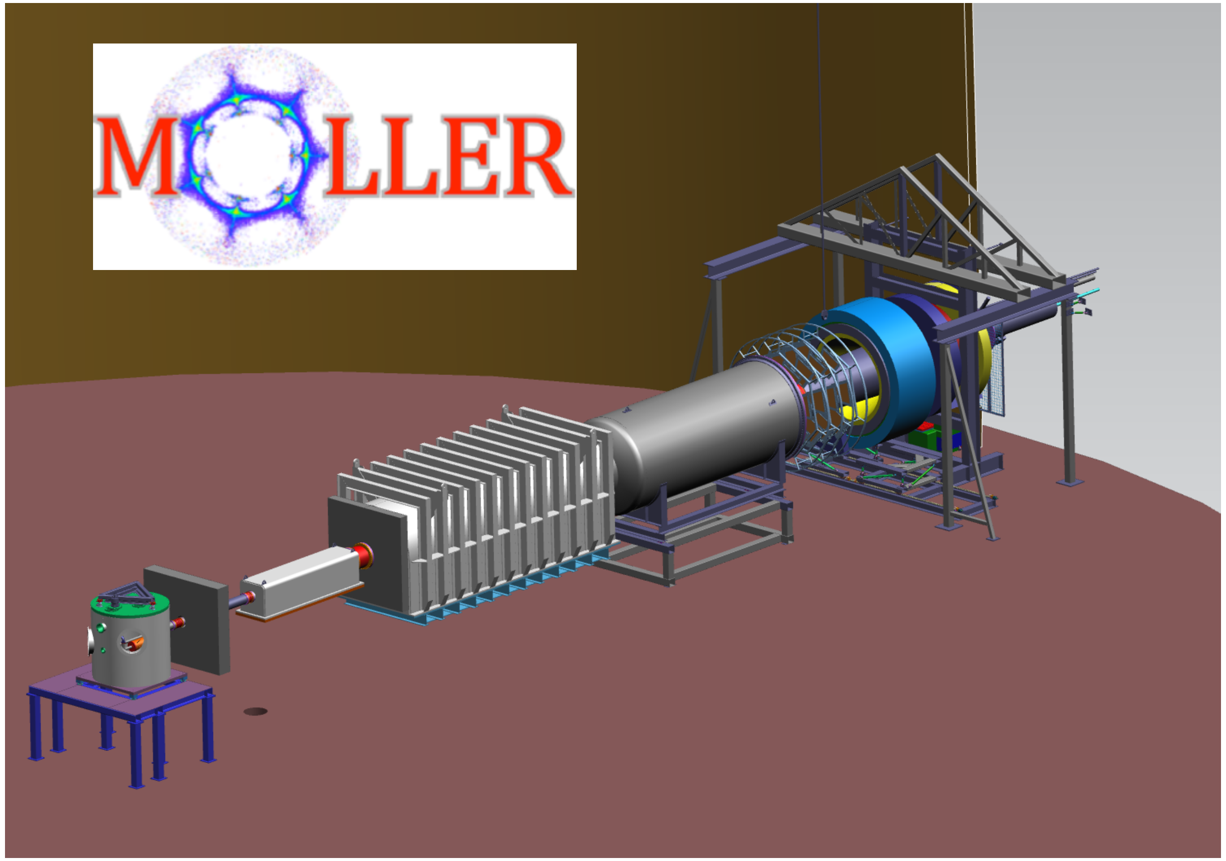
Shower-max Detector System



Dustin McNulty – Idaho State University

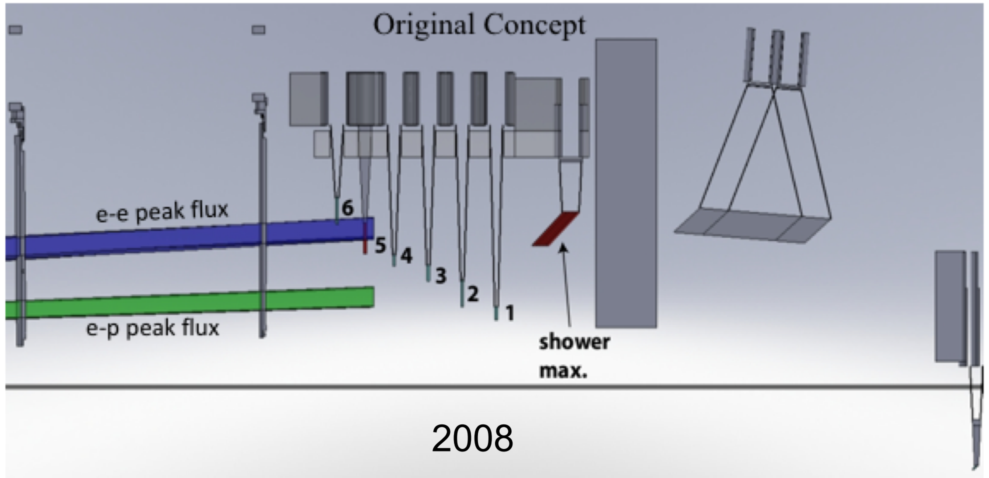
MOLLER MIE Level 2 Technical Lead for WBS 1.06 Hall Infrastructure

Outline

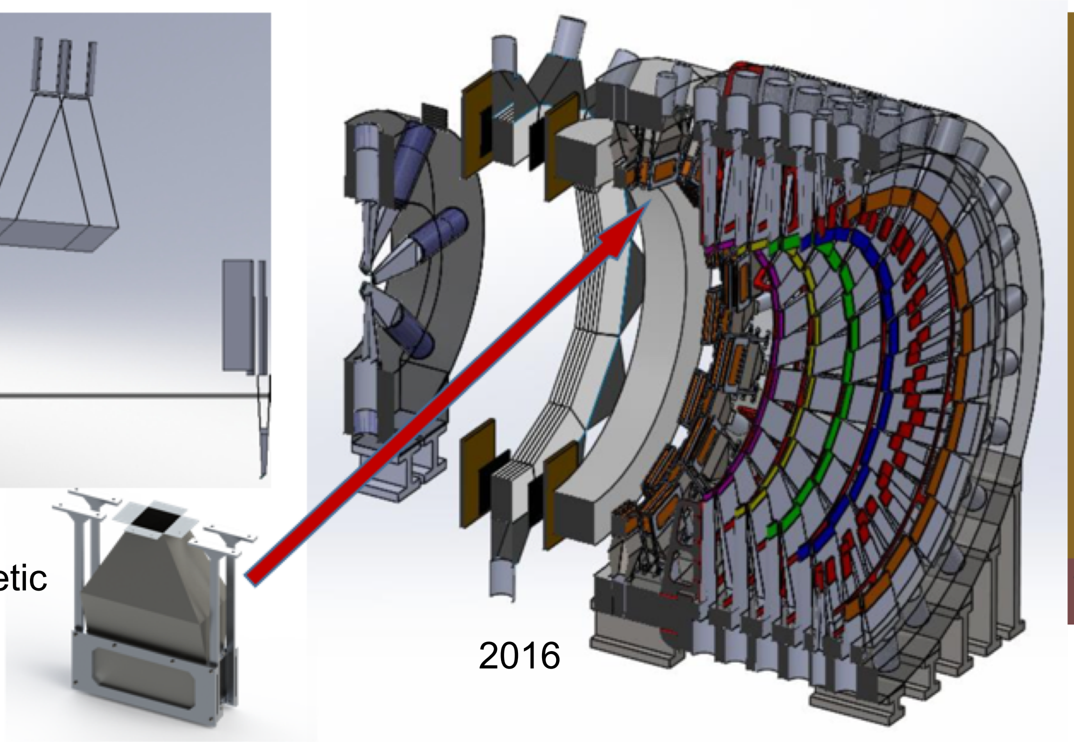
- Scope
  - Subsystem Description
  - Relation of Subsystem to Systematic Uncertainty Budget
  - Requirements on Subsystem
- Conceptual Design, Prototyping and Testing
- Deliverables and Acceptance Criteria
- Construction Plans
- Milestone Schedule
- Budget – equipment/materials
- Labor
- Risk assessment
- EH&S considerations
- Summary

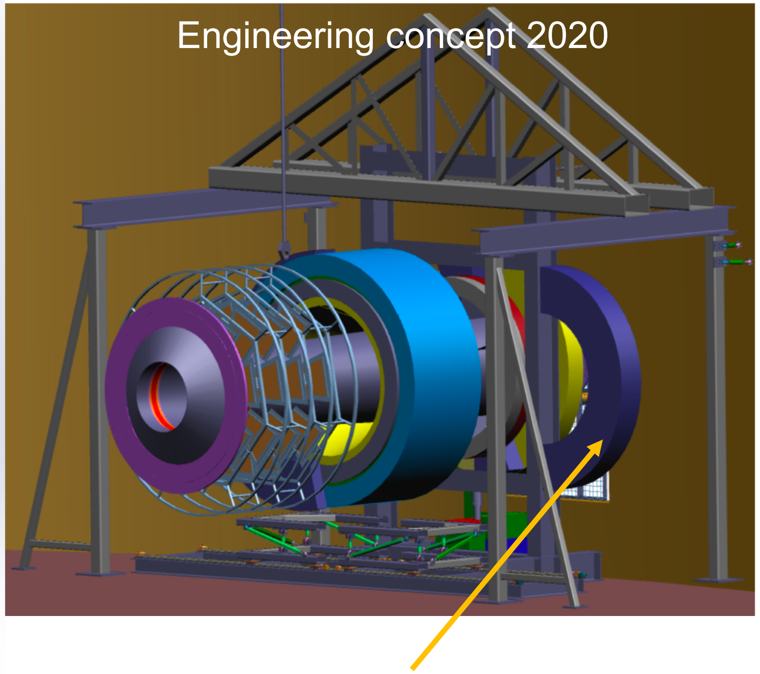
Shower-max Description

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.



Electromagnetic sampling calorimeter





Shower-max Clam shell

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

Relation of Shower-max to Systematic Uncertainty Budget

The Shower-max subsystem addresses the highlighted uncertainties

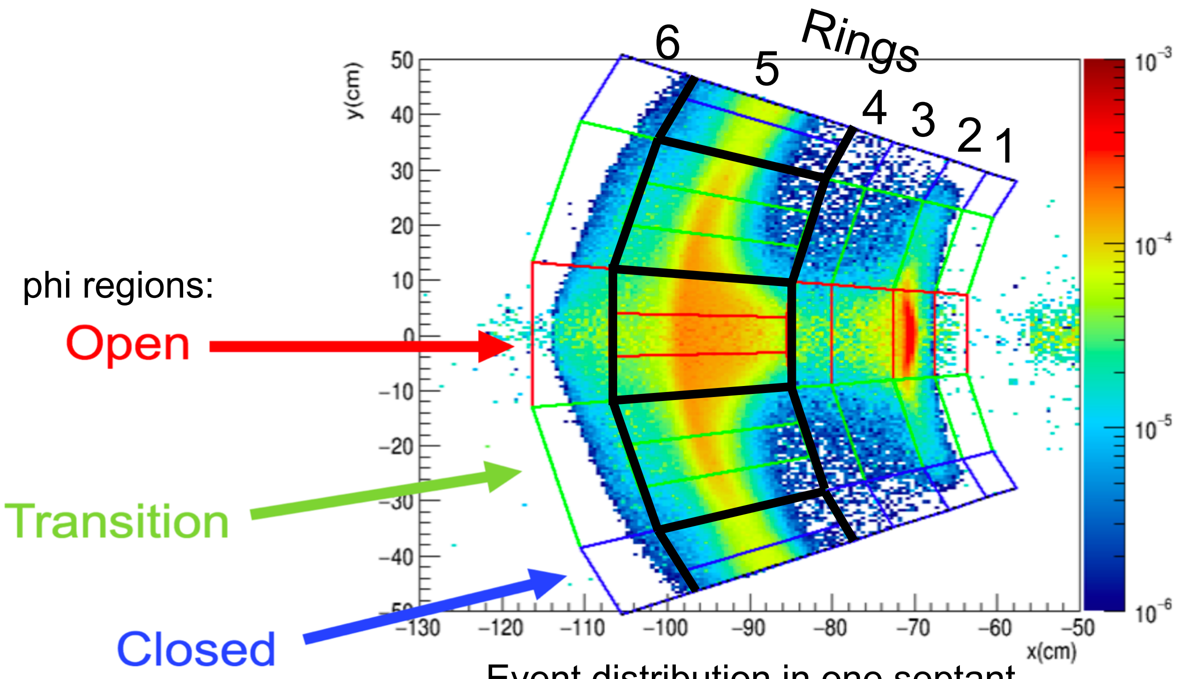
Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Norm. of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \to e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \to e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \to (\pi, \mu, K) + X$	0.3
Transverse polarization	0.2
Neutral background (soft photons, neutrons)	0.1
Linearity	0.1
Total systematic	**1.1**

- Performs independent measurement of Moller signal flux asymmetries with similar analyzing power and statistical precision as Ring-5
- Plays a role in pion/muon background ID with the pion and tracking systems
- Performs independent meas. of trans. Pol. contamination signature around azimuth
- Less sensitive to neutral backgrounds

Requirements on Shower-max

Requirements Table from MOLLER-NSF CDR

Parameter	Value
Radial segmentation	1
Azimuthal segmentation	28
Total number of detector channels	28
Quartz element sizes	∼ 12 cm x 25 cm x 1.0 cm
Quartz surface polish	20 Angstroms or better
Quartz bar parallelism	3 arc minutes between faces
Quartz bar perpendicularity	15 arc minutes
Tungsten element sizes	∼ 11 cm x 25 cm x 0.8 cm
Detector resolution from 2 - 8 GeV	∼ 25%
Radiation hardness of detector elements	> 70 MRad



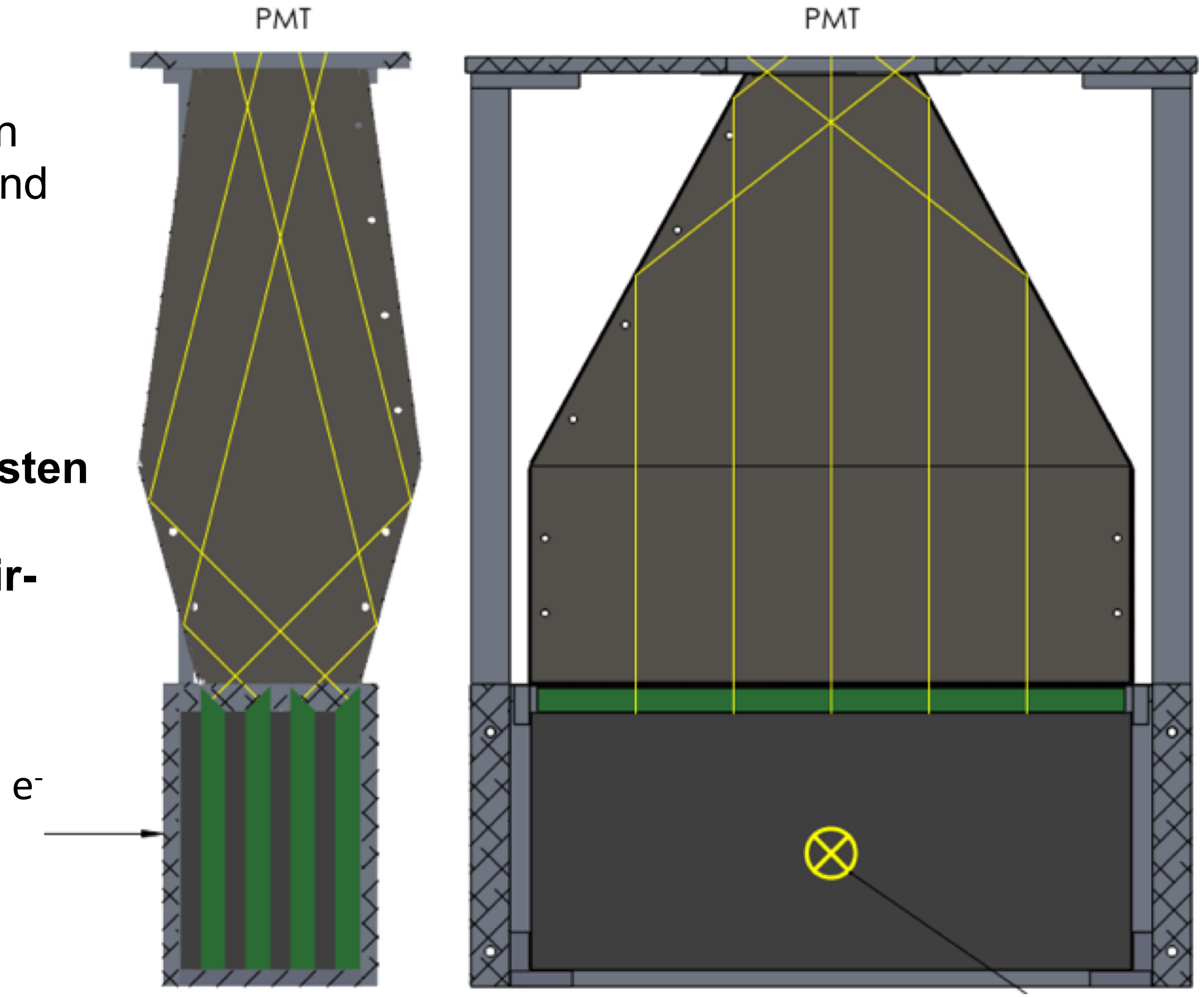
Event distribution in one septant

- Shower-max required to ~match flux acceptance of Ring-5 but with a 3:1 reduction in azimuthal segmentation
- Quartz elements optically polished with stringent geometrical tolerances for TIR considerations
- Tungsten is high purity (99.95%) with dimensional tolerances of ±0.005 inch
- Detector resolution for single-electron response at least 25% to avoid excessive error inflation
- Optical detector elements must be sufficiently radiation-hard to allow Shower-max to preform as required for the duration of the experiment

Shower-max: Detector Concept and Materials

- Detector concept uses a layered "stack" of tungsten and fused silica (quartz) to induce EM showering and produce Cherenkov light

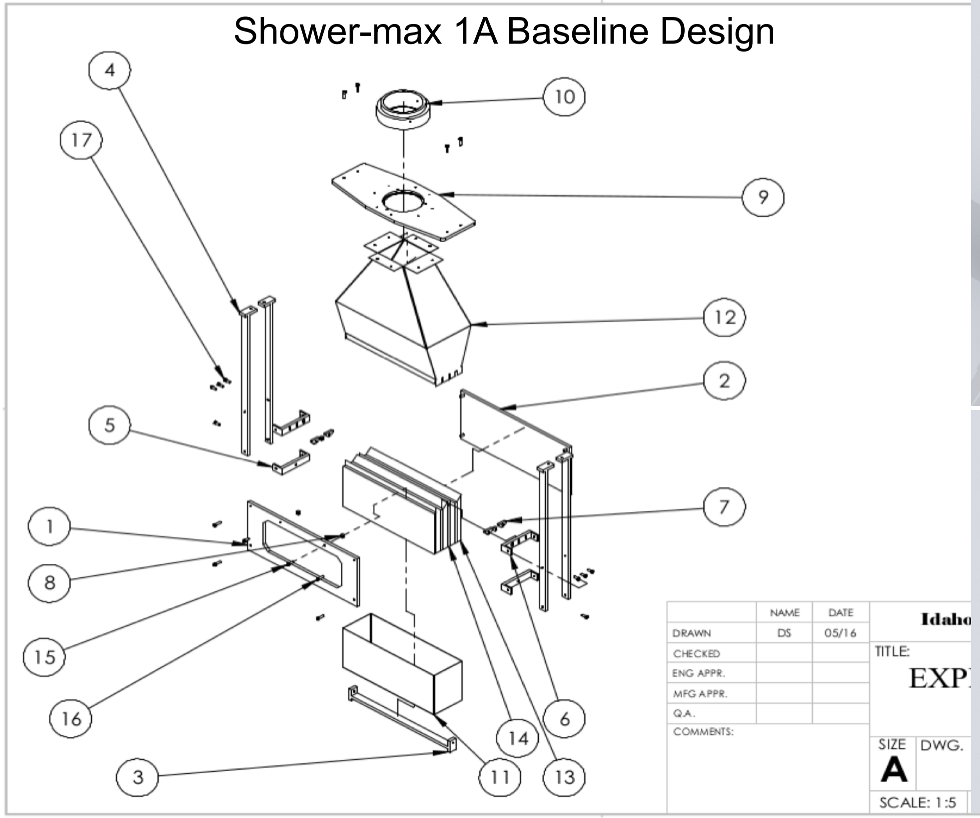
- "Baseline" design developed using GEANT4 optical MC simulation:
  - Design uses a **4-layer "stack"** with **8 mm tungsten** and **10 mm quartz** pieces
  - Cherenkov light directed to **3 inch PMT** using **air-core, aluminum light guide**

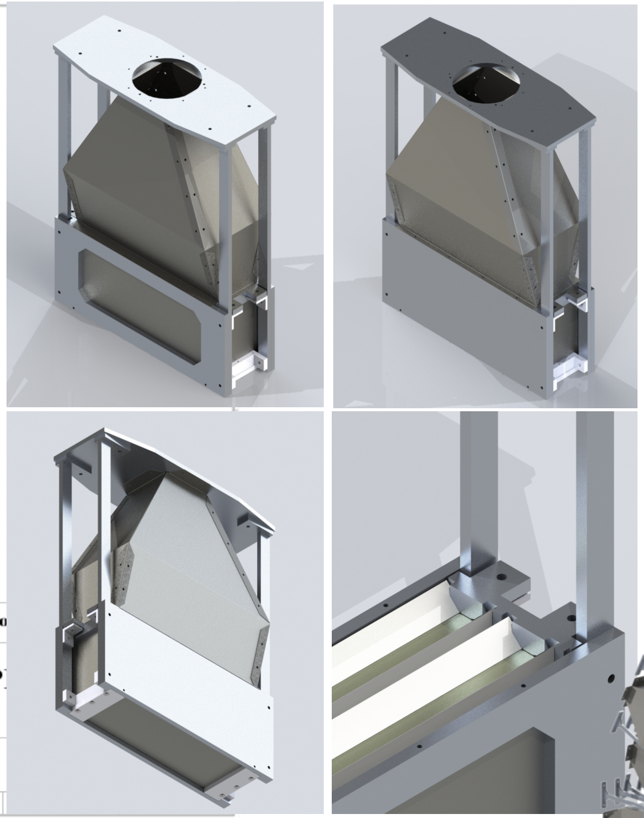


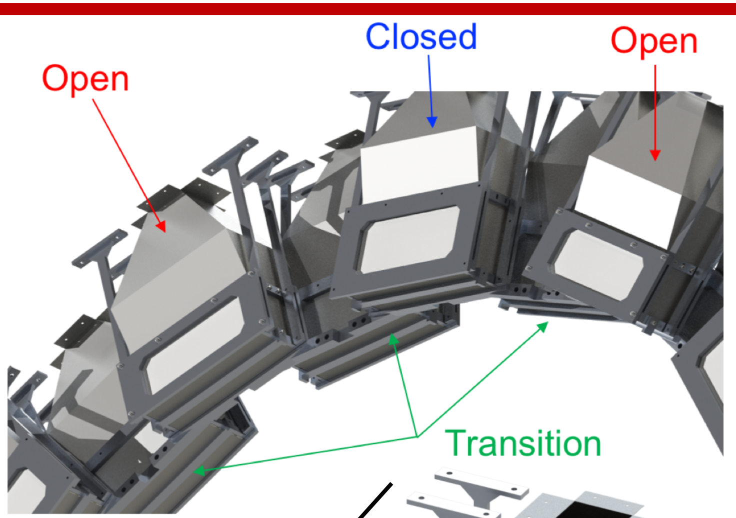
Materials:

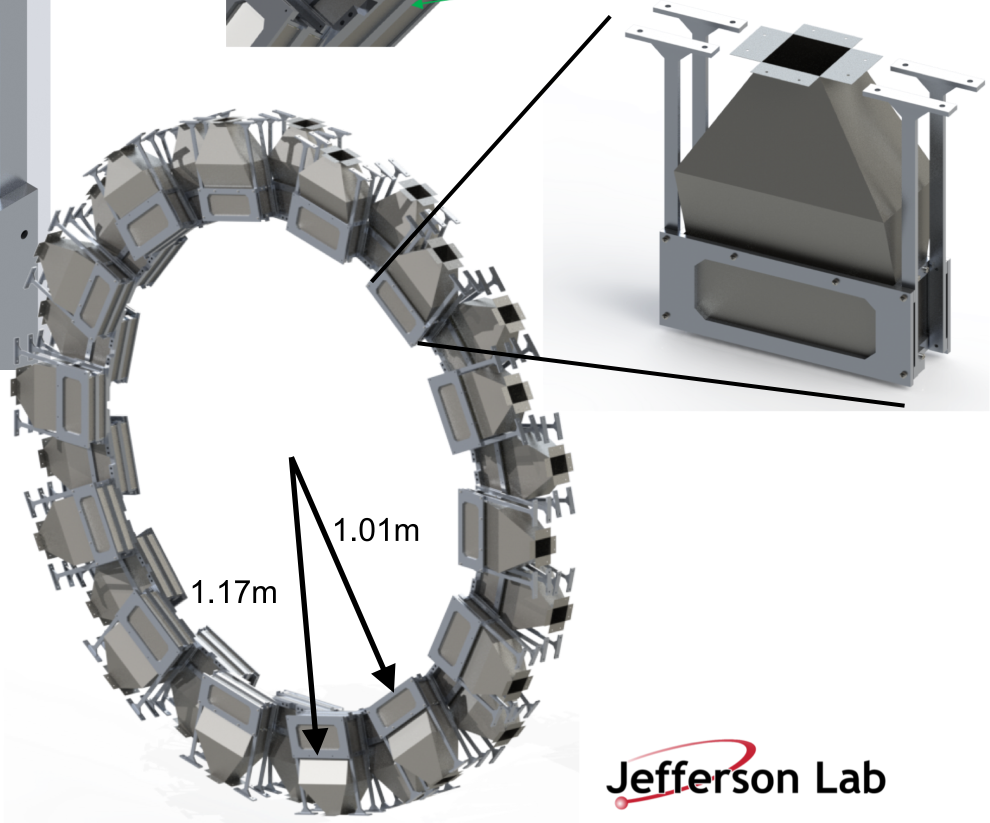
- Aluminum chassis
- Light guides are aluminum specular reflectors (Anolux Miro-silver 27)
- High purity tungsten and quartz
- Total radiation length: 9.1 X_0 tungsten + 0.4 X_0 quartz = 9.5 X_0; Molière radius ~ 1.1 cm

Shower-max: Design Status and ring geometry









- Engineered shop drawings for full-scale prototypes
- Shower-max ring design concept: staggered in $\hat{z}$ with reinforced struts and brackets. 28 detectors in ring: 7 Open, 7 Closed, and 14 Transition
- Constructed two full-scale prototypes in 2018 and tested at SLAC with 3, 5.5, and 8 GeV electron testbeam

Shower-max: Prototyping and Testbeam

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

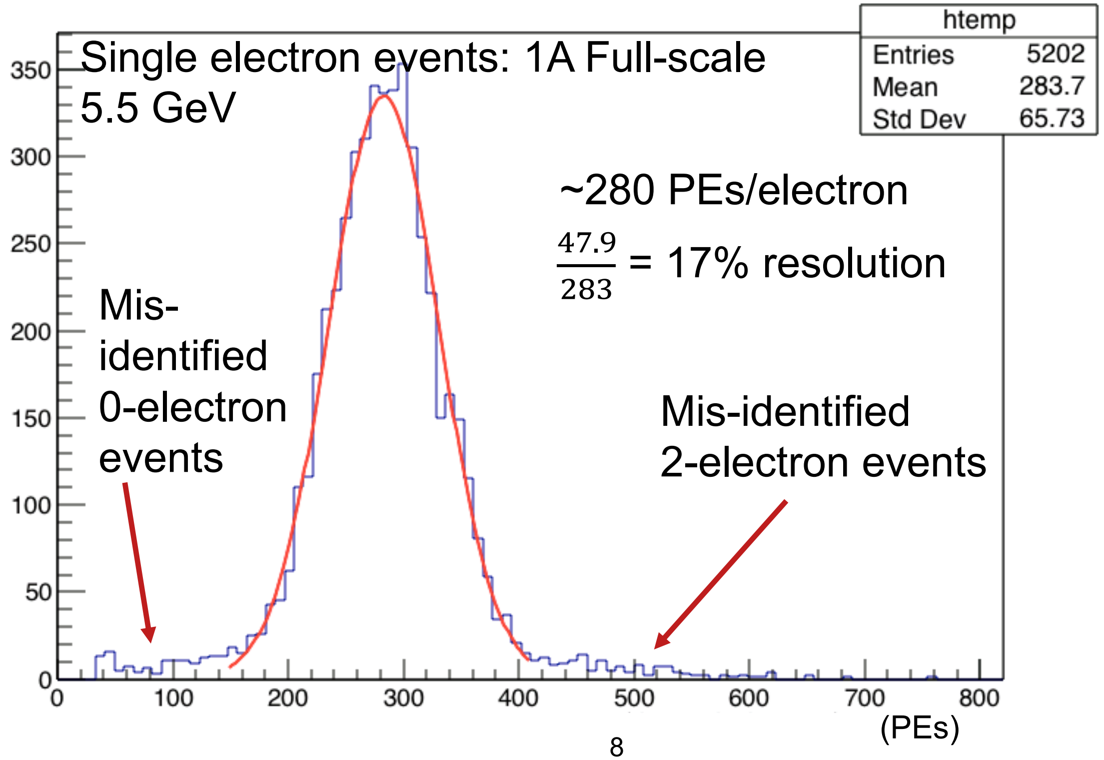
- 8 mm thick tungsten and 10 mm thick quartz (1A)
- 8 mm thick tungsten and 6 mm thick quartz (1B)

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

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

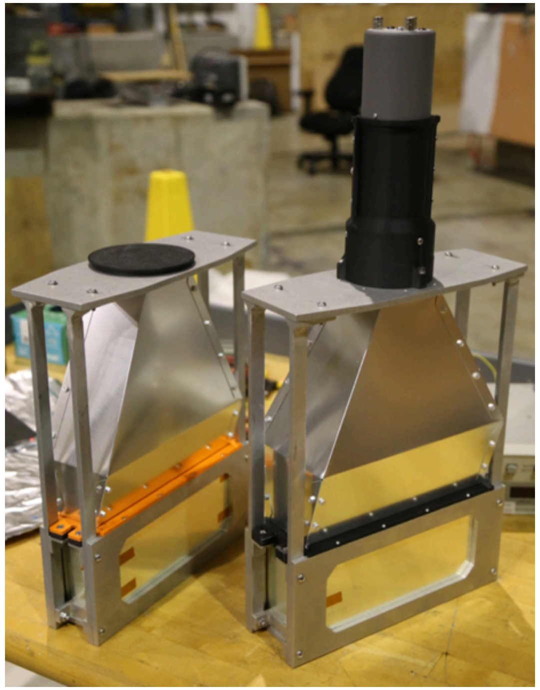
--Stack design validated: number of layers/thicknesses; yields and resolutions match G4 predictions

- Prototype beam performance sufficient for MOLLER and 2nd pass mechanical design improvements underway



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

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



Deliverables and Acceptance Criteria

Subsystem Deliverable	Acceptance Criteria	Validation
WBS 2.04.03: Shower Max Detector: Construction and successful operation of Shower-max detector system	Thirty-one modules tested with single-electron photo-electron response resolution < 25% for electron energies between 3 and 8 GeV	A combination of electron testbeam and cosmic ray muons will be used. Shower-max detector module pulse height distributions, for 3 to 8 GeV single electrons--from the SLAC End Station Test Beam facility, will be used to validate the module design construction and operation. The corresponding pulse height distribution for cosmic rays will also be acquired for the testbeam-validated modules. Benchmarked or tuned optical simulations of both testbeam and cosmic ray real data will be used to establish a procedure to test/validate all 31 modules using cosmic rays.

Construction Plans

Half Post-doc or Technical labor force responsible for fabrication, parts procurement, assembly, and test-validating each constructed module

- All work is planned to be done at Idaho State University
- Year-1: includes minor design tweaks, optical and mechanical, based on initial SLAC testbeam results; construction of a “production-level” prototype and second beamtest at SLAC in late 2021
- Year-2: design finalized and reviewed before planned large equipment purchases
- Year-3: construction/assembly and testing of all 28 production + 3 spare modules
- Year-4: shower-max modules delivered to Jefferson Lab. Note that shower-max *stack layers* will need to be disassembled for transport and reassembled at JLab

Milestone Schedule

WBS 2.04.03: Shower-max Detector	
Shower-max Preliminary Design Review	Aug 2021
Shower-max Prototype Module Complete and Tested	Dec 2021
Shower-max Design 90% Complete	Feb 2022
Shower-max Final Design Review	May 2022
Order placed for tungsten, PMTs, and bases	Oct 2022
Order placed for quartz	Oct 2022
First Production Shower-max Module Complete and Tested	June 2023
31 Modules Assembled and Tested	20-May-24

- Milestones are set given extensive pre-R&D activities and experience with past projects
- The final "Assembled and Tested" milestone has 76 working days of float relative to the DOE MOLLER MIE project's milestone "All Equipment Ready for Hall" early finish date of 4-Sep-24.

Budget – equipment/materials

Equipment & Materials Budget for WBS 2.04.03 Shower Max Detector

Item	Cost (FY20$)	Cost (at-year $)
Quartz (127 pieces)	$200K (VE, PE)	$212K (FY22 $)
Tungsten (124 pieces)	$118K (VE, EJ)	$125K (FY22 $)
PMTs (31)	$51.5K (VE)	$55K (FY22 $)
PMT bases (31)	$10.7K (VE)	$11K (FY22 $)
Light Guides (31)	$12.5K (EJ, VE)	$13K (FY22 $)
Module chassis (31)	$15.5K (EJ, VE)	$16.5K (FY22 $)
Misc. consumables	$1.7K (EJ, PE)	$1.8K (FY22 $)

- Large cost items, requiring formal review before purchase, are high-lighted
- FY20 costs have been increased by 3% per year to account for expenditures in FY22. The average equipment and material cost per module is $14K (FY22 $)

Labor

Labor Budget for WBS 2.04.03 Shower Max Detector

Labor category	FY2021 NSF Midscale Funding	FY2021 Other Funding Source	FY2022 NSF Midscale Funding	FY2022 Other Funding Source	FY2023 NSF Midscale Funding	FY2023 Other Funding Source	FY2024 NSF Midscale Funding	FY2024 Other Funding Source
Graduate student								1@100%FTE
Post doc	1@50%FTE		1@50%FTE		1@50%FTE			
Undergrad student	2@500 hrs per year		2@500 hrs per year		2@500 hrs per year		2@500 hrs per year	

- Labor includes parts fabrication and procurement, assembly, and testing of 31 individual modules
- Undergraduates supported in past made substantial contributions while gaining experiences that often led to grad school: CAD, 3D-printing, supporting benchtop optical measurements and analyses
- FY2024 other funding source is the DOE MIE project, where additional labor support, if needed, could be supplied in the form of graduate student or other technical labor support

Risk assessment

Experiment Risks:

- Quartz radiation hardness tests show more transmission losses than anticipated (low)
  --Mitigation: build more replacement spare modules using remaining SM scope in MIE project funding
- PMT cathode lifetime (given SM's higher light yields) (medium)
  --Mitigation: purchase more replacement pmts; swap pmts between "closed" and "open" regions

Scope Risk:

- Material costs higher than estimated and cannot deliver all 28 SM modules (low)
  --Mitigation: use remaining SM scope in MIE project funding to purchase more modules

Schedule Risks:

- Vendors cannot deliver components on time (low)
  --Mitigation: available schedule float can accommodate at least a 4 month delay
- Delays in radiation-testing (possible Covid 19 impact) would delay quartz purchase decision (low)
  --Mitigation: available schedule float can accommodate at least a 4 month delay

EH&S Considerations

Detector Modules:

– Working with common tools (e.g. potential for cutting) – implement best practices

– PMT HV – implement electrical and on the job training for workers

Mechanical:

– Working with common tools as well as Shop tools– workers must pass Machine Shop safety course

Electronics:

– 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 (use fume hoods, etc.)

Radiation:

– All workers will have ISU radiation safety training -- https://www.isu.edu/radiationsafety/

- All activities and deliverables in accord with Jlab EH&S manual and Jlab's Integrated Safety Management System
- All institutional EH&S rules will be followed (Idaho State University EH&S: https://www.isu.edu/ehs/)

Answer to Review Committee Question

3) The NSF-centric CDR states for the shower-max detector: "Sufficient azimuthal segmentation is needed to match the azimuthal segmentation of the thin-quartz detector array." However, the shower-max conceptual design has 4 azimuthal segments per septant, while the thin-quartz radial ring #5, to which it should be matched, is described in the full Moller CDR as having 12 segments per septant. In what sense does this represent "matched" segmentation?

- The higher segmentation of Ring-5 makes the quartz 'azimuthal-width' nearly same as 3" pmt window, which precludes the need for a negative lightguide taper (avoiding light collection efficiency losses—every PE is precious) and optimizes the photo-electron yield in the most important Ring. We avoided 5" pmts because larger area means larger soft background.

- So why not same azimuthal segmentation for Shower-max? Two issues: For a ~10 R.L. detector, the Molière radius makes efficiency fall off a few mm (or more) from the edges and we do not want this to be a significant piece of the fiducial area. Also, showers spread so the phi dependence to the efficiency (due to the light guide taper) is less of an issue.

Summary

- Shower-max deliverables well defined: 28 production + 3 spare complete and tested detector modules
- Acceptance criteria defined ($\frac{\sigma}{\langle n \rangle} \leq 25\%$), and validation procedure articulated: using electron testbeam and cosmic-ray data, combined with simulations that correlate the two real-data sets.
- Cost, schedule and labor-needs developed and validated with vendor quotes, past experience and engineering judgment
- EH&S considerations incorporated into work planning process
- Risks identified and mitigation strategies developed or under development

Appendix – backup slides

Shower-max: Prototyping

- Prototypes constructed in 2018: both Full-scale and Bench-marking 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)

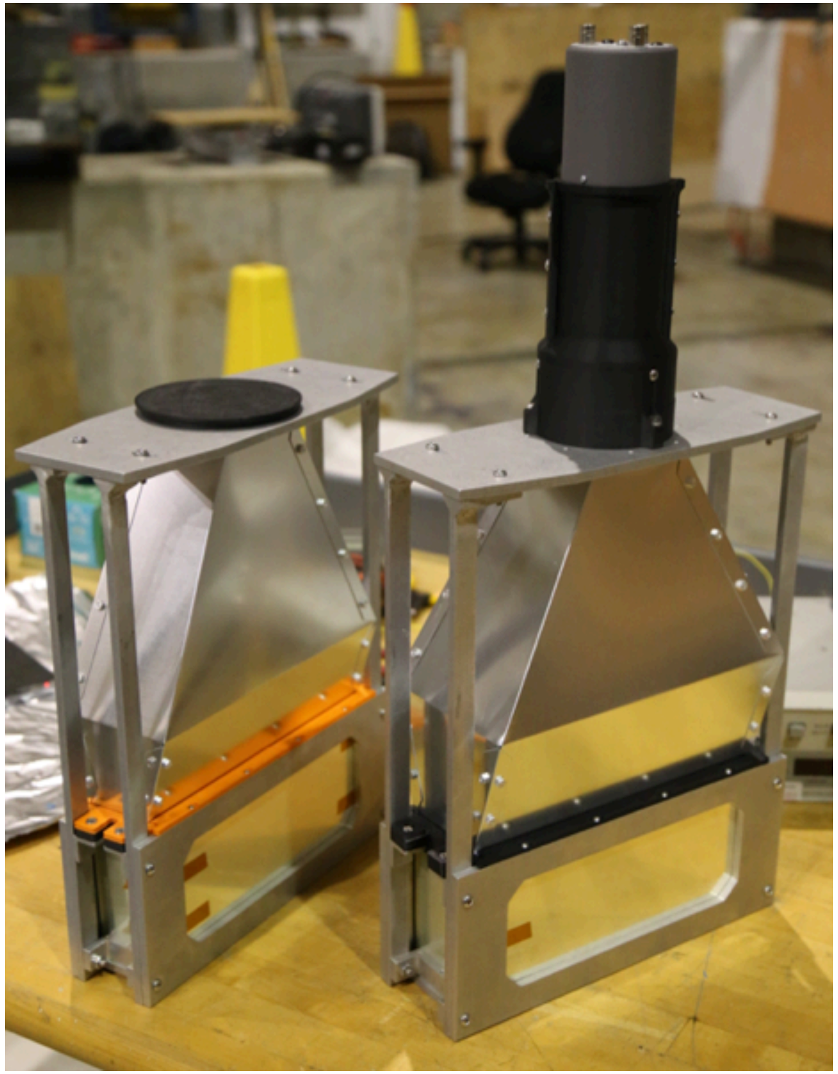
Full-scale: 12 cm x 25 cm active area

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

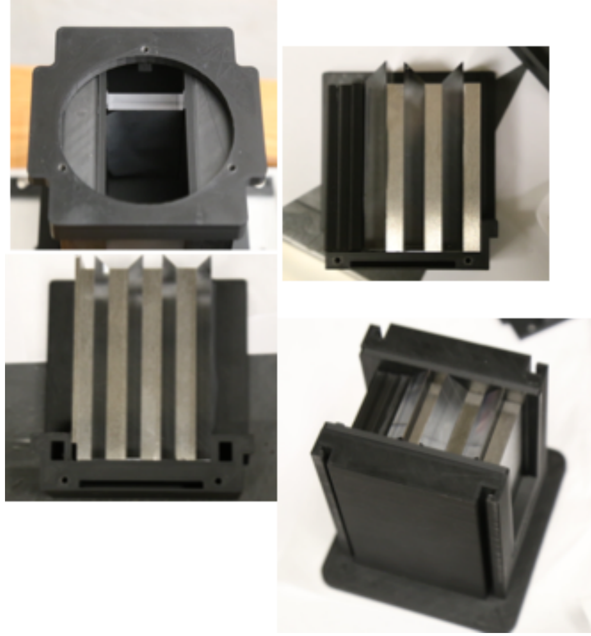
Bench-marking: 4 cm x 8 cm active area (no lightguide)

- Concept allows stack to be assembled and beam-tested one layer at a time for detailed Monte Carlo benchmarking study

Bench-marking



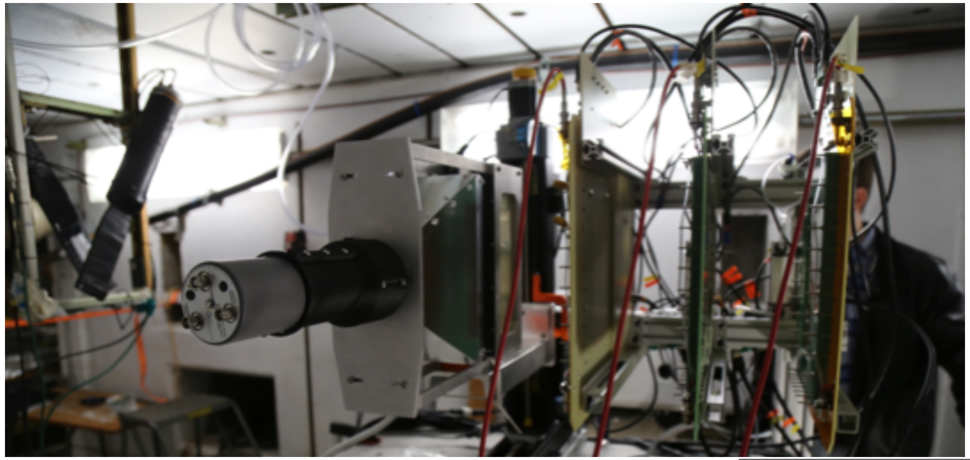
Full-scale

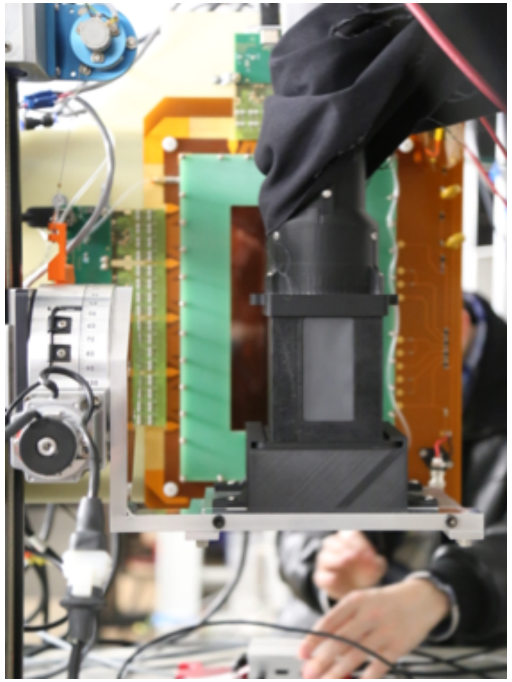


Shower-max: Testbeam

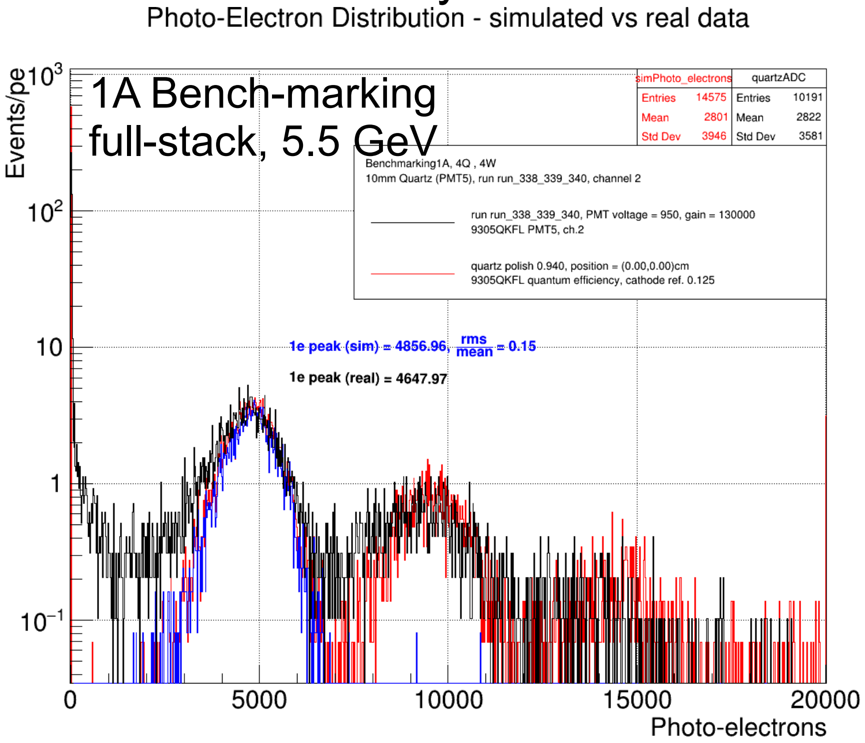
SLAC testbeam T-577 run: Dec 6 – 12, 2018

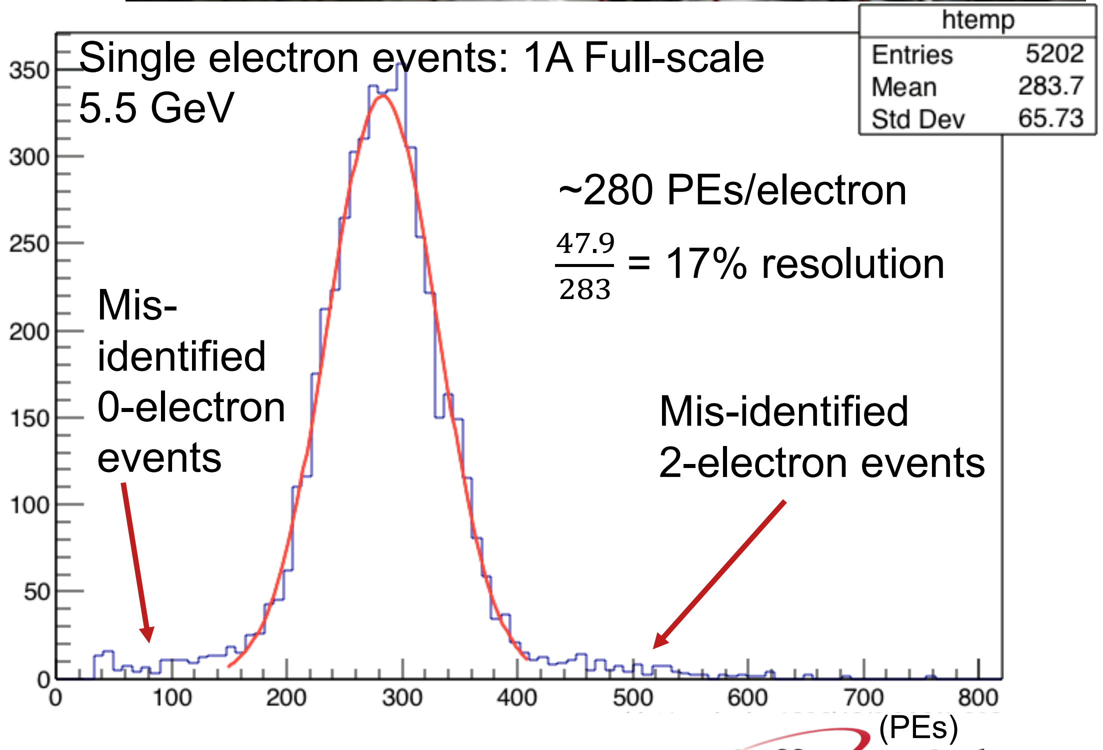
- Exposed prototypes to 3, 5.5, and 8 GeV electrons
- Validated our optical Monte Carlo quartz and cathode properties and G4's EM showering processes (but not the light guide yet)
- Stack design validated--number of layers/thicknesses; yields and resolutions match G4 predictions
- Prototype beam performance sufficient for MOLLER and 2nd-pass mechanical design improvements underway





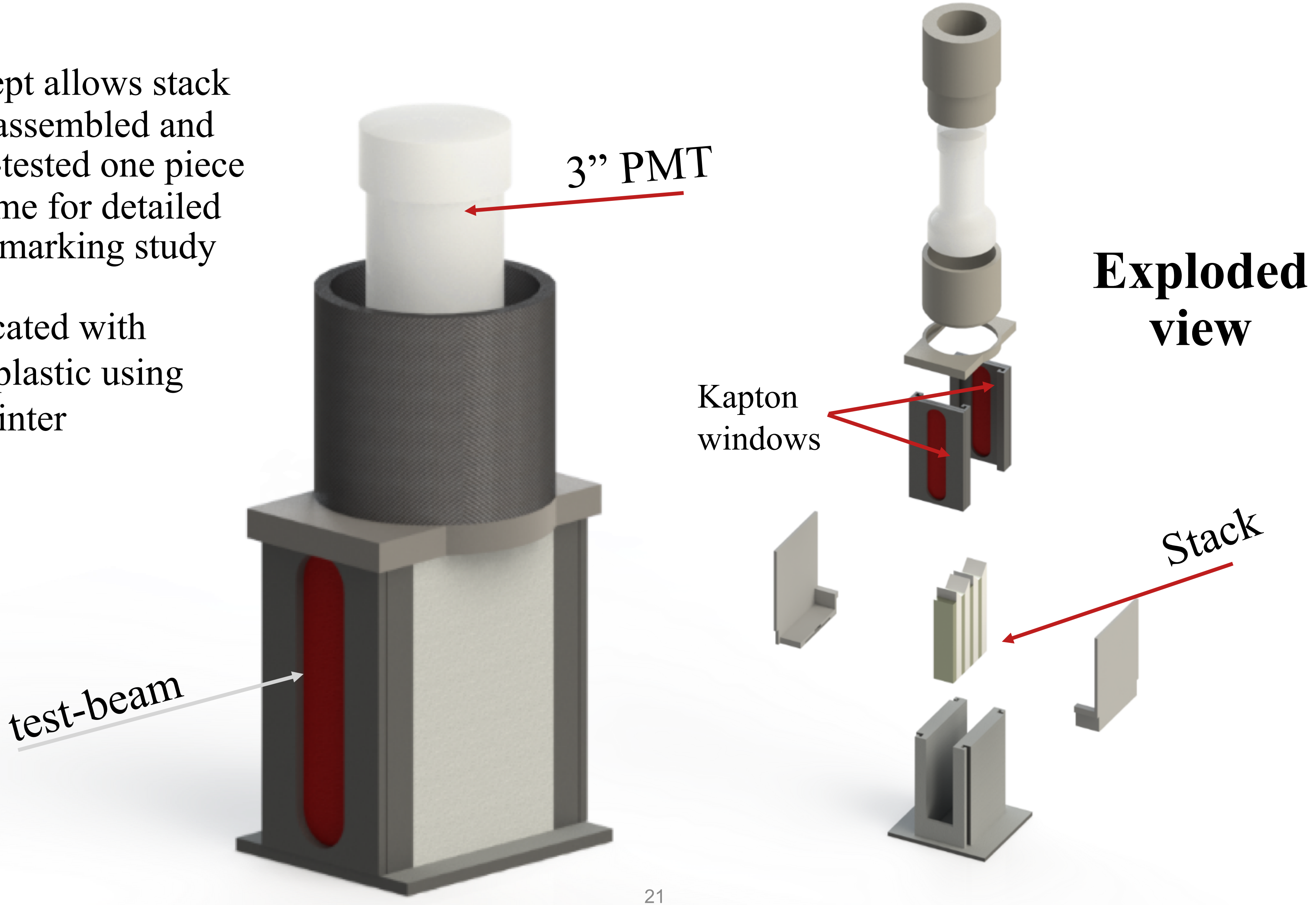
MOLLER Shower-max





Shower-max Benchmarking Prototype Concept

- Concept allows stack to be assembled and beam-tested one piece at a time for detailed benchmarking study
- Fabricated with ABS plastic using 3D printer



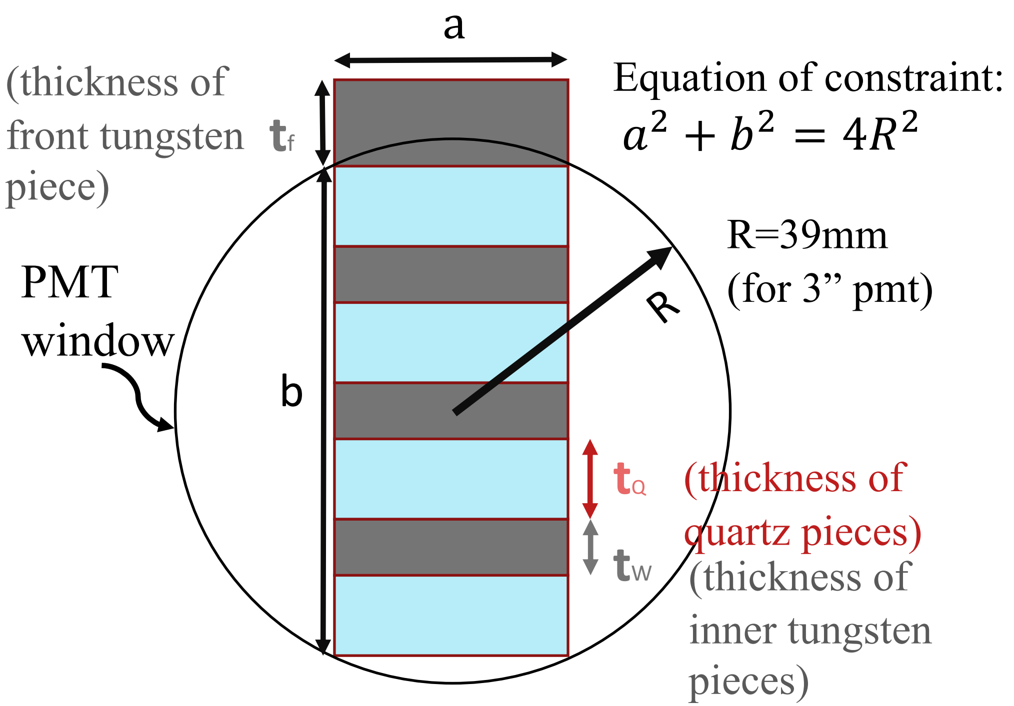
Benchmarking Stack Configurations

Highlighted columns show changes due to quartz thickness change: Examined 6 mm and 10 mm thick tiles

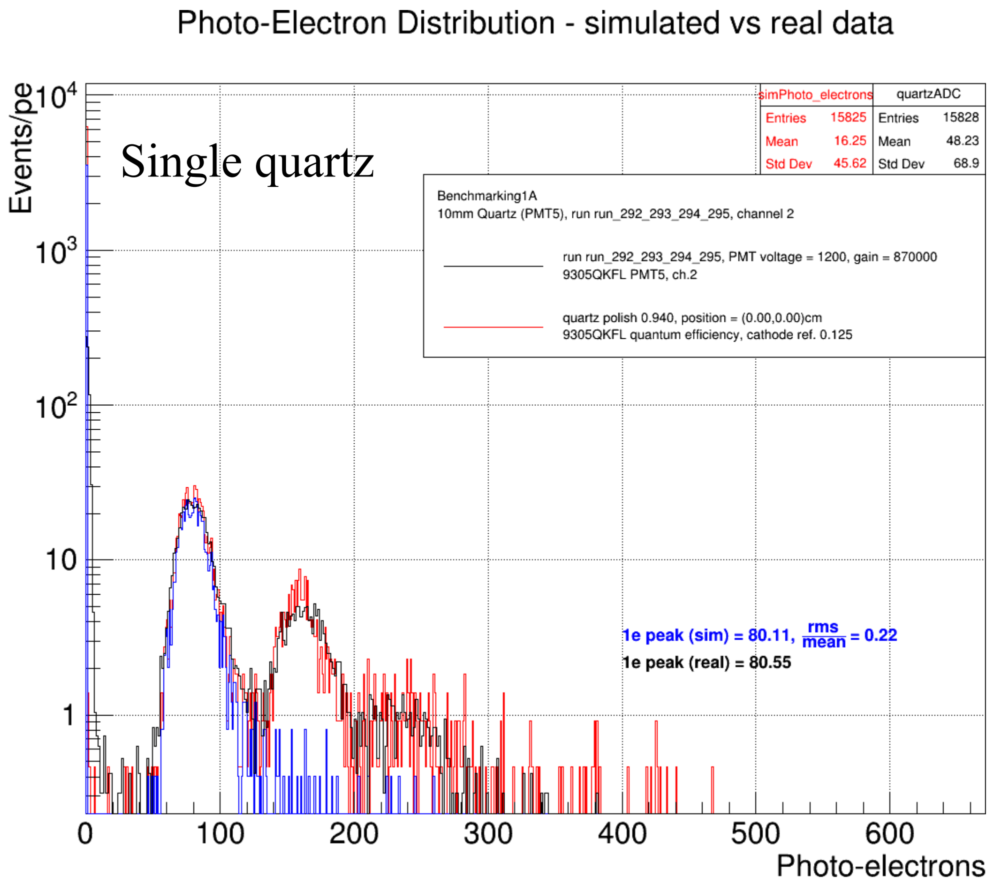
Config #	t_f (mm)	t_Q (mm)	t_W (mm)	b (mm)	a (mm)	X_0	R_{molier} (mm)
1A	8	10	8	64	44	9.5	11.0
2A	17	10	5	55	55	9.5	11.0
3A	14	10	6	58	52	9.5	11.0
4A	6	10	6	58	52	7.3	11.5

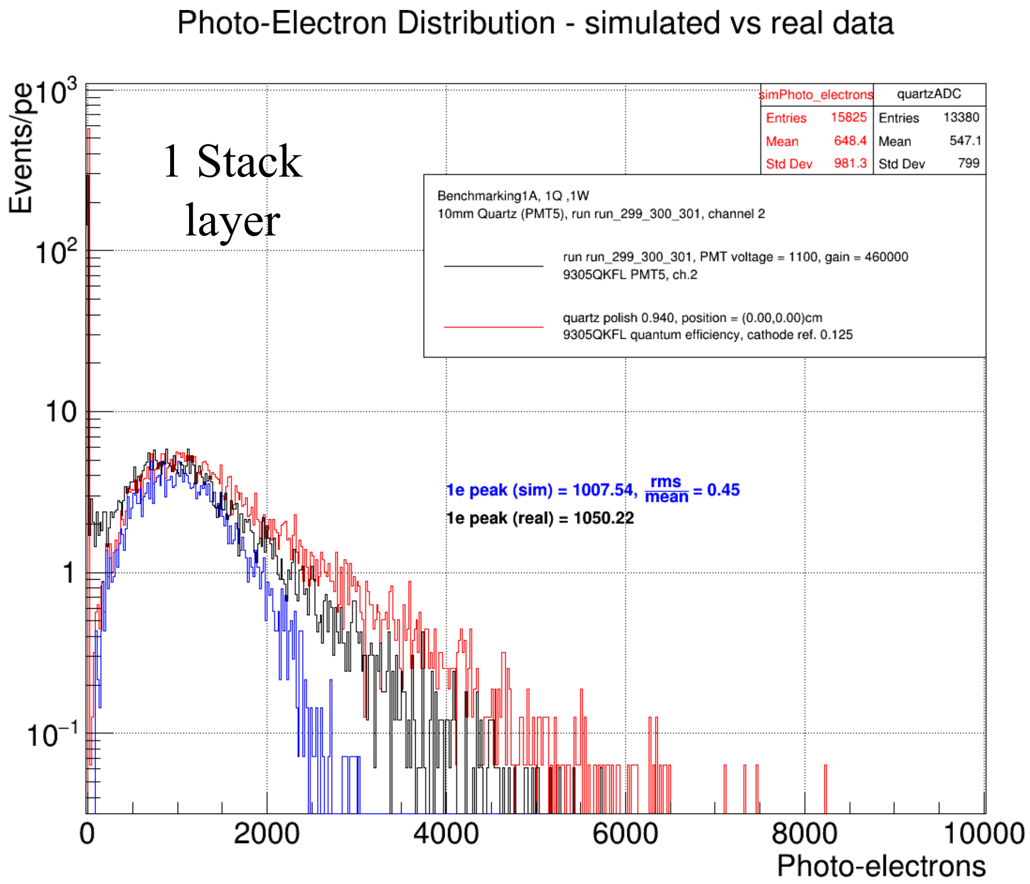
Config #	t_f (mm)	t_Q (mm)	t_W (mm)	b (mm)	a (mm)	X_0	R_{molier} (mm)
1B	8	6	8	48	61	9.5	11.0
2B	17	6	5	39	67	9.5	11.0
3B	14	6	6	42	65	9.5	11.0
4B	6	6	6	42	65	7.3	11.5

- Key benefit here is that the parameter “a” (the width of the benchmarking quartz tiles) can now be comfortably large to ensure negligible transverse shower leakage.



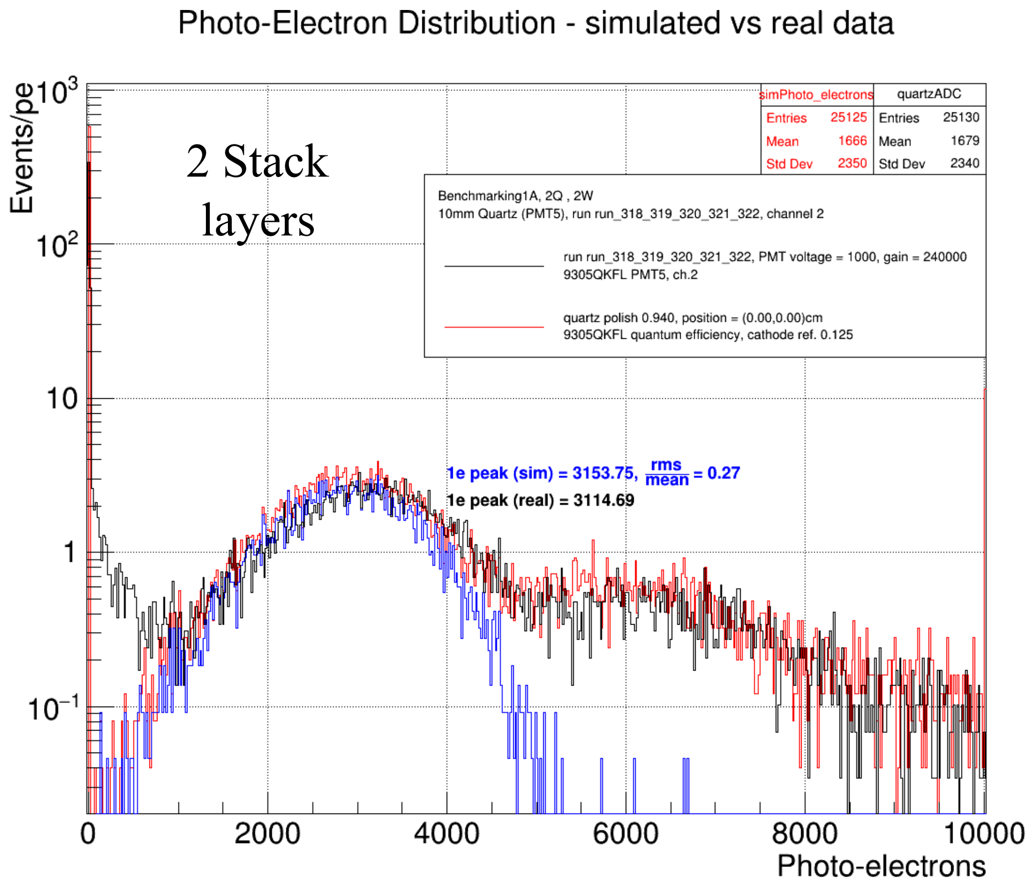
Benchmarking 1A testbeam results compared with simulation (5.5 GeV electron response vs. stack layers)

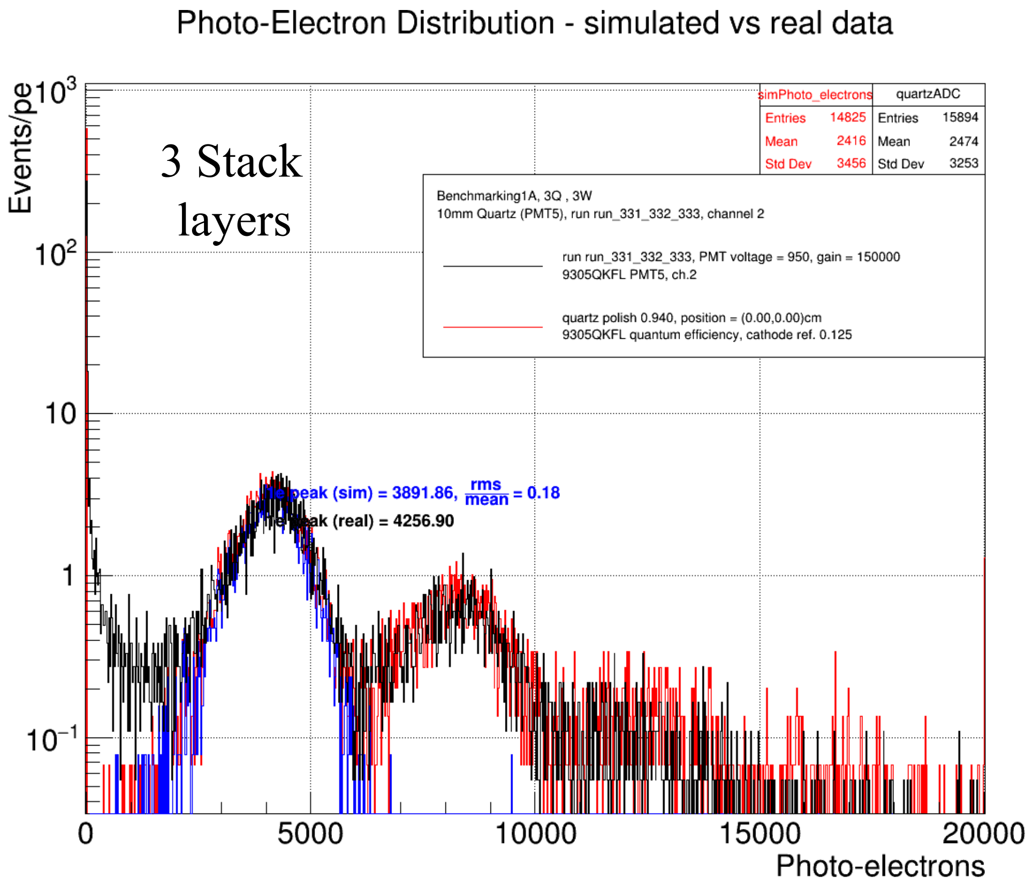




- Single quartz data used to benchmark quartz optical polish parameter
- With quartz polish calibrated, simulations performed with successively more stack layers and compared with SLAC data

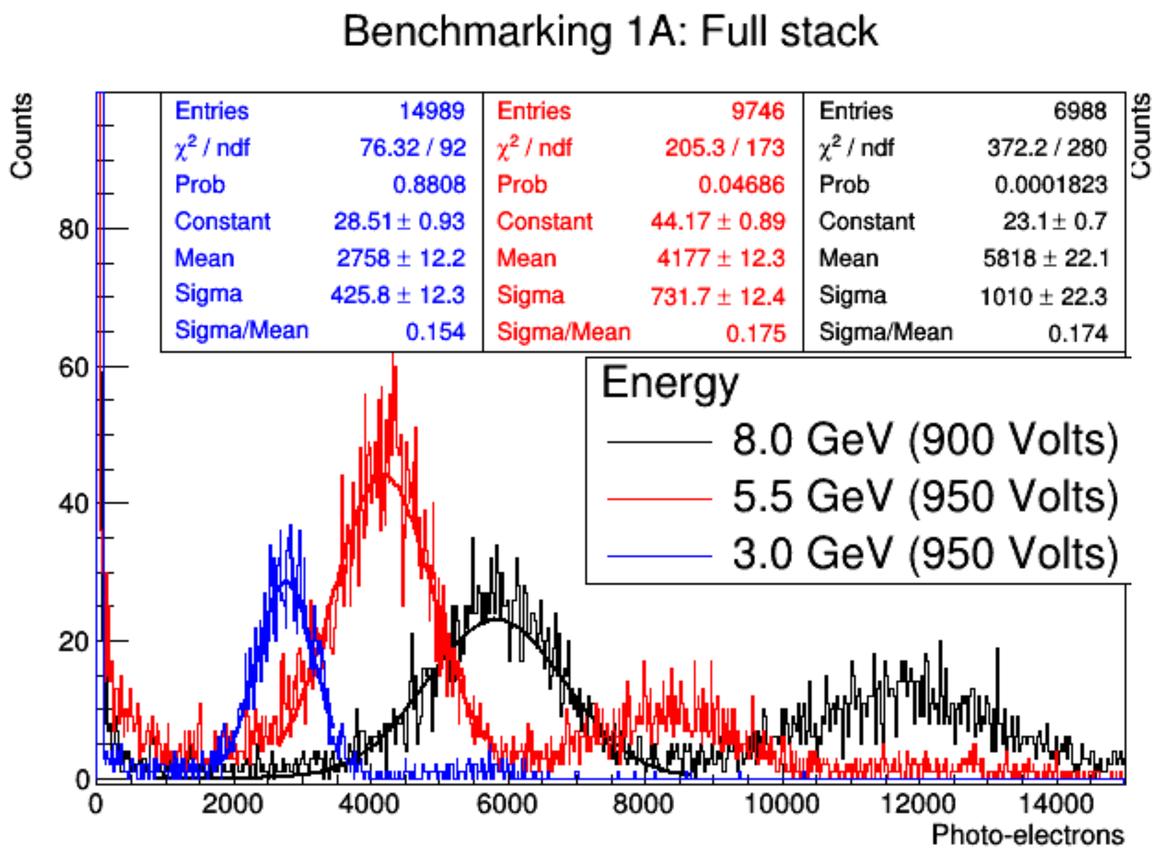
Benchmarking 1A testbeam results compared with simulation (5.5 GeV electron response vs. stack layers)

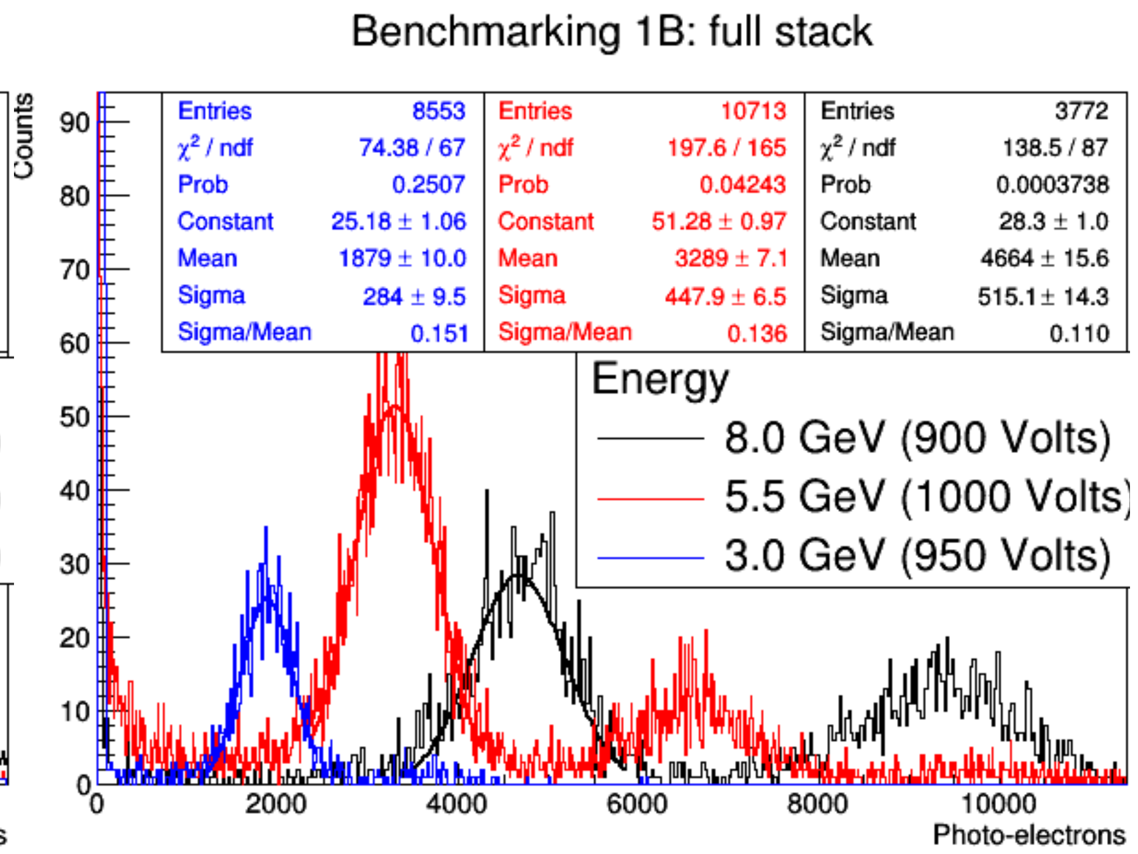




- Data and simulation agree well (at 10% level)
- Resolution of single electron photo-peak goes from 27% to 18% (simulated)

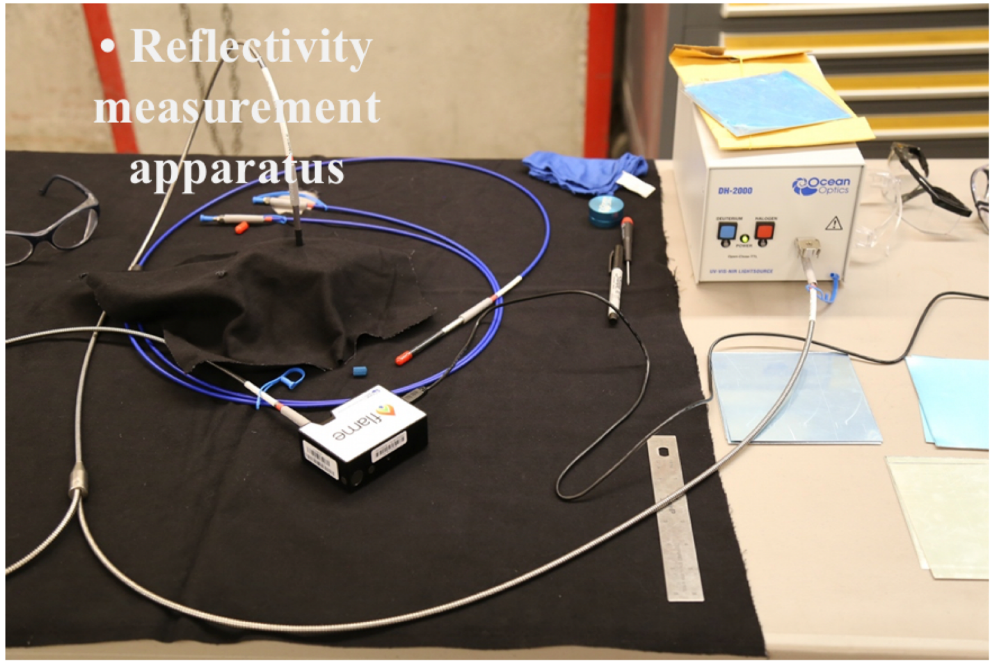
ShowerMax Benchmarking Prototype Testbeam Results (1A and 1B full stack response vs energy)





- Comparing these results with previous simulations:
- ➢ For 1A simulation: Mean PEs are ~1800, ~4300, and ~6800 for 2, 5, and 8 GeV, respectively
- ➢ For 1A real data: Mean PEs are ~2760, ~4200, and ~5800 for 3, 5.5, and 8 GeV, resp.
- Comparisons are promising, new simulations are underway and further refinement of data analysis

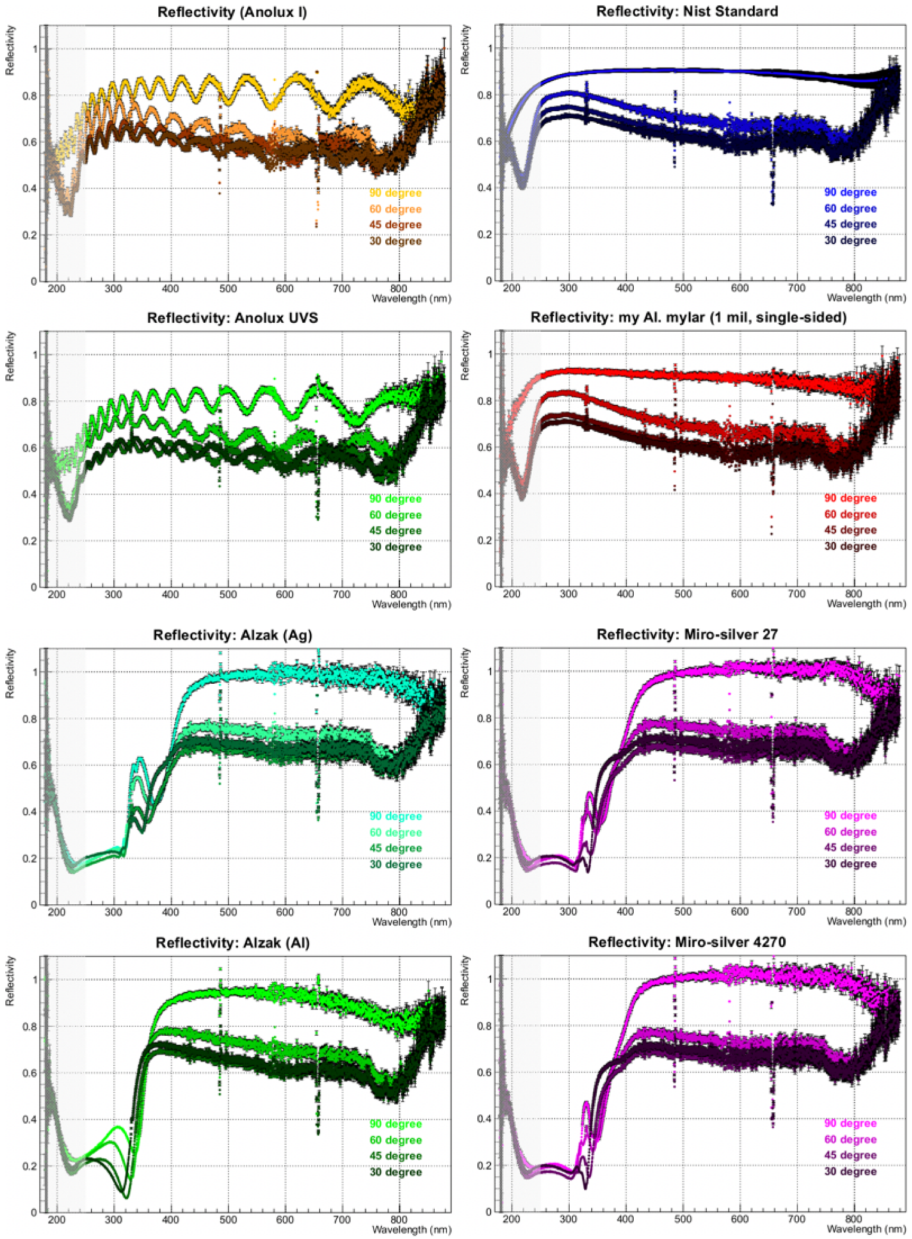
- Measuring light guide (LG) reflectivity as function of angle (10 – 90°) and λ (200 – 800nm); ongoing



- Light source: Ocean Optics DH2000: 200 - 800nm, 25W Deuterium bulb
- Spectrometer: Ocean Optics USB Flame, enhanced sensitivity, UV-VIS grating
- NIST specular calibration standard

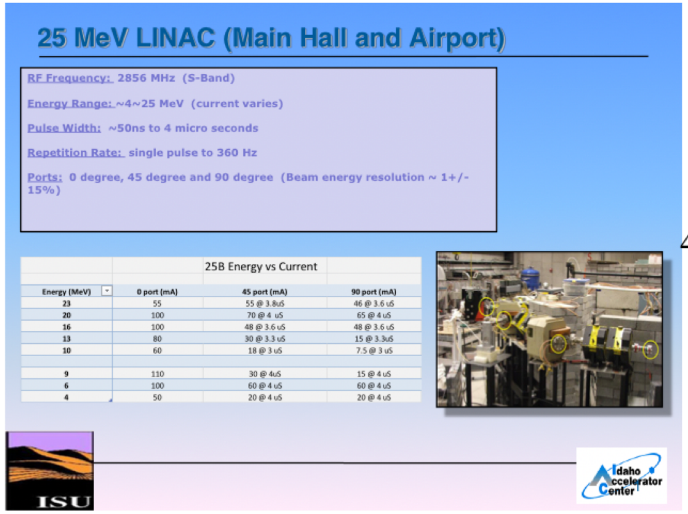
Light guide materials tested:

Miro-silver 4270	Miro-silver 27
Anolux I and UVS	Alzak-Al and Alzak-Ag
Miro 2000Ag (diffuse)	1 mil, single-sided aluminized mylar



Reflectivity vs. λ for various materials at diff. angles

Lightguide Irradiation and Reflectivity Study



25 MeV LINAC (Main Hall and Airport)

RF Frequency: 2856 MHz (S-Band)

Energy Range: ~4~25 MeV (current varies)

Pulse Width: ~50ns to 4 micro seconds

Repetition Rate: single pulse to 360 Hz

Ports: 0 degree, 45 degree and 90 degree (Beam energy resolution ~ 1+/- 15%)

25B Energy vs Current

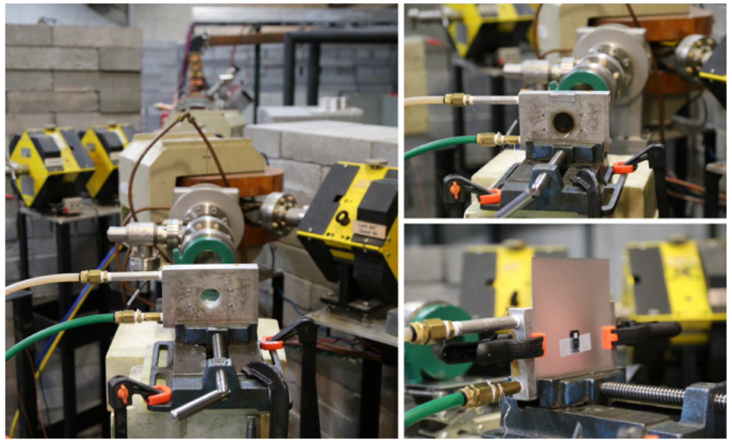
Energy (MeV)	0 port (mA)	45 port (mA)	90 port (mA)
23	55	55 @ 3.8uS	46 @ 3.6 uS
20	100	70 @ 4 uS	65 @ 4 uS
16	100	48 @ 3.6 uS	48 @ 3.6 uS
13	80	30 @ 3.3 uS	15 @ 3.3uS
10	60	18 @ 3 uS	7.5 @ 3 uS
9	110	30 @ 4uS	15 @ 4 uS
6	100	60 @ 4 uS	60 @ 4 uS
4	50	20 @ 4 uS	20 @ 4 uS

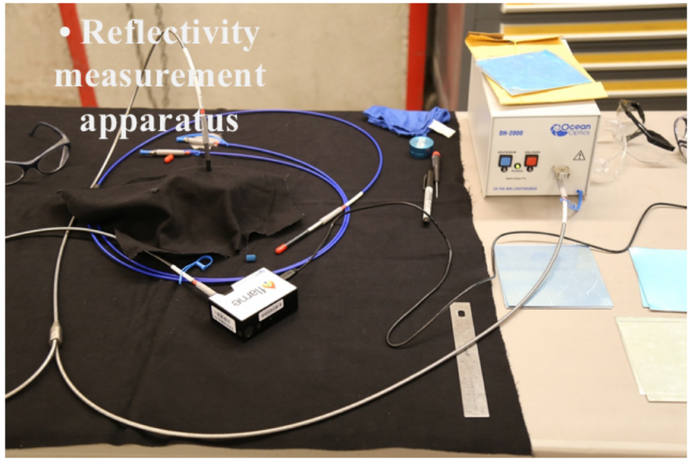
ISU

Idaho Accelerator Center

- Used 8 MeV e^- beam, 65 - 110mA I_{peak}, 4μs pulse width at 250 Hz, 310 – 880 W

- Water-cooled (15° C) aluminum brick w/ 1.5 cm radius hole (for beam) – more than adequate cooling.





Irradiated several light guide material samples over a 3 day period from Mar 22 - 24, 2016:

Miro-silver 4270

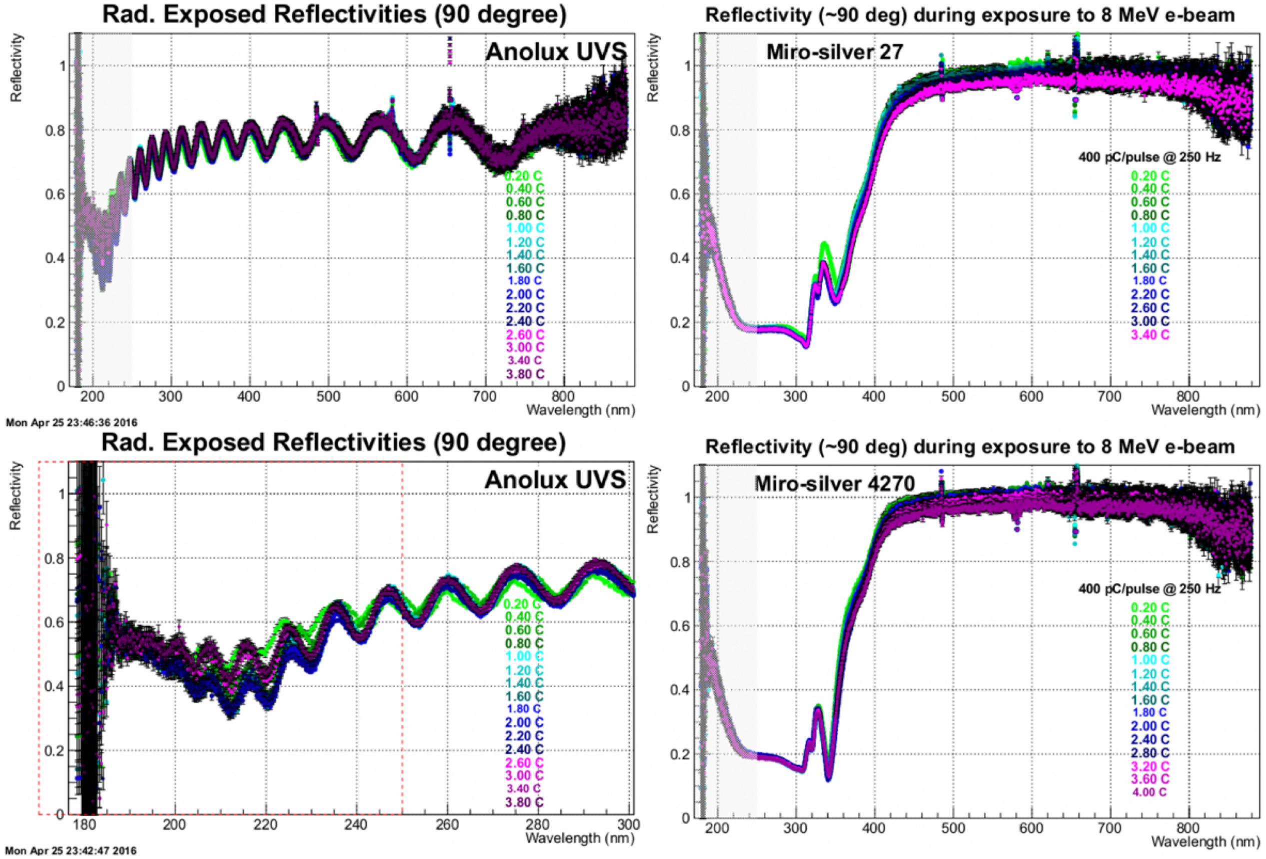
Anolux UVS

Miro 2000Ag (diffuse)

Miro-silver 27 (from Michael)

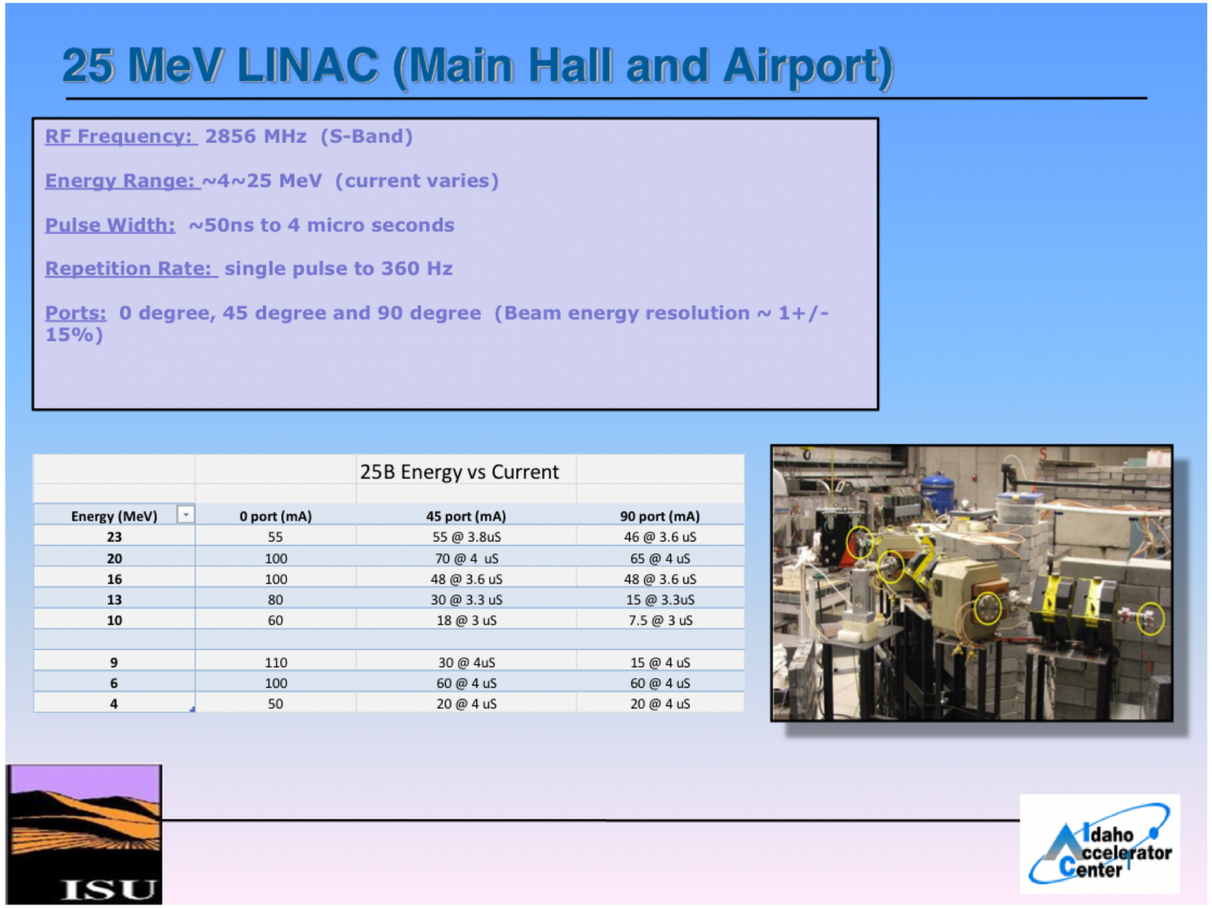
Alzak-Al and Alzak-Ag (from KK)

1 mil, single-sided aluminized mylar



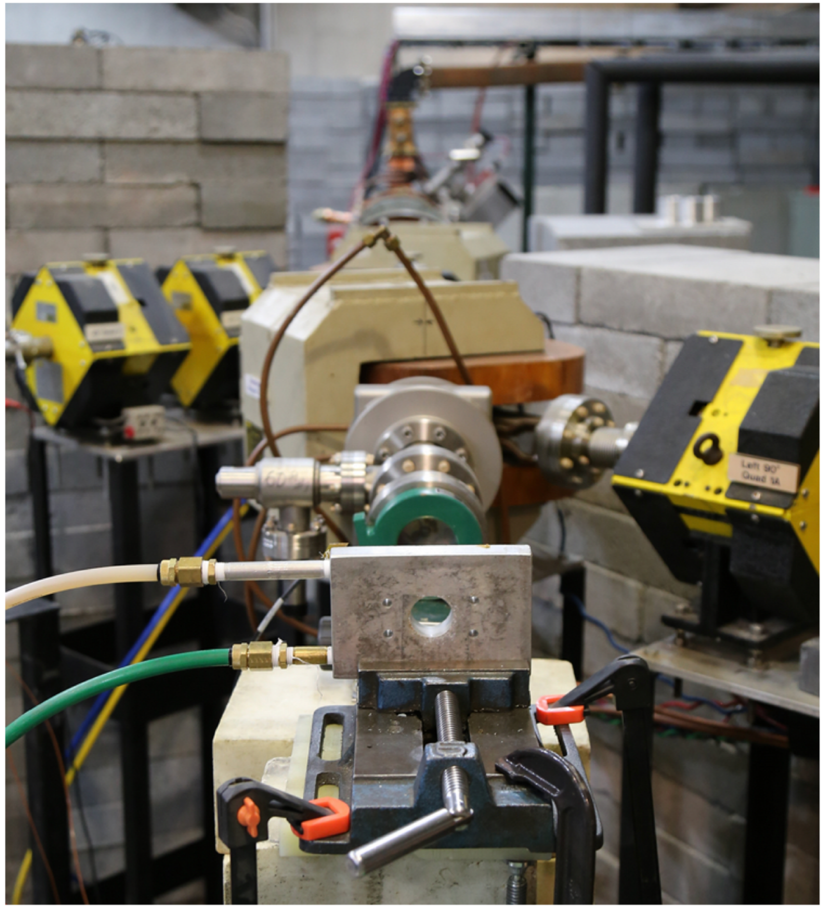
Radiation Hardness QA for quartz and other components

- Performed 1 day irradiation study on Spectrosil 2000 quartz and 3D printed ABS plastic samples
- Tests performed on May 31, 2018 at the Idaho Accelerator Center (IAC) using 8 GeV electrons
- Dose exposure rates calibrated using thermographic film dosimetry measurements
- Quartz transparency measurements taken at 10, 30, and 60 MRad exposure levels
- Plastic dogbones radiated at similar levels and tensile strength (stretching) measurements made



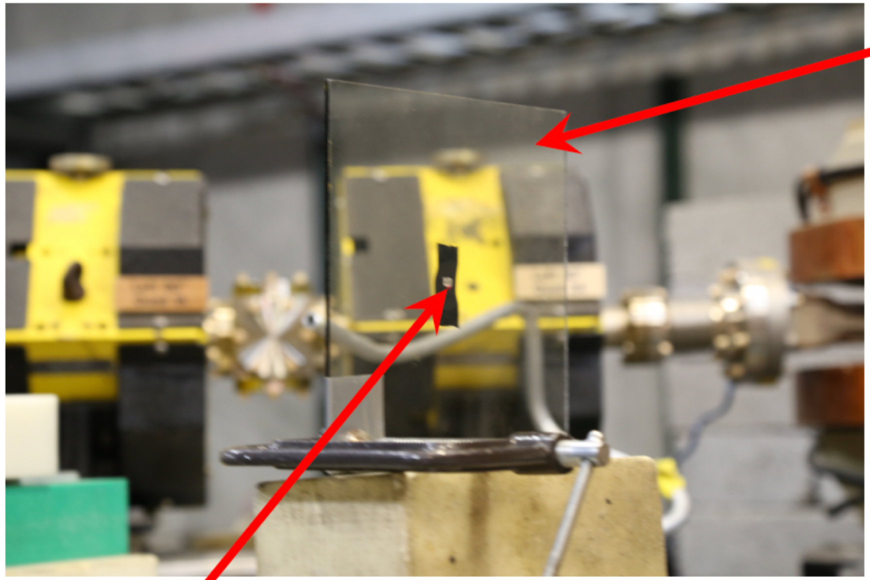
25B Energy vs Current

Energy (MeV)	0 port (mA)	45 port (mA)	90 port (mA)
23	55	55 @ 3.8uS	46 @ 3.6 uS
20	100	70 @ 4 uS	65 @ 4 uS
16	100	48 @ 3.6 uS	48 @ 3.6 uS
13	80	30 @ 3.3 uS	15 @ 3.3uS
10	60	18 @ 3 uS	7.5 @ 3 uS
9	110	30 @ 4uS	15 @ 4 uS
6	100	60 @ 4 uS	60 @ 4 uS
4	50	20 @ 4 uS	20 @ 4 uS



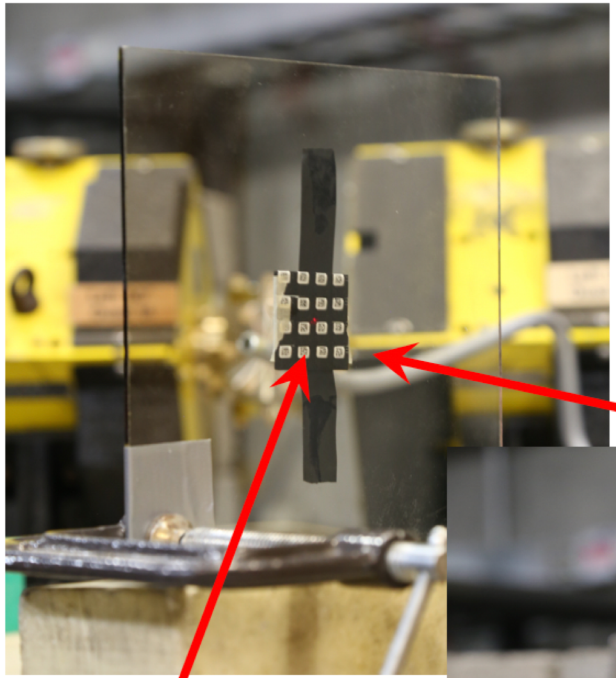
Beam Dose Exposure Rate Calibrations (May 2018)

ISU MS degree student Connor Harper's thesis based on this work: https://www2.cose.isu.edu/~mcnudust/publication/studentWork/connorHarperThesis.pdf



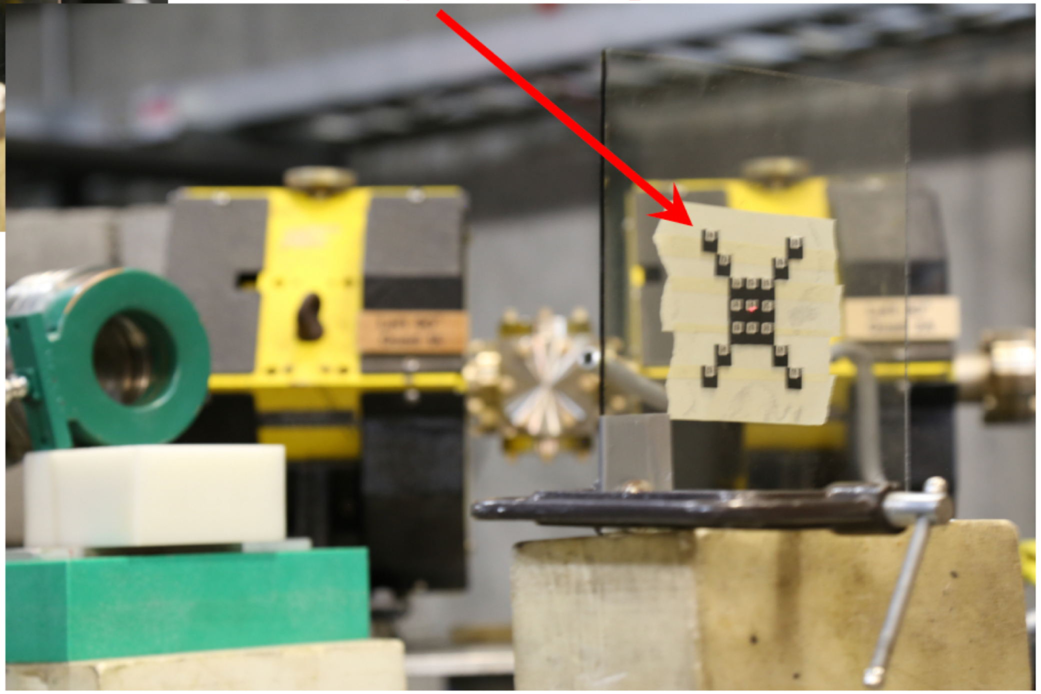
Glass slide for spot profile measurements

Optically Stimulated Luminescence (OSL) dosimeter (~ 7 mm by 7 mm square)

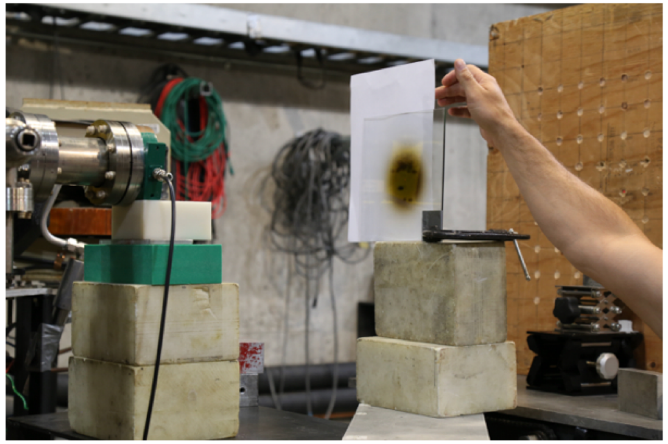


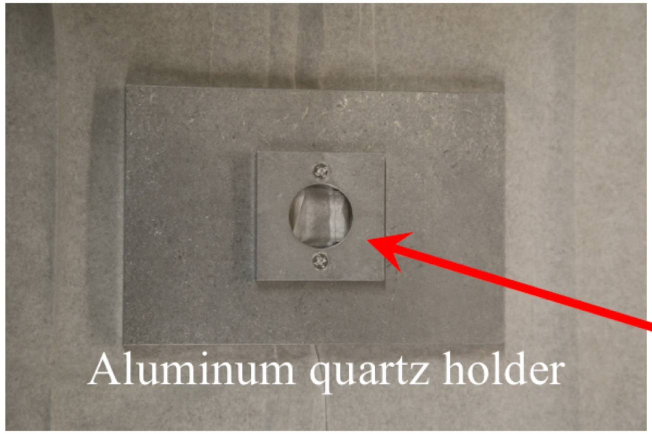
Laser alignment

OSL arrays for dose profile measurements

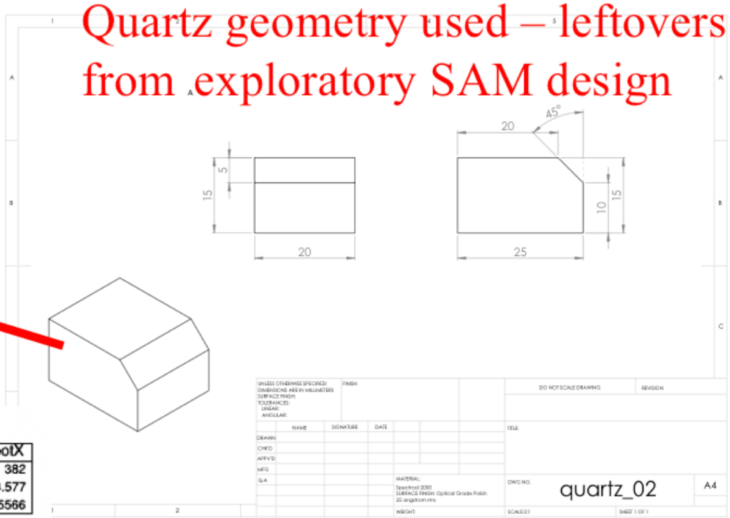


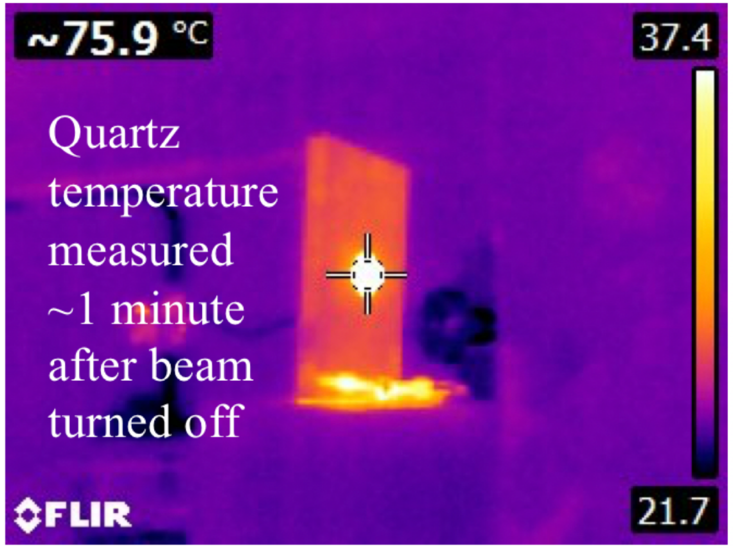
Quartz Irradiations (May 2018)



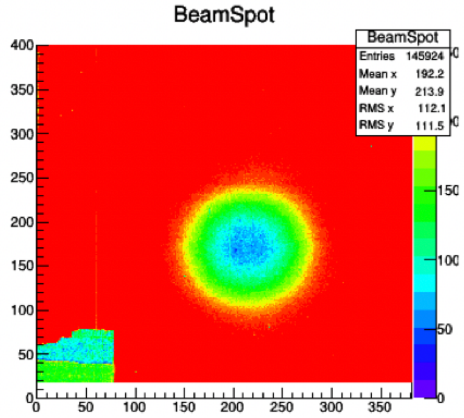


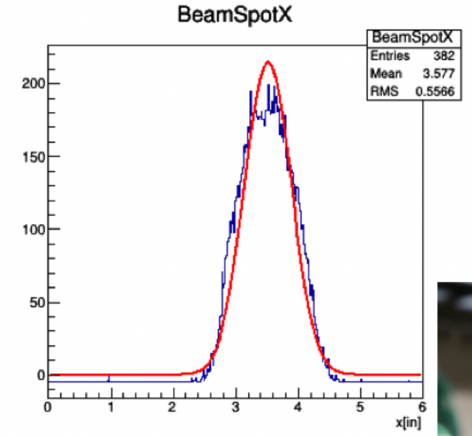
Quartz geometry used – leftovers from exploratory SAM design



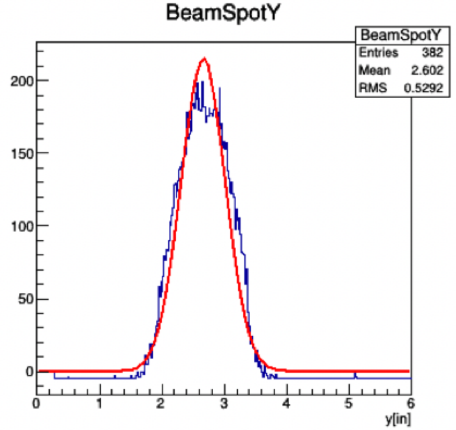


Quartz temperature measured ~1 minute after beam turned off





Bright Cerenkov light generation during irradiation

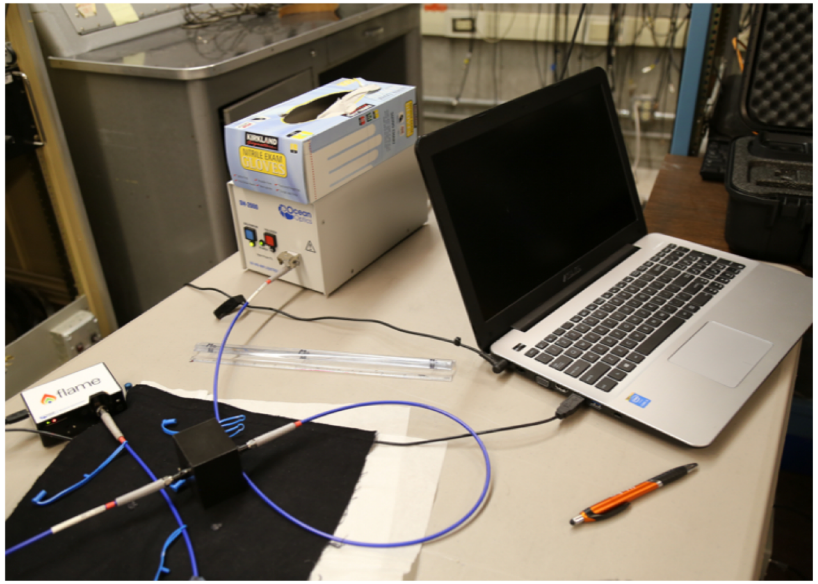


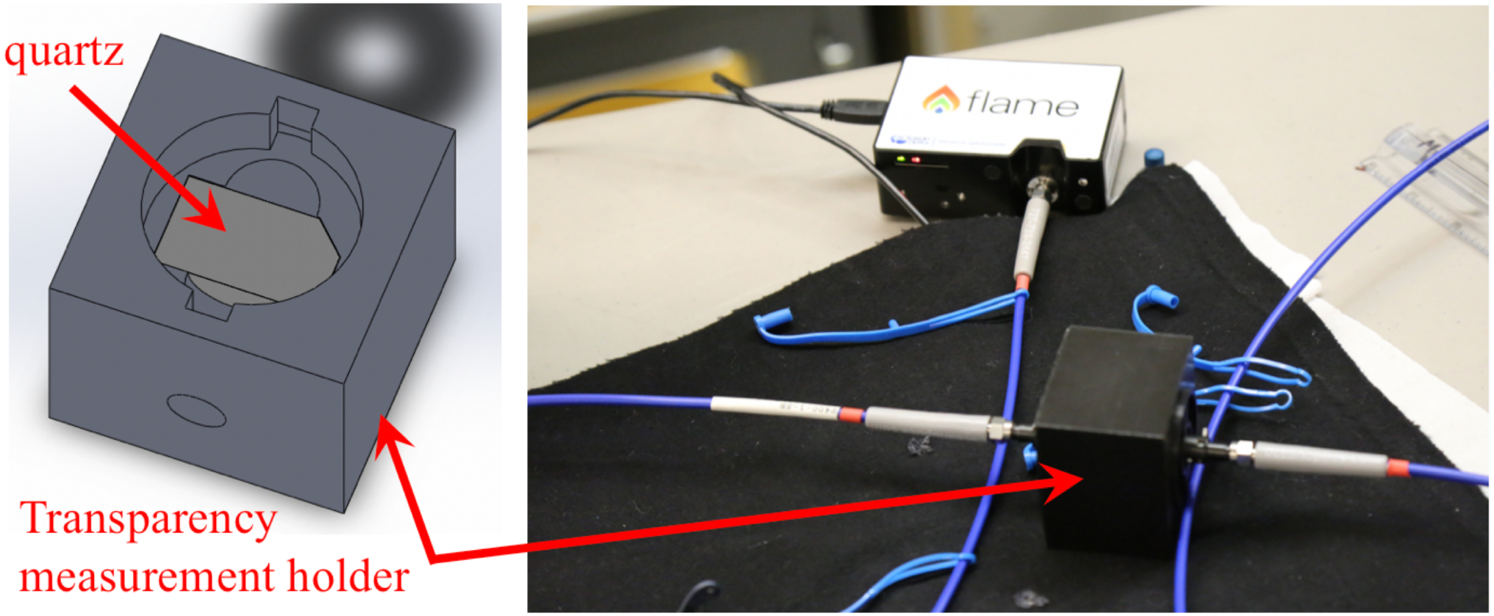
2018-05-31_15-01_Pulses_1006_50cm.png

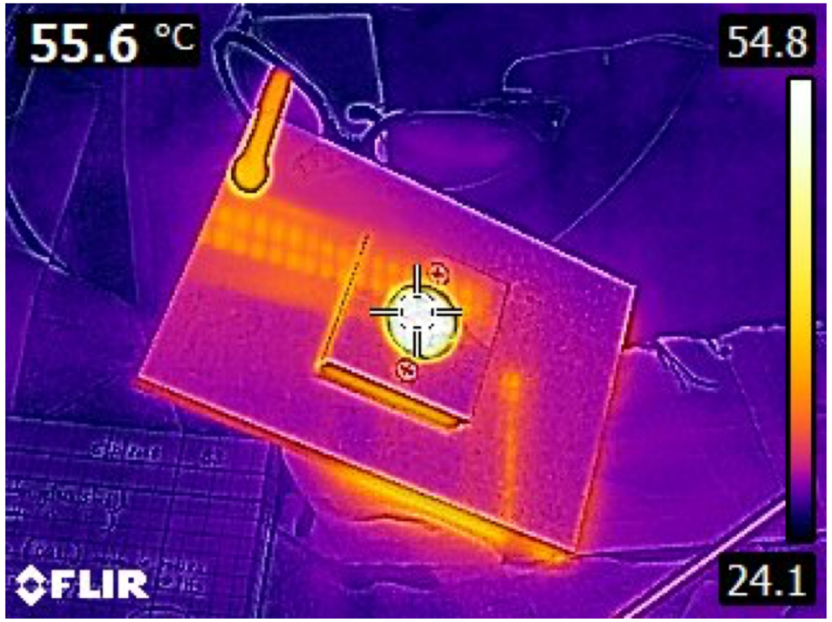
x-center = 3.512 in, y-center = 2.661 in

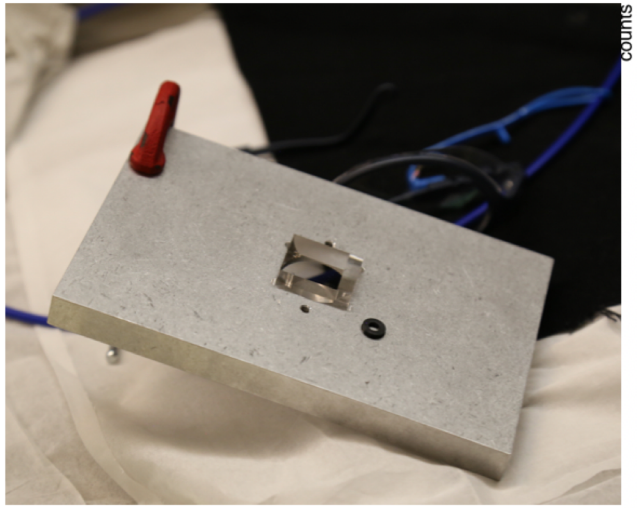
glass plate at 50cm from beam window

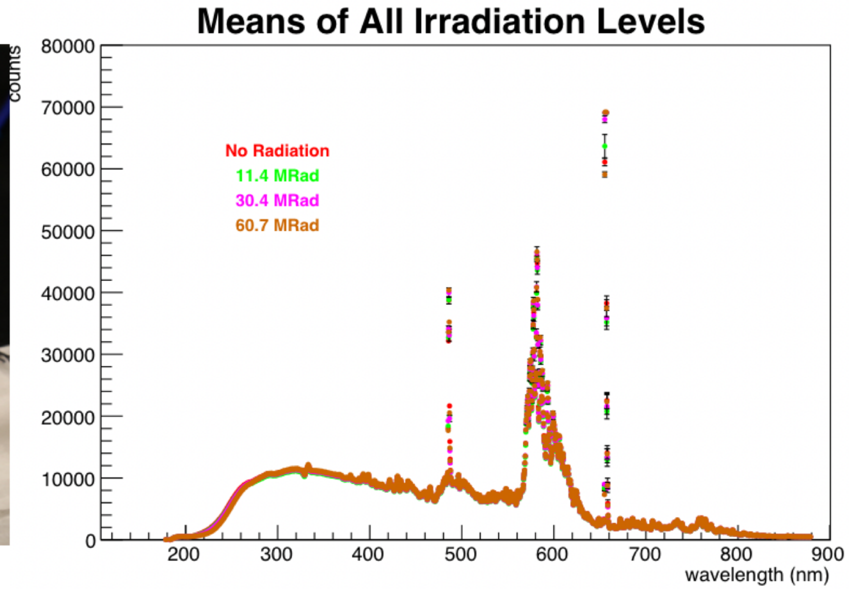
Quartz Transparency Measurements



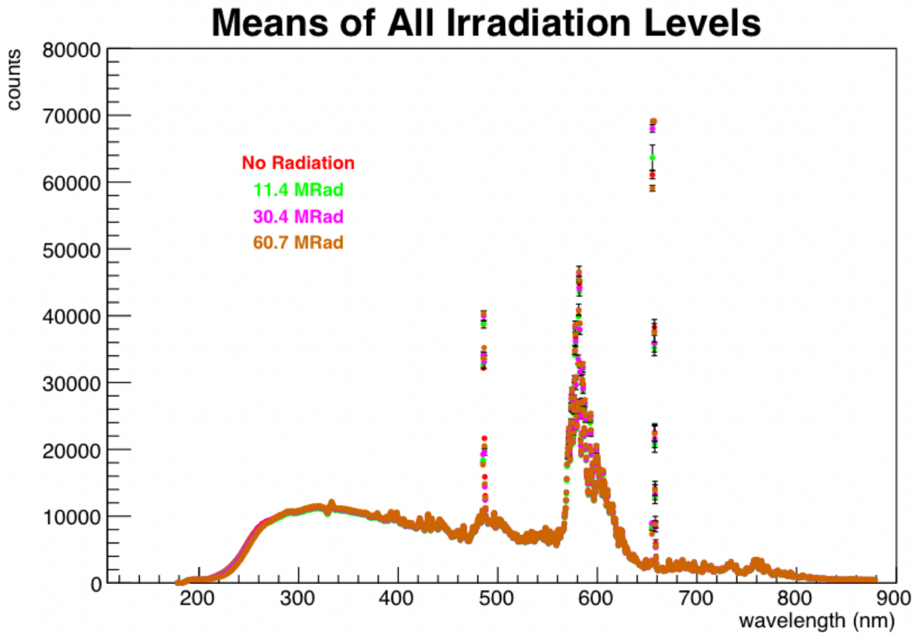




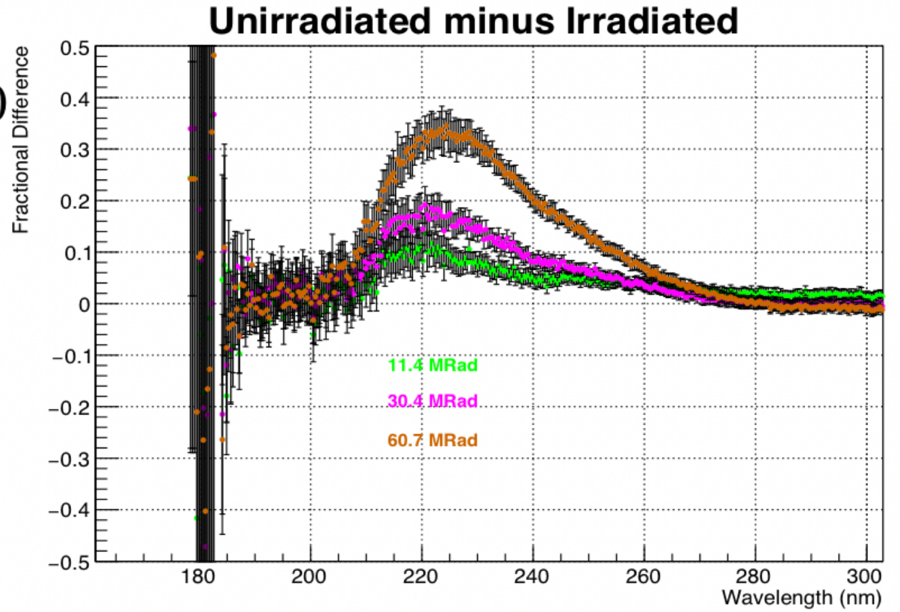


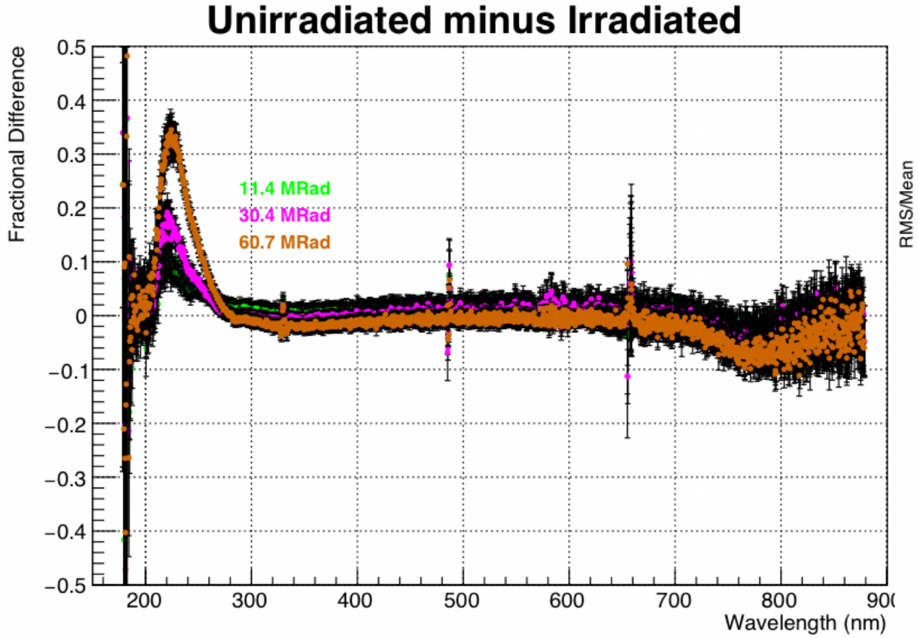


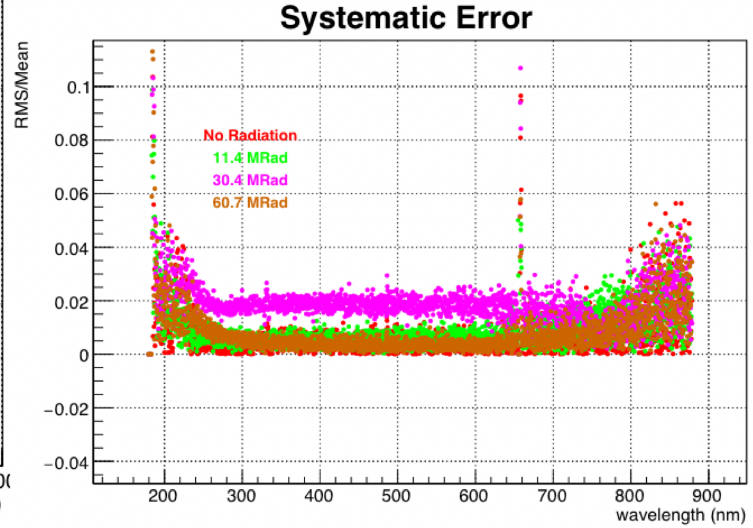
Quartz Transparency Preliminary Results

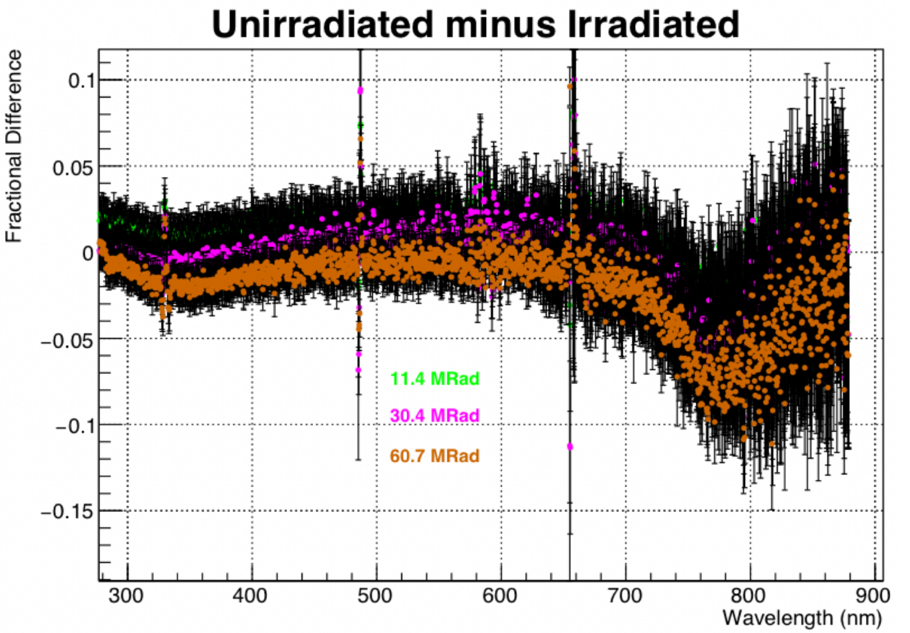


- Beam setup: 8 MeV, 50 mA I_{peak}, 500 ns pulse width at 250 Hz rep-rate
- Quartz sample mounted 0.5 m from beampipe exit window
- Dose exposure calibrations give ~253 Rad/pulse
- Irradiated sample for 3, 8, and then 16 minutes
- Measured light transmission (four times) after each irradiation and averaged

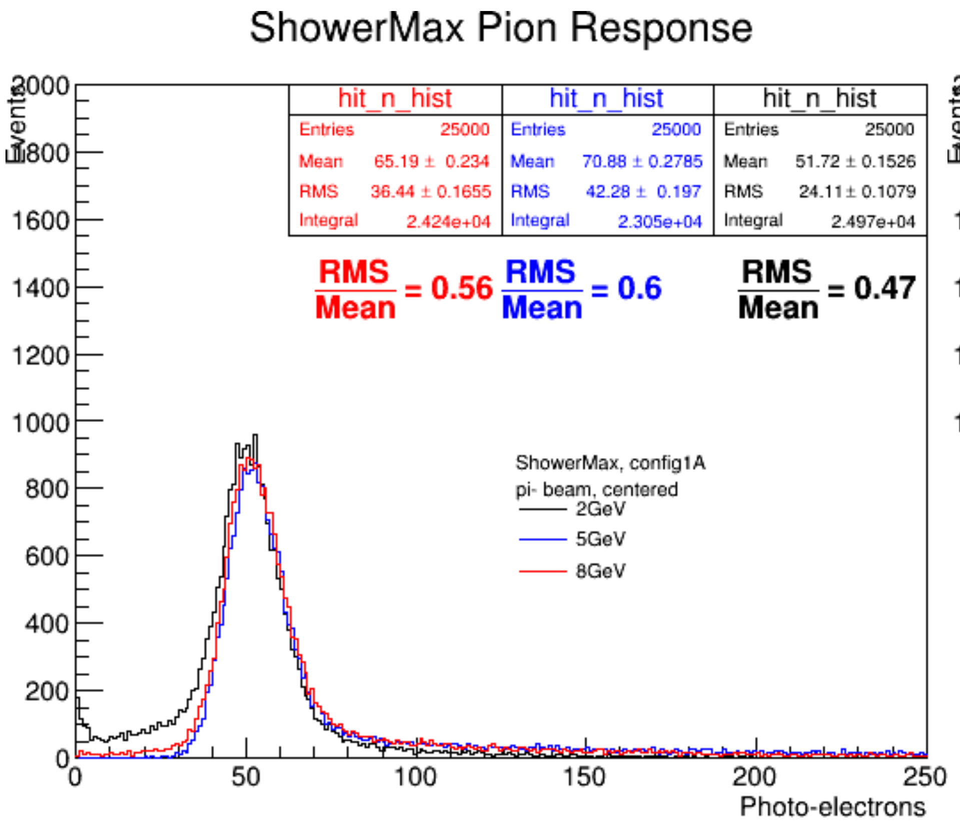


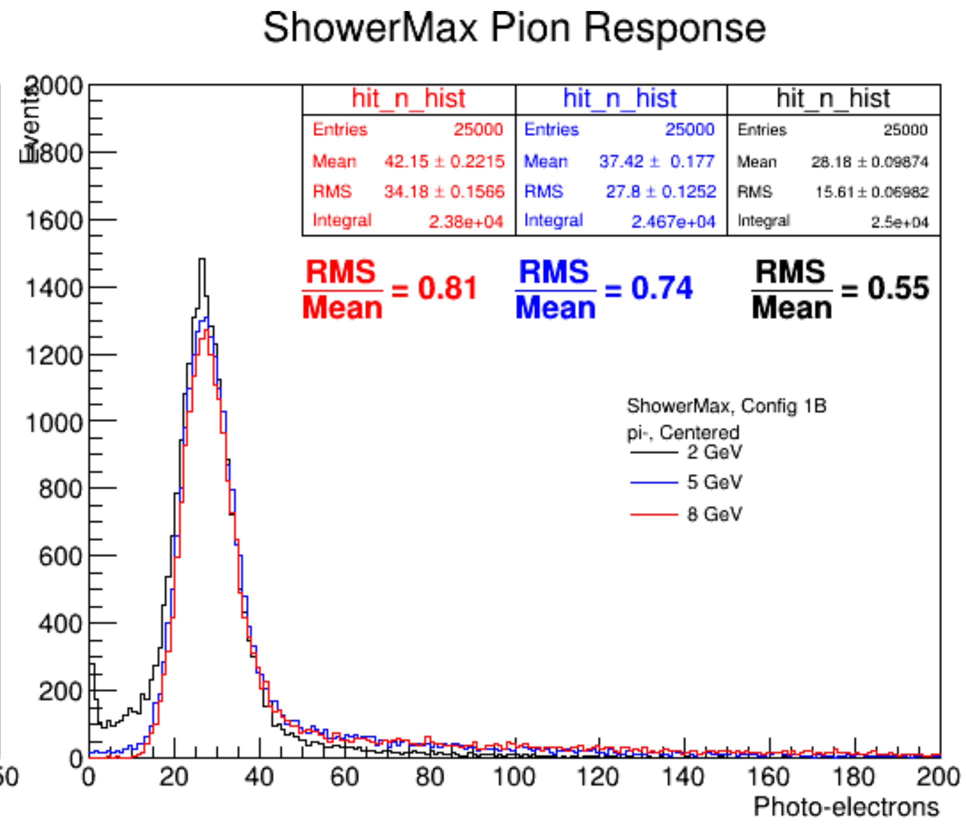






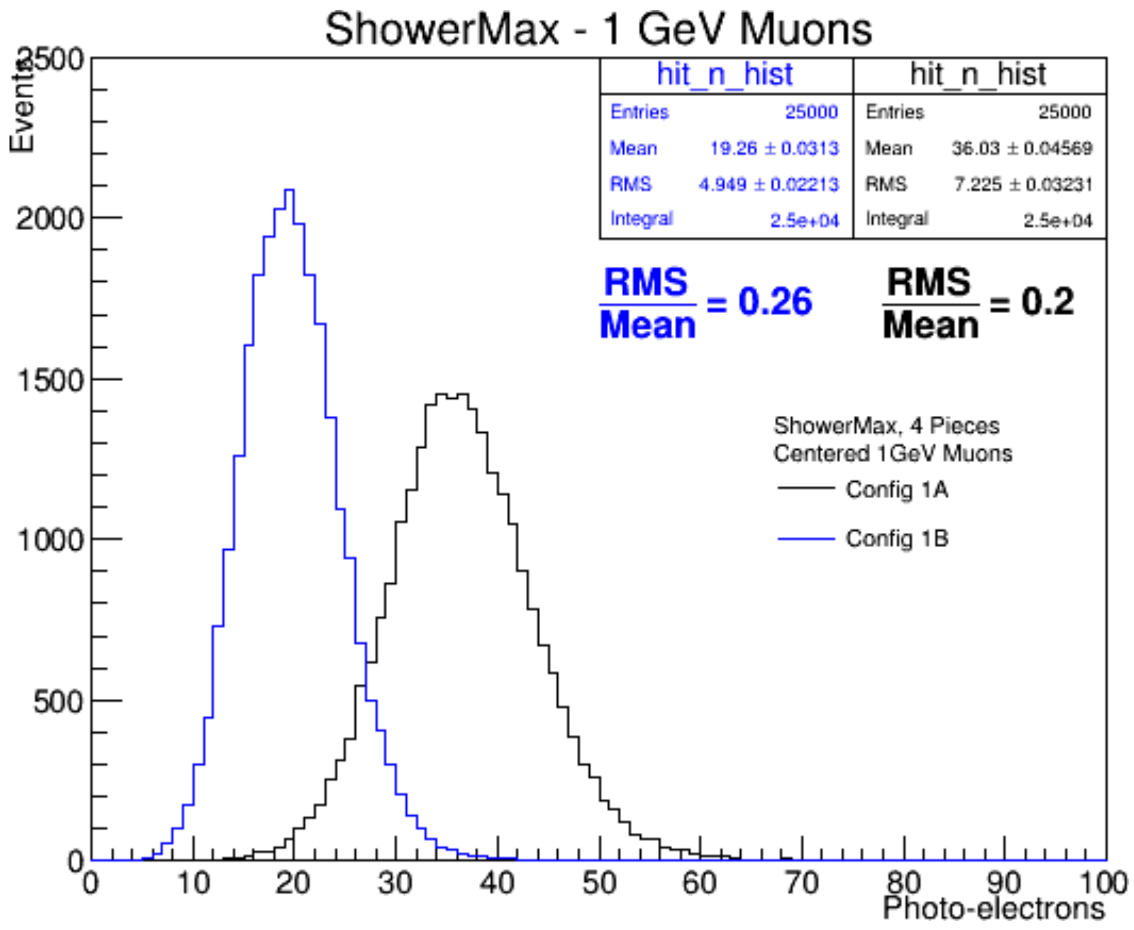
Shower-max Pion response (simulated)



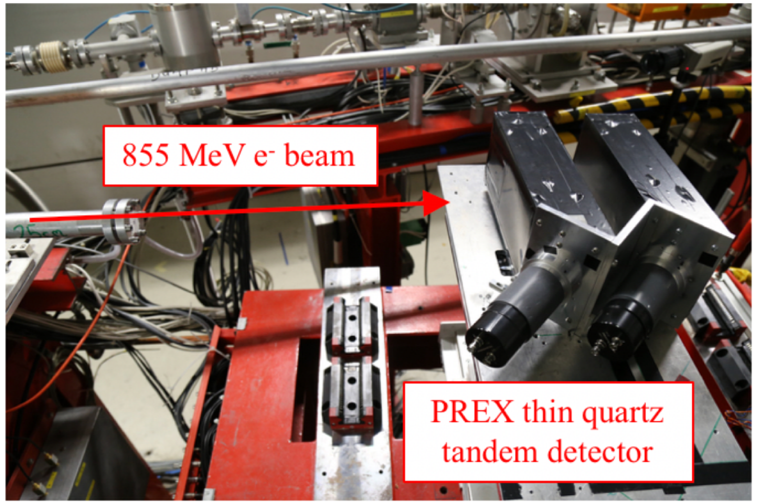


- Simulated SM photo-electron response for Pions is ~5 - 15% of the equivalent-energy electron response, which will allow an extra identification-tag during Pion-dilution measurements

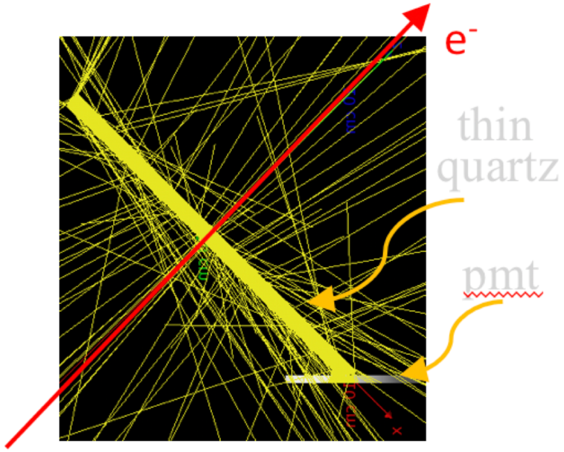
Shower-max Muon response (simulated)



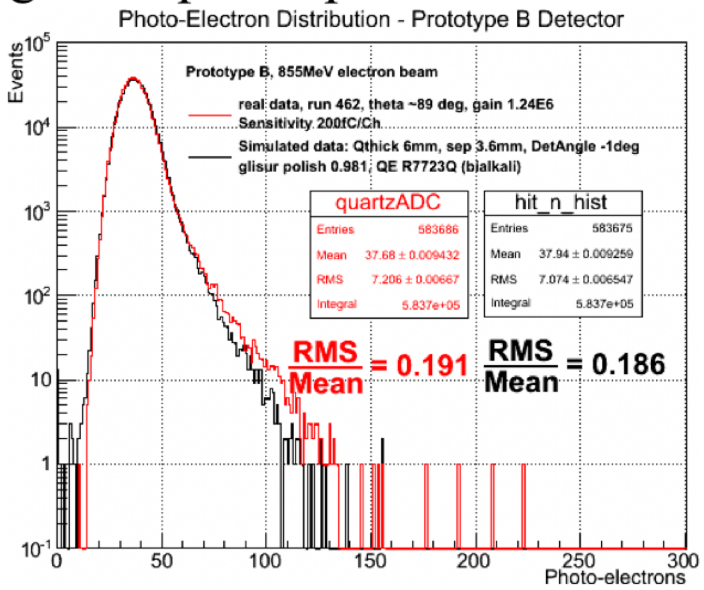
- Quartz optical G4 properties benchmarked at MAMI: Glisur ground polish parameter ~0.981



MAMI testbeam with PREX detector



G4 event visualization for PREX detector

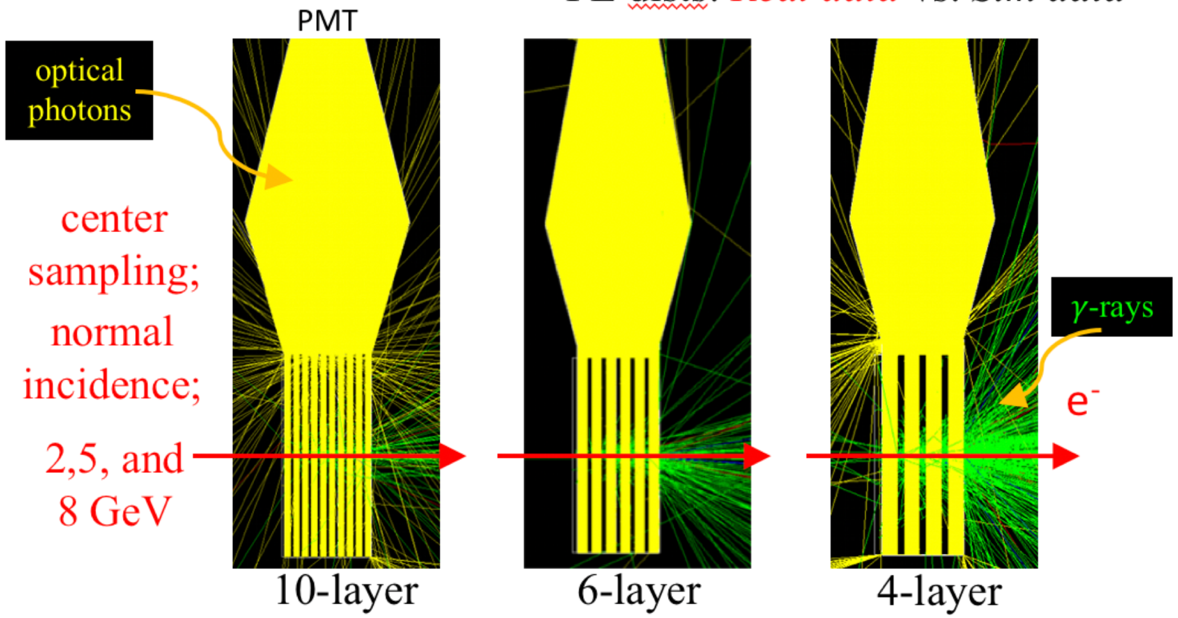


PE dists: *Real data* vs. *Sim data*

- Stack configuration MC study:
  - Stack thicknesses all same (7.2 X_0)
  - 2, 5, and 8 GeV incident electrons
  - PE dists generated using tuned polish parameter and 60% LG reflectivity

Conclusion:

4-layer gives comparable performance to 10-layer
(and is easier and cheaper to build)



Shower-max event visualizations