Neutrino Factory and Muon Collider
R&D

Muon Production, Capture and Acceleration R&D
directed at Physics with Intense Muon Beams

The Neutrino Factory and Muon Collider Collaboration
A Bit of History

Since 1995 the Neutrino Factory and Muon Collider Collaboration (a.k.a. Muon Collaboration) has pursued an active R&D program that has focused on muon production, capture and acceleration. Initially the physics emphasis was on muon colliders (both a Higgs Factory and an energy frontier machine). By 2000 the focus of the collaboration had shifted to studying the feasibility of a Neutrino Factory. Recently new ideas in muon ionization cooling have reinvigorated the collaboration's efforts on the investigation of energy frontier muon colliders. I will:

1. Review the physics motivation for our activities
2. Describe the Collaboration's program
3. Explore the synergy between Neutrino Factory and Muon Collider facilities both from the point of view of the physics program and the accelerator complex
NFMCC Mission

To study and develop the theoretical tools, the software simulation tools, and to carry out R&D on the hardware that is unique to the design of Neutrino Factories and Muon Colliders

- Extensive experimental program to verify the theoretical and simulation predictions

NFMCC WEB site: http://www.cap.bnl.gov/mumu/
Current Organization

DOE/NSF

Laboratories/MCOG
P. Bond, S. Holmes, J. Siegrist

MUTAC
R. Kephart

Collaboration Spokespersons
A. Bross, H. Kirk

Project Manager
M. Zisman

Executive Board

Technical Board

Collaborating Institutions

Neutrino Factory and Muon Collider Collaboration (NFMCC)

R&D Tasks
Simul., µCOOL, Target, MICE, Other
Collaborating Institutions

**US**
- National Labs
  - Argonne
  - BNL
  - Fermilab
  - LBNL
  - Oak Ridge
  - Thomas Jefferson
- Universities
  - Columbia
  - Cornell
  - IIT
  - Indiana
  - Michigan State
  - Mississippi
  - Northern Illinois
  - Princeton
  - UC-Berkeley
  - UC-Davis
  - UC-Los Angeles
  - UC-Riverside
  - University of Chicago

**International**
- National Labs
  - Budker
  - DESY
  - INFN
  - JINR, Dubna
  - KEK
  - RAL
  - TRIUMF
- Universities
  - Karlsruhe
  - Imperial College
  - Lancaster
  - Osaka
  - Oxford
  - Pohang
  - Tel Aviv

**Corporate Partners**
- Muons Inc*
- Tech-X Corporation

*SBIR Funding
- 9 Phase I
- 6 Phase II
- Currently 8 FT Ph.D.
Core Program

Targetry R&D: Mercury Intense Target Experiment (MERIT)
- Co-Spokesperson: Kirk McDonald
- Co-Spokesperson & PM: Harold Kirk

Ionization Cooling R&D: MuCool and MICE
- MuCool Spokesperson: Alan Bross
- MICE Deputy Spokesperson: Mike Zisman
- US MICE Leader: Dan Kaplan

Simulations & Theory
- Coordinator: Rick Fernow

Muon Collider Task Force*
* @ Fermilab
Physics Motivation

*Is Muon Production, Capture and Acceleration R&D worth the investment?*
Evolution of a Physics Program

1. Intense Low-energy muon physics
   - \( \mu \ e \) conversion experiment

2. Neutrino Factory
   - High Energy 10-20 GeV
     - Possible Low Energy 4 GeV option

3. Energy Frontier Muon Collider
   - 1.5 - 4 TeV+

PRSTAB 2002
Footprint and the Energy Frontier

The VLHC is the largest machine to be seriously considered to date:
- Stage 1 – 40 TeV
  - > 2 TeV
- Stage 2 – 200 TeV
  - > 10 TeV

Muon Facilities are different
Low-Energy Muon Physics
\[\mu \text{ to } e \text{ conversion - } \text{Mu2e}\]

- **Sensitive tests of Lepton Flavor Violation (LFV)**
  - In SM occurs via $\nu$ mixing
    - Rate well below what is experimentally accessible
  - Places stringent constraints on physics beyond SM
    - Supersymmetry
      - Predictions at $10^{-15}$

- **Requirement - Intense low energy $\mu$ beam**
  - Cooling improves stopping efficiency in target of experiment
    - Might be an appropriate option for a Mu2e expert.
      - Time Scale is issue
  - Test bed for Muon Ionization Cooling for NF and MC with intense $\mu$ beam
Neutrino Factories

Why a Neutrino Factory?
- Strong case for precision neutrino program
  - Very Rich Experimental Program
- Want Very Intense $\nu$ beam with well-understood systematics
Low-Energy NF
Neutrino Factory Lite

ISS Preliminary Design

25-50 GeV

4 GeV

40% Cost Reduction
3ν Mixing Model

Know to some extent

\begin{align*}
\sin^2 \theta_{23} & \\
\cos \delta & =
\end{align*}

Don’t know

\begin{align*}
\sin^2 \theta_{13} & \\
|\sin \theta_1| & \\
\Delta m^2_{atm} & \\
\Delta m^2_{sol} & \\
\end{align*}

\begin{align*}
\text{NORMAL} & \\
\text{INVERTED} & \\
\end{align*}

Fractional Flavor Content varying \( \cos \delta \)

Is a Neutrino Factory needed in order to fill in the blanks?

O. Mena and S. Parke, hep-ph/0312131
Neutrino Factory - ISS

Best possible reach in $\theta_{13}$ for all performance indicators $\rightarrow$ Neutrino factory

$(3\sigma, \Delta m_{31}^2 = 0.0022 \text{ eV}^2)$
Theoretical Indications That $\theta_{13}$ may be small

Projections of the allowed regions from the global oscillation data at 90%, 95%, 99%, and $3\sigma$ C.L.

<table>
<thead>
<tr>
<th>parameter</th>
<th>best fit</th>
<th>$2\sigma$</th>
<th>$3\sigma$</th>
<th>$4\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2$ [10^{-5}eV^2]</td>
<td>8.1</td>
<td>7.5–8.7</td>
<td>7.2–9.1</td>
<td>7.0–9.4</td>
</tr>
<tr>
<td>$\Delta m_{31}^2$ [10^{-3}eV^2]</td>
<td>2.2</td>
<td>1.7–2.9</td>
<td>1.4–3.3</td>
<td>1.1–3.7</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.30</td>
<td>0.25–0.34</td>
<td>0.23–0.38</td>
<td>0.21–0.41</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.50</td>
<td>0.38–0.64</td>
<td>0.34–0.68</td>
<td>0.30–0.72</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.000</td>
<td>$\leq 0.028$</td>
<td>$\leq 0.047$</td>
<td>$\leq 0.068$</td>
</tr>
</tbody>
</table>

$\sin^2\theta_{13}$ Model Predictions

Histogram of the number of models for each $\sin^2\theta_{13}$ bin.

Neutrino Factory
To Build or Not to Build

We Don’t Know –
But
There is a Natural Decision Point
≈ 2012

After NOvA and T2K
If $\theta_{13}$ not seen
or
seen at 3$\sigma$
Consider Major Upgrades or
New Facility

In order to make an informed
decision about a New Facility
and if the NF plays a role –
Will need a RDR ready at this
time (IDS)
This defines the R&D Program
Muon Collider - Motivation

Reach Multi-TeV Lepton-Lepton Collisions at High Luminosity

Muon Colliders may have special role for precision measurements.
Small $\Delta E$ beam spread - Precise energy scans

Small Footprint - Could Fit on Existing Laboratory Site
Muon Collider at the Energy Frontier

- **Comparisons with Energy Frontier e⁺e⁻ Collider**
  - For many processes - Similar cross sections
  - Advantage in s-channel scalar production
    - Cross section enhancement of $(m_\mu/m_e)^2 \approx 40,000$
  - Beam polarization also possible
    - Polarization likely easier in e⁺e⁻ machine
  - More precise energy scan capability
    - Beam energy spread and Beamstrahlung limits precision of energy frontier (3TeV) e⁺e⁻ machines
  - Muon decay backgrounds in MC do have detector implications, however
For larger values of $\tan \beta$ there is a range of heavy Higgs boson masses ($H_0$, $A_0$) for which discovery at LHC or $e^+e^-$ linear collider may not be possible due to suppression of coupling to gauge bosons.
ATLAS
$\sqrt{s} = 200$ GeV
$\mathcal{L} = 200$ pb$^{-1}$

$\sqrt{s} = 189$ GeV
$\mathcal{L} = 175$ pb$^{-1}$

$t \rightarrow bH^+, H^+ \rightarrow \tau\nu$

$h \rightarrow \gamma\gamma$ and $Wh/tth, h \rightarrow \gamma\gamma$

$tth, h \rightarrow bb$

$A/H \rightarrow \mu\mu$

$A/H \rightarrow \tau\tau$

$H \rightarrow hh \rightarrow bb\gamma\gamma$

$A \rightarrow Zh \rightarrow llbb$

$A/H \rightarrow tt$

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

Davide Costanzo
hep-ex/0105033v2
Key Ingredients of the Facilities
Needs Common to NF and MC Facility

- Proton Driver
  - primary beam on production target
- Target, Capture, and Decay
  - create π's; decay into μ's
- Phase Rotation
  - reduce ΔE of bunch
- Cooling
  - reduce emittance of the muons
    - Cost-effective for NF
    - Essential for MC
- Acceleration
  - Accelerate the Muons
- Storage Ring
  - store for ~1000 turns
But there are Key Differences

<table>
<thead>
<tr>
<th>Neutrino Factory</th>
<th>Muon Collider</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cooling</strong></td>
<td><strong>Cooling</strong></td>
</tr>
<tr>
<td>Reduce transverse emittance</td>
<td>Reduce 6D emittance</td>
</tr>
<tr>
<td>$\epsilon_\perp \sim 7$ mm</td>
<td>$\epsilon_\perp \sim 3-25$ $\mu$m</td>
</tr>
<tr>
<td><strong>Acceleration</strong></td>
<td><strong>Acceleration</strong></td>
</tr>
<tr>
<td>Accelerate to 20-40 GeV</td>
<td>Accelerate to 1-2 TeV</td>
</tr>
<tr>
<td>May be as low as 5-7 GeV</td>
<td></td>
</tr>
<tr>
<td><strong>Storage Ring</strong></td>
<td><strong>Storage Ring</strong></td>
</tr>
<tr>
<td>No intersecting beams</td>
<td>Intersecting beams</td>
</tr>
</tbody>
</table>
Key R&D Issues

- **High Power Targetry - NF & MC** *(MERIT Experiment)*
- **Initial Cooling - NF & MC** *(MICE (4D Cooling))*
- **200 MHz RF - NF & MC** *(MuCool and Muon’s Inc)*
  - Investigate operation of vacuum RF cavities in presence of high magnetic fields
  - Investigate Gas-Filled RF cavities
    - Operation in B field and Beam-Induced Effects
  - While obtaining high accelerating gradients (~16MV/m)

- **Intense 6D Cooling - MC**
  - RFOFO “Guggenheim”
  - Helical Channel Cooling *(MANX Proposal)*
  - Parametric Resonance Ionization Cooling

- **Bunch Recombination**

- **Acceleration** - A cost driver for both NF & MC, but in very different ways
  - FFAG’s - *(Electron Model Muon Accelerator - EMMA Demonstration)*
  - Multi-turn RLA’s

- **Storage Ring(s) - NF & MC**

- **Theoretical Studies NF & MC**
  - Analytic Calculations
  - Lattice Designs
  - Numeric Simulations

*Note: Almost all R&D Issues for a NF are currently under theoretical and experimental study*
Muon Ionization Cooling

Momentum loss is opposite to motion, $p, p_x, p_y, \Delta E$ decrease

Large emittance

Absorber

Momentum gain is purely longitudinal

Accelerator

Small emittance

Transverse

Longitudinal - Emittance Exchange

Wedge Absorber reduces energy spread

Dipole introduces dispersion ($\eta$)

$\mu$-beam

$\delta p$
NF, Muon Collider - Synergy

Neutrino Factory - ISS Preliminary

Muon Collider Schematic
Additional Technologies Needed for a Muon Collider

• Although a great deal of R&D has been done (or is ongoing) for a Neutrino Factory and is applicable to a MC, the Technological requirements for a Muon Collider are Much More Aggressive
  • Bunch Merging is required
  • MUCH more Cooling is required (MAKE OR BREAK FOR MC!)
    • 1000X in each transverse dimension, ≈ 10X in longitudinal

---

Palmer et al:
RFOFO Ring
Guggenheim
50-60T Solenoid Channel

Muons Inc.
High pressure gas-filled cavities
Helical Cooling Channel
Reverse Emittance Exchange
Parametric Resonance Induced Cooling

• Acceleration to much higher energy (20-40 GeV vs. 1.5-3 TeV)
• Storage rings
  • Colliding beams
  • Energy loss in magnets from muon decay (electrons) is an issue
6 Dimensional Cooling

RFOFO Ring

Guggenheim "Ring"
Helical Cooling Channel

- Magnetic field is solenoid $B_0$ + dipole + quad + ...
- System is filled with H2 gas, includes rf cavities
- Cools 6-D (large E means longer path length)

6D-MANX Experiment To Test
Extreme $\mu$ Cooling - PIC & REMEX

- **Parametric-Resonance Ionization Cooling**
  - Drive a $\frac{1}{2}$-integer parametric resonance
  - Hyperbolic Motion
    - $xx'=\text{constant}$

- **Reverse Emittance Exchange**
  - Increase longitudinal $\varepsilon$ in order to decrease transverse $\varepsilon$

*Space-Charge Effects Could be Critical*
Low-Emittance Muon Collider (LEMC) Concept

Parameter List:

- $E_{cm} = 1.5$ TeV
- Peak $L = 7 \times 10^{34}$
- #µ's/bunch = $10^{11}$
- Av Dipole B = 10T
- $\delta p/p = 1\%$
- $\beta^*(cm) = 0.5$ (!)

Proton driver:
- $E = 8$ GeV
- Power $\approx 1$ MW

ILC Accelerating Structure Envisioned

Fits on 2.6 X 0.6 km footprint
Average acc gradient 25 MeV/m
Scientific Program

R&D Initiatives
Targetry, Muon Cooling, Theory and Simulation
MERIT

Mercury Intense Target
MERIT - Mercury Intense Target

- Test of Hg-Jet target in magnetic field (15T)
- Submitted to CERN April, 2004 (approved April 2005)
- Located in TT2A tunnel to ISR, in nTOF beam line
- Physics Data Run – Oct-Nov, 2007
  - Single pulse tests equivalent to 4 MW Power On Target
    - 40 Hz @ 24 GeV
Movies of viewport #2, SMD camera, 0.1 ms/frame

ORNL 2006 Nov 28 runs
10 m/s

nozzle A before reaming

ORNL 2006 Nov 29 run, uprighted image
Nozzle C 20 m/s

nozzle A after reaming
Magnet and Hg Jet system installed in TT2A tunnel at CERN
MuCool
Muon Cooling: MuCool

Component R&D

- MuCool
  - Component testing: RF, Absorbers, Solenoids
    - RF - High Gradient Operation in High B field
  - Uses Facility @Fermilab (MuCool Test Area - MTA)
  - Supports Muon Ionization Cooling Experiment (MICE)
Phase I of RF Cavity Closed Cell
Magnetic Field Studies (805 MHz)

- Data seem to follow universal curve
  - Max stable gradient degrades quickly with B field
- Sparking limits max gradient
- Copper surfaces the problem

### Safe Operating Gradient Limit vs Magnetic Field Level at Window for the three different Coil modes

<table>
<thead>
<tr>
<th>Gradient in MV/m</th>
<th>Peak Magnetic Field in T at the Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
</tr>
<tr>
<td>37.66</td>
<td></td>
</tr>
<tr>
<td>33.9</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
</tr>
<tr>
<td>28.5</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td></td>
</tr>
<tr>
<td>25.75</td>
<td></td>
</tr>
<tr>
<td>25.5</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
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<td>22.5</td>
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<td>21.9</td>
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<td>20</td>
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<tr>
<td>19.5</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td></td>
</tr>
<tr>
<td>16.5</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
</tr>
<tr>
<td>13.5</td>
<td></td>
</tr>
</tbody>
</table>

(Opposing) Red
(Single Coil) Black
(Solenoid) Yellow
Next 805 MHz study - Buttons

- Button test
  - Evaluate various materials and coatings
  - Quick Change over

Tantalum
Tungsten
Molybdenum-zirconium alloy
Niobium
Niobium-titanium alloy
Stainless steel
The 201 MHz Cavity is now operating tested to design gradient - 16MV/m at B=0 and at B= a few hundred Gauss

Note: This cavity was assembled at TJNL using techniques/procedures used for SCRF
Future Tests of 201 MHz Cavity Operation in Magnetic Field

- Need Coupling Coil (2.5T) MICE design
  - Shown in green schematically
  - THIS IS A CRUCIAL TEST FOR MICE AND FOR NF & MC in general
    - High Gradient RF operation in a magnetic field
High Pressure H$_2$ Filled Cavity Work
Muon’s Inc

- High Pressure Test Cell
- Study breakdown properties of materials in H$_2$ gas
- Operation in B field
  - No degradation in M.S.O.G. up to $\approx 3.5$T

![Diagram of cavity and test cell]

- Cu Data: max gradient 49.9 MV/m
- Mo Data: max gradient 63.8 MV/m
- Be Data: max gradient 52.3 MV/m
- Mo Data: max gradient 65.5 MV/m at B=3T

No Difference B=0 & B=3T

![Graph showing pressure vs. density]
Absorber R&D

- Two LH$_2$ absorber designs are being studied
  - Handle the power load differently
- Also considering LiH (solid) for NF Cooling
Muon Ionization Cooling Experiment (MICE)

**MICE**
Measurement of Muon Cooling Emittance Measurement @ $10^{-3}$
First Beam January 2008

Neutrino Factory Decision Point
≈ 2012
US MICE

- Tracker Module
  - Solenoids
  - Fiber ribbons
  - VLPC System
    - VLPCs, Cryostats and cryo-support equipment, AFEIIIt (front-end readout board), VME memory modules, power supplies, cables, etc
- Absorber Focus Coil Module
  - LH$_2$ and vacuum safety windows
- RF Module
  - Coupling Coils (with ICST of Harbin University, China)
  - RF Cavities
- Particle ID
  - Cerenkov
Design and Simulation
Key Simulation Studies

- **Muon Capture and Bunch Rotation**
  - Uses "standard" cooling components
  - Keeps both $\mu^+$ and $\mu^-$

- **Performance of Open Cell RF lattice**
  - Might mitigate problems with high-gradient RF in B field if not solved in RF R&D program

- **Full optimization of acceleration scheme for NF**
  - Past year spent on International Scoping Study $\rightarrow$ International Design Study for a NF
    - Arrive at Reference Design Report

- **Full simulation and performance evaluation of PIC and REMEX**
- **Complete baseline cooling scheme for a Muon Collider**
- **Acceleration scheme for a Muon Collider**
- **Design of low-beta collider ring**
Acceleration

Dogbone RLA - footprint

$\mu^+$ $\mu^-$

$z$ [cm]

$x$ [cm]

-15000 -10000 -5000 0 5000 10000 15000 20000 25000 30000 35000
NFMCC 5 Year Budget Plan

- Summary of baseline (flat-flat) case is

<table>
<thead>
<tr>
<th>Activity</th>
<th>FY05</th>
<th>FY06</th>
<th>FY07</th>
<th>FY08</th>
<th>FY09</th>
<th>FY10</th>
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<tr>
<td>Cooling</td>
<td>492</td>
<td>345</td>
<td>345</td>
<td>705</td>
<td>615</td>
<td>225</td>
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<td>Targetry</td>
<td>713</td>
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<td>295</td>
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<tr>
<td>MICE</td>
<td>300</td>
<td>620</td>
<td>635</td>
<td>700</td>
<td>790</td>
<td>1280</td>
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<tr>
<td>TOTAL</td>
<td>1700</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
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</table>

Base Program funds: remain as in FY06: BNL ($0.9M); Fermilab ($0.6M); LBNL ($0.3M)

Including Base: About $3.6M per year plus supplemental ($400k in FY06)
Conclusions

- **Neutrino Factory**
  - Compelling case for a precision neutrino program exists
    - With present assumptions Neutrino Factory out-performs other options. However, more is needed before concluding this is the right path
      - What the on-going Neutrino Physics program tells us ($\theta_{13}$)
      - Cost and schedule considerations
  - The collaboration is making excellent progress on R&D on the major sub-systems
    - Targetry – MERIT
    - Muon Cooling – MuCool and MICE
    - Acceleration Design Studies
      - FFAG
        - Also participating in the EMMA experiment in the UK
      - RLA
  - Strong Participation in the recently completed International Scoping Study
    - Move on to the International Design Study
      - Goal is to deliver a RDR by 2012
Conclusions II

- **Muon Collider**
  - New concepts in muon cooling improve the prospects for a multi-TeV Muon Collider
    - Many new ideas emerging
  - Front-end is the same or similar as that for a Neutrino Factory
  - First end-to-end muon cooling scenario for a Muon Collider has been developed

- **Much more to do**
  - Detailed simulation and analysis of cooling designs
    - Space charge and loading effects particularly important in final stages
    - 6D Cooling experiment(s)
      - Converge on a preferred cooling scheme
  - Acceleration
  - Collider ring

- **The NFMCC will work closely with the Fermilab MCTF**
  - **Muon Collider Coordination Group**
    - Kirk, Bross, Zisman, Shiltsev, Geer