Muon Accelerators for High Energy Physics Applications: νSTORM, NuMAX & Beyond...

Mark Palmer
Director, US Muon Accelerator Program

ICHEP, Valencia, July 2-9, 2014
Muon Accelerators for HEP

• \( \mu \) – an elementary charged lepton:
  – 200 times heavier than the electron
  – 2.2 \( \mu s \) lifetime at rest

• Physics potential for the HEP community using muon beams
  – Tests of Lepton Flavor Violation
  – Anomalous magnetic moment \( \Rightarrow \) hints of new physics (g-2)
  – Can provide equal fractions of electron and muon neutrinos at high intensity for studies of neutrino oscillations – the Neutrino Factory concept
  – Offers a large coupling to the “Higgs mechanism”
  \[ \frac{m_{\mu}^2}{m_{e}^2} \approx 4 \times 10^4 \]
  – As with an \( e^+e^- \) collider, a \( \mu^+\mu^- \) collider would offer a precision leptonic probe of fundamental interactions

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

• Why Neutrino Factories?

• Neutrino Factory Concepts
  – Short baseline ⇨ STORM
  – Long Baseline
    • The IDS-NF Reference Design
    • Options for a staged implementation:
      – The MAP Muon Accelerator Staging Study
      – The staged NuMAX Concept
  – Accelerator R&D Needs

• Going Beyond a Neutrino Factory Facility
  – Possibilities for a future Muon Collider Capability

• Conclusion
WHY NEUTRINO FACTORIES?
The Key Issues

- What things must we understand in the neutrino sector?
  - $\delta_{CP}$
  - The mass hierarchy
  - The value of $\theta_{23} - \pi/4$: +, - or zero?
  - Resolve the LSND and other short baseline experimental anomalies
  - And enable the search for new physics
Can we probe the CP violation in the neutrino sector at the same level as in the CKM Matrix?

0.025 IDS-NF: 700kW target, no cooling, $2 \times 10^8$ s running time, 10-15 kTon detector

P. Coloma, P. Huber, J. Kopp, W. Winter – arxiv:1209.5973
Microscopes for the $\nu$ Sector

• Superbeam technology will continue to drive initial observations in the coming years

• However, anomalies and new discoveries will drive our need for precision studies to develop a complete physical understanding

• Neutrino Factory capabilities (both long- and short-baseline) offer a route to controlled systematics and precision measurements to fully elucidate the relevant physics principles

⇒ Precision Microscopes for the $\nu$ sector
NEUTRINO FACTORY CONCEPTS
Neutrino Factory Overview

• Short Baseline NF
  – nuSTORM
    • Definitive measurement of sterile neutrinos
    • Precision $\nu_e$ cross-section measurements (systematics issue for long baseline SuperBeam experiments)
    • Would serve as an HEP muon accelerator proving ground…

• Long Baseline NF with a Magnetized Detector
  – IDS-NF (International Design Study for a Neutrino Factory)
    • 10 GeV muon storage ring optimized for 1500-2500km baselines
    • “Generic” design (ie, not site-specific)
  – NuMAX (Neutrinos from a Muon Accelerator CompleX)
    • Site-specific: FNAL $\Rightarrow$ SURF (1300km baseline)
    • 4-6 GeV beam energy optimized for CP studies
      – Flexibility to allow for other operating energies
    • Can provide an ongoing short baseline measurement option
    • Detector options
      – Magnetized LAr is the goal
      – Magnetized iron provides equivalent CP sensitivities using ~3x the mass
νSTORM

μ decay ring: $P = 3.8 \text{ GeV/c} \pm 10\%$

See talk by J-B. Lagrange
Neutrino Physics Session:
Friday 16:00

No new technologies required!
Could be deployed now!
Example of Potential νSTORM Leverage for Long Baseline Experiments: T2HK

NuMAX+ targets equivalent sensitivity to CP violation in the ν sector as has been achieved in the flavor sector.

nuSTORM + T2HK offers significantly improved sensitivity vs T2HK alone.
νStorm as an R&D platform

- A high-intensity pulsed muon source
- $100 < p_\mu < 300$ MeV/c muons
  - Using extracted beam from ring
  - $10^{10}$ muons per 1 μsec pulse

- Beam available simultaneously with physics operation

- νSTORM also provides the opportunity to design, build and test decay ring instrumentation (BCT, momentum spectrometer, polarimeter) to measure and characterize the circulating muon beam
The Long Baseline Neutrino Factory

- IDS-NF: the ideal NF
  - Supported by MAP
- MASS working group: A staged approach - *NuMAX@5 GeV⇒SURF*

<table>
<thead>
<tr>
<th>Accelerator facility</th>
<th>Value</th>
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<tr>
<td>Muon total energy</td>
<td>10 GeV</td>
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<tr>
<td>Production straight muon decays in $10^7$ s</td>
<td>$10^{21}$</td>
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<tr>
<td>Maximum RMS angular divergence of muons in production straight</td>
<td>0.1/γ</td>
</tr>
<tr>
<td>Distance to long-baseline neutrino detector</td>
<td>1500–2500 km</td>
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</table>

**Magnetized Iron Neutrino Detector (MIND):**

- IDS-NF baseline:
  - Intermediate baseline detector:
    - 100 kton at 2500–5000 km
  - Magic baseline detector:
    - 50 kton at 7000–8000 km
  - Appearance of “wrong-sign” muons
  - Toroidal magnetic field $> 1$ T
    - Excited with “superconducting transmission line”

- Segmentation: 3 cm Fe + 2 cm scintillator
- 50-100 m long
- Octagonal shape
- Welded double-sheet
  - Width 2m; 3mm slots between plates

Bross, Soler
The MAP Muon Accelerator Staging Study ⇒ NuMAX

- **PIP-II**: 0.8 GeV
- **PIP-III**: 2.2 GeV
- **μ pre-Linac**: 1.0 GeV 325 MHz
- **Dual-Use (p & μ) Linac**: 3.75 GeV 650 MHz
- **μ⁺ & μ⁻ Chicane**
- **NuMAX**: 650 MHz
- **NuMAX Staging**:
  - **Commissioning**
    - 1MW Target
    - No Cooling
    - 10kT Detector
  - **NuMAX+**
    - 2.75 MW Target
    - 6D Cooling
    - 34kT Detector

---

Front End

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<thead>
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<th>PIP-II</th>
<th>0.8 GeV</th>
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<td>1MW Target</td>
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<td>10kT Detector</td>
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<td><strong>NuMAX+</strong></td>
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<td>2.75 MW Target</td>
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<td>6D Cooling</td>
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<td>34kT Detector</td>
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### NF Staging (MASS)

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<th>System</th>
<th>Parameters</th>
<th>Unit</th>
<th>nuSTORM</th>
<th>NuMAX Commissioning</th>
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<th>NuMAX+</th>
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<tr>
<td><strong>Performance</strong></td>
<td>Nu or νμ to detectors/year</td>
<td>-</td>
<td>3×10^{17}</td>
<td>4.9×10^{19}</td>
<td>1.8×10^{20}</td>
<td>5.0×10^{20}</td>
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<td>Stored μ+ or μ-/year</td>
<td>-</td>
<td>8×10^{17}</td>
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<td>MIND / Mag LAr</td>
<td>MIND / Mag LAr</td>
<td>MIND / Mag LAr</td>
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<td>100 / 30</td>
<td>100 / 30</td>
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<td>m</td>
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<td>281</td>
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<td>Charge per bunch</td>
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<td>Single-pass Linacs</td>
<td>GeV/c</td>
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<td>325, 650</td>
<td>325, 650</td>
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<td>No</td>
<td>Initial</td>
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<td><strong>Proton Driver</strong></td>
<td>Proton Beam Power</td>
<td>MW</td>
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<td>1</td>
<td>1</td>
<td>2.75</td>
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<td></td>
<td>Proton Beam Energy</td>
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<td>120</td>
<td>6.75</td>
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<td>Protons/year</td>
<td>1×10^{21}</td>
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<td>9.2</td>
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<td>Repetition Frequency</td>
<td>Hz</td>
<td>0.75</td>
<td>15</td>
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</table>
Possibilities for NF Capabilities at Fermilab:

νSTORM ➔ NuMAX

Possible to deploy subsequent muon collider capabilities

Remains fully compatible with the PIP-II ➔ III staging option

νSTORM

To Near Detector(s) for Short Baseline Studies

0.8 GeV Proton Linac (PIP-II)

0.8-3 GeV Proton Linac (PIP-III)

1 GeV Muon Linac (325MHz)

3-7 GeV Proton & 1-5 GeV Muon Dual Species Linac

νSTORM R&D Facility

LBNF Superbeam

To SURF

NuMAX: vs to SURF

Accumulator, Buncher, Combiner

Front End

Target

Initial Cool

Final Cool
Staged Performance of NuMAX

\[ \Delta \delta \text{ at } 1\sigma \]

\[ \theta_{23} = 40^\circ \]

**Comparison of Potential Performance of the Various Advanced Concepts (courtesy P. Huber)**

- LBNE10 (1.2MW, 10kt)
- LBNE (1.2MW, 34kt)
- T2HK (0.7MW, 560kt)
- LBNE + Project X (2.3MW, 34kt)
- Daedalus (2.5MW) + T2HK\(_y\)
- Daedalus (\(1.25 + 2.5\)MW) + T2HK\(_y\)
- NuMAX to SURF (1MW, 10kt)
- NuMAX to SURF (1MW, 34kt)
- NuMAX+ to SURF (3MW, 10kt)
- NuMAX+ to SURF (3MW, 34kt)
Accelerator R&D Effort (U.S. MAP)

Design Studies
- Proton Driver
- Front End
- Cooling
- Acceleration and Storage
- Collider
- Machine-Detector Interface
- Work closely with physics and detector efforts

Technology R&D
- RF in magnetic fields
- SCRF for acceleration chain (Nb on Cu technology)
- High field magnets
  - Utilizing HTS technologies
- Targets & Absorbers
- MuCool Test Area (MTA)

Major System Demonstration
- The Muon Ionization Cooling Experiment – MICE
  - Major U.S. effort to provide key hardware: RF Cavities and couplers, Spectrometer Solenoids, Coupling Coil(s), Partial Return Yoke
  - Experimental and Operations Support
MICE Experiment @RAL

2015 Data

MICE Step IV: Study of Absorber Materials

Commission in 2017 (expedited schedule)

MICE Step V: Demonstration of Muon Cooling w/RF re-acceleration

See following talk by Ken Long

US-UK
GOING BEYOND NEUTRINO FACTORY CAPABILITIES
Features of the Muon Collider

• Superb Energy Resolution
  – SM Thresholds and s-channel Higgs Factory operation

• Multi-TeV Capability (≤ 10TeV):
  – Compact & energy efficient machine
  – Luminosity > 10^{34} \text{ cm}^{-2} \text{ s}^{-1}
  – Option for 2 detectors in the ring

• For $\sqrt{s} > 1$ TeV: Fusion processes dominate
  ⇒ an Electroweak Boson Collider
  ⇒ a discovery machine complementary to a very high energy pp collider
  – At >5TeV: Higgs self-coupling resolutions of <10%

What are our accelerator options if new LHC data shows evidence for a multi-TeV particle spectrum?
Muon Colliders extending high energy frontier with potential of considerable power savings

Lepton Colliders
Wall Plug Power

Lepton Colliders Figure of Merit: Luminosity per wall plug power
NF/MC Synergies

Neutrino Factory (NuMAX)

- Proton Driver
- Front End
- Cooling
- Acceleration
- μ Storage Ring

μ Factory Goal: \(10^{21} \mu^+ \& \mu^-\) per year within the accelerator acceptance

μ-Collider Goals:
- 126 GeV \(\Rightarrow \sim 14,000 \) Higgs/yr
- Multi-TeV \(\Rightarrow \) Lumi > \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)

Muon Collider

- Proton Driver
- Front End
- Cooling
- Acceleration
- Collider Ring

\(E_{\text{CoM}}\): Higgs Factory to \(\sim 10\) TeV

Share same complex

Accelerators:
- Single-Pass Linacs
- Linacs, RLA or FFAG, RCS
The plan consists of a series of facilities with increasing complexity, each with performance characteristics providing unique physics reach:

- **nuSTORM:** a short-baseline Neutrino Factory-like ring enabling a definitive search for sterile neutrinos, as well as neutrino cross-section measurements that may ultimately be required for precision measurements at any long-baseline experiment.
- **NuMAX:** an initial long-baseline Neutrino Factory, operating close to SURF, affording a precise and well-characterized neutrino beam with the capabilities of conventional superbeam technology.
- **NuMAX+:** a full-intensity Neutrino Factory, operating as the ultimate source to enable precision CP-violation measurements in the neutrino sector.
- **Higgs Factory:** a collider whose baseline and operations are capable of providing between 3500 (during startup operations) and 15,000 Higgs events per year (10^7 sec) with exquisite energy resolution.
- **Multi-TeV Collider:** if warranted by LHC results, a multi-TeV Muon Collider likely offers the best performance and least cost for any lepton collider operating in the multi-TeV regime.
A 6 TeV Muon Collider would have a similar circumference as the Tevatron Ring
Muon Collider Conceptual Layout

- Accelerate hydrogen ions to 8 GeV using SRF technology.
- Compressor Ring: Reduce size of beam.
- Target: Collisions lead to muons with energy of about 200 MeV.
- Muon Cooling: Reduce the transverse motion of the muons and create a tight beam.
- Initial Acceleration: In a dozen turns, accelerate muons to 20 GeV.
- Recirculating Linear Accelerator: In a number of turns, accelerate muons up to 2 TeV using SRF technology.
- Collider Ring: Located 1,000 meters underground.
- Muons live long enough to make about 1,000 turns.

Concept for a Muon Accelerator Complex at Fermilab:

- Multi-TeV Lepton Collider
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Startup Operation</th>
<th>Production Operation</th>
<th>High Resolution</th>
<th>High Luminosity</th>
<th>Multi-TeV Baselines</th>
<th>Accounts for Site Radiation Mitigation</th>
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<tr>
<td>CoM Energy</td>
<td>TeV</td>
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<td>0.126</td>
<td>0.35</td>
<td>0.35</td>
<td>1.5</td>
<td>3.0</td>
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<tr>
<td>Avg. Luminosity</td>
<td>$10^{34}$cm$^2$s$^{-1}$</td>
<td>0.0017</td>
<td>0.008</td>
<td>0.07</td>
<td>0.6</td>
<td>1.25</td>
<td>4.4</td>
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<td>Beam Energy Spread</td>
<td>%</td>
<td>0.003</td>
<td>0.004</td>
<td>0.01</td>
<td>0.1</td>
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<td>Higgs* or Top* Production/10$^7$sec</td>
<td></td>
<td>3,500*</td>
<td>13,500*</td>
<td>7,000*</td>
<td>60,000*</td>
<td>37,500*</td>
<td>200,000*</td>
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<td>Circumference</td>
<td>km</td>
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<td>0.3</td>
<td>0.7</td>
<td>0.7</td>
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<td>$\beta^*$</td>
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<td>1.7</td>
<td>1.5</td>
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<td>1 (0.5-2)</td>
<td>0.5 (0.3-3)</td>
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<td>4</td>
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<td>3</td>
<td>2</td>
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<tr>
<td>No. bunches/beam</td>
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<td>1</td>
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<td>1</td>
<td>1</td>
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<td>Norm. Trans. Emittance, $\varepsilon_{TN}$</td>
<td>$\pi$ mm-rad</td>
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<td>0.2</td>
<td>0.2</td>
<td>0.05</td>
<td>0.025</td>
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<td>1.5</td>
<td>1.5</td>
<td>10</td>
<td>70</td>
<td>70</td>
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<td>Bunch Length, $\sigma_z$</td>
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<tr>
<td>Proton Driver Power</td>
<td>MW</td>
<td>$4^2$</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
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</tbody>
</table>

* Could begin operation with Project X Stage II beam

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts $\Rightarrow$ several $\times 10^{32}$

Site Radiation mitigation with depth and lattice design: $\leq 10$ TeV
CONCLUSION
Concluding Remarks

- Neutrino Factory capabilities offer the precision microscope that will likely be needed to fully probe the physics of the neutrino sector

- For the last 3 years US Muon Accelerator Program has pursued options to deploy muon accelerator capabilities
  - Near term ($\nu$STORM)
  - Long term (NuMAX)
  - Along with the possibility of a follow-on muon collider option

- In light of the recent P5 recommendations that this directed facility effort no longer fits within the budget-constrained US research portfolio, the US effort is entering a ramp-down phase

- Nonetheless, the precision capabilities offered by Neutrino Factories represent a key option for the future of $\nu$ physics