Low Emittance Muon Collider Options

Rolland Johnson,
Muons, Inc.

SBIR-STTR funding requires innovations
Necessarily “out of the box”
Options we investigate are projects
length and funds well defined
each project has research partner
mutual compatibility of projects/options not necessary
<table>
<thead>
<tr>
<th>Year</th>
<th>Project</th>
<th>Expected Funds</th>
<th>Research Partner</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>Company founded</td>
<td></td>
<td></td>
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<tr>
<td>2002-5*</td>
<td>High Pressure RF Cavity</td>
<td>$600,000</td>
<td>IIT</td>
</tr>
<tr>
<td>2003-7*</td>
<td>Helical Cooling Channel</td>
<td>$850,000</td>
<td>JLab</td>
</tr>
<tr>
<td>2004-5†</td>
<td>MANX demo experiment</td>
<td>$ 95,000</td>
<td>FNAL TD</td>
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<tr>
<td>2004-7*</td>
<td>Phase Ionization Cooling</td>
<td>$745,000</td>
<td>JLab</td>
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<tr>
<td>2004-7*</td>
<td>H2 Cryostat (HTS HS)</td>
<td>$795,000</td>
<td>FNAL TD</td>
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<tr>
<td>2005-8</td>
<td>Reverse Emittance Exch.</td>
<td>$850,000</td>
<td>JLab</td>
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<td>2005-8</td>
<td>Capture, ph. rotation</td>
<td>$850,000</td>
<td>FNAL AD</td>
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<tr>
<td>2006-9</td>
<td>G4BL Sim. Program</td>
<td>$850,000</td>
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<td>2006-9</td>
<td>MANX 6D Cooling Demo</td>
<td>$850,000</td>
<td>FNAL TD</td>
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<tr>
<td>2007-8</td>
<td>Stopping Muon Beams</td>
<td>$100,000</td>
<td>FNAL APC</td>
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<tr>
<td>2007-8</td>
<td>HCC Magnets</td>
<td>$100,000</td>
<td>FNAL TD</td>
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<tr>
<td>2007-8</td>
<td>Compact, Tunable RF</td>
<td>$100,000</td>
<td>FNAL AD (NP)</td>
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</table>

**Total: $6,785,000**

† Not continued to Phase II  *Closed

DOE 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 11 PAC07 papers on progress, 21 in preparation for EPAC08)
Primary Goal: High-Energy High-Luminosity Muon Colliders

- precision lepton machines at the energy frontier
- possible with new inventions and new technology
  - can take advantage of ILC advances
- achieved in physics-motivated stages
  - stopping muon beams
  - neutrino factory
  - Higgs factory
  - Z’ factory (lower luminosity, perhaps LHC inspired)
  - Energy-frontier muon collider

Secondary Goal: Business opportunities for Stability
SBIR-STTR Inventions/Developments

- **New Ionization Cooling Techniques**
  - Emittance exchange with continuous absorber for longitudinal cooling
  - Helical Cooling Channel (HCC)
  - Momentum-dependent Helical Cooling Channel
    - 6D Precooling device, muon stopping beam
    - 6D cooling demonstration experiment (MANX)
    - 6D cooling segments between RF sections
  - Ionization cooling using a parametric resonance (PIC)

- **Methods to manipulate phase space partitions**
  - Reverse emittance exchange using absorbers (REMEX)
  - Bunch coalescing (NF and MC can share injector)

- **Technology for better cooling**
  - Pressurized RF cavities (HPRF)
    - simultaneous energy absorption and acceleration and
    - phase rotation, bunching, cooling to increase initial muon capture
    - higher gradient in magnetic fields than in vacuum cavities
  - Helical Solenoid (HS)
  - High Temperature Superconductor
    - HCC final stages
    - High field solenoid cooling
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: \( E_{\text{com}} = 5 \text{ TeV}, \langle L \rangle = 10^{35} \)
  - Another design goal is 1.5 TeV to complement the LHC

- Many new ideas in the last 6 years. A new ball game!
  - (many new ideas have been developed with DOE SBIR funding)
One Scheme

- A six-dimensional (6D) ionization cooling channel based on helical magnets surrounding RF cavities filled with dense hydrogen gas is the basis for one plan to build 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 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.
  - Crucial radiation tests of HP RF will be done at Fermilab next year.

- New cooling ideas, such as Parametric-resonance Ionization Cooling and Reverse Emittance Exchange, will be employed to further reduce transverse emittances to a few mm-mr to allow high luminosity with fewer muons.

- 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-like RF to accelerate positive and negative muons in a 10-pass RLA.

- A new precooling idea based on a HCC with $z$ dependent fields is being developed for MANX, an exceptional 6D cooling experiment.
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
Neutrino Factory use of 8 GeV SC Linac

Beam cooling allows muons to be recirculated in the same linac that accelerated protons for their creation. Running the Linac CW can put a lot of cold muons into a small aperture neutrino factory storage ring.
Muon Collider use of 8 GeV SC Linac

Or a coalescing ring (also new for COOL07) can prepare more intense bunches for a muon collider.

23 GeV Coalescing Ring

~ 700m Active Length

Target and Muon Cooling Channel

Recirculating Linac for Neutrino Factory
5 TeV ~ SSC energy reach
~5 X 2.5 km footprint
Affordable LC length (5 km), includes ILC people, ideas
More efficient use of RF: recirculation and both signs
High L from small emittance!
with fewer muons than originally imagined:
  a) easier p driver, targetry
  b) less detector background
  c) less site boundary radiation

This recirculating linac approach is much like CEBAF at Jlab. However a single linac with teardrop return arcs looks better and is a subject of a new SBIR proposal.
Alternative technological paths to a LEMC are emerging

- **6-d Cooling** – (first 6 orders of 6D cooling)
  - HCC with imbedded High-Pressure RF (original),
  - MANX HCC segments alternating with RF, and/or
  - Guggenheim Helix

- **Extreme Transverse Cooling** – (2 orders)
  - Parametric-resonance Ionization Cooling,
  - Reverse Emittance Exchange REMEX,
  - High-Temperature Superconductor for high B, and
  - Designs using clever field suppression for RF
Muon Collider Design Options

Low emittance option
Very challenging option so far:
- need convincing ideas of how to incorporate RF into HCC
- need proof that HPRF will work under ionizing beam
- needs viable design for the next cooling stages – PIC/REMEX
- needs collider lattice design with necessary parameters

High emittance option
a rather solid ground under the feet, but not without its risks and deficiencies:
- high muon bunch intensity $2 \cdot 10^{12}$
- slow cooling resulting in poor muon transmission
- high p-driver bunch intensity

MCTF scenario
tries to alleviate the shortcoming of the high emittance option by borrowing some ideas from the low emittance option:
- faster 6D cooling by using HCC and/or FOFO snake
- bunch merging at high energy (20-30GeV)
- additional cooling using Fernow lattice or PIC (may become possible due to later bunch merging and lower total intensity)
- increased rep-rate to compensate for reduction in peak luminosity
FY08 MCTF Design & Simulations Plan

Collider ring:
- Optimization of the collider ring design
- Study of implications of the “dipole first” option for detector protection
- Beam-beam simulations
- Detailing of the design with corrector circuits, injection and collimation systems

Basic 6D ionization cooling:
- “Guggenheim” RFOFO channel:
  - More realistic modeling of the magnetic field
  - Alternative design with open cell RF cavities with solenoids in the irises
- Helical cooling channel
  - Design of RF structure which can fit inside the “slinky” helical solenoid
  - Design and simulation of the segmented channel
- FOFO snake:
  - tracking simulations and optimization
- Side-by-side comparison of the three structures to choosing the baseline scheme

Final cooling:
- Complete design of the 50T channel with required matching between the solenoids
- Channel design incorporating Fernow’s lattice with zero magnetic field in RF
- Feasibility study of the PIC/REMEX scheme
RF power requirements for the Muon collider linac

V. Yakovlev, N. Solyak

03/13/2008

Feature of the muon collider linac – high bunch population, 1-2e12.

ILC linac – 2e10.

Problems:

1. Strong cavity loading by a single bunch;
2. Energy spread in the bunch;
3. Bunch timing;
4. Transverse kick and emittance dilution;
5. RF – kick.
Parameter Spreadsheet

- On workshop web page
- A working document to connect pieces
- Consistent beginning to end connections
  - Example: change collider E, see P on target change
- Will become basis for design report
- Includes play pages for “what-if” scenarios
- See Mary Anne or me with suggestions for additions and improvements e.g. Site boundary radiation levels, wall-plug power, linac wakefield and beam loading parameters, cost, etc.
Muons, Inc.

**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: $\varepsilon = 200 \mu m$, $100 \mu m$
  - Parametric-resonance IC: $\varepsilon = 25 \mu m$, $100 \mu m$
  - Reverse Emittance Exchange: $\varepsilon = 2 \mu m$, $2 \text{cm}$

At 2.5 TeV on 2.5 TeV

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

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.
Updated Letter of Intent to Propose
MANX, A 6D MUON BEAM COOLING EXPERIMENT

Robert Abrams¹, Mohammad Alsharo’a¹, Charles Ankenbrandt², Emanuela Barzi², Kevin Beard³, Alex Bogacz³, Daniel Broemmelsiek², Alan Bross², Yu-Chiu Chao³, Mary Anne Cummings¹, Yaroslav Derbenev³, Henry Frisch⁴, Stephen Geer², Ivan Gonin², Gail Hanson⁵, Martin Hu², Andreas Jansson¹*, Rolland Johnson¹*, Stephen Kahn¹, Daniel Kaplan⁶, Vladimir Kashikhin², Sergey Korenev¹, Moyses Kuchnir¹, Mike Lamm², Valeri Lebedev², David Neuffer², David Newsham¹, Milorad Popovic², Robert Rimmer³, Thomas Roberts¹, Richard Sah¹, Vladimir Shiltsev², Linda Spentzouris⁶, Alvin Tollestrup², Daniele Turrioni², Victor Yarba², Katsuya Yonehara², Cary Yoshikawa², Alexander Zlobin²

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Rol -3/20/2008 NFMCC Meeting FNAL 18
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
    • $5.5^8 \sim 10^6$ 6D emittance reduction with 8 HCC sections of absorber alternating with (SC?)RF sections.
  – New technology
Phase II Proposals Due April 18

• HCC Magnets
  – Magnet Technology: HTS, HS
  – Incorporate RF, Improve simulations

• Stopping Muon Beams
  – Improve mu2e with HCC and other new ideas

• Compact, tunable RF
  – New ideas for FFAGs, commercial uses:
    • Booster, MI, cancer therapy
Low Emittance Muon Collider
Prospects: we are getting closer!

• 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

• LEMC Workshop April 21-25 here at Fermilab!
It will be warmer!

New subtopics:

Linac parameters such as bunch intensities, power,…

High Power Project-X

Even more theoretical food for thought! Thanks Estia