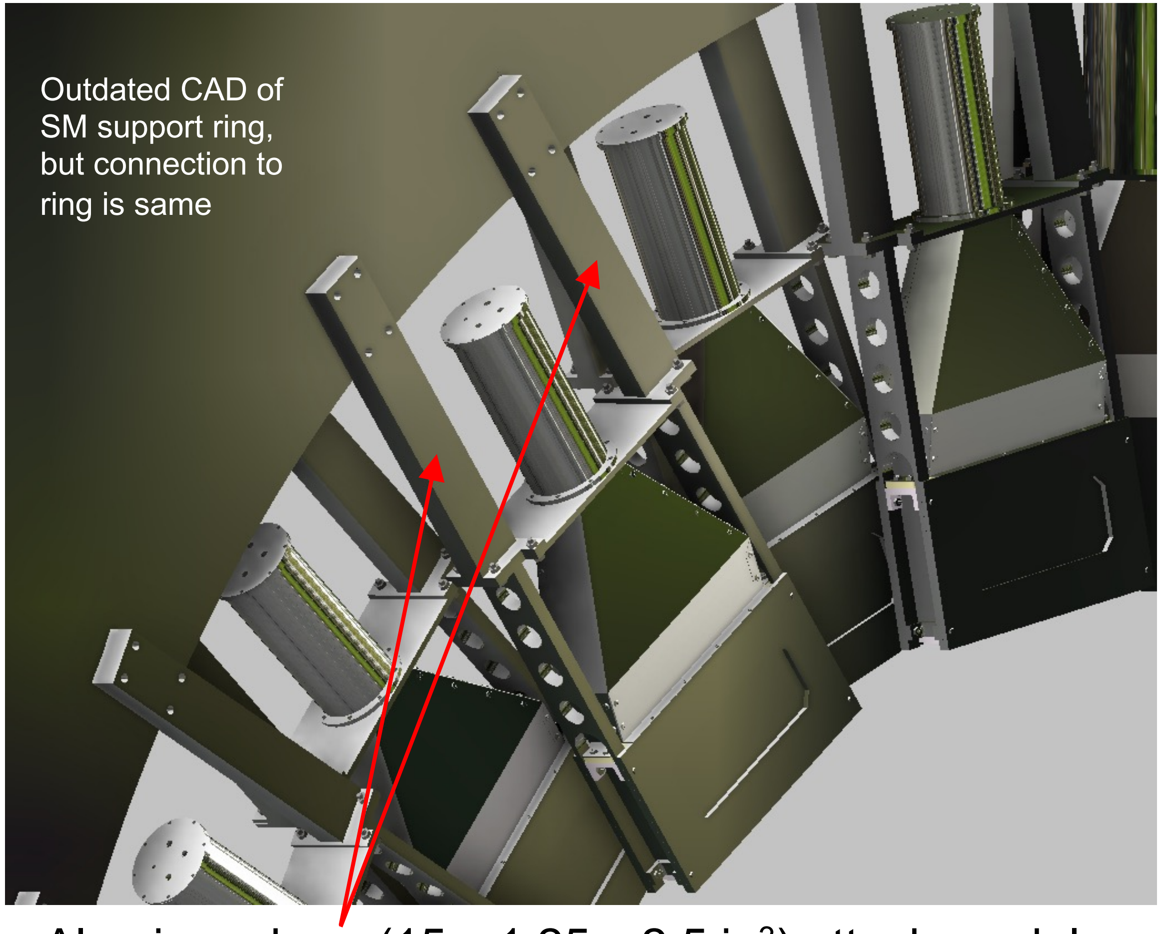
- Shower-max overview
- Design and Engineering
- Prototyping, Testbeam and Pre-production Plans
- Risks and Mitigation
- ES&H and Quality Assurance
- Radiation Hardness Studies: Quartz, Plastic and pmt Base Electronics
- Summary



Questions?

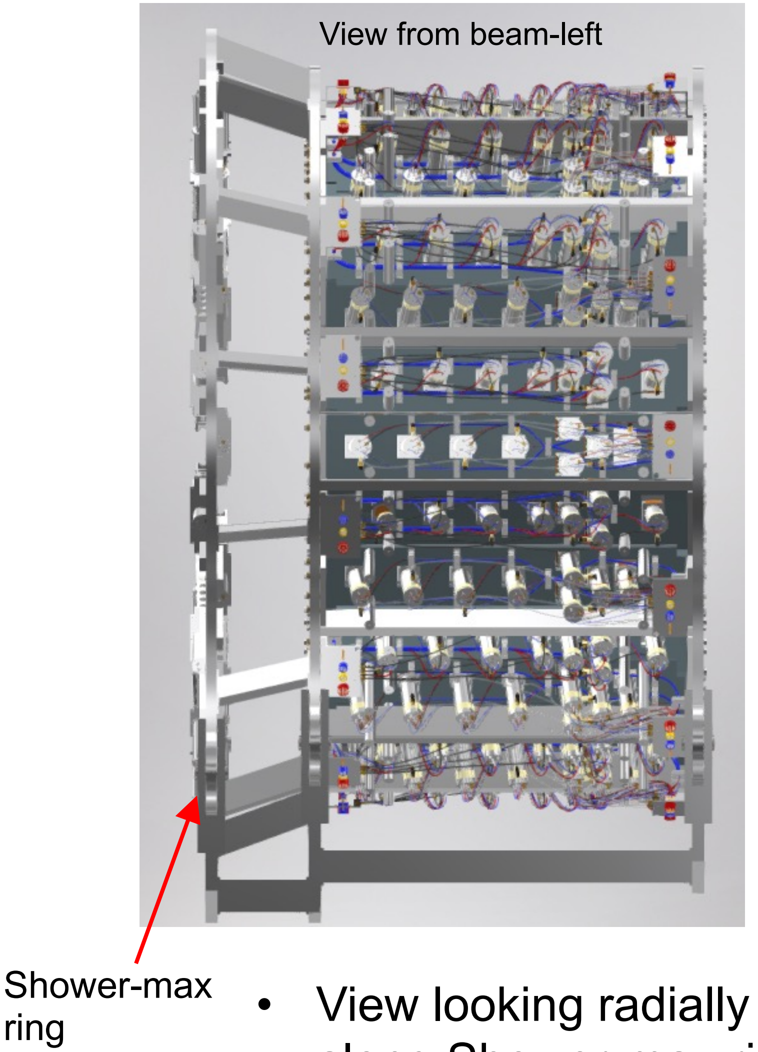
Appendix Slides

Shower-max Ring Support Structure



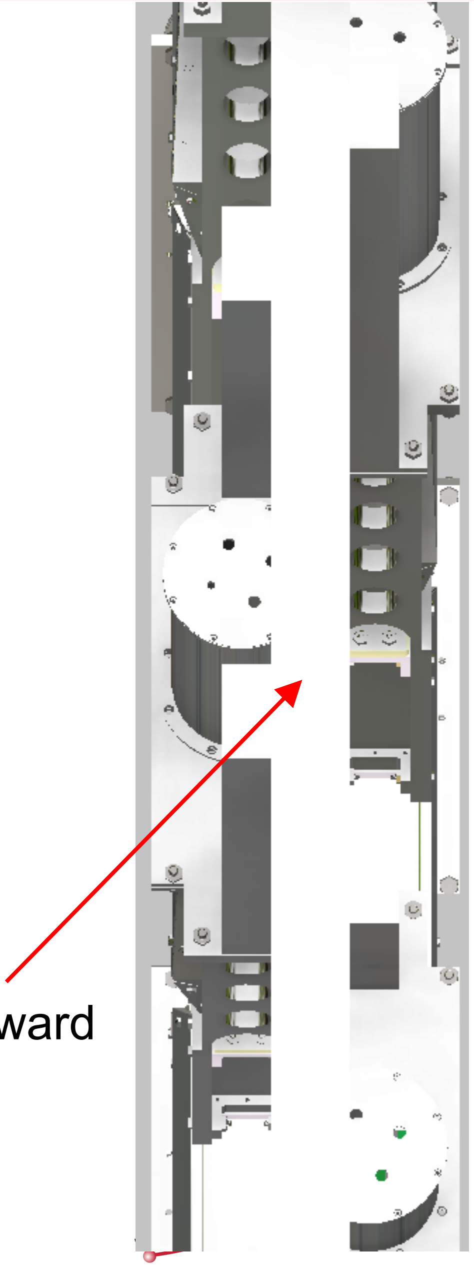
Outdated CAD of SM support ring, but connection to ring is same

- Aluminum bars (15 x 1.25 x 2.5 in^3) attach modules to ring structure--which is 2 inch thick (along z)
- Staggered modules are mounted to US and DS face of support ring (in alternating pattern)



View from beam-left

Shower-max ring



- View looking radially inward along Shower-max ring
- Shows reasonable clearance for cabling

Shower-max dose simulations using remoll

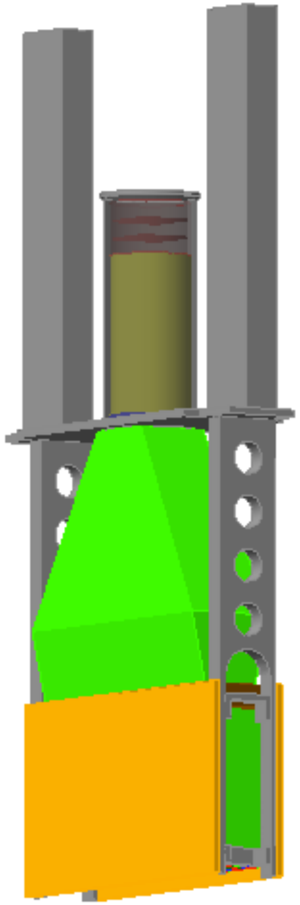
Shower-max ring in remoll GDML:

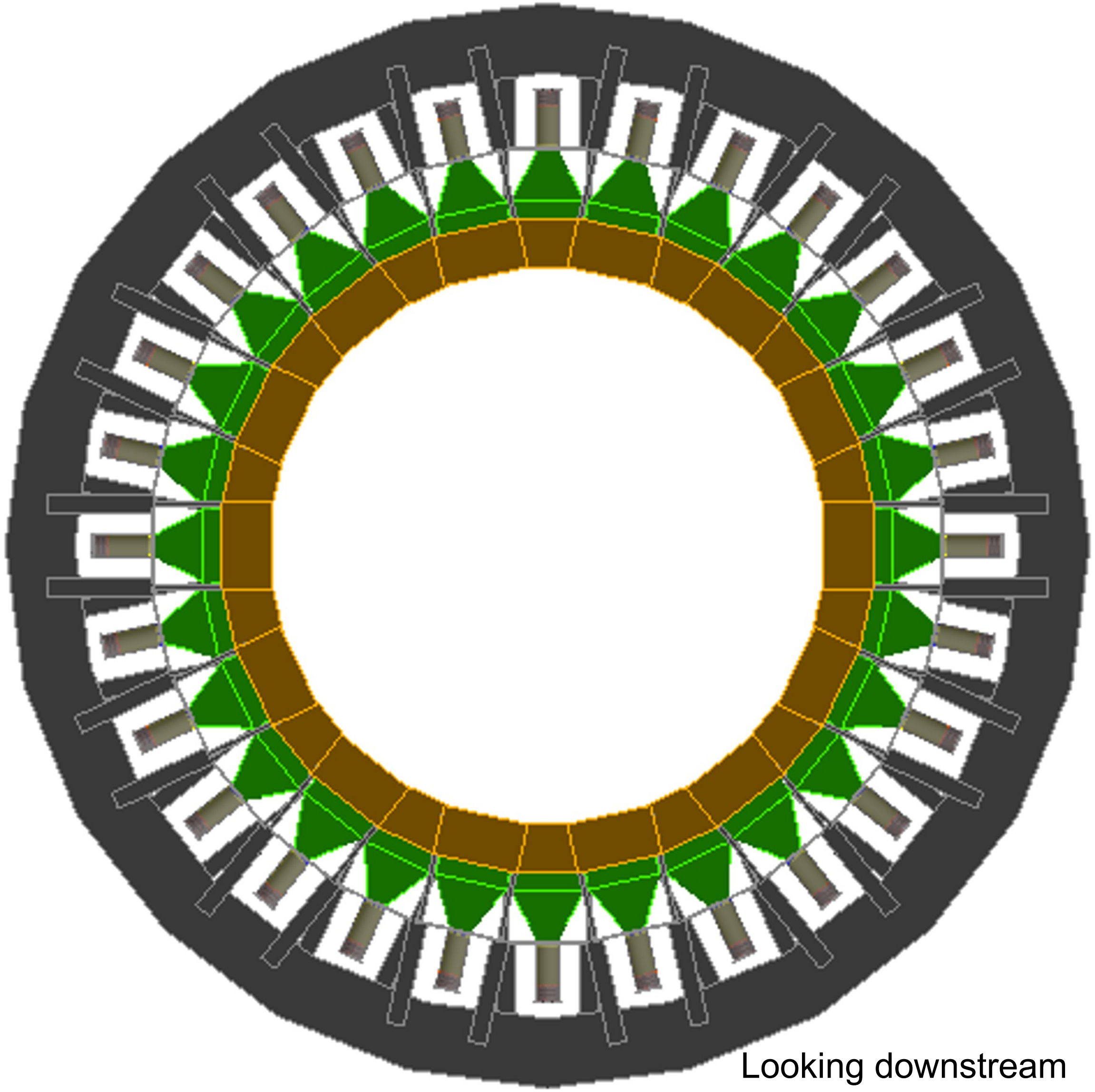
- Work done by Sudip Bhattarai

--We have estimated total dose in each quartz layer of Shower-max during MOLLER lifetime

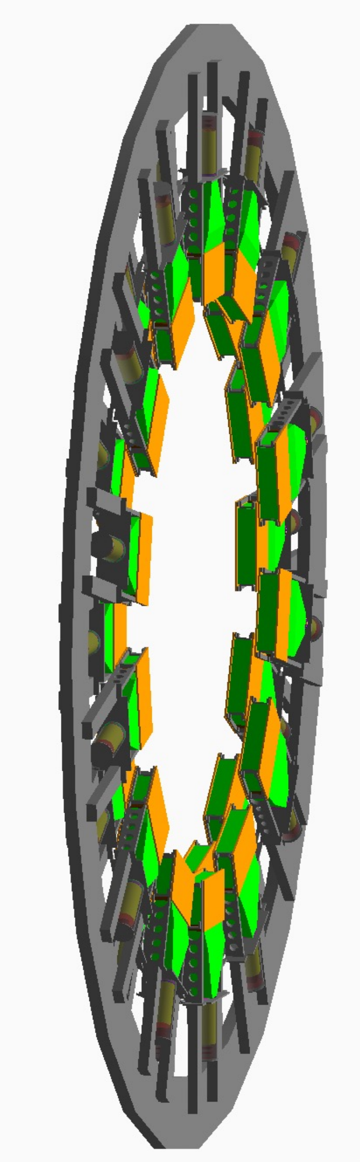
--We also have estimates for the LP filter, PMT window, and pre-amp Si wafers

[docDB #866]





Looking downstream

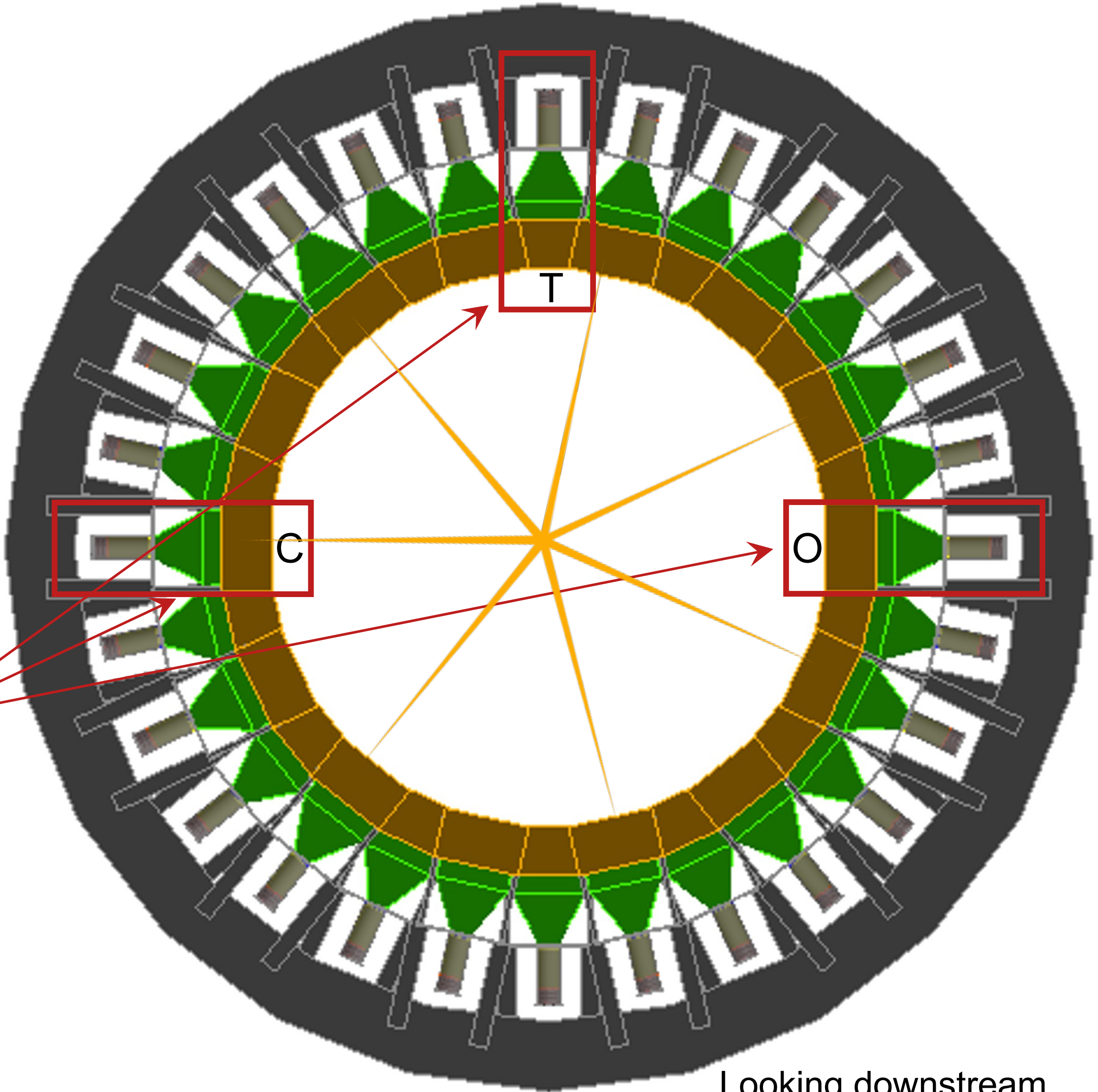


Shower-max dose simulations using remoll

Open and Closed region detectors are upstream of Transition region detectors in the ring

Quartz layer dose study:

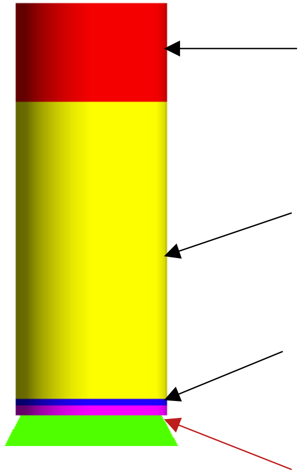
Made each quartz layer sensitive for individual Open, Closed, and Transition detectors located at these specific positions



Looking downstream

PMT region dose study:

Sensitive volumes:



Voltage divider base/pre-amp, two Si wafer planes, 0.5 mm thick

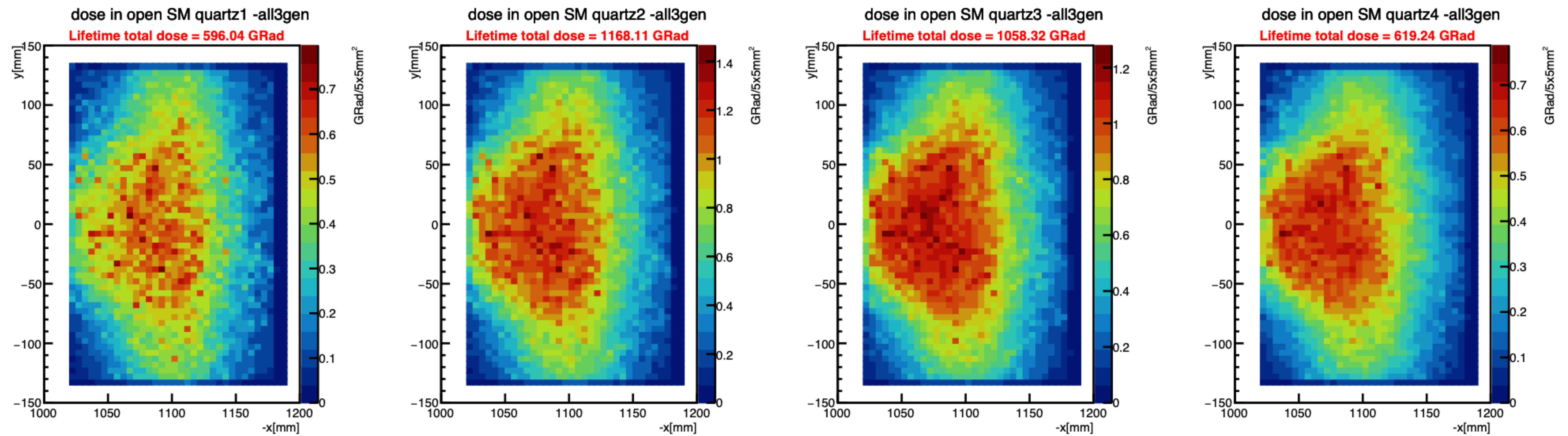
PMT, G4_galactic, 15 cm thick

PMT window, G4_quartz, 3 mm thick

Long pass filter + attenuator, G4_quartz, 5mm thick

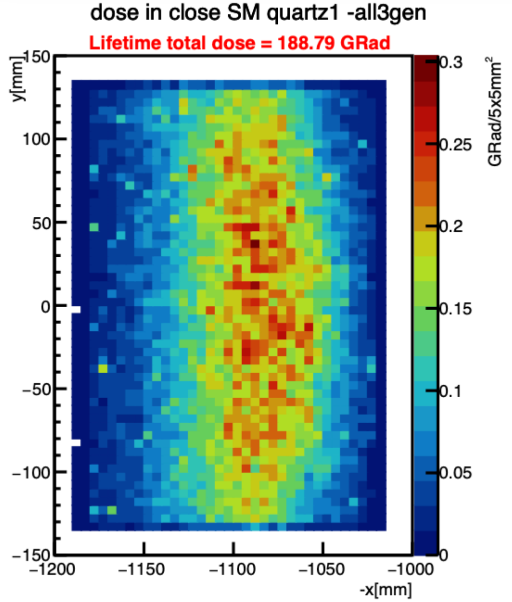
Shower-max quartz layer lifetime dose estimates

- These are Open-region detector results (worst case)

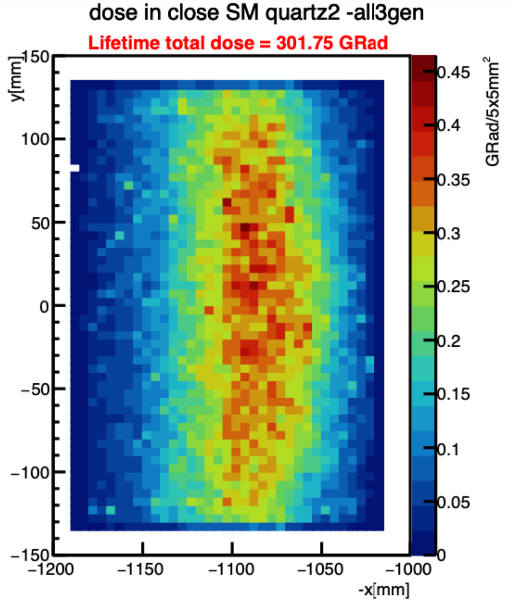


- Ran 5M Moller, ep-elastic and ep-inelastic generator events
- Peak dose density is in 2nd layer at 1.2 Grad/5x5mm^2 pixel
- Closed region are 4x lower and Transition are ~3 times lower

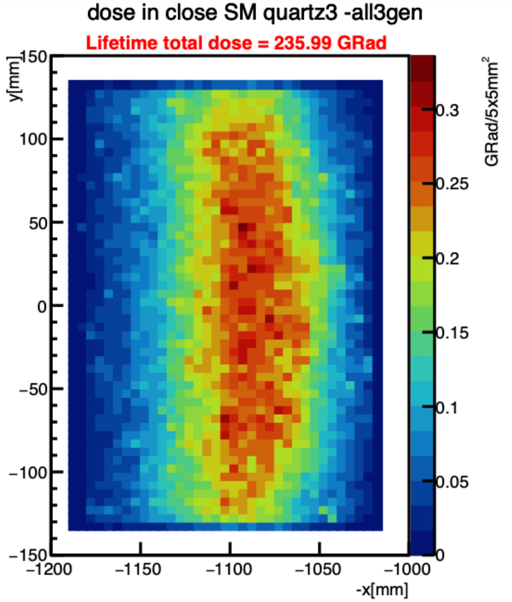
Shower-max quartz layer lifetime dose estimates


dose in close SM quartz1 -all3gen

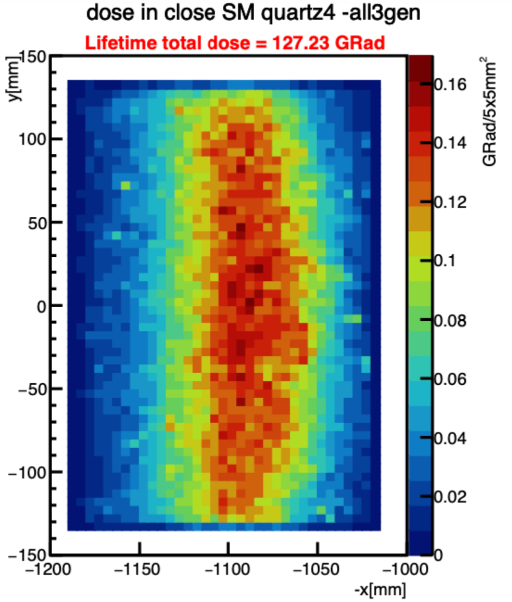
Lifetime total dose = 188.79 GRad


dose in close SM quartz2 -all3gen

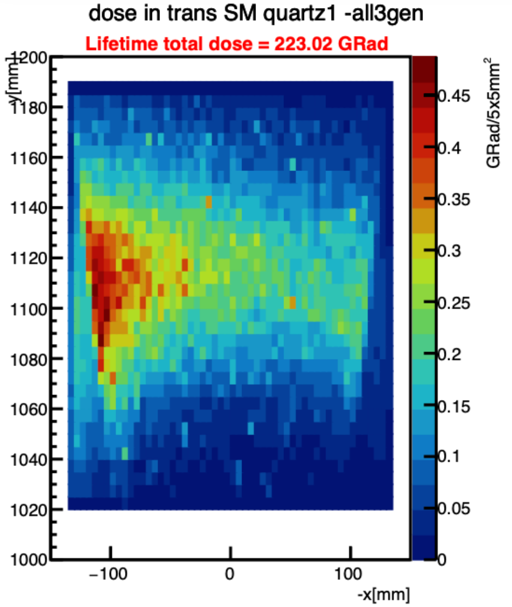
Lifetime total dose = 301.75 GRad


dose in close SM quartz3 -all3gen

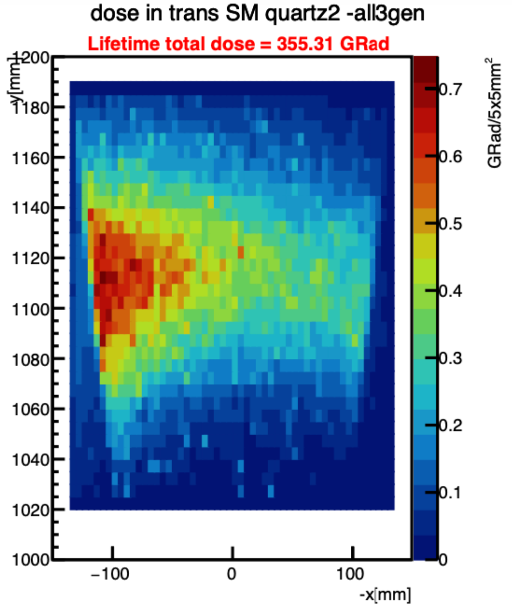
Lifetime total dose = 235.99 GRad


dose in close SM quartz4 -all3gen

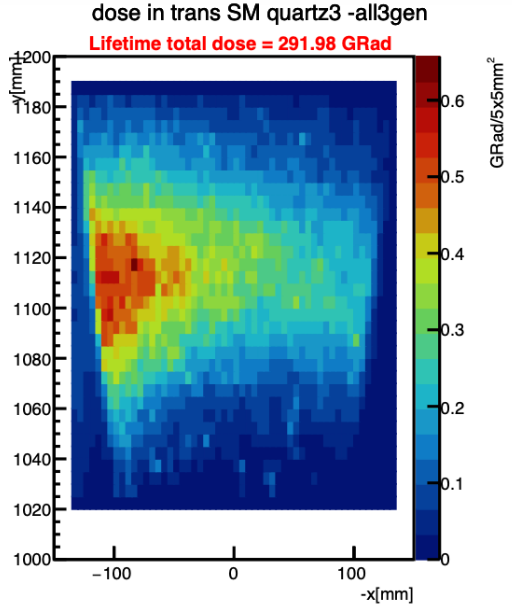
Lifetime total dose = 127.23 GRad


dose in trans SM quartz1 -all3gen

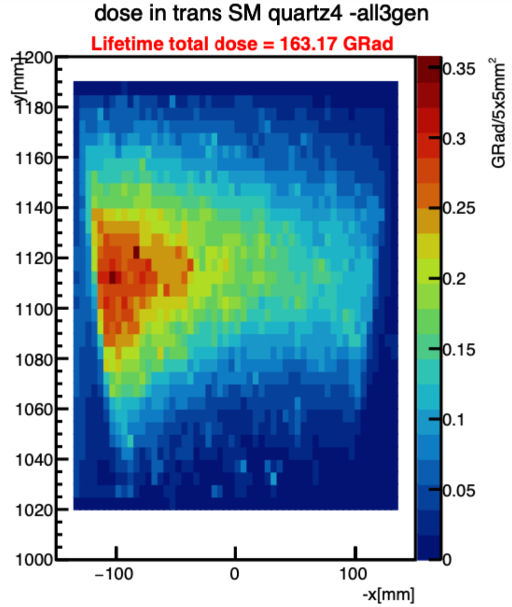
Lifetime total dose = 223.02 GRad


dose in trans SM quartz2 -all3gen

Lifetime total dose = 355.31 GRad


dose in trans SM quartz3 -all3gen

Lifetime total dose = 291.98 GRad


dose in trans SM quartz4 -all3gen

Lifetime total dose = 163.17 GRad

Shower-max long pass filter and PMT window lifetime dose

Open region

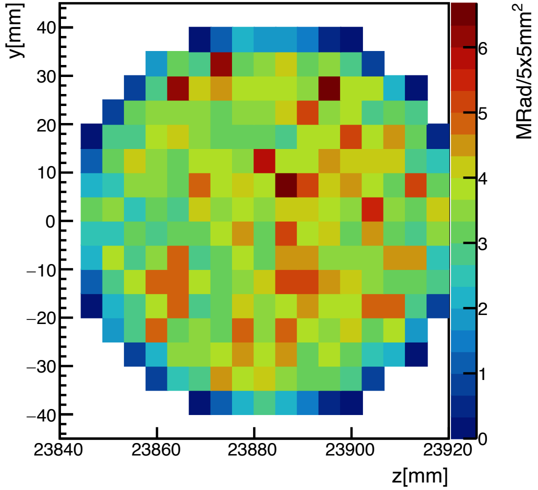
Closed region

Trans region

Filter region

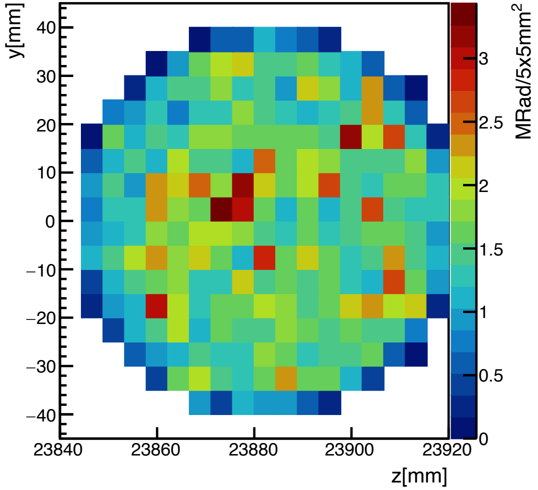
dose in open pmt region(filter) - ee-ep gen - allParticles

Lifetime mean dose/pixel = 3321.43±80.53 kRad



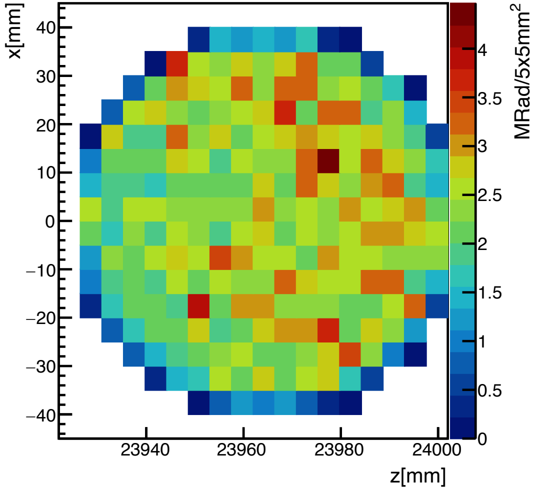
dose in closed pmt region(filter) - ee-ep gen - allParticles

Lifetime mean dose/pixel = 1448.68±39.22 kRad



dose in trans pmt region(filter) - ee-ep gen - allParticles

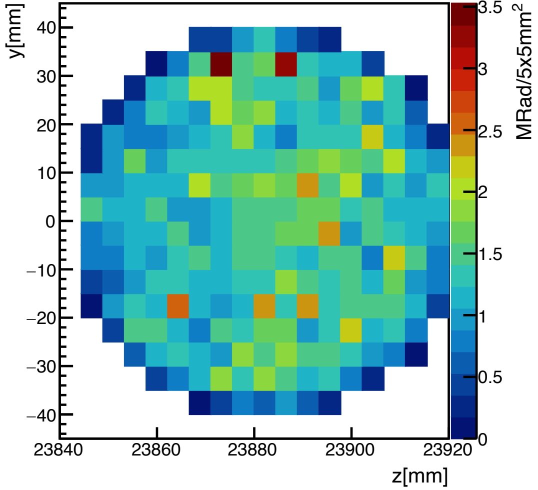
Lifetime mean dose/pixel = 2209.47±52.42 kRad



Window

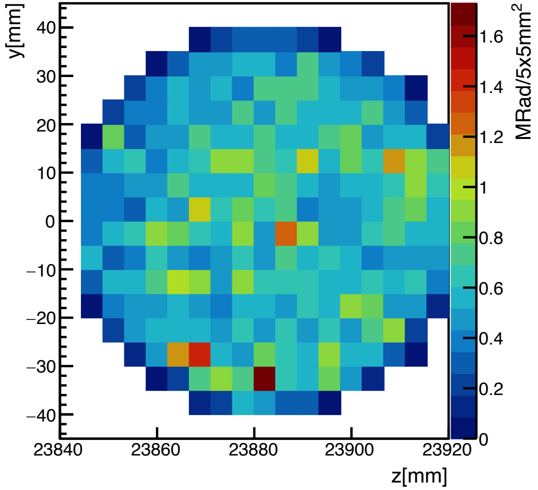
dose in open pmt region(window) - ee-ep gen - allParticles

Lifetime mean dose/pixel = 1233.54±33.79 kRad



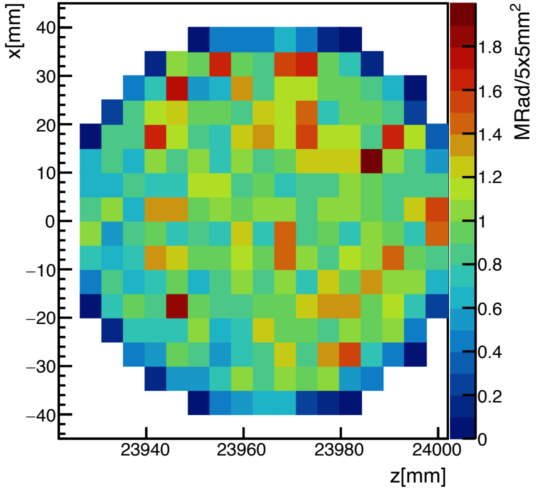
dose in closed pmt region(window) - ee-ep gen - allParticles

Lifetime mean dose/pixel = 550.74±15.87 kRad



dose in trans pmt region(window) - ee-ep gen - allParticles

Lifetime mean dose/pixel = 885.99±23.24 kRad



Average lifetime doses (Mrad/pixel):

- Filter region:
  Open: ~3.3
  Closed: ~1.4
  Trans: ~2.2
- The 5 mm thick filter models both a 3 mm LP filter + 2 mm ND filter
- PMT window:
  Open: ~1.2
  Closed: ~0.6
  Trans: ~0.9

Shower-max pre-amp Si chip lifetime doses

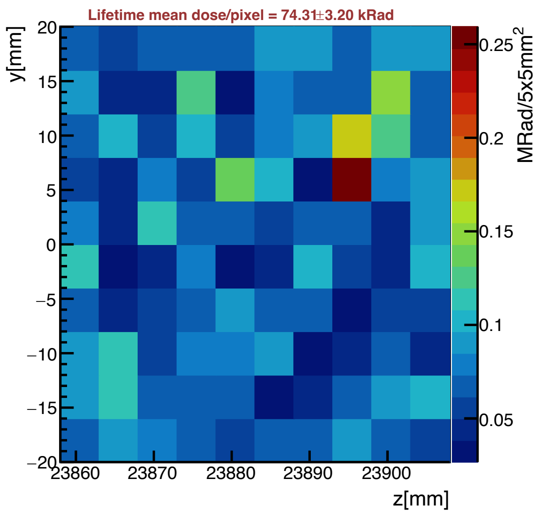
Open region

Closed region

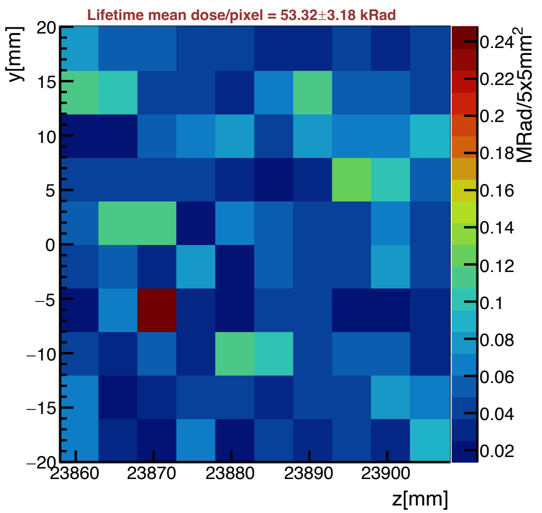
Trans region

Inner chip plane

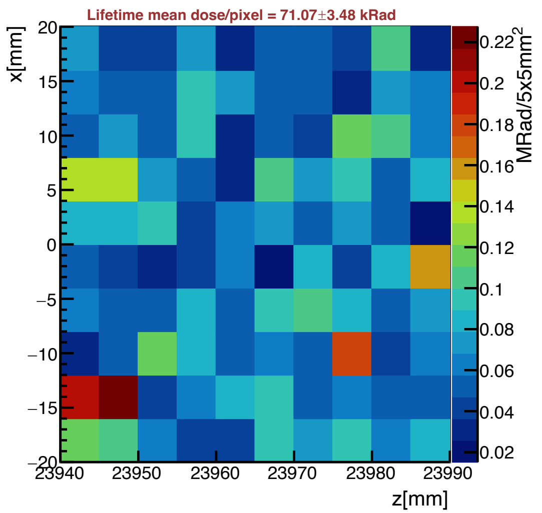
dose in open pmt region(SiChip1) - ee-ep gen - allParticles



dose in closed pmt region(SiChip1) - ee-ep gen - allParticles

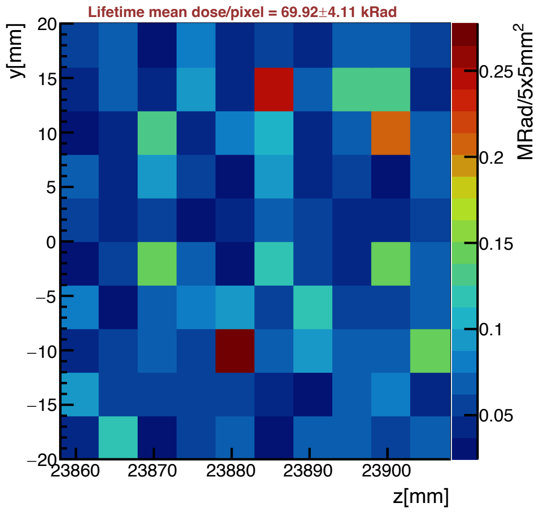


dose in trans pmt region(SiChip1) - ee-ep gen - allParticles

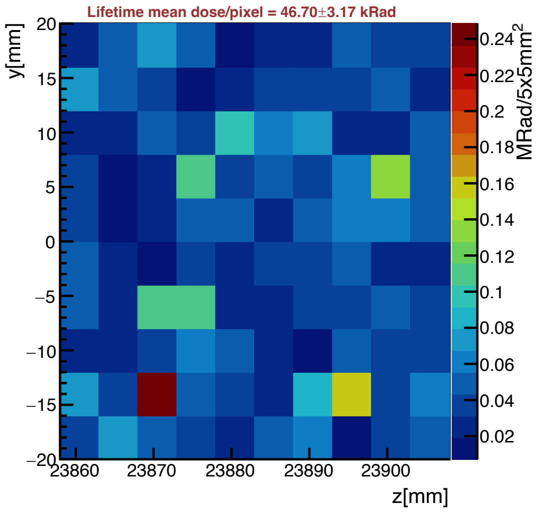


Outer chip plane

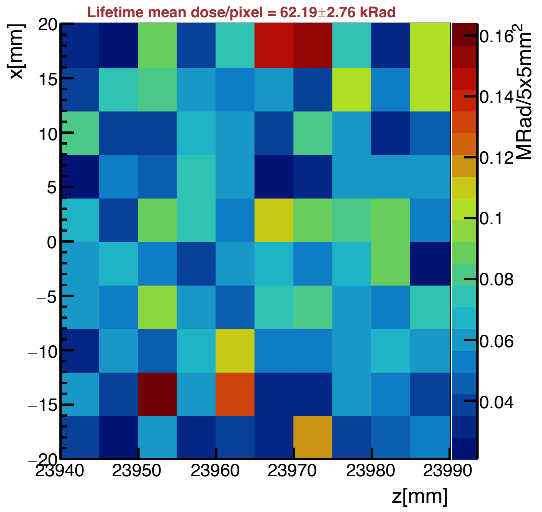
dose in open pmt region(SiChip2) - ee-ep gen - allParticles



dose in closed pmt region(SiChip2) - ee-ep gen - allParticles



dose in trans pmt region(SiChip2) - ee-ep gen - allParticles



- Average lifetime dose (krad/pixel):

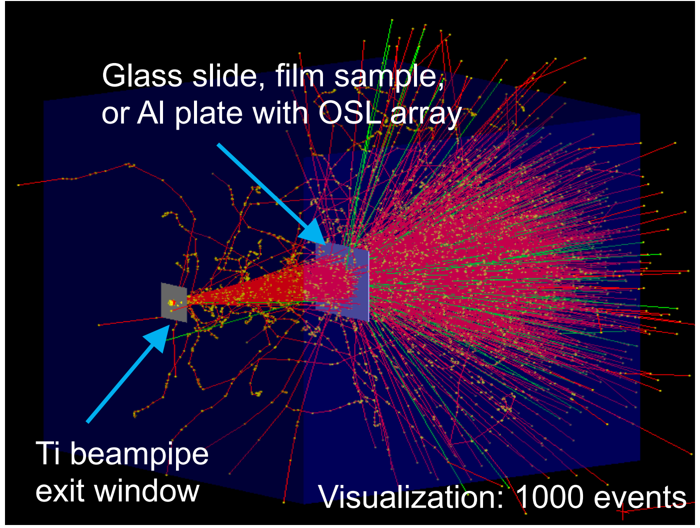
  Open: ~75
  Closed: ~50
  Trans: ~70

- Peak doses per pixel can fluctuate as high as 100 to 200+ krad

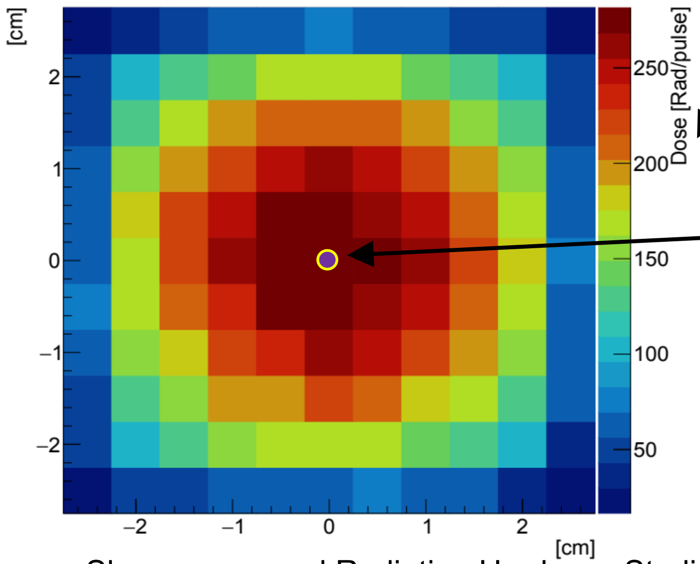
- Simulated Si wafers are 0.5 mm thick but have a huge area (4 x 5 cm^2) to give broad spatial dose sampling

Dose simulation for quartz irradiations

G4 simulation for quantifying dose



Dose Profile Quartz 5x5x10 [mm]



Simulated beam calibrated with beamspot measurements at 3 distances

Sample irradiated at 50 cm

Beam energy scans taken at beginning and end of tests

Beam charge data acquired throughout exposures

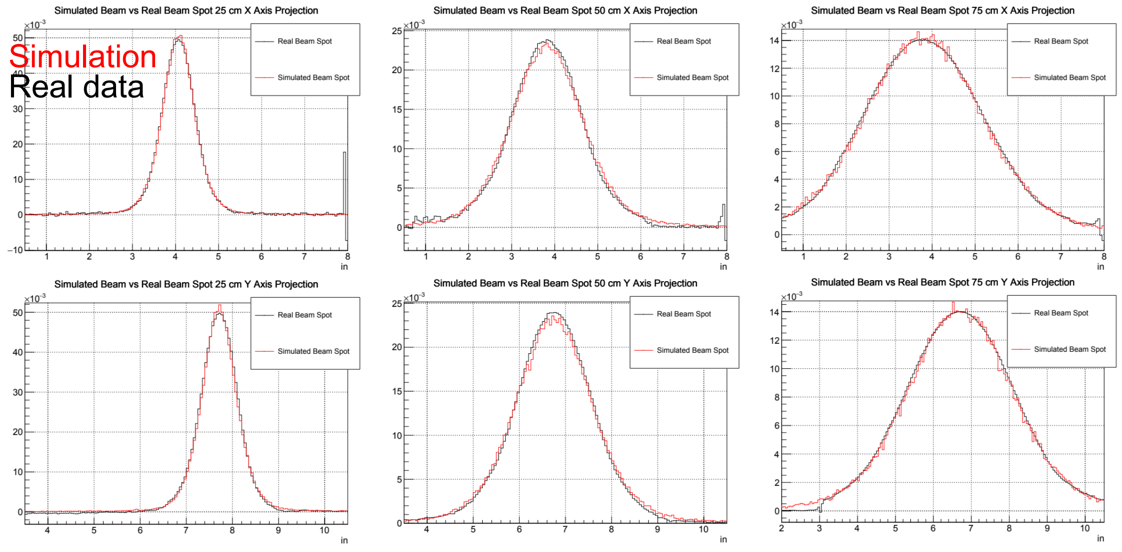
Simulated dose per 5x5 mm^2 normalized to average charge per beam pulse

Sample thickness is 10 mm

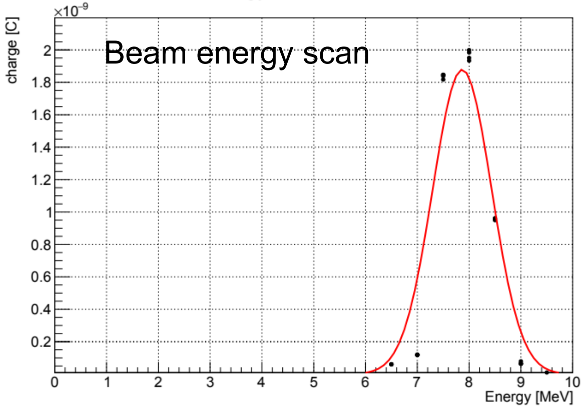
Location of light transmission measurements (within single 5 x 5 mm^2 pixel)

Beamspot measurement scans

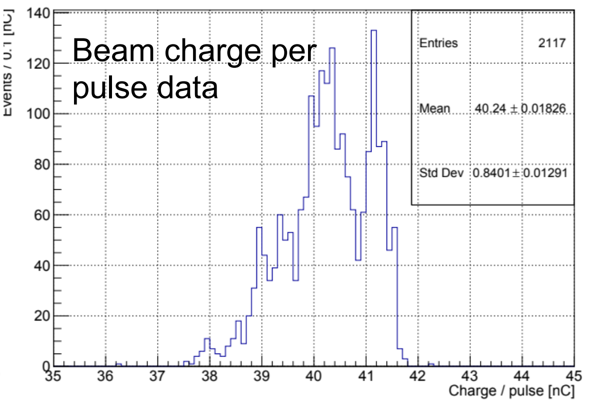
Distance from beampipe window:



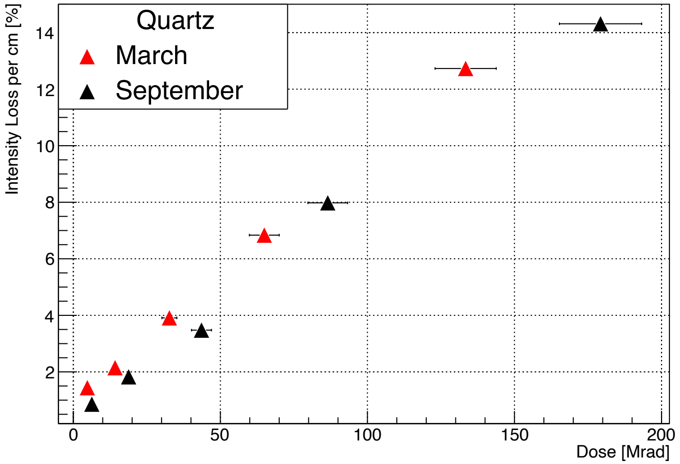
Beam Energy Distribution 09/02/2021

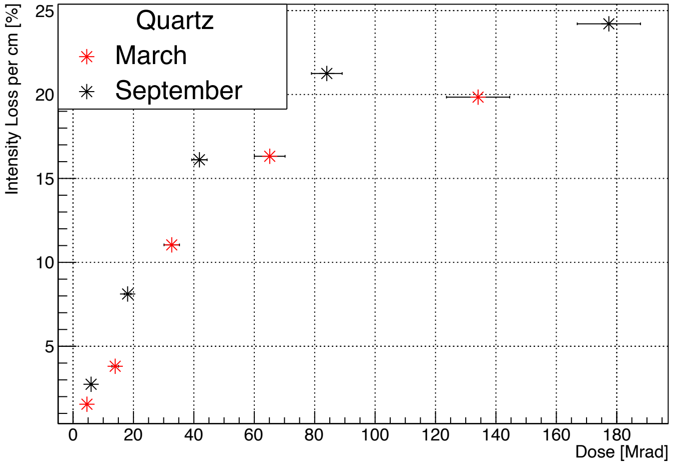


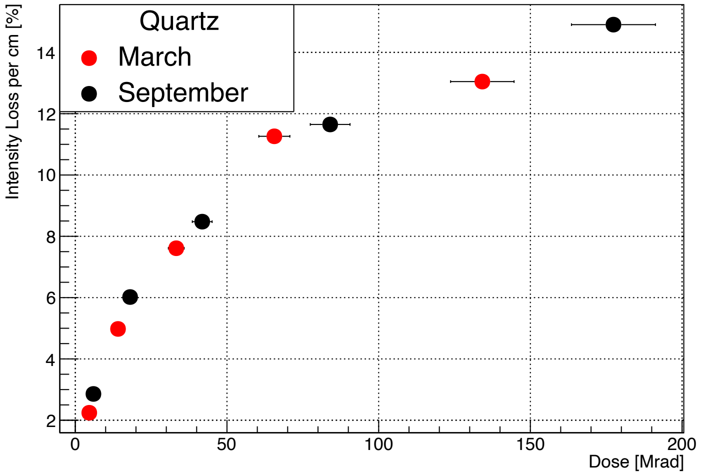
Beam Charge Distribution for all Sample runs

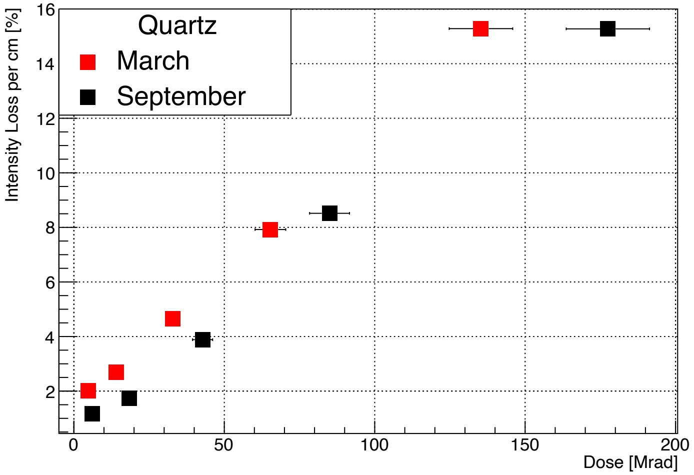


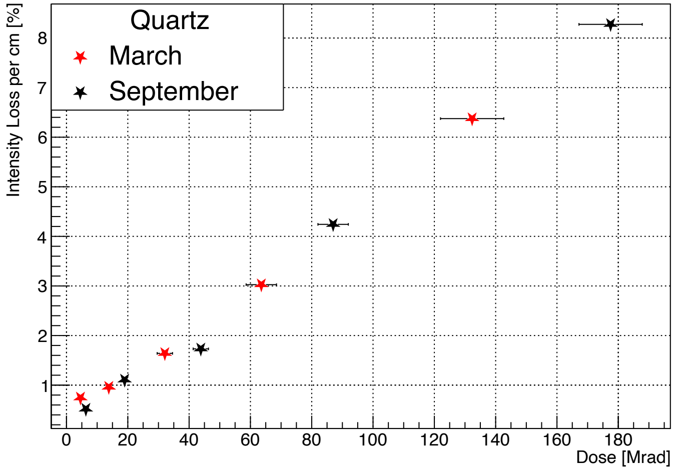
Quartz radiation-hardness results : loss vs. dose

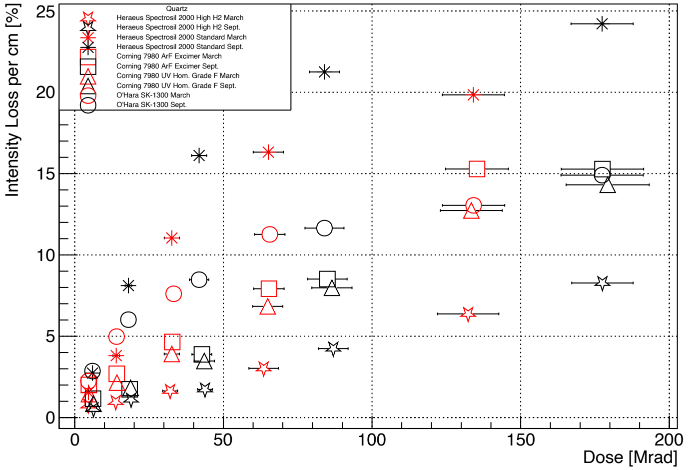

Corning 7980 UV Hom. Grade F


Heraeus Spectrosil 2000 Standard


O'Hara SK-1300

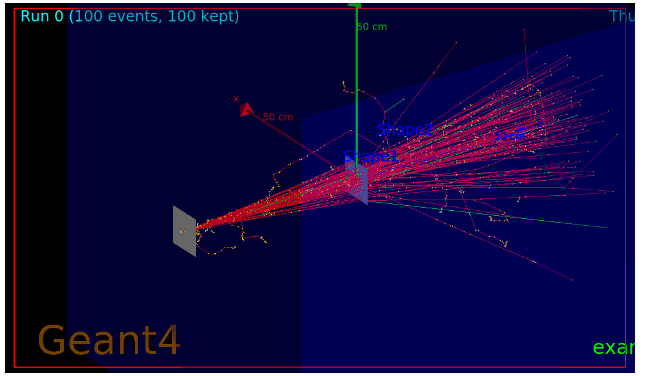

Corning 7980 ArF Excimer

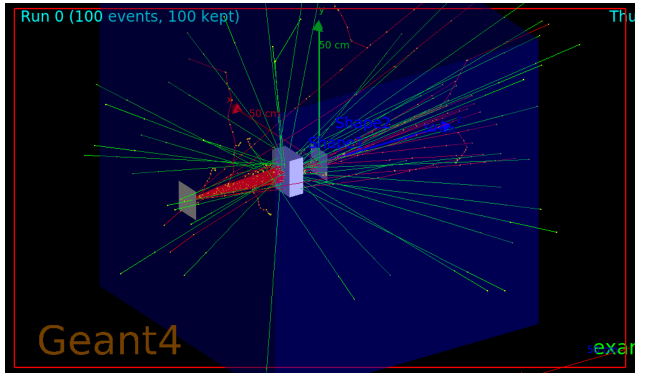

Heraeus Spectrosil 2000 High H2

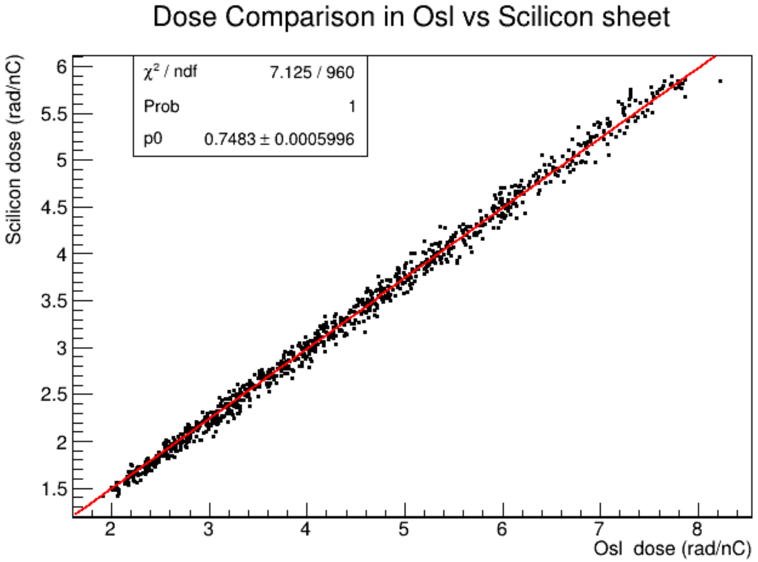

Total Intensity Loss Across Wavelengths 220-400 [nm]

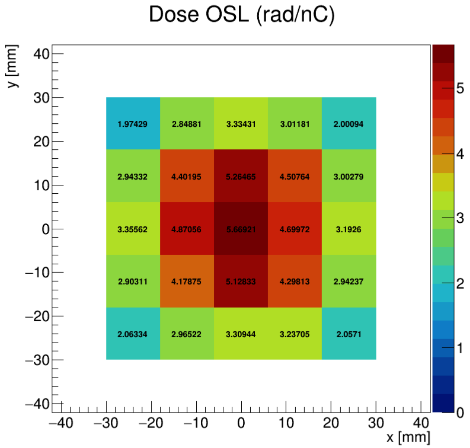
PMT electronics irradiation tests (Simulations)

- Realistic geometry: beam exit window, air, collimator, and sensitive volumes of either OSL array or Si sheet (0.6 mm thick)
- Use similar technique as used for quartz tests – vary beam parameters to sample phase space of possible beam profiles (~30 x 30 different simulations for OSL array and separately for Si sheet)
- Bin the Si sheet data into 1.2 x 1.2 mm^2 pixels to match the OSL array simulation and real data measurements; tally energy deposition in bins
- Plot Si sheet dose/nC versus OSL dose/nC – gives linear correlation
- Conclusion: sample receives 75% of OSL dose

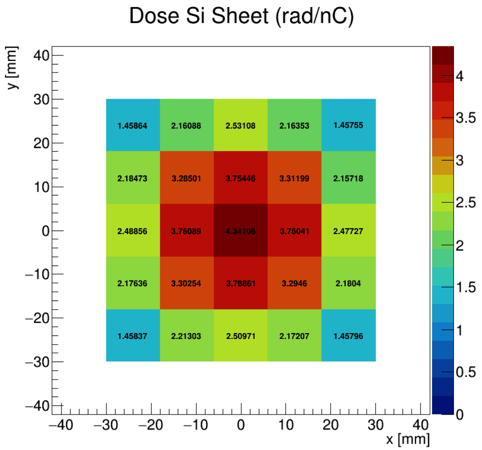








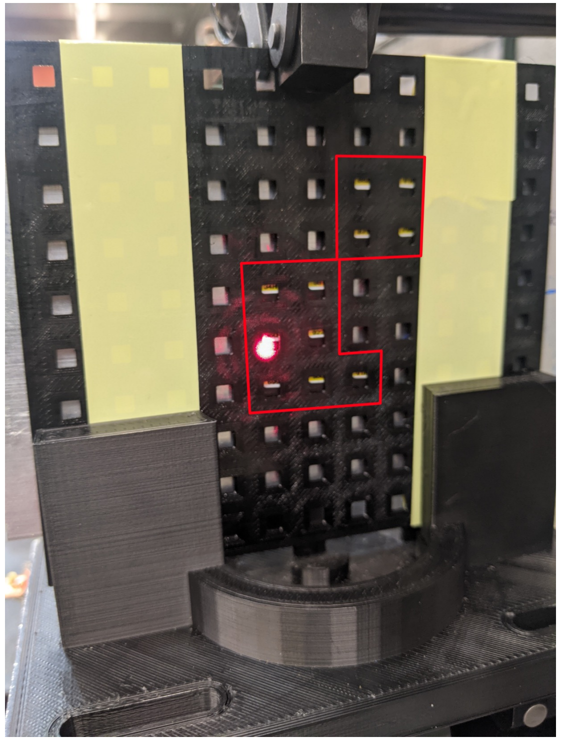
1.97429	2.84881	3.33431	3.01181	2.00094
2.94332	4.40195	5.26465	4.50764	3.00279
3.35562	4.87056	5.66921	4.69972	3.1926
2.90311	4.17875	5.12833	4.29813	2.94237
2.06334	2.96522	3.30944	3.23705	2.0571



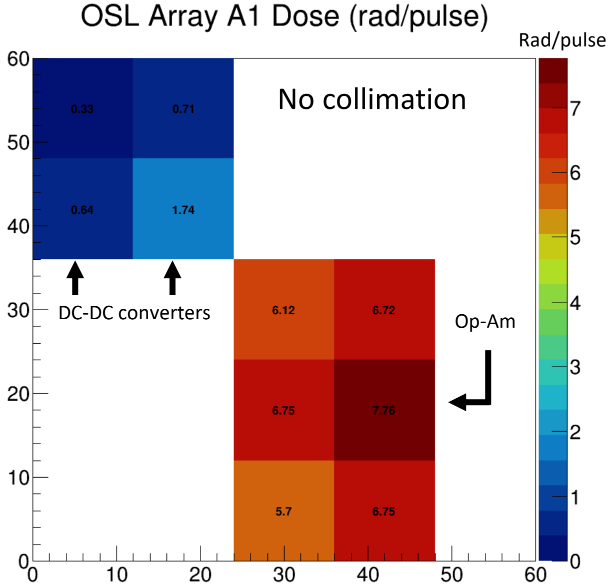
1.45864	2.16088	2.53108	2.16353	1.45755
2.18473	3.28501	3.75446	3.31199	2.15718
2.48856	3.76089	4.34106	3.76041	2.47727
2.17636	3.30254	3.78861	3.2946	2.1804
1.45837	2.21303	2.50971	2.17207	1.45796

PMT electronics irradiation tests (Beam pulse dosimetry)

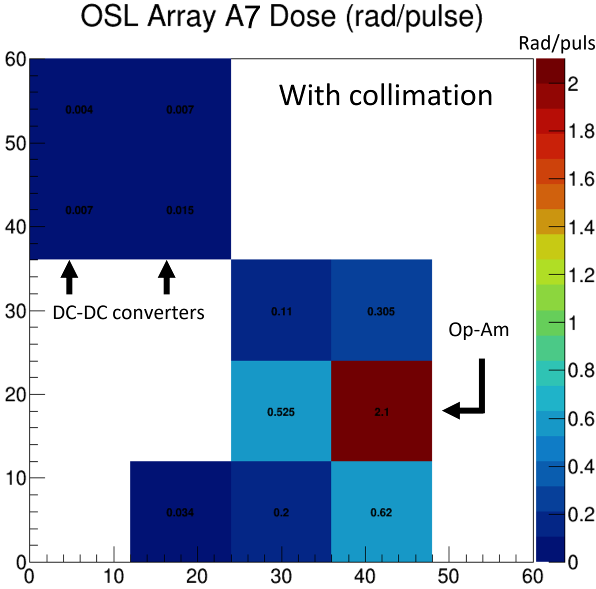
- Performed beam dose measurements with specialized OSL array shapes overlaying the chip locations of interest



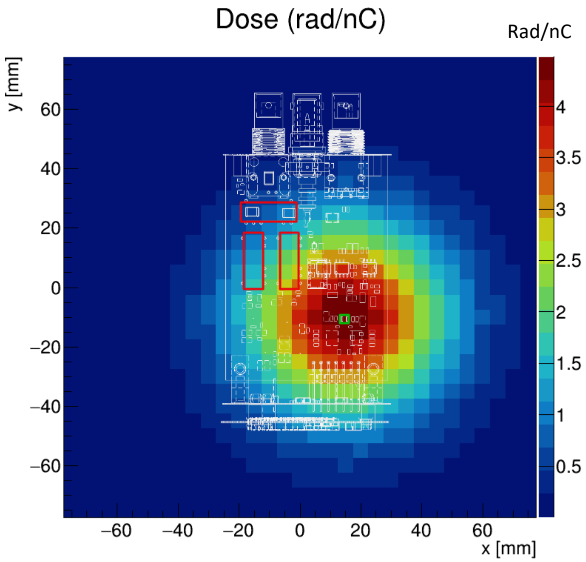
Beam center on Op Amp



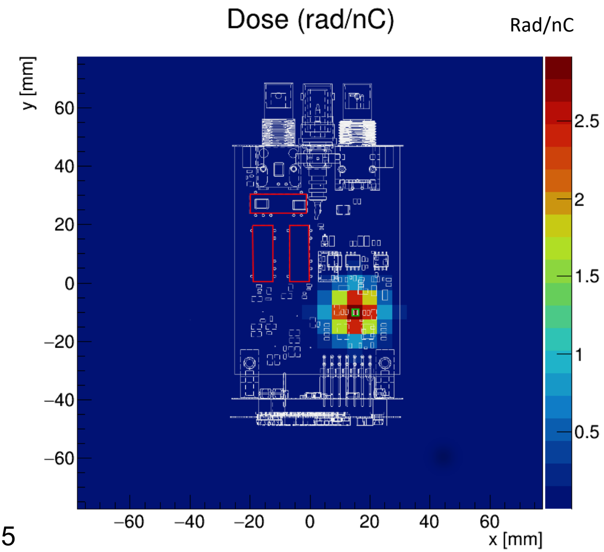
OSL Array A1 Dose (rad/pulse)



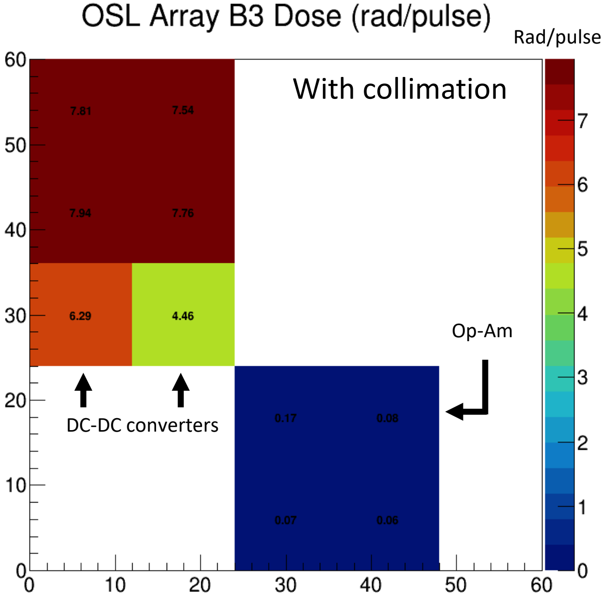
OSL Array A7 Dose (rad/pulse)



Dose (rad/nC)

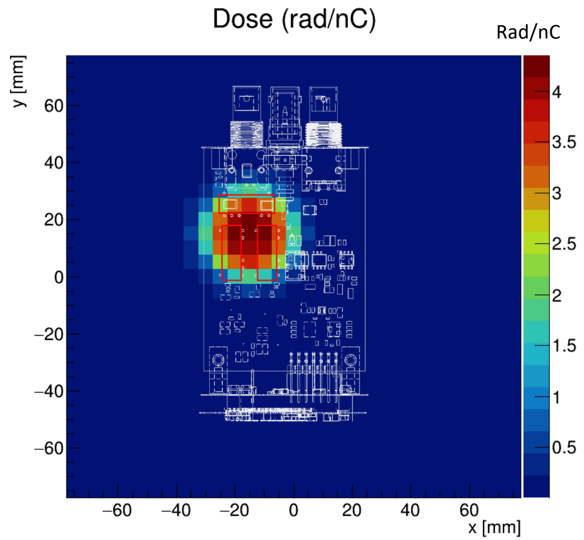


Dose (rad/nC)



OSL Array B3 Dose (rad/pulse)

Beam center on DC-DC converters



Dose (rad/nC)

PMT electronics irradiation tests (preliminary results)

- Dose levels per run determined from OSL measurements, beam charge/pulse measurements and conversion factor from simulation

PMT Base 1: Op amp	Dose	Total Dose
Run 0	106 kRad	106 kRad
Run 1	106 kRad	212 kRad
Run 2	210 kRad	422 kRad
Run 3	210 kRad	633 kRad
Run 4	106 kRad	739 kRad
Run 5	106 kRad	845 kRad
Run 6	106 kRad	951 kRad
Run 7	318 kRad	1,270 kRad
Run 8	106 kRad	1,480 kRad
Run 9	210 kRad	1,586 kRad

Started to fail → Run 6

PMT Base 2: DC-DC Converters	Dose	Total Dose
Run 1	206 kRad	206 kRad

failed ← Run 1

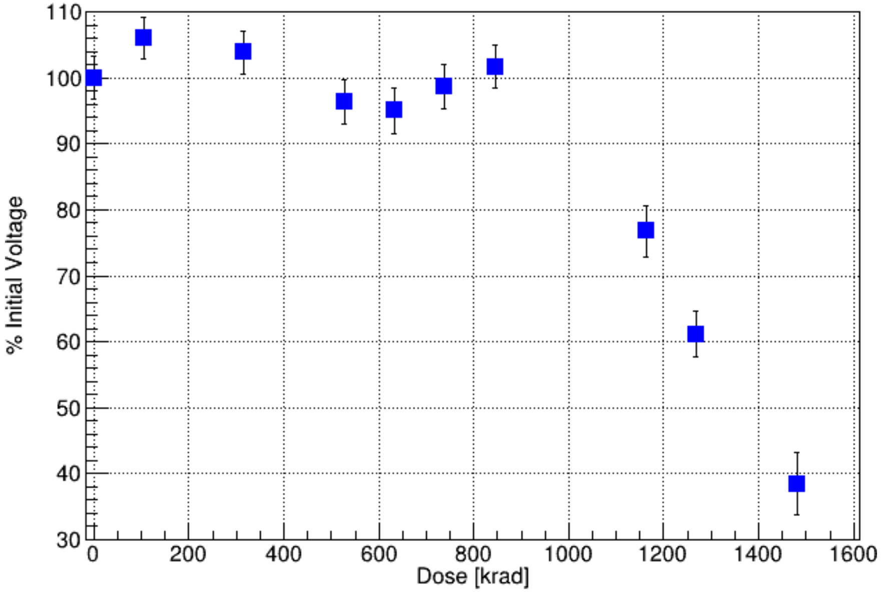
PMT Base 1: DC-DC Converters	Dose	Total Dose
Run 1	10.5 kRad	10.5 kRad
Run 2	42 kRad	52 kRad
Run 3	53 kRad	104 kRad

failed ← Run 3

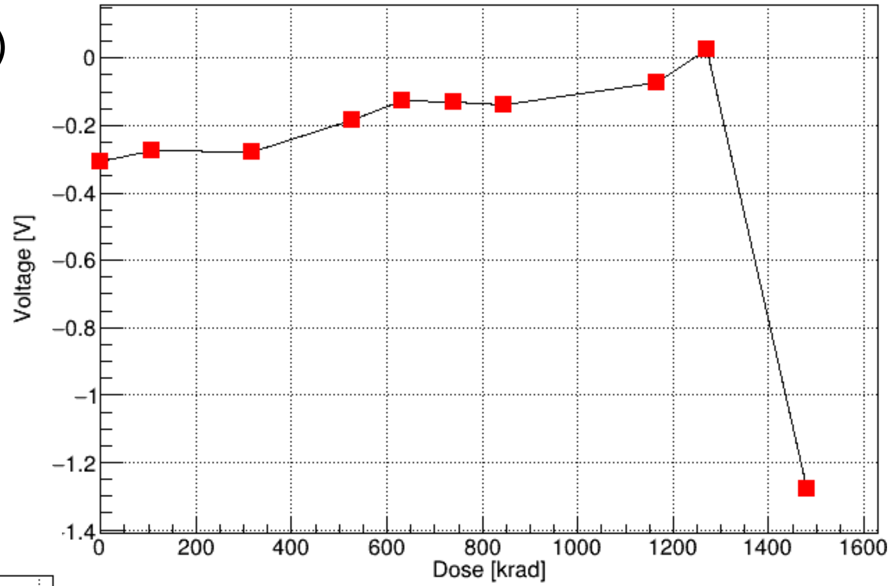
PMT electronics irradiation tests (preliminary results)

- Integrating op-amp functionality/gain tests performed using 200 kOhm preamp setting, pmt at -795 V and four cathode currents (2, 5, 20, and 27 nA)

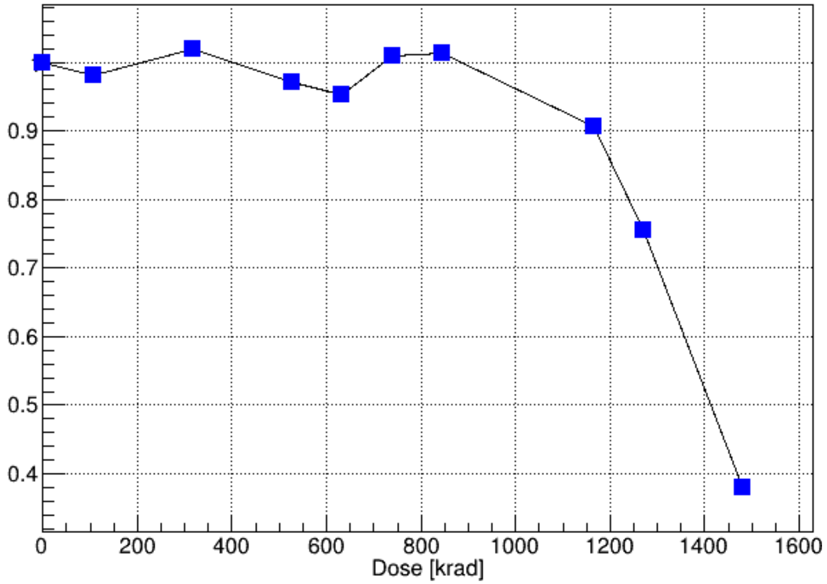
Voltage Drop for 2 nA LED



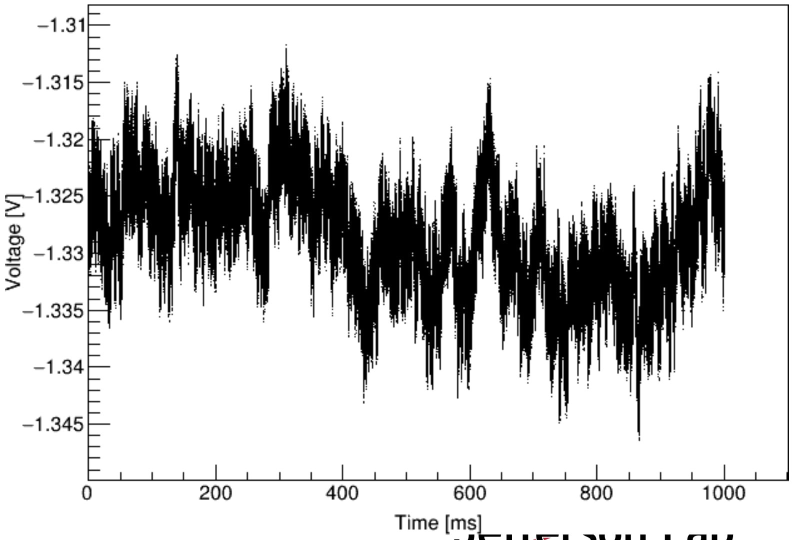
Mean Voltage with LED Off



Voltage Drop for 27 nA LED

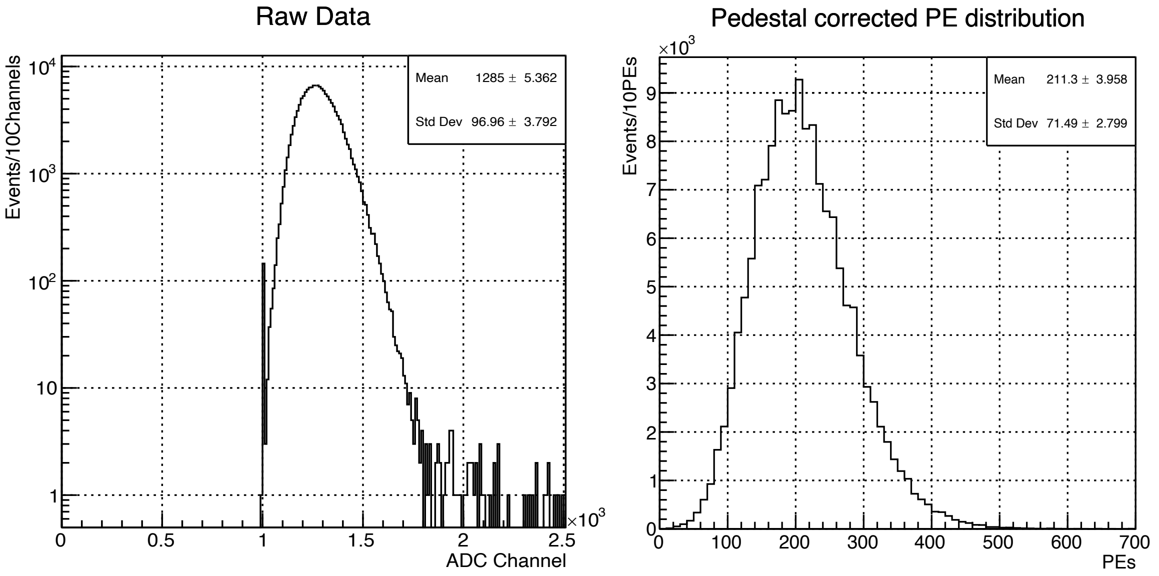


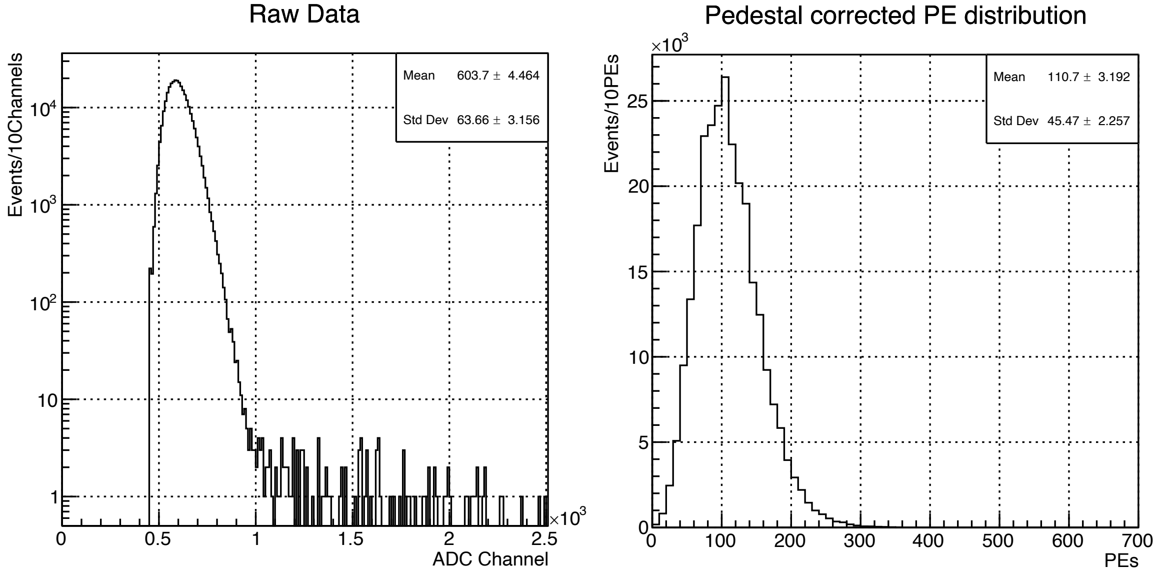
1480 krad: 2 nA



Cosmic-ray stand for Shower-max testing in Idaho

Shower-max: MAMI testbeam Results





Conditions:

- E_{beam} = 855 MeV (well below avg energy of accepted electrons during MOLLER)
- Beam rate 3 - 5 KHz
- HV = -1300 V, pmt gain = $1.67 \pm 0.12 \times 10^6$, 200 fC/channel ADC sensitivity

Results:

Aluminized-mylar wrapped quartz

- Mean yield 211 PE's per electron with RMS width of 71 PE's (34% resolution)

Unwrapped (bare) quartz

- Mean yield 111 PE's per electron with RMS width of 45 PE's (41% resolution)

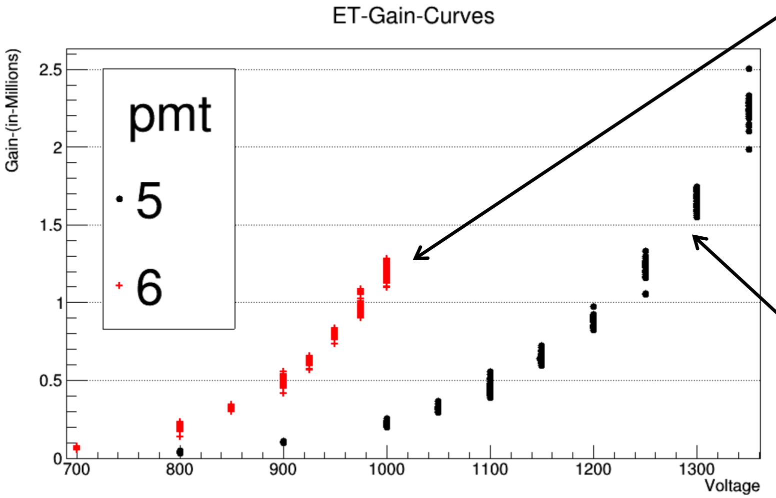
Shower-max: MAMI testbeam data and simulation comparison

- Prior to testbeam, we simulated our expected PE distribution from MAMI testbeam for the non-wrapped, bare quartz configuration: --Results: 97 PE mean and 36 PE width. **The data agree very well with this!**

Test Conditions:

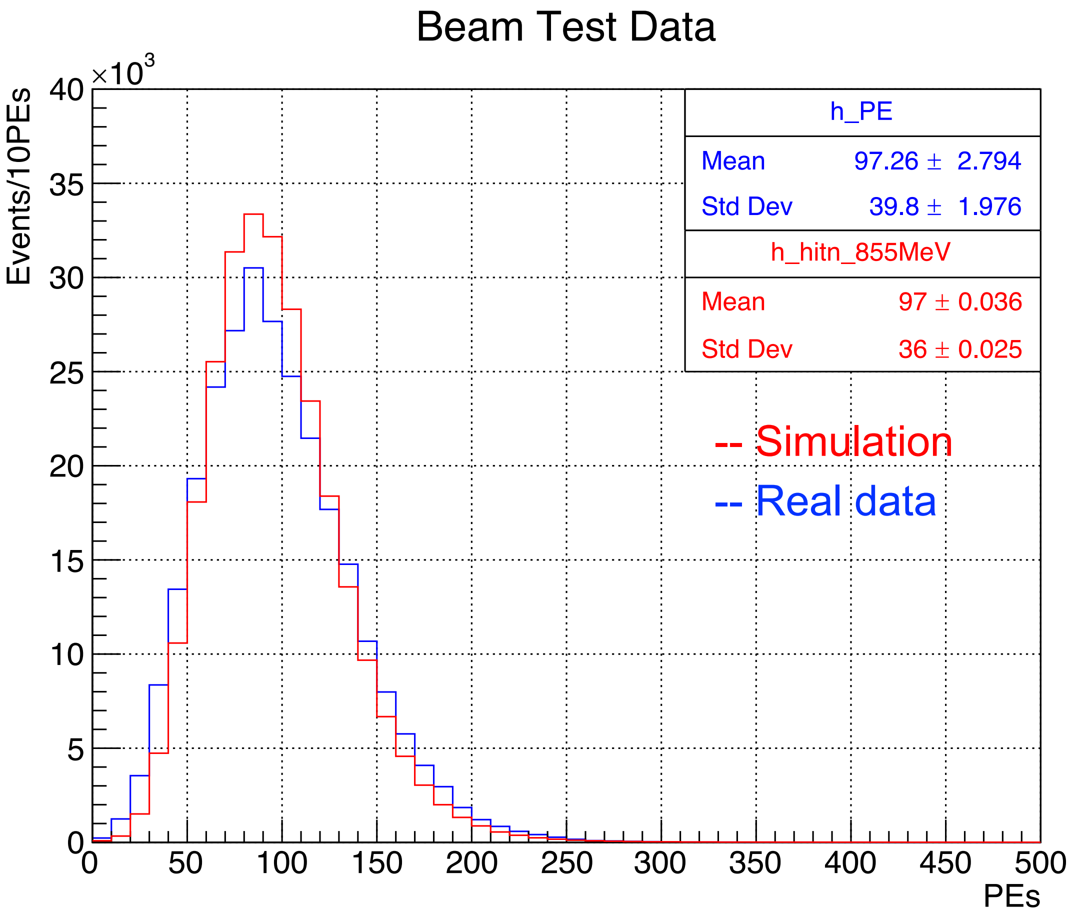
- E_{beam} = 855 MeV (note, this is well below average energy of accepted electrons during MOLLER)
- Beam rate 3 - 5 kHz
- HV = -1300 V, pmt gain = 1.67 ± 0.12 x10^6, 200 fC/channel ADC sensitivity

- PMT gain measurements



Different PMT using different base designed for high pulsed linearity

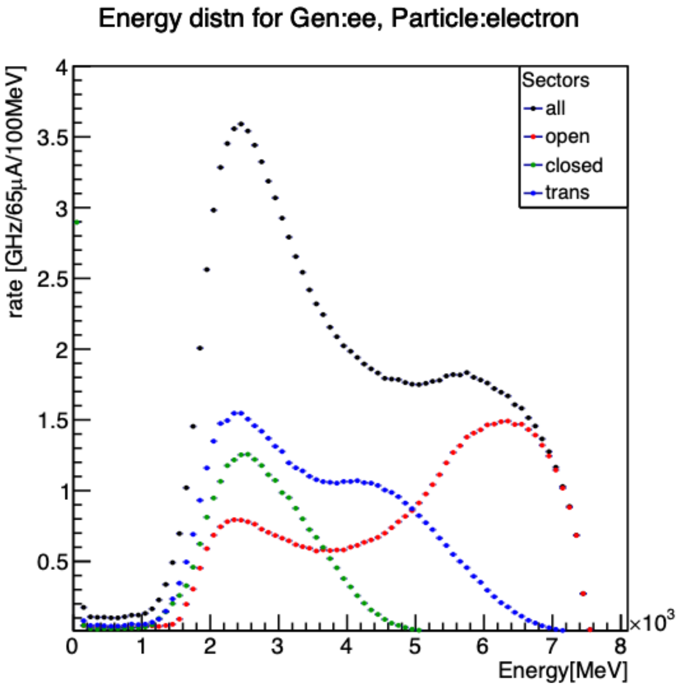
PMT and base combo used during testbeam



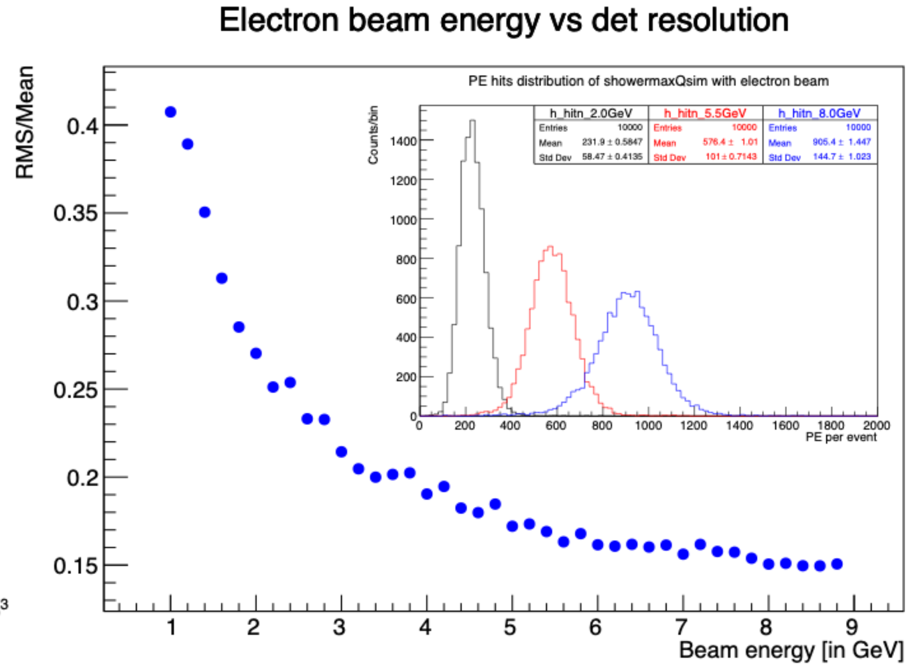
Simulation results and performance

- Rate weighted, Moller energy acceptance for each shower-max Open, Closed, and Transition region module

- Detector resolution vs. electron energy with inset PE response dists for 2, 5.5 and 8 GeV



Energy distn for Gen:ee, Particle:electron



Electron beam energy vs det resolution

- Detector rates per module: includes Moller, background e-p processes and gamma-rays

- Mean PE yields per detected particle for each module

	Open		Closed		Transition		Ring Total	
	e^-	γ	e^-	γ	e^-	γ	e^-	γ
Rate [GHz]	9.3	83.3	3.9	29.4	4.8	50.9	159.8	1501
Mean PE yield [PEs]	564	3.8	320	3.1	352	2.7		

Past prototyping and testbeam

Prototypes constructed in 2018: both Full-scale and Benchmarking versions with two different “stack” configurations:

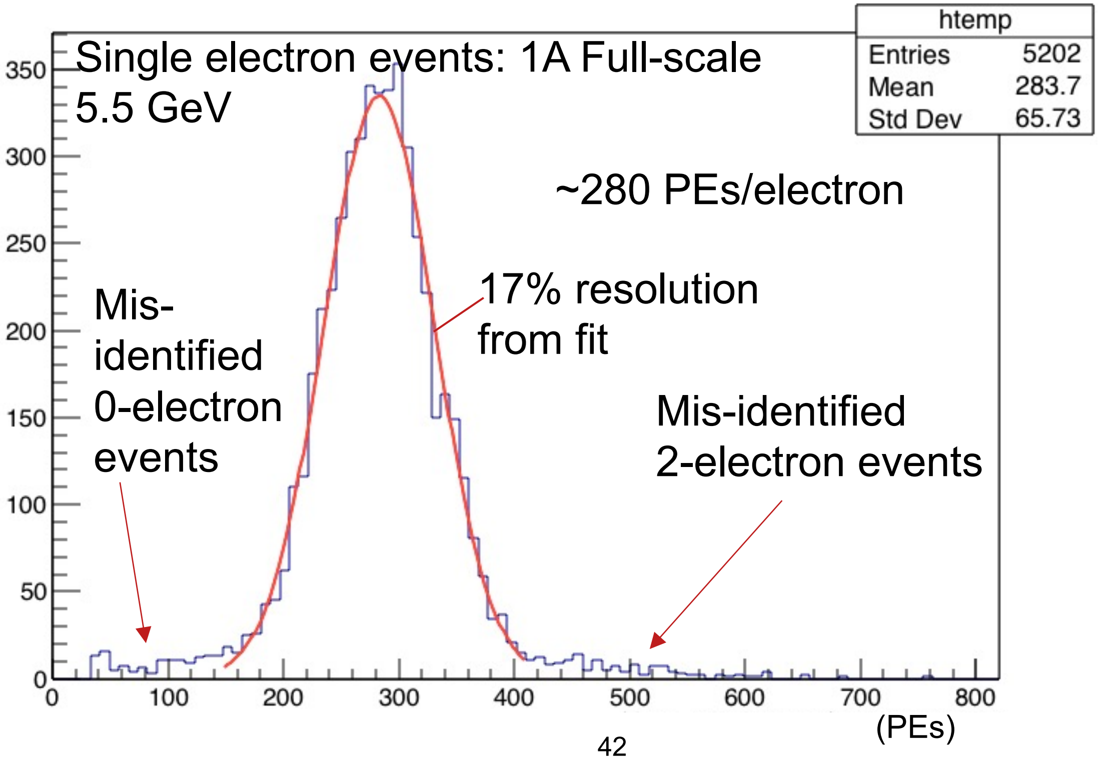
- 8 mm thick tungsten and 10 mm thick quartz (1A)
- 8 mm thick tungsten and 6 mm thick quartz (1B)

SLAC testbeam T-577 run: Dec 6 – 12, 2018

- Exposed prototypes to 3, 5.5, and 8 GeV electrons with Poisson beam multiplicity
- Validated our optical Monte Carlo with benchmarking prototype

--Stack design validated: number of layers/thicknesses; yields and resolutions match G4 predictions

- 2018 prototype beam performance sufficient for MOLLER →
- 2022 prototype testbeam taking place at MAMI in fall 2022



Single electron events: 1A Full-scale 5.5 GeV

~280 PEs/electron

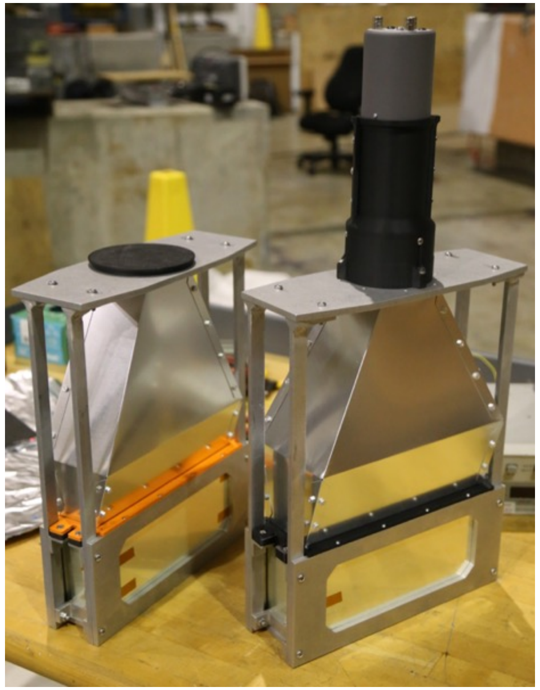
17% resolution from fit

Mis-identified 0-electron events

Mis-identified 2-electron events

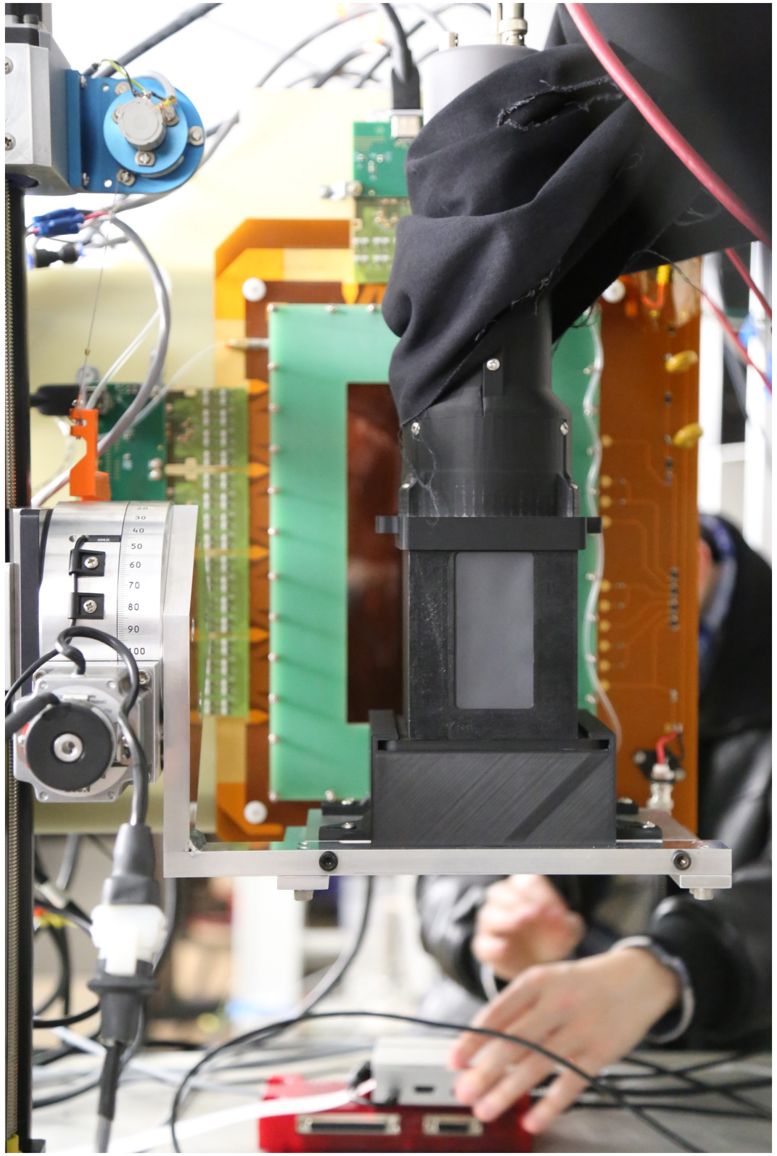
Full-scale prototype: 12 cm x 25 cm active area

- 1st-pass engineered design concept vetted
- Light guide construction techniques developed



Past prototyping and testbeam results

T-577: SLAC
Testbeam Setup:
Benchmarking
ShowerMax



Past prototyping and testbeam results

Photo-Electron Distribution - simulated vs real data

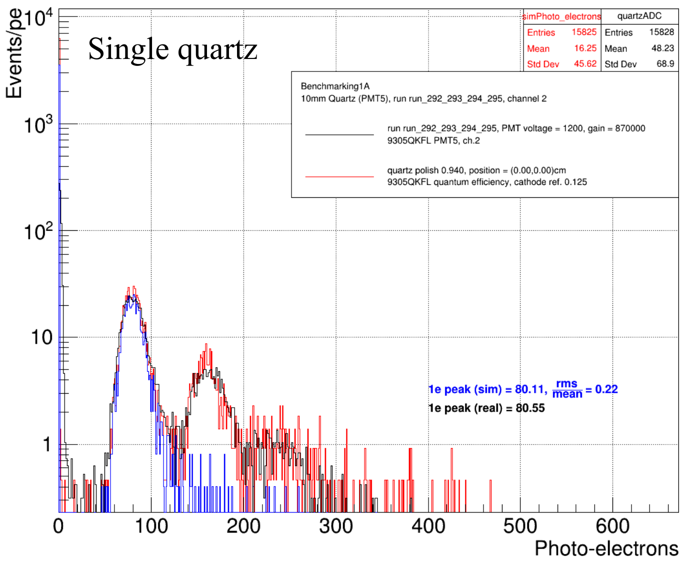


Photo-Electron Distribution - simulated vs real data

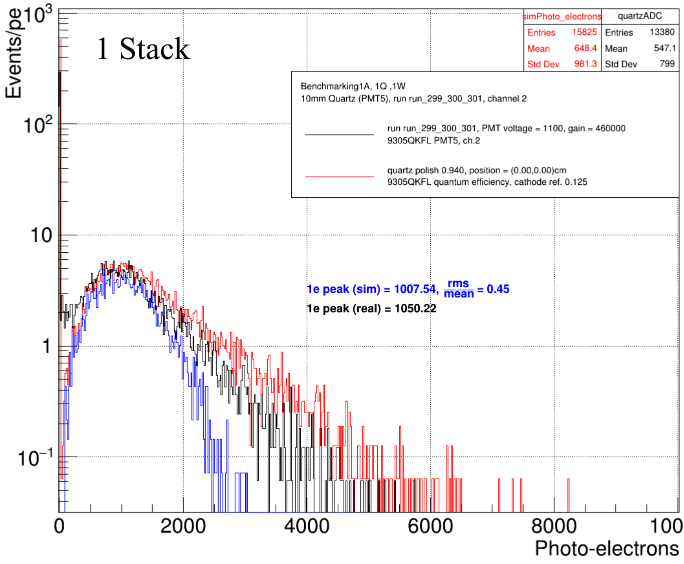


Photo-Electron Distribution - simulated vs real data

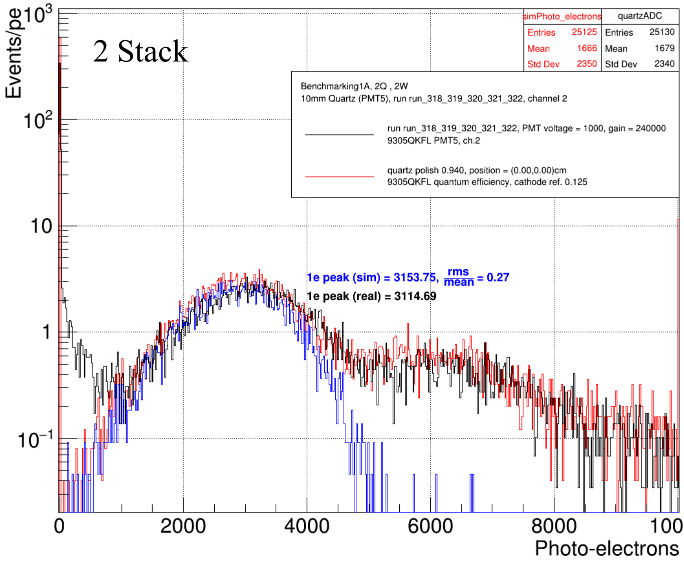


Photo-Electron Distribution - simulated vs real data

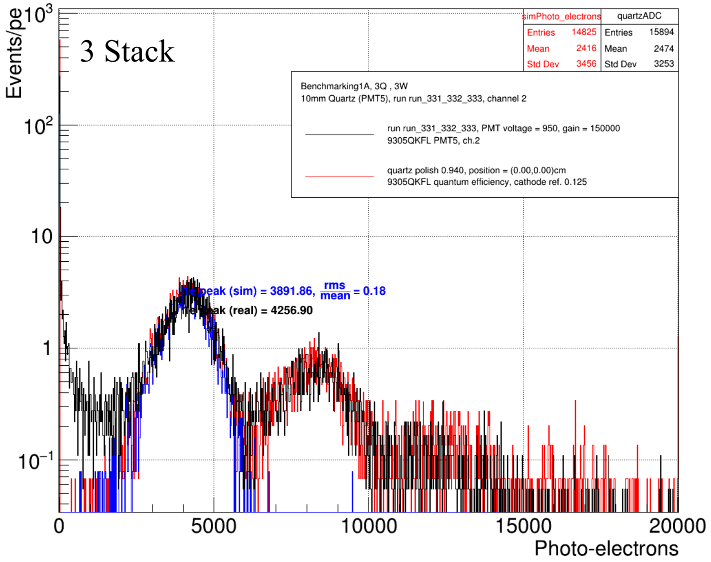
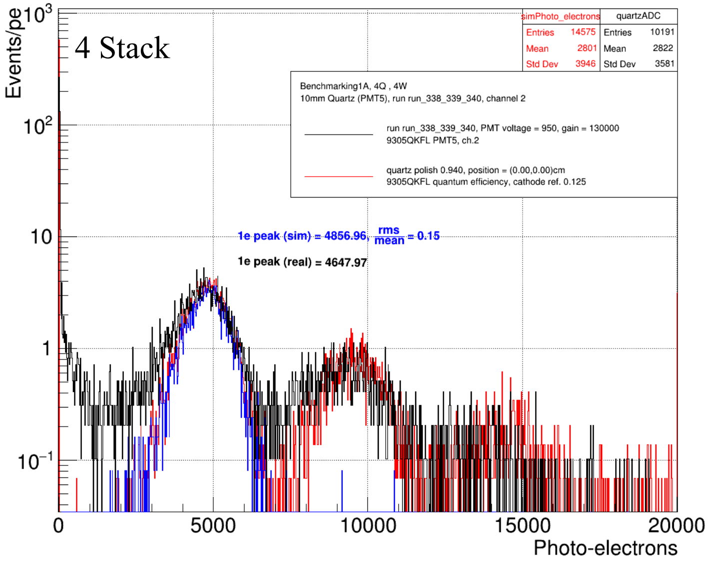


Photo-Electron Distribution - simulated vs real data



- Single quartz data used to benchmark quartz optical polish parameter in optical simulation
- With quartz polish calibrated, simulations performed with successively more stack layers and compared with SLAC data
- Data and simulation agree well (at 10% level); resolution steadily increases as more layers added