



Muons, Inc.



MANX- Toward Bright Muon Beams for Colliders, Neutrino Factories, and Muon Physics

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Muons, Inc. (<http://www.muonsinc.com/>)

New inventions are improving the prospects for high luminosity muon colliders for Higgs or Z' factories and at the energy frontier. Recent analytical calculations, numerical simulations, and experimental measurements are coming together to make a strong case for a series of devices or machines to be built, where each one is a precursor to the next. If chosen correctly, each device or machine with its own unique experimental and accelerator physics programs can drive the development of muon cooling and acceleration theory and technology. This strategy can achieve an almost unlimited program of experimental physics based on the cooling and acceleration of muon beams. The very first step of the program is to develop stopping muon beams by using a 6D muon cooling segment (momentum-dependent Helical Cooling Channel with emittance exchange using a homogeneous energy absorber) to test the theory and simulations and to improve the mu2e experiment.

<http://www.muonsinc.com/>



Ultimate Goal: High-Energy High-Luminosity Muon Colliders

- precision lepton machines at the energy frontier
- achieved in physics-motivated stages that require developing inventions and technology, e.g.
 - MANX (demonstrate HCC concept)
 - high-intensity proton driver (simultaneous muon beams)
 - stopping muon beams (HCC, EEXwHomogeneous absorber)
 - neutrino factory (HCC with HPRF, RLA in CW Proj-X)
 - Z' factory (low Luminosity collider, HE RLA)
 - Higgs factory (extreme cooling, low beta, super-detectors)
 - energy-frontier muon collider (more cooling, lower beta)



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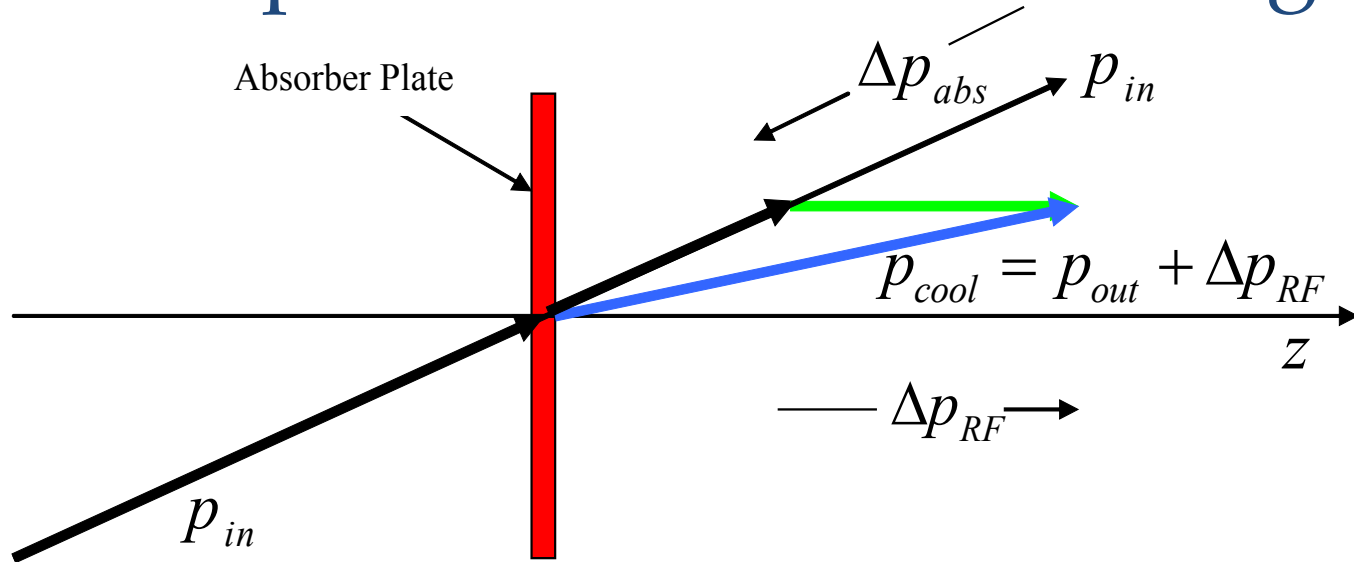
Project History

Year	Project	Expected Funds	Research Partner
2002	Company founded		
2002-5	High Pressure RF Cavity	\$600,000	IIT (Dan K.)
2003-7	<u>Helical Cooling Channel</u>	\$850,000	Jlab (Slava D.)
2004-5 ⁺	<u>MANX demo experiment</u>	\$ 95,000	FNAL TD (Victor Y.)
2004-7	Phase Ionization Cooling	\$745,000	Jlab (Slava D.)
2004-7	<u>HTS Magnets</u>	\$795,000	FNAL TD (Victor Y.)
2005-9	Reverse Emittance Exch.	\$850,000	Jlab (Slava D.)
2005-9	<u>Capture, ph. rotation</u>	\$850,000	FNAL AD (Dave N.)
2006-9	G4BL Sim. Program	\$850,000	IIT (Dan K.)
2006-9	<u>MANX 6D Cooling Demo</u>	\$850,000	FNAL TD (M. Lamm)
2007-10	<u>Stopping Muon Beams</u>	\$750,000	FNAL APC (Chuck A.)
2007-10	<u>HCC Magnets</u>	\$750,000	FNAL TD (Sasha Z.)
2007-8 ⁺	Compact, Tunable RF	\$100,000	FNAL AD (Milorad)
2008-9	Pulsed Quad RLAs	\$100,000	Jlab (Alex B.)
2008-9	Fiber Optics for HTS	\$100,000	FSU (Justin S.)
2008-9	RF Breakdown Studies	\$100,000	LBNL (Derun L.)
2008-9	Rugged RF Windows	\$100,000	Jlab (Bob Rimmer)
2008-9	H2-filled RF Cavities	\$100,000	FNAL APC (Katsuya)
2008-9	<u>MANX, Collider low beta</u>	\$150,000	NIU DCEO(D. Hedin)

Underlined are explicitly related to HCC ~\$3.5M spent, \$1.3 M left



Principle of Ionization Cooling



- Each particle loses momentum by ionizing a low-Z absorber
- Only the longitudinal momentum is restored by RF cavities
- The angular divergence is reduced until limited by multiple scattering
- Successive applications of this principle with clever variations leads to small emittances for many applications
- Early work: Budker, Ado & Balbekov, Skrinsky & Parkhomchuk, Neuffer

Transverse Emittance IC

- The equation describing the rate of cooling is a balance between cooling (first term) and heating (second term):

$$\frac{d\varepsilon_n}{ds} = - \frac{1}{\beta^2} \frac{dE_\mu}{ds} \frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3} \frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0}$$

Bethe-Bloch

Moliere (with low Z mods)

- Here ε_n is the normalized emittance, E_μ is the muon energy in GeV, dE_μ/ds and X_0 are the energy loss and radiation length of the absorber medium, β_\perp is the transverse beta-function of the magnetic channel, and β is the particle velocity.



Wedges or Continuous Energy Absorber for Emittance Exchange and 6d Cooling

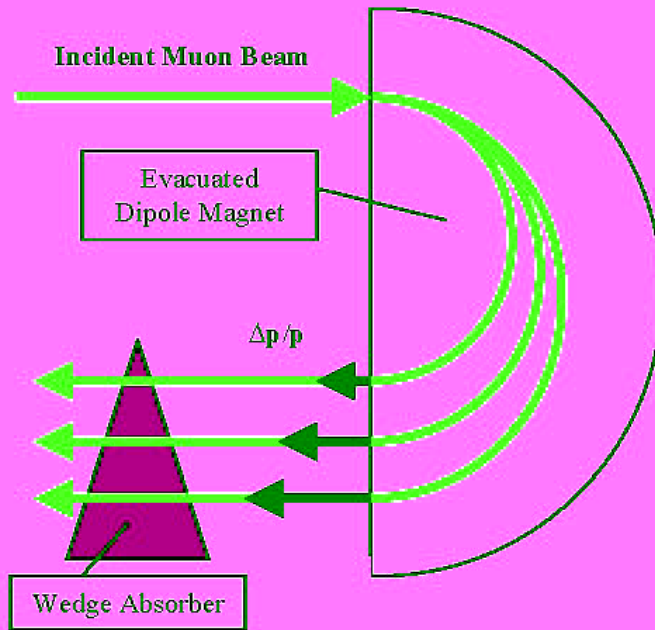


Figure 1. Use of a Wedge Absorber for Emittance Exchange

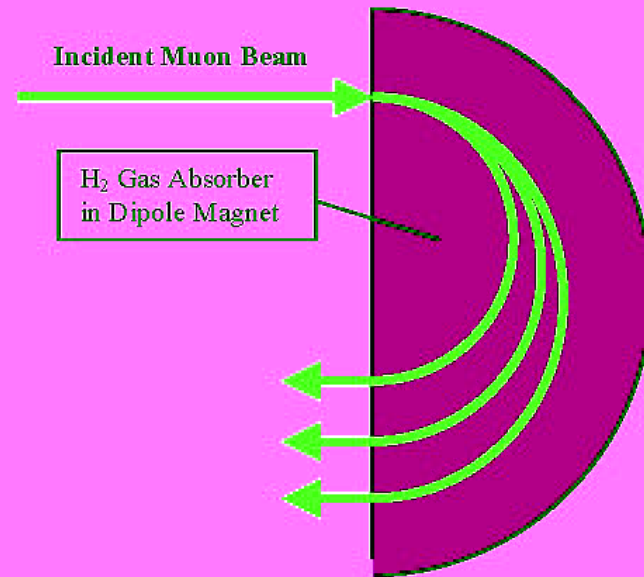


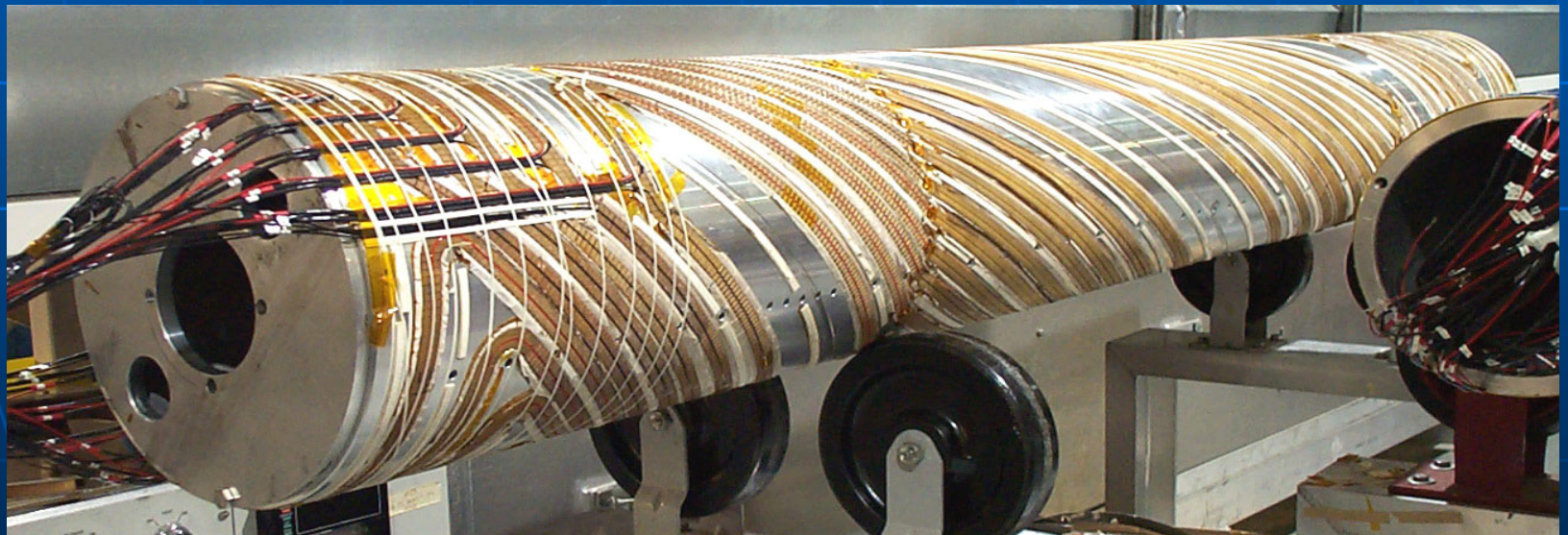
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Ionization Cooling is only transverse. To get 6D cooling, emittance exchange between transverse and longitudinal coordinates is needed.

THIS RH CONCEPTUAL PICTURE BE REALIZED? A MANX GOAL!

Helical Cooling Channel

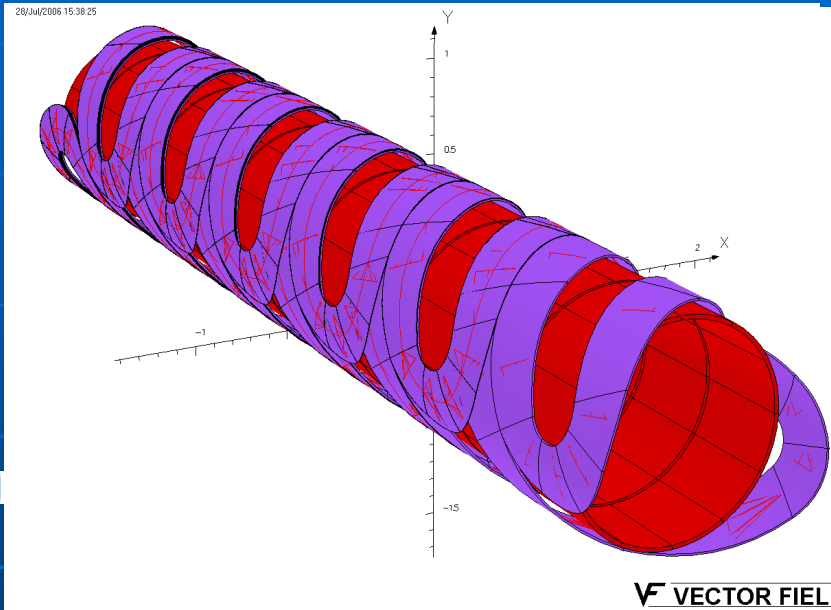
- Continuous, homogeneous energy absorber for longitudinal cooling
- Helical Dipole magnet component for dispersion
- Solenoidal component for focusing
- Helical Quadrupole for stability and increased acceptance



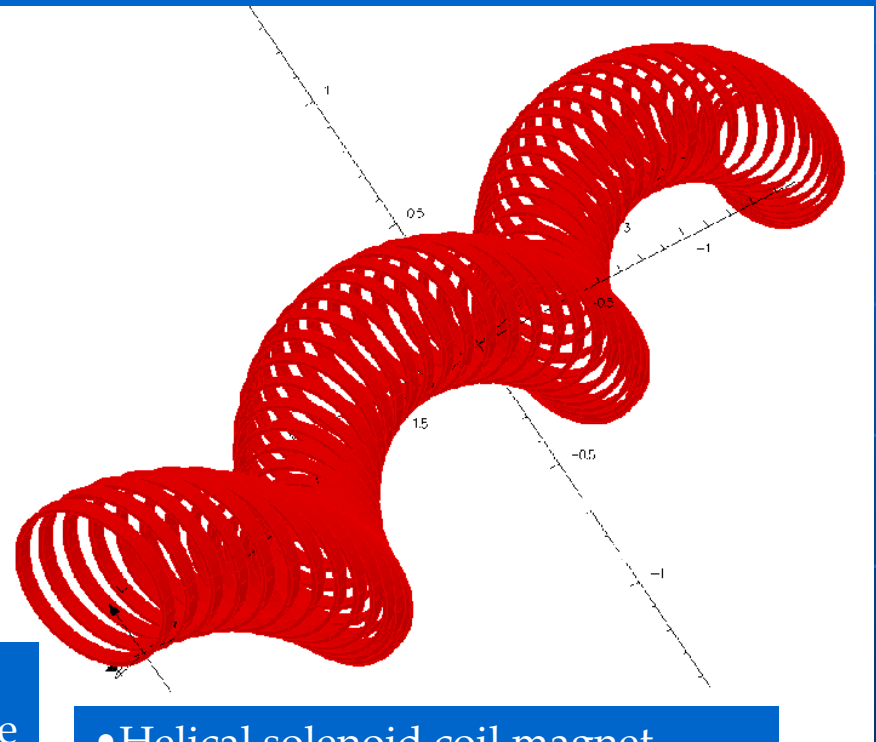
BNL Helical Dipole magnet for AGS spin control

Two Different Designs of Helical Cooling Magnet

Great new innovation!



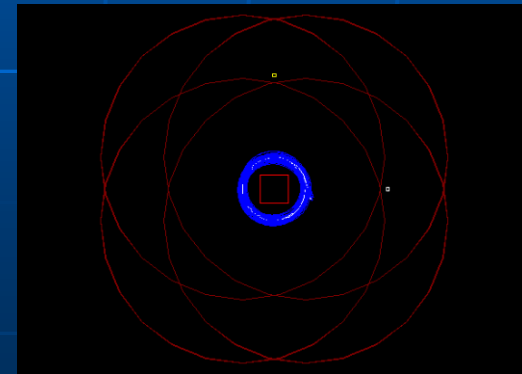
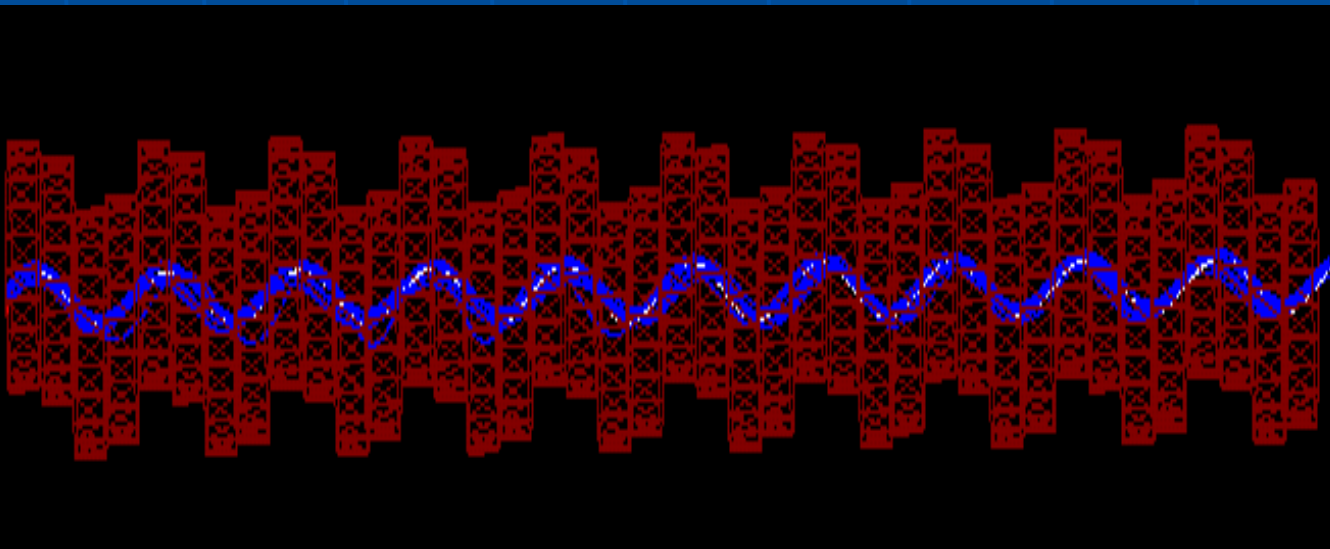
- Siberian snake type magnet
- Consists of 4 layers of helix dipole to produce tapered helical dipole fields.
- Coil diameter is 1.0 m.
- Maximum field is more than 10 T.



- Helical solenoid coil magnet
- Consists of 73 single coils (no tilt).
- Maximum field is 5 T
- Coil diameter is 0.5 m.

6-Dimensional Cooling in a Continuous Absorber

- Helical cooling channel (HCC)
 - Continuous absorber for emittance exchange
 - Solenoidal, transverse helical dipole and quadrupole fields
 - Helical dipoles known from Siberian Snakes
 - z- and time-independent Hamiltonian
 - Derbenev & Johnson, Theory of HCC, April/05 PRST-AB
 - <http://www.muonsinc.com/reports/PRSTAB-HCCtheory.pdf>

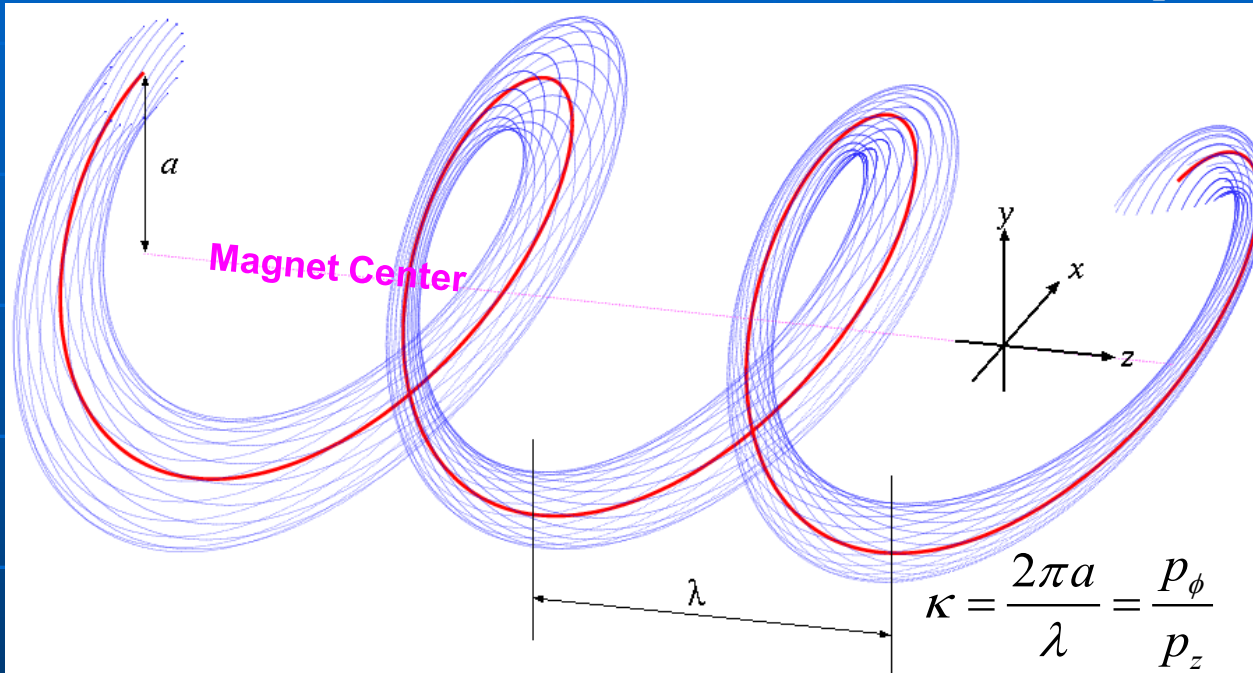




Particle Motion in a Helical Magnet

Combined function magnet (invisible in this picture)

Solenoid + Helical dipole + Helical Quadrupole



Red: Reference orbit
Blue: Beam envelope

Dispersive component makes longer path length for higher momentum particles and shorter path length for lower momentum particles.

Opposing radial forces

$$F_{h-dipole} \approx p_z \times B_{\perp}; \quad b \equiv B_{\perp}$$

$$F_{solenoid} \approx -p_{\perp} \times B_z; \quad B \equiv B_z$$

Transforming to the frame of the rotating helical dipole leads to a time and z – independent Hamiltonian

b' added for stability and acceptance



Some Important Relationships

Hamiltonian Solution $p(a) = \frac{\sqrt{1+\kappa^2}}{k} \left[B - \frac{1+\kappa^2}{\kappa} b \right] \quad k = 2\pi/\lambda \quad \kappa = ka$

Equal cooling decrements $q \equiv \frac{k_c}{k} - 1 = \beta \sqrt{\frac{1+\kappa^2}{3-\beta^2}} \quad k_c = B\sqrt{1+\kappa^2}/p$

Longitudinal cooling only $\hat{D} \equiv \frac{p da}{a dp} = 2 \frac{1+\kappa^2}{\kappa^2} \quad q = 0$

~Momentum slip factor $\eta = \frac{d}{d\gamma} \frac{\sqrt{1+\kappa^2}}{\beta} = \frac{\sqrt{1+\kappa^2}}{\gamma\beta^3} \left(\frac{\kappa^2}{1+\kappa^2} \hat{D} - \frac{1}{\gamma^2} \right) \quad \frac{\kappa^2}{1+\kappa^2} \hat{D} \sim \frac{1}{\gamma_{transition}^2}$



HCC Virtues

new concept

not FODO, but based on a theory
time and z-independent Hamiltonian
solenoid, helical dipole, helical quad fields

large acceptance

for huge muon beam emittances

large resonance driving terms

homogeneous field

minimal resonant losses

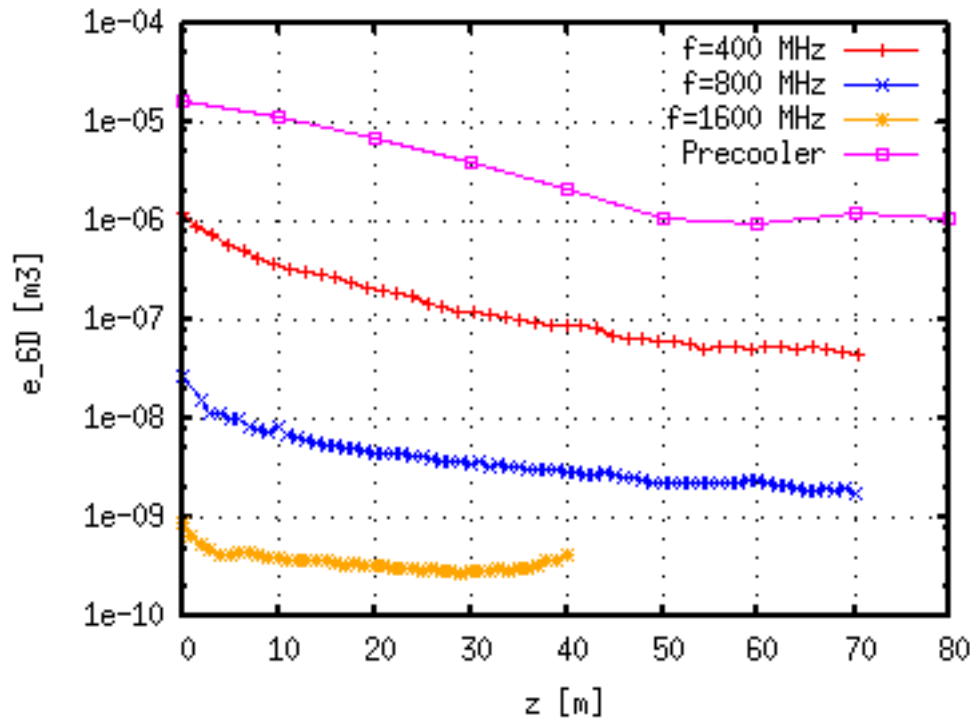
- DE/E for a million in 6D reduction implies a long channel



Precooler + HCCs With first engineering constraints



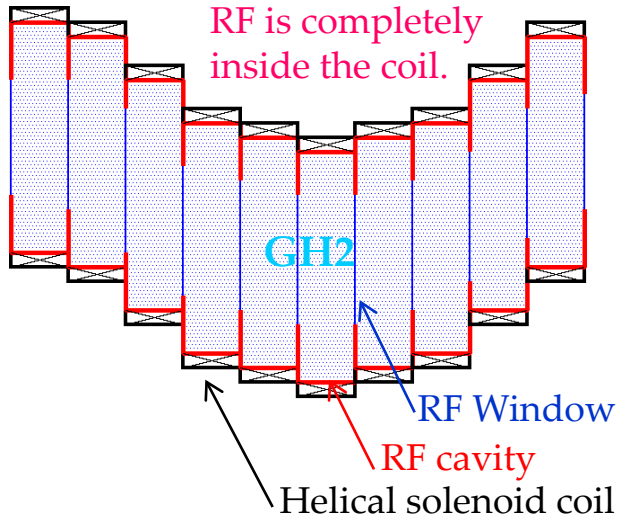
Solenoid + High Pressurized RF



- The acceptance is sufficiently big.
- Transverse emittance can be smaller than longitudinal emittance.
- Emittance grows in the longitudinal direction.



Engineering HCC with RF



- Use a pillbox cavity (but no window this time).
- RF frequency is determined by the size of helical solenoid coil.
 - Diameter of 400 MHz cavity = 50 cm
 - Diameter of 800 MHz cavity = 25 cm
 - Diameter of 1600 MHz cavity = 12.5 cm
- The pressure of gaseous hydrogen is 200 atm at room temp to adjust the RF field gradient to be a practical value.
 - The field gradient can be increased if the breakdown would be well suppressed by the high pressurized hydrogen gas.

<i>parameter</i>	λ	κ	Bz	bd	bq	bs	f	<i>Inner d of coil</i>	<i>Expected Maximum b</i>	E	<i>RF phase</i>
<i>unit</i>	<i>m</i>		<i>T</i>	<i>T</i>	<i>T/m</i>	<i>T/m2</i>	<i>GHz</i>	<i>cm</i>	<i>T</i>	<i>MV/m</i>	<i>degree</i>
<i>1st HCC</i>	1.6	1.0	-4.3	1.0	-0.2	0.5	0.4	50.0	6.0	16.4	140.0
<i>2nd HCC</i>	1.0	1.0	-6.8	1.5	-0.3	1.4	0.8	30.0	8.0	16.4	140.0
<i>3rd HCC</i>	0.5	1.0	-13.6	3.1	-0.6	3.8	1.6	15.0	17.0	16.4	140.0



Muons, Inc. many new ideas under development:

- H₂-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
- Very High Field Solenoid magnets for better cooling
- p-dependent HCC
 - precooler
 - HTS for extreme transverse cooling
 - MANX 6d Cooling Demo
 - improved mu2e design

See <http://www.muonsinc.com/>

"papers and reports"

42 Abstracts for PAC09

21 Papers from EPAC08

13 Papers from PAC07

MANX, A 6D MUON BEAM COOLING EXPERIMENT

Robert Abrams¹, Mohammad Alsharo'a¹, Andrei Afanasev¹, Charles Ankenbrandt¹,
Emanuela Barzi², Kevin Beard¹, Alex Bogacz³, Daniel Broemmelsiek²,
Yu-Chiu Chao³, Linda Coney⁴, Mary Anne Cummings¹, Yaroslav Derbenev³,
Henry Frisch⁵, Ivan Gonin², Gail Hanson⁴, David Hedin⁶, Martin Hu², Valentin Ivanov¹,
Rolland Johnson¹, Stephen Kahn¹, Daniel Kaplan⁷, Vladimir Kashikhin²,
Moyses Kuchnir¹, Michael Lamm², James Maloney⁶, Michael Neubauer¹,
David Neuffer², Milord Popovic², Robert Rimmer³, Thomas Roberts¹, Richard Sah¹,
Pavel Snopok⁴, Linda Spentzouris⁷, Melanie Turenne¹, Daniele Turrioni²,
Victor Yarba², Katsuya Yonehara², Cary Yoshikawa¹, Alexander Zlobin²

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⁴*University of Chicago*

⁵*University of California at Riverside*

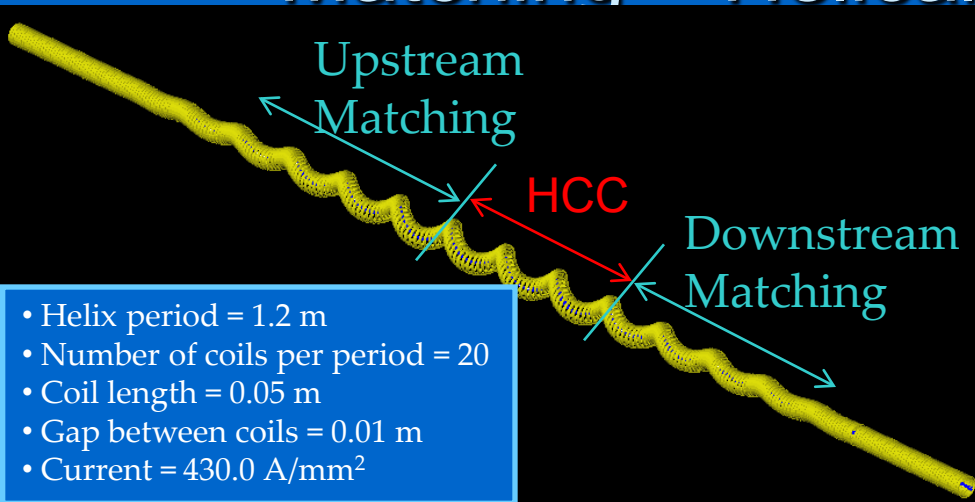
⁶*Illinois Institute of Technology*

* Contact, rol@muonsinc.com, (757) 870-6943



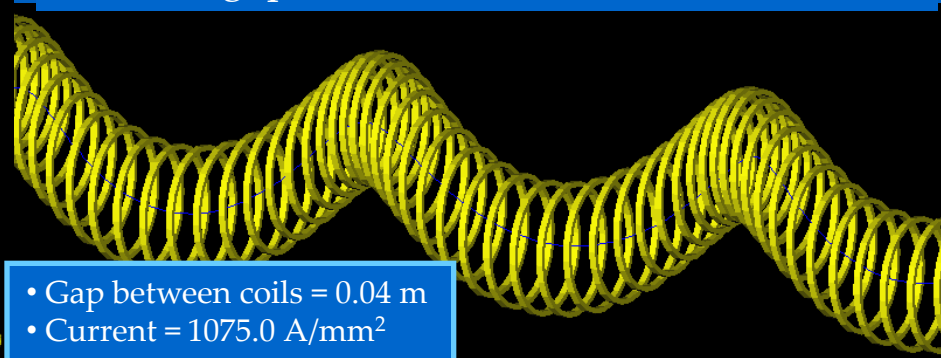


Matching + Helical Cooling Magnets

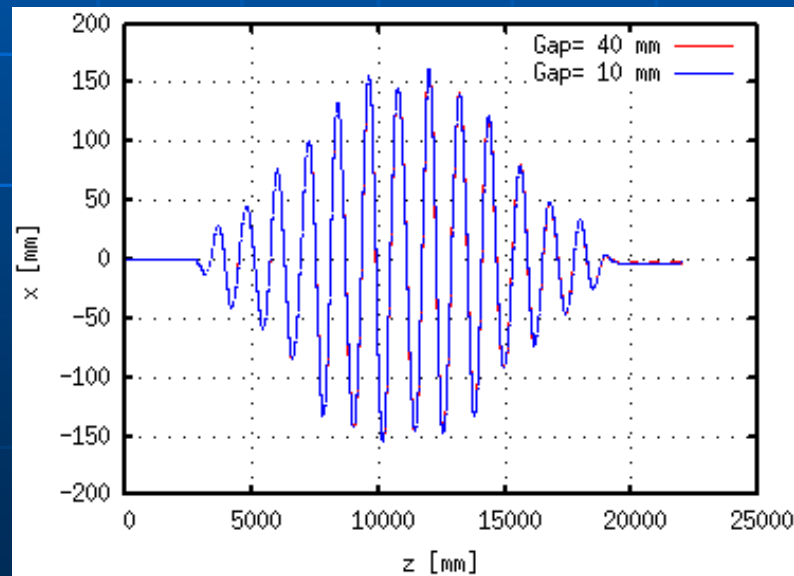
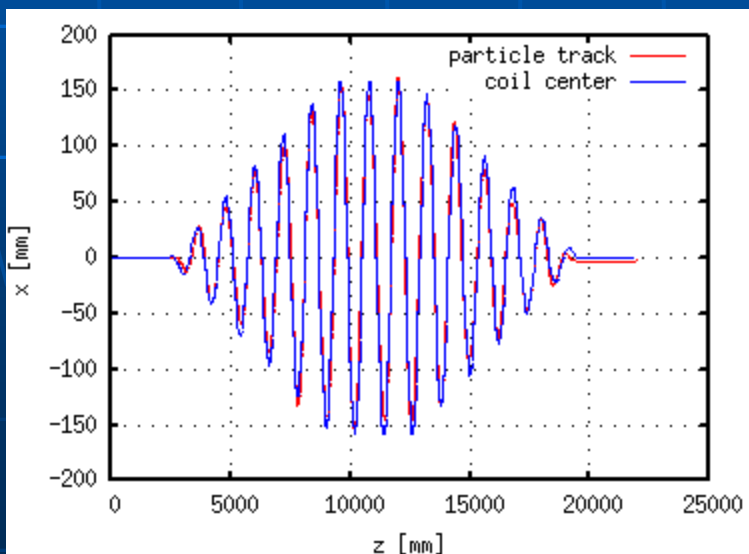


- Helix period = 1.2 m
- Number of coils per period = 20
- Coil length = 0.05 m
- Gap between coils = 0.01 m
- Current = 430.0 A/mm²

Increase gap between coils from 10 to 40 mm



- Gap between coils = 0.04 m
- Current = 1075.0 A/mm²

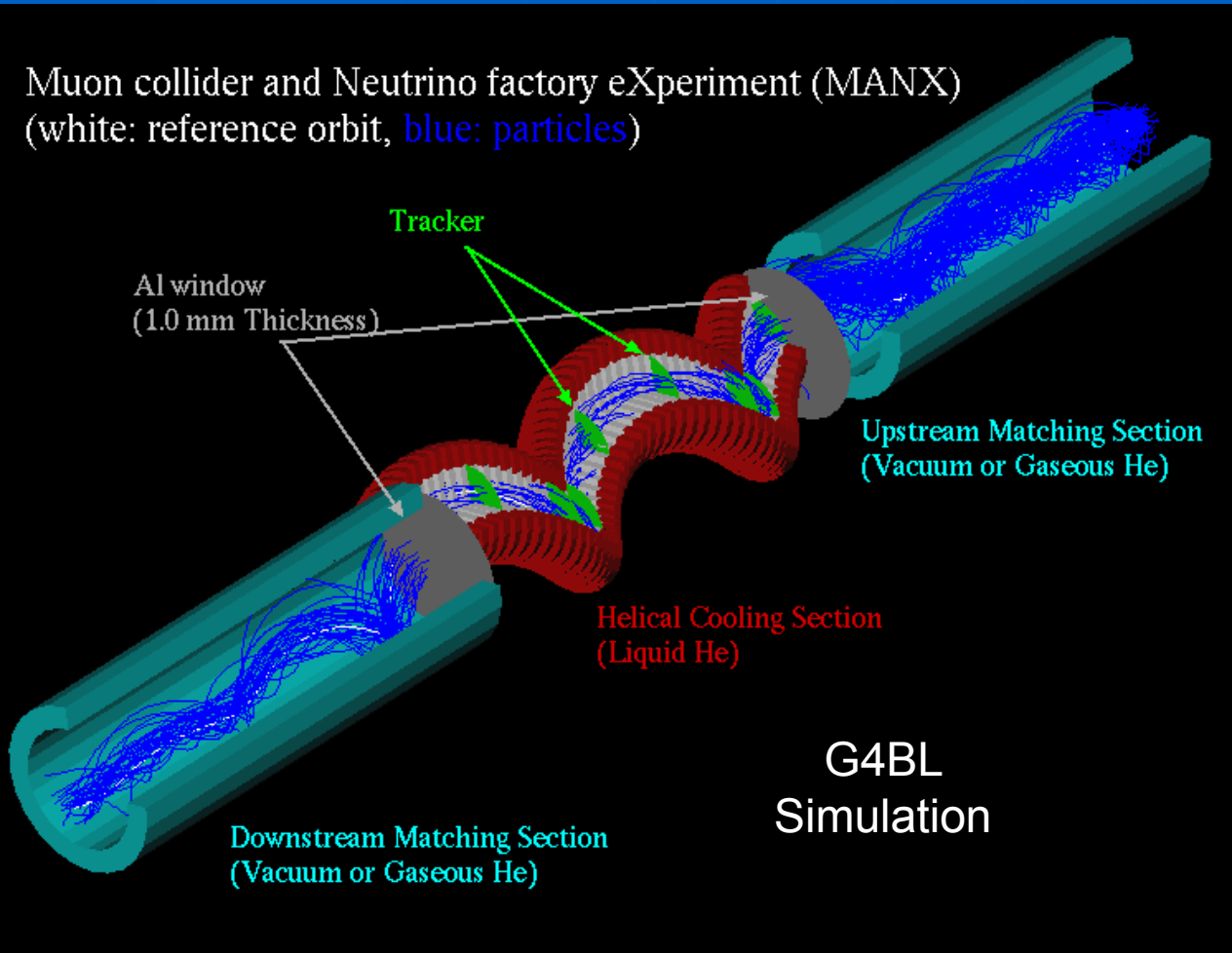




Overview of MANX channel



Muon collider and Neutrino factory eXperiment (MANX)
(white: reference orbit, blue: particles)



- Use Liquid He absorber
- No RF cavity
- Length of cooling channel: 3.2 m
- Length of matching section: 2.4 m
- Helical pitch κ : 1.0
- Helical orbit radius: 25 cm
- Helical period: 1.6 m
- Transverse cooling: ~ 1.3
- Longitudinal cooling: ~ 1.3
- 6D cooling: ~ 2

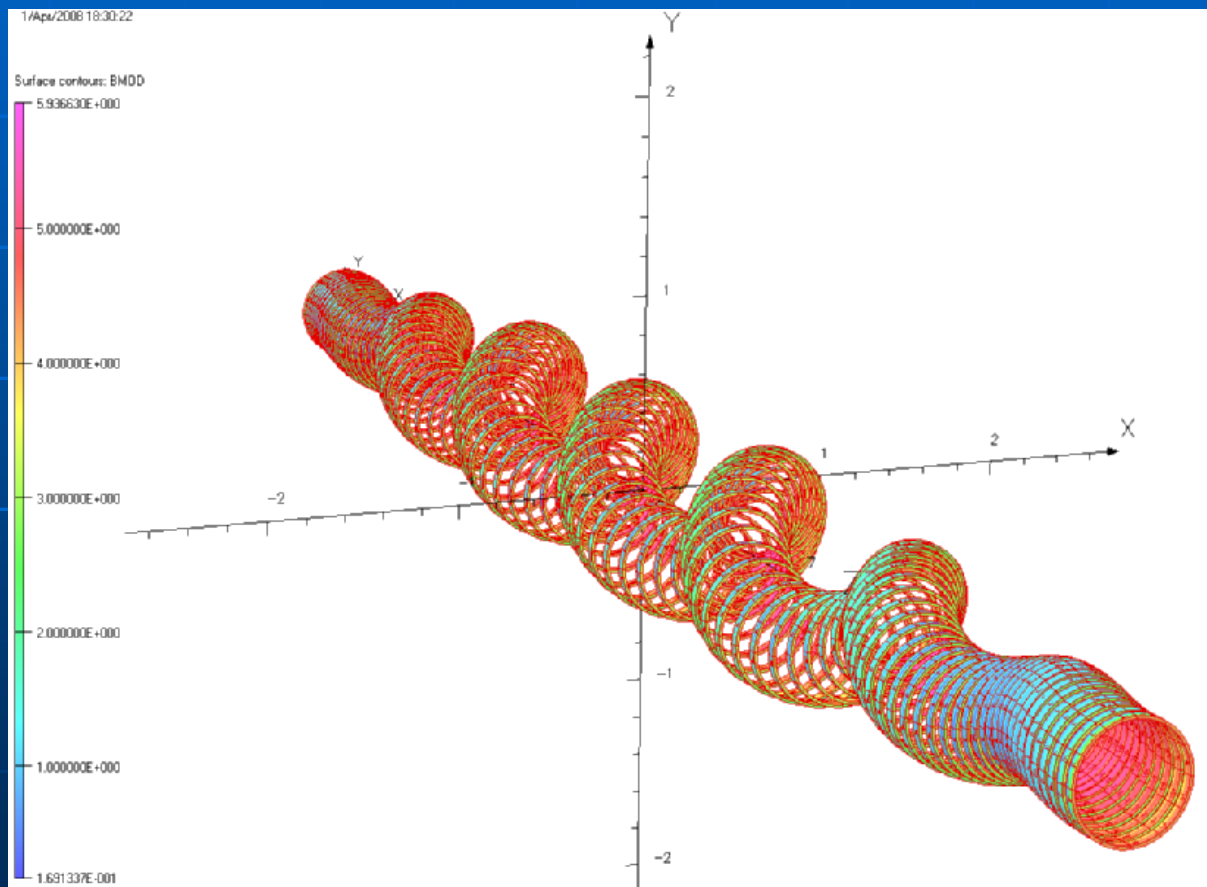
Most Simulations use
G4Beamline (Muons, Inc.)
and/or ICOOL (BNL)



HS for Cooling Demonstration Experiment

Goals: cooling demonstration, HS technology development

Features: SSC NbTi cable, $B_{\max} \sim 6$ T, coil ID ~ 0.5 m, length ~ 10 m





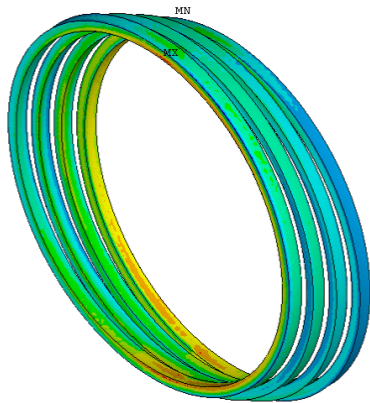
HCC Magnets for MANX

Von Mises Stress

```

ANSYS 11.0
FEB 29 2008
14:36:53
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV      (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.944E-05
SMN =429306
SMX =.448E+07
429306
879481
.133E+07
.178E+07
.223E+07
.268E+07
.313E+07
.358E+07
.403E+07
.448E+07

```



Max. Stress: 4.48MPa

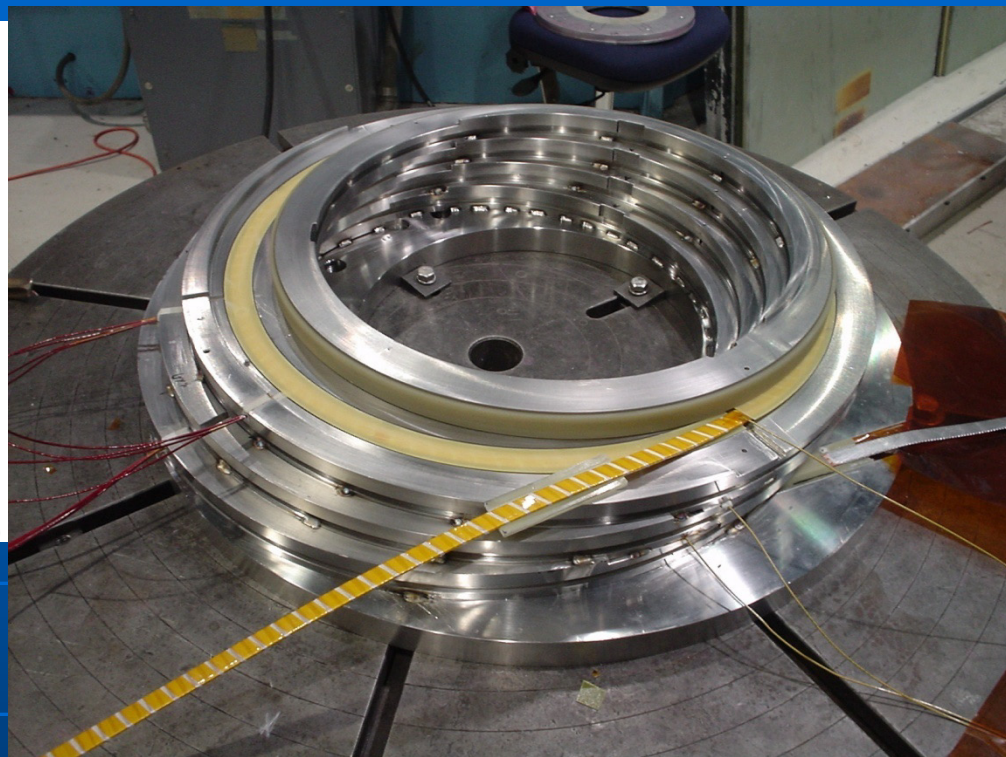
Von Mises Stress

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FEB 29 2008
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TIME=1
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EFACET=1
AVRES=Mat
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SMN =.110E-04
SMX =.112E-03
.110E-04
.222E-04
.335E-04
.447E-04
.560E-04
.672E-04
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.897E-04
.101E-03
.112E-03

```

Max. Strain: 0.0112%

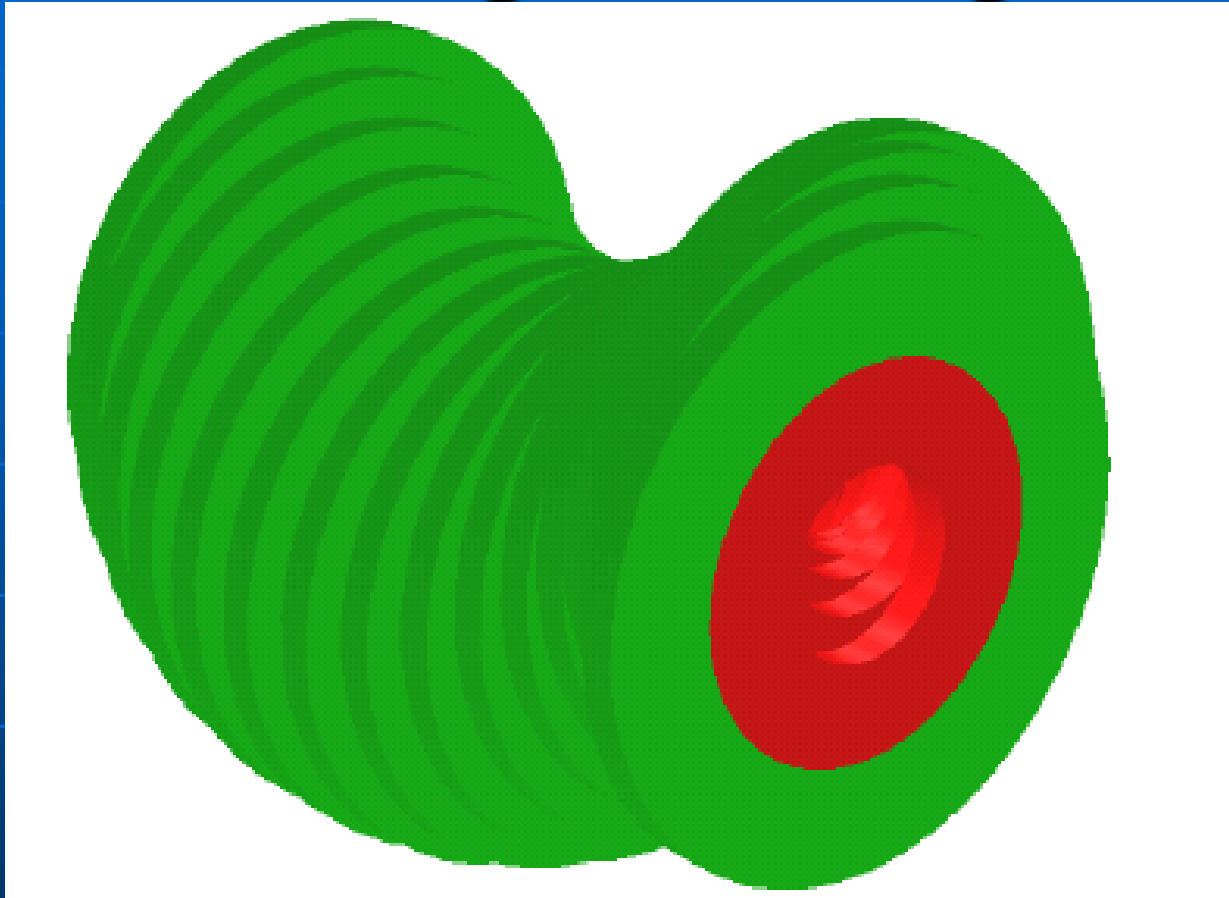


Prototype coils for MANX have been designed and modeled. Construction of a 4-coil assembly using SSC cable is complete. Tests in the TD vertical Dewar will start soon. Since the MANX matching sections are made of coils with varying offset, they are more expensive than the cooling region. Consequently the total magnet cost can be drastically reduced if the matching sections are not needed.



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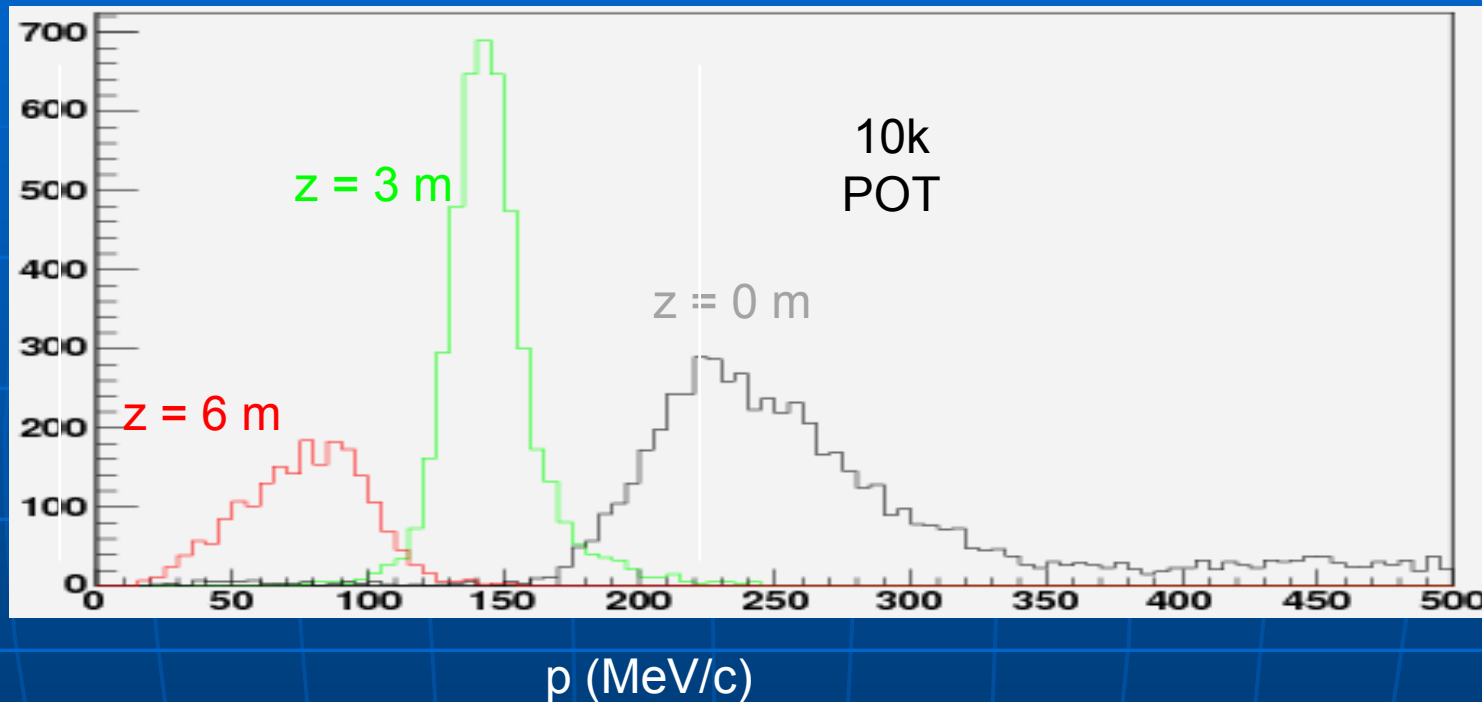
HCC Magnets using HTS



Beam cooling to reduce the size of a muon beam depends on the magnetic field strength. The Phase II proposal to develop this hybrid scheme has been approved. Here a hybrid magnet of Nb₃Sn (green) and HTS (red) could provide up to 30 T in an HCC design.



MANX as a Pre-cooler

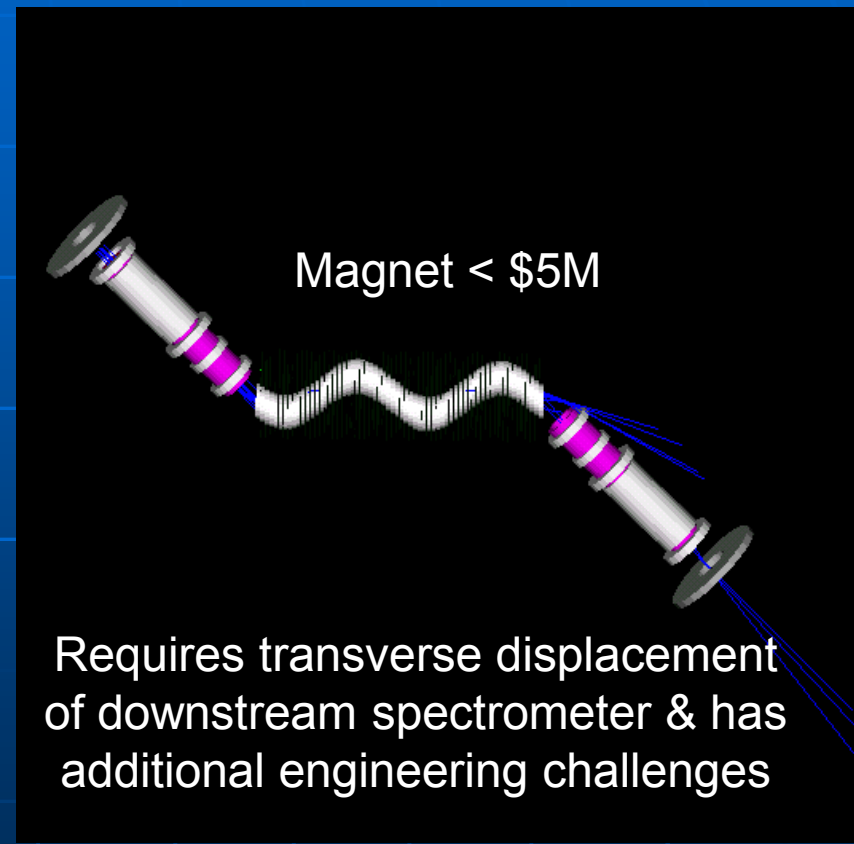
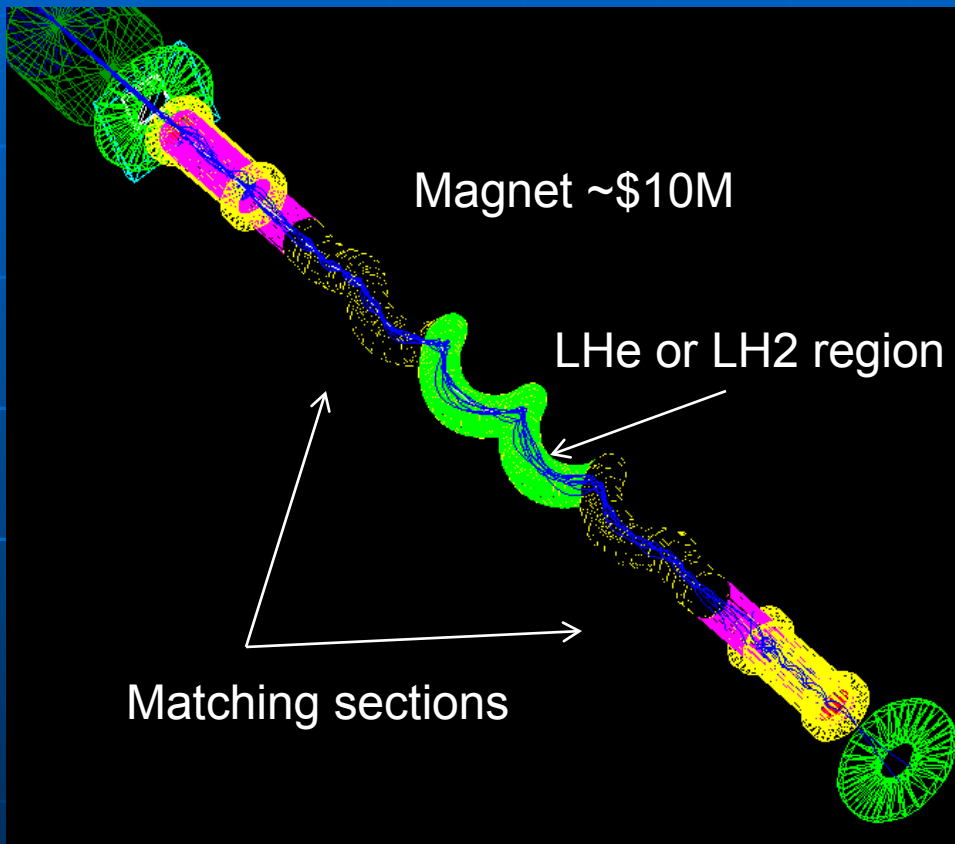


- Used LiH plate in this simulation
- Good transmission



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Simpler Option without Matching Sections





Summary: MANX



- Will Test:
 - Theory of Helical Cooling Channel (HCC)
 - p-dependent HCC with continuous absorber
 - Helical Solenoid Magnet (HS) and absorber
 - similar to that required for upgrade to mu2e experiment
 - Simulation programs (G4BL, ICOOL)
- Minimizes costs and time
 - no RF, uses normalized emittance,
 - ~ 5 m LHe E absorber
 - RF is developed in parallel with new concepts
 - builds on MICE, improves 6-D capability,
 - \sim ps detectors

AAC Charge/Response

- If successfully executed does the MANX proposal provide a validation of 6-D ionization cooling, based on requirements for a Muon Collider. What does the Committee view as the optimum mix of simulations and experimental demonstration required to provide such validations?
 - Collection, cooling, extreme cooling, transport, acceleration of muon beams for MC
 - Require new techniques and technologies
 - MANX demonstrates a new HCC approach to cooling large emittance beams
 - Homogeneous magnetic fields can cope better with resonances
 - MANX demonstrates a new method of emittance exchange
- If successfully executed does the MANX proposal provide a validation of an upgrade of the mu2e experiment based on a collection scheme that reduces “flash” deadtime and the use of the ionization-cooling energy-absorber to range out hadronic backgrounds? What does the Committee view as the optimum mix of simulations and experimental demonstration required to provide such validations?
 - Degrading the higher p, higher flux part of pi + muon production spectrum
 - Gets higher mu/p, without magnetic mirrors that imply long flash time gate
 - Longitudinal cooling with EEX concentrates the stopping beam in the target while
 - Hadronic backgrounds are ranged out (reduces flash gate time?)

AAC Charge/Response

- What are the primary technical risks within the MANX proposal and are they appropriately mitigated through the development period?
 - Timely commitment of manpower and funds
 - MICE delays
 - Engineering escalations for additional capabilities beyond liquid helium
 - vacuum, hydrogen E degrader
 - with Individually powered coils: power supplies, SC leads,
- Given the anticipated timelines within the Muon five year proposal and the mu2e development plan, what is the appropriate schedule for implementation of MANX, either at Fermilab or at RAL?
 - If following MICE, need coordination and continuity
- Do the MANX resource requirements appear reasonably estimated?
 - Iteration on 4-coil design will improve magnet estimates
 - Cryostat, power supplies, matching sections, reuse of MICE detectors, designs
- Can the MANX approach to a mu2e upgrade impact the outlook for Project X?
 - If the energy absorber approach works,
 - higher mu flux is possible, and higher p flux required

