



Muons, Inc.

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



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Muons, Inc. Project History

Year	Project	Expected Funds	Research Partner
■ 2002	Company founded		
■ 2002-5*	High Pressure RF Cavity	\$600,000	IIT
■ 2003-7*	Helical Cooling Channel	\$850,000	JLab
■ 2004-5†	MANX demo experiment	\$ 95,000	FNAL TD
■ 2004-7*	Phase Ionization Cooling	\$745,000	JLab
■ 2004-7*	H2 Cryostat (HTS HS)	\$795,000	FNAL TD
■ 2005-8	Reverse Emittance Exch.	\$850,000	JLab
■ 2005-8	Capture, ph. rotation	\$850,000	FNAL AD
■ 2006-9	G4BL Sim. Program	\$850,000	IIT
■ 2006-9	MANX 6D Cooling Demo	\$850,000	FNAL TD
■ 2007-8	Stopping Muon Beams	\$100,000	FNAL APC
■ 2007-8	HCC Magnets	\$100,000	FNAL TD
■ 2007-8	Compact, Tunable RF	<u>\$100,000</u>	FNAL AD (NP)
		\$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 (HCC)
 - Helical Cooling Channel
 - 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 $10^{34}/\text{s-cm}^2$ 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  New Phase II grant
 - 100 m (with HP RF, maybe phase rotation)
- 6D HCC cooling, ending with 50 T magnets  Detailed theory in place, simulations underway.
 - 200 m (HP GH2 RF or LH2 HCC and SCRF)
- Parametric-resonance Ionization Cooling  Detailed theory in place, simulations underway.
 - 100 m
- Reverse Emittance Exchange (1st stage)  Detailed theory in place, simulations underway.
 - 100 m
- Acceleration to 2.5 GeV  Detailed theory in place, simulations underway.
 - 100 m at 25 MeV/c accelerating gradient
- Reverse Emittance Exchange (2nd stage)  Detailed theory in place, simulations underway.
 - 100 m
- Inject into Proton Driver Linac
- Total effect:
 - Initial 40,000 mm-mr reduced to 2 mm-mr in each transverse plane
 - Initial $\pm 25\%$ $\Delta p/p$ 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.

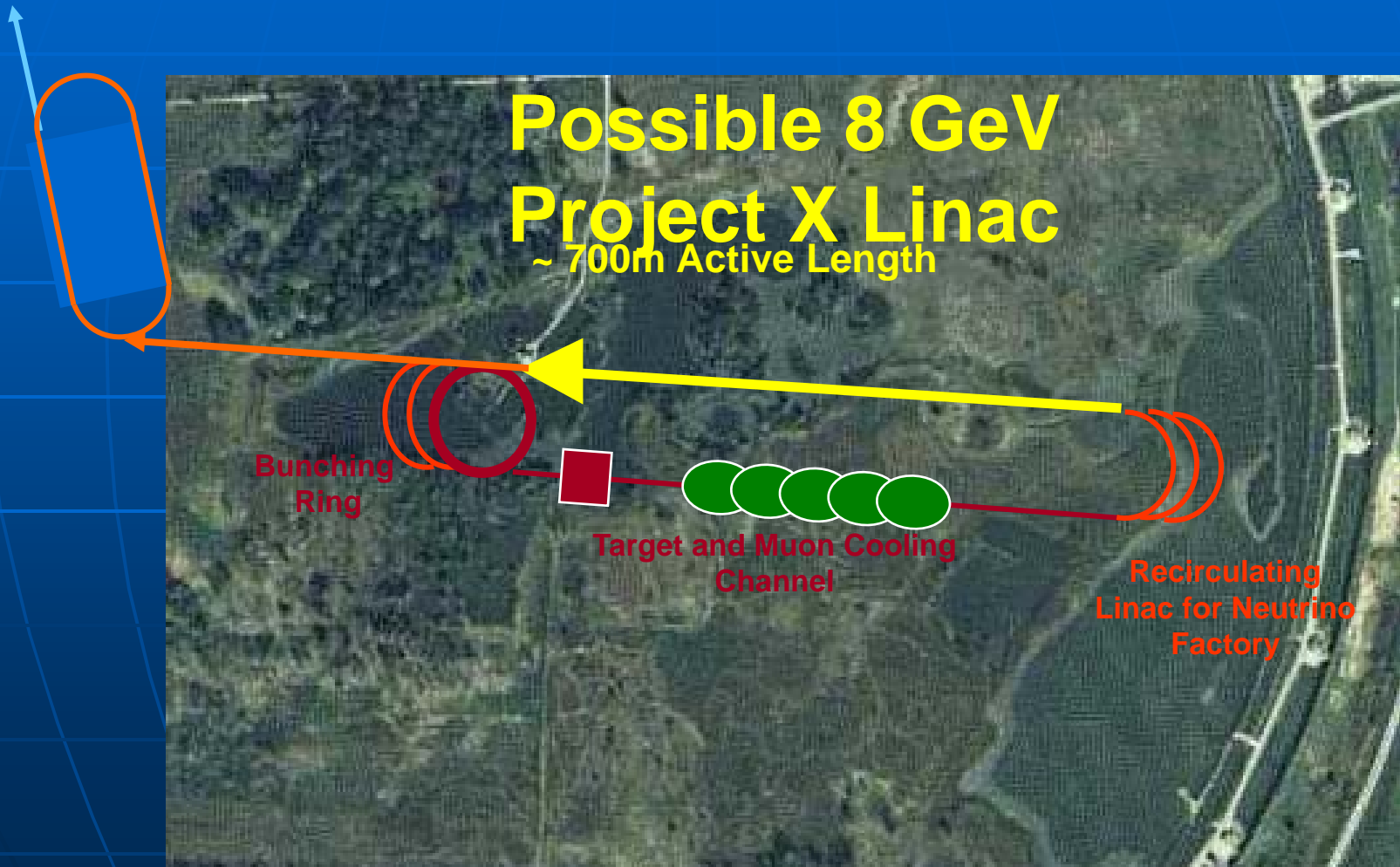
New Phase II grant



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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.

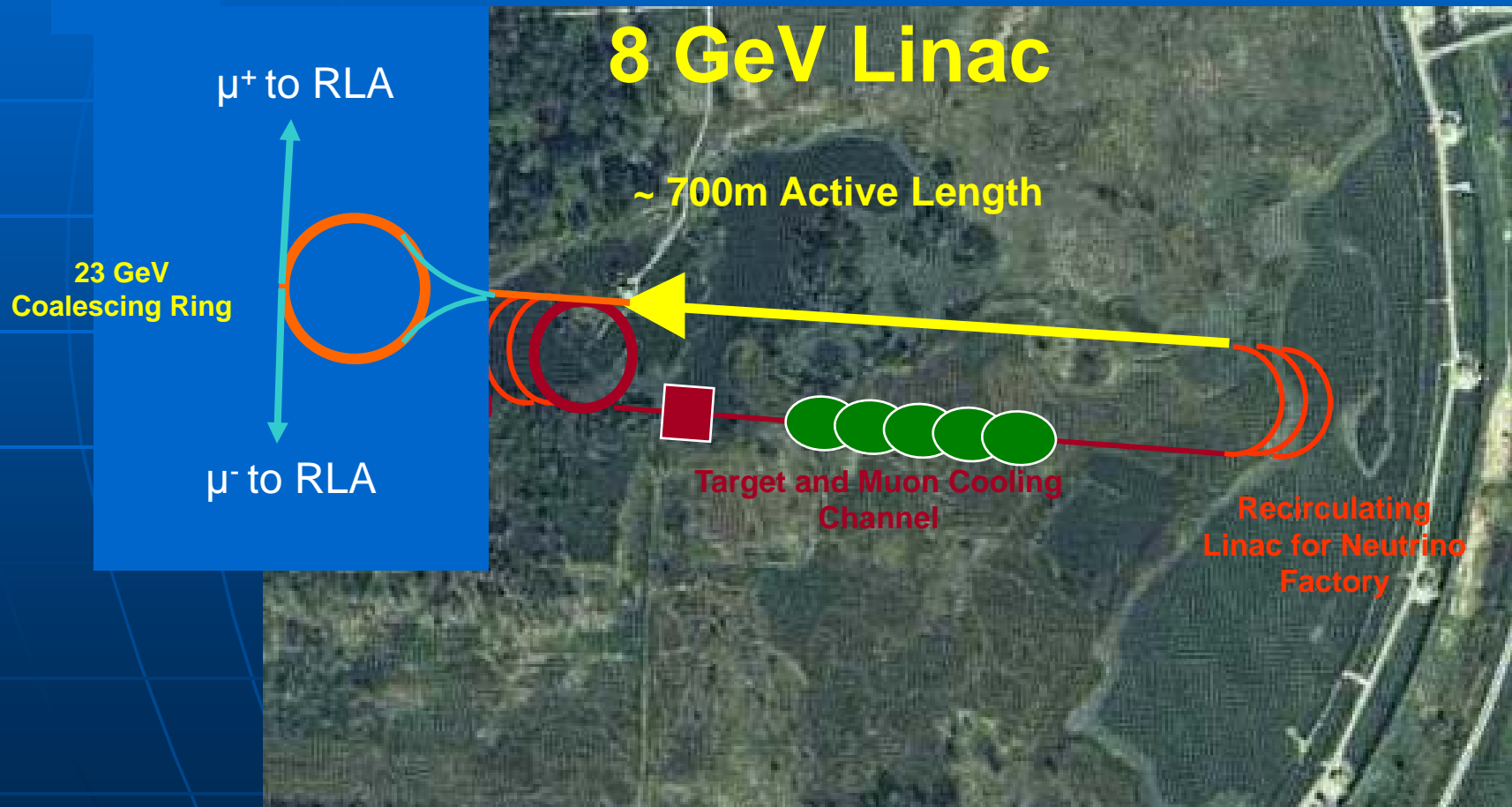




Muons, Inc.

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





5 TeV ~ SSC energy reach

~5 X 2.5 km footprint

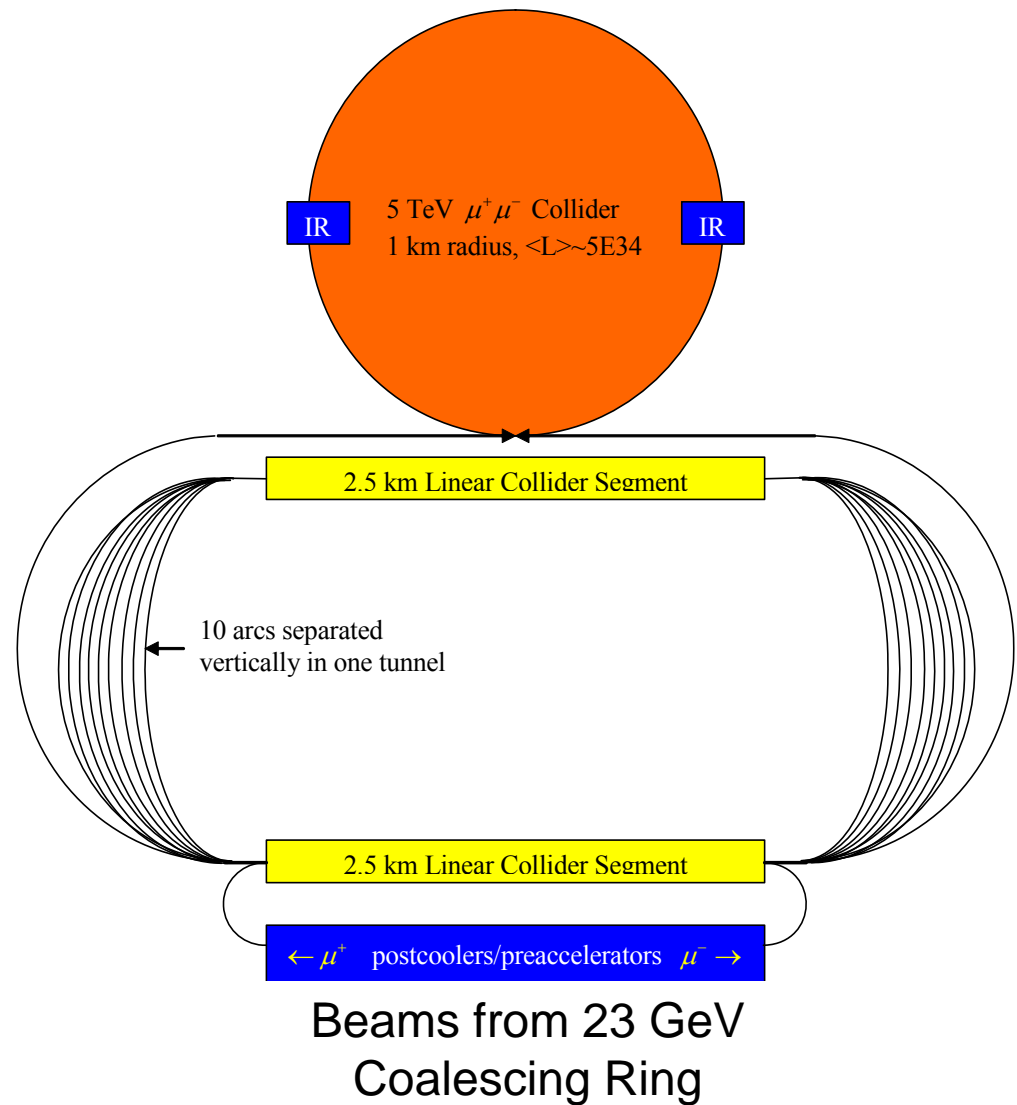
Affordable LC length (5 km),
includes ILC people, ideas

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, $1\text{-}2 \times 10^{12}$.

ILC linac – 2×10^{10} .

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.



Muon Collider Emittances and Luminosities

• After:	ε_N tr	ε_N long.
– Precooling	20,000 μm	10,000 μm
– Basic HCC 6D	200 μm	100 μm
– Parametric-resonance IC	25 μm	100 μm
– Reverse Emittance Exchange	2 μm	2 cm

At 2.5 TeV on 2.5 TeV

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

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

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

$$\Delta v = 0.06 \quad \beta^* = 0.5 \text{ cm}$$

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

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

20 Hz Operation:

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

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

$$0.3 \mu^\pm / p$$



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 Jansson^{2*}, Rolland Johnson^{1*}, 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

¹*Muons, Inc.*

²*Fermi National Accelerator Laboratory*

³*Thomas Jefferson National Accelerator Facility*

⁴*University of Chicago*

⁵*University of California at Riverside*

⁶*Illinois Institute of Technology*

- ^{*} Contact, rol@muonsinc.com, (757) 870-6943
- ^{*} Contact, jansson@fnal.gov, (630) 840-2824



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!



Low Emittance Muon Collider Workshop

Fermi National Accelerator Laboratory

April 21-25, 2008

Sponsored by Fermilab and Muons, Inc.

• NFMCC Members:

- Fermilab
- Thomas Jefferson Lab
- Brookhaven National Lab
- Argonne National Lab
- Lawrence Berkeley National Lab
- Illinois Institute of Technology
- Michigan State University
- University of California at Los Angeles
- University of California at Riverside
- University of Mississippi
- KEK
- Muons, Inc.

• Non-NFMCC Members:

- Fermilab
- Thomas Jefferson Lab
- Illinois Institute of Technology
- University of Michigan
- University of Tsukuba / Waseda University
- Osaka University
- KEK
- Hbar Technologies, LLC
- Muons, Inc.

34

8

1

2

1

1

2

5

2

2

2

1

8

It will be warmer!

New subtopics:

Linac parameters such as
bunch intensities, power,...

31

18

2

2

1

1

2

1

1

2

High Power Project-X

Even more theoretical food
for thought! Thanks Estia