Muons, Inc. Update

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

Muons, Inc. has a very rich program, too much for 25 minutes

- http://www.muonsinc.com/ has links to papers

Muons, Inc.

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	$100,000	FNAL AD (NP)
			$6,785,000	

† Not continued to Phase II *Closed

DOE SBIR/STTR funding: Solicitation September, Phase I proposal due November, Winners ~May, get $100,000 for 9 months, Phase II proposal due April, Winners June, can 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

Muons, Inc.

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 (mu2e)
    - 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)
  - High Energy 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_{com}=5 TeV, <L>=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)

Another 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 this year.
- New cooling ideas, such as Parametric-resonance Ionization Cooling, Reverse Emittance Exchange, and high field solenoids, 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 multi-pass RLA.
- a new precooling idea based on a HCC with *z* dependent fields is being developed for MANX, an exceptional 6D cooling experiment.

Muons, Inc.

700 m muon Production and Cooling (showing approximate lengths of sections)

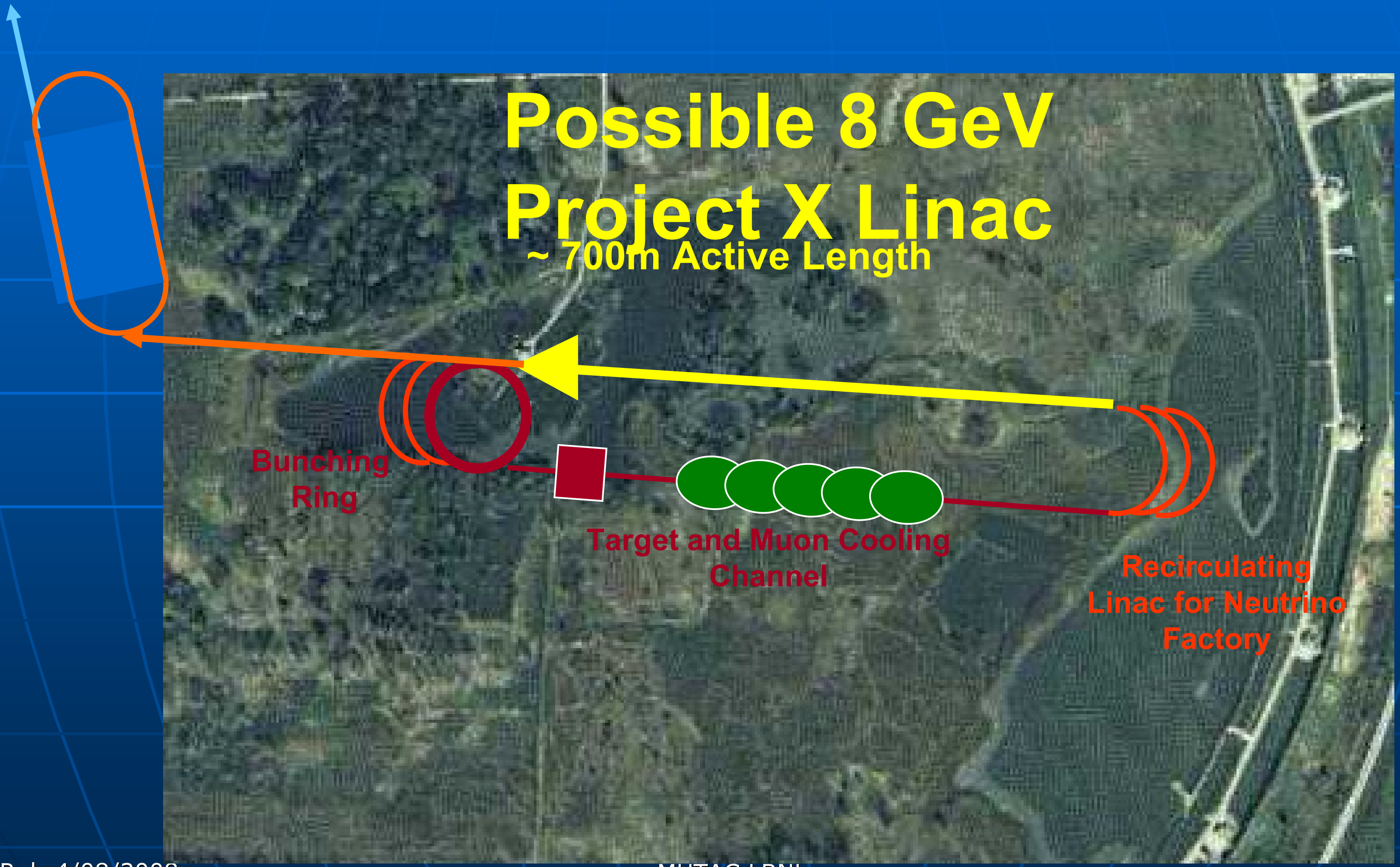
- 8 GeV Proton storage ring, loaded by Linac
  - 2 T average implies radius=8000/30x20~14m
- Pi/mu Production Target, Capture, Precool sections ← Phase II grant
  - 100 m (with HP RF, maybe phase rotation)
- 6D HCC cooling, ending with 50 T magnets
  - 200 m (HP GH2 RF or LH2 HCC and SCRF)
- Parametric-resonance 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

Detailed theory in place, simulations underway. (→ 6D HCC cooling; Parametric-resonance Ionization Cooling; Reverse Emittance Exchange (1st stage))

Phase II grant (→ Acceleration to 2.5 GeV)

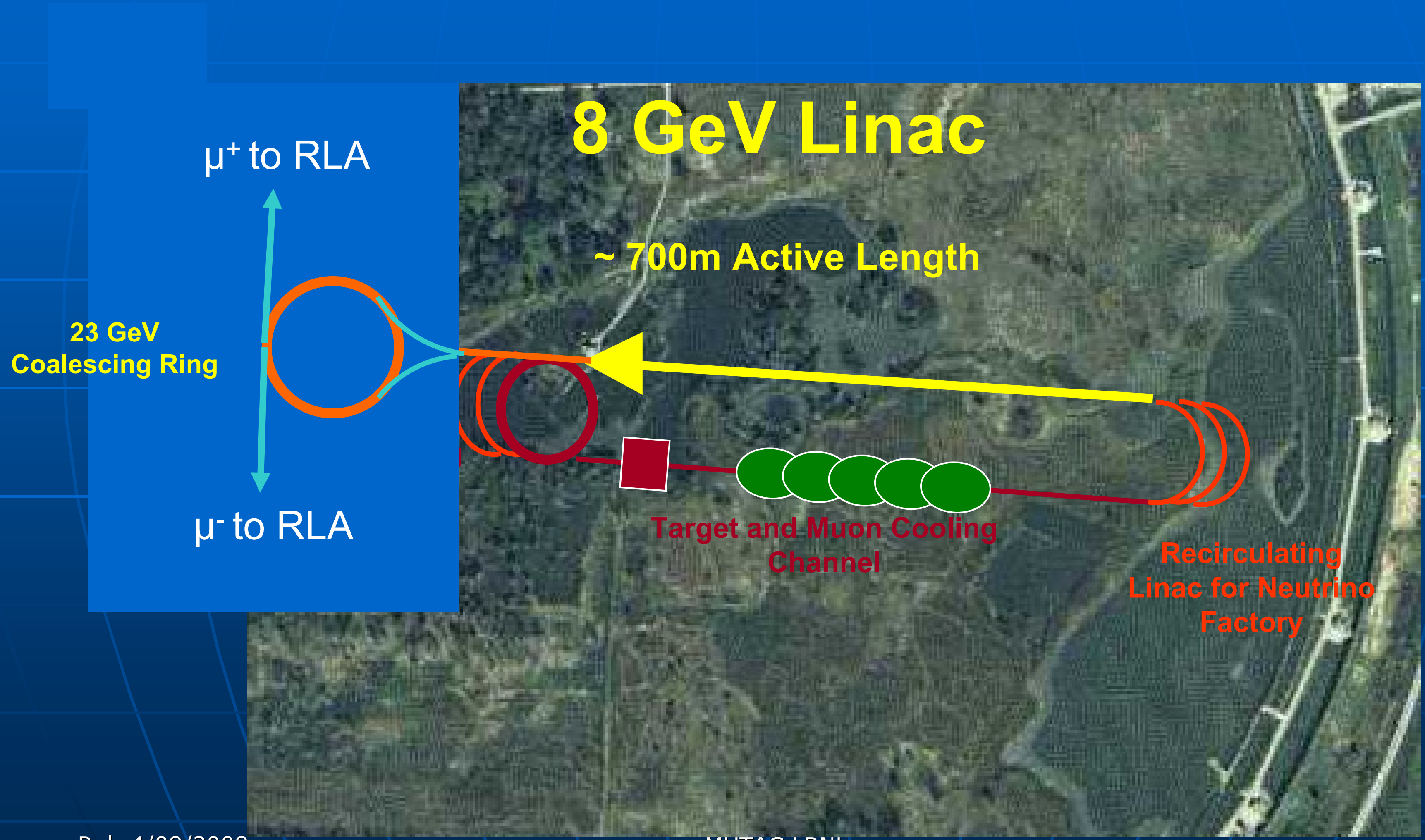
Neutrino Factory use of 8 GeV SC Linac

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.

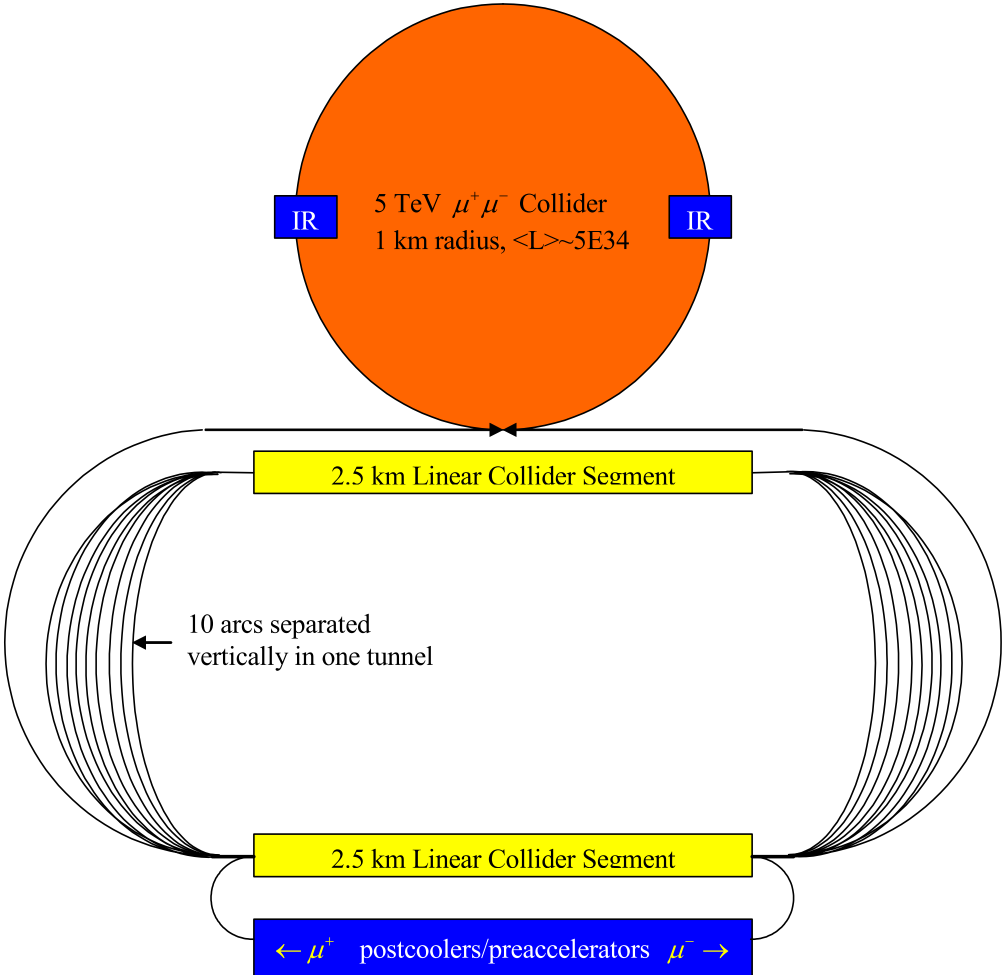


Muon Collider use of 8 GeV SC Linac

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



- 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



Beams from 23 GeV Coalescing Ring

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.

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

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

$\gamma \approx 2.5\times10^4$ $n = 10$

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

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

$\sigma_z = 3\,mm$ $\Delta\gamma/\gamma = 3\times10^{-4}$

$\tau_\mu \approx 50\,ms \Rightarrow 2500\,turns/\tau_\mu$

20 Hz Operation:

$$\langle L\rangle \approx 4.3\times10^{34} / cm^2 - s$$

$$Power = (26\times10^9)(6.6\times10^{13})(1.6\times10^{-19}) = 0.3MW$$

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

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.

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

RoI comment: Biggest difference between HEMC and LEMC is not emittance.
LEMC bunch intensity ~1-2e11 (2e10 when E<23 GeV)

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

ILC linac – 2e10.

Problems:

Strong cavity loading by a single bunch;
Energy spread in the bunch;
Bunch timing;
Transverse kick and emittance dilution.
RF – kick.

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

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

Robert Abrams[1], Mohammad Alsharo'a[1], Charles Ankenbrandt[2], Emanuela Barzi[2], Kevin Beard[3], Alex Bogacz[3], Daniel Broemmelsiek[2], Alan Bross[2], Yu-Chiu Chao[3], Mary Anne Cummings[1], Yaroslav Derbenev[3], Henry Frisch[4], Stephen Geer[2], Ivan Gonin[2], Gail Hanson[5], Martin Hu[2], Andreas Jansson[2*], Rolland Johnson[1*], Stephen Kahn[1], Daniel Kaplan[6], Vladimir Kashikhin[2], Sergey Korenev[1], Moyses Kuchnir[1], Mike Lamm[2], Valeri Lebedev[2], David Neuffer[2], David Newsham[1], Milorad Popovic[2], Robert Rimmer[3], Thomas Roberts[1], Richard Sah[1], Vladimir Shiltsev[2], Linda Spentzouris[6], Alvin Tollestrup[2], Daniele Turrioni[2], Victor Yarba[2], Katsuya Yonehara[2], Cary Yoshikawa[2], Alexander Zlobin[2]

[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

- Purpose: test theory and simulations
  - Helical Cooling Channel (HCC)
    - With continuous RF for best cooling
    - Also pion decay channel
  - Momentum-dependent HCC
    - Stopping muon beams
    - Precooler
    - Dp/p control in HTS solenoid scheme
    - Alternate to continuous RF
    - MANX
- And demonstrate
  - Helical Solenoid technology
  - Longitudinal cooling
  - 6D cooling in continuous absorber
- Plan to have proposals ready this fall to FNAL and RAL

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

Titles of 2008 Muons, Inc. DOE Proposals (grant decisions due by May 1, 2008)

	topic	partner	title
HEP	49a	JLab	Pulsed RLA
HEP	49a	JLab	Achromatic Low Beta Design
NP	36a	JLab	Rugged Ceramic Window for RF
BES	3b	JLab	High Power SRF Coupler for 1.4 GHz
NN	45d	Jlab	User-Friendly Detector Simulations
HEP	50a	FNAL	Pressurized RF Cavities for Muon Beam Cooling
HEP	49a	FNAL	Novel Muon Collection Techniques
NP	36a	FNAL	Metallic Deposition
HEP	52a	FNAL	Multipixel-Photon Counters for HEP Experiments
HEP	49a	BNL	Plasma Lenses for Pion Collection
HEP	51b	FSU	HTS for High Magnetic Field Applications
HEP	51b	FSU	HTS Quench Detection and Protection
BES	3a	UC	Graphical User Interface for Radiation Simulations
HEP	50a	LBNL	RF Breakdown studies using Pressurized Cavities

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 and RAL
- LEMC Workshop April 21-25 at Fermilab!

Muons, Inc.

Muons at Fermilab

An implementation plan with affordable, incremental, independently-fundable steps based on the SC PD Linac, each with HEP and Accelerator goals:

1. attractive 6D Cooling experiment (MANX!)
2. triple-duty SC PD Linac (p's, μ's, ILC test) (HINS!)
3. intense stopping muon beams (mu2e!)
   p accumulator/buncher, target, muon cooling
4. exceptional neutrino factory (23 GeV)
   more cooling, recirculation, PDL upgrade, decay racetrack
5. Z' factory
   more cooling, recirculation, lower luminosity required, use more existing infrastructure
6. Higgs factory (~300 GeV com)
   more cooling, RLA, coalescing & collider rings, IR
7. energy frontier muon collider (5 TeV com)
   more RLA, deep ring, IRs

Low Emittance Muon Collider Workshop

Fermi National Accelerator Laboratory

April 21-25, 2008

Sponsored by Fermilab and Muons, Inc.

- **NFMCC Members: 34**
  - Fermilab 8
  - Thomas Jefferson Lab 1
  - Brookhaven National Lab 2
  - Argonne National Lab 1
  - Lawrence Berkeley National Lab 1
  - Illinois Institute of Technology 2
  - Michigan State University 5
  - University of California at Los Angeles 2
  - University of California at Riverside 2
  - University of Mississippi 2
  - KEK 1
  - Muons, Inc. 8
- **Non-NFMCC Members: 31**
  - Fermilab 18
  - Thomas Jefferson Lab 2
  - Illinois Institute of Technology 2
  - University of Michigan 1
  - University of Tsukuba / Waseda University 1
  - Osaka University 2
  - KEK 1
  - Hbar Technologies, LLC 1
  - Muons, Inc. 2

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