Development of a Fiber Continuity and Light Calibration Device for NOνA

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Master's Plan B Project

Outline

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- NOνA (NuMI Off-axis ν_e Appearance Experiment)
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Physics Motivation

- **Neutrino oscillations**
  - Bruno Pontecorvo (and others) proposed that although neutrinos interact with matter as flavor eigenstates (ν_e ν_μ ν_τ) they travel through space as a superposition of mass eigenstates (ν_1 ν_2 ν_3).
  - It is possible to rotate from one basis to another.

- **Two-neutrino mixing formalism**
  - For muon and electron neutrinos the rotation is given by:

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

  - The probability of the appearance of an electron neutrino in a muon neutrino beam is

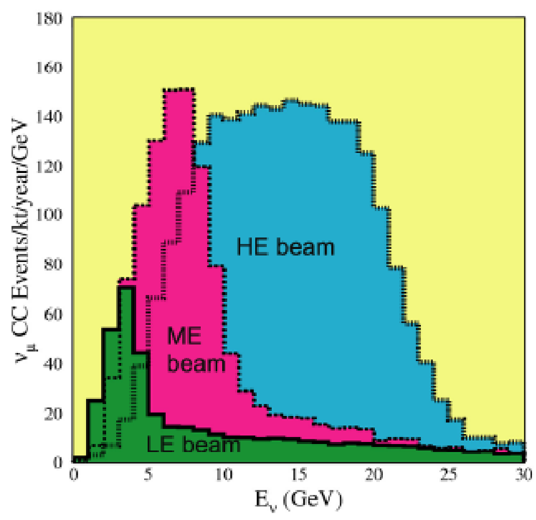
$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{21} \sin^2\left(\frac{1.27\Delta m_{21}^2 L}{E} \right)$$

NOνA Overview

- **Goals**
  - Observe the appearance of ν_e in an initially pure ν_μ beam in the L/E range of atmospheric neutrinos, from 100 to 1,000 km/GeV
  - Limit or measure the mass mixing parameters for this oscillation:

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$

- **NuMI beam and detectors**
  - Muon neutrinos produced at Fermilab, travel 810 km through the earth to northern Minnesota
  - Two detectors (near & far) positioned off-axis from the beam; optimizes the number of neutrino events in the energy range of oscillations
  - Detectors constructed from long PVC extrusions filled with liquid scintillator and a looped wavelength-shifting fiber.

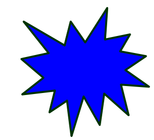


Interaction of a particle in the detector

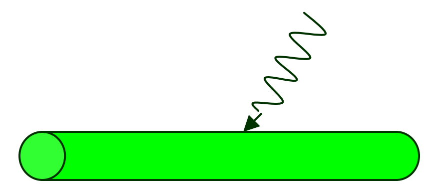
Neutrino interacting with nucleon in the liquid scintillator produces a charged lepton (electron neutrino produces an electron)

$\nu_e N \rightarrow e^- X$

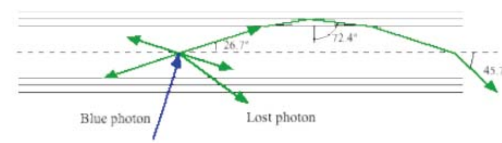
The liquid scintillator fluoresces in response (emits photons of a longer wavelength – blue)



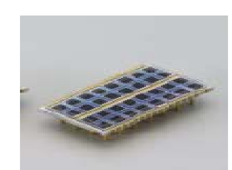
The flash of light is collected by a WLS fiber; the core contains a dye that shifts the blue light wavelength to green.



Approximately 4% of the light is trapped inside the multiclad fiber by total internal reflection

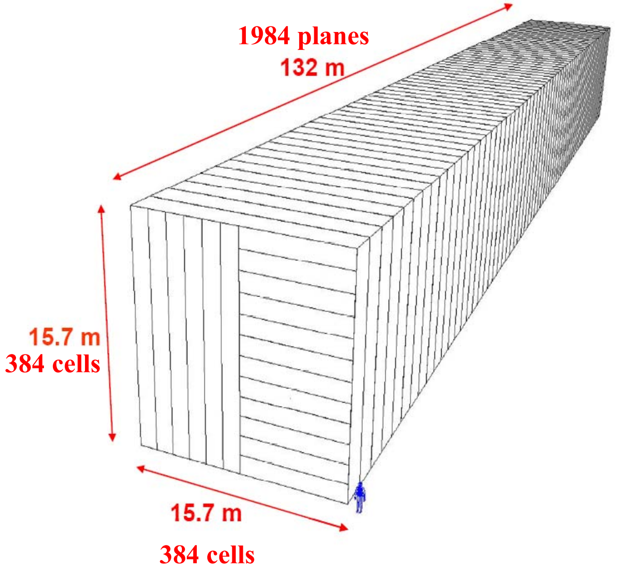


Light transmitted through the fiber to a photodetector (avalanche photodiode)

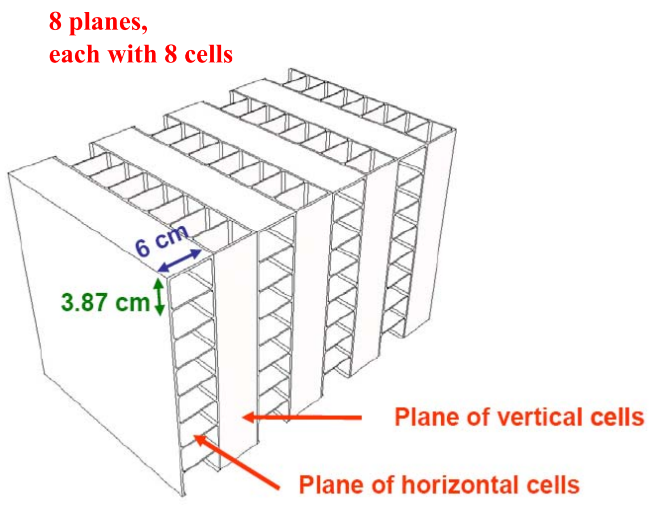


NOνA detector design

- **Far Detector (MN)**
  - Total mass 30 metric kilotons*
  - Located at the surface, 12 km off-axis from beam
  - Each plane contains 12 extrusion modules, with alternating vertical and horizontal alignment
  - Each module contains 32 cells with dimensions 3.87 cm x 6.0 cm x 15.7 m



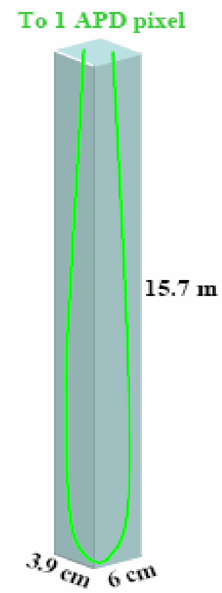
- **Near Detector (Fermilab)**
  - Similar design to far detector but smaller dimensions
  - Refine understanding of the background, detector response, and neutrino beam energy spectrum

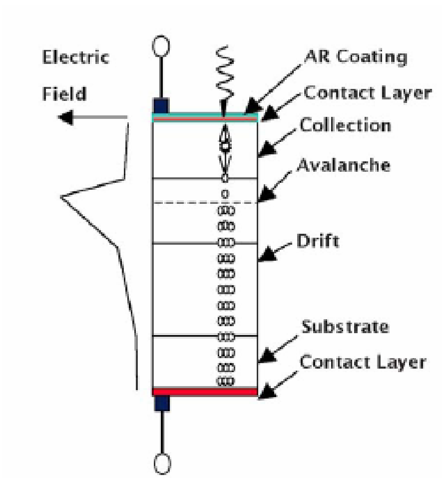


*Geometry described in the March 2005 proposal

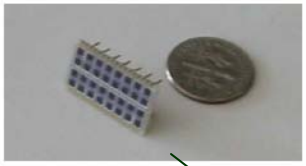
Light Collection

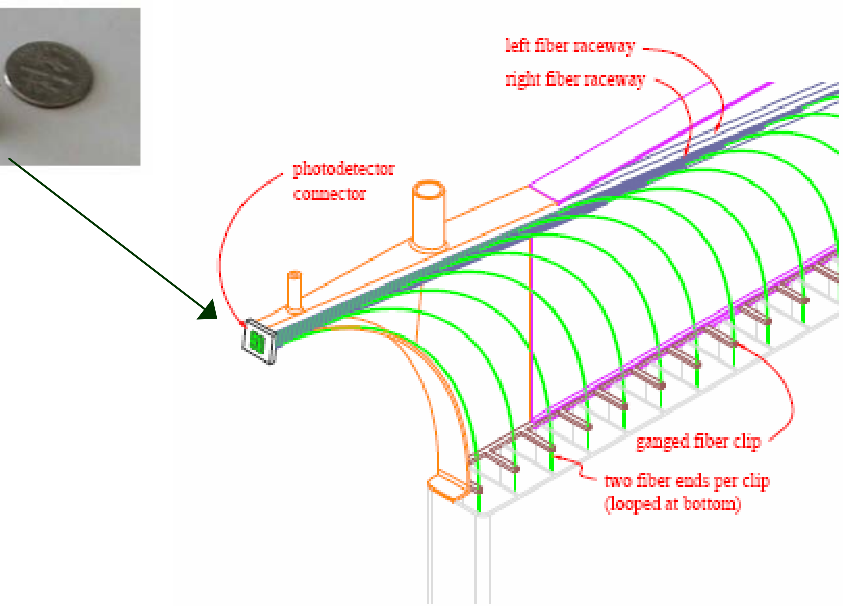
- Each RPVC extrusion cell filled with liquid scintillator, 5% pseudocumene in a mineral oil base
- Encloses a looped WLS fiber of diameter 0.8mm
- Two ends of fiber are directed by a manifold and optical connector to one pixel of a photodetector (avalanche photodiode) to convert the optical signal to an electrical signal.





Avalanche Photodiode (APD)



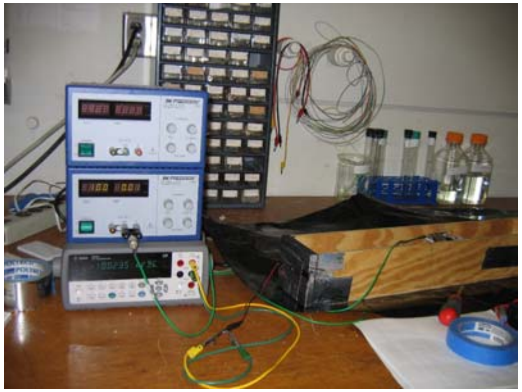


Fiber Characterization Experiments

- **Motivation**
  - During factory assembly, one important task is to test the fiber continuity (check the fibers for damage) after insertion into the modules.
  - This requires a non-invasive procedure (device) to measure the light transmission of fibers mounted in an optical connector.

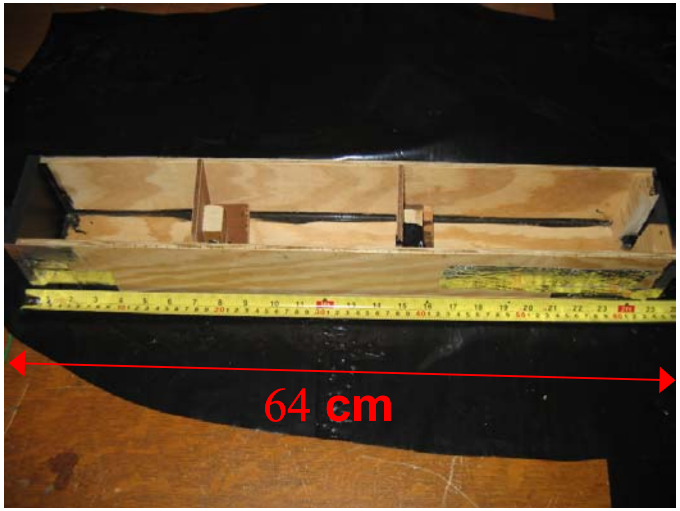
- **Semester-long project goals**
  - Investigate fiber parameters to inform the design of the fiber continuity testing device
  - Achieve reliable light output measurements from the WLS fiber at the 3% level of variation (target driven by the intrinsic variation of light output performance from one batch of fiber to another)

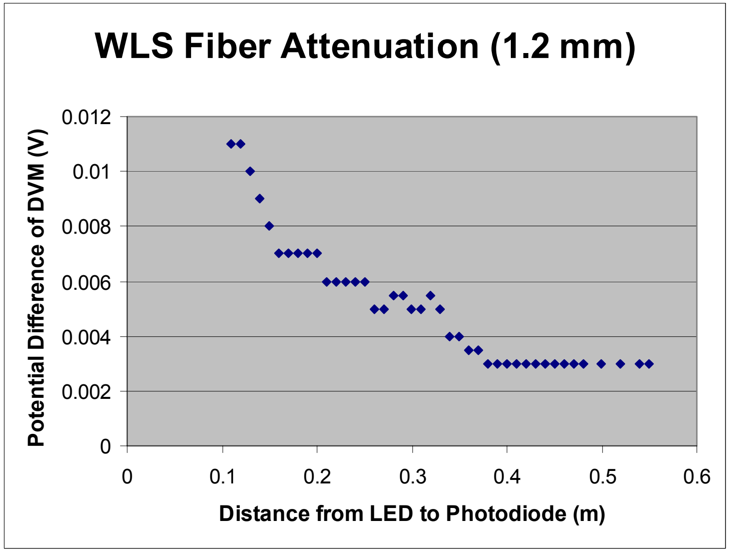
- **Getting Started**
  - Some time was required for acquisition of new/used equipment for this and related NOνA tasks



Initial Tests

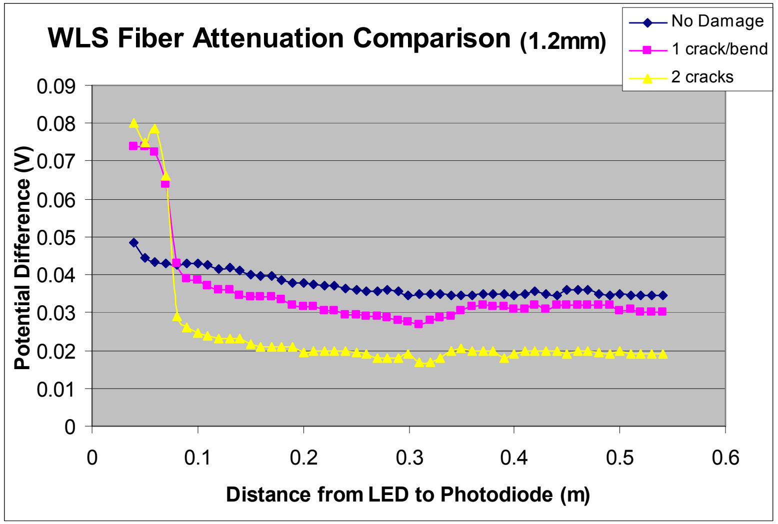
- **WLS fiber attenuation**
  - Obtained a light-tight plywood box of dimensions 64 cm x 10 cm x 10 cm with blue light emitting diode (LED) wood dividers (light shines through a column perpendicularly onto fiber), holes for the fiber at each box end
  - One end of the fiber filed, and glued (Elmer's) to the end of the box near a Si PIN photodiode. LED powered by a 6V lantern battery.
  - Fiber light transmission measurements (1.2mm) as a function of LED distance from a PIN photodiode with a handheld DVM, across a 100 kΩ resistor in series with the photodiode.





Initial Tests cont'd

- **WLS fiber attenuation (damaged and undamaged fiber)**
  - Undamaged fiber, then damage to the same fiber by bending.
  - There was a detectable decrease in the light output with damage to the fiber; shining the LED between the damage site and the photodiode increased the light output (reflections in fiber)

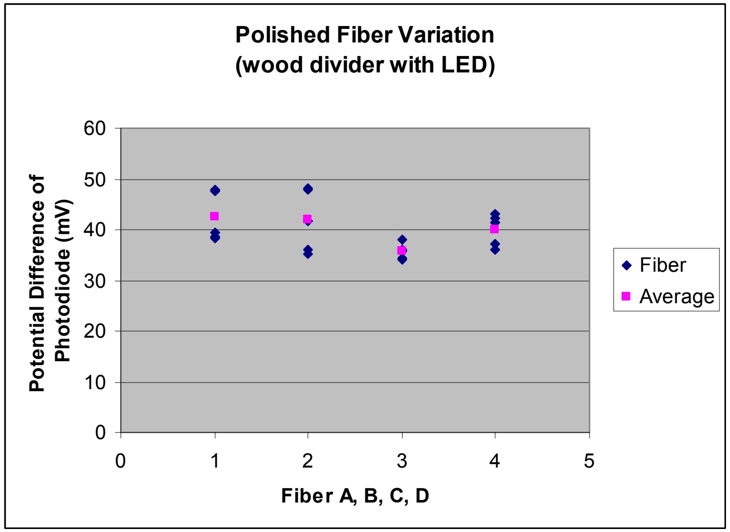


- **Blind Test**
  - Matthew Strait prepared 7 fibers, some nicked with a scalpel and some undamaged, and covered them with rubber tubing.
  - I measured the light output of the fibers, and could detect decreased light transmission in only 1 of the 3 fibers he damaged (fiber ends were trimmed to remove glue).
  - We were informed that neglecting to polish the fiber ends can give up to 30% variation in measurements between fibers.

Fiber Variation Tests

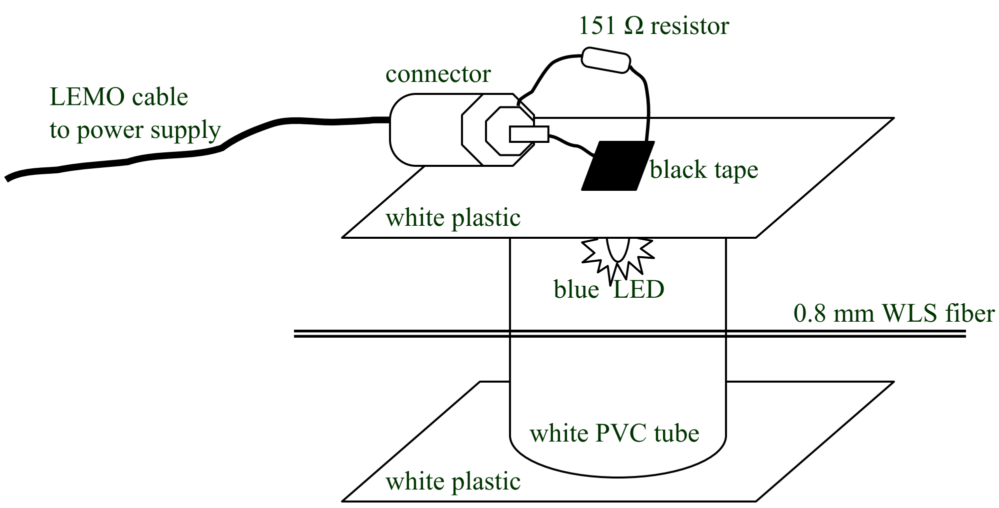
- **Changes to the setup:**
  - New power supply; connected the LED to 10V. New digital multimeter with 6-digit precision.
  - Replaced the box ends with sintra expanded PVC, and a tighter hole for the fiber (eliminates need for gluing)
  - 8 mm diameter WLS fiber, hand polish one end

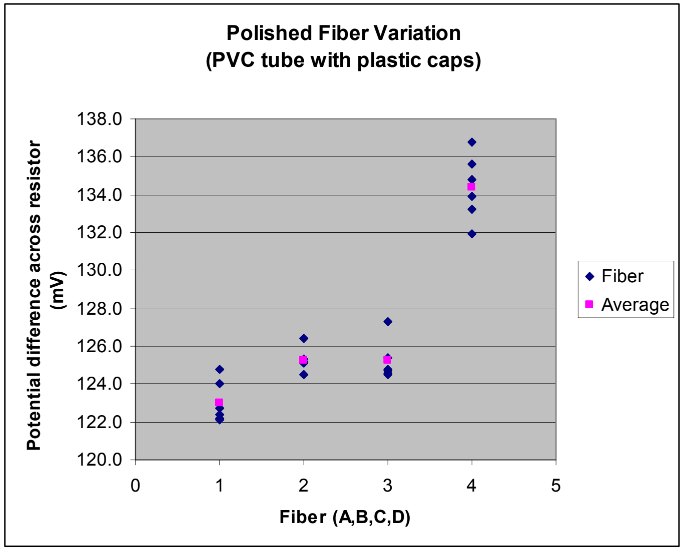
- **WLS fiber variation**
  - Polished four 0.8mm diameter fibers the same length of the box (~64 cm)
  - Measured the potential difference across the resistor with the LED divider at a single position (40 cm from photodiode).
  - Removed and reinserted each fiber into the box several times.
  - Within fiber variation ranged from 5.4% to 15.6%, and the total variation in all measurements was 17.1%.



Fiber Variation Cont'd

- **More changes to the setup:**
  - A NOνA collaborator suggested that using diffuse reflection of light (shining on all sides of the fiber) and a wider solid angle could improve consistency of fiber illumination measurements.
  - The wood LED cart was replaced by a white PVC tube and an LED shining through the top cap (first paper caps, then white plastic)
  - Repeated measurements with the LED at a single position (40 cm)
  - Light output higher. Within fiber variation ranged from 0.8% to 1.8%, and the total variation in all measurements was 5.7%.

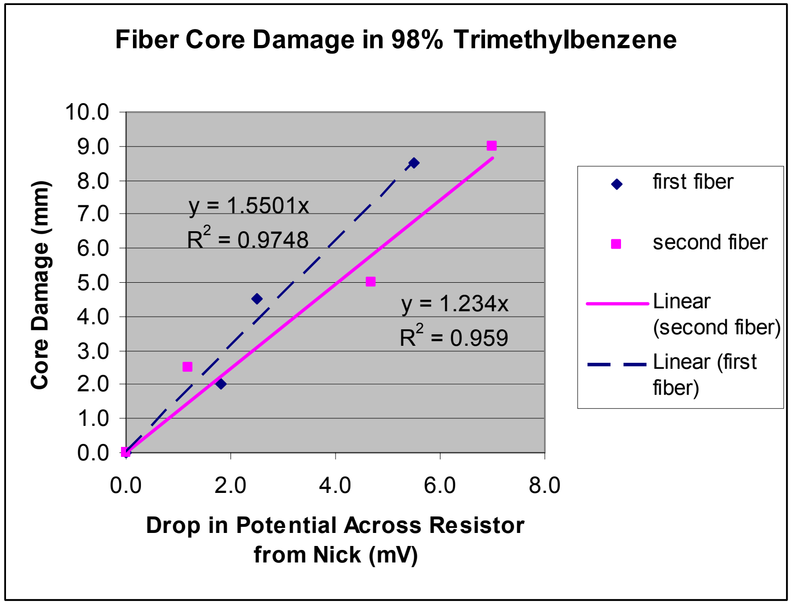




Additional Tests

- **Condensation Tests**
  - Concern that condensation of fiber sections outside the liquid scintillator could affect light transmission.
  - Tested this by lowering a portion of the fiber into a water dish and removing it. There was not a measurable change in the light output of the fiber due to water droplets on the cladding.

- **Pseudocumene Tests**
  - It has been established that pseudocumene damages the polystyrene + wavelength shifter core of the fibers
  - Two 1.2mm diameter fibers were each nicked with a scalpel in three sections and the light output measured. The fibers were submersed in 98% trimethylbenzene for a day and the (visible) core damage in mm was measured.



Summary & Conclusions

- **Semester project goals**
  - The target was to achieve reliable light output measurements from WLS fibers at the 3% level of intrinsic variation.
  - The most recent tests gave variations less than 2% for the same fiber, and 5.7 % between different fibers from the same spool.
  - Although this was not at the desired level, it was substantial improvement from earlier measurements.

- **Considerations for the NOνA factory fiber continuity device:**
  - Controlling the fiber distance from the photodetector, fiber stability, and polishing the surface are essential
  - Diffuse lighting of the fiber (reflections on all sides) and a wide solid angle provided more reproducible measurements

- **Remaining work:**
  - Test longer fibers (actual length of the NOνA design) looped to the true bend radius of an extrusion cell.
  - Replace the PIN photodiode with the APD used in NOνA.
  - Repeat damage studies with varying concentrations of pseudocumene.
  - Assess temperature dependence of fiber measurements.

Acknowledgements

- Project adviser Dan Cronin-Hennessy
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