Muon Cooling and Future Muon Facilities

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Joint Meeting of Pacific Region Particle Physics Communities (DPF2006 & JPS 2006)
Sheraton Waikiki Hotel, Honolulu, HI
29 October – 3 November, 2006
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

⇒ 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?

- 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:

  - 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 $\propto m^2_{\text{lepton}}$
Why a Neutrino Factory?

- Neutrino mixing raises fundamental questions:

1. What is the neutrino mass hierarchy?
   - “natural”
     - $\nu_3$
   - “inverted”
     - $\nu_2$
   - OR?
     - $\nu_1$
     - $\nu_3$

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

   - CKM matrix:
     - $\theta_{12} \approx 12.8^\circ$
     - $\theta_{23} \approx 2.2^\circ$
     - $\theta_{13} \approx 0.4^\circ$
     - hierarchical & nearly diagonal

   - PMNS matrix:
     - $\theta_{12} = 30^\circ$ (solar)
     - $\theta_{23} = 45^\circ$ (atmospheric)
     - $\theta_{13} < 13^\circ$ (Chooz limit)

   $\begin{pmatrix}
   \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin \theta_{13} e^{i\delta} \\
   \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\
   \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2}
   \end{pmatrix}$

3. How close to zero are the small PMNS parameters $\theta_{13}, \delta$?
   - → are they suppressed by underlying dynamics? symmetries?
Why a Neutrino Factory?

• Neutrino mixing raises fundamental questions:

1. What is the neutrino mass hierarchy?

   “natural”………………………………………………………………………………………………………………………………………………………
   \[ \nu_3 \hspace{1cm} \nu_2 \hspace{1cm} \nu_1 \]

   “inverted”……………………………………………………………………………………………………………………………………………………
   \[ \nu_1 \hspace{1cm} \nu_2 \hspace{1cm} \nu_3 \]

   OR?

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

   CKM matrix: \( \theta_{12} \approx 12.8^\circ \), \( \theta_{23} \approx 2.2^\circ \), \( \theta_{13} \approx 0.4^\circ \) (hierarchical & nearly diagonal)

   PMNS matrix: \( \theta_{12} = 30^\circ \) (solar), \( \theta_{23} = 45^\circ \) (atmospheric), \( \theta_{13} < 13^\circ \) (Chooz limit)

   \[ \begin{pmatrix} \approx \frac{\sqrt{2}}{2} & \approx -\frac{\sqrt{2}}{2} & \sin \theta_{13} \ e^{i\delta} \\ \approx 1/2 & \approx 1/2 & \approx -\frac{\sqrt{2}}{2} \\ \approx 1/2 & \approx 1/2 & \approx \frac{\sqrt{2}}{2} \end{pmatrix} \]

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

   \( \rightarrow \) 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 ➔

Oscillation-parameter comparison ↓

(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

  neutrino beam
  storage ring
  20 GeV
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- $\mu^+\mu^-$ collider:

  proton driver

  target
  mini–cooling
  3.5 m of LH, 10 m drift

  bunching 56 m
  cooling 108 m

  Linac 2 GeV

  storage ring
  20 GeV

  300kW proton

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

  2.5 km Linear Collider Segment

  10 arcs separated vertically in one tunnel

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

  (Muons, Inc. version)
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  neutron beam

- 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)

  5 TeV $\mu^+\mu^-$ Collider
  1 km radius, $<L> \sim 5 \times 10^{34}$

  2.5 km Linear Collider Segment
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  $\mu^+ \leftarrow$ postcoolers/preaccelerators $\mu^-$

  storage ring
  20 GeV

  target
  mini-cooling
  3.5 m of LH, 10 m drift
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  proton driver

  10 arcs separated vertically in one tunnel

  300kW proton driver

  Tgt

  H C C
“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

- 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?
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A: There is only one, and it works only for muons:
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**Ionization Cooling:**

\[ \mu \rightarrow \frac{\text{d}E}{\text{d}x} \rightarrow \frac{\text{d}E}{\text{d}x} \rightarrow \frac{\text{d}E}{\text{d}x} \rightarrow \text{r.f.} \rightarrow \text{r.f.} \rightarrow \text{r.f.} \]

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

→ A brilliantly simple idea!
Ionization Cooling:

- Two competing effects:
  
  - Absorbers:
    \[ E \to E - \langle \frac{dE}{dx} \rangle \Delta s \]
    \[ \theta \to \theta + \theta_{\text{rms}} \]

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

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

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

- Two competing effects:

- Absorbers:
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\[
\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2} \langle \frac{dE_\mu}{ds} \rangle \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2\beta^3 E_\mu m_\mu X_0} \Rightarrow \text{want strong focusing, large } X_0 \text{ (low } Z), \text{ and low } E_\mu
\]

→ 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**
  - $B_z(\text{max}) = 3.4$ (T)
  - $\frac{dB_z}{dz(\text{max})} = 15$ (T/m)

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

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

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

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

- Performance:

  - SC coil: 106 A/mm²
  - rf cavity: 201.25 MHz
  - 15.25 MV/m
  - LiH 1 cm³
  - Be 25 μm
  - (Absorbers integrated with cavity windows)
  - ±2.8 T
  - Cooling channel (80 m)

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

- **Performance:**

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

- **Performance:**

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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
  ⇒ 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 $d(dE/dx)/dE$

→ Emittance-exchange concept:

- Promising paper designs exist, e.g.,...
Some 6D Cooling Approaches

"Tetra" ring (Balbekov)

The Two Cell Dipole only Ring (Garren & Kirk)

RFOFO ring (Palmer)

"Guggenheim" version (Klier)

RFOFO Ring Performance:

![Graph showing ring performance with different window types](image_url)
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:

\( \lambda = 1.0 \text{ m} \quad \lambda = 0.8 \text{ m} \quad \lambda = 0.6 \text{ m} \quad \lambda = 0.4 \text{ m} \)

Transverse emittance (rad m)

Longitudinal emittance (m)

6-Dimensional emittance (m^3)

z (m)
Helical Cooling Channel Performance example:

\( \lambda = 1.0 \text{ m} \quad \lambda = 0.8 \text{ m} \quad \lambda = 0.6 \text{ m} \quad \lambda = 0.4 \text{ m} \)

- \(10^5\) 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:

- $10^5$ 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

→ International Lepton Collider!
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):
Ongoing Studies

• International Scoping Study:
  – year-long international (Europe, Japan, US) study spearheaded by UK
  – launched at NuFact05 Workshop (Frascati, Italy
  – goals: evaluate the physics case for a future neutrino facility along with options for the
    accelerator complex and detectors)
  – results shown at NuFact06 Workshop (Irvine, CA, August ’06)
  – written report in progress
  – 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)

Prototype 201-MHz cavity

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

**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 ($n$TOF 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 μ 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)**
  
  - **STEP I: 2007**
    - Characterize beam
    - Calibrate Spect. 1
  
  - **STEP II**
    - Intercalibrate Spect. 2 w.r.t. Spect. 1; demonstrate 0.1% emittance measurement
  
  - **STEP III**
    - Study 1st abs./focus-coil pair; check dE/dx and scattering
  
  - **STEP IV: 2008**
    - Cooling study w/1/2 lattice cell
  
  - **STEP V**
    - Cooling study w/full lattice cell & realistic field flip
  
  - **STEP VI**

- **Phase 2 (in negotiation)**
  
  - **STEP I: 2007**
    - Characterize beam
    - Calibrate Spect. 1
  
  - **STEP II**
    - Intercalibrate Spect. 2 w.r.t. Spect. 1; demonstrate 0.1% emittance measurement
  
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  - **STEP VI**
MANX (Muon collider And Neutrino factory eXperiment)

R. Johnson (Muons, Inc.) et al.

- 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...
Outlook

Crystal ball slightly hazy, but...

• Around 2010, should know
  – whether $\exists$ low-mass Higgs &/or SUSY
    ⇒ whether ILC will proceed
  – cost & feasibility of $\nu$ Factory & $\mu$ 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!
Pressurized vs. Vacuum Cavities
(FNAL, IIT, Muons Inc.)

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

- Pressurizing the cavity helps! (Paschen effect)