The Low Emittance Muon Collider Workshop

http://www.muonsinc.com/mcwfeb06

Goals:

- Merge several new ideas with older ones into a self-consistent muon collider (MC) design with new parameters
  - Many essential JLab contributions from Derbenev and Bogacz

- Make a Fermilab-site specific baseline MC design based on ILC RF technology
  - Using proposed proton driver Linac to also accelerate muons

- Create a staged plan to get to the energy frontier, where each step is a funding package with an exciting experimental physics goal
  - Implies an exceptional neutrino factory as an intermediate step
Muon Colliders: Back to the Livingston Plot
A lepton collider at the energy frontier!

Modified Livingston Plot taken from: W. K. H. Panofsky and M. Breidenbach, Rev. Mod. Phys. 71, s121-s132 (1999)
Workshop Desirables

- At least one complete design of a LEMC
- An implementation plan with affordable, incremental, independently-fundable, sequential, steps:

  1. attractive 6D Cooling experiment (5)
  2. double-duty proton driver Linac (400)
  3. exceptional neutrino factory (23 GeV) (1000)
      P buncher, target, cooling, recirculation, PDL upgrade, decay racetrack
  4. intense stopping muon beam (100)
      Experimental hall, beamlines
      Add more cooling, RLA, coalescing & collider rings, IR
  6. energy frontier muon collider (5 TeV com) (2000)
      More RLA, deep ring, IRs

(Rol WAG $M)
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 for lower cost
  - Affordable neutrino factory, which by coalescing, becomes
  - A muon collider injector for

- A low-emittance high-luminosity collider
  - high luminosity with fewer muons
  - LEMC goal: $E_{cm} = 5$ TeV, $<L> = 10^{35}$

- Many new ideas in the last 5 years. A new ball game!
  - (many new ideas have come from DOE SBIR funding)
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.
Recent Inventions and Developments

- **New Ionization Cooling Techniques**
  - Emittance exchange with continuous absorber for longitudinal cooling
  - Helical Cooling Channel
    - Effective 6D cooling (simulations: cooling factor 50,000 in 150 m)
  - Momentum-dependent Helical Cooling Channel
    - 6D Precooling device
    - 6D cooling demonstration experiment (>500% 6 D cooling in 4 m)
    - 6D cooling segments between RF sections
  - 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
  - High Temperature Superconductor for up to 50 T magnets
    - Faster cooling, smaller equilibrium emittance
Ionization Cooling (reduction in angular divergence of a muon beam)

\[ \min \epsilon_{xN} = \frac{\beta \epsilon_s^2}{2 \beta mc^2 L_R} \left| \frac{dE}{dz} \right| \]

\[ \beta_\perp = \frac{2 p_z}{c B_z} \]

Fast enough for muons
Only works for muons
Pressurized High Gradient RF Cavities

see Kaplan, Popovic, Moretti, Johnson, Paul, Neuffer, Hanlet

- 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
- Cu and Be have same breakdown limits (~50 MV/m), Mo ~20% better
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
6D Cooling factor ~ 50,000

G4BL (Geant4) results

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

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
See Kashikhin, Yonehara, Kuchnir, Yarba

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
HCC with Z-dependent fields
see Yonehara, Paul, Derbenev

Light blue: pion decay channel (L = 40 m)

White: pre-cooler (L = 5 m)

Blue: muon+

Red: pion+

40 m evacuated helical magnet pion decay channel followed by a 5 m liquid hydrogen HCC (no RF)
New Invention: HCC with fields that decrease with momentum. Here the beam decelerates in liquid hydrogen (white region) while the fields diminish accordingly.
First G4BL Precooler Simulation
see Yonehara, Roberts

Equal decrement case.
~x1.7 in each direction.

Total 6D emittance reduction ~factor of 5.5

Note this would require serious magnets: ~10 T at conductor for 300 to 100 MeV/c deceleration

MANX results with B <5.5 T will also work!
below show LHe absorber
MANX 6-d demonstration experiment
Muon Collider And Neutrino Factory eXperiment
see Roberts, Yonehara, Derbenev
NEED EXPERIMENTERS!!!

- To Demonstrate
  - Longitudinal cooling
  - 6D cooling in cont. absorber
  - Prototype precooler
  - Helical Cooling Channel
  - Alternate to continuous RF
    - $5.5^8 \sim 10^6$ 6D emittance reduction with 8 HCC sections of absorber alternating with (SC?)RF sections.
  - New technology

Thomas J. Roberts et al., A Muon Cooling Demonstration Experiment, PAC05
G4BL MANX with MICE spectrometers
Muon Trajectories in 3-m MANX

The design of the coils and cryostat are next steps for MANX.
Emittance evolution in LHe HCC
LHe MANX Summary

- Maximum field can be less than 5.5 T at \( r = 35 \text{ cm} \).
- Cooling factor is \( \sim 500\% \).
- Studying matching of emittance between MANX and spectrometers.
- Really great opportunity for HEP people to get involved. Maybe use spectrometers stored in meson lab.
Technology Development in Technical Division
see Kashikhin, Kuchnir, Yonehara

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. 

Licia Del Frate et al., Novel Muon Cooling Channels Using Hydrogen Refrigeration and HT Superconductor, PAC05
MANX/Precooler H2 or He Cryostat (Kuchnir)

Five meter long MANX cryostat schematic. The use of Liquid He at 4 K is possible, with Nb3Sn or NBTi magnets. Thin Al windows designed for MICE will be used (see Cummings).
50 Tesla HTS Magnets for Beam Cooling
See Kahn, Palmer, Kuchnir

- We plan to use high field solenoid magnets in the near final stages of cooling.
- The need for a high field can be seen by examining the formula for equilibrium emittance:

\[
\min \epsilon_{xN} = \frac{\beta_{\perp} E_z^2}{2\beta mc^2 L_R \frac{dE}{dz}}
\]

\[
\beta_{\perp} = \frac{2p_z}{cB_z}
\]

- The figure on the right shows a lattice for a 15 T alternating solenoid scheme previously studied.
Current Carrying Capacity for HTS Tape in a Magnetic Field
Scale Factor is relative to 77ºK with self field
**Parametric-resonance Ionization Cooling**

*see Derbenev, Johnson, Beard*

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 $xx'=const$ 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.

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**Diagram:**

- Elliptical phase space motion becomes hyperbolic
- Use $xx'=const$ to reduce $x$, increase $x'$
- Use IC to reduce $x'$
- Absorber plate
- $P_{\text{in}}$, $P_{\text{cool}} = P_{\text{out}} + \Delta P_{\text{RF}}$, $\Delta P_{\text{abs}}$
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.
Evolution of transverse and longitudinal phase space through 8 triplet solenoid cells, without (left) and with (right) RF cavities. Alex Bogacz

- Start
- After 2 cells
- After 4 cells
- After 6 cells
- After 8 cells

After 8 cells: one synchrotron period

Longitudinal cooling needed!
Reverse Emittance Exchange, Coalescing
see Derbenev, Ankenbrandt

- $p(\text{cooling})=100\text{MeV/c}$, $p(\text{colliding})=2.5\text{TeV/c} \Rightarrow$ room in $\Delta p/p$ 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.
Capture, Bunching, and Precooling using HP GH2 RF

see Neuffer, Paul, Hanlet

- Simultaneous muon capture, RF bunch rotation, and precooling in the first stage of a muon beam line
- Phase rotation and beam cooling will be simulated
- Continuation of the HP RF development in the MTA with high magnetic field and high radiation environment

- We need data from the MTA with the LBNL solenoid and the promise of the MTA beamline for a strong Phase II proposal

Increase in muons captured when 2 m of bunch rotation RF is applied starting 5 m from target.
Protons, Pions, and Muons

Target

RF Bucket
Simulations of RF phase rotation

Figure 1. Momentum versus time of flight of muons 5 meters from the production target. Before phase-energy rotation.

Figure 2. Momentum versus time of flight of muons 7 meters from the production target, after passing through 2 meters of high-gradient phase-energy rotation RF cavities.
Simulations of phase rotation to improve muon capture rate

Figure 3. Fraction of muons within the 200 to 300 MeV/c momentum range as a function of distance from the target for the case of the phase rotation RF on or off.
Schematic of the LINAC+Coalescing Ring

Chandra Bhat

Bunch train
with 1.3GHz structure
Bunch LE~ 0.03 eVs
dE~ 20 MeV
Muon Coalescing Ring.

Based on the information given to Bhat by Chuck Ankenbrandt following parameters are derived for the Coalescing Ring (also see Bogaczring)

- Injection beam : 1.3GHz bunch structure
- # of bunches/train = 17
- Ring Radius = 52.33m; Revolution period= 1.09μs
- Energy of the muon = 20 GeV (gamma = 189.4)
- gamma_t of the ring = 4
- If we assume
  - Ring-Radius/rho (i.e., fill factor) = 2, then B-Field = 2.54T
  - (This field seems to be reasonable)
- h for the coalescing cavity = 42, 84
- Number of trains/injection = less than 37
  - (assuming ~100ns for injection/extraction)
- RF voltage for the coalescing cavity = 1.9 MV (h=42)
  - = 0.38 MV (h=84)
- f_sy ~ 5.75E3Hz
- T_sy/4 = 43.5us
- Number of turns in the ring ~40

Constraints:

- Muon mean-life = 2.2us (rest frame)
- Muon half-life in lab = 288us for 20 GeV beam
- Time (90% survival) = 43.8us
2nd Scenario

- A pre-linac to give a tilt in the Longitudinal Phase-space

Bunch train before the special purpose pre-linac

Muon Bunches after pre-linac

• And next inject the beam into the Coalescing Ring
Muon Bunch train in the Coalescing Ring
T=0 sec
Muon Bunch train in the Coalescing Ring

$T = 46 \, \mu \text{sec}$

- $dE \approx 100 \, \text{MeV}$
- Bunch Length $\approx 4 \, \text{ns}$
End of survey of some new ideas
Now discuss their use at Fermilab

- $\text{H}_2$-Pressurized RF Cavities
- Continuous Absorber for Emittance Exchange
- Helical Cooling Channel
- Z-dependent HCC
- MANX 6d Cooling Demo
- Parametric-resonance Ionization Cooling
- Reverse Emittance Exchange
- RF capture, phase rotation, cooling in HP RF Cavities
- Bunch coalescing
The Fermilab/ILC Neutrino Factory
see Popovic, Foster

- neutrino factory based on
  - extreme muon cooling
  - ILC RF
  - Muon recirculation through p-driver Linac
  - High rep rate capability (See Foster)
Neutrinos from an 8 GeV SC Linac

Muon cooling to reduce costs of a neutrino factory based on a storage ring. Cooling must be 6D to fit in 1.3 GHz SC RF, where the last 6.8 GeV of 8 GeV are $\beta=1$. New concept: Run Linac CW, increase rep rate from 10 to 100 or more, for more vs.
700 m muon Production and Cooling
(showing approximate lengths of sections)

- 8 GeV Proton storage ring, loaded by Linac
  - 2 T average implies radius=8000/30x20~14m
- Pi/mu Production Target, Capture, Precool sections
  - 100 m (with HP RF, maybe phase rotation)
- 6D HCC cooling, ending with 50 T magnets
  - 200 m (HP GH2 RF or LH2 HCC and SCRF)
- Parametric-resonance Ionization Cooling
  - 100 m
- Reverse Emittance Exchange (1st stage)
  - 100 m
- Acceleration to 2.5 GeV
  - 100 m at 25 MeV/c accelerating gradient
- Reverse Emittance Exchange (2nd stage)
  - 100 m
- Inject into Proton Driver Linac
- Total effect:
  - Initial 40,000 mm-mr reduced to 2 mm-mr in each transverse plane
  - Initial ±25% Δp/p reduced to 2%, then increased
    - exchange for transverse reduction and coalescing
  - about 1/3 of muons lost during this 700 m cooling sequence
- Then recirculate to 23 GeV, inject into racetrack NF storage ring

Detailed theory in place, simulations underway.
The Fermilab/ILC Muon Collider

- After three passes through the PDL the muons reach $2.5 + 3 \times 6.8 = 22.9$ GeV
- RF cavities operating off-frequency at the end of the Linac create a momentum-offset for the bunches in each batch
- Positive and negative muons are injected into a 23 GeV storage ring
- Waiting for $\sim 50$ turns, the bunches in a batch are aligned and recaptured in a 1.3 GHz bucket
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 10x1.6x10¹⁰ muons/bunch become 10 bunches of 1.6x10¹¹/bunch. Plus and minus muons are coalesced simultaneously. Then 10 bunches of each sign get injected into the RLA (Recirculating Linear Accelerator).
Recirculating muons in the PDL

- Proton accumulator & muon coalescing tunnel
- Recirculating muon path
5 TeV ~ SSC energy reach
~5 X 2.5 km footprint
Affordable LC length (half of baseline 500 GeV ILC), includes ILC people, ideas
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
Muon Collider Emittances and Luminosities
(parameters & calculations need updating)

- After:
  - Precooling: $\epsilon_N \text{tr} = 20,000 \mu m$, $\epsilon_N \text{long} = 10,000 \mu m$
  - Basic HCC 6D: $\epsilon_N = 200 \mu m$, $\epsilon_N = 100 \mu m$
  - Parametric-resonance IC: $\epsilon_N = 25 \mu m$, $\epsilon_N = 100 \mu m$
  - Reverse Emittance Exchange: $\epsilon_N = 2 \mu m$, $\epsilon_N = 2 \text{cm}$

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

$\gamma \approx 2.5 \times 10^4 \quad n = 10$

$f_0 = 50 kHz \quad N_1 = 10^{11} \mu^-$

$\Delta \nu = 0.06 \quad \beta^* = 0.5 cm$

$\sigma_z = 3 mm \quad \Delta \gamma / \gamma = 3 \times 10^{-4}$

$\tau_\mu \approx 50 ms \Rightarrow 2500 \text{turns} / \tau_\mu$

$0.3 \mu^+ / p$
My interpretation of Theory talks

• If the LHC shows no interesting physics to be explored in the reach of the ILC
  – An energy frontier muon collider is needed
  – ILC R&D is only useful for a low emittance muon collider

• If the LHC indicates interesting physics in the reach of the ILC
  – A muon collider to do precision measurements is needed since the beams in an ILC are not so precise
  – An energy frontier muon collider is needed for the higher mass states that must be above the reach of the ILC

• The energy frontier is always the way to go and muons may have a special advantage
First Annual Low Emittance Muon Collider Workshop

• By next year we should have a complete cooling scheme with end-to-end simulations to support the analytical theory that has been developed

• And a really good 6D cooling demonstration experiment designed and proposed to Fermilab