The IDS Neutrino Factory Detectors

Muon Accelerator Program Collaboration Meeting
March 2012

Jorge G. Morfín, Fermilab
The Neutrino Factory Concept

\[ \mu^+ \rightarrow \nu_\mu + \nu_e + e^+ \quad \mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^- \]

O(10^{21}) Muon Decays/year

Beam

Muon Storage Ring

\( (\nu + \bar{\nu}) \)
Example Event Rate Energy Distribution
25 GeV $\mu^-$
Motivation for the Neutrino Factory
Oscillation Channel Studies

$E_{\mu} = 25 \text{ GeV}$  $E_{\nu} = 0-25 \text{ GeV}$
Oscillation Channels

$E_\mu = 25 \text{ GeV}$  
$E_\nu = 0-25 \text{ GeV}$

Source: $\mu^+$  
Detector: $\mu^+, \tau^+, e^-, \mu^-$

$\nu_e$: 50% survival, subdominant oscillation
$\bar{\nu}_\mu$: 50% survival, dominant oscillation
$\nu_\tau$: subdominant oscillation
$\bar{\nu}_\tau$: subdominant oscillation
Oscillation Channels

$E_\mu = 25 \text{ GeV}$  $E_\nu = 0-25 \text{ GeV}$
Far Detectors: Magnetised Iron Neutrino Detector (MIND)

- Far detector: 100 kton at 2500-5000 km
- 2nd detector: 50 kton at 7500 km - “magic”
- Appearance of “wrong-sign” muons
- Toroidal magnetic field > 1 T

- Segmentation: 3 cm Fe + 2 cm scintillator
- 50-100 m long
- Octagonal shape

EVENT RATES
At 4000 km, for $10^{21}$ $\mu$ decays/year
100 kton MIND for $\mu^+$ decay:
Unoscillated $\nu_e$ CC would be $7.1 \times 10^5$
MIND Scintillator

- Scintillator: x-view and y-view planes 1 cm thick each plane
  - Baseline: rectangular scintillator strips (3.5 cm wide, $\sigma \sim 1$ cm)
  - Alternative: triangular strips ($\sigma \sim 5$ mm) - 2.3 times more channels
  - Co-extrusion fibre-scintillator (makes project ~20% more expensive)

- Wavelength shifting fibres
  - Kuraray currently is the only manufacturer in the world that can deliver WLS fibres of consistently good performance

- Numbers: 788 scint./module x 2800 modules = 2.2 M bars
  - 25,000 km of WLS fibre (~€1/m)
Plate engineering:
- Plates: two welded layers (0.5mm gaps)
- 3 mm slots between Plates (2 m wide)

Toroidal field:
- Small field gaps and jumps
- 1.2-2.2 T with 100 kA turn

Homogeneous field
MIND Magnetic Field

- Required for identification of wrong sign muons.

Magnetic field to be induced by superconducting transmission line

- Transmission line 7.8 cm in diameter.
- Contained in a 10 cm hole in the iron.

Small distortions caused by slots between strips

- Simulated using a 100 kA excitation current
Magnetic Field Excitation

Superconducting Transmission Line

- SCTL not simply a “concept” – prototyped, tested and costed for the VLHC Project at Fermilab
Alternative: Fine-Resolution Totally Active Far Detector (Low-E Neutrino Factory)

- 3333 Modules (X and Y plane)
- Each plane contains 1000 slabs
- Total: 6.7M channels

- Momenta between 100 MeV/c to 15 GeV/c
- Magnetic field considered: 0.5 T
- Reconstructed position resolution ~ 4.5 mm

Alan Bross  
IDS Meeting RAL  
January 16, 2008
Active Detector Has to be Magnetized
Super Conducting Transmission Line
Neutrino Factory Near Detector(s)

$E_\mu = 25 \text{ GeV} \pm 80 \text{ MeV}$

Straight section length = 600 m

Muon angular spread 0.5 mrad

Event Rates

2.5e20 $\mu$-decays/year

3 Years of $\mu^+$ and $\mu^-$

Fid.Mass 3.5 Tons

$\nu^+$:
- $\nu_u$-CC: 1.8e9 Events
- IMD: 1.3e6 Events
- $\nu_u e$ Elas: 1.1e6 Events

$\nu^-:
- \bar{\nu}_u$-CC: 0.9e9 Event
- $\nu_u e$ Elas: 1.5e6 Event
Near Detector Physics Tasks

- **Determination of the neutrino flux (through the measurement of neutrino-electron scattering)**

- Measurement of the neutrino-beam properties that are required for the flux to be extrapolated with accuracy to the far detectors;

- Measurement of the charm production cross sections;

- Measurement of the $\nu N$ deep inelastic, quasi-elastic, and resonant-scattering cross sections;

- Search for Non Standard Interactions (NSI).
Determination of the neutrino flux

- **Measure the muon beam in the straight sections:**
  - beam intensity by Beam Current Transformer like device – “good” confidence that relative precision of few $10^{-3}$ can be reached (task on its own);
  - beam divergence by specialized device inside or around the beam pipe;
  - muon polarisation – averages out to zero;

- **Calculate the neutrino flux:**
  - muon decay properties incl. radiative corrections are extremely well known → can we rely on MC?

- **Independent measurement of the neutrino flux in the near detector – crucial cross-check to experimentally confirm calculations.**
Importance of flux knowledge for systematics

2.5% error on flux makes big difference in CP coverage
To achieve the kind of accuracy we want on the neutrino flux measurement, we will have constructed a detector ideally suited for advanced studies of neutrino-nucleus interactions – the “other” physics.

This in turn can be grouped into standard processes:
- Quasi-elastic
- Resonance Production
- Transition: Resonance to DIS
- DIS, Structure Functions. and high-x PDFs
- Coherent Pion Production
- Strange and Charm Particle Production
- Generalized Parton Distributions
- Nuclear Effects

and more exotic…
- NSI such as the measurement of $\nu_\tau$ in the near detector
Near Detector Design Requirements

- Vertex detector for charm and $\tau$ production (NSI)
- Low Z high resolution target for flux and cross-section measurement ($\nu_\mu$ and $\nu_e$)
- Magnetic field for muon momentum ($\delta p/p \sim 1\%$)?
- Muon catcher and capability for $e^+/e^-$ identification
- Good resolution on neutrino energy for flux extrapolation (much better than Far Detector) – goal $\delta E/E \sim 1\%$
Block-diagram design

Near Detector design will have three sections:

- High granularity detector for charm/tau measurement;
- High resolution detector (Scintillating Fibres tracker or Straw Tube tracker) for precise measurement of the event close to the vertex;
- Mini-MIND detector for higher energy muon measurement
High-granularity Vertex Detector

◆ **Stack of OPERA-like emulsion sheets**: 150 sheets, overall volume ~500 cm$^3$, mass ~ 1 kg, thickness - 4.6 cm (0.2 $X_0$), capacity ~ 5000 neutrino events out of ~5x10$^5$ $\nu_\mu$ CC interactions per year for this mass;

◆ **Silicon vertex detector like NOMAD-STAR detector**: ~50 kg, ~7x10$^5$ charm events reconstructed per year, sensitivity for $P_{\mu\tau} < 3 \times 10^{-6}$ at 90% C.L.
Measurement of the neutrino flux by $\nu$-$e$ scattering

$\nu$ - e CC quasi-elastic scattering:
- absolute cross-section can be calculated theoretically with enough confidence;
- two processes of interest for neutrinos from $\mu^-$ decays. 11 GeV Threshold

Inverse Muon Decay (IMD)

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$

$$\sigma = \frac{G_F^2 (s - m_\mu^2)^2}{\pi s} = 4 \times 10^{-41} \text{cm}^2$$

for 15 GeV $\nu_\mu$;

it is $\sim 10^{-3}$ of $\sigma_{\text{total}}$(\nuN)
ν-e NC elastic scattering

\[
\sigma(\nu_e \rightarrow \nu_e) = \frac{G^2 \mu m_e E_\nu}{2\pi} \left[ 1 - 4 \sin^2 \theta_W + \frac{16}{3} \sin^4 \theta_W \right]
\]

\[
\sigma(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \frac{G^2 \mu m_e E_\nu}{2\pi} \left[ \frac{1}{3} - \frac{4}{3} \sin^2 \theta_W + \frac{16}{3} \sin^4 \theta_W \right]
\]

\[
\sim 10^{-42} (E_\nu / \text{GeV})^{-1} \text{ cm}^2
\]

\(\sin^2 \theta_W\) is known to better than 1% for this \(Q^2\) domain.
Two Options, First: Scintillating Fiber Tracker
M. Bogomilov, Y. Khradzov, R. Matev, R. Tzenov – Univ. Sofia

- 0.5 T dipole magnetic field;
- 20 modules with \( \sim 50 \) cm air gaps in between;
- 5 layers of scintillating bars (3 \( \times \) 1 \ cm\(^2\)) in absorber section;
- 4+4 layers of cylindrical (\( \varnothing 1 \) mm) scintillating fibers in tracker station;
- air gaps are covered by one layer of scintillating bars;
- silicon photomultipliers (SiPM) detect photons from all fibers;
- overall detector dimensions are \( \sim 1.5 \times 1.5 \times 11 \) m\(^3\);
- \( \sim 2.7 \) tons of polystyrene (\([C_6H_5CHCH_2]_n\)).
IMD signal extraction (linear fit)

Use linear extrapolation of event rates in region between cut1 and cut2 to estimate background under the signal peak.

<table>
<thead>
<tr>
<th>Selection eff.</th>
<th>Overall eff.</th>
<th>Purity</th>
<th>All events</th>
<th>Signal events</th>
<th>Signal events from fit</th>
<th>$\mu$ decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>85 %</td>
<td>45 %</td>
<td>85 %</td>
<td>3312</td>
<td>2801</td>
<td>2828 ± 58</td>
<td>$2.3 \times 10^{19}$</td>
</tr>
</tbody>
</table>
ES$^-$ signal extraction ($\mu^-$ decay mode)

Use linear extrapolation of event rates in region between cut1 and cut2 to estimate background under the signal peak.

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</tr>
</thead>
<tbody>
<tr>
<td>70 %</td>
<td>32 %</td>
<td>61 %</td>
<td>7355</td>
<td>4491</td>
<td>4479 ± 86</td>
<td>$2.3 \times 10^{19}$</td>
</tr>
</tbody>
</table>
Second Alternative: Straw-tube Tracker Design
S. Mishra – Univ. S. Carolina

High resolution magnetised detector (*HiResMν*) – LBNE Standard Near detector
Builds on NOMAD experience, ATLAS TRT and COMPASS detector designs

\[
B = 0.4 \, \text{T}
\]

Density = 0.1 g/cm³, 85% in the radiator foils.

- Transition Radiation ⇔ e⁻/e⁺ ID ⇒ γ (w. Kinematics)
- dE/dx ⇔ Proton, π⁺/⁻, K⁺/⁻ ID
- Magnet/Muon Detector ⇔ μ⁺/⁻
A $\nu_\mu$ CC candidate in NOMAD
### Salient steps of the IMD-Analysis

<table>
<thead>
<tr>
<th>Condition</th>
<th>$\nu_\mu$-IMD</th>
<th>$\nu_\mu$-CC</th>
<th>$\nu_\mu$-CCQE</th>
<th>$\bar{\nu}_e$-CC</th>
<th>$\nu_\mu$-NC</th>
<th>$\bar{\nu}_e$-NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 negative Track</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Neutral Veto ($E_\gamma \geq 0.1$ GeV)</td>
<td>1,000,000</td>
<td>67,851</td>
<td>414,856</td>
<td>102,961</td>
<td>14,219</td>
<td>14,679</td>
</tr>
<tr>
<td>Neutral Veto ($E_{neutron} \geq 0.5$ GeV)</td>
<td>1,000,000</td>
<td>34,660</td>
<td>411,019</td>
<td>57,765</td>
<td>4,722</td>
<td>5,891</td>
</tr>
<tr>
<td>Neutral Veto ($E_{K_s,K_L} \geq 0.5$ GeV)</td>
<td>1,000,000</td>
<td>20,703</td>
<td>375,027</td>
<td>33,536</td>
<td>2,454</td>
<td>3,348</td>
</tr>
<tr>
<td>$E &gt; 11$ GeV</td>
<td>983,355</td>
<td>13,544</td>
<td>257,736</td>
<td>661</td>
<td>341</td>
<td>419</td>
</tr>
<tr>
<td>$\zeta_\mu &lt; 0.001$ GeV</td>
<td>979,403</td>
<td>831</td>
<td>16,614</td>
<td>49</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$\zeta_\mu &lt; 0.0001$ GeV</td>
<td>959,227</td>
<td>50</td>
<td>829</td>
<td>8</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

**Efficiency** $\Rightarrow$ 95% $\delta e-0\delta$
Summary and Outlook
Near Detectors

- Near detector(s) at the Neutrino factory is a valuable tool for neutrino flux measurement and standard and non-standard neutrino interactions study;
- Set-up: high granularity vertex detector, high resolution tracker, muon catcher – the design is dictated mostly by requirements for flux measurement;
- Two options considered for the high-resolution sub-detector: SciFi OR Straw-tube tracker. To join silicon vertex detector + mini-MIND.
- Further tasks:
  - determination of the Near detector baseline design via full simulation;
  - determination of systematic errors from near/far extrapolation (migration matrices);
  - expectation on cross-section measurements;
  - other physics studies: electroweak parameters, PDFs, etc.;
  - sensitivity to non-standard interactions (τ-lepton production);
  - R&D efforts to validate technology (e.g. vertex detectors, tracking detectors, etc.)
NEXT STEPS: Detector Design

- **MIND R&D Effort**
  - Prototype detectors with SiPM and extruded scintillator
  - Measure charge mis-ID rate
  - Develop CERN test beam for neutrino detector R&D – European AIDA proposal to make H8 into low E beam

- **Near Detectors**
  - Determine procedure for deciding between two alternative high-resolution near detectors for baseline

- **Systematics**
  - Determine elements in the overall covariant error matrix (systematic).
  - Get best understanding of how the size of these errors are involved in determining CP-violation.
  - Work with LBNE that is at a similar stage in study of systematics?
Neutrino Factory Performance
Flexible design of Neutrino Factory

- Optimisation for one baseline as function of $\theta_{13}$

**Contours of CP coverage**

For large $\theta_{13}$:
- Energy 10 GeV
- Baseline 2000 km
- 100 kton MIND

For small $\theta_{13}$:
- Energy $\sim$25 GeV
- Baseline $\sim$4000 km
- 100 kton MIND

$\sin^2 2\theta_{13} = 0.1$

$\sin^2 2\theta_{13} = 0.01$

$\sin^2 2\theta_{13} = 0.001$

$\sin^2 2\theta_{13} = 0.0001$
Overall Conclusions

- International Design Study is progressing on course
  - Interim Design Report delivered March 2011
  - We had successful ECFA review May 2011 (final report due soon)
  - On target to produce Reference Design Report, including performance and costs by 2013

- Main concepts for accelerator systems have been defined
  - Main areas of work are at interfaces between components

- Two Magnetised Iron Neutrino Detectors (MIND) at standard Neutrino Factory (25 GeV) is small $\theta_{13}$ baseline:
  - 2500-5000 km with 100 kton mass
  - 7000-8000 km (magic baseline) with 50 kton

- 10 GeV Neutrino Factory with one 100 kton MIND shows best performance for large $\theta_{13}$ ($\sin^2 \theta_{13} > 10^{-2}$)

- Conceptual design for near detector being established
Backups
Where will we be at the time of NF – ND
Dominated by systematics: Mainly Flux Errors

- The neutrino factory experiments will occur after MINERvA and LBNE will have taken and analyzed their data. Examples:
  - Combined many charged lepton data sets on many different nuclei
  - MINERvA provides He, C, Fe, Pb
Neutrino-nucleus Scattering Physics at NF-ND
post MINERvA and LBNE

- Take advantage of much-increased knowledge of the flux:
  - absolute cross-sections

- Take advantage of much-increased event rate:
  - use of H$_2$ and D$_2$ targets as well as higher A,
  - study of rare topologies,
  - high-x phenomena …..

- Take advantage of extended kinematic coverage:
  - study lower-x phenomena at reasonable Q$^2$,
  - extended reach in Q$^2$

- Certainly to be other benefits…
Neutrino flux through the detector at 100 m from the straight end

$1 \times 10^{20}$ $\mu$ - decays/year
Cross section measurements

- Measurement of cross sections in DIS, QEL and RES.
- Coherent and diffractive $\pi$, $\rho$, ...
- Different nuclear targets: $H_2$, $D_2$
- Nuclear effects, nuclear shadowing, reinteractions

Expected cross-section errors from T2K, Minerva and LBNE dominated by absolute flux error before compared to Neutrino Factory.

At NF, with modest size targets one can obtain very large statistics, but is <1% error achievable?
Improvements over the NOMAD: HiResMnu-Concept

🌟 Tracking Charged Particles
   ✧ x6 more hits in the Transverse-Plane (X-Y)
   ✧ x2 more hits along Z-axis

🌟 Electron/Positron ID
   ✧ Continuous TR providing e+/e- ID

🌟 Calorimetry: 4π-Coverage
   ✧ Downstream ECAL: fine Longitudinal & Transverse segmentation
   ✧ Barrel & Upstream ECAL

🌟 μ-ID
   ✧ 4π-Coverage: $\min-P_\mu \geq 0.3$ GeV
Sensitivity Analysis

**VEl:** \( \nu_{\mu}(\bar{e}e) + e^- \rightarrow e^- + \nu_e \) (Single, forward e-)

- \( \nu_{\mu}(\bar{e}e) \)-N NC background due to single, asymmetric \( \gamma \rightarrow e^-e^+ \) and \( \pi^-/\mu^-/\mu^+ \)

<table>
<thead>
<tr>
<th>( \gamma \rightarrow e^-e^+ )</th>
<th>( \bar{\nu}_e )</th>
<th>( \nu_\mu )</th>
<th>( \bar{\nu}_{\mu}\text{-CC} )</th>
<th>( \nu_{\mu}\text{-CC} )</th>
<th>( \bar{\nu}_{\mu}\text{-NC} )</th>
<th>( \nu_{\mu}\text{-NC} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positron/muon veto</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Hadron Veto</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>40,168</td>
<td>50,219</td>
<td>1,000,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Photon Conversion &amp; ( E_{e^+} &lt; 0.05 ) GeV</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>81</td>
<td>79</td>
<td>460</td>
<td>340</td>
</tr>
<tr>
<td>20 planes</td>
<td>333,179</td>
<td>836,172</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( E_e &gt; 0.5 ) GeV</td>
<td>748,786</td>
<td>794,086</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( z &lt; 0.001 ) GeV</td>
<td>733,723</td>
<td>785,240</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Efficiency** => 66% 71% \( \sim 10^{-6} \)
Motivation: measure charm cross-section to validate size of charm background in wrong-sign muon signature (charm cross-section and branching fractions poorly known, especially close to threshold)

Motivation: tau production in near detector is a signal for non-standard interactions

Vertex detector of high granularity is needed.

Silicon strips or emulsion sheets?
HiResMv design parameters

**Resolutions in HiResMv**

- \( \rho \approx 0.1 \text{gm/cm}^3 \)
- Space point position \( \approx 200 \mu \)
- Time resolution \( \approx 1 \text{ns} \)

- CC-Events Vertex: \( \Delta(X,Y,Z) \approx O(100 \mu) \)
- Energy in Downstream-ECAL \( \approx 6\%/\sqrt{E} \)
- \( \mu \)-Angle resolution (\( \sim 5 \text{ GeV} \)) \( \approx O(1 \text{ mrad}) \)

- \( \mu \)-Energy resolution (\( \sim 3 \text{ GeV} \)) \( \sim 3.5\% \)
- e-Energy resolution (\( \sim 3 \text{ GeV} \)) \( \sim 3.5\% \)