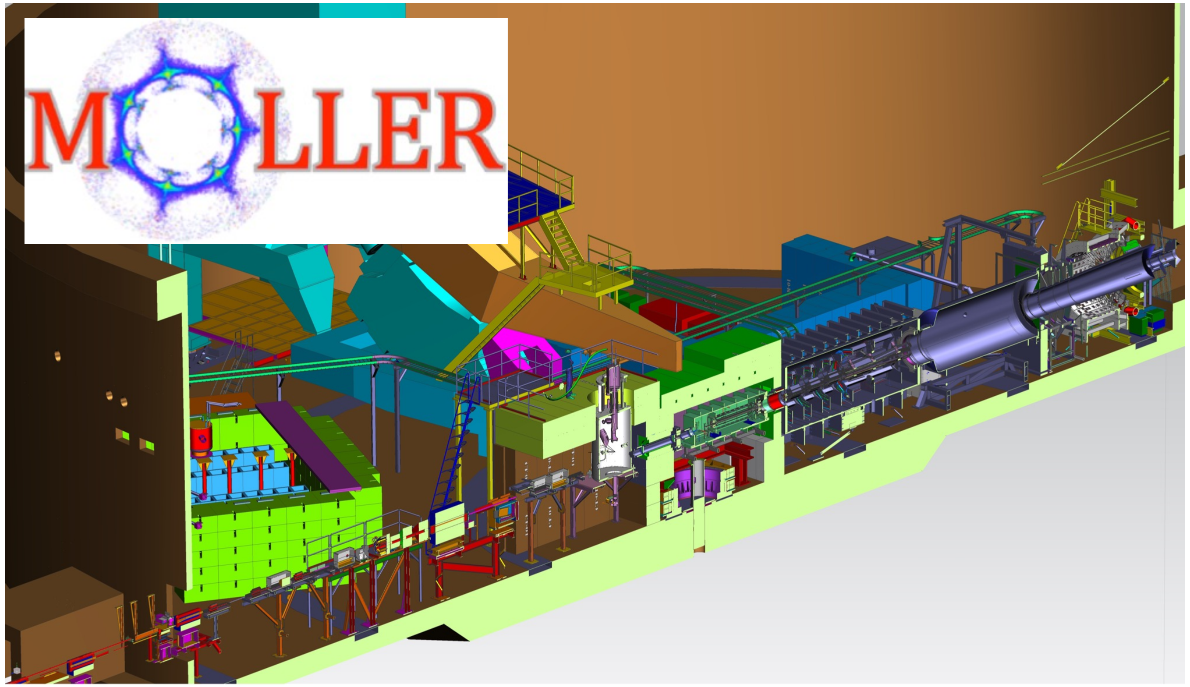
MOLLER Annual Status and CD-3a Review

Shower-max and Radiation Hardness Studies



Dustin McNulty

Idaho State University

January 10 - 12, 2023

Jefferson Lab

Outline

- Shower-max overview
- Design and Engineering
- Prototyping and testbeam
- Simulated performance
- ES&H and Quality Assurance
- Irradiation Studies: quartz, plastic and electronics
- Summary

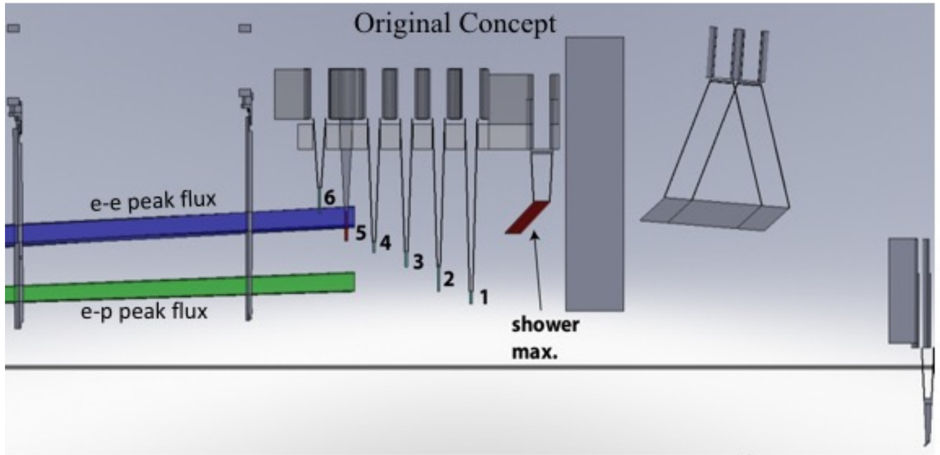
- Team Members:
  - D. McNulty. Idaho State U.
  - Michael Gericke, U. Manitoba
  - Krishna Kumar, U. Massachusetts
  - Larry Bartoszek, Bartoszek Engineering
  - Carl Zorn, Jefferson Lab

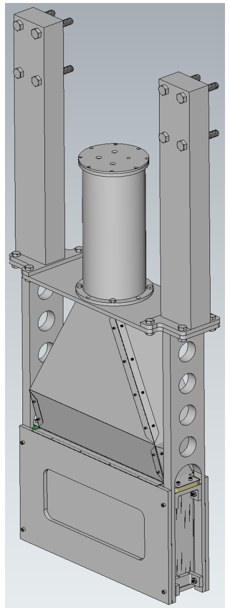
  Grad students:
  - Sudip Bhattarai
  - Justin Gahley
  - Sagar Regmi
  - Jared Insalaco

  Undergraduates
  - Edwin Sosa
  - Coltyn Fisher
  - Freddy Kouakou
  - Gabriel Ladipo
  - Mitchell Frasure

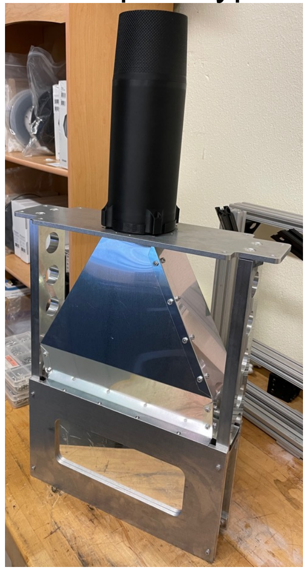
Shower-max Subsystem Overview

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.

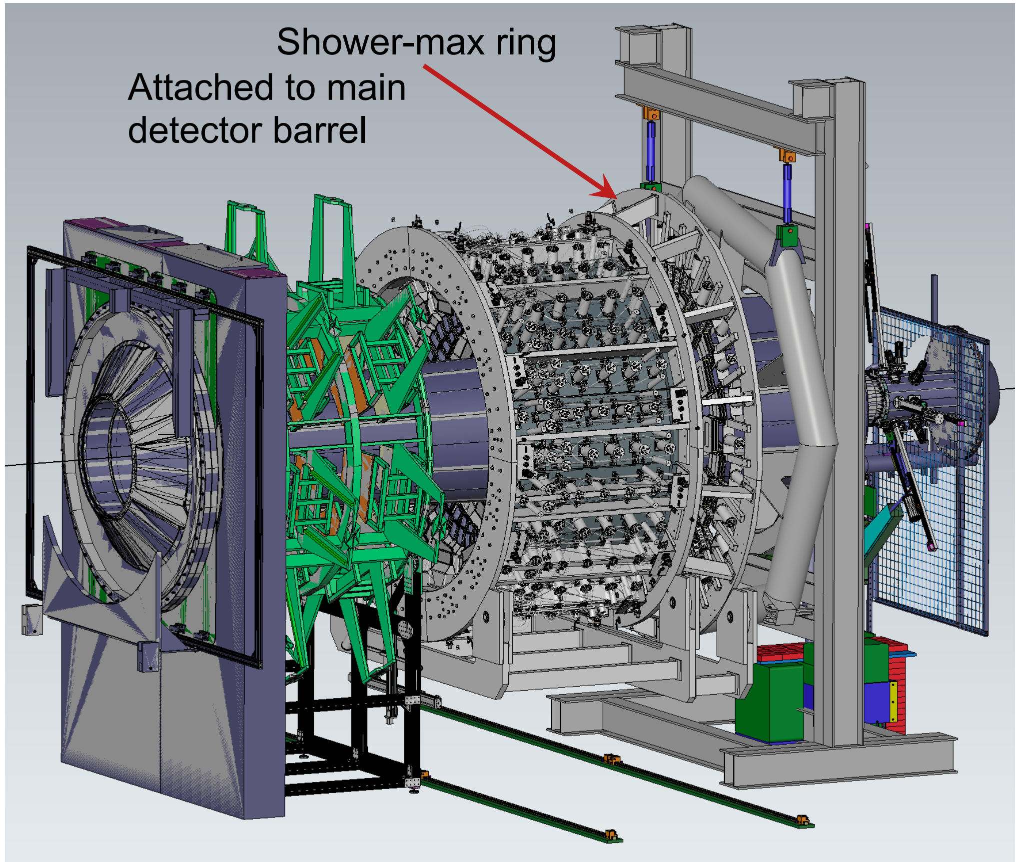




2022 prototype



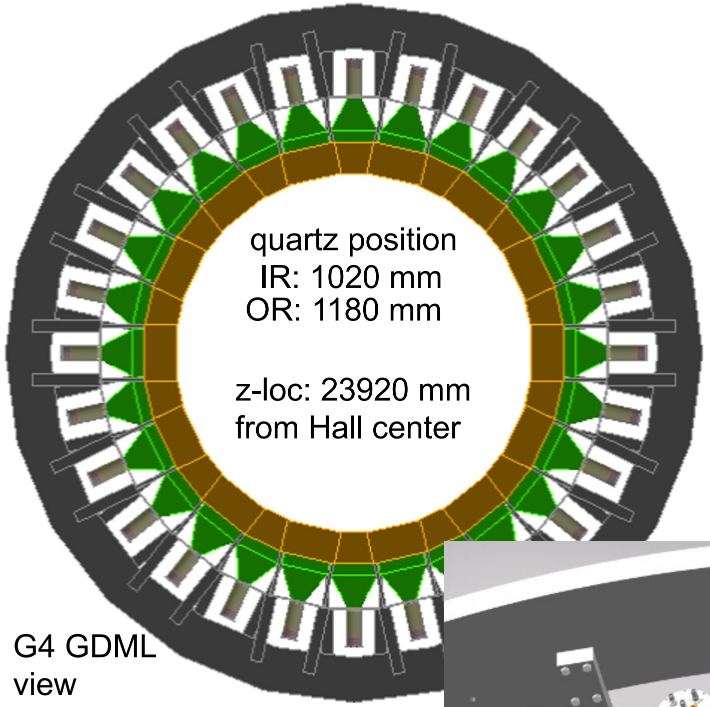
Shower-max:
An electromagnetic sampling calorimeter



- Provides additional measurement of Ring-5 integrated flux
- Weights flux by energy $\Longrightarrow$ less sensitive to low energy and hadronic backgrounds
- Also operates in event mode for calibrations and can give additional handle on background pion identification
- Will have good resolution over full energy range ($\lesssim 25\%$), and radiation hard with long term stability and good linearity

Shower-max module and ring geometry

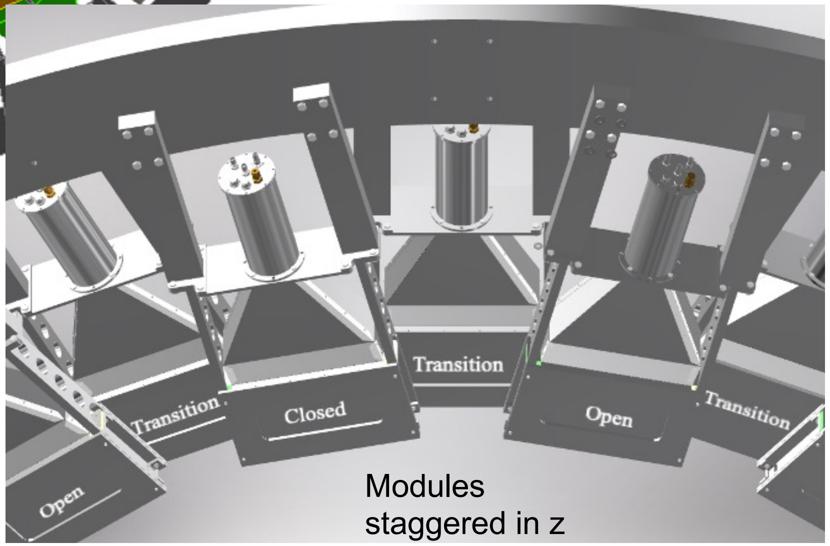
ShowerMax detector: ring of 28 sampling calorimeters intercepting physics signal flux ~1.7 m downstream of ring 5



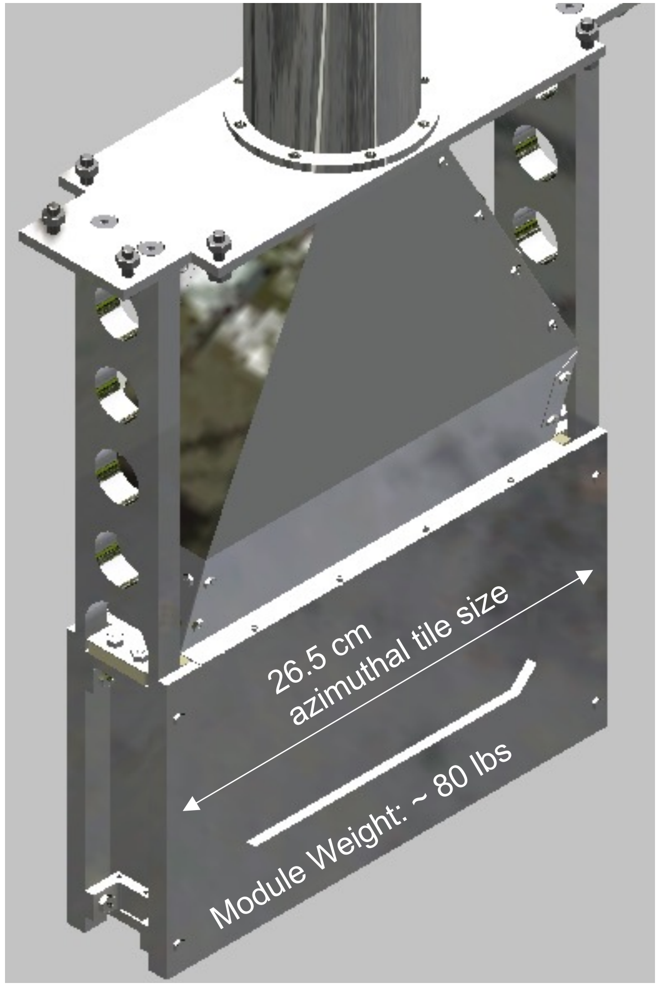
G4 GDML view

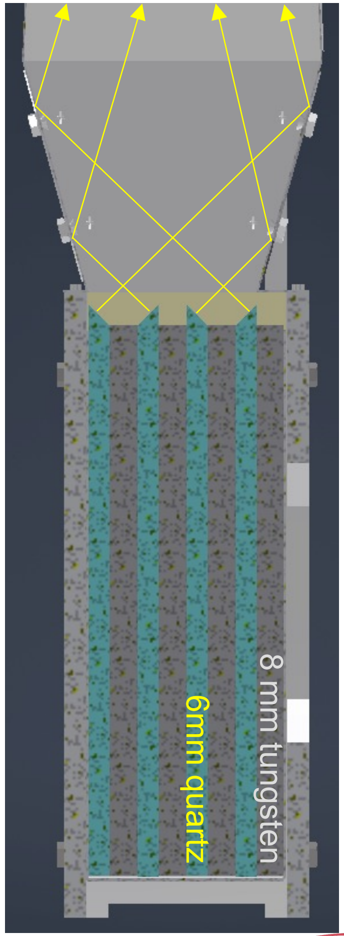
- Al. 6061 chassis and air-core light guide
- 99.95% pure tungsten and HPFS (quartz) radiators
- Rad. length: ~9.5 X_0
- Molière radius ~ 1.1 cm

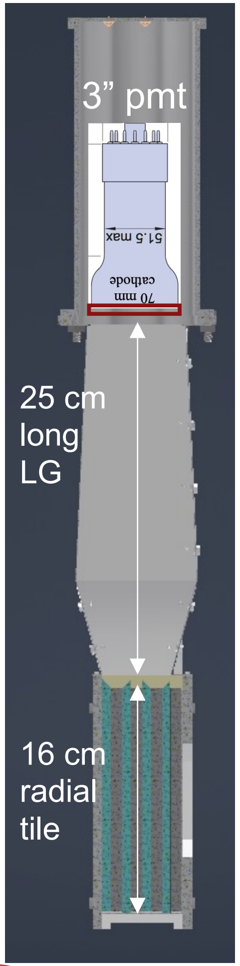
- See L. Bartoszek's talk for details of the SM and Main detector support structure



- Using Electron Tubes 9305QKB pmt







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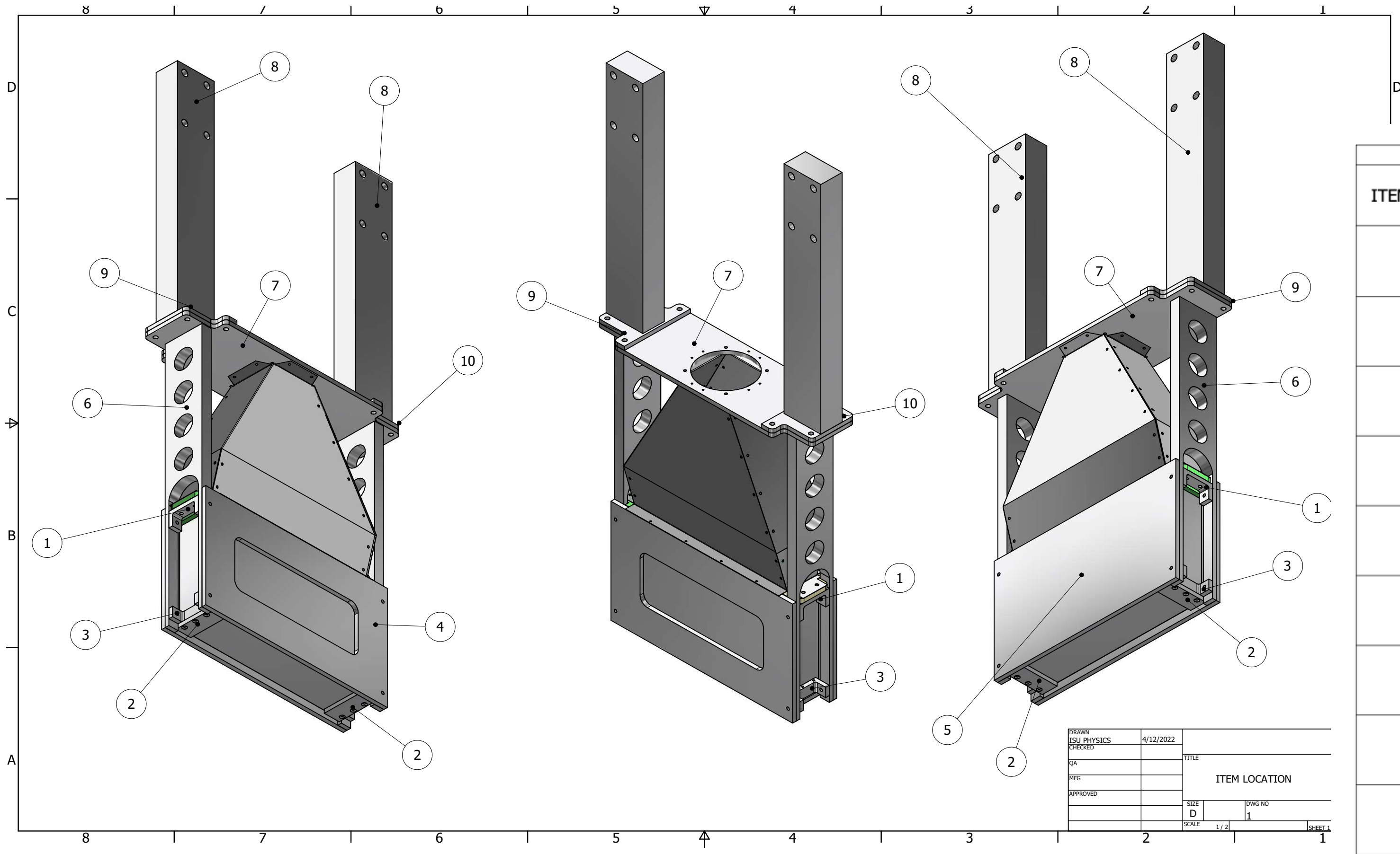
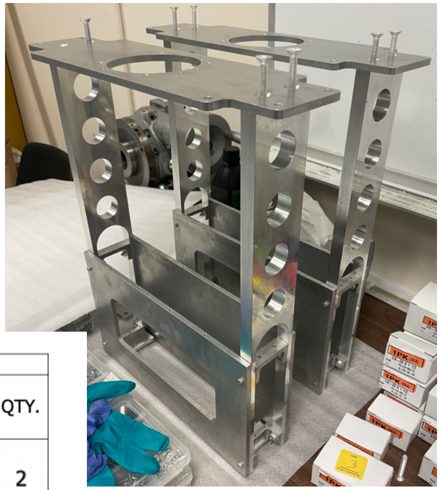
Shower-max Chassis parts

- Shop drawings created for prototyping

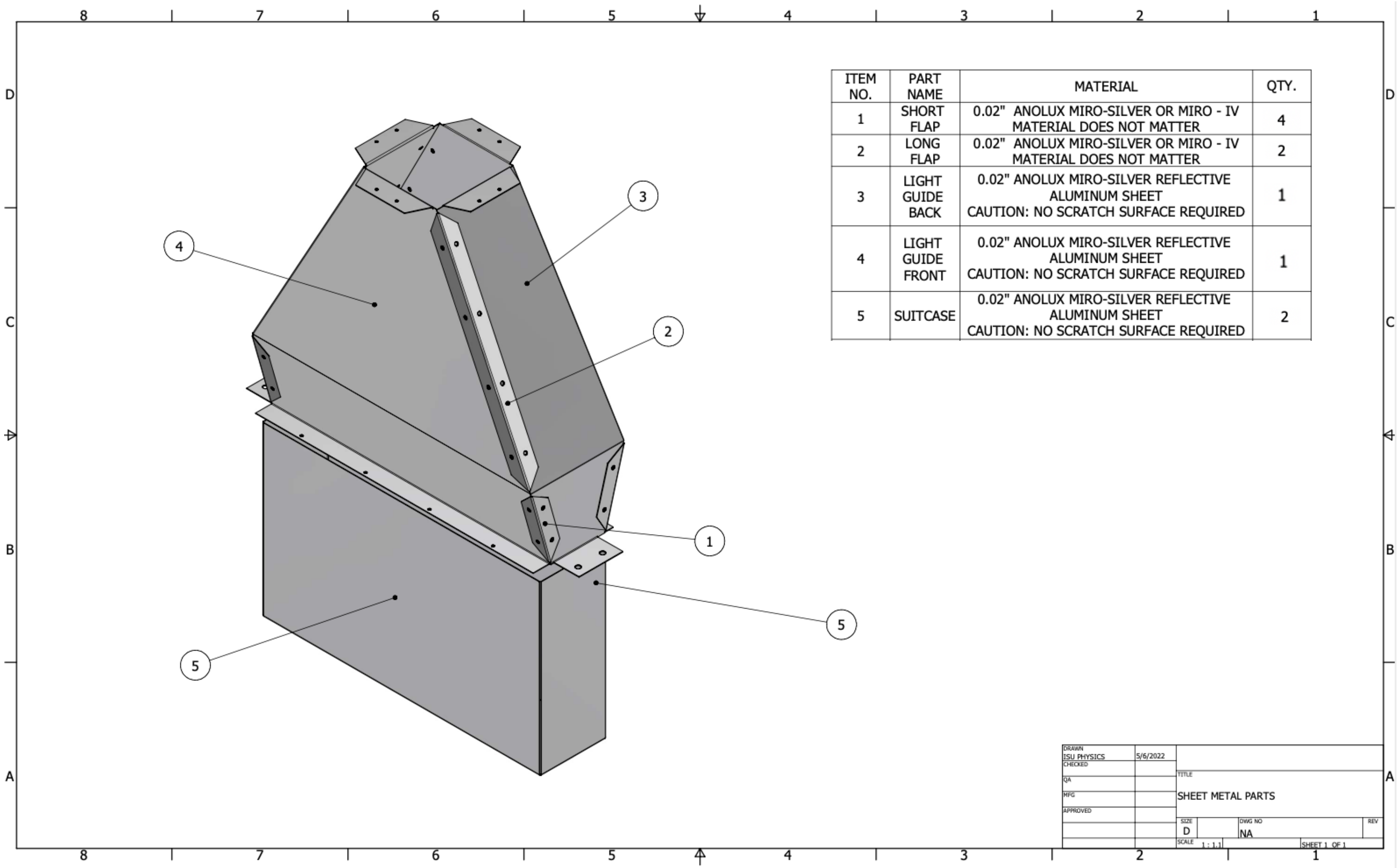




SHOWER MAX PARTS			
ITEM NO.	PART NAME/MATERIALS LIST	Material	QTY.
1	UPPER U CHANNEL	(1/4)" x 2" ALUMINUM 6061	2
2	FLOOR PLATE	0.25 (1/4) THICK 6061-T651 ALUMINUM PLATE	2
3	LOWER U CHANNEL	0.25 (1/4) THICK 6061-T651 ALUMINUM PLATE	2
4	FACE PLATE	0.25 (1/4) THICK 6061-T651 ALUMINUM PLATE	1
5	BACK PLATE	0.25 (1/4) THICK 6061-T651 ALUMINUM PLATE	1
6	WEB PLATE	0.625 (5/8)" THICK ALUMINUM 6061	2
7	TOP PLATE	0.25 (1/4) THICK 6061-T651 ALUMINUM PLATE	1
8	SUPPORT STRUT	1.5 (3/2)" THICK ALUMINUM 6061	2
9	LEFT FOOT PLATE	0.25 (1/4) THICK 6061-T651 ALUMINUM PLATE	1
10	RIGHT FOOT PLATE	0.25 (1/4) THICK 6061-T651 ALUMINUM PLATE	1

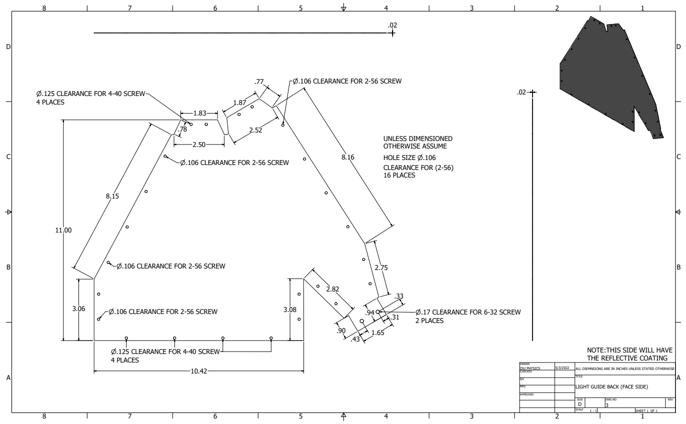
Shower-max Light guide parts

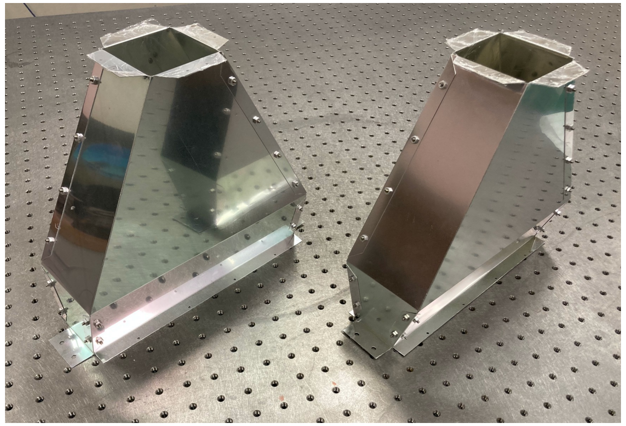
- Shop drawings created and light guide parts fabricated using Anolux Miro IV



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

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





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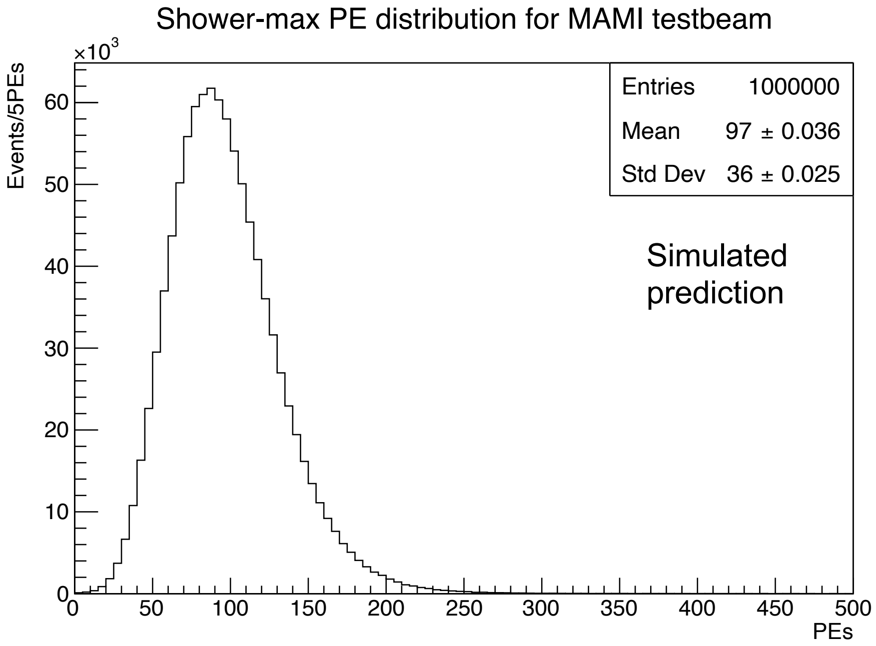
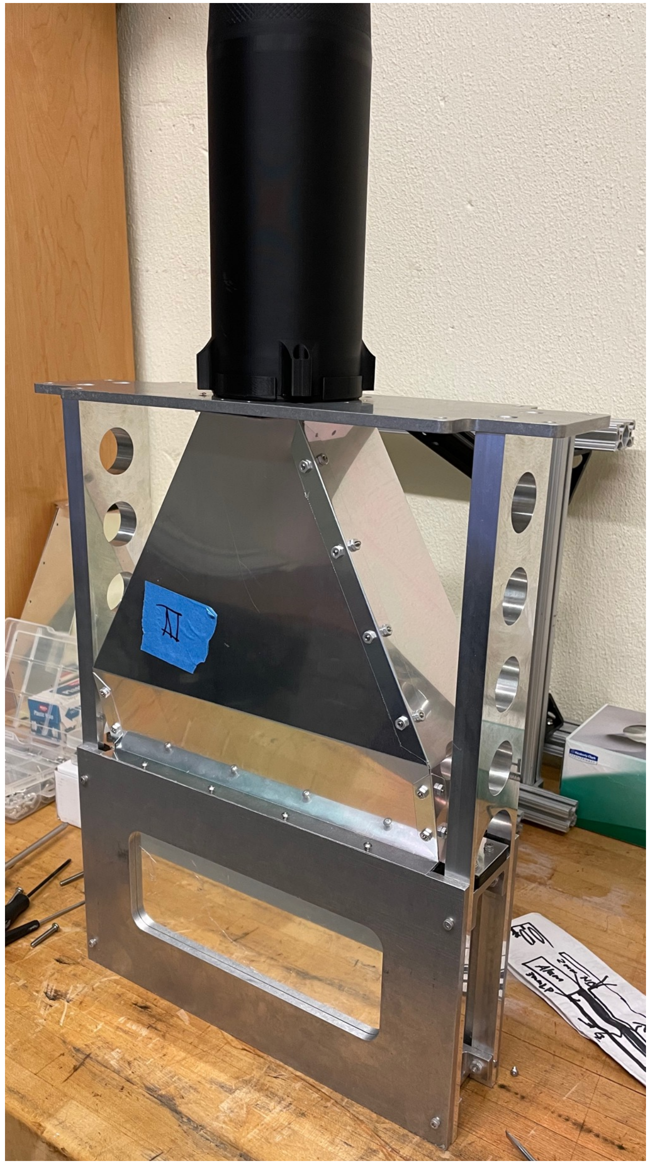
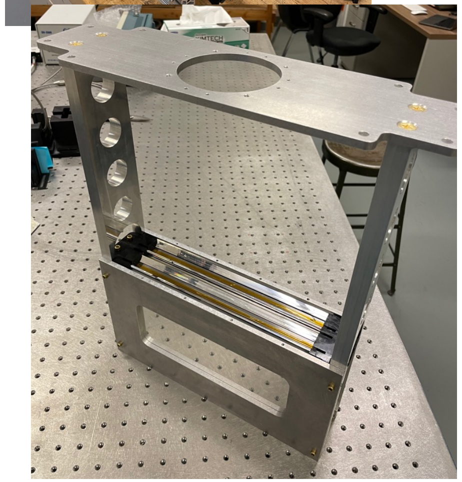
Shower-max: Prototyping and Testing

- New prototype constructed in summer 2022 for cosmic-ray tests and testbeam and in preparation for FDR
- Developed preliminary assembly fixture and techniques
- Prototyping some parts with 3D-printed plastic before fabricating with aluminum
- Prototype tests performed Nov 21 – 28, 2022 using 855 MeV electron beam at MAMI

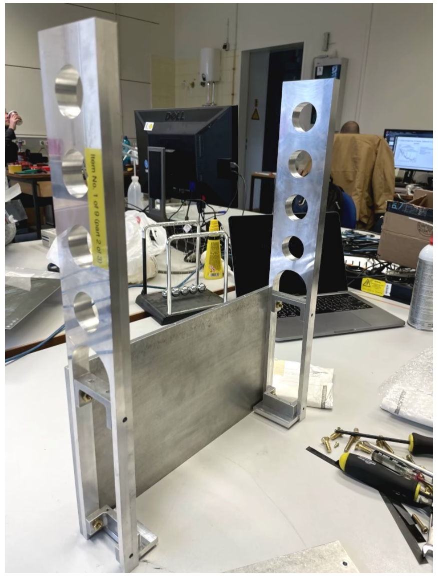


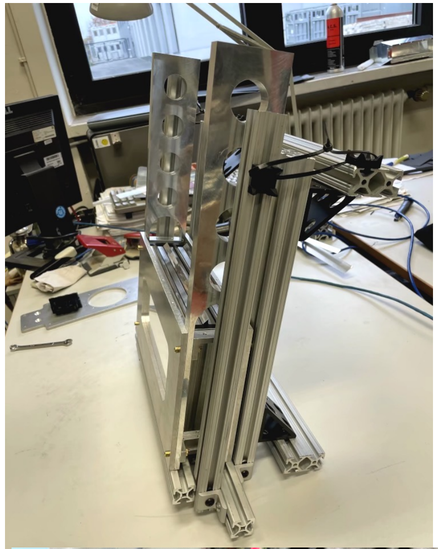


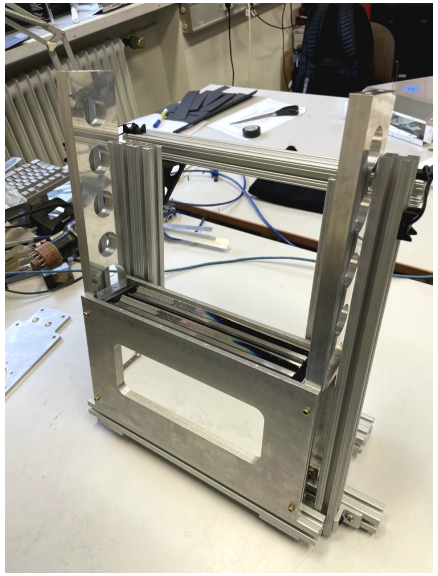


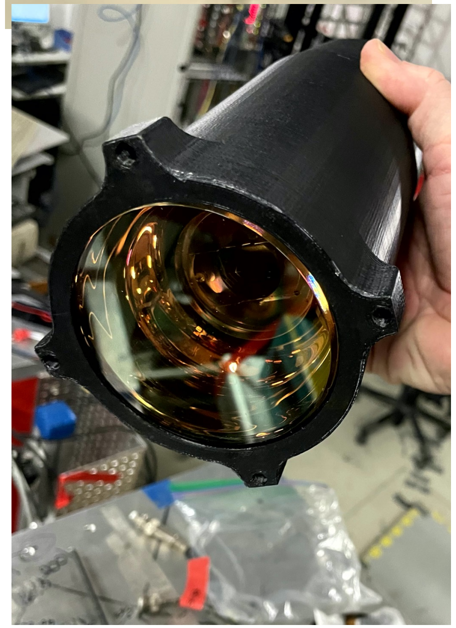
Shower-max: MAMI testbeam (Nov 21 – 28, 2022)

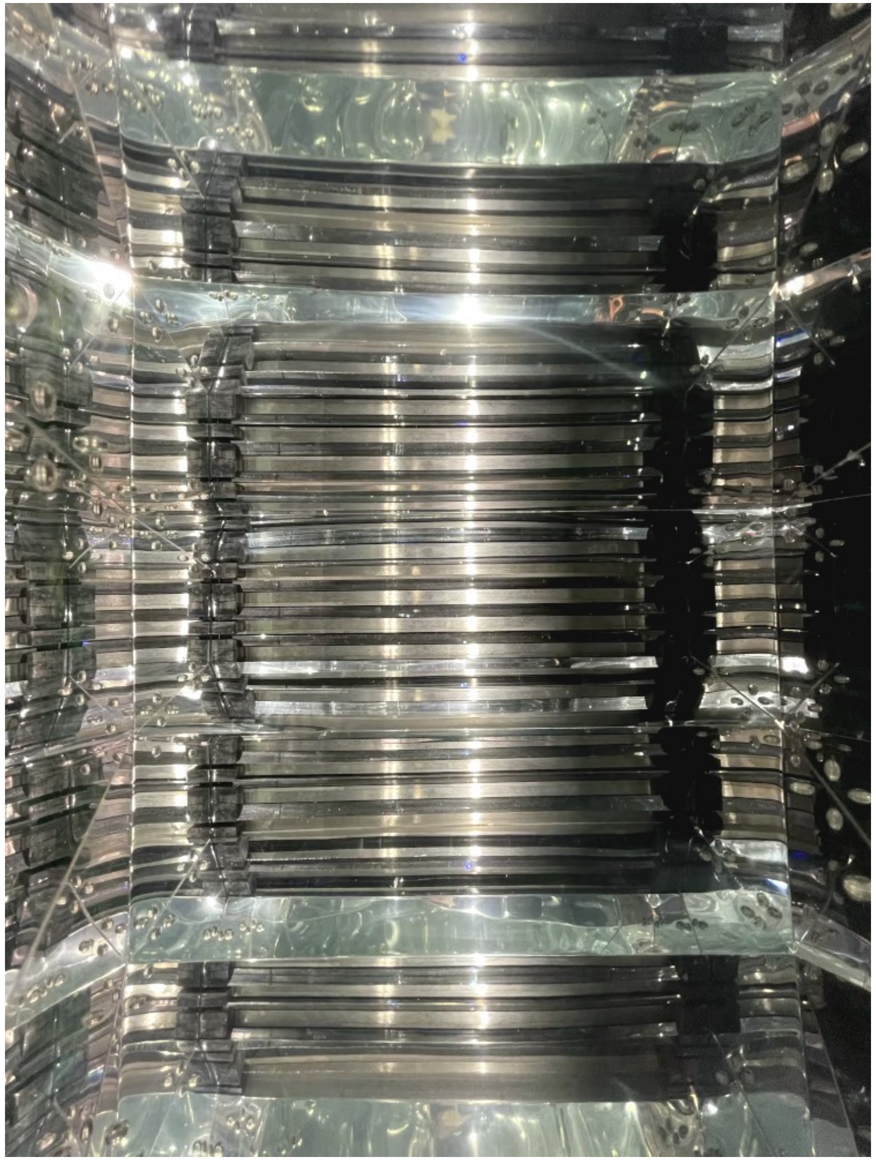
Assembly Photos







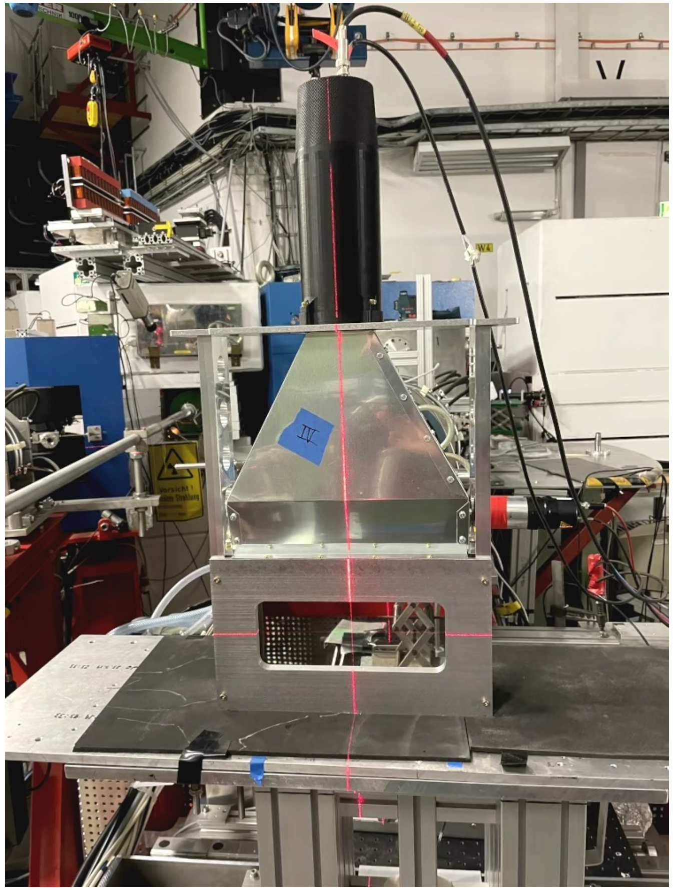


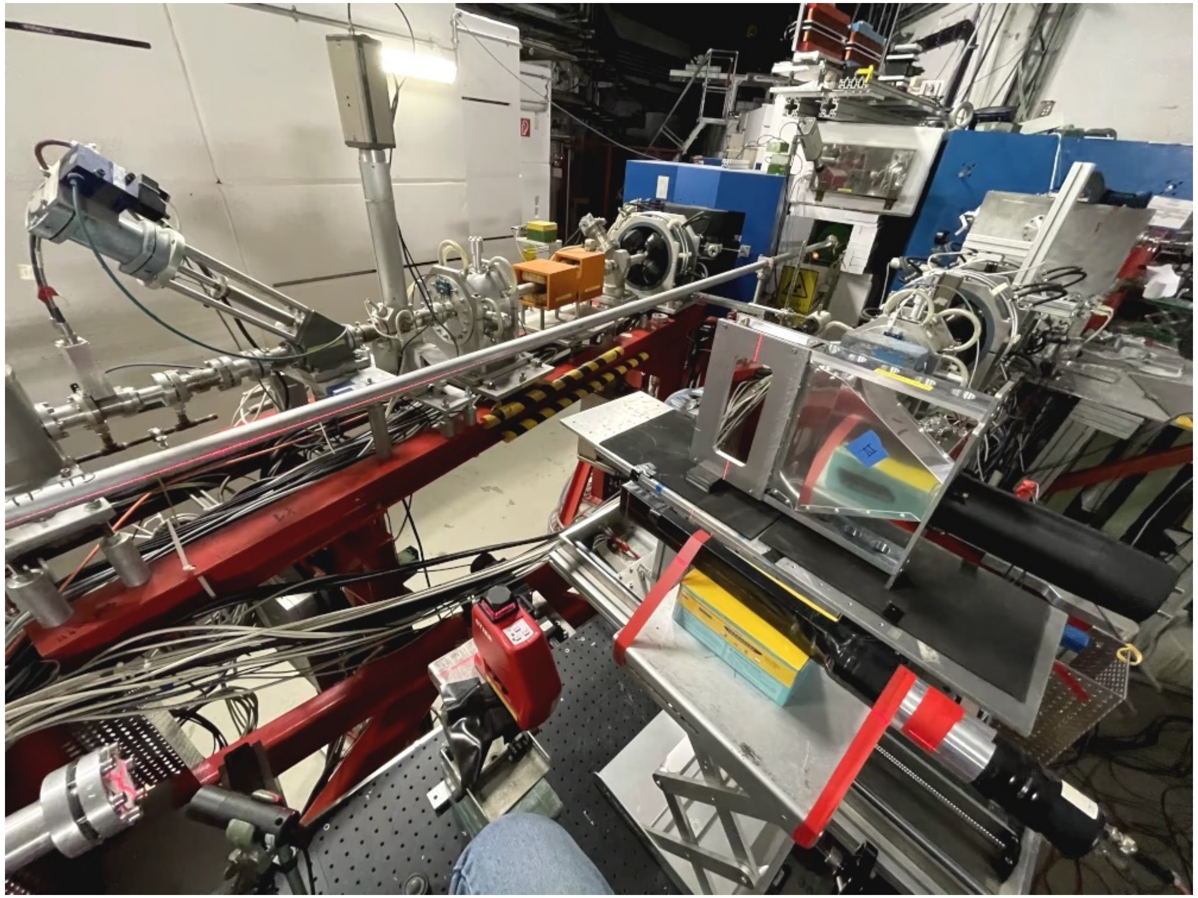


Shower-max: MAMI testbeam Setup

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





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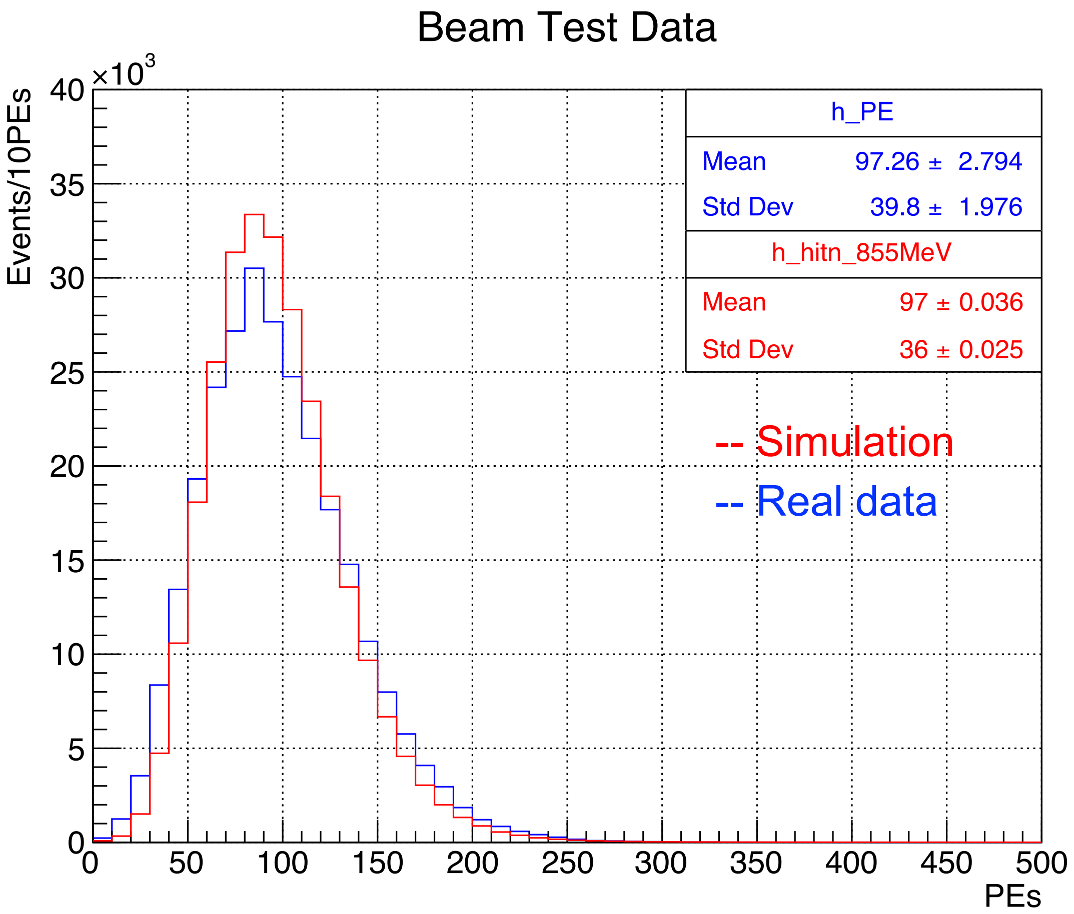
Shower-max: MAMI testbeam data and simulation comparison

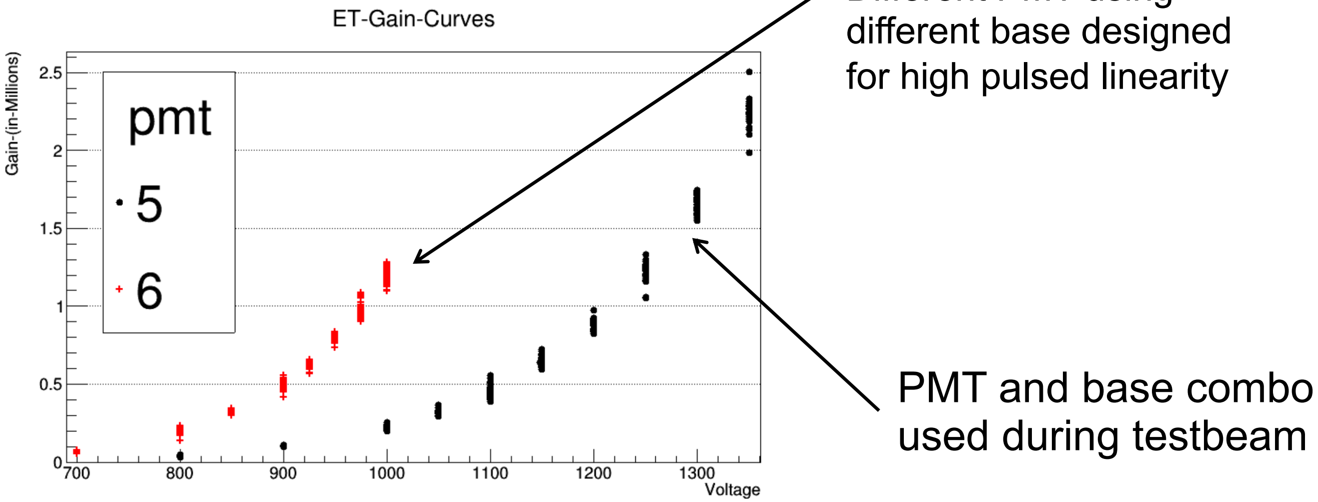
- Prior to testbeam, we simulated our expected PE distribution from MAMI testbeam for the non-wrapped, bare quartz configuration: --Results: 97 PE mean and 36 PE width. **The data agree very well with this!**

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 $\pm$ 0.12 x10^6, 200 fC/channel ADC sensitivity

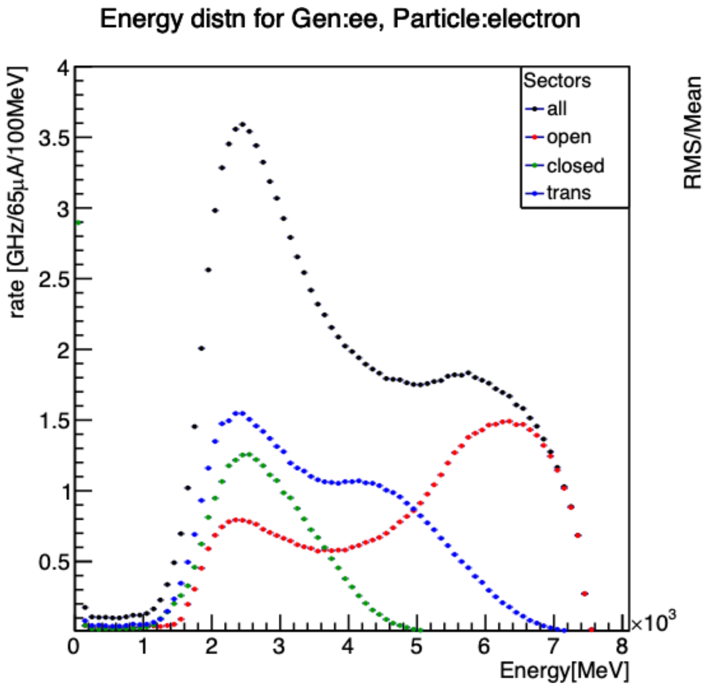


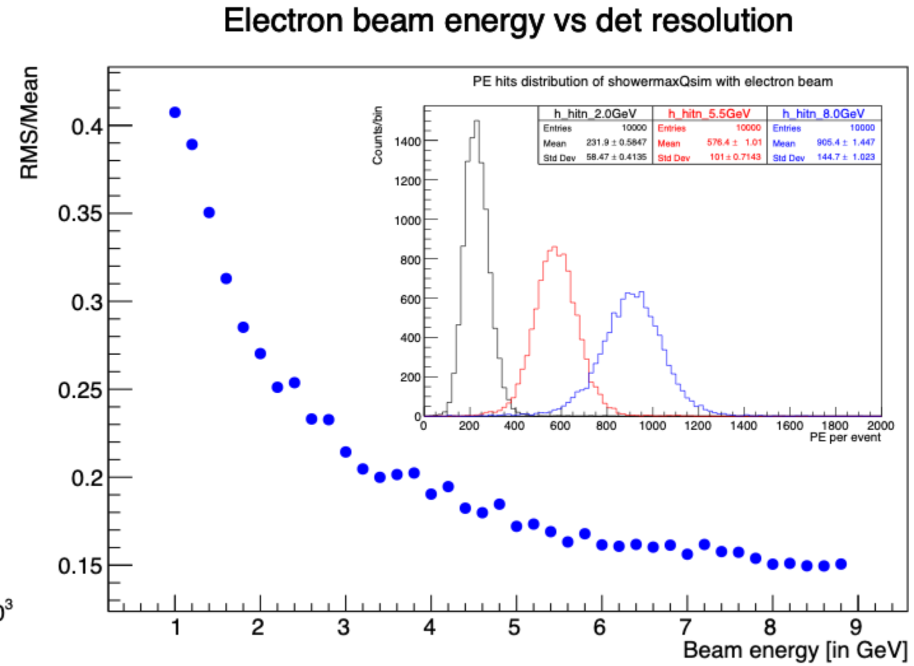
- PMT gain measurements



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





- 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		

Risks and Mitigation Strategy

- Given high rates on Shower-max and the nature of the calorimeter, lifetime dose densities in the quartz layers are high:
  --ranging from 150 Mrad to 1.3 Grad

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 combined with high rates also lead to high pmt cathode currents

- Longpass filters in front of the pmts eliminate the UV light contribution to the signal thus reducing affects of radiation damage to quartz and lowering pmt cathode currents

- Lifetime dose estimates in pmt and electronic components
  --LP filters are corning 7980 HPFS
  --pmt windows are fused silica

	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

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/CO_2 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

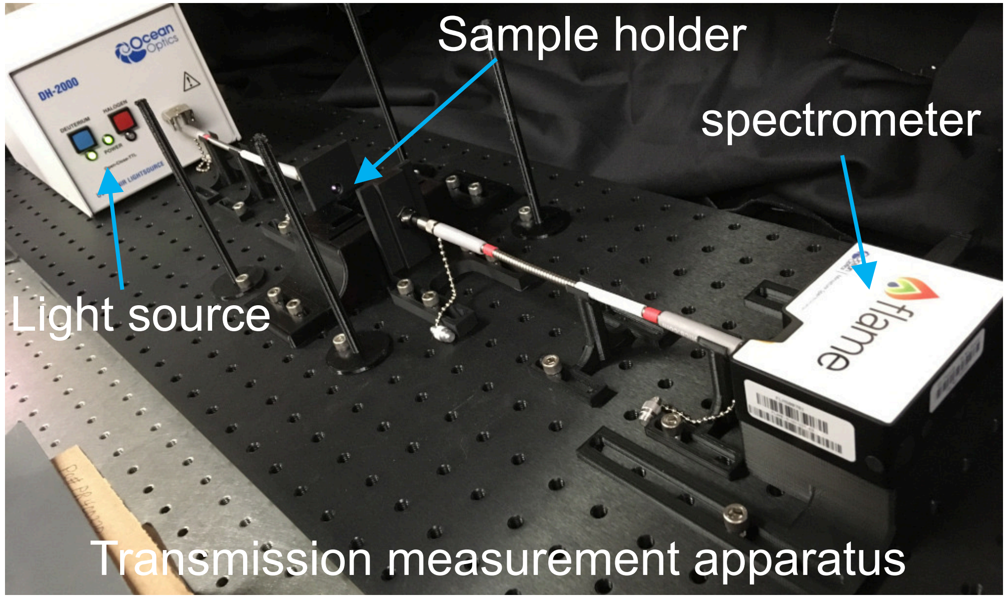
Shower-max Summary

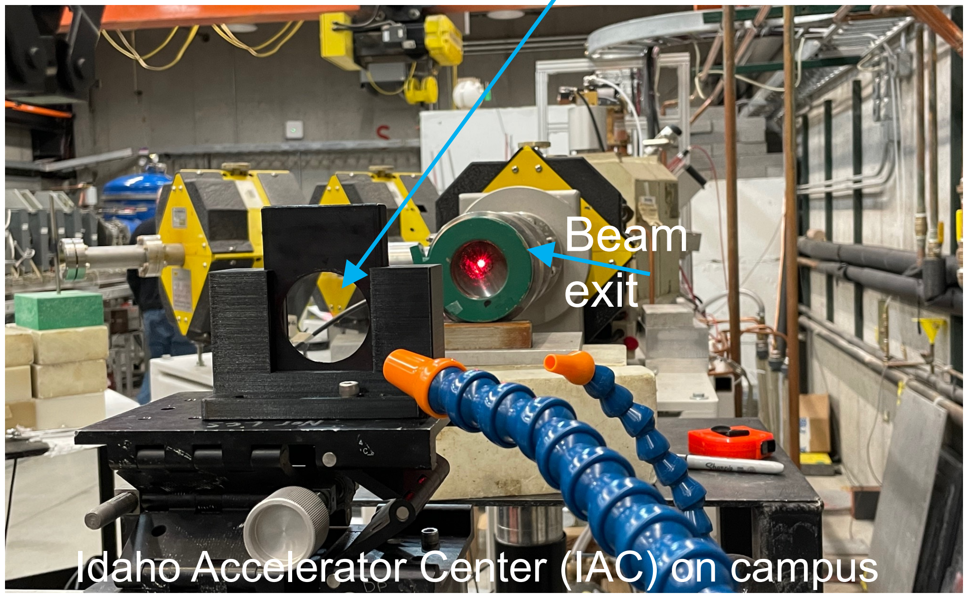
- **We are ready to proceed with parts procurement and construction of all Shower-max modules**
- Shower-max prototype parts fabrication, module assembly and testing went extremely well. MAMI testbeam results have validated its design, construction, and function
- Testbeam results have validated our optical simulation framework; we will use 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
- Risks and mitigation strategies have been identified. Using longpass filters eliminates UV light from the signal while reducing pmt cathode currents to acceptable levels; exact filter settings are being determined
- PMT non-linearity characterizations using full readout electronics chain to start soon; still need to determine best pmt and preamp gain combination for Shower-max

Irradiation Studies: quartz (completed)

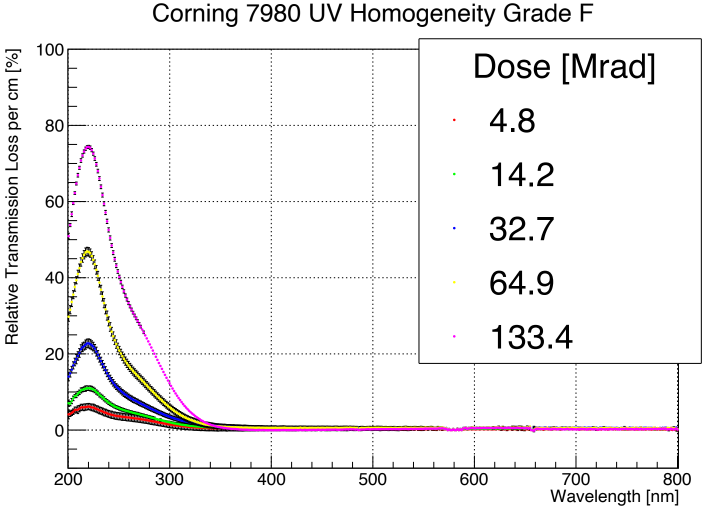
- Goal: quantify light transmission losses in detector radiators due to damage from anticipated radiation dose (for lifetime of MOLLER) – 45 Mrad peak and 120 Mrad peak per 5x5 mm^2 for ring 5 and ring 2, respectively
- Five candidate fused silica (quartz) samples chosen for testing: from Corning, Ohara, 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]

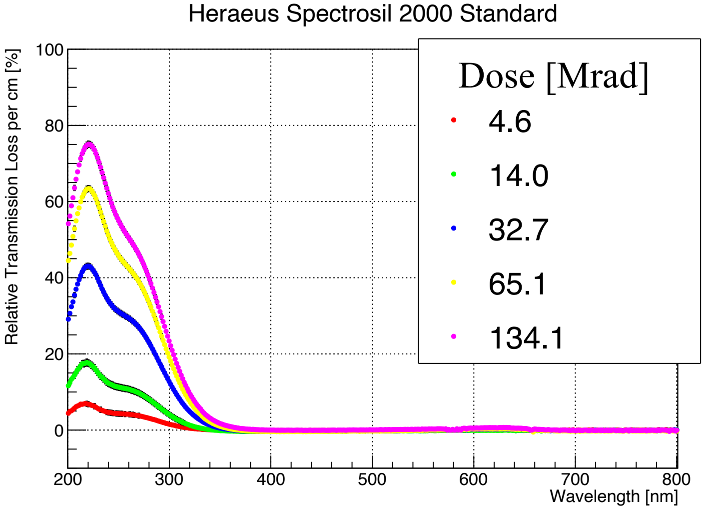
Samples: 5 cm diameter or square, 1 cm thick; polished faces

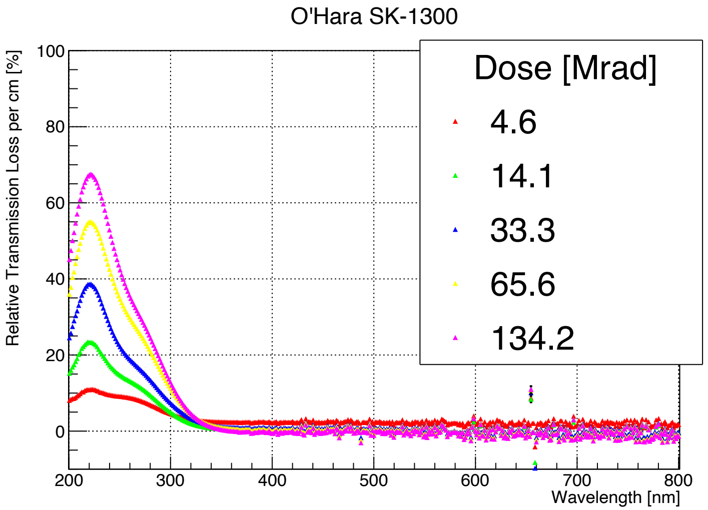


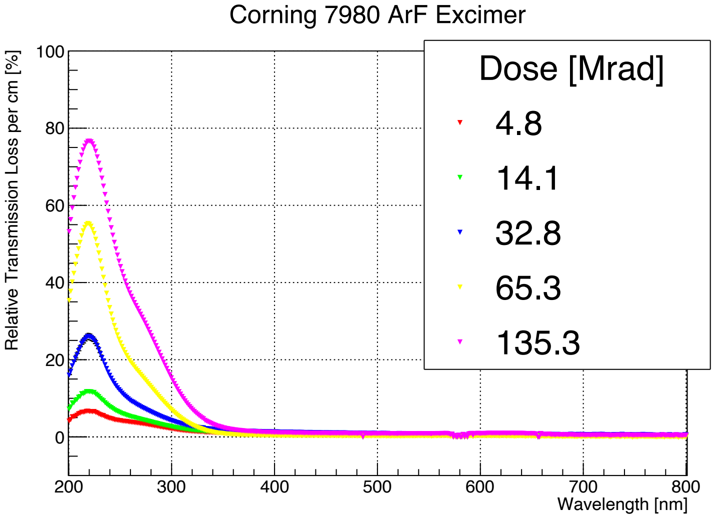


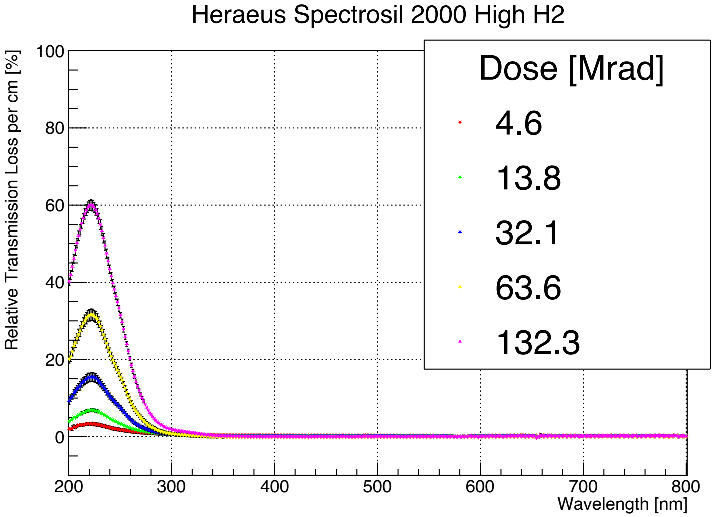
Quartz radiation-hardness results: light loss











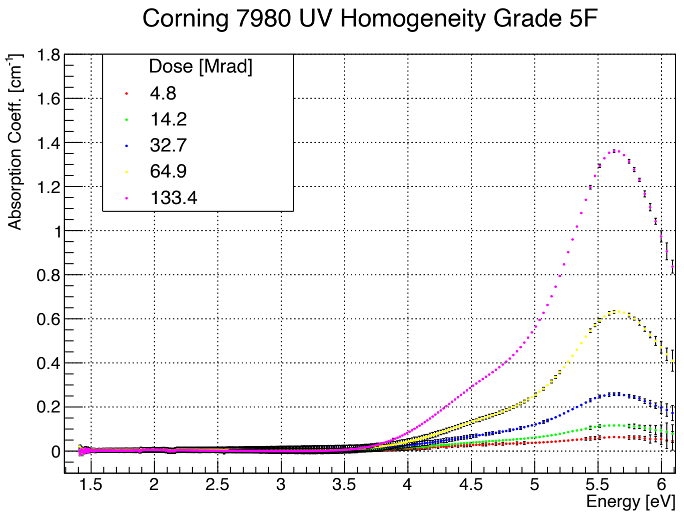
--All samples are wet (> 200 ppm OH content), except SK-1300 which is dry; doped Heraeus has high OH and high H2 content

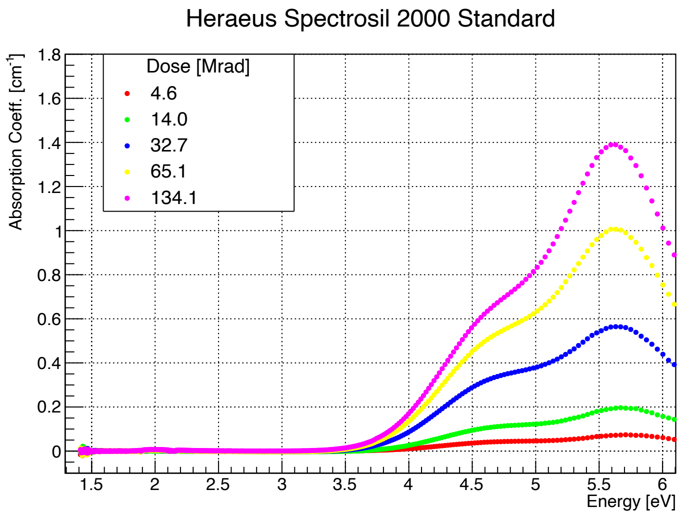
--Main absorption center at 5.6 eV is the E' – unavoidable point-like defects that cause dangling Si atoms which absorb light

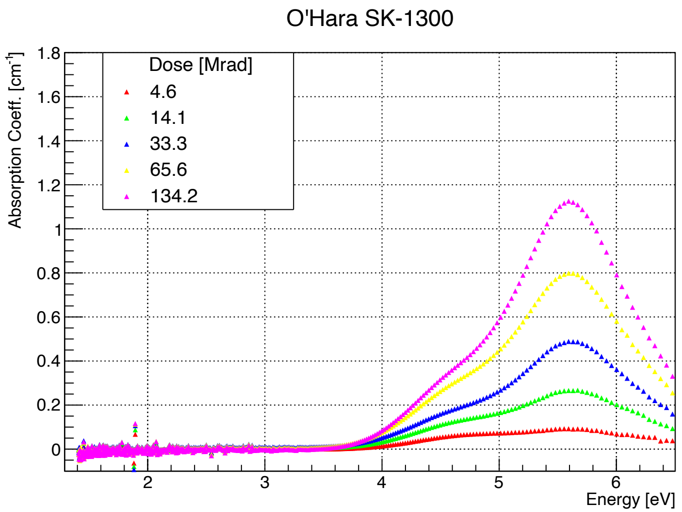
--The shoulder structures are from non-binding hydroxide absorption centers around 4.5 – 5 eV

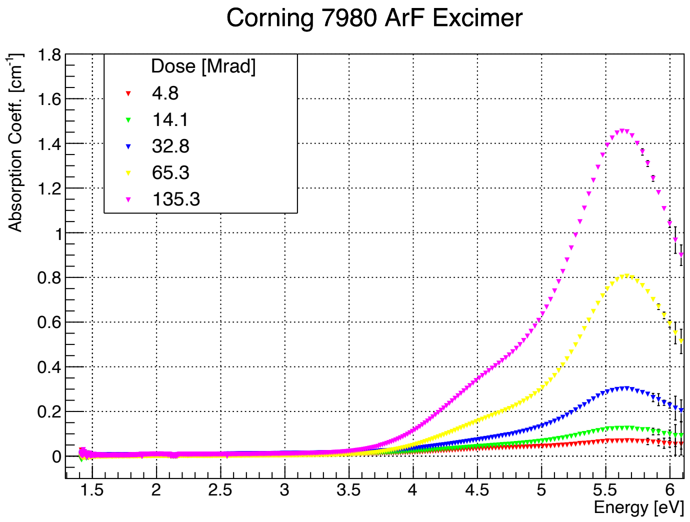
--the doped Heraeus shows very little of this damage center at our doses

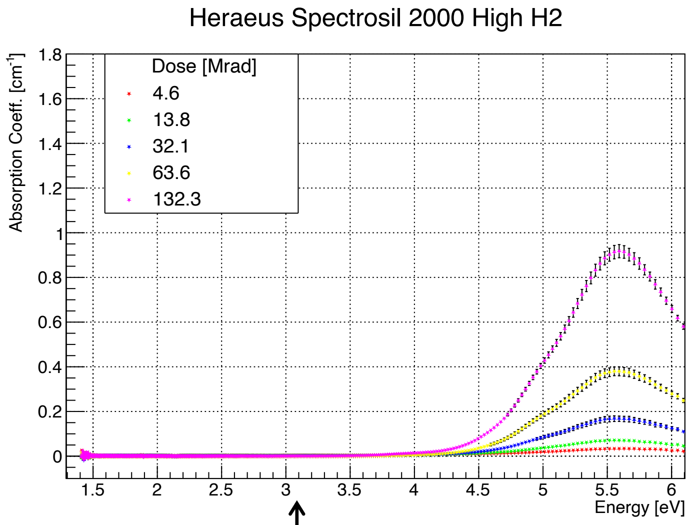
Quartz radiation-hardness results : Absorption Coeff’s











↑
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

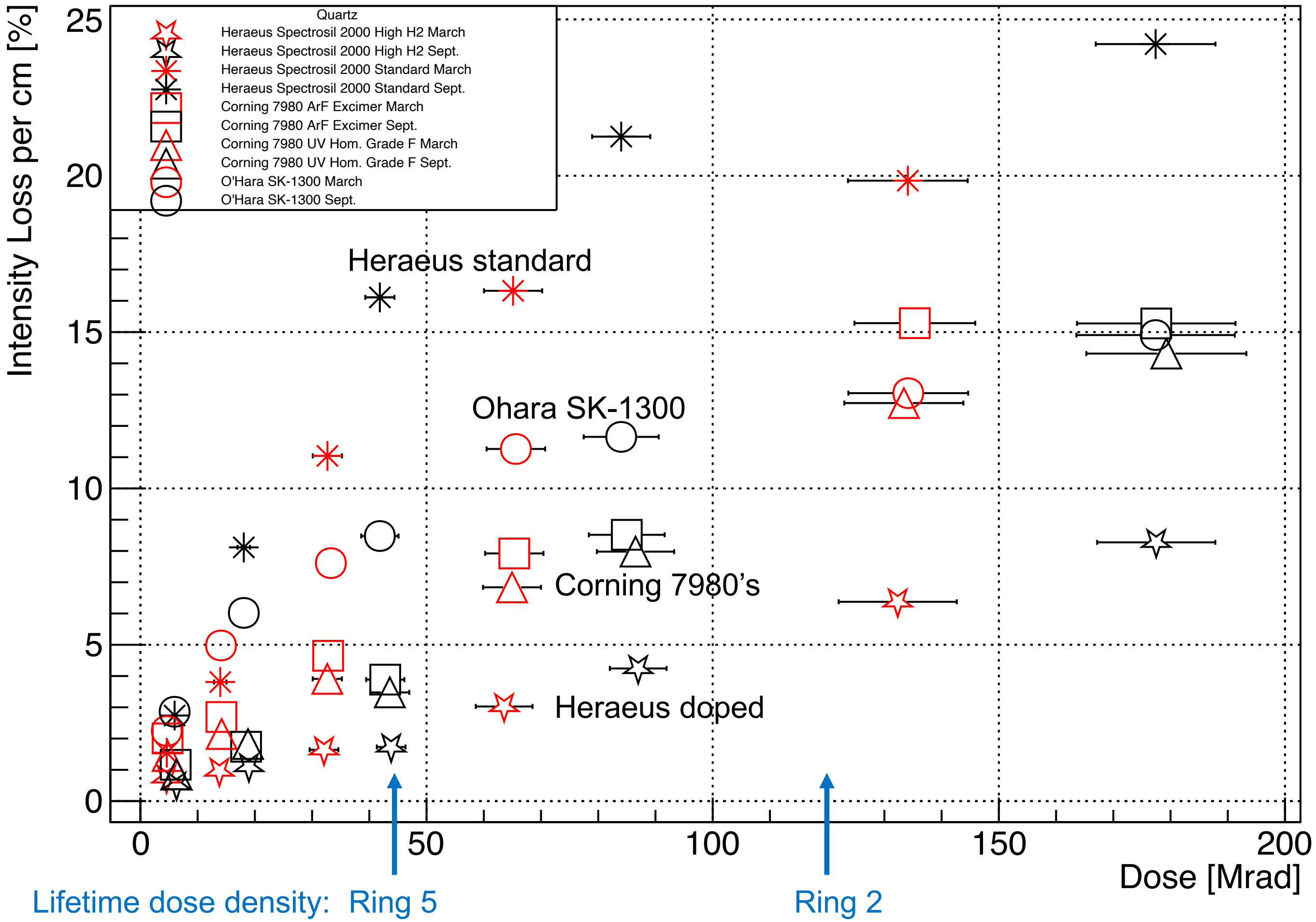
--The shoulder structures are from non-binding hydroxide absorption centers around 4.5 – 5 eV

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

Quartz Irradiation Study Summary

- Quartz radiation damage study completed; the data needed to inform our optical simulations is in hand
- Dose estimates for our 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
- Ordered 3” LP filters, also Corning 7980 (two each: 350 and 400 nm); will radiation test them early next month

Total Intensity Loss Across Wavelengths 220-400 [nm]



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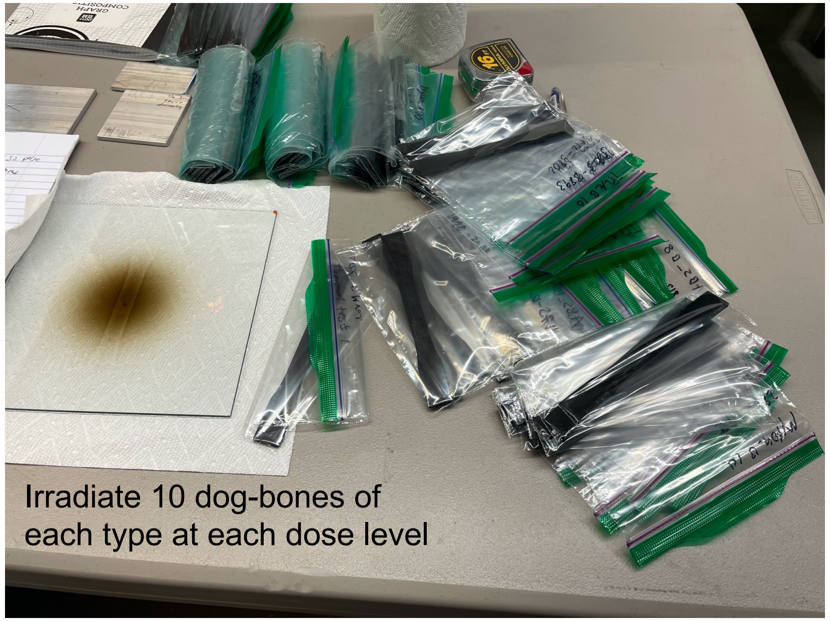
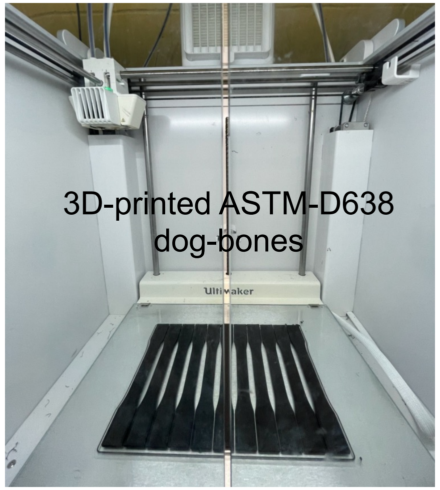
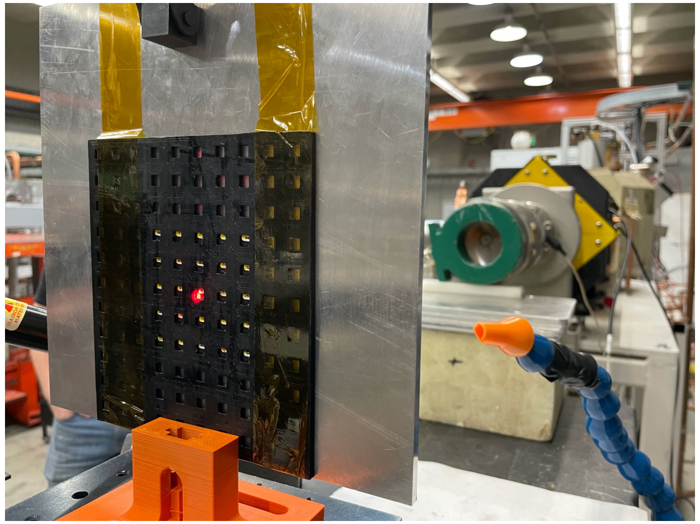
3D-printed Plastic Irradiation tests (ongoing)



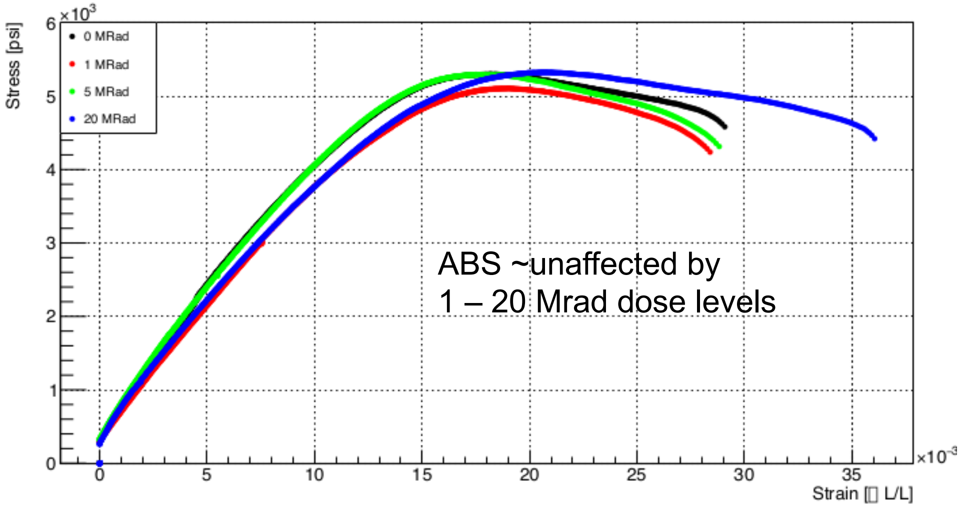


Nanodot
OSL array
beam
dosimetry

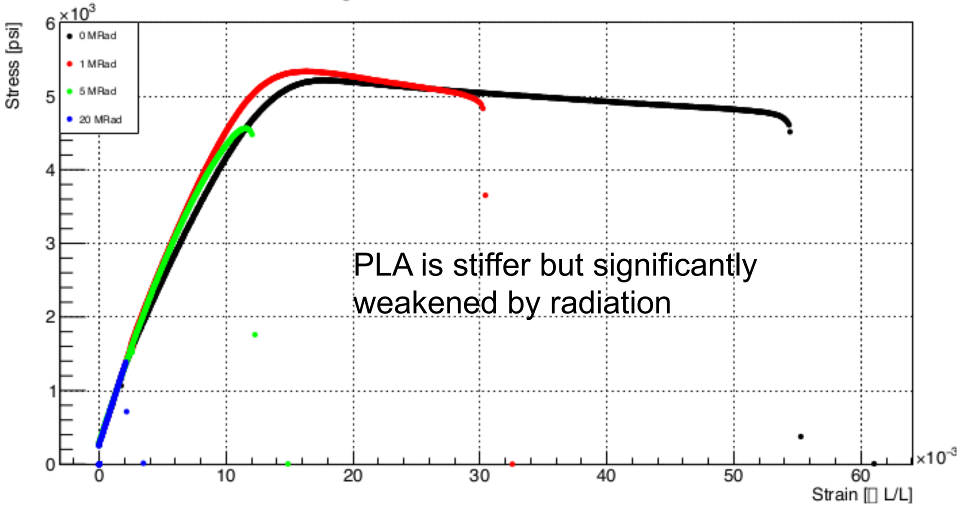


Tensile strength
testing apparatus

ABS Stress-Strain Curves



Tough PLA Stress-Strain Curves



Irradiation studies

Preliminary results for 3D-printed plastics:

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

- Tensile strength results for non-irradiated plastic

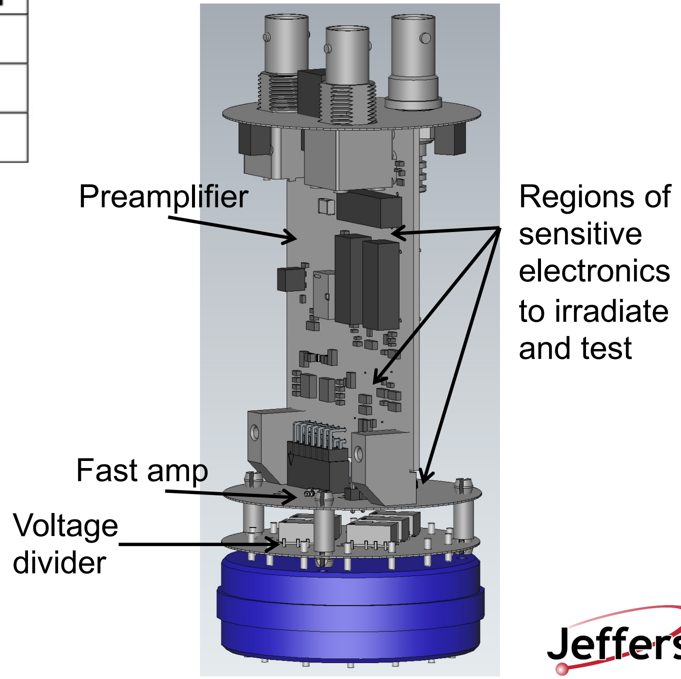
	0 Mrad (baseline)	
Material	Modulus [ksi]	Yield [ksi]
ABS	390 ± 20	4.7 ± 0.2
tough PLA	430 ± 20	4.8 ± 0.2
Nylon	250 ± 30	6.1 ± 0.2
C-fiber Nylon	520 ± 50	5.6 ± 0.3

	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

Plans for electronics:

- Sensitive SI chips will be dosed from 5 – 100+ krad and tested for functionality and performance
- First Irradiation tests took place on Dec 13 and 14, 2022 at Idaho Accelerator Center (IAC)
- Beam dose per pulse lower by 100x compared to plastic and quartz studies

PMT electronics



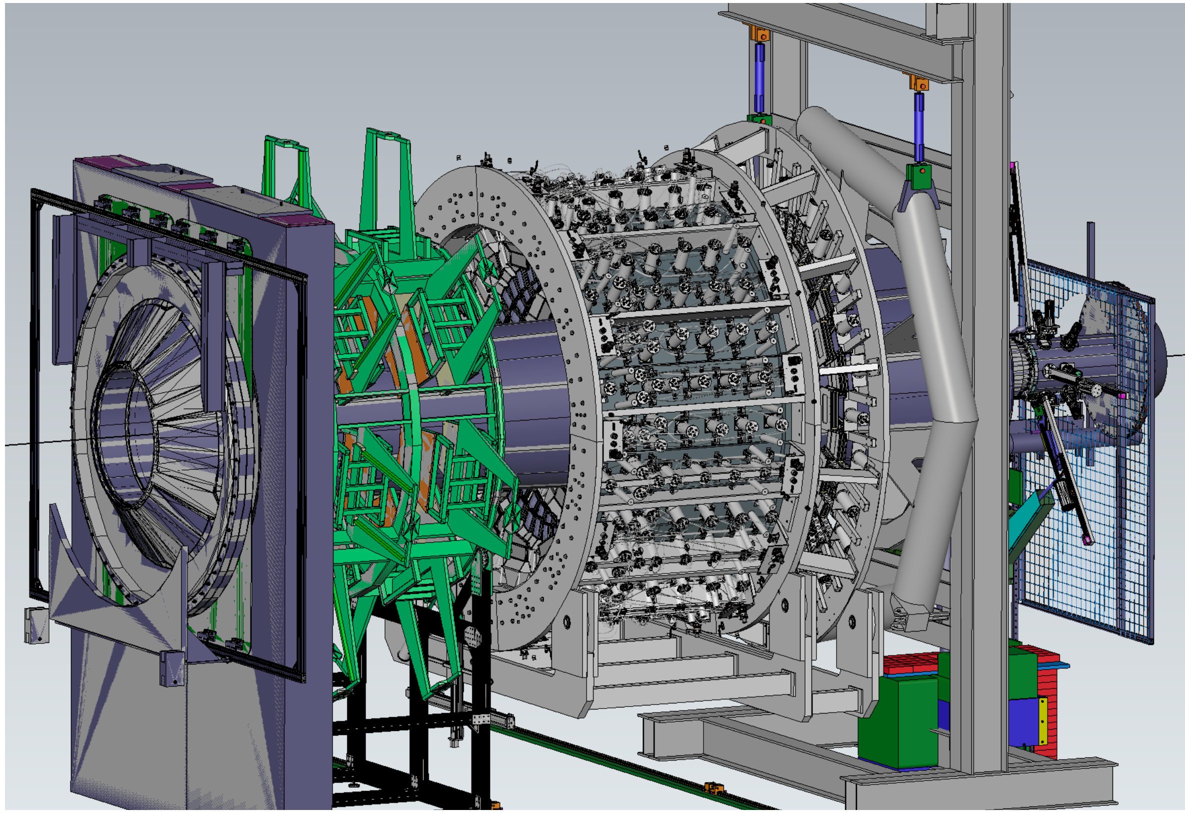
Plastic and Electronics Irradiation Study Summary

- Plastic irradiation studies are still ongoing. We will test 3D printed materials from UMass this month: Onyx® (carbon-nylon) and a laser-sintered material
- 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 the stiffness and strength of the various printed plastics informing our choice of material and deflection analyses of the CAD model
- There seem to be several options for 3D printed plastics that are sufficiently radiation resistant for MOLLER; we plan to finalize our study in early 2023
- Electronics testing started last month. We had an engineering run and follow-up tests will take place in Jan. and Feb. to finalize the study
- Electronics dosing estimates for tests will be refined, and event and integrate mode electronics testing setups and procedures will be fine tuned for the final run
- Summary documents will be written and posted in the Document DB

Questions?

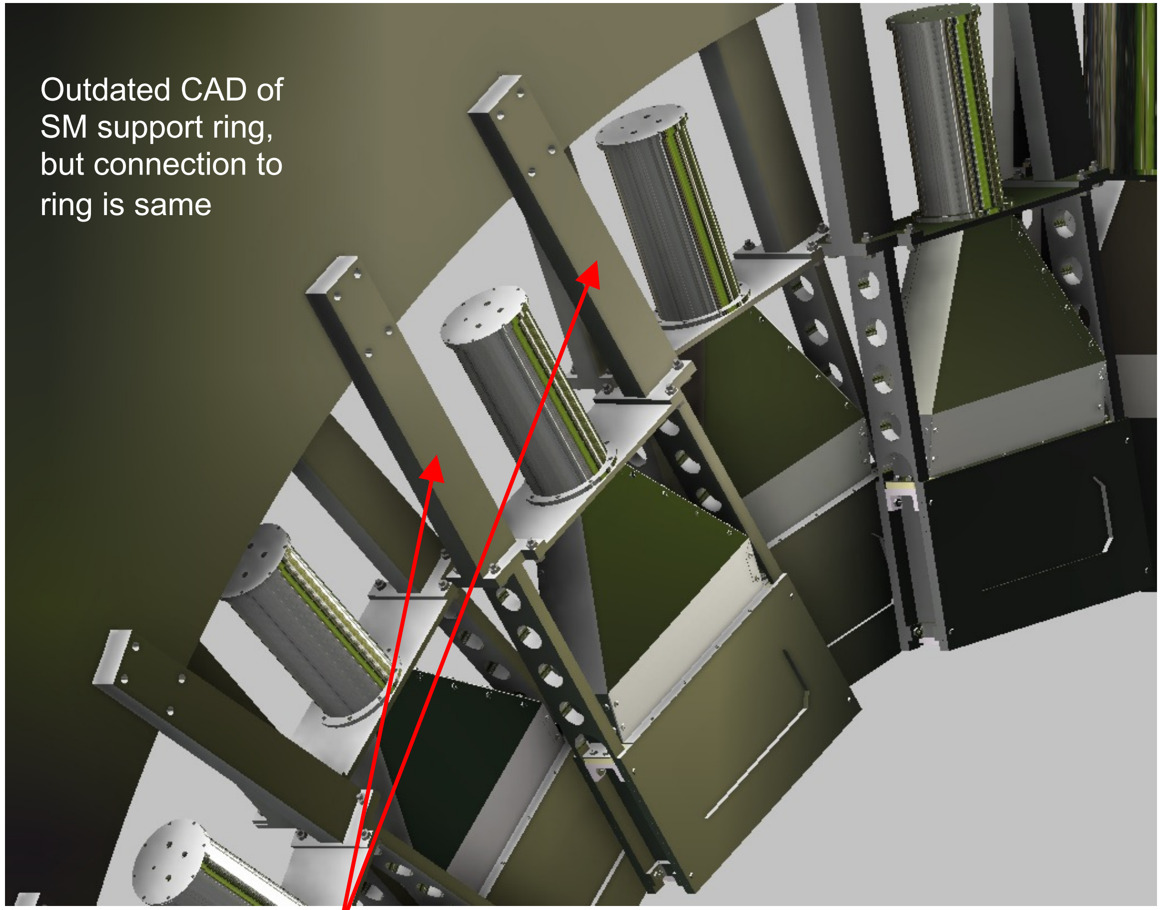
D. McNulty
mcnulty@jlab.org

- Shower-max overview
- Design and Engineering
- Prototyping and testbeam
- Simulated performance
- ES&H and Quality Assurance
- Irradiation Studies: quartz, plastic and electronics
- Summary

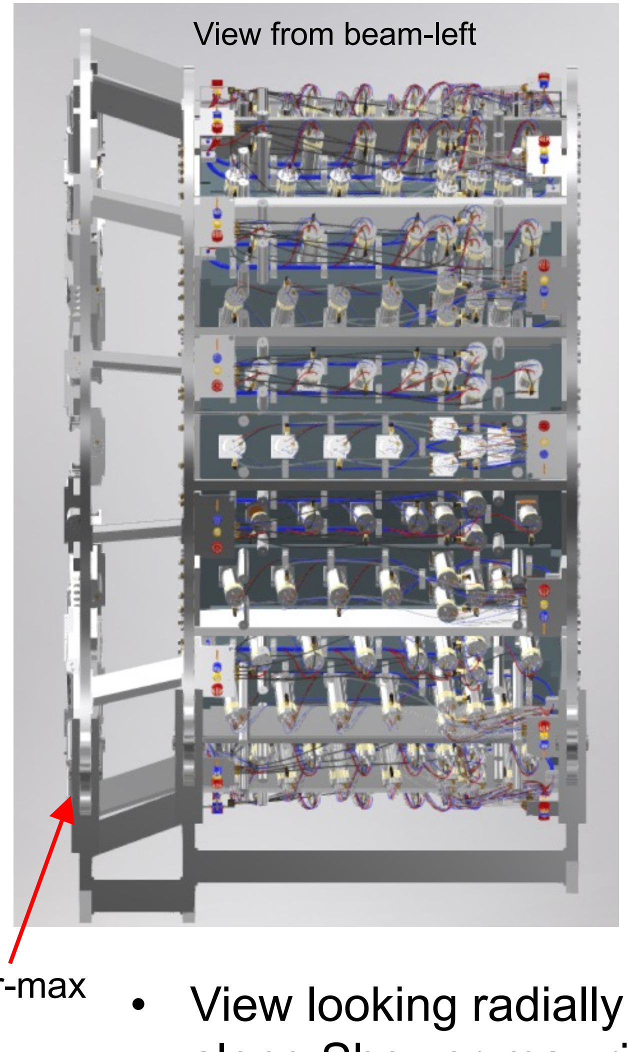


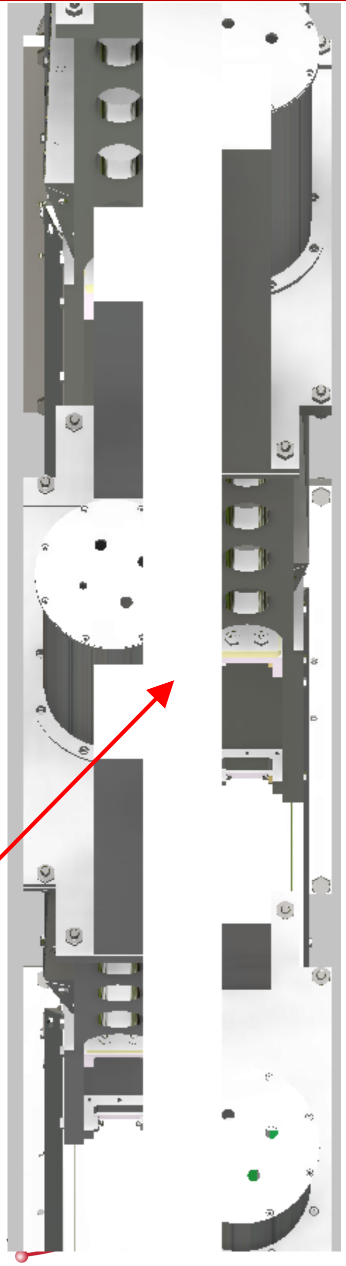
Appendix Slides

Shower-max Ring Support Structure



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

Shower-max dose simulations using remoll

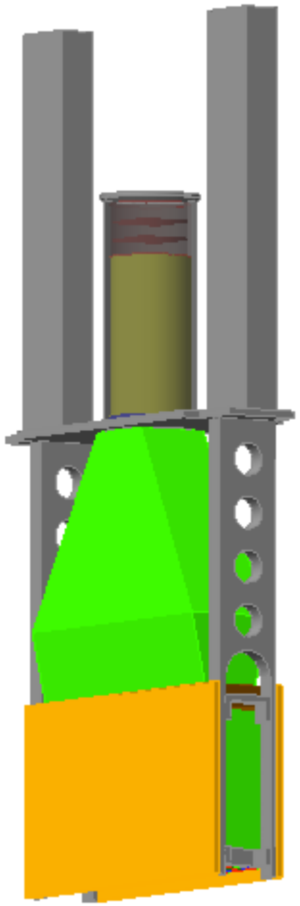
Shower-max ring in remoll GDML:

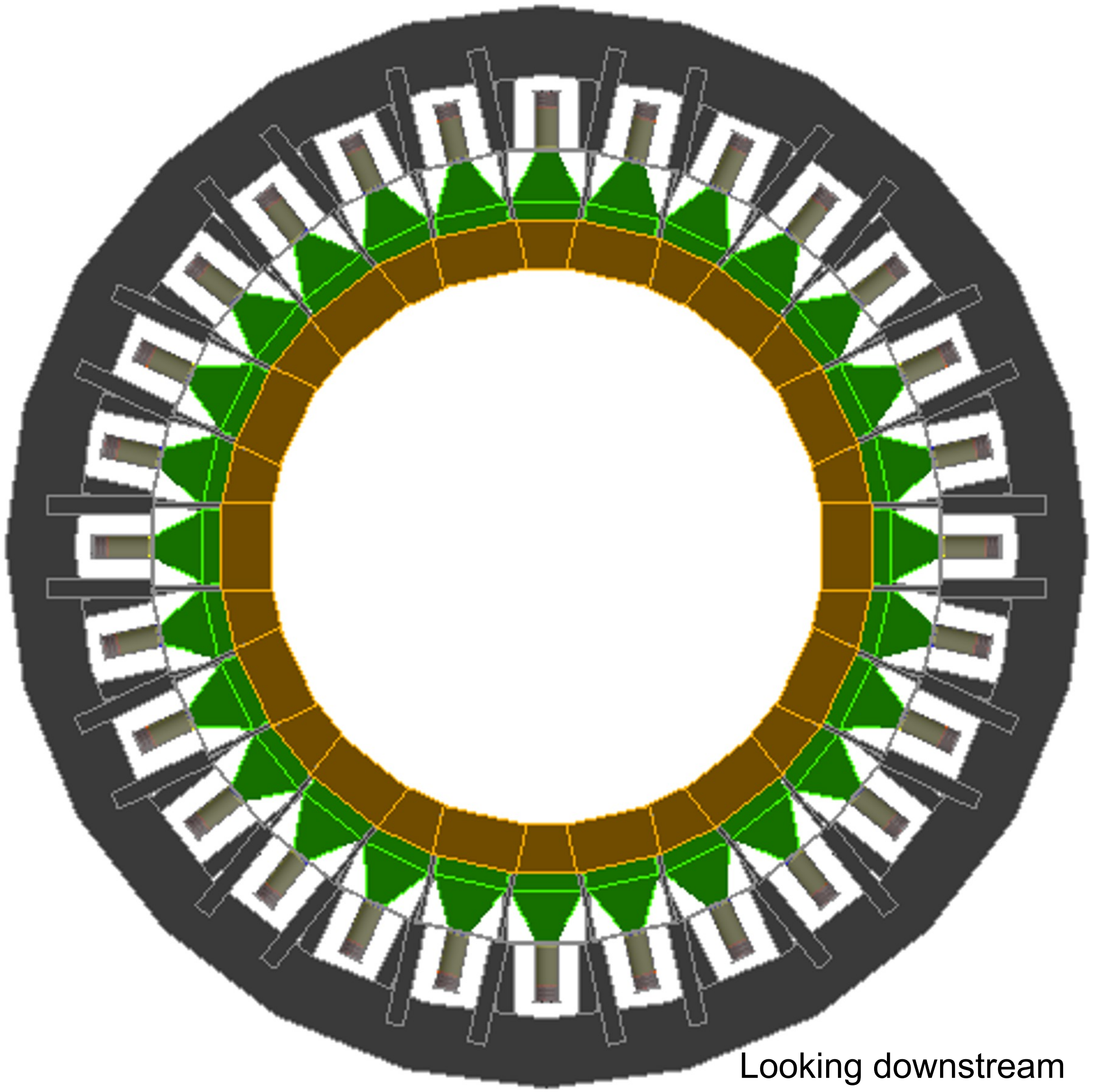
- Work done by Sudip Bhattarai

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

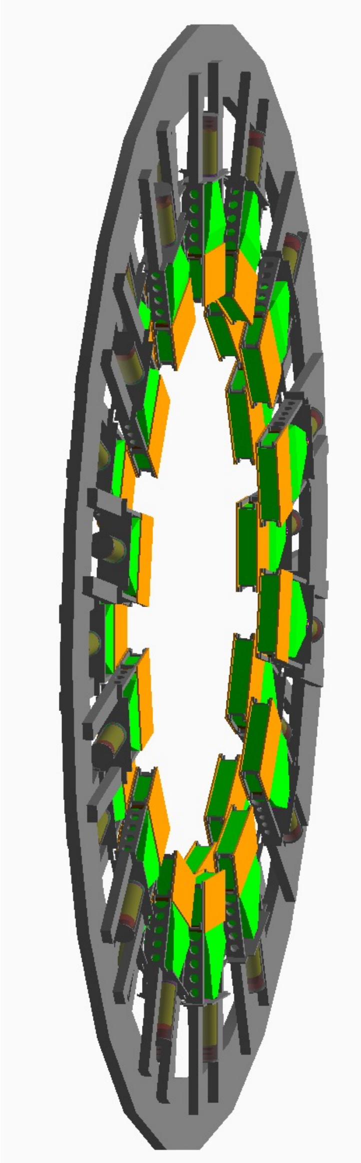
--We also have estimates for the LP filter, PMT window, and pre-amp Si wafers

[docDB #866]





Looking downstream

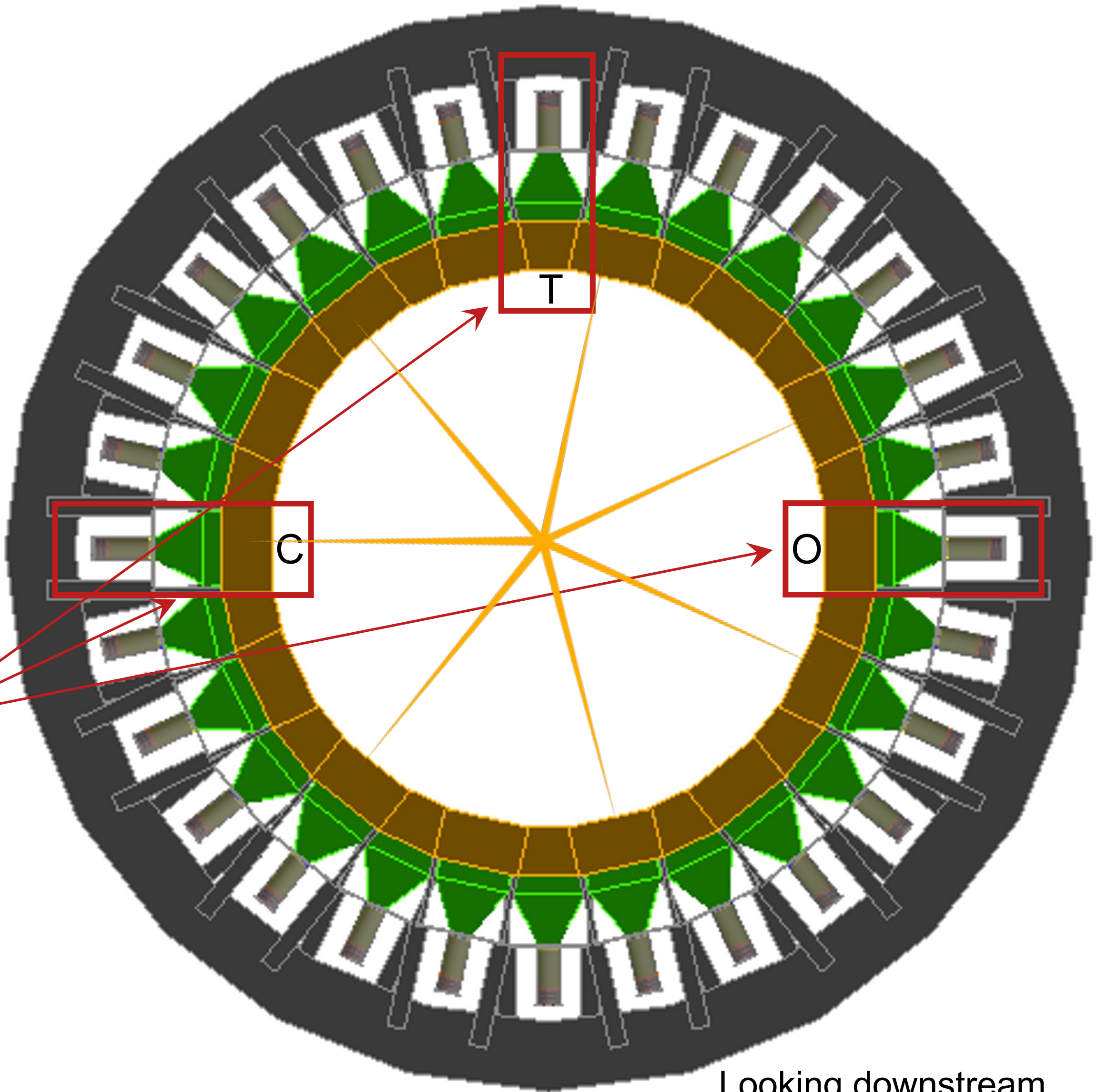


Shower-max dose simulations using remoll

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

Quartz layer dose study:

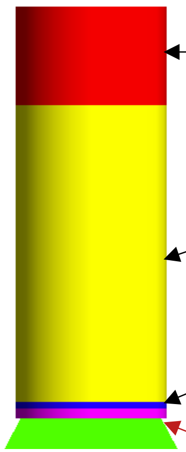
Made each quartz layer sensitive for individual Open, Closed, and Transition detectors located at these specific positions



Looking downstream

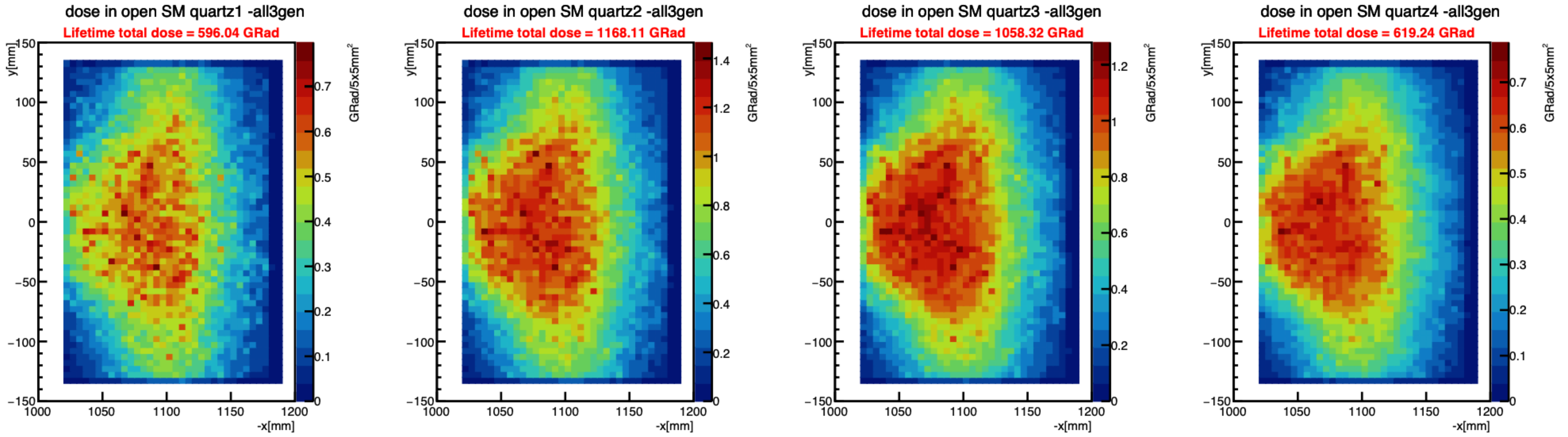
PMT region dose study:

Sensitive volumes:



Shower-max quartz layer lifetime dose estimates

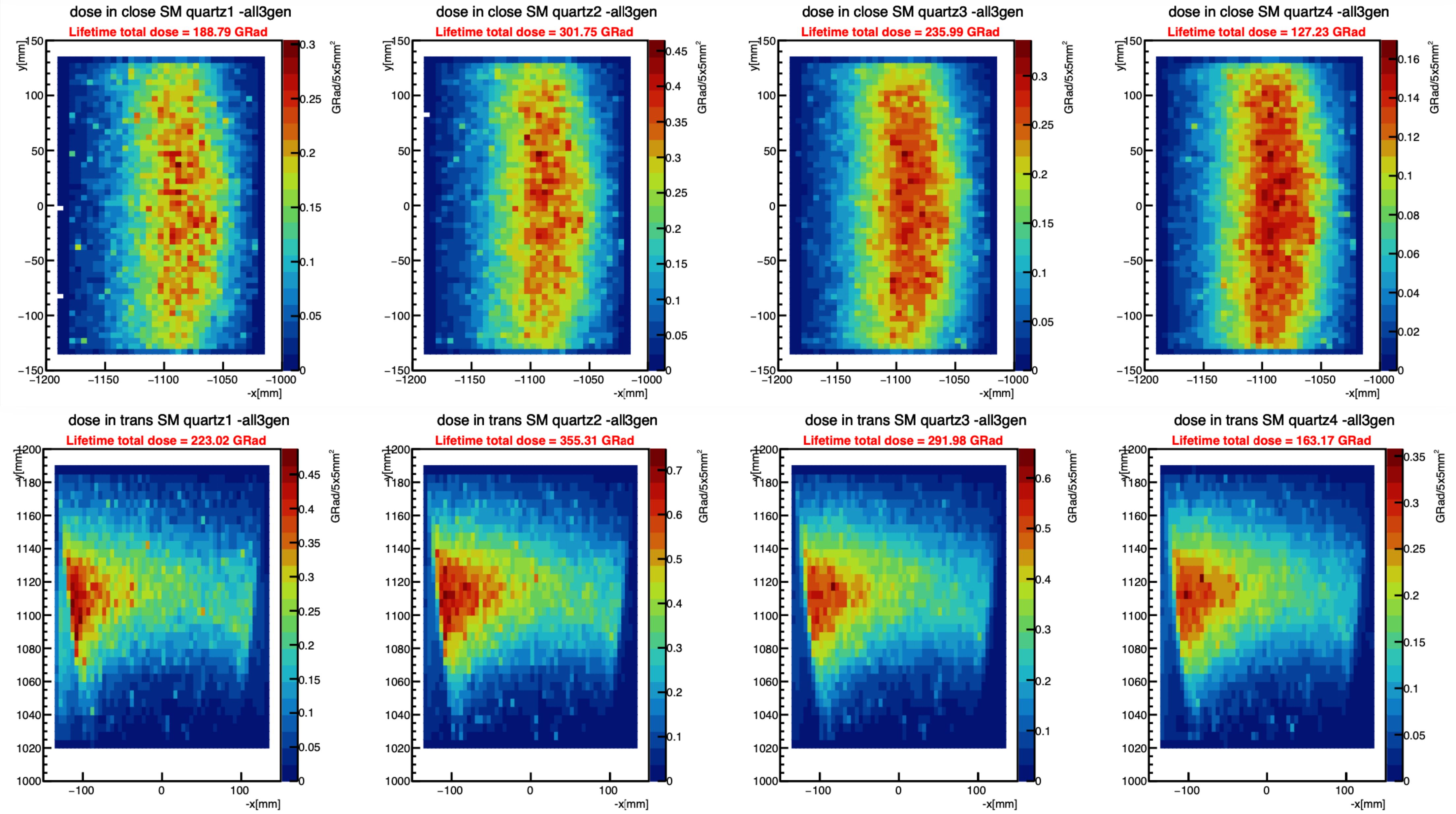
- These are Open-region detector results (worst case)



- Ran 5M Moller, ep-elastic and ep-inelastic generator events
- Peak dose density is in 2nd layer at 1.2 Grad/5x5mm² pixel
- Closed region are 4x lower and Transition are ~3 times lower

Jefferson Lab

Shower-max quartz layer lifetime dose estimates

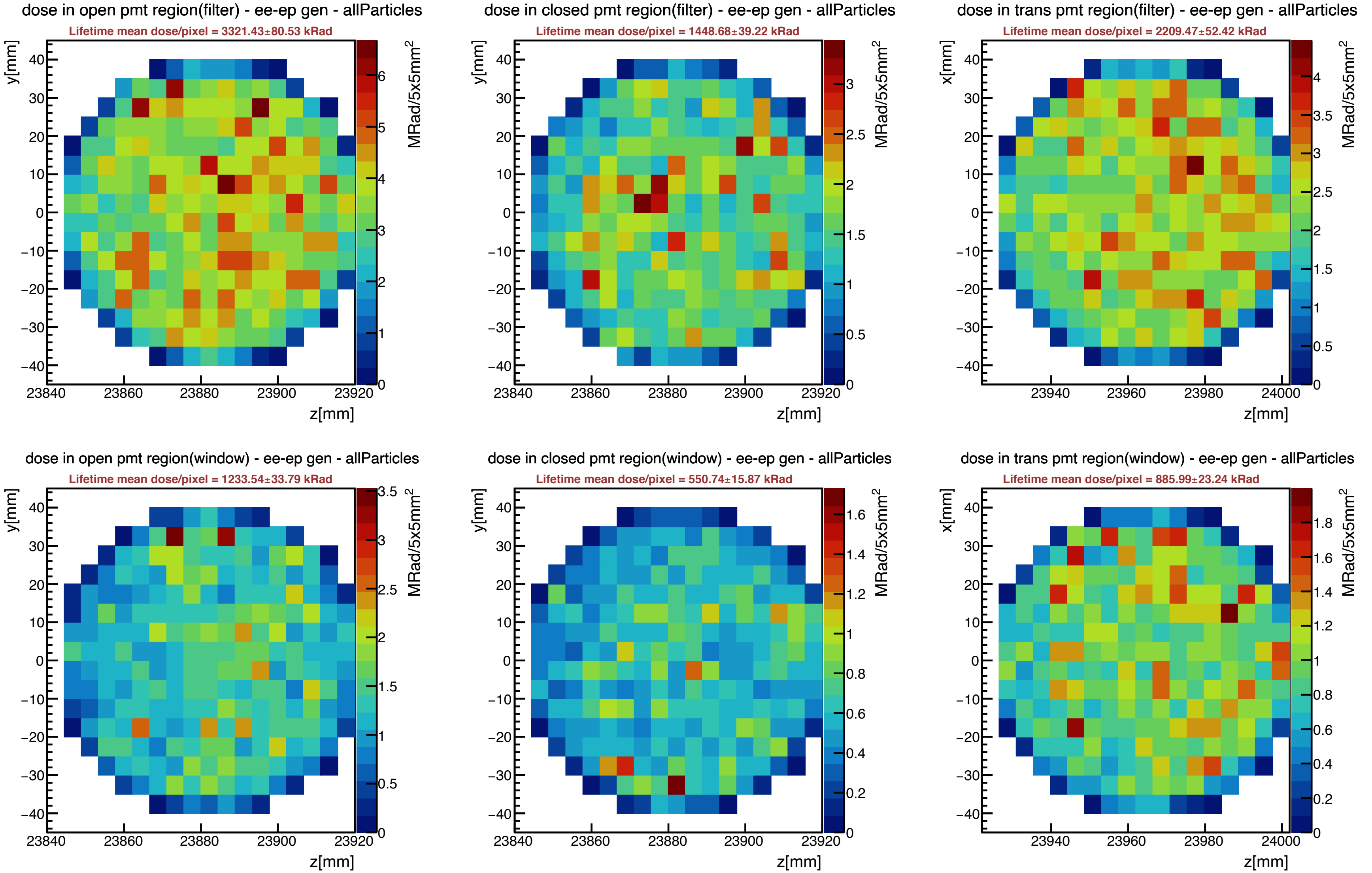


Shower-max long pass filter and PMT window lifetime dose

Open region | Closed region | Trans region

Filter region

Window



Average lifetime doses (Mrad/pixel):

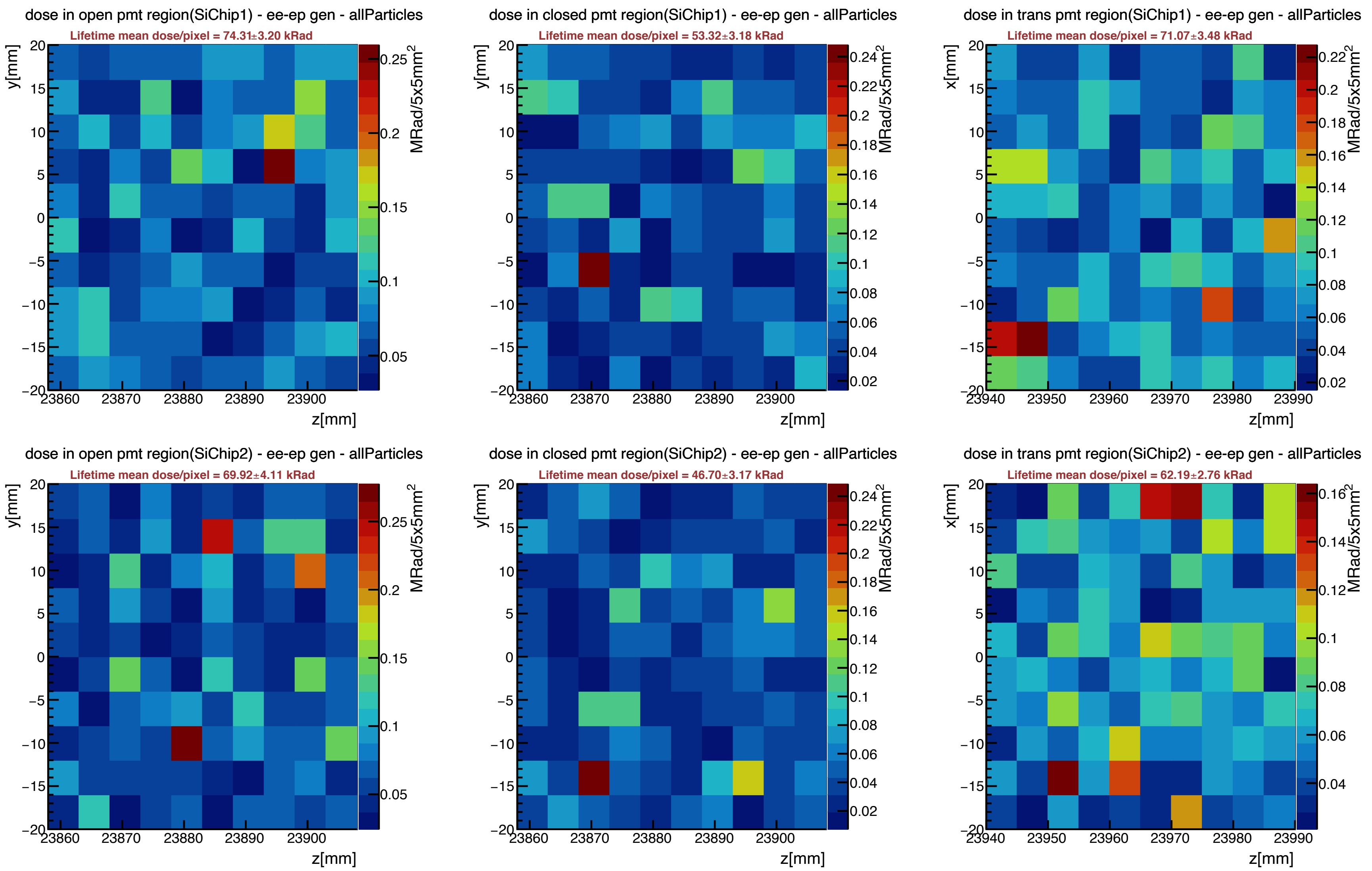
- Filter region:
  Open: ~3.3
  Closed: ~1.4
  Trans: ~2.2
- The 5 mm thick filter models both a 3 mm LP filter + 2 mm ND filter
- PMT window:
  Open: ~1.2
  Closed: ~0.6
  Trans: ~0.9

Shower-max pre-amp Si chip lifetime doses

Open region | Closed region | Trans region

Inner chip plane

Outer chip plane



- Average lifetime dose (krad/pixel):

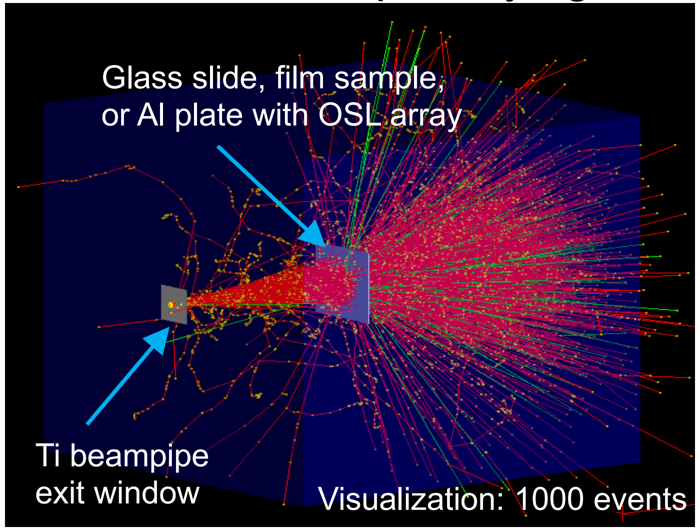
  Open: ~75
  Closed: ~50
  Trans: ~70

- 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



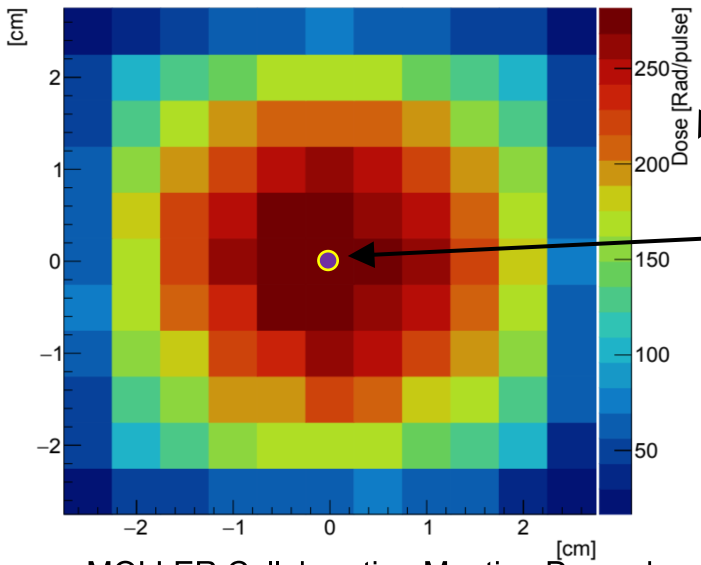
Simulated beam calibrated with beamspot measurements at 3 distances

Sample irradiated at 50 cm

Beam energy scans taken at beginning and end of tests

Beam charge data acquired throughout exposures

Dose Profile Quartz 5x5x10 [mm]

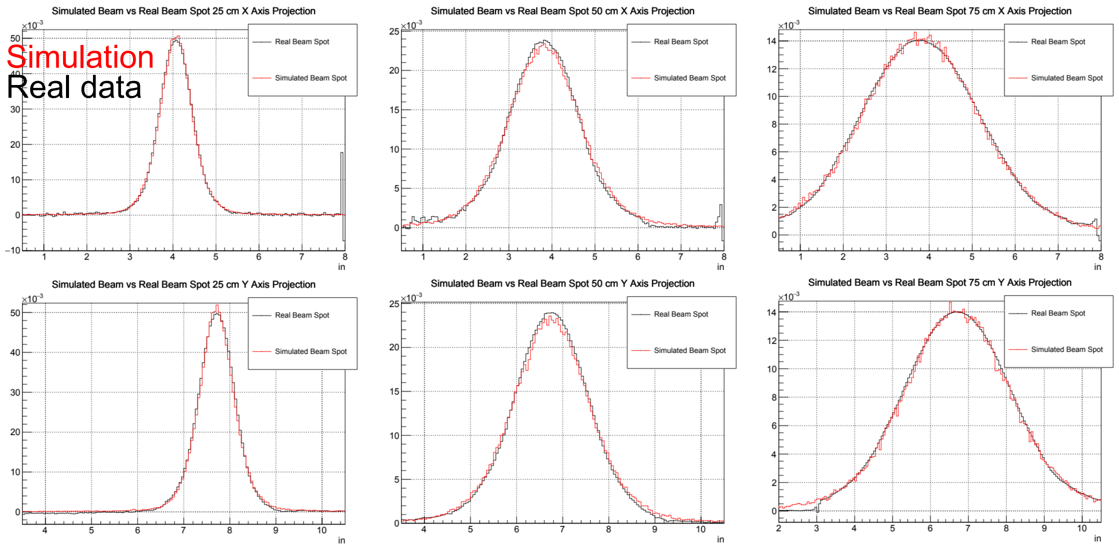


Simulated dose per 5x5 mm^2 normalized to average charge per beam pulse

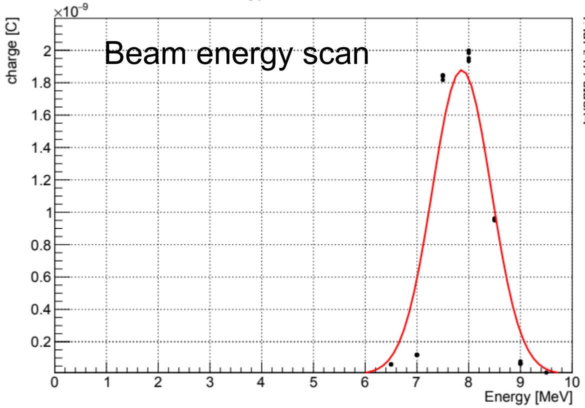
Sample thickness is 10 mm

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

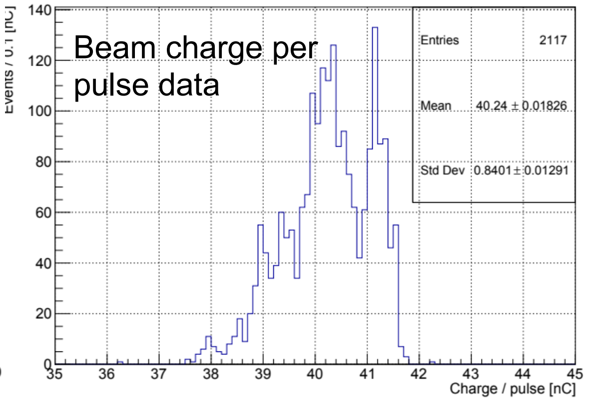
Beamspot measurement scans



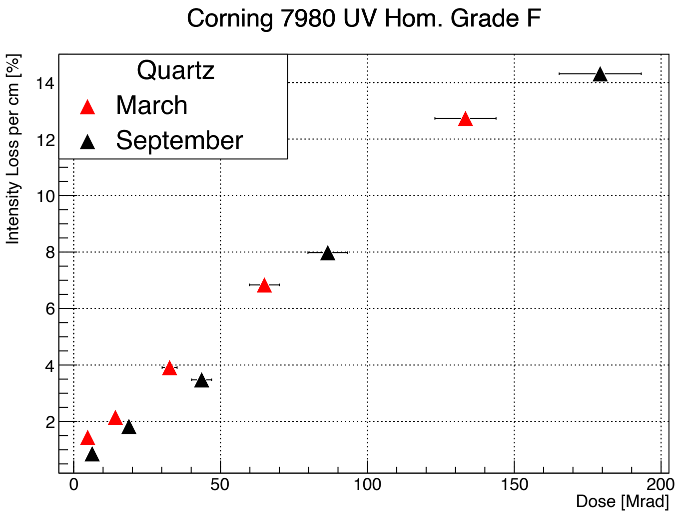
Beam Energy Distribution 09/02/2021

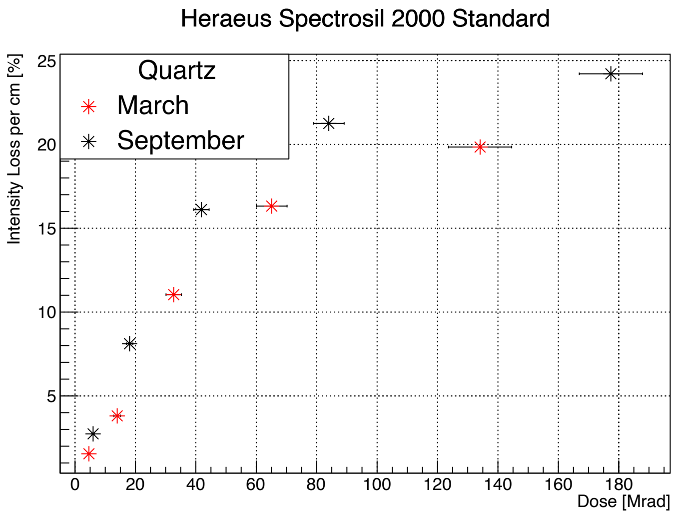


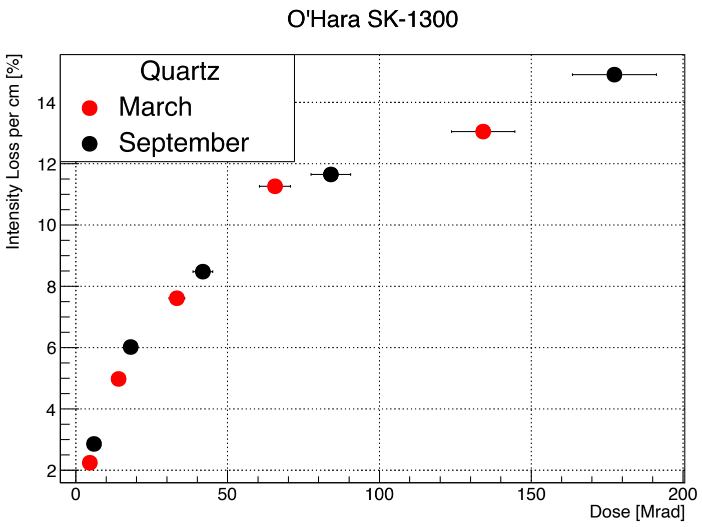
Beam Charge Distribution for all Sample runs

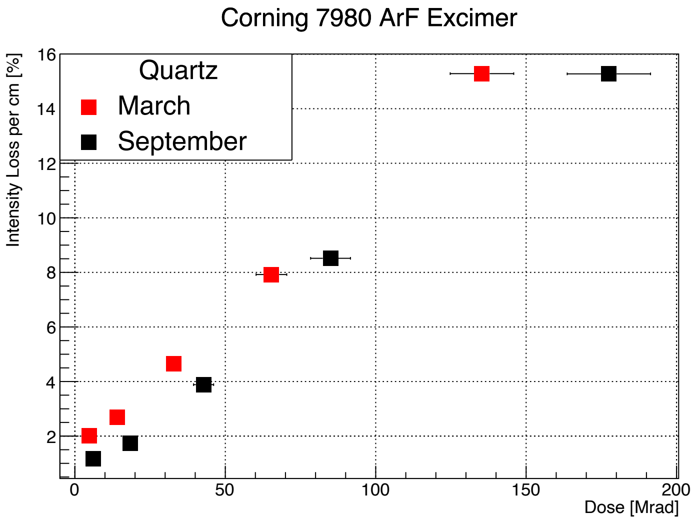


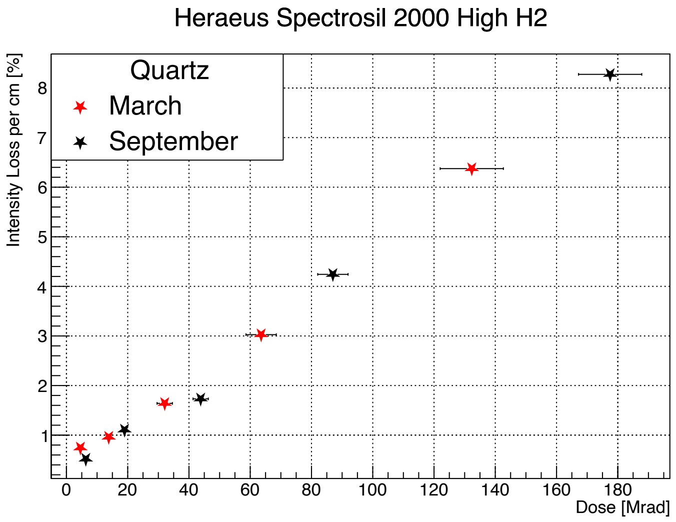
Quartz radiation-hardness results : loss vs. dose

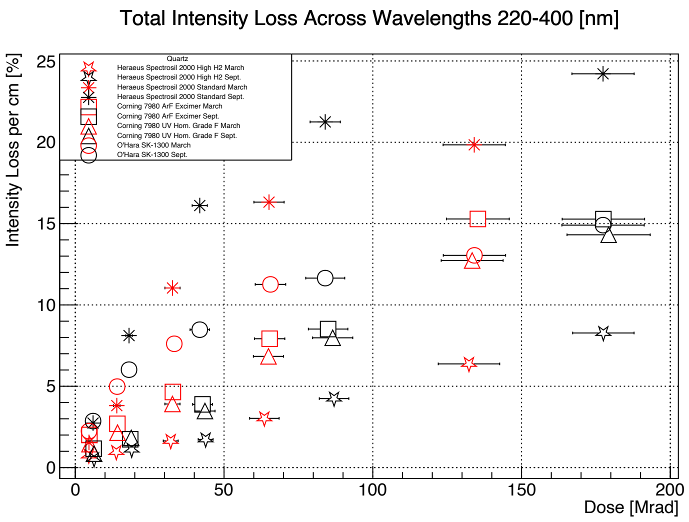




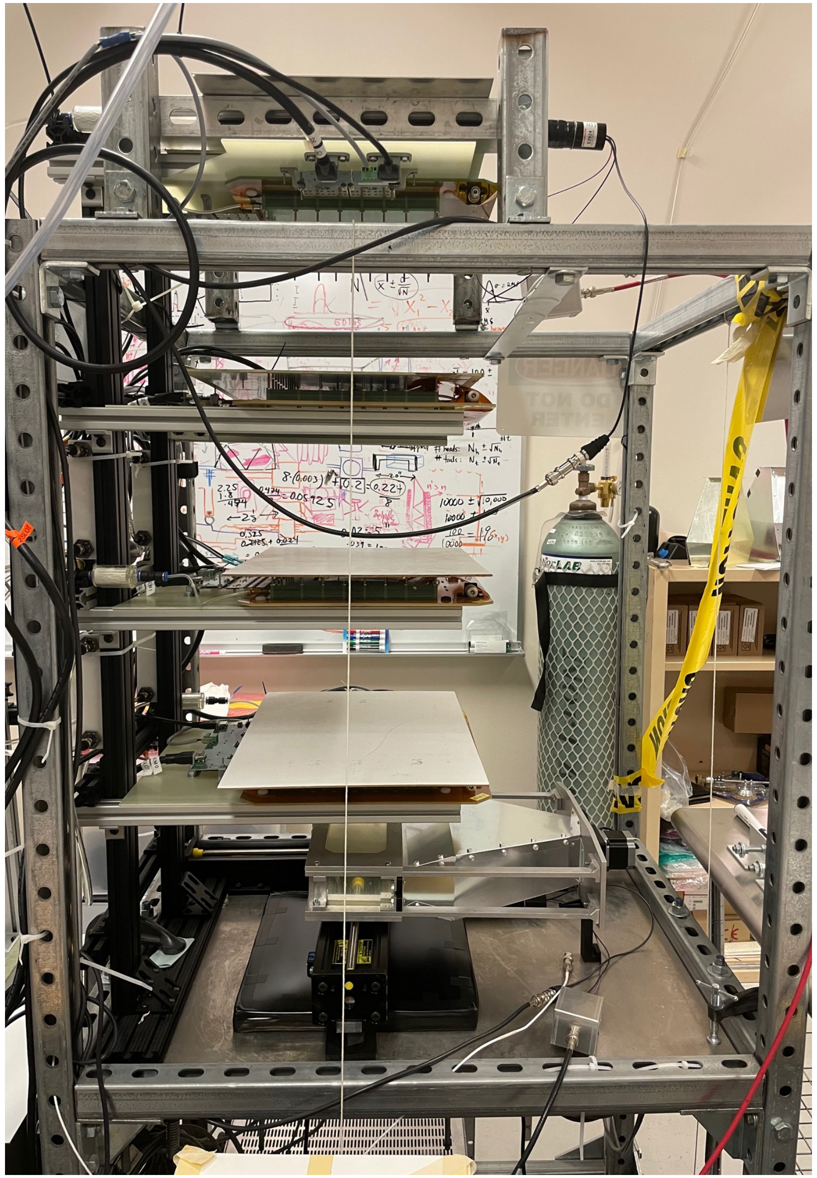


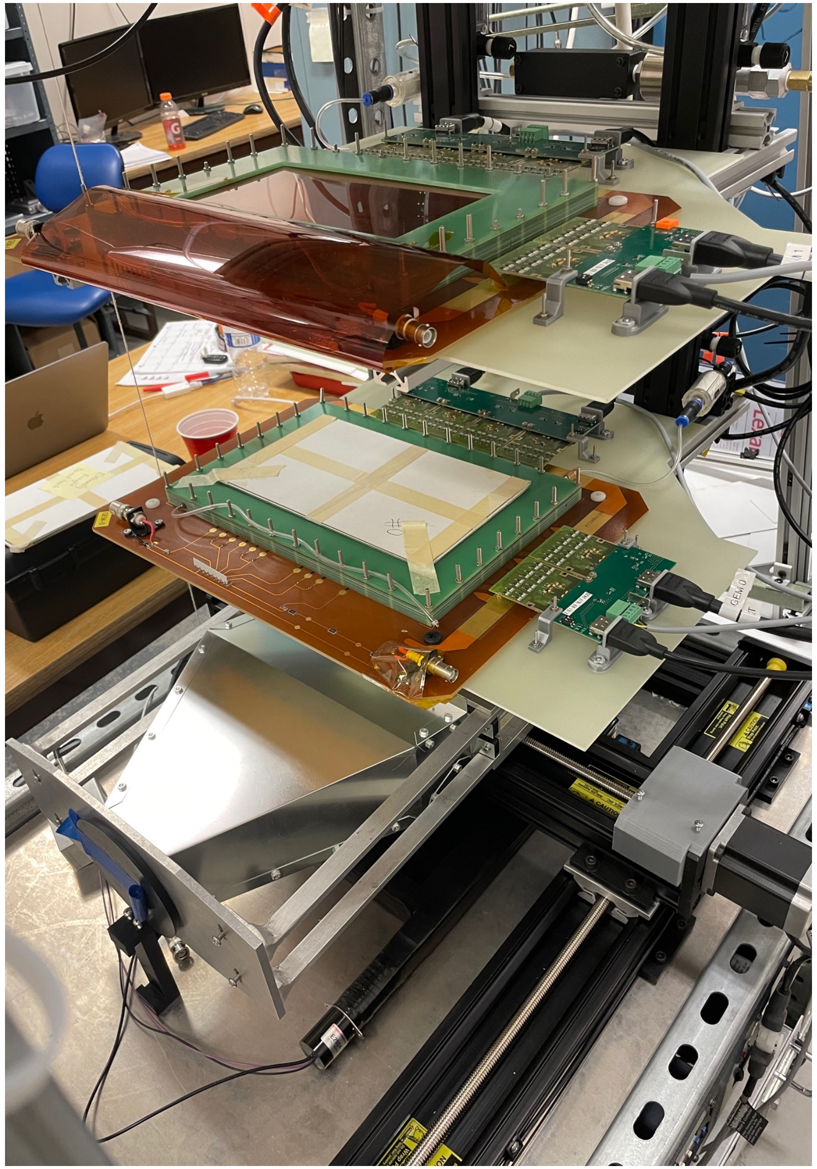


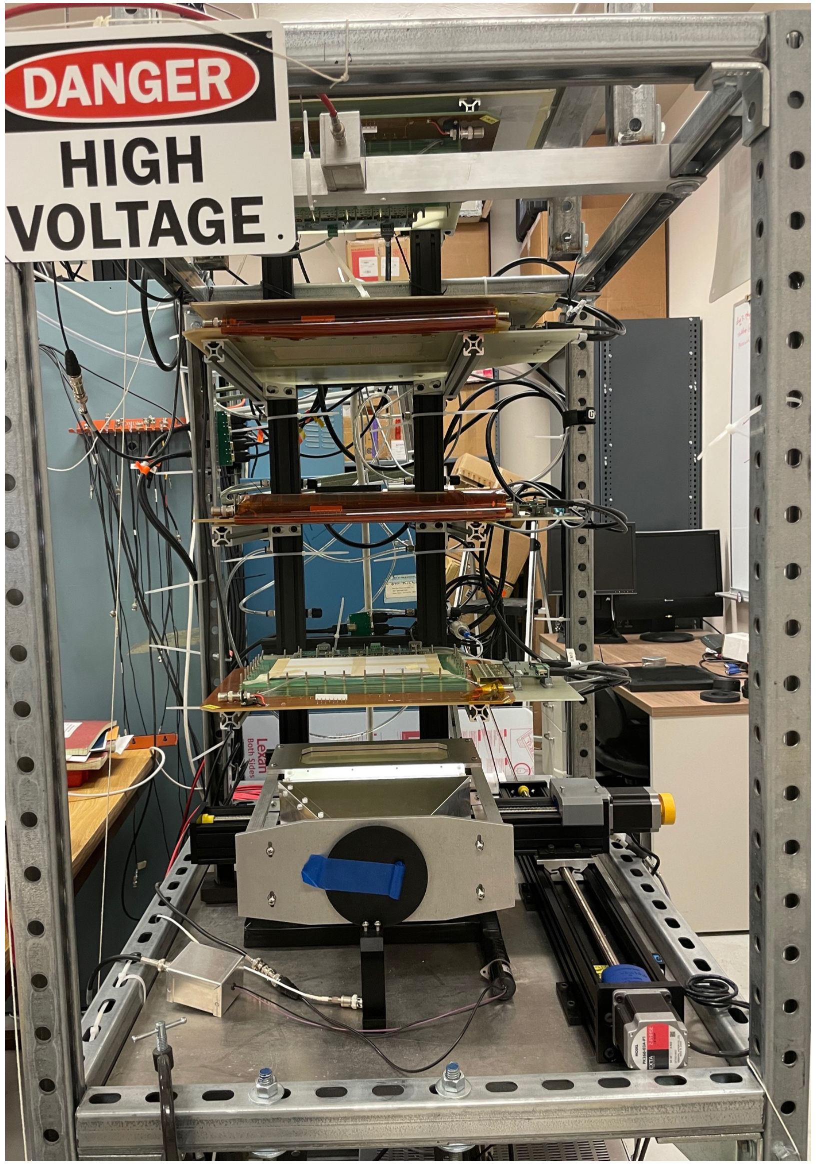




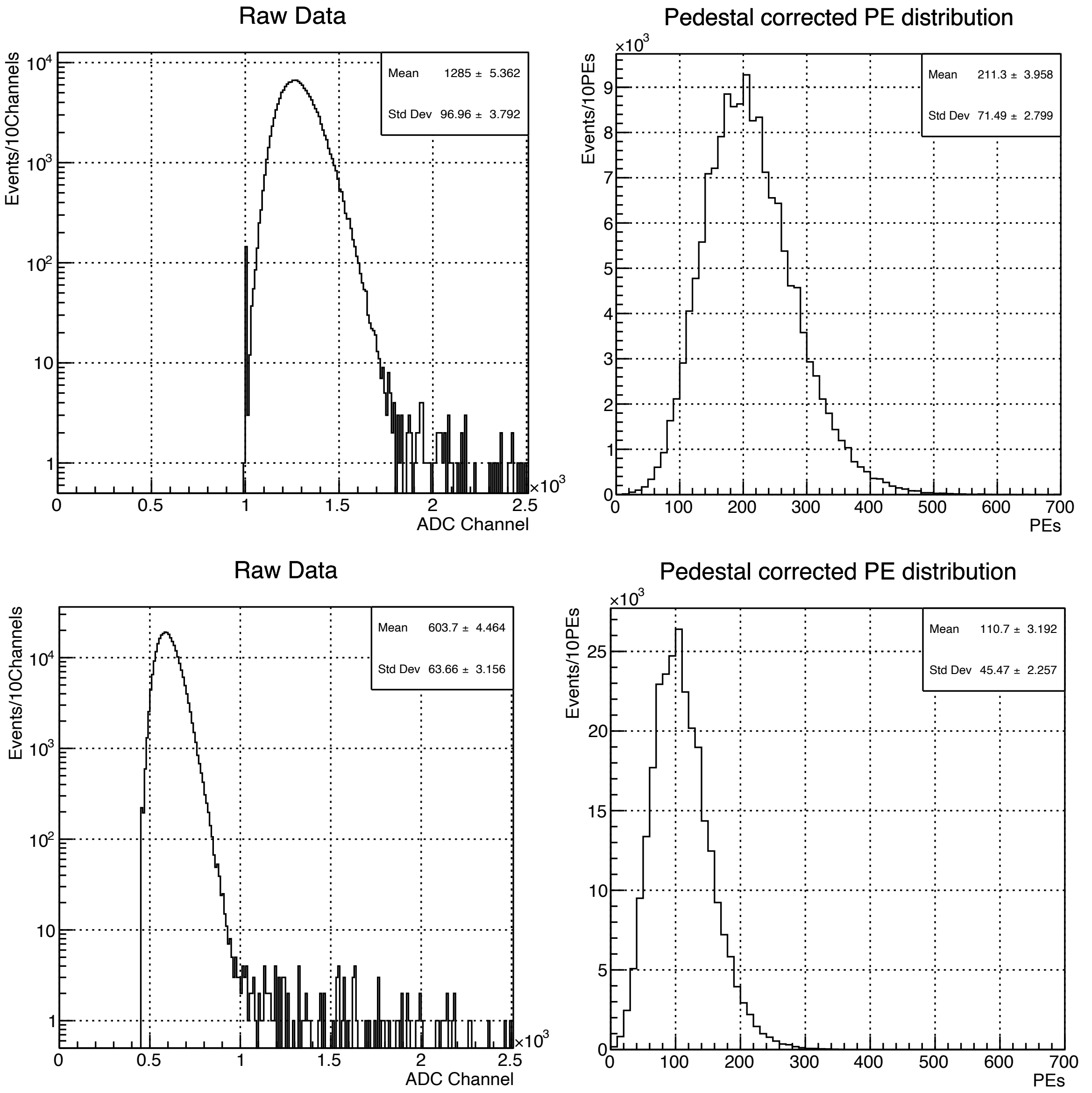
Cosmic-ray stand for Shower-max testing in Idaho







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 x10^6, 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)

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)

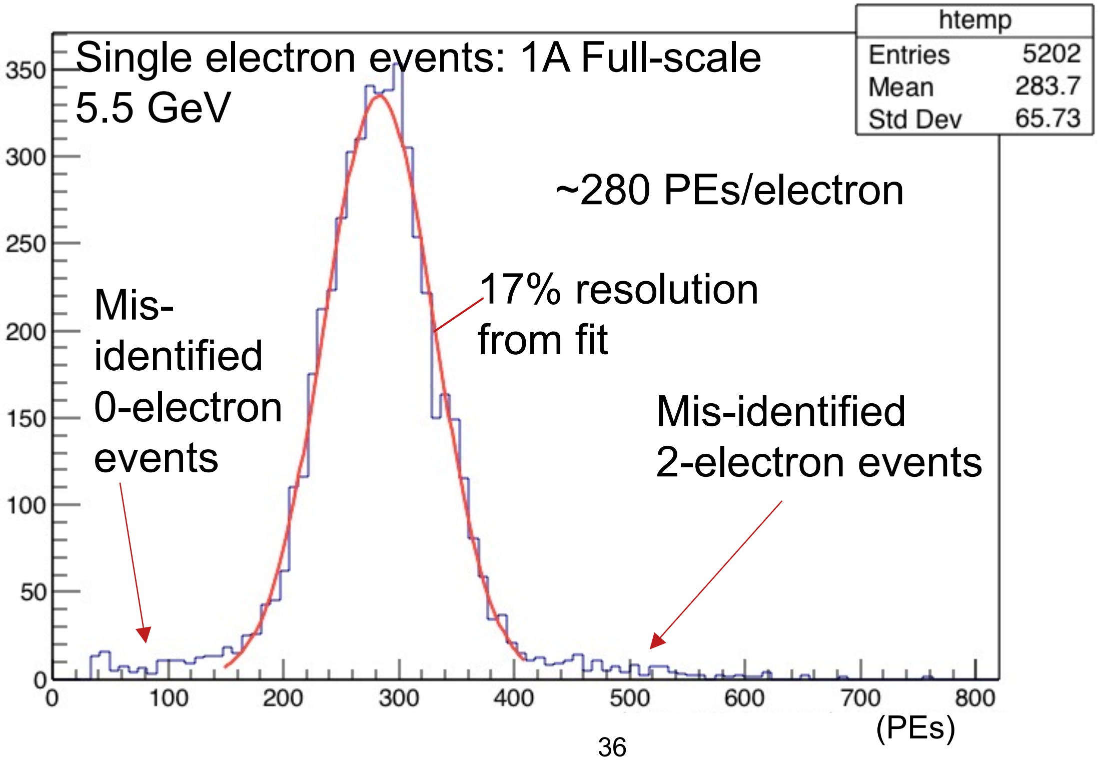
SLAC testbeam T-577 run: Dec 6 – 12, 2018

- 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

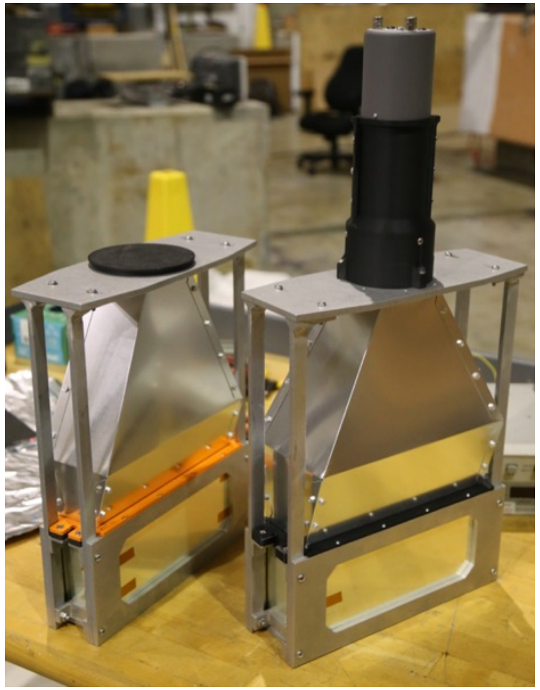
- 2018 prototype beam performance sufficient for MOLLER

- 2022 prototype testbeam taking place at MAMI in fall 2022



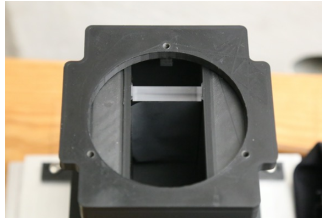
Full-scale prototype: 12 cm x 25 cm active area

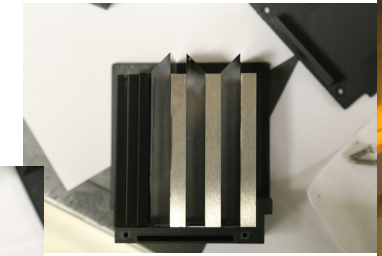
- 1st-pass engineered design concept vetted
- Light guide construction techniques developed

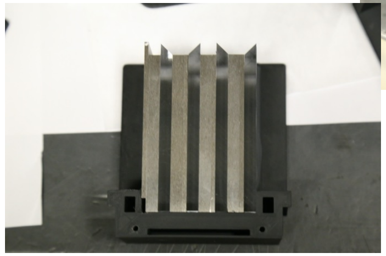


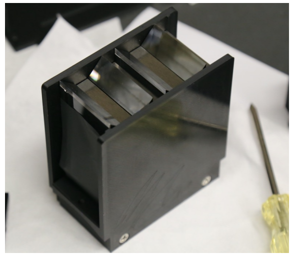
Past prototyping and testbeam results

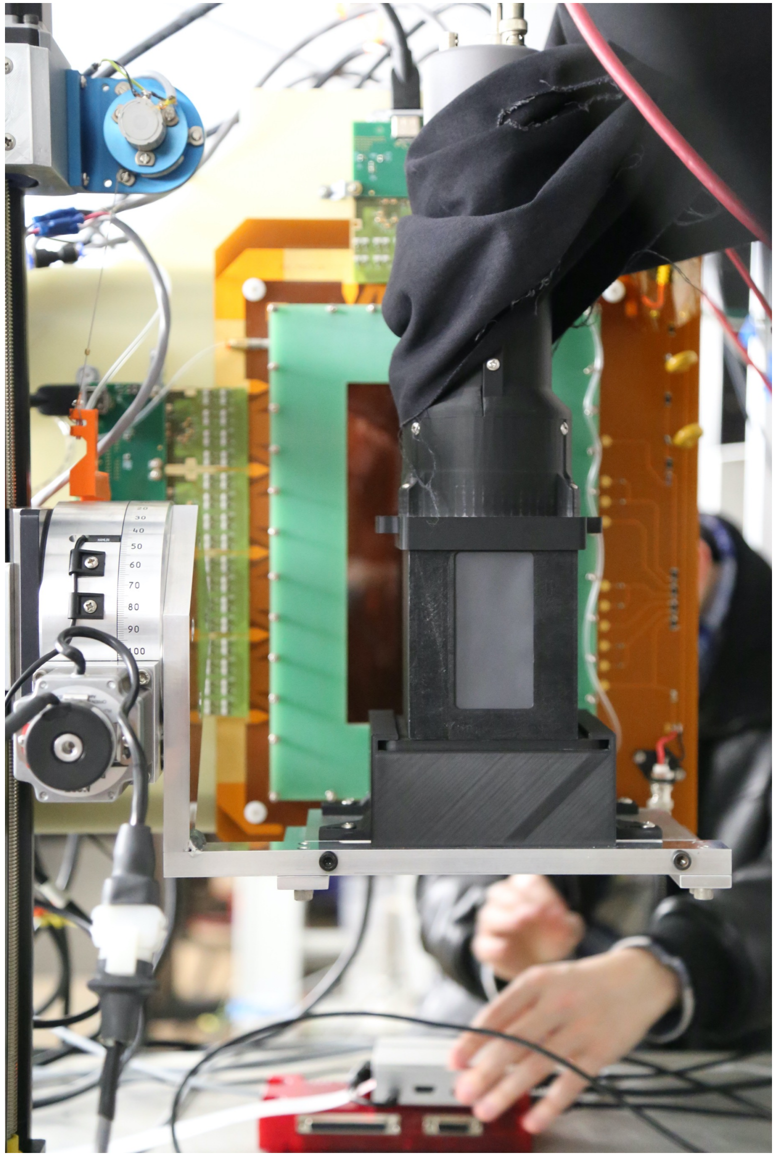
T-577: SLAC Testbeam Setup: Benchmarking ShowerMax



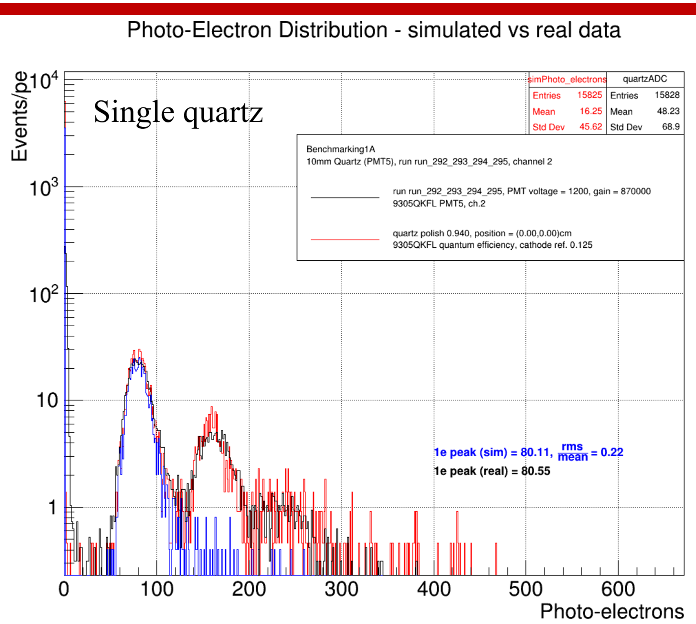


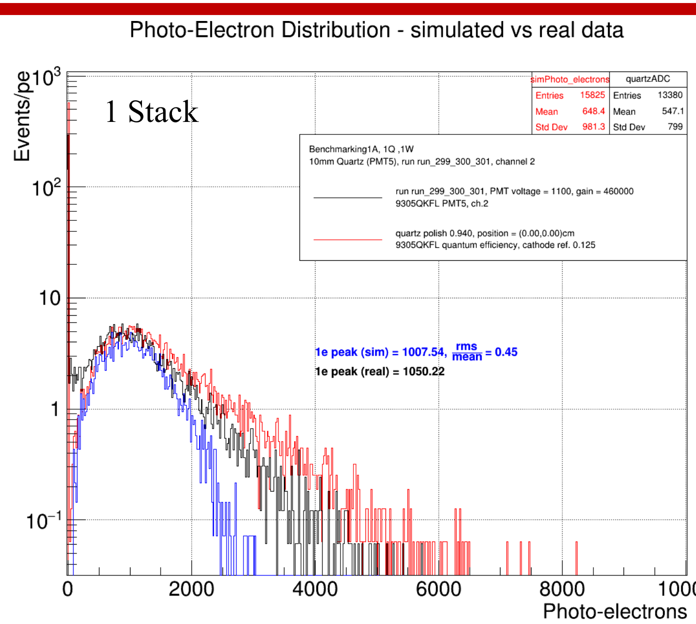


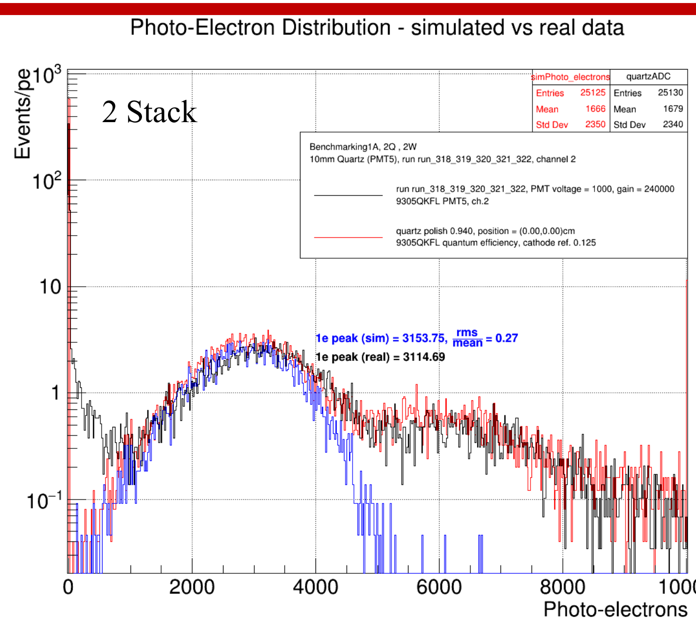


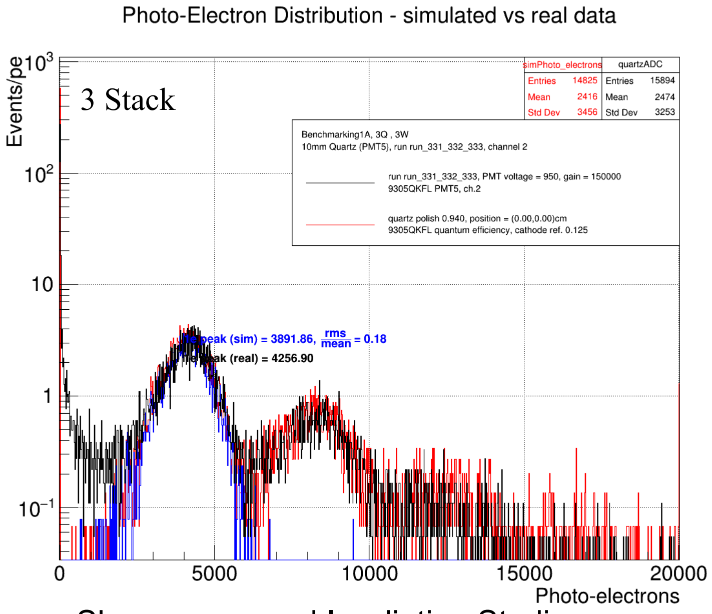


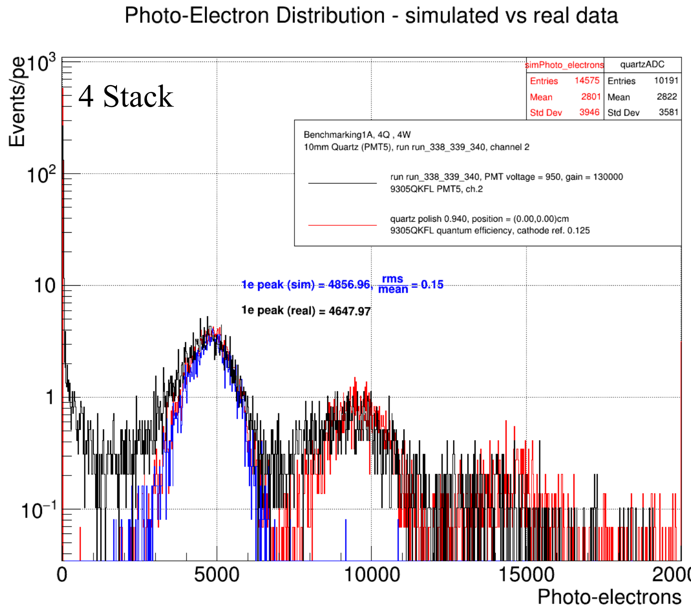
Past prototyping and testbeam results











- 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