A Staged Muon Accelerator Facility for Neutrino and Collider Physics

J.P Delahaye / SLAC
on behalf of the MAP collaboration
(and the MASS team)
Muons are leptons like electrons & positrons but with a mass 207 times larger

- Negligible synchrotron radiation emission ($\alpha \ m^{-2}$)
  - Multi-pass collisions (1000 turns) in ring
    - High luminosity with reasonable beam power and power consumption
    - Relaxed beam emittances & sizes, alignment & stability
  - Multi-detectors supporting broad physics communities
  - Large time (15 $\mu$s) between bunch crossings
- No beam-strahlung at collision:
  - Narrow luminosity spectrum
- Multi-pass acceleration:
  - Cost effective construction & operation
  - Compact acceleration system and collider
- No cooling by synchrotron radiation in standard damping rings
  - Requires development of novel cooling method
Muon Colliders extending high energy frontier with potential of considerable cost savings

Lepton Colliders
Peak (1%) all IPs Luminosity

Circular

Muons

Linear

FCC
80-100km

Lepton Colliders
Overall facility Extension

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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

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Muon Colliders extending high energy frontier with potential of considerable power savings

As with an $e^+e^-$ collider, a $\mu^+\mu^-$ collider offers a precision probe of fundamental interactions without energy limitations

- By synchrotron radiation as $e^+e^-$ circular colliders
- By beams-trahlung as $e^+e^-$ linear colliders

Muon Collider the ideal technology to extend high energy frontier in the multi-TeV range with reasonable dimension, cost and power consumption

If it works!
Muons: Issues & Challenges

- Limited lifetime: 2.2 μs at rest
  - Race against death: generation, acceleration & collision before decay
  - Muons decay in accelerator and detector
    - Shielding of detector and facility irradiation
    - Physics feasibility with large background?
  - Decays in neutrinos:
    - Ideal source of well defined electron and muon neutrinos in equal quantities:
      \[
      \begin{align*}
      \mu^+ & \rightarrow e^+ \nu_e \bar{\nu}_\mu \\
      \mu^- & \rightarrow e^- \bar{\nu}_e \nu_\mu
      \end{align*}
      \]
      The neutrino factory concept
  - Generated as tertiary particles in large emittances
    - powerful MW(s) driver
    - novel (fast) cooling method

Development of novel technologies with key accelerator and detector challenges
Muon Collider Concept
Muon Accelerator Program (MAP)

Proton source:
Up to 4 MW, with 2±1 ns long bunches

Goal:
Produce a high intensity $\mu$ beam whose 6D phase space is reduced by a factor of $\sim10^6$ from its value at the production target

Fast acceleration mitigating muon decay

Collider up to 6-10 TeV
2 detectors:

$\sqrt{s} = 3$ TeV
Circ: 4.5 km
$L = 3 \times 10^{34}$ cm$^{-2}$s$^{-1}$
Technical challenges

Feasibility addressed by MAP

Technology Challenges – Tertiary Production

- A multi-MW proton source, e.g., Project X, will enable O(10^{22}) muons/year to be produced, bunched and cooled to fit within the acceptance of an accelerator.

Technology challenges - Target

- The MERIT Experiment at the CERN PS
  - Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid and hit with a 115 KJ/pulse beam!
  - Jets could operate with beam powers up to 8 MW with a repetition rate of 70 Hz
- MAP staging aimed at initial 1 MW target

Technology Challenges – Capture Solenoid

- A Neutrino Factory and/or Muon Collider Facility requires challenging magnet design in several areas:
  - Target Capture Solenoid (15-20 T with large aperture)
  - $E_{\text{stored}} \sim 3$ GJ
  - O(10 MW) resistive coil in high radiation environment
  - Possible application for High Temperature Superconducting magnet technology

Technology & Design Challenges

Ring, Magnets, Detector

- Emittances are relatively large, but muons circulate for ~1000 turns before decaying
  - Lattice studies for 126 GeV, 1.5 & 3 TeV CoM
- High field dipoles and quadrupoles must operate in high-rate muon decay backgrounds
  - Magnet designs under study
- Detector shielding & performance
  - Initial studies for 126 GeV, 1.5 TeV, and 3 TeV using MARS background simulations
  - Major focus on optimizing shielding configuration

Technology Challenges - Acceleration

- Muons require an ultrafast accelerator chain
  ⇒ Beyond the capability of most machines
- Solutions include:
  - Superconducting Linacs
  - Recirculating Linear Accelerators (RLAs)
  - Fixed-Field Alternating-Gradient (FFAG) Machines
  - Rapid Cycling Synchrotrons (RCS)

Backgrounds and Detector

Much of the background is soft and out of time
- Nanosecond time resolution can reduce backgrounds by three orders of magnitude

<table>
<thead>
<tr>
<th>Cut</th>
<th>Rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracker hits</td>
<td>1 ns, dE/dx, 9x10^{-4}</td>
</tr>
<tr>
<td>Calorimeter neutrons</td>
<td>2 ns, 2.4x10^{-3}</td>
</tr>
<tr>
<td>Calorimeter photons</td>
<td>2 ns, 2.2x10^{-3}</td>
</tr>
</tbody>
</table>

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Novel Ionization Cooling Method

- Muons cool via $dE/dx$ in low-Z medium

\[ E \rightarrow E - \frac{dE}{dx} \Delta s \]
\[ \theta \rightarrow \theta + \frac{\Delta \theta}{\beta^2} \]

- Absorbers:
  - Ionization energy loss multiple Coulomb scattering
  - RF cavities between absorbers replace $\Delta E$
  - Net effect: reduction in $p_{\perp}$ at constant $p_{\parallel}$, i.e., transverse cooling

\[ \frac{d\epsilon_{\parallel}}{d\epsilon_{\perp}} = -\frac{1}{\beta^2} \frac{dE_{\mu}}{ds} \frac{\epsilon_{\parallel}}{E_{\mu}} + \frac{\beta_{\parallel}(0.014 \text{ GeV})^2}{2\beta^3E_{\mu}m_{\mu}X_0} \]  
(emittance change per unit length)

- TOF spectrometer I
- TOF spectrometer II
- 4T spectrometer I
- 4T spectrometer II
- RFCC (US)
- RFCC (US)
- SS (US)
- SS (US)

SciFi solenoidal spectrometers measure emittance with 1% precision and 1‰ resolution (muon by muon)

The Muon Ionization Cooling Experiment (MICE) in Rutherford (UK):
Demonstrate in steps the method and validate the cooling simulations
Progress on MICE @ RAL (Int. Collaboration)
Muon Ionization Cooling Experiment

All detectors have been built and tested

Construction of magnets, RF, RF power system

Step IV without acceleration completed by March 2015
Step V with acceleration completed by 2017

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R&D outstanding achievements

Successful Operation of 805 MHz Cavity in 3T Magnetic Field
MuCool Test Area/MuonsInc

World Record HTS-only Coil
15T on-axis field
16T on coil
PBL/BNL

High Pressure RF Cavity in 3T Magnetic Field with Beam
MuCool Test Area

Breakthrough in cable fabrication with High Temperature Superconductor (HTS)
FNAL-Tech Div
T. Shen-Early Career Awardee

1% Dry Air (0.2% O2) in GH2
50X reduction in RF power dissipation

Accelerating field (MV/m)
Magnetic field (T)

Time [µs]

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exploring the feasibility of staged facilities

• Intermediate facilities and physics capabilities in staged approach including evaluation of Physics and accelerator R&D at each stage.
• In the specific FNAL context
CERN, a success story

Staged approach

Multi-purpose applications

CERN Accelerator Complex

- LHC
  - ALICE
  - ATLAS
  - CMS
  - LHCb
- SPS
  - T12
  - TT10
  - TT60
- Booster
  - AD
  - LINAC 2
  - LINAC 3
  - PS
  - Leir
  - CTR
- ISOLDE

- Neutrons
- Protons
- Antiprotons
- Ions

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
PS: Proton Synchrotron
AD: Antiproton Decelerator
CTF3: Clic Test Facility
LEIR: Low Energy Ion Ring
LINAC: Linear Accelerator
n-ToF: Neutrons Time Of Flight

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Principles of an ideal project scenario

Series of STAGED facilities

• physics interest at each stage
• Technology with increasing complexity progressively developed and validated

Preferably MULTIPURPOSE

• maximizing supported physics community and funding!

Affordable budget (< 1B$) from one facility to next

• Stage built-on previous stage with additional facilities

Taking advantage of existing facilities

• synergy between present and future program
Unique opportunity of Muon based accelerators to enable facilities at both High Intensity and High Energy Frontiers in a staged approach

Neutrino Factory (NuMAX) at High Intensity Frontier

Proton Driver

SC Linac
Accumulator
Buncher

Front End

Cooling

Acceleration

μ Storage Ring

μ⁺
5 GeV

μ⁻
281m

ν

ν Factory Goal:
$10^{21} \mu^+ & \mu^-$ per year within the accelerator acceptance

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

ν

μ⁻

μ⁺

μ-Collider at High Energy Frontier

Proton Driver

SC Linac
Accumulator
Buncher
Combiner

Front End

Cooling

Acceleration

Collider Ring

Accelerators:
Linacs, RLA or FFAG, RCS

$E_{\text{CM}}$: Higgs Factory to
$\sim 10 \text{ TeV}$
An attractive staging scenario of facilities with physics interest at each stage

Intensity Frontier
- NuMAX+
- IDS-NF
- Neutrino Factory
- NuMAX
- NuSTORM
- Precision $\nu$ physics
- CP violation
- New $\nu$ physics exploration
- Sterile $\nu$
- $\nu$ cross sections

Energy Frontier
- Multi-TeV Muon Colliders
- Beyond Standard Model
- Upgraded
- TOP Factory
- Nominal
- Higgs properties
- Direct mass & width
- Top properties
- Higgs properties
- Direct mass & width

Energy Frontier vs. Colliding Beam Energy (GeV)
- Luminosity (cm$^{-2}$ sec$^{-1}$)
- Beam Energy (GeV)

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Taking advantage of and leveraging FNAL future projects:

- Proton Improvement Plan (PIP),
- Long Baseline Neutrino Facility (LBNF)

Proton Improvement Program (PIP) as proton driver

- Starting with 1MW for an early and realistic start (beam power, target…..)
- Upgradable to the highest beam power when available

Sanford Underground Research Facility (SURF) host of long distance detector of a Neutrino Factory

- Great synergy with LBNF about detector and facility
- Neutrino Factory energy of 5 GeV compatible with 1300 km distance of FNAL to Sanford
nuSTORM

neutrinos from STOred Muons

An entry-level NF?

DOES NOT

Require Development of
ANY New Technology

nuSTORM

Low energy, low luminosity muon storage ring. Provides with \(1.7 \times 10^{18}\) \(\mu^+\) stored, the following oscillated event numbers

\[
\begin{align*}
\nu_e \rightarrow \nu_\mu \text{ CC} & \quad 330 \\
\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \text{ NC} & \quad 47000 \\
\nu_e \rightarrow \nu_e \text{ NC} & \quad 74000 \\
\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \text{ CC} & \quad 122000 \\
\nu_e \rightarrow \nu_e \text{ CC} & \quad 217000 \\
\end{align*}
\]

and each of these channels has a more than 10 \(\sigma\) difference from no oscillations

With more than 200 000 \(\nu_e\) CC events a \% level \(\nu_e\) cross section measurement should be possible

10^{10} \(\mu\) / 1\(\mu\)s pulse

Ideal R&D platform

to get experience, test & validate muon technology
NuMAX (Neutrinos from Muon Accelerator CompleX)
5GeV staged Neutrino Factory with far detector at SURF

δ = CP violating phase

NuMAX complementary to LBNF
# Staged Neutrino Factory and Muon Colliders

Increasing complexity and challenges

## Neutrino Factory at intensity frontier

<table>
<thead>
<tr>
<th>System</th>
<th>Parameters</th>
<th>Unit</th>
<th>nuSTORM</th>
<th>NuMAX Commissioning</th>
<th>NuMAX</th>
<th>NuMAX+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>v_e or v_µ 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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<tr>
<td></td>
<td>Stored μ^+ or μ^-year</td>
<td>-</td>
<td>8×10^{17}</td>
<td>1.25×10^{20}</td>
<td>4.65×10^{20}</td>
<td>1.3×10^{21}</td>
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<tr>
<td>Far Detector:</td>
<td>Type</td>
<td>SuperBIND</td>
<td>MIND / Mag LAr</td>
<td>MIND / Mag LAr</td>
<td>MIND / Mag LAr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Distance from Ring</td>
<td>km</td>
<td>1.9</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
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<tr>
<td></td>
<td>Mass</td>
<td>kT</td>
<td>1.3</td>
<td>100 / 30</td>
<td>100 / 30</td>
<td>100 / 30</td>
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<tr>
<td></td>
<td>Magnetic Field</td>
<td>T</td>
<td>2</td>
<td>0.5-2</td>
<td>0.5-2</td>
<td>0.5-2</td>
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<tr>
<td>Near Detector:</td>
<td>Type</td>
<td>SuperBIND</td>
<td>Suite</td>
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<td>Suite</td>
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<tr>
<td></td>
<td>Distance from Ring</td>
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<td>50</td>
<td>100</td>
<td>100</td>
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<td>Mass</td>
<td>kT</td>
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<td></td>
<td>Magnetic Field</td>
<td>T</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Neutrino Ring</td>
<td>Ring Momentum</td>
<td>GeV/c</td>
<td>3.8</td>
<td>5</td>
<td>5</td>
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<tr>
<td></td>
<td>Circumference (C)</td>
<td>m</td>
<td>480</td>
<td>737</td>
<td>737</td>
<td>737</td>
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<tr>
<td></td>
<td>Straight section</td>
<td>m</td>
<td>184</td>
<td>281</td>
<td>281</td>
<td>281</td>
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<tr>
<td></td>
<td>Number of bunches</td>
<td></td>
<td>60</td>
<td>60</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Charge per bunch</td>
<td>1×10^8</td>
<td>6.9</td>
<td>26</td>
<td>35</td>
<td></td>
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<tr>
<td>Acceleration</td>
<td>Initial Momentum</td>
<td>GeV/c</td>
<td>-</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
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<tr>
<td></td>
<td>Single-pass Linacs</td>
<td>GeV/c</td>
<td>-</td>
<td>1.0, 3.75</td>
<td>1.0, 3.75</td>
<td>1.0, 3.75</td>
</tr>
<tr>
<td></td>
<td>MHz</td>
<td>-</td>
<td>325,650</td>
<td>325,650</td>
<td>325,650</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Repetition</td>
<td>Hz</td>
<td>-</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Cooling</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Initial</td>
<td>Initial</td>
<td></td>
</tr>
</tbody>
</table>

## Muon Collider at the energy frontier

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Startup</th>
<th>Operation</th>
<th>Production</th>
<th>High Resolution</th>
<th>High Luminosity</th>
<th>Multi-TeV Baselines</th>
<th>Accounts for Site Radiation Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoM Energy</td>
<td>TeV</td>
<td>0.126</td>
<td>0.126</td>
<td>0.35</td>
<td>0.35</td>
<td>1.5</td>
<td>3.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Ave. 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>
<td>12</td>
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<tr>
<td>Beam Energy Spread</td>
<td>%</td>
<td>0.003</td>
<td>0.004</td>
<td>0.01</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Higgs* or Top* Production/10^7 sec</td>
<td>3.5×10^9</td>
<td>13.5×10^9</td>
<td>7×10^9</td>
<td>60×10^9</td>
<td>37.5×10^9</td>
<td>200×10^9</td>
<td>820×10^9</td>
<td></td>
</tr>
<tr>
<td>Circumference</td>
<td>km</td>
<td>0.3</td>
<td>0.3</td>
<td>0.7</td>
<td>0.7</td>
<td>2.5</td>
<td>4.5</td>
<td>6</td>
</tr>
<tr>
<td>No. of IPs</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Repetition Rate</td>
<td>Hz</td>
<td>30</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>12</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>β*</td>
<td>cm</td>
<td>3.3</td>
<td>1.7</td>
<td>1.5</td>
<td>0.51 (0.5-2)</td>
<td>0.5 (0.3-3)</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>No. muons/bunch</td>
<td>10^{12}</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>No. bunches/beam</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Norm. Trans. Emittance, σ_n</td>
<td>π mm-rad</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.05</td>
<td>0.025</td>
<td>0.025</td>
<td>0.035</td>
</tr>
<tr>
<td>Norm. Long. Emittance, e_n</td>
<td>π mm-rad</td>
<td>1</td>
<td>1.5</td>
<td>1.5</td>
<td>10</td>
<td>70</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Bunch Length, σ_k</td>
<td>cm</td>
<td>5.6</td>
<td>6.3</td>
<td>0.9</td>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<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>
<td>1.6</td>
</tr>
</tbody>
</table>

**Cooling**
- 6D no final
- Full 6D
R&D platform at each Physics stage

Principle:
• MAP novel technologies to be tested and validated
• Dedicated test facilities usually very expensive and not useful for Physics
• Novel concept of test facility integrated into actual facility stage aiming at development & validation of technology required by next stage

nuSTORM as R&D platform for 6D cooling at moderate intensity
• Source of $10^{10}$ muons per pulse
• 6D cooling validation for HIGGS factory and/or Muon Collider

NuMAX as R&D platform for initial cooling
• Source of $10^{11}$ muons per pulse
• Initial cooling validation for NuMAX+

NuMAX+ as R&D platform for 6D cooling at high intensity
• Source of $10^{12}$ muons per pulse
• Complementary to cooling experiment @ MICE at (very) low intensity
• 6D cooling validation for HIGGS factory and Muon Collider

HIGGS factory as R&D platform for final cooling
• Final cooling validation for Muon Collider
Progressive installation in stages with technology validation at each stage

PIPII

0.8GeV

2.2GeV

PIPIII
Progressive installation in stages with technology validation at each stage

Dual use Linac

3.75 GeV SC 650 MHz

6.7 GeV Protons

To MI for LBNF upgrade

PII
0.8 GeV
2.2 GeV

PIII

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Progressive installation in stages with technology validation at each stage

NuMAX commissioning

PIPII
0.8GeV

PIPII
2.2GeV

PIPIII
dual use

Linac

3.75GeV
SC 650MHz

6.75 GeV
Protons

1 MW
Target
Buncher
Accumulator

To MI for
LBNF upgrade

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Progressive installation in stages with technology validation at each stage

NuMAX commissioning

Dual use Linac

3.75 GeV SC 650 MHz

Accumulator

Target

Buncher

To MI for LBNF upgrade

Front-end

255 MeV/c Muons

1 MW

μ Preinjector

1.0 GeV 325 MHz

0.8 GeV

2.2 GeV

PIPII

PIPIII

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Progressive installation in stages with technology validation at each stage

Initial Cooling

Test Facility

Front-end

Target

Buncher

Accumulator

To MI for LBNF upgrade

Dual use Linac

3.75 GeV SC 650 MHz

Preinjector

1.0 GeV 325 MHz

Muons

255 MeV/c

2.2 GeV

0.8 GeV

PIPII

PIPIII

NuMAX commissioning

6.75 GeV Protons

To MI for LBNF upgrade

NuMAX

5 GeV

= 0.35 km

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Progressive installation in stages with technology validation at each stage

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PIPII
0.8 GeV

PIPIII
2.2 GeV

μ
Preinjector

1.0 GeV
325 MHz

3.75 GeV
SC 650 MHz

6.75 GeV
Protons

255 MeV/c
Muons

Initial Cooling

Front-end

1 MW
Target

Buncher

Accumulator

To MI for
LBNF upgrade

Dual use
Linac

NuMAX

To MI for
LBNF upgrade

MW
1

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IPAC14 (June 18, 2014)
Progressive installation in stages with technology validation at each stage
Progressive installation in stages with technology validation at each stage

- 6D Cooling Test Facility
- Dual use Linac
- 6.75 GeV Protons
- 255 MeV/c Muons
- Charge separator
- 6D cooling
- Bunch merge
- 6D cooling
Progressive installation in stages with technology validation at each stage

Sub-TeV Collider
Higgs or Top Factory

μ Preinjector

Linac

Accumulator

Buncher

Target

Combiner

Front-end

Initial Cooling

6D Cooling

Charge separator

255MeV/c Muons

6D Cooling

Bunch merge

6D cooling

2.2GeV

0.8GeV

Higgs Factory

125GeV

300 m

3.75GeV

SC 650MHz

1.0 GeV

325MHz

Dual use

6.75 GeV Protons

To MI for LBNF upgrade

MW

4

J.P.Delahaye IPAC14 (June 18, 2014)
Progressive installation in stages with technology validation at each stage

Sub-TeV Collider
Higgs or Top Factory

Dual use
Linac

3.75GeV
SC 650MHz

Accumulator
Combiner
Target
Front-end

Initial Cooling

6D Cooling

255MeV/c Muons

6D Cooling
Bunch merge
6D cooling
Charge separator

0.25 GeV

0.8GeV

2.2GeV

μ Preinjector

3.75GeV
1.0 GeV
325MHz

6.75 GeV
Protons

Final cooling

Final Cooling
Test Facility

To MI for LBNF upgrade

Higgs Factory

125GeV
300 m

J.P.Delahaye IPAC14 (June 18, 2014)
Progressive installation in stages with technology validation at each stage

Multi-TeV Collider

- **PIPII**
  - 0.8 GeV
  - 2.2 GeV

- **PIPIII**
  - 0.25 GeV
  - 1.0 GeV
  - 3.75 GeV
  - 6.75 GeV

**Preinjector**

**Linac**
- 3.75 GeV
- SC 650 MHz

**Buncher**

**Muons**
- 255 MeV/c

**Protons**
- 6.75 GeV

**Accumulator**

**Final cooling**

**Post-cooling Accelerator**

**Initial Cooling**

**Front-end**

**Target**

**Combiner**

**Accumulator**

**6D Cooling**

**Bunch merge**

**Charge separator**

**RLA**

**Muon Collider**
- 1.5 to 6 (10) TeV
- 2.5 to 6 km
- 4 MW

**To MI for LBNF upgrade**

J.P. Delahaye

IPAC14 (June 18, 2014)
Progressive installation in stages with technology validation at each stage

J.P.Delahaye IPAC14 (June 18, 2014)
A Potential Muon Accelerator Complex at Fermilab: 
νSTORM ➔ NuMAX ➔ Higgs Factory

Staging scenario fully compatible with the PIP-II stage option
A Potential Muon Accelerator Complex at Fermilab:
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νSTORM $\rightarrow$ NuMAX

$\rightarrow$ Higgs Factory

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A Potential Muon Accelerator Complex at Fermilab:

νSTORM ➔ NuMAX ➔ Higgs Factory

Staging scenario fully compatible with the PIP-II stage option

Later upgradable to a Muon Collider with Tevatron size at 6 TeV
# MAP timeline

<table>
<thead>
<tr>
<th>2010</th>
<th>~2020</th>
<th>~2030</th>
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<tbody>
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<td>MAP Feasibility Assessment</td>
<td>Advanced Systems R&amp;D</td>
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- Indicates a date when an informed decision should be possible

**MAP timeline**

→ *providing informed decisions points*

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M.A. Palmer
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## MAP timeline

(providing informed decisions points)

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- **Muon Accelerator R&D Phase**
  - MAP Feasibility Assessment
  - Advanced Systems R&D
  - Muon Ionization Cooling Experiment (MICE)

- **Proton Improvement Plan @ FNAL**
  - PIP-II
  - And Further Proton Source Improvements

- **Intensity Frontier**
  - IDS-NF RDR
  - Proposed Muon Storage Ring Facility (νSTORM)
  - Option for Long Baseline ν Factory

- Indicates a date when an informed decision should be possible
### MAP timeline

#### Muon Accelerator R&D Phase
- **2010**: Muon Ionization Cooling Experiment (MICE)
- **~2020**: Advanced Systems R&D
- **~2030**: Proposed Muon Storage Ring Facility (νSTORM)

#### Proton Improvement Plan @ FNAL
- **2010**: Muon Ionization Cooling Experiment (MICE)
- **2020**: PIP-II
- **~2030**: And Further Proton Source Improvements

#### Intensity Frontier
- **2010**: IDS-NF RDR
- **~2020**: Proposed Muon Storage Ring Facility (νSTORM)
- **~2030**: Option for Long Baseline ν Factory

#### Energy Frontier
- **~2020**: Collider Conceptual
- **~2030**: Option for μ Collider

- Indicates a date when an informed decision should be possible
Conclusion

Muon based technology unique opportunity to enable facilities at both the high intensity and the high energy frontiers

• High precision neutrino physics and lepton colliders extension into multi-TeV range with reasonable dimensions, cost & power consumption
• MAP focused on feasibility demonstration of novel & challenging technology

Attractive Muon based Accelerators Staged Scenario

• Series of facilities with increasing complexity built-up on previous stage
• Integrated R&D platform at each stage for validation of novel technology
• Informed decision on following stages with risk mitigation
• Flexibility of adaptation to physics requirements

Especially appealing at FNAL taking advantage & leveraging of projects or then existing facilities: PIP, LBNF

• Neutrino Factory (NuMAX) natural complement of Long Baseline Neutrino Facility (LBNF) if warranted by Neutrino Physics at the time
• Multi-TeV lepton collider when and if required by (new) Physics in the future

Plea for long term R&D support
MAP related contributions to IPAC14

Posters

MOPME043 Modeling and Simulation of Beam-Induced Plasma in Muon Cooling Devices – R. Samulyak, et al.
MOPRI007 Design and Simulation of High Intensity Muon Beam Production for Neutrino Experiments – D. Stratakis, et al.
TUPME010 The Physics Programme of Next MICE Step IV – J.C. Nugent, et al.
TUPME014 Development of Six-Dimensional Helical Muon Beam Cooling Channel for Muon Colliders – K. Yonehara, et al.
TUPME017 Design and Simulation of a Matching System into the Helical Cooling Channel – C. Yoshikawa, et al.
TUPME019 Design and Simulation of a High Field-low energy Muon Ionization Cooling Channel – D. Stratakis, et al.
TUPME020 A Complete Six-dimensional Muon Cooling Channel for a Muon Collider – D. Stratakis, et al.
TUPME021 Theoretical Framework to Predict Efficiency of Ionization Cooling Lattices – D. Stratakis, D. Neuffer
TUPME022 Design and Optimization of a Particle Selection System for Muon-based Accelerators – D. Stratakis, et al.
TUPME023 Overview of a Muon Capture Section from Muon Accelerators – D. Stratakis, et al.
TUPME024 A Hybrid Six-Dimensional Muon Cooling Channel with Gas Filled Cavities – D. Stratakis, et al.
TUPRI002 RF Design and Operation of a Modular Cavity for Muon Ionization Cooling R&D – Y. Torun, et al.
TUPRI006 Target System Concept for a Muon Collider/Neutrino Factory – K.T. McDonald, et al.
TUPRI009 Target System Concept for a Muon Collider/Neutrino Factory with 6.75 GeV Proton Driver – K.T. McDonald, et al.
TUPRI010 Instrumentation for Characterizing 201-MHz MICE Cavity at Fermilab – Y. Torun, et al.
TUPRI012 The Fermilab MuCool Test Area and Experimental Program – Y. Torun, et al.
TUPRI019 Energy Deposition in the Target System of a Muon Collider/Neutrino Factory – K.T. McDonald, et al.

Presentations

MOOCA02 RF Design and Operation of a Modular Cavity for Muon Ionization Cooling R&D – Y. Torun, et al.
Supporting slides
The beauty of Muons

- Strong coupling to Higgs mechanism by s channel
  - Cross section enhanced by \((m_\mu/m_e)^2 = 40000\) with sharp peak at 126GeV resonance
  - Higgs factory allowing energy scan with high energy resolution for direct mass and width measurements at half colliding beam energy and 10^3 less luminosity than with e+/e-
  - Requires colliding beam with extremely small momentum spread (4 \(10^{-5}\)) and high stability

As with an e^+e^- collider, a \(\mu^+\mu^-\) collider offer a precision probe of fundamental interactions without limitations in energy:
- By synchrotron radiation as e^+e^- circular colliders
- By beams-trahlung as e^+e^- linear colliders
An attractive staging scenario in the FNAL context

a series of facilities with increasing complexity, each with performance characteristics providing unique physics reach:

**nuSTORM (neutrinos from STOred Muons):** a short-baseline 3.8 GeV Neutrino Factory-like facility enabling a definitive search for sterile neutrinos, as well as neutrino cross-section measurements

**NuMAX (Neutrinos from Muon Accelerator compleX):** a long-baseline 5GeV Neutrino Factory, optimized for a detector at the Sanford Underground Research Facility (SURF) to be built in phases,

- **A commissioning phase** based on a limited proton beam power of 1MW on the muon production target with no cooling for an early and realistic start with conventional technology
- **NuMAX upgraded** from the commissioning phase by adding a limited amount of 6D cooling (by a factor 50), affording a precise and well-characterized neutrino source
- **NuMAX+:** a full-intensity Neutrino Factory, upgraded from NuMAX by multiplying the proton beam power on target and detector upgrade for performance as the ultimate source for precision CP-violation measurements and potential exploration of new physics in the neutrino sector

**Higgs Factory:** 125 GeV collider providing up to 13,500 Higgs events per year \((10^7 \text{ sec})\) with exquisite energy resolution enabling direct Higgs mass and width measurements (s channel coupling).

Possible upgrade to a **Top Factory** with production of up to 60000 top particles per year \((10^7 \text{ sec})\).

**Multi-TeV Collider:** if warranted by LHC results, with an ultimate energy reach up to 10 TeV, offering the best performance, least cost and power consumption of any lepton collider in the multi-TeV regime.
Cooling System: Emittance path
6 orders of magnitude in 6 Dimensions

For acceleration to multi-TeV collider

For acceleration to Higgs Factory

Final Cooling

post-merge 6D Cooling

pre-merge 6D Cooling (original design)

Bunch Merge

Exit Front End (15mm, 45mm)

Target

Phase Rotator
FNAL Proton Improvement Plan (PIP) Possible future upgrade

PIPII: 200 kW @ 0.8 GeV
PIPIII: ~1 MW @ 3 GeV
PIPIV: 2-4 MW @ 8 GeV?

S. Holmes @ P5 Dec16, 2013