Muon Cooling and Future Muon Facilities

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Outline:

1. Muon Colliders
2. Neutrino Factories
3. Muon Cooling
4. MERIT, MICE, MANX, EMMA
5. Summary
Why Muon Colliders?

• A pathway to high-energy lepton colliders
  – unlike $e^+e^-$, $\sqrt{s}$ not limited by radiative effects
  $\Rightarrow$ a muon collider can fit on existing laboratory sites even for $\sqrt{s} > 3$ TeV:
Why Muon Colliders?

• A pathway to *high-energy* lepton colliders
  – unlike $e^+ e^-$, $\sqrt{s}$ not limited by radiative effects

$\Rightarrow$ a muon collider can fit on existing laboratory sites even for $\sqrt{s} > 3$ TeV:

• Also...
Why Muon Colliders?

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  – unlike $e^+e^-, \sqrt{s}$ not limited by radiative effects
  $\Rightarrow$ a muon collider can fit on existing laboratory
  sites even for $\sqrt{s} > 3$ TeV:

- E.g., $\mu\mu$-collider resolution can separate
  near-degenerate scaler and pseudo-scalar
  Higgs states of high-$\tan\beta$ SUSY

• Also...
  $s$-channel coupling of Higgs to lepton
  pairs $\propto m_{\text{lepton}}^2$
Why a Neutrino Factory?

- Neutrino mixing raises fundamental questions:

1. What is the neutrino mass hierarchy?

   - "natural"
   - "inverted"

   \[ \nu_3 \quad \nu_2 \quad \nu_1 \]
   \[ \nu_2 \quad \nu_1 \quad \nu_3 \]

   OR?

2. Why is pattern of neutrino mixing so different from that of quarks?

   CKM matrix:
   \[ \begin{align*}
   \theta_{12} &\equiv 12.8^\circ \\
   \theta_{23} &\equiv 2.2^\circ \\
   \theta_{13} &\equiv 0.4^\circ
d\end{align*} \]

   (hierarchical & nearly diagonal)

   PMNS matrix:
   \[ \begin{pmatrix}
   \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin \theta_{13} e^{i\delta} \\
   \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\
   \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2}
d\end{pmatrix} \]

   \[ \begin{align*}
   \theta_{12} &\equiv 30^\circ \text{ (solar)} \\
   \theta_{23} &\equiv 45^\circ \text{ (atmospheric)} \\
   \theta_{13} &< 13^\circ \text{ (Chooz limit)}
d\end{align*} \]

3. How close to zero are the small PMNS parameters \( \theta_{13}, \delta \)?

   \[ \rightarrow \text{ are they suppressed by underlying dynamics? symmetries?} \]
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   \end{pmatrix} \]

→ are they suppressed by underlying dynamics? symmetries?

• These call for a program to measure the PMNS elements as well as possible.
Neutrino Factory Physics Reach

- Neutrino Factory is most sensitive technique yet devised
  see e.g. M. Lindner, hep-ph/0209083
  & C. Albright et al., Fermilab-FN-692 (2000)

CP-sensitivity comparison $\rightarrow$

Oscillation-parameter comparison $\downarrow$

(plots from A. Blondel, NO-VE Workshop, Venice, Dec. 03)
Muon Facility Examples:

- Neutrino Factory:

  (Feasibility Study-II)

  - Induction linac No.1
    - 100 m
    - drift 20 m
  - Induction linac No.2
    - 80 m
    - drift 30 m
  - Induction linac No.3
    - 80 m
  - recirculator Linac
    - 2 – 20 GeV
  - proton driver
  - target
  - mini–cooling
    - 3.5 m of LH , 10 m drift
  - bunching 56 m
  - cooling 108 m
  - Linac 2 GeV
  - storage ring
    - 20 GeV
  - neutrino beam
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  neutrino beam

- $\mu^+\mu^-$ collider:

  proton driver

  target

  mini–cooling
  3.5 m of LH, 10 m drift

  bunching 56 m

  cooling 108 m

  Linac 2 GeV

  2.5 km Linear Collider Segment

  storage ring
  20 GeV

  $\mu^+$ postcoolers/preaccelerators $\mu^-$

  2.5 km Linear Collider Segment

  $\mu^+$

  IR

  5 TeV $\mu^+\mu^-$ Collider
  1 km radius, $<L>\sim 5E34$

  IR

  H

  C

  C

  Tgt

  300 kW proton driver

  10 arcs separated vertically in one tunnel

(Muons, Inc. version)
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  20 GeV

- Common features:

  1. $p$ on tgt $\rightarrow \pi \rightarrow \mu$, collected in focusing channel

  2. $\mu$ cooling, acceleration, & storage

     – then:

     3. neutrino beam via $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ – or – $\mu^+\mu^-$ collisions

- $\mu^+\mu^-$ collider:

  
  (Muons, Inc. version)
“A Brief History of Muons”

• Muon storage rings are an old idea:
  – Charpak et al. \((g-2)\) (1960), Tinlot & Green (1960), Melissinos (1960)

• Muon colliders suggested by Tikhonin (1968)

• But no concept for achieving high luminosity until ionization cooling
  – O’Neill (1956), Lichtenberg et al. (1956),
  applied to muon cooling by Skrinsky & Parkhomchuk (1981), Neuffer (1983)

• Realization (Neuffer and Palmer) that a high-luminosity muon collider might be feasible stimulated series of workshops & formation (1995) of Neutrino Factory and Muon Collider Collaboration
  – has since grown to 47 institutions and >100 physicists

• Snowmass Summer Study (1996)
  – study of feasibility of a 2+2 TeV Muon Collider [Fermilab-conf-96/092]


• See also:
  – Neutrino Factory Feasibility Study I (2000) and II (2001) reports;
  – Recent Progress in Neutrino Factory and Muon Collider Research within the Muon Collaboration, Phys. Rev. ST Accel. Beams 6, 081001 (2003);
  – APS Multidivisional Neutrino Study, www.aps.org/neutrino/ (2004);
  – Recent innovations in muon beam cooling, AIP Conf. Proc. 821, 405 (2006);
Muon Cooling – The Challenge:

$$\tau_\mu = 2.2 \ \mu s$$

Q: What cooling technique works in microseconds?
A: There is only one, and it works only for muons:
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Ionization Cooling:

A. N. Skrinsky and V. V. Parkhomchuk, Sov. J. Part. Nucl. 12, 223 (1981)

→ A brilliantly simple idea!
Ionization Cooling:

- Two competing effects:
  
  - Absorbers:
    $$ E \rightarrow E - \left\langle \frac{dE}{dx} \right\rangle \Delta s $$
    $$ \theta \rightarrow \theta + \theta_{\text{rms}} $$

  - RF cavities between absorbers replace $\Delta E$

- Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

$$ \frac{d\epsilon_N}{ds} = - \frac{1}{\beta^2} \left\langle \frac{dE_\mu}{ds} \right\rangle \epsilon_N + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2 \beta^3 E_\mu m_\mu X_0} $$
Ionization Cooling:

- Two competing effects:
  
  - Absorbers: \[
  E \rightarrow E - \left< \frac{dE}{dx} \right> \Delta s \\
  \theta \rightarrow \theta + \theta_{\text{rms}} \text{space}
  \]

  - RF cavities between absorbers replace \( \Delta E \)

  - Net effect: reduction in \( p_\perp \) at constant \( p_\parallel \), i.e., transverse cooling

  \[
  \frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2} \left< \frac{dE_\mu}{ds} \right> \epsilon_N + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2\beta^3 E_\mu m_\mu X_0}
  \]

  \( \Rightarrow \) want strong focusing, large \( X_0 \) (low \( Z \)), and low \( E_\mu \)

→ How can this be achieved...?
E.g., Double-Flip Cooling Channel
V. Balbekov & D. Elvira (FNAL)

• To get low $\beta \rightarrow$ big S/C solenoids & high fields!

⇒ expensive
• Various lattice designs have been studied:

   - Alternating Solenoid
     \[ B_z(\text{max}) = 3.4 \ (\text{T}) \]
     \[ \frac{dB_z}{dz(\text{max})} = 15 \ (\text{T/m}) \]

   - FOFO
     \[ B_z(\text{max}) = 3.4 \ (\text{T}) \]
     \[ \frac{dB_z}{dz(\text{max})} = 9.4 \ (\text{T/m}) \]

   - Super FOFO
     \[ B_z(\text{max}) = 2.6 \ (\text{T}) \]
     \[ \frac{dB_z}{dz(\text{max})} = 7 \ (\text{T/m}) \]

→ Alternating gradient allows low \( \beta \) with much less superconductor
Example: APS 6-Month Neutrino Study Cooling Channel

COOLING LATTICE

- SC coil: 106 A/mm²
- rf cavity: 201.25 MHz
- 15.25 MV/m
- LiH 1 cm⁻¹
- Be 25 m
- (Absorbers integrated with cavity windows)

R. Palmer (BNL) et al.

Magnetic Field on axis

Cooling channel (80 m)

±2.8 T

11-May-2004
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**Performance:**

- Magnetic Field on axis
  - $B_z$ component
  - Cooling channel (80 m)
  - ±2.8 T

- Graphs showing $\varepsilon_T$ and $\mu/p$ with specified values:
  - $\varepsilon_T$: 15.0 and 7.1
  - $\mu/p$: 0.176 and 0.10

R. Palmer (BNL) et al.
Example: APS 6-Month Neutrino Study Cooling Channel

COOLING LATTICE

- SC coil: 106 A/mm²
- rf cavity: 201.25 MHz
- LiH 1 cm
- Be 25 µm
  (Absorbers integrated with cavity windows)

μ beam

±2.8 T

Cooling channel (80 m)

Performance:

→ 80m “FS2a” cooling channel shrinks $\epsilon_T \times 7.1/15.0 \approx 0.5$, & increases $\mu/p$-on-tgt $\times 0.176/0.10 \approx 1.8$
**Example: APS 6-Month Neutrino Study Cooling Channel**

- **Performance:**

  \[ \varepsilon_T \times 7.1/15.0 \approx 0.5, \]
  & \[ \mu/p \text{-on-tgt} \times 0.176/0.10 \approx 1.8 \]

  \( \Rightarrow \) Cost-effective for NF
**Longitudinal Cooling?**

- Transverse ionization cooling self-limiting due to longitudinal-emittance growth, leading to particle losses
  - caused e.g. by straggling plus finite $dE$ acceptance of cooling channel
  $\Rightarrow$ need longitudinal cooling for muon collider; could also help for νF

- Possible in principle by ionization (at momenta above ionization minimum), but inefficient due to straggling and small slope $d(dE/dx)/dE$

$\rightarrow$ *Emittance-exchange* concept:

- Promising paper designs exist, e.g.,...
Recent work by R. Johnson, Ya. Derbenev, et al. (Muons, Inc.) points to possibility of cooling + emittance exchange in helical focusing channel (solenoid + rotating dipole and quadrupole) filled with dense low-Z gas or liquid.
Helical Cooling Channel Performance example:

- Transverse emittance (rad m)
- Longitudinal emittance (m)
- 6-Dimensional emittance (m³)

(Muons, Inc.)
Helical Cooling Channel Performance example:
(Muons, Inc.)

- $10^5$ 6D-emittance reduction in 160 m
- Ideas for further cooling under investigation
- Suggests feasibility of cooling muons well enough to accelerate them in ILC cavities!
- Muon Collider could be ILC energy upgrade
Helical Cooling Channel Performance example:

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→ International Lepton Collider!
Ongoing Studies

- **International Scoping Study:**
  - year-long international (Europe, Japan, US) study spearheaded by UK
  - launched at NuFact05 Workshop (Frascati, Italy)
  - results to be reported at NuFact06 Workshop (Irvine, CA, August ’06)
  - goals: evaluate the physics case for a future neutrino facility along with options for the accelerator complex and detectors
  - intended to lead to international, multi-year design study
  - website: http://www.hep.ph.ic.ac.uk/iss/

- **Muon Collider Task Force:**
  - group based at Fermilab holding regular meetings to explore options for a Muon Collider

- **Also ongoing program of hardware prototyping and testing by Neutrino Factory and Muon Collider Collaboration, e.g.,...**
RF Cavity R&D
(ANL, LBNL, FNAL, IIT, JLab, UMiss)

- Muon Cooling calls for high-gradient, moderate-frequency, normal-conducting RF cavities operable in high focusing magnetic fields
- Tests in progress at MuCool Test Area (MTA) near Fermilab Linac with full-scale and 1/4-scale closed-cell (pillbox) cavities (with novel Be windows)

Feasibility Demonstrations:

1. Multi-MW targets: MERIT @ CERN nTOF facility
2. Transverse ionization cooling: MICE @ RAL ISIS synchrotron
3. 6D helical cooling: MANX proposal
4. Non-scaling FFAG acceleration: EMMA @ DL
**MERIT (MERcury Intense Target):**

H. Kirk (BNL), K. McDonald (Princeton), et al.

- Proof-of-principle demonstration of Hg-jet target for 4-MW proton beam, contained in a 15-T solenoid for maximal collection of soft secondary pions

**BNL E-951 (2001)  MERIT cutaway view:**

- **Key parameters:**
  - 24-GeV $p$ beam, $\leq 8$ bunches/pulse, up to $7 \times 10^{12} p$/bunch
  - $\sigma_r$ of proton bunch = 1.2 mm, beam axis at 67 mrad to magnet axis
  - Hg jet of 1 cm diameter, $v = 20$ m/s, jet axis at 33 mrad to magnet axis
  - Each proton intercepts the Hg jet over 30 cm = 2 interaction lengths

**Timetable:**

- 2003: LOI’s to CERN and JPARC
- 2004: Proposal to CERN; contract let to fabricate 15-T LN$_2$-cooled NC magnet
- 2005: MERIT approved by CERN
- 2006: Commission magnet at MIT
  - Fabricate mercury delivery system and test with magnet at MIT
  - Fabricate cryogenic system
- 2007: Install experiment at CERN (nTOF area) and run
MICE (Muon Ionization Cooling Experiment)
A. Blondel (U. Genève), M. S. Zisman (LBNL), et al. (www.mice.iit.edu)

• **Goals:**

1. show feasibility of cooling channel giving desired performance for a Neutrino Factory;
2. operate in $\mu$ beam, measure performance in various modes and beam conditions.

• **Large international, interdisciplinary collaboration:**
  - $>100$ particle and accelerator physicists and engineers from Belgium, Bulgaria, China, Italy, Japan, Netherlands, Russia, Switzerland, UK, USA
Avatars of MICE

- Measurement precision relies crucially on precise calibration & thorough study of systematics:

  **Phase 1** (fully funded)
  - 2007: Characterize beam
  - 2008?: Intercalibrate Spect. 2 w.r.t. Spect. 1; demonstrate 0.1% emittance measurement
  - Phase 2 (in negotiation)
  - 2009?: Cooling study w/ 1/2 lattice cell
  - 2009?: Cooling study w/ full lattice cell & realistic field flip
• Proposed follow-on to MICE:
  – insert LHe-filled helical-channel segment between MICE spectrometers

• Obtain large cooling factor (~0.5) in few m using graded $B$ fields to match decreasing $p_\mu$

• Optimization under study

• Proposal submitted to Fermilab (May 2006) to design and build helical magnet
**EMMA (Electron Model of Muon Accelerator)**

R. Edgecock (RAL) et al.

- APS Neutrino Study FS2a proposed novel, non-scaling FFAG for muon acceleration
  - constant $B$ field allows rapid acceleration
  - “out”- + “in”-bends give large momentum acceptance
  - new idea: “stochastic” acceleration between buckets
  - costs seem lower than RLA or scaling FFAG

- Proof of principle demo proposed at Daresbury

- International collaboration

- Have completed:
  - lattice design
  - tracking studies
  - hardware specs
  - hardware outline design
  - costing

- Funding:
  - UK Basic Technology program
  - 2 rounds; “highly ranked” in 1st
  - 2nd round: submitted 27th July
  - funding hoped ~ start 2007
  - 1st beam before end 2009
Outlook

Crystal ball slightly hazy, but...
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Crystal ball slightly hazy, but...

- Around 2010, should know
  - whether ∃ low-mass Higgs &/or SUSY
    ⇒ whether ILC will proceed
  - cost & feasibility of ν Factory & μ Collider

- Will be ready to proceed with final design & construction of one or both of these muon facilities

- Each appears to be considerably cheaper than ILC

- Either or both could be operational before 2020
Summary

• Muon storage rings are potentially a uniquely powerful option for future HEP facilities

• After much R&D, muon cooling looks feasible
  – both in transverse and longitudinal phase planes

• Coming demonstration experiments should establish this by ~2010

• New techniques could yield muon emittances comparable to ILC values

• Future looks bright for muon colliders and neutrino factories!
Some 6D Cooling Approaches

"Tetra" ring (Balbekov)
Bending magnet: R=52 cm
field : B=1.4548
RF freq = 198.5 MHz
RF gradV= 18.0 MV/m
Hard edge, classic solen field

"Guggenheim" version (Klier)

The Two Cell Dipole only Ring
(Garren & Kirk)

RFOFO Ring Performance:

RFOFO ring (Palmer)
After cooling $\times \sim 10^5$ by series of helical channels ($\sim 10^2$ m), can cool beam further with 2 new approaches:

- Parametric-resonance Ionization Cooling (PIC)

- Reverse Emittance Exchange (REMEX):
Cavity R&D Results

Failure of atomic bonds in metal

Failure at defects

Failure of large, ‘dirty’ samples

Cu windows

Hassanein et al.
Pressurized vs. Vacuum Cavities
(FNAL, IIT, Muons Inc.)

- Solenoidal $B$-field demonstrated to degrade vacuum-cavity performance

![Graph showing pressure vs. density with data points for different materials (Cu, Mo, Be, Mo at B=3T) and gradient values.]

- Pressurizing the cavity helps! (Paschen effect)