Wavelength-Shifting Fiber Studies for the Mu2e Cosmic-Ray Veto Detector

13 July 2021

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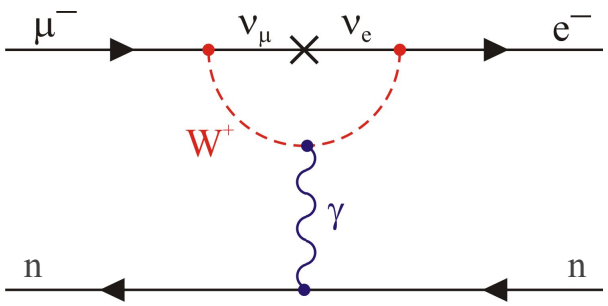
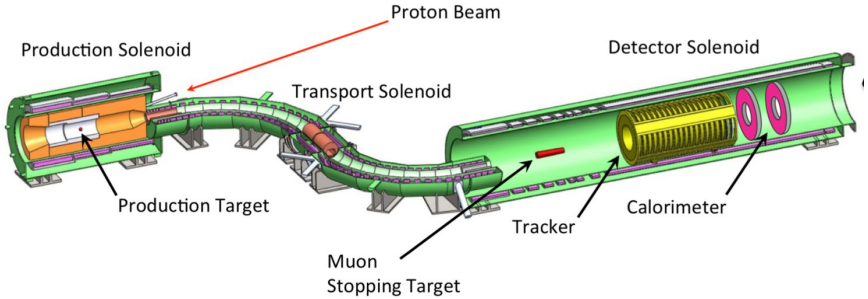
Mu2e Experiment Searches for New Physics

The ***Muon-to-Electron Conversion (Mu2e)*** experiment is a high-energy particle physics experiment mounted at ***Fermilab*** to search with great precision (four-orders of magnitude below current sensitivity limits) for a ***neutrino-less*** muon to electron conversion in the presence of a nucleus, causing never-before observed ***charged lepton flavor violation (CLFV)***.

- Probes masses up to a 10^4 TeV energy scale
- Beyond the Standard Model (BSM) physics
- Largest background induced by cosmic-ray muons



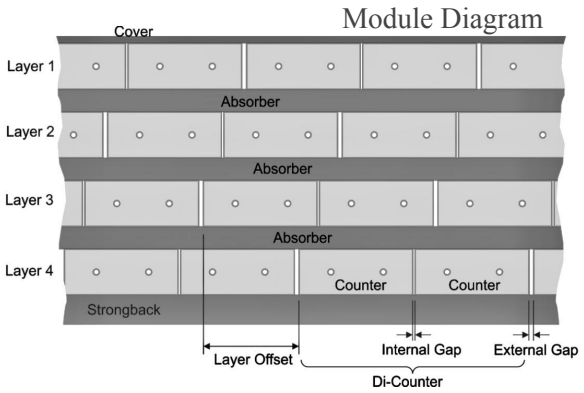
Negligible/Unobservable Standard Model (SM) Process

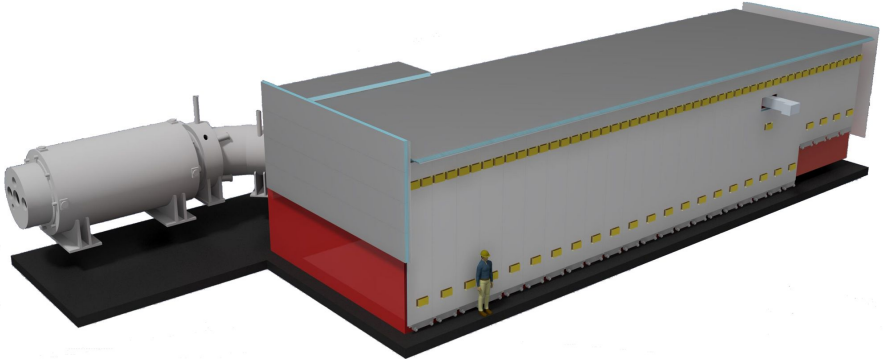


CRV Detector Needed to Track False Signals

The **Cosmic-Ray Veto (CRV) Detector** surrounds the Mu2e apparatus and consists of layered scintillators (with fiber) and absorber sheets, and detects **cosmic-ray muons** that would produce **false signals**.

- Overall efficiency of 99.99% required
  - Background summation requirement: < 1 event over the experiment's lifetime
- Low dead time
- Operation in high-intensity environment

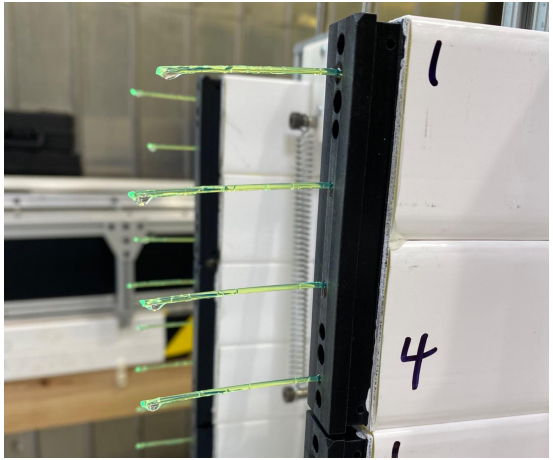




Mu2e-doc-38714-v1

CRV Detector Fabrication

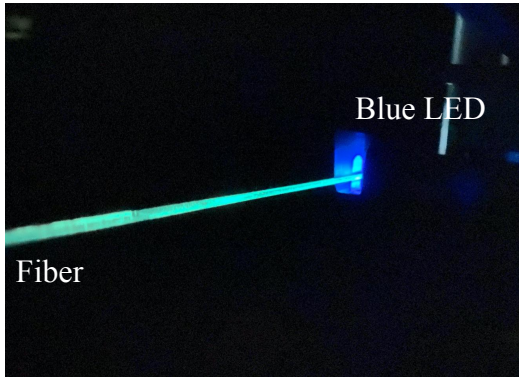
@ UVa's High-Energy Physics Lab

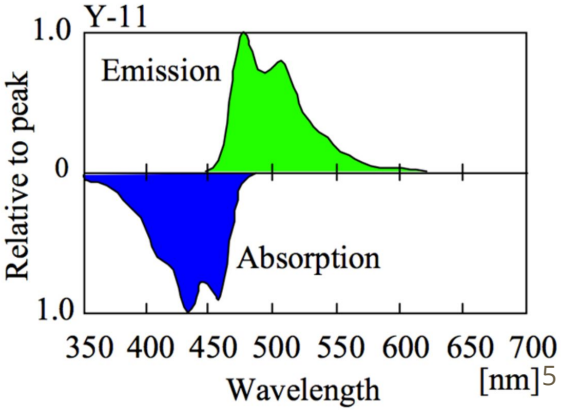


Wavelength-Shifting (WLS) Fibers Decrease Incident Light Frequency for Detectors to Read

Kuraray Y11 fiber contains fluorescent dye which absorbs blue (375-475 nm) light and re-emits green (450-600 nm) light

- Shifts high-frequency light to low-frequency light
- Higher light wavelength = better attenuation length
  - Therefore, shifting wavelengths to green light is desired for long, multi-meter counters
- Data read out by silicon photomultipliers (SiPMs)



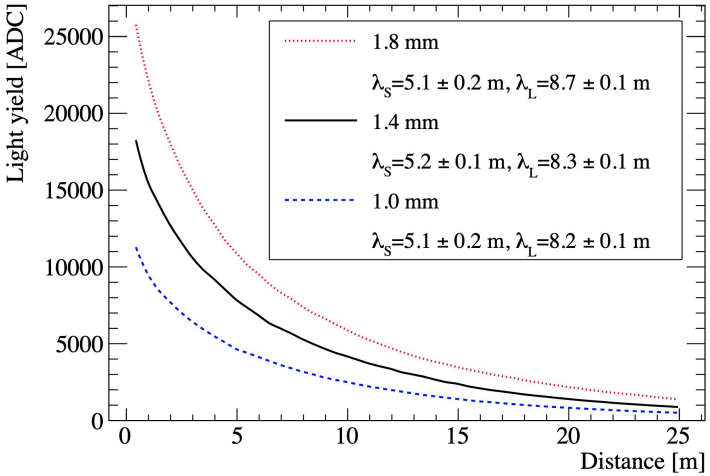


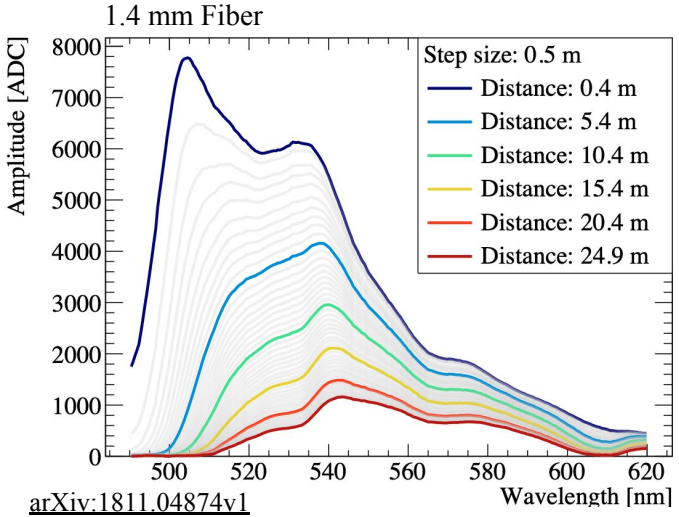
1.4 mm Fiber Performance was Originally Sufficient …

1.4 mm diameter fiber was originally chosen as the optimal fiber diameter (in 2018)

- Light Yield
- Attenuation Properties
- Overall Cost

However, light yield degradation over time and scintillator aging was observed





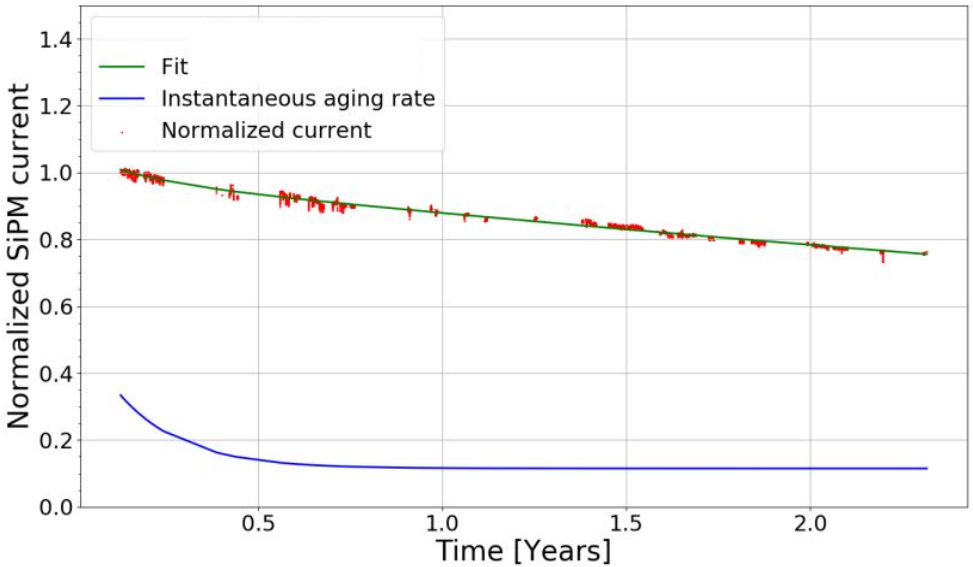
arXiv:1811.04874v1

Di-counter Aging Leads to Fiber Diameter Change Decision

- Design predicated on scintillator extrusion aging estimate of 3% per year (~ 9% early measurement actual aging)

- To compensate for light yield decline, a larger diameter fiber was ordered: 1.4 mm → 1.8 mm

- Must test the 1.8 mm fiber to ensure it meets quality specifications

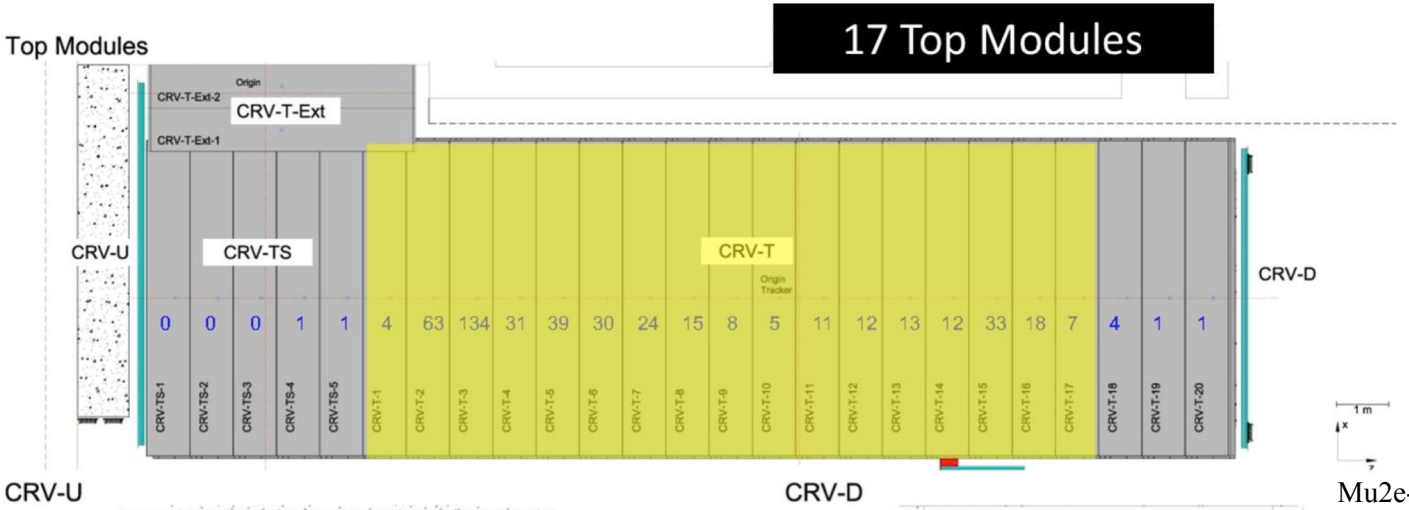


Nucl.Instrum.Meth.A 890 (2018) 84-95

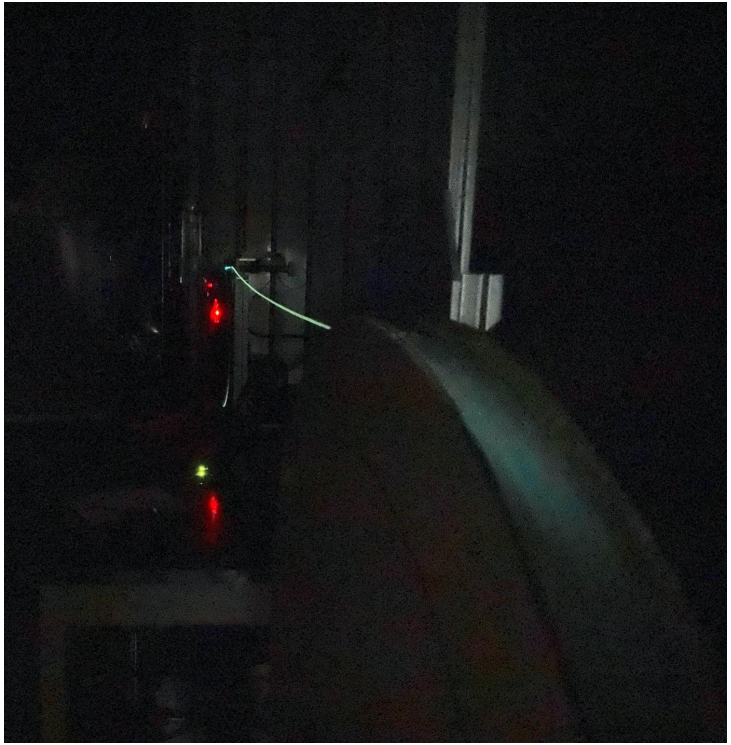
Critical CRV-T Modules Will Contain 1.8 mm Fiber

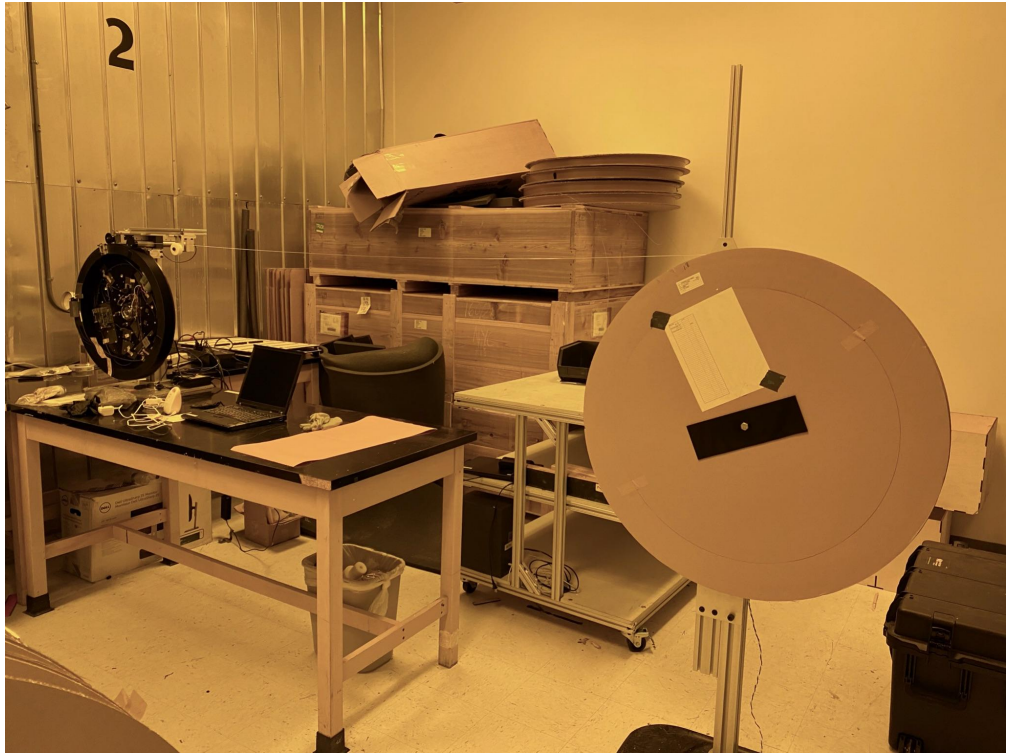
The CRV Detector's 17 most important modules (CRV-T) will hold the better and longer performing 1.8 mm fiber, while the other CRV sides still contain 1.4 mm fiber.

- 14 km of 1.8 mm fiber ordered
- 1.8 mm fiber recorded ~24% greater light yield than 1.4 mm fiber (as measured in test beam)

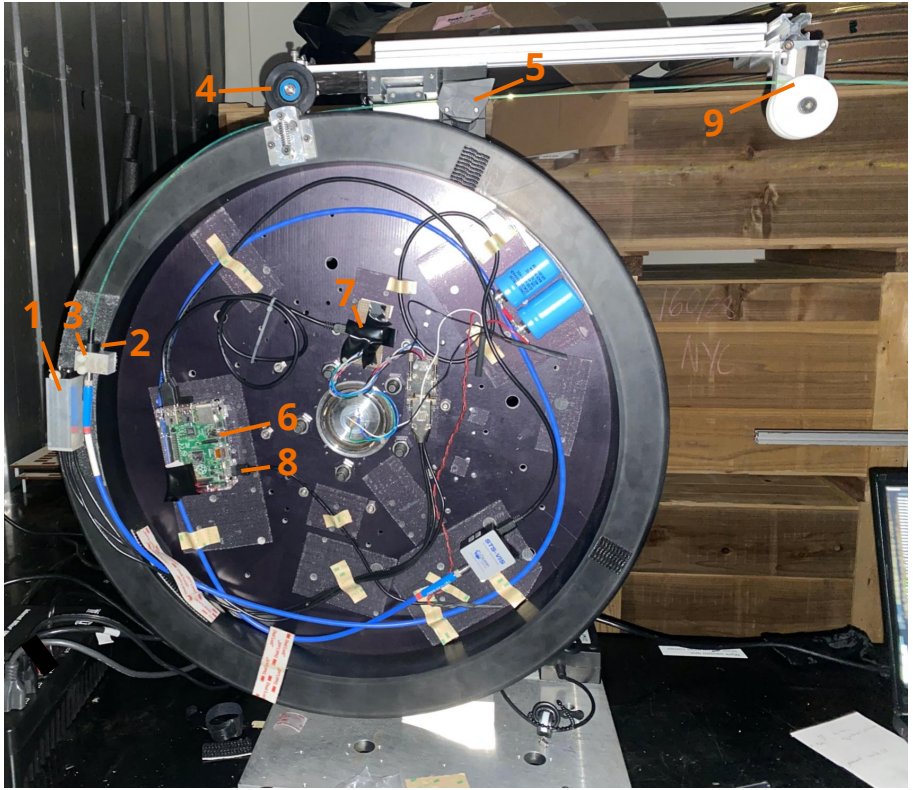


Fiber Testing System Layout @ UVa





Fiber Testing Drum Components @ UVa



1. Photodiode Port

2. Fiber Guide

3. Spectrometer Port

4. Drum Roller

5. Blue LED

6. Raspberry Pi

7. Orange Light (under electrical tape)

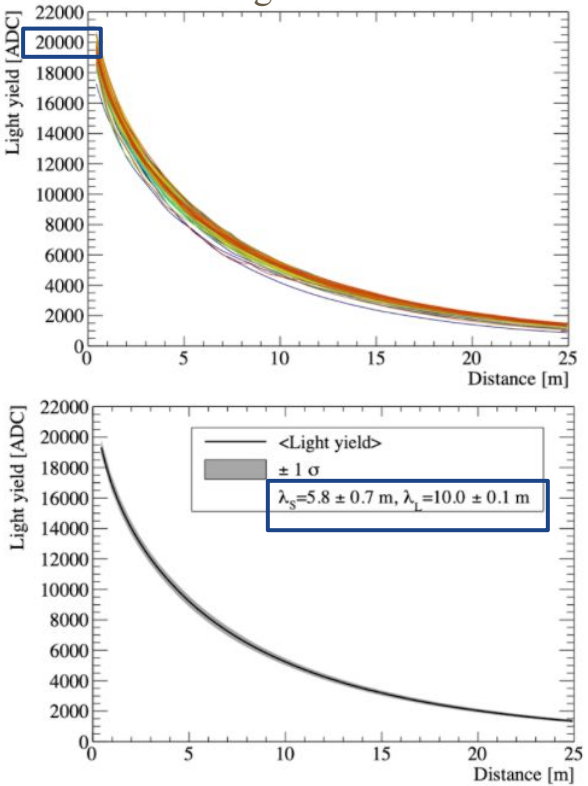
8. Raspberry Pi Power Cord

9. Fiber Track with Magnetic Cap

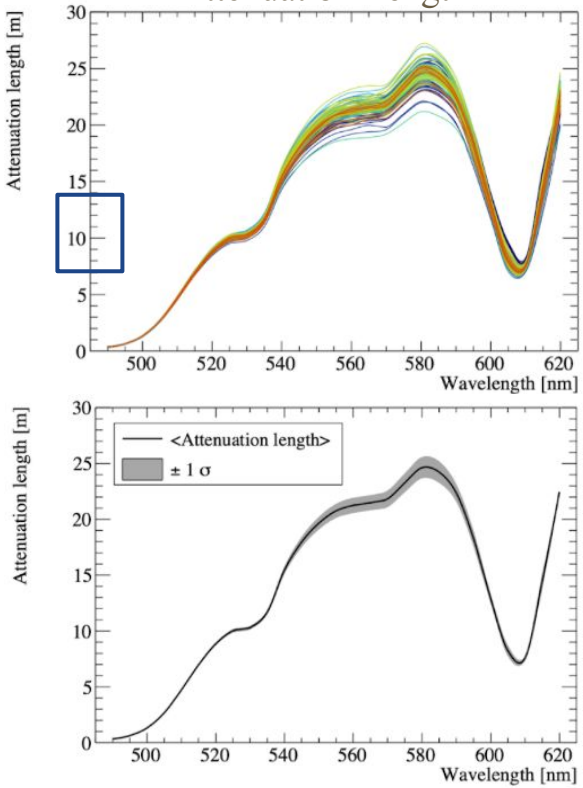
For More Details: arXiv:1811.04874v1

Prior 1.4 mm Results & 1.8 mm Areas of Improvement

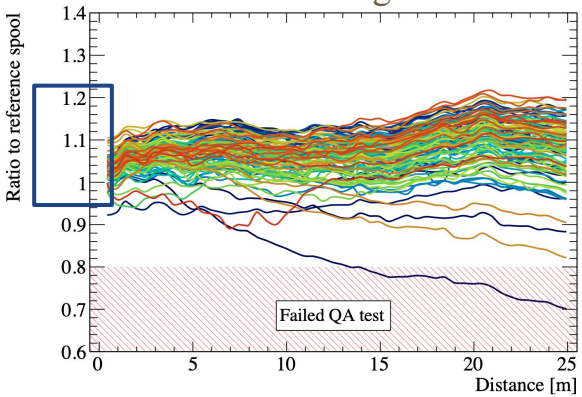
Light Yield



Attenuation Length



Attenuation Length Ratio



Report: arXiv:1811.04874v1

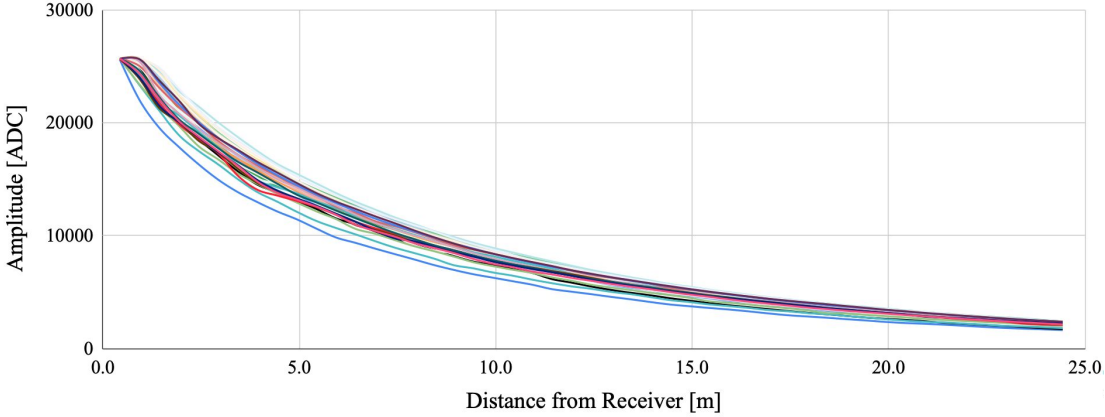
New Fiber Produces Higher Light Yield

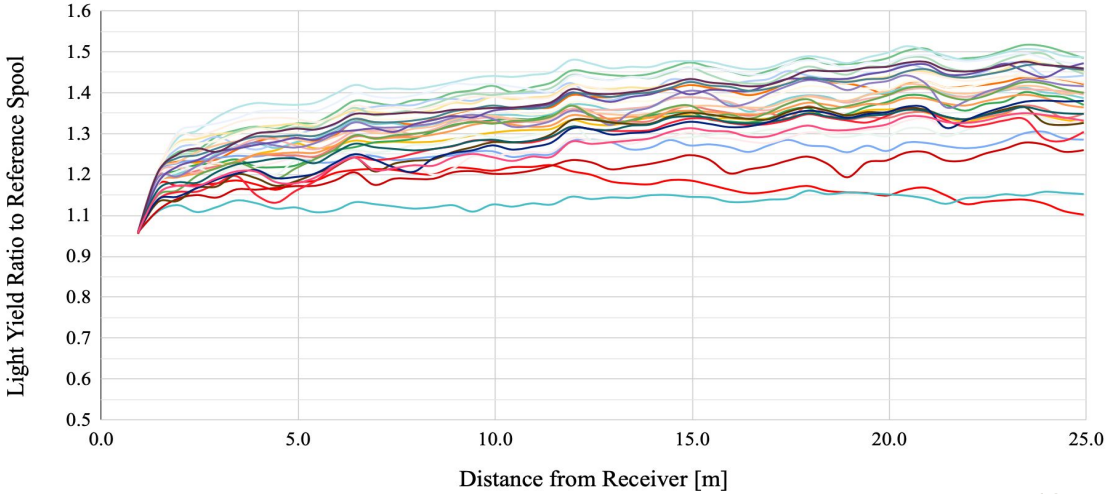
Old Mu2e 1.8 mm fiber was used as a Reference Spool (*from 2015*)

- Higher initial light yield for 1.8 mm fiber
- Lowest light yield data line is the Reference Spool

New 1.8 mm fiber shows 10-50% higher light yield than the Reference Spool

- A tighter ratio to reference is seen in older fiber (greater variance in new 1.8 mm fiber data)



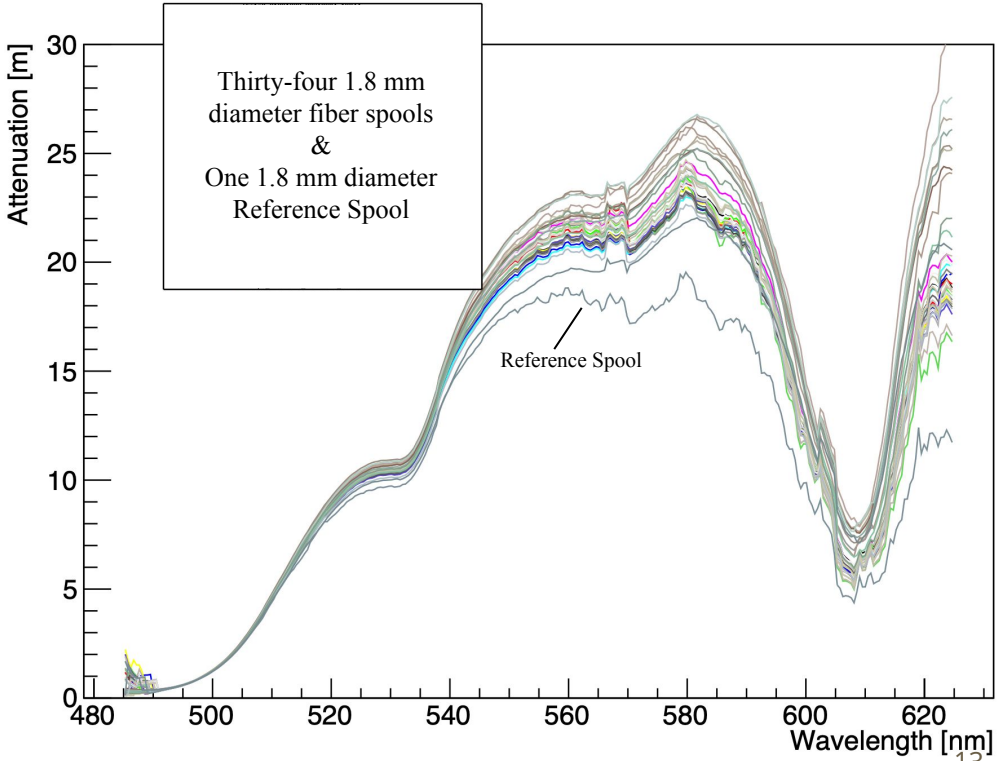


Attenuation Lengths Verify that Signal Light Will Reach Data Collectors

Single attenuation length measurements were calculated per wavelength by fitting each spool's spectral light intensity data as a function of distance from the source to an exponential.

Overall longer attenuation lengths achieved in reference to 1.4 mm fiber

- Lowest attenuation line is the old 1.8 mm Mu2e fiber (Reference Spool)
    - Shifted calibration constants



Signal Data will Reach SiPMs (Short Attenuation Length)

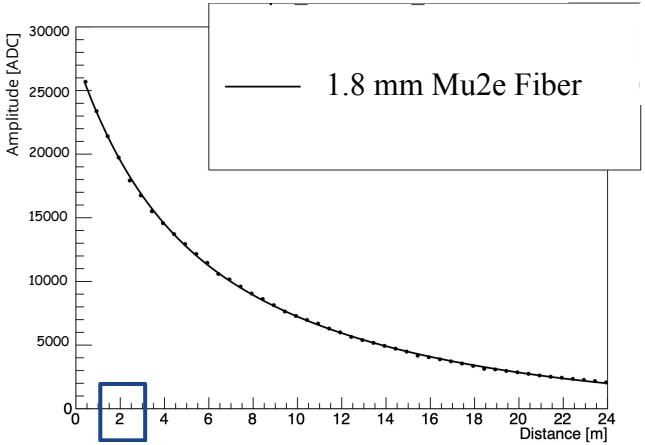
Attenuation Length: The distance at which 1-1/e (63%) of the incident light intensity has been absorbed

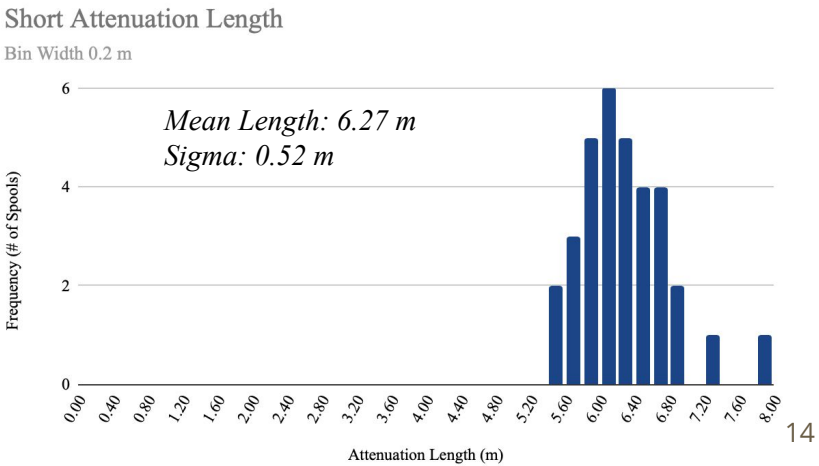
The short attenuation length calculation includes fiber data from 1 to 3 meters

- Old 1.4 mm fiber had an average short attenuation length of 5.8 meters (*compared to 1.8 mm fibers: 6.27 m*)

Outliers

- Retested for confirmation





Signal Data will Reach SiPMs (Long Attenuation Length)

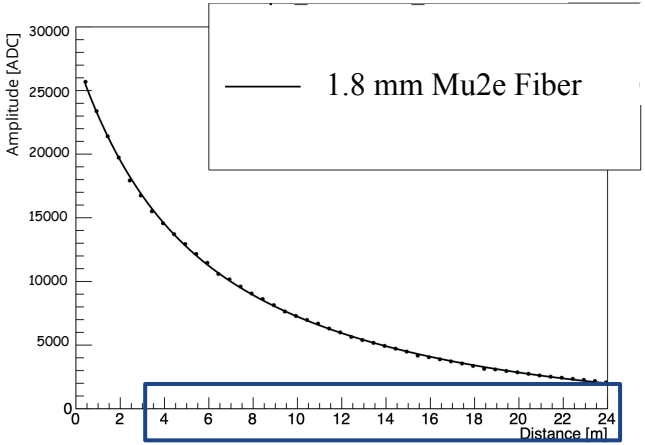
Attenuation Length: The distance at which 1-1/e (63%) of the incident light intensity has been absorbed

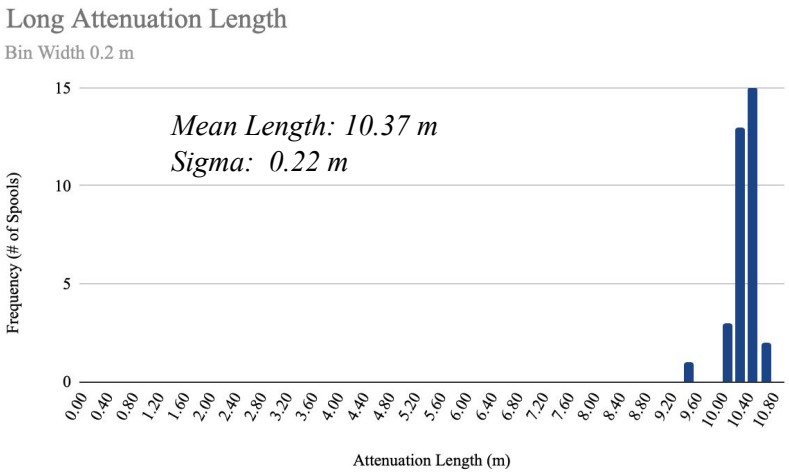
The long attenuation length calculation includes fiber data from 3 to 25 meters (*end of tested fiber*)

- Old 1.4 mm fiber had an average long attenuation length of 10.0 meters (*compared to 1.8 mm fibers: 10.37 m*)

Outliers

- Retested for confirmation



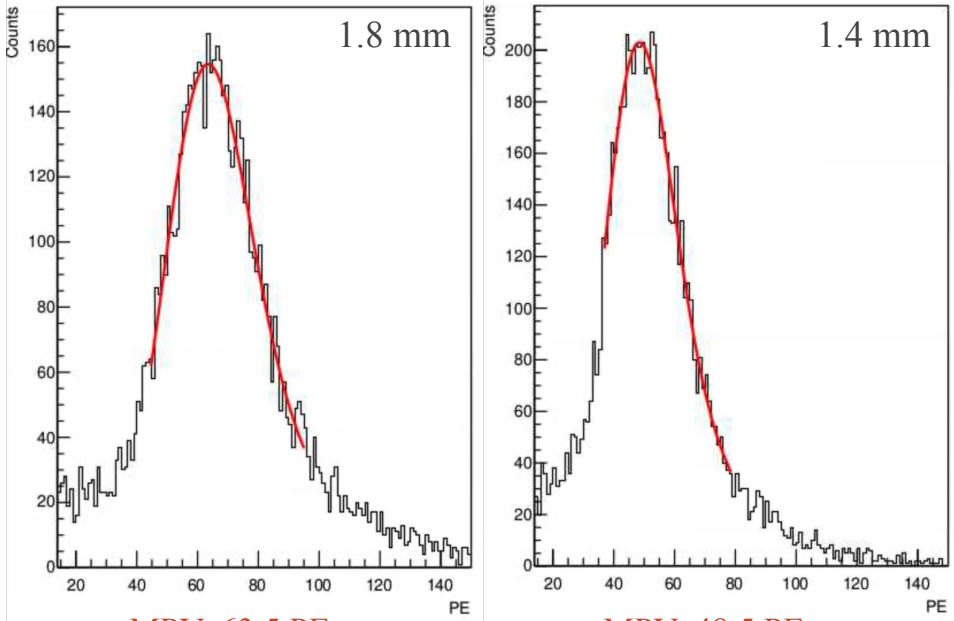


Greater Light Yield Achieved in Di-counters with New 1.8 mm Fiber

A sample di-counter was created to compare 1.4 mm and 1.8 mm light yield performance

- Cosmic data was taken with UVa's test stand
- New 1.8 mm fiber recorded ~25% greater light yield than 1.4 mm fiber
- Desired result (increased light yield) was achieved with 1.8 mm fiber

Photoelectron (PE) Distribution per Fiber Diameter



MPV: 63.5 PEs
FWHM: 36.0 PEs

MPV: 48.5 PEs
FWHM: 29.5 PEs

Conclusion

All thirty-four new 1.8 mm diameter wavelength-shifting fiber spools were quality tested, both by Kuraray and UVa, and are ready for CRV-T production

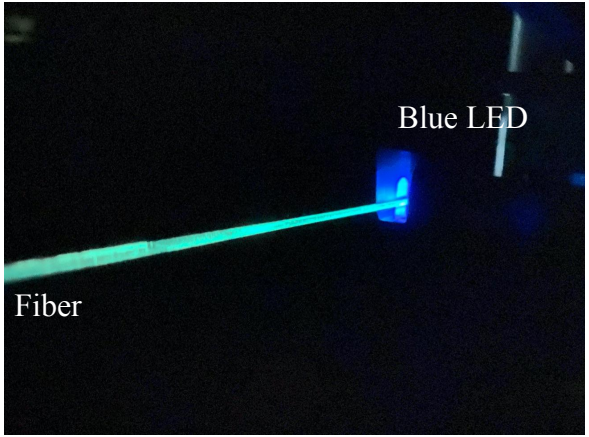
- Overall higher light yield (~25%) recorded by fiber tester *(with reference to 1.4 mm fiber)*
- Increased light yield (~25%) recorded in sample di-counter by UVa's cosmic test stand *(with reference to 1.4 mm fiber)*
- Attenuation lengths suitable for multi-meter long modules
- Displayed light yield increase needed for the CRV's most important scintillators (CRV-T)

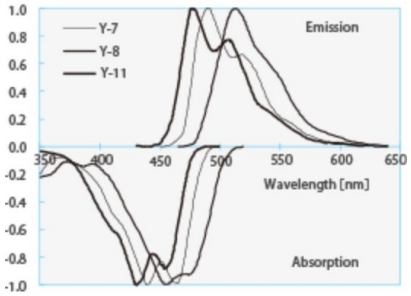
Backup Slides

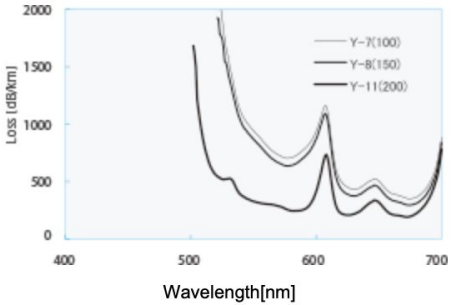
Wavelength-Shifting (WLS) Fibers

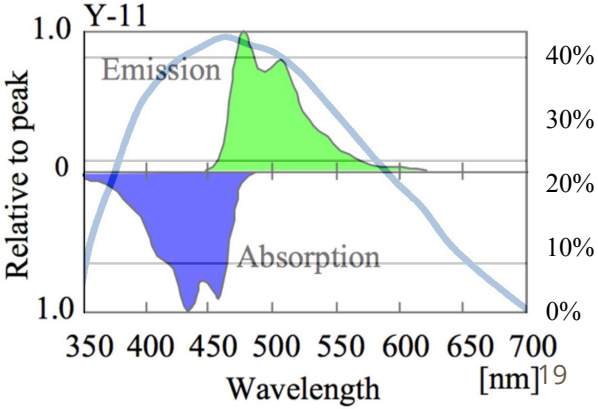
Kuraray Y11 fiber contains fluorescent dye which absorbs blue (375-475 nm) light and re-emits green (450-600 nm) light

- Shifts high-frequency light to low-frequency light
- Data read out by silicon photomultipliers (SiPMs)
  - Shifted wavelengths correspond better to optimal SiPM quantum efficiency/sensitivity range (peak at 450 nm, 80% peak at 550 nm)









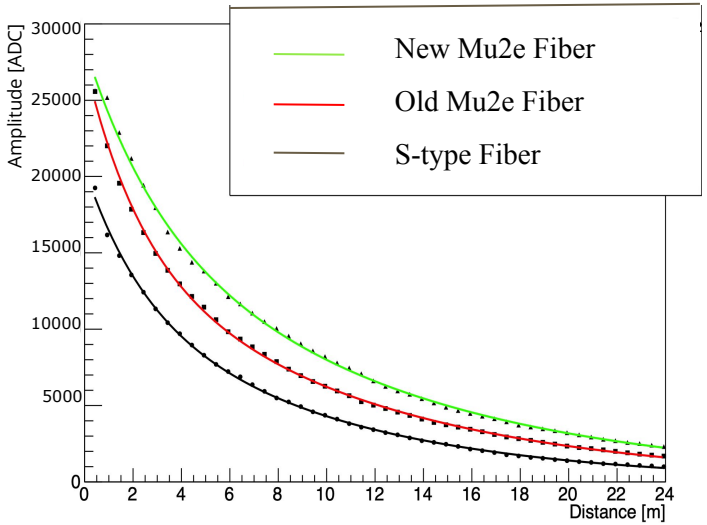
Optimal Mu2e Fiber Characteristics

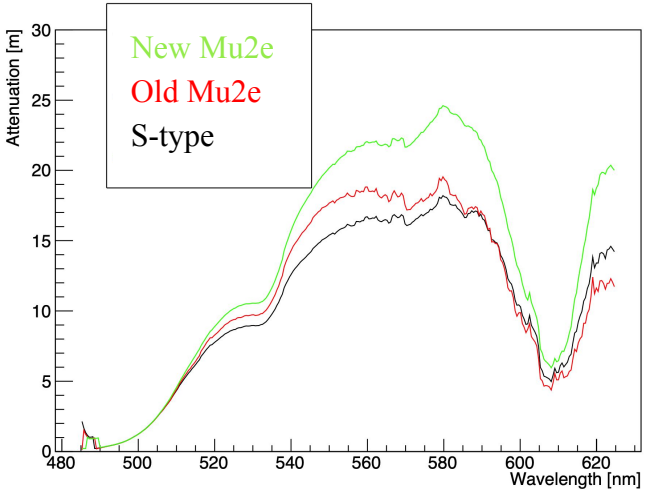
Multiclad fiber (vs. single clad fiber)

- Greater light yield than single cladding due to higher trapping efficiency
- All tested fiber is multiclad

Non-S-type fiber

- More transparent (> 10% longer attenuation length)
  - See comparison with S-type fiber
- No molecular core (Polystyrene chain) orientation
  - Less flexible than S-type





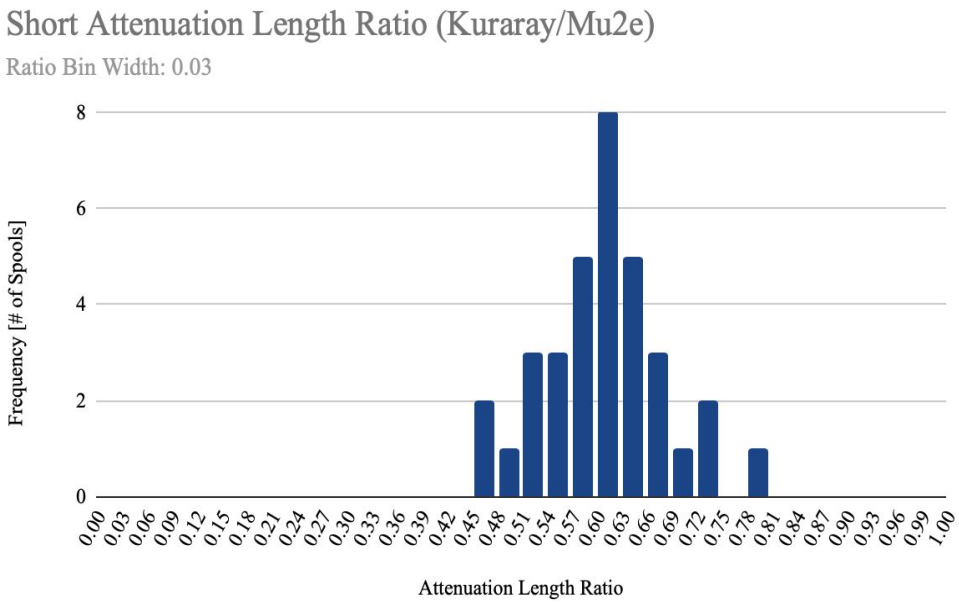
Attenuation Length Ratio

Kuraray's Attenuation Length procedure differs from UVa's process

- Kuraray only measures fiber's short attenuation length before shipment
- UV lamp (*vs. blue LED*)
- PMT specific to discrete wavelength range (*vs. photodiode's steady response across visible spectrum*)

Overall trend observation between Kuraray and UVa data

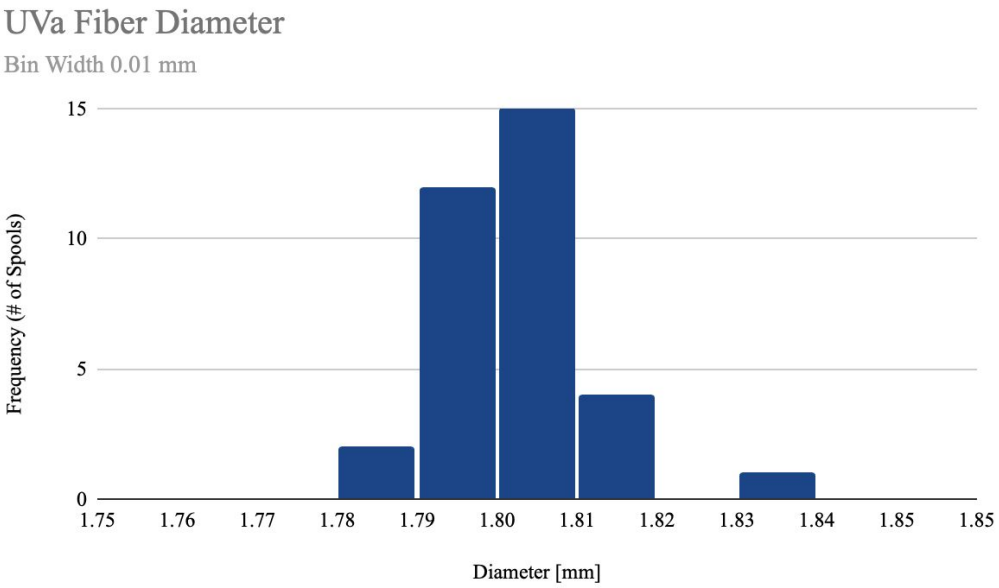
- Gaussian Distribution
- Confidence in data

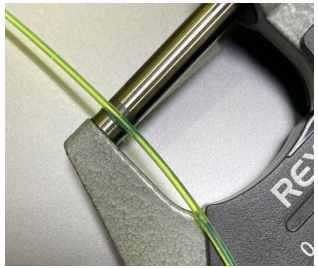


Fiber Diameter Confirmed

Single diameter measurements recorded near fiber's end

- Kuraray conducted measurements with a greater precision tool
- Both average values and error distributions were in agreement

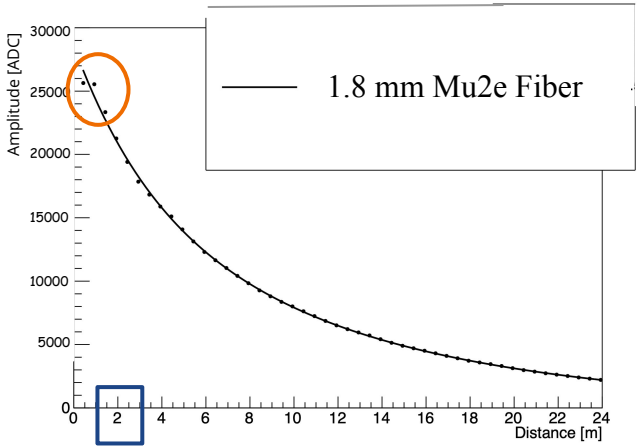




	Mean Diameter (mm)	Sigma
UVa	1.801	0.009
Kuraray	1.8002	0.0004

Attenuation Length (Short)

Attenuation Length: The distance at which 1-1/e (63%) of the incident light intensity has been absorbed



The Short Attenuation Length calculation includes fiber data from 1 to 3 meters (*alteration from 2016*)

- First data point (0.5 m) excluded from fit due to bad data across wide range of tests
- Old 1.4 mm fiber had an average short attenuation length of 5.8 meters (*compared to 1.8 mm fibers: 6.27 m*)

Outliers

- Zero-suppressed horizontal axis
- Retested for confirmation