Muon Beam Cooling for Colliders, Neutrino Factories, and Experiments

Rolland Johnson,
Muons, Inc.

- New inventions are improving the prospects for high luminosity Higgs factory and energy frontier muon colliders, intense neutrino factories, and new muon beams.

- Papers and presentations can be found on http://muonsinc.com with an invitation to 2nd annual "Snowmass-style" workshop on Low Emittance Muon Colliders this month at Fermilab Feb 12-16. Accelerators, Technology, Detectors, Experiments, Theory. Please come!

February 5, 2007 is Muons, Inc. 5 year anniversary!

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Muons, Inc. Small Business Innovation Research History

	Year	Project	Expected Funds	Research Partner
▪	2002	Company founded		
▪	2002-5	High Pressure RF Cavities	$600,000	IIT
▪	2003-6	Helical Cooling Channel	$850,000	JLab
▪	2004-5†	MANX demo experiment	$ 95,000	FNAL TD
▪	2004-7	Parametric-resonance I.C.	$745,000	JLab
▪	2004-7	Hydrogen Cryostat	$795,000	FNAL TD
▪	2005-8	Reverse Emittance Exch.	$850,000	JLab
▪	2005-8	Capture, ph. rotation	$850,000	FNAL AD
▪	2006-7*	6DMANX cooling demo	$100,000	FNAL TD
▪	2006-7*	G4Beamline	$100,000	IIT

* additional Phase II may be granted in June 2007 up to $750,000

† 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 up to $750,000 for 2 years

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New 2007 Phase I Proposals

- ANL- **Advanced HEP Simulation Tools Based on Geant4**
- BNL- **HTS High-Field Magnets for Muon Cooling**
- LBNL- **Breakdown in Pressurized RF Cavities**
- FNAL- **Compact, Tunable RF Cavities**
- FNAL- **Magnets for Muon 6D Helical Cooling Channels**
- FNAL- **Quench Protection for High-Field HTS Magnets**
- FNAL- **Stopping Muon Beams**
- FNAL- **Ultra-pure Metallic Deposition for RF Cavities**
- JLAB- **Recirculating Linacs for Muon Acceleration**
- JLAB- **High Power SRF Couplers for 1.3 GHz Applications**

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Muons, Inc. SBIR/STTR Collaboration:

- Fermilab:
  - Victor Yarba, Emanuela Barzi, Ivan Gonin, Timer Khabiboulline, Vadim Kashikhin, Vladimir Kashikhin, Gennady Romanov, Daniele Turrioni, Katsuya Yonehara, Sasha Zlobin
  - Dave Neuffer, Chuck Ankenbrandt, Al Moretti, Milorad Popovic, Jim Griffin
- IIT:
  - Dan Kaplan, Linda Spentzouris
- JLab:
  - Yaroslav Derbenev, Alex Bogacz, Kevin Beard, Yu-Chiu Chao, Robert Rimmer
- Muons, Inc.:
  - Rolland Johnson, <u>Bob Abrams</u>, Mohammad Alsharo'a, Mary Anne Cummings, Stephen Kahn, <u>Sergey Korenev</u>, Moyses Kuchnir, David Newsham, <u>Tom Roberts</u>, <u>Richard Sah</u>, <u>Cary Yoshikawa</u>
- Plus new proposals for 2007 with
  - ANL- Sasha Vaniachine
  - BNL- Ramesh Gupta
  - LBNL- Derun Li

First named are subgrant PI. Underlined are new/new status employees.

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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
    - Higher Gradient in magnetic fields than in vacuum cavities
  - High Temperature Superconductor for up to 50 T magnets
    - Faster cooling, smaller equilibrium emittance

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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_{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)

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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 (see LEMC workshop main page)
- 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?

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Progress on new ideas would be 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 Rick Fernow and Bob Palmer have another path to low emittance that looks promising.

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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

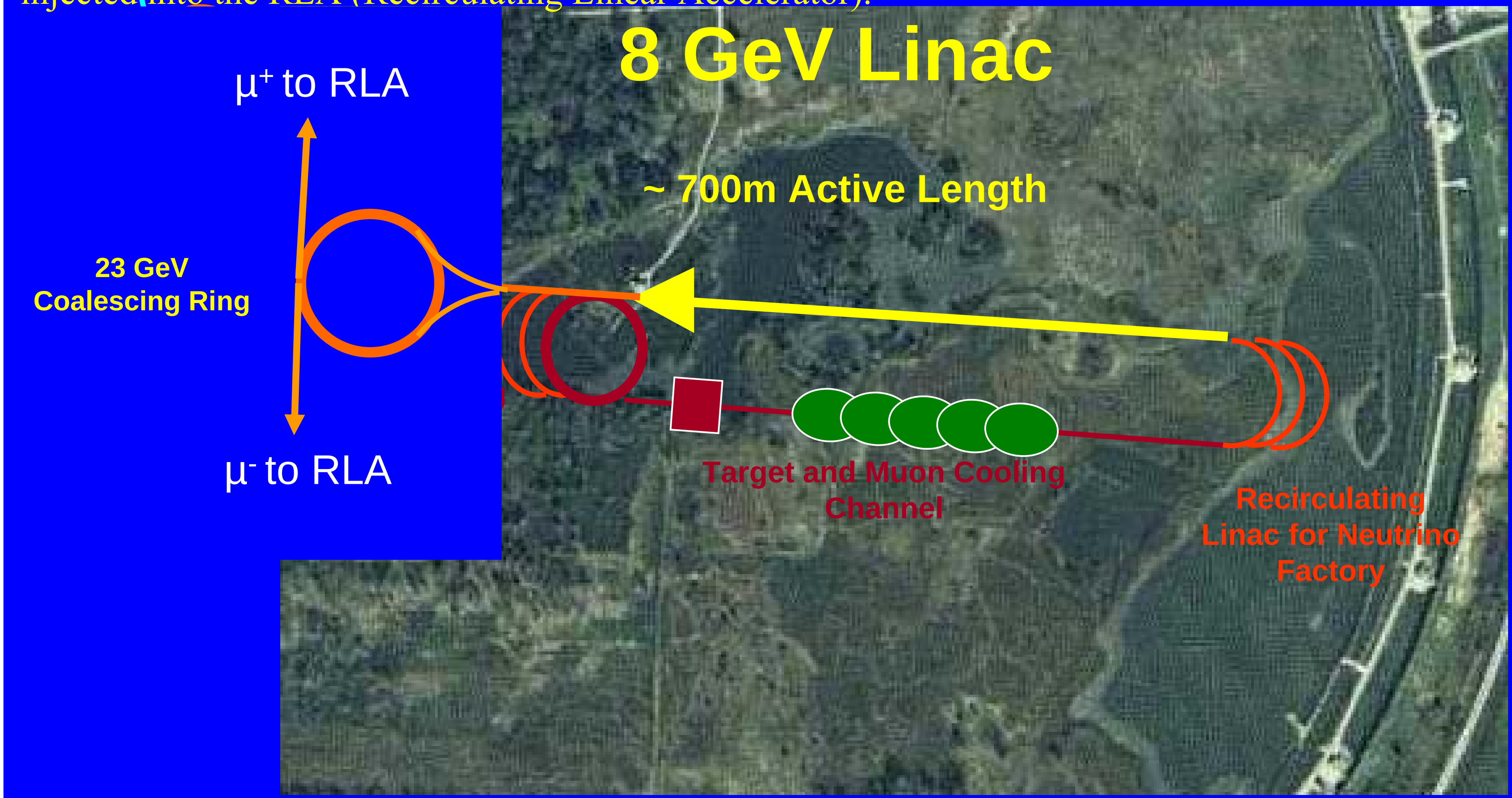
New Phase II grant

Detailed theory in place, simulations underway.

New Phase II grant

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 $10 \times 1.6\ 10^{10}$ muons/bunch become 10 bunches of 1.6×10^{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+3x6.8=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

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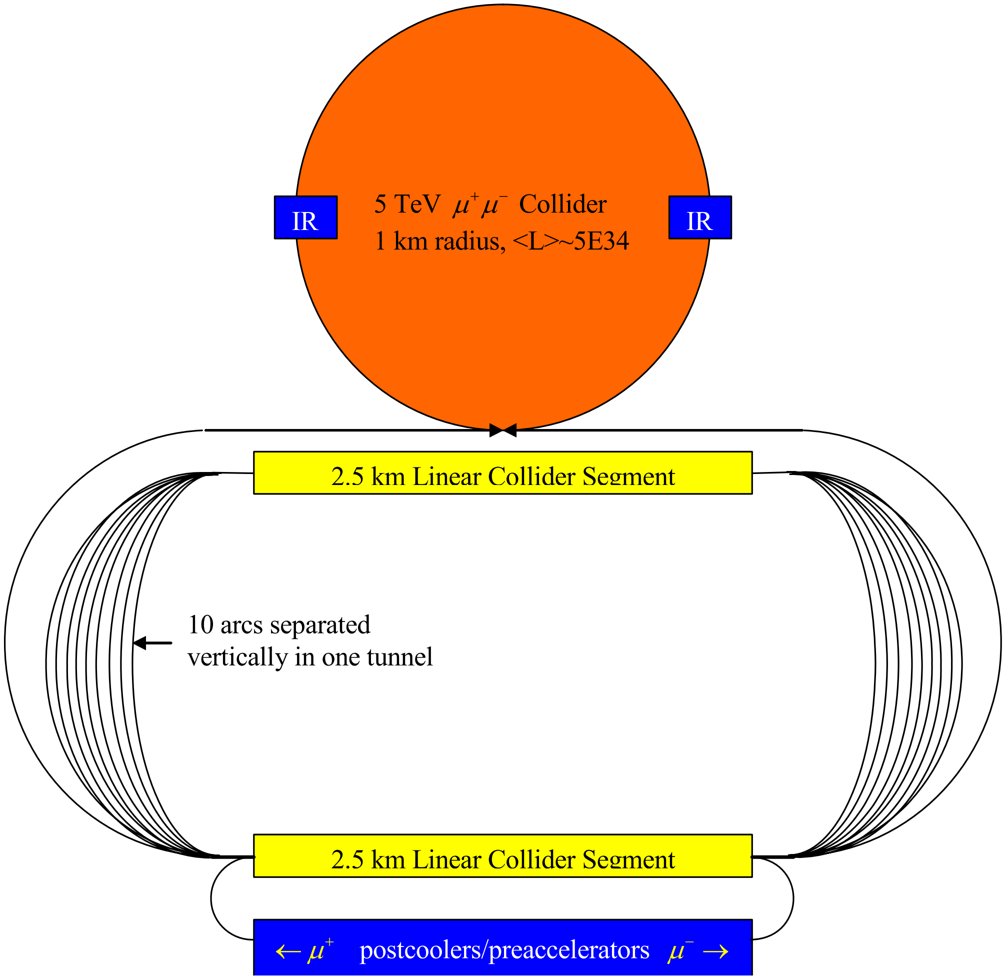
- 5 TeV ~ SSC energy reach
- ~5 X 2.5 km footprint
- Affordable LC length (half of baseline 500 GeV ILC), includes ILC people, ideas
- More efficient use of RF: recirculation and both signs
- High L from small emittance!
- 1/10 fewer muons than originally imagined:
  a) easier p driver, targetry
  b) less detector background
  c) less site boundary radiation



Beams from 23 GeV Coalescing Ring

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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

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

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

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

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

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

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

20 Hz Operation:

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

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

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

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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.

Low Emittance Muon Collider Workshop Goals for 2007

- A detailed plan for a 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,
- And a really good 6D cooling demonstration experiment proposed to Fermilab
  – (Next Slides on the status of MANX, a really good 6D cooling demonstration experiment)

Letter of Intent to propose a
SIX-DIMENSIONAL MUON BEAM COOLING EXPERIMENT FOR FERMILAB

Ramesh Gupta, Erich Willen
Brookhaven National Accelerator Laboratory

Charles Ankenbrandt, Emanuela Barzi, Alan Bross, Ivan Gonin, Stephen Geer, Vladimir Kashikhin, Valeri Lebedev, David Neuffer, Milorad Popovic, Vladimir Shiltsev, Alvin Tollestrup, Daniele Turrioni, Victor Yarba, Katsuya Yonehara, Alexander Zlobin
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

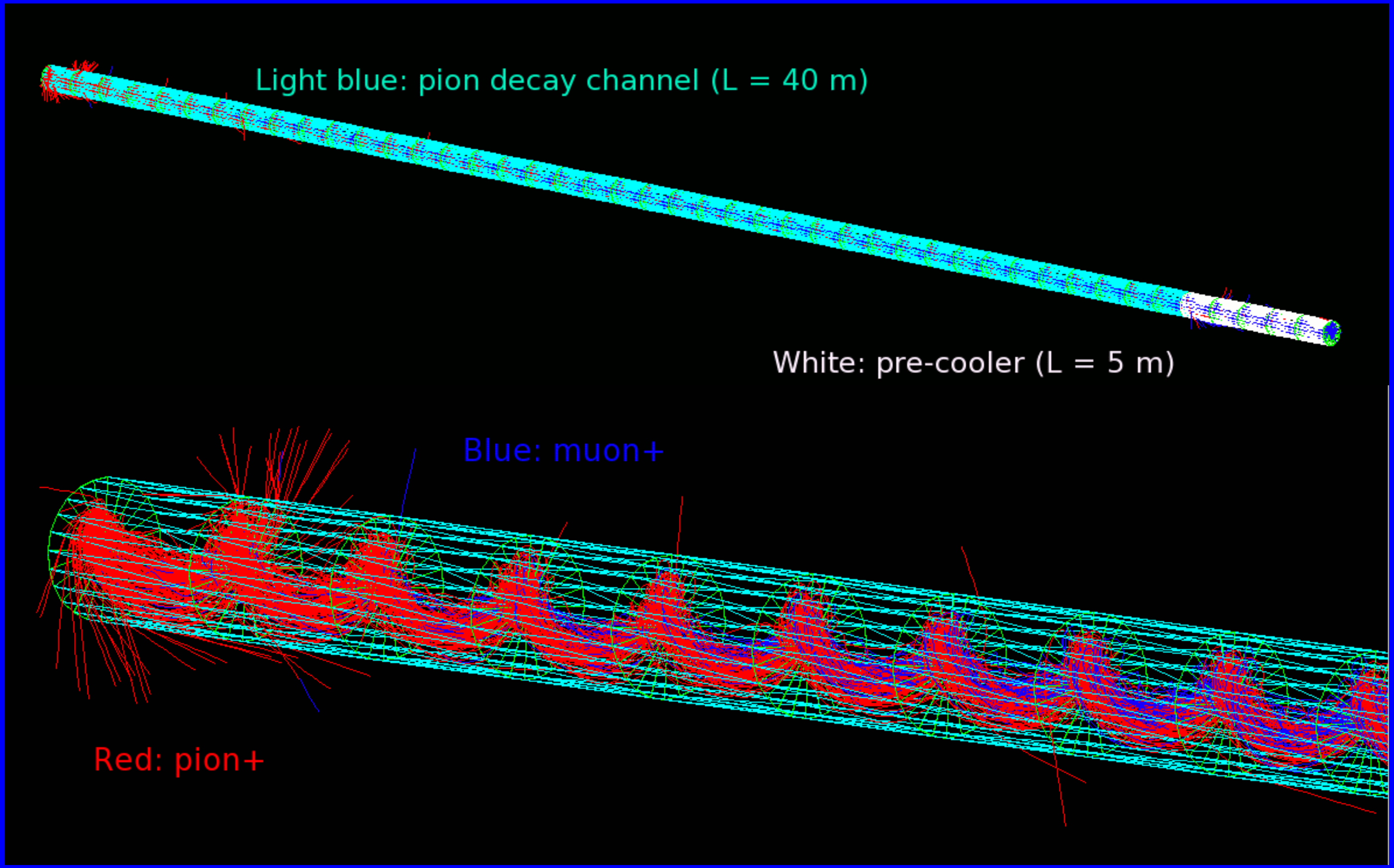
Submitted to Fermilab 5/9/2006

6DMANX demonstration experiment

Muon Collider And Neutrino Factory eXperiment

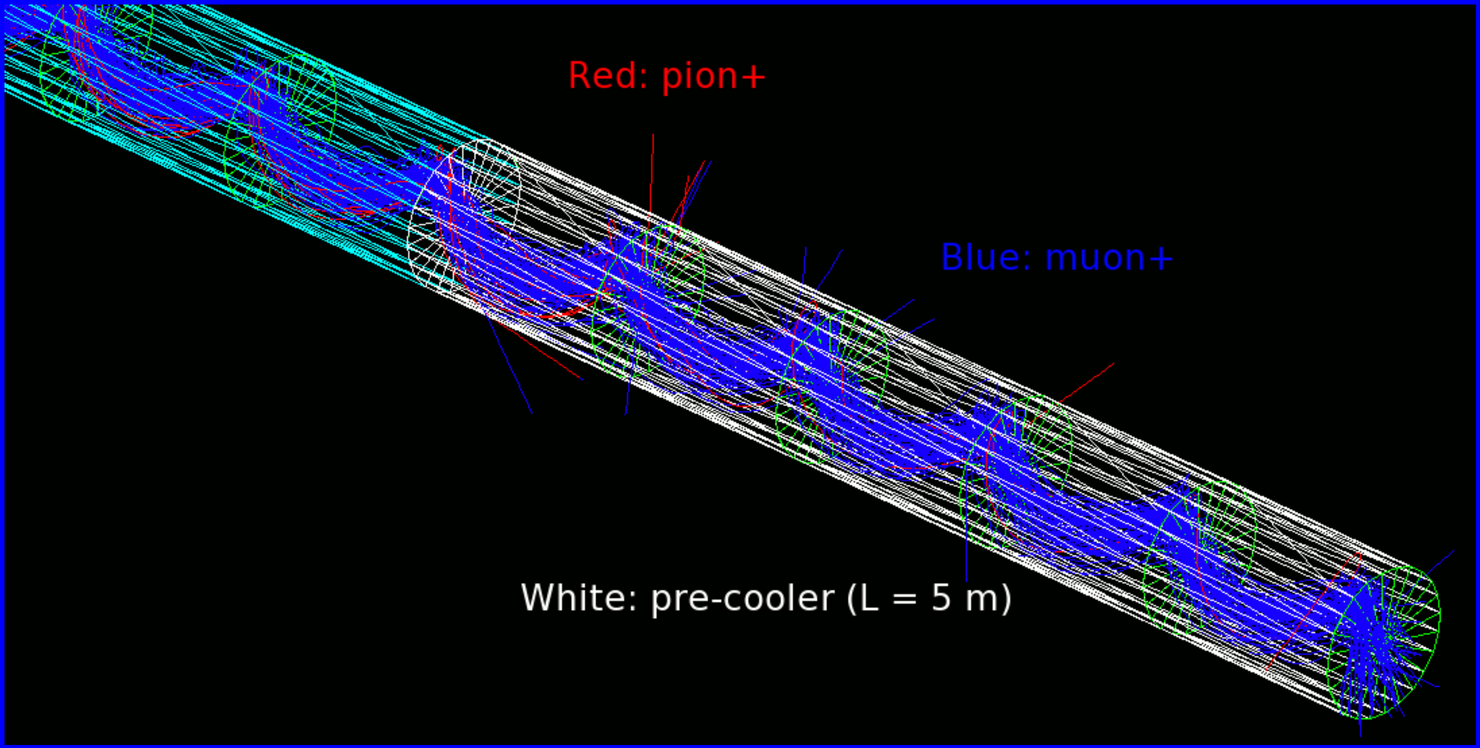
- To Demonstrate
  - Longitudinal cooling
  - 6D cooling in cont. absorber
  - Prototype precooler
  - Helical Cooling Channel
  - Alternate to continuous RF
    - 5.5^8 ~ 10^6 6D emittance reduction with 8 HCC sections of absorber alternating with (SC?)RF sections.
  - New technology

HCC with Z-dependent fields



40 m evacuated helical magnet pion decay channel followed by a 5 m liquid hydrogen HCC (no RF)

5 m Precooler and MANX



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

Equal decrement case.

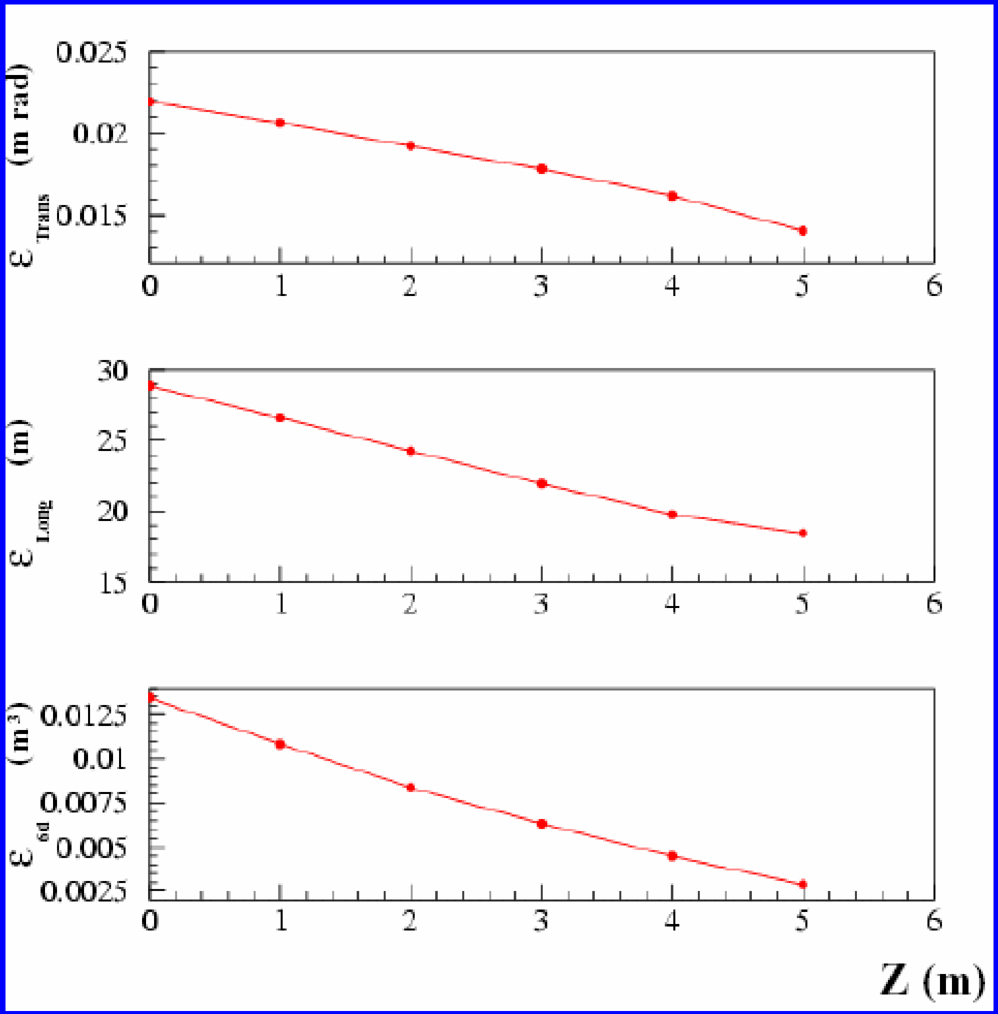
~x1.7 in each direction.

Total 6D emittance reduction ~factor of 5.5

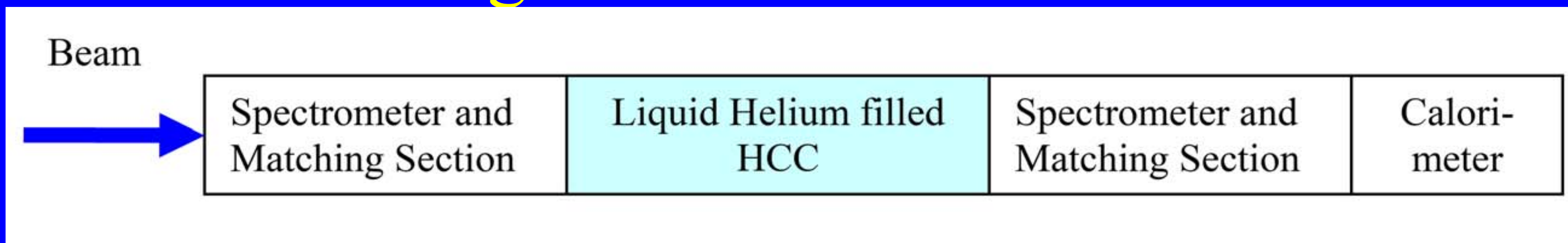
Note this would require serious magnets: ~10 T at conductor for 300 to 100 MeV/c deceleration

MANX results with B <5.5 T will also work!

below show LHe absorber



Turning the Precooler into MANX



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: Creating realistic z-dependent fields

Designing the matching sections

Simulating the experiment with scifi detectors

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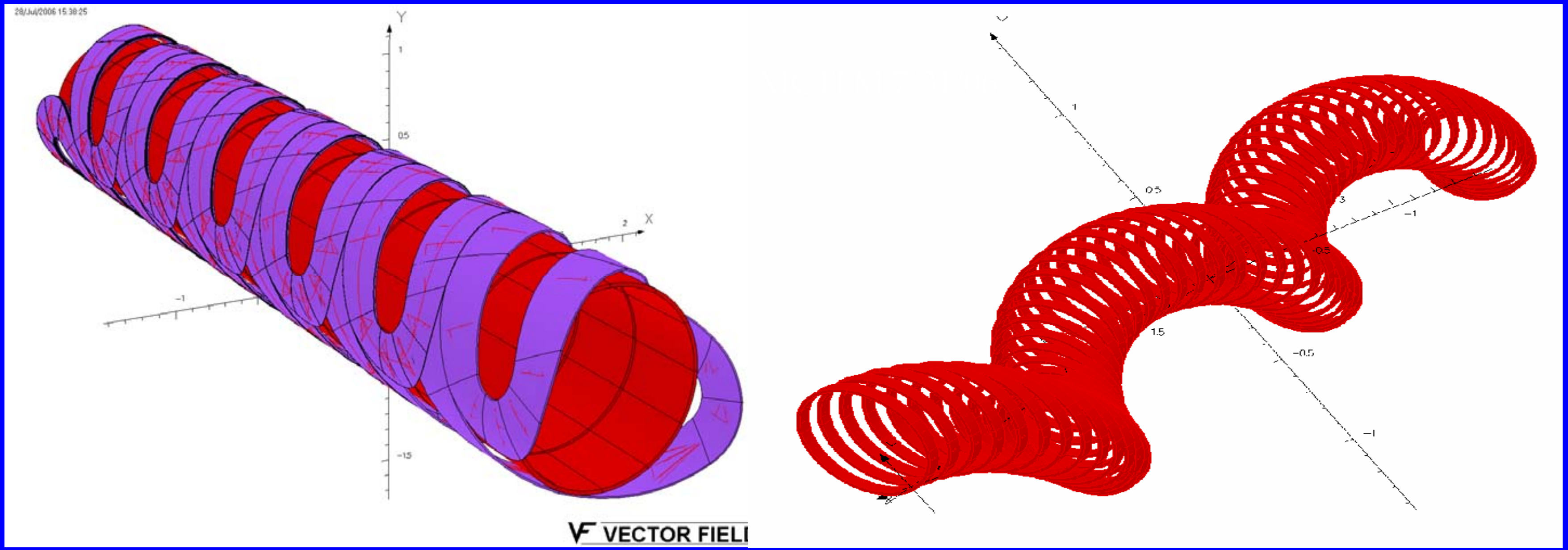
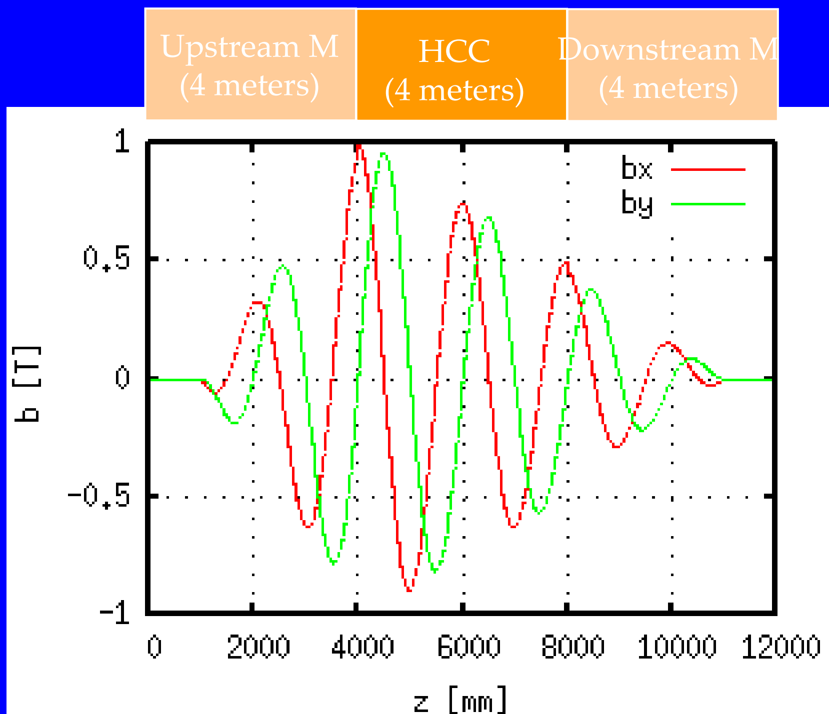
Possible MANX magnet designs

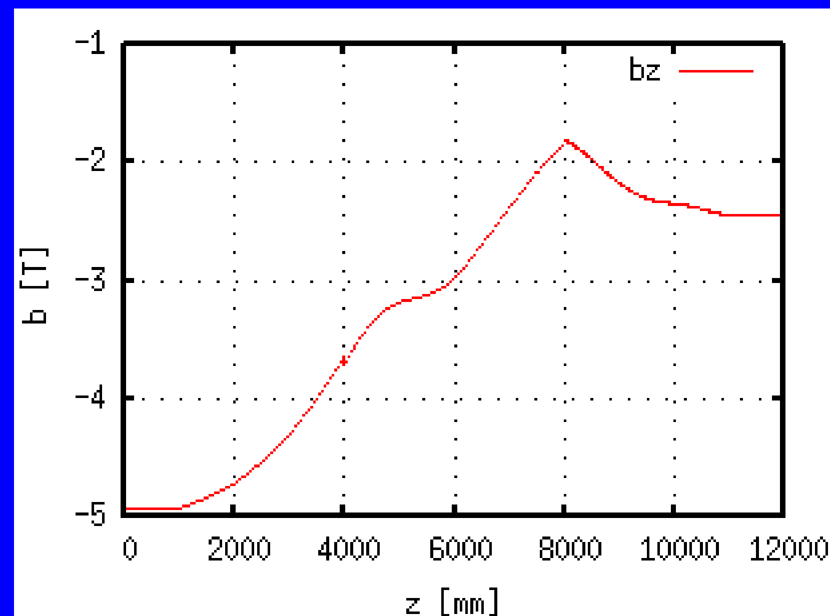


- Snake type MANX
- Consists of 4 layers of helix dipole
- Maximum field is ~7 T (coil diameter: 1.0 m)
- Field decays very smoothly
- Hard to adjust the field configuration

- 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

$$b_{matching} = \alpha b_0 z$$

b_0: Amplitude of initial helical dipole magnet

α: Ramping rate

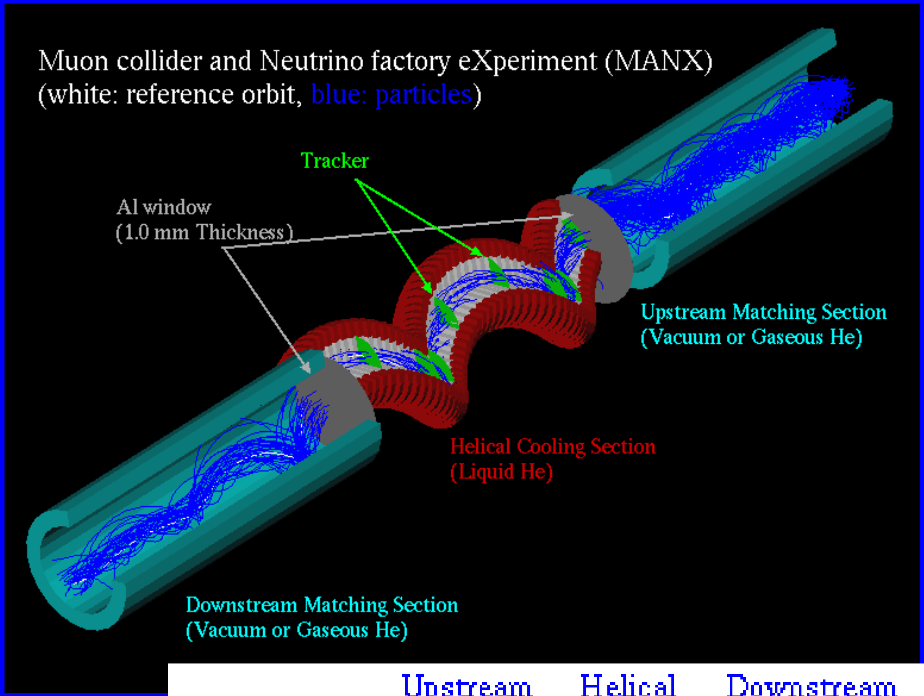
Adjust solenoid strength to connect to a proper helical orbit.

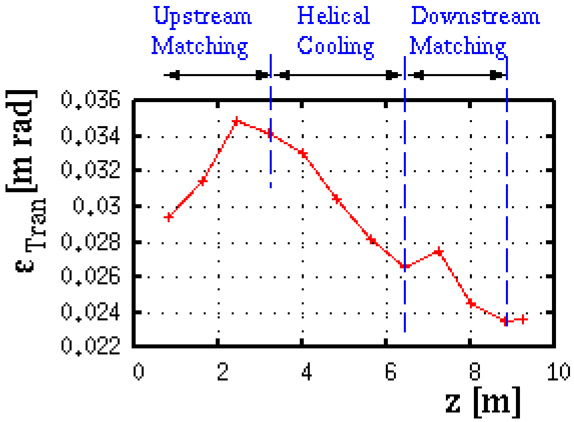
Katsuya's Simulation study

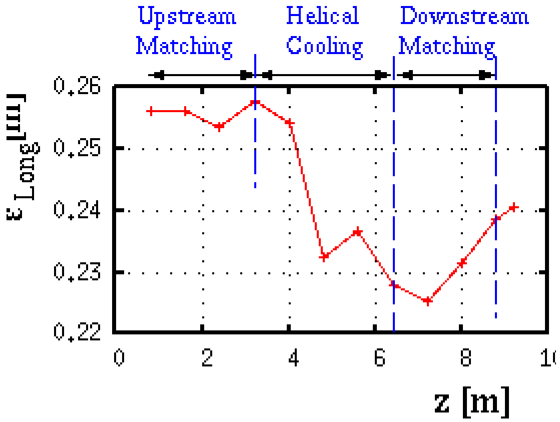
Initial beam profile

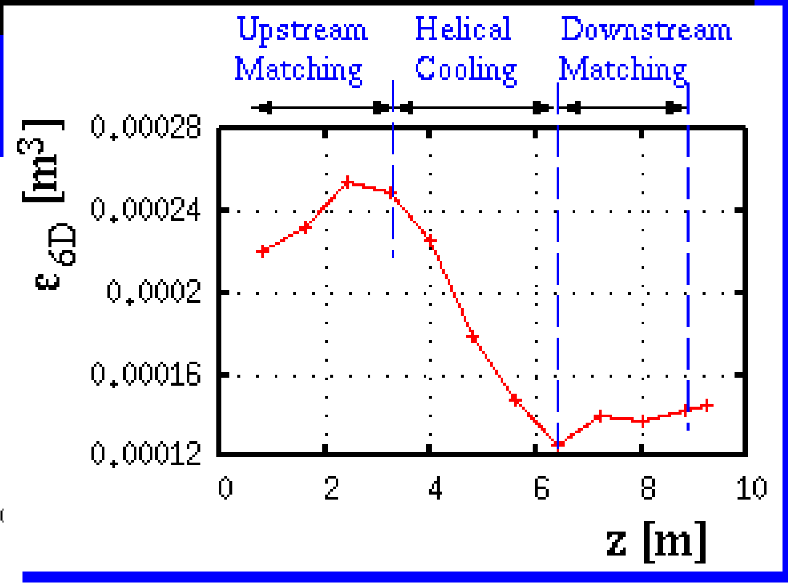
- Beam size (rms): ± 60 mm
- $\Delta p/p$ (rms): ± 40/300 MeV/c
- x′ and y′ (rms): ± 0.4

- Obtained cooling factor: ~200%
- Transmission efficiency: 32%









Phase II Proposals Due April 13

- G4BL
  - More user support
  - Finish upgrades (inc. XP, MacOS)
  - Phase II plans (esp. polarization)
- 6DMANX
  - Draft Fermilab Experimental Proposal
  - Plan for Phase II activities

- **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

Please come to the next

LEMC Workshop

February 12-16 2007!