Shower-max Detector System and radiation hardness tests of detector components

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Hall A Collaboration meeting

Jan 21-22, 2026

Idaho State University

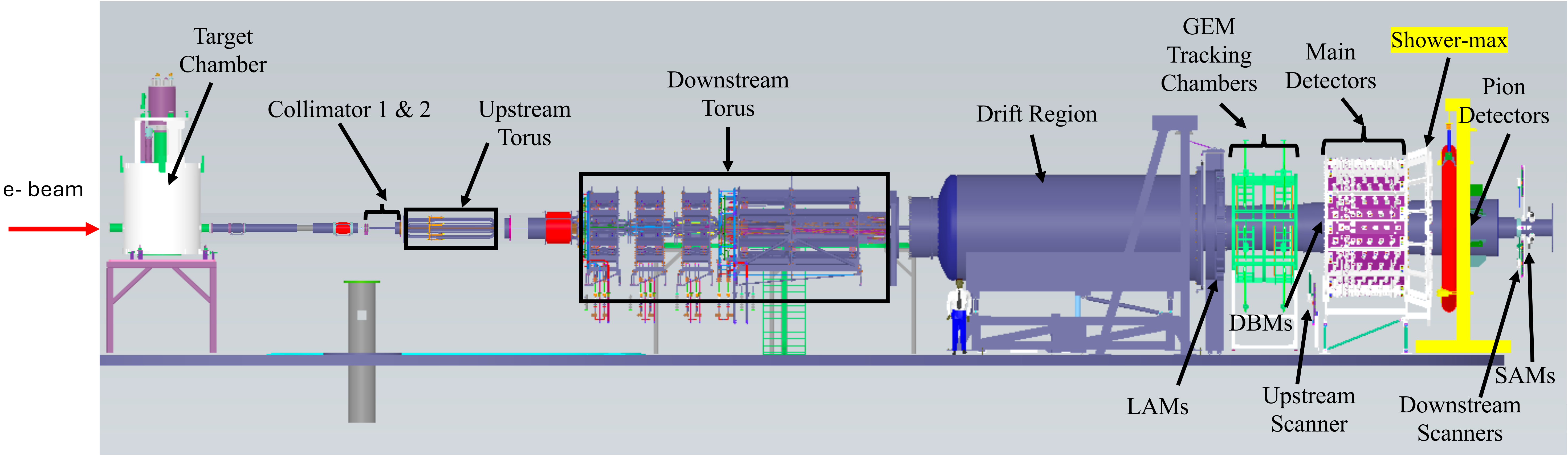
U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

Jefferson Lab

MOLLER Apparatus (Jefferson Lab Hall A)

Target, spectrometer, and detector systems

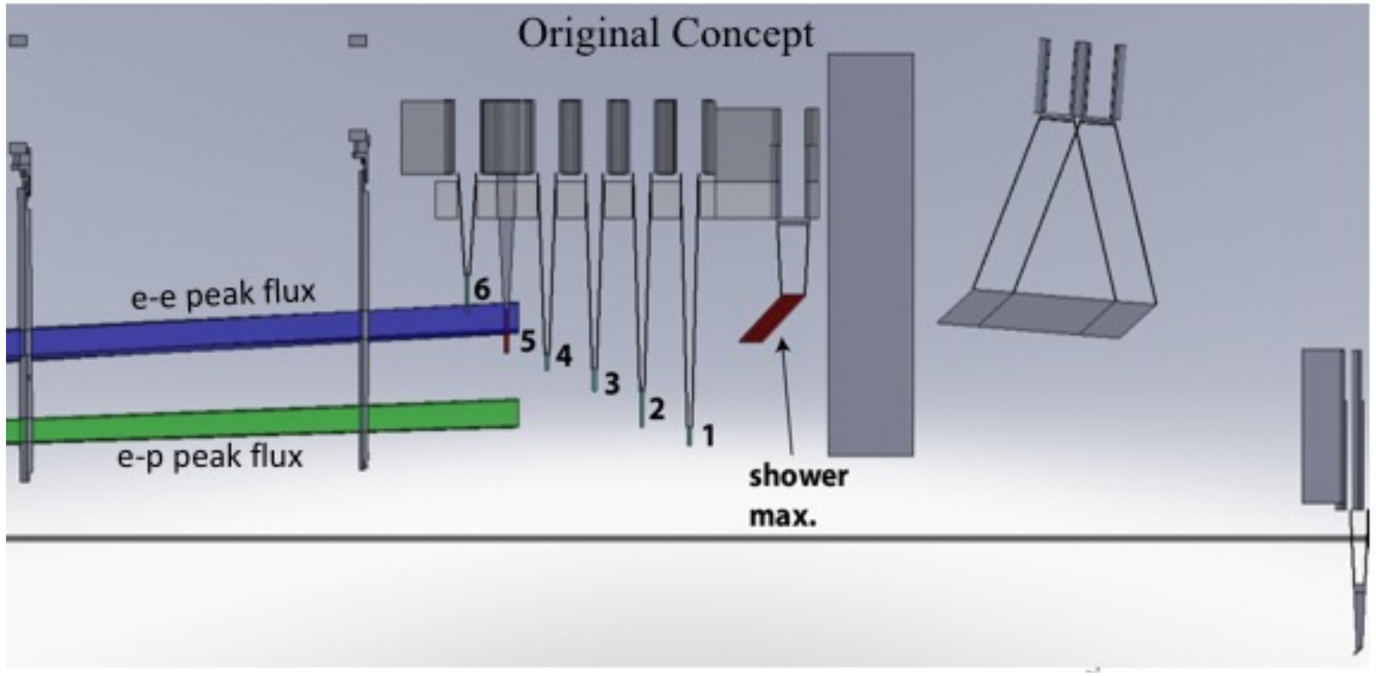


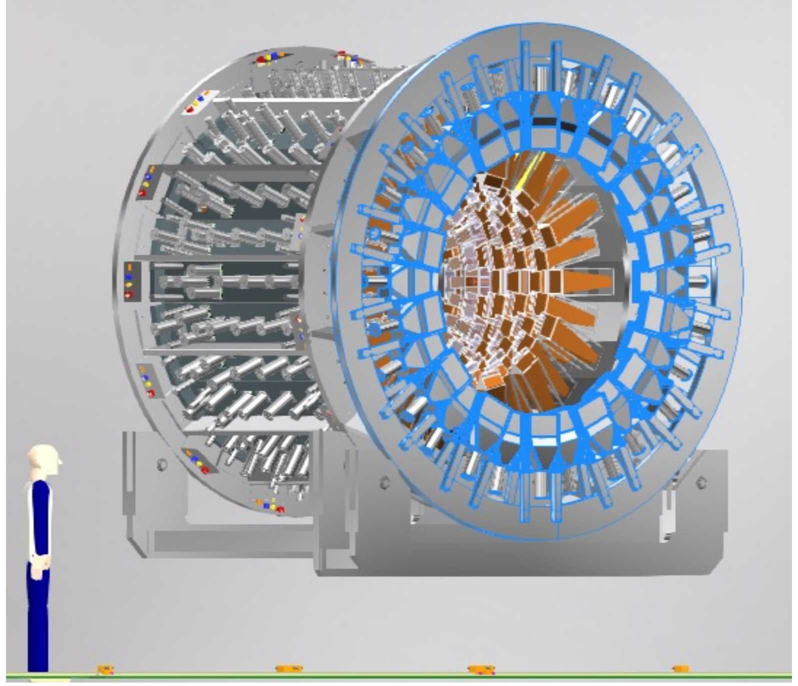
Outline

MOLLER

- **Introduction to Shower-max Detector System**
- **Detector response testing**
- **Production and assembly**
- **Radiation hardness testing of detector components**
- **Summary**

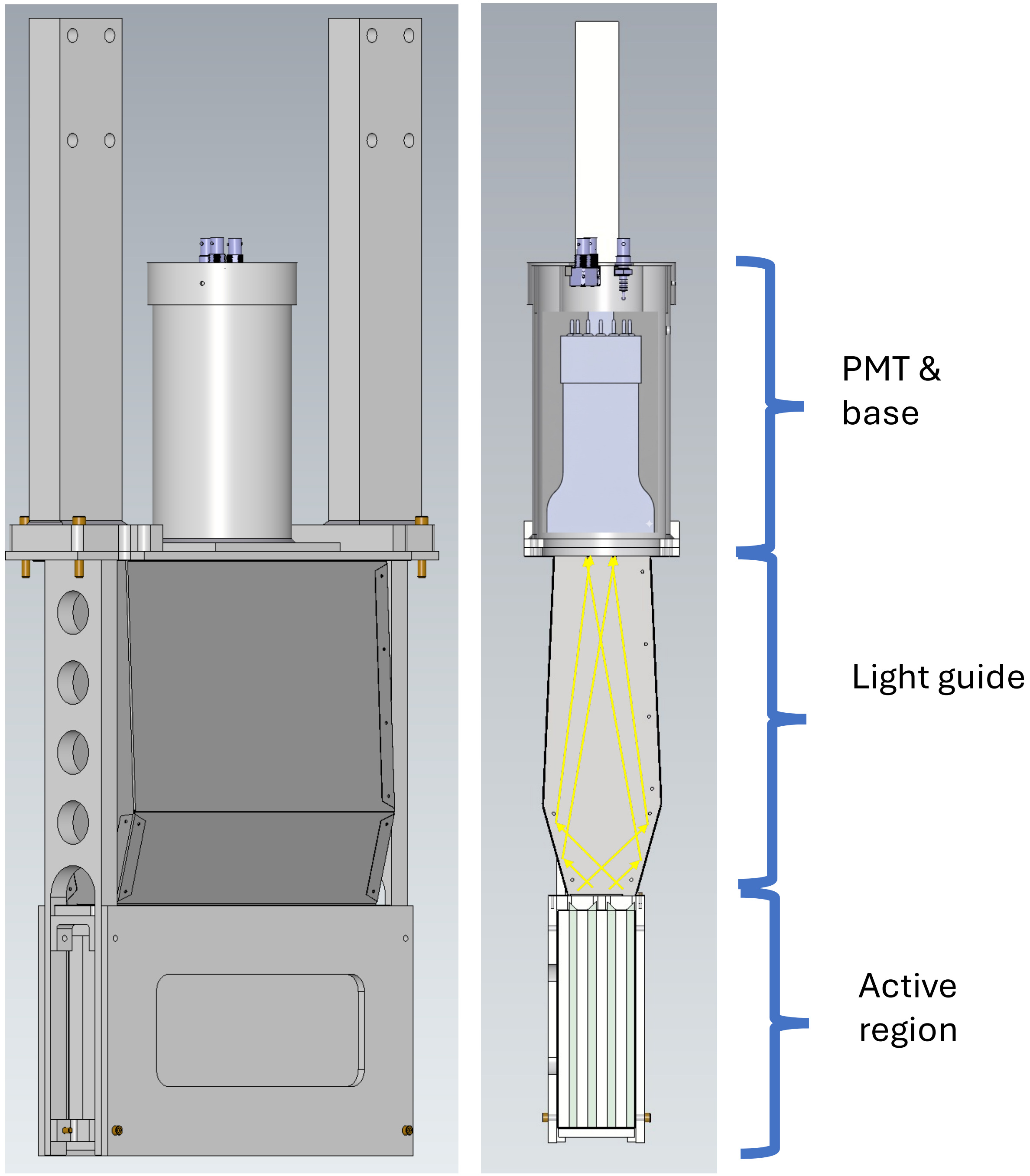
Shower-max Detector System for MOLLER Experiment





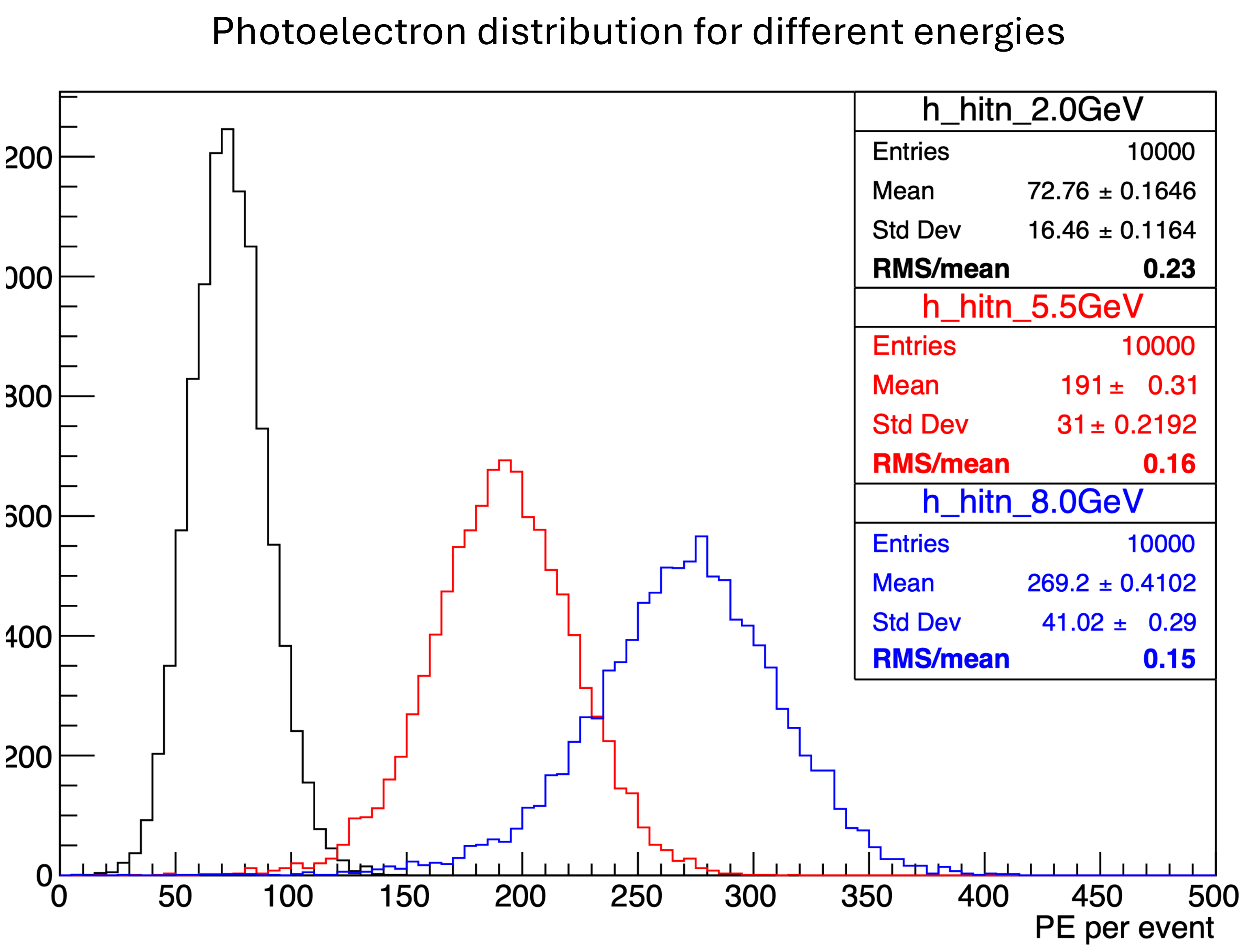
- Shower-max : Cherenkov-based electromagnetic sampling calorimeter
  - Ring of 28 detector modules
  - Response proportional to energy of incident particle
- **Provides additional measurement of the Moller Parity-violating asymmetry: A_{PV}**
  - Positioned ~1.7 m downstream of Ring-5 to intercept the same Møller scattering flux.
  - With comparable analyzing power and statistical uncertainty to Main Detector, but different systematics
- **Less sensitive to:**
  - Low energy background
  - Hadronic background

Introduction to Shower-max detector



- **Active region:**
  - four 99.95 % pure Tungsten plates (265mm x 160mm x 8mm)
  - four high purity fused silica (quartz) radiators (265mm x 160mm x 8mm)
  - Radiation length: 9.5 X_0
  - Shower Moliere radius: ~ 1.1cm
  - Module Weight: ~80 lbs.
- **Light guide:** Air core MIRO-IV Aluminum
- **Photo multiplier tube:**
  - 3 inch, Quartz window tube
  - Bialkali photo-cathode, 25 % Quantum Efficiency (at 430 nm)

Shower-max detector response



- From Geant4 - based optical simulation application, Qsim, the shower-max detector yields ~36 PEs/GeV for electrons and gammas hitting the center of the active area.
- Qsim application is benchmarked using MAMI electron test beam results. (more information in following slides)

Detector testing

- **Beam Tests:**
  - 2018 (SLAC): 3, 5.5, and 8 GeV electrons, tested benchmarking and early full-scale prototypes
  - 2022 (MAMI): 855 MeV electrons, tested the quartz wrapping to improve performance; new chassis and light guide
  - 2023 (MAMI): 855 MeV electrons, tested production quartz and long pass filter performance
  - 2025 (JLab HallD): 3 - 6 GeV positrons, testing signal yield and resolution over large energy range. Full analysis in process.
- **Cosmic-ray Testing:**
  - 2022 - 2025 (Idaho)
  - 2025 - present (JLab testlab)

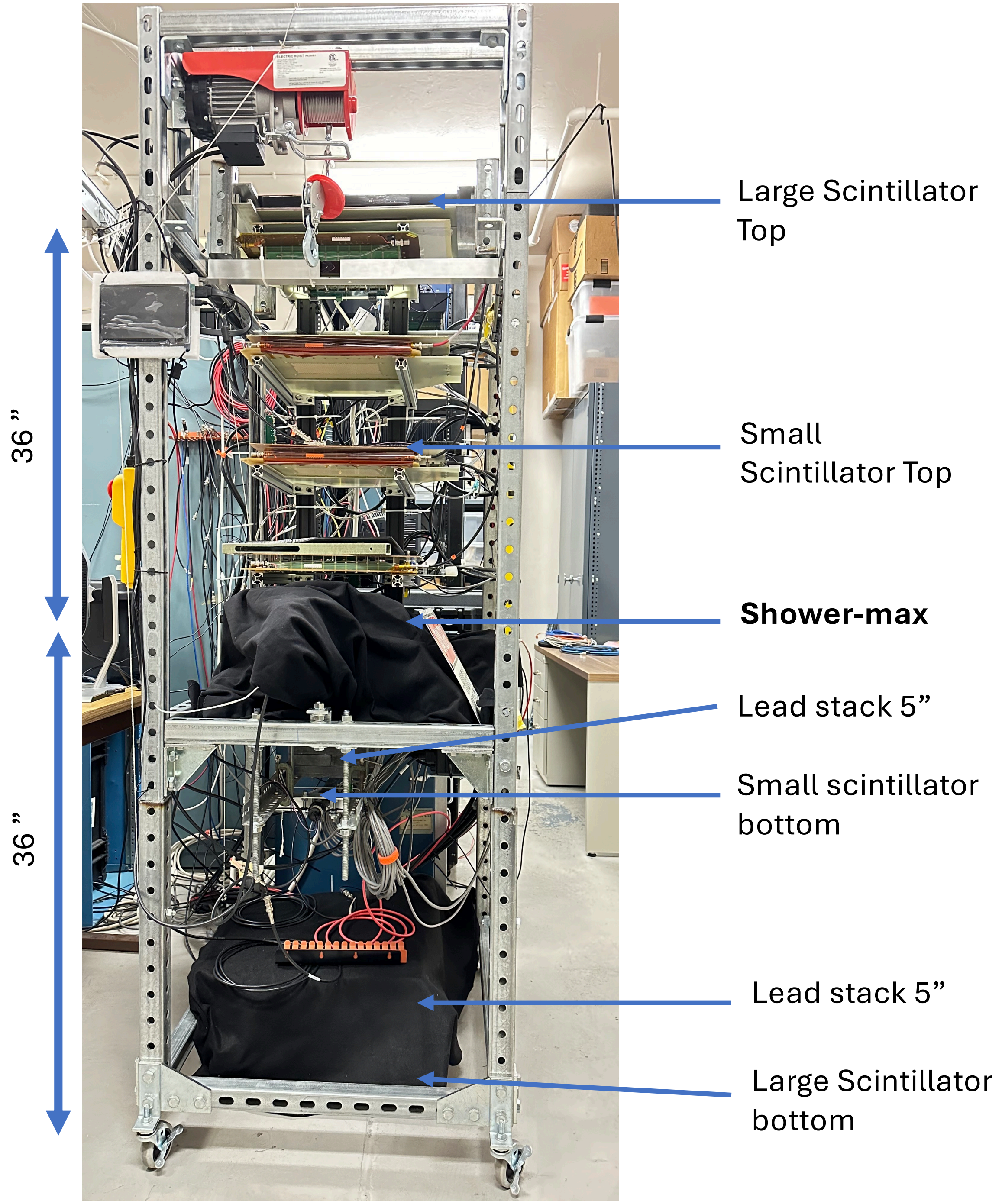


Fig: Cosmic testing stand at Idaho State University

MAMI Testbeam 2023 Sept geometry

Shower-max Retro-version2:

- Tungsten (2018): 246 mm x 105 mm x 8 mm
- Quartz (2023): 265 mm x 160 mm x 6 mm
- Chassis from 2022 design that fits 2023 quartz

- Spaces are filled by 3D printed ABS materials
- Polished quartz from production vendor (2023)
- Quartz are wrapped in aluminized-mylar
- Miro-IV light guide

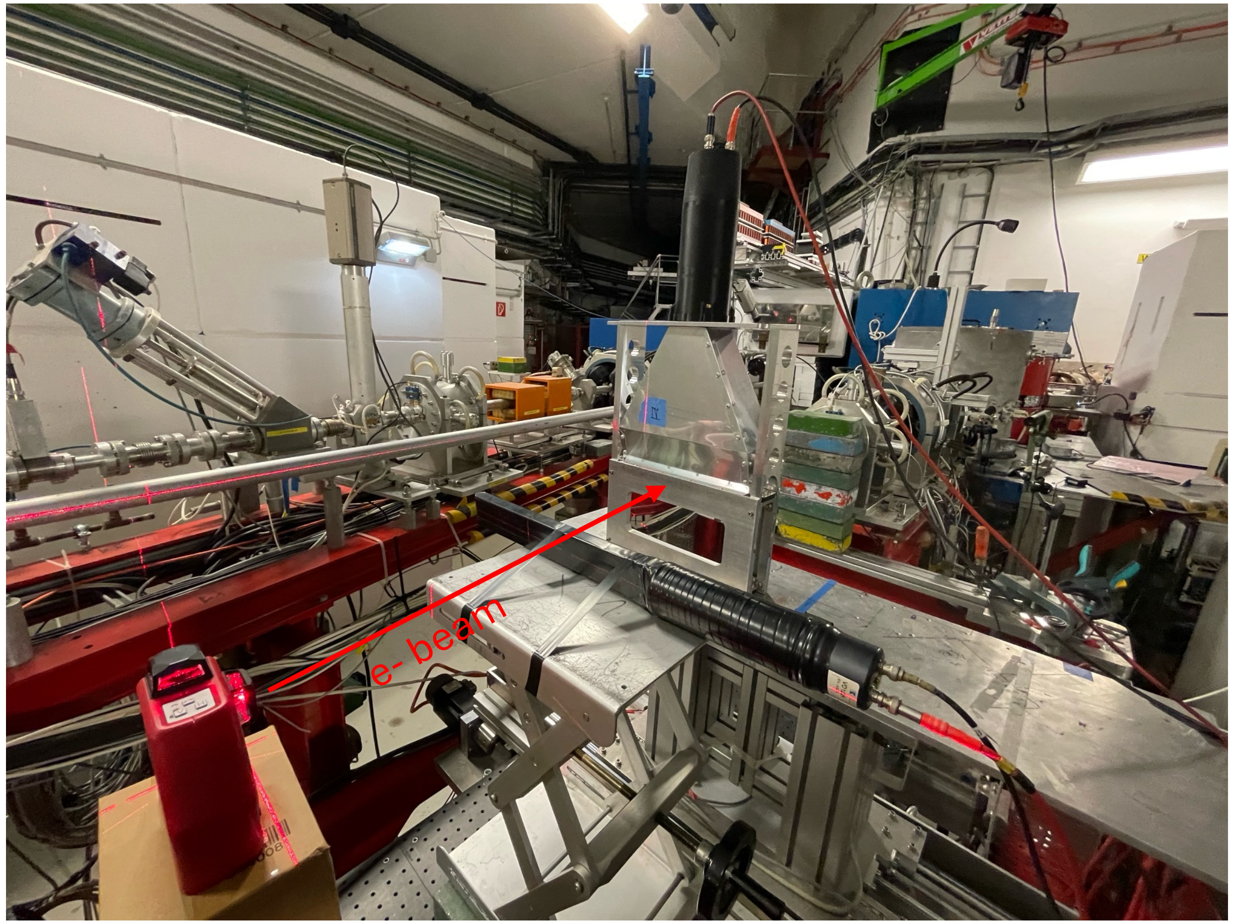


Fig: Shower-max retro-v2 on the Testbeam bench

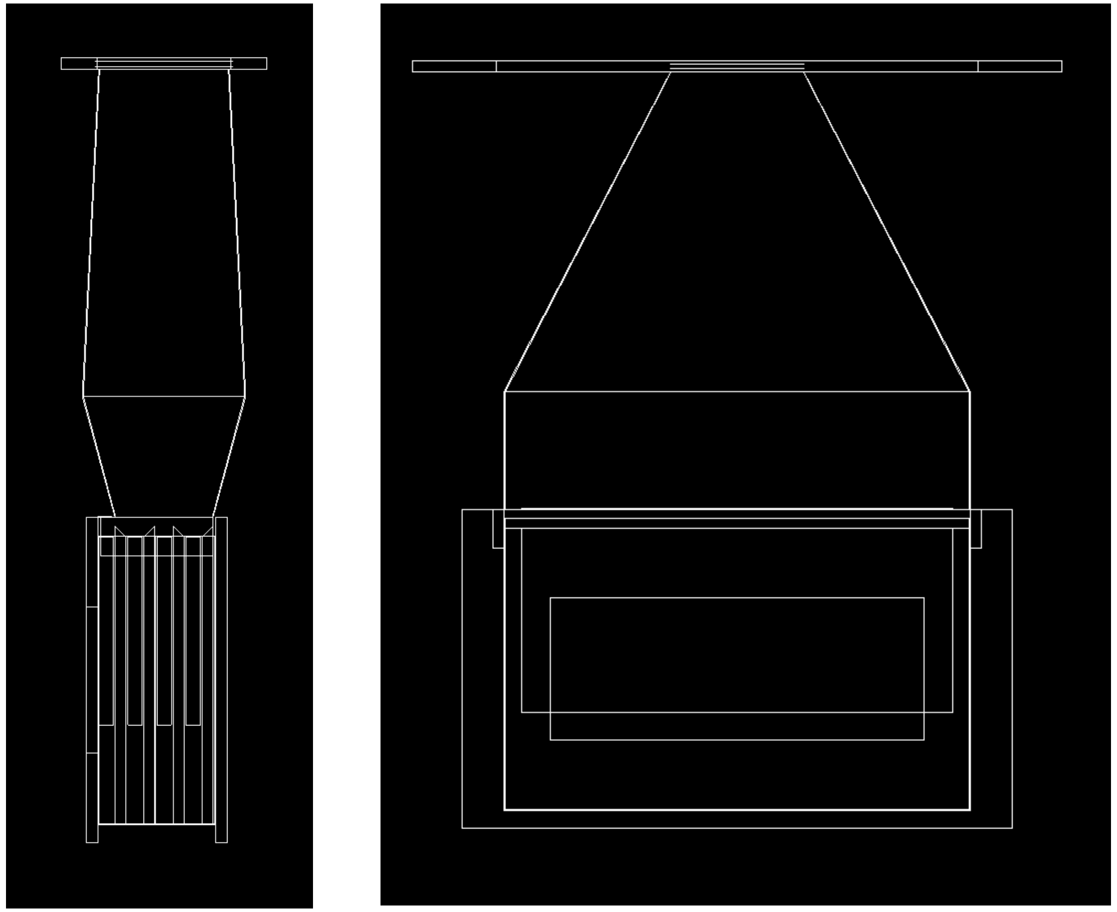
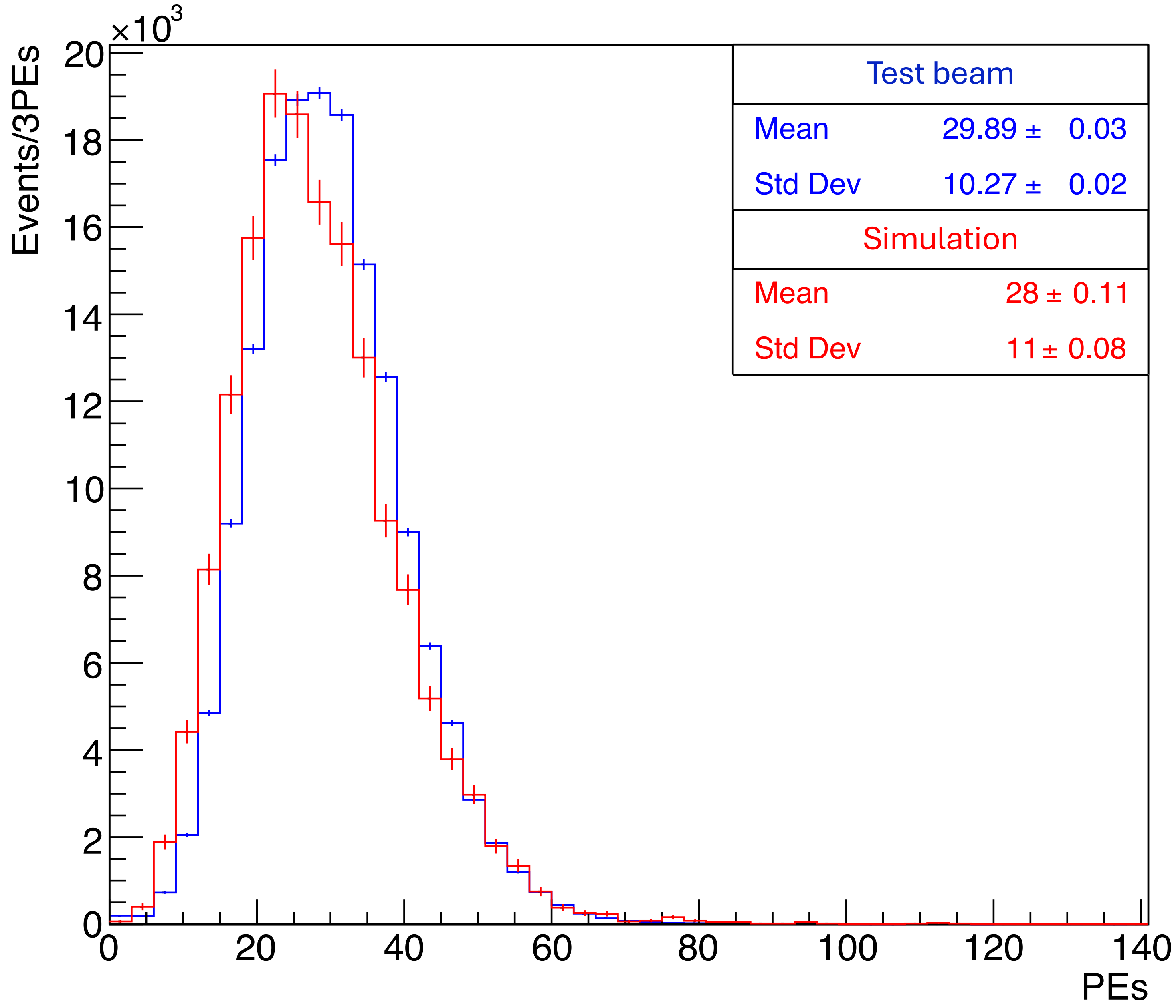


Fig: Shower-max retro-v2 side and front view from qsim

Detector response: Number of Photoelectrons

Pulse height distribution for MAMI 855 MeV electron

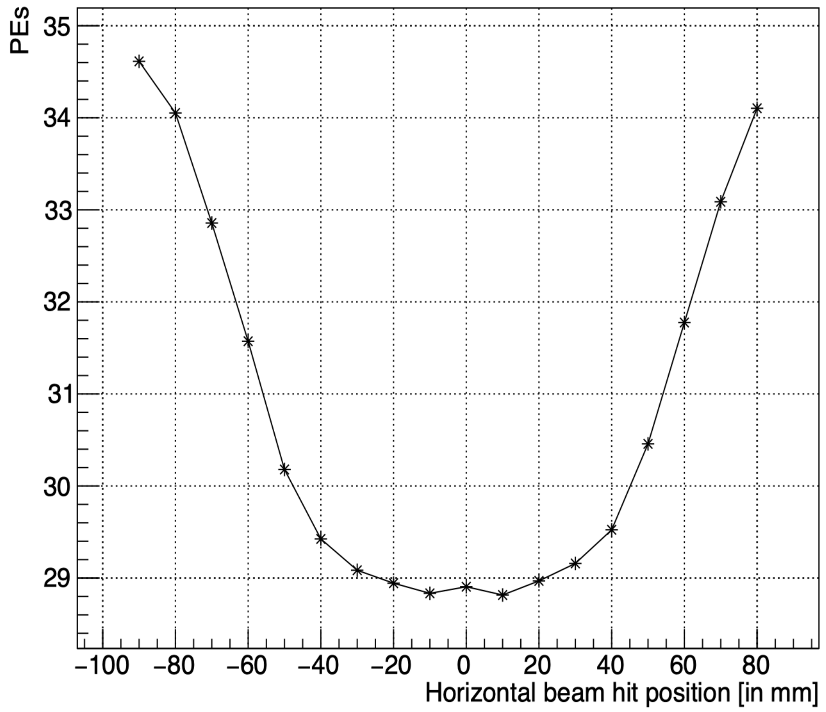


- **Mainz Microtron (MAMI) test beam**
  - Nov 2022 and Sep 2023
  - 855 MeV electron beam
- **Photo-electrons from PMT Cathode = ~29**
- **Detector resolution** $\left(\frac{RMS}{Mean}\right) = 0.35$

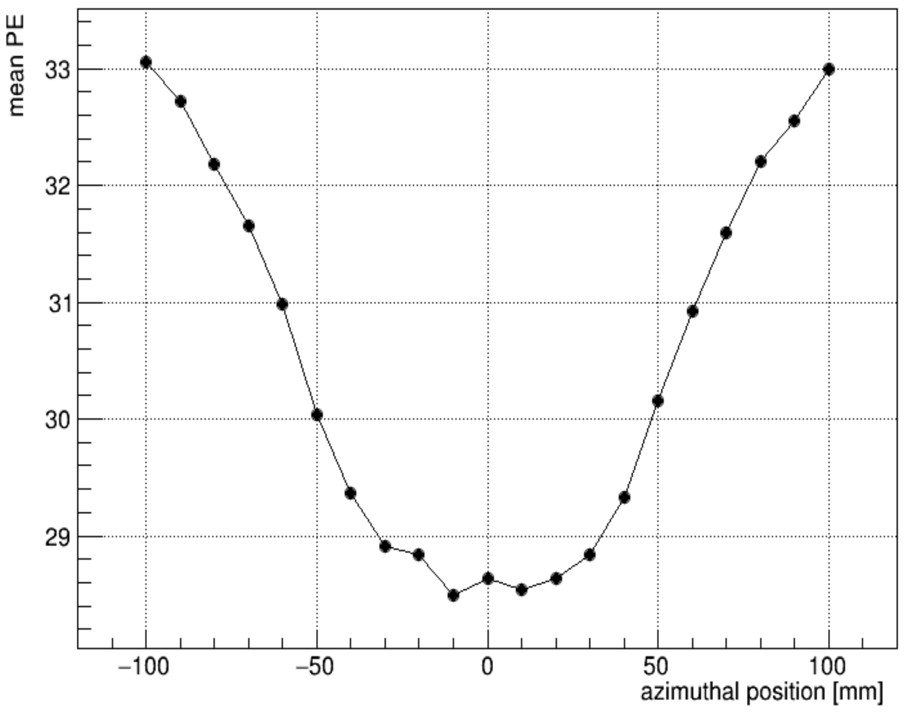
Azimuthal Scan

- Azimuthal scan at ~20 mm above the center of the quartz and simulation was done with a similar configuration.
- Simulation and test beam data in agreement at 10% level

Test beam azimuthal scan



Simulation azimuthal scan



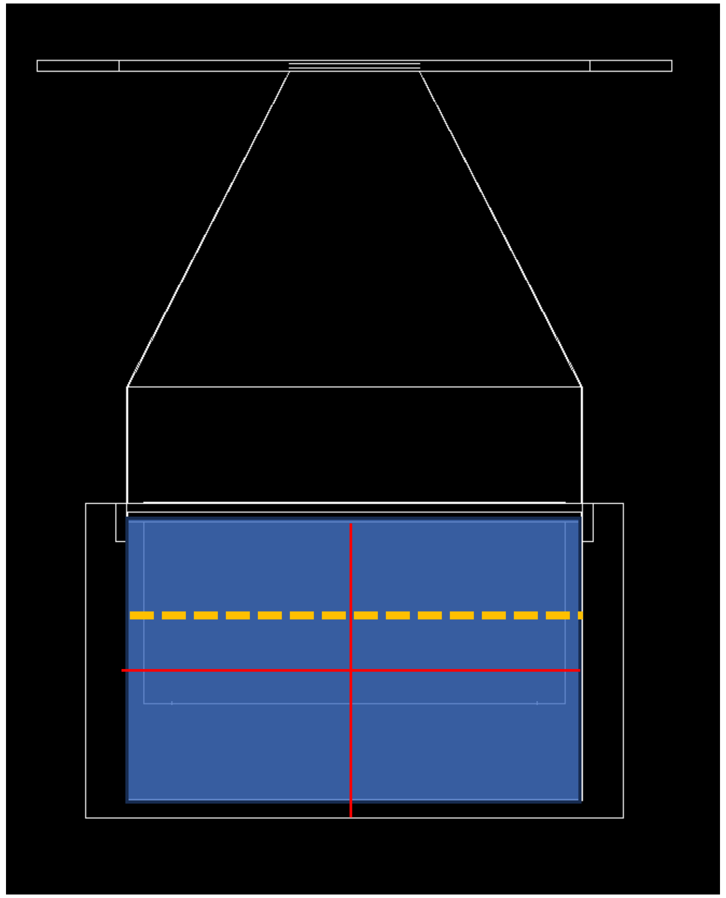
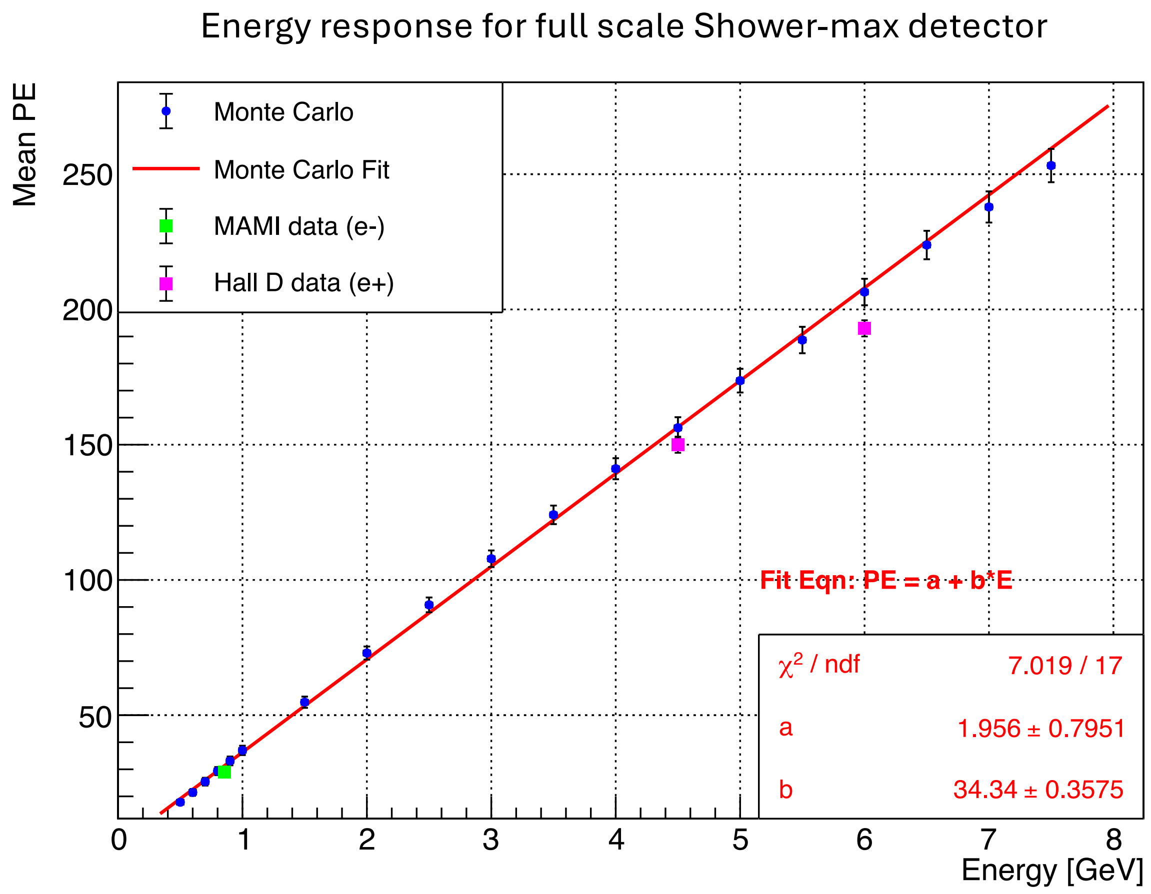
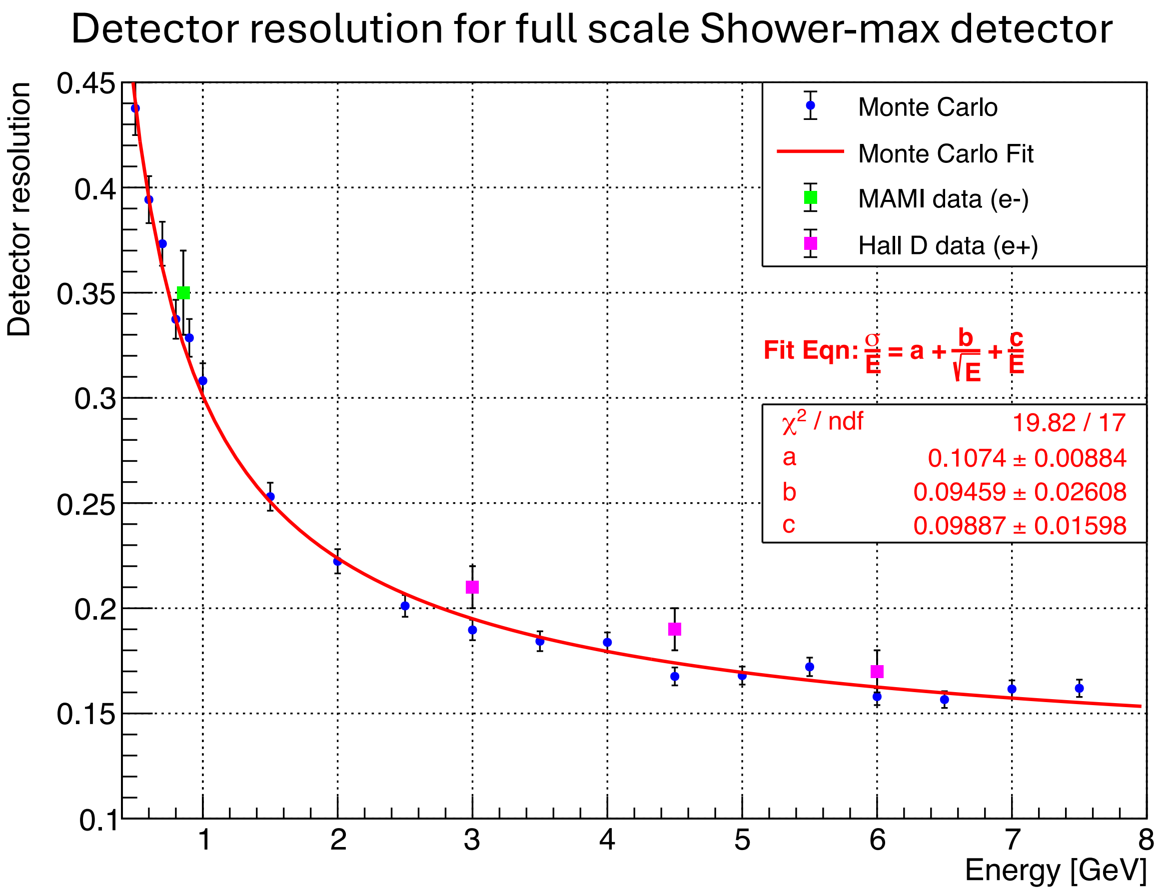


Fig: Shower-max retro v2 with its full-size quartz (blue), quadrant separating lines (red), and the approximate azimuthal scan line of the beam hit (yellow)

Detector response to energy





- **Energy dependent response**
  - ~Linear with ~35 PEs/GeV of electron energy
  - Hall D data is "Preliminary", analysis is ongoing
- **Detector resolution**
  - Useful parameter to calculate the excess noise above counting statistics
  - Requirement is < 25% resolution for energy > 2GeV

Shower-max module production

- **Procurement:**
  - 2024: All 130 quartz plates, 124 tungsten plates, 31 PMTs, 31 chassis and light guide assemblies (received and inspected)
  - 2025: Support struts for ring mount, alignment and lifting fixtures, custom 78 mm longpass filters (received and inspected)
- **Assembly:**
  - All 31 modules assembled, and cosmic ray tested in Idaho
  - Partially disassembled and shipped to Jlab in 3 separate shipments (Sept 2024, Nov 2024, and Feb 2025)
  - All modules reassembled at Testlab and stored
  - PMT cradle design finalized, 3D printing in process
  - PMT front-end electronics assembly and testing in process at Idaho
  - Light-tightening Kapton wrap design complete and in production
- **Ready to transport to hall A by end of April.**

Fig: Assembled modules in Idaho

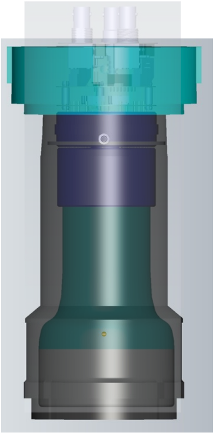


Fig: PMT Cradle

Fig: Assemble modules stored in high bay area of Testlab

Image courtesy: Dustin McNulty

Detector ring test

- Two fully assembled Shower-max modules are installed in adjacent positions.
- The process went smooth with no major issue.
- Important test for verifying fitment and validating/developing assembly procedures in the Hall

Fig: Shower-max lifted for detector ring test

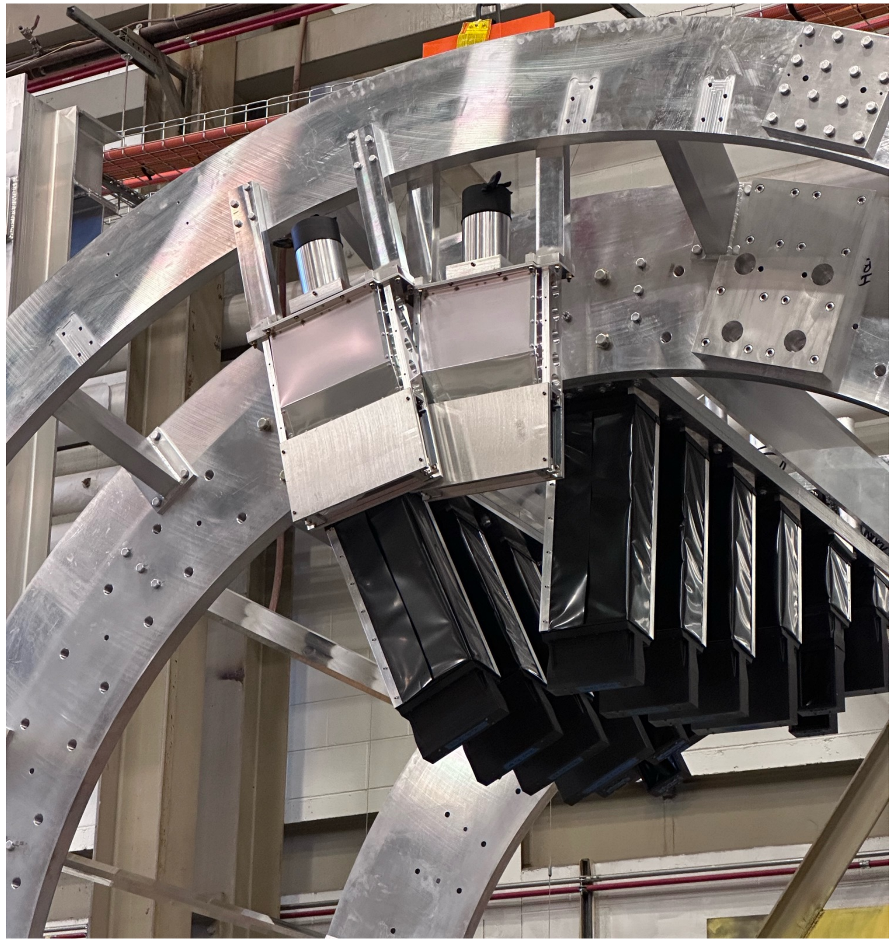


Fig: Two adjacent Shower-max installed in the ring

Radiation hardness testing: Quartz

- **Irradiation :**
  - conducted at the Idaho Accelerator Center (IAC)
  - 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
- **Goal:**
  - Quantify the relative transmission loss before and after irradiation (radiation damage)
  - Anticipated MOLLER lifetime dose: 45 MRad peak and 120 MRad peak per 5x5 mm^2 for ring 5 and ring 2, respectively
- Technical summary document (MOLLER DocDB 886-v1)

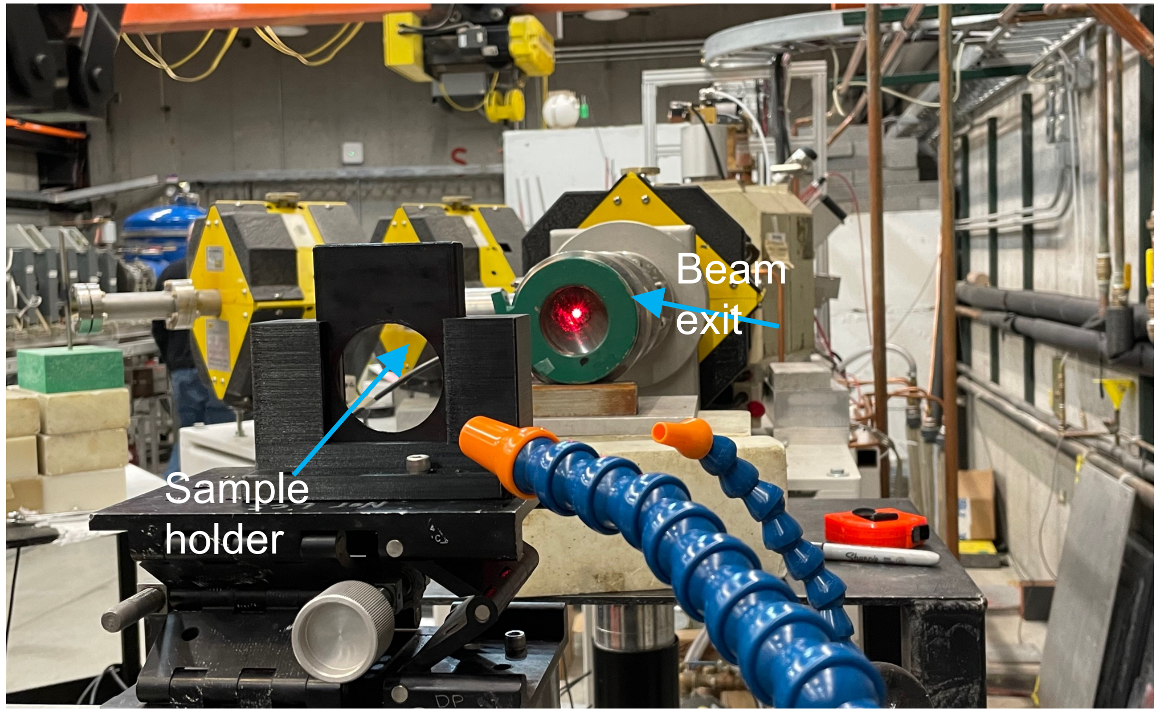
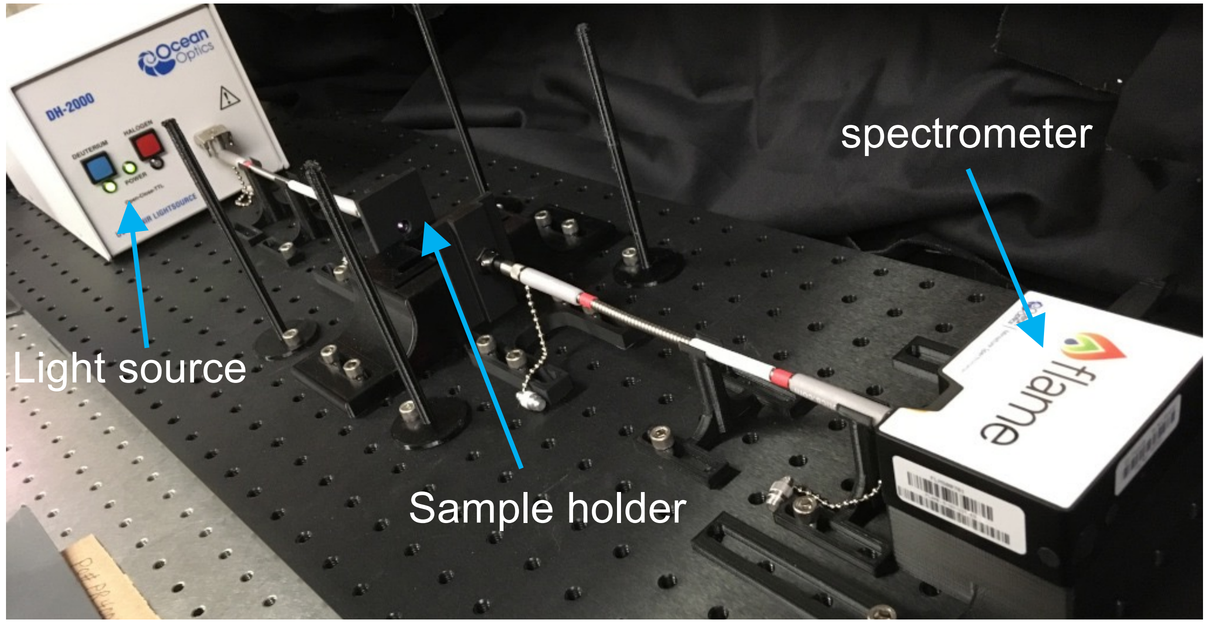


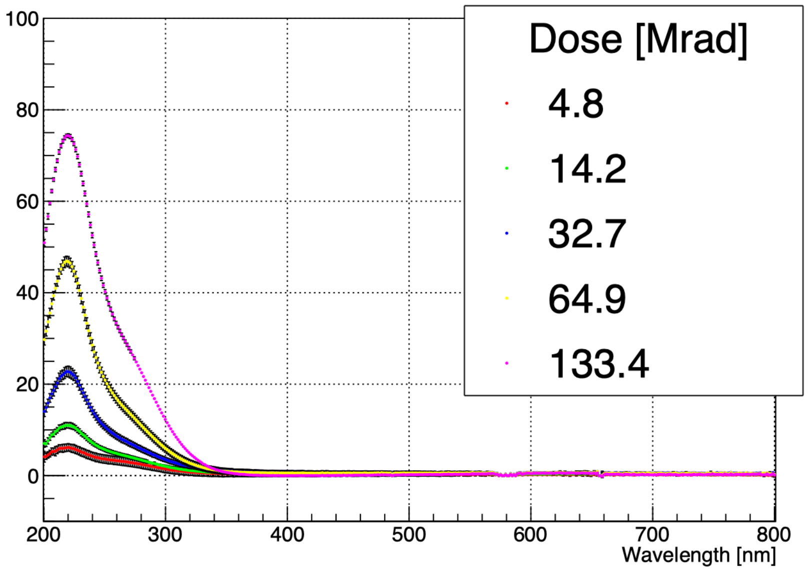
Fig: Idaho Accelerator Center on Campus (top) and Transmission measurement apparatus (bottom)



Picture courtesy: Dustin McNulty

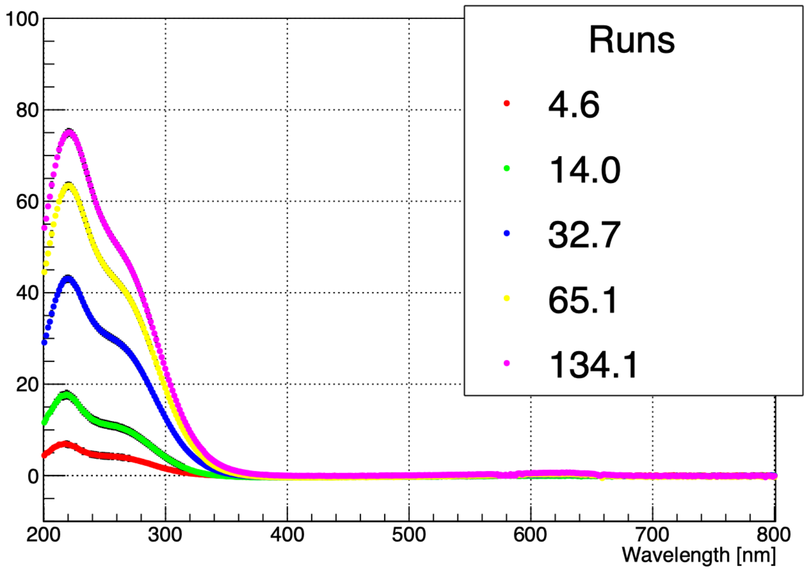
Quartz radiation hardness result: Light Loss

Corning 7980 UV Homogeneity Grade F

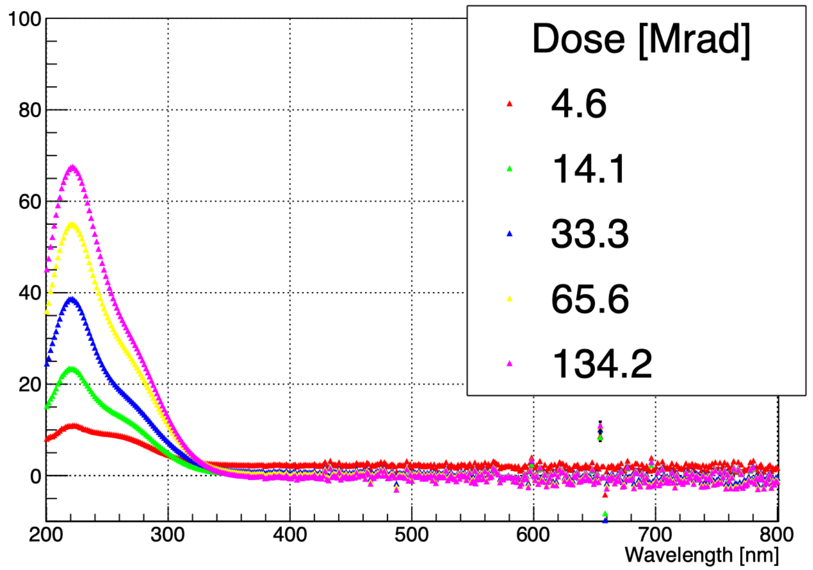


Used by Shower-max and Aux det

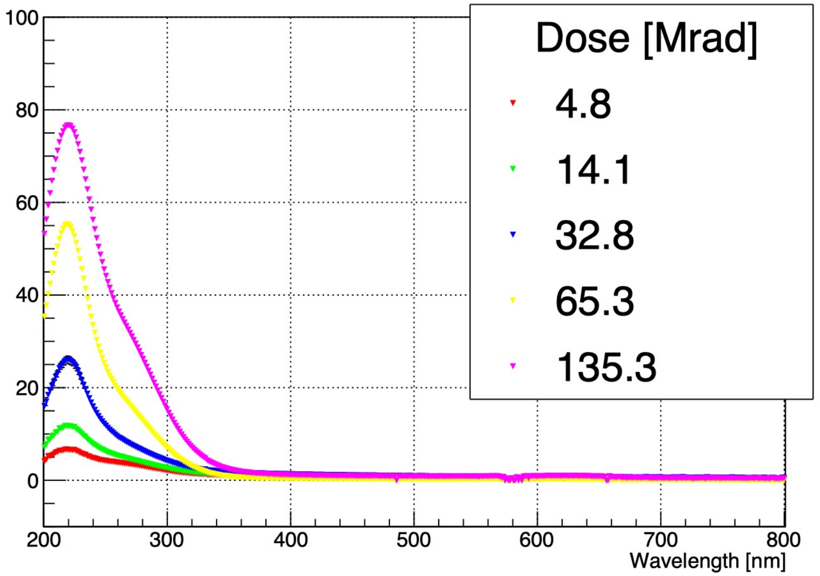
Heraeus Spectrosil 2000 Standard



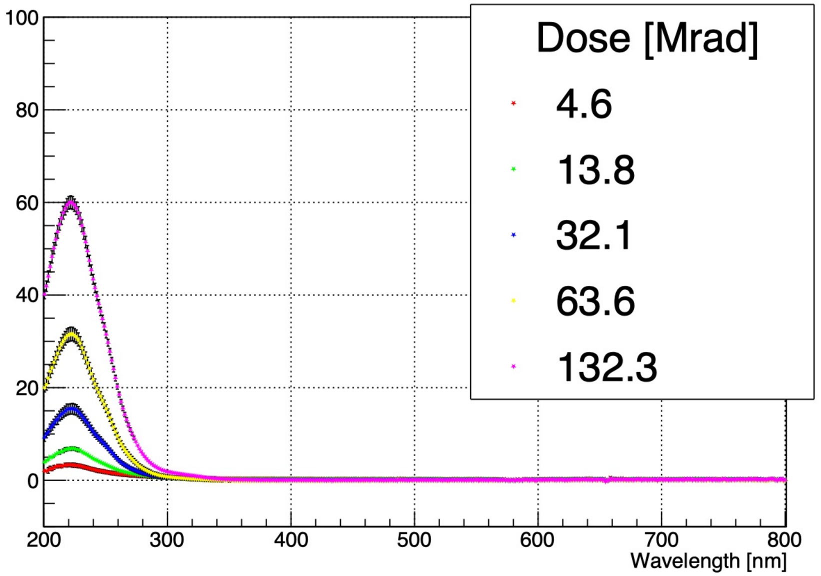
O'Hara SK-1300



Corning 7980 ArF Excimer



Heraeus Spectrosil 2000 High H2



Used by main det

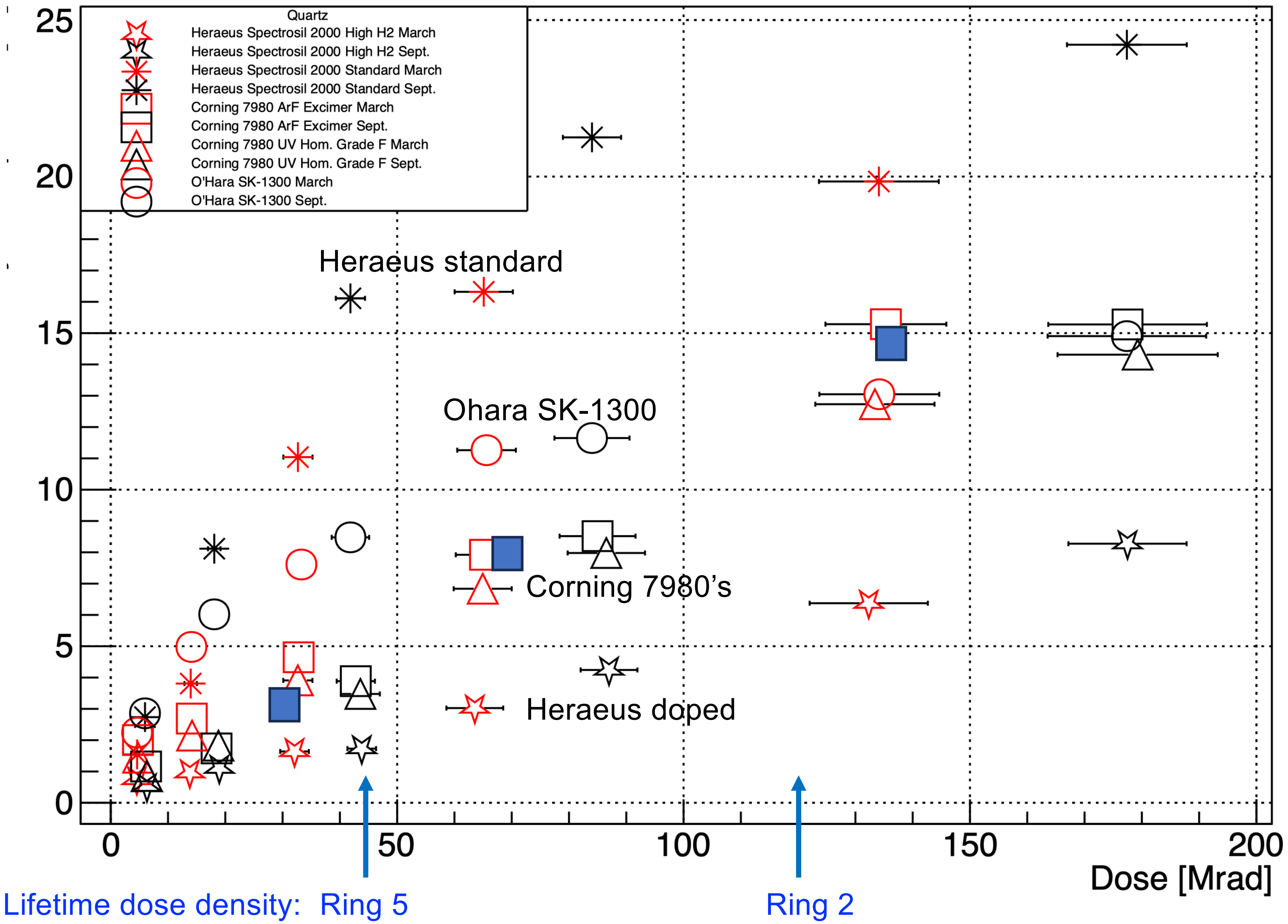
- Five samples from three vendors (Corning, Ohara, and Heraeus)
- **Best choice:** Heraeus Spectrosil 2000 High H2 shows the least radiation damage at our doses (first best) and Corning 7980 UV Grade 5F is the second best.

Plots courtesy: Justin Gahley

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 H2 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 LP filters made with Corning 7980 to ~10 MRad; we observed no measurable transmission loss
- Recently QA tested Corning 7980 samples from new vendor (■)

Total Intensity Loss Across Wavelengths 220-400 [nm]



Slide courtesy: Dustin McNulty

Radiation hardness testing: 3D-printed plastics

MOLLER

- **Goal:** Quantify the tensile properties (modulus and yield strength) of 3D printed plastics under radiation loads up to 150 MRad
- **Samples:** PLA, ABS, Nylon, CF-ABS (dry and wet), CF-Nylon, Onyx, UltrasintPA11, and PEEK
- **Process:**
  - We irradiate 3D-printed plastic dog bone samples (ASTM D638 Type I standard) to various dose levels
  - We break them in tensile strength machine measuring elastic moduli and yield strength

Fig: 3D Printer with dogbones

Fig: Tensile strength machine

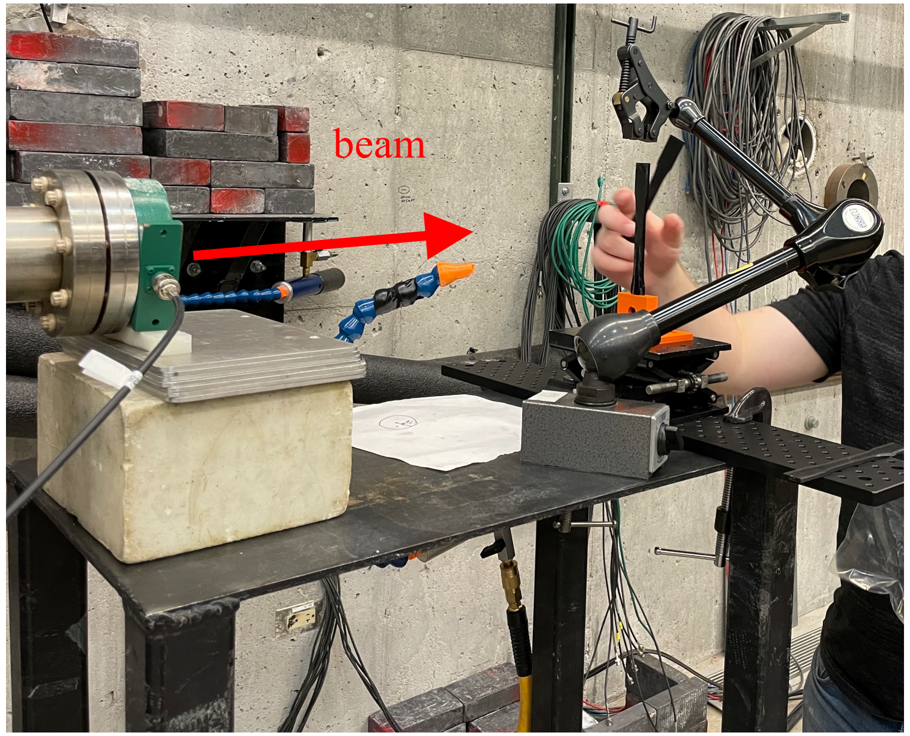
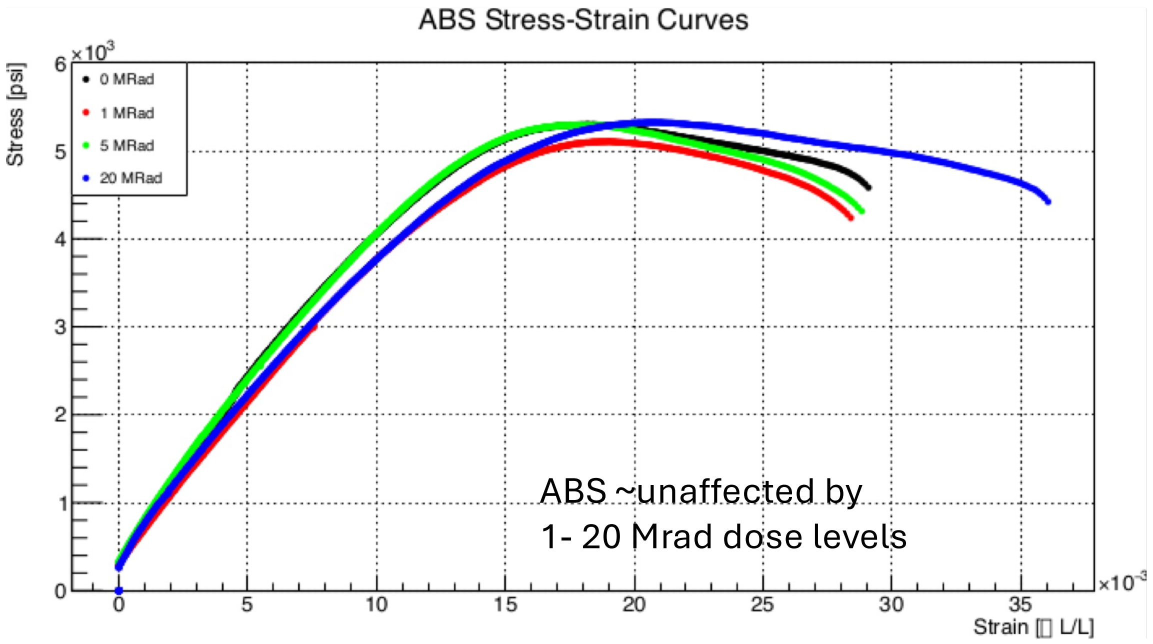


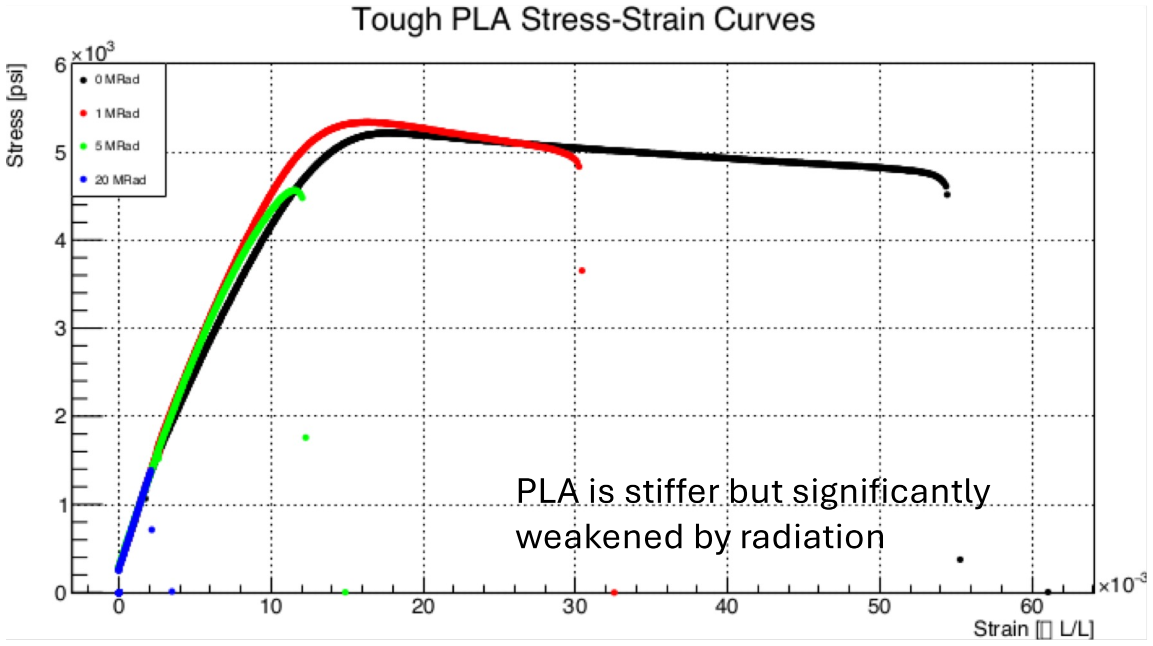
Fig: Dogbones being positioned in the beamline at IAC

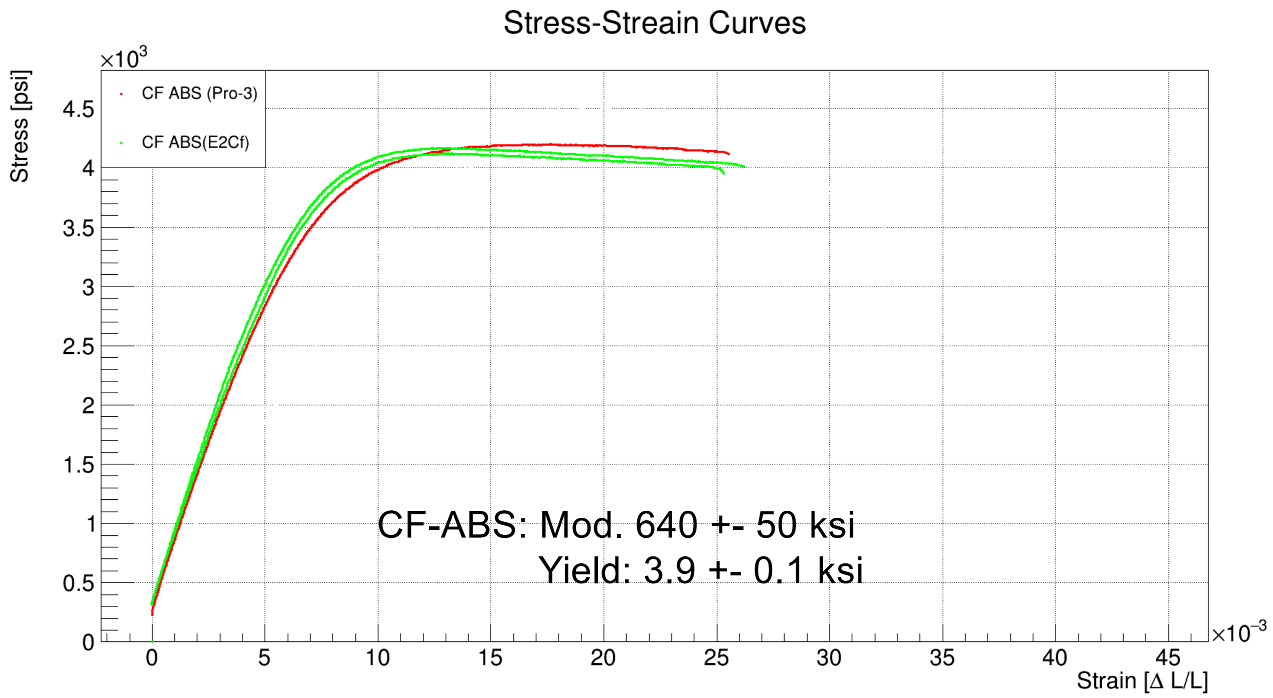
3D-printed plastic Irradiation test results

MOLLER



- **Results following irradiations:**
  - ABS is ~unaffected by radiation levels exceeding 150 MRad
  - PLA has high stiffness but is quickly weakened by radiation
  - CF-ABS is 40% stiffer and also ~unaffected by radiation at these levels





Plots courtesy: Elena Insalaco

Radiation hardness testing: PMT electronics

- **Goal:** Quantify pmt base functionality in both integrate and event mode following successive radiation dosing ~localized to specific components
- Lifetime dose levels on main detector and shower-max pmt electronics is ~60 – 70 kRad. We irradiated to ~120 kRad for factor of 2 safety margin
- Components tested include main integrate and event mode op-amp chips, voltage regulators, and two different types of DC-DC converters
- **Result:** All components survived the 120 kRad limit except DC-DC converter (both types) Now removed from the pmt base assembly and installed separately (easier replacement)

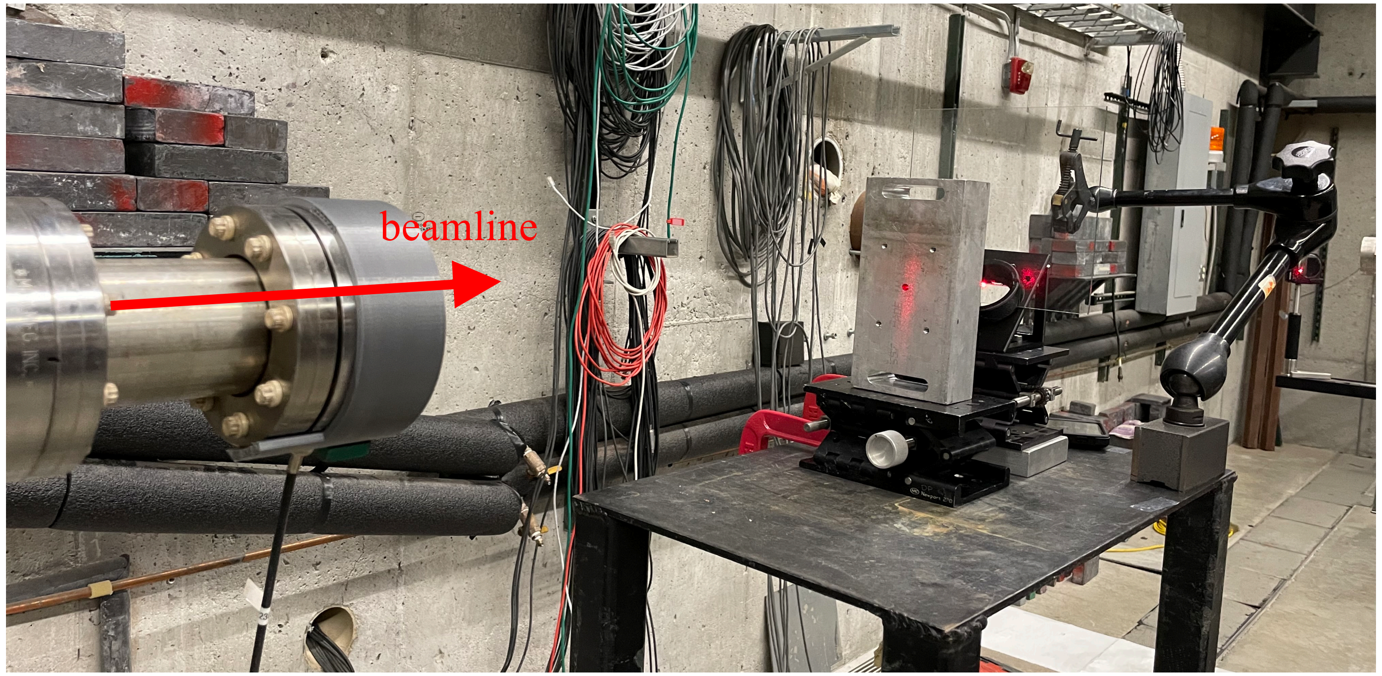


Fig: IAC beam line with collimator and sample stand

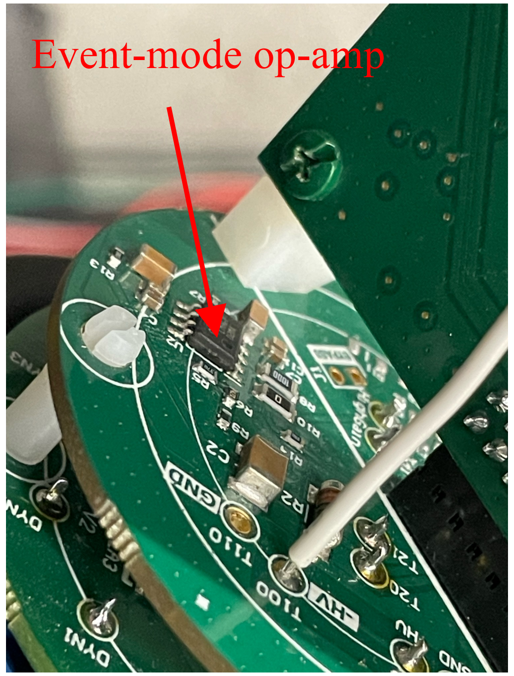


Fig: PMT base assembly

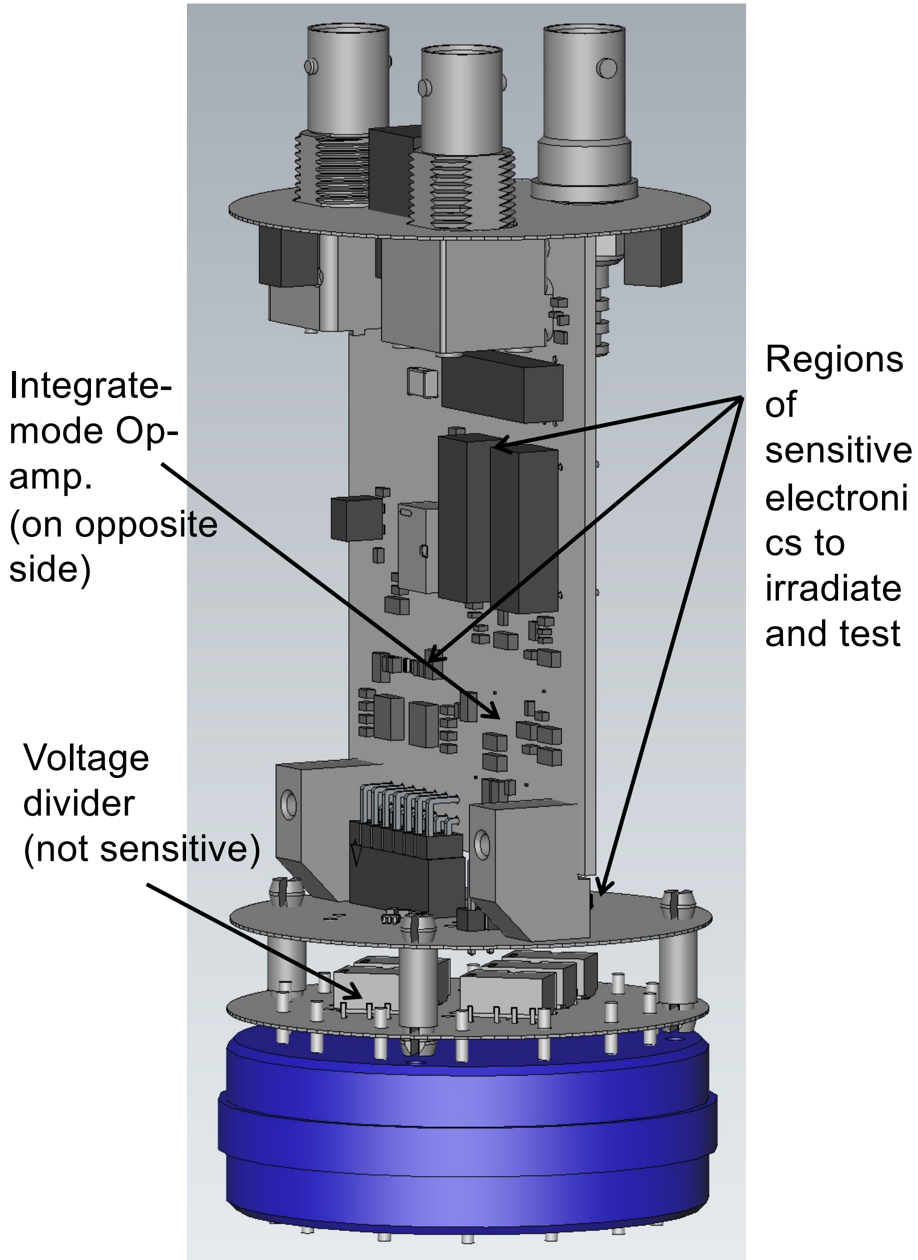


Fig: CAD of PMT base assembly showing the irradiating components

Summary

- **Shower-max detector summary**:
  - It is a Cherenkov based sampling calorimeter system that provides an additional measurement of the Moller A_{PV}
  - The PE yield from simulation and multiple beam tests is approximately 35 PEs/GeV of incident electron energy with detector resolution < 25 %.
  - All 28 detectors modules/components are constructed, cosmic tested and ready to move to the hall by April.
- **Radiation hardness test conclusions:**
  - Heraeus Spectrosil 2000 High H2 found to be the best (used by main det) and Corning 7980 UV Grade 5F is second best and most economical (used by Shower-max and aux det).
  - CF-ABS plastics is 40% stiffer than ABS while yield strength is 20% lower; both plastics are ~unaffected by radiation at 150 MRad level. The main detector uses CF-ABS for some components
  - All electronic components survived the 120 kRad limit except the DC-DC converters. We have now removed the DC-DC converter from the pmt base and installed in a separate enclosure (with pin socket) for easier replacement.

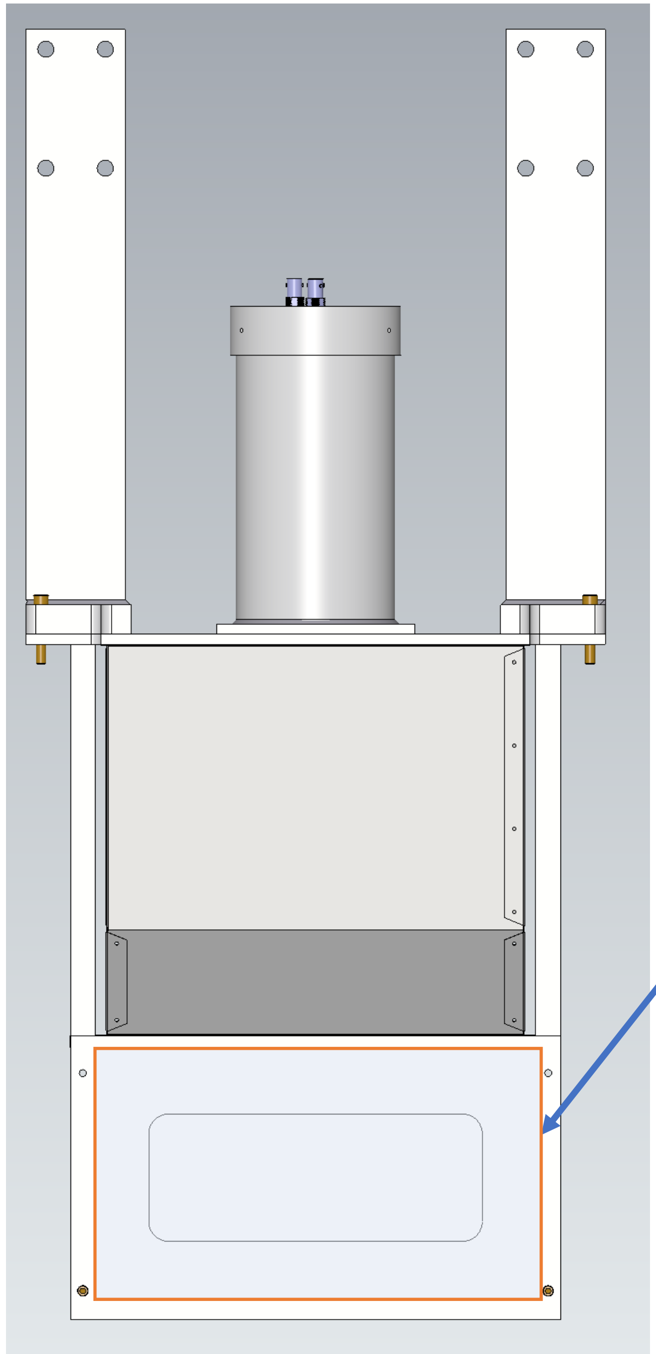
Acknowledgement:

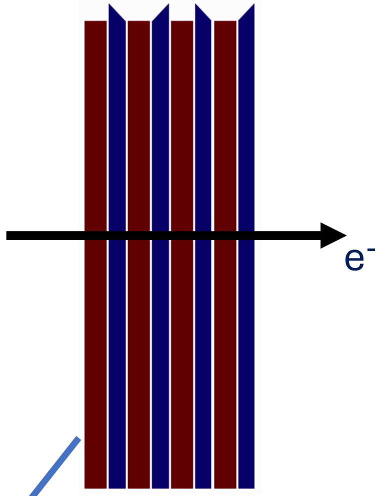
- Dr. Dustin E. McNulty, Professor and Chair, Department of Physics, Idaho State University
- Department of Energy, Office of Science
- National Science Foundation
- Thomas Jefferson National Accelerator Facility, Newport News, VA
- Idaho Accelerator Center
- MOLLER Collaboration

Thank you

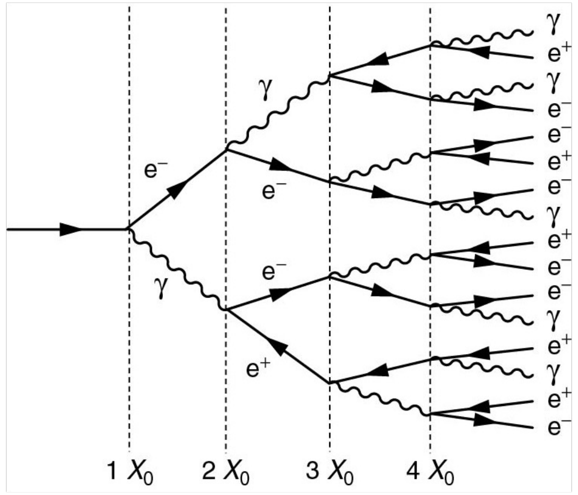
Additional Slides

Detector working principle: Active region

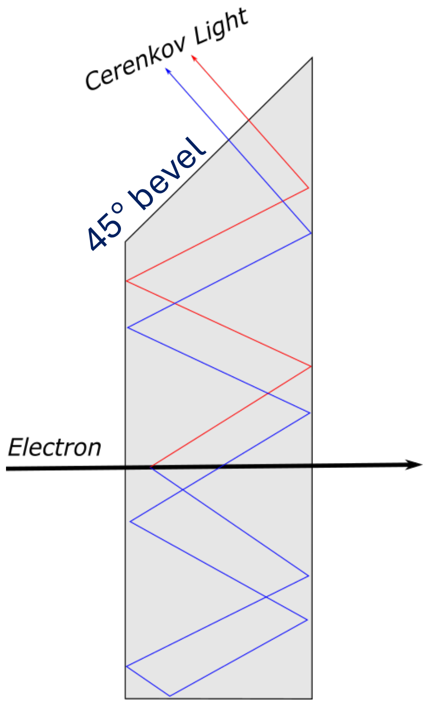




Four layers of Tungsten interleaved with 4 layers of quartz



Electromagnetic shower production inside the Tungsten layer



Cherenkov light production inside the Quartz layer

Moller to background ratio

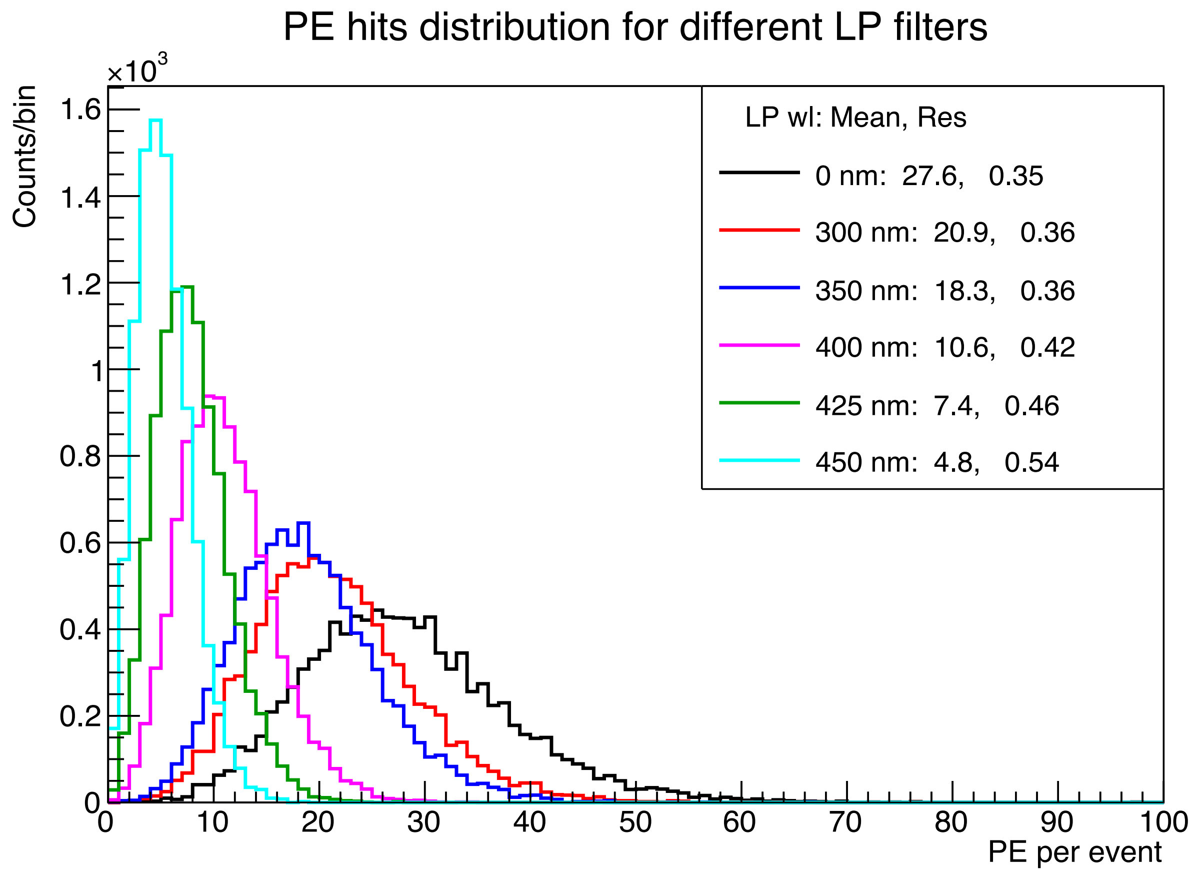
Generator	Particle	Rate		Rate*Energy	
		Value [GHz]	% contrib	Value [GHz*GeV]	% contrib
ee	e-	124.9	31.86	424.9	77.89
	γ	214.9	54.82	76.7	14.06
epel	e-	8.9	2.27	35.2	6.45
	γ	42	10.71	7.1	1.30
epin	e-	0.3	0.08	1.3	0.24
	γ	1	0.26	0.3	0.05
Total		392	100	545.5	100

Takeaway:

- For rate weighted signal, Moller to background % contribution ratio is 87:13.
- For rate*energy weighted signal, Moller to background % contribution ratio is 92:8.

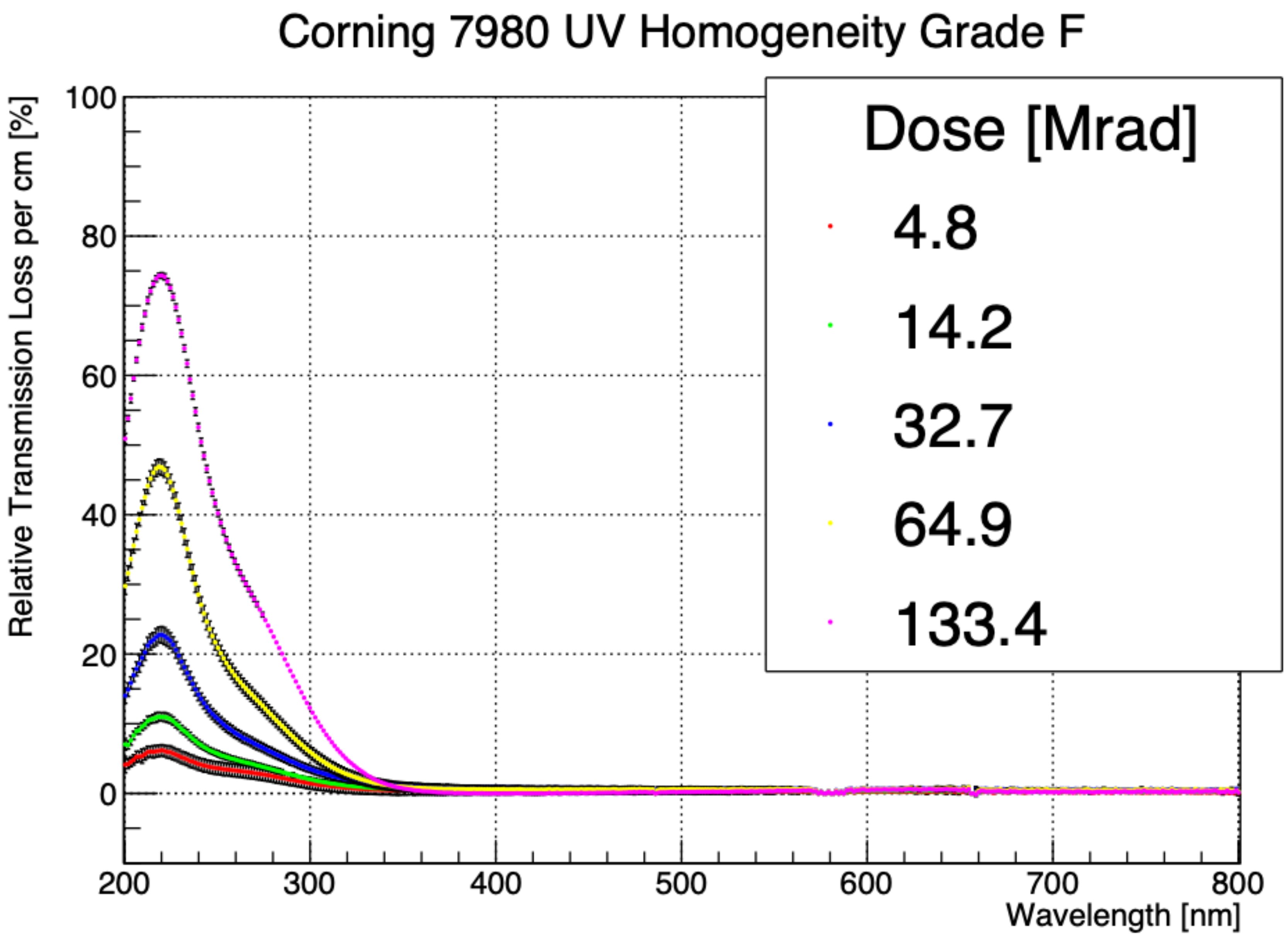
Cathode current estimates for Shower-max detector

Sector	Rate [GHz]	CC per det [nA]	CC /det with LP filter	Anode current with PMT gain of 500
open	31.6	232	51	26
closed	13.2	56	19	9
transition	179	65	27	11



- **Long pass filters:**
    - Open sector: 450 nm, 22% light preserved
    - Transition and Closed sector: 425 nm, 33% light preserved
- **Assuming a pmt gain of 500, Shower-max anode currents would be: 26 uA (open), 9 uA (closed), and 11 uA (transition)**

Radiation hardness test of Quartz

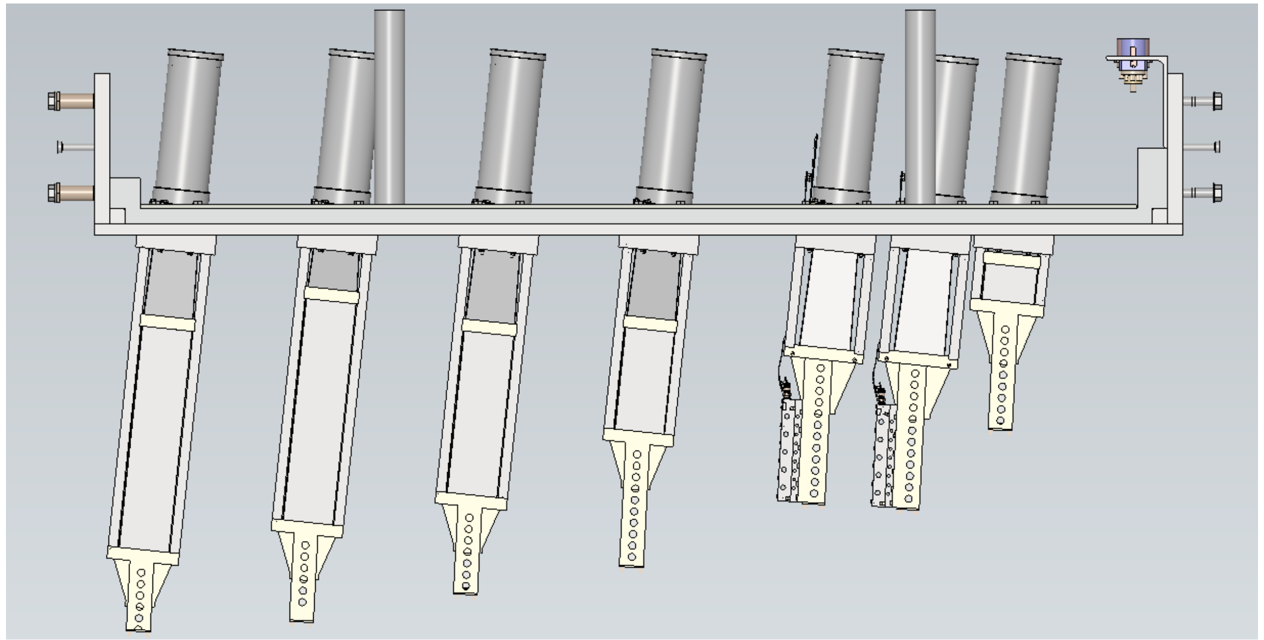


- During the MOLLER experiment, detectors must withstand high radiation, requiring radiation-resistant components.
- Simulations estimate the Shower-Max quartz radiators will receive about 1 GRad per 5 x 5 mm^2 pixel over the experiment's lifetime.
- Quartz samples tested at the Idaho Accelerator Center show Heraeus Spectrosil 2000 (with interstitial hydrogen) has minimal transmission loss for $\lambda \geq 350$ nm; Corning 7980 is the next best.

Plot courtesy: Justin Gahley

MOLLER Main Integrating Detector

- **Thin Quartz Main Detector**
  - **Simpler and well understood design**
  - **Successfully used in several previous parity violation scattering experiments**
  - **Sensitive to:**
    - **Low energy particles**
    - **Hadronic and photon background**
  - **Double counting in overlaps**



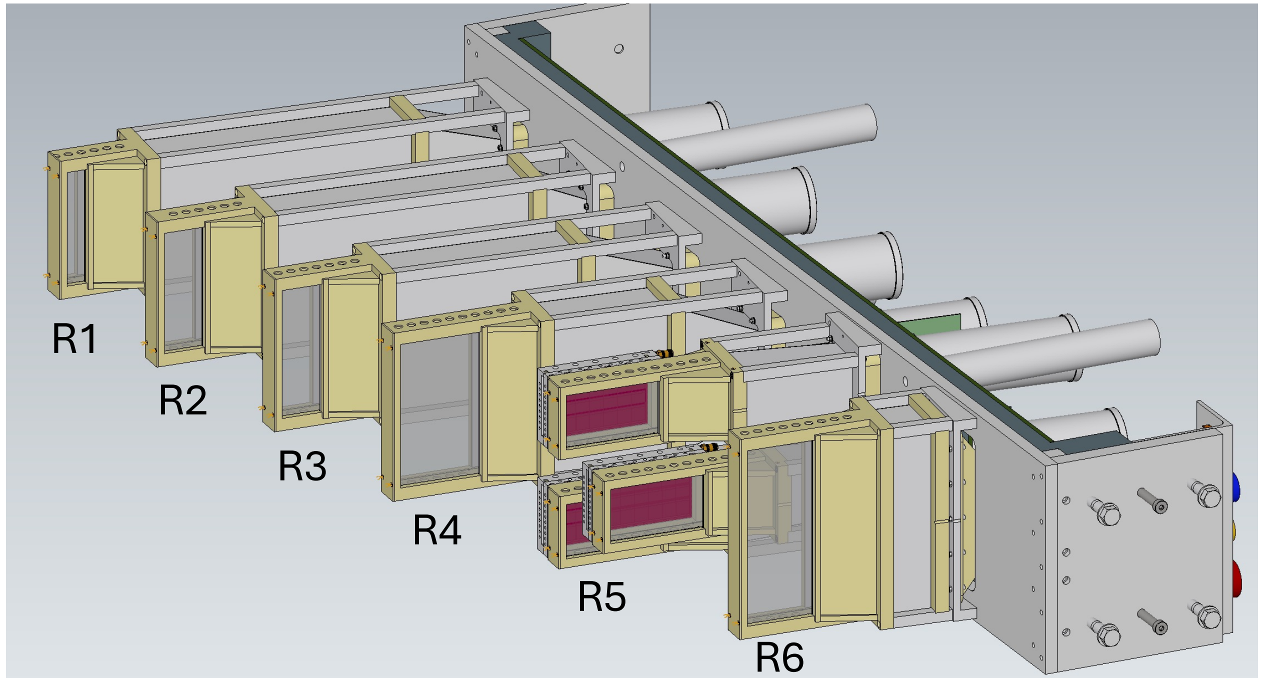


Fig: CAD model of a segment of the main integrating detector

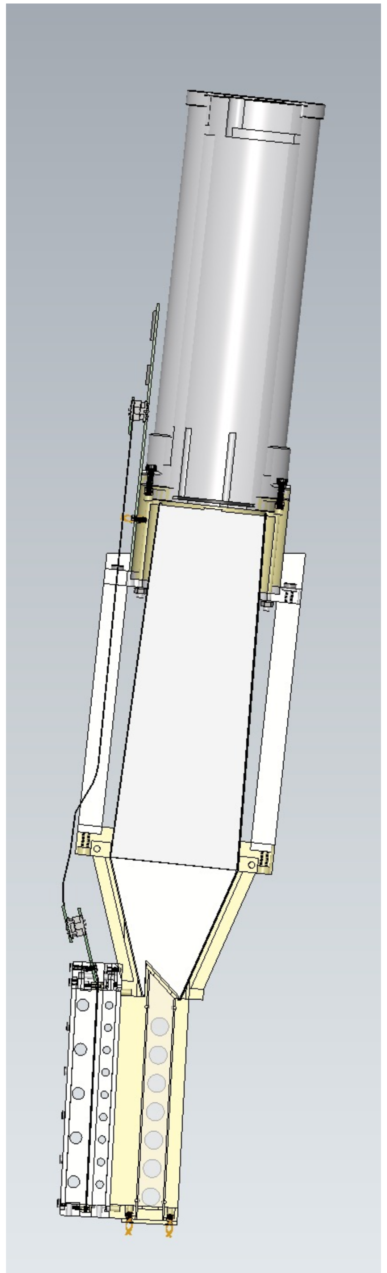
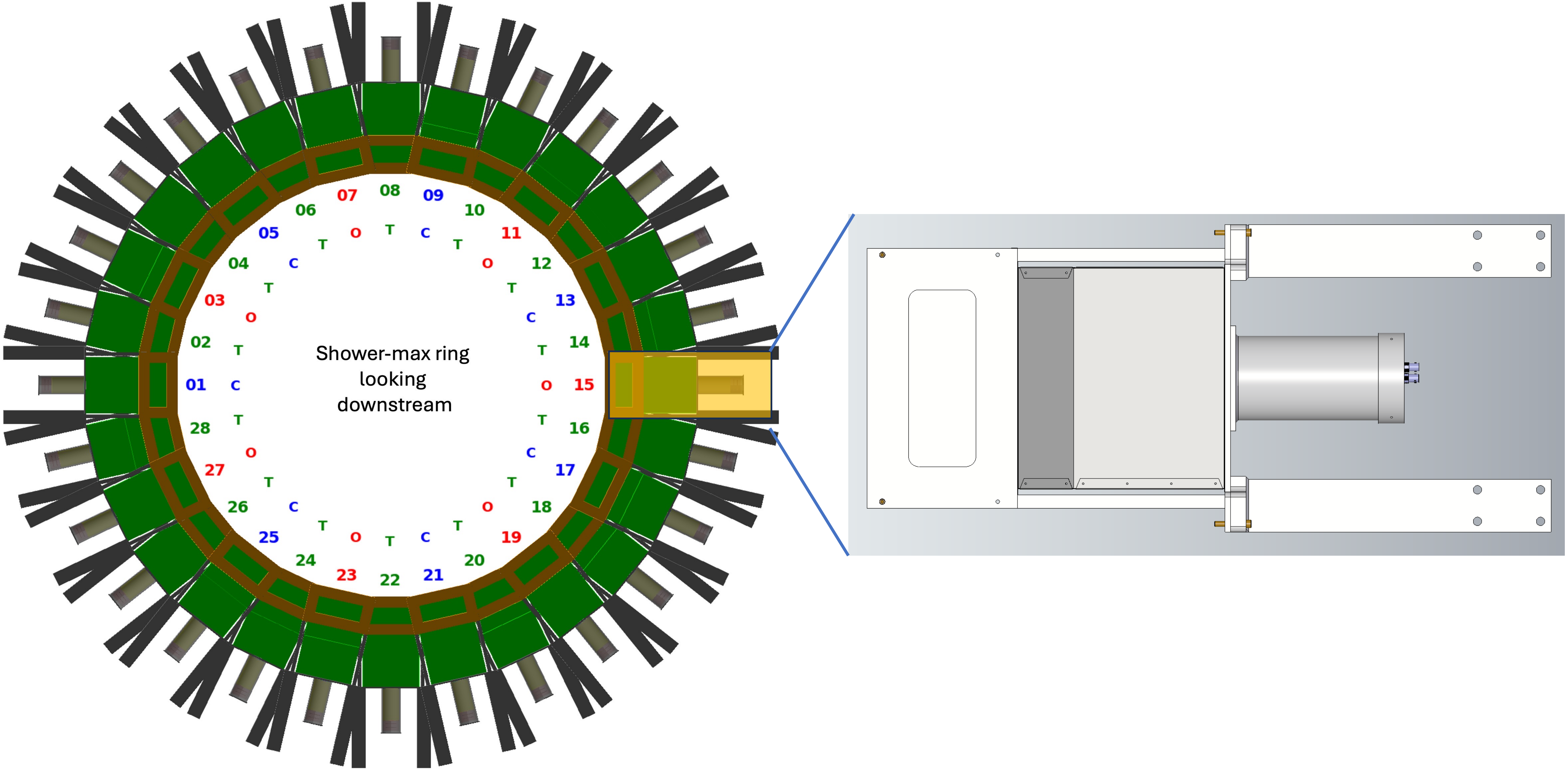
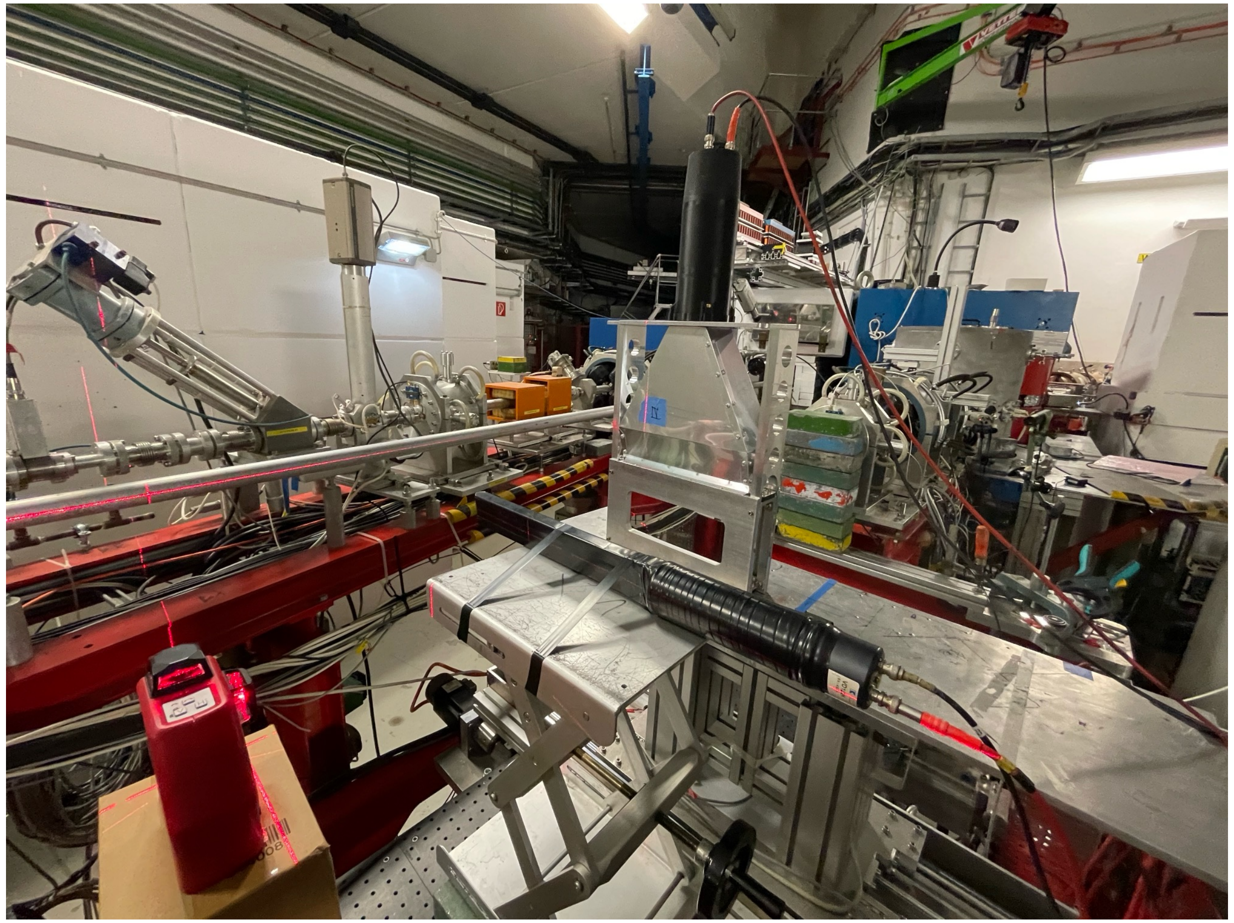


Fig: R5 module section view

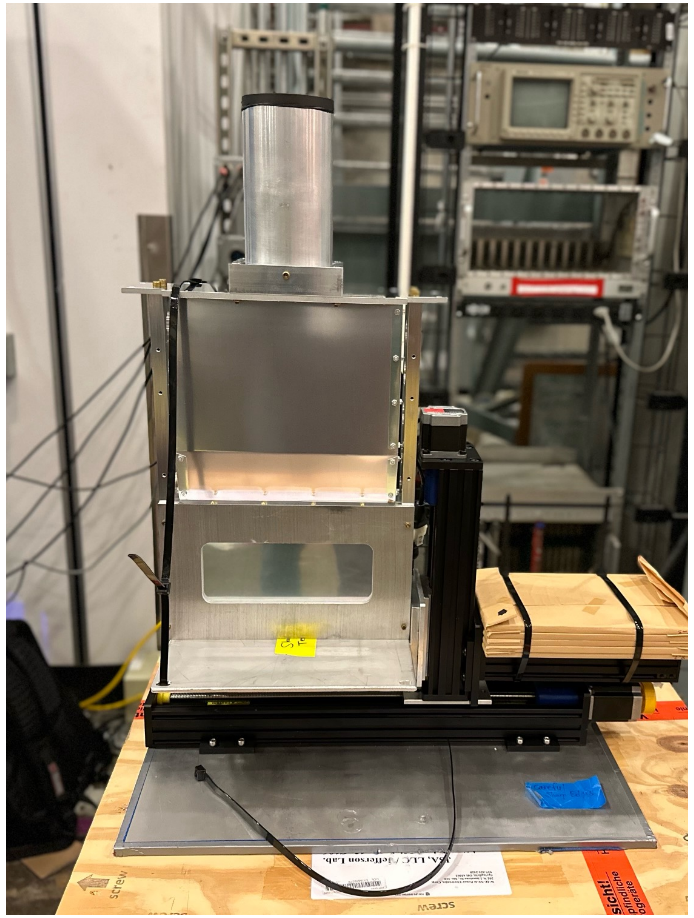
Shower-max ring



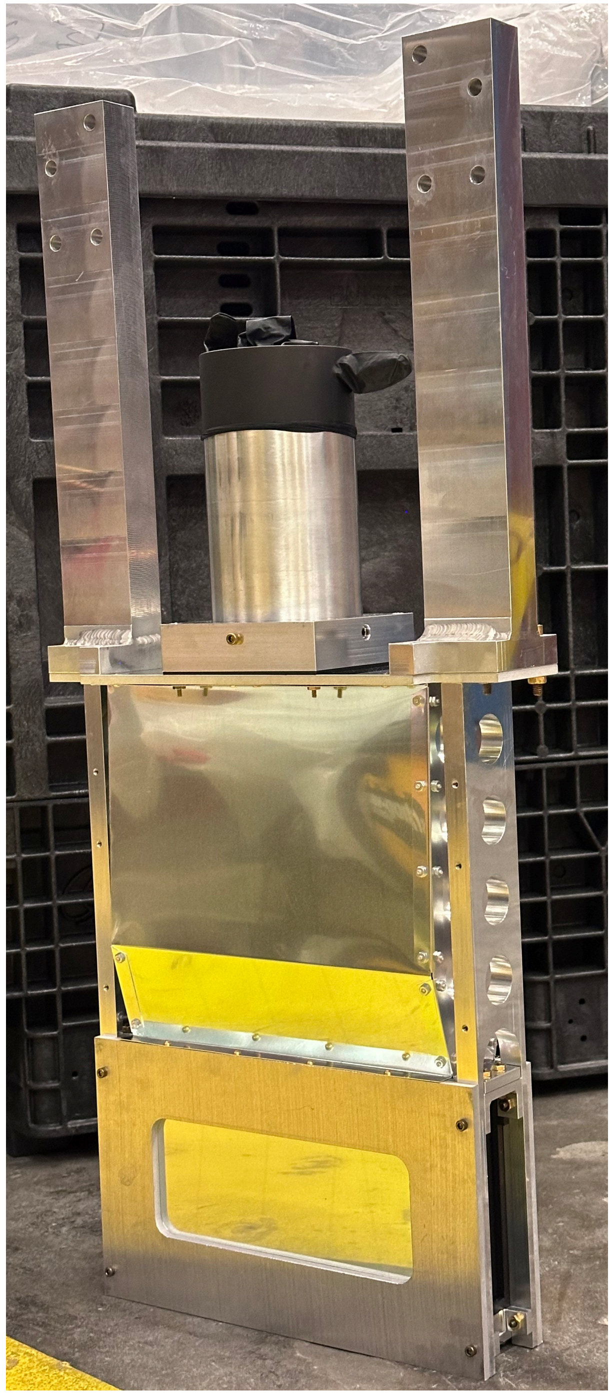
Shower-max modules



2023 Sept: At MAMI test beam facility in Germany, using 855 MeV electron to test the prototyes



2025 May: At Jefferson lab testlab testing the motion control system before taking it to Hall D parasitic test beam.



Jlab HallD Test beam

- Hall D Pair spectrometer test beam of range 3-6 GeV
- Capable of moving the detector in vertical and horizontal direction using motion control system

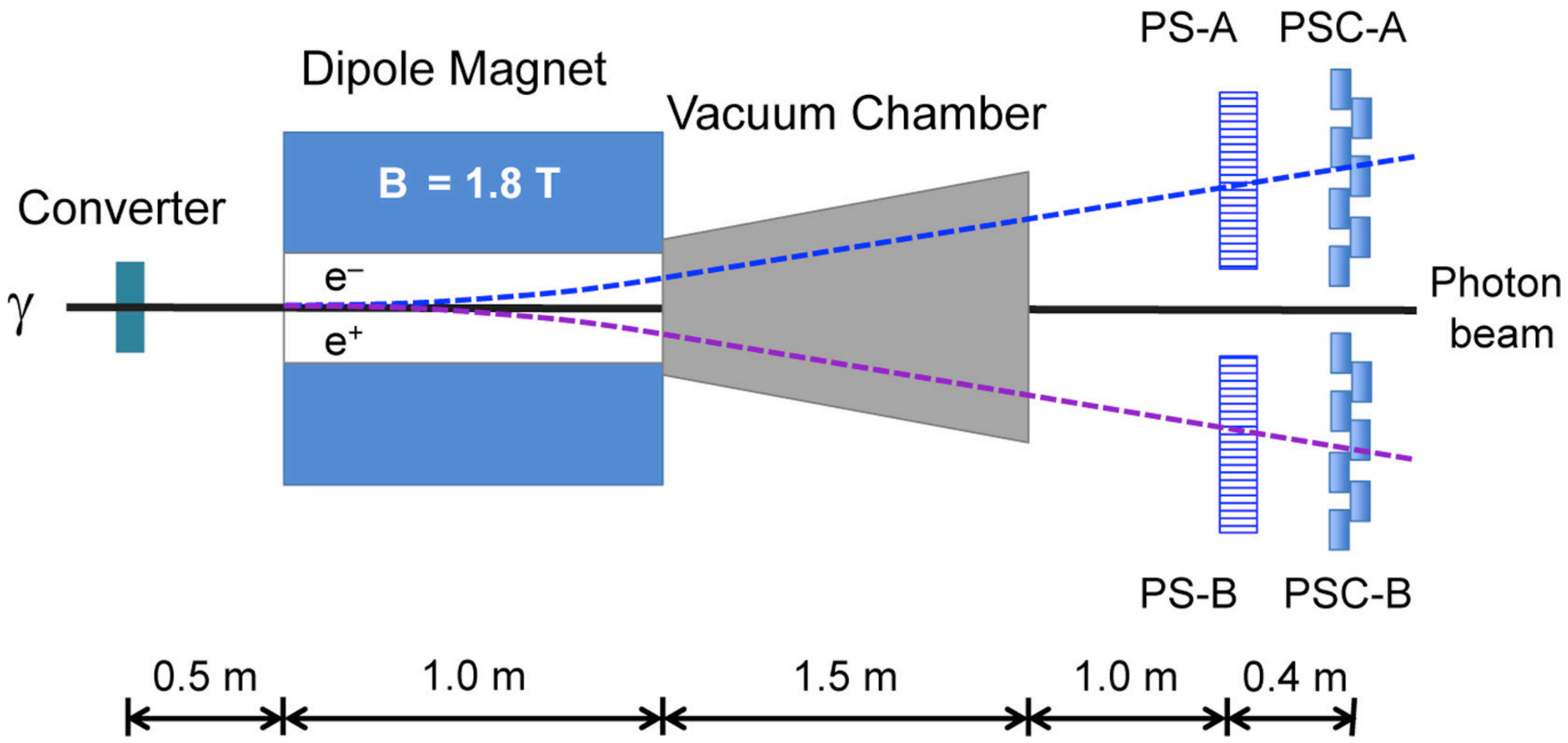


Fig: Schematics of the hallD PS region

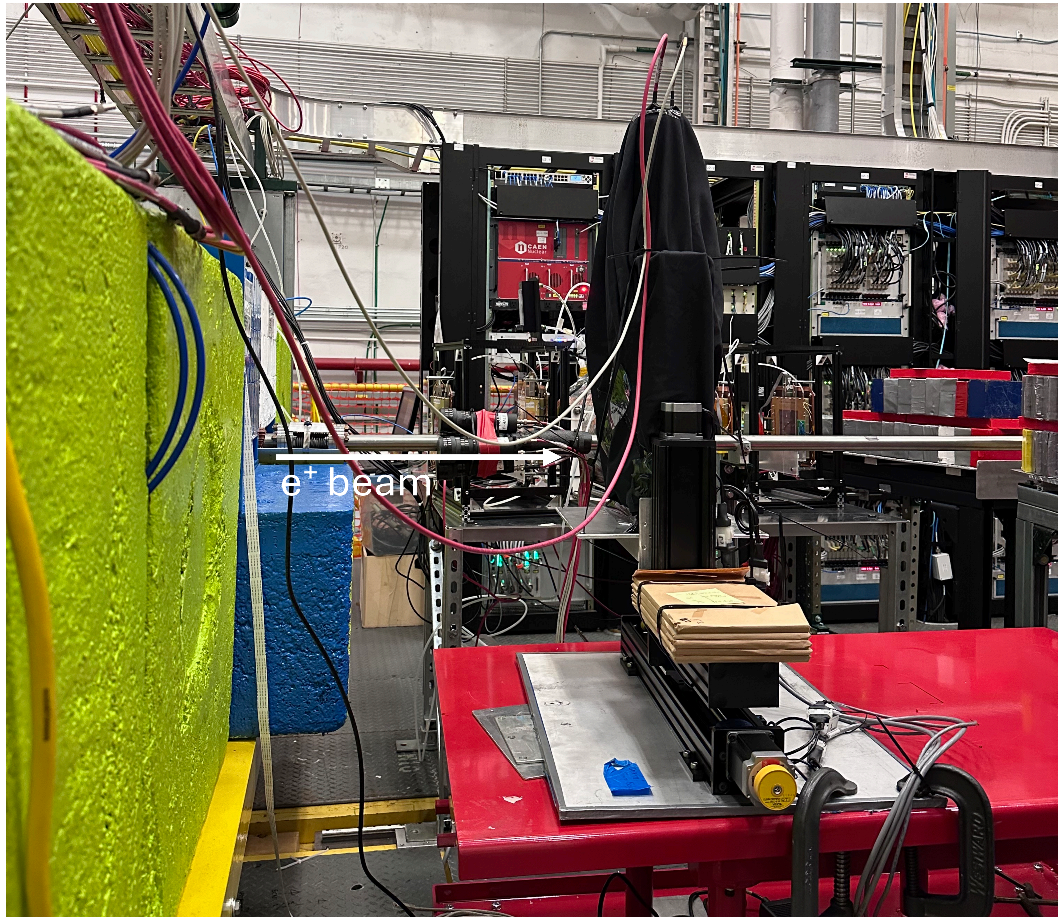
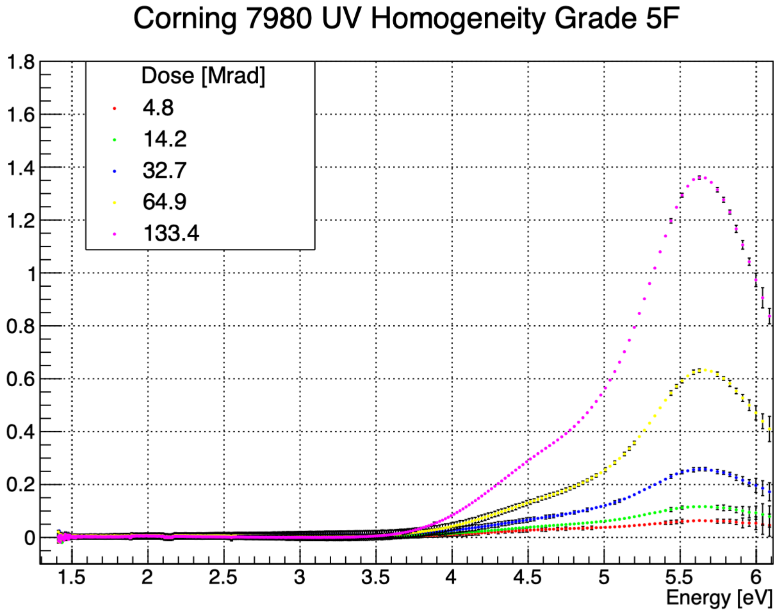
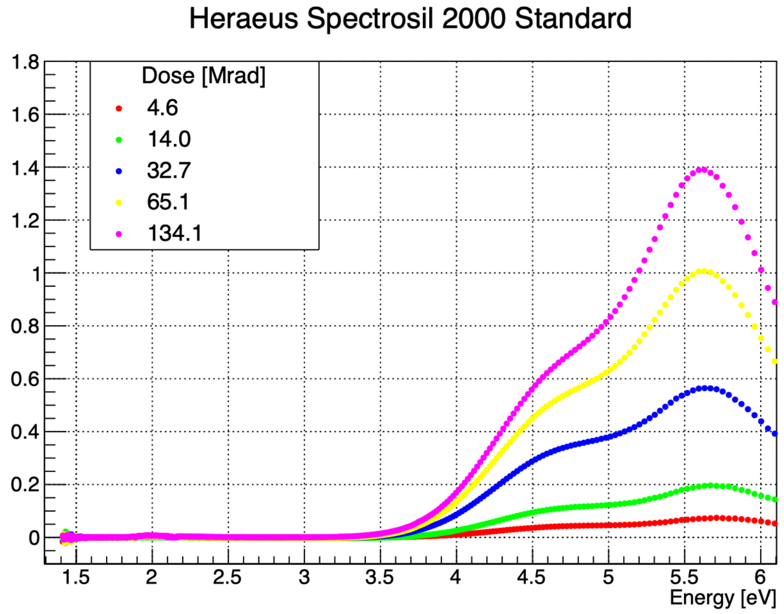
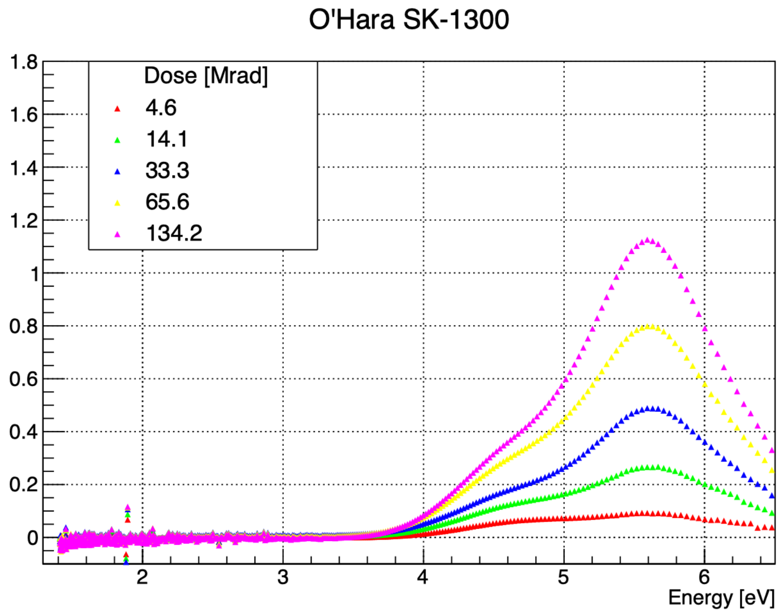


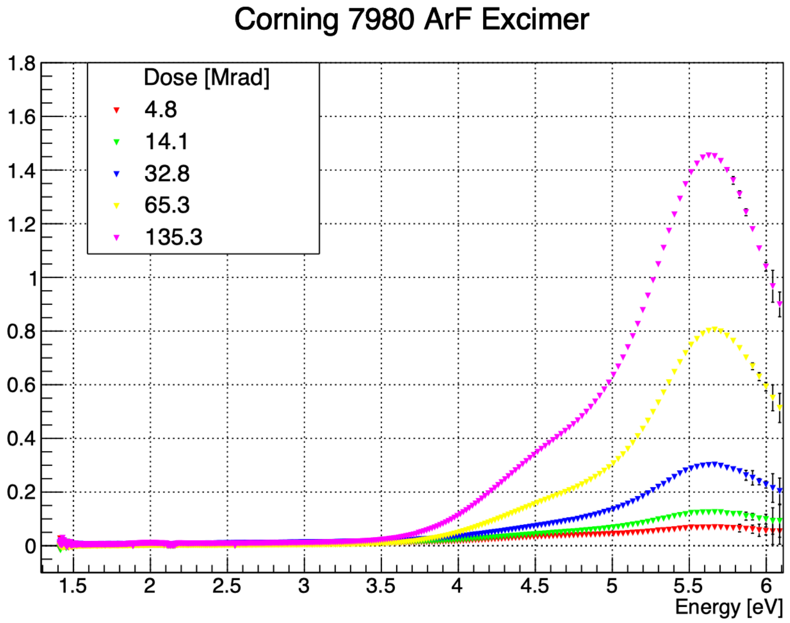
Fig: Shower-max placed at PS testbeam stand in hallD

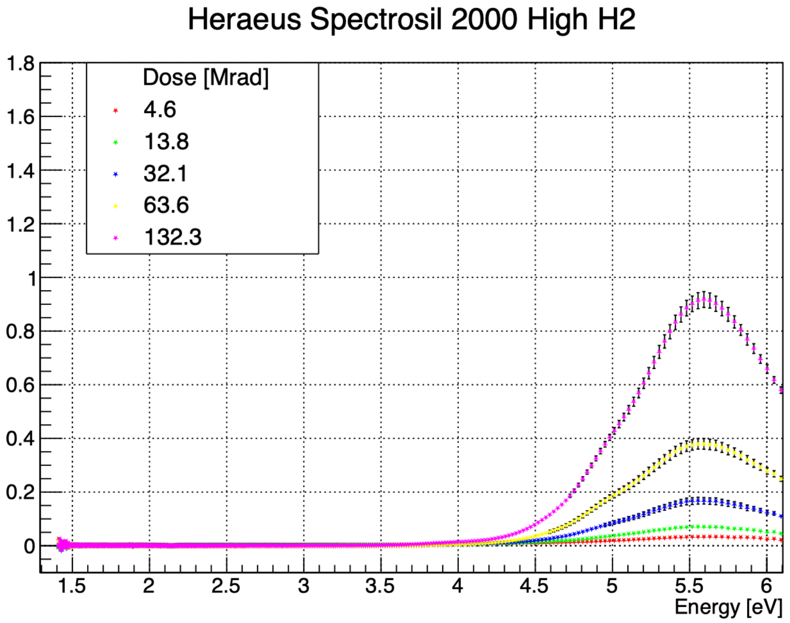
Quartz Radiatio Hardness Result: Absorption Coeff's











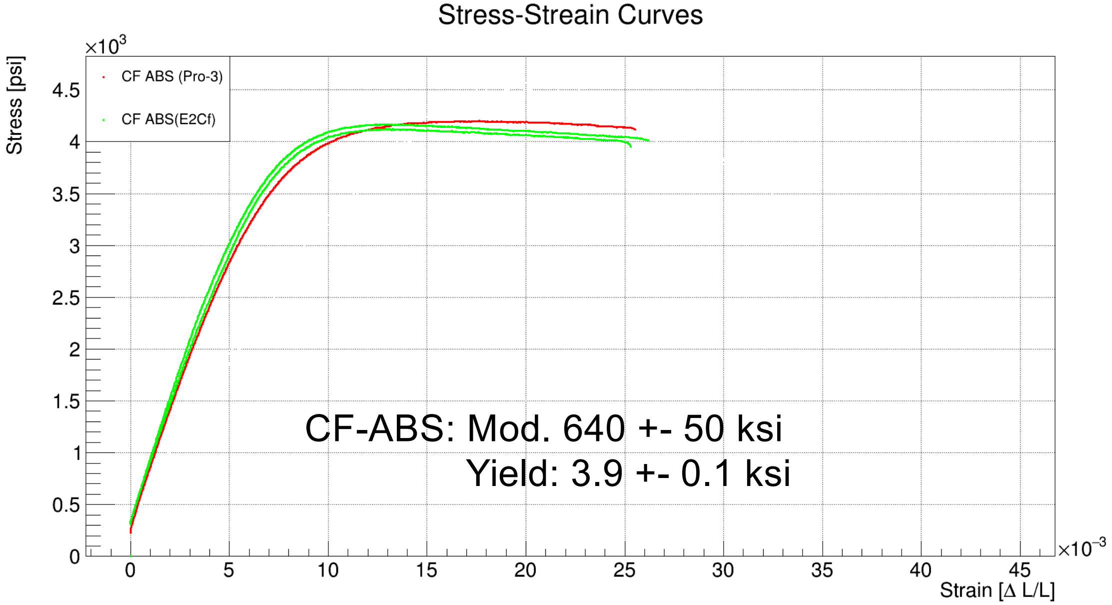
- All samples are wet (> 200 ppm OH content), except SK-1300 which is dry; doped Heraeus has high OH and high H2 content
- Main absorption center at 5.6 eV is the E' – unavoidable point-like defects that cause dangling Si atoms which absorb light
- The shoulder structures are from non-binding hydroxide absorption centers around 4.5 – 5 eV
- The high H2 doped Heraeus shows very little of this damage center at our doses

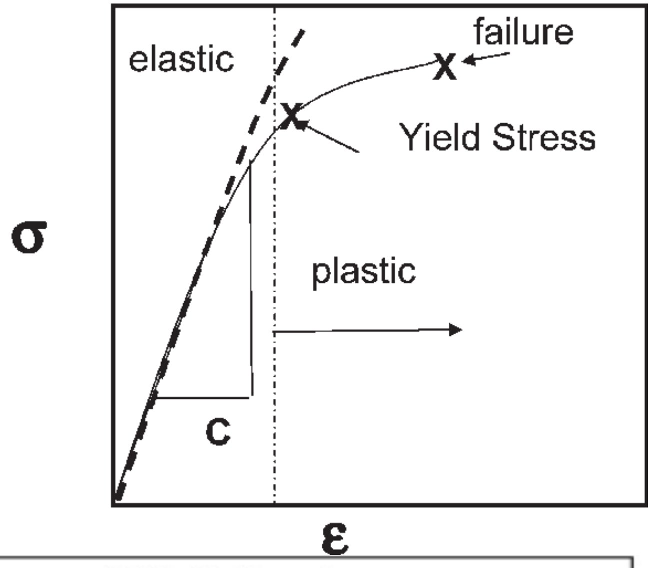
Plots courtesy: Justin Gahley

3D-printed plastics radiation hardness test result

- Modulus of elasticity: $\frac{\text{strain } (\frac{\Delta L}{L})}{\text{stress}}$
- Yield point (elastic limit): deformation starting point

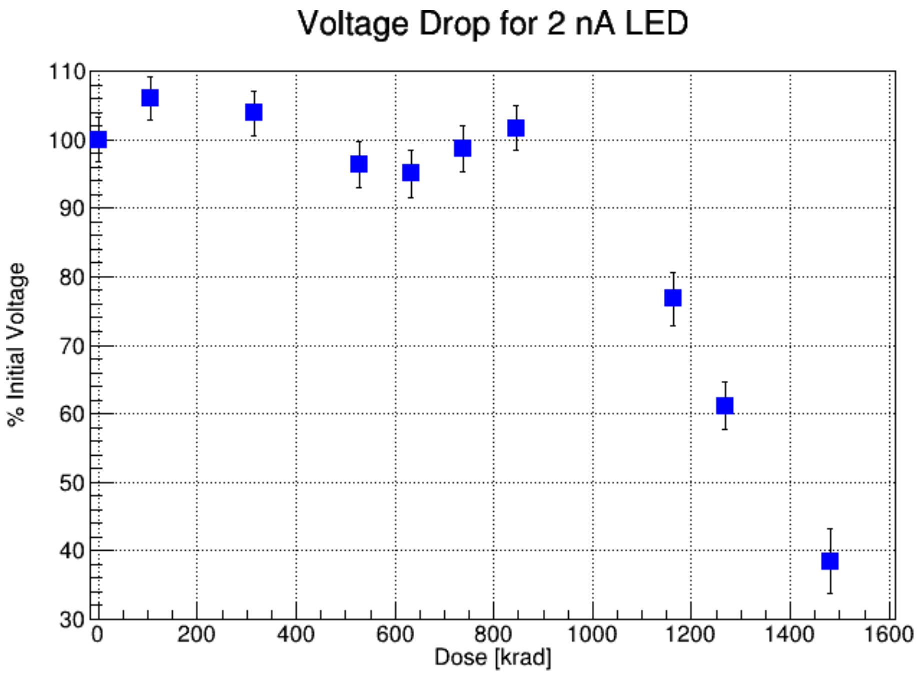
	0 Mrad (baseline)	
Material	Modulus [ksi]	Yield [ksi]
ABS	390 ± 20	4.7 ± 0.2
tough PLA	430 ± 20	4.8 ± 0.2
Nylon	250 ± 30	6.1 ± 0.2
C-fiber Nylon	520 ± 50	5.6 ± 0.3

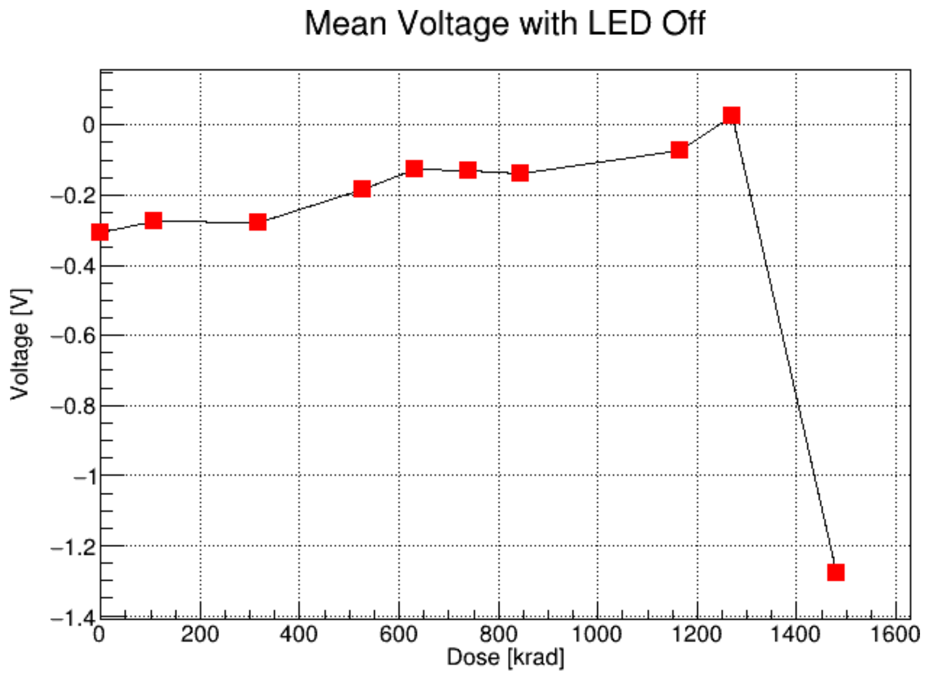


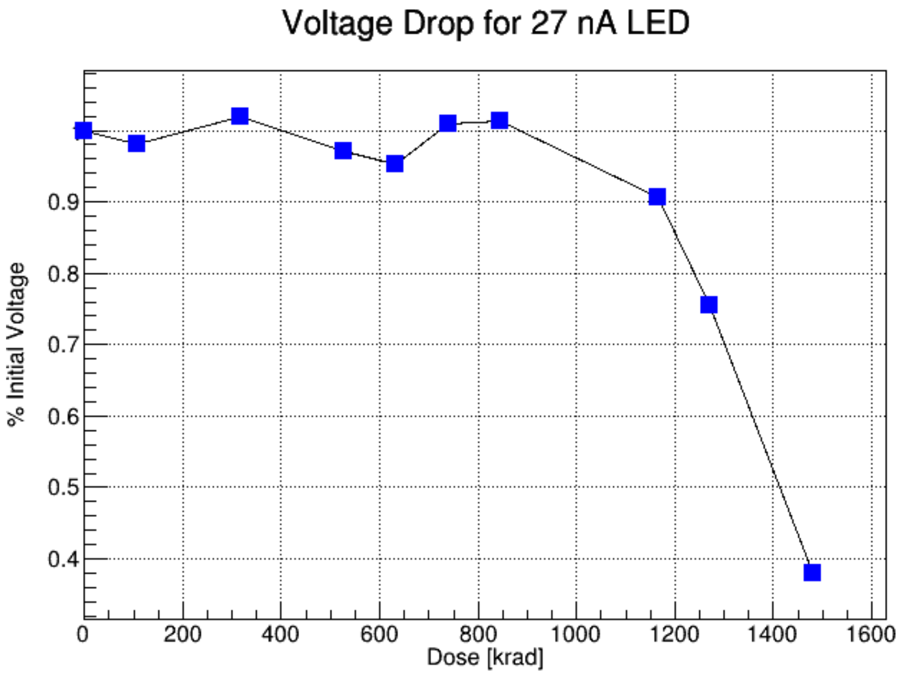


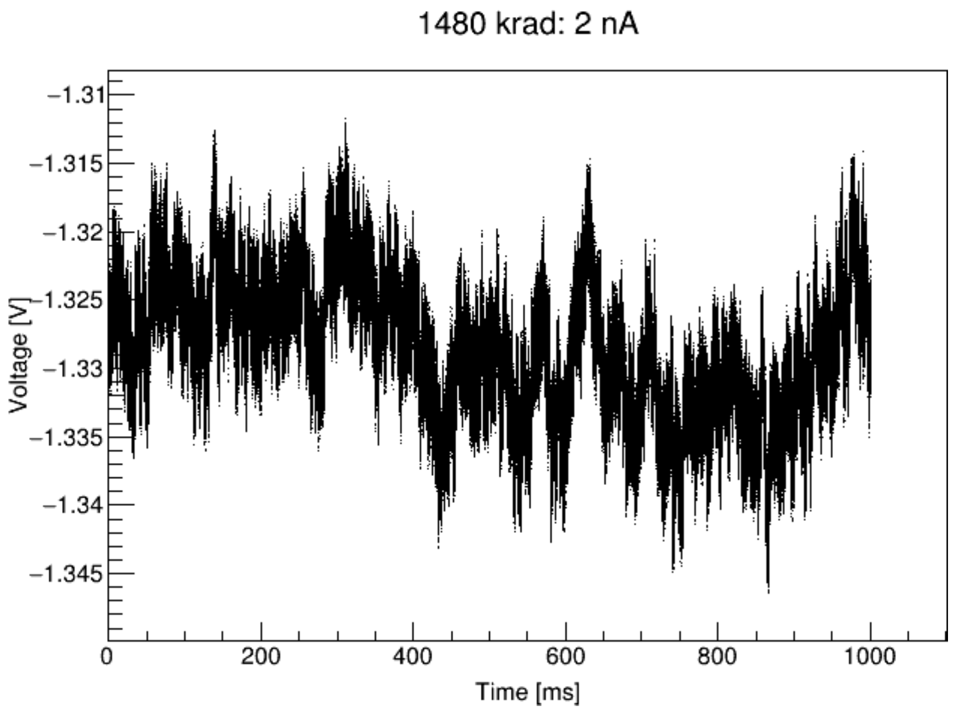
	1 Mrad		5 Mrad		20 Mrad	
Material	Modulus [ksi]	Yield [ksi]	Modulus [ksi]	Yield [ksi]	Modulus [ksi]	Yield [ksi]
ABS	390 ± 30	4.7 ± 0.2	380 ± 20	4.7 ± 0.2	370 ± 30	4.7 ± 0.2
toughPLA	480 ± 20	5.1 ± 0.2	460 ± 30	4.3 ± 0.1	480 ± 30	1.2 ± 0.1
Nylon	380 ± 30	5.0 ± 0.2	230 ± 70	6.2 ± 0.3	220 ± 60	6.1 ± 0.1

PMT electronics irradiation test results



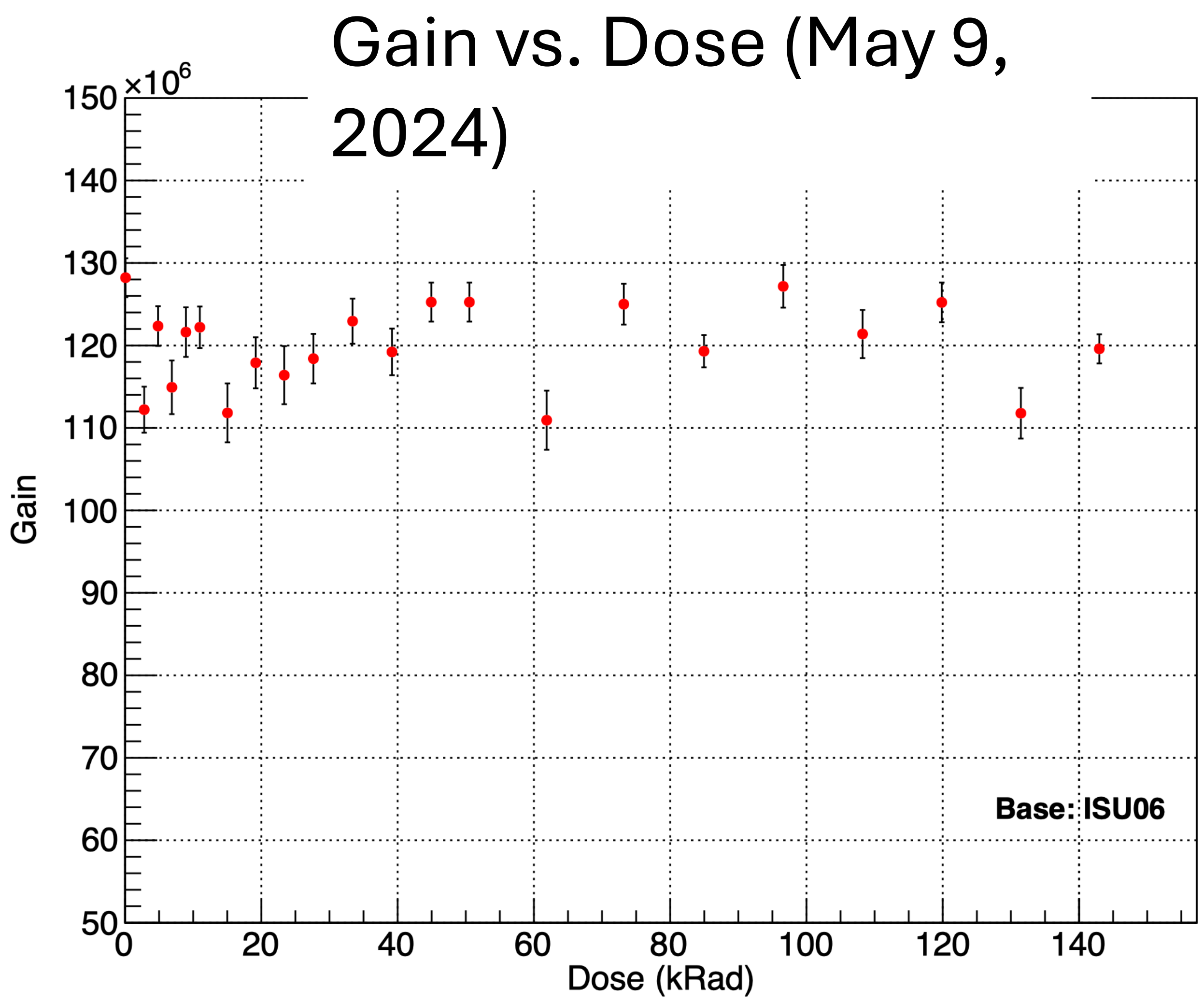






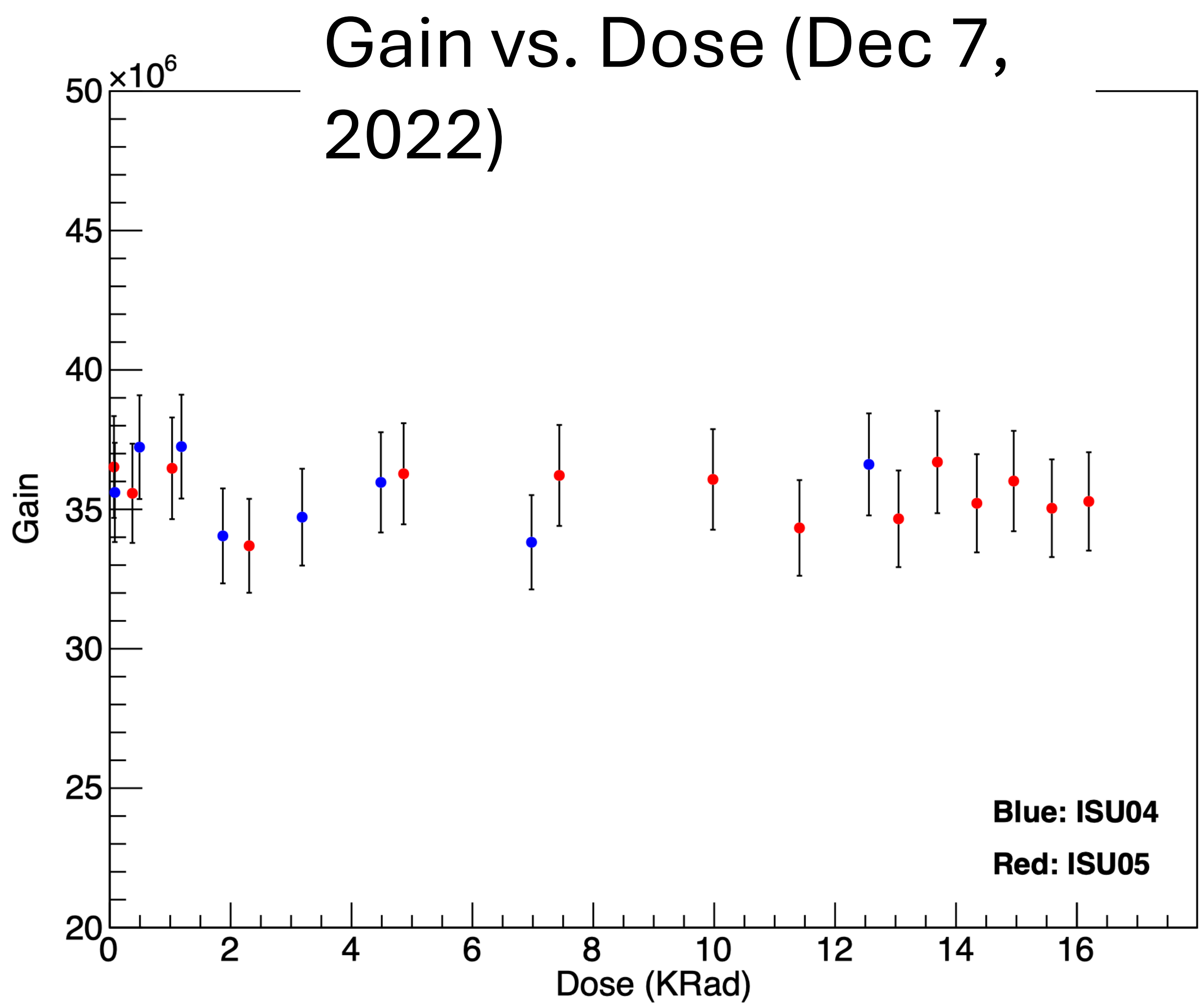
- Integrating op-amp functionality/gain tests performed using 200 kOhm preamp setting, pmt at -795 V and four cathode currents (2, 5, 20, and 27 nA)

PMT electronics irradiation test results



Event-mode op-amp dosing

Never died; went up to ~140 kRad



DC-DC (10 V) converter dosing

Tested two bases: Both died around ~20 kRad