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

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Abstract: 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/tiki-index.php?page=Papers+and+Reports

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, HS, & EEX concepts
  - high-intensity proton driver
    - simultaneous intense muon beams
  - stopping muon beams
    - useful 6D cooling w HCC, EEX
  - neutrino factory
    - HCC with RF, RLA in CW Proj-X
  - Z' factory
    - low Luminosity collider, HE RLA
  - Higgs factory
    - extreme 6D cooling, low beta, super-detectors
  - energy-frontier muon collider
    - more cooling, lower beta

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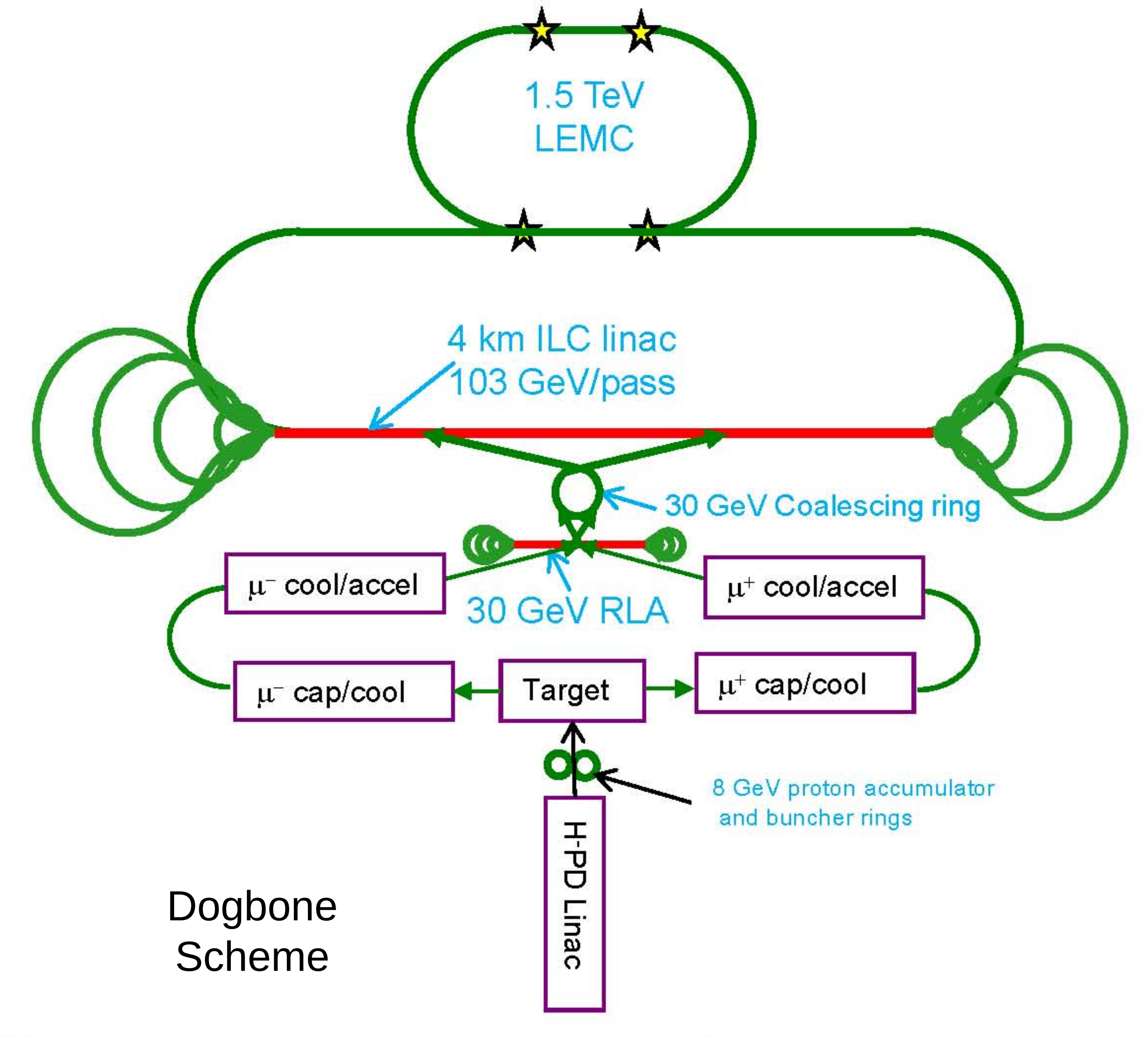
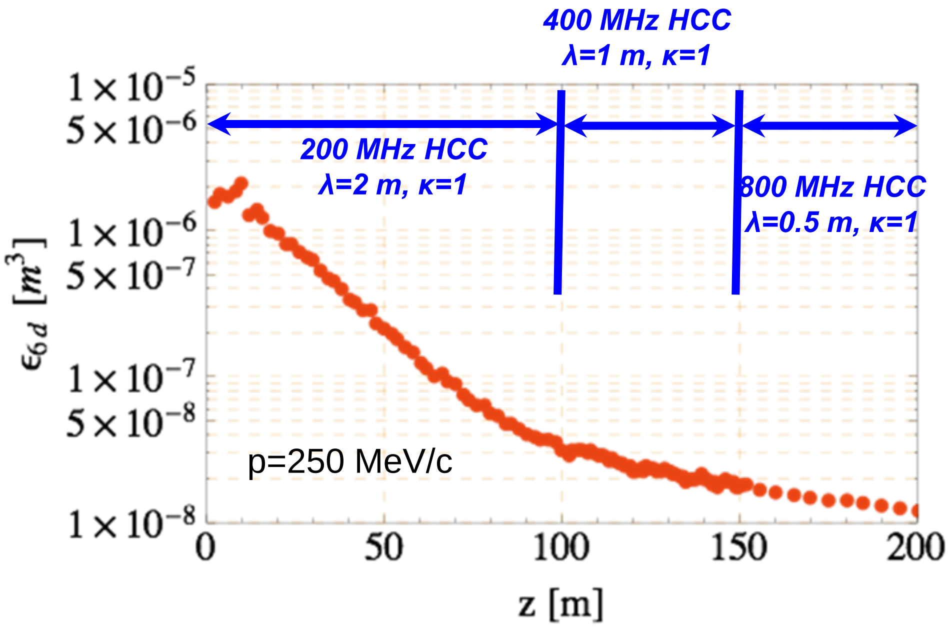
LEMC Scenario

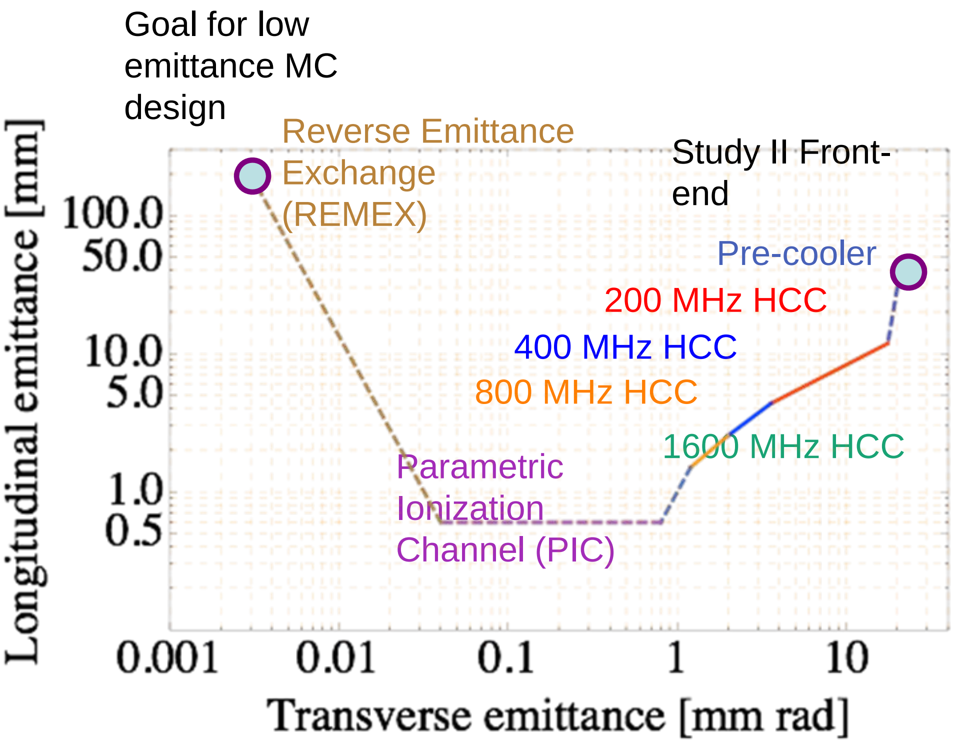


Dogbone
Scheme

Simulation study of HCC for Muon Collider (MC)



6D Phase space evolution in current HCC



Phase space evolution for Muon Collider

(solid line: complete simulation, dashed line: in progress)

Yonehara talk

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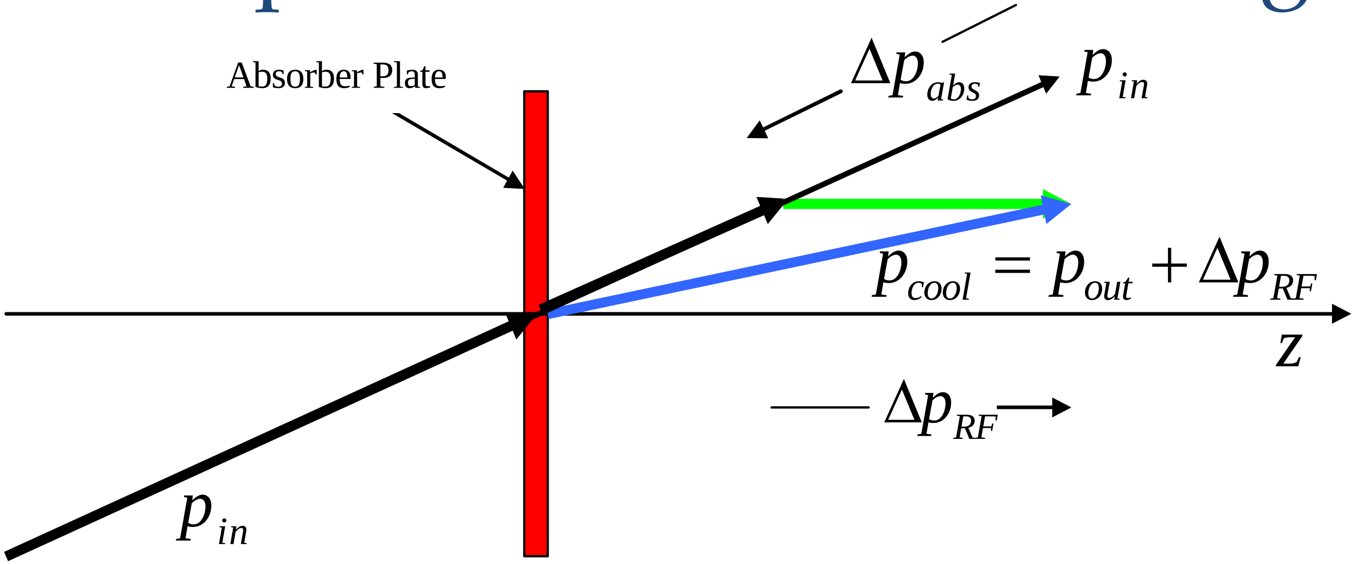
Muons, Inc. Project History

Year	Project	Expected Funds	Research Partner
2002	Company founded		
2002-5	High Pressure RF Cavity	$600,000	IIT (Dan K.)
2003-7	Helical Cooling Channel	$850,000	Jlab (Slava D.)
2004-5[†]	MANX demo experiment	$ 95,000	FNAL TD (Victor Y.)
2004-7	Phase Ionization Cooling	$745,000	Jlab (Slava D.)
2004-7	HTS Magnets	$795,000	FNAL TD (Victor Y.)
2005-9	Reverse Emittance Exch.	$850,000	Jlab (Slava D.)
2005-9	Capture, ph. rotation	$850,000	FNAL AD (Dave N.)
2006-9	G4BL Sim. Program	$850,000	IIT (Dan K.)
2006-9	MANX 6D Cooling Demo	$850,000	FNAL TD (M. Lamm)
2007-10	Stopping Muon Beams	$750,000	FNAL APC (Chuck A.)
2007-10	HCC Magnets	$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	MANX, Collider low beta	$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, $\beta_\perp$ is the transverse beta-function of the magnetic channel, and β is the particle velocity.

- Note that $\frac{d\varepsilon_n}{\varepsilon_n} \approx -\frac{dE_\mu}{E}$ which implies a ~1.5 GeV linac for 10^{-6}

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

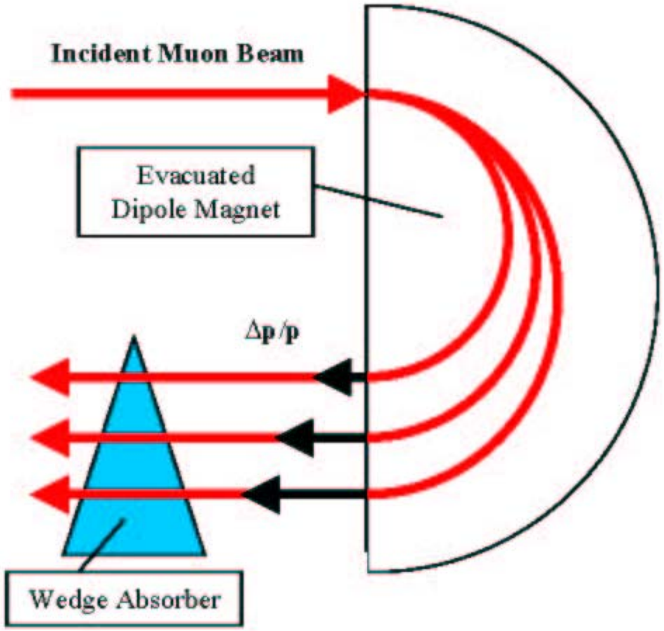


Figure 1. Use of a Wedge Absorber for Emittance Exchange

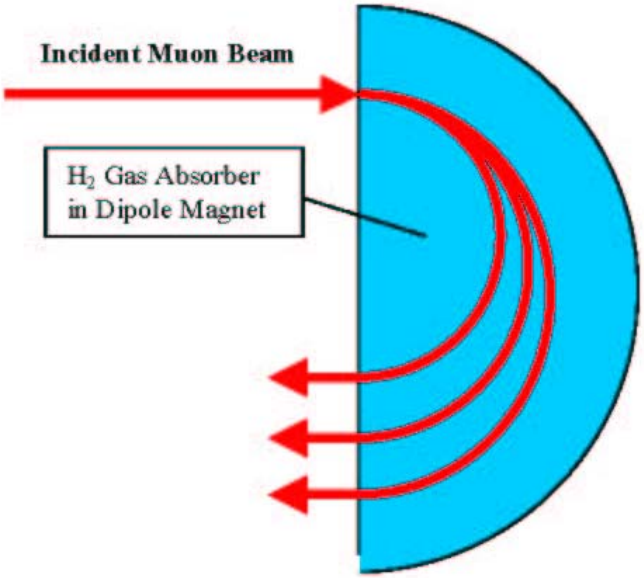


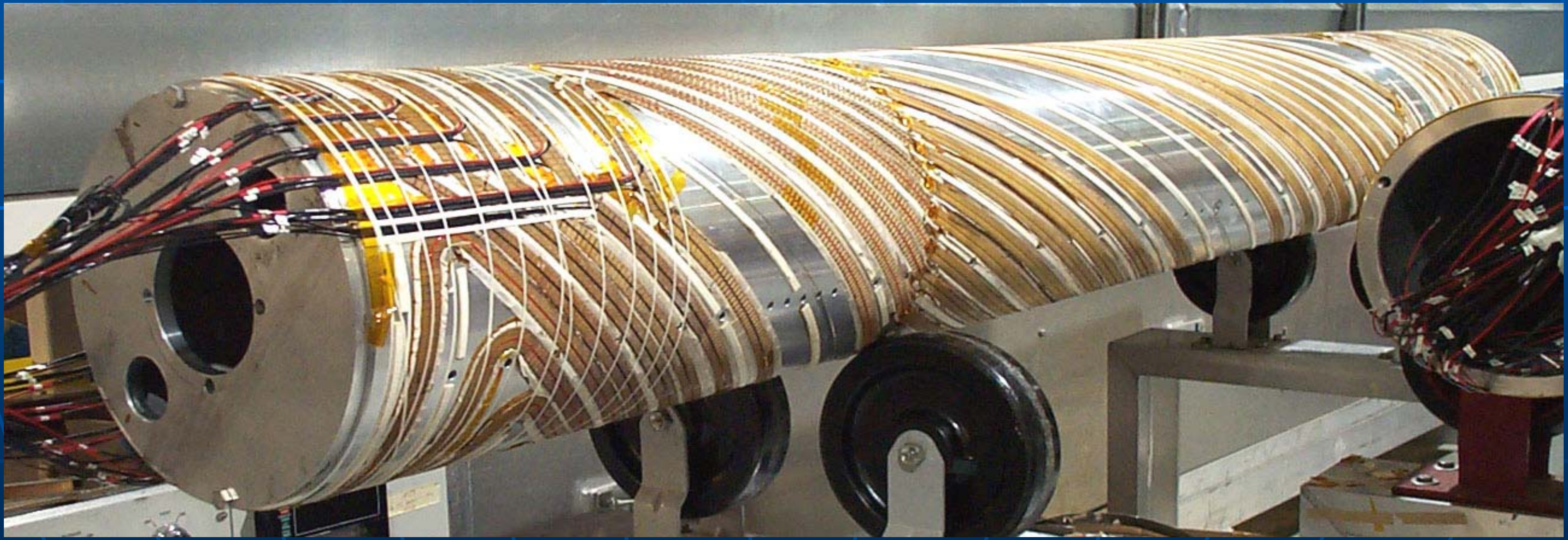
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

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

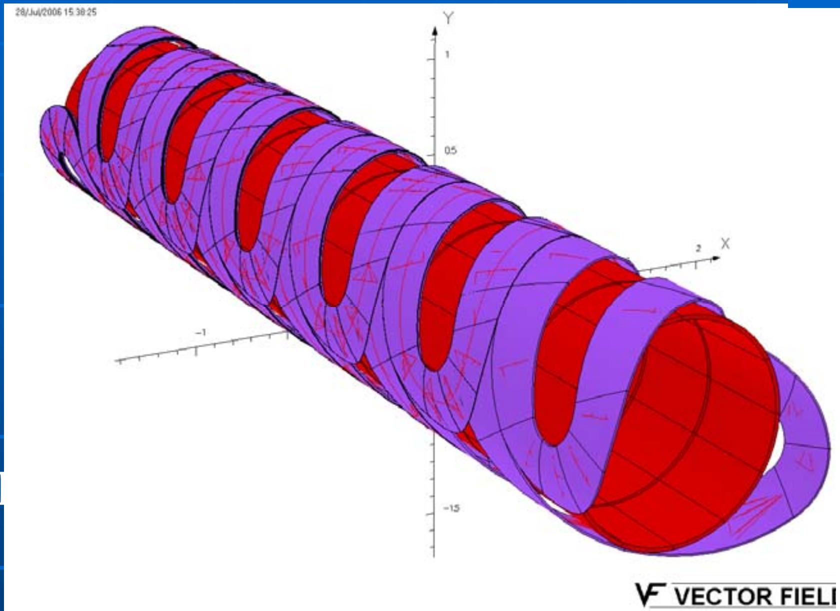
Continuous, homogeneous energy absorber for longitudinal cooling
Helical Dipole magnet component for dispersion
Solenoidal component for focusing
Helical Quadrupole for stability and increased acceptance

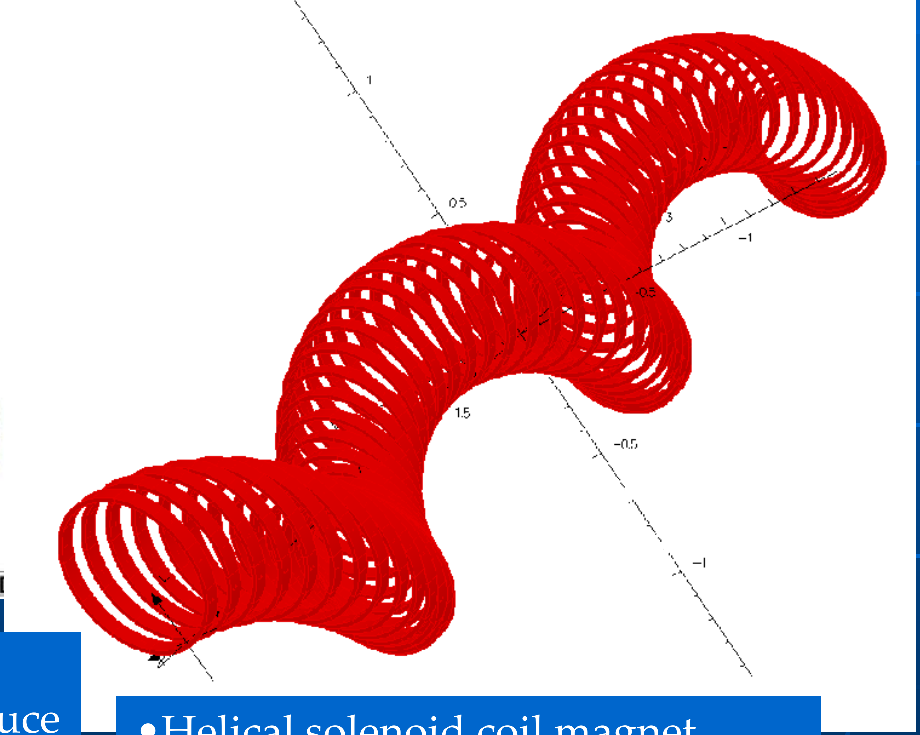


BNL Helical Dipole Siberian Snake magnet for AGS spin control

Two Different Designs of Helical Cooling Magnet

Great new Kashikhin-Yonehara innovation!



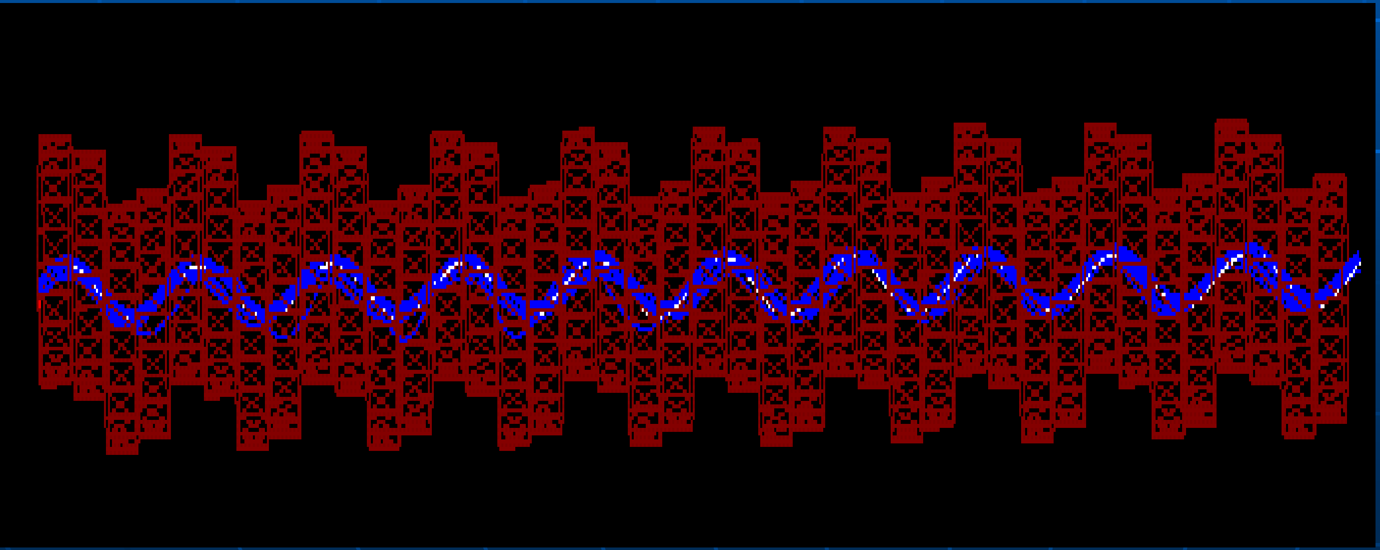


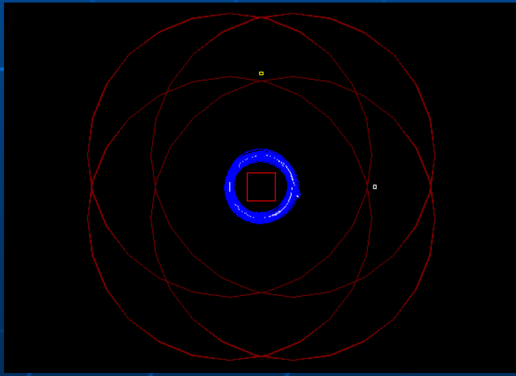
- Siberian snake type magnet
- Consists of 4 layers of helix dipole to produce tapered helical dipole fields.
- Coil diameter is 1.0 m.
- Maximum field is more than 10 T.

- 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





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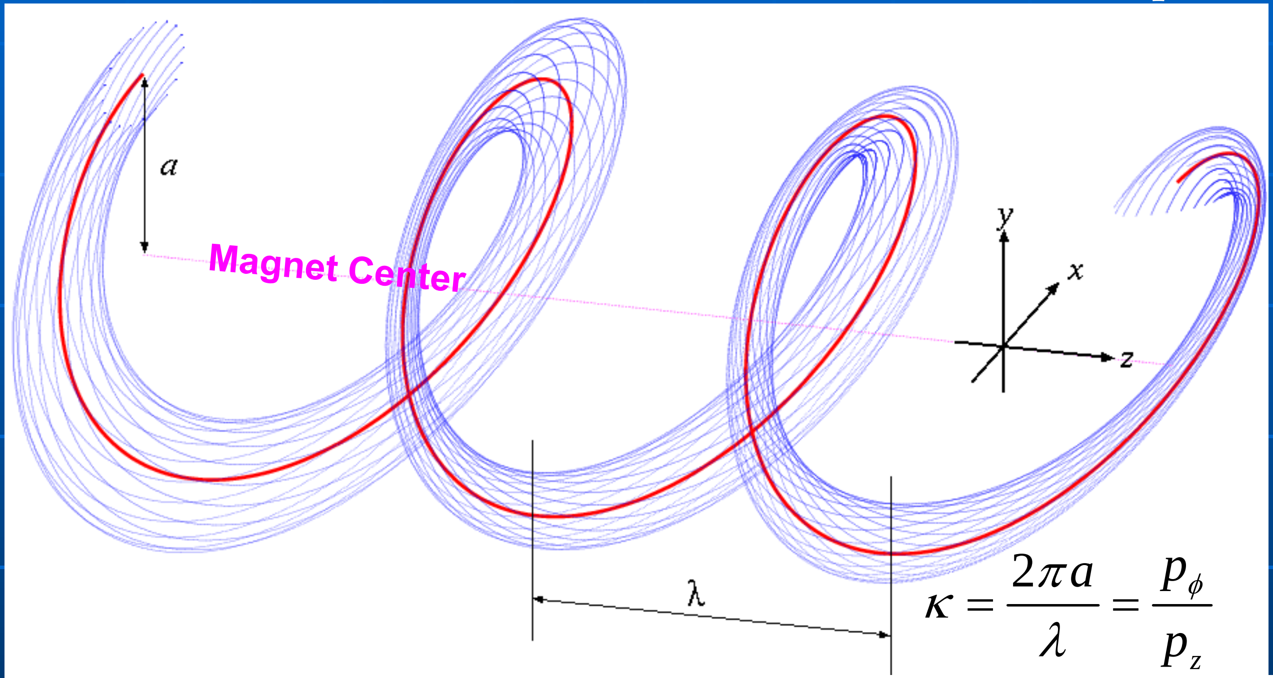
Particle Motion in a Helical Magnet

Combined function magnet (invisible in this picture)

Solenoid + Helical dipole + Helical Quadrupole



$$\kappa = \frac{2\pi a}{\lambda} = \frac{p_\phi}{p_z}$$

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

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

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

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

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

Equal cooling decrements

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

Longitudinal cooling only

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

~Momentum slip factor

$$\eta = \frac{d}{d\gamma}\frac{\sqrt{1+\kappa^2}}{\beta} = \frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left(\frac{\kappa^2}{1+\kappa^2}\hat{D} - \frac{1}{\gamma^2}\right) \qquad \frac{\kappa^2}{1+\kappa^2}\hat{D} \sim \frac{1}{\gamma^2_{transition}}$$

HCC Virtues

New concept
- not FODO, but based on a theory (theory by Derbenev)
  - time and z-independent Hamiltonian
  - solenoid, helical dipole, helical quad fields
- two versions: with or without RF

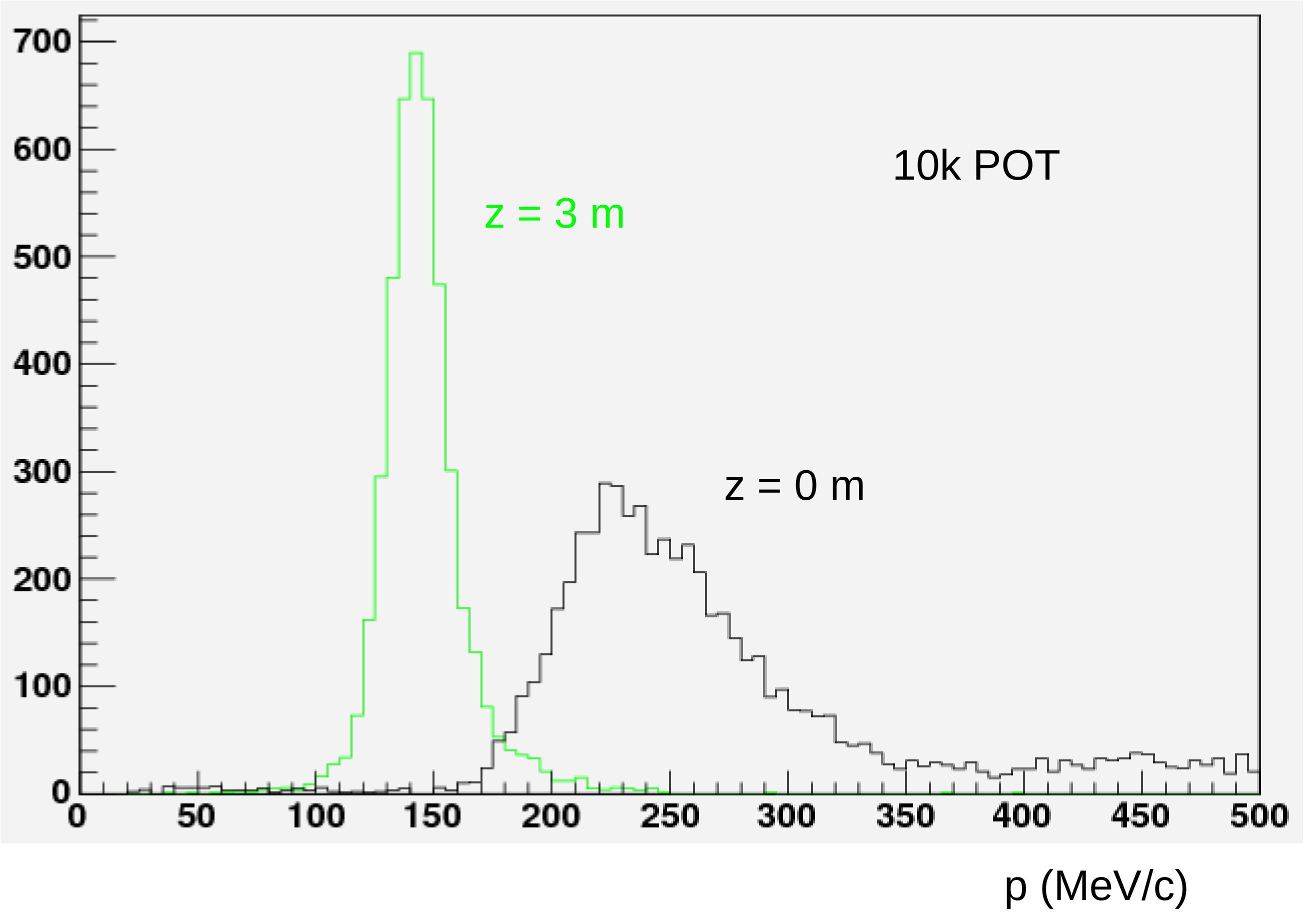
Large acceptance
- for huge muon beam emittances
  - large resonance driving terms

Homogeneous field
- minimal resonant losses
  - DE/E for a million in 6D reduction implies a long channel

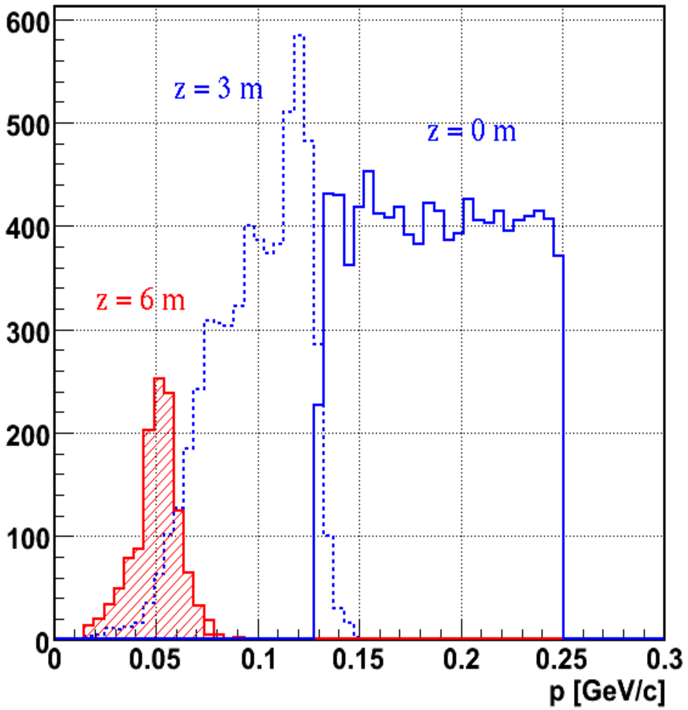
Many uses for muon beams (overview by Mary Anne)

Example of longitudinal cooling in a HCC overcomes $1/\beta^2$ dependence of energy loss to keep the momentum spread small while undergoing energy degradation to slow a muon beam.

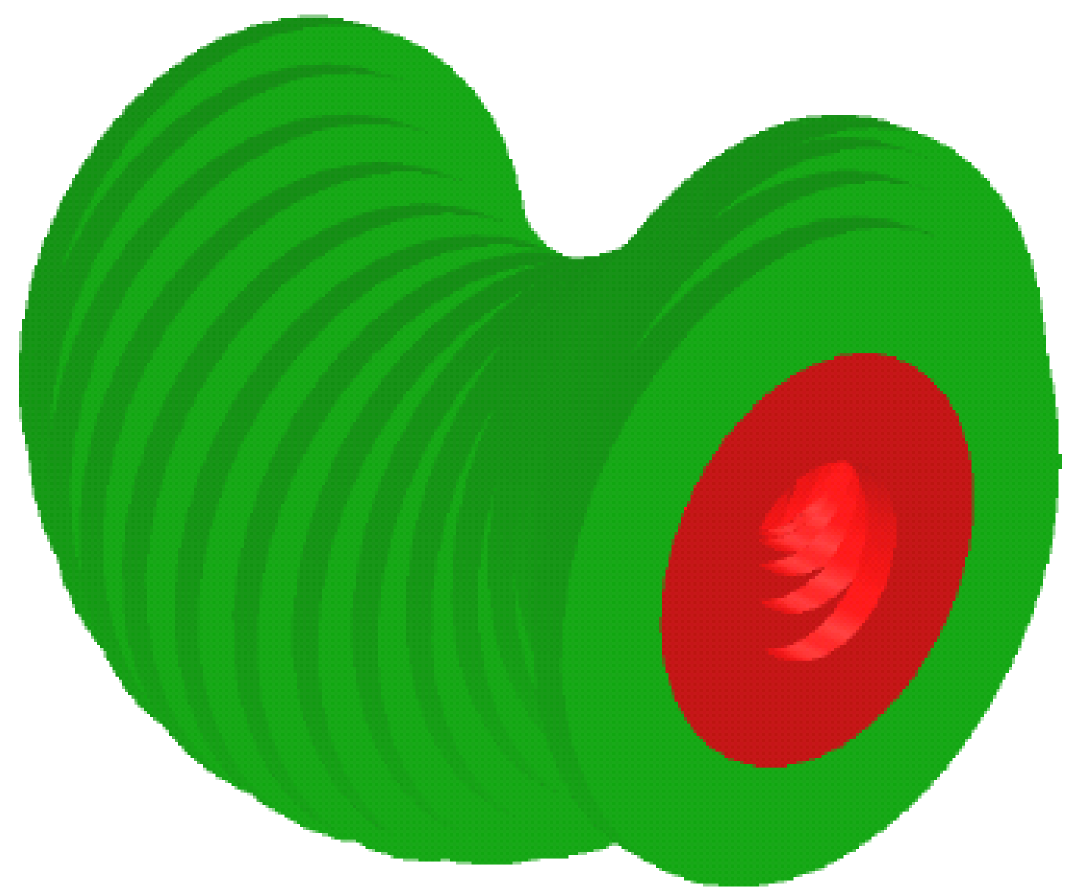
MERIT-like targetry into NF/MC Front End up to End of Energy/Phase Rotator into HCC w/o RF w/ tapered LiH wedges variably spaced to match energy loss while maintaining reference radius of 50 cm. The z value refers to depth from start of HCC.



Example of HCC use for the mu2e experiment discussed by Ankenbrandt and Yonehara



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.

many new ideas under development:

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
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

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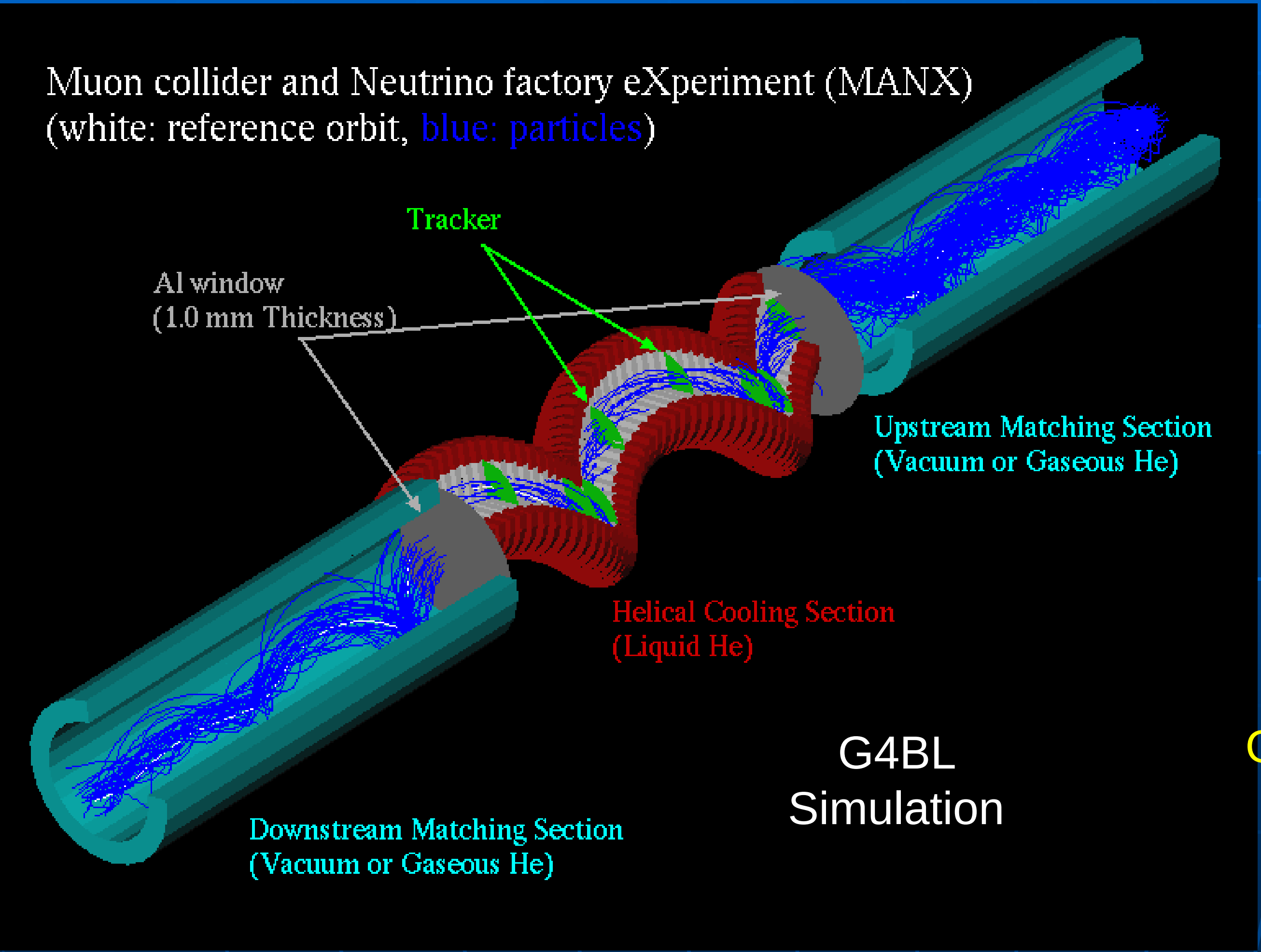
Overview of MANX channel



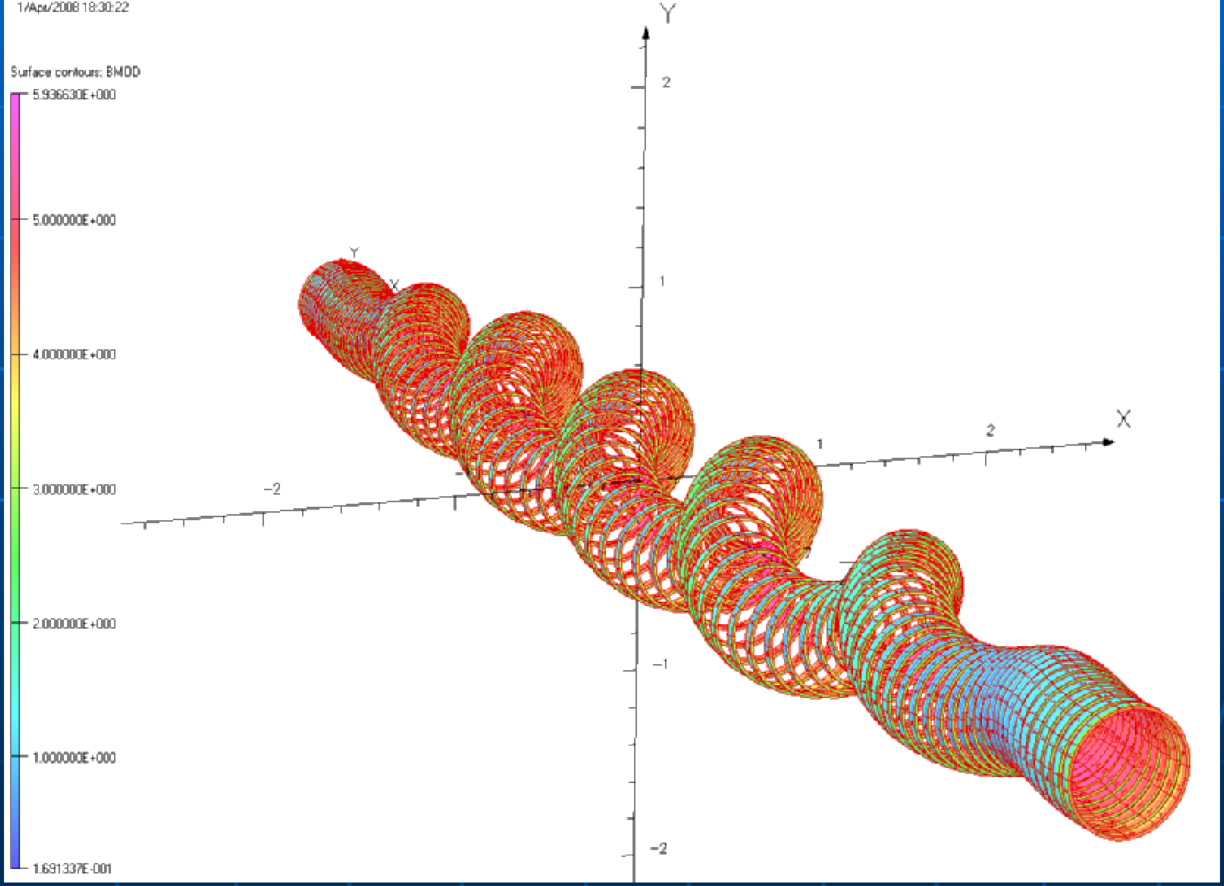
- Use Liquid He absorber
- No RF cavity
- Length of cooling channel: 3.2 m
- Length of matching section: 2.4 m
- Helical pitch κ: 1.0
- Helical orbit radius: 25 cm
- Helical period: 1.6 m
- Transverse cooling: ~1.3
- Longitudinal cooling: ~1.3
- 6D cooling: ~2

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

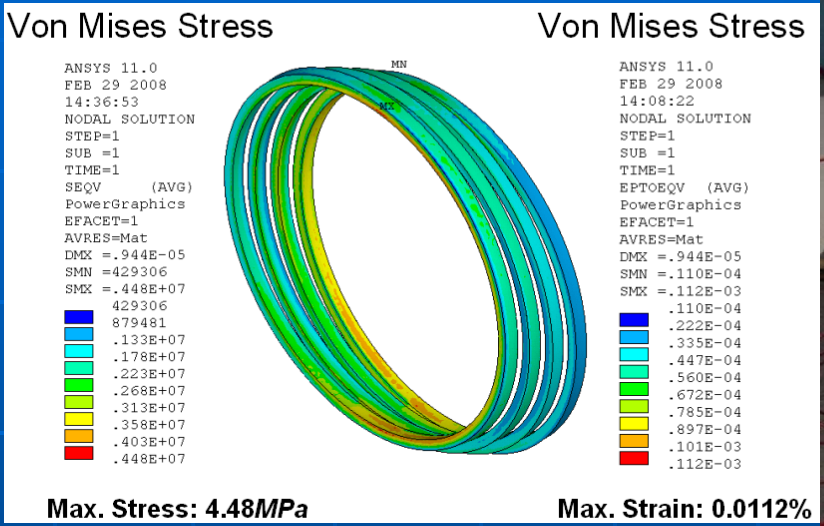
HS for Cooling Demonstration Experiment

Goals: cooling demonstration, HS technology development

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

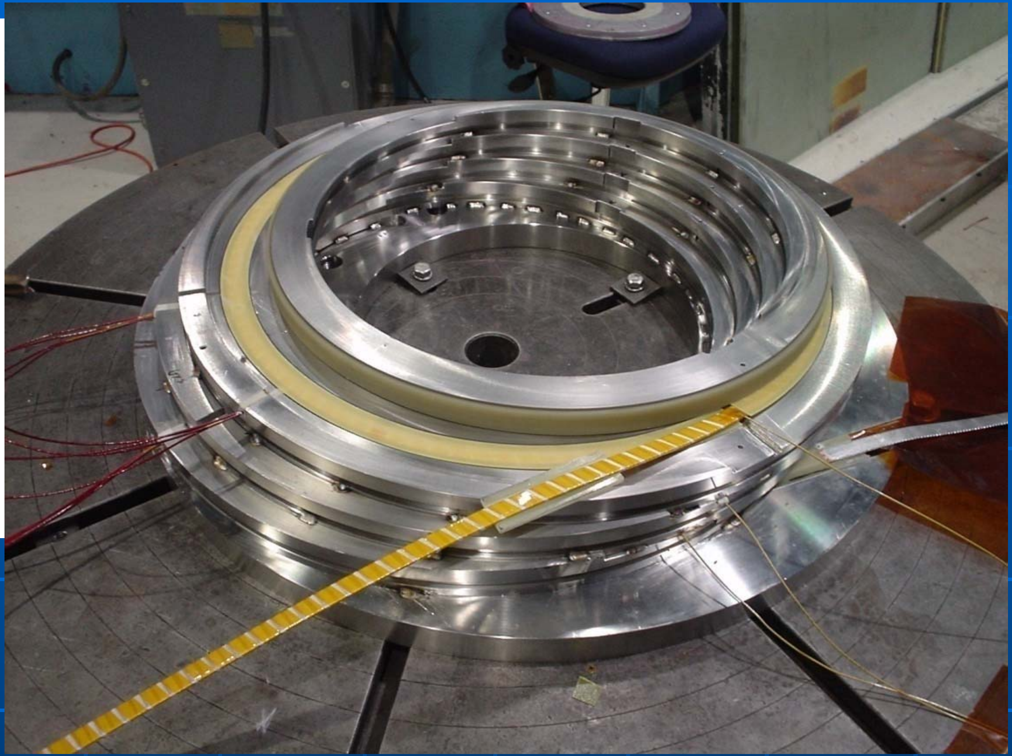


HCC Magnets for MANX



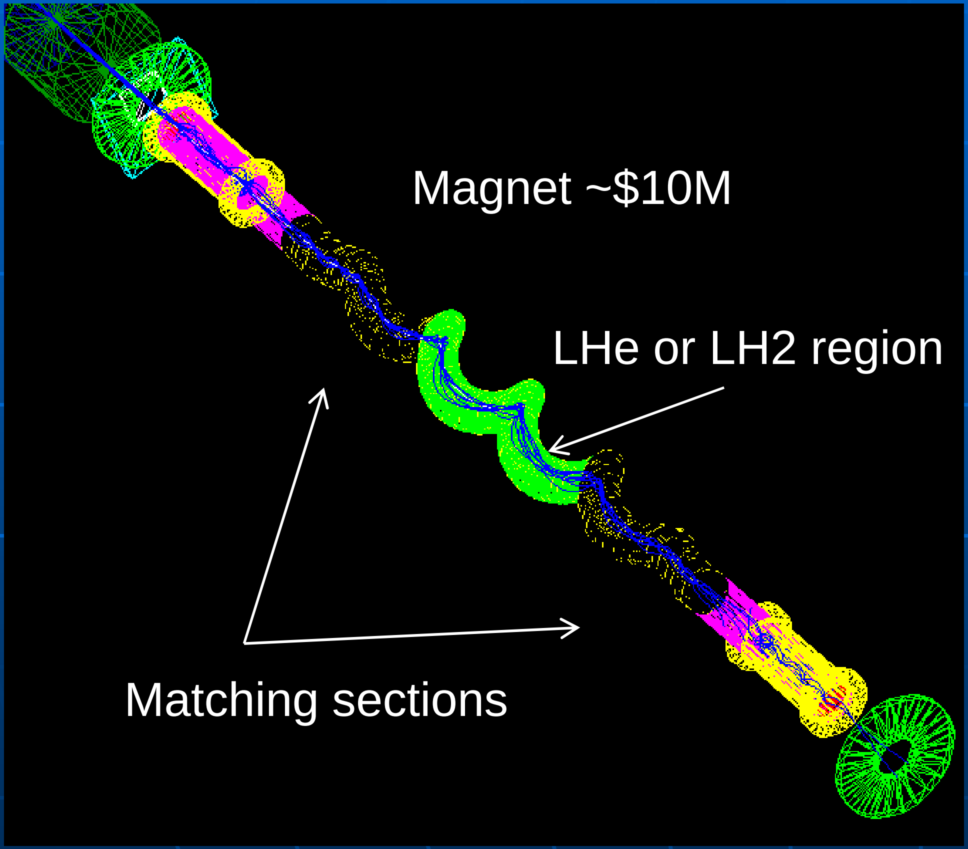
Max. Stress: 4.48*MPa*

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 are complete. 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. See talk by Kashikhin.

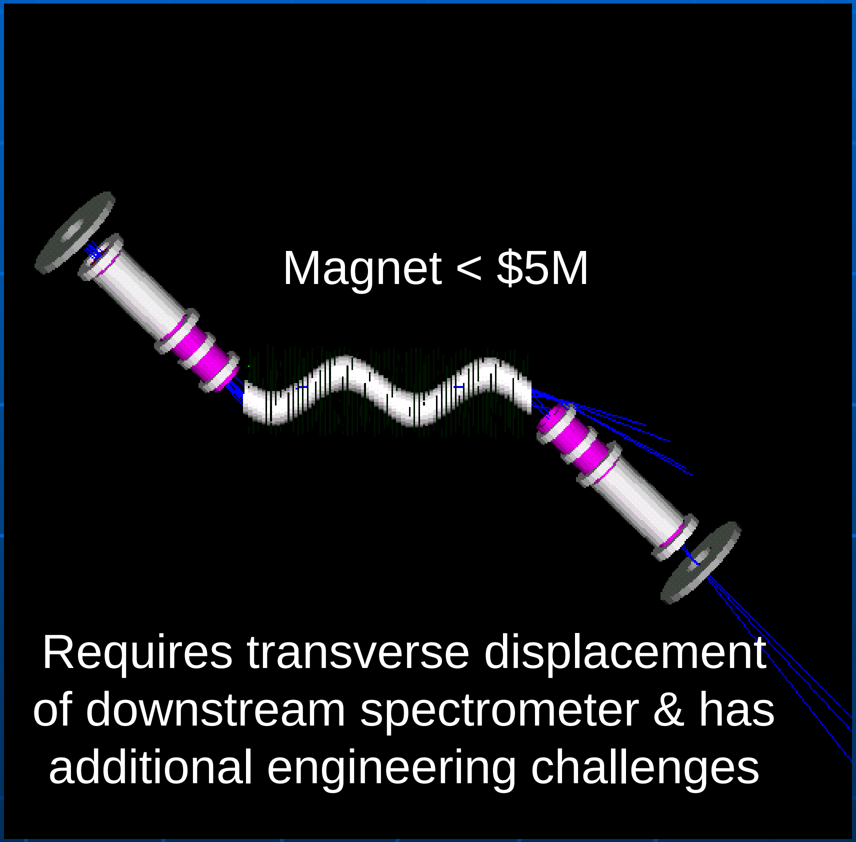
Simpler Option without Matching Sections



Magnet ~$10M

LHe or LH2 region

Matching sections



Magnet < $5M

Requires transverse displacement of downstream spectrometer & has additional engineering challenges

Summary: MANX

- Will Test:
    - Theory of Helical Cooling Channel (HCC)
        - p-dependent HCC with continuous absorber
    - Helical Solenoid Magnet (HS) and absorber
        - similar to those required to upgrade the mu2e experiment
    - Simulation programs (G4BL, ICOOL)
- Encourages wider interest in muon cooling for Fermilab's future
    - Adds Energy Frontier and Stopping Muon Beam HEP Experimenters
    - Local universities especially important
    - RAL and MICE connect to European and Asian communities
- Minimizes costs and time
    - no RF, uses normalized emittance, ~5 m LHe E absorber
    - builds on MICE, improves 6-D capability, ~ps detectors
    - RF is developed in parallel with new concepts
- Collaborators have been asked to address AAC charge:

AAC Charge/Possible Responses

- 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 several 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 momentum, higher flux part of π and μ production spectra
    - Gets higher mu/proton, without magnetic mirrors that imply a long flash gate
  - Longitudinal cooling with EEX concentrates the stopping beam in the target while
  - Hadronic backgrounds are ranged out (also reduces flash gate time)

AAC Charge/Possible Responses

- 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?
  - To follow MICE at RAL, coordination and continuity are required
  - Sooner would be better
- 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

AAC Agenda

8:30-8:50	Slava Derbenev	**Theory of the HCC**
	History, derivation, epicyclic channel	
8:50-9:10	Mary Anne Cummings	**Uses of the HCC**
	Muon collection, 6D and extreme cooling, for MC, NF, and mu2e	
9:10-9:35	Chuck Ankenbrandt	**Mu2e applications**
	Overview, upgrade to HCC-MANX magnet, relationship to Project X	
9:35-9:55	Vladimir Kashikhin	**Helical Solenoid**
	Magnet concept, 4-coil model, cost estimates	
9:55-10:20	break	
10:10-10:40	Katsuya Yonehara	**MANX**
	HCC concepts, MC goals, simulations	
10:40-11:00	Bob Abrams	**MANX design**
	Detectors, relationship to MICE	
11:00-11:20	Tom Roberts	**G4 simulations, MANX@RAL**
	Simulation questions, timeline, MICE viewpoint	