The US Muon Collider R&D Program

"Who Ordered That?"

Exploring the Energy Frontier without ever Going Off Site

Alan Bross
Fermilab
Neutrino Factory and Muon Collider R&D in the US

"Two Mints in One?"
When he first heard of the discovery of the muon in 1936, Isidor Rabi asked, "Who ordered that?" At the time, the muon didn't fit into the understanding of the subatomic world.

- We now know better

- When some physicists argue that Muon Accelerator Facilities should (must) play an expanded role in future High Energy Physics Facilities: Neutrino Factory, Muon Collider

- Others question - "Who ordered THAT?"
  - Some of us think we know better
A Bit of History

Since the late 1990s, 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. (Out-growth of Snowmass 96 work on 4TeV $\mu^+\mu^-$ Collider.) 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. In 2006 the Muon Collider Task Force was formed at Fermilab R&D program aimed at the technologies required to support the long term prospects of a Muon Collider.

We now have it all rolled into the Muon Accelerator Program MAP
Outline

My Talk

• Why Muon Accelerator Facilities? *Inspirational*
  - Physics motivation for and nature of possible future facilities based on ultra-high intensity muon beams
  - Explore the synergy between Neutrino Factory and Muon Collider facilities both from the point of view of the physics program and the accelerator complex

• Muon Collider Fundamentals

• What technologies are crucially central to making the above a reality. *Technical R&D Overview*

• Getting Involved

• I hope to give you Overview of our activities but will have to leave out many technical details
  - http://www.fnal.gov/pub/muon_collider/
Physics in Evolution

What we might do at a Muon Accelerator Facility
A \( \mu \) source providing \( 1-2 \times 10^{21} \) \( \mu/yr \) supports a rich physics program:

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

2. **Neutrino Factory**
   - Low Energy 4 GeV
   - High Energy 25 GeV

3. **Energy Frontier Muon Collider**
   - 1.5 - 4 TeV+
     - With maybe a lower Ecom machine (Higgs, Z') first.

From Snowmass 96

PRSTAB 2002
Low-Energy Muon Physics: $\mu \rightarrow e$ conversion

- 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 $10^{-15}$
- Mass Reach to $\approx 4 \times 10^4$ TeV
6D Muon Ionization Cooling

- Increase the Intensity of low energy $\mu$ beam & improve target stopping power
  - Cooling increases 6D particle density
  - Test bed for Muon Ionization Cooling for NF and MC with intense $\mu$ beam

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Neutrino Factory Accelerator Facility

Baseline out of International Scoping Study

- **Proton Driver**
  - 4 MW, 2 ns bunch

- **Target, Capture, Drift** ($\pi \rightarrow \mu$) & Phase Rotation
  - Hg Jet
  - 200 MHz train

- **Cooling**
  - 30 $\pi$mm ($\perp$)
  - 150 $\pi$mm (L)

- **Acceleration**
  - 103 MeV $\rightarrow$ 25 GeV

- **Decay rings**
  - 7500 km L
  - 4000 km L
    - Baseline is race-track design
    - Triangle interesting possibility (C. Prior)

Common to MC & NF

ISS Accelerator WG report: RAL-2007-023
IDS-NF Interim Design Report - imminent

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International Scoping Study
Physics Reach

3σ contours shown


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

Hierarchy

$\delta CP$

SPL: 4MW, 1MT H$_2$OC, 130 km BL
T2HK: 4 MW, 1MT H$_2$OC, 295 km BL
WBB: 2MW, 1MT H$_2$OC, 1300 km BL

NF:  4MW, 100KT MIND, 4000 & 7500 BL
BB350: $\gamma=350$, 1MT H$_2$OC, 730 km BL

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The Neutrino Factory is the facility of choice for the study of neutrino oscillations: it has the best discovery reach; offers the best precision; and, by varying the stored-muon energy, source-detector distance, and perhaps detector technology, it has the flexibility to respond to changes in our understanding of neutrino oscillations and the discovery of new phenomena.
Beyond Filling in the Blanks

- Determine parameters with precision sufficient to determine the structure of the underlying theory
  - Explore very large mass scale
- Beyond the $S_{\nu M}$
  - NSI
  - Sterile $\nu$
  - Mass Varying $\nu$ (MVN)
Sterile $\nu$ and Reactor Experiments

  - Re-evaluation of nuclide decay rates leads to an increase in neutrino flux at reactors
- Observed rate/predicted rate @ near detectors → 0.937 from 0.979
$\nu_e$ disappearance experiment using stored $\mu$ beam

**Looking into ways to do this Soon(ish)**

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The Energy Frontier
Footprint and the Energy Frontier

The VLHC is the largest machine to be seriously considered to date:
- Stage 1 - 40 TeV, \( \sigma > 2 \text{ TeV} \)
- Stage 2 - 200 TeV, \( 3 \sigma > 10 \text{ TeV} \)

Muon Facilities:
- ILC
- CLIC
- LHC

Muon Facilities are different:
- ILC
- CLIC
- LHC

- Stage 1 - 40 TeV
- Stage 2 - 200 TeV
- \( 3 \sigma \text{ TeV} \)
The Energy Frontier via $\mu^+ \mu^-$ Collisions

3 TeV Machine based on Recirculating Linear Accelerators & ILC SC RF

4 TeV Machine based on Rapid Cycling Synchrotron

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## Complexity of Colliders

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>MC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>state of the art magnets</strong></td>
<td>√</td>
<td>√</td>
<td>-</td>
</tr>
<tr>
<td><strong>state of the art RF system</strong></td>
<td>-</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td><strong>state of the art beam dynamics</strong></td>
<td>-</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td><strong>Total # of elements</strong></td>
<td>~4000</td>
<td>~4000</td>
<td>~200,000</td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>&gt;1e34</td>
<td>&gt;1e34</td>
<td>&gt;1e34</td>
</tr>
</tbody>
</table>
Muon Complex Evolution At Fermilab

- Starting with a high-intensity proton source: Project X
  - We see a natural evolution of “muon” program for Fermilab
- Project X → Low-Energy NF (pointing to Homestake) → High-Energy NF → 1.5 TeV MC → 4 TeV MC
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

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Why consider a Muon Collider?

The Supersymmetric Particle Zoo

- Independent of actual supersymmetric mass scale and the reach of the ILC, the 2004 CLIC Study conclusions are still valid
  - “A Multi-TeV machine is needed for extended coverage of the mass range
Snowmass Supersymmetric Benchmark

cMSSM ILC Benchmark

SPS1a' mass spectrum

- $h^0$, $A^0$, $H^0$, $H^\pm$
- $\tilde{t}_l$, $\tilde{t}_2$, $\tilde{b}_1$, $\tilde{b}_2$, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$, $\tilde{\chi}_2^\pm$, $\tilde{\chi}_1^\pm$

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But the Physics Landscape has New Features since 2001

A typical sample “compressed” Higgs and superpartner mass spectrum with $\Omega_{DM} h^2 = 0.11$

An unfortunate feature, quite common to this scenario for dark matter, is that no visible superpartners would be within reach of a linear collider with $\sqrt{s} = 500$ GeV

Also New results from $e^+e^- \rightarrow \pi\pi(\gamma)$ (TAU08)

Strengthener?) Case for considering Multi-TeV Lepton Collider

Stephen Martin
hep-ph/0703097
March, 2007

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Why consider a Muon Collider?

**Precision Energy Scans**

- **Excellent energy resolution**
  - **MC:** 95% luminosity in $\Delta E/E \sim 0.1\%$
  - **CLIC:** 35% luminosity in $\Delta E/E \sim 1\%$

---

**Diagram**

- **3 TeV Muon Collider**
- **3 TeV CLIC**

**Graphs**

- **Beamstrahlung in any e+e- collider**
  - $\delta E/E \propto \gamma^2$

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**CLIC Curves:** Lucie Linssen, SPC, 15/6/2009

- $\mu^+\mu^-$ with ISR + BStr (Eichten)
- $e^+e^-$ with ISR
- $-e^+e^-$ with ISR+BStr

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**Presentation Details**

- **Alan Bross**
- **Food for Thought**
- **March 8, 2011**
U.S. Muon Acceleration R&D Community
History

• **NFMCC (Neutrino Factory & Muon Collider Collab.)**
  - National collaboration funded since 1999.
  - Pursues Neutrino Factory & Muon Collider R&D.
  - NF R&D pursued with international partners

• **MCTF (Muon Collider Task Force)**
  - Task Force established at Fermilab in 2006
  - Pursues Muon Collider R&D, utilizing FNAL assets and extends & complements the NFMCC program

• **MCCC (Muon Collider Coordinating Committee)**
  - Leadership of NFMCC (Bross, Kirk, Zisman) and MCTF (Geer, Shiltsev)
  - Co-ordinates NFMCC & MCTF plans to optimize the overall program ... has worked well and resulted in a joint 5 year plan for future activities.
Oct 1, 2009 letter from Denis Kovar to FNAL Director:

“Our office believes that it is timely to mount a concerted national R&D program that addresses the technical challenges and feasibility issues relevant to the capabilities needed for future Neutrino Factory and multi-TeV Muon Collider facilities. …”

Letter requested a new organization for a national Muon Collider & Neutrino Factory R&D program, hosted at FNAL. Muon Accelerator Program Organization is now in place & functioning: 214 participants at birth from 14 institutions:

- ANL, BNL, FNAL, Jlab, LBNL, ORNL, SLAC, Cornell, IIT, Princeton, UCB, UCLA, UCR, U-Miss

MAP R&D proposal reviewed August 2010 … committee concluded that the “proposed work was very important to the field of high energy physics.”
ORGANIZATION/FUNDING EVOLUTION

First ~10 years

NFMCC
~4 M$

FY07 - FY09

NFMCC + MCTF
~9 M$

Now (FY10/11)

Interim MAP
~10 M$

≥FY11

MAP
~15 M$ (requested)

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March 8, 2011
Muon Collider Design

Emphasis on Cooling
## Parameters of Different MC options

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low Emit.</th>
<th>High Emit.</th>
<th>MCTF07</th>
<th>MCTF08</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (TeV)</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Av. Luminosity ($10^{34}$/cm$^2$/s) *</td>
<td>2.7</td>
<td>1</td>
<td>1.33-2</td>
<td></td>
</tr>
<tr>
<td>Av. Bending field (T)</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Mean radius (m)</td>
<td>361.4</td>
<td>500</td>
<td>500</td>
<td>495</td>
</tr>
<tr>
<td>No. of IPs</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Proton Driver Rep Rate (Hz)</td>
<td>65</td>
<td>13</td>
<td>40-60</td>
<td></td>
</tr>
<tr>
<td>Beam-beam parameter/IP</td>
<td>0.052</td>
<td>0.087</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>$\beta^*$ (cm)</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Bunch length (cm)</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>No. bunches / beam</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>No. muons/bunch ($10^{11}$)</td>
<td>1</td>
<td>20</td>
<td>11.3</td>
<td></td>
</tr>
<tr>
<td>Norm. Trans. Emit. ($\mu$m)</td>
<td>2.1</td>
<td>25</td>
<td>12.3</td>
<td></td>
</tr>
<tr>
<td>Energy spread (%)</td>
<td>1</td>
<td>0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Norm. long. Emit. (m)</td>
<td>0.35</td>
<td>0.07</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Total RF voltage (GV) at 800MHz</td>
<td>$407 \times 10^3 \alpha_c$</td>
<td>0.21**</td>
<td>0.84**</td>
<td>0.3†</td>
</tr>
<tr>
<td>Muon survival $N_{\mu}/N_{\mu0}$</td>
<td>0.31</td>
<td>0.07</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>$\mu^+$ in collision / proton</td>
<td>0.047</td>
<td>0.01</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>8 GeV proton beam power</td>
<td>3.62***</td>
<td>3.2</td>
<td>1.9-2.8</td>
<td></td>
</tr>
</tbody>
</table>

* $\alpha_c$ is the correction factor for the beam-beam parameter.
Muon Collider Facility

Scheme

- Project X
- Existing
- Same as Neutrino Factory
- 8 GeV SC Linac
- Recycler
- Main Injector to 56 GeV
- Buncher
- Hg Target
- 20 T Capture Solenoid
- Phase Rotation to 12 bunches
- Linear Transverse Cooling
- \( \mu^+ \) and \( \mu^- \)
- 6 D Cooling
- Merge 12 to One Bunch
- 6 D Cooling
- Transverse Cooling in 50 T
- Linac
- RLA(s)
- Preliminary Ring Designs
- HE Acceleration
- Collider Ring

Options

- Guggenheim *
- HCC
- Guggenheim + gas Wiggler
- 50 T solenoids *
- REMX
- LEMC
- RLA
- Pulsed Synchrotron *
- FFAG

* Probably favored at this time & used in following slides

The next slide will show the evolution of emittances from production to start of acceleration.

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

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Muon Collider Design Progress

- Muon Collider designs start with a NF front-end, but require a much more ambitious cooling channel (6D cooling ~ $O(10^6)$ c.f. 4D cooling ~ $O(100)$).

- In the last 5 years concepts for a complete end-to-end self consistent cooling scheme have been developed
  - Requires beyond state-of-art components: need to be developed
  - Hardware development and further simulations need to proceed together to inform choices between alternative technologies

- Also progress on acceleration scheme & Collider ring design, but the cooling channel presently provides the main Muon Collider challenge
A Muon Collider Cooling Scenario

Scheme

Long Emittance (mm)

10^3

10^2

10

1.0

0.1

10^2

10

1.0

0.1

2 4 6 8 10

2 4 6 8

10^3

10^4

50-60 T Solenoids (Muons Inc)

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

Standard Study 2a Capture and Phase Rot \rightarrow 20 bunches
Muon Ionization Cooling

Basic Concepts
Muon Ionization Cooling - Transverse

2D Transverse Cooling

\[
d\epsilon_N = -\frac{1}{\beta^2} \frac{dE_\mu}{ds} \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2\beta^3 E_\mu m_\mu L_R}
\]

\[
\epsilon_{N,\text{min}} = \frac{\beta_\perp (14 \text{ MeV})^2}{2\beta m_\mu \frac{dE_\mu}{ds} L_R}
\]

Figure of merit: \( M = L_R \frac{dE_\mu}{ds} \)

\( M^2 \) (4D cooling) for different absorbers

<table>
<thead>
<tr>
<th>Material</th>
<th>( \langle \frac{dE}{ds} \rangle_{\text{min}} ) (MeV g(^{-1})cm(^2))</th>
<th>( L_R ) (g cm(^{-2}))</th>
<th>Merit</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH(_2)</td>
<td>4.103</td>
<td>61.28</td>
<td>1.03</td>
</tr>
<tr>
<td>LH(_2)</td>
<td>4.034</td>
<td>61.28</td>
<td>1</td>
</tr>
<tr>
<td>He</td>
<td>1.937</td>
<td>94.32</td>
<td>0.55</td>
</tr>
<tr>
<td>LiH</td>
<td>1.94</td>
<td>86.9</td>
<td>0.47</td>
</tr>
<tr>
<td>Li</td>
<td>1.639</td>
<td>82.76</td>
<td>0.30</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>2.417</td>
<td>46.22</td>
<td>0.20</td>
</tr>
<tr>
<td>Be</td>
<td>1.594</td>
<td>65.19</td>
<td>0.18</td>
</tr>
</tbody>
</table>

H\(_2\) is clearly Best - Neglecting Engineering Issues Windows, Safety

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Muon Ionization Cooling – Longitudinal Emittance Exchange

Dipole (bend)

$\mu$-beam

Dipole introduces dispersion ($\eta$)

$x \rightarrow x_0 + \eta \frac{dp}{p}$

Wedge Absorber reduces energy spread

---

Figure 1. Use of a Wedge Absorber for Emittance Exchange

Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

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Guggenheim RFOFO - Simulations

Multilayer scheme

- liquid $H_2$
- RF
- solenoid

Pavel Snopok
Helical Cooling Channel

- Magnetic field is solenoid B0+ dipole + quad
- System is filled with H₂ gas, includes rf cavities
- Cools 6-D (large E means longer path length)
- But, incorporating RF is Engineering challenge!
Helical solenoid (HS):
Smaller coils than in a “snake” design
  • Smaller peak field
  • Lower cost
Field components in HS determined by geometry
  • Over constrained
  • Coil radius is not free parameter
4 Coil Demonstration Model
  • Validate mechanical structure and fabrication methods
  • Study quench performance and margins, field quality, quench protection
  • Use SSC conductor

Outer bandage rings

Inner bobbin

Superconducting coils (one layer, hard bend wound)

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Final Cooling

- LH$_2$ absorbers tested in MICE
- 50 T Solenoids
  - The "National Very High Field Superconducting Magnet Collaboration" was formed in the US
    - 2 Year $4M program to study HTS conductor and cable
Alternate Cooling Concepts

"Frictional Cooling"
Muon Cooling With an Inverse Cyclotron

R. Palmer’s ICOOL model

G4beamline model

Terry Hart

VORPAL 3D Simulations with space-charge

Kevin Paul

B_z = 2 T  B_z = -0.5 T

θ

r_{max}

r_{ave}

r_{min}

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Remember that 1/e transverse cooling occurs by losing and re-gaining the particle energy. That occurs every 2 or 3 foils in the frictional channel.
Acceleration
Acceleration - Overview

• RLA: get more passes
  ◆ Ramp linac magnets, get more passes (12)
  ◆ Non-scaling FFAG arcs: get 2 passes per arc, maybe more

• Fast ramping synchrotron (RCS)
  ◆ Potential for many more passes

• FFAG: not studied much as yet for Muon Collider
Acceleration and Collider

- **Acceleration**
- **Rapid acceleration in linacs and RLAs**, <90MW wall plug for 3TeV
- **Lower cost option** – pulsed synchrotrons
- **FFAGs** might also play a role

- **Collider Ring**
  - 1.5 TeV designed
- **To be studied**: Detector background with early dipole scheme
- Dipoles oppose at injection, then act in unison at extraction. Edge focusing changes during the cycle. Can quads correct? Try to simulate focusing with OPTIM.
Addressing the Technological Challenges of The Muon Collider
R&D Program Overview

Indicating some areas common to NF

- High Power Targetry - NF & MC (MERIT Experiment)
- Initial Cooling - NF & MC (MICE (4D Cooling))
- 200 (& 805) MHz RF - NF & MC (MuCool and Muon’s Inc)
  - Investigate RF cavities in presence of high magnetic fields
  - Obtain high accelerating gradients (~15MV/m)
  - Investigate Gas-Filled RF cavities
- Intense 6D Cooling - MC
  - RFOFO “Guggenheim”
  - Helical Channel Cooling
  - Parametric Resonance Ionization Cooling
- Bunch Recombination - MC
- Acceleration- A cost driver for both NF & MC, but in very different ways
  - Multi-turn RLA’s - a BIG cost reducer
  - RCS for MC
  - FFAG's - (EMMA Demonstration)
- Storage Ring(s) - NF & MC
- Theoretical Studies NF & MC
  - Analytic Calculations
  - Lattice Designs
  - Numeric Simulations
**Experiment Completed (CERN)**
- Beam pulse energy = 115kJ
- B-field = 15T
- Jet Velocity = 20 m/s
- Measured Disruption Length = 28 cm
- Required “Refill” time is then 28cm/20m/s = 14ms
  - Rep rate of 70Hz
  - Proton beam power at that rate is 115kJ * 70 = 8MW

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ν-factory (MC) Front End baseline

- Drift - 56.4m
  - B = 2T

- Bunch - 31.5m
  - $P_1 = 280\text{MeV}/c$, $P_2 = 154\text{ MeV}/c$, $\delta n_{rf} = 10$; $V_{rf}$ = 0 to 15 MV/m

- $\phi$-E Rotate - 36m -
  - $V_{rf} = 15\text{MV/m}$, $B = 2T$
  - (240 -> 201.5 MHz)

- Match and cool (80m)
  - Alternating solenoid (2.8T)
  - LiH or $H_2$ absorbers
  - $V_{rf} = 16$, 201.25 MHz

- Obtains $\sim 0.085\,\mu/8\text{GeV}\,p$

Transverse emittance

$\mu/p$ within acceptance

$1.4 \times 10^{21}\,\mu/\text{year}$
MuCool

Component R&D and Cooling Experiment

MuCool

- Component testing: RF, Absorbers, Solenoids
  - With High-Intensity Proton Beam
- Uses Facility @Fermilab (MuCool Test Area - MTA)
- Supports Muon Ionization Cooling Experiment (MICE)

MuCool Test Area

50 cm Ø Be RF window

MuCool LH₂ Absorber Body

MuCool 201 MHz RF Testing

Alan Bross
Food for Thought
March 8, 2011
MuCool has the primary responsibility to carry out the RF Test Program

- Study the limits on Accelerating Gradient in NCRF cavities in magnetic field
- Fundamental Importance to both NF and MC – RF needed in
  - Muon capture, bunching, phase rotation
  - Muon Cooling
  - Acceleration

Arguably the single most critical Technical challenge for the NF & MC
The Basic Problem – B Field Effect

805 MHz Studies

- Data seem to follow universal curve
  - Max stable gradient degrades quickly with B field
- Re-measured
  - Same results

![Graph showing Safe Operating Gradient Limit vs Magnetic Field Level at Window for the three different Coil modes](image)

- >2X Reduction @ required field

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Polaroid Pictures of Field emitters

- Inserting polaroids near the window,
  
- Gives a picture of how the field emitters change with rf field.
  
8.8 - 17.6 MV/m
RF R&D – 201 MHz Cavity Test
Treating NCRF cavities with SCRF processes

• The 201 MHz Cavity – 21 MV/m Gradient Achieved (Design - 16MV/m)
  - Treated at TNJLAB with SCRF processes - Did Not Condition
201 MHz Cavity Running

Flat Cu Windows
TiN coated

Curved Be Windows
TiN coated

Design Gradient

Number of sparks, gradient MV/m and Magnetic field in Tesla

Number of pulses

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The MAP NCRF Program
R&D Strategy

Technology Assessment (continuation of existing multi-pronged program & explore new ideas)

- Surface Processing
  - Reduce (eliminate?) surface field enhancements
    - SCRF processing techniques
      - Electro-polishing (smooth by removing) + HP H₂O rinse
    - More advanced techniques (Atomic-Layer-Deposition (ALD))
      - Smooth by adding to surface (conformal coating @ molecular level)

- Materials studies: Use base materials that are more robust to the focusing effects of the magnetic field
  - Cavity bodies made from Be or possibly Mo

- Magnetic Insulation
  - Inhibit focusing due to applied B

- High-Pressure Gas-filled (H₂) cavities
- Measure transverse (4D) Muon Ionization Cooling
  - 10% cooling - measure to 1% ($10^{-3}$)
- Single-Particle Experiment
  - Build input & output emittance from $\mu$ ensemble
MICE Schedule

MICE Schedule as of March 2010

STEP I
STEP II
STEP III/III.1
STEP IV
STEP V
STEP VI

Run date:
(running now) -> Aug2010

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Progress on MICE

- Beam Line Complete
  - First Beam 3/08
  - Running now
- PID Installed
  - CKOV
  - TOF
  - EM Cal
- First Spectrometer
  - Jan 2012

Fiber Tracker

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Muon Collider Machine-Detector Interface

If a Multi-TeV Muon Collider is built
Can a detector be designed that will do the physics?
Muons Collider Detector Issues

Shielding Backgrounds

- MC detector backgrounds studied actively 10 years ago (1996-1997).
  - Large background from decay electrons

- Shielding strategy
  - Electron “sweeping” & IP shielding high-Z cone

- New studies have advanced our understanding and show that this strategy can work extremely well.
  - Note: Tungsten cone in forward direction with angle 10°
    - CLIC detector uses 7° cone

MARS simulation - 1.5 TeV MC

Total dose in Si detector $\approx \frac{1}{2}$ that at LHC @ $L=10^{34}$
Background Levels

- Detailed shielding design done plus background simulations using two codes (MARS & GEANT) → consistent results. Tungsten cone in forward direction with angle 20° (c.f. CLIC = 7°).
  - With modern detector technologies, perhaps angle can be reduced & tungsten can be instrumented.
- Hit densities at, r=5cm are 0.2 hits/mm². Comparable to CLIC estimates. Also, ideas on how to further reduce hits by x100.
- SYNERGY with CLIC Detector R&D and design studies.
  - LHC Detector Technologies
SiD ILC detector in the muon collider framework
MUON COLLIDER 2011
PHYSICS - DETECTORS - ACCELERATORS

June 27-July 1, 2011
The Peaks Resort, Telluride, Colorado

http://conferences.fnal.gov/muon11/
The Way Forward

Road “MAP”
MAP 6 Year Program

- **US Program**
  - A measured program based on the solid muon accelerator R&D achievements of the last decade
  - Sufficiently ambitious to make substantial progress before the next round of long-term decisions by the particle physics community
  - Includes accelerator, physics & detector studies - The physics & detector studies will be in a separate proposal.

- **Meets our existing commitments (NF-RDR, MICE) and in addition will deliver:**
  - MC performance requirements based on physics
  - A first end-to-end MC simulation
  - Critical component development & proof-of-principle experiments
  - A first MC cost estimate
Muon Collider Design
Feasibility Study

MUON COLLIDER PROPOSAL

NOW  PROPOSED MC-DFS
End of 6 Year Program

1. Basic Idea
2. Technical Concept
3. Component R&D
4. Early sub-system Bench Tests
5. Semi-realistic sub-systems
6. Sub-System Beam Tests
7. System Prototype

Target & Dump
Bunch / Phase
Initial Cooling
6D Cooling
Final Cooling
Pre-Acceleration
Acceleration
Ring
Not Quite Getting There
Luminosity vs. Cooling

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Participation
MAP has a diverse and very rich R&D Program

- **Technology Development**
  - High gradient RF - MuCool
    - SC also for the accelerators
  - Very-high field magnets - HTS development
  - High-power targetry

- **System Tests**
  - MICE
    - Much more scientific effort is needed on MICE
      - Hardware
        - RF, Magnet systems
      - Online systems
        - Monitoring/data quality
      - Software development
        - Reconstruction
        - Data Analysis
  - Planning for follow-on experiment to MICE
    - High-power 6D cooling demonstration

- **Accelerator systems simulation work**
  - Capture, Cooling, Acceleration, Collider

- **Machine-Detector Interface**

- **Detector simulations**
Where are we headed?

• We believe ~2013 will be a pivotal time in HEP
  ◆ LHC Physics Results
  ◆ Neutrino Data from Reactor and Accelerator Experiments
    ♦ Double Chooz Daya Bay
    ♦ MINOS, T2K, Nova
  ◆ Major Studies for Frontier Lepton-Colliders Completed
    ♦ ILC EDR
    ♦ CLIC CDR

• There are likely to be many exciting results – Will point us in Some Direction
  ◆ We Don’t Know Which One Yet, But the NF and/or the MC may be part of our future
Acknowledgments

I want to thank all my colleagues in the Neutrino Factory and Muon Collider Collaboration and the Fermilab Muon Collider Task force for all the hard work and for the many conversations I have had with them on this subject.

In particular I want to thank Bob Palmer, Steve, Geer, Vladimir Shiltsev and Mike Zisman