Terra Cognita: technological aspects of MINOS & NOvA

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"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) $4 \times 10^{13}$ protons/pulse (0.4 MW beam)
  - Near detector: multiple 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
Co-extruded scintillator strip + reflector use wavelength shifting (WLS) fibers as readout.
MINOS technology in a glance

- **Near Det**: 1 fiber/pixel
- **Far Det**: 8 fibers/pixel

- **Clear Fiber cables**
- **Multi-anode PMT**
- **U V planes +/- 45°**
- **2.54 cm Fe**
- **5.9 cm Scintillator**
- **WLS fiber**
- **Extruded PS scint. 4.1 x 1 cm**
- **M16**: 8 fibers/pixel
- **M64**: 1 fiber/pixel

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SELECTION OF RAW MATERIALS

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

WHITE CAPSTOCKING
- Polystyrene with 12% TiO₂ – 0.25 mm thick

GREEN FIBER
- K-27 fiber – 1.2 mm diameter

Polystyrene Handling
- Dry PS purged with nitrogen
- PS mixed with PPO+POPOP
- Hopper purged with nitrogen
- PS mixture purged with nitrogen

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Module Assembly II

Scenes from Minnesota Module Factory

- Glue WLS fibers
- Install top of light case
- Allow Fiber Epoxy to cure

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• Identical construction (modulo a mirror image) for all 45° modules.
• The longest manifold part but with relatively easy fiber routing constraints.
Module Assembly

Crimp light case edges

A finished connector

Flycut optical connector

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NearDet construction (finished in Dec’2004)
Radioactive source mapping

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Plane assembly

Steel Welded and modules placed.

Plane lifted to vertical

Crane carries plane down the hall for installation

FarDet Installation by Week

6-8 Planes per week

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veto - target - $\mu$ 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

View of the Near Detector Hall
nearing end of detector construction

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Running since July 2003
- 2 Supermodules
- 5.4 kT
- 484 scint. planes
- CR veto shield (2,070 mwe)
- 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}

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Multi-anode PMTs + fibers

Response Uniformity

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M16 alignment
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 $10^{-6}$. 

Light yield in MINOS modules
Far Detector

![Graph showing light yield in MINOS modules for Far Detector. The graph plots strip response (photo-electrons) against distance from strip center (m). Two subplots are shown: one for strip response at different distances, and another for relative light output with entries and sigma values.]
**Expected sources of singles**
- PMT dark noise
- Natural radioactivity

**Unexpected**
- Spontaneous emission from fibers
- Decays with time exp (-t / 100 days)

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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
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

<table>
<thead>
<tr>
<th>Test condition</th>
<th>Initial rate (Hz/m)</th>
<th>Asymptotic rate (Hz/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kuraray WLS fiber in</td>
<td>75 ± 4</td>
<td>9 ± 1</td>
</tr>
<tr>
<td>Epon 815C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bicron WLS fiber free</td>
<td>35 ± 4</td>
<td>−3 ± 3</td>
</tr>
<tr>
<td>Kuraray clear fiber free</td>
<td>8 ± 2</td>
<td>0 ± 2</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Fiber length (m)</th>
<th>Initial rate (Hz/m)</th>
<th>Asymptotic rate (Hz/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R (Hz)</td>
<td>a (Hz/m)</td>
</tr>
<tr>
<td>1</td>
<td>29 ± 2</td>
<td>35 ± 7</td>
</tr>
<tr>
<td>2</td>
<td>38 ± 2</td>
<td>28 ± 2</td>
</tr>
<tr>
<td>4</td>
<td>77 ± 5</td>
<td>33 ± 2</td>
</tr>
<tr>
<td>8</td>
<td>81 ± 3</td>
<td>25 ± 1</td>
</tr>
</tbody>
</table>

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MINOS Calibration Detector – 2 GeV events

Electron

Pion

Muon

Proton

Caldet Data

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MINOS Calibration Detector Response

Energy resolution

Stopping CR muons:
MINOS Energy Unit (MEU)

Had: \[ \frac{56\%}{\sqrt{E}} \pm 2\% \]

EM: \[ \frac{21.4\%}{\sqrt{E}} \pm 4.1\% \]
NOvA Detectors

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

- 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.
NO$\nu$A Far Detector we would like to build

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

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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

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

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

### Component Table

<table>
<thead>
<tr>
<th>Component</th>
<th>Purpose</th>
<th>Mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>mineral oil</td>
<td>solvent</td>
<td>94.4%</td>
</tr>
<tr>
<td>pseudocumene</td>
<td>scintillant</td>
<td>5.5%</td>
</tr>
<tr>
<td>PPO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bis-MSB</td>
<td>waveshifter #1</td>
<td>0.1%</td>
</tr>
<tr>
<td>Stadis-425</td>
<td>waveshifter #2</td>
<td>0.002%</td>
</tr>
<tr>
<td>tocopherol</td>
<td>anti-static agent</td>
<td>0.0003%</td>
</tr>
<tr>
<td></td>
<td>anti-oxidant</td>
<td>0.0010%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

### Light output results
3-cell full-length prototype

### Noise vs. Temperature at Gain = 100

- Noise < 310 e- at T = -15 C (5° F)
Structural challenges

- FEA calculations and tests (on-going)

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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 $0.15 \times X_0$
- 2 GeV muon traverses ~60 planes
2000 $\nu_e$ 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)
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
Examples of spectral properties
NEMO-3 uniformity

Simulation

Measurement

Profile of Detected Photons

Ratio = Simulation/Measurement

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Challenge for NOvA

Gabe Elpers
(conducting fiber measurements)

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Challenge for NOvA

Along-axis fiber illuminations

Spectral profile vs. fiber length, longitudinal illumination with 470 nm LED

Spectral profile vs. fiber length, longitudinal illumination with 400 nm LED

Spectral profile vs. fiber length, longitudinal illumination with 430 nm LED
Challenge for NOvA

dsider fiber illuminations

Spectral profile vs. fiber length, transverse illumination with 470 nm LED

Spectral profile vs. fiber length, transverse illumination with 400 nm LED

Spectral profile vs. fiber length, transverse illumination with 430 nm LED
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
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