Low Emittance Muon Colliders

Rolland Johnson,
Muons, Inc.

In February, Muons, Inc. and the Fermilab TD sponsored the second annual low-emittance muon collider workshop at Fermilab (~85 participants). Muon Colliders are looking more feasible. Synergies with the ILC and Neutrino Factories can be important.

Papers can be found at http://www.muonsinc.com
workshop link is at http://www.muonsinc.com/mcwfeb07/ also see http://www.muonsinc.com/mcwfeb06/presentations/LEMCWorkshop.pdf
Related Muon Work at PAC07

MOPAS012 - Magnets for the MANX Cooling Demonstration Experiment
  V. Kashikhin...

MOPAN117 - Magnet Systems for Helical Muon Cooling Channels
  S. A. Kahn...

MOPAN118 - High Field HTS Solenoid for Muon Cooling
  S. A. Kahn...

WEPMS071 - Evidence for Fowler-Nordheim behavior in RF Breakdown
  M. BastaniNejad...

THPAN103 - G4BeamLine Program for Matter-dominated Beam Lines
  T. J. Roberts...

THPMN096 - Stopping Muons Beams
  M. A. C. Cummings...

THPMN110 - Design of the MANX 6D Demonstration Experiment
  K. Yonehara...

THPMN094 - Simulations of Parametric-resonance Ionization Cooling
  D. Newsham...

THMNN095 - Muon Bunch Coalescing
  R. P. Johnson...

THPMN106 - Use of Harmonic RF Cavities in Muon Capture for NFs or MCs
  D. Neuffer...
New inventions, new possibilities

- Muon beams can be cooled to a few mm-mr (normalized)
  - allows HF RF (implies Muon machines and ILC synergy)

- Muon recirculation in ILC cavities => high energy, lower cost
  - Each cavity used 10 times for both muon charges
  - Potential 20x efficiency wrt ILC approach offset by
    - Muon cooling
    - Recirculating arcs
    - Muon decay implications for detectors, magnets, and radiation

- A low-emittance high-luminosity collider
  - high luminosity with fewer muons
  - First LEMC goal: $E_{\text{com}} = 5 \text{ TeV}, <L> = 10^{35}$
  - Revised goal is 1.5 TeV to complement the LHC

- Many new ideas in the last 5 years. A new ball game!
  - (many new ideas have been developed with DOE SBIR-STTR funding)
Muons, Inc. SBIR/STTR Collaboration:

- Fermilab:
  - Victor Yarba, Ivan Gonin, Timer Khabiboulline, Gennady Romanov, Daniele Turrioni
  - Dave Neuffer
  - Mike Lamm
  - MCTF-APC, V. Shiltsev, S. Geer, A. Jansson, M. Hu, D. Bromelsiek, Y. Alexehin, ...
  - Chuck Ankenbrandt, Katsuya Yonehara
  - Milorad Popovic, Al Moretti, Jim Griffin
  - Sasha Zlobin, Emanuela Barzi, Vadim Kashikhin, Vladimir Kashikhin

- IIT:
  - Dan Kaplan, Linda Spentzouris

- JLab:
  - Yaroslav Derbenev, Alex Bogacz, Kevin Beard, Yu-Chiu Chao, Robert Rimmer

- Muons, Inc.:
  - Rolland Johnson, Bob Abrams, Mohammad Alsharo’a, Mary Anne Cummings, Stephen Kahn, Sergey Korenev, Moyses Kuchnir, David Newsham, Tom Roberts, Richard Sah, Cary Yoshikawa (underlined are new-3 are from Lucent)

First named are subgrant PI.
Recent Inventions and Developments

- **New Ionization Cooling Techniques**
  - Emittance exchange with continuous absorber for longitudinal cooling
  - Helical Cooling Channel (HCC)
    - Effective 6D cooling (simulations: cooling factor > 50,000 in 160 m)
  - Momentum-dependent Helical Cooling Channel
    - 6D Precooling device (e.g. stopping muon beams)
    - 6D cooling demonstration experiment (MANX)
  - Ionization cooling using a parametric resonance

- **Methods to manipulate phase space partitions**
  - Reverse emittance exchange using absorbers
  - Bunch coalescing (neutrino factory and muon collider share injector)

- **Technology for better cooling**
  - Pressurized RF cavities
    - simultaneous energy absorption and acceleration and
    - phase rotation, bunching, cooling to increase initial muon capture
    - Higher Gradient in magnetic fields than in vacuum cavities
  - High Temperature Superconductor for very high field magnets
    - Faster cooling, smaller equilibrium emittance
Pressurized High Gradient RF Cavities

- Copper plated, stainless-steel, 800 MHz test cell with GH2 to 1600 psi and 77 K in Lab G, MTA
- Paschen curve verified
- Maximum gradient limited by breakdown of metal
  - fast conditioning seen, no limitation by external magnetic field!
- Cu and Be have same breakdown limits (~50 MV/m), Mo ~60, W ~70
MuCool Test Area (MTA)

- 5T Solenoid
- Pressure barrier
- Wave guide to coax adapter
- 800 MHz Mark II Test Cell

Muons, Inc.
HPRF Test Cell Measurements in the MTA

Results show no B dependence, much different metallic breakdown than for vacuum cavities. **Need beam tests to prove HPRF works.**
Understanding RF Breakdown in High Pressure Cavities: Scanning Electron Microscope Pictures of HP Electrodes

Be

Mo

See WEPMS071 - Evidence for Fowler-Nordheim behavior in RF Breakdown
Technology Development in Technical Division

HTS at LH2 shown, in LHe much better

Fig. 9. Comparison of the engineering critical current density, $J_E$, at 14 K as a function of magnetic field between BSCCO-2223 tape and RRP Nb$_3$Sn round wire.

Emanuela Barzi et al., Novel Muon Cooling Channels Using Hydrogen Refrigeration and HT Superconductor, PAC05
6-Dimensional Cooling in a Continuous Absorber
see Derbenev, Yonehara, Johnson

- Helical cooling channel (HCC)
  - Continuous absorber for emittance exchange
  - Solenoidal, transverse helical dipole and quadrupole fields
  - Helical dipoles known from Siberian Snakes
  - z-independent Hamiltonian
  - Derbenev & Johnson, Theory of HCC, April/05 PRST-AB
Particle Motion in Helical Magnet

Combined function magnet (invisible in this picture)
Solenoid + Helical dipole + Helical Quadrupole

Red: Reference orbit
Blue: Beam envelope
Dispersion component makes longer path length for higher momentum particle and shorter path length for lower momentum particle.

\[ f_{\text{central}} = \frac{e}{m} (b_\phi \cdot p_z - b_z \cdot p_\phi) \]

\[ f_\uparrow \propto b_\phi \cdot p_z \quad \text{Repulsive force} \]
\[ f_\downarrow \propto -b_z \cdot p_\phi \quad \text{Attractive force} \]

terms have opposite sign
6D Cooling factor ~ 50,000

G4BL (Geant4) results

Transverse emittance (rad m)

Longitudinal emittance (m)

6-Dimensional emittance (m³)

λ = 1.0 m  λ = 0.8 m  λ = 0.6 m  λ = 0.4 m

Figure 1. Use of a Wedge Absorber for Emittance Exchange

Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange
Hydrogen Cryostat for Muon Beam Cooling

Technology for HCC components:

- HTS (nice BSSCO data from TD Ph I), Helical magnet design,
- low T Be or Cu coated RF cavities, windows, heat transport, refrigerant

Cryostat for the 6DMANX cooling demonstration experiment (proposal 7)

BNL Helical Dipole magnet for AGS spin control
Simple concept simultaneously provides solenoidal, helical dipole, and helical quadrupole fields needed for HCC. Also provides momentum-dependent HCC.

See Kashikhin et al.
Precooler + HCCs

• The acceptance is sufficiently big.
• Transverse emittance can be smaller than longitudinal emittance.
• Emittance grows in the longitudinal direction.
Incorporate RF cavity in helical solenoid coil

- Use a pillbox cavity (but no window this time).
- RF frequency is determined by the size of helical solenoid coil.
  - Diameter of 400 MHz cavity = 50 cm
  - Diameter of 800 MHz cavity = 25 cm
  - Diameter of 1600 MHz cavity = 12.5 cm
- The pressure of gaseous hydrogen is 200 atm to adjust the RF field gradient to be a practical value.
  - The field gradient can be increased if the breakdown would be well suppressed by the high pressurized hydrogen gas.

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<th>( \lambda )</th>
<th>( \kappa )</th>
<th>( B_z )</th>
<th>( b_d )</th>
<th>( b_q )</th>
<th>( b_s )</th>
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Cooling required for 5 TeV COM, $10^{35}$ Luminosity Collider, shown later. Need to also look at losses from muon decay to get power on target. Higher magnetic fields from HTS can get required HCC performance.
Parametric-resonance Ionization Cooling

Excite \( \frac{1}{2} \) integer parametric resonance (in Linac or ring)
- Like vertical rigid pendulum or \( \frac{1}{2} \)-integer extraction
- Elliptical phase space motion becomes hyperbolic
- Use \( xx' = \text{const} \) to reduce \( x \), increase \( x' \)
- Use IC to reduce \( x' \)

Detuning issues being addressed (chromatic and spherical aberrations, space-charge tune spread). Simulations underway. New progress by Derbenev.

See Sah, Newsham, Bogacz
Example of triplet solenoid cell on $\frac{1}{2}$ integer resonance with RF cavities to generate synchrotron motion for chromatic aberration compensation.

P-dependent focal length is compensated by using rf to modulate p.

OptiM (Valeri Lebedev) above and G4beamline (Tom Roberts) below.
**Reverse Emittance Exchange, Coalescing**

- \( p(\text{cooling}) = 100 \text{MeV/c}, \ p(\text{colliding}) = 2.5 \text{TeV/c} \Rightarrow \text{room in } \Delta p/p \text{ space} \)
- Shrink the transverse dimensions of a muon beam to increase the luminosity of a muon collider using wedge absorbers
- 20 GeV Bunch coalescing in a ring a new idea for ph II
- Neutrino factory and muon collider now have a common path

**Concept of Reverse Emittance Exch.**

- Incident Muon Beam
- Evacuated Dipole
- Wedge Abs

**Diagram:**

- Drift
- RF
- Cooled at 100 MeV/c
- RF at 20 GeV
- Coalesced in 20 GeV ring
- 1.3 GHz Bunch Coalescing at 20 GeV
Bhat et al. Coalescing

20 GeV muons in a 100 m diameter ring
6DMANX demonstration experiment
Muon Collider And Neutrino Factory eXperiment

See Kashikhin, Yonehara

- To Demonstrate
  - Longitudinal cooling
  - 6D cooling in cont. absorber
  - Prototype precooler
  - Helical Cooling Channel
  - Use for stopping muon beams
  - New technology
Katsuya’s Simulation study

Initial beam profile

- Beam size (rms): ± 60 mm
- $\Delta p/p$ (rms): ± 40/300 MeV/c
- $x'$ and $y'$ (rms): ± 0.4

- Obtained cooling factor: ~200%
- Transmission efficiency: 32%
- But is matching necessary?!!
Progress on new ideas described:

H$_2$-Pressurized RF Cavities
Continuous Absorber for Emittance Exchange
Helical Cooling Channel
Parametric-resonance Ionization Cooling
Reverse Emittance Exchange
RF capture, phase rotation, cooling in HP RF Cavities
Bunch coalescing
Z-dependent HCC
MANX 6d Cooling Demo

(For other paths to LEMCs, see
THPMS090  A Complete Scheme of Ionization Cooling for a Muon Collider, - Palmer et al., and
THPMS082  Muon Acceleration to 750 GeV in the Fermilab Tevatron Tunnel for a 1.5 TeV mu+ mu- Collider - Summers et al.)
Muon Collider use of 8 GeV SC Linac

Instead of a 23 GeV neutrino decay racetrack, we need a 23 GeV Coalescing Ring. Coalescing done in 50 turns (~1.5% of muons lost by decay). 10 batches of $10 \times 1.6 \times 10^{10}$ muons/bunch become 10 bunches of $1.6 \times 10^{11}$/bunch. Plus and minus muons are coalesced simultaneously. Then 10 bunches of each sign get injected into the RLA (Recirculating Linear Accelerator).
5 TeV ~ SSC energy reach
~5 X 2.5 km footprint
Affordable LC length (half of baseline 500 GeV ILC), includes ILC people, ideas
More efficient use of RF: recirculation and both signs
High L from small emittance!
1/10 fewer muons than originally imagined:
a) easier p driver, targetry
b) less detector background
c) less site boundary radiation
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Muon Collider Emittances and Luminosities

• After:
  – Precooling  \( \varepsilon_{N \text{ tr}} = 20,000 \ \mu m \)  \( \varepsilon_{N \text{ long.}} = 10,000 \ \mu m \)
  – Basic HCC 6D  \( \varepsilon_{N \text{ tr}} = 200 \ \mu m \)  \( \varepsilon_{N \text{ long.}} = 100 \ \mu m \)
  – Parametric-resonance IC  \( \varepsilon_{N \text{ tr}} = 25 \ \mu m \)  \( \varepsilon_{N \text{ long.}} = 100 \ \mu m \)
  – Reverse Emittance Exchange  \( \varepsilon_{N \text{ tr}} = 2 \ \mu m \)  \( \varepsilon_{N \text{ long.}} = 2 \ \text{cm} \)

At 2.5 TeV on 2.5 TeV

\[
L_{\text{peak}} = \frac{N_1 n \Delta \nu}{\beta^* r_\mu} f_0 \gamma = 10^{35} / cm^2 - s
\]

20 Hz Operation:

\[
\langle L \rangle \approx 4.3 \times 10^{34} / cm^2 - s
\]

\[
Power = (26 \times 10^9)(6.6 \times 10^{13})(1.6 \times 10^{-19}) = 0.3 MW
\]

\[
0.3 \mu^+ / p
\]
Benefits of low emittance approach

Lower emittance allows lower muon current for a given luminosity.
This diminishes several problems:

– radiation levels due to the high energy neutrinos from muon beams circulating and
decaying in the collider that interact in the earth near the site boundary;
– electrons from the same decays that cause background in the experimental detectors and
heating of the cryogenic magnets;
– difficulty in creating a proton driver that can produce enough protons to create the
muons;
– proton target heat deposition and radiation levels;
– heating of the ionization cooling energy absorber; and
– beam loading and wake field effects in the accelerating RF cavities.

Smaller emittance also:

– allows smaller, higher-frequency RF cavities with higher gradient for acceleration;
– makes beam transport easier; and
– allows stronger focusing at the interaction point since that is limited by the beam
extension in the quadrupole magnets of the low beta insertion.

See the LEMC Workshop web page. And please
come to the next workshop in February, 2008!
Low Emittance Muon Collider
Next Steps: we are getting close!

• A detailed plan for at least one complete cooling scheme with end-to-end simulations of a 1.5 TeV com MC,

• Advances in new technologies; e.g. an MTA beamline for HPRF tests, HTS for deep cooling, HCC magnet design

• And a really good 6D cooling demonstration experiment proposed to Fermilab
High-Energy High-Luminosity Muon Colliders

• Are precision lepton machines at the energy frontier
• Are possible and affordable with new inventions and new technology
• Can take advantage of ILC advances
• Can be achieved in physics-motivated stages
• Require more effort from DPB and DPF communities
  – Please join in!