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

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Muons, Inc.

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6D Muon and Neutrino Experiment (6DMANX)

(outline of presentation)

- 6D muon beam cooling enables several new accelerator possibilities
- A Helical Cooling Channel (HCC) with continuous absorber is a new concept for 6D muon cooling
  - Combined Solenoidal, Helical Dipole, Helical Quadrupole fields
  - Especially effective with hydrogen-pressurized RF cavities
- 6DMANX is a prototype HCC precooler
  - Used as a simple demonstration of new 6D cooling principles
  - No RF (invariant emittance measurements show cooling)
  - Pressurized hydrogen not needed, use liquid helium energy absorber
  - Beam cools as it slows down, magnetic fields must diminish with p
- The experiment is to measure the HCC cooling properties
  - Need up and downstream spectrometers, matching sections, particle ID
  - ~300 MeV/c muon beam, e.g. RAL or Fermilab
- Some funding through SBIR program for designs and simulations
  - Construction, execution, and alternative studies beyond SBIR funding
  - Must solve matching problems and make cost estimates for the proposal

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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}
- Many new ideas in the last 5 years. A new ball game!
  - (many new ideas have been developed with DOE SBIR funding)

Low Emittance Muon Collider Workshop

Fermi National Accelerator Laboratory
February 6 - 10, 2006
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

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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.

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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 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

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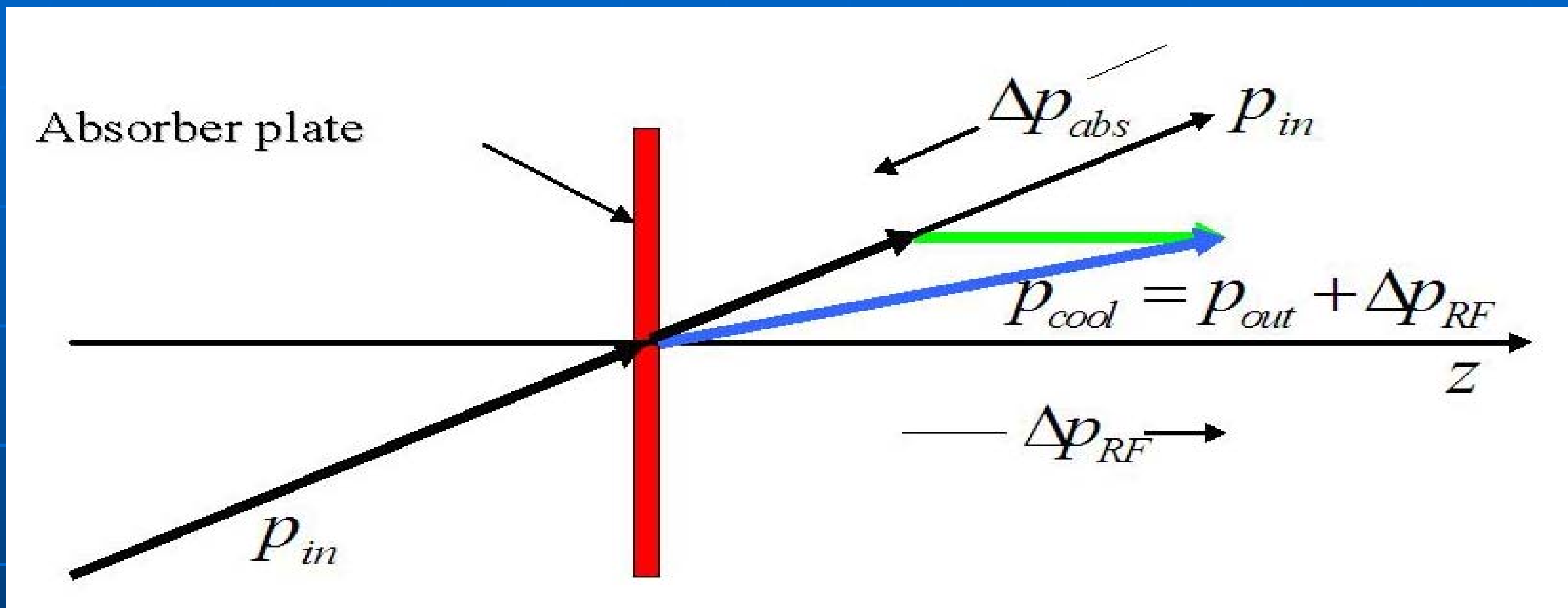
Desirables

- At least one <u>complete design</u> of a LEMC
- An implementation plan with affordable, incremental, independently-fundable, sequential, steps:
- (RoI WAG $M hardware)

1. attractive 6D Cooling experiment (5)
2. triple-duty proton driver Linac (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
5. Higgs factory (~300 GeV com) (2000)
   Add more cooling, RLA, coalescing & collider rings, IR
6. energy frontier muon collider(5 TeV com) (2000)
   Add more RLA, deep ring, IRs

Ionization Cooling (reduction in angular divergence of a muon beam)



$$\min \epsilon_{xN} = \frac{\beta_{\perp} E_s^2}{2 \beta m c^2 L_R \left| \frac{dE}{dz} \right|}$$

$$\beta_{\perp} = \frac{2 p_Z}{c B_Z}$$

Fast enough for muons

Only works for muons

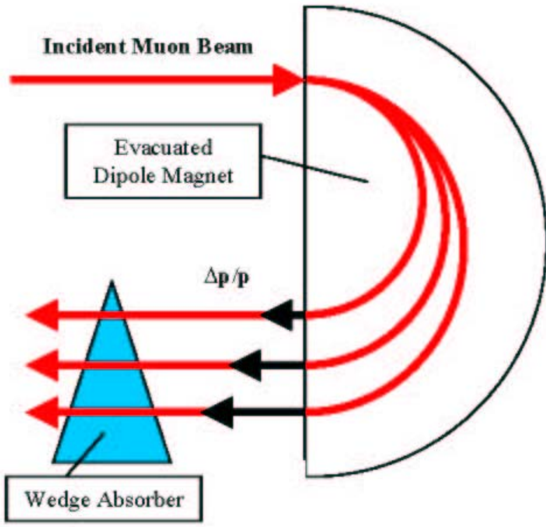


Figure 1. Use of a Wedge Absorber for Emittance Exchange

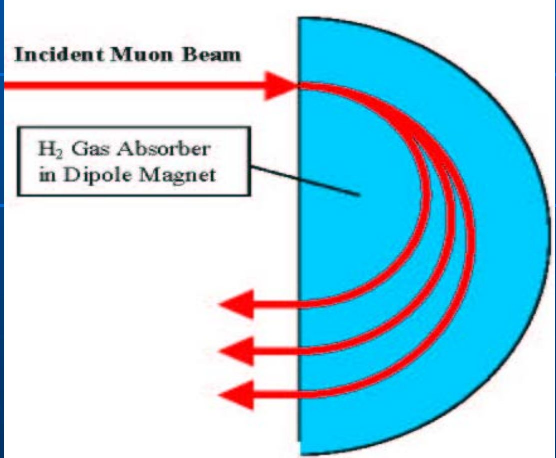
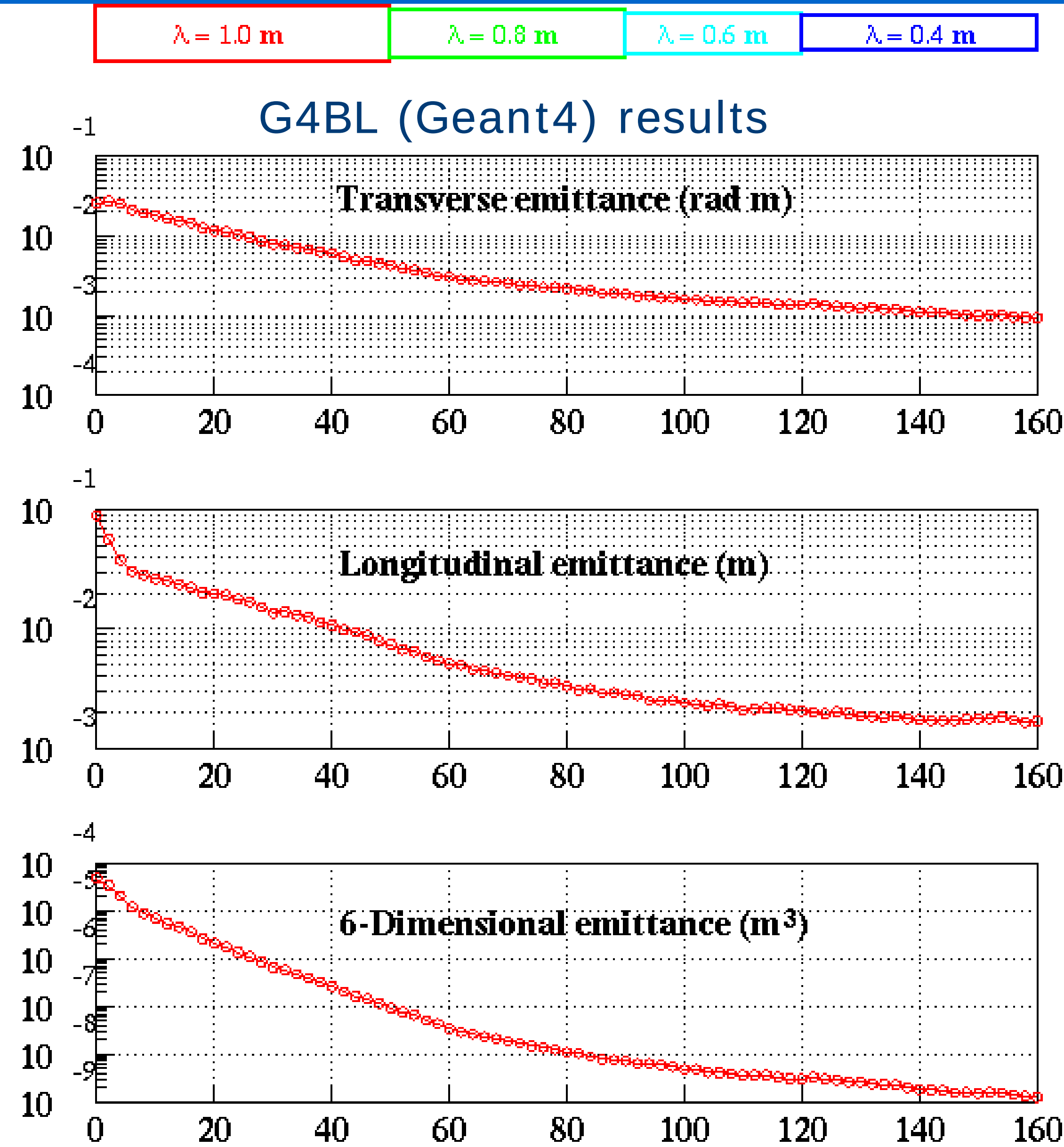


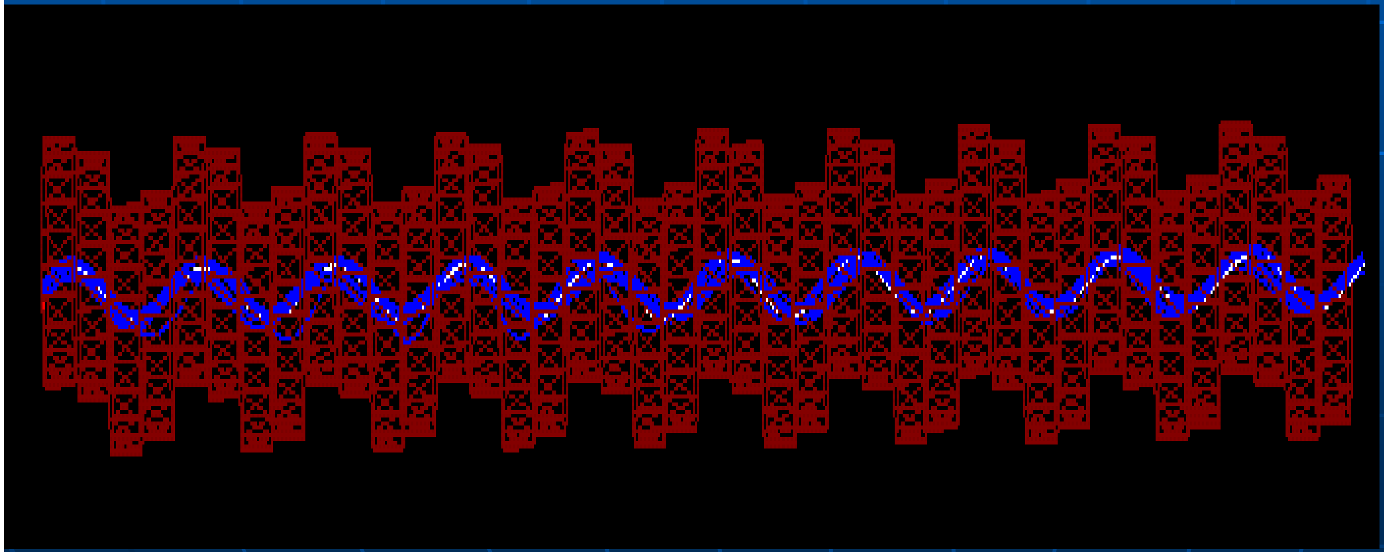
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

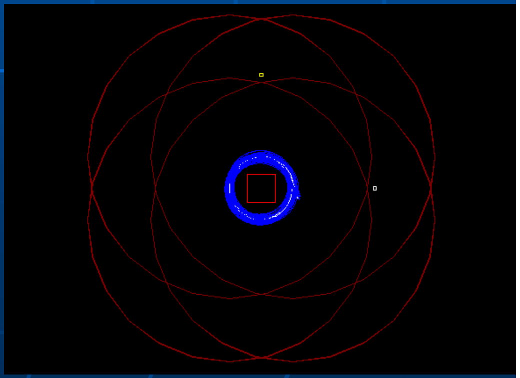


6D Cooling factor ~ 50,000

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





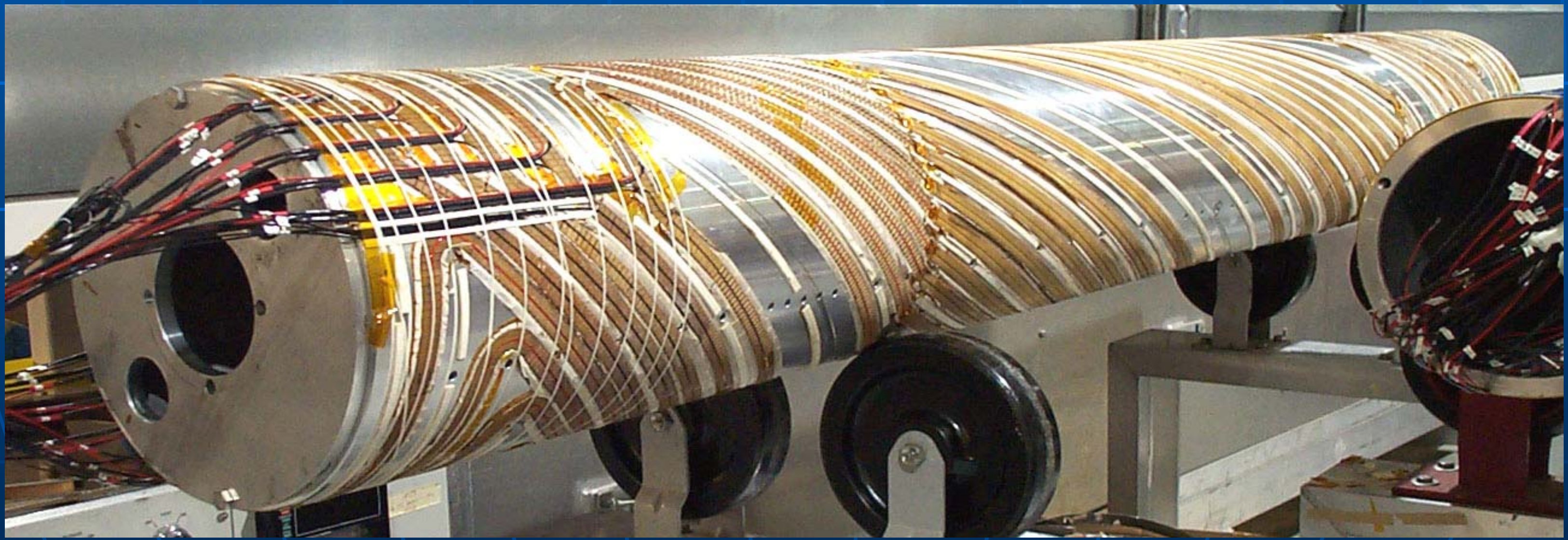
Hydrogen Cryostat for Muon Beam Cooling

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

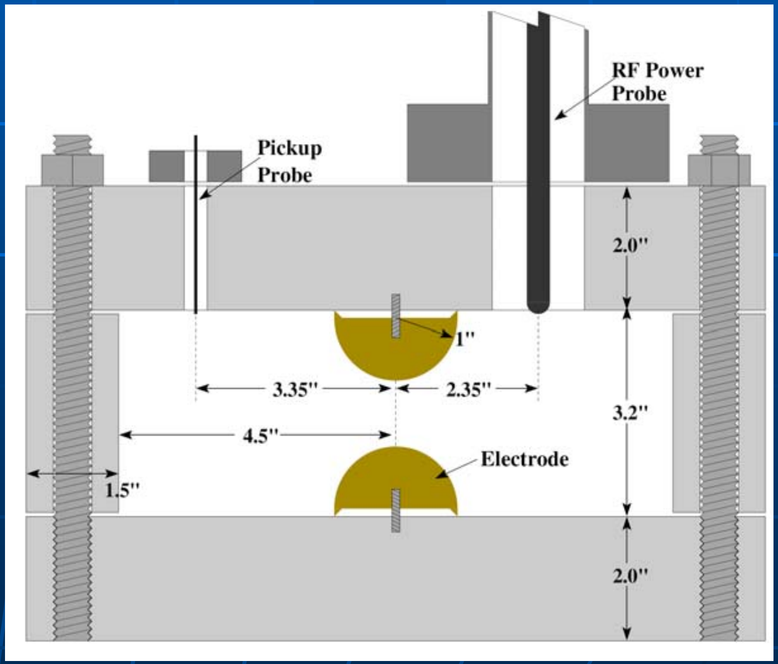
Cryostat for the 6DMANX cooling demonstration experiment



BNL Helical Dipole magnet for AGS spin control

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)

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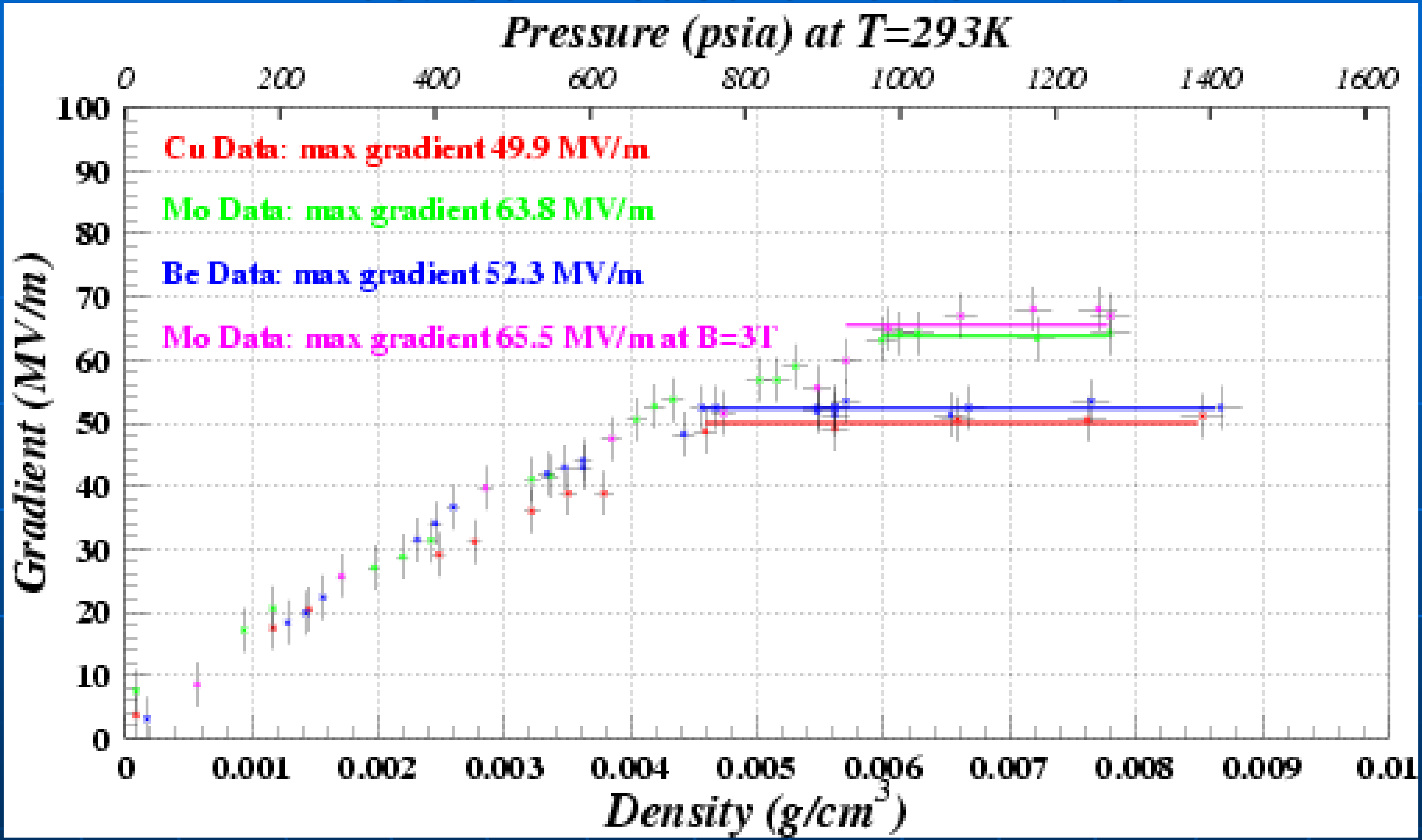
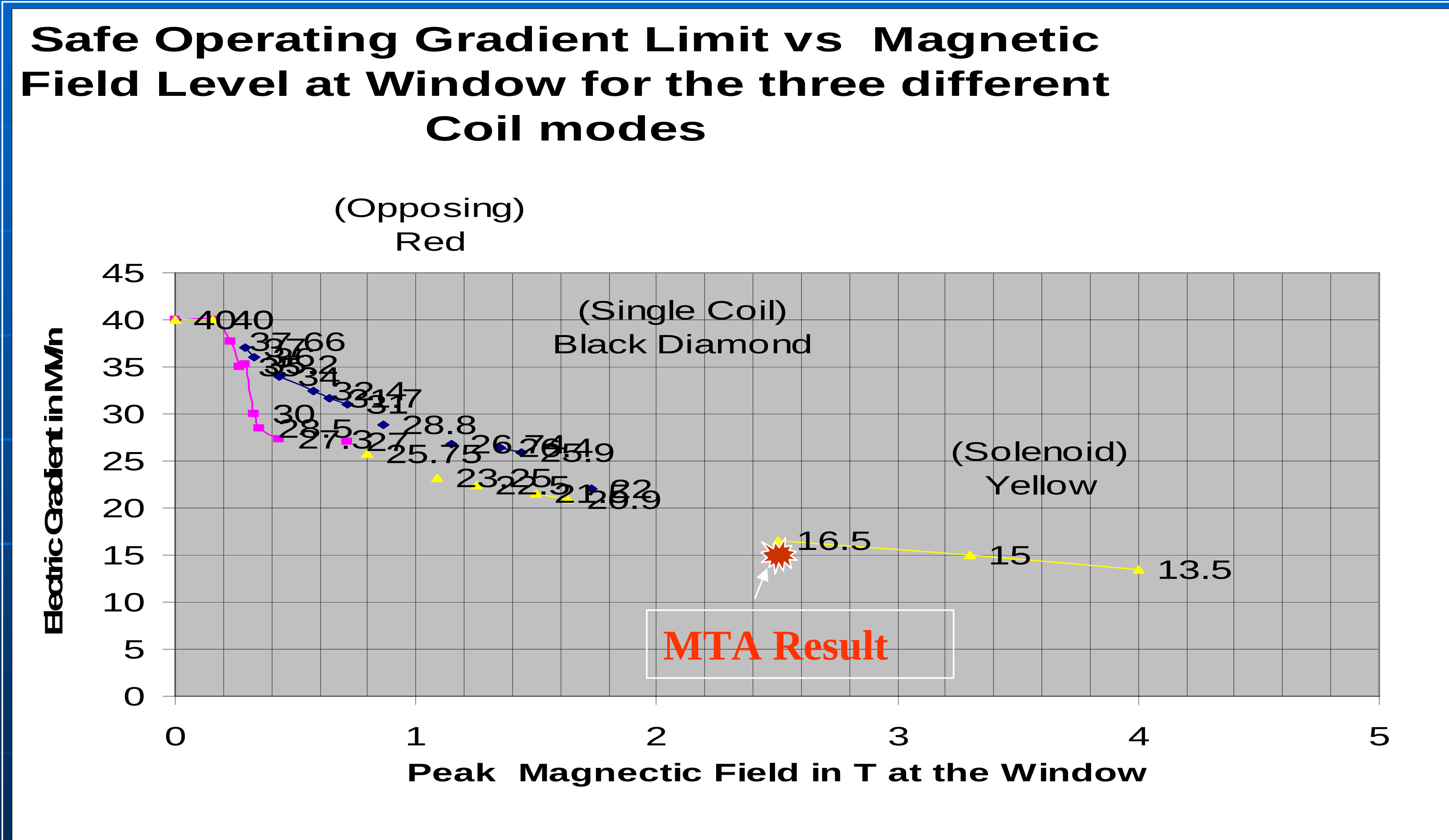
HPRF Test Cell Measurements in the MTA



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 $B_{external}$
From Al Moretti, MICE meeting IIT, 3/12/06



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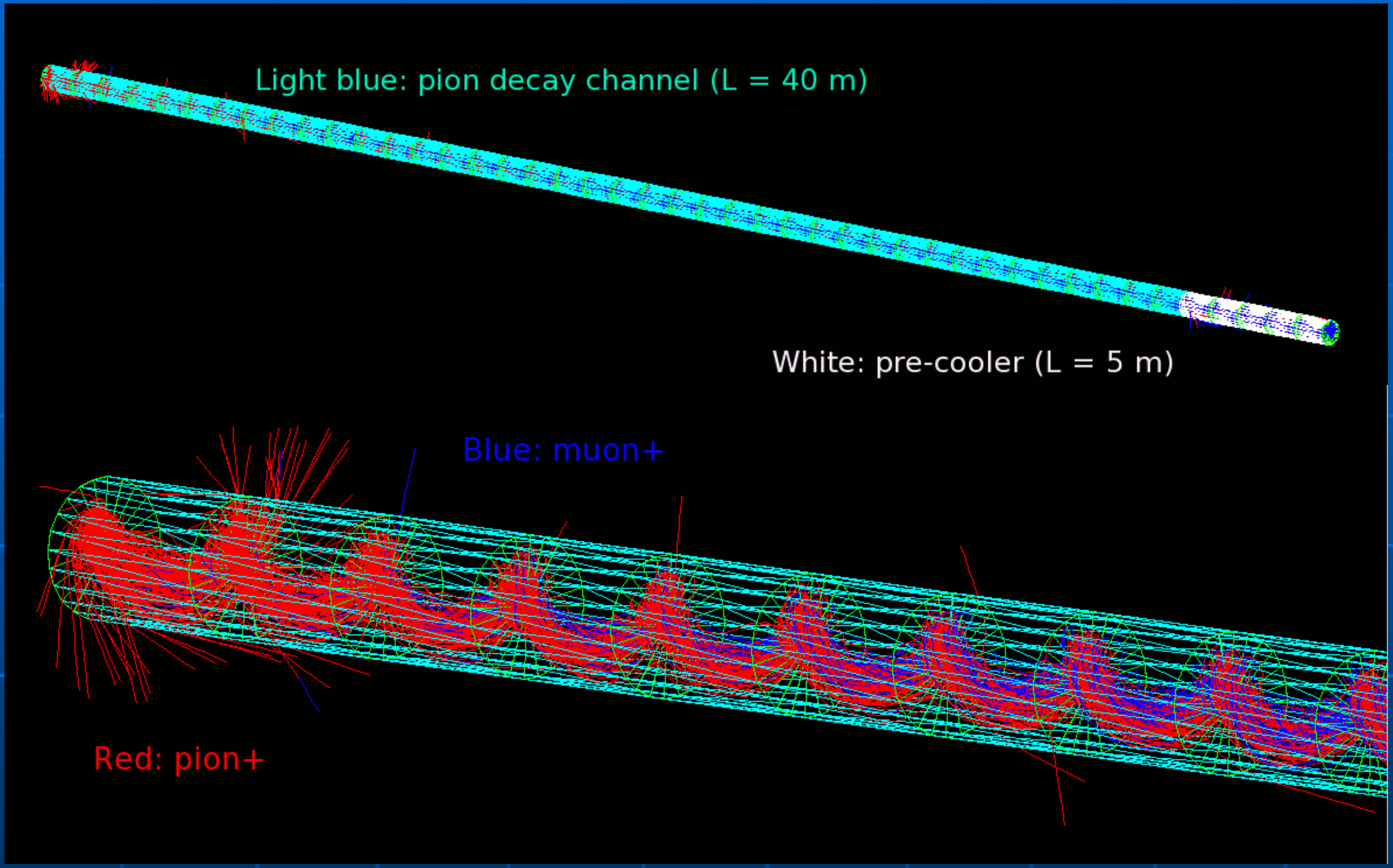
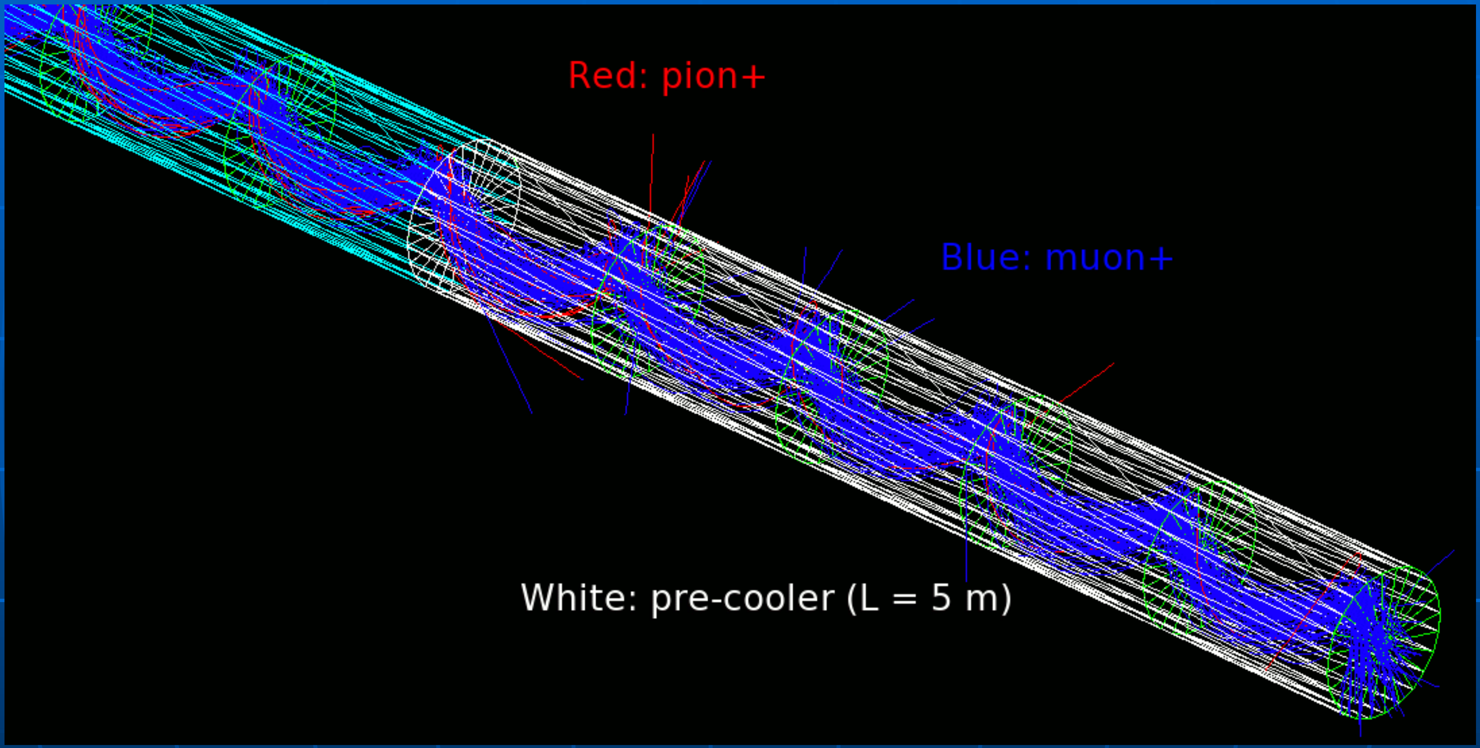
HCC with Z-dependent fields



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.

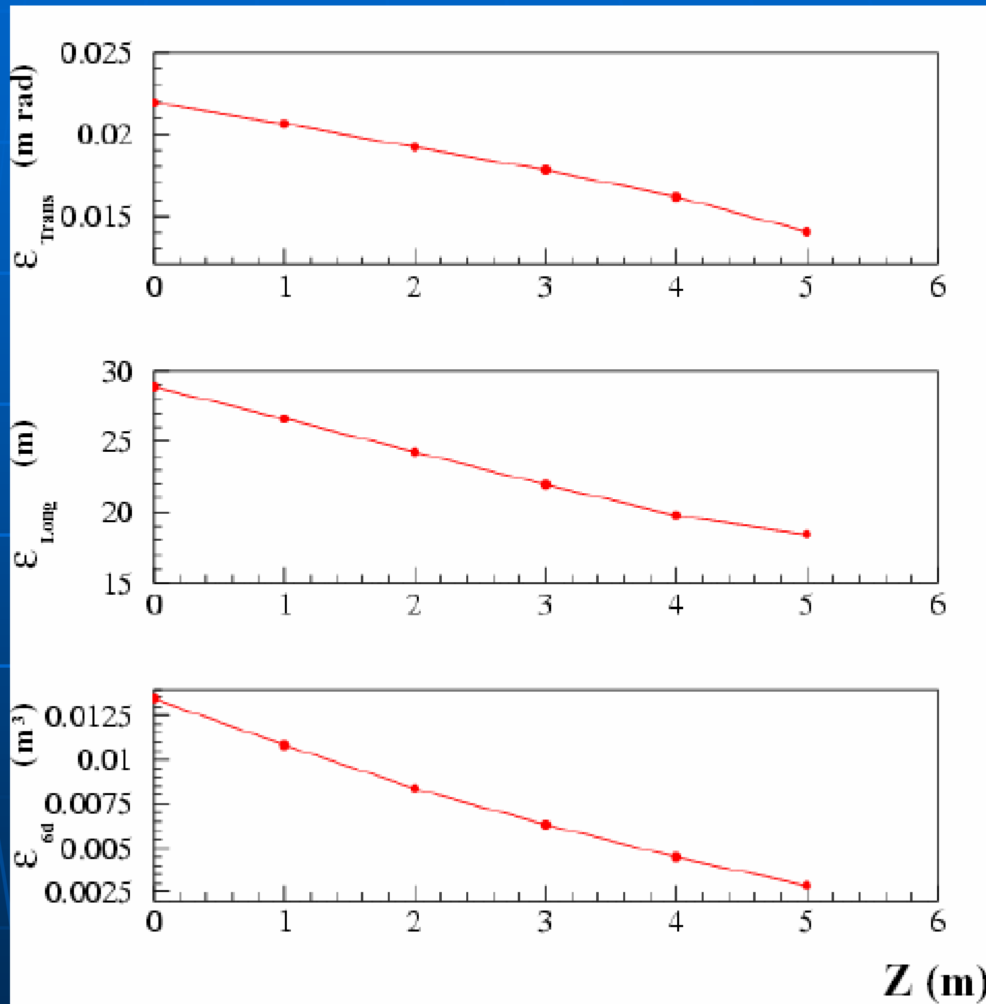
~x1.7 in each direction.

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



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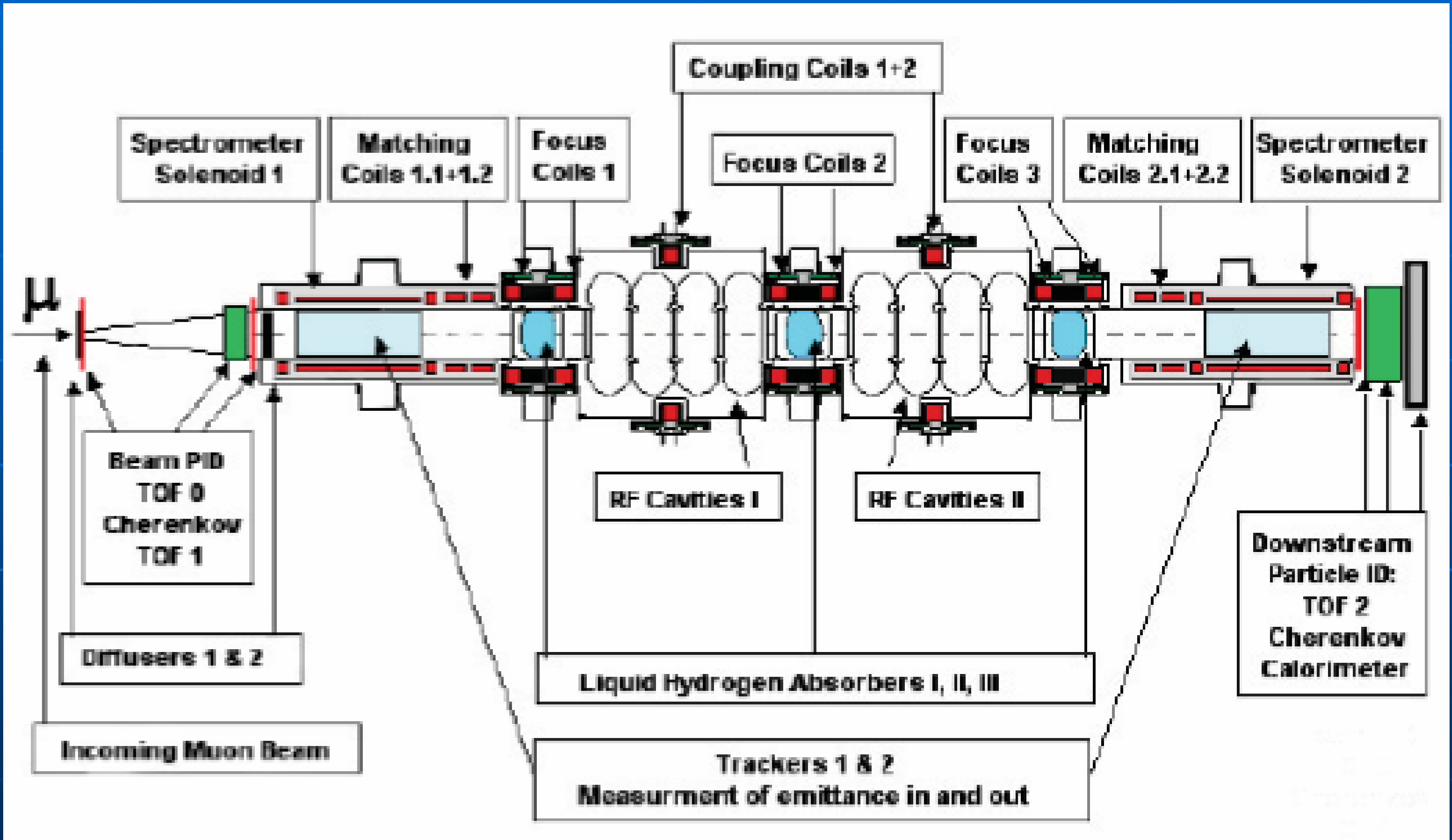
6DMANX demonstration experiment

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

MICE "facility" at RAL



Muons, Inc. has started discussions to use the MICE spectrometers for MANX.

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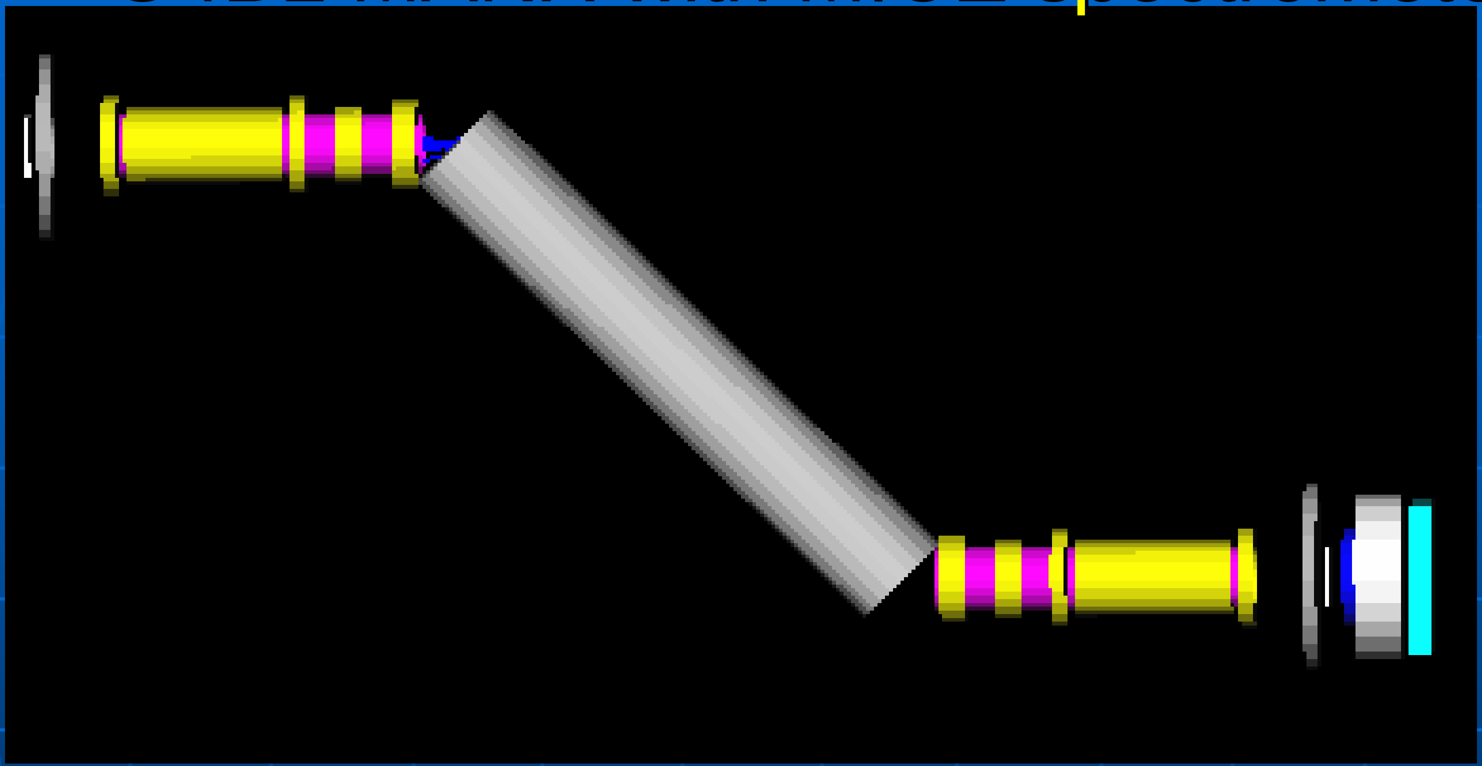
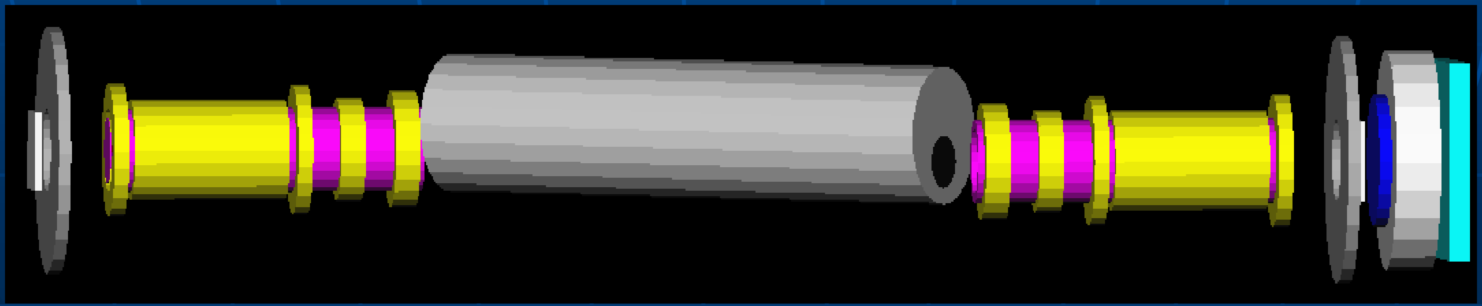
G4BL MANX with MICE spectrometers





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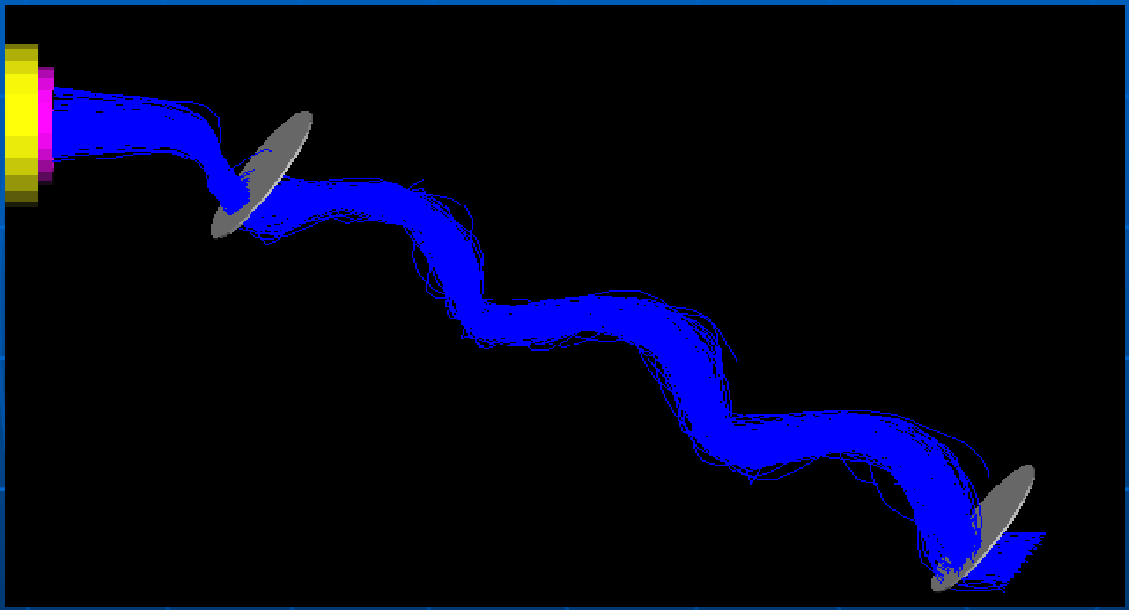
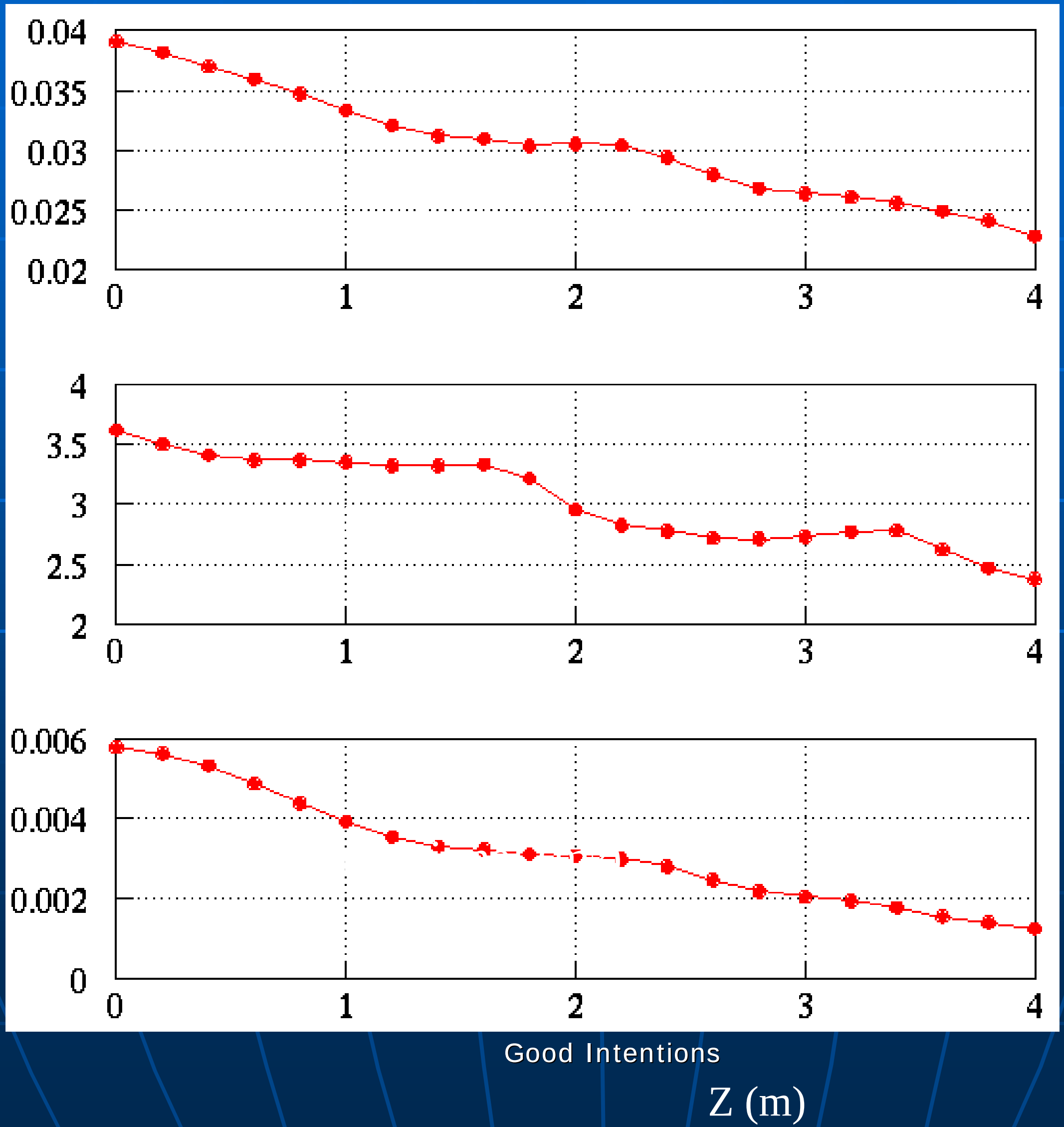
Muon Trajectories in 3-m MANX

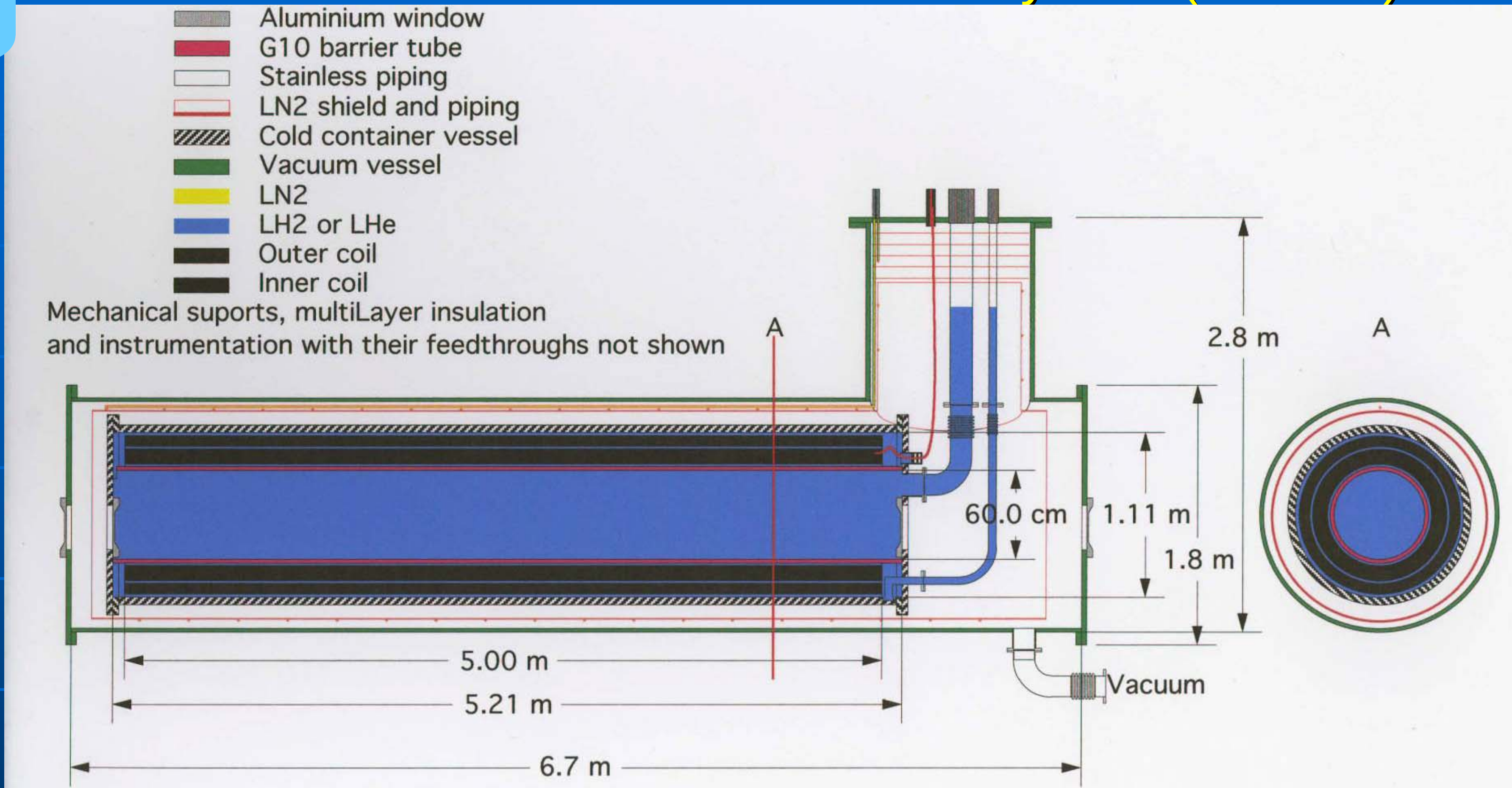


The design of the coils and cryostat are next steps for MANX.

Emittance evolution in LHe HCC



MANX/Precooler H2 or He Cryostat (Kuchnir)



Five meter long MANX cryostat schematic.
The use of Liquid He at 4 K is possible, with Nb3Sn or NBTi magnets.
Thin Al windows designed for MICE will be used.

HCC parameters

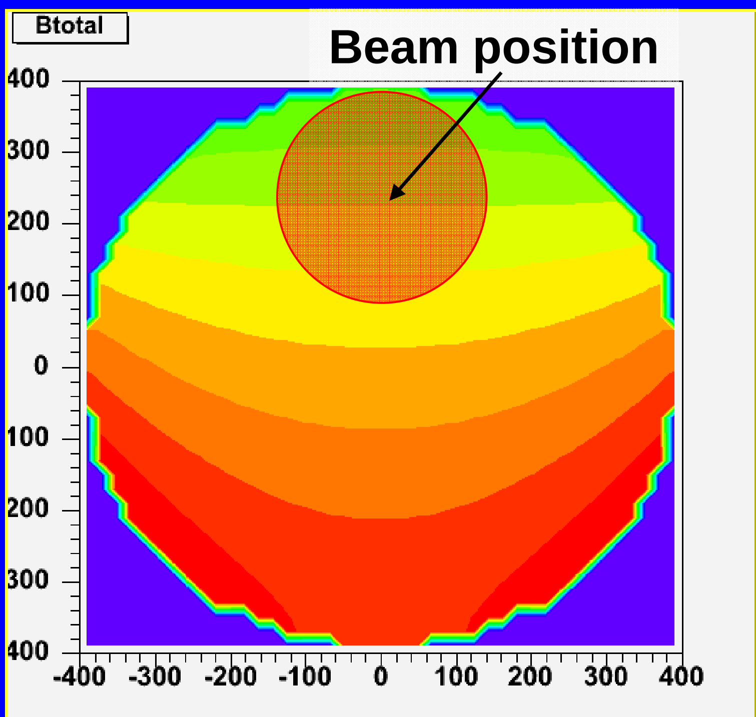
Helical magnet

- Total length = 4 meters
- Magnet bore diameter = 0.8 ~ 1.0 meters
- Helix period = 2 meters
- $\kappa = 0.8$
- Initial/Final Bz on ref orbit = - 4.4/-2.2 T
- Initial/Final b (dipole) on ref orbit = 0.95/0.45 T
- Initial/Final b′ (quad) on ref orbit = 0.60/0.40 T/m
- Initial/Final b′′ (sext) on ref orbit = -0.26/-0.15 T/m^2

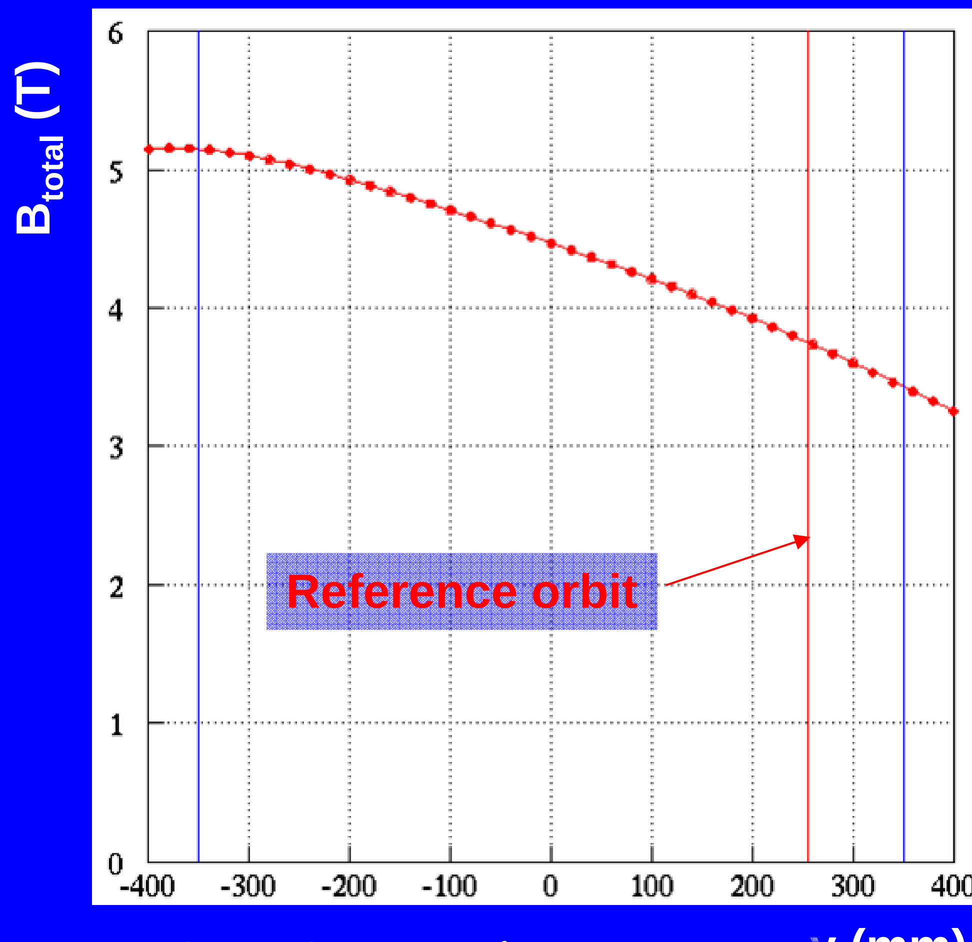
Beam

- Initial <P> = 300 MeV/c
- Final <P> = ~ 150 MeV/c
- $\Delta P/P \sim \pm 7$ %
- Beam diameter ~ 20 cm

Maximum B_{total} field in LHe HCC

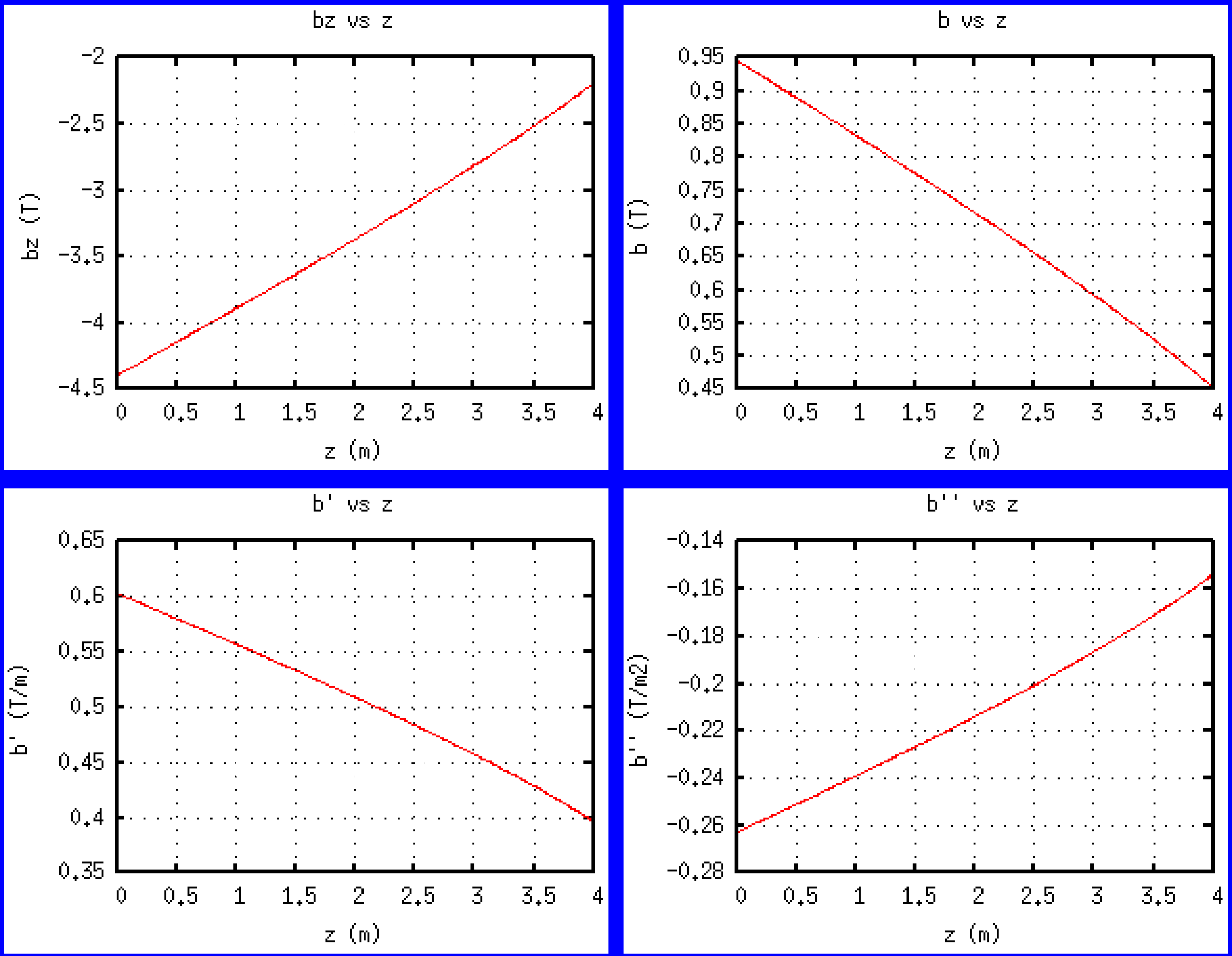


Contour plot of B_{total} in LHe HCC
(red: > 5 T, green 3.5 T, blue = 0)



Cross Section of B_{total} on y axis

Field strength reduction on reference orbit

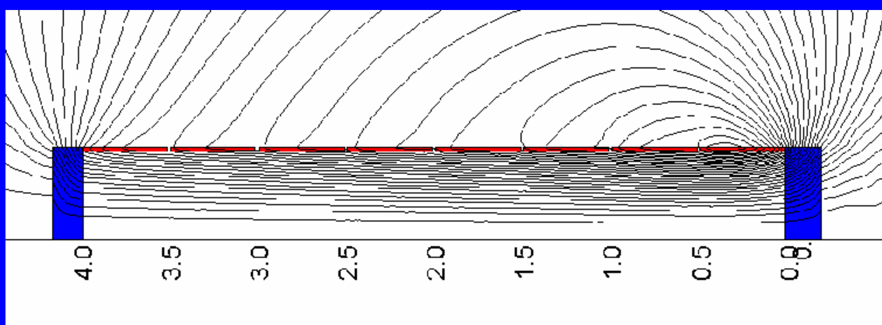


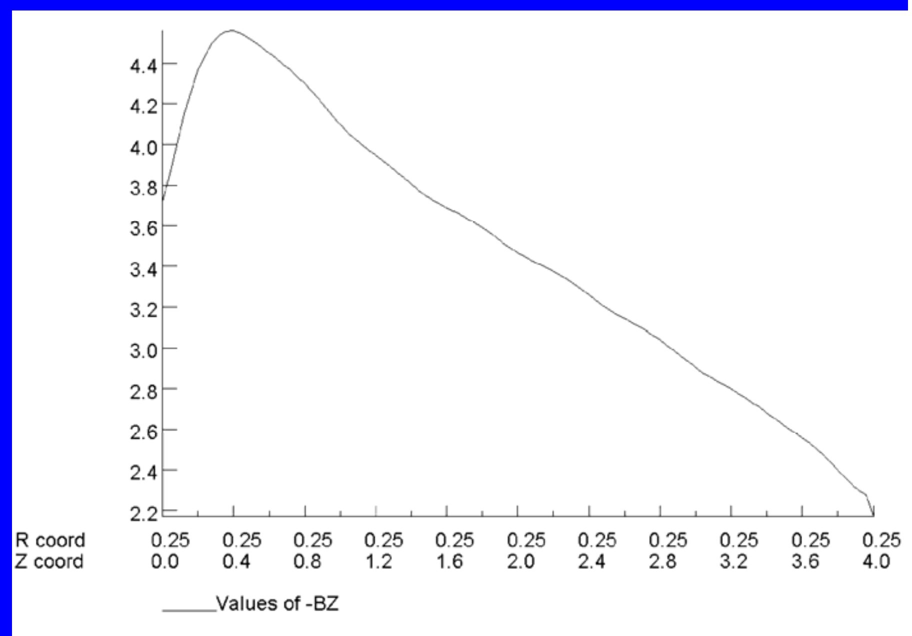
Field strength on a reference orbit (a = 25.5 cm)

Muon Cooling Channel Superconducting Magnet System

V.S. Kashikhin, FNAL Meeting on May 16, 2006

- HCC Solenoid magnet design well advanced
  - uses leftover LHC cable
  - 1 circuit; reduction of number of turns as function of z



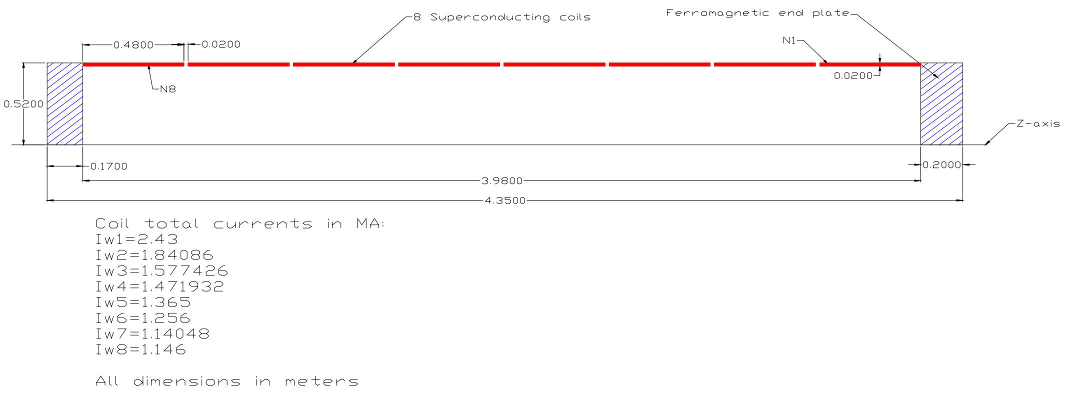


Specified linear solenoidal field decay along Z axis

provided by proper chosen number of turns for each section:

W1= 243	**W5 = 136**
W2 = 184	**W6 = 126**
W3 = 158	**W7 = 114**
W4 = 147	**W8 = 114**

Superconducting Solenoid



Total solenoid ampere-turns	12 MA
Current	10 kA
Number of turns	1200
Superconducting cable length	3960 m

LHC Cables parameters:

Inner cable 14 kA at 7 T & 4.2 K

Outer cable 8.5 kA at 7 T & 4.2 K

LHC short samples:

Jc = 2750 A/mm^2 at 5 T & 4.2 K

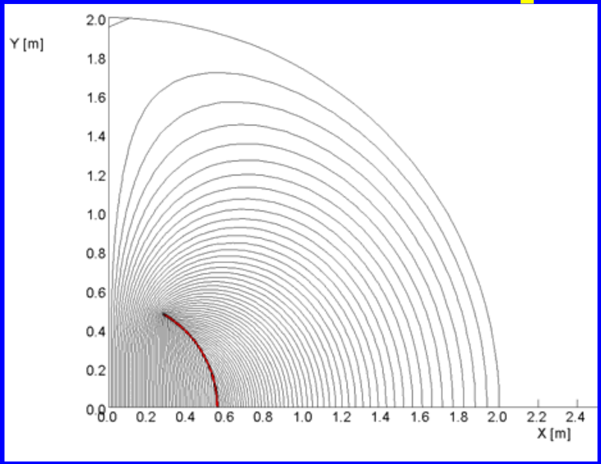
LHC cables leftover:

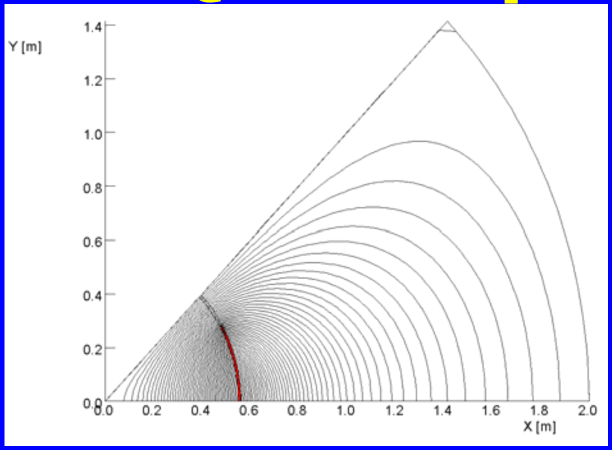
Inner cable - 1400 m

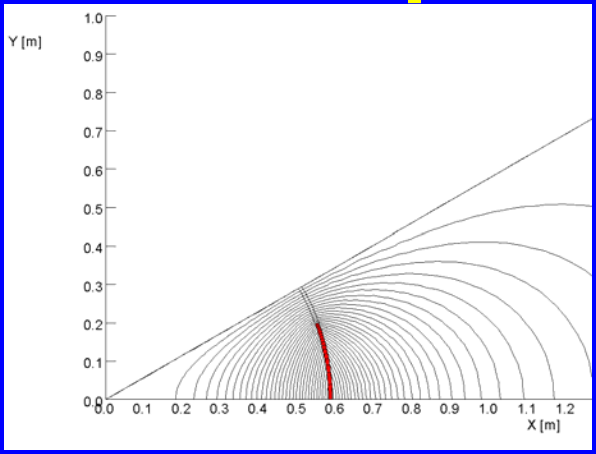
Outer cable - 2660 m

- **Solenoid has 8 sections wound separately on identical bobbins**
- **All sections connected in series**
- **Ferromagnetic end plates improve ends field quality**
- **Holes in end plates provide path for muon beam inlet and outlet**
- **Needed coil mechanical stability provided by SS or Al bandage**

Helical Dipole, Quadrupole, Sextupole







Parameter	Dipole	Quadrupole	Sextupole
Maximum field strength	0.95 T	0.6 T/m	-0.26 T/m^2
Minimum field strength	0.88 T	0.4 T/m	0.15 T/m^2
Coil Ampere-turns/pole	862 kA	78.5 kA	25.6 kA
Coil Lorentz force Fx	208 kN/m	2.4 kN/m	0.25 kN/m
Coil Lorentz force Fy	-289 kN/m	-6.2 kN/m	-0.97 kN/m
Energy of magnetic field	752 kJ/m	133 kJ/m	2.1 kJ/m
Coil inner radius	0.55 m	0.57 m	0.59 m
Superconductor max field	1.81 T	0.33 T	0.027 T

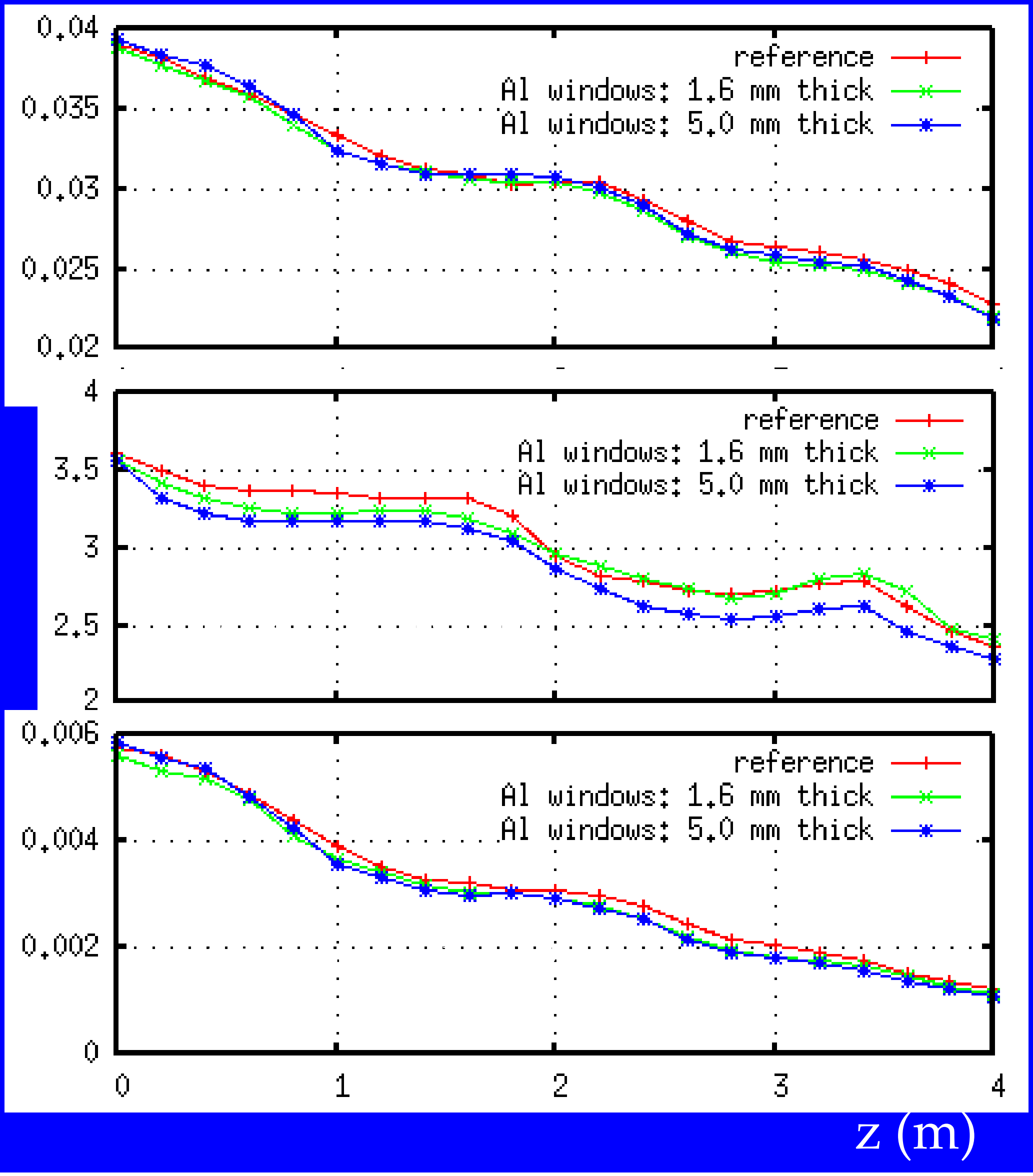
All Helix Coils have length 1 m

and wound one after other. They will be epoxy impregnated together.

Support cylinder will provide mechanical stability.

Because of relatively low field decay 1 m long sections will be enough for proper field approximation.

Window effects



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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
2005-6*	Reverse Emittance Exch.	$100,000	JLab
2005-6*	Capture, ph. rotation	$100,000	FNAL AD
2006-7	6DMANX cooling demo	$100,000[#]	FNAL TD
2006-7	G4Beamline	$100,000[#]	IIT

- * Phase II may be granted in June 2006 up to $750,000

† Not continued to Phase II

Support 6DMANX design efforts

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

Next Steps to the 6DMANX Proposal

(target date is 6 months from now)

- MICE/MANX synthesis approach
  - HCC Magnet design with cost/time estimates
  - Matching magnet solution with cost/time estimates
  - Simulations to verify experimental significance
- New (FNAL?) beam line approach, also need to:
  - Identify best beamline possibility, cost/time estimates
  - Design or borrow spectrometers, PID systems
  - Simulations to verify experimental significance
    - Comparing single particle measurements, with
    - Beam profile monitor measurements