THE RESEARCH AND DEVELOPMENT PROGRAM TOWARDS AN ENERGY-FRONTIER MUON COLLIDER

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On Behalf of the Neutrino Factory and Muon Collider Collaboration (NFMCC), Muon Collider Task Force (MCTF), and Muon Accelerator Program (MAP)
OUTLINE

• Introduction and History
• Physics Motivation
• Conceptual Layout
• Progress and Challenges
• R&D Program
• Physics and Detector Studies
INTRODUCTION AND HISTORY

• Muons in a storage ring decay producing a beam of neutrinos → Neutrino Factory
• Colliding $\mu^+$ and $\mu^-$ in storage ring → Muon Collider
• Muon colliders first proposed by G.I. Budker and A.N. Skrinsky in the late 1960’s and early 1970’s
• The necessary concept of ionization cooling was developed by Skrinsky and V.V. Parkhomchuk and expanded by D. Neuffer in the early 1980’s and later by R.B. Palmer
• A Muon Collider Collaboration was formed in 1996; Neutrino Factory added in 1999 (NFMCC)
• Fermilab Muon Collider Task Force (MCTF) formed in 2006
• U.S. NFMCC and MCTF activities being merged into new national Muon Acceleration Program (MAP), hosted at Fermilab
PHYSICS MOTIVATION

• Muons are fundamental particles, so same advantage as $e^+ e^-$ colliders: full energy of particles in collision

• Synchrotron radiation by muons is less than for electrons by factor of $(m_e/m_\mu)^4 \approx 6 \times 10^{-10}$
  – Compact, multi-pass acceleration, lower cost for RF power
  – Muon beam can have narrow energy spread
  – High energy collider can be much smaller – a ring

• Multi-pass collisions $\sim 1000$ turns

Will decide energy for next lepton collider $\sim 2014$ based on LHC discoveries!
A MUON COLLIDER IS COMPACT

A 4 TeV muon collider would fit on the Fermilab site
PHYSICS MOTIVATION

$\sqrt{s} < 500$ GeV:

- Threshold regions
  - top pairs
  - EW boson pairs
  - Zh production
- Enhanced $s$-channel production for Higgs-like particles
  
  Proportional to $(m_\mu/m_e)^2 \sim 4 \times 10^4$
  
  Narrow energy spread – resolve nearly degenerate states
  
  Could be important for $H^0, A^0$
\[ \sqrt{s} > 500 \text{ GeV}: \]

- Fusion processes increasingly dominate s-channel processes
- Probing reach addresses all major outstanding questions

\[ \sigma(s) = C \ln \left( \frac{s}{M_X^2} \right) + \ldots \]
SCHEMATIC LAYOUT

Same front-end design for Neutrino Factory and Muon Collider in current baseline design

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**CONCEPTUAL LAYOUT**

Muon Collider Conceptual Layout

**Project X**
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 Capture and Cooling**
Capture, bunch and cool muons to 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**
Bring positive and negative muons into collision at two locations 100 meters underground.
EXAMPLE 1.5 TeV MUON COLLIDER SCENARIOS

<table>
<thead>
<tr>
<th></th>
<th>LEMC</th>
<th>HEMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$)</td>
<td>2.7</td>
<td>1</td>
</tr>
<tr>
<td>Avg. bending field (T)</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Proton driver repetition rate (Hz)</td>
<td>65</td>
<td>15</td>
</tr>
<tr>
<td>$\beta^*$ (cm)</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Muons per bunch ($10^{11}$)</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Muon bunches in collider (each ring)</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Norm. Transv. Emittance ($\mu$m)</td>
<td>2.1</td>
<td>25</td>
</tr>
<tr>
<td>Norm. Long. Emittance (m)</td>
<td>0.35</td>
<td>0.07</td>
</tr>
<tr>
<td>Energy spread (%)</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Low-emittance muon collider (LEMC); high-emittance muon collider (HEMC)
PROGRESS AND FUTURE R&D

• Proton Source
  – Upgraded Project-X (4 MW, 1–3 ns bunch length)
  – See R. Tschirhart talk “Project-X at Fermilab”

• Target
  – MERIT Experiment at CERN PS
  – Mercury jet in a 15 T solenoid 1 cm

  Measured disruption length = 28 cm
PROGRESS AND FUTURE R&D

• Decay, Bunching and Phase Rotation
  – Muons come from decay of pions produced in target, so large emittances and energy spreads
  – Front end captures pions produced from target, bunches the muons, and reduces the energy spread
  – Decay and capture uses Neutrino Factory Feasibility Study 2 solenoid channel
  – Neuffer 12-bunch scheme for bunching and phase rotation suitable for either Neutrino Factory or Muon Collider
  – Further R&D needed to make realistic

In common with Neutrino Factory
PROGRESS AND FUTURE R&D

- Initial Cooling
  - Neutrino Factory Feasibility Study 2a channel (lithium hydride absorber instead of liquid hydrogen)
  - Will study using hydrogen gas absorber in place of (or in addition to) LiH

In common with Neutrino Factory

Front End: R&D on RF in magnetic field needed
PROGRESS AND FUTURE R&D

- 6-Dimensional Cooling
  - Three options: “Guggenheim” (helical RFOFO), FOFO snake, Helical Cooling Channel
  - Each has been simulated, choice in 2012
  - R&D on RF in magnetic field needed
  - Demonstration proposal 2016

201-MHz Guggenheim Channel
PROGRESS AND FUTURE R&D

• Final Cooling
  ✷ 50-T Linear Channel – R&D on very high field magnets

• Acceleration
  ✷ Low-energy Acceleration
    • Linac followed by two dog-bone RLAs + FFAG (EMMA)
    • Techniques similar to Neutrino Factory
PROGRESS AND FUTURE R&D

• Acceleration (continued)
  ✷ Acceleration to High Energy
    • Fast-cycling synchrotrons
    • R&D on rapid-cycling magnets ongoing

• Collider Ring
  ✷ Good progress on lattice design, ±1.2% momentum acceptance, 4.7σ dynamic aperture (without errors)
  ✷ Closely tied to design of detectors
TECHNOLOGY DEVELOPMENT AND SYSTEM TESTS

- RF Cavities in Magnetic Field
  - Copper RF cavities (normal-conducting) have been shown to break down in multi-Tesla fields at lower gradients than needed for cooling channels
  - R&D program to establish viable options (treating, high-pressure gas, atomic layer deposition, orientation of magnetic field)

- Magnet Development
  - Very high field solenoids
  - Helical solenoids
  - Very fast ramping magnets
  - HTS solenoids
TECHNOLOGY DEVELOPMENT AND SYSTEM TESTS

• MUCOOL Test Area at Fermilab
  ✷ Ionization cooling component testing – 5-T magnet, 805- and 201-MHZ RF cavity testing, LH$_2$ handling, 400 MeV beam from linac

• Muon Ionization Cooling Experiment (MICE)
  ✷ Experimental demonstration of ionization cooling
  ✷ Under way at RAL
MUON ACCELERATOR PROGRAM (MAP)

Proposal submitted March 1, 2010
DOE Review August 24-26, 2010
214 participants from 14 institutes
R&D PROGRAM DEVELOPMENT

First
~ 10 years

NFMCC

Last couple
of years

NFMCC + MCTF

Now
(FY10)

Interim MAP

FY11

MAP
6-7 years

Now (FY10)

First ~ 10 years

Last couple of years

FY11

MAP 6-7 years
MUON ACCELERATOR PROGRAM (MAP)

MAP deliverables:

• Design Feasibility Study Report (DFSR) for a multi-TeV muon collider, including indicative cost range
• Technology development and system tests needed to inform the muon collider DFSR studies and enable down-selection
• Contributions to the International Neutrino Factory Design Study to produce a Reference Design Report by 2013
PHYSICS AND DETECTORS

• Physics and Detector studies not part of MAP – separate group forming. Kick-off workshop was held at Fermilab in November 2009; second workshop in Fall 2010

• Machine-Detector Interface group revisited background calculations, using consistent muon collider lattice, with different cone configurations

• Compared to most optimistic old 1996 configuration, peak values for backgrounds are down factor of 5-10 for all particles, except photons

• Background fluxes of particles provided as input to physics simulations
Total absorbed dose in silicon at 4 cm radius

- Muon Collider: 0.1 MGy/yr
- CMS: 0.2 MGy/yr at $10^{34}$ cm$^{-2}$ s$^{-1}$
PHYSICS AND DETECTORS

• With today’s pixel detector technologies occupancies should be quite manageable in the barrel region (and easier compared to CLIC)

• Impact on precision physics of large radius of first layer of vertex detector:
  – ILC: radii of 1.5 → 6 cm
  – MC: radii of 5 → 20 cm

• Resolution factor of 2 worse for low $p_T$ compared to ILC

• Physics implications to be studied

![IP resolution graph]

\[ \sigma_z = \sigma_{hit} \sqrt{1 + \frac{r_i}{r_o}} \]

\[ 1 - \frac{r_i}{r_o} \]
SUMMARY AND CONCLUSIONS

• Considerable progress on muon collider R&D

• Options delineated and encouragement from DOE to form a Muon Accelerator Program (MAP) hosted at Fermilab – proposal submitted

• Within 6-7 years we will have a Design Feasibility Study and cost range for a multi-TeV muon collider; configurations chosen and end-to-end simulation by 2014

• Plan initiated to form a national lepton collider program for physics and detectors in the US

• Decision on energy for next lepton collider depending on LHC results