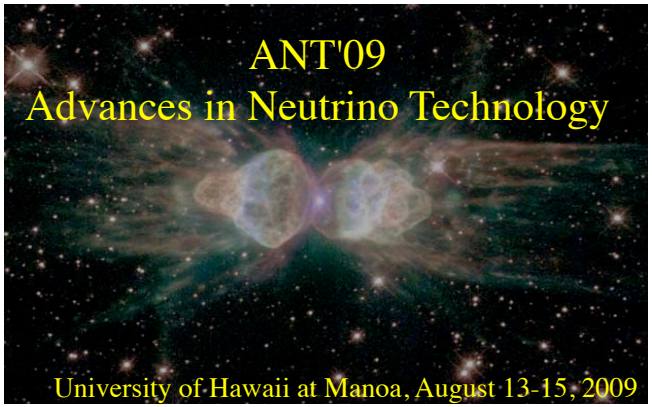
Terra Cognita:
technological aspects of MINOS & NOvA

Karol Lang

The University of Texas at Austin



"Anyone who has never made a mistake has never tried anything new."

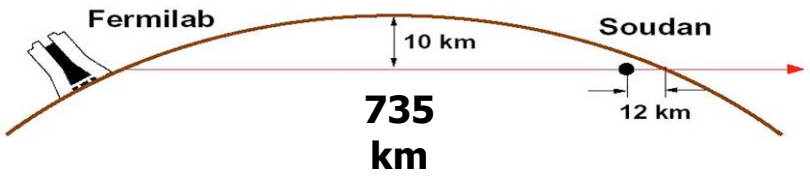
Albert Einstein

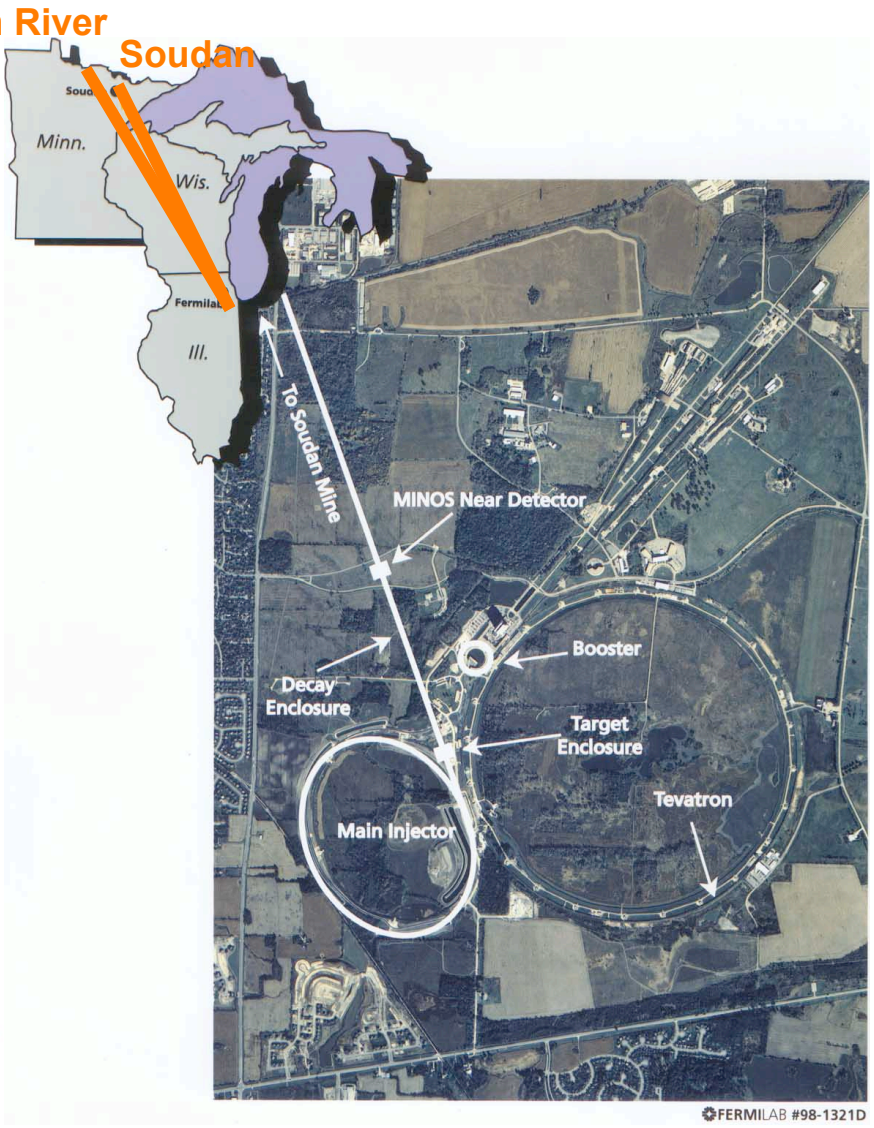
Outline:

- How MINOS does it
  - technological issues
  - work "fronts"
  - lessons learned (hopefully)
- How NOvA will do it
- Simulations (scintillator +)

Strategy for precision measurements:

- Two-detector measurement
  - ⇨ long baseline
    - ❒ on-axis MINOS-735km
    - ❒ 14 mrad off-axis NOvA-810km
- High intensity beam from 120 GeV Main Injector
  - ⇨ (up to) 4×10^{13} protons/pulse (0.4 MW beam)
  - ⇨ Near detector: mutiple events/8.67 μs
- Flexible & well-controlled beam
  - ⇨ two parabolic magnetic horns
  - ⇨ movable target (→energy spectrum)
- Identify muon- and electron-neutrinos
  [taus are (almost) hopeless]



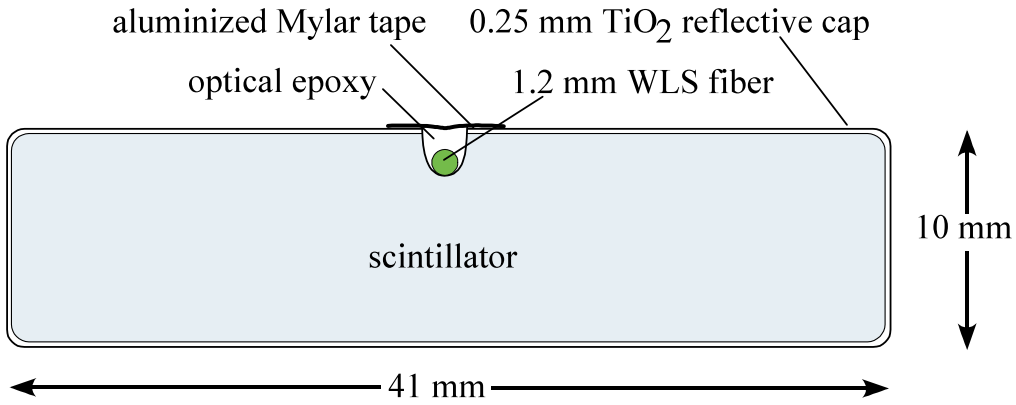


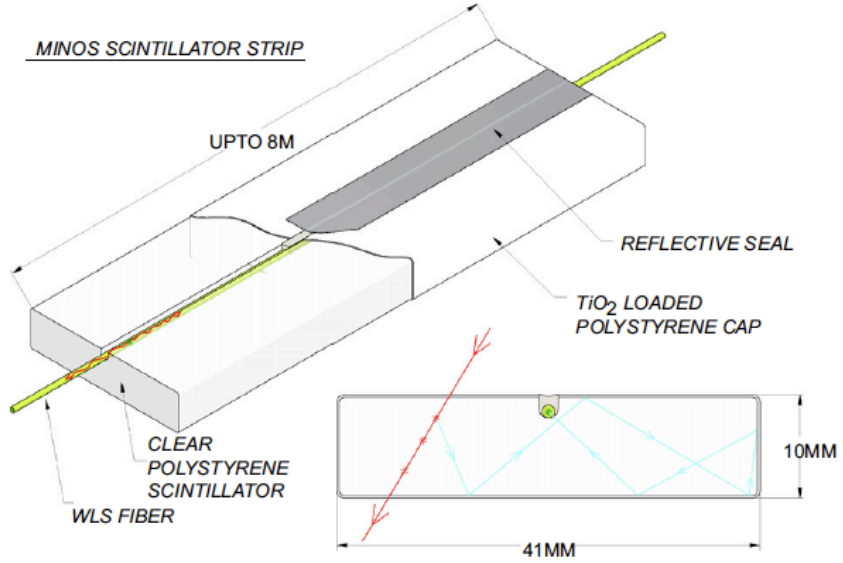
Detector technology R&D

- Factors
  - ⇨ Cost / kilo-tons mass (not mega-tons)
  - ⇨ Best energy resolution possible in GeV to multi-GeV range
  - ⇨ Multiple event pattern recognition (high event rate (!))
  - ⇨ Muon range and momentum (sign) measurements
  - ⇨ Shower-muon recognition (segmentation)
- Several active and passive technologies considered:
  - ⇨ Active
    - ❒ RPC
    - ❒ Iarocci
    - ❒ Liquid scintillator + wavelength-shifting (WLS) fiber →→→→ MINOS
    - ❒ Solid scintillator + WLS fiber →→→→ NOvA
  - ⇨ Passive
    - ❒ Iron →→→→ MINOS
    - ❒ Iron/Lead
    - ❒ Wood
    - ❒ Water
    - ❒ "nothing" ("Totally Active Scintillator Detector") →→→→ NOvA

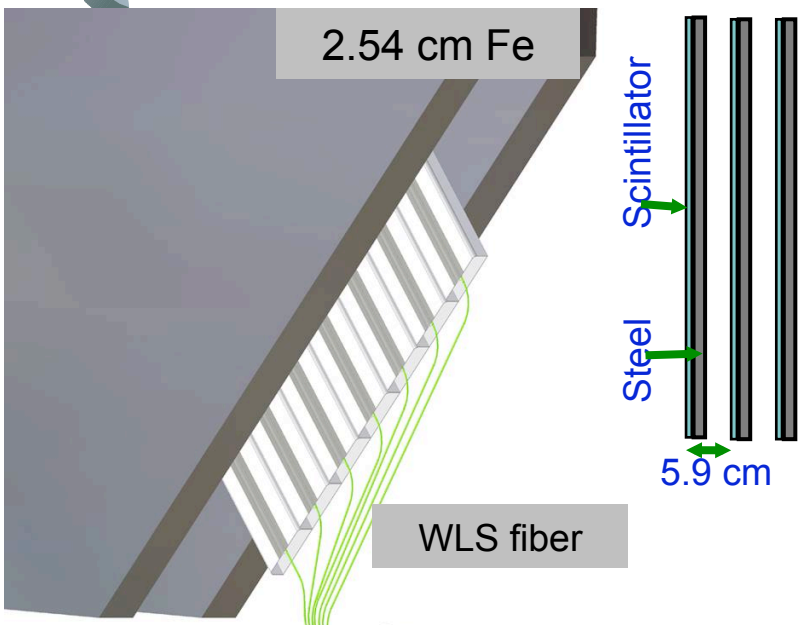
MINOS: EXTRUDED SCINTILLATORS

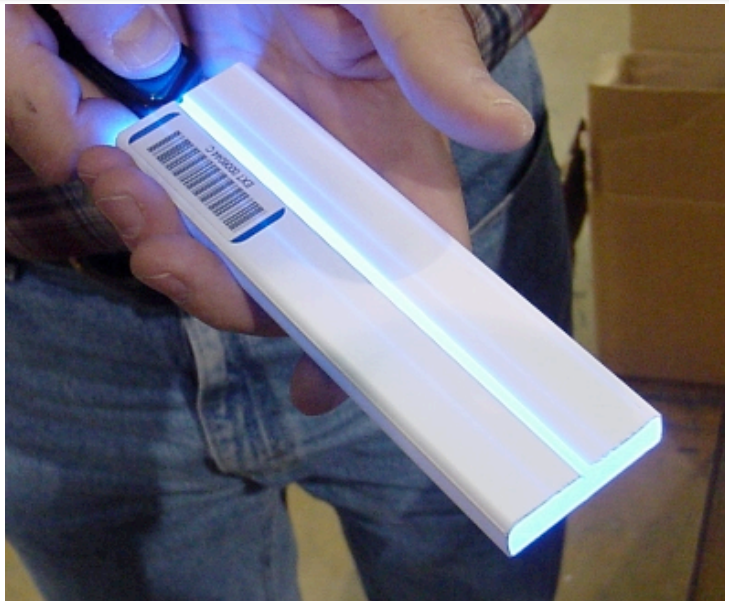
Co-extruded scintillator strip + reflector
use wavelength shifting (WLS) fibers as readout.





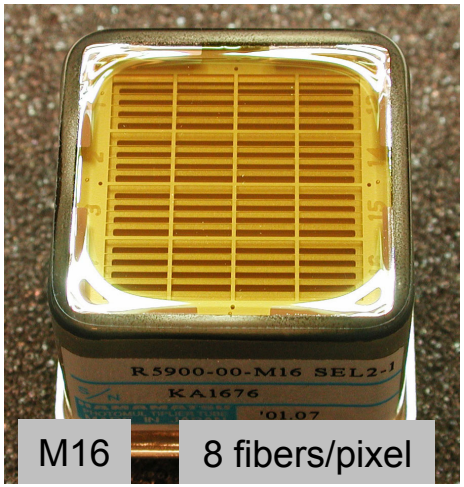
MINOS technology in a glance





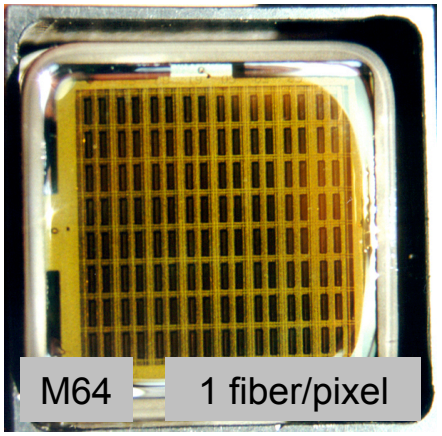
Extruded
PS scint.
4.1 x 1 cm

Far Det



M16 8 fibers/pixel

Near Det



M64 1 fiber/pixel

SELECTION OF RAW MATERIALS

BLUE SCINTILLATOR CORE

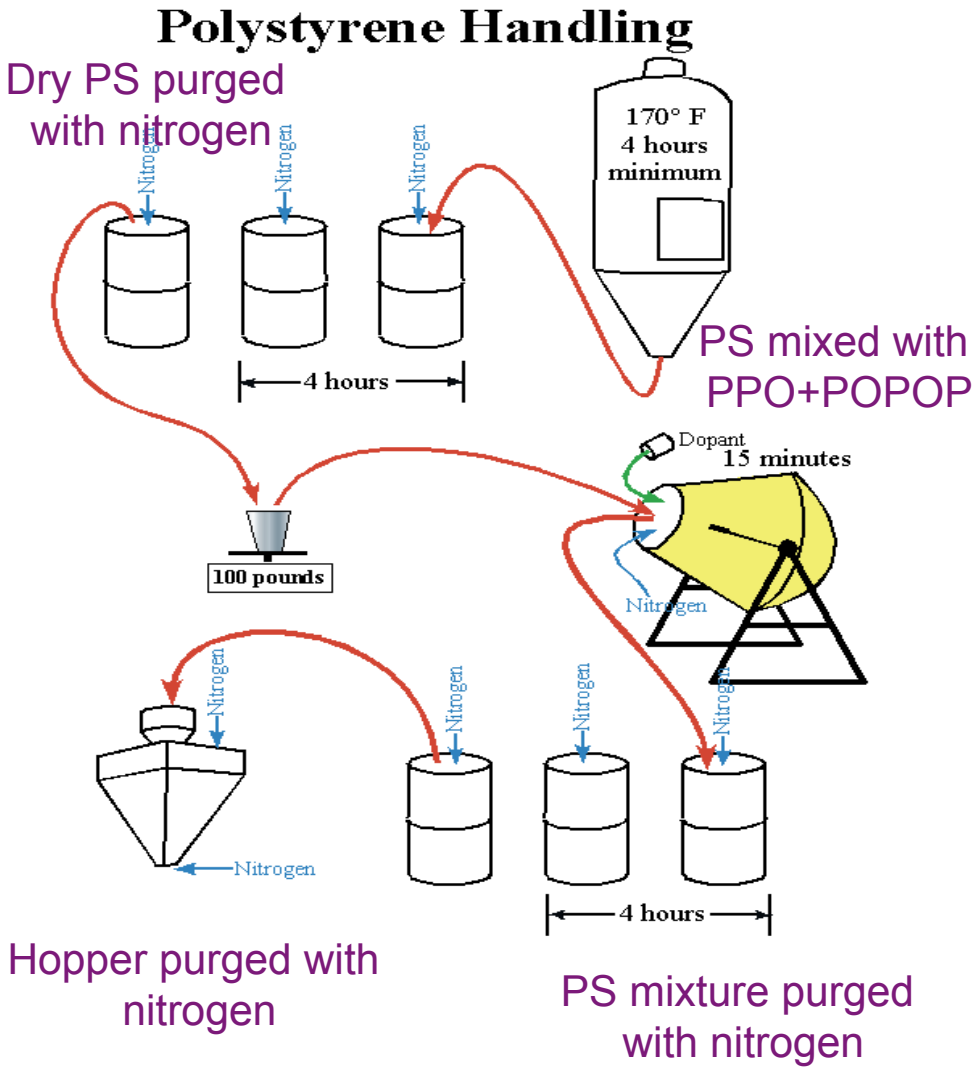
- Polystyrene: Dow Styron 663 W
- Dopants: 1% PPO + 0.03% POPOP

WHITE CAPSTOCKING

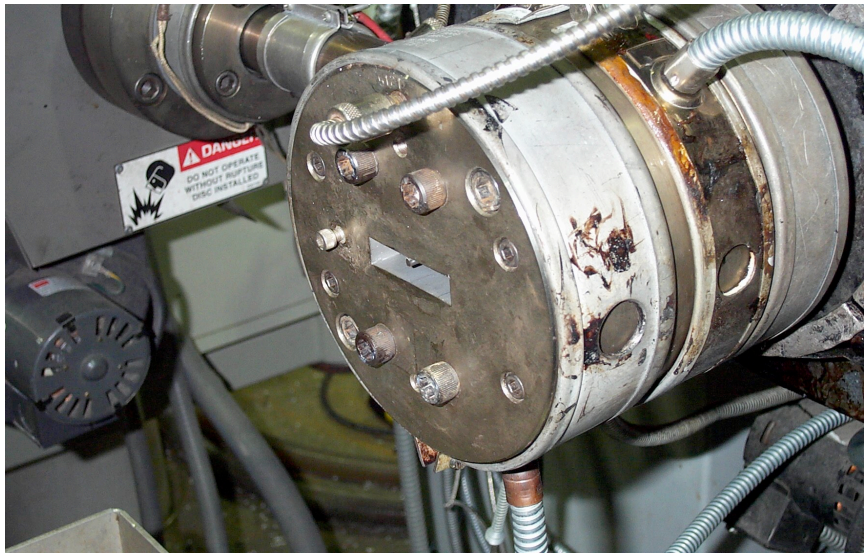
- Polystyrene with 12% TiO_2 – 0.25 mm thick

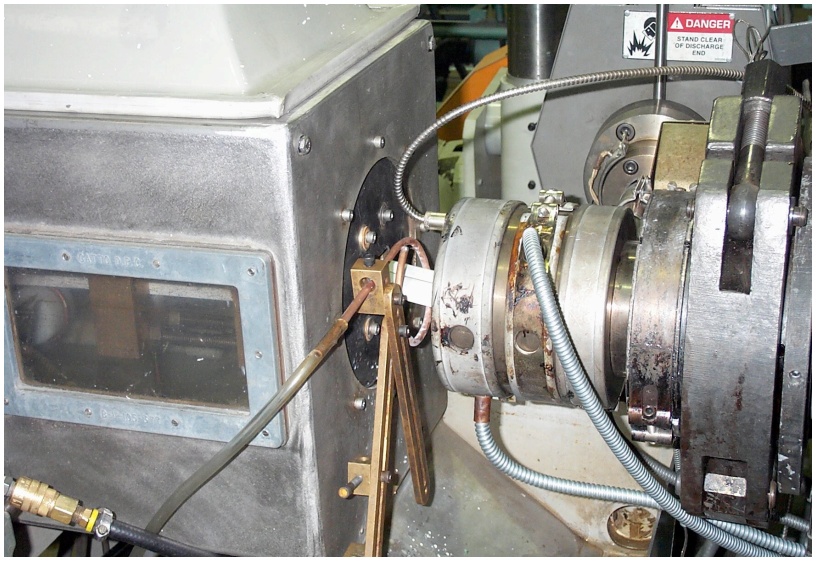
GREEN FIBER

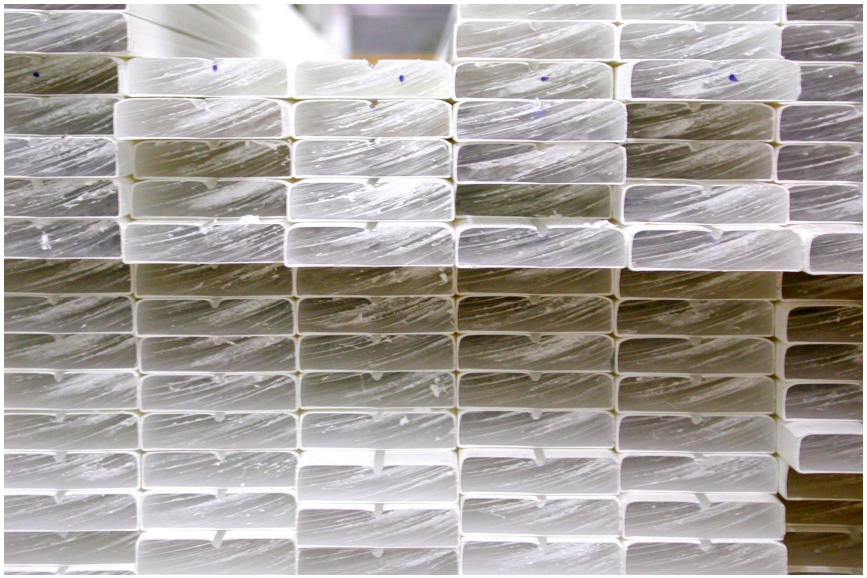
- K-27 fiber – 1.2 mm diameter

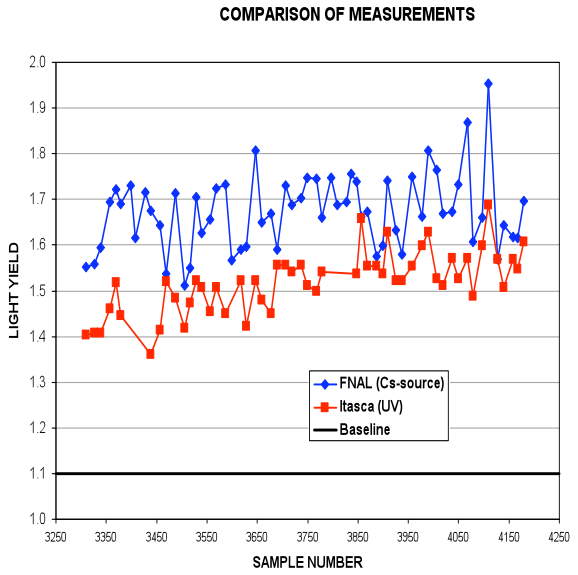


EXTRUSION AT ITASCA PLASTICS





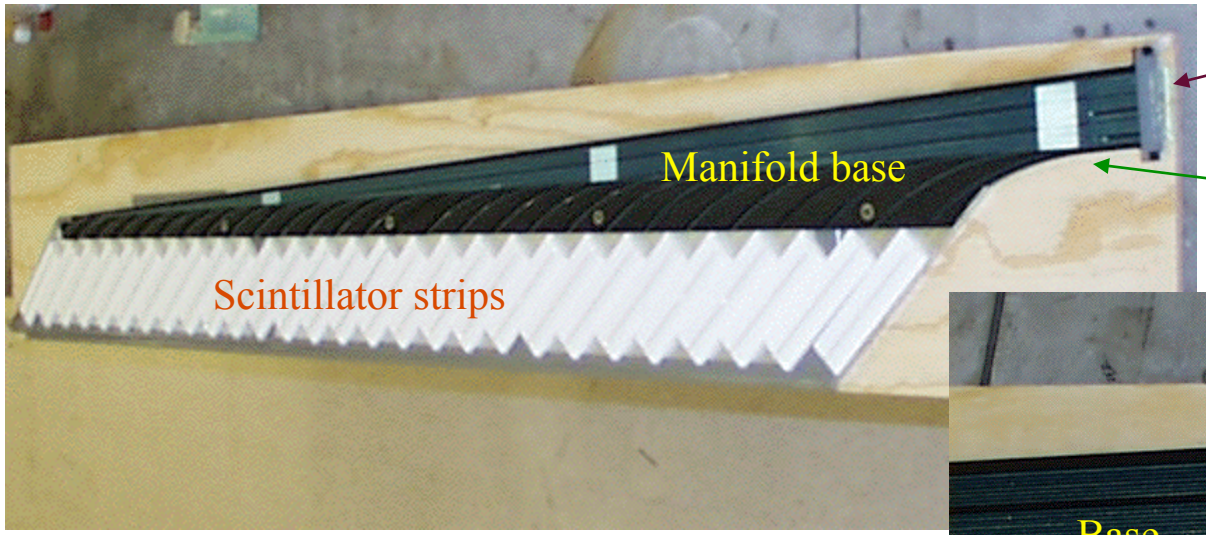


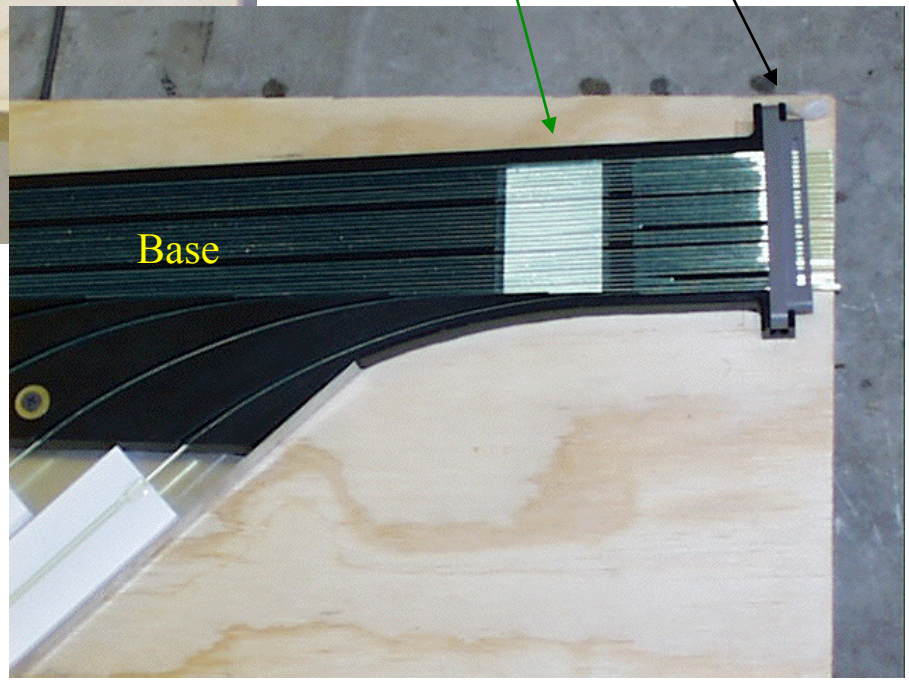


Module Assembly II

Scenes from Minnesota Module Factory

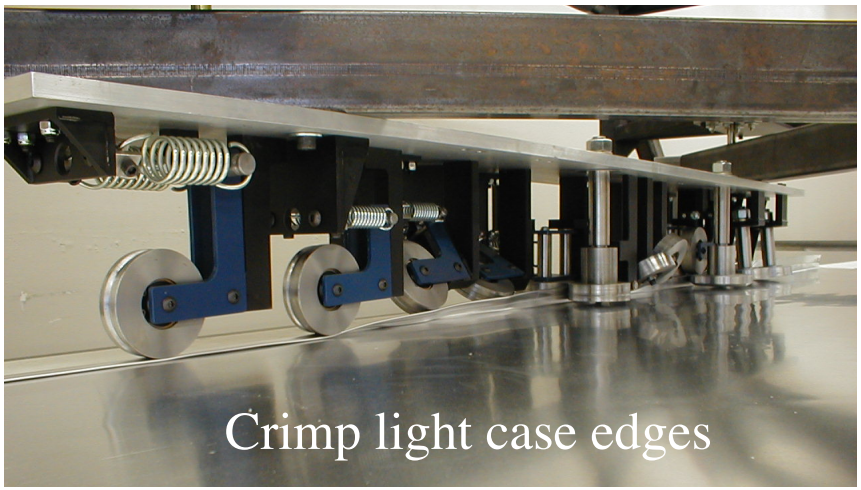
45 Degree End Manifold

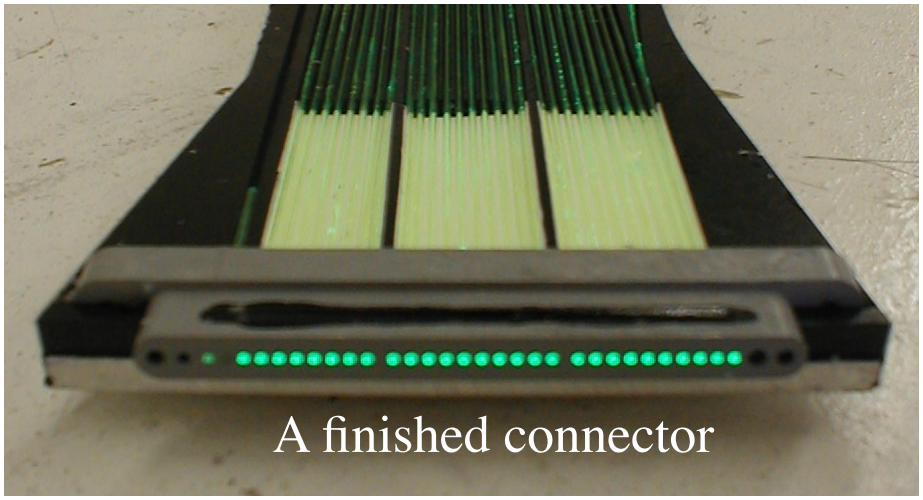




- Identical construction (modulo a mirror image) for all 45^{o} modules.
- The longest manifold part but with relatively easy fiber routing constraints.

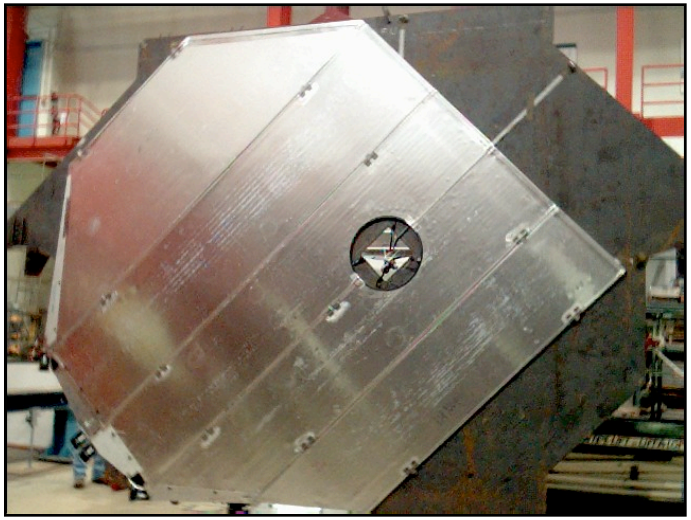
Module Assembly

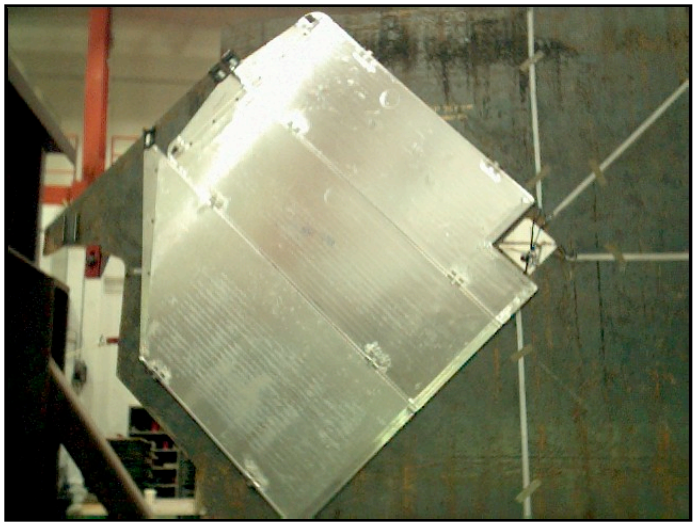




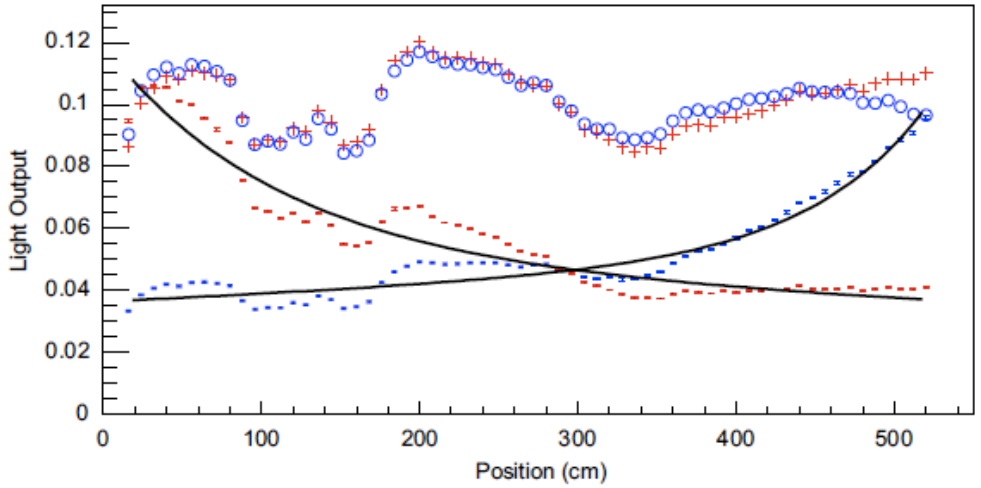
Scenes from Minnesota Module Factory

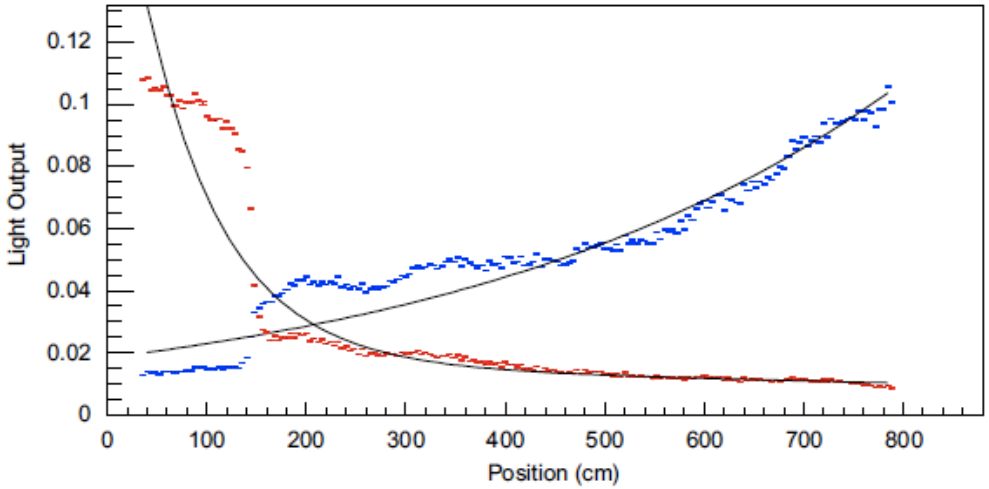
NearDet construction (finished in Dec'2004)





Radioactive source mapping



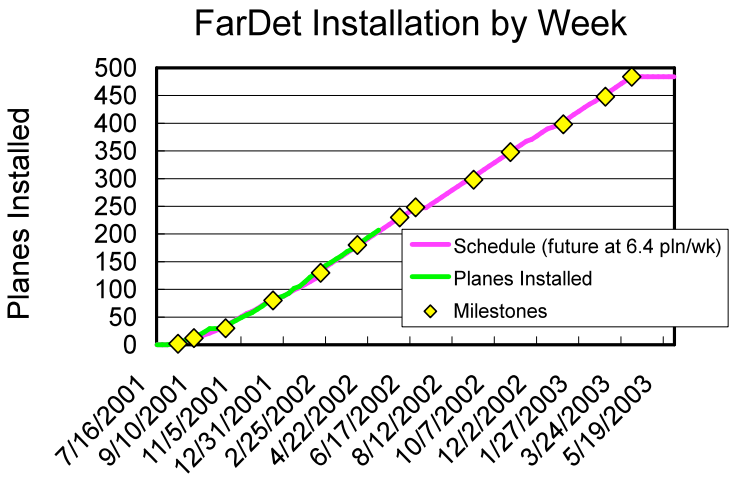


Plane assembly


Steel Welded and modules placed.

Plane lifted to vertical

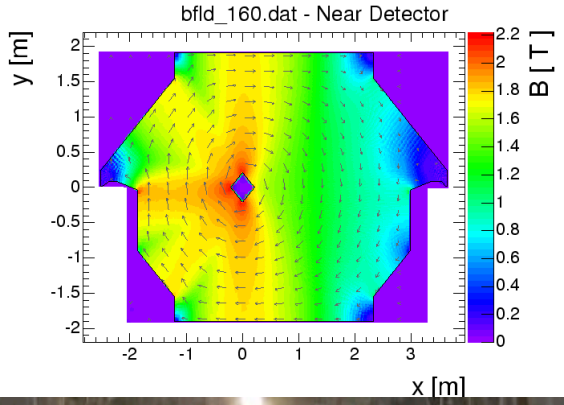
Crane carries plane down the hall for installation



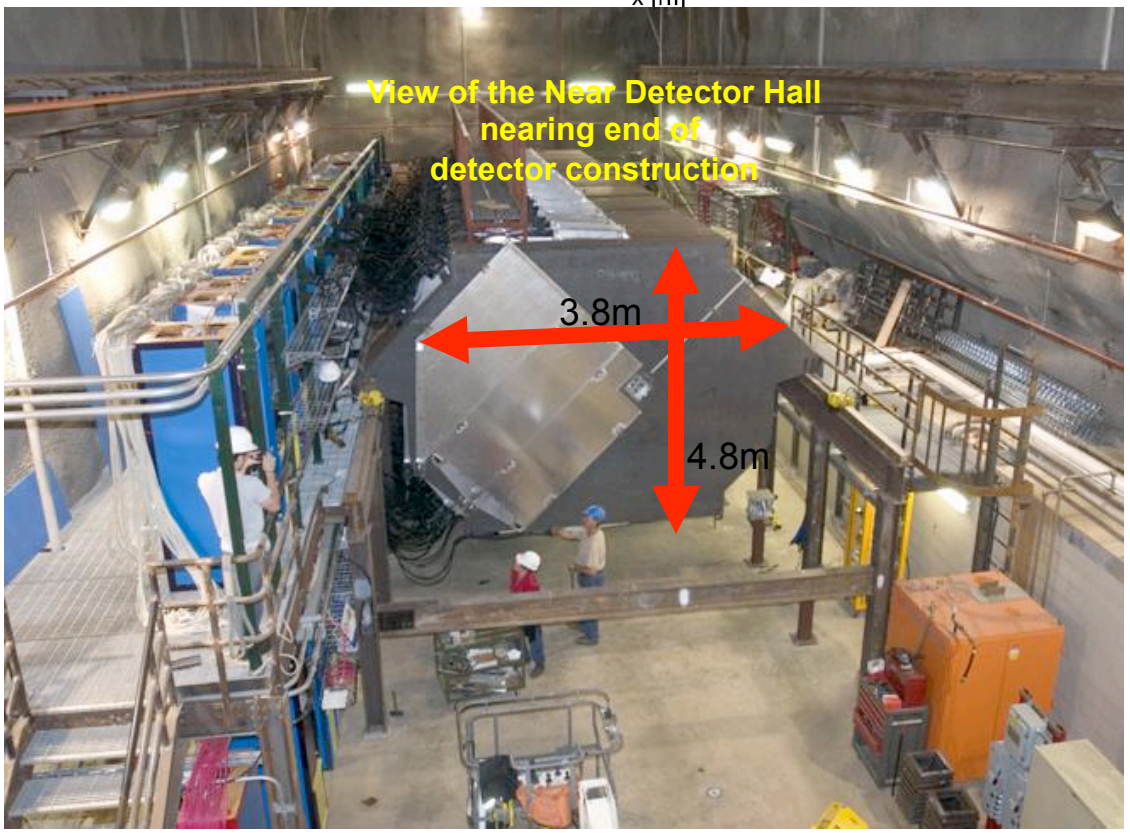
6-8 Planes per week

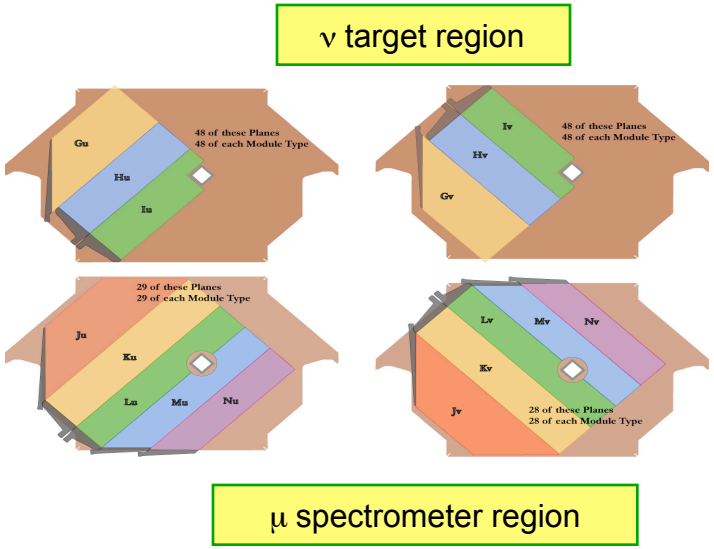
Near Detector – 1,040 m from the target at Fermilab

- veto - target - μ spectrometer
- mass = 1 kT
- 153 scintillator planes
- QIE-based front-end
- **3.8 x 4.8 "squeezed" octagon**
- **12,300 scint.strips**
- **1-end readout**
- **no-multiplexing**
- **220 M64s**
- **282 steel planes**
- **65 km WLS fiber**
- **51 km clear fiber**



103 m underground

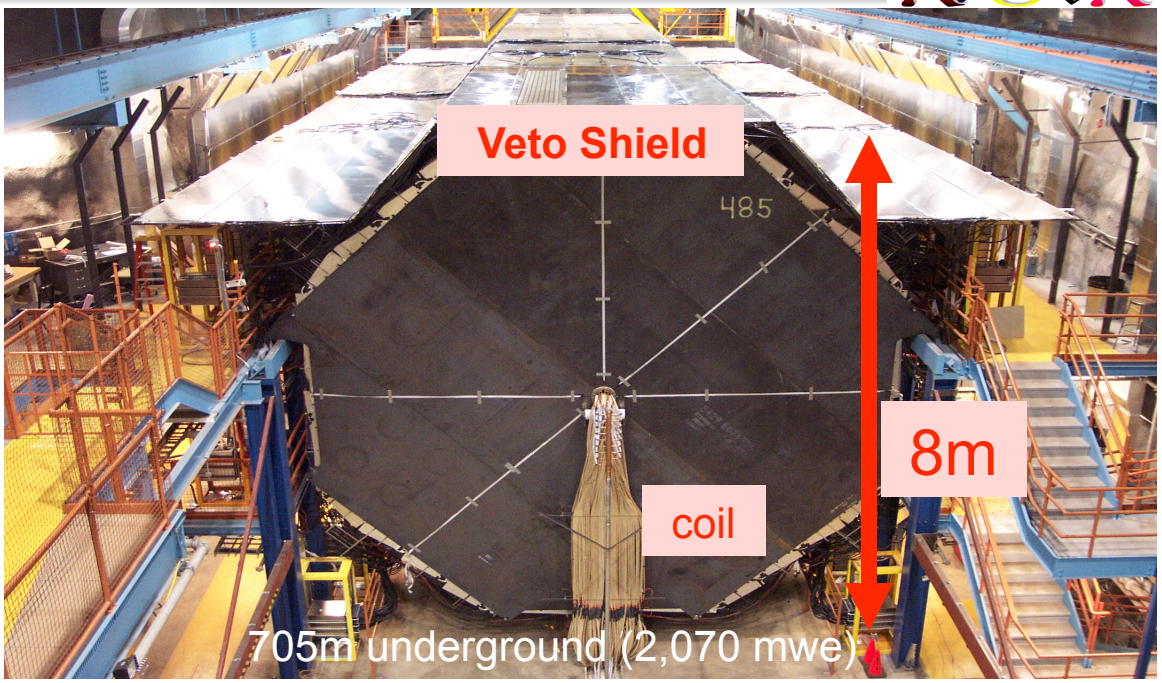


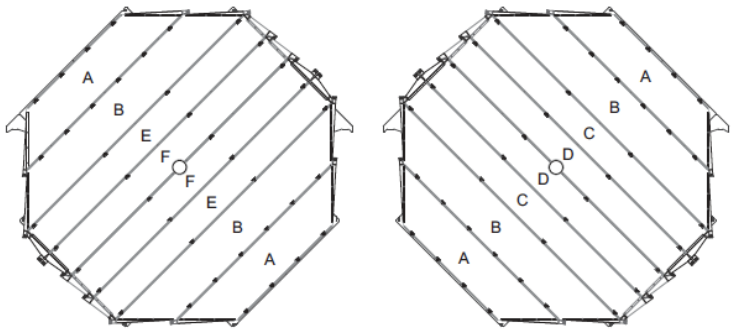


Far Detector – 735.3 km away (Soudan Mine, Mn)

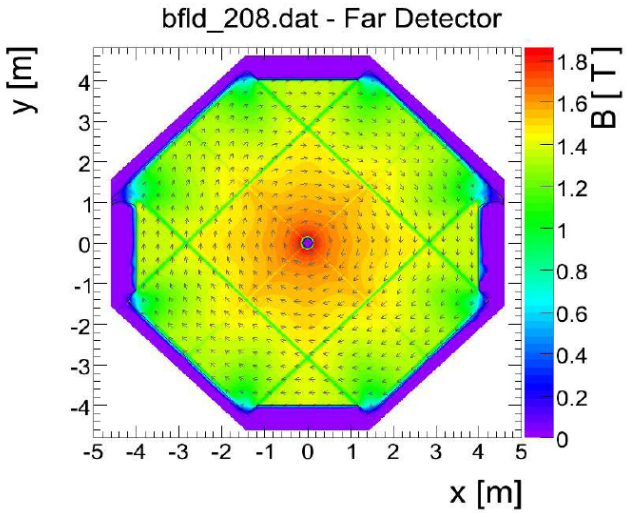
Running since July 2003

- 2 Supermodules
- 5.4 kT
- 484 scint. planes
- CR veto shield (2,070mwe)
- B ~ 1.5T (R=2m)
- 93,120 strips (4.1 x 1.0 cm)
- 8-fold MUXed 2-ended readout
- 1551 M16s
- 722 km of WLS fiber
- 794 km of clear fiber
- HAD = 56% / $E^{1/2}$
- EM = 23% / $E^{1/2}$

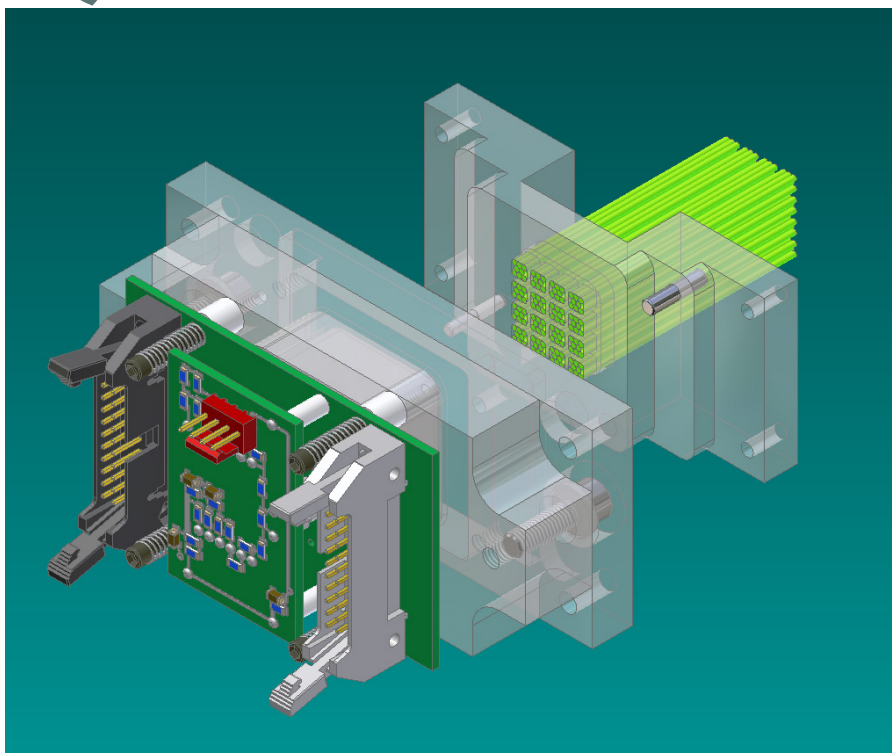


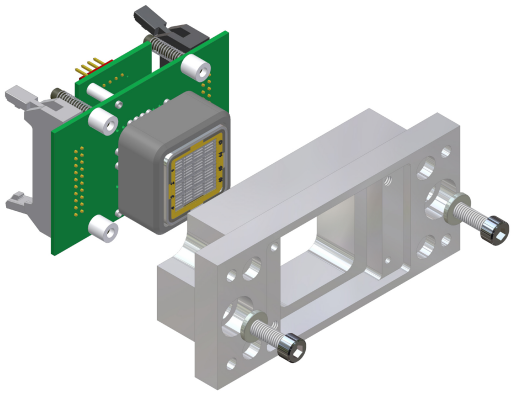


Scintillator Plane (8 modules, 192 strips)

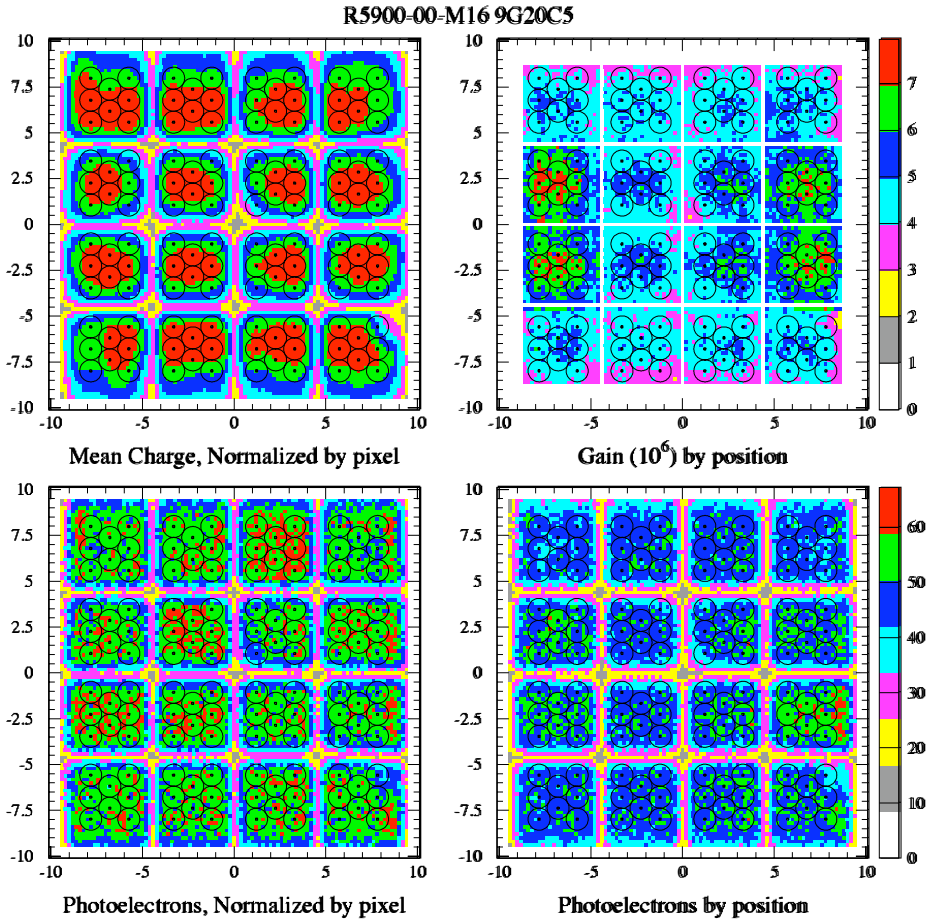


Multi-anode PMTs + fibers

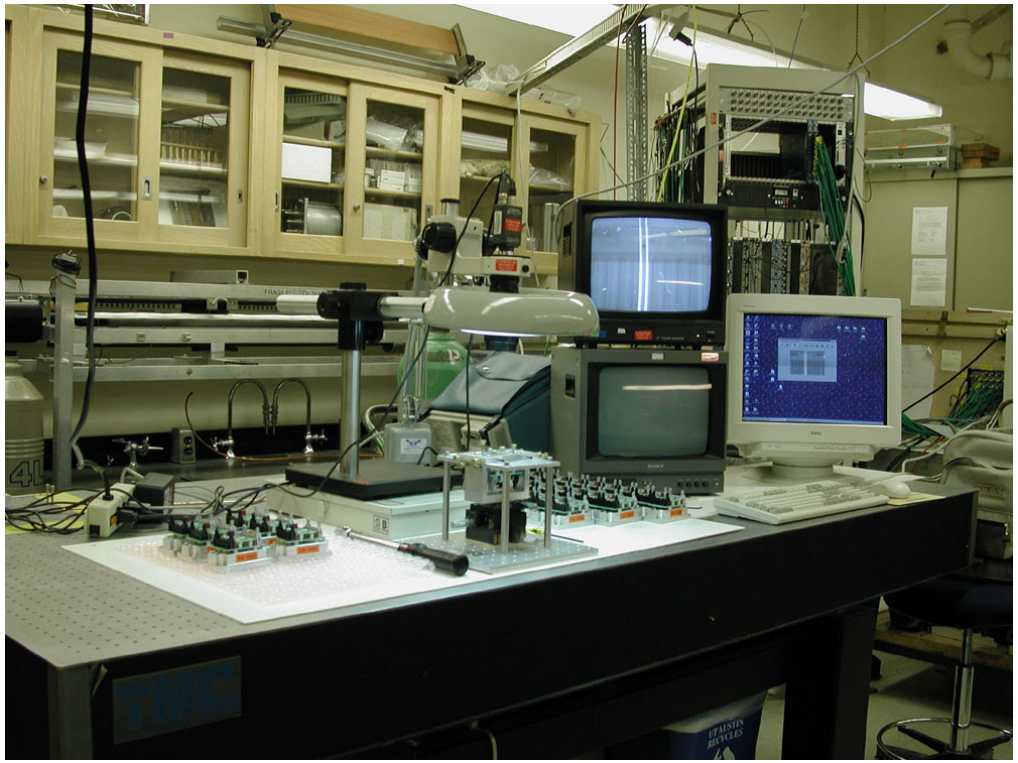


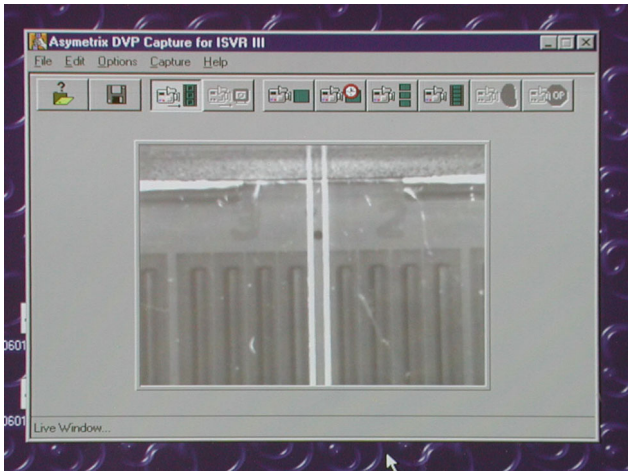


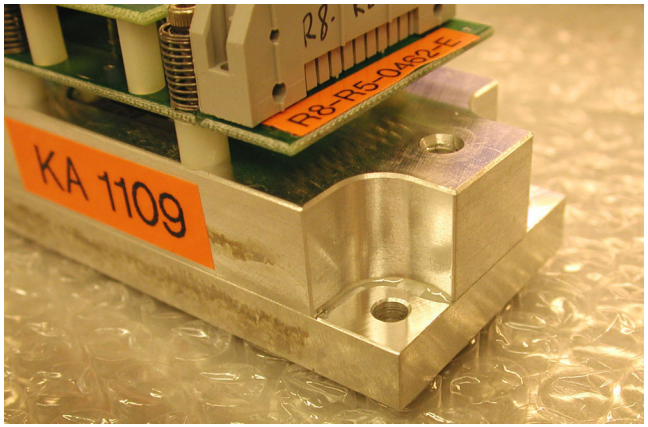
Response Uniformity



M16 alignment







M16 cross talk

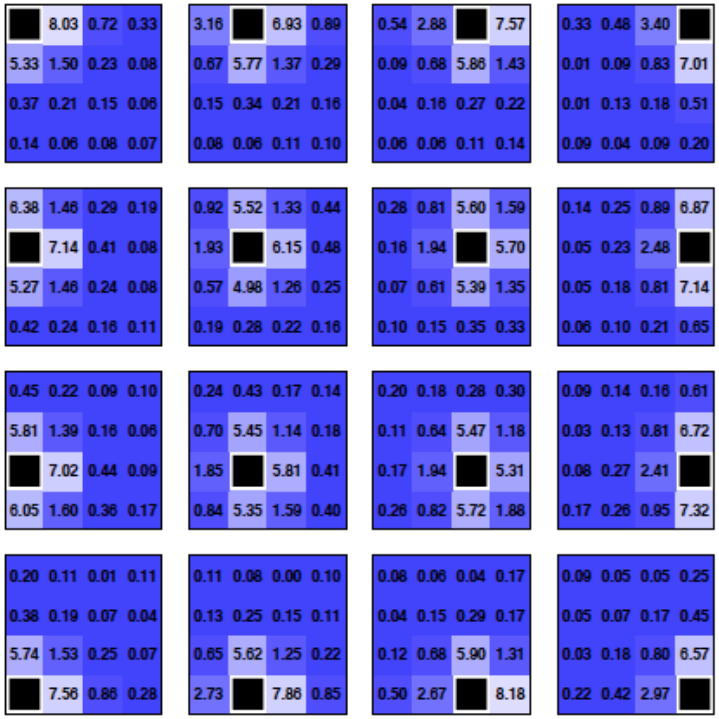
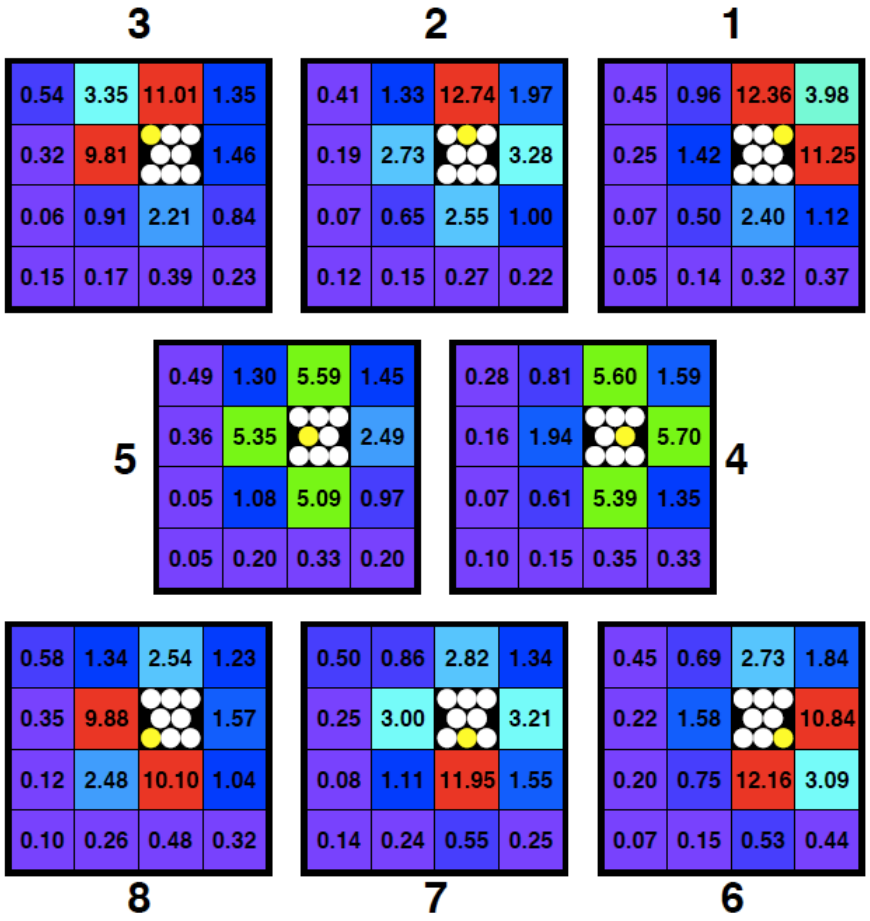
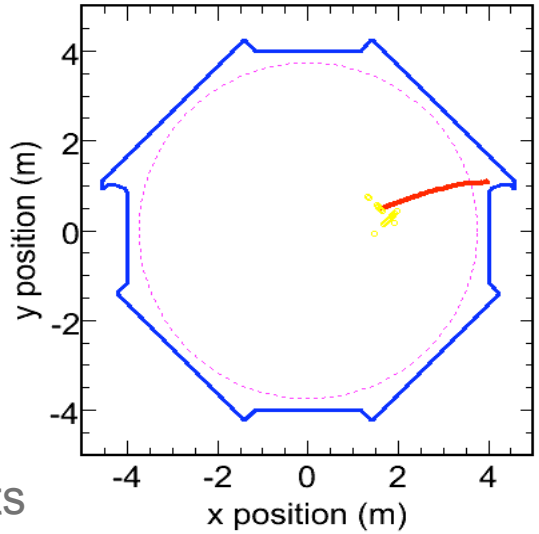


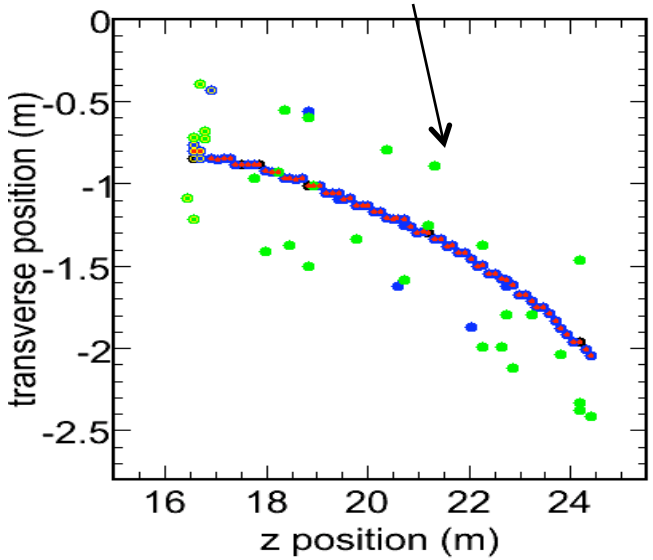
Fig. 11. The fraction of charge detected in a pixel due to optical cross-talk. The black square indicates the illuminate fiber #4 was illuminated. Results are in units of 10^{-3}.



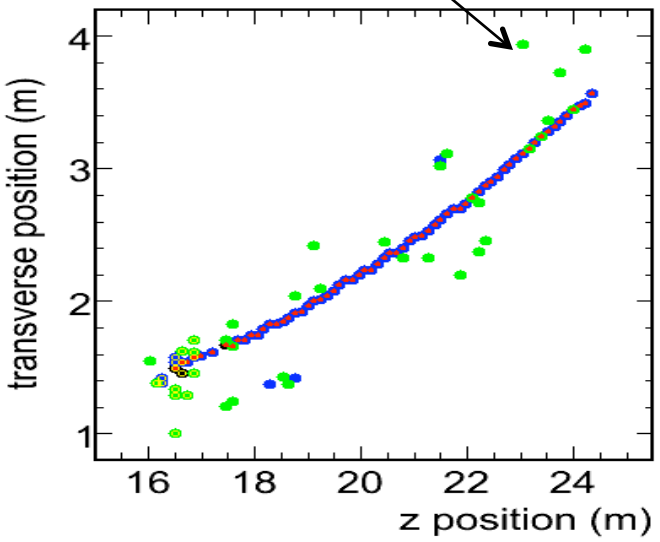
Event display



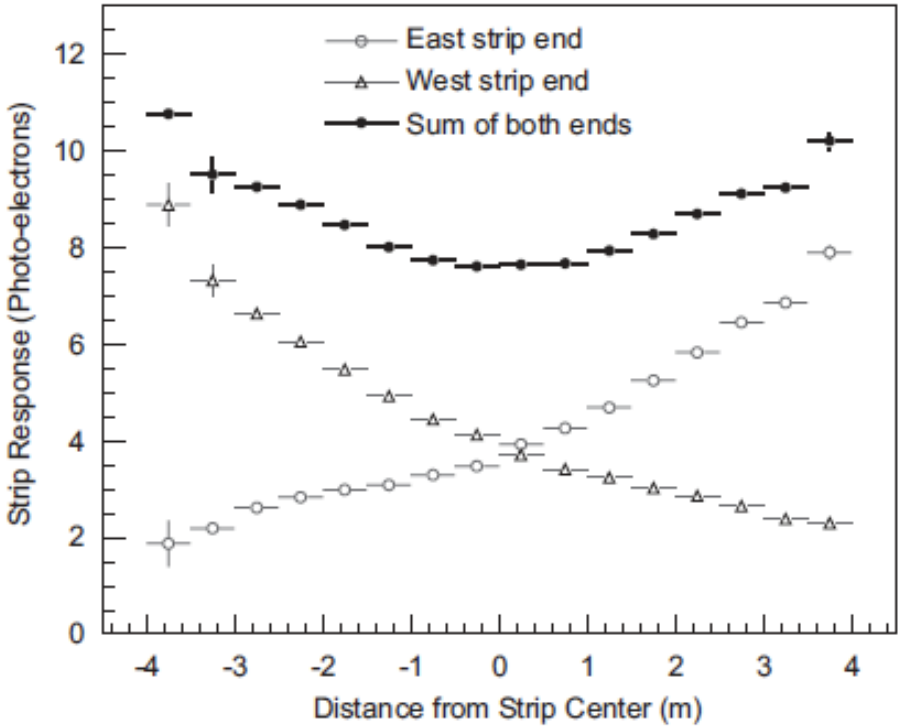
Cross talk hits

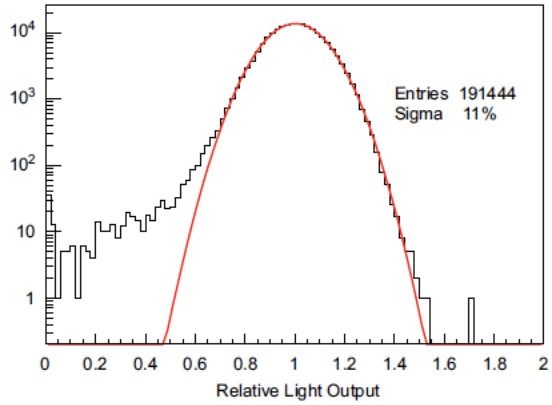


Cross talk hits



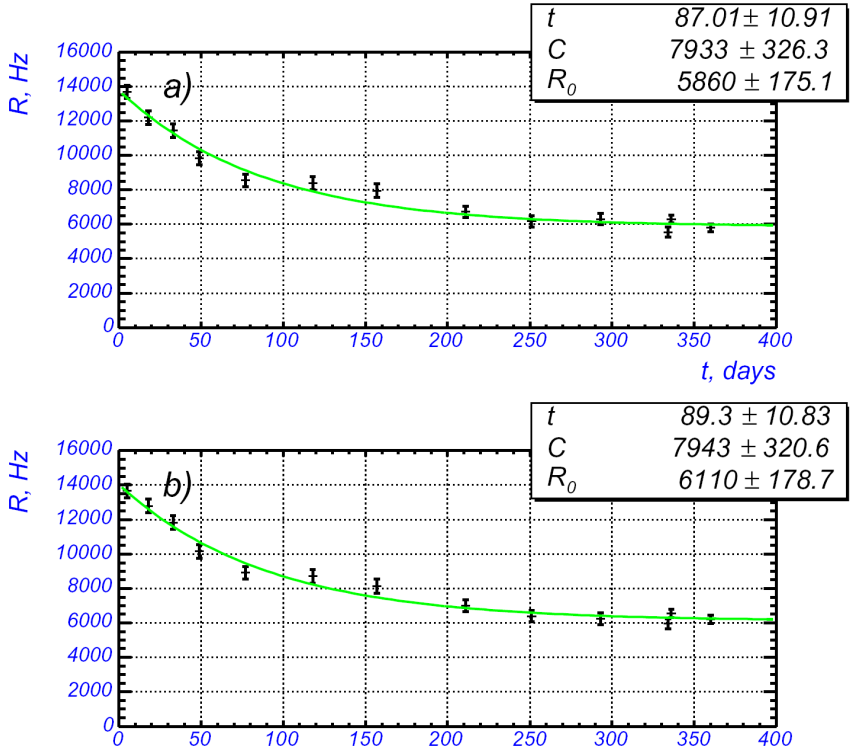
Light yield in MINOS modules
Far Detector





Surprise!

- **Expected sources of singles**
  - ⇨ **PMT dark noise**
  - ⇨ **Natural radioactivity**
- **Unexpected**
  - ⇨ **Spontaneous emission from fibers**
  - ⇨ **Decays with time exp (-t / 100days)**



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Spontaneous light emission from fibers in MINOS

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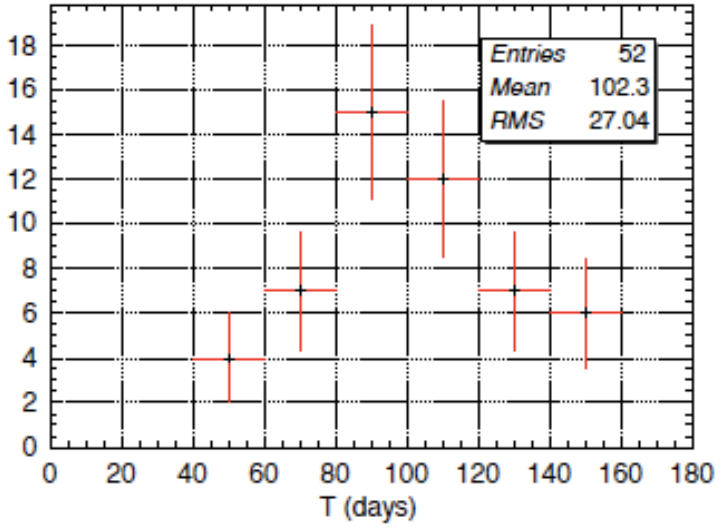
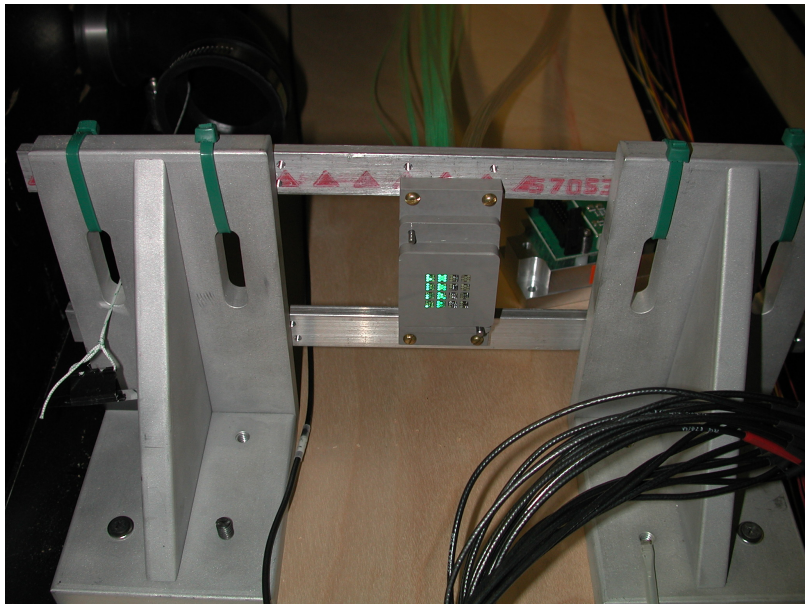
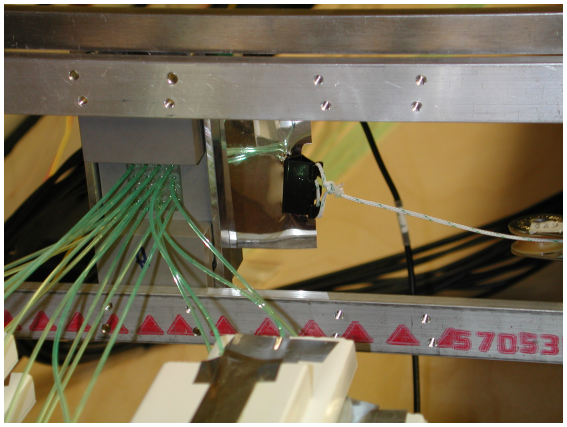
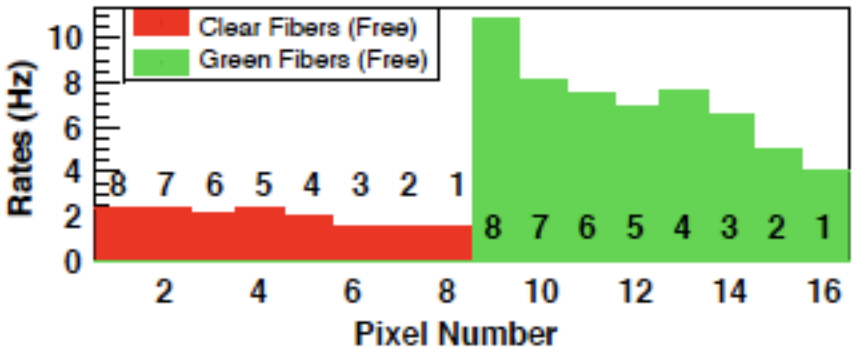


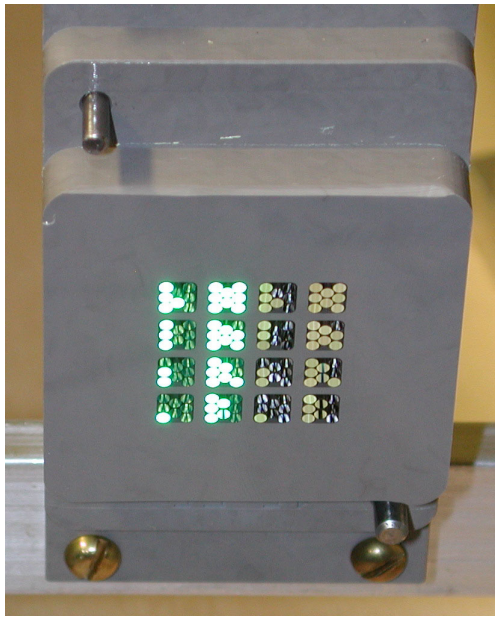
Fig. 2. A distribution of decay time constants determined from fits to the data from 51 fully commissioned planes (between detector plane 61 to 120). We used a simple exponential function of the form $R = C + R_0 e^{-t/T}$. Examples of such fits are shown in Fig. 1.

Special tests of spontaneous light emission by WLS fibers









Spontaneous rate / length

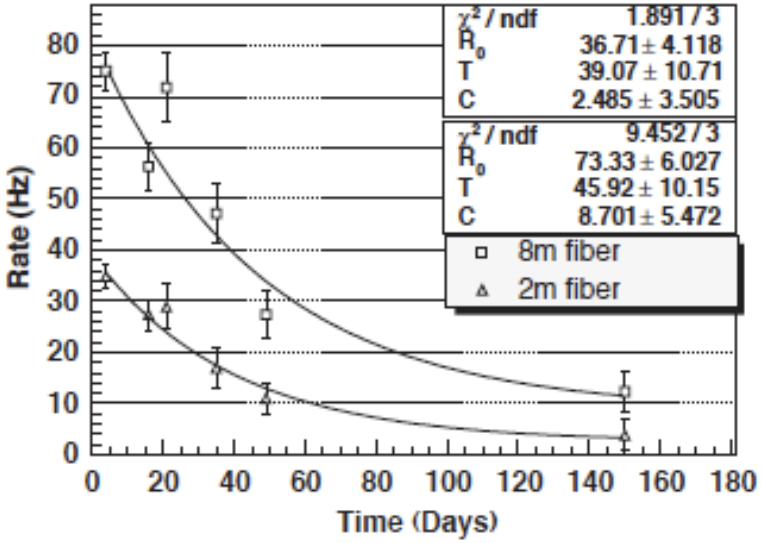


Fig. 8. Rates measured for 2- and 8-m-long free fibers as a function of time.

Table 2
Attenuation corrected emission rates for exponential and asymptotic components of WLS fiber emission for fibers glued with Epon [9], free Bicron fibers [16], and clear fibers

Test condition	Initial rate (Hz/m)	Asymptotic rate (Hz/m)
Kuraray WLS fiber in Epon 815C	75 ± 4	9 ± 1
Bicron WLS fiber free	35 ± 4	−3 ± 3
Kuraray clear fiber free	8 ± 2	0 ± 2

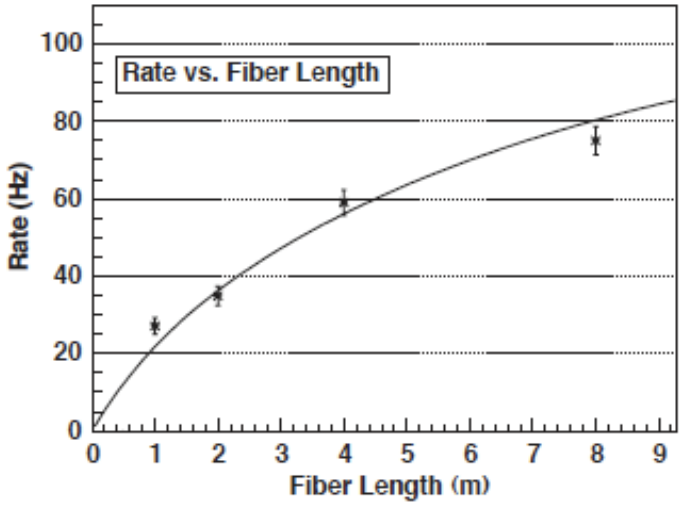


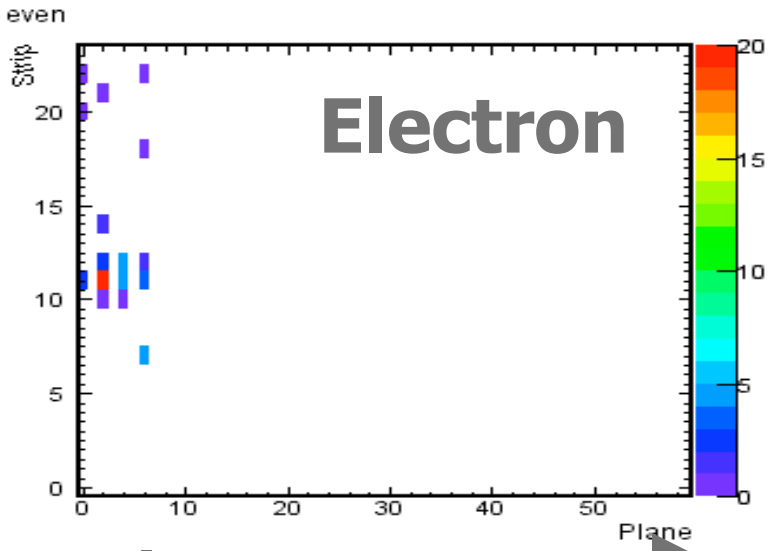
Fig. 7. Measured rates for groups of free wavelength-shifting fibers of different lengths installed in grooves in wooden strips. The line is a fit to the data using equation 1 with a, the overall normalization, as the only free parameter. The fit yields $a = (27 \pm 1)$ Hz/m.

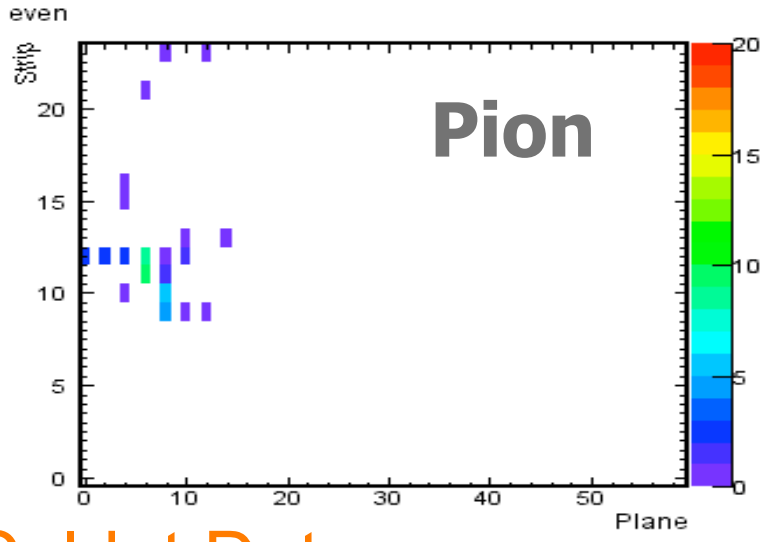
$$R = \int_0^L \frac{a}{2}(e^{-x/\lambda_1} + e^{-x/\lambda_2})\,dx = \frac{a}{2}[\lambda_1(1 - e^{-L/\lambda_1}) + \lambda_2(1 - e^{-L/\lambda_2})]. \quad (1)$$

Table 1
Attenuation corrected emission rates for exponential and asymptotic components of WLS fiber emission

Fiber length (m)	Initial rate		Asymptotic rate	
	R (Hz)	a (Hz/m)	R (Hz)	a (Hz/m)
1	29 ± 2	35 ± 7	2 ± 1	3 ± 1
2	38 ± 2	28 ± 2	2 ± 2	2 ± 2
4	77 ± 5	33 ± 2	10 ± 4	5 ± 2
8	81 ± 3	25 ± 1	9 ± 3	3 ± 1

MINOS Calibration Detector – 2 GeV events

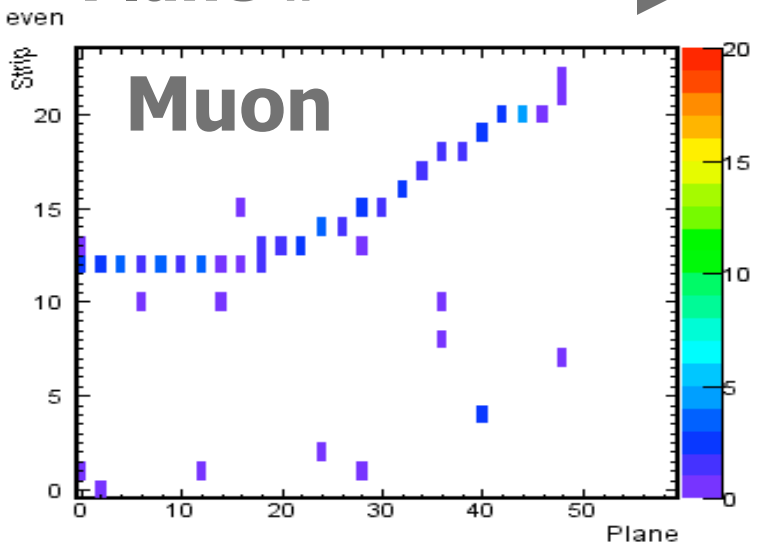


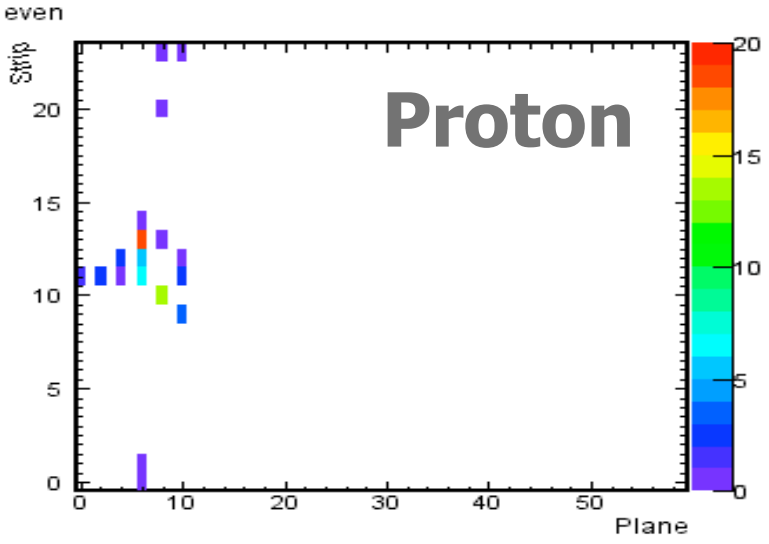


Strip#

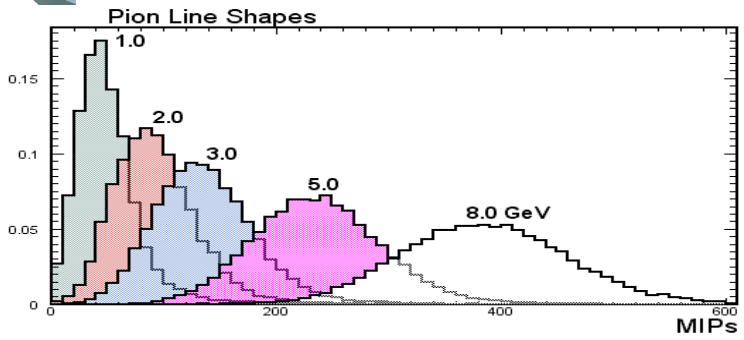
Plane #

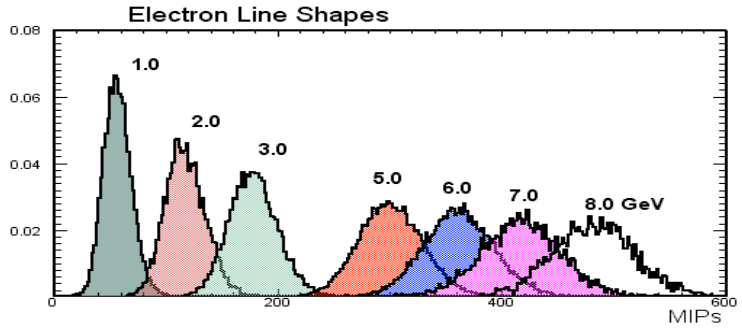
Caldet Data



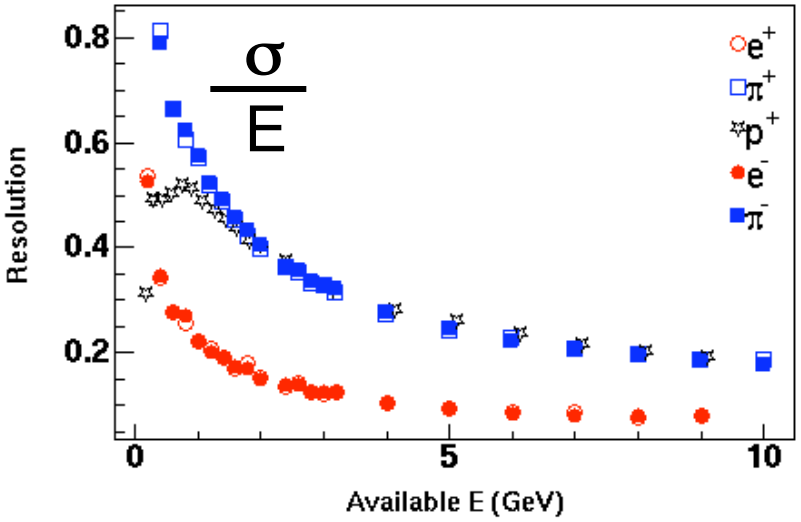


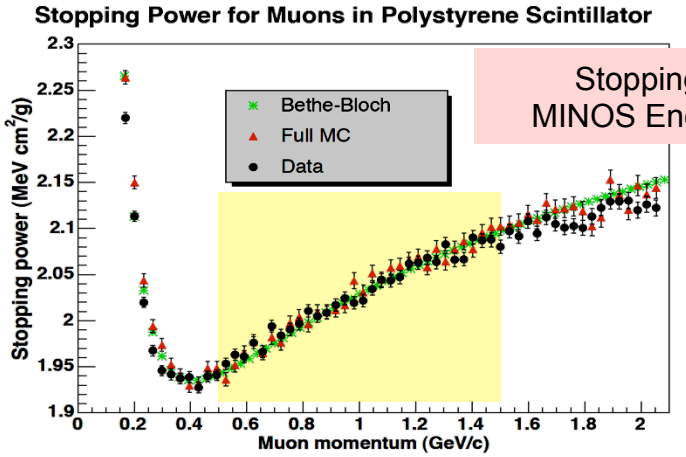
MINOS Calibration Detector Response





Energy resolution





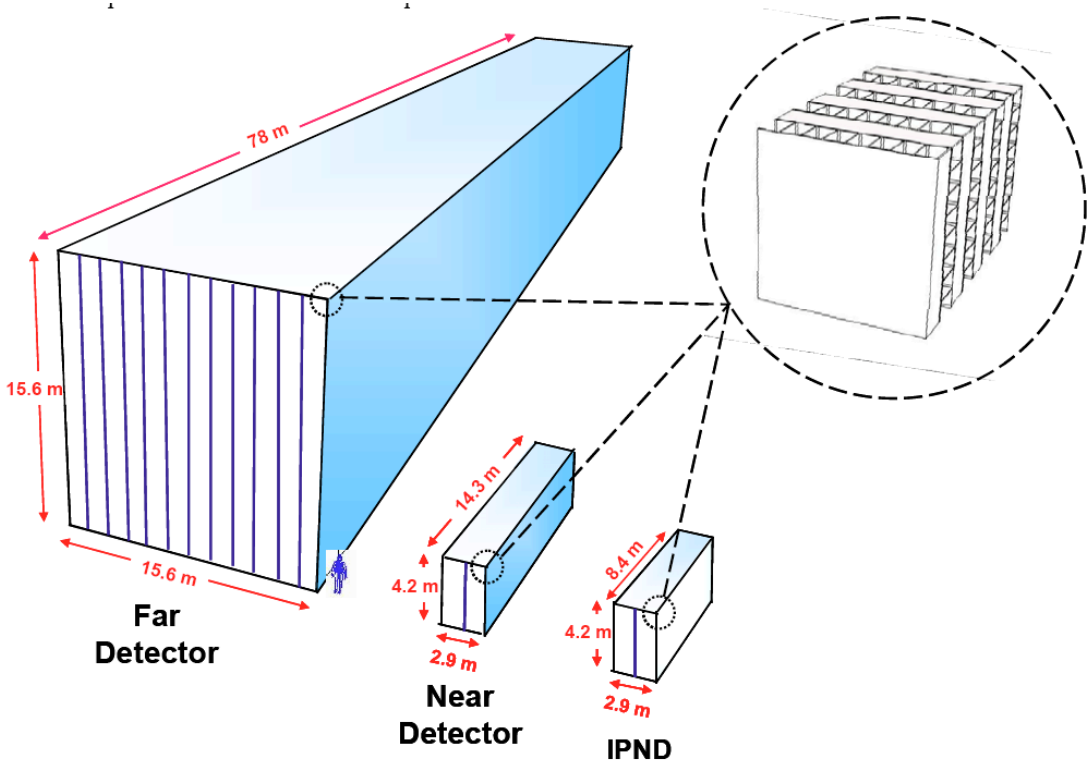
Stopping CR muons:
MINOS Energy Unit (MEU)

Had: $\frac{56\%}{\sqrt{E}} \oplus 2\%$

EM: $\frac{21.4\%}{\sqrt{E}} \oplus \frac{4.1\%}{E}$

NOvA Detectors

- The cells are made from 32-cell extrusions.
- 12 extrusion modules make up a plane.
- The planes alternate horizontal and vertical.



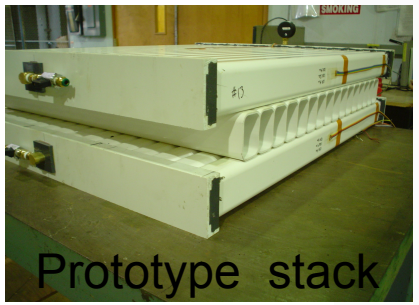
Full-size Modules

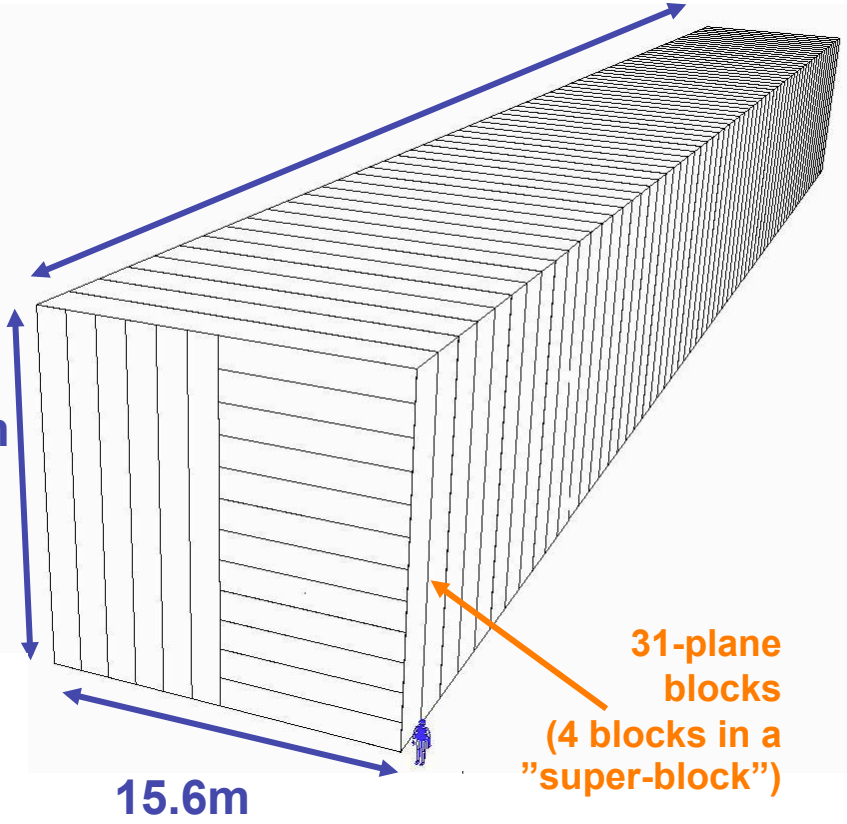
- There are 1003 planes, for a total mass of 15 kT. There is enough room in the building for 18 kT, which can be built if we can preserve half of our contingency.

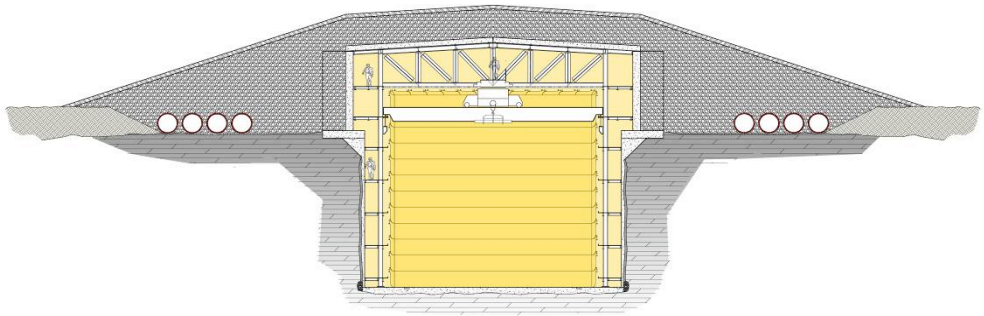
- The detector can start taking data as soon as blocks are filled and the electronics connected.

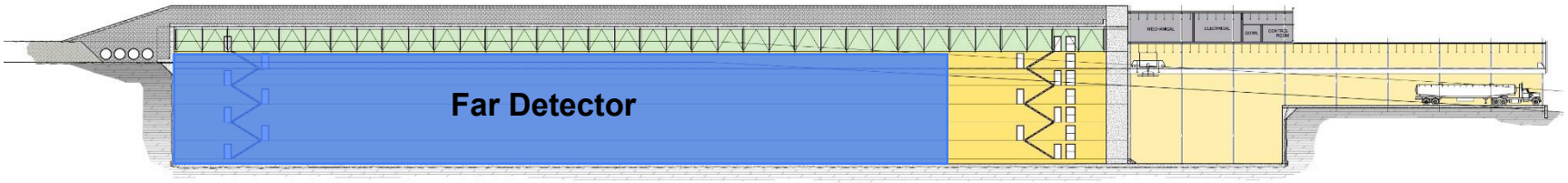
NOνA Far Detector we would like to build

- TAD = Totally Active Detector
  PVC = passive material
- mass N kT (N large)
  ~70% scintillator
  ~30% PVC extrusions
- Modular structure
  32 cells/extrusion
  12 extrusions/plane
  ~1000 planes
  ~400,000 cells
- Cell dimensions:
  3.9 cm x 6 cm x 15.6m
- U-shaped 0.7 mm WLS fiber into APD
- X_0 = 44 cm ρ_M = 10 cm

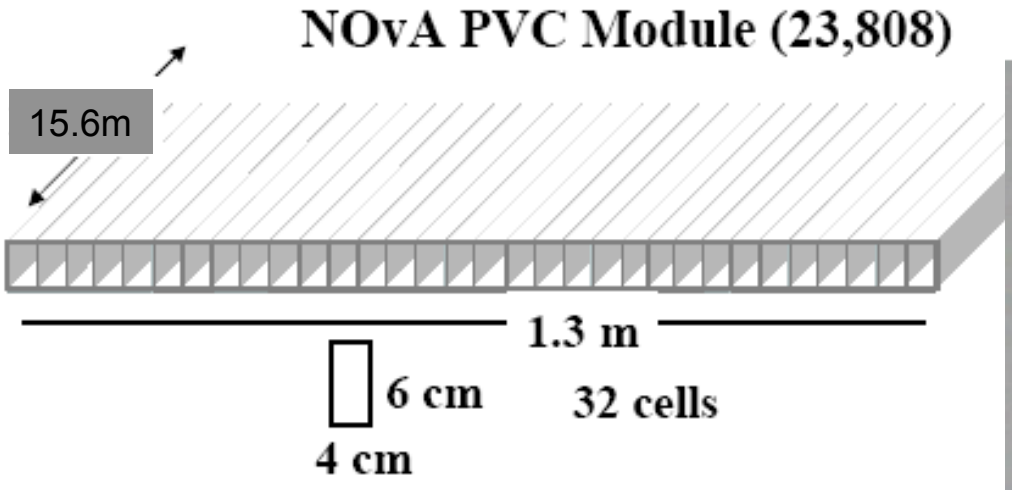


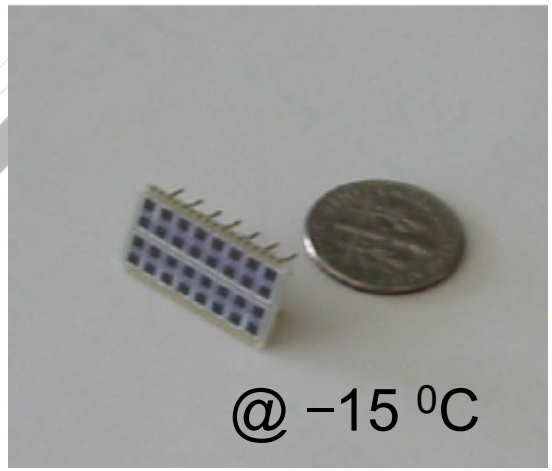


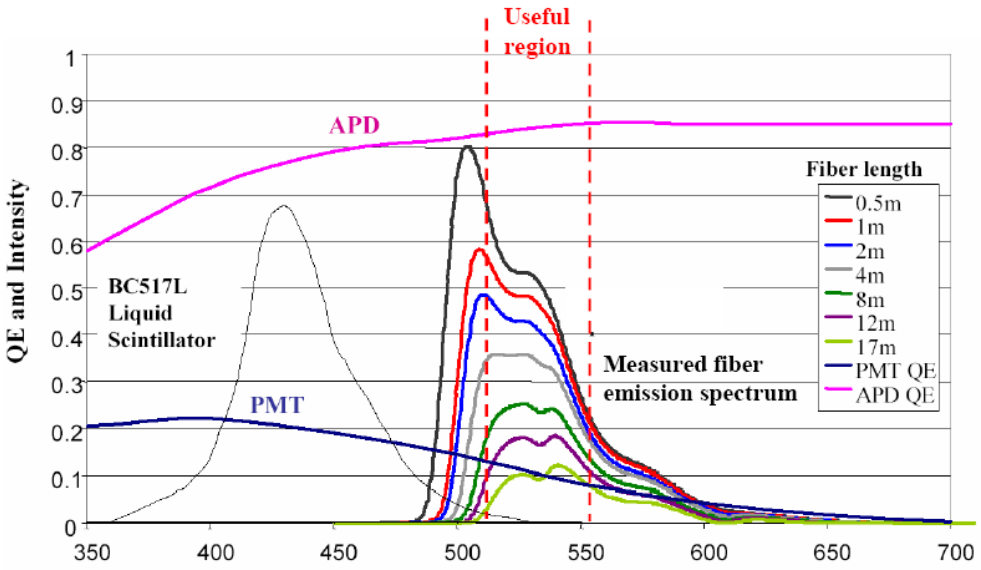




Detector technology

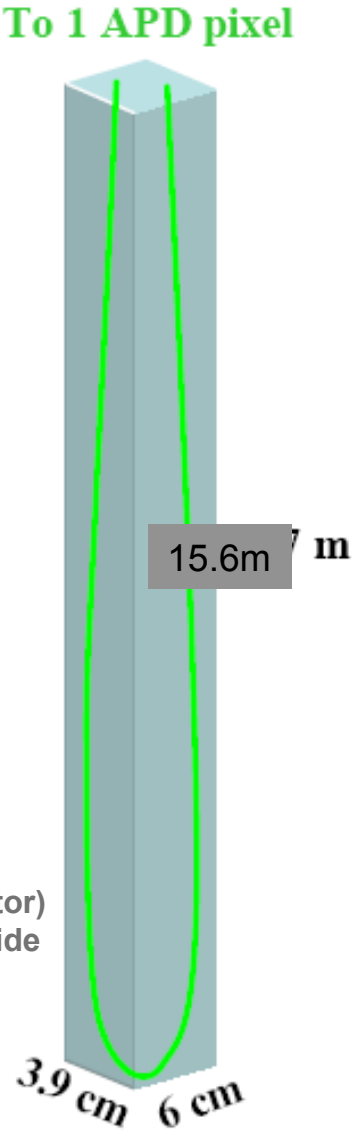






Active readout components:

- ❑Liquid scintillator
  - filled cells.
- ❑WLS fiber
  - 0.7 mm diameter
  - looped end (“perfect” reflector)
  - readout both ends on one side
- ❑Avalanche Photodiode
  - Hamamatsu multi-pixel
  - 85% QE

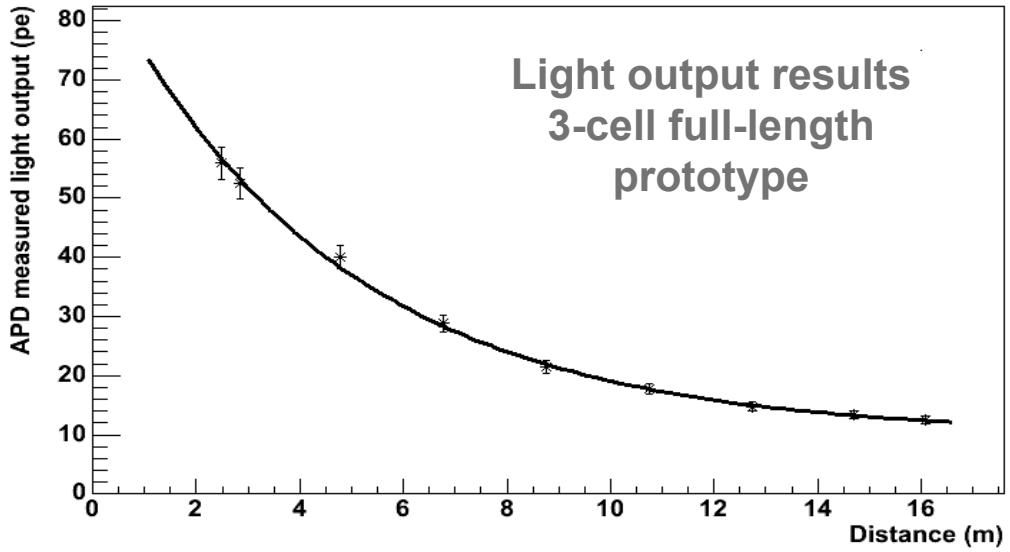


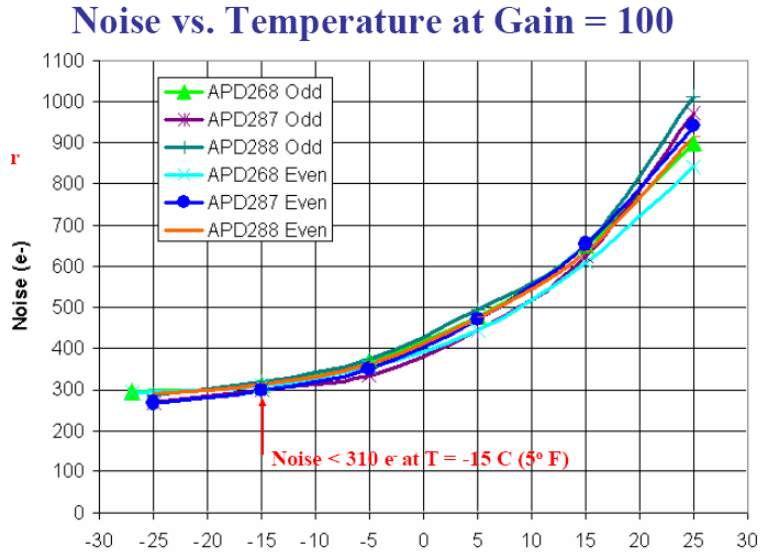
Scintillator, light yield

- NOνA recipe
  Equivalent to Saint-Gobain (Bicron) BC-517P or Eljen Technology EJ-321P

- Requirement: 20PE's for a MIP at far extrusion-end

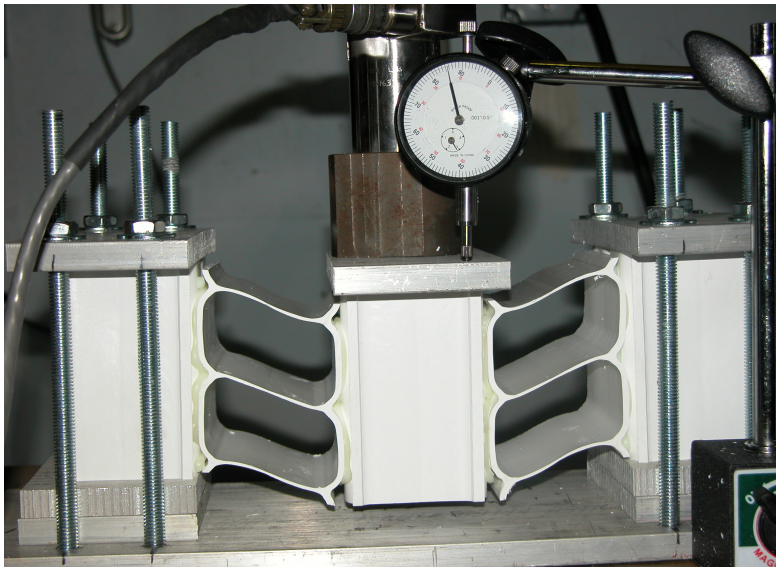
Component	Purpose	Mass fraction
mineral oil	solvent	94.4%
pseudocumene	scintillant	5.5%
PPO	waveshifter #1	0.1%
bis-MSB	waveshifter #2	0.002%
Stadis-425	anti-static agent	0.0003%
tocopherol	anti-oxidant	0.0010%
TOTAL		**100%**



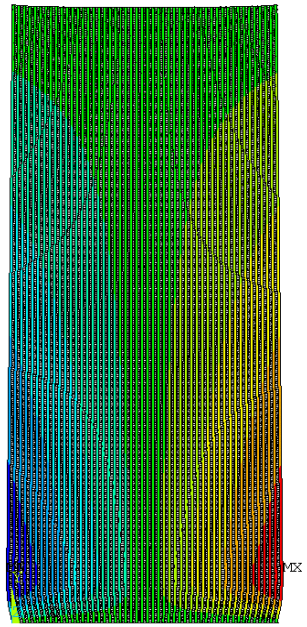


Structural challenges

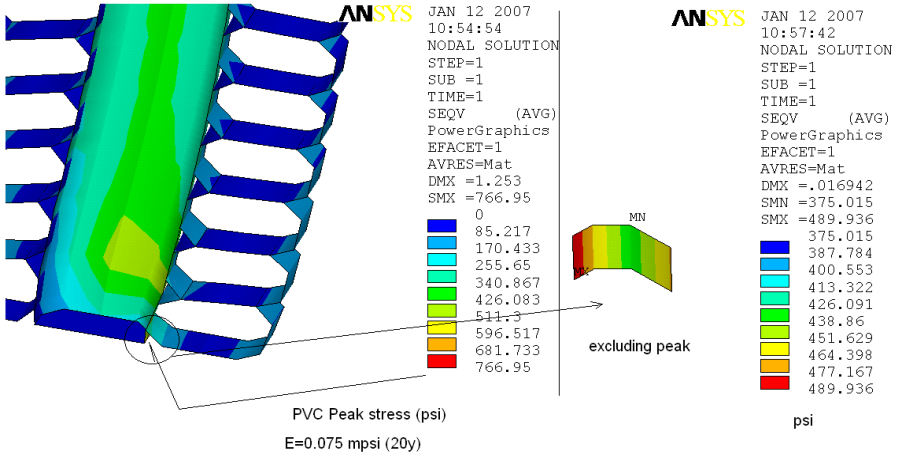
- FEA calculations and tests (on-going)



31-plane block



deflection for 99 planes block

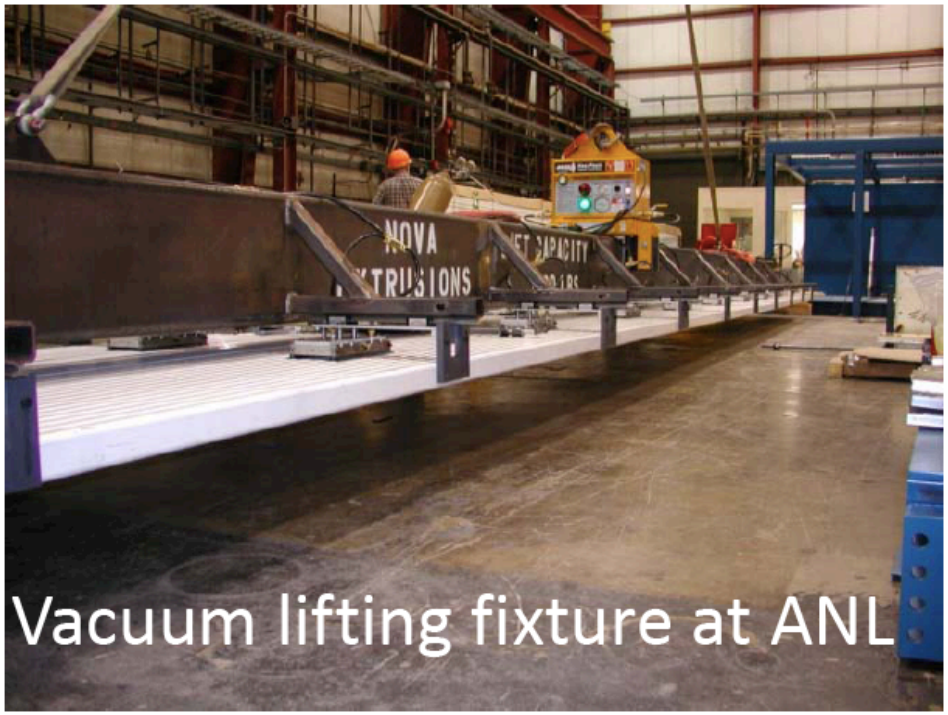


Tests

- A full pressure scintillator leak test is underway in C0 at the Tevatron.

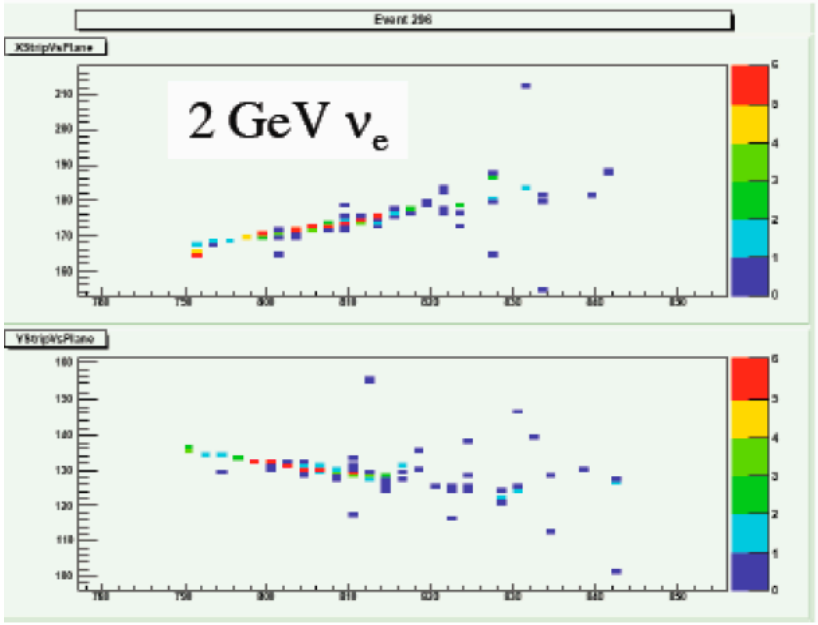
  No leaks so far.

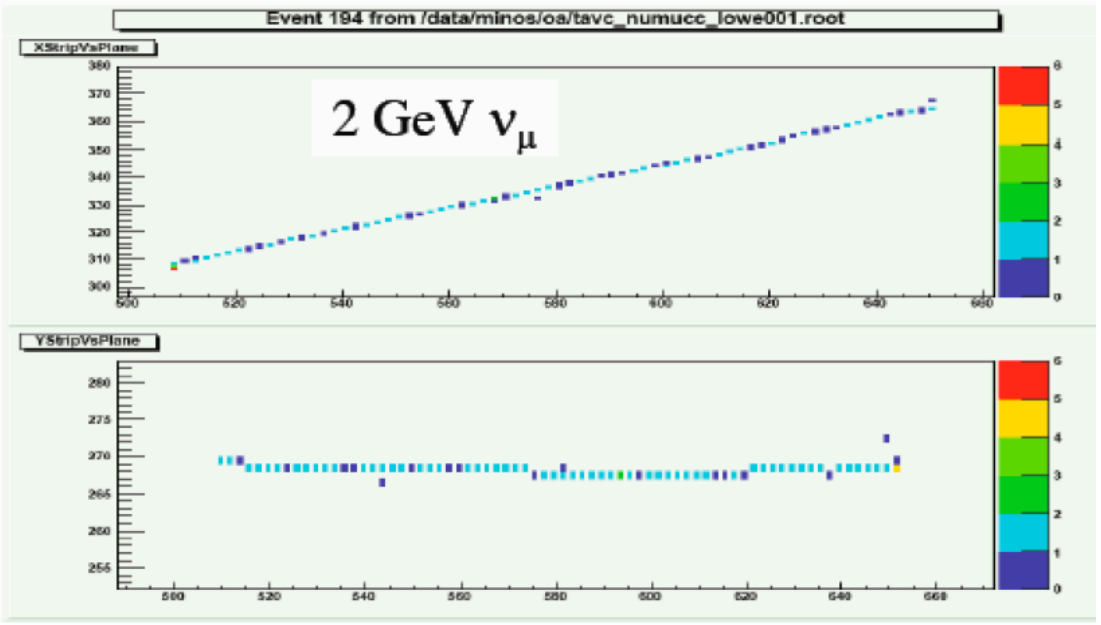
- A Full Height Engineering Prototype is planned for the CDF pit



Event classification

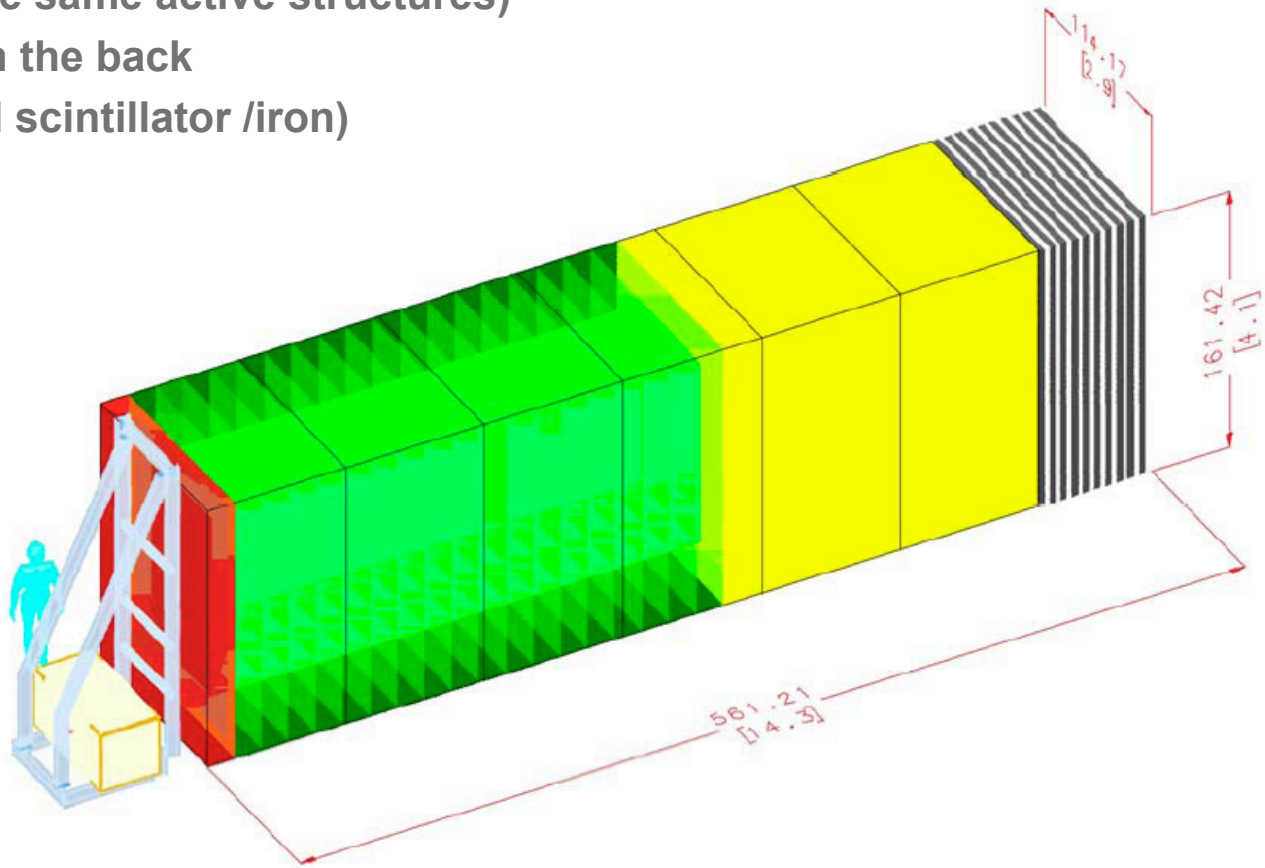
- Longitudinal sampling every 0.15 X_0
- 2 GeV muon traverses ~60 planes





Near Detector

- 2000 ν_e CC events per year
- 20 tons fiducial volume
- Muon catcher in the back
- Red, green and yellow reflect logical assignment
  (all 186 planes made the same active structures)
- Muon catcher (black) in the back
  (10 planes [1.7m] liquid scintillator /iron)

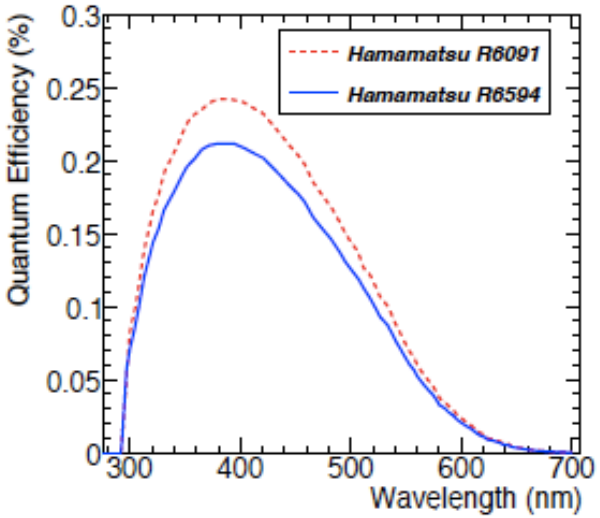


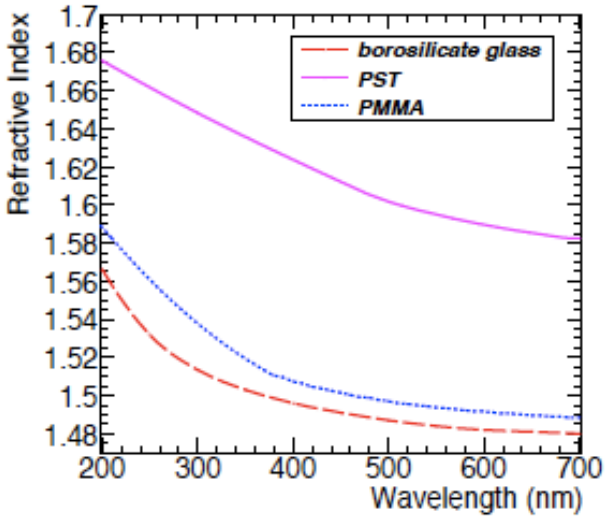
Scintillator simulations

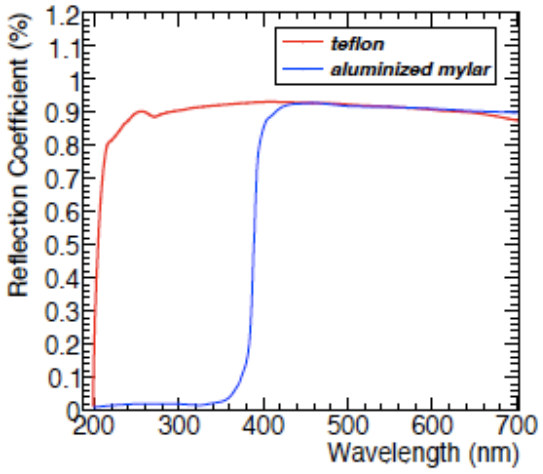
- Developed for calorimeters used and planned for NEMO-3 (now running) and SuperNEMO ($0\nu\beta\beta$ experiments) and … NOvA
  - ⇨ Energy resolution of the order of 7-8% at 1 MeV is needed in SuperNEMO
- Used GEANT4 framework which is supplied with *spectral properties* of *all materials* to (more) treat the photon transport
  - ⇨ Bulk attenuations PS and PVT
  - ⇨ Stokes shifting
  - ⇨ Reflectivity, indices of refraction, QE,…
- Initially validated on MINOS data and bench-top CR experiments
- Reproduce NEMO-3 data (spectral data improve the agreement)
  - ⇨ Energy resolution
  - ⇨ Uniformity
- Help design SuperNEMO blocks
- Will use for NOvA

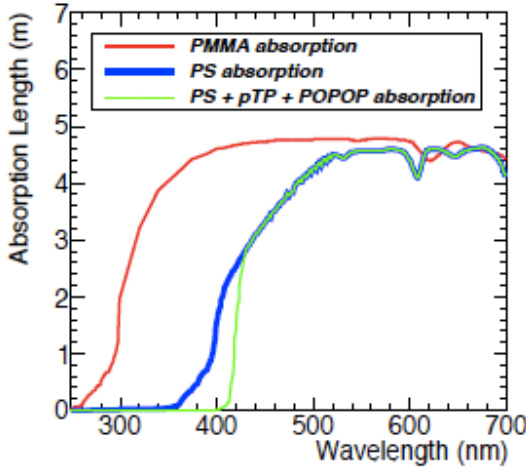
Benton Pahlka
(a man behind this)

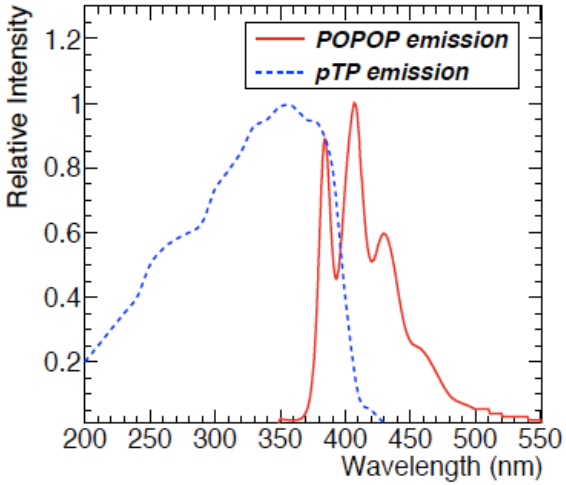
Examples of spectral properties



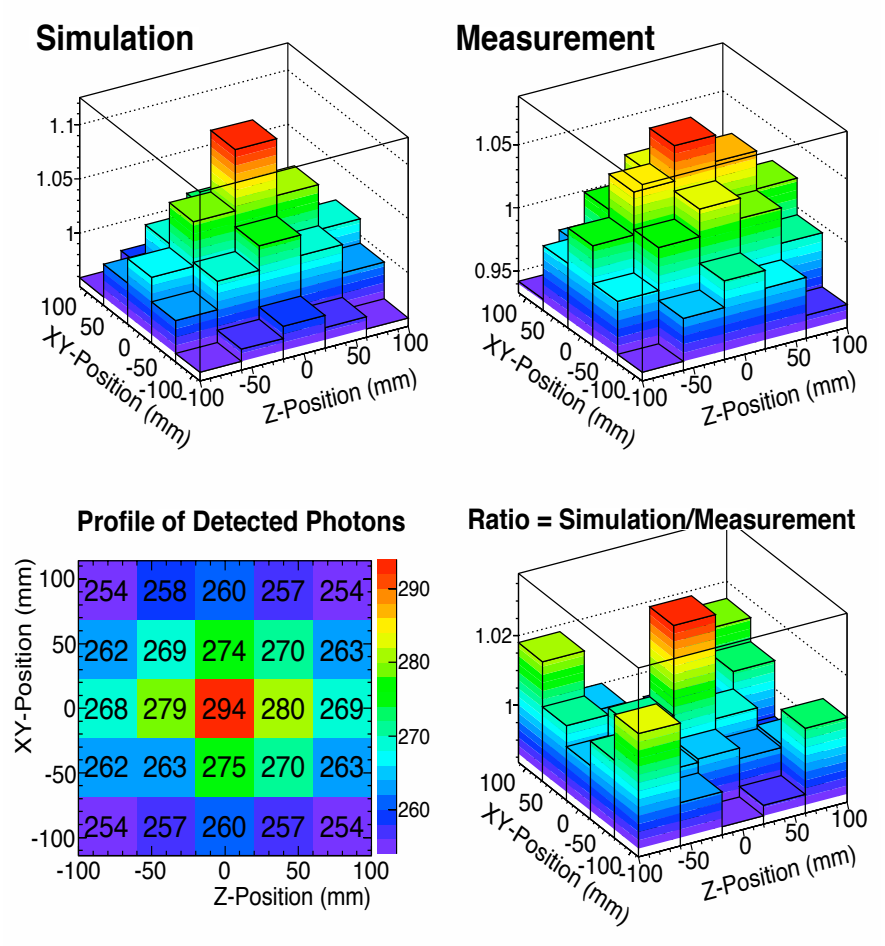


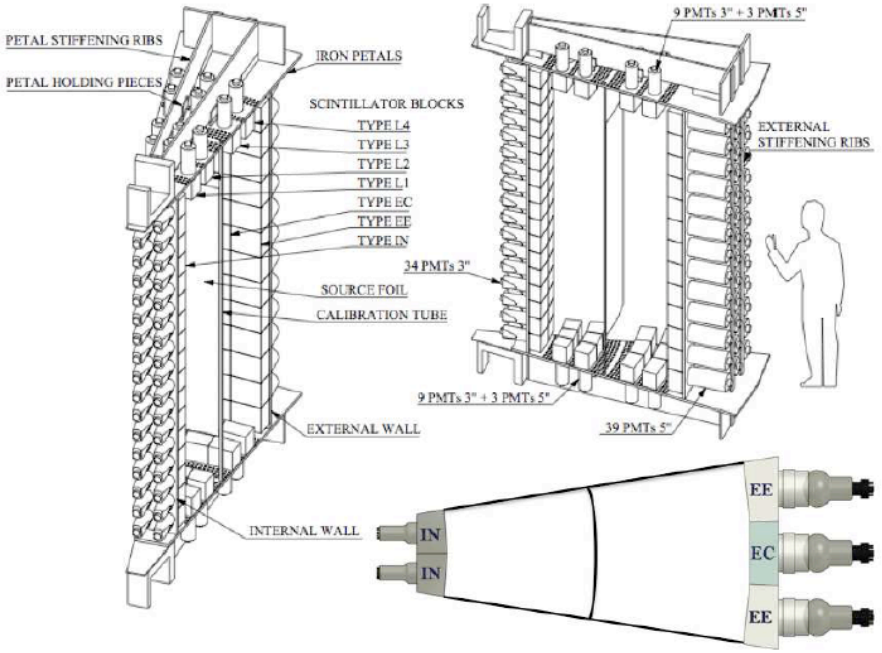




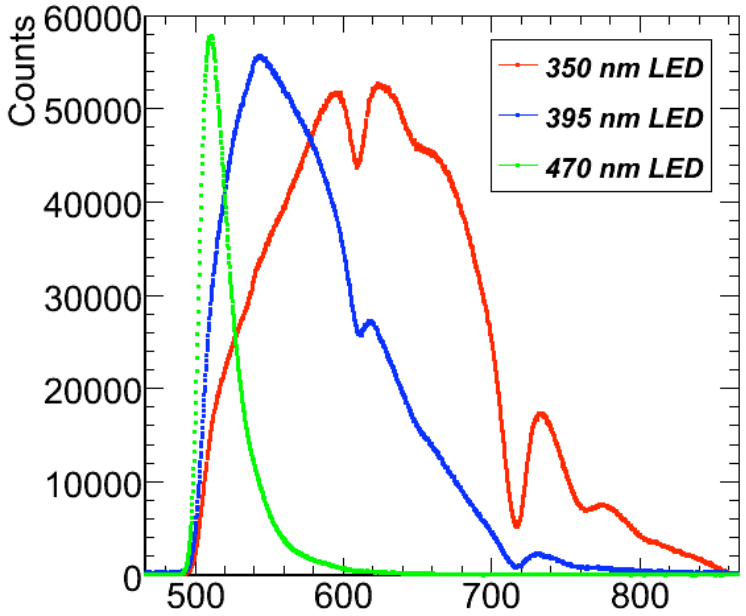


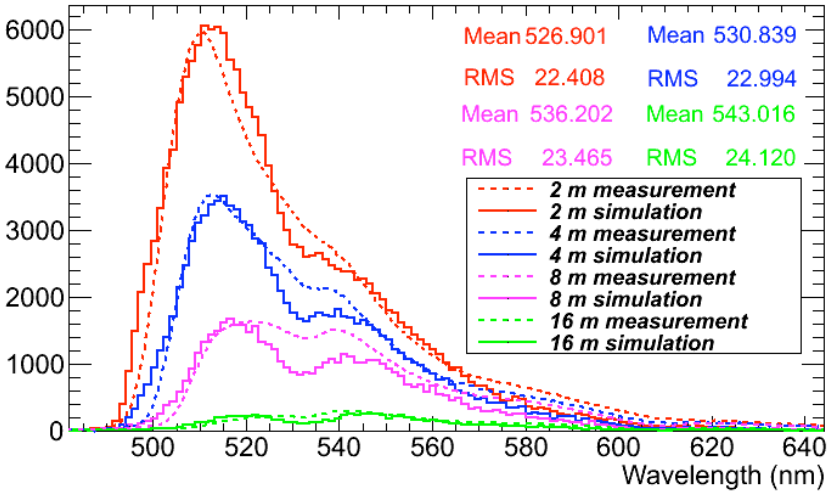
NEMO-3 uniformity

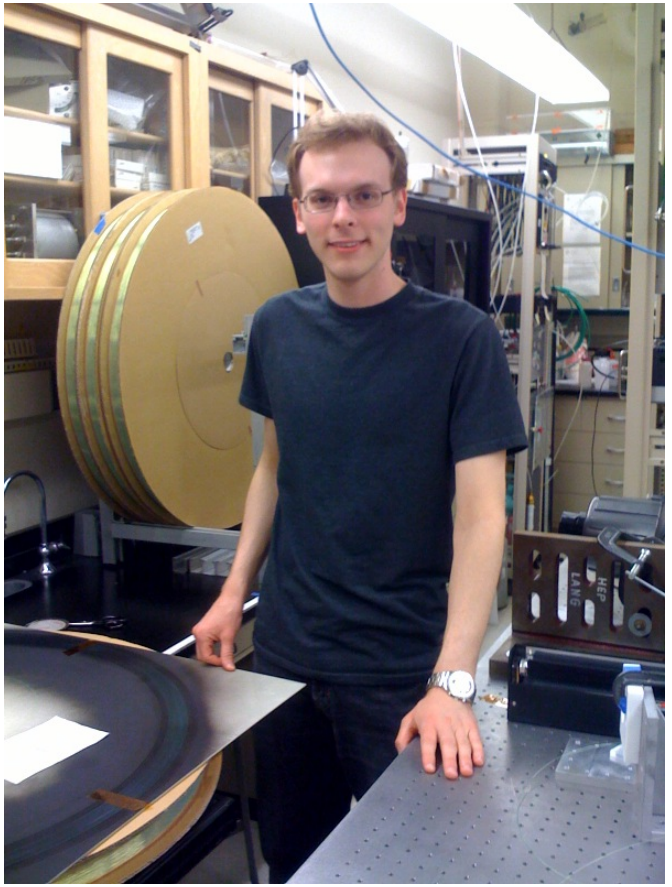




Challenge for NOvA



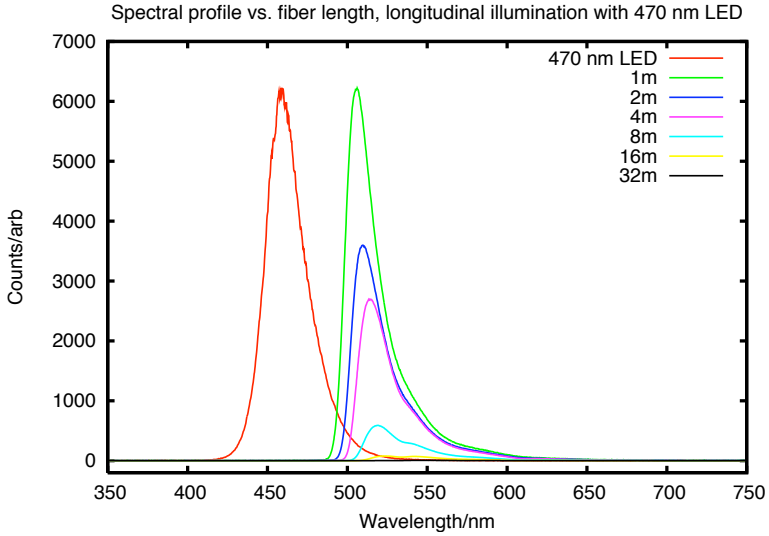


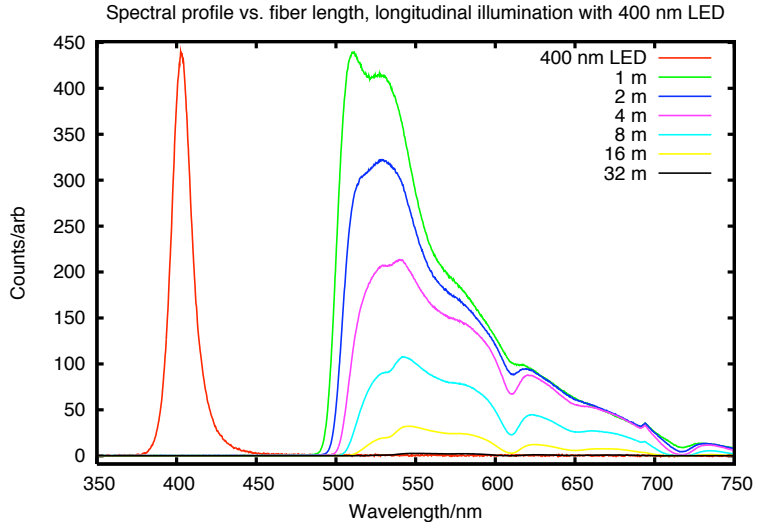


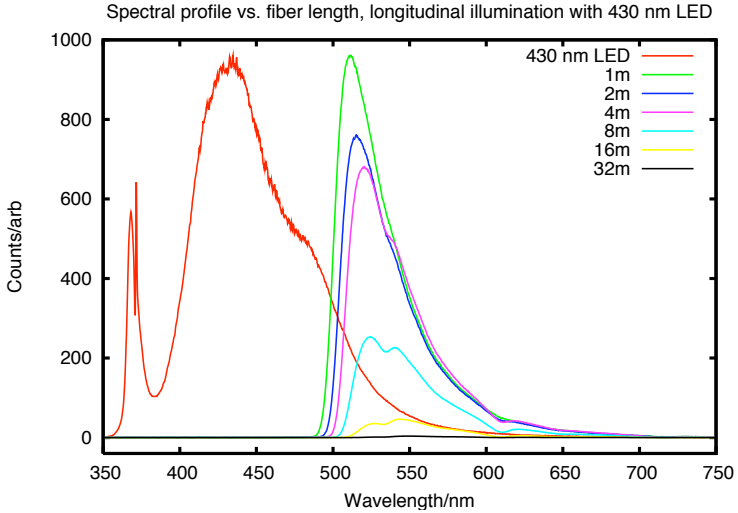
Gabe Elpers
(conducting fiber measurements)

Challenge for NOvA

Along-axis fiber illuminations

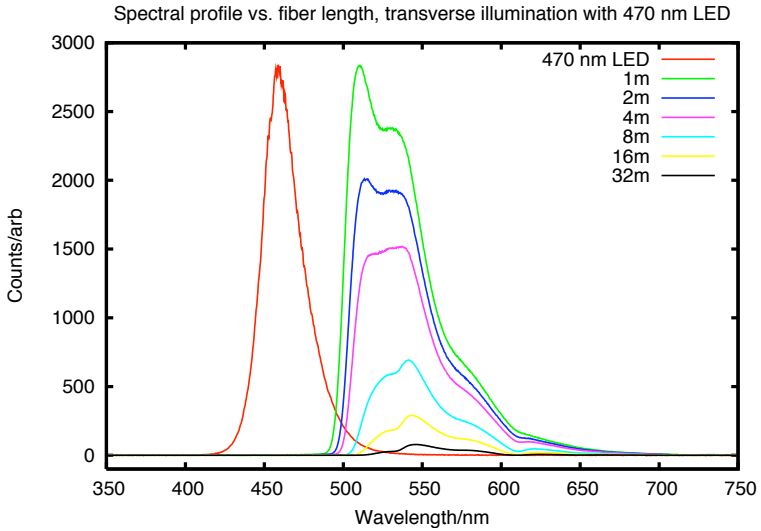


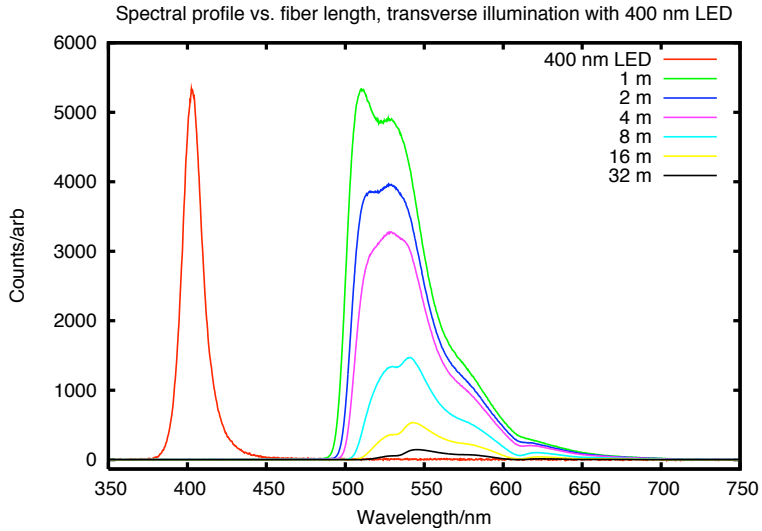


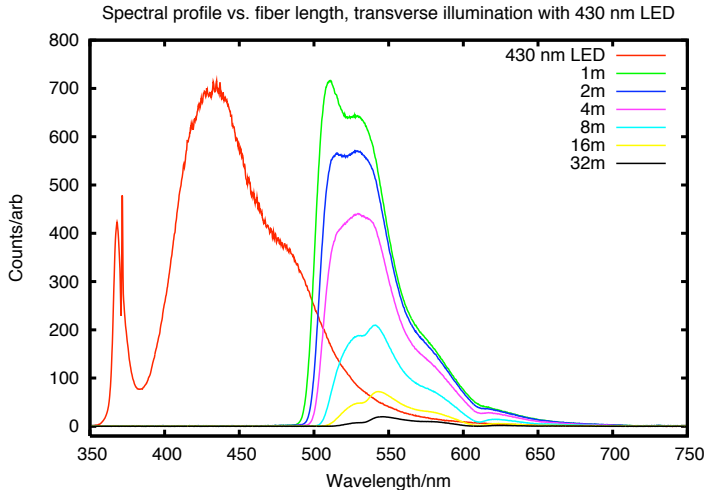


Challenge for NOvA

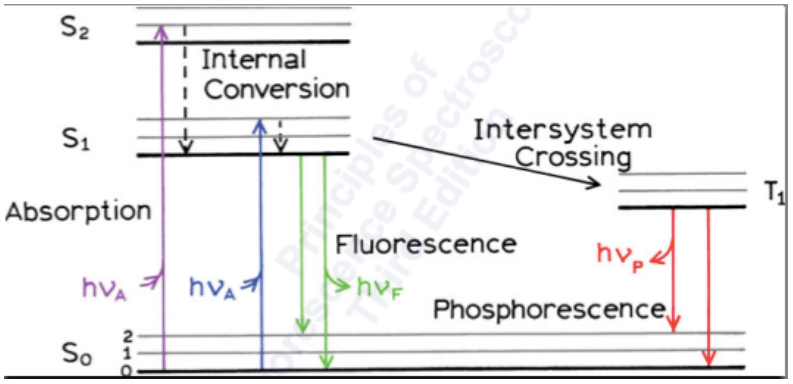
side fiber illuminations

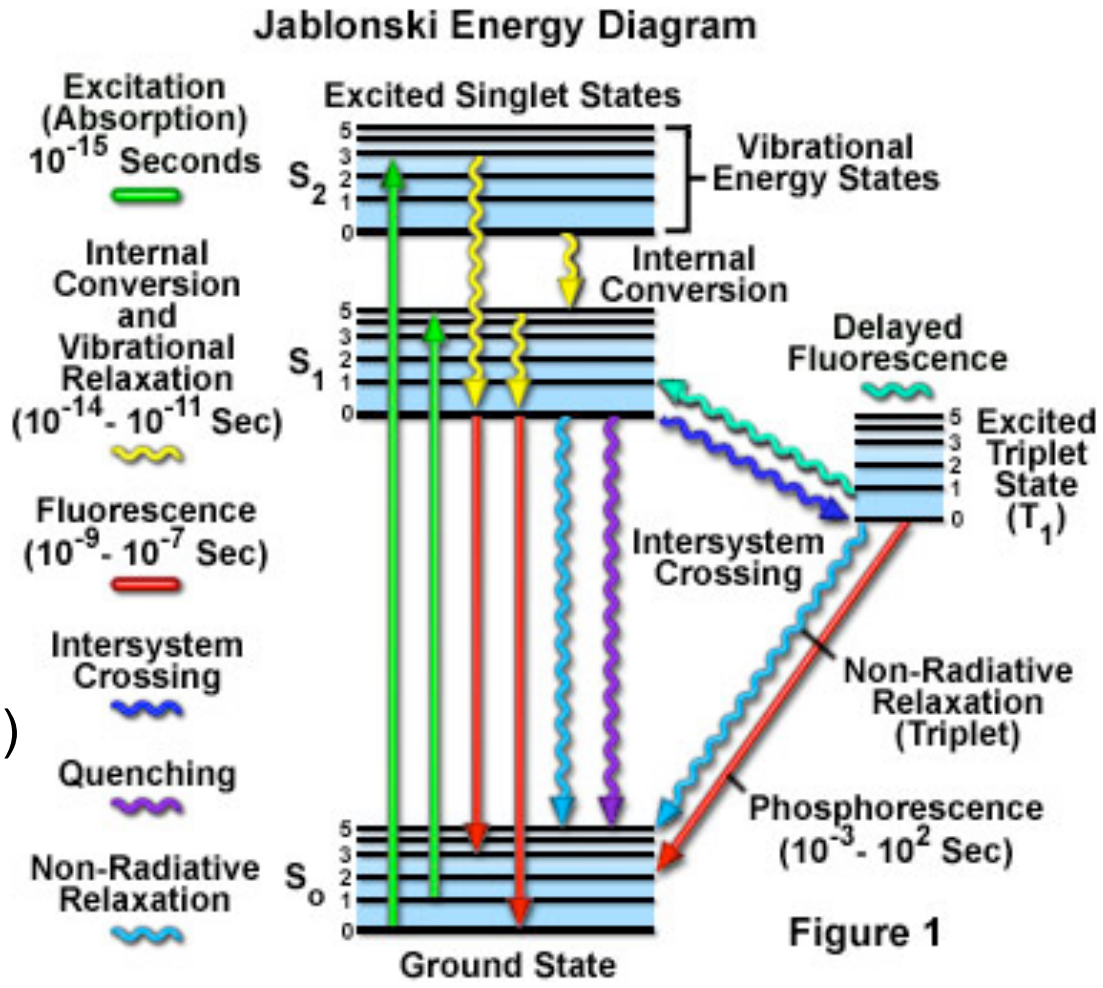






Fluorescence





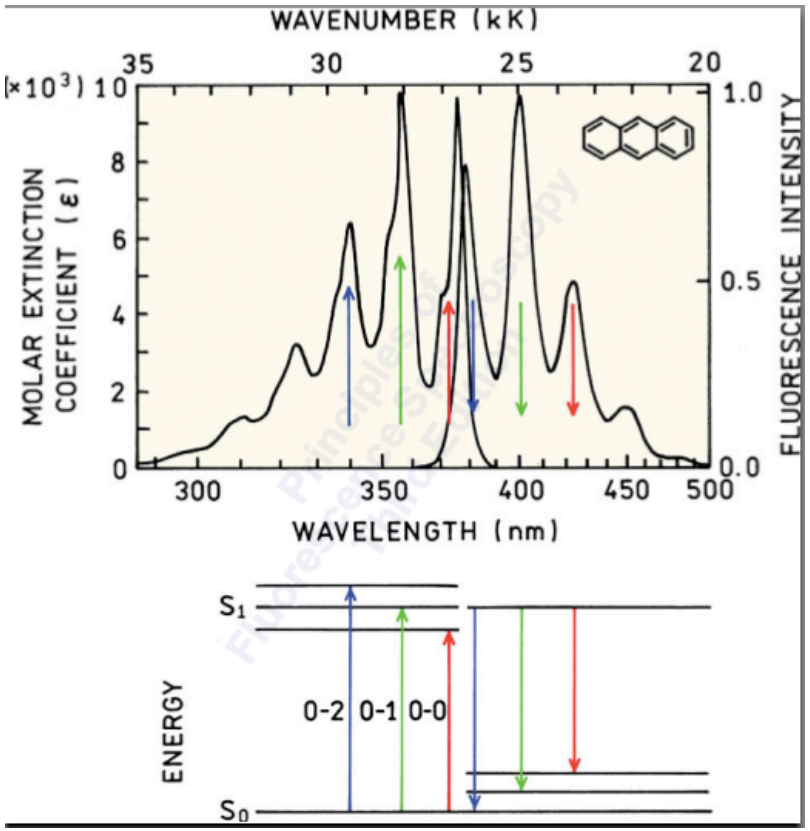
STEPS:

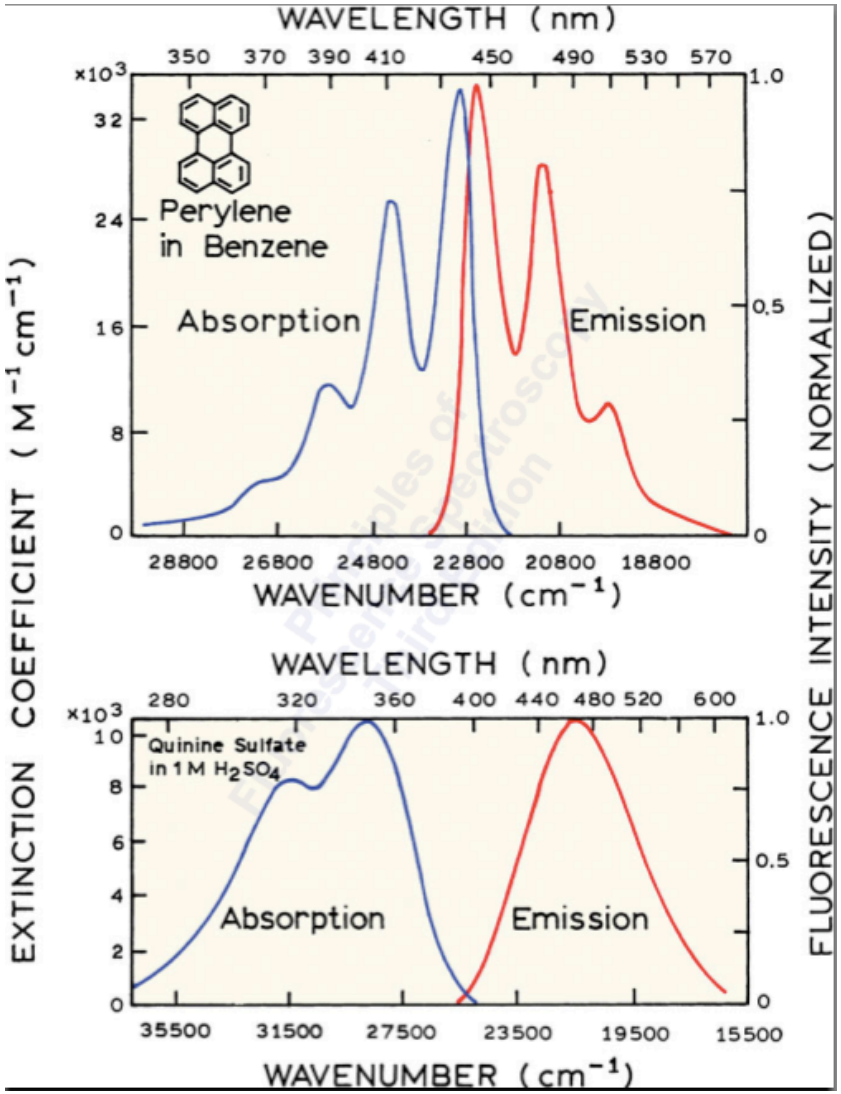
1. **Absorption** (instantaneous)
2. **Internal conversion** to lowest vibrational state
3. **Fluorescence** (from thermally equilibrated excited state)

http://micro.magnet.fsu.edu/primer/techniques/fluorescence/images/fluorescenceintrofigure1.jpg

Mirror Images

Spacing of the vibrational energy levels of the excited states is similar to that of the ground state -> vibrational structures in the absorption/emission spectra are similar.





Summary

- MINOS
  - ⇨ Quality control
    - ❒ Pelets, fluors, strips, fibers, gluing, optical connectors, MUX boxes, PMTs,
  - ⇨ Vertical access
    - ❒ Classical issues of “building a ship in the bottle”
- NOvA
  - ⇨ The largest size with WLS fiber readout (?)
  - ⇨ Liquid mixing and transport
- Simulations/modeling
  - ⇨ Spectral details necessary
  - ⇨ Improvements of GEANT4 needed
- Megaton detectors
  - ⇨ Not possible using MINOS/NOvA approach
  - ⇨ Light transport, absorption, photodetector are key issues