THE MUON ACCELERATOR RESEARCH AND DEVELOPMENT PROGRAM

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Gail G. Hanson, University of California, Riverside
On Behalf of the Muon Accelerator Program (MAP)
OUTLINE

• Why A Muon Collider?
• Muon Accelerator Program (MAP)
• Muon Collider Facility
  – Proton Driver
  – Target and Capture
  – Phase Rotation
  – Cooling
  – Acceleration
  – Collider Ring
• Critical Issues
• MuCool Test Area
• Summary and Conclusions
WHY A MUON COLLIDER?

• LHC hints need for higher energy (ILC is 0.5 TeV)

Compare with CLIC

<table>
<thead>
<tr>
<th></th>
<th>$\mu^+\mu^-$</th>
<th>$\mu^+\mu^-$</th>
<th>$e^+e^-$CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>C of m Energy</td>
<td>1.5</td>
<td>3</td>
<td>TeV</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1</td>
<td>4</td>
<td>$10^{34}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Ring &lt;bending field&gt;</td>
<td>6</td>
<td>8.4</td>
<td>T</td>
</tr>
<tr>
<td>Accelerator circ./length</td>
<td>6</td>
<td>12</td>
<td>km</td>
</tr>
<tr>
<td>rms bunch height</td>
<td>6</td>
<td>4</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Proton Driver power</td>
<td>4.</td>
<td>3.2</td>
<td>MW</td>
</tr>
<tr>
<td>Lepton power</td>
<td>7</td>
<td>11</td>
<td>MW</td>
</tr>
<tr>
<td>Wall power</td>
<td>$\approx$147</td>
<td>$\approx$159</td>
<td>MW</td>
</tr>
</tbody>
</table>

• Wall power 1/3 of 3 TeV CLIC, 2/3 of 0.5 TeV ILC
WHY A MUON COLLIDER?

- Large muon mass greatly reduces beamstrahlung
Muon Collider Fits on Fermilab Site

Layout at FNAL

3 TeV

Collider Ring

RCS Accelerator

To scale, but not located
• Of course, much development is still needed.

• The Muon Accelerator Program (MAP), hosted by Fermilab, was formed to coordinate the R&D that had been carried out by the Neutrino Factory and Muon Collider Collaboration (NFMCC) and the Muon Collider Task Force (MCTF) over 10 years.

• A review of the program was held at Fermilab 24-26 August 2010.

• MAP was approved by the U.S. Department of Energy in March 2011.

• Search for a Director is underway.

• URL http://map.fnal.gov/
GOALS OF MAP

• Complete Design Feasibility Study (DFS) Report for a multi-TeV muon collider, including cost range
• Contribute to the International Neutrino Factory Design Study (IDS-NF) to produce a Reference Design Report by 2013
• Carry out supporting technology R&D needed to inform the muon collider DFS and enable down-selection
• Participate in system tests of 4D and 6D cooling – Muon Ionization Cooling Experiment (MICE) and 6D “bench test” (no beam)
• Time scale of 6-7 years
MUON COLLIDER FACILITY

### Scheme

- Project X
- Existing
- Same as Neutrino Factory

#### Options

- * Probably favored
  - Guggenheim
  - HCC
  - Guggenheim + gas
  - Wiggler
  - 40 T solenoids
  - REMX
  - RLA
  - Pulsed Synchrotron
  - FFAG

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More R&D needed to confirm viability and narrow the options

(Palmer)
PROTON DRIVER

• Upgrade of Project X – Task Force
• For Muon Collider, want 4 MW at 8 GeV
• CW SC Linac – 1 mA to 3 GeV – increase to 5 mA pulsed Linac 3-8 GeV
TARGET AND CAPTURE

• Target
  – Successful demonstration experiment – MERIT at CERN PS
  – Mercury jet in a 15 T solenoid

• Capture in 20 T solenoid
  – Shielding and radiation issues being studied
PHASE ROTATION

• Produce, collect, and cool as many muons as possible
• Start with IDS-NF study and reoptimize for collider
  – Shorter bunch train
  – Larger gradients
• Bunch recombiner
**PHASE ROTATION**

- Large $\Delta E$, small $\Delta t \rightarrow$ small $\Delta E$, larger $\Delta t$
- $\approx 48\%$ of longitudinal phase space captured
COOLING

- Since muons decay, need ionization cooling

Transverse (4D)

Longitudinal (6D)

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COOLING

Scheme

Long Emittance (mm)

10^3

10^2

10^1

10.0

1.0

0.1

Trans emittance (mm mrad)

10^2

10^3

2

4

6

8

2

4

5

6

7

8

9

1/3 scale 805 MHz Ring or Guggenheim

Combine → 1 bunch

201 MHz RFOFO Guggenheim

50 m S2a Linear Cooling 200 MHz

1/2 Scale RFOFO Guggenheim 402 MHz

40T Solenoids

Initial

Standard Study, Capture and Phase Rot

20 bunches

NF FRONT END?

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COOLING

• 4D Initial Cooling
  – Based on Neutrino Factory Feasibility Study 2a
  – Vacuum RF (gradients to 18 MV/m)
  – SC solenoids (2 T)
  – LiH absorbers
  – 0.15 $\mu/p$ (each sign)
COOLING

• 6-Dimensional Cooling
  ✷ Tapered Guggenheim (helical RFOFO)
  – Simulated in approximation
  – RF gradient 16 MV/m
  – Maximum magnetic field on axis 2.3 T to 10.6 T
  – Wedge absorbers
  ✷ Other options: Helical FOFO Snake, Helical Cooling Channel
COOLING

• 4D Final Cooling

- 30-40T HTS magnets operating at 4K
- RF cavities and Induction linacs
- LH$_2$ forced-flow absorbers
- Only option that can achieve $\varepsilon_\perp < 25 \ \mu m$ in simulation
ACCELERATION

- Low-energy Acceleration
  - Re-optimize IDS-NF design
  - LINAC and Two RLA’s
  - Exploring dog-bone RLA’s – less costly
ACCELERATION

- Acceleration to High Energy
  - Fast-ramping synchrotron – synchrotrons less expensive than racetracks
  - High average bend field (8 T)
  - Magnets ramped extremely fast -1.8 T to 1.8 T at 400 Hz
COLLIDER RING

• Challenging design criteria (compared with existing colliders):
  – Much larger momentum acceptance with much smaller $\beta^*$
  – As large Dynamic Aperture with much stronger beam-beam effect
  – Very small momentum compaction factor
• Design taking IR’s into account
• Large heat load into magnets in plane of ring due to $\mu$ decays.
CRITICAL ISSUES

1. Operation of high-gradient NCRF in high magnetic fields
   • Needed in capture, bunching, phase rotation, and cooling

805 MHz studies: Maximum stable gradient degrades quickly with magnetic field
CRITICAL ISSUES

• Pursuing multiple studies at Fermilab MuCool Test Area:
  ◇ Reduce/eliminate field emission
    → Process cavities using SCRF techniques
    → Surface coatings – Atomic Layer Deposition
  ◇ Material studies
    → Non-Cu bodies (Al, Be)
  ◇ RF cavities filled with high-pressure gas (H₂)
    → Use Paschen effect to stop breakdown
    → Test underway at Fermilab MuCool Test Area
  ◇ Magnetic insulation
    → Eliminate magnetic focusing
2. Neutrino radiation
   - To stay below Federal limits at 3 TeV need to be well underground – in-depth study needed
   - Incorporate mitigation into ring design
3. R&D on very high field and fast-ramping magnets
4. End-to-end simulation of complete Muon Collider
5. Space charge and wake field questions
6. Successful completion of the Muon Ionization Cooling Experiment (MICE)
**MUOCool TEST AREA AT FERMILAB**

- Component testing: RF, Absorbers, Solenoids with High-Intensity Proton Beam – now taking data!
- Uses MuCool Test Area (MTA) at Fermilab
- Supports Muon Ionization Cooling Experiment (MICE)

**Most Important:** Studying the limits on accelerating gradient in NCRF cavities in high magnetic field

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SUMMARY AND CONCLUSIONS

• Muon Acceleration Program (MAP) approved by U.S. Department of Energy
• The Neutrino Factory Design Study (IDS-NF) Reference Design Report will be completed
• Within 5-6 years we will have a Design Feasibility Study and cost range for a multi-TeV muon collider
• Considerable progress on Muon Collider R&D but many challenges remain!
• Decision on energy for next lepton collider depending on LHC results