Advances in Beam Cooling for 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.

Several of the techniques to cool muon beams have been invented and are under development supported by DOE Small Business Innovation Research and Small business Technology Transfer Research grants.

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
Abstract

- A six-dimensional (6D) ionization cooling channel based on helical magnets surrounding RF cavities filled with dense hydrogen gas is the basis for the latest plans for muon colliders. This helical cooling channel (HCC) has solenoidal, helical dipole, and helical quadrupole magnetic fields, where emittance exchange is achieved by using a continuous homogeneous absorber. Momentum-dependent path length differences in the dense hydrogen energy absorber provide the required correlation between momentum and ionization loss to accomplish longitudinal cooling. Recent studies of an 800 MHz RF cavity pressurized with hydrogen, as would be used in this application, show that the maximum gradient is not limited by a large external magnetic field, unlike vacuum cavities. Two new cooling ideas, Parametric-resonance Ionization Cooling and Reverse Emittance Exchange, will be employed to further reduce transverse emittances to a few mm-mr, which allows high luminosity with fewer muons than previously imagined. We describe these new ideas as well as a new precooling idea based on a HCC with z dependent fields that is being developed for an exceptional 6D cooling demonstration experiment. Present concepts for a 1.5 to 5 TeV center of mass collider with average luminosity greater than $10^{34}$/s-cm$^2$ include ILC RF structures to accelerate positive and negative muons in a 10-pass recirculation Linac. The status of the designs, simulations, and tests of the cooling components for a high luminosity, low emittance muon collider will be reviewed.
LEMC Workshop Theory Talks: Renewed HEP Theoretical Interest

- Chris Quigg
  - CLIC studies relevant
  - Something has to happen

- Kong
  - Excellent muon collider resolution
    - (no synchrotron radiation or beamstrahlung)
  - may be important handle on dark matter, extra dimensions

- Dobrescu and Skands (2006)
  - Muons as members of 2\textsuperscript{nd} generation of particles have new possibilities

- Lively discussions, interesting talks
  - Is there a killer need for a muon collider?
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: $E_{\text{com}}=5$ 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 funding)
# Muons, Inc. Project History

<table>
<thead>
<tr>
<th>Year</th>
<th>Project</th>
<th>Expected Funds</th>
<th>Research Partner</th>
</tr>
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<td>2007-8</td>
<td>Stopping Muon Beams</td>
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<td>HCC Magnets</td>
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<td>2007-8</td>
<td>Compact, Tunable RF</td>
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* Submitted for phase II for +$750,000 and +2 years
† Not continued to Phase II

SBIR/STTR funding: Solicitation September, Phase I proposal due December, Winners ~May, get $100,000 for 9 months, Phase II proposal due April, Winners June, get $750,000 for 2 years

(see 12+3 PAC07 papers on progress)
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
    - Effective 6D cooling (simulations: cooling factor >50,000 in 160 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
    - Higher Gradient in magnetic fields than in vacuum cavities
  - High Temperature Superconductor for up to 50 T magnets
    - Faster cooling, smaller equilibrium emittance
Muon Beam Cooling Implications

- Although I speak of new inventions for PR reasons, I want to clearly acknowledge the pioneering work and creative energy that many of our colleagues, present and not, have put into the muon cooling endeavor.

- We can reestablish the principle that a neutrino factory should be on the direct path to a muon collider.

- Muon Colliders need small transverse emittance and low muon flux for many reasons (discussed later).

- A Neutrino Factory using a very cool muon beam which is accelerated in a superconducting ILC proton driver Linac seems cost-effective, and large flux can come from improving the Linac repetition rate. Will this be obvious to ISS’ once we develop efficient cooling?
Pressurized High Gradient RF Cavities
(IIT, Dan Kaplan)

- 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 ~28% better
MuCool Test Area (MTA)

- Pressure barrier
- Wave guide to coax adapter
- 800 MHz Mark II Test Cell
- 5T Solenoid
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.**
800 MHz Vacuum cavity Max Gradient vs $B_{\text{external}}$
From Al Moretti, MICE meeting IIT, 3/12/06

Safe Operating Gradient Limit vs Magnetic Field Level at Window for the three different Coil modes

![Graph showing safe operating gradient limit vs magnetic field level at window for different coil modes.](image)
Understanding RF Breakdown in High Pressure Cavities: Scanning Electron Microscope Pictures of HP Electrodes

See Mahzad and Mageed poster
Technology Development in Technical Division

HTS at LH2 shown, in LHe much better

![Graph showing comparison of 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.](image)

**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
50 Tesla HTS Magnets for Beam Cooling

- 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:

\[
\min \epsilon_{xN} = \frac{\beta_\perp E_z^2}{2\beta m c^2 L_R \left| \frac{dE}{dz} \right|}
\]
\[
\beta_\perp = \frac{2p_L}{cB_Z}
\]

- The figure on the right shows a lattice for a 15 T alternating solenoid scheme previously studied.

See Palmer, Kahn, Fernow
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
Two Different Designs of Helical Cooling Magnet

- **Siberian snake type magnet**
  - Consists of 4 layers of helix dipole to produce tapered helical dipole fields.
  - Coil diameter is 1.0 m.
  - Maximum field is more than 10 T.

- **Helical solenoid coil magnet**
  - Consists of 73 single coils (no tilt).
  - Maximum field is 5 T
  - Coil diameter is 0.5 m.
  - Flexible field by adding a correction coils.

New great innovation!
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
Dispersive component makes longer path length for higher momentum particle and shorter path length for lower momentum particle.

\[ \kappa = \frac{2\pi a}{\lambda} = \frac{p_\phi}{p_z} \]

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

Terms have opposite sign

\[ f_\uparrow \propto b_\phi \cdot p_z \]
Repulsive force

\[ f_\downarrow \propto -b_z \cdot p_\phi \]
Attractive force
RF cavity is needed to compensate ionization energy loss.

Continuous acceleration is more effective.
Emittance in series of HCC

- Use continuous 200 MHz cavity in a whole channel.
- $E=31$ MV/m in 400 atm GH2.
- 6D cooling factor in the series of HCC is $\sim 50,000$.
- The realistic RF field is tested in the single helical cooling channel (bottom plot).
- This test is proved the predicted cooling performance in the Slava and Rol’s paper.
- However, this design requires a very large magnetic field.

We need to solve this question.
**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>Bz</th>
<th>bd</th>
<th>bq</th>
<th>bs</th>
<th>f</th>
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<th>Maximum b</th>
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<td>12.5</td>
<td>34.0</td>
<td>16.0</td>
<td>140.0</td>
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</table>
Yonehara HCC
Fernow-Neuffer Plot

Initial point
PIC and REMEX Progress

- The PIC and REMEX concepts have been invented and developed to provide the crucial final beam cooling in a muon collider. Their use can greatly reduce the final beam emittance and can permit the construction of a high-luminosity collider that requires fewer muons.

- Significant progress has been made in the design of these cooling channels and in the corresponding particle-tracking simulations.

- Reflection symmetry in the cooling channel design can be used effectively to cancel the largest geometric aberration in the beamline optics.
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.
Dispersion Prime

- Initial beam at $x = x' = y = y' = 0$
- 100 trajectories with Momentum Spread up to $\pm 5\%$, but $\delta$ is not matched to $x'$
- $P_0 = 100$ MeV/c
Reverse Emittance Exchange, Coalescing
see Derbenev, Ankenbrandt, Bhat

- \( p(\text{cooling})=100\text{MeV/c}, p(\text{colliding})=2.5 \text{ TeV/c} \Rightarrow \text{room in } \Delta p/p \text{ space} \)
- 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.
Bhat et al. Coalescing

20 GeV muons in a 100 m diameter ring
Capture, Bunching, and Precooling using HP GH2 RF

- 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

Increase in muons captured when 2 m of bunch rotation RF is applied starting 5 m from target.
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

Now an example of their use at Fermilab.

(Note that Bob Palmer’s has another path to low emittance that looks promising due to him, Rick Fernow, and Steve Kahn.)
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 to decay during this 700 m cooling sequence
- Then recirculate to 23 GeV, inject into racetrack NF storage ring

New Phase II grant
Detailed theory in place, simulations underway.
New Phase II grant
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).
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 ~50 turns, the bunches in a batch are aligned and recaptured in a 1.3 GHz bucket
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

Beams from 23 GeV Coalescing Ring
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: $200 \mu m$, $100 \mu m$
  - Parametric-resonance IC: $25 \mu m$, $100 \mu m$
  - Reverse Emittance Exchange: $2 \mu m$, $2 \text{ cm}$

At 2.5 TeV on 2.5 TeV

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

20 Hz Operation:

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

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

$0.3 \mu^2 / p$

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

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

$\Delta \nu = 0.06$, $\beta^* = 0.5 \text{ cm}$

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

$\tau_\mu \approx 50 ms \Rightarrow 2500 \text{ turns} / \tau_\mu$
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.
Letter of Intent to propose a
SIX-DIMENSIONAL MUON BEAM COOLING
EXPERIMENT FOR FERMILAB

Ramesh Gupta, Erich Willen
Brookhaven National Accelerator Laboratory

Fermi National Accelerator Laboratory

Daniel Kaplan, Linda Spentzouris
Illinois Institute of Technology

Alex Bogacz, Kevin Beard, Yu-Chiu Chao, Yaroslav Derbenev, Robert Rimmer
Thomas Jefferson National Accelerator Facility

Mohammad Alsharo’a, Mary Anne Cummings, Pierrick Hanlet, Robert Hartline, Rolland Johnson*, Stephen Kahn, Moyses Kuchnir, David Newsham, Kevin Paul, Thomas Roberts
Muons, Inc.

* Contact, rol@muonsinc.com, (757) 870-6943

Submitted to Fermilab 5/9/2006
Muon Collider Task Force Charge from Pier Oddone

• Charge

i) Cooling Channel and Collider Design Concept.
Taking into account recent developments in muon cooling ideas, develop a plan to form a design and simulation study group that will develop a coherent concept for a Muon Collider with a center-of-mass energy of 1.5 TeV, based upon a low emittance parameter set. The group’s focus should be to outline the general scheme, the parameter choices, and the 6D ionization cooling channel requirements to support a usable luminosity, and in addition identify the primary design challenges beyond the 6D cooling systems. Progress should be documented in reports in September 2007 and September 2008. The initial plan for creating the study group should include an estimate of the required Fermilab effort and the expected contributions from outside of Fermilab, and should be documented in a brief report in September 2006.

ii) Cooling Channel R&D.
• Prepare a one year study plan to (a) evaluate the technical feasibility of the components (rf cavities, magnets, absorbers, etc) needed for a muon collider class 6D cooling channel as identified in i), (b) identify the technical issues that must be addressed before a 6D cooling channel could be built, and (c) formulate a plan for the associated component R&D and 6D cooling tests that must be performed to establish basic viability of the cooling channel. The study plan should be documented in a short report in September 2006. The results of the one year study should be documented in a more detailed report in September 2007.
• iii) **Component Development and Testing.**

• (a) Prepare a plan to implement, in FY07, the beam and experimental setup required to test the high-gradient operation of a high-pressure gas-filled rf cavity operated in a multi-Tesla magnetic field and exposed to an ionizing beam. The implementation plan should be documented in a short report made available in September 2006. This plan should include a description of the measurements to be made, should be formulated in collaboration with Muons Inc, and should document the connection between these activities and charge elements i) and ii)

• b) Design, and prepare a plan to build, a helical solenoid suitable for a 6D cooling channel section test. The implementation plan should be described in a short report made available in September 2006, developed in collaboration with Muons Inc. and documenting the connection between this activity and charge elements i) and ii). A complete prototype design and fabrication plan should be described in a concise report in September 2007.

• c) Prepare an R&D plan to explore the feasibility of building a very high field (~50Tesla) high-Tc superconducting solenoid suitable for the final stages of a muon cooling channel for a Muon Collider. The R&D plan should be documented in a short report made available in September 2006, including documenting the connection between this activity and charge elements i) and ii).
6DMANX demonstration experiment
Muon Collider And Neutrino Factory eXperiment

- To Demonstrate
  - Longitudinal cooling
  - 6D cooling in cont. absorber
  - Prototype precooler
  - Helical Cooling Channel
  - Alternate to continuous RF
    - 6D emittance reduction with HCC sections of absorber alternating with (SC?) RF sections.
  - New technology
MANX parts

<table>
<thead>
<tr>
<th>Beam</th>
<th>Spectrometer and Matching Section</th>
<th>Liquid Helium filled HCC</th>
<th>Spectrometer and Matching Section</th>
<th>Calorimeter</th>
</tr>
</thead>
</table>

Features:
- Z-dependent HCC (fields diminish as muons slow in LHe)
- Normalized emittance to characterize cooling
- No RF for simplicity (at least in first stage)
- LHe instead of LH2 for safety concerns
- Use ~300 MeV/c muon beam wherever it can be found with MICE collaboration at RAL or at Fermilab

Present Efforts:
- Designing/building 3-coil helical solenoid prototype
- Simulating the experiment with G4MANX with scifi
- Improving the matching sections
- Sweating the phase II proposal
Possible MANX magnet designs
See Kashikhin

- Snake type MANX
  - Consists of 4 layers of helix dipole
  - Maximum field is ~7 T (coil diameter: 1.0 m)
  - Field decays very smoothly
  - Hard to adjust the field configuration

- New MANX
  - Consists of 73 single coils (no tilt)
  - Maximum field is ~5 T (coil diameter: 0.5 m)
  - Field decays roughly
  - Flexible field configuration
Shorter matching and HCC field map

Use linear function for first trial

\[ b_{\text{matching}} = \alpha b_0 z \]

\( b_0 \): Amplitude of initial helical dipole magnet
\( \alpha \): Ramping rate

Adjust solenoid strength to connect to a proper helical orbit.

See Yonehara
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?!!
Where to put MANX?

• Several options studied, 3 discussed at this LEMC workshop:
  – MTA new beamline
  – Meson Lab test beam
  – Using recycler to transfer 8 GeV beam to a debuncher or accumulator stretcher ring
  – MICE Phase III
Phase II Proposals submitted April 13

- **G4BL**
  - More user support, e.g. use processor farms, join GEANT4 collaboration
  - Finish upgrades (runs on Linux, XP, MacOS)
  - Phase II plans (polarization, space charge, low E)

- **MANX**
  - Fermilab Experimental Proposal
  - G4MANX, 3-coil HCC prototype
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
Discussion at the LEMC workshop

Memo: Muon Collider R&D Status
Date: Feb 21, 2007
To: P. Oddone
From: A. Tollestrup, M. Zisman, S. Geer, A. Sessler, V. Shiltsev, R. Johnson, R. Palmer

During the Low Emittance Muon Collider Workshop, we had a discussion session on the status of the muon collider R&D and the overall understanding of the problems connected with the ultimate construction of such a machine. A summary of this discussion follows.

General Conclusion
If the present R&D effort, as defined by: (1) the ongoing NFMCC program, (2) the proposed MCTF program, and (3) the ongoing work of Muons, Inc. is successful, then the consensus was that it should be possible to develop a realistic design for a muon collider with a c.m. energy of 1.5 TeV, or greater and a luminosity of the order of $10^{34} \text{ cm}^2/\text{sec}$.

Key Elements of an R&D Program
An exciting and innovative program has been proposed that if funded and pursued vigorously would allow, in two or possibly three years, a feasibility study similar to that carried out for the neutrino factory (i.e., a rather detailed conceptual design and a rough estimate of the cost of the facility). Such a study is crucial for establishing the feasibility of a muon collider. Generating a coherent design will pull together the diverse and innovative ideas being presently pursued and indicate the direction of additional work.
The proposed R&D Program

The proposed R&D Program has four key elements. They are:

1. An experimental study of the behavior of gas filled and vacuum RF cavities in a beam and with a strong axial magnetic field. This is dependent on getting a proton beam to MTA expeditiously.
   (1st STTR with IIT, present STTR ph II project with Fermilab)

2. The development of suitable conductor, a material properties data-base for materials used in high field magnets, and a model magnet program aimed at developing 20 to 50 T HTS solenoids.
   (1st STTR with Fermi TD, New SBIR ph I proposal with BNL)

3. Fabrication and testing of a model helical cooling magnet, provided the study described in the MCTF charge validates its use in a cooling channel.
   (New SBIR ph II proposal, with wonderful phase I results)

4. Theoretical studies, both analytic and numerical simulation, on how to actually incorporate the new ideas into a coherent design for a collider.
   (Several SBIR-STTR projects at JLab, Fermilab, and IIT underway and proposed)
From 2006 Workshop (red = new)

• An implementation plan with affordable, incremental, independently-fundable, sequential, steps:

(Rol WAG $M)

1. attractive 6D Cooling experiment (MANX!) (5)
2. double-duty PD Linac (HINS!) (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 (mu2e!, new Phase I grant)
   Add more cooling, RLA, coalescing & collider rings, IR
6. energy frontier muon collider (>3 TeV com) (2000)
   More RLA, deep ring, IRs (1.5 TeV study an intermediate step)
High-Energy High-Luminosity Muon Colliders

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