# Shower-max Requirements and Status

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Jefferson Lab MOLLER
Design Review

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MOLLER

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

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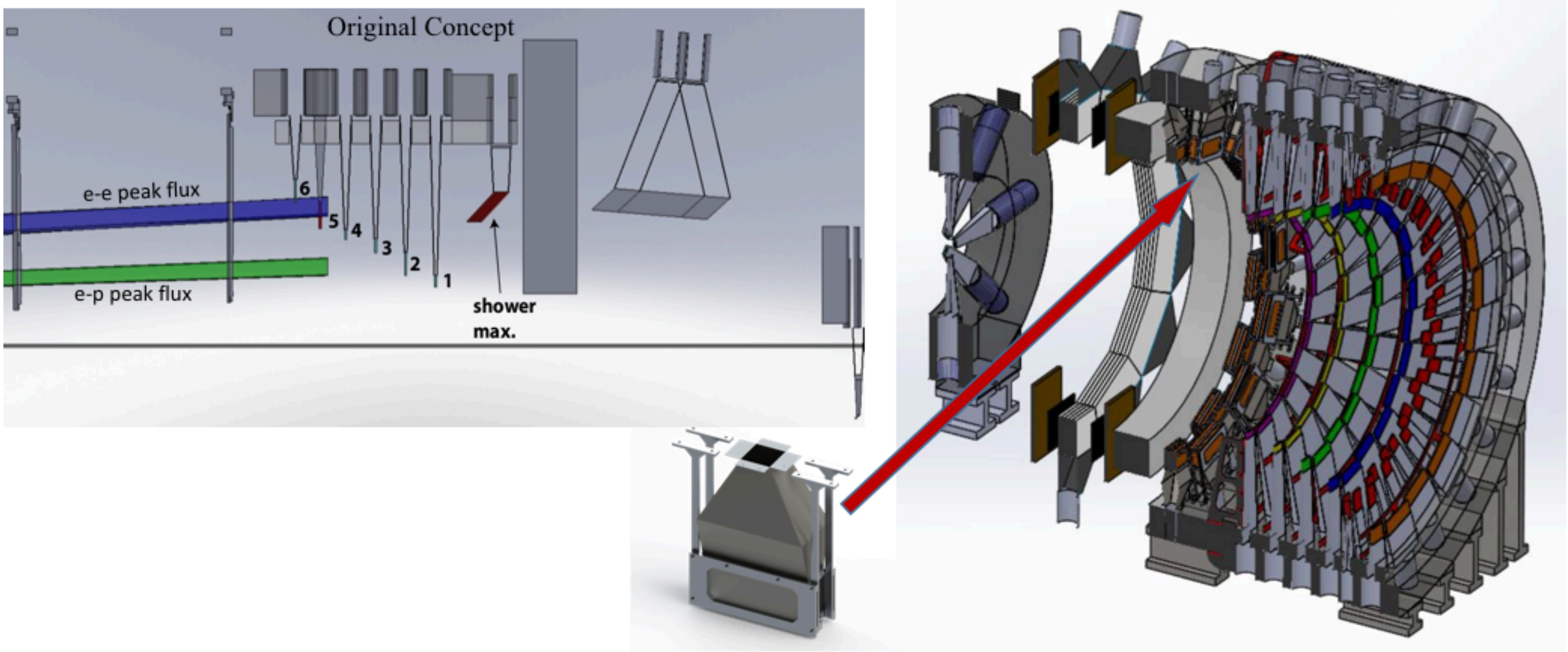
# Outline

- System motivation and requirements
- Design Concept and Status
- Acceptances and resolutions
- Prototyping and initial testbeam
- Summary

# Shower-max: Motivation and Requirements




- Provides additional measurement of e-e ring integrated flux
- Weights flux by energy ⟹ less sensitive to low energy and hadronic backgrounds
- Will also operate in tracking mode to give additional handle on background pion identification – gives MIP-like signal
- Will have good resolution over full energy range ($\frac{\sigma}{\langle n \rangle} \lesssim 30\%$), radiation hard with long term stability and good linearity



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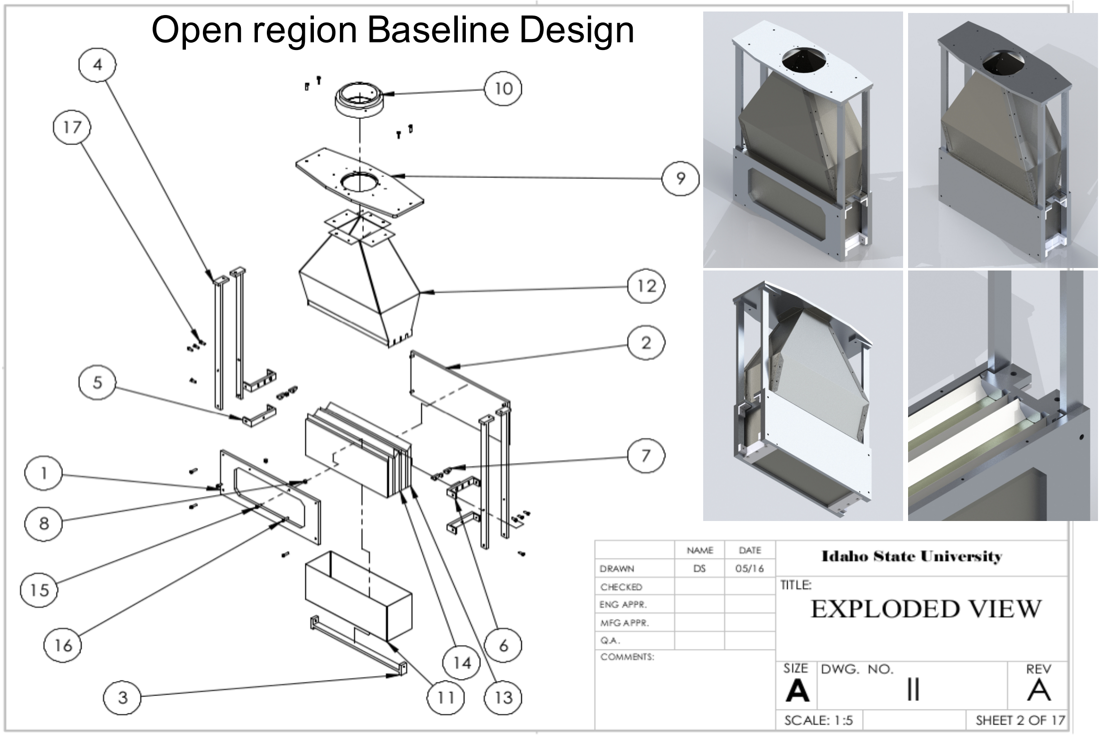
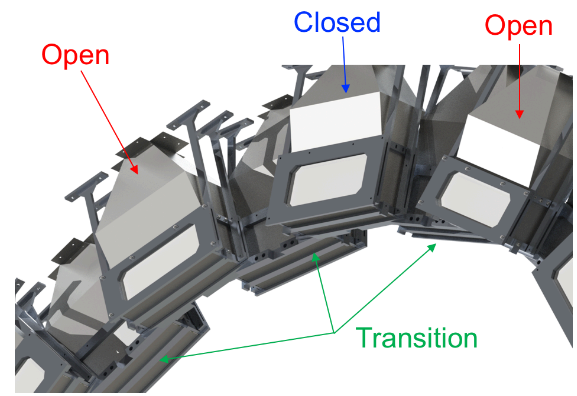
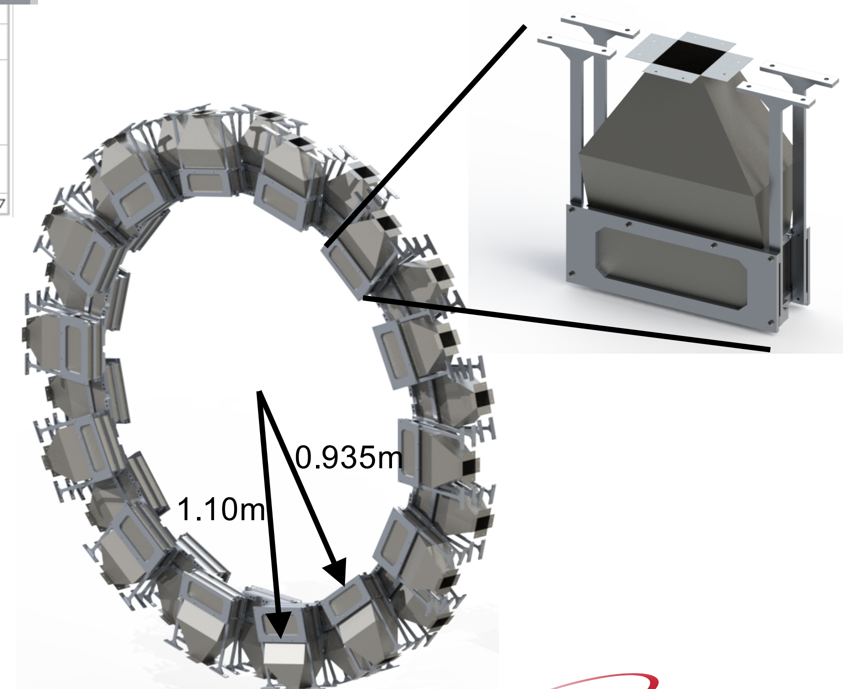
# Shower-max: Design Status and ring geometry




- 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



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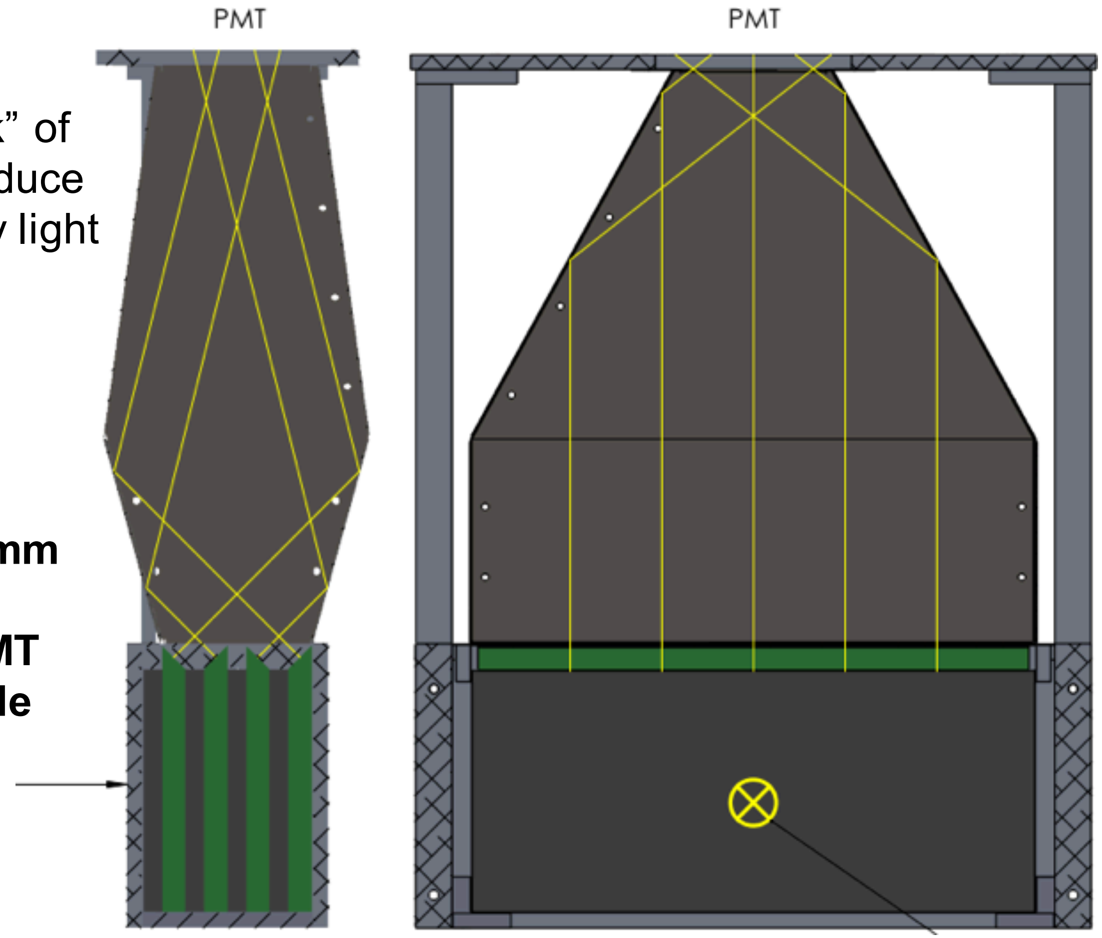
# Shower-max: Detector Concept and Materials

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

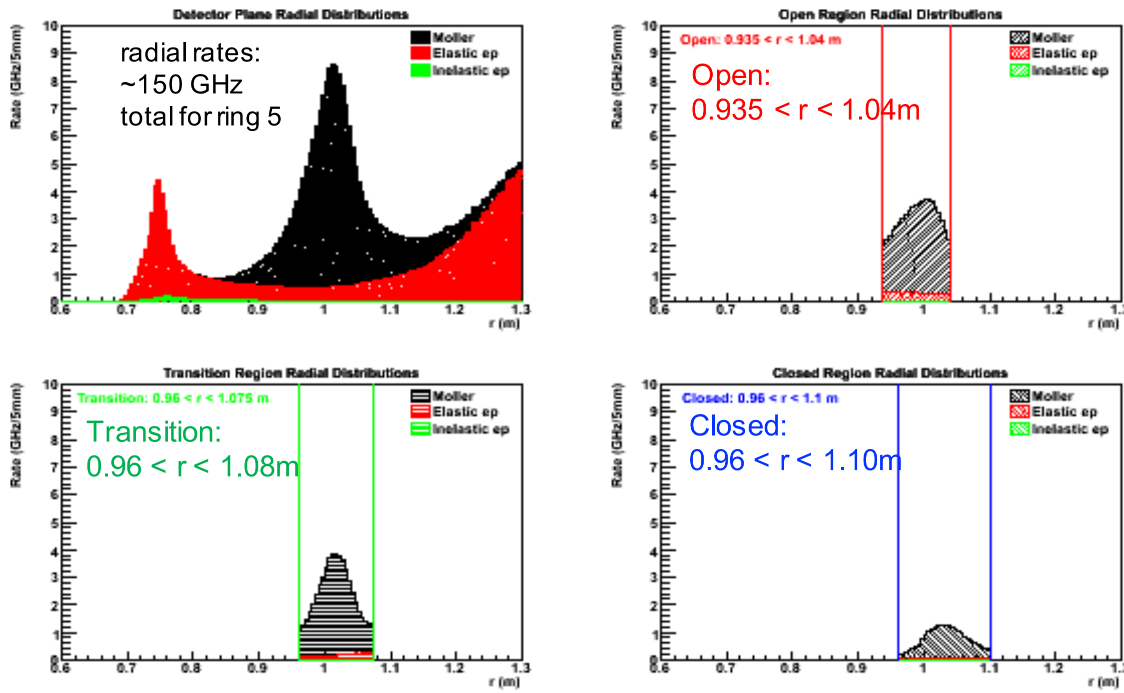
- "Baseline" design developed using GEANT4 optical MC simulation:
  - ➢ Design uses a **4-layer stack** with **8 mm tungsten** and **10 mm quartz** pieces
  - ➢ Cherenkov light directed to **3inch PMT** using **air-core, aluminum light guide**

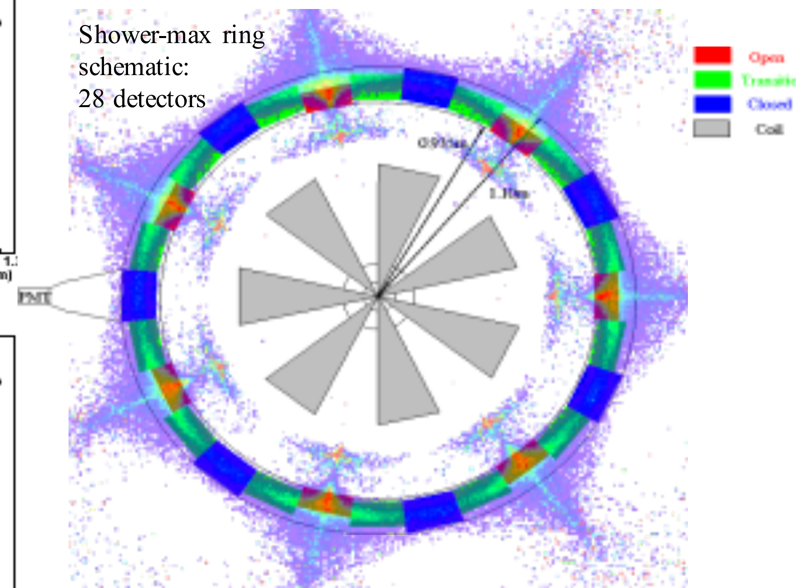


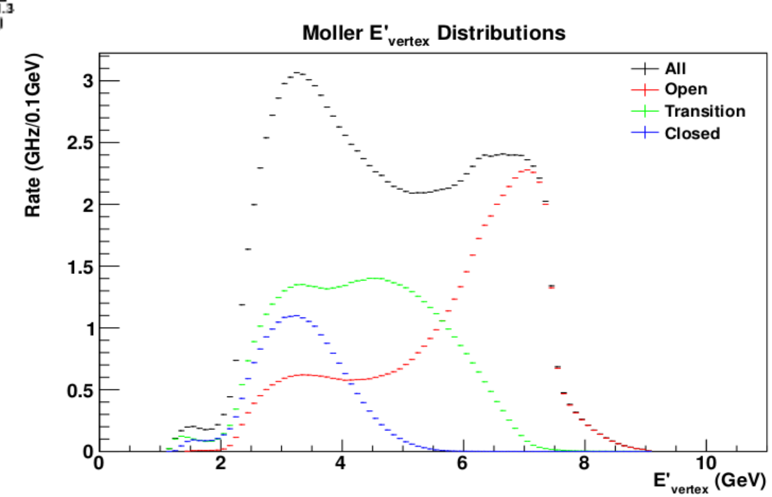

*Materials (all rad-hard):*

- Tungsten is high purity (99.95%) and quartz is optically polished Spectrosil 2000
- Light guides are aluminum specular reflectors (Miro-silver 27, Anolux, or aluminized mylar, …)
- Total radiation length: 9.1 $X_0$ tungsten + 0.4 $X_0$ quartz = 9.5 $X_0$

# Shower-max: Energy and rate acceptances




- Large range of rates and energies for different phi-region detectors:

- Open ~9 GHz/det; 2 - 9 GeV, peak at 7 GeV…
- Closed ~3.5 GHz/det; 2 - 5 GeV, peak at ~3 GeV
- Transition ~4.5 GHz/det; 2 - 7 GeV, 3 – 5 GeV plateau



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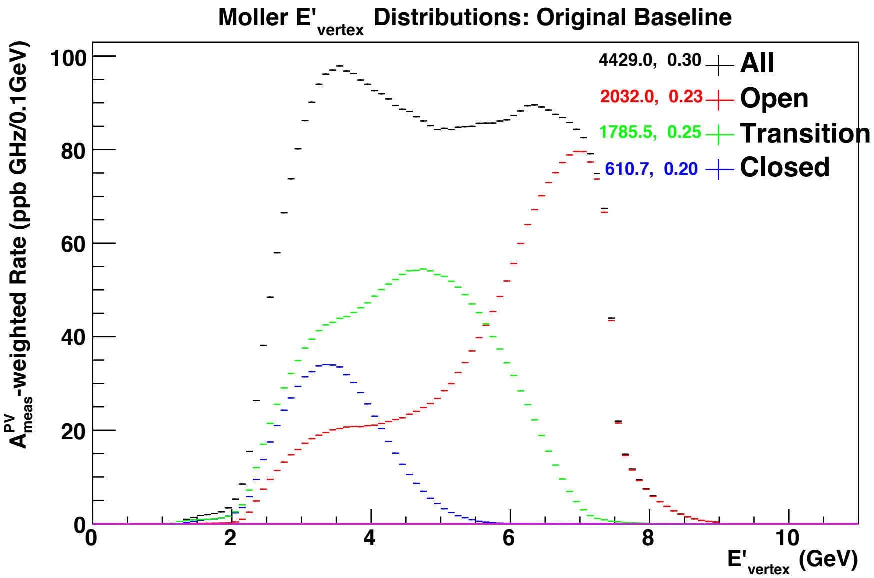
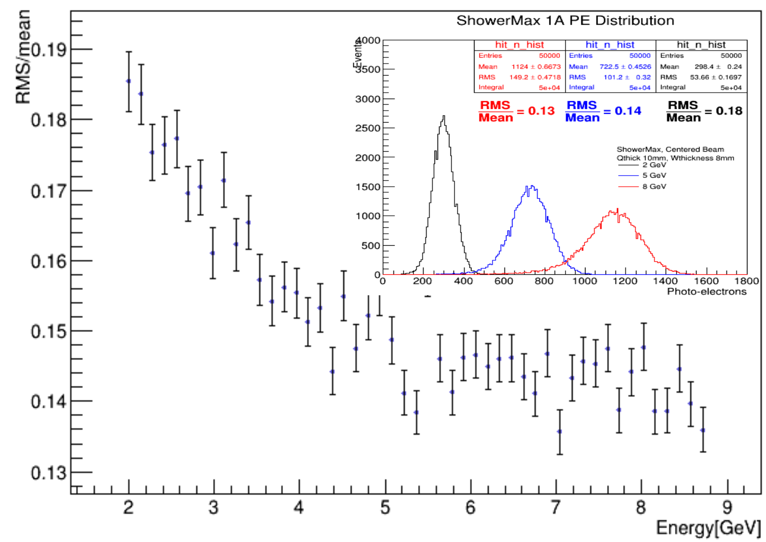
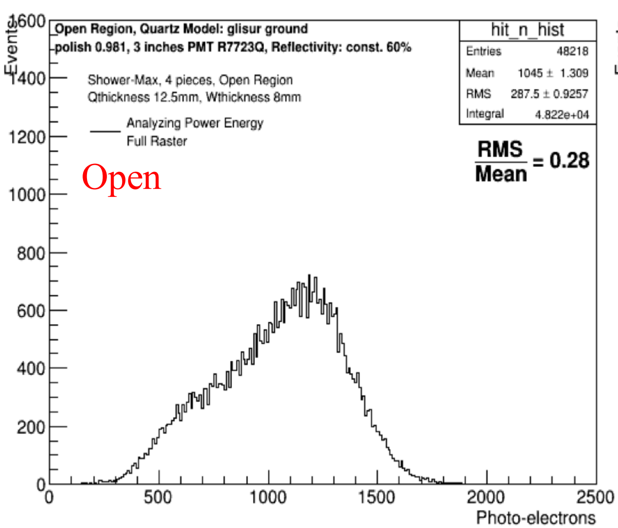
# Shower-max: Resolutions



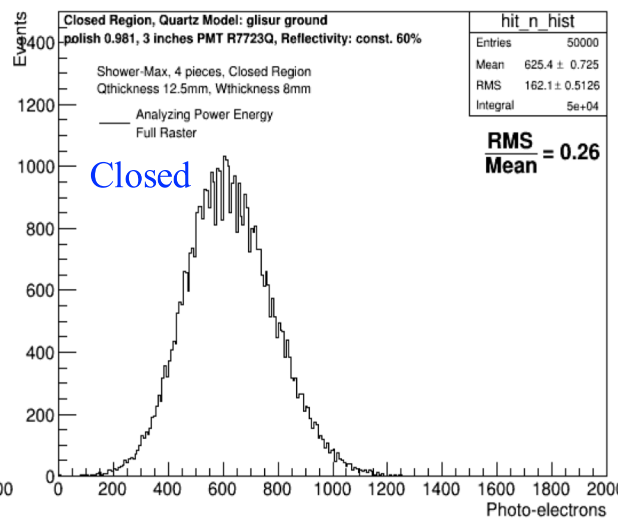

Resolution vs. Energy



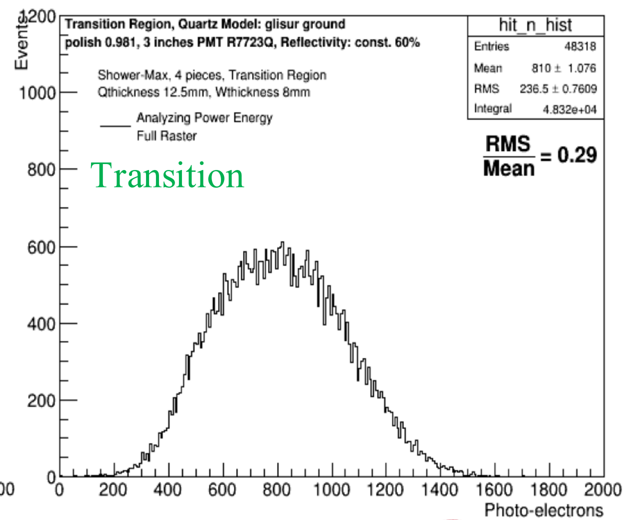

Open ShowerMax Photo-Electron Distribution




Closed ShowerMax Photo-Electron Distribution

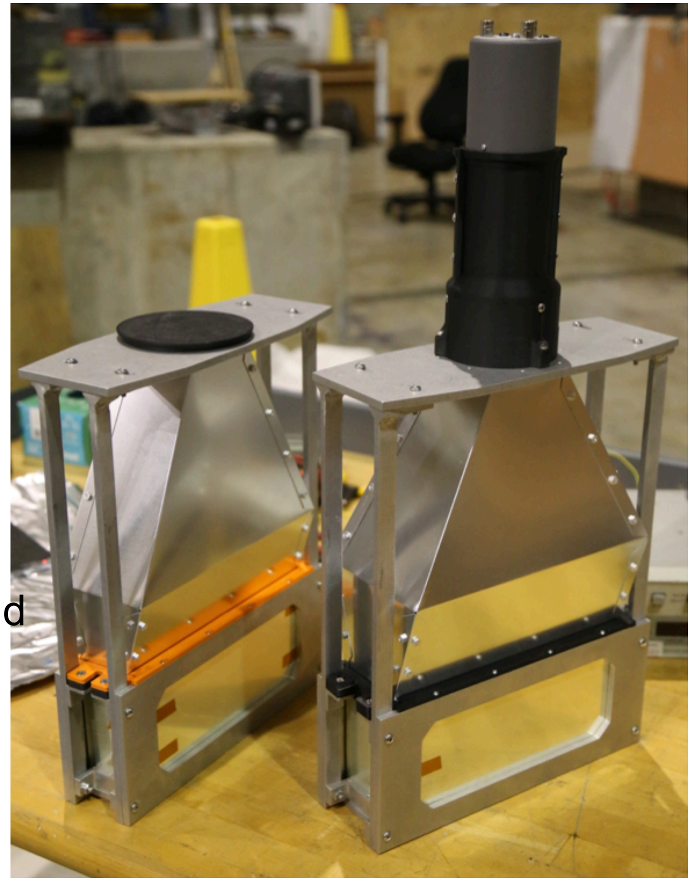


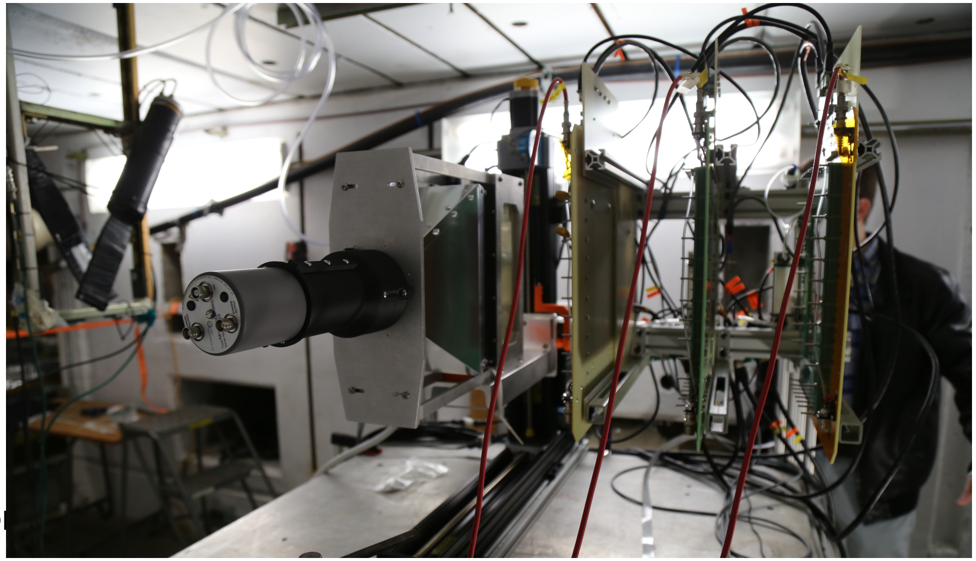

Transition ShowerMax Photo-Electron Distribution



# Shower-max: Prototyping and testbeam

- First prototypes constructed: two different "stack" configs: 8 mm thick tungsten and 10 mm thick or 6 mm thick quartz
  - 1st-pass engineered design concept vetted
  - Light guide construction techniques developed
- SLAC testbeam T-577 run: Dec 6 – 12, 2018
  - Exposed prototype 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





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# Summary

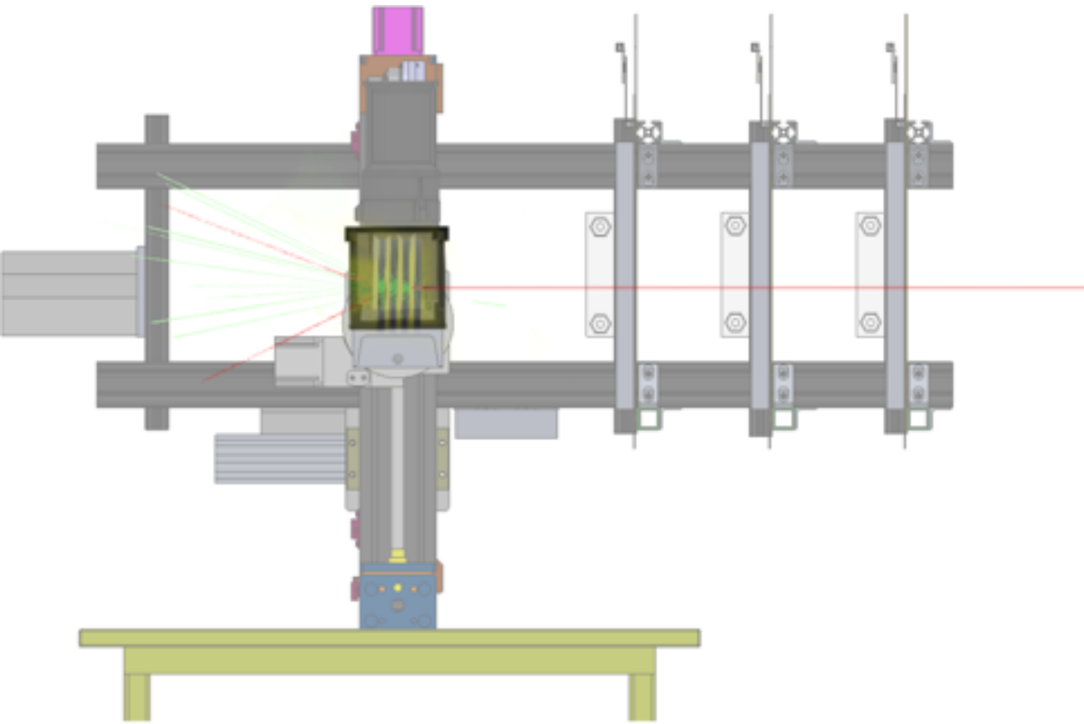
- Baseline design concept meets requirements:
  - Proportional energy response and background suppression
  - Large light yields and good resolution
  - Radiation hard material construction
- 1st pass mechanical design validated through prototype construction: support frame design and light guide assembly
- Initial beamtest performance validated optical MC and stack design; baseline prototype (as is) is sufficient for MOLLER
- Future testbeam runs will be used to finalize the design mechanics and light guide

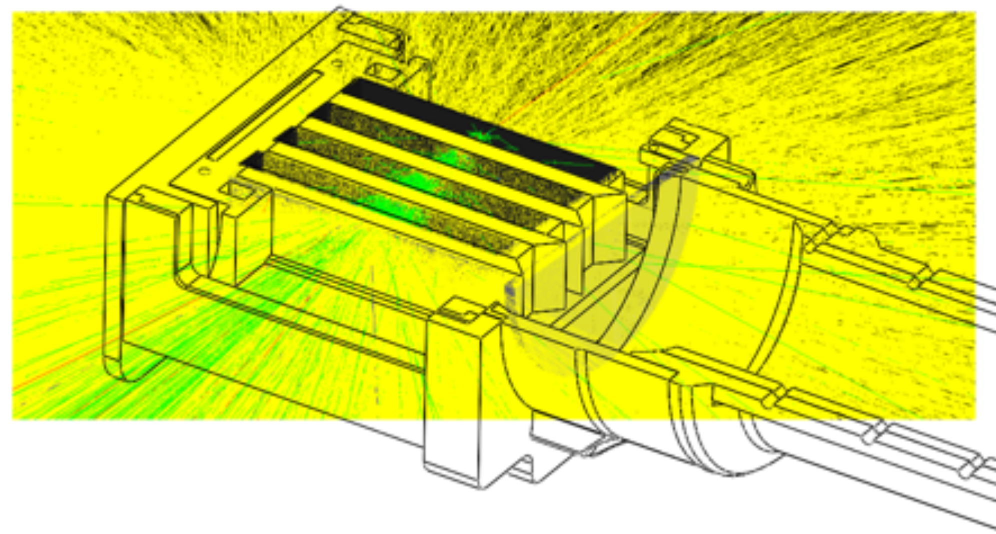
- Thank You

# Shower-max: Back-up Slides

December 11, 2019

# Benchmarking Testbeam stand CAD and MC Visualization (1B prototype)





# 1A and 1B Benchmarking single-quartz Testbeam

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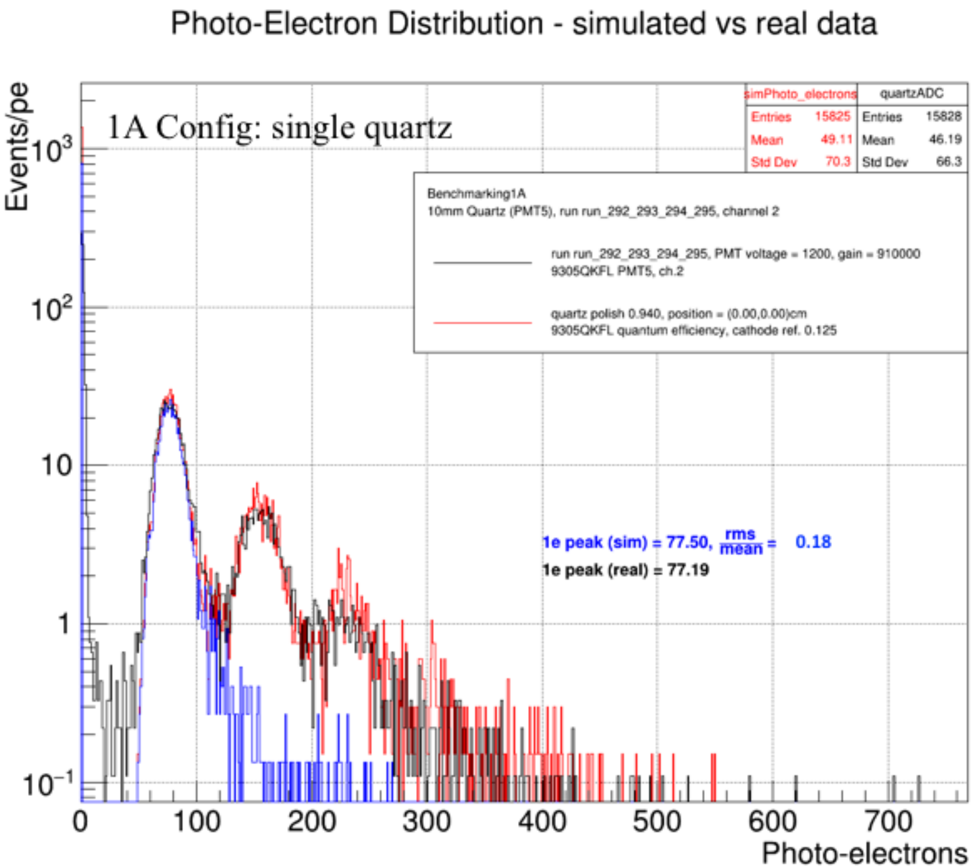
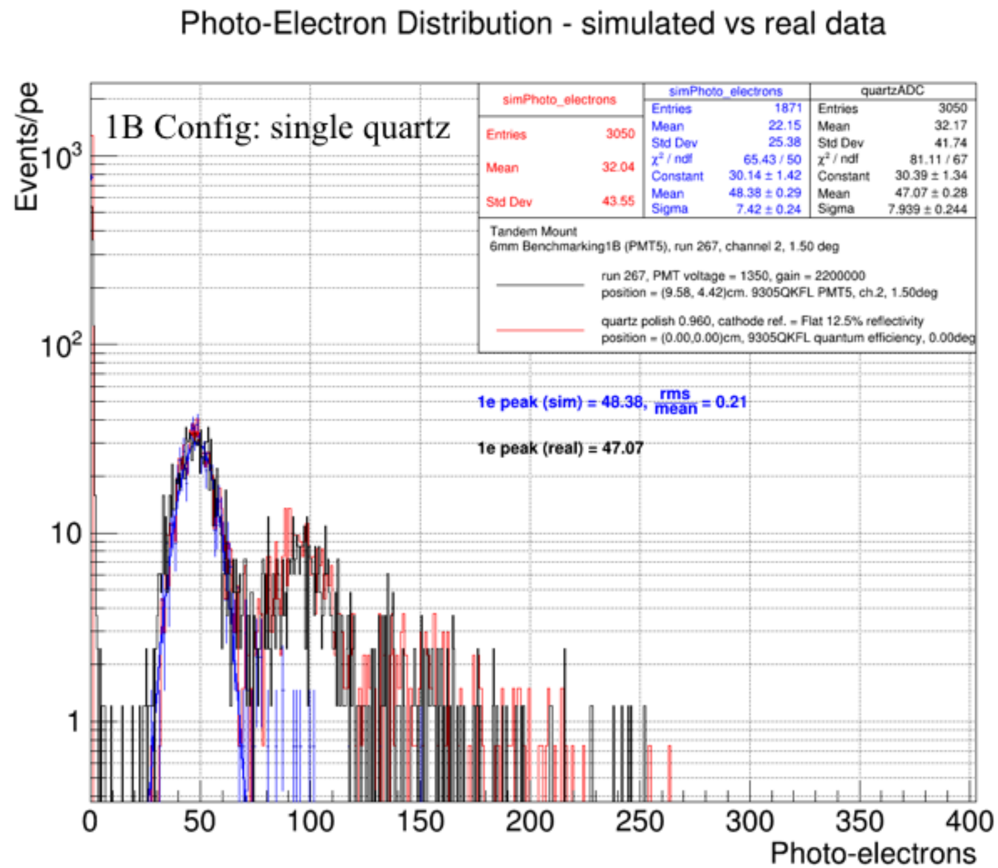
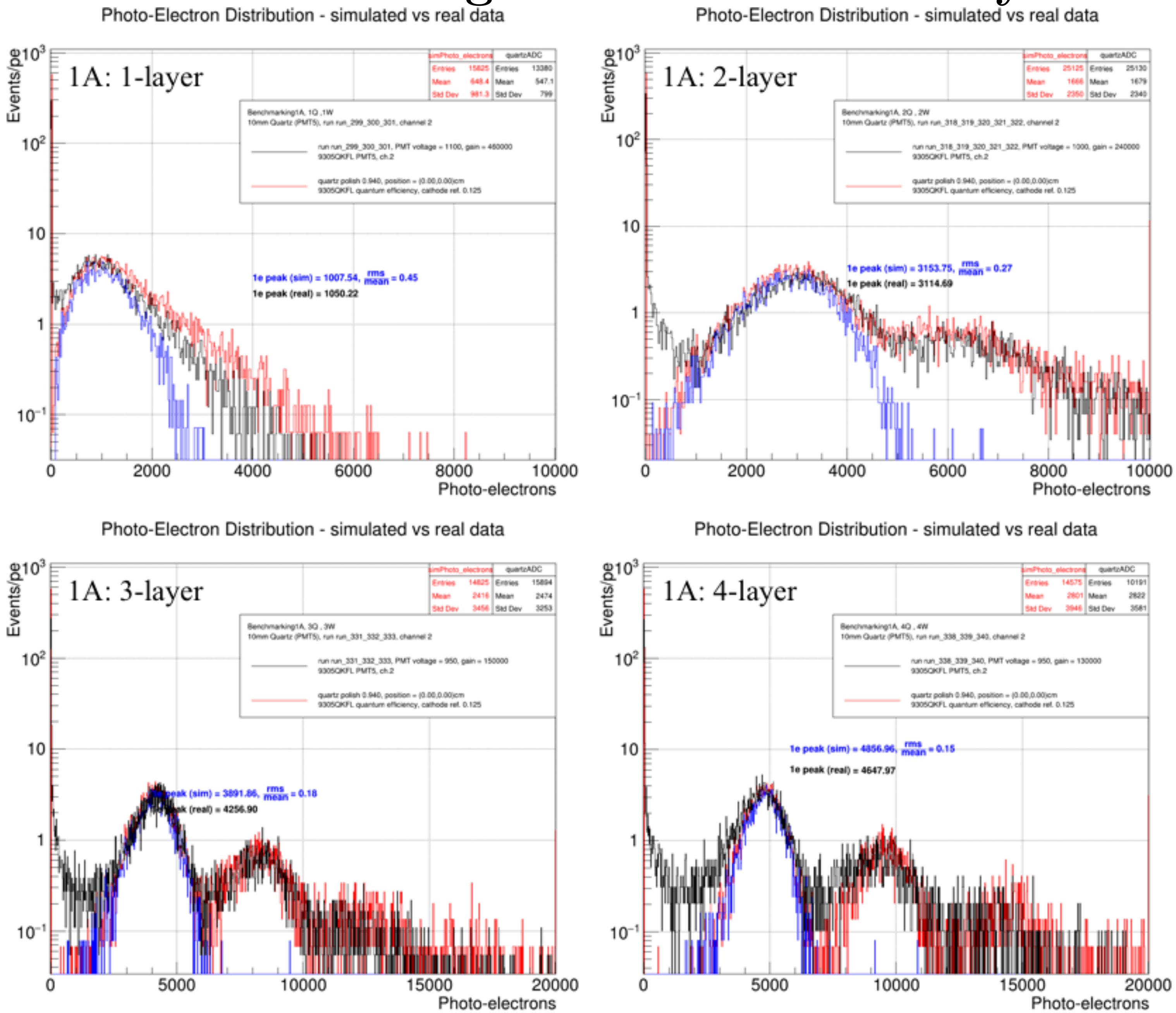
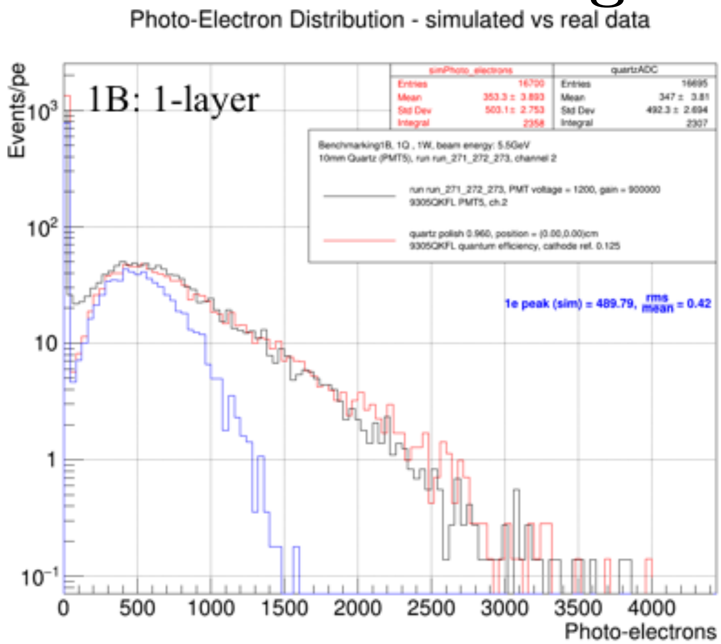


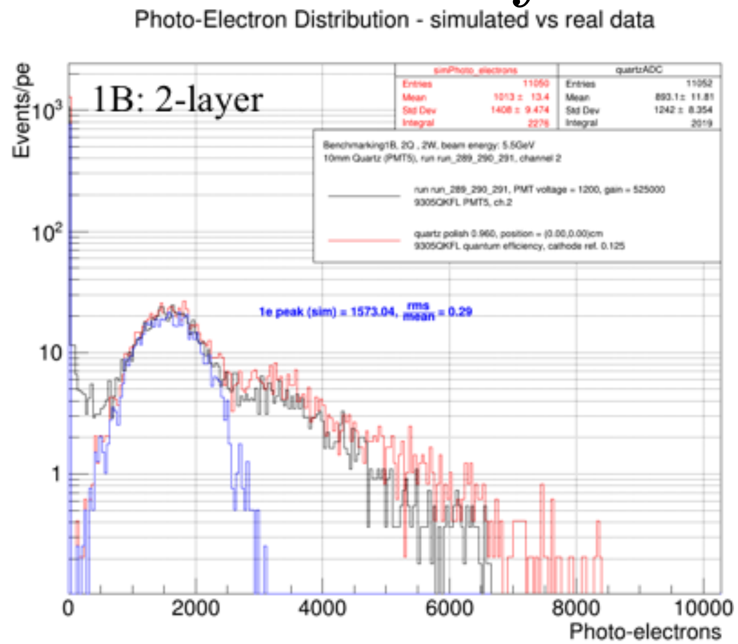



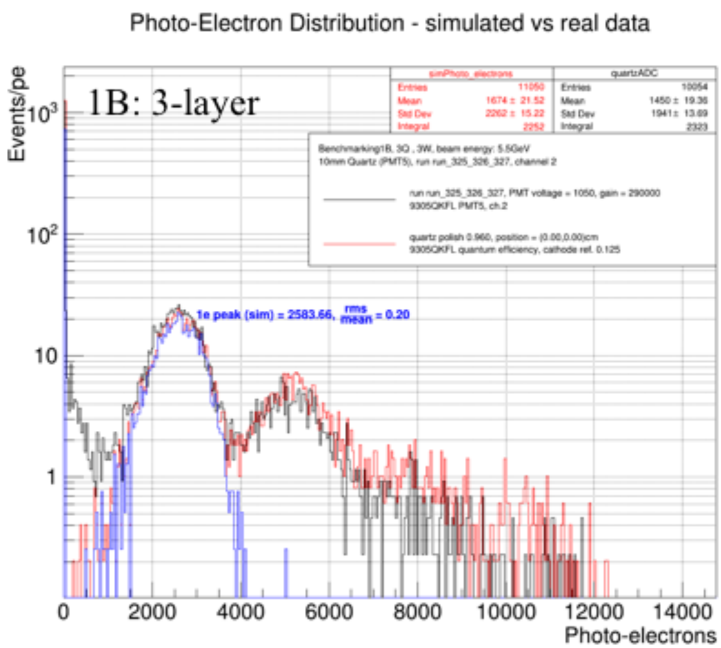
# 1A Benchmarking Results for stack-layer study

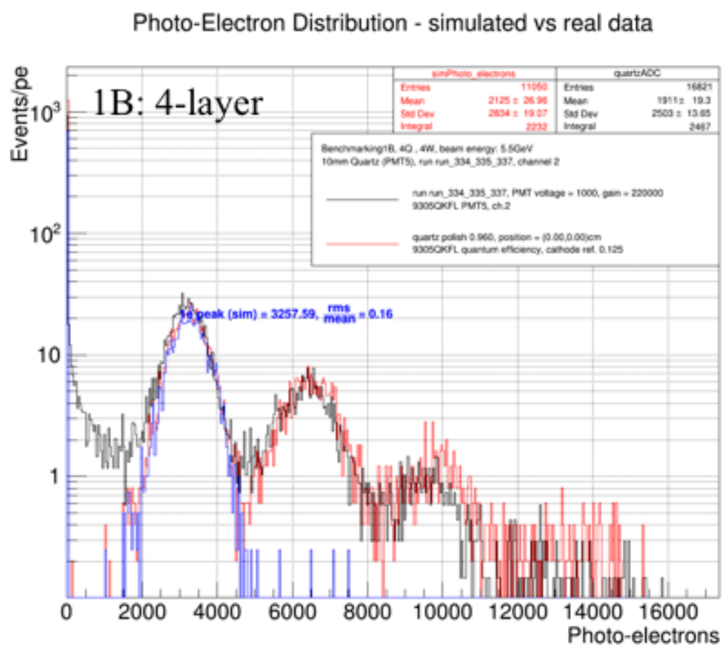


# 1B Benchmarking Results for stack-layer study

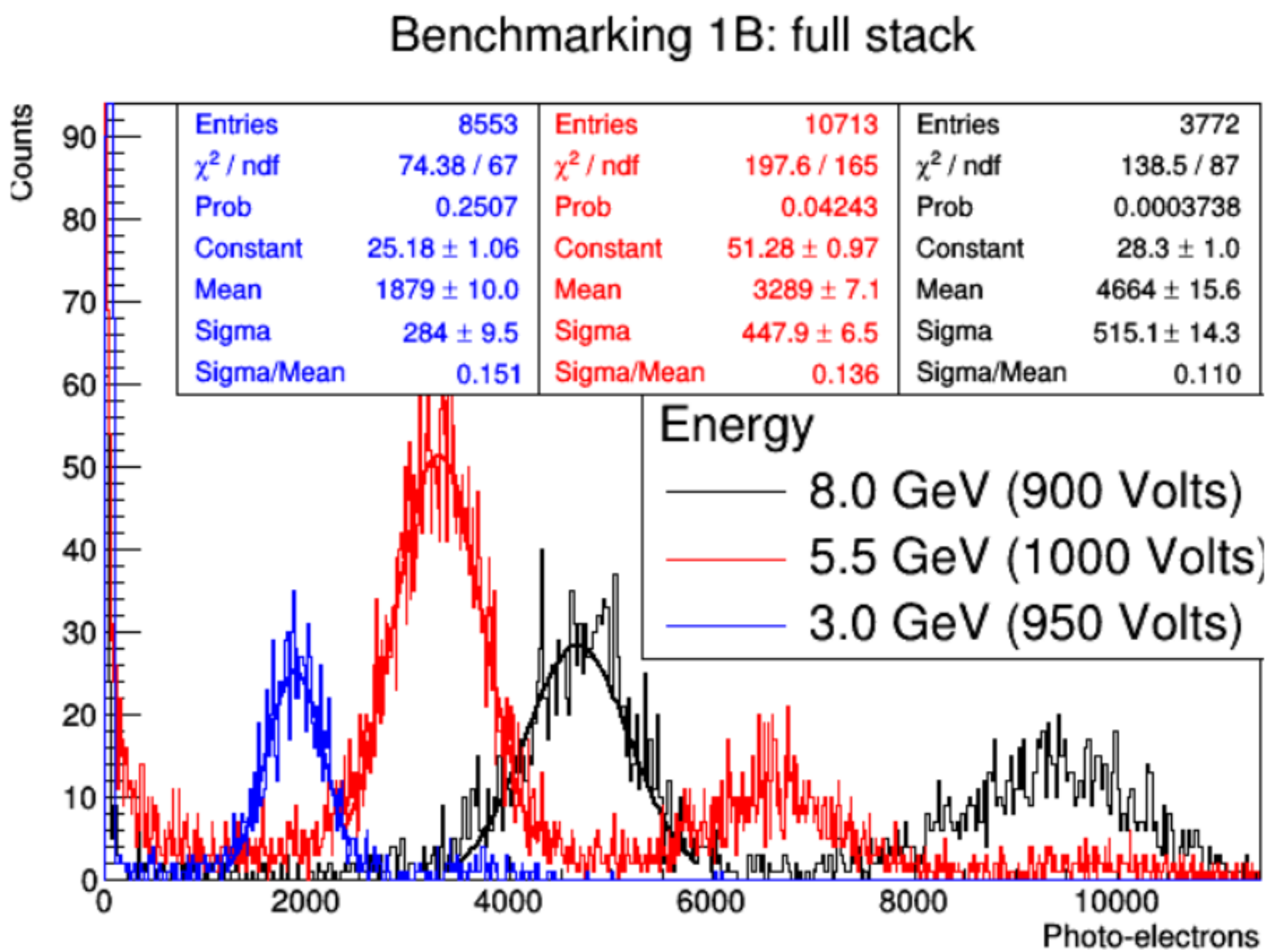


# ShowerMax Benchmarking Prototype Testbeam Results (1B full stack response vs energy)



# Full Scale 1A and 1B PE response Simulations

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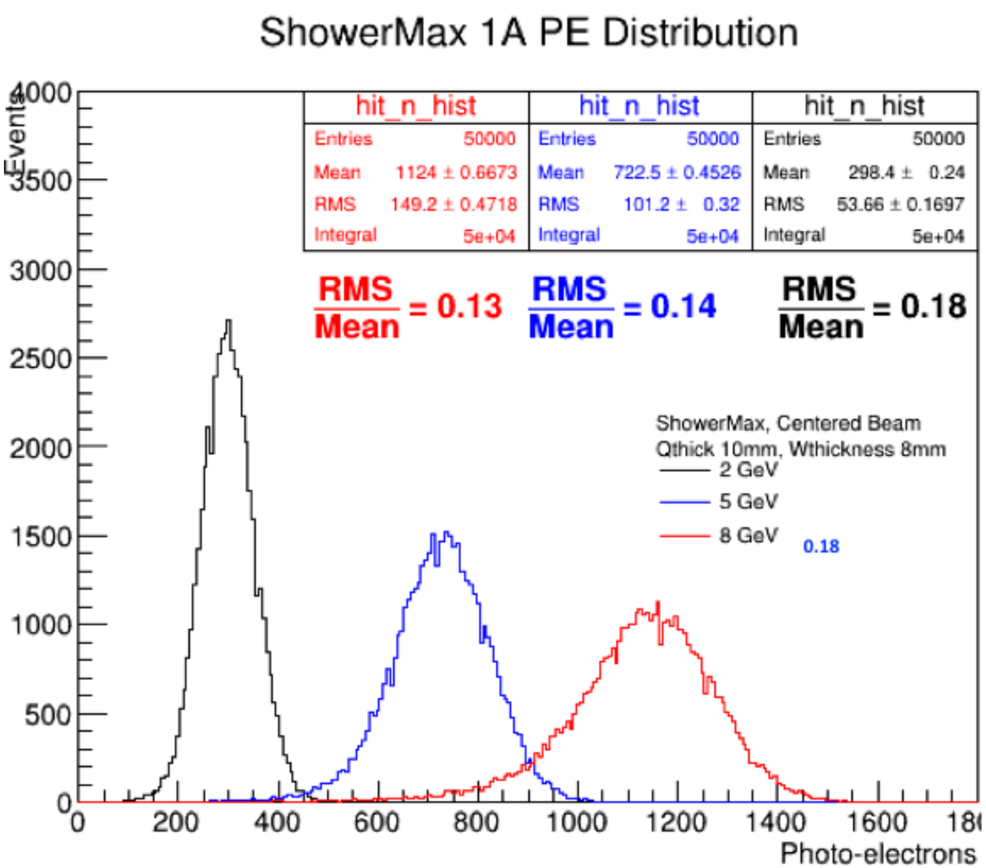
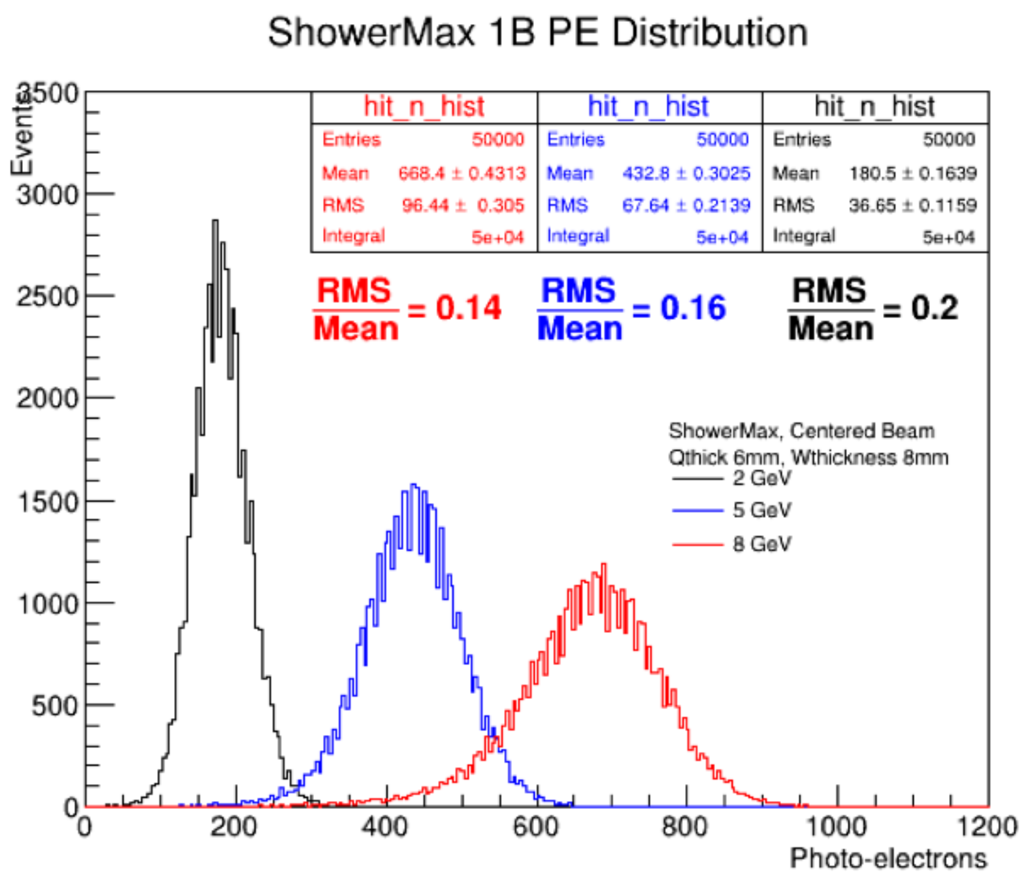
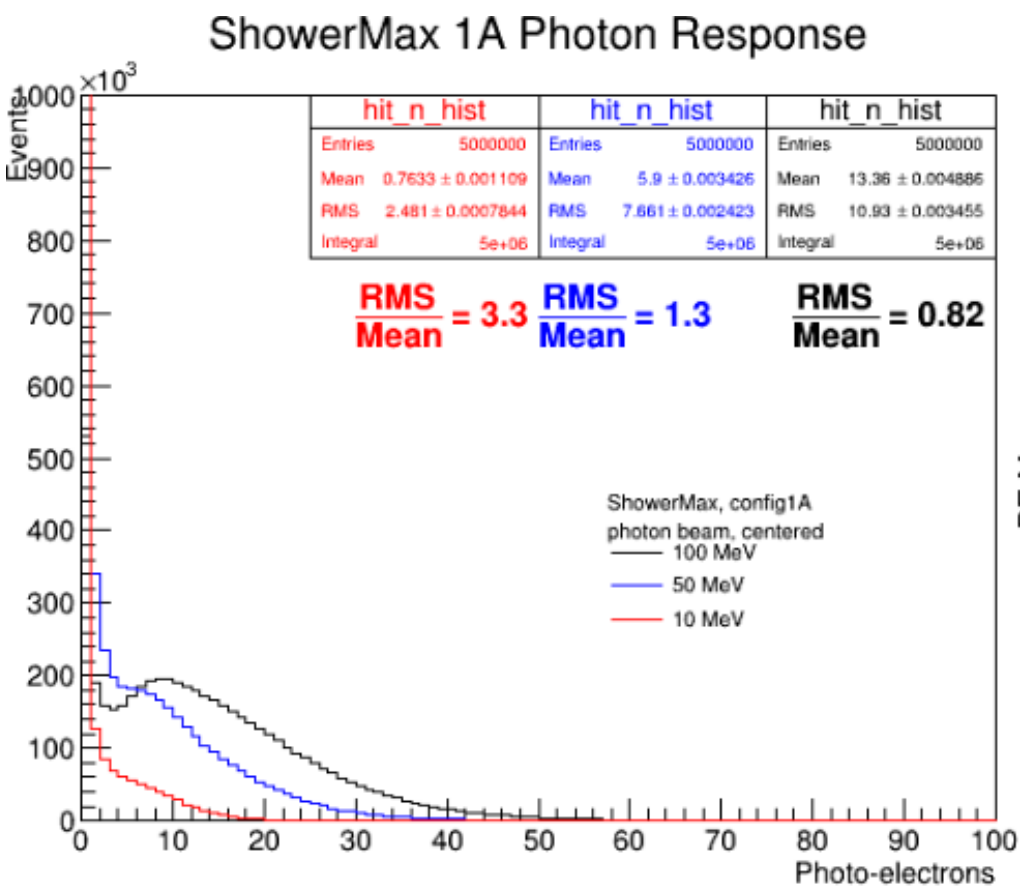
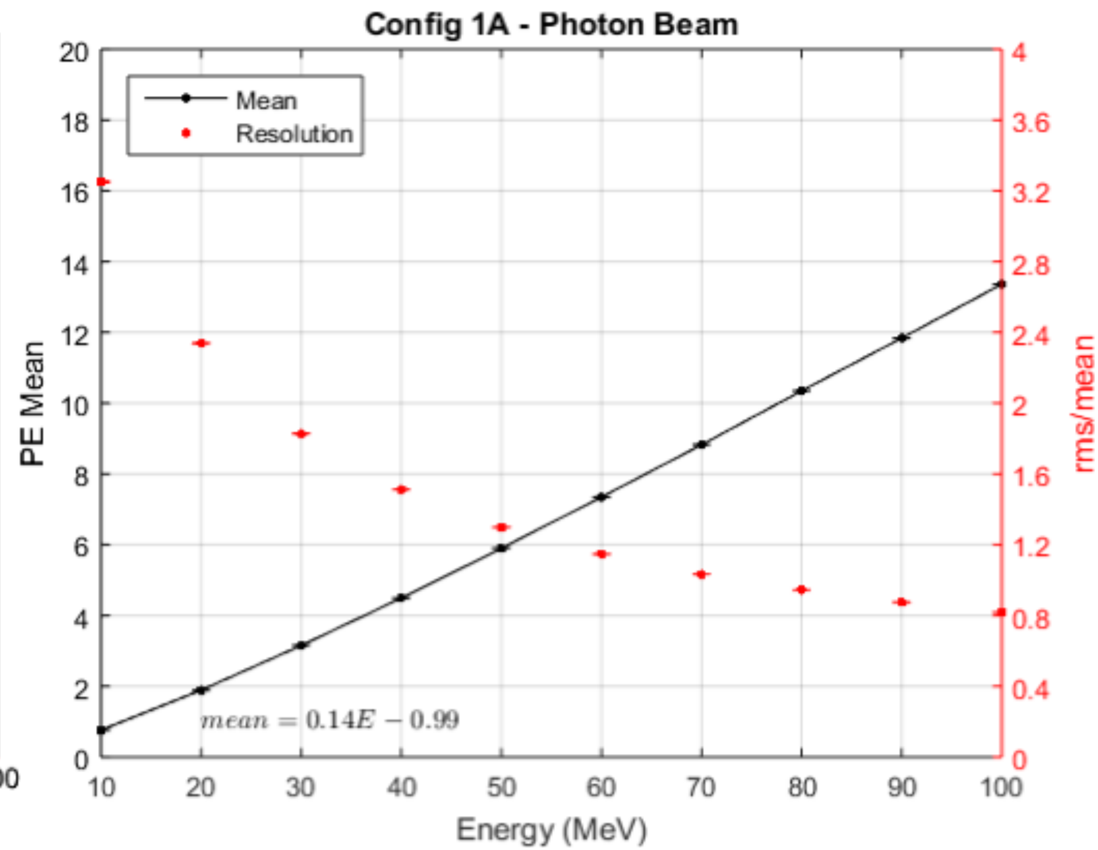


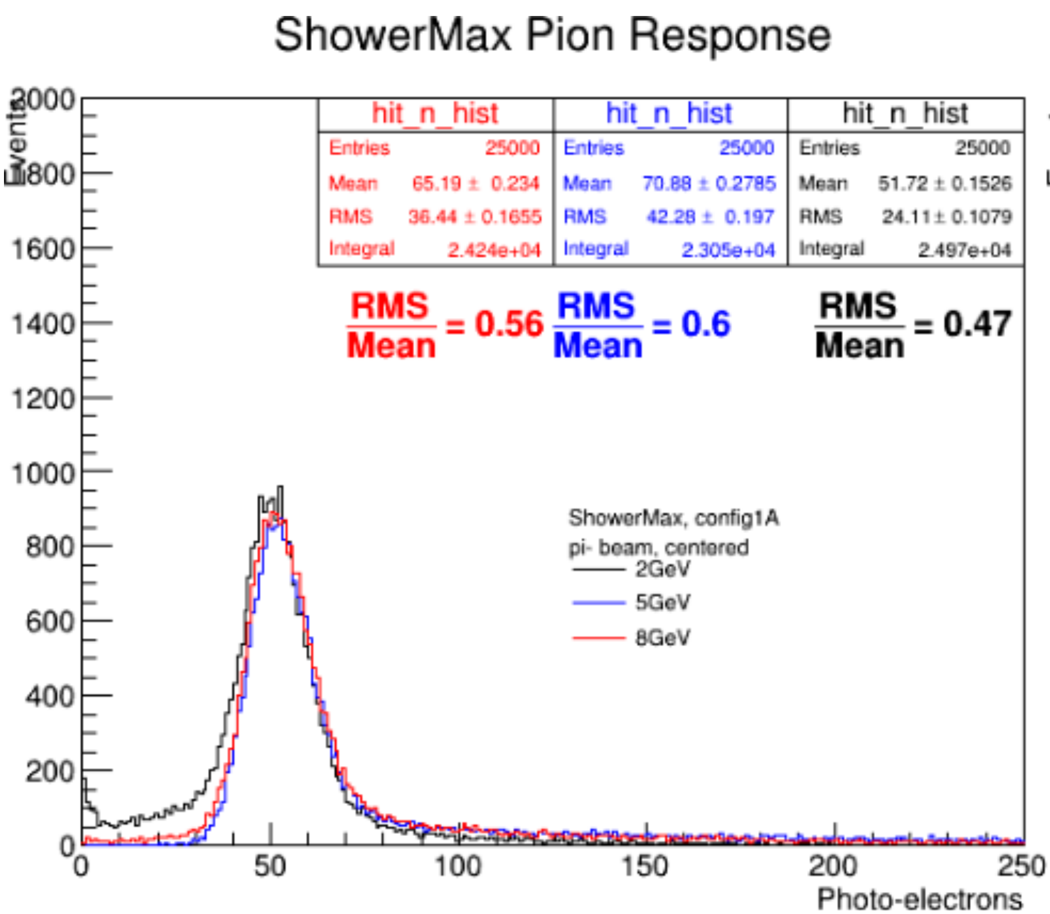



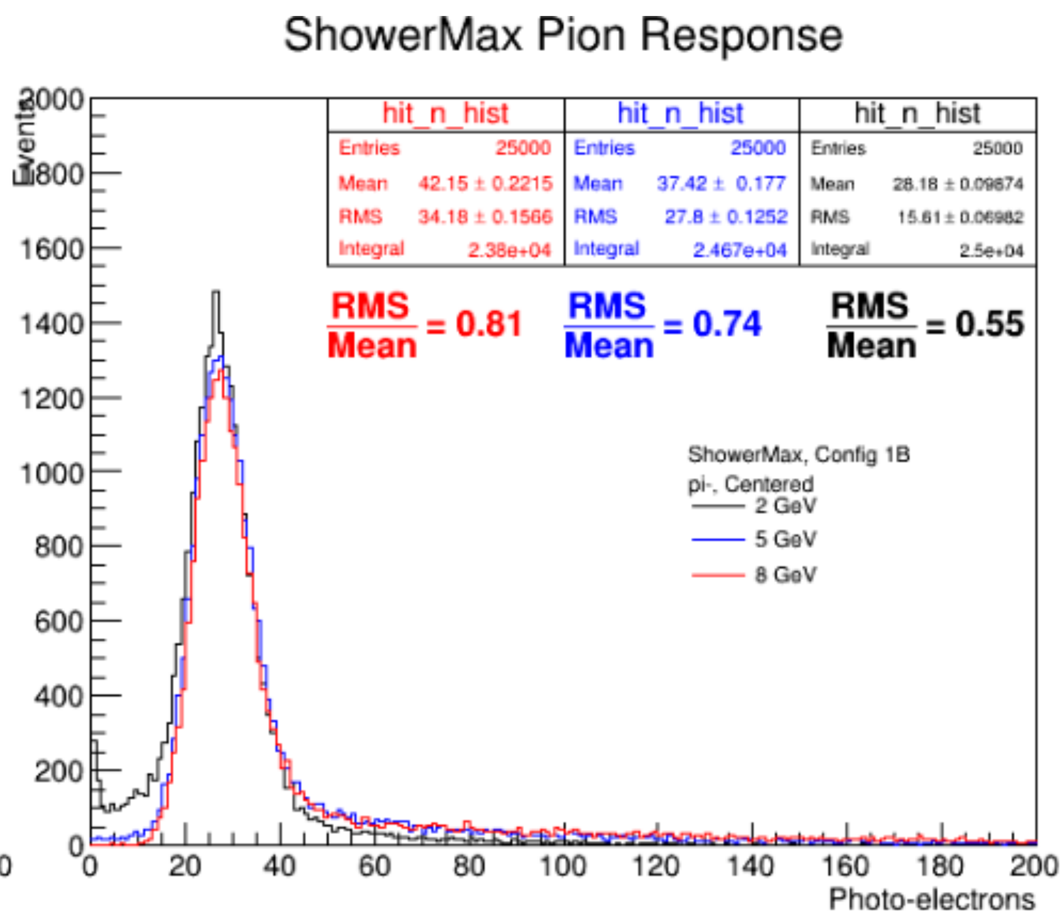
# Simulated Yields from Photons (1A Full-scale)



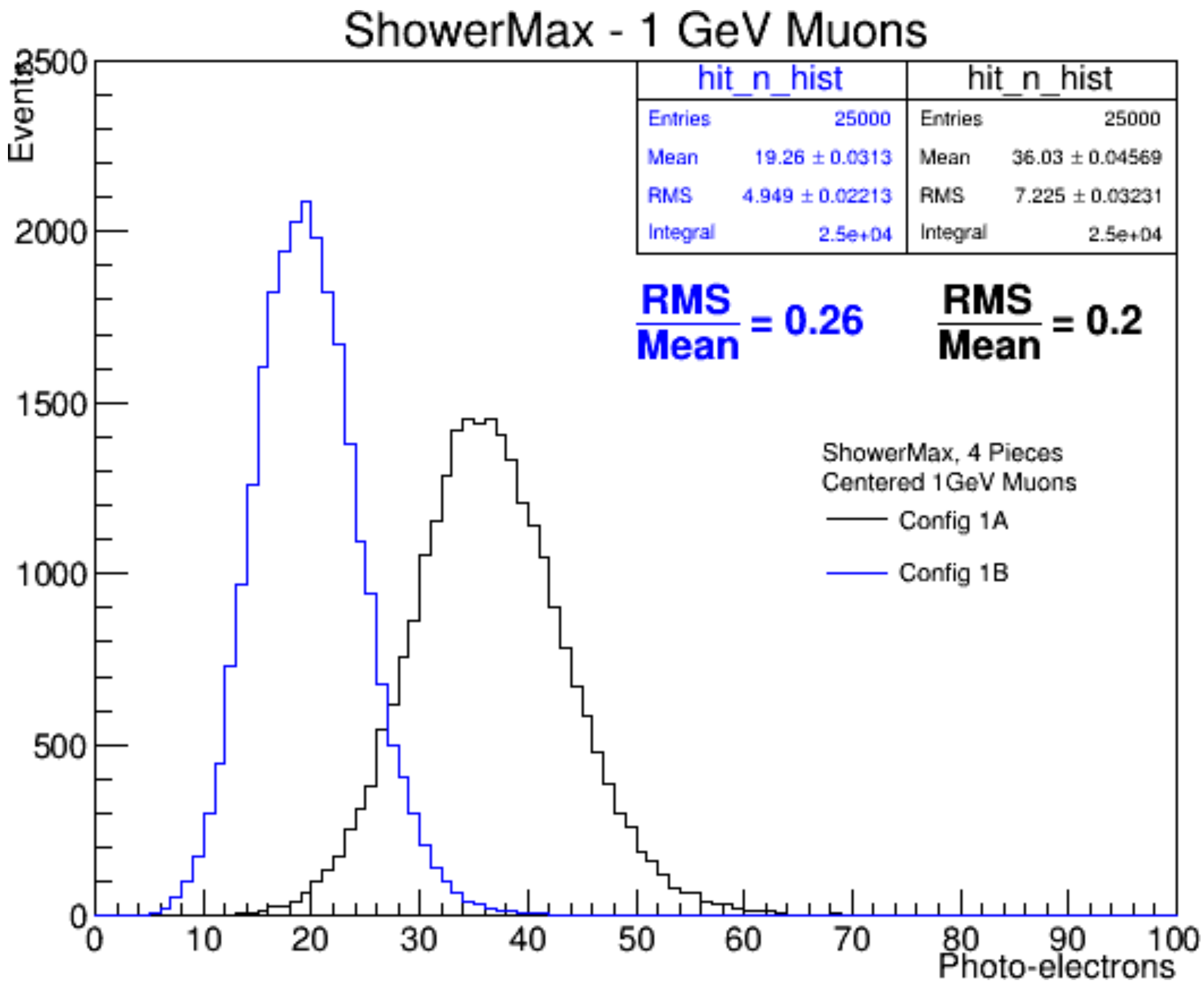



# Simulated Yields from Pions (1A & 1B Full-scale)



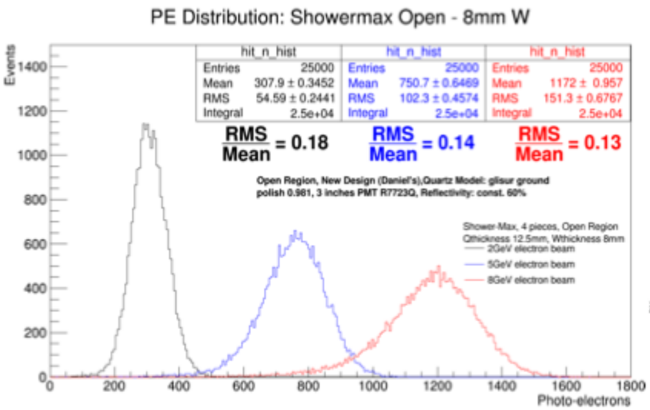



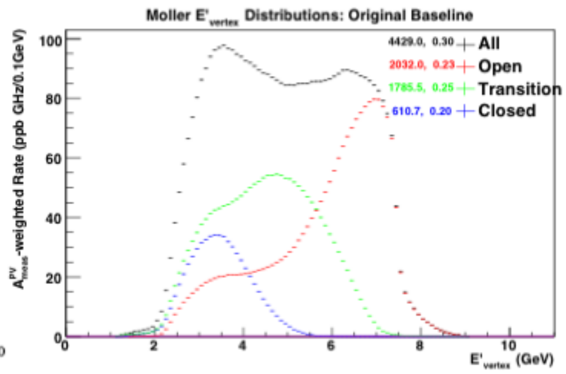
# Simulated MIP signal for cosmic-ray tests (Full-scale)

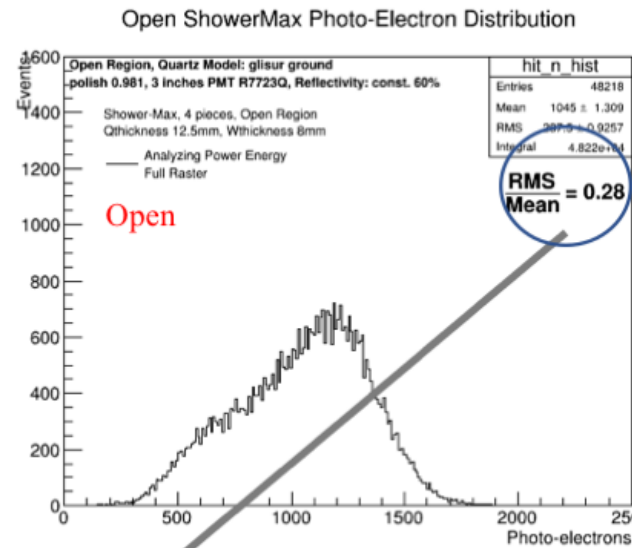


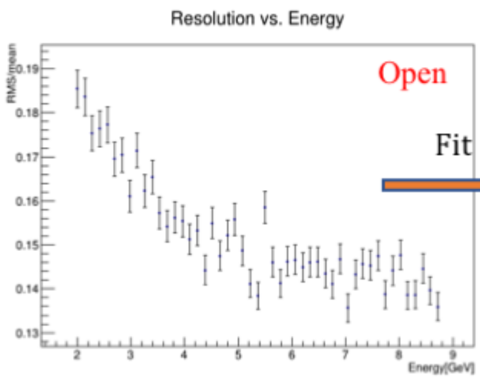
# What is Resolution of Showermax (Open Septant)

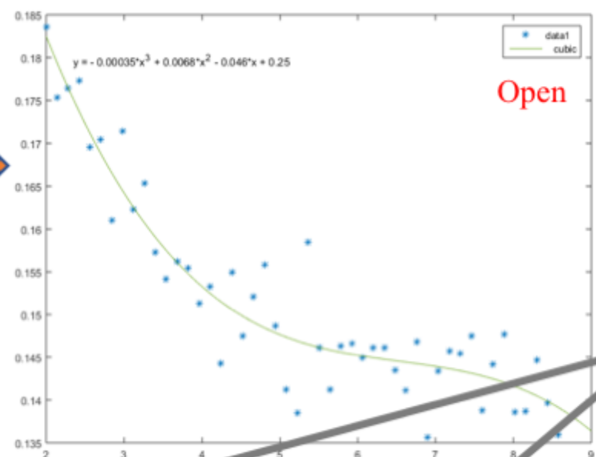
How well does the Showermax count electrons?

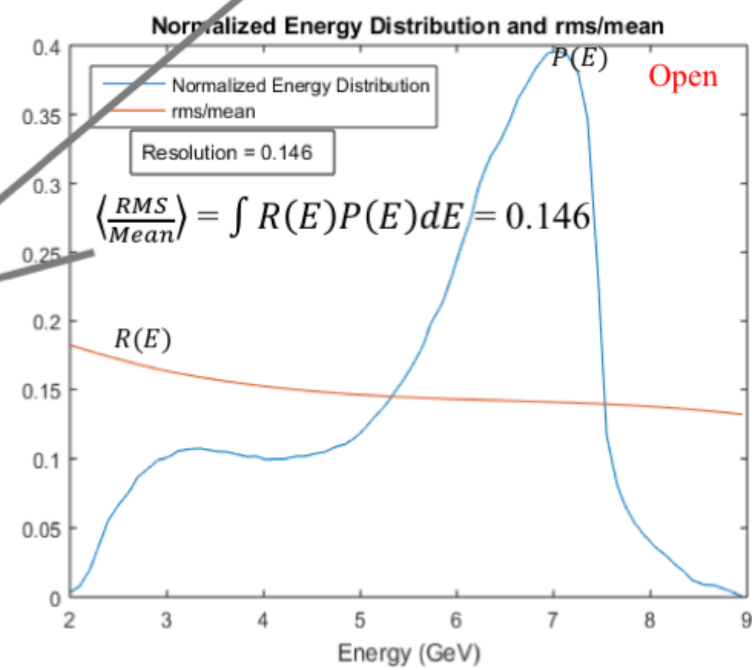



Individually, it counts electrons with 14.6% resolution on average. Using this leads to:

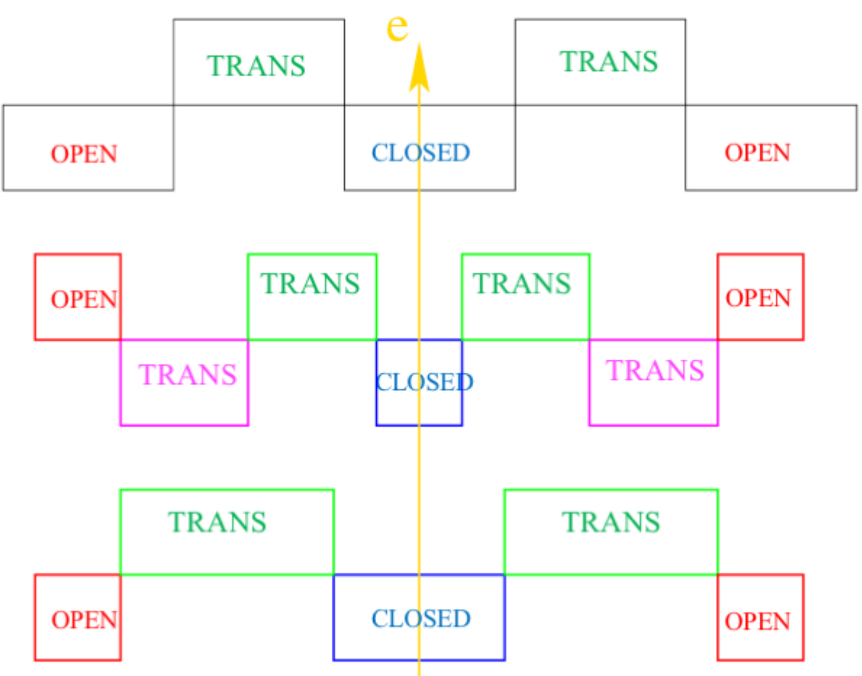
- ❖ Excess Noise = $\sqrt{1 + \langle \frac{RMS}{Mean} \rangle^2} - 1 = 1.1\%$

However collectively, it counts the group with ~30% resolution overall, which leads to:

- ❖ Excess Noise = $\sqrt{1 + \left(\frac{RMS}{Mean}\right)^2} - 1 = 4.4\%$

# Attempts to improve Showermax resolution

Exploring Different phi Segmentation for Shower-max



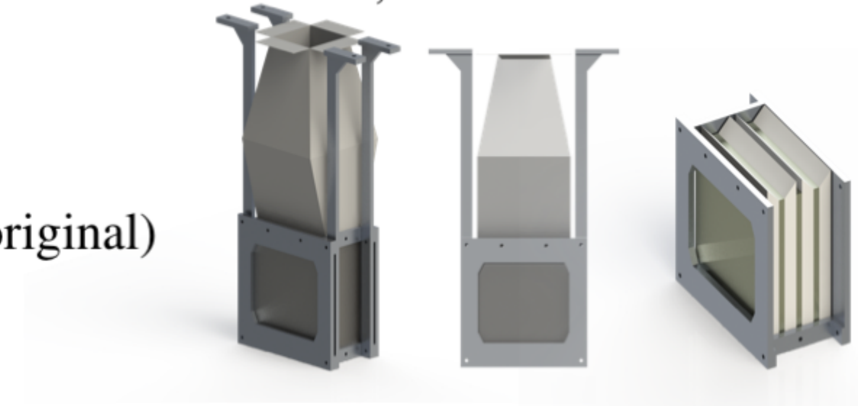

← Baseline (original)

← HalfOpen/HalfClosed

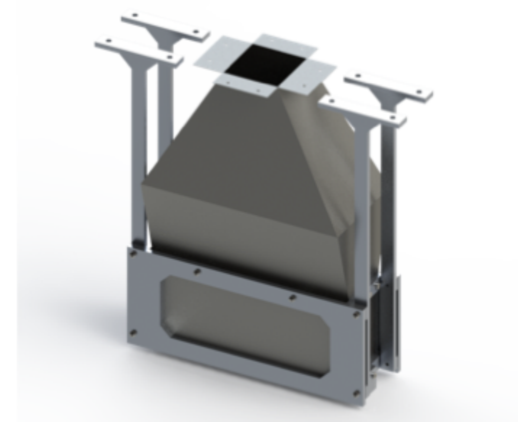
← HalfOpen/FullClosed

Radial view of various phi segmentation ideas

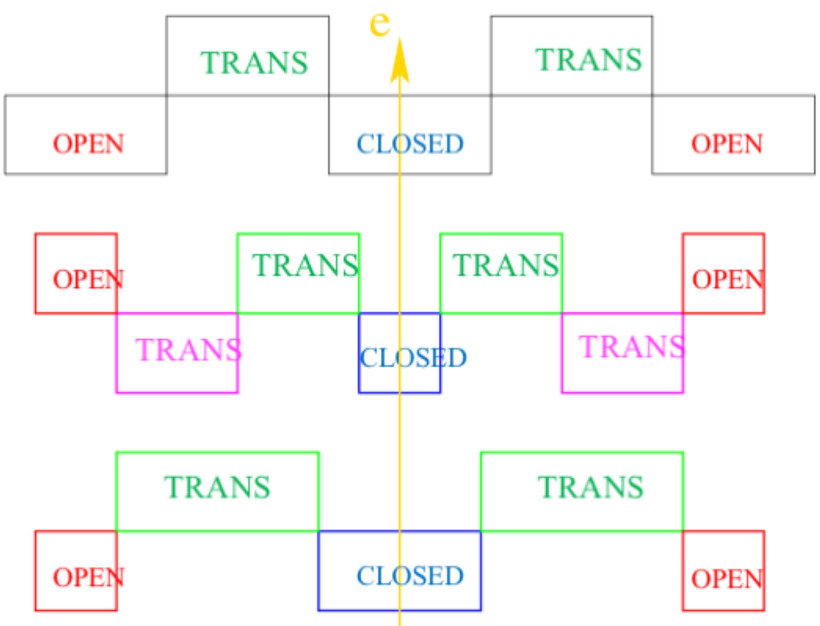
Half-width, "full-stack" Shower-max



Full-width, "full-stack" Shower-max



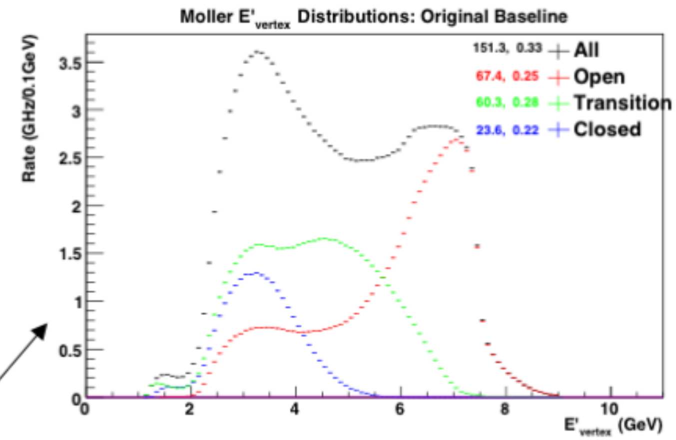
# Energy Acceptance for Different phi Segmentation

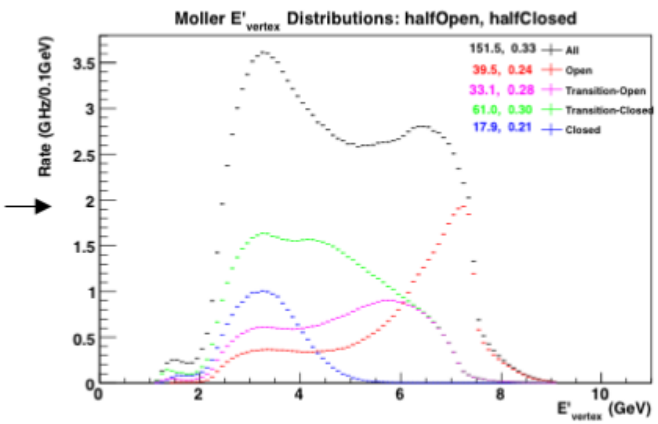


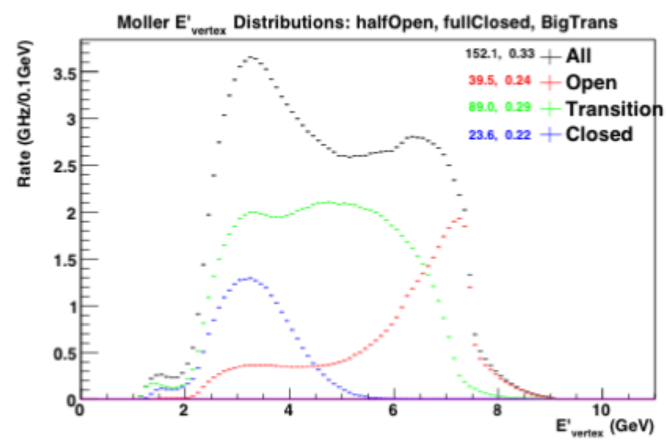

← Baseline (original)

← HalfOpen/HalfClosed →

← HalfOpen/FullClosed



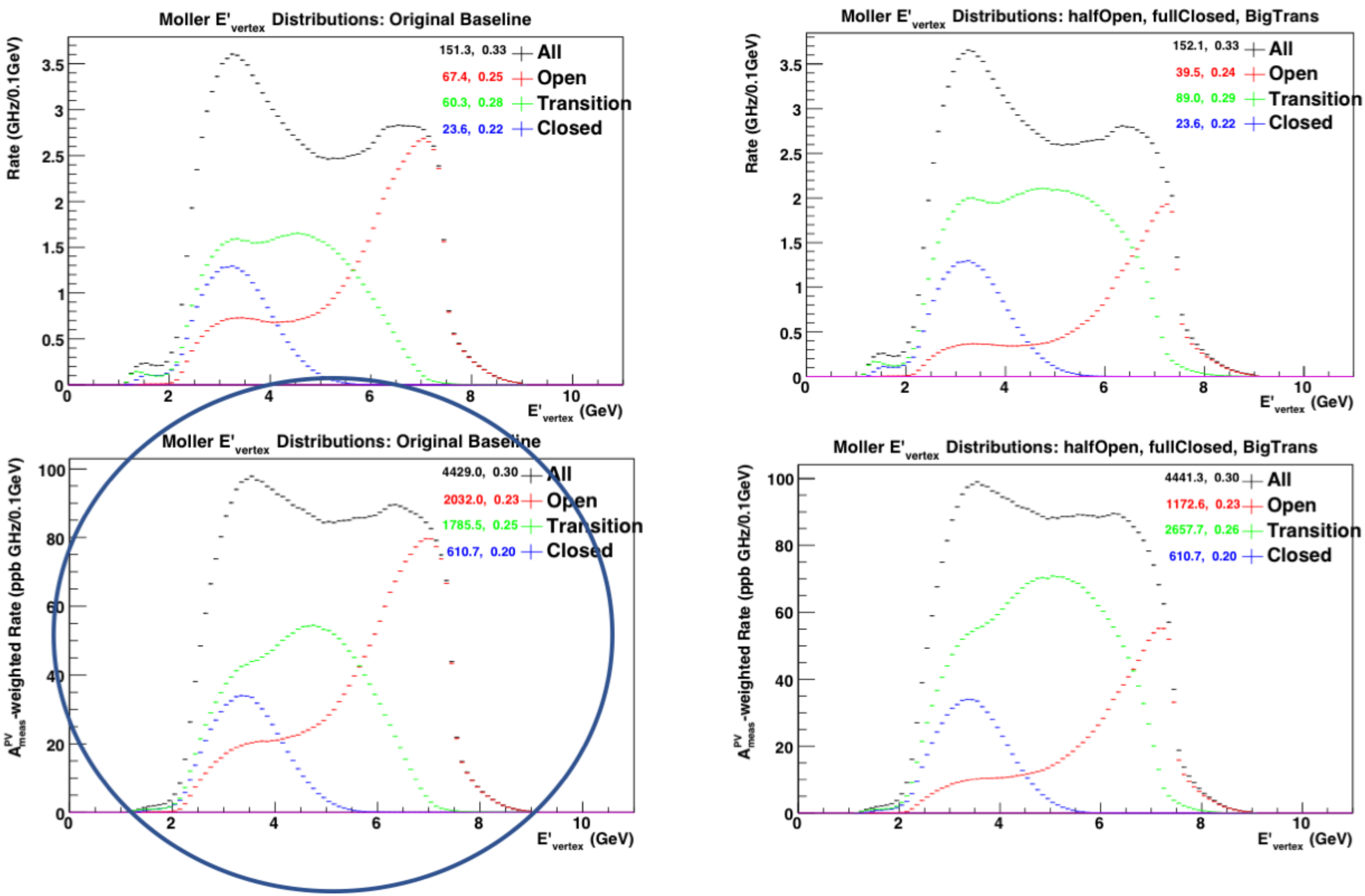




Radial view of various phi segmentation ideas

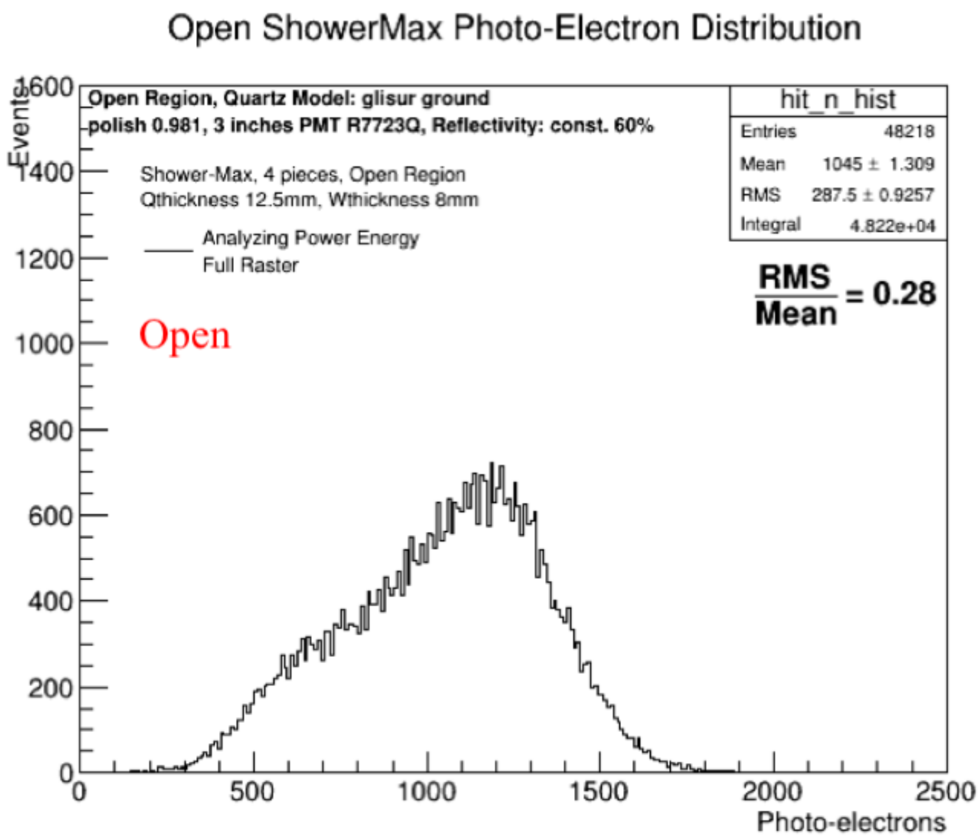
- These ideas give no improvement due to the spectrometer's significant phi defocusing…The original segmentation is best

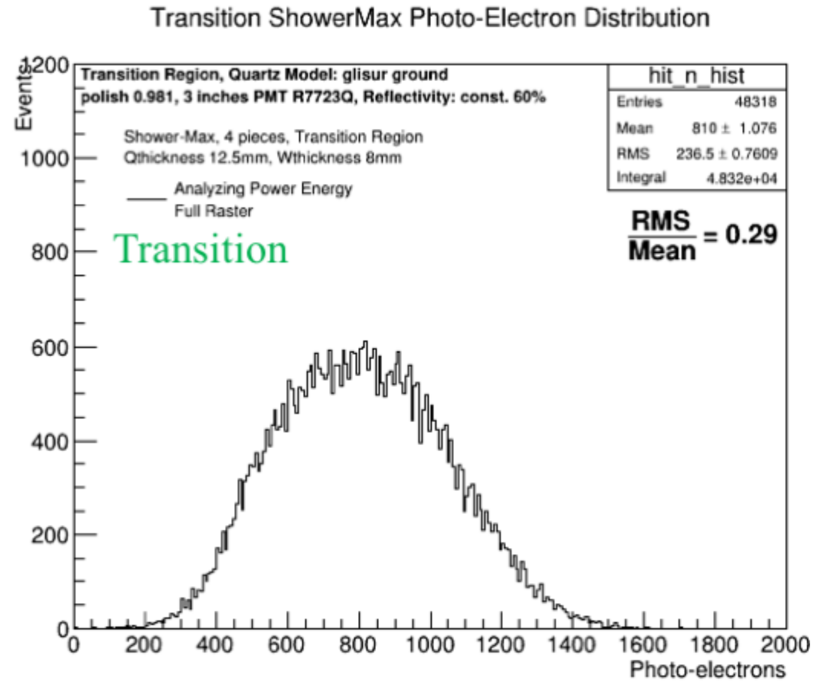
# Rate and $A^{PV}_{meas}$*Rate – weighted Energy Acceptance

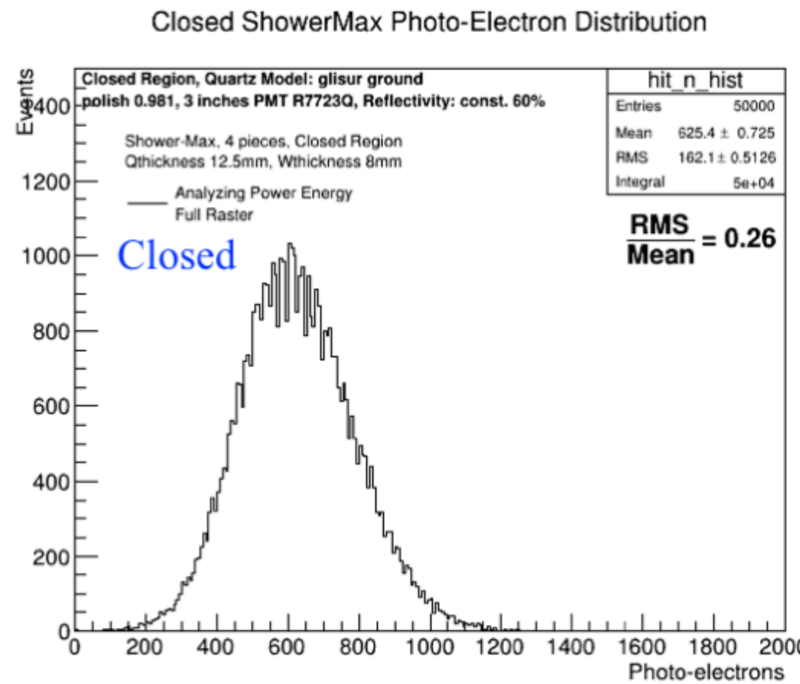
Original Baseline | half Open/ Full Closed



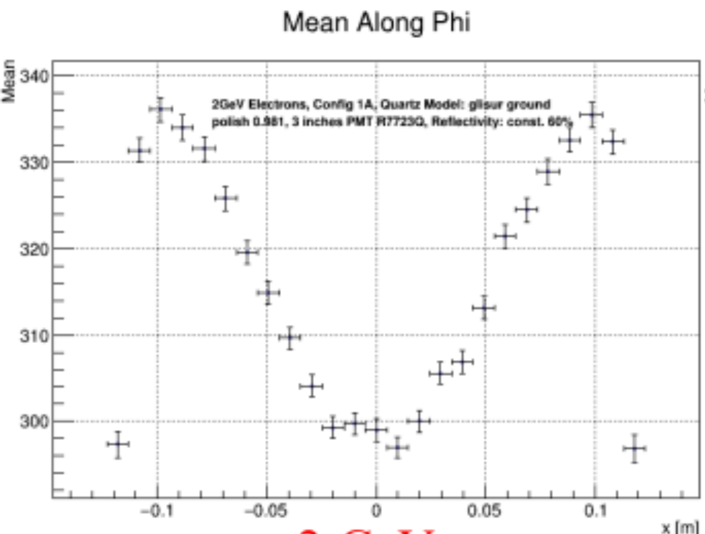
# Baseline PE distributions weighted by $A^{meas}_{PV}$

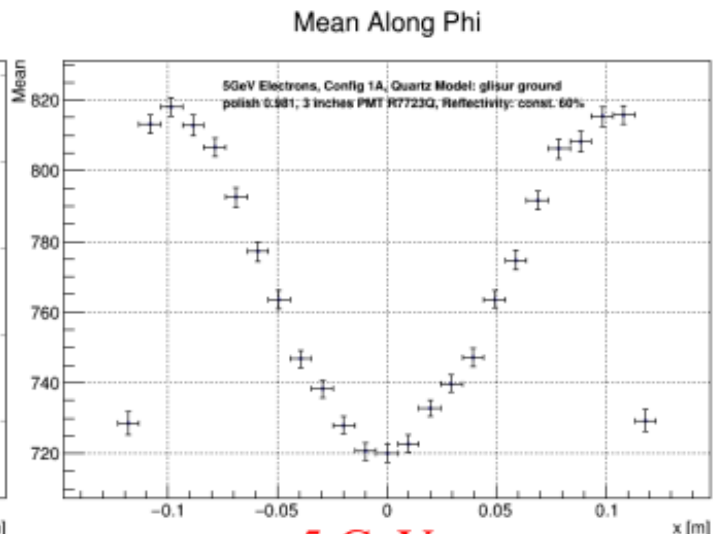


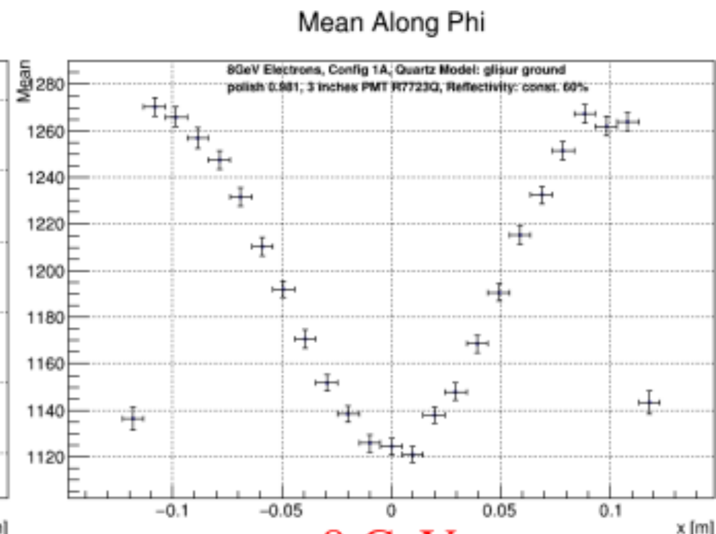



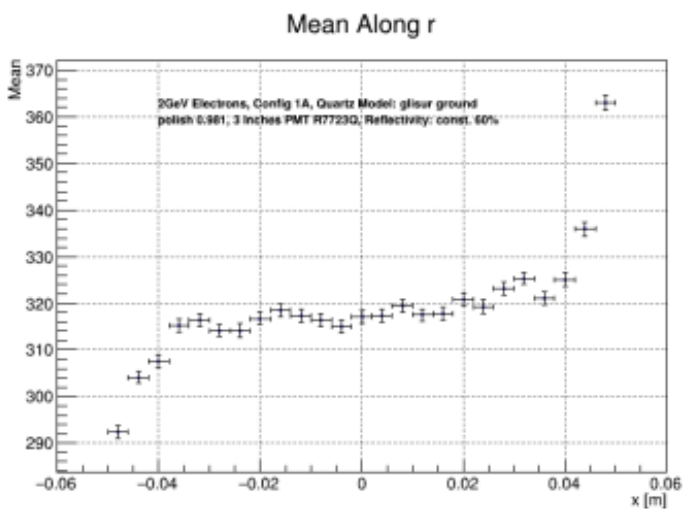
# Uniformity Studies: 1A PE means along $\phi$ and $r$

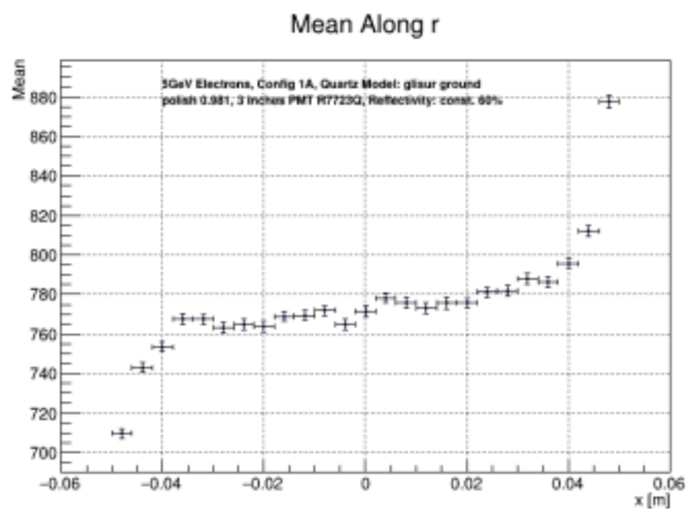


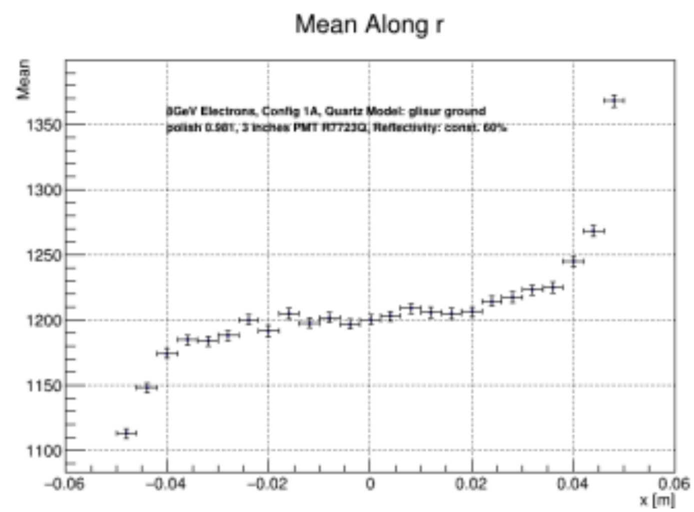



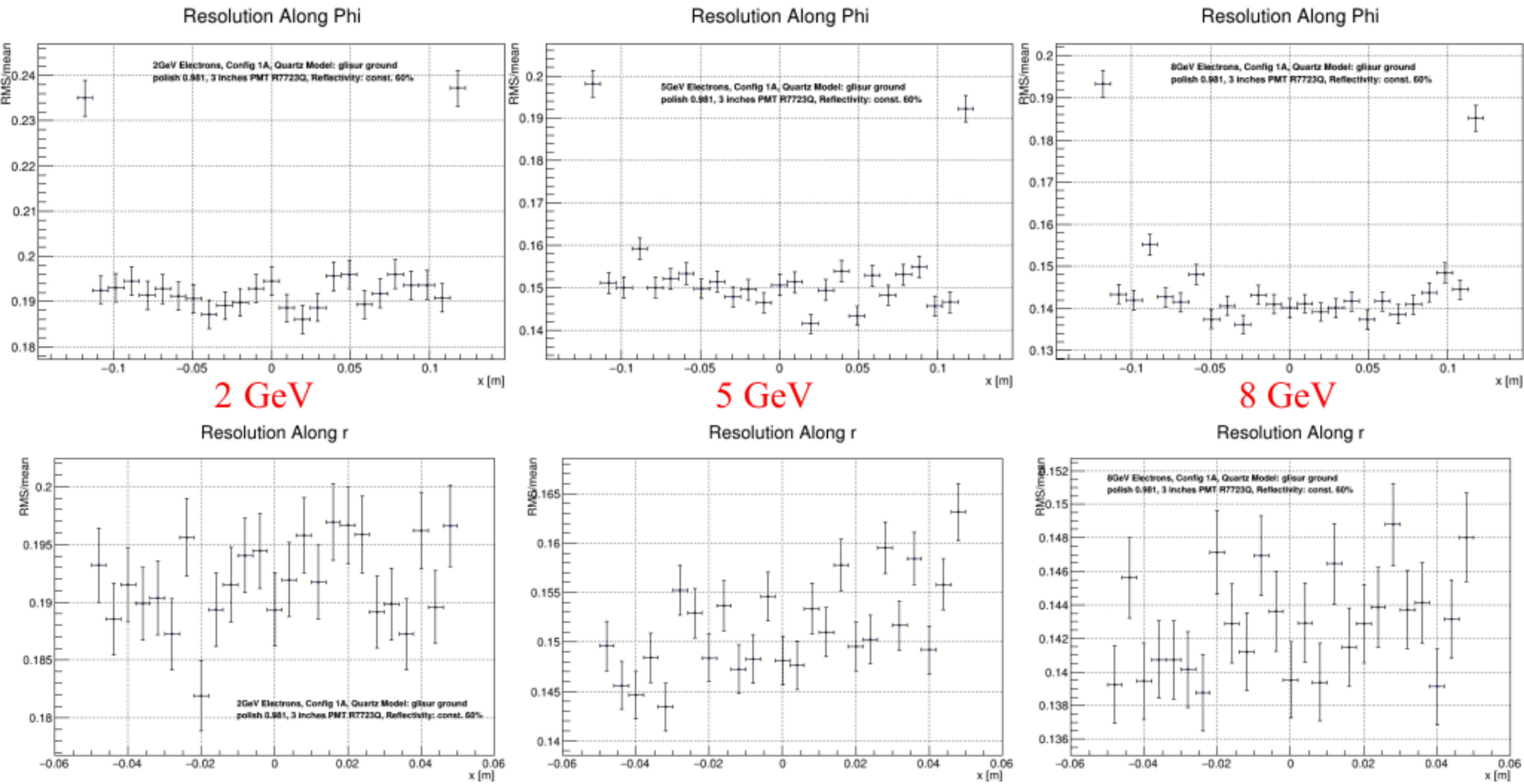

2 GeV 5 GeV 8 GeV



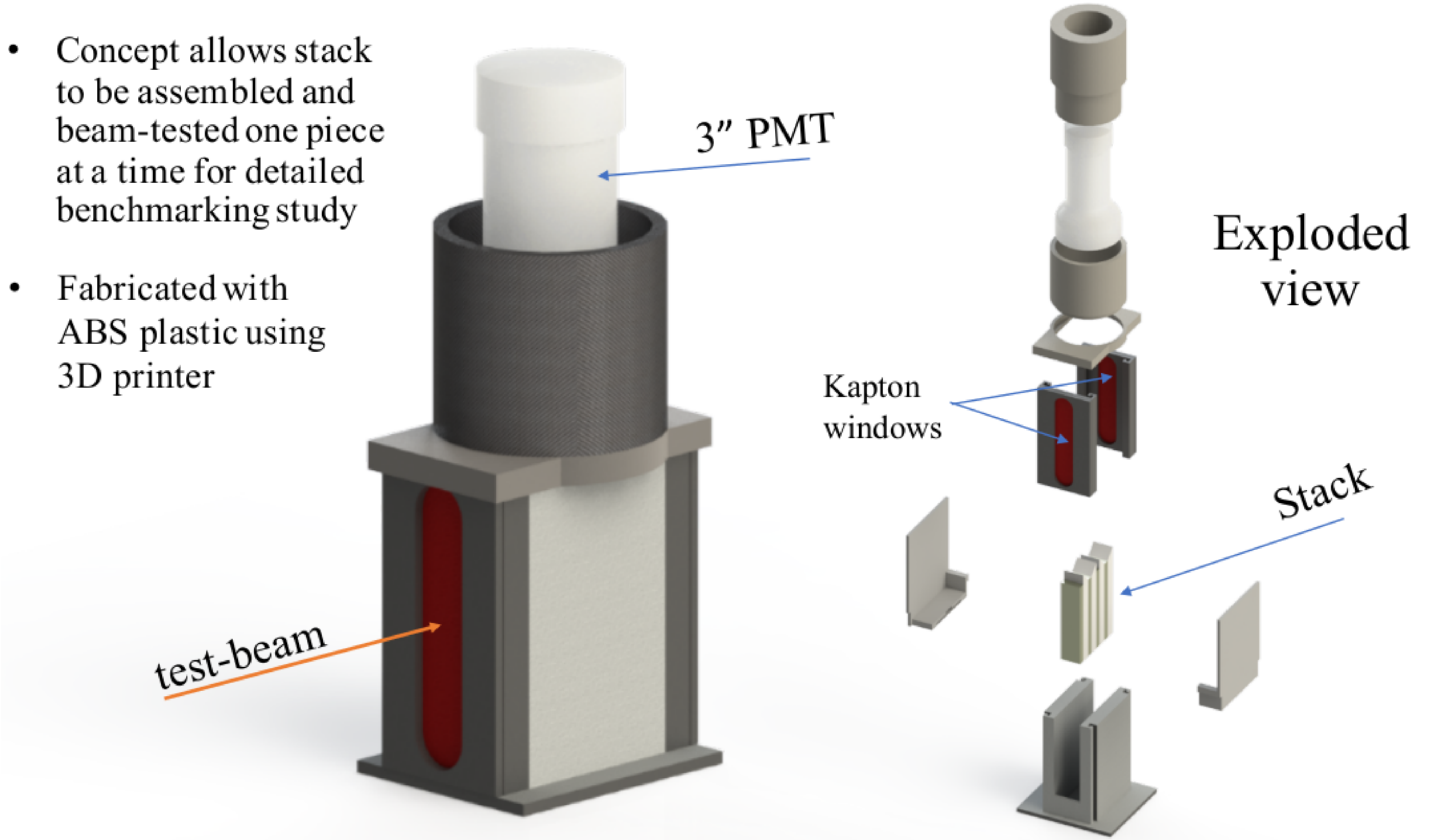
# Uniformity Studies: 1A Resolutions along $\phi$ and $r$



# Prototype Designs for Testbeam

# 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




**Config #1** (original baseline) benchmarking Prototype

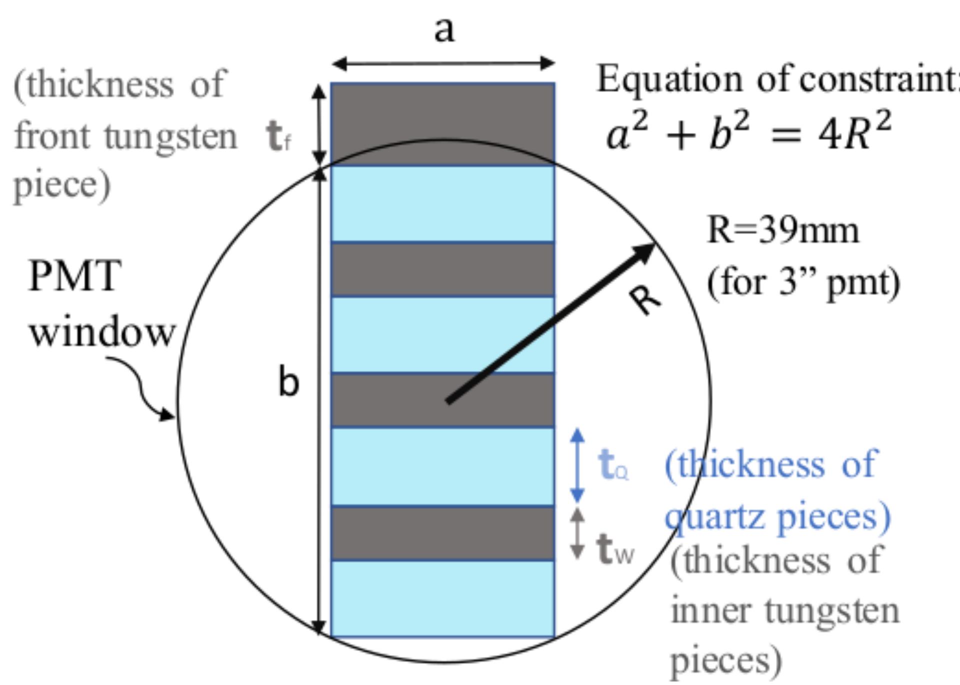
# Benchmarking Stack Configurations

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.



# Lateral size of EM Shower: Moliere Radius

- Lateral or transverse EM shower development and size dominated by multiple scattering
- One Moliere radius contains 90% of shower and characterizes width of shower; two Moliere radii contain ~95%
- For single material calorimeter:

Moliere Radius: $R_M = \frac{E_s}{E_c} X_0 \simeq 7\frac{A}{Z}\ (\frac{\text{g}}{\text{cm2}})$

--where $E_s = \sqrt{\frac{4\pi}{\alpha}}\, mc^2 = 21.2$ MeV (Multiple Scattering Energy for electrons)

> $E_c \sim 610/(Z+1.2)$ MeV (Critical Energy)

- For a mixed, homogenous material calorimeter:

Moliere Radius$^{-1}$: $\frac{1}{R_M} = \sum_i \frac{w_i}{R_{Mi}} = \frac{1}{E_s}\sum_i \frac{E_{ci}}{X_{0i}}$

–where $w_i$ is the weight fraction of the ith material in the stack

| Material | $\rho \cdot R_M$ (g/cm$^2$) | $R_M$ (cm) | $X_0$ (g/cm) | $X_0/\rho$ (cm) | $Z$ | $E_c(e)$ (MeV) |
|---|---|---|---|---|---|---|
| tungsten | 18.00 | 0.933 | 6.76 | 0.35 | 74 | 8.0 |
| Copper | 14.05 | 1.57 | 12.9 | 1.44 | 29 | 20 |
| $SiO_2$ | 11.3 | 5.15 | 27.05 | 12.3 | ~11 | 57 |

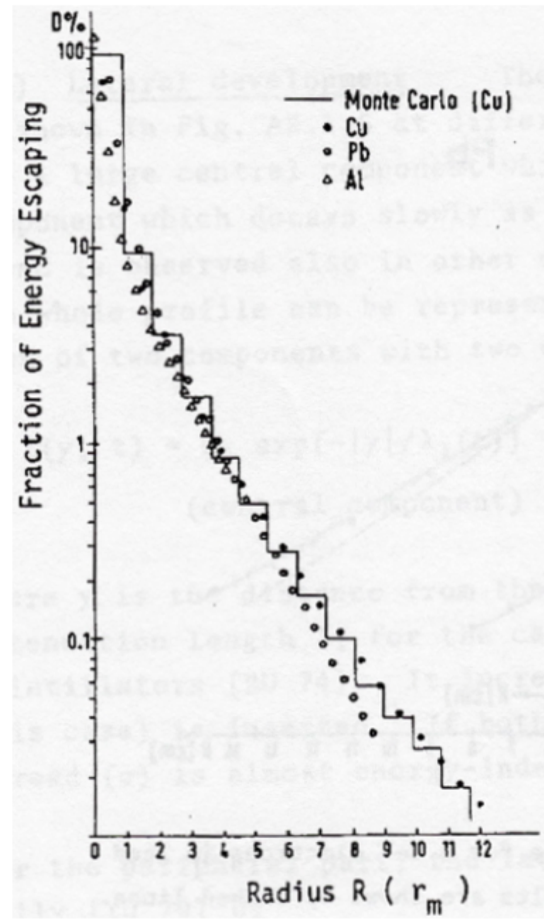
- For the baseline design:

$w_{tungsten} \simeq 0.812$
$w_{quartz} \simeq 0.188$
$R_M \simeq 1.10cm$

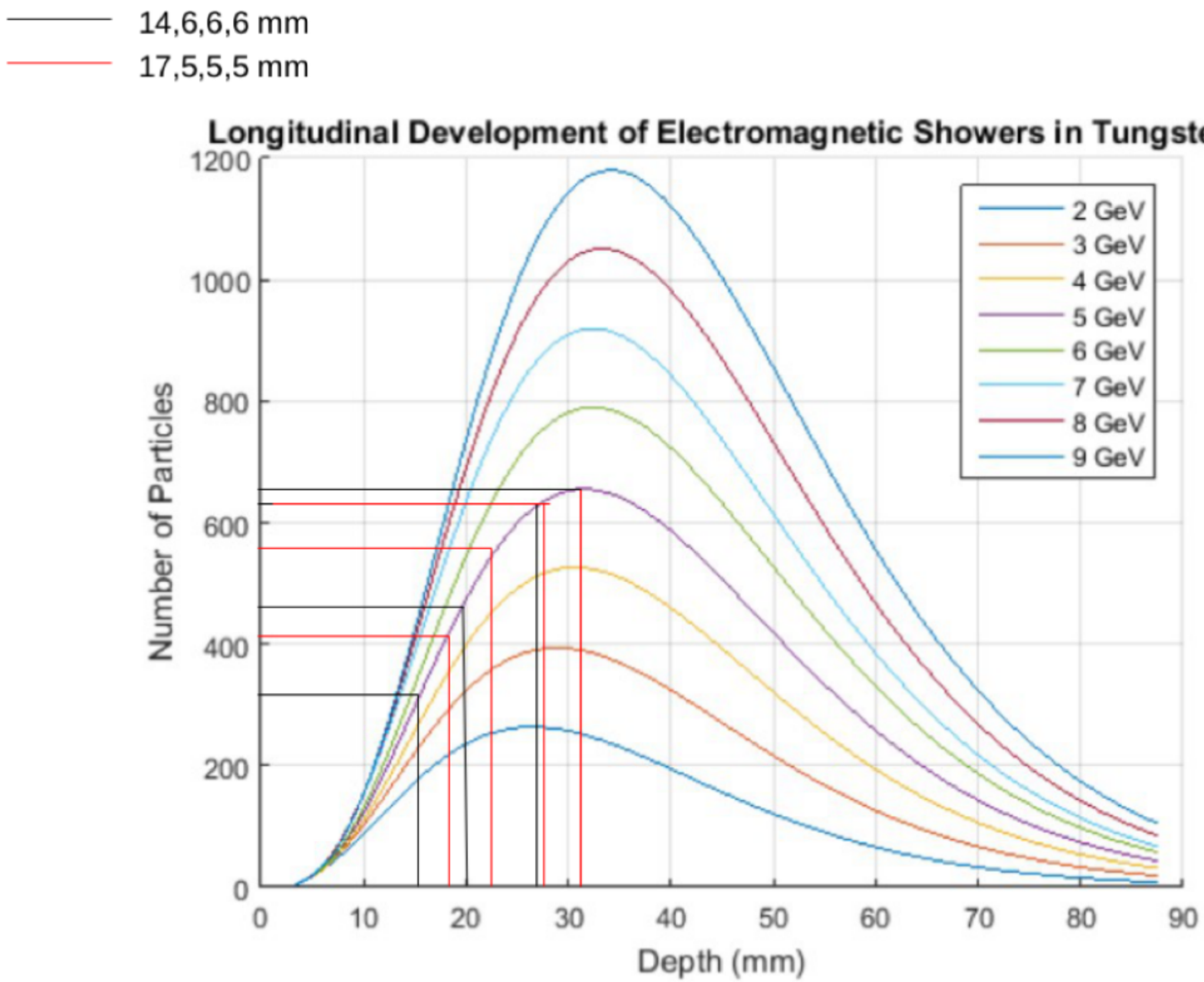
- If use 10/90 Cu/W:

$w_{tungsten} \simeq 0.724$
$w_{quartz} \simeq 0.196$
$w_{copper} \simeq 0.080$
$R_M \simeq 1.16cm$

- Also note for tungsten, at shower max: $\langle\theta_{SM}\rangle \simeq m_e/E_c \simeq 3.6^o$



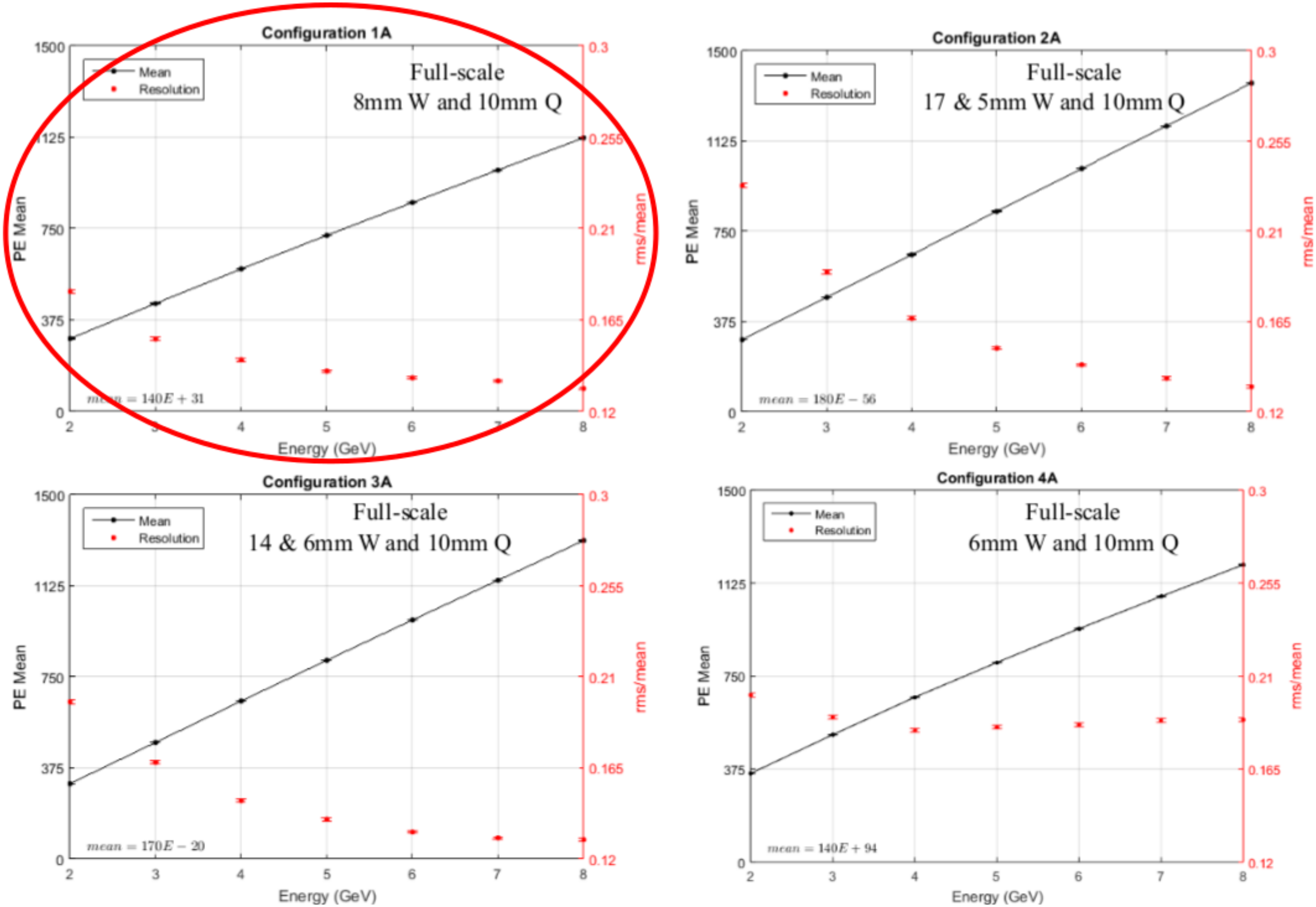
# Longitudinal Development of EM Shower




- Red and black lines indicate points of quartz sampling for Config #2 and #3 (see next slide)
- The shower maximum depth scales logarithmically with particle energy, while the peak # of particles scales linearly
- For pure tungsten, shower max occurs at ~24mm for 2 GeV and ~33mm for 8 GeV

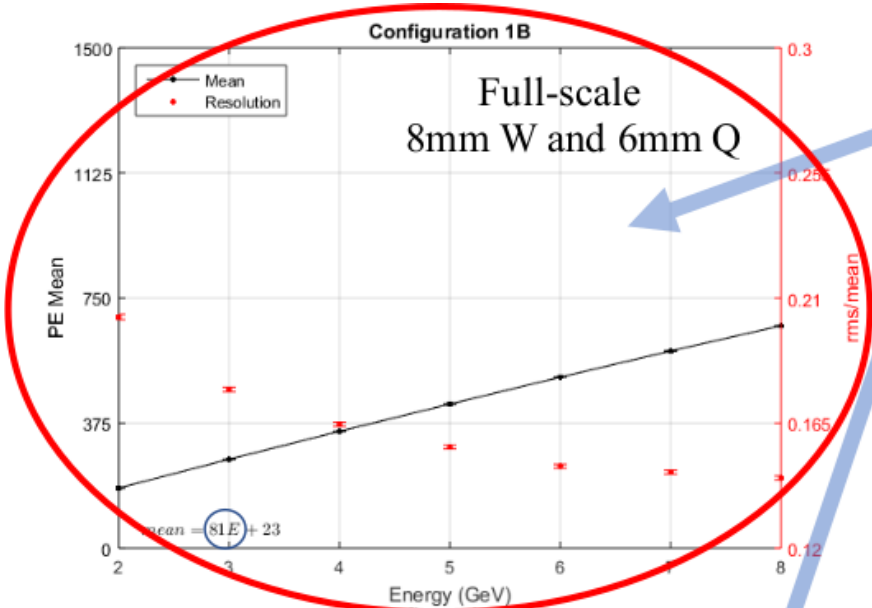
  --Baseline design uses 32mm of tungsten (and 50 mm of quartz)

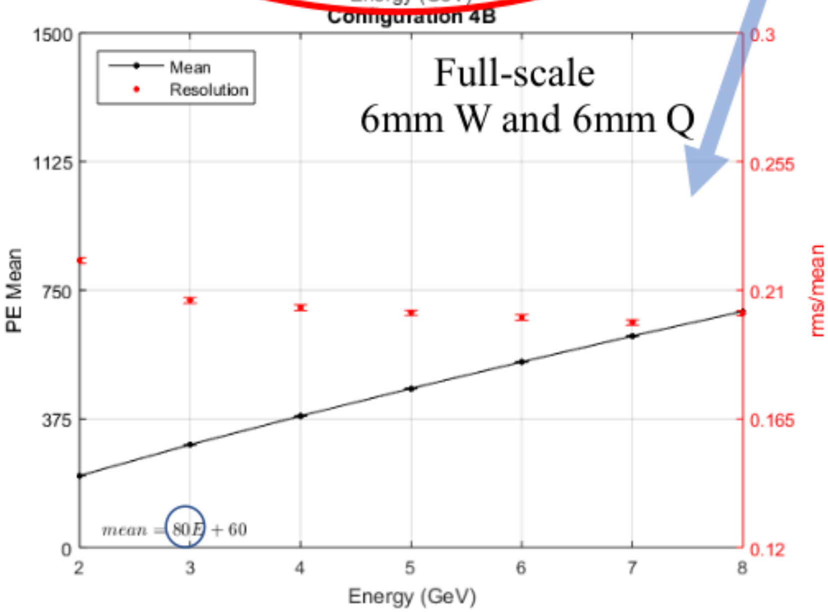
# 1A - 4A Mean PE and Resolution versus Energy

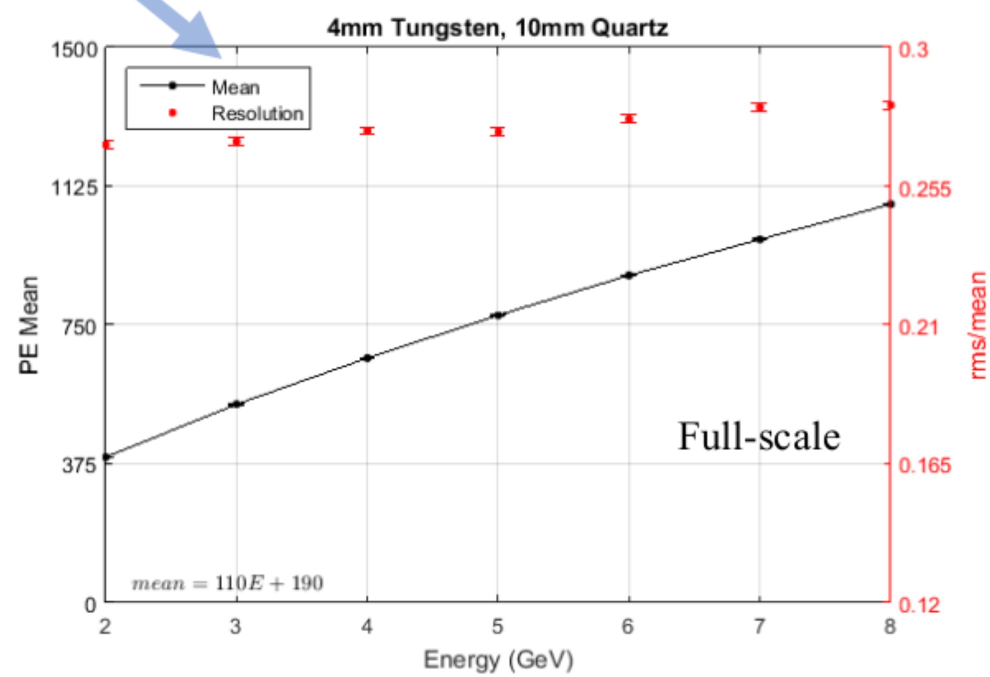


# Simulation results for B configs (6mm quartz)

- The B configs have ~half the slope of the other configs – 80 PEs/GeV – while maintaining good resolution and with lower light levels.
- The reduced slope means less variation in PE yields with energy--which will reduce the widths measured during helicity window (it seems a potential win win win situation)
- Also interesting is that if you reduce the layers of tungsten to 4mm, the resolution worsens ~drastically (even with 10 mm quartz)



# Prototype Construction and SLAC Testbeam Run

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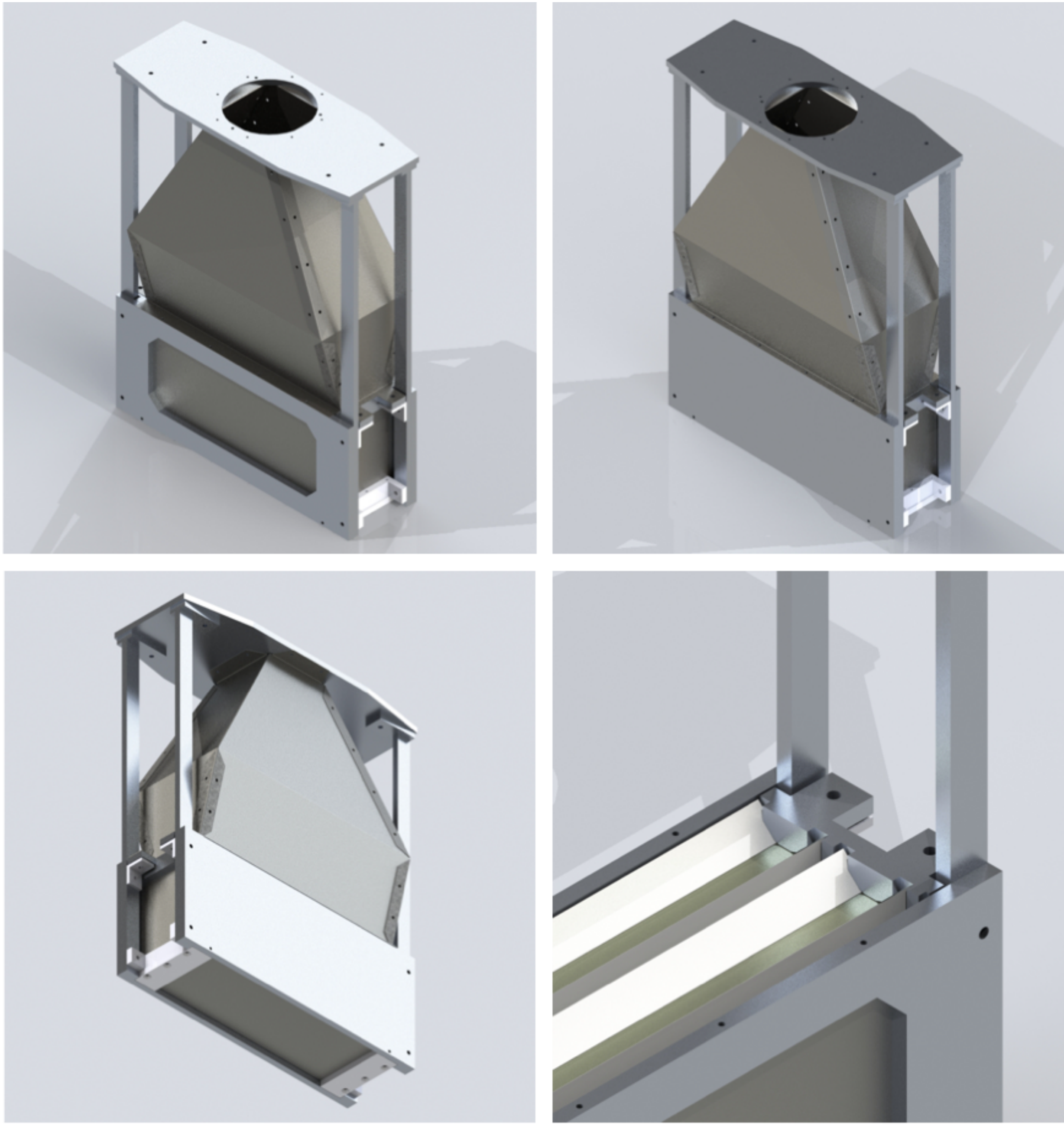
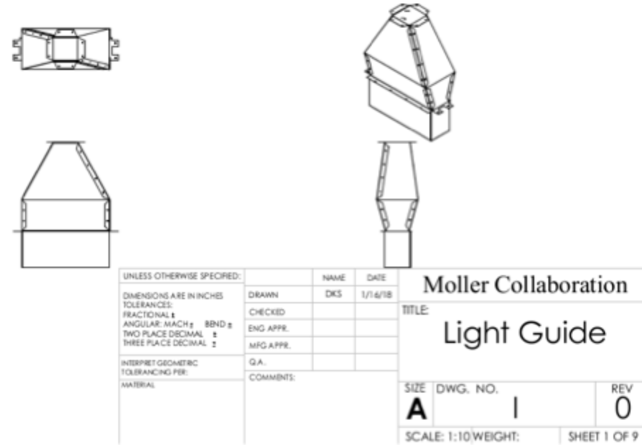
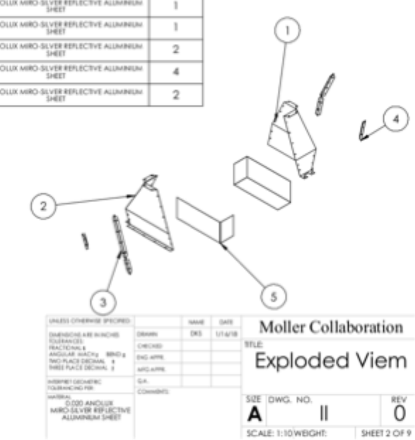
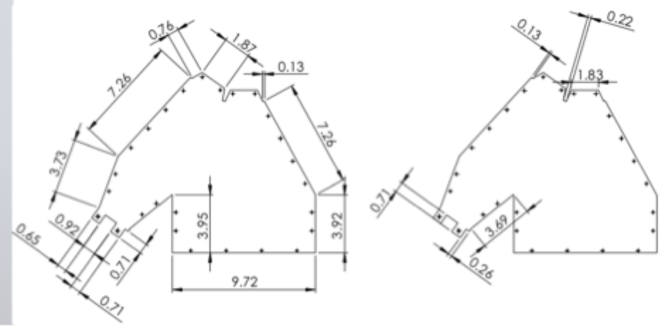
# Updated Full-Scale Prototype (1A) for Testbeam



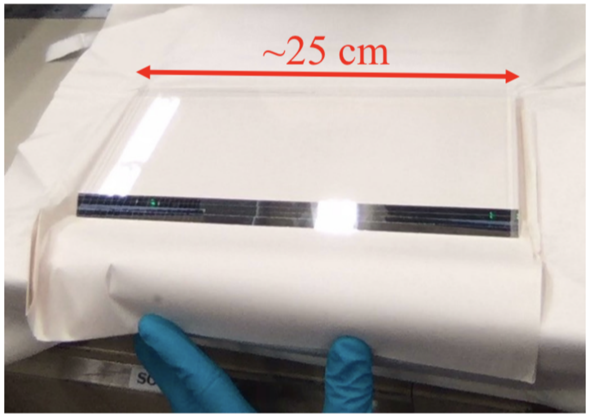



| ITEM NO. | PART | MATERIAL | QTY. |
| --- | --- | --- | --- |
| 1 | Light Guide - Back | 0.020 ANOLUX MIRO-SILVER REFLECTIVE ALUMINIUM SHEET | 1 |
| 2 | Light Guide - Front | 0.020 ANOLUX MIRO-SILVER REFLECTIVE ALUMINIUM SHEET | 1 |
| 3 | Long Flap | 0.020 ANOLUX MIRO-SILVER REFLECTIVE ALUMINIUM SHEET | 2 |
| 4 | Short Flap | 0.020 ANOLUX MIRO-SILVER REFLECTIVE ALUMINIUM SHEET | 4 |
| 5 | Suitcase | 0.020 ANOLUX MIRO-SILVER REFLECTIVE ALUMINIUM SHEET | 2 |

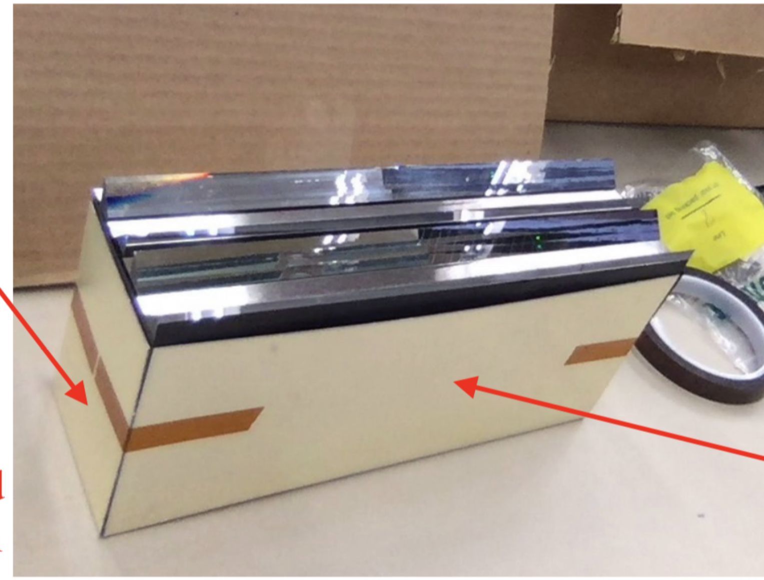


# 1A Full-scale Stack Assembly at SBU, June 2018

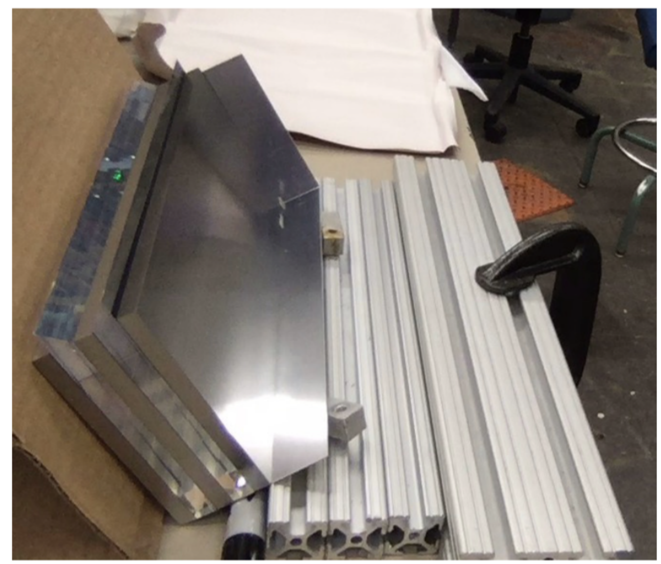



Aluminum sheet coffin



Fully assemb
stack weighs
~40 lbs

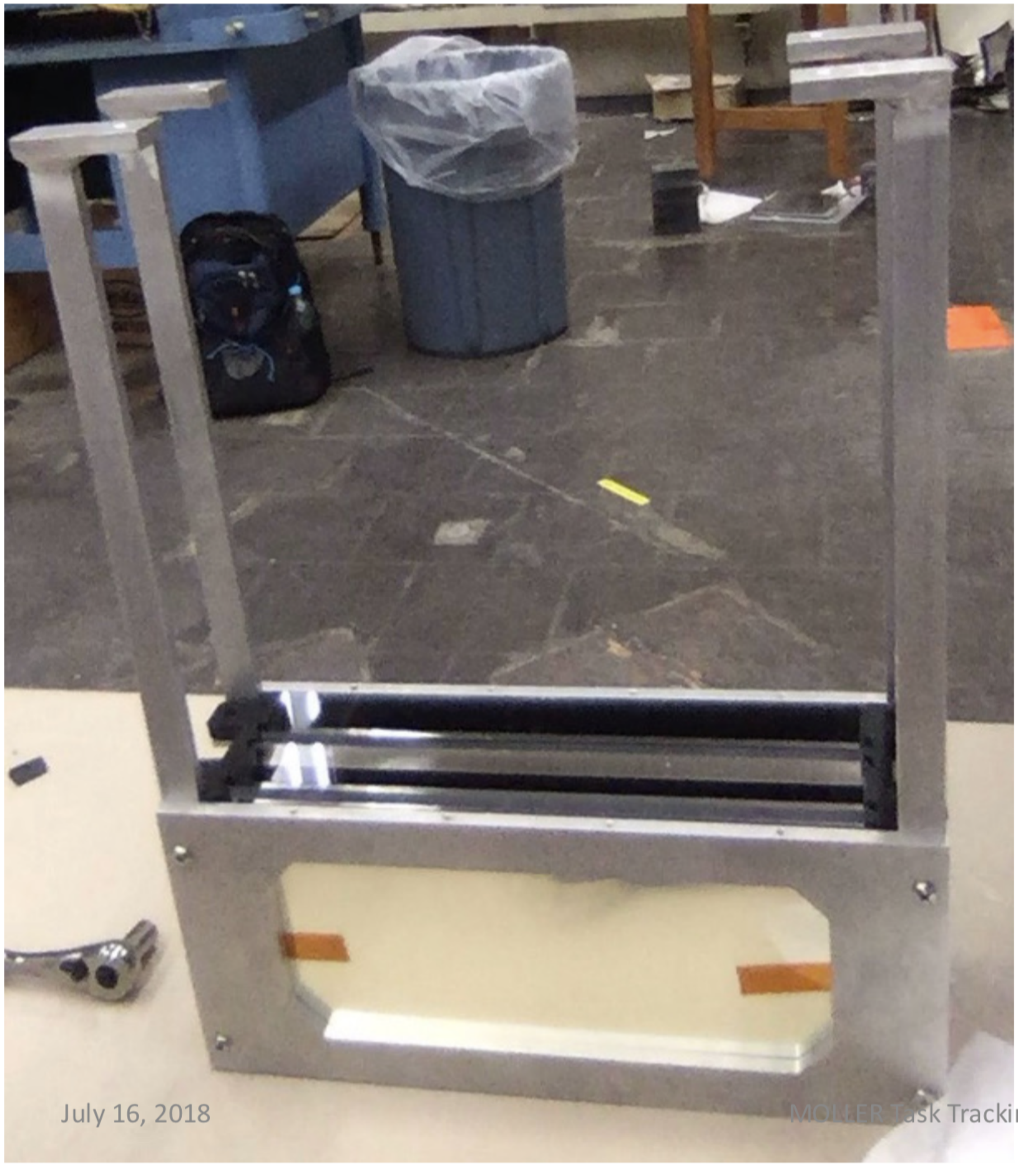
Quartz wrapped in black Kapton

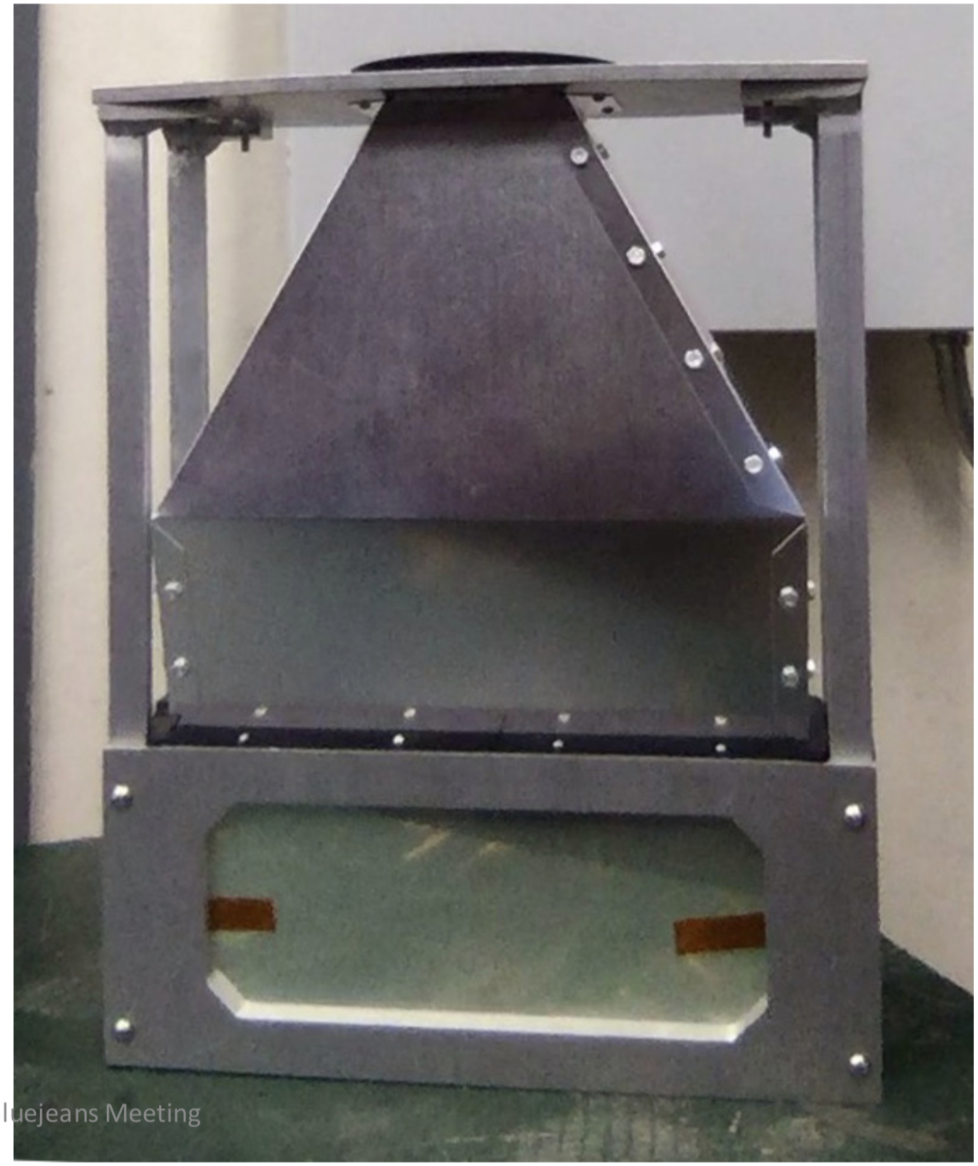


8 mm thick 99.95% pure tungsten plates

July 16, 2018 MOLLER Task Tracking Bluejeans Meeting 15

# Assembled 1A Full-scale ShowerMax Prototype

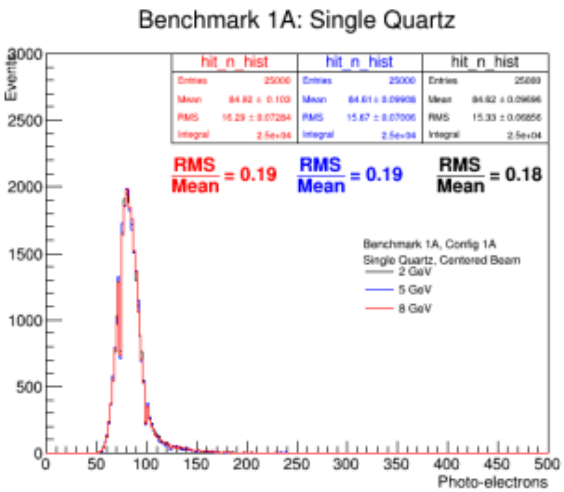


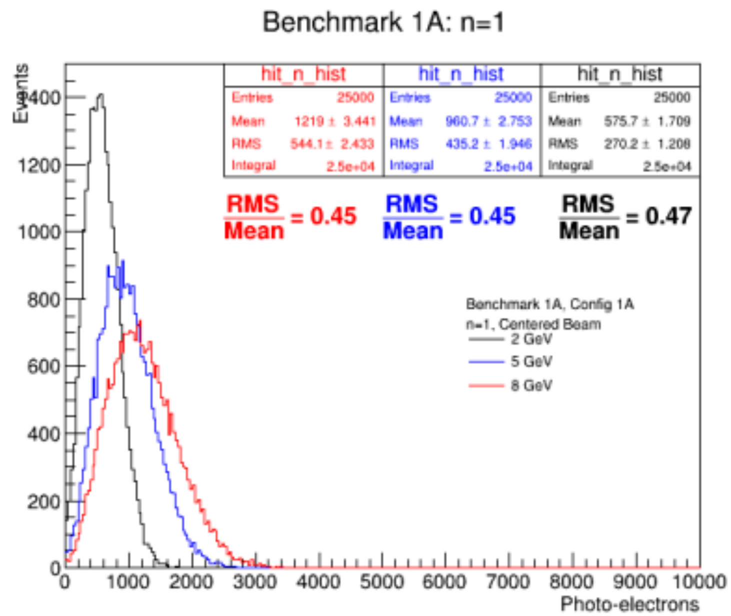



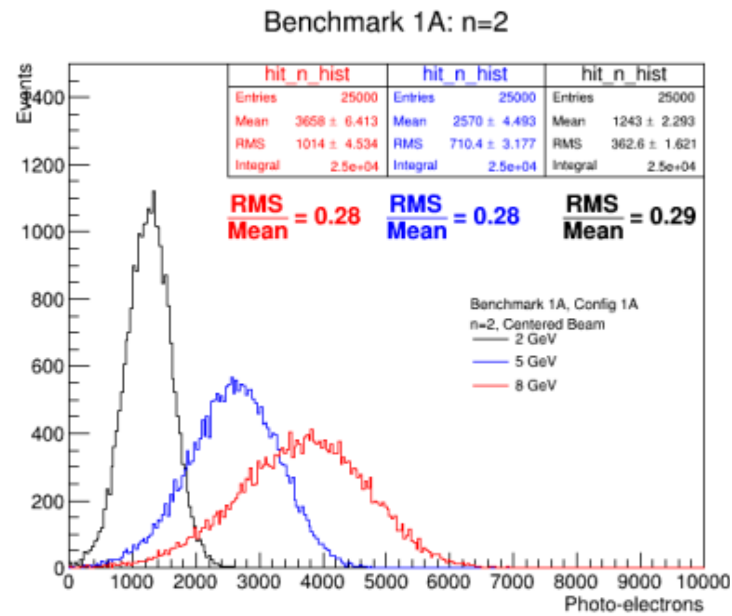
# Testbeam and MC benchmarking strategy

- Engineer benchmarking prototype capable of operation with systematically more stack layers added and with no light guide
- Basic strategy outline:
  - First take data with only one piece of quartz
  - Then add the front tungsten plate and take data, then the next layer of tungsten and quartz, then next, then next
  - This will facilitate benchmarking of optical quartz properties and G4's showering process without light guide complication
- Also construct and test full scale prototypes (with same exact stack configuration as benchmarking prototype) and with full light guide; this will be constructed with machined aluminum

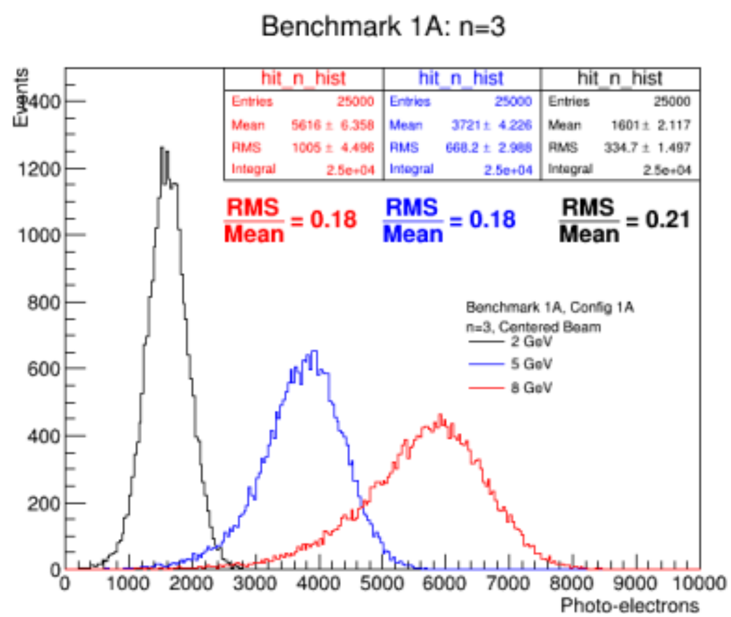
# Benchmarking Prototype (1A) Expectations

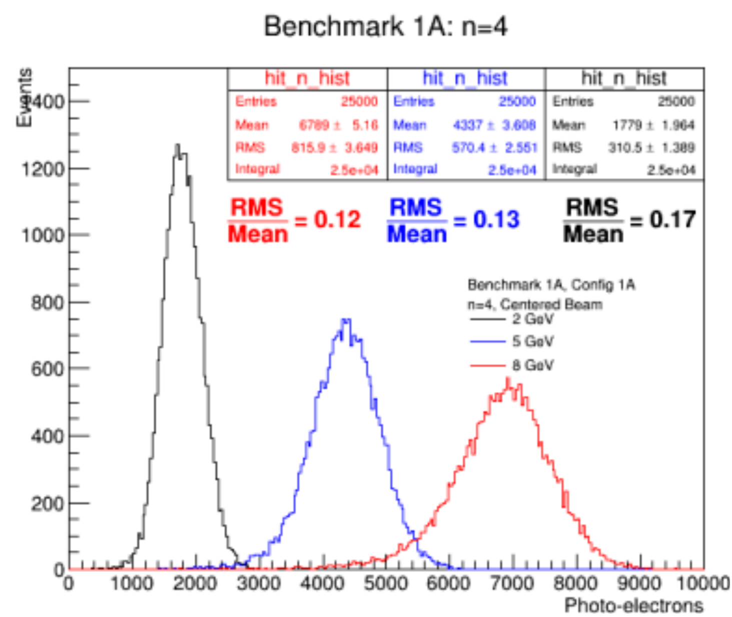


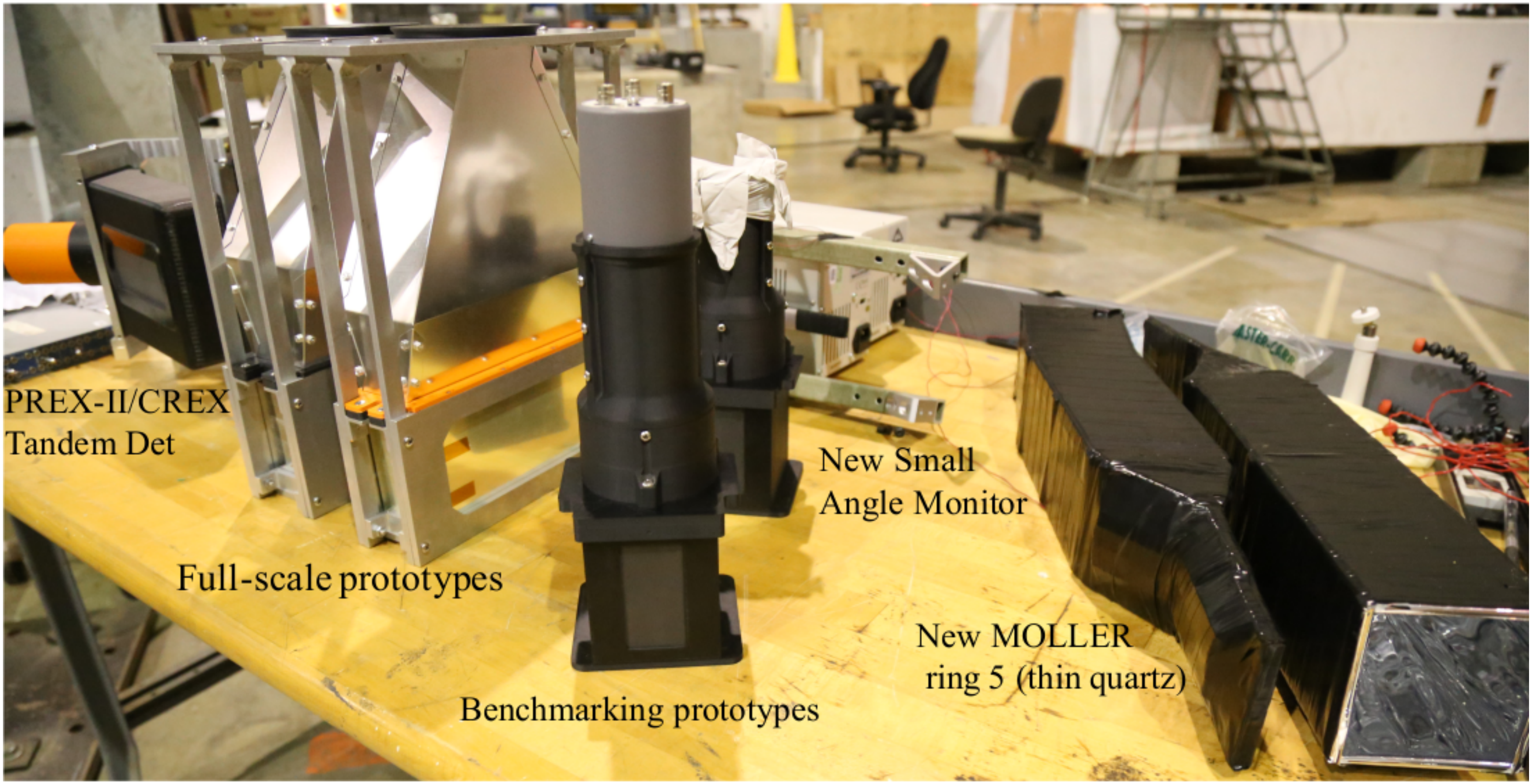

- •Benchmarking PE yields are incredibly high for n =1 to 4
- •Will use 3" ET PMTs: 9305QKB



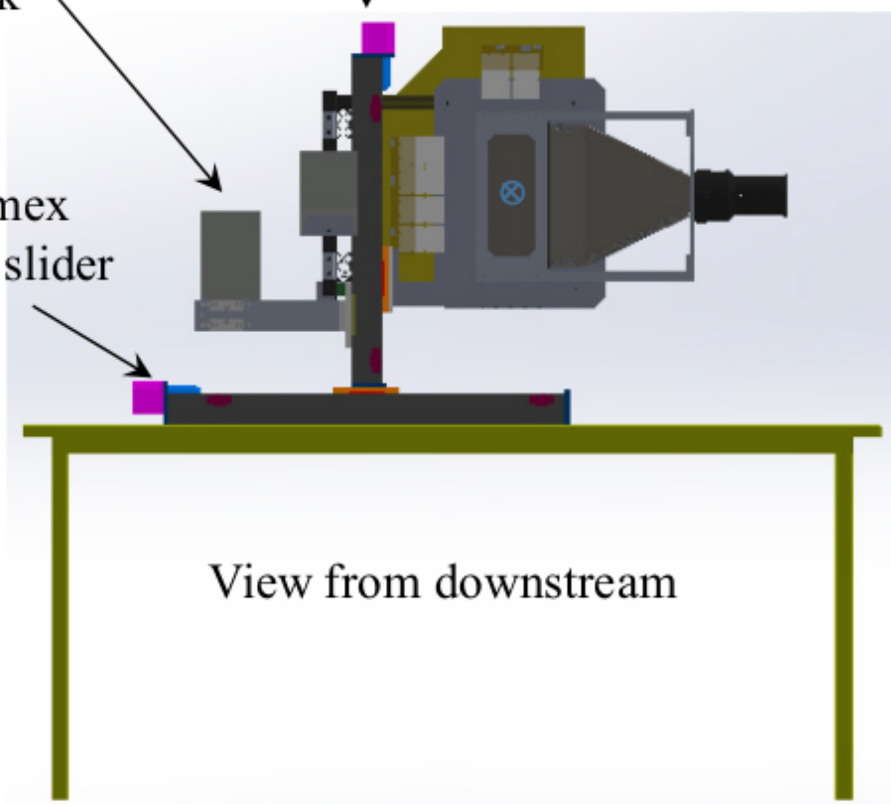
# T-577: SLAC Testbeam, Dec 6 – 12, 2018

- Tested ShowerMax full-scale and benchmarking detectors and new ring5 thin detector designs
- Used 3, 5.5 and 8 GeV electrons with multiplicity of a Poisson distribution with $\mu \approx 1$
- Overall beam rate only 5 Hz (parasitic from LCLS beam) with ~1/3 of those being single $e^-$

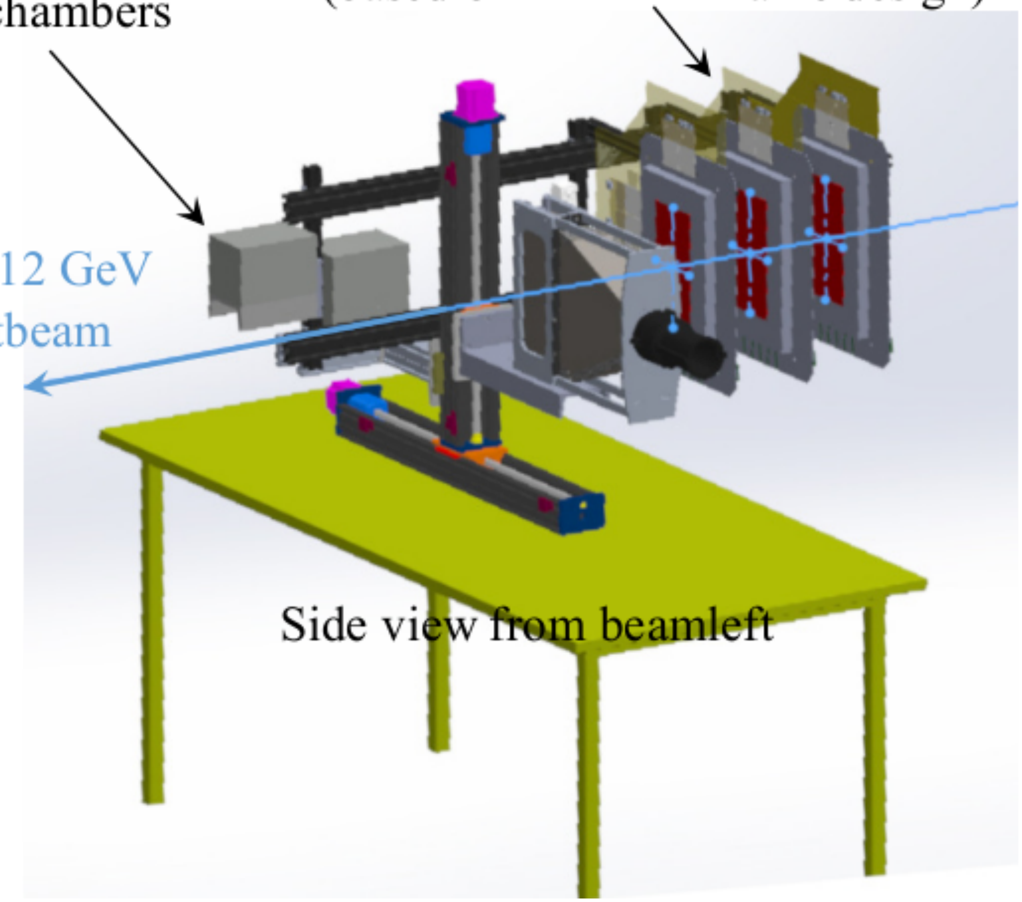


# CAD of the SLAC testbeam setup

- Testbeam scheduled for Dec 5 – 10 (we may get more time)
- Setup allows testbeam to cover entire active area of full-scale prototypes

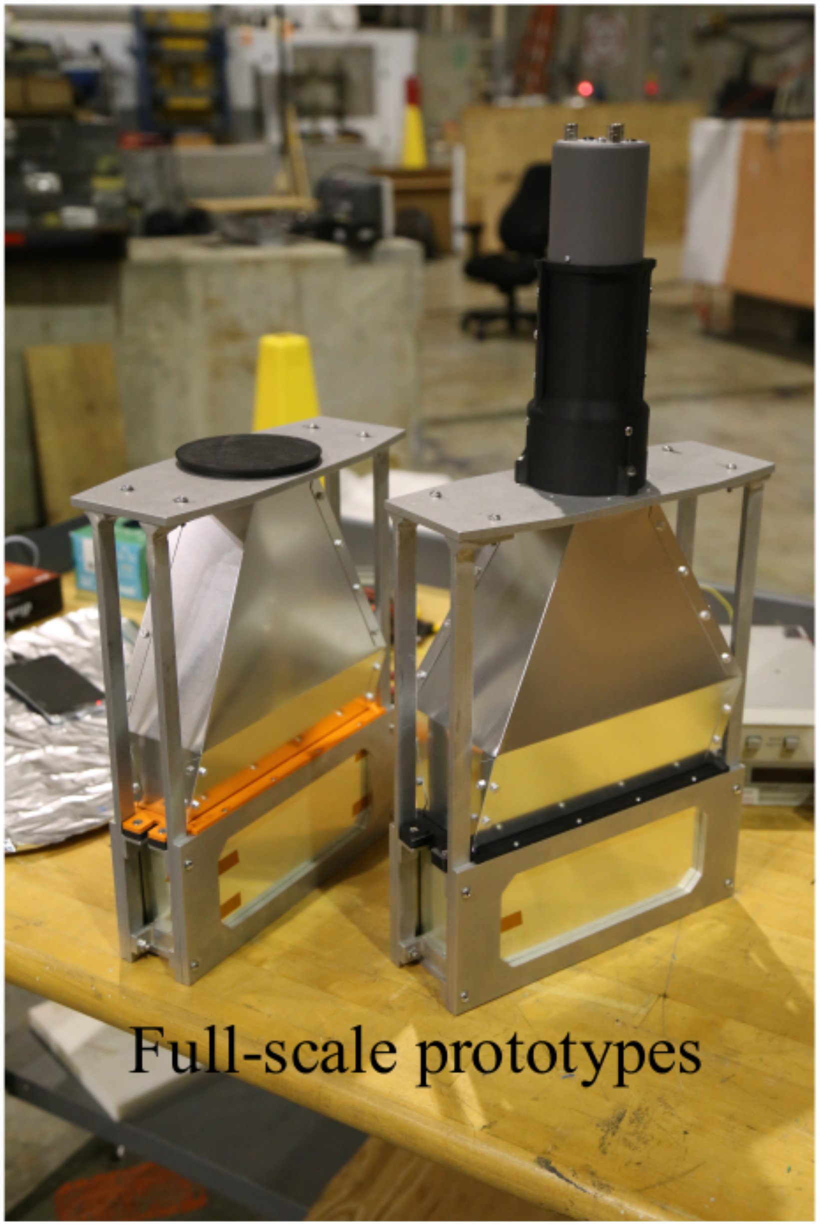


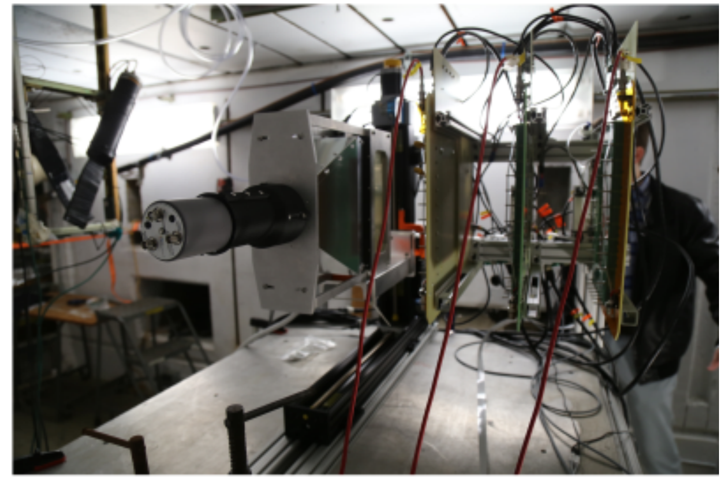

View from downstream

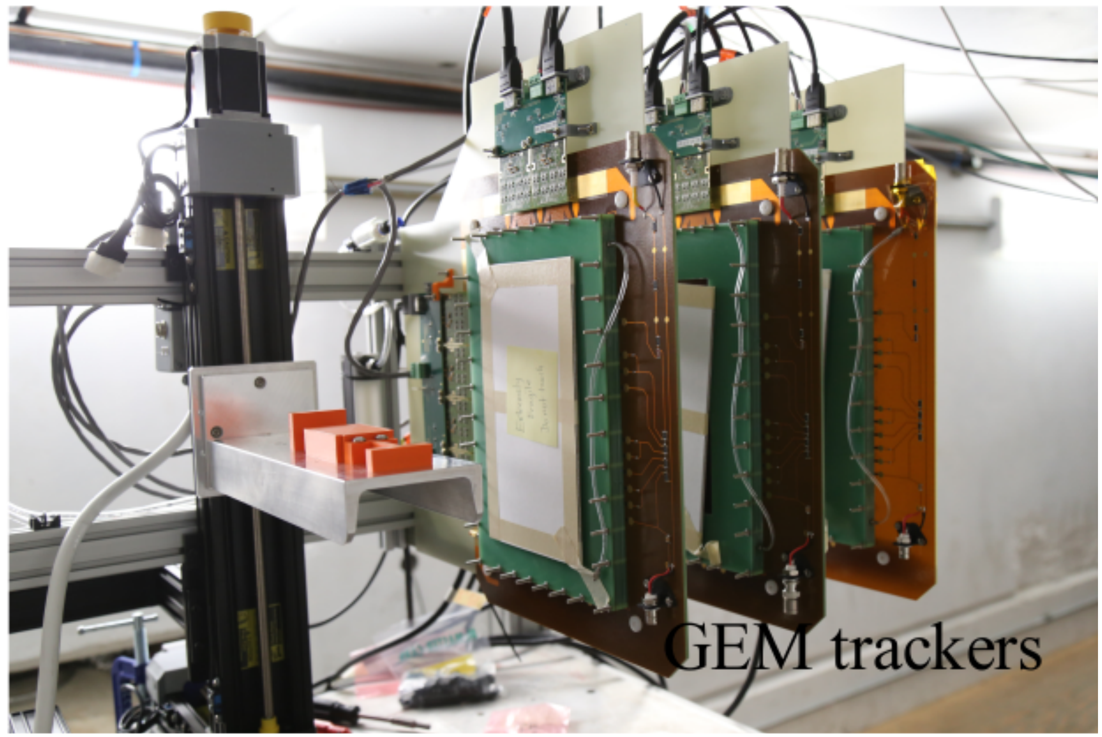



Side view from beamleft

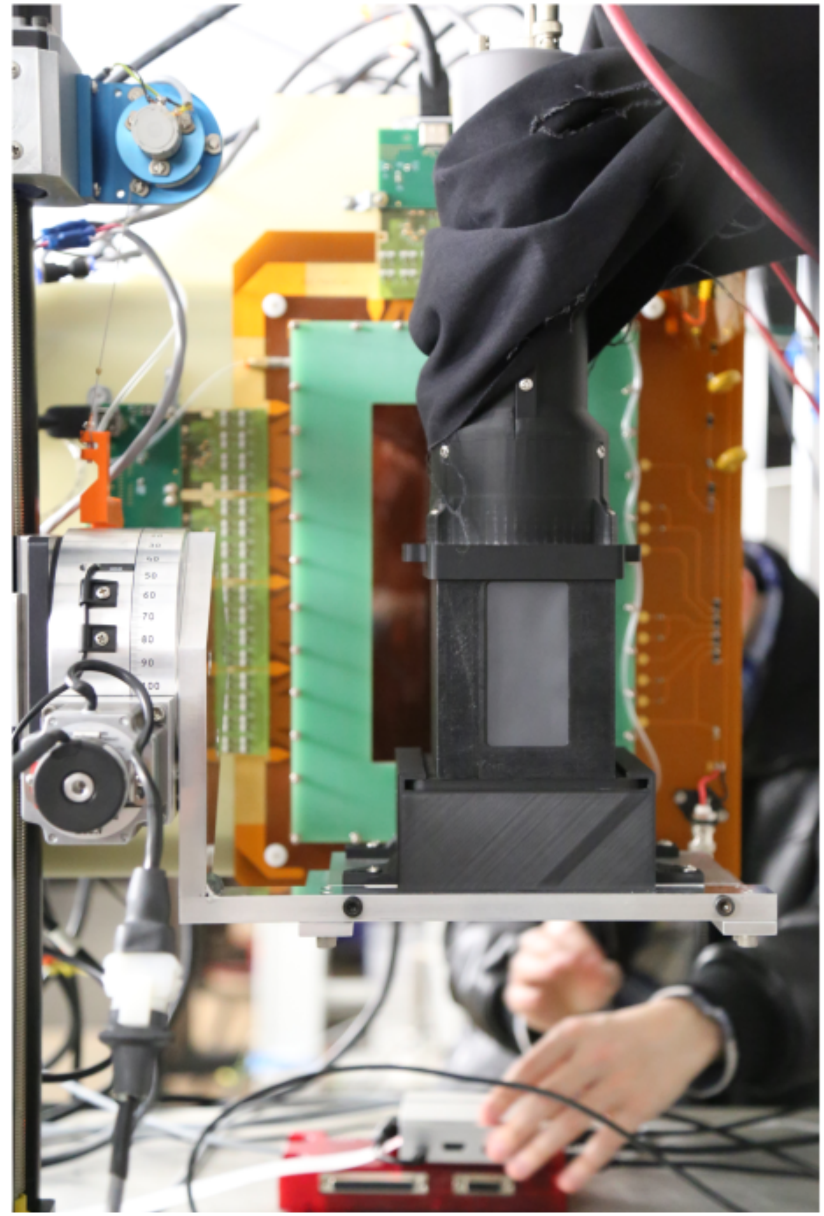
# T-577: SLAC Testbeam Setup for Full-Scale ShowerMax



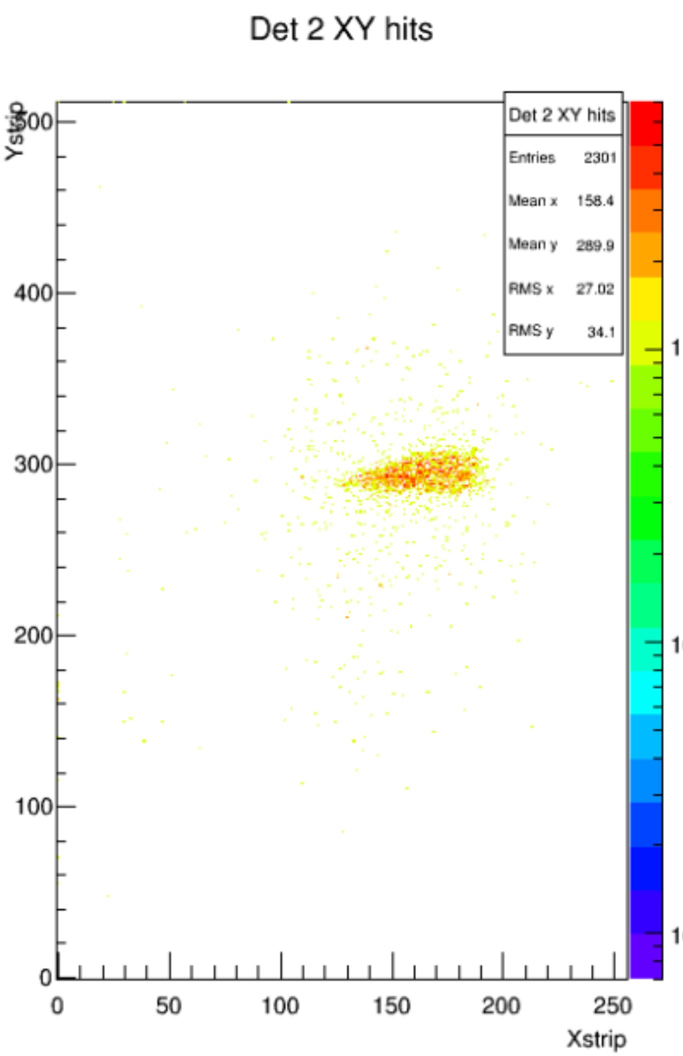



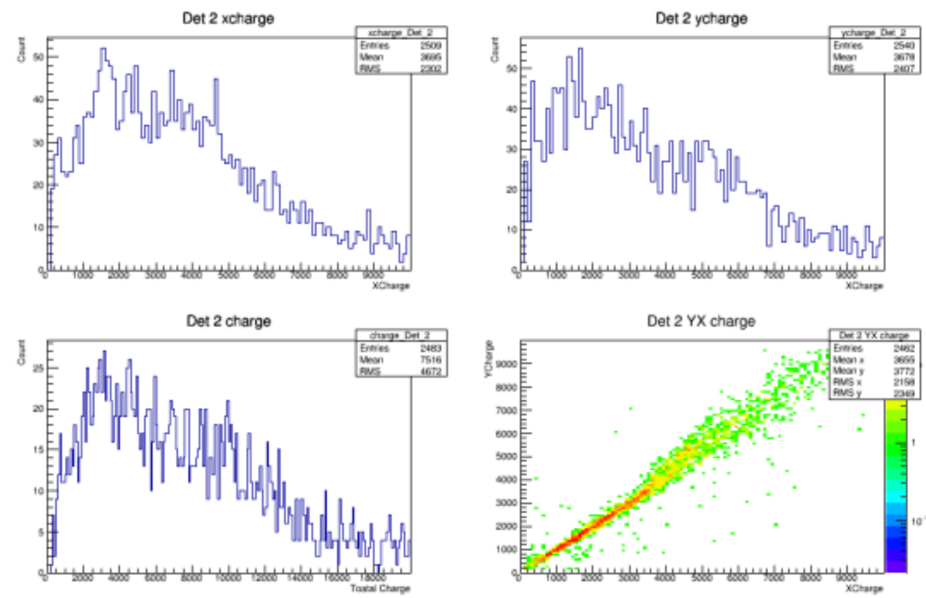


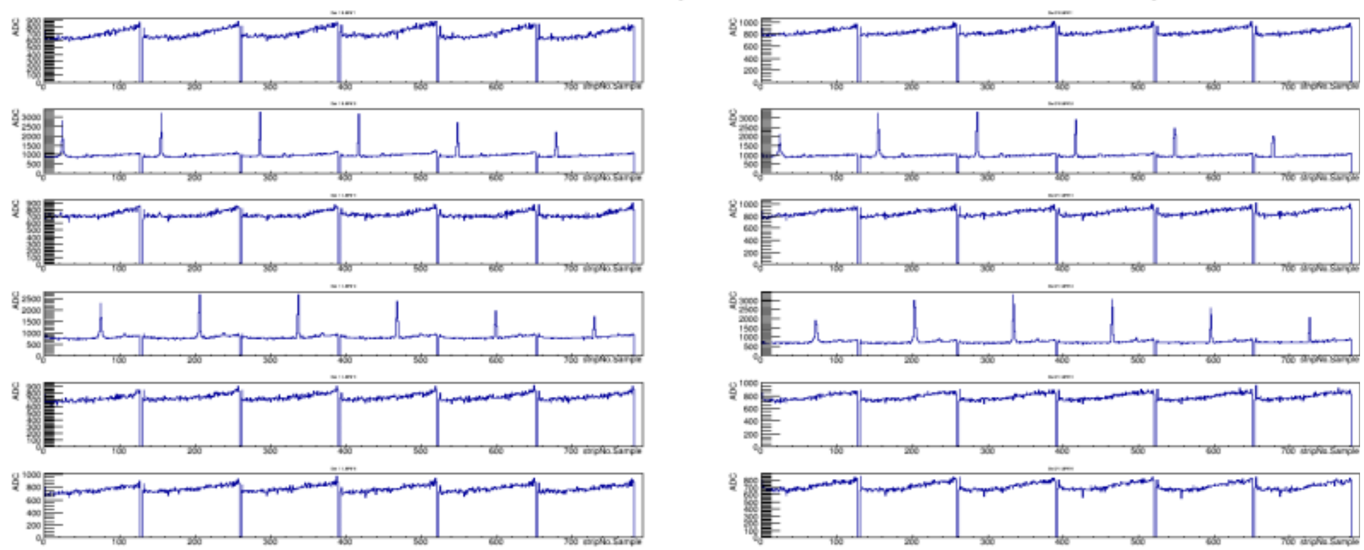
# T-577: SLAC Testbeam Setup: Benchmarking ShowerMax



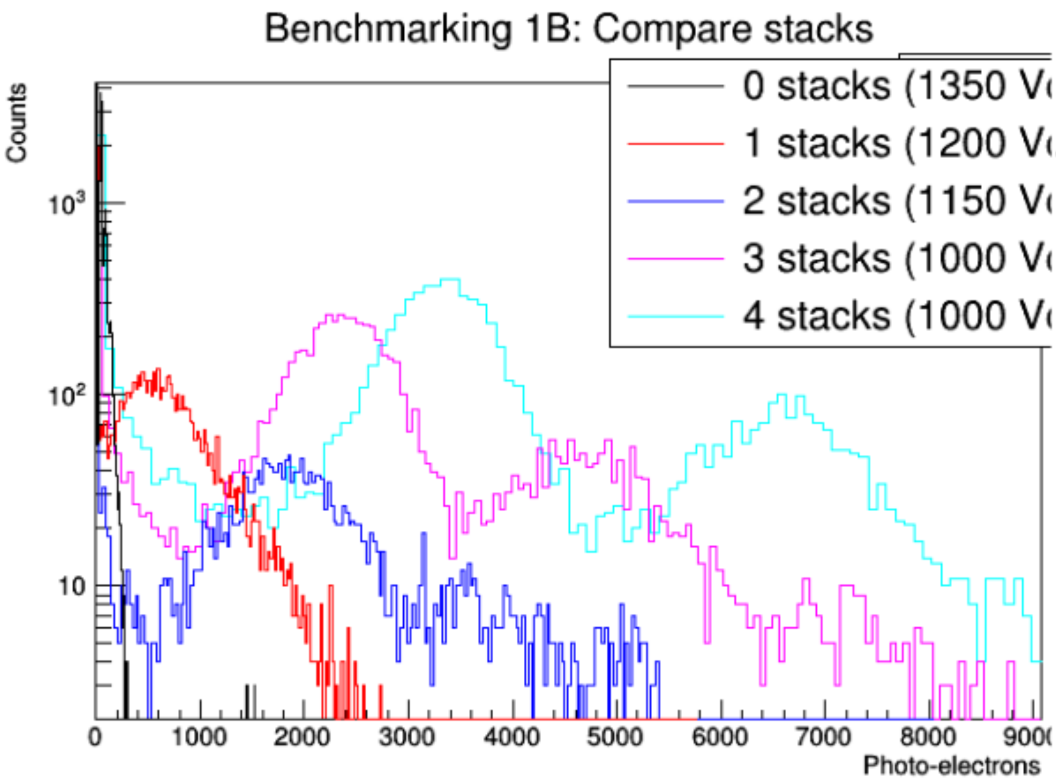
# Beam Spot (5.5 GeV): ~1 cm by 2 cm

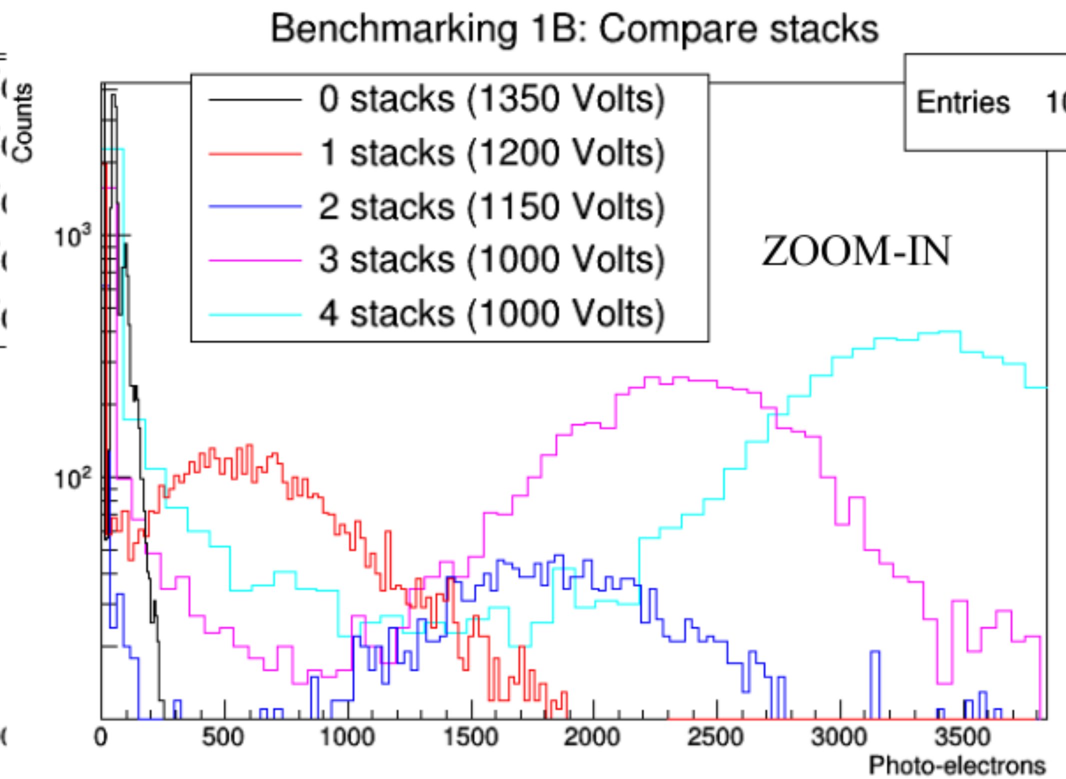


# ShowerMax Benchmarking Prototype Testbeam Results (1B response vs. stack layers)

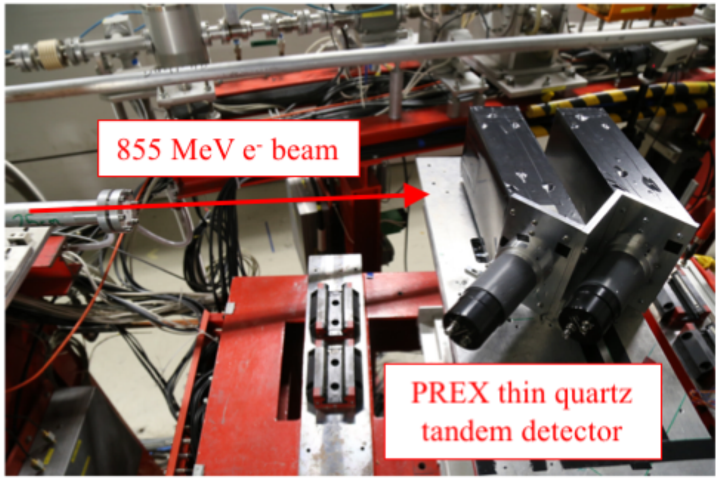


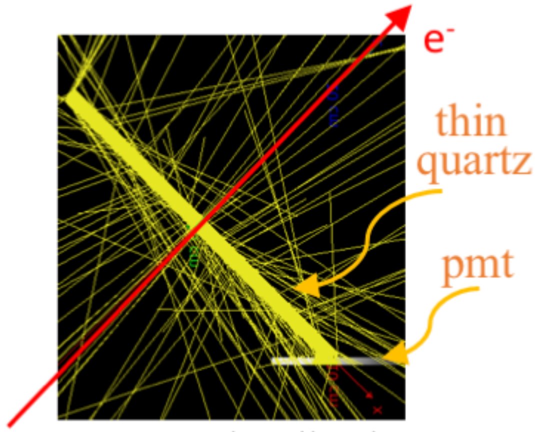

- Results are very reasonable—the means and relative widths behave as expected
- Simulations are underway for comparison and MC tuning/benchmarking

# Monte Carlo tuning and Shower-max Simulations

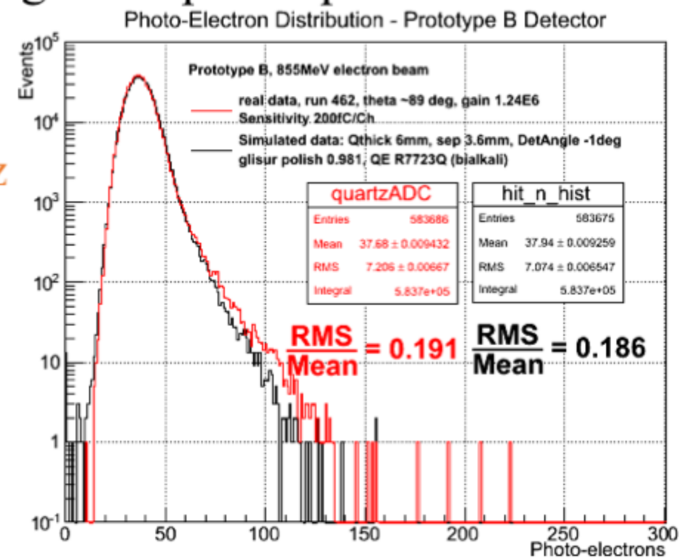
- Quartz optical G4 properties benchmarked at MAMI: Glisur ground polish parameter ~0.981




MAMI testbeam with PREX detector




G4 event visualization for PREX detector

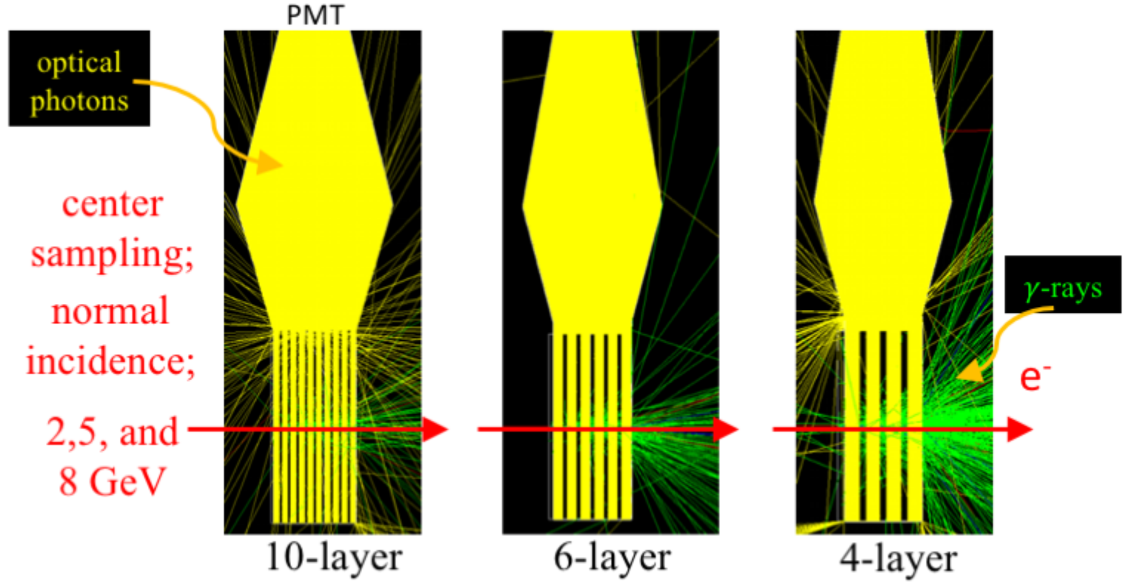



PE dists: *Real data* vs. *Sim data*

- 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

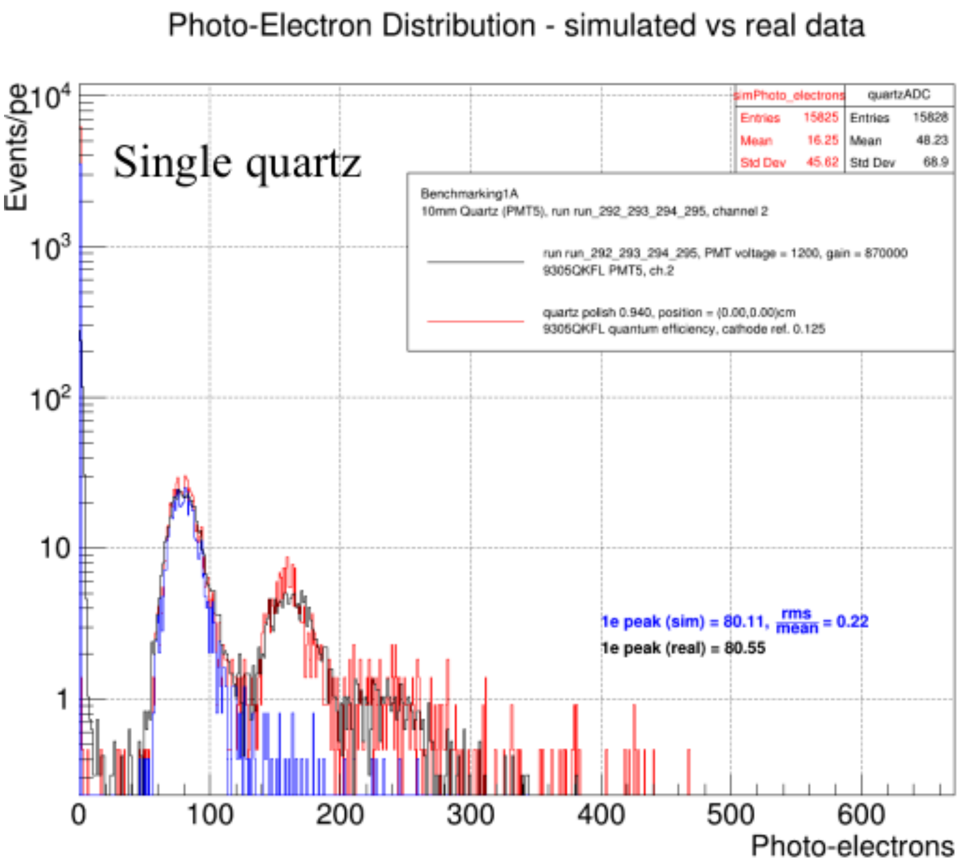
## Conclusion:

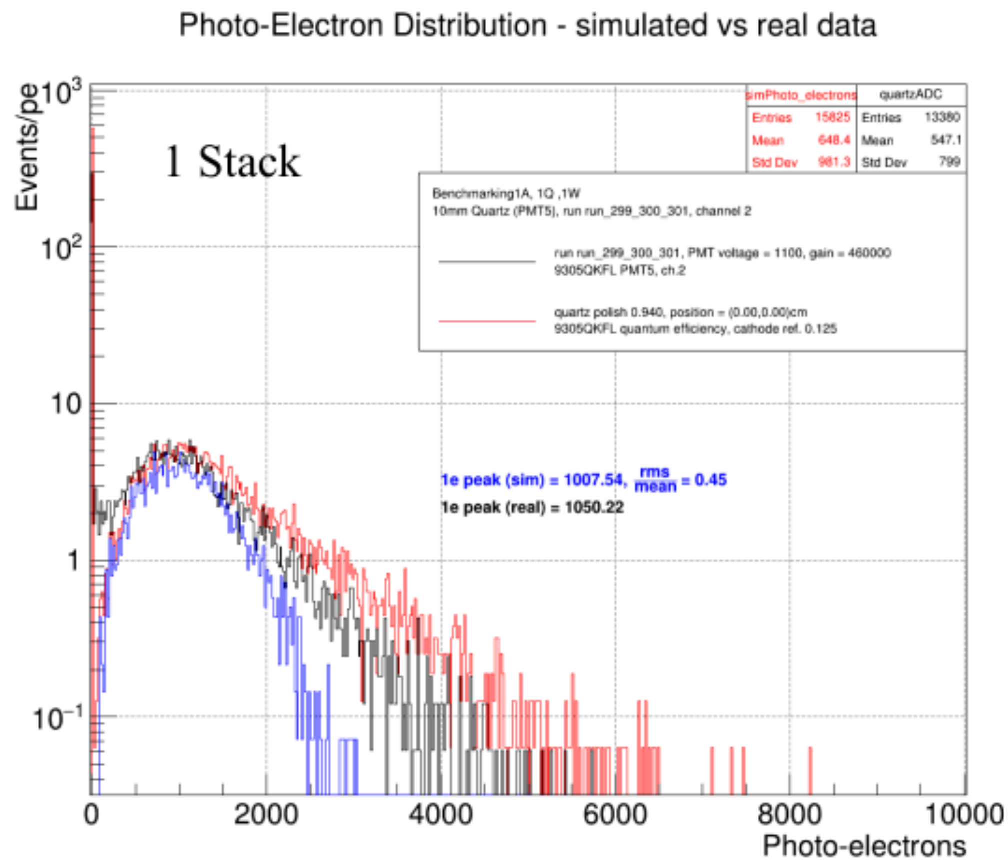
4-layer gives comparable performance to 10-layer (and is easier and cheaper to build)




Shower-max event visualizations

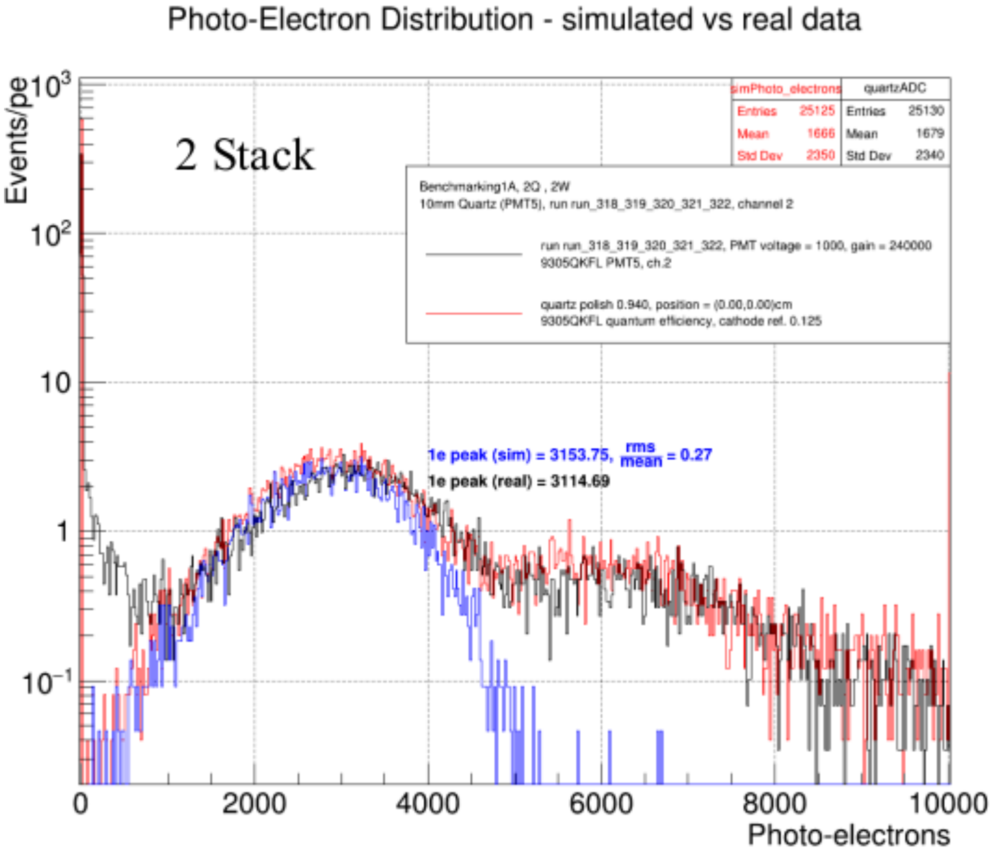
# Benchmarking 1A testbeam results compared with simulation (5.5 GeV electron response vs. stack layers)

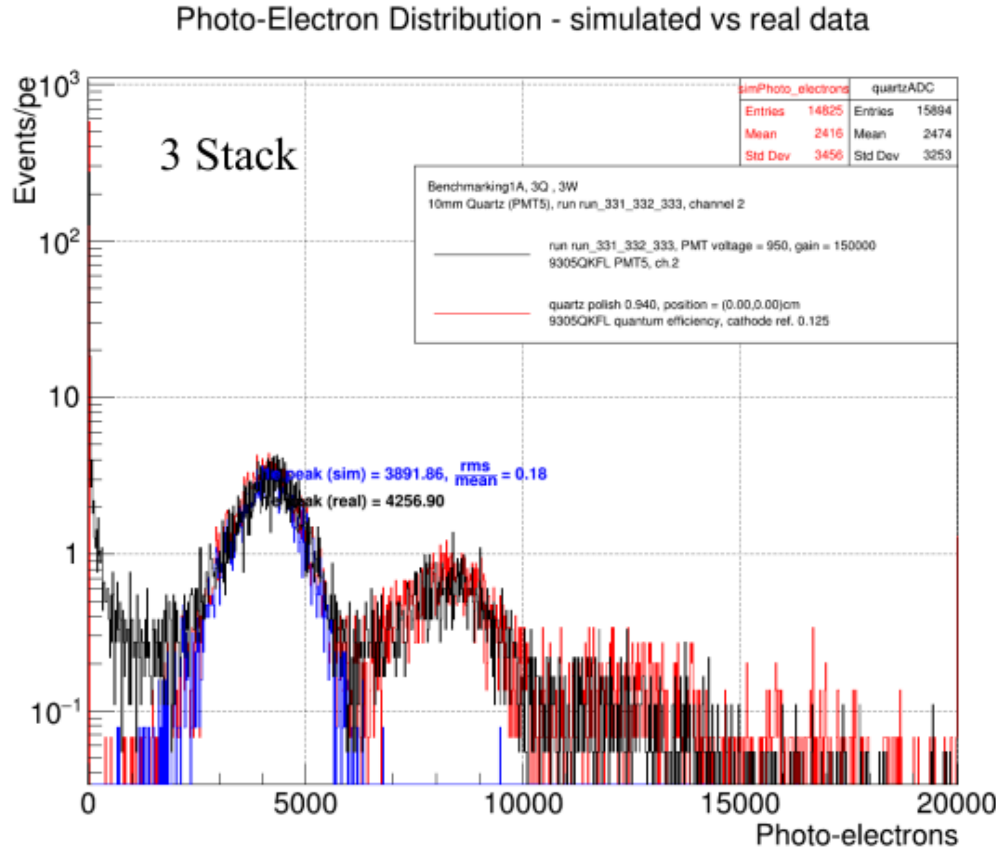



- Single quartz data used to benchmark quartz optical polish parameter
- With quartz polish calibrated, simulations performed with successively more stack layers and compared with SLAC data

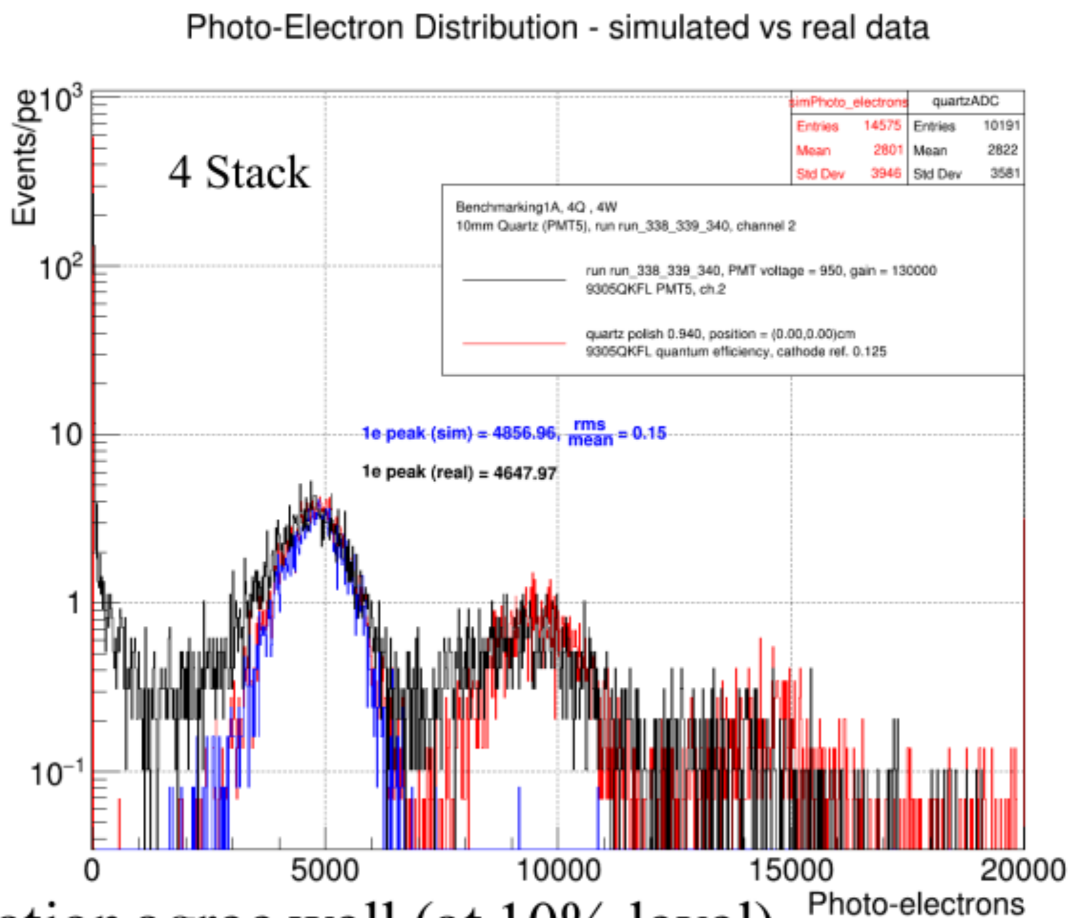
# Benchmarking 1A testbeam results compared with simulation (5.5 GeV electron response vs. stack layers)



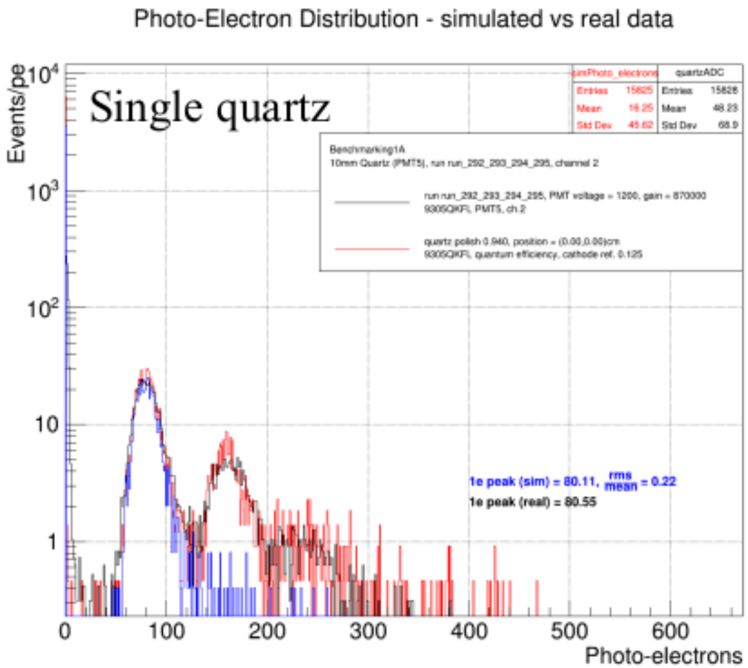

- Data and simulation agree well (at 10% level)
- Resolution of single electron photopeak goes from 27% to 18% (simulated)

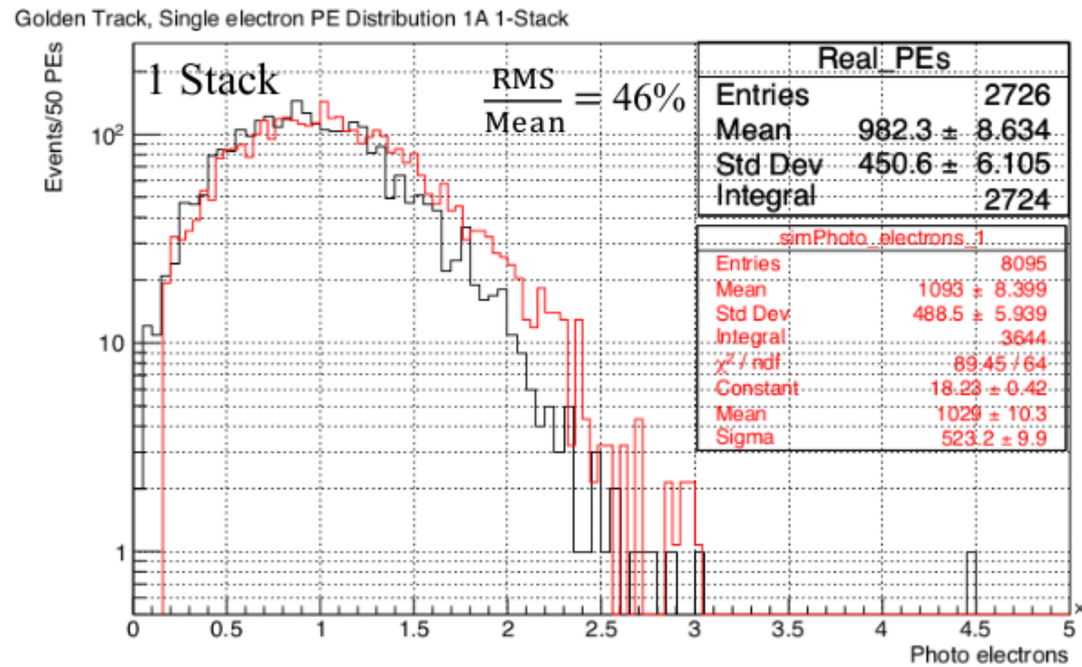
# Benchmarking 1A testbeam results compared with simulation (5.5 GeV electron response vs. stack layers)




- Data and simulation agree well (at 10% level)
- Resolution of single electron photopeak is 15% (simulated). Analysis of real data resolutions are on-going using GEM tracking data

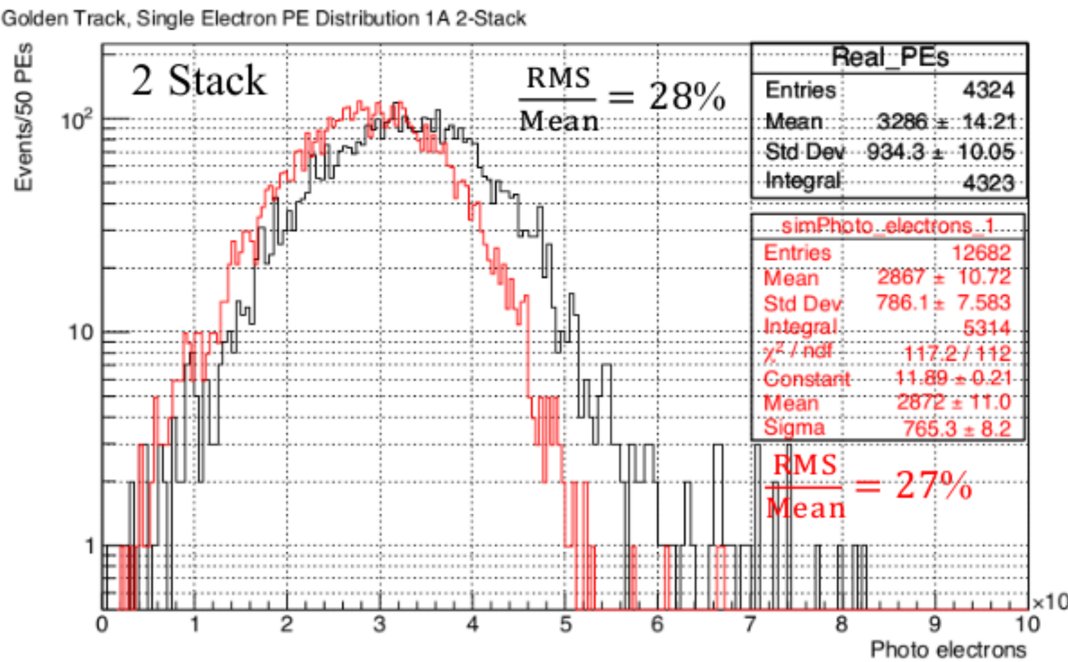
# Benchmarking 1A Golden Track, single e⁻ data compared with simulation (5.5 GeV electron response vs. stack layers)

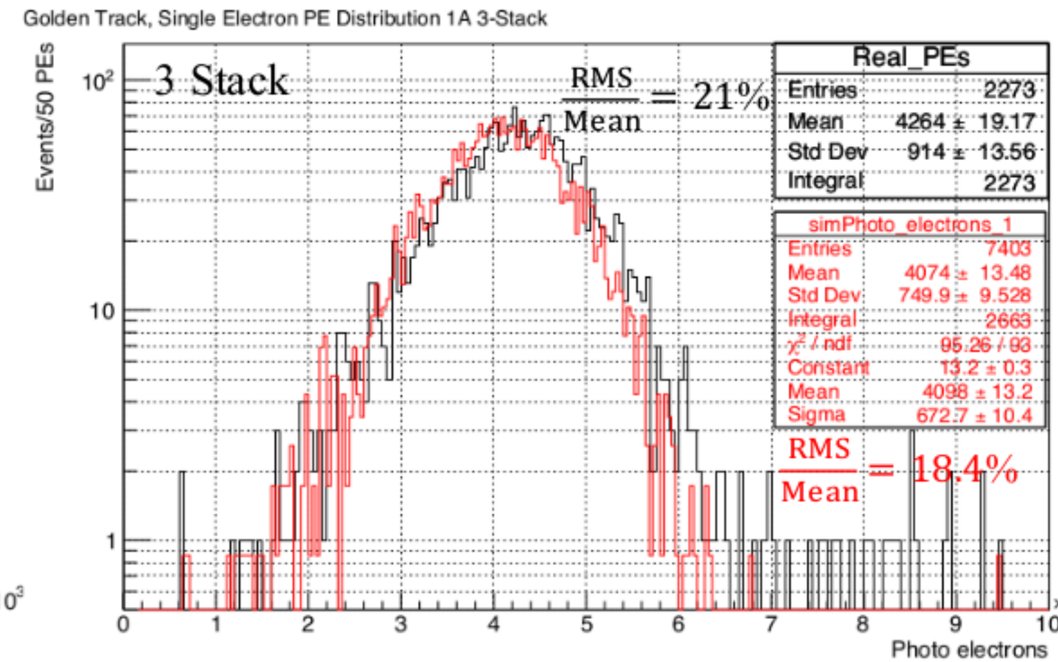



- Note that polish parameter was decreased from 0.98 (PREX)to 0.94 (4% decrease)
- Simulation uses state of the art understanding of optical properties of active material including attenuation and dispersion inside quartz and pmt window, reflectivity at air-pmt window interface & photocathode, and factory QE of photocathode
- Note: All comparisons and polish benchmarking rely on knowing operational pmt gain (5 – 10% uncertainty (as well as QDC charge sensitivity))

# Benchmarking 1A Golden Track, single e⁻ data compared with simulation (5.5 GeV electron response vs. stack layers)



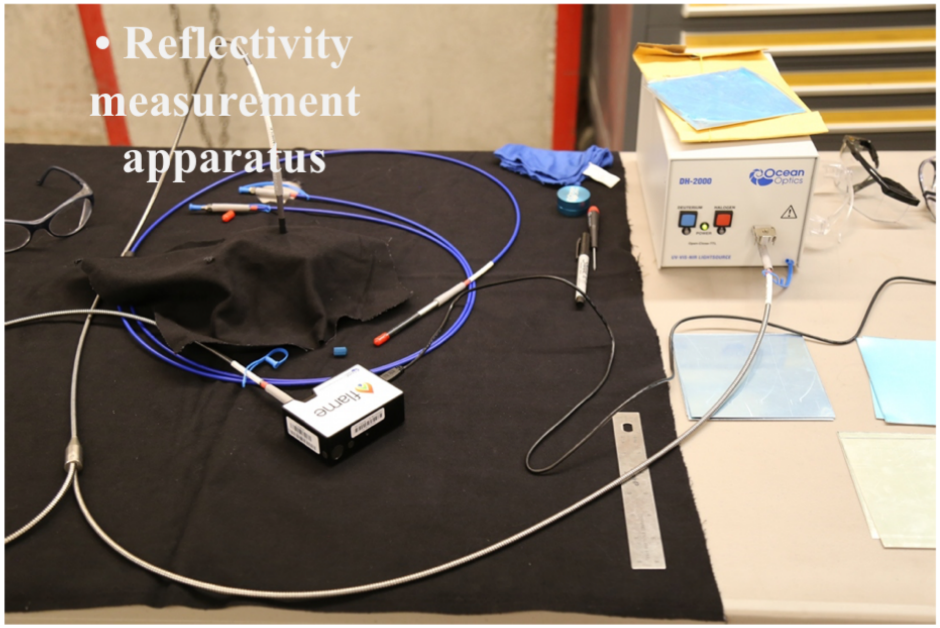

- Data and simulations agree at 10% level
- Data shows larger high-light tails indicating potential mis-identified single e⁻ tracks
- Resolutions get steadily better and agree well with simulated distributions
  --This tells us there was good alignment and minimal lateral shower leakage

## Summary and future work

- Showermax baseline prototypes constructed and tested
  - Analyses of testbeam data still ongoing but converging fast
  - Preliminary results for benchmarking prototypes in good agreement with simulations
  - Full-scale results and uniformity scans still in progress
- First results for full-scale tests show significant difference between data and sims–PE yields ∼2.5x lower than expected; likely culprit is light guide but could also include broken TIR–due to excessive pressure on Kapton quartz wrapping

# Light guide reflectivity measurements

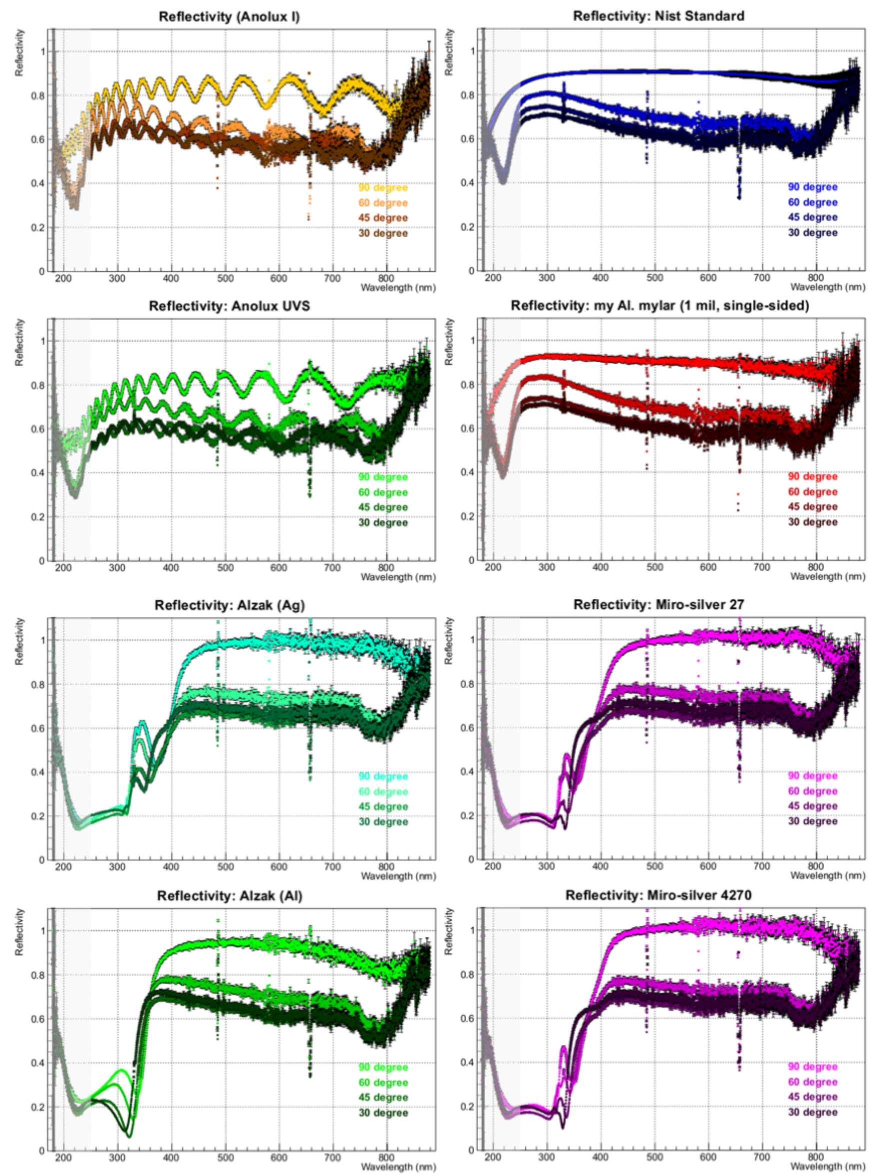
- Measuring light guide (LG) reflectivity as function of angle (10 – 90°) and $\lambda$ (200 – 800nm); ongoing




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

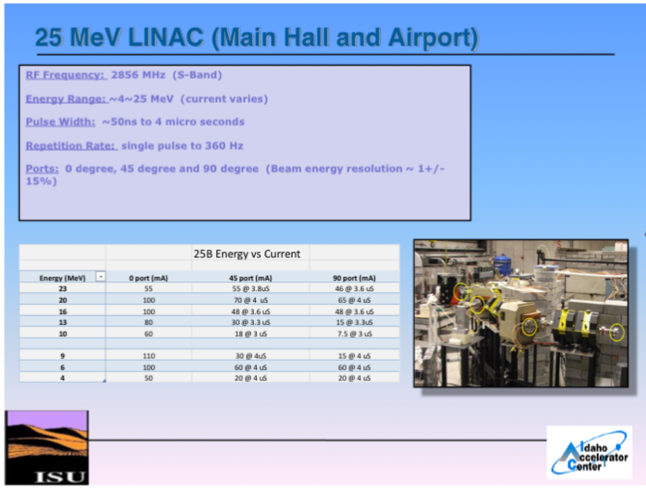
Light guide materials tested:

| | |
|---|---|
| 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. $\lambda$ for various materials at diff. angles

# LG reflectivity radiation hardness study

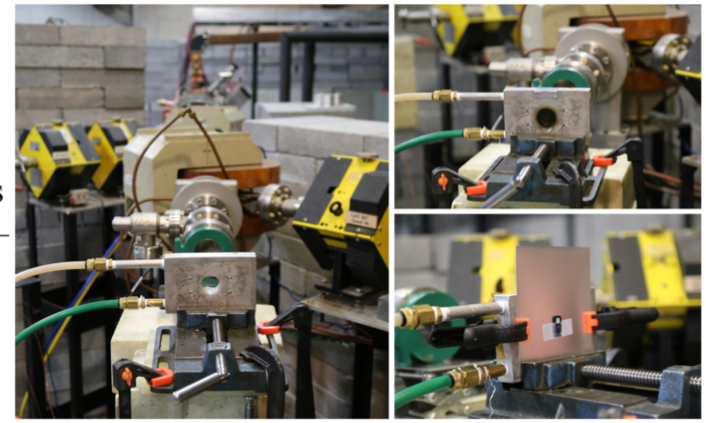


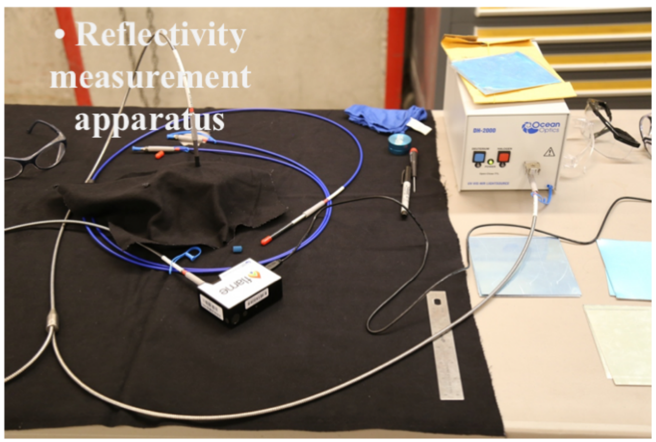

25B Energy vs Current

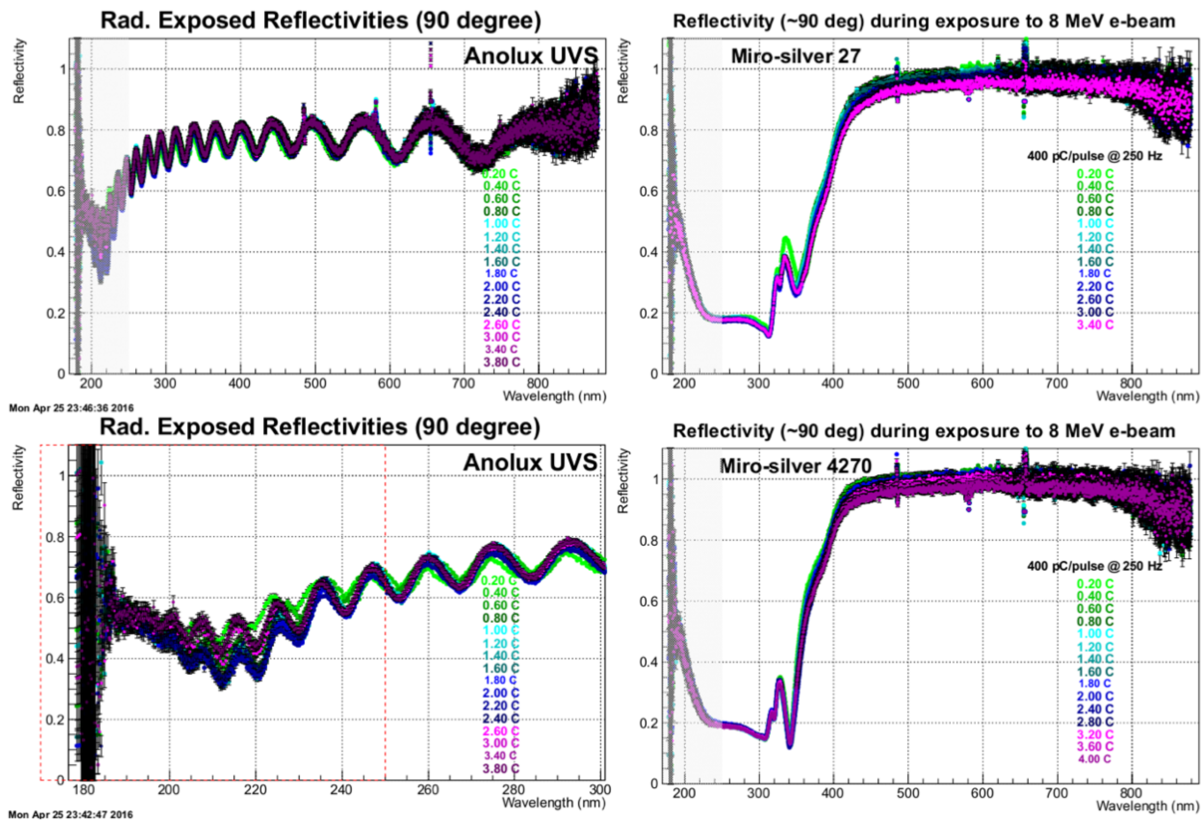
| Energy (MeV) | 0 port (mA) | 45 port (mA) | 90 port (mA) |
|---|---|---|---|
| 23 | 55 | 55 @ 3.8uS | 46 @ 3.6 uS |
| 20 | 100 | 70 @ 4 uS | 65 @ 4 uS |
| 16 | 100 | 48 @ 3.6 uS | 48 @ 3.6 uS |
| 13 | 80 | 30 @ 3.3 uS | 15 @ 3.3uS |
| 10 | 60 | 18 @ 3 uS | 7.5 @ 3 uS |
| | | | |
| 9 | 110 | 30 @ 4uS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

- 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.



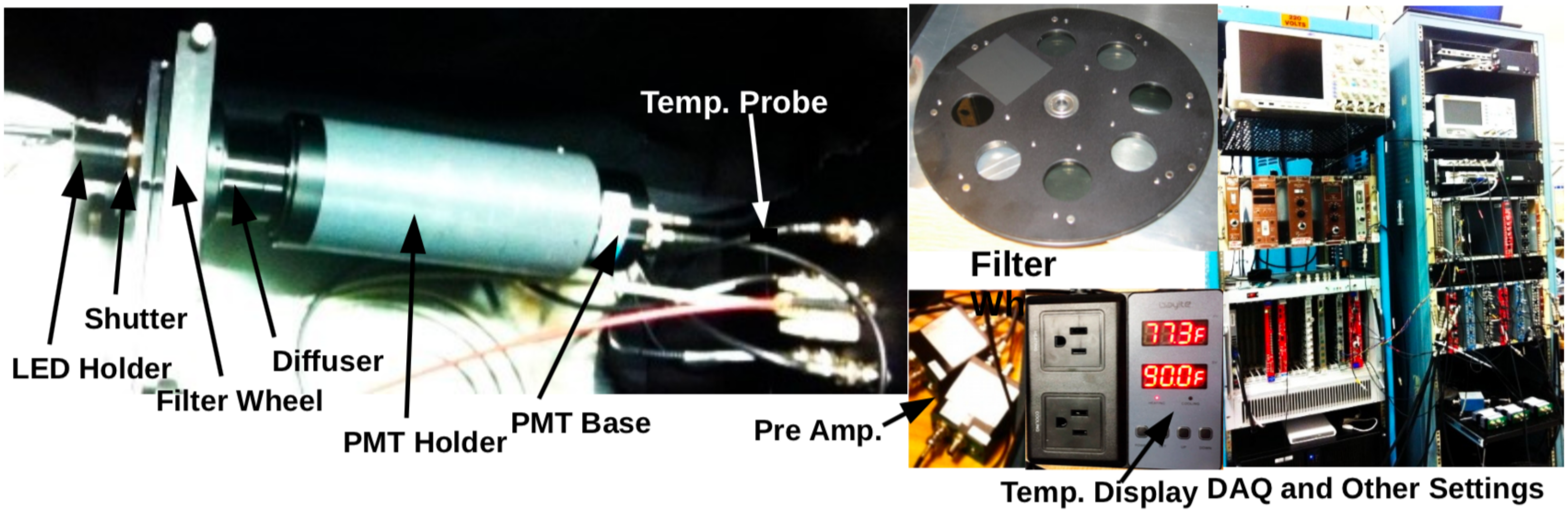



**Irradiated several light guide material samples over a 3 day period from Mar 22 - 24, 2016:**

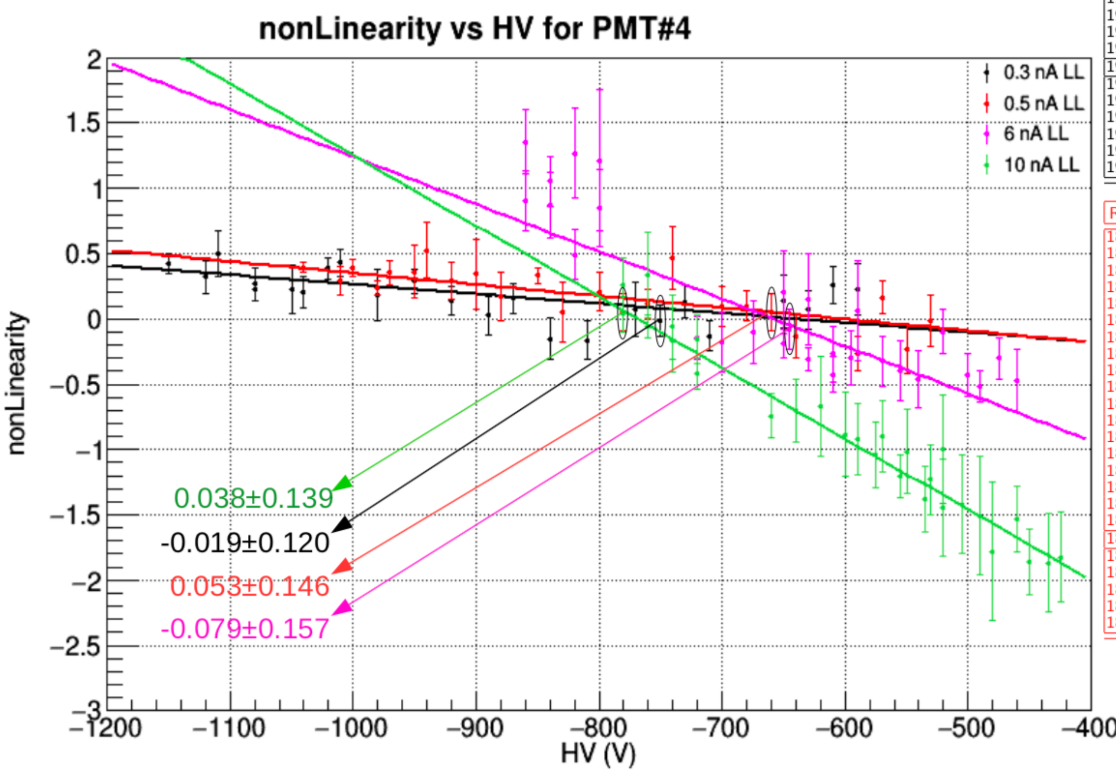
Miro-silver 4270
Anolux UVS
Miro 2000Ag (diffuse)
Miro-silver 27 (from Michael)
Alzak-Al and Alzak-Ag (from KK)
1 mil, single-sided aluminized mylar

# Linearity Test Box And Integrating DAQ




- LED Holder ⟶ holds two LEDs, each with 2 mm diameter collimation
- Electronic Shutter ⟶ has now been connected with a relay to turn it "ON" and "OFF" automatically at any interval with computer script
- Filter Wheel ⟶ Computer Controlled Edmund Optics' Absorptive ND filters (400-700 nm) with 8 (100, 79, 63, 50, 40, 25, 10, 1)% transmission settings (~randomly ordered)
- Filter Wheel is now controlled automatically using a shell script
- UV Diffuser ⟶ Edmund Optics' ground fused silica
- PMT Holder ⟶ 2" PMT with modified base for improved linearity
- Different pre-Amp settings with different resistances and offsets tested (MAIN, LUMI, KDPA, and SNS)

# Summary for PMT#4




LL = 0.3 nA

| Run | HV | PreAmp | non-Lin | Error | $\chi^2$/6df |
|---|---|---|---|---|---|
| 1896 | -1150 | 0.5 | 0.426 | 0.075 | 2.420 |
| 1897 | -1120 | 0.5 | 0.320 | 0.123 | 5.564 |
| 1898 | -1080 | 0.5 | 0.228 | 0.093 | 2.871 |
| 1899 | -1040 | 0.5 | 0.200 | 0.120 | 5.120 |
| 1905 | -1110 | 0.6 | 0.502 | 0.172 | 7.533 |
| 1906 | -1080 | 0.6 | 0.268 | 0.125 | 8.046 |
| 1907 | -1050 | 0.6 | 0.227 | 0.186 | 8.355 |
| 1908 | -1020 | 0.6 | 0.389 | 0.083 | 2.008 |
| 1901 | -1010 | 1.0 | 0.431 | 0.102 | 3.712 |
| 1902 | -980 | 1.0 | 0.182 | 0.193 | 16.58 |
| 1903 | -950 | 1.0 | 0.287 | 0.091 | 2.936 |
| 1904 | -920 | 1.0 | 0.137 | 0.112 | 3.769 |
| 1910 | -890 | 2.0 | 0.027 | 0.146 | 7.582 |
| 1912 | -870 | 2.0 | 0.159 | 0.116 | 3.802 |
| 1913 | -840 | 2.0 | -0.154 | 0.160 | 4.930 |
| 1914 | -810 | 2.0 | -0.162 | 0.151 | 7.075 |
| 1919 | -770 | 4.0 | 0.072 | 0.210 | 7.561 |
| 1916 | -750 | 4.0 | -0.019 | 0.120 | 4.032 |
| 1917 | -730 | 4.0 | 0.133 | 0.130 | 3.262 |
| 1918 | -710 | 4.0 | -0.130 | 0.117 | 3.480 |
| 1920 | -650 | 10.0 | 0.139 | 0.202 | 8.691 |
| 1921 | -630 | 10.0 | 0.071 | 0.150 | 4.912 |
| 1922 | -610 | 10.0 | 0.256 | 0.144 | 2.719 |
| 1923 | -590 | 10.0 | 0.223 | 0.195 | 6.154 |

LL = 0.5 nA

| Run | HV | PreAmp | non-Lin | Error | $\chi^2$/6df |
|---|---|---|---|---|---|
| 1863 | -1040 | 0.5 | 0.393 | 0.039 | 0.7648 |
| 1865 | -1010 | 0.5 | 0.289 | 0.108 | 4.324 |
| 1866 | -980 | 0.5 | 0.238 | 0.051 | 0.9041 |
| 1867 | -950 | 0.5 | 0.360 | 0.202 | 19.54 |
| 1857 | -1000 | 0.6 | 0.393 | 0.064 | 1.595 |
| 1859 | -970 | 0.6 | 0.354 | 0.095 | 3.488 |
| 1860 | -940 | 0.6 | 0.525 | 0.212 | 15.26 |
| 1861 | -920 | 0.6 | 0.297 | 0.142 | 5.493 |
| 1868 | -900 | 1.0 | 0.344 | 0.269 | 29.49 |
| 1869 | -880 | 1.0 | 0.170 | 0.184 | 11.66 |
| 1870 | -850 | 1.0 | 0.331 | 0.062 | 0.7265 |
| 1872 | -830 | 1.0 | 0.055 | 0.231 | 13.05 |
| 1873 | -800 | 2.0 | 0.206 | 0.148 | 5.657 |
| 1874 | -780 | 2.0 | 0.055 | 0.144 | 7.464 |
| 1875 | -760 | 2.0 | 0.113 | 0.114 | 3.686 |
| 1876 | -740 | 2.0 | 0.469 | 0.237 | 16.29 |
| 1877 | -700 | 4.0 | 0.095 | 0.157 | 6.243 |
| 1878 | -680 | 4.0 | 0.097 | 0.114 | 2.977 |
| 1879 | -660 | 4.0 | 0.053 | 0.146 | 4.984 |
| 1881 | -640 | 4.0 | -0.130 | 0.166 | 8.138 |
| 1883 | -590 | 10.0 | -0.266 | 0.130 | 3.332 |
| 1884 | -570 | 10.0 | 0.166 | 0.124 | 3.616 |
| 1885 | -550 | 10.0 | -0.237 | 0.186 | 6.346 |
| 1886 | -530 | 10.0 | -0.009 | 0.197 | 5.260 |

LL = 6.0 nA

| Run | HV | PreAmp | non-Lin | Error | $\chi^2$/6df |
|---|---|---|---|---|---|
| 1843 | -860 | 0.1 | 0.904 | 0.227 | 16.77 |
| 1844 | -840 | 0.1 | 0.869 | 0.251 | 25.18 |
| 1845 | -820 | 0.1 | 1.269 | 0.346 | 26.10 |
| 1846 | -800 | 0.1 | 0.848 | 0.295 | 29.19 |
| 1847 | -860 | 0.1 | 1.355 | 0.247 | 15.99 |
| 1848 | -840 | 0.1 | 1.054 | 0.194 | 14.76 |
| 1849 | -820 | 0.1 | 0.492 | 0.194 | 17.84 |
| 1850 | -800 | 0.1 | 1.211 | 0.541 | 98.22 |
| 1834 | -720 | 0.3 | -0.148 | 0.163 | 9.668 |
| 1835 | -700 | 0.3 | -0.179 | 0.229 | 9.338 |
| 1837 | -675 | 0.3 | -0.104 | 0.242 | 13.89 |
| 1838 | -650 | 0.3 | 0.205 | 0.316 | 24.99 |
| 1830 | -650 | 0.5 | -0.190 | 0.111 | 2.923 |
| 1831 | -630 | 0.5 | 0.148 | 0.348 | 39.38 |
| 1832 | -610 | 0.5 | -0.268 | 0.213 | 9.548 |
| 1833 | -595 | 0.5 | -0.301 | 0.208 | 7.082 |
| 1839 | -645 | 0.6 | -0.079 | 0.157 | 6.576 |
| 1851 | -630 | 0.6 | -0.308 | 0.084 | 2.558 |
| 1841 | -610 | 0.6 | -0.424 | 0.134 | 5.048 |
| 1842 | -590 | 0.6 | 0.065 | 0.383 | 29.23 |
| 1826 | -570 | 1.0 | -0.325 | 0.190 | 7.729 |
| 1827 | -555 | 1.0 | -0.397 | 0.228 | 9.533 |
| 1828 | -540 | 1.0 | -0.460 | 0.221 | 15.22 |
| 1829 | -520 | 1.0 | -0.099 | 0.170 | 5.098 |
| 1819 | -500 | 2.0 | -0.428 | 0.166 | 5.703 |
| 1820 | -490 | 2.0 | -0.518 | 0.124 | 3.582 |
| 1821 | -475 | 2.0 | -0.301 | 0.159 | 4.882 |
| 1822 | -460 | 2.0 | -0.469 | 0.241 | 9.740 |

LL = 10.0 nA

| Run | HV | PreAmp | non-Lin | Error | $\chi^2$/6df |
|---|---|---|---|---|---|
| 1786 | -780 | 0.1 | 0.038 | 0.139 | 9.707 |
| 1785 | -760 | 0.1 | 0.333 | 0.330 | 21.84 |
| 1782 | -740 | 0.1 | -0.163 | 0.244 | 18.23 |
| 1783 | -720 | 0.1 | -0.160 | 0.187 | 11.51 |
| 1787 | -780 | 0.1 | 0.262 | 0.204 | 22.53 |
| 1788 | -760 | 0.1 | -0.057 | 0.092 | 3.948 |
| 1789 | -740 | 0.1 | -0.060 | 0.247 | 20.74 |
| 1790 | -720 | 0.1 | -0.417 | 0.122 | 7.334 |
| 1791 | -660 | 0.3 | -0.743 | 0.171 | 5.325 |
| 1792 | -640 | 0.3 | -0.698 | 0.241 | 12.76 |
| 1793 | -620 | 0.3 | -0.672 | 0.380 | 23.75 |
| 1794 | -600 | 0.3 | -0.885 | 0.325 | 35.99 |
| 1799 | -590 | 0.5 | -0.920 | 0.274 | 26.76 |
| 1800 | -570 | 0.5 | -0.901 | 0.271 | 16.07 |
| 1801 | -550 | 0.5 | -1.015 | 0.320 | 33.61 |
| 1802 | -530 | 0.5 | -1.231 | 0.265 | 14.08 |
| 1795 | -575 | 0.6 | -1.042 | 0.254 | 10.40 |
| 1796 | -555 | 0.6 | -1.205 | 0.164 | 5.487 |
| 1803 | -535 | 0.6 | -1.378 | 0.253 | 16.20 |
| 1798 | -520 | 0.6 | -1.446 | 0.374 | 21.15 |
| 1804 | -520 | 1.0 | -0.998 | 0.411 | 29.96 |
| 1805 | -505 | 1.0 | -1.421 | 0.379 | 23.99 |
| 1806 | -490 | 1.0 | -1.506 | 0.458 | 25.02 |
| 1807 | -480 | 1.0 | -1.780 | 0.528 | 53.54 |
| 1808 | -460 | 2.0 | -1.530 | 0.253 | 12.60 |
| 1809 | -450 | 2.0 | -1.865 | 0.252 | 16.29 |
| 1810 | -435 | 2.0 | -1.870 | 0.376 | 26.69 |
| 1811 | -425 | 2.0 | -1.823 | 0.348 | 17.32 |

## Plans for MOLLER pmt Linearity Measurements

- Apparatus and technique validated for PREX pmts at 240 Hz ff
  - Conclusion: want pmt $I_C \lesssim 15$nA and $I_A \sim 20$ - 30 $\mu$A
  - Anticipate $< 0.5\%$ non-linearity systematic for PREX-II and even better for CREX
  - Measurements routinely find HV and preamp settings with non-linearity deviations at 0.1 - 0.2% level
- While 30, 120, and 240 Hz ff data give very similar/same results, we see differences at 480 Hz ff–possibly a result of thermal or other instabilities in the flashing LED
- To address expected problems at 960 Hz ff, we plan to implement a chopper wheel setup with phase-locked controller to shutter the LED instead of flash it (M. Gericke's idea)

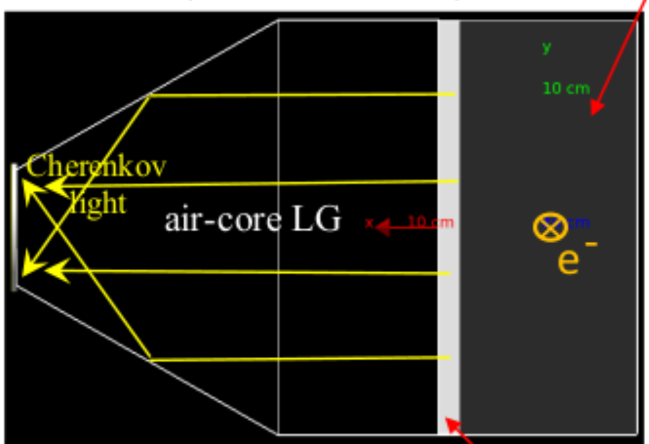
## Plans for MOLLER pmt Linearity Measurements

- ISU group has two ET 9305KQB pmts with factory bases in hand to start testing this fall
  - Anticipated light levels or PE ($I_C$) currents for central-open ring5 pmts at ∼16 nA (∼4 GHz, ∼25 PEs/$e^-$)
  - Will require custom tuned base divider to achieve desired 0.1% non-linearity
  - M. Gericke and group will design bases for future tests; for now, two different factory bases were purchased: one standard circuit and one tapered (for high pulsed linearity)
- A non-trivial complication for precision measurements is calibrating the incident light level or photocathode current. We use special unity gain bases for PREX/CREX; need this for MOLLER

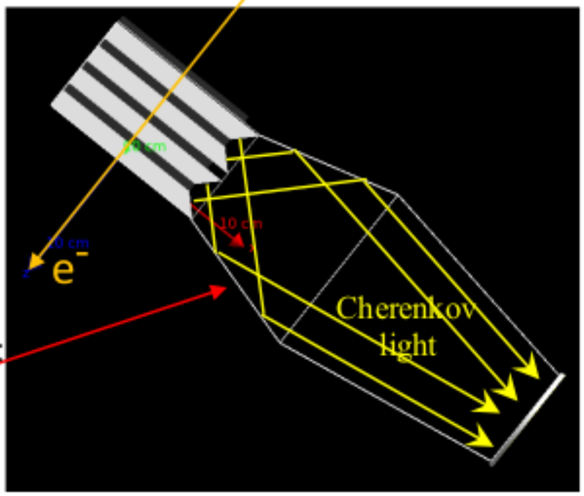
# Baseline Design Stack and Light Guide Concepts

- 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:
  - Current 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**

"Baseline" LG Design (front face view)




4-layer Stack: 8mm thick tungsten (dark grey), interleaved with 10 mm thick quartz (white)




"Baseline" Design (side view)

*Materials (all rad-hard):*

- Tungsten is high purity (99.95%) and quartz is optically polished Spectrosil 2000
- Light guides are aluminum specular reflectors (Miro-silver 27, Anolux, or al. mylar, …)
- Total radiation length: 9.1 $X_0$ tungsten + 0.4 $X_0$ quartz = 9.5 $X_0$

# Quartz and Tungsten Ordered in Nov 2017

- For "benchmarking" prototype stack:
  - Quartz: 6 mm (thick) by 86 mm (tall) by 40 mm (wide) --4 pieces ($975/piece = $3.9k)
  - Quartz: 10 mm (thick) by 90 mm (tall) by 40 mm (wide) --4 pieces ($1005/piece = $4.0k)
  - Tungsten: 6 mm (thick) by 80 mm (tall) by 40 mm (wide) – 4 pieces ($85/piece = $340)
  - Tungsten: 8 mm (thick) by 80 mm (tall) by 40 mm (wide) – 4 pieces ($110/piece = $440)
  - Tungsten: 2 mm (thick) by 80 mm (tall) by 40 mm (wide) – 4 pieces ($25/piece = $100)
- For "full-scale" prototype stack:
  - Quartz: 6 mm (thick) by 111 mm (tall) by 246 mm (wide) -- 4 pieces (~$1750/piece = $7.0k)
  - Quartz: 10 mm (thick) by 115 mm (tall) by 246 mm (wide) -- 4 pieces (~$1940/piece = $7.8k)
  - Tungsten: 6 mm (thick) by 105 mm (tall) by 246 mm (wide) – 4 pieces ($600/piece = $2.5k)
  - Tungsten: 8 mm (thick) by 105 mm (tall) by 246 mm (wide) – 4 pieces ($820/piece = $3.2k)
  - Tungsten: 2 mm (thick) by 105 mm (tall) by 246 mm (wide) – 4 pieces ($200/piece = $0.8k)

Purchasing these pieces allows for Configs 1, 3, and 4 (A and B) to be tested

Total quartz: $25k, total tungsten: $7.5k: Total = $32.5k

- This purchase enables construction of two benchmarking and two full-scale prototype sets
- Building two sets of prototypes will allow for more efficient testing during both SLAC testbeam and cosmic tests at SBU and ISU. We can each build a different configuration to test

# MOLLER Task Tracking: ISU Tasks

| Subsystem | Task | Description | Status | Owner | Relation to Director's Review Report | Estimated Completion Date |
|---|---|---|---|---|---|---|
| **Detectors** | Radiation hardness of detector components | Investigate which detector components need radiation testing and carry out 50 MRad test | Michael and Dustin devise a plan. Status: Initial list being established | Dustin | Page 12:``…, all components in the scattered beam envelope should show negligible damage up to 50 MRad." | May 2019 |
| **Detectors** | QC plan for main detector quartz | Devise plan to evaluate robustness of main detector quartz (Redundant with ``radiation hardness of detector components") | Michael and Dustin to devise a plan? Not yet started | Dustin | Page 12: Recommendation: ``Conduct radiation damage tests to at least 50 MRad to qualify fused silica for use in the thin detector | May 2019 |
| **Detectors** | Shower-Max module mechanical assembly design | This task incorporates the physical design and prototyping of the showerMax detector, as well as the associated mechanical mounting structure | Advanced state of first prototype design, including mechanical assembly | Dustin | Not explicitly mentioned | May 2018 |

# Radiation Hardness Test plan Update

•Radiation hardness testing of mechanical assembly materials and parts (ISU, UM)

- ❖ Irradiated several light-guide (LG) material samples over a 3 day test run from Mar 22 - 24, 2016 at the Idaho Accelerator Center (IAC) using 8 MeV, 65 mA $I_{peak}$, 4μs pulse width at 250 Hz rep-rate (dose exposure rate was calculated but too high to measure):
  - Measured LG specular reflectivity for 200 – 800 nm at 90, 60, 45, and 30 degrees.
  - No measurable change in reflectivity was detected for >>50 MRad exposure
- ❖ Other assembly materials to test could include Kapton and Tedlar (light tight wrappings) and possibly 3D-printed custom plastic assembly components (Nylon, ABS, PLA, …) as well as high-density shielding plastics, epoxies, …

•Radiation hardness testing of electronic components: active bases, preamps, …(ISU, UM)

•Main Detector Quartz Robustness (radiation hardness, QA, etc.) (ISU, UM)

- ❖ Apparatus developed to make relative transparency measurements between 200 – 800 nm
  - Uses Ocean Optics USB spectrometer, UV-Visible light source, custom holder/stand
- ❖ Energy deposition calculations (dE/dx and brem) underway for 8 MeV beam and 1.5 cm thick quartz—for heating and thermal expansion considerations (do not want to crack quartz)
- ❖ Developed plan to calibrate and monitor beam dose exposure during study
- ❖ Had a 1 day IAC test run on May 31, 2018; dose exposure rates calibrated; performed preliminary quartz irradiation test

# Radiation Hardness QA for quartz and other components

## 25 MeV LINAC (Main Hall and Airport)

RF Frequency: 2856 MHz (S-Band)

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

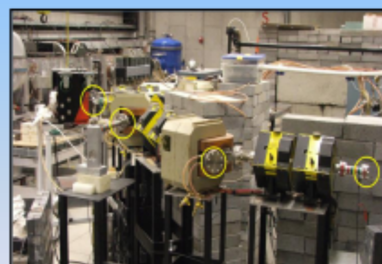
Pulse Width: ~50ns to 4 micro seconds

Repetition Rate: single pulse to 360 Hz

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

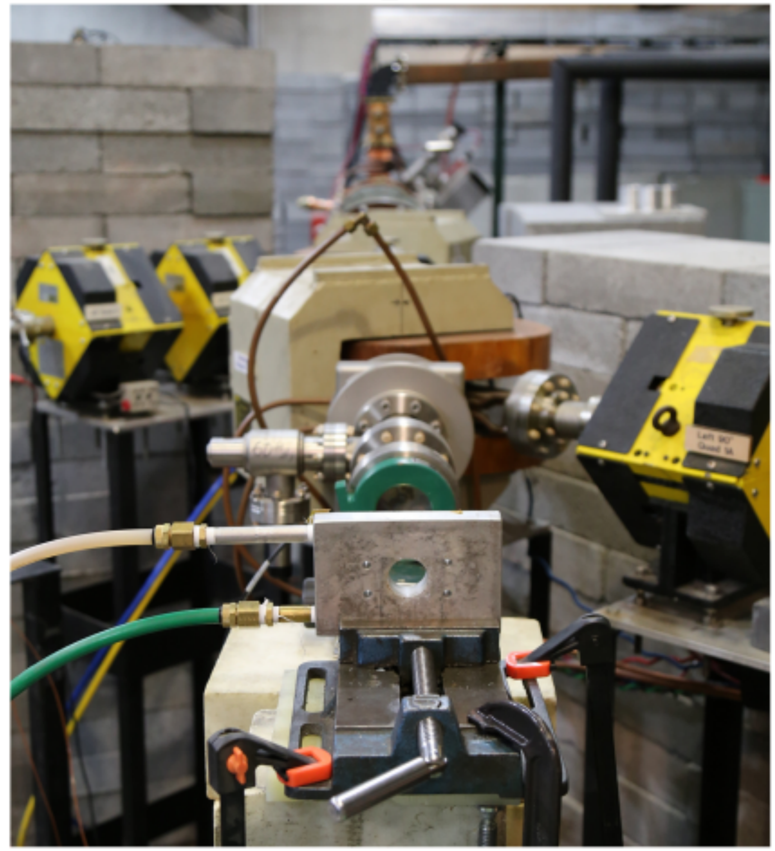
25B Energy vs Current

| 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 |

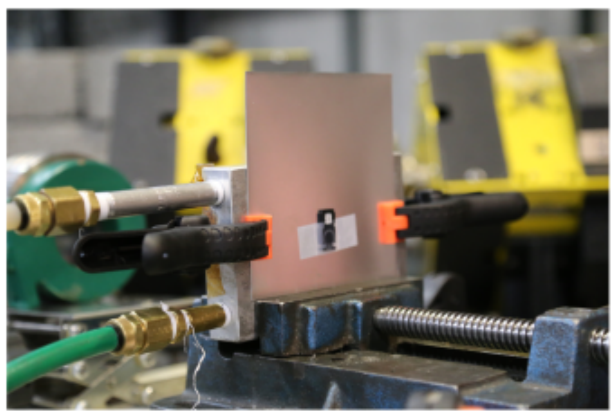


ISU

Idaho Accelerator Center



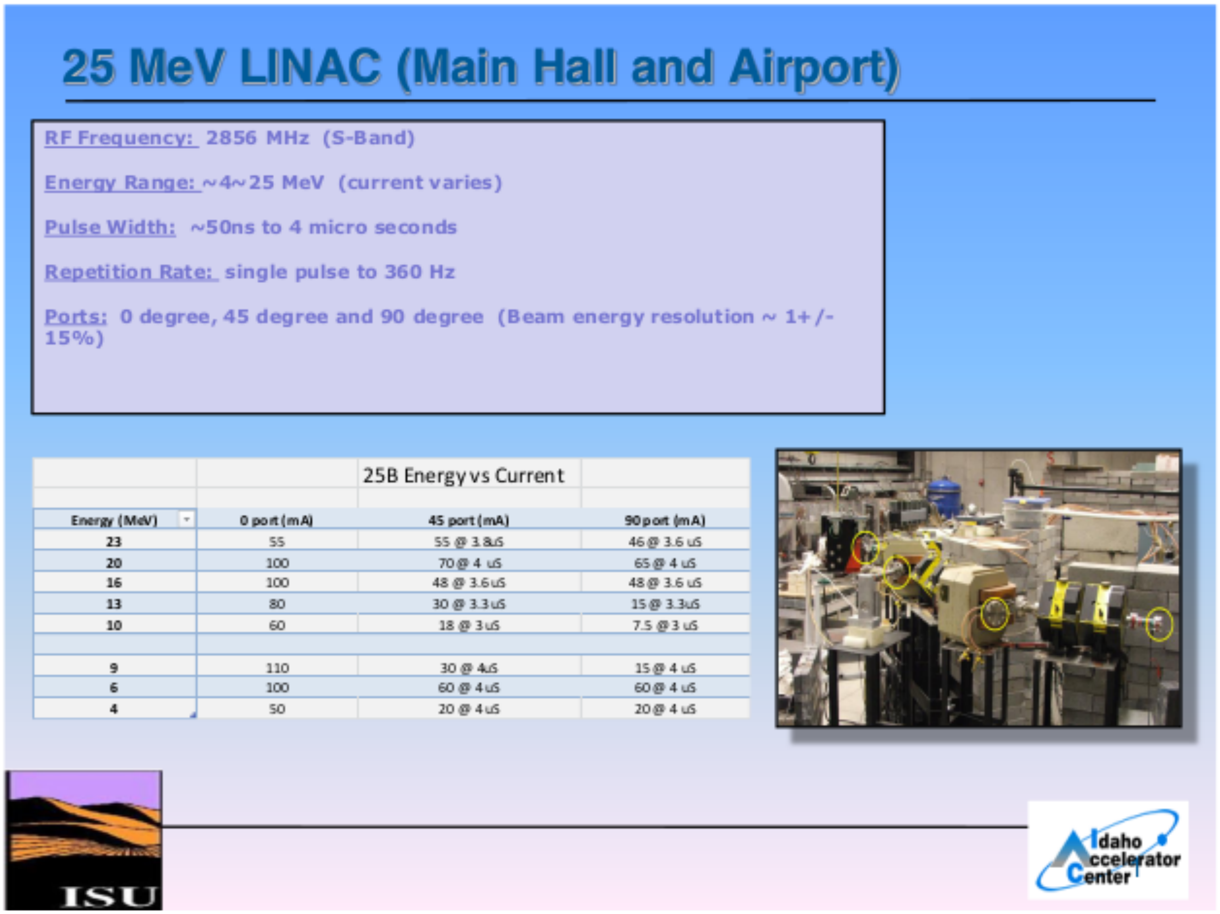
- The key issue is how well can we calibrate dose exposure?



- Performed a 1 day engineering run this past spring to address this question as well as perform preliminary radiation hardness QA quartz studies

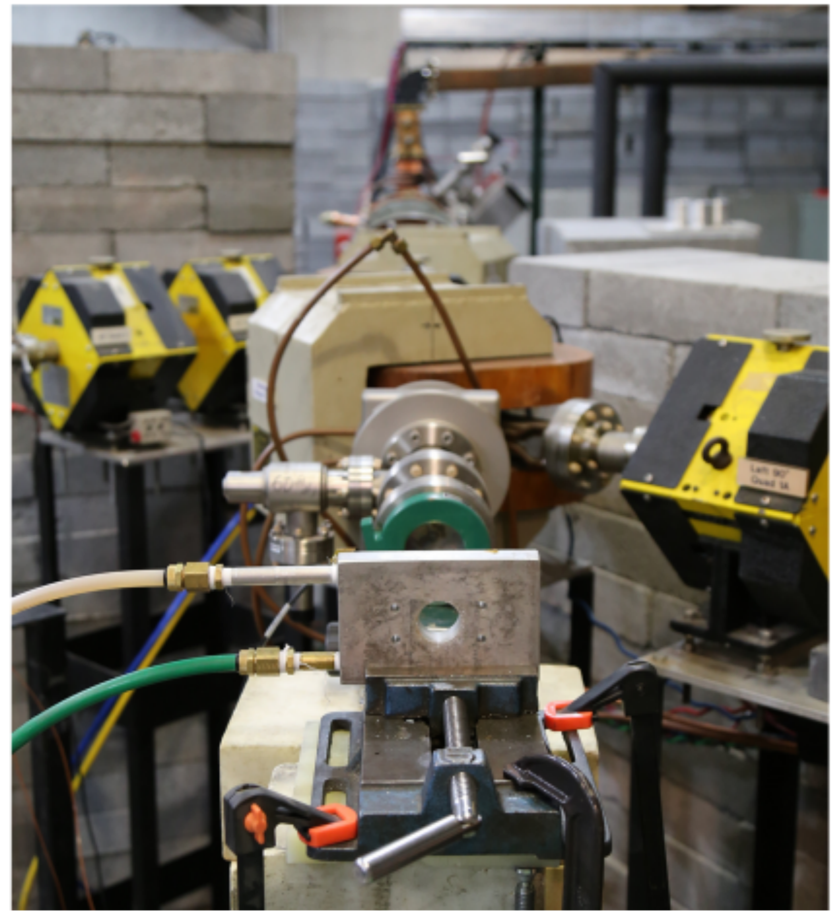
# Radiation Hardness QA for quartz and other components

- 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

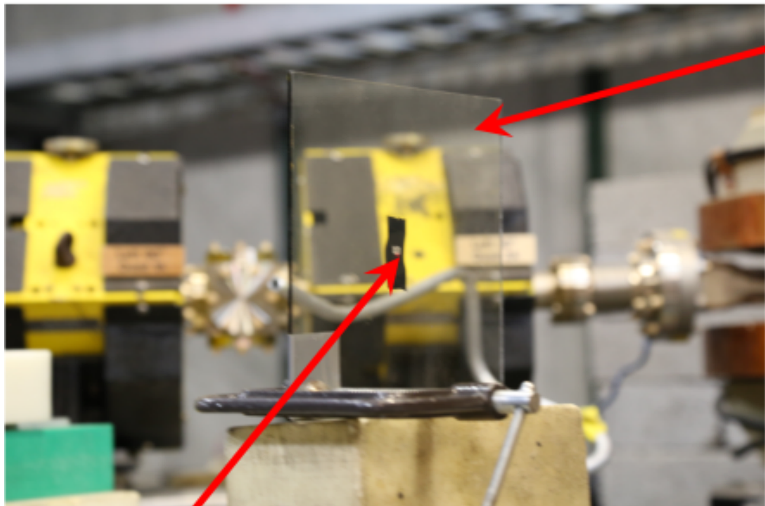



25B Energy vs Current

| 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 |

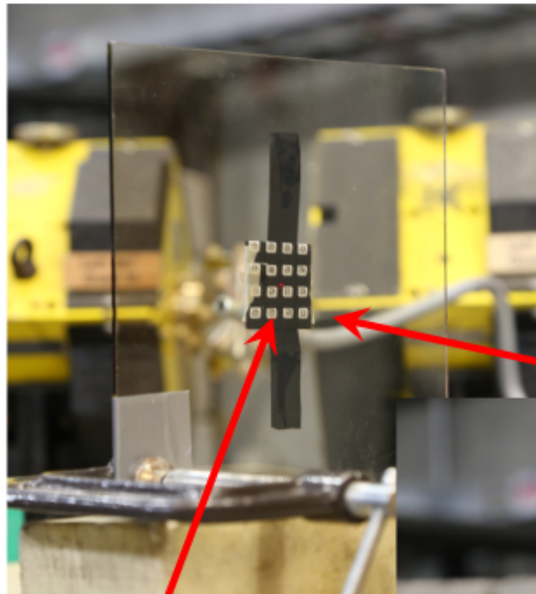


# Beam Dose Exposure Rate Calibrations (May 2018)



Glass slide for spot profile measurements

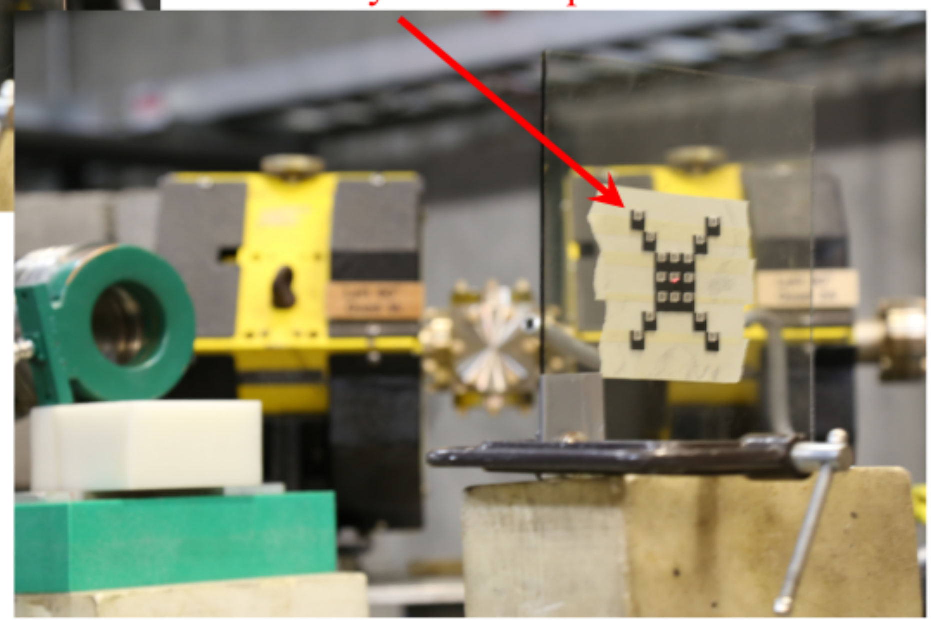
Optically Stimulated Luminescence (OSL) dosimeter (~ 7 mm by 7 mm square)



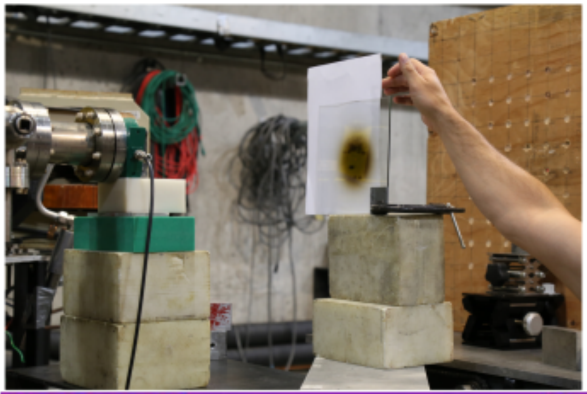
ISU MS degree student Connor Harper's thesis based on this work: https://www2.cose.isu.edu/~mcnudust/publication/studentWork/connorHarperThesis.pdf

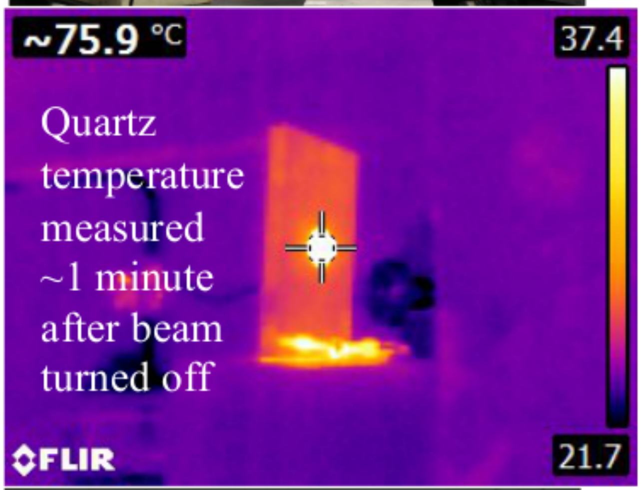
OSL arrays for dose profile measurements

Laser alignment

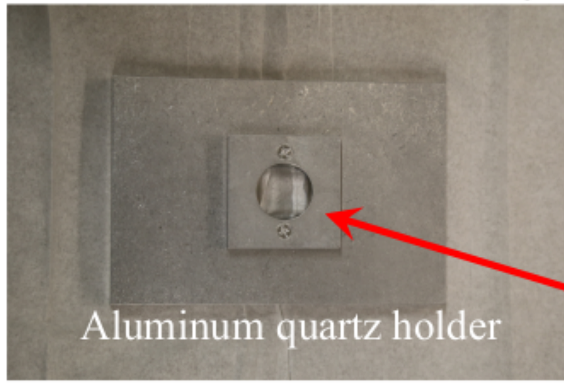


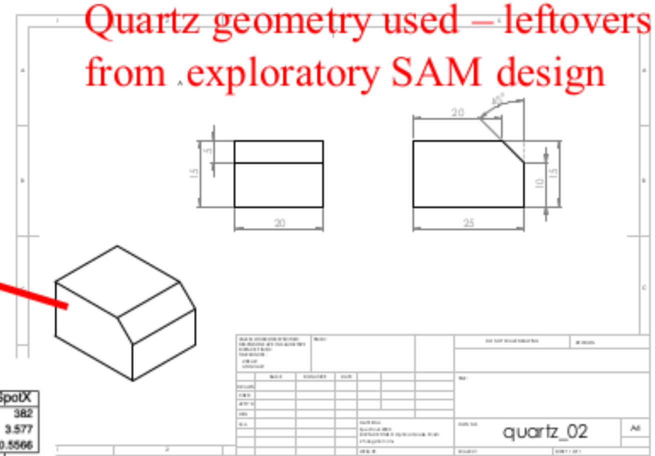
# Quartz Irradiations (May 2018)

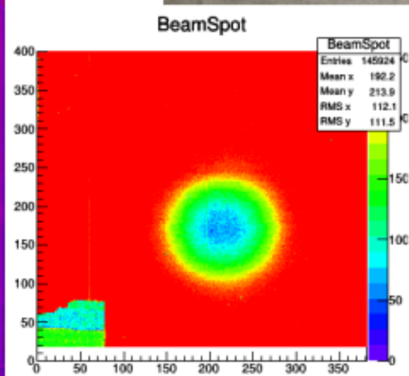


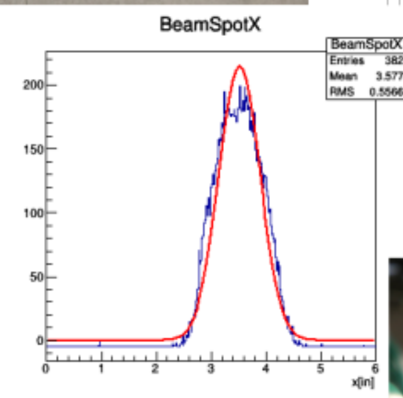


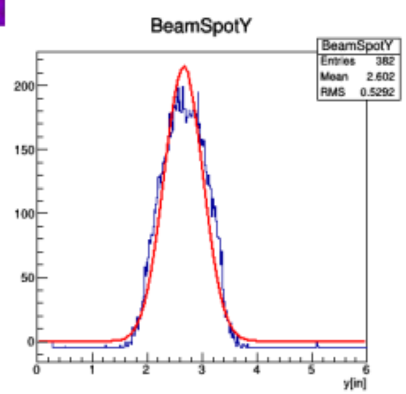




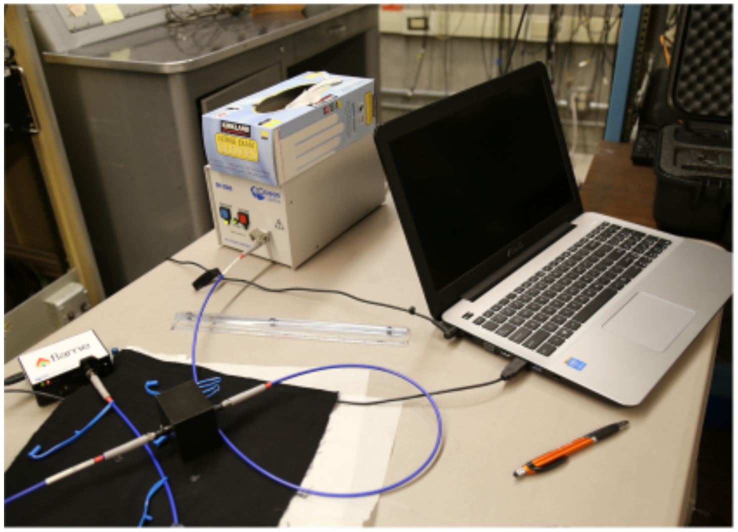



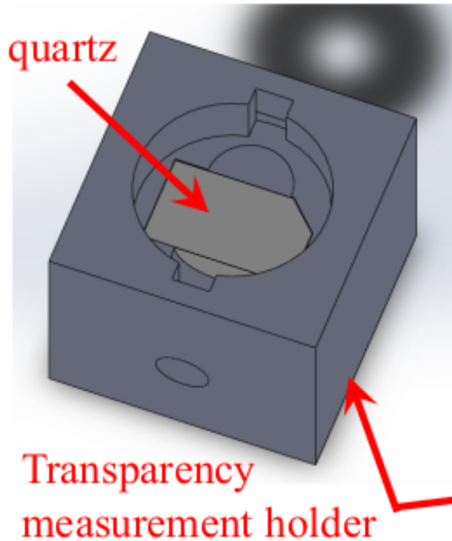

**2018-05-31_15-01_Pulses_1006_50cm.png**

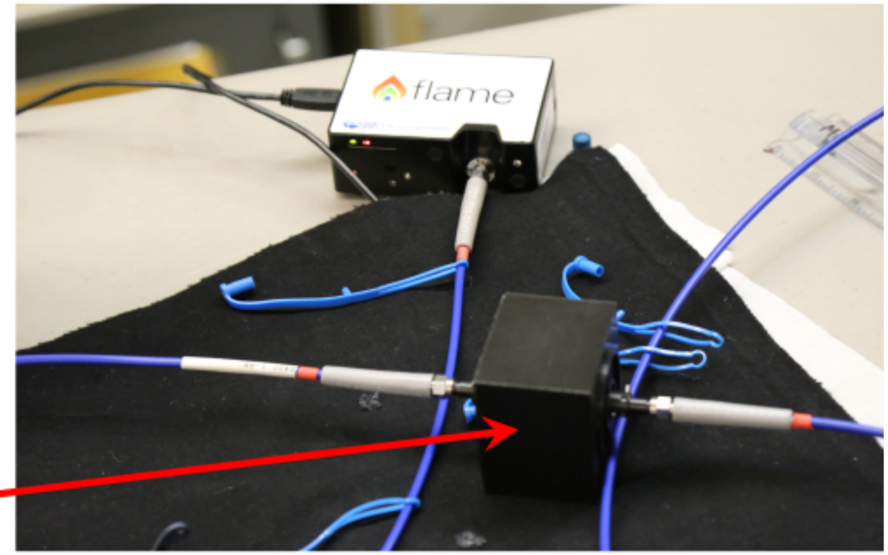
**x-center = 3.512 in, y-center = 2.661 in**

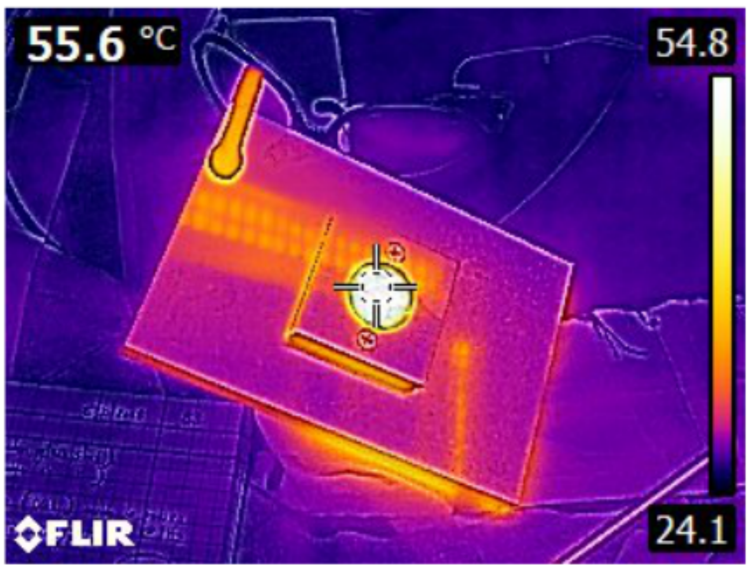
**glass plate at 50cm from beam window**

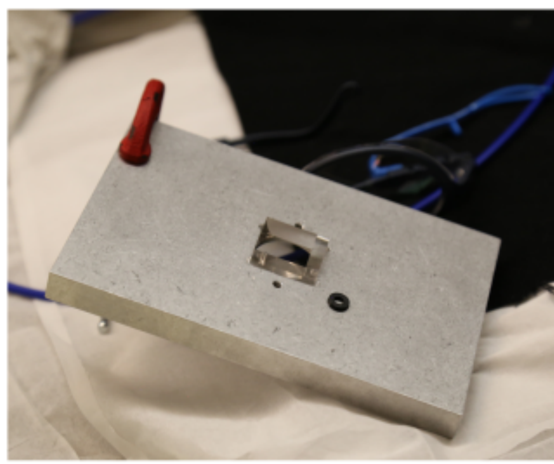
# Quartz Transparency Measurements

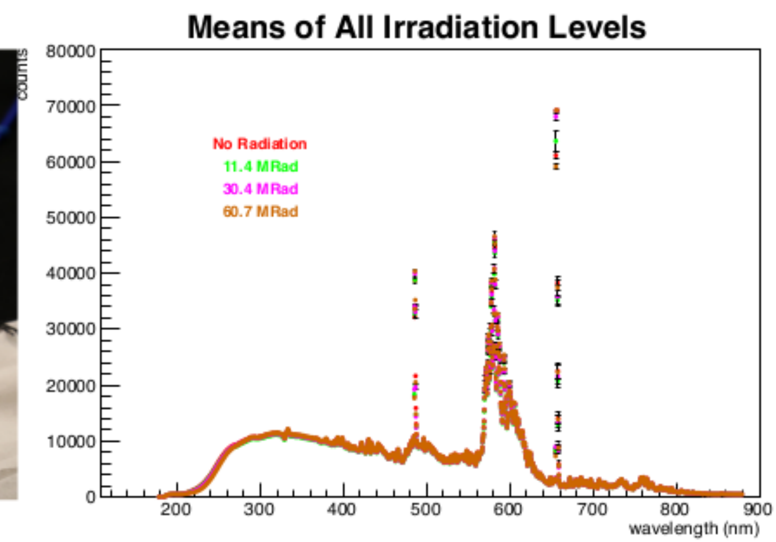




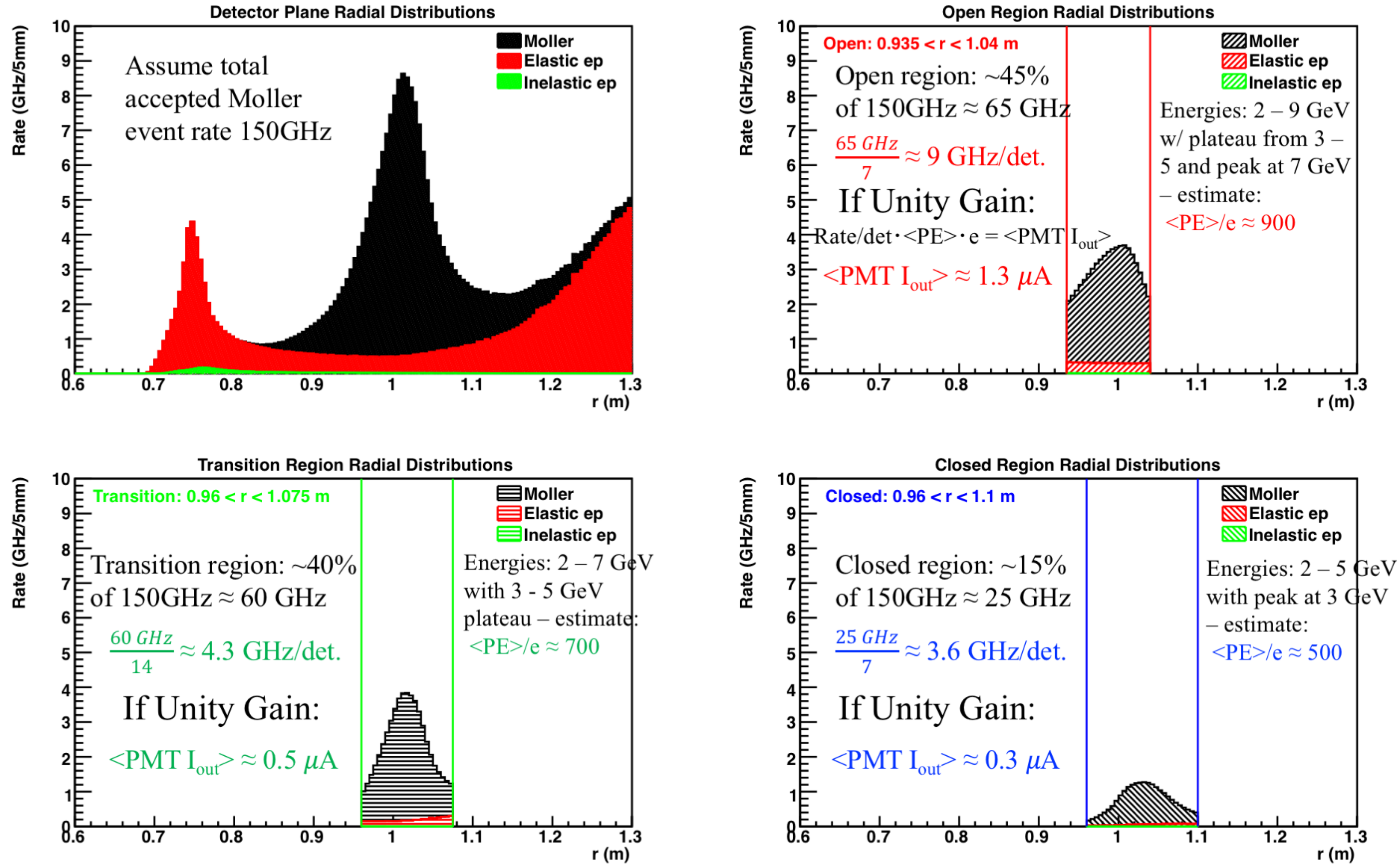





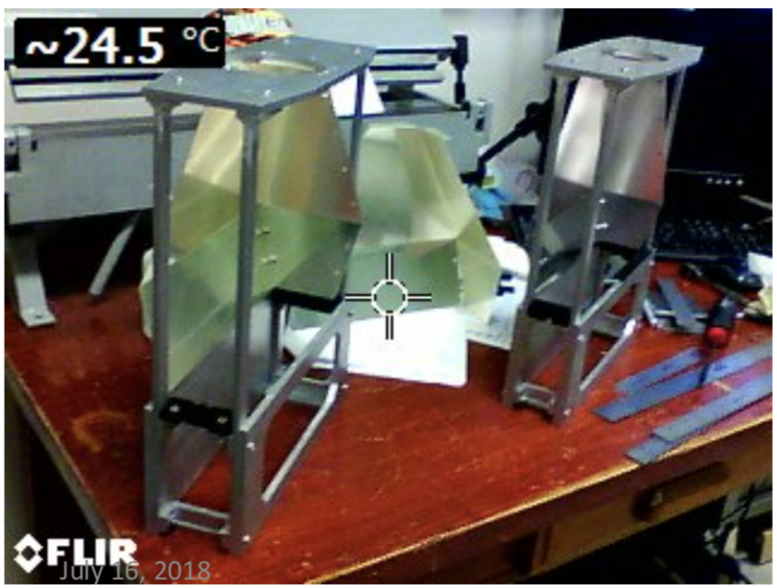
# Unity Gain operation with Baseline design?




- Could be possible to use conventional 3" pmts with electronic switching between unity gain base (integrating mode) and high gain base (counting mode)

## ShowerMax Prototype Construction Timeline


- Feb - Mar 2018: Benchmarking prototype frames fabricated with 3D-printer using ABS plastic (configs 1A and 1B)
- April 2018: Full-scale aluminum frame and light guide cut-outs fabricated at machine shop
- May 2018: Light guide bending and frame assembly at ISU for full-scale configs 1A and 1B
- June 2018: Config 1A full-scale and benchmarking prototype frames and LG delivered to SBU for stack assembly and installation





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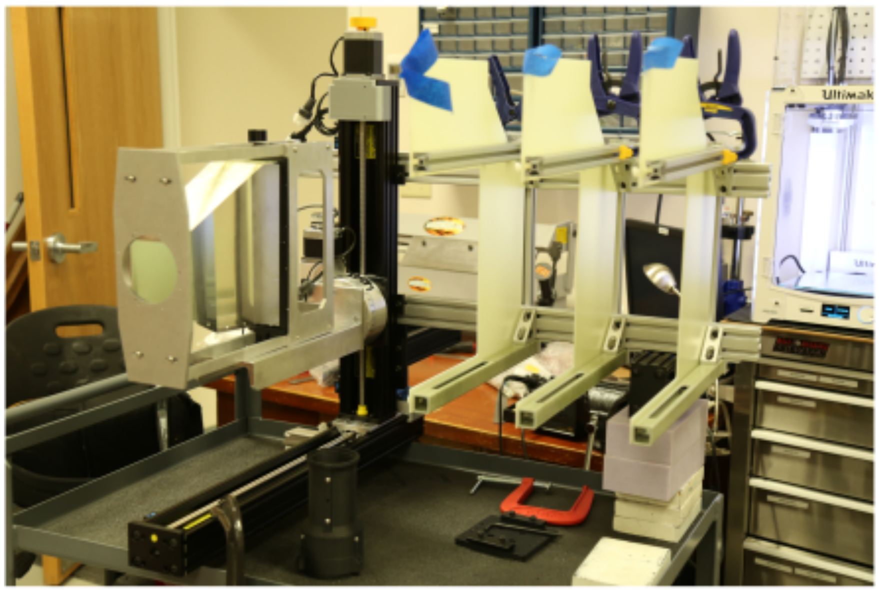
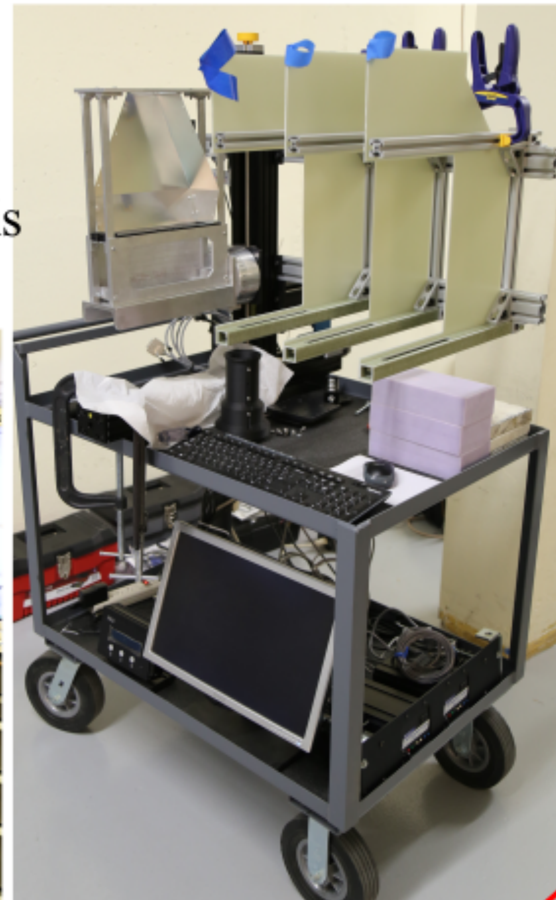
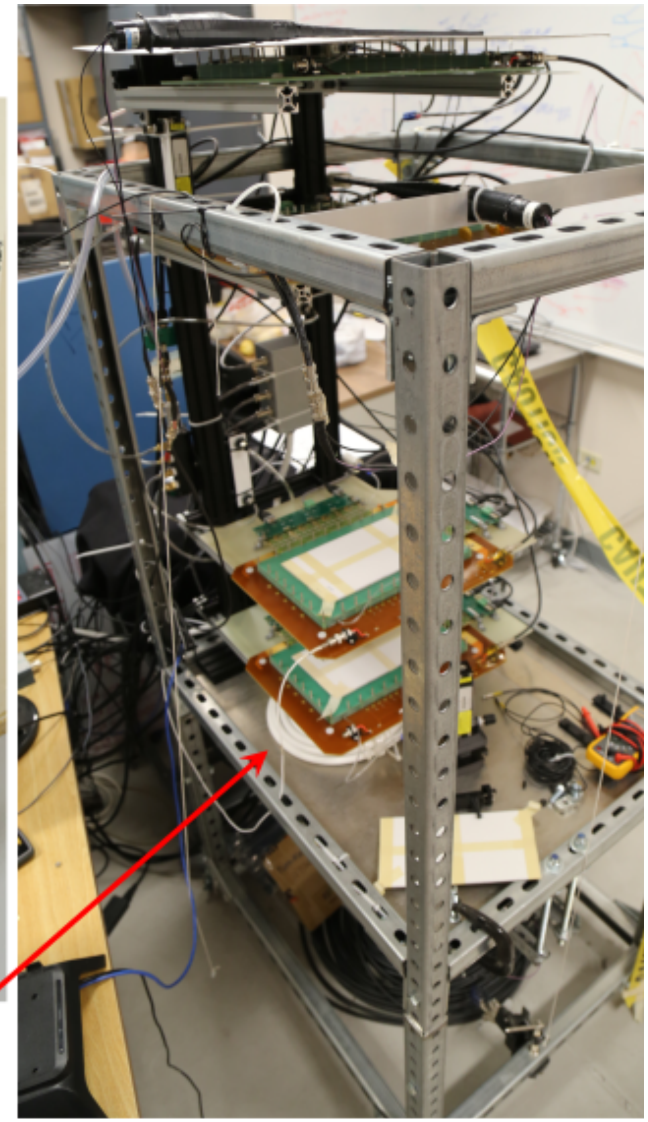
# Teatbeam Apparatus under construction

- Testbeam stand under construction
- Motion control system in place
- GEM system is operational, analysis software under development

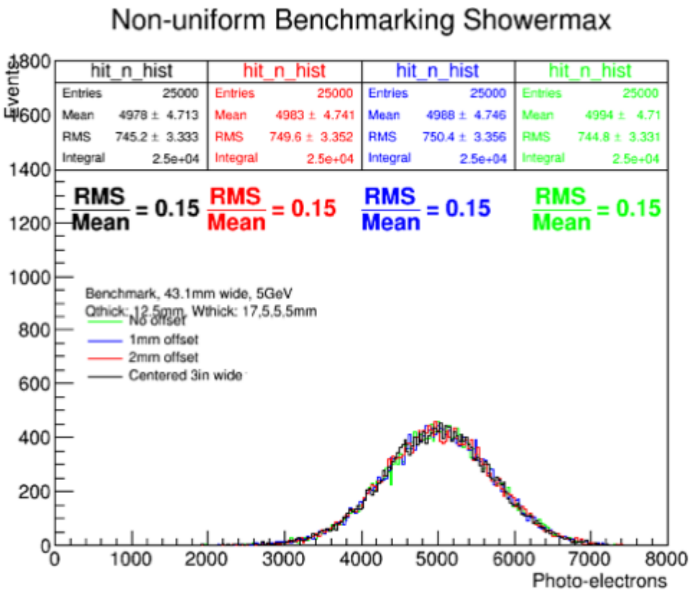




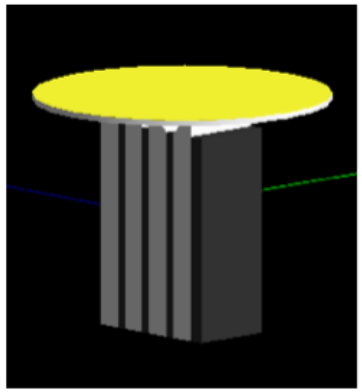


ISU Cosmic stand with 4 GEM chambers

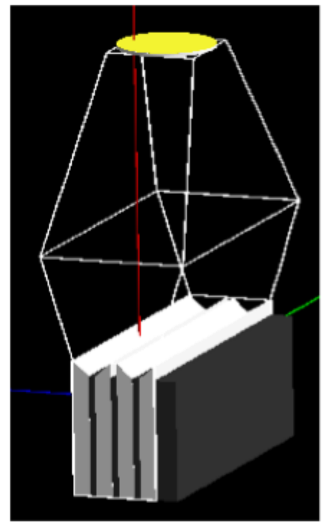
# Candidate Design for Stack Prototype: Config #2

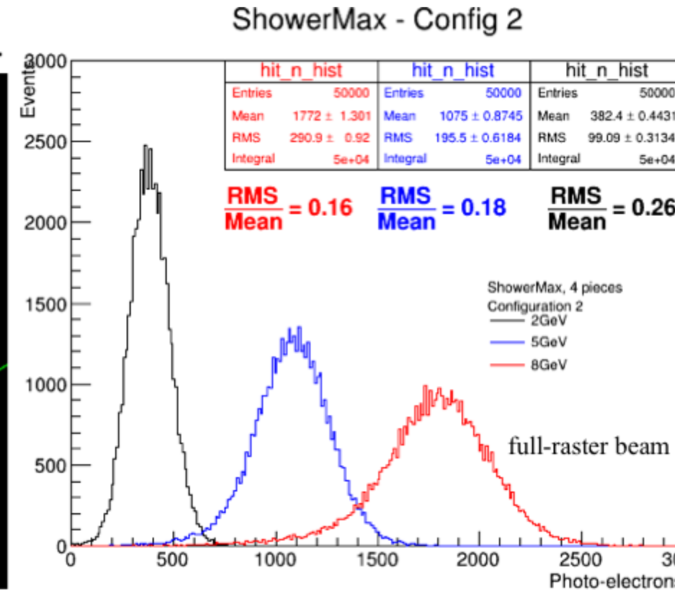



BenchMarking MC Visualization



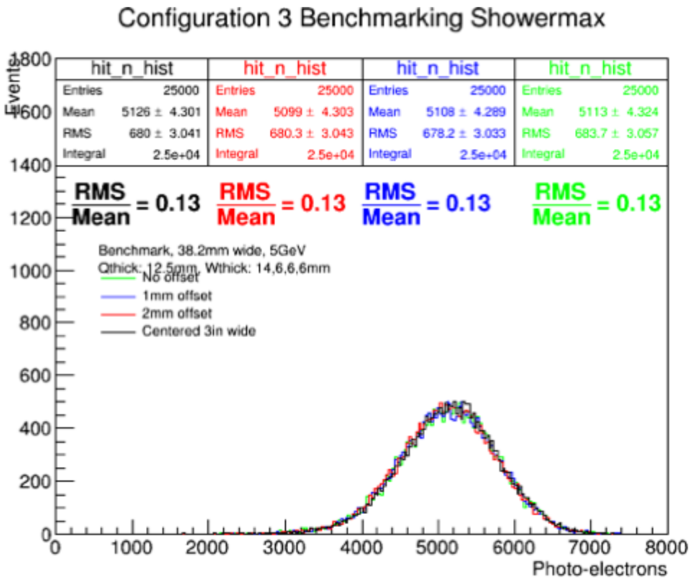
Full Scale MC Vis.



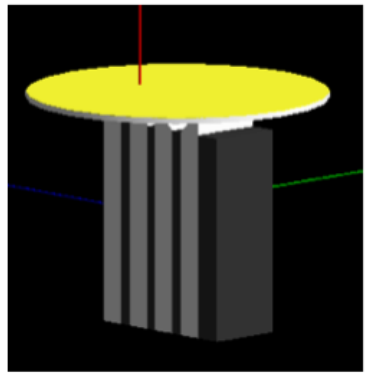



| Config # | $t_f$ (mm) | $t_Q$ (mm) | $t_W$ (mm) | b (mm) | a (mm) | $X_0$ | $R_{mol}$ (mm) | Leakage (%) 2, 5, 8 GeV from G4 MC | 1mm offset Leakage (%) | 2mm offset Leakage (%) | Bench. Mean PEs | Bench. RMS / Mean | full-scale Mean PEs | full-scale RMS / Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 17 | 12.5 | 5 | 65 | 43.2 | 9.5 | 11.0 | ~0<br>~0 | ~0<br>~0 | ~0<br>~0 | 2412<br>4994 | 0.19<br>0.15 | 382<br>1075<br>1772 | 0.26<br>0.18<br>0.16 |

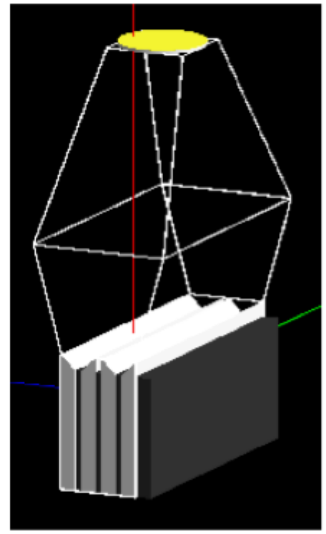
# Candidate Design for Stack Prototype: Config #3

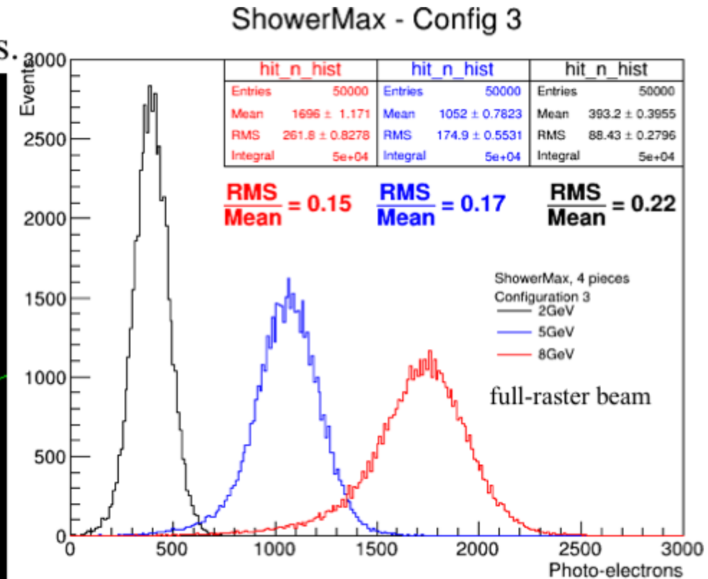



BenchMarking MC Visualization



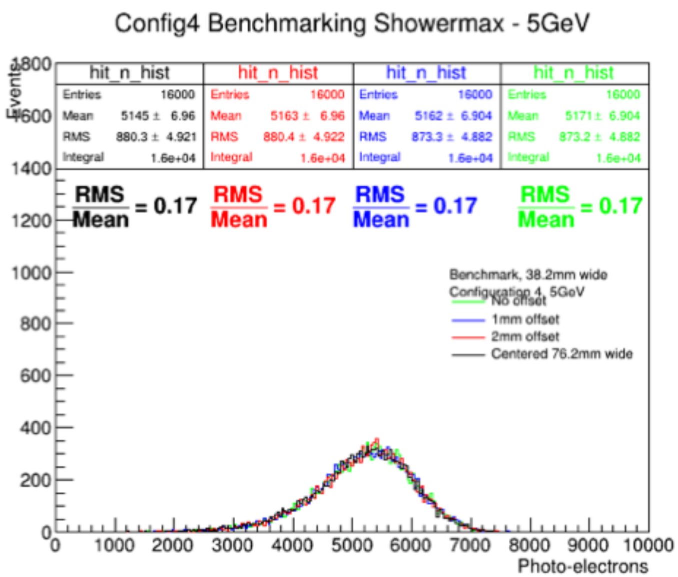
Full Scale MC Vis.



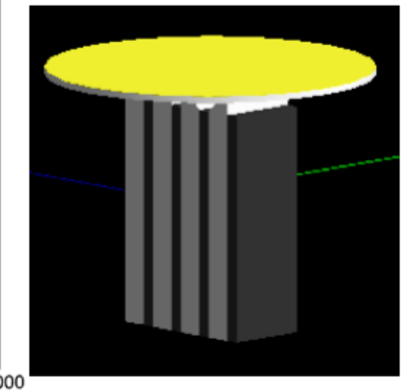



| Config # | $t_f$ (mm) | $t_Q$ (mm) | $t_W$ (mm) | b (mm) | a (mm) | $X_0$ | $R_{mol}$ (mm) | Leakage (%) 2, 5, 8 GeV from G4 MC | 1mm offset Leakage (%) | 2mm offset Leakage (%) | Bench. Mean PEs | Bench. RMS / Mean | full-scale Mean PEs | full-scale RMS / Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 14 | 12.5 | 6 | 68 | 38.2 | 9.5 | 11.0 | 0.5<br>0.3 | 0.6<br>0.4 | 0.8<br>0.5 | 2412<br>5113 | 0.19<br>0.13 | 393<br>1052<br>1696 | 0.22<br>0.17<br>0.15 |

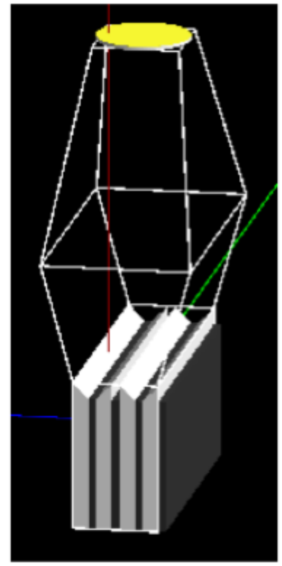
# Candidate Design for Stack Prototype: Config #4

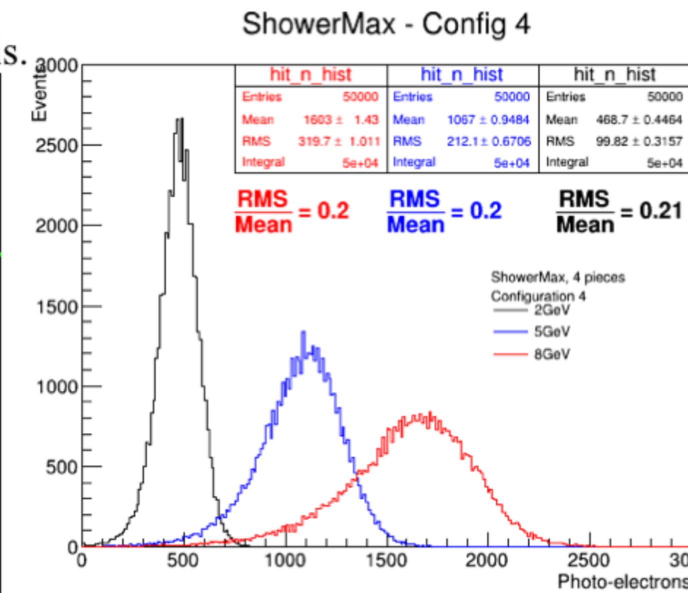



BenchMarking MC Visualization



Full Scale MC Vis.






| Config # | $t_f$ (mm) | $t_Q$ (mm) | $t_W$ (mm) | b (mm) | a (mm) | $X_0$ | $R_{mol}$ (mm) | Leakage (%) 2, 5, 8 GeV from G4 MC | 1mm offset Leakage (%) | 2mm offset Leakage (%) | Bench. Mean PEs | Bench. RMS / Mean | full-scale Mean PEs | full-scale RMS / Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 6 | 12.5 | 6 | 68 | 38.2 | 7.3 | 11.0 | ~0<br>~0 | ~0<br>~0 | ~0<br>~0 | 5171 | 0.17 | 469<br>1067<br>1603 | 0.21<br>0.20<br>0.20 |

# Simulation Results for new Stack Configs

| Config # | t_f (mm) | t_q (mm) | t_w (mm) | b (mm) | Max A (mm) | X | Tungsten Weight (N) | Quartz Weight (N) | Total Weight (N) | Moliere R_m (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1A | 8 | 10 | 8 | 64 | 44.59 | 9.46 | 156.09 | 35.57 | 191.66 | 11.00 |
| 1B | 8 | 6 | 8 | 48 | 61.48 | 9.33 | 156.09 | 35.57 | 191.66 | 11.00 |
| 4A | 6 | 10 | 8 | 64 | 44.59 | 8.89 | 146.33 | 35.57 | 181.91 | 11.11 |
| 4B | 6 | 6 | 6 | 42 | 65.73 | 7.04 | 117.07 | 35.57 | 152.64 | 11.53 |

| | Benchmark - 2GeV | | | |
|---|---|---|---|---|
| Config # | RMS/Mean | Leakage (%) | Leakage 2mm offset (%) | Leakage 2° angle (%) |
| 1A | 0.17 | 0 | 0 | -0.1 |
| 1B | 0.19 | 0 | 0 | 0.2 |
| 4A | 0.19 | 0 | 0 | - |
| 4B | 0.21 | 0 | 0 | - |

| | Full Scale ShowerMax – 2GeV | | |
|---|---|---|---|
| Config # | RMS | Mean | RMS/Mean |
| 1A | 63.36 | 315.9 | 0.20 |
| 1B | 45.46 | 197.7 | 0.23 |
| 4A** | 60.16 | 300.2 | 0.20 |
| 4B** | 39.67 | 179.3 | 0.22 |

| | Benchmark - 5GeV | | | |
|---|---|---|---|---|
| Config # | RMS/Mean | Leakage (%) | Leakage 2mm offset (%) | Leakage 2° angle (%) |
| 1A | 0.13 | 0.04 | 0.09 | -0.4 |
| 1B | 0.14 | 0 | 0 | 0.2 |
| 4A | 0.17 | 0.06 | 0.3 | - |
| 4B | 0.19 | 0 | 0 | - |

| | Full Scale ShowerMax – 5GeV | | |
|---|---|---|---|
| Config # | RMS | Mean | RMS/Mean |
| 1A | 123.7 | 768.5 | 0.16 |
| 1B | 87.82 | 473.6 | 0.19 |
| 4A** | 126.8 | 677.4 | 0.19 |
| 4B** | 80.61 | 397.4 | 0.20 |

| | Benchmark – 8GeV | | | |
|---|---|---|---|---|
| Config # | RMS/Mean | Leakage (%) | Leakage 2mm offset (%) | Leakage 2° angle (%) |
| 1A | 0.12 | 0 | 0 | - |
| 1B | 0.13 | 0 | 0 | - |
| 4A* | 0.18 | 0 | 0 | - |
| 4B | 0.19 | 0 | 0 | - |

| | Full Scale ShowerMax – 8GeV | | |
|---|---|---|---|
| Config # | RMS | Mean | RMS/Mean |
| 1A | 183.2 | 1197 | 0.15 |
| 1B | 129.1 | 732.3 | 0.18 |
| 4A** | 187.9 | 1012 | 0.19 |
| 4B** | 118.8 | 591.3 | 0.20 |