Update on Muons, Inc. Activities

Mary Anne Cummings
Muons, Inc.
(http://www.muonsinc.com/)

MUTAC Review
April 6, 2009
Fermilab

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Highlights since last MUTAC meeting

- SBIR-STTR collaboration is growing:
  - Laboratories: Fermilab, JLab, LBNL, NHMFL , BNL*, SNS*, Cornell*
  - Universities: IIT, ODU, FSU, NIU, HU*,UC* *proposed
- 5 new Phase I grants, to be submitted for Phase II by 4/17/2009
  - Fiber optics for HTS (FSU)
  - RF windows (JLab)
  - HPRF (Fermilab)
  - Pulsed RLA (JLab)
  - RF breakdown (LBNL)
- 2 new Phase II grants
  - mu2e with FNAL APC
  - HTS HCC with FNAL TD
- 42 abstracts for PAC09
  - see http://www.muonsinc.com/tiki-index.php?page=Papers+and+Reports
- 19 Phase I proposals (13 HEP, 2 NP, 3 BES, 1 DOD)
  - DOE award announcements ~May 1
- MANX 6D cooling experiment presented to Fermilab AAC
  - as part of mu2e upgrade development for project-X era (AAC report pending)
- Supported 2 Muon Collider Workshops (MC design JLab and LEMC Fermilab)
- Joined MICE

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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 (pushing CW project-X)
  - stopping muon beams
    - useful 6D cooling w HCC, EEX, mu2e experiment
  - 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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People Power

Subgrant PIs

JLAB

- Slava Derbenev
- Alex Bogacz
- Bob Rimmer

Fermilab

- Victor Yarba
- Milorad Popovic
- David Neuffer
- Mike Lamm
- Sasha Zlobin
- Katsuya Yonehara

IIT

- Dan Kaplan

LBNL

- Derun Li

FSU-NHMFL

- Justin Schwartz

Senior Staff

- Robert Abrams
- Andrei Afanasev
- Charles Ankenbrandt*
- Kevin Beard
- Mary Anne Cummings
- Valentin Ivanov*
- Rolland Johnson
- Stephen Kahn
- Moyses Kuchnir
- Michael Neubauer*
- Thomas Roberts
- Richard Sah
- Cary Yoshikawa*

*new

Post Docs

- Shahid Ahmed (IIT)
- Mohammad Alsharo'a (MI)
- Frank Hunte (FSU)
- Guimei Wang (ODU)

Ph.D. Students

- Mahzad BastaniNejad (ODU)
- Jim Maloney (NIU)
- Ana Samolov (ODU)
- Melanie Turenne (FSU)

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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 Y.)
2008-9	MANX, Collider low beta	$150,000	NIU DCEO	(D. Hedin)

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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

Dielectric-filled RF cavities
Particle refrigerator

See http://www.muonsinc.com/ "papers and reports"
42 Abstracts for PAC09
21 Papers from EPAC08
13 Papers from PAC07

LEMC Scenario

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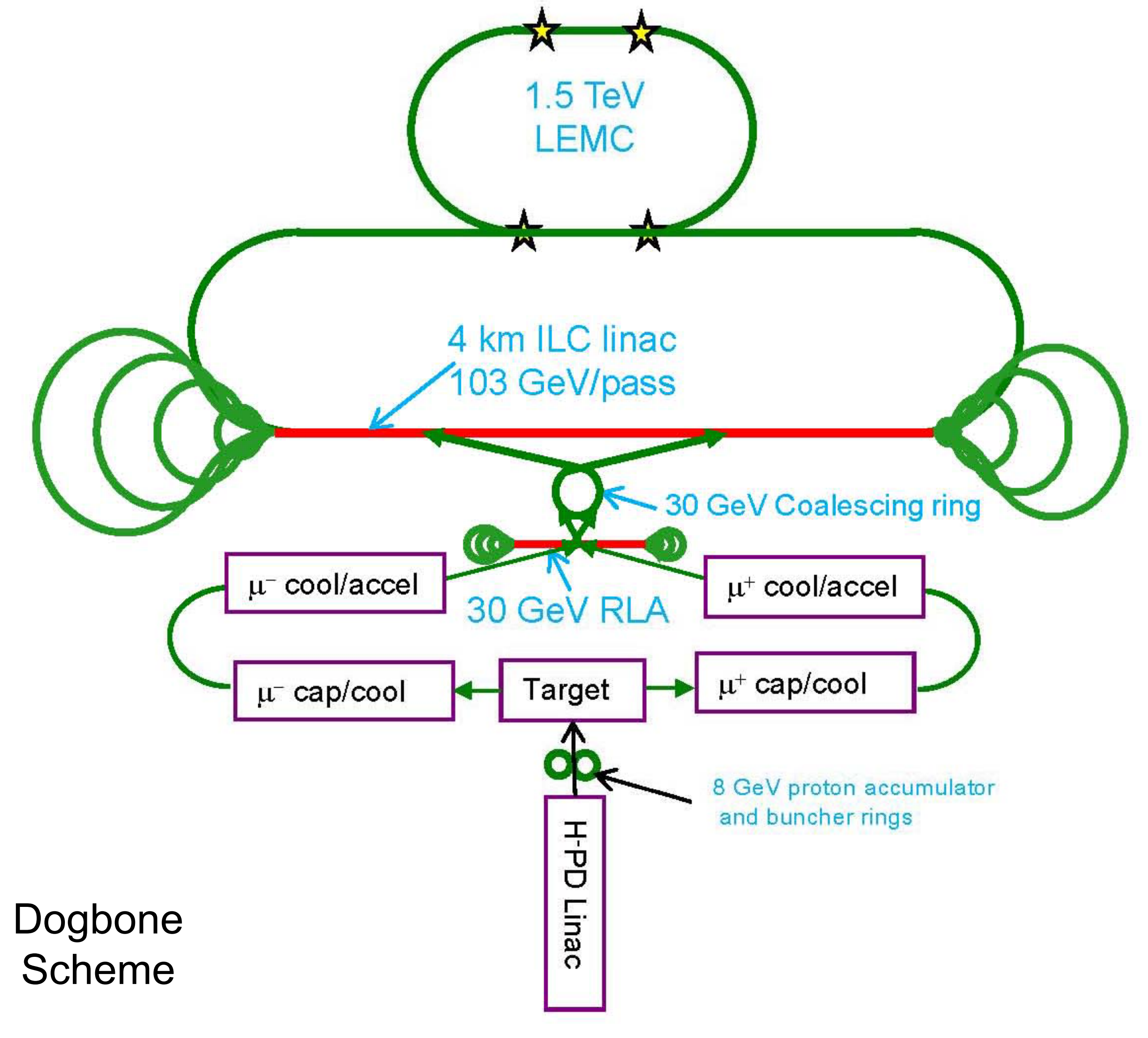
Existing and proposed Muons, Inc. SBIR-STTR projects include most aspects of MC conceptual design, from proton driver to IP detector design, with a special interest in muon cooling.



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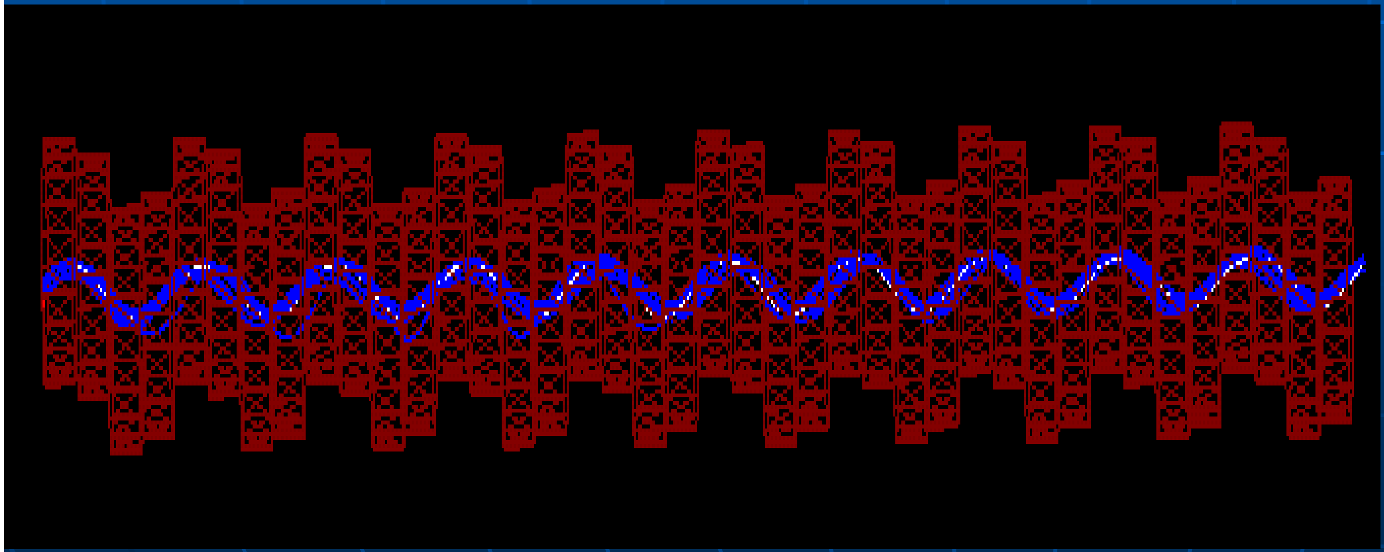
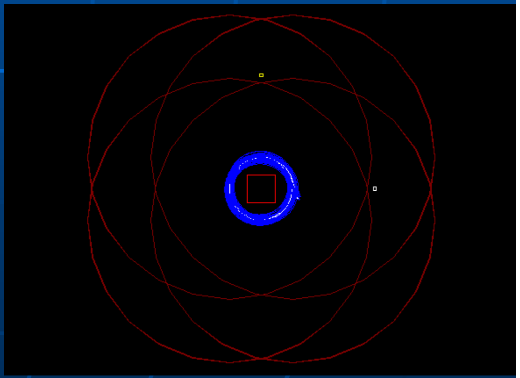
6-Dimensional Cooling in a Continuous Absorber

- 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

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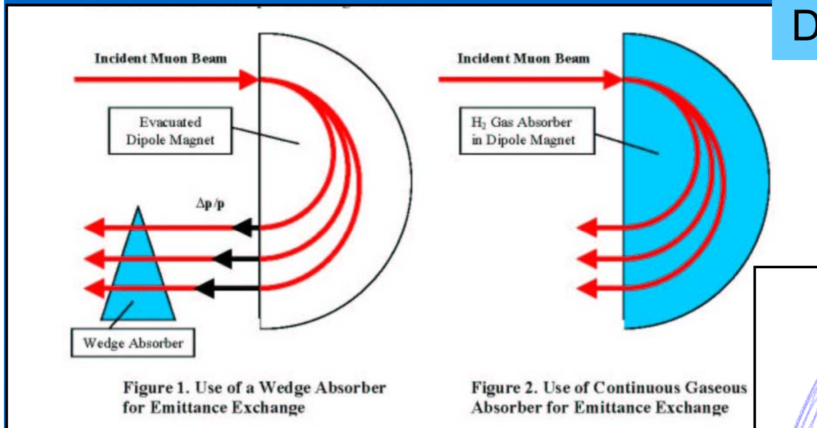


Figure 1. Use of a Wedge Absorber for Emittance Exchange

Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

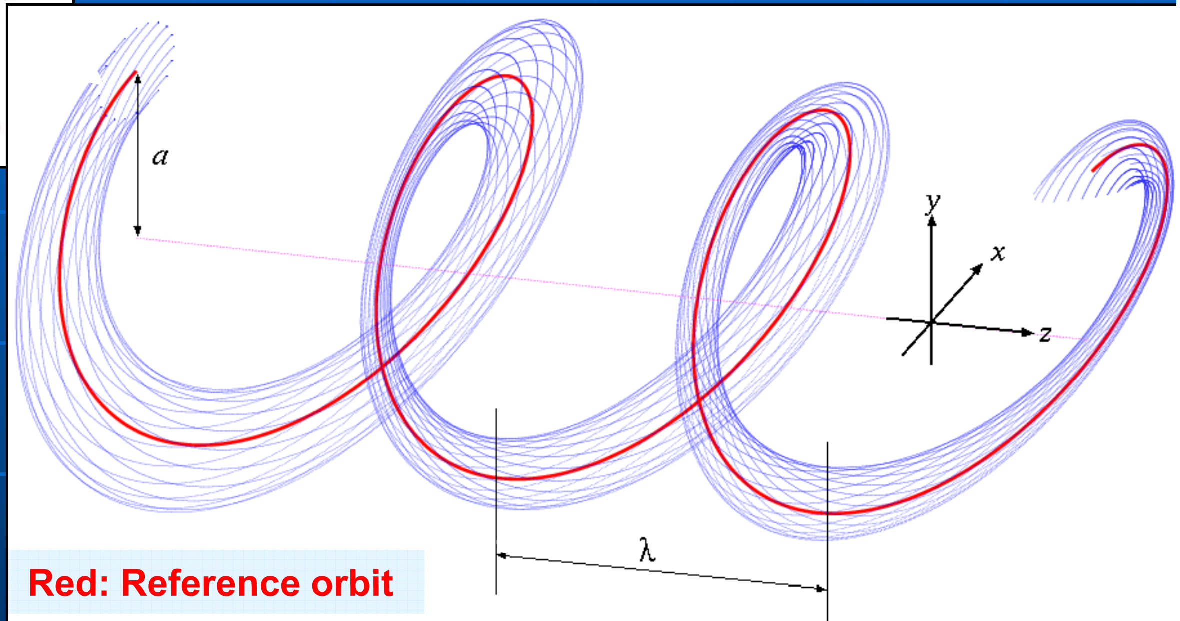
Dipole → Dipole + Solenoid (+Quad for stability)

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

$$\} \; f_{central} = \frac{e}{m}(b_\varphi \cdot p_z - b_z \cdot p_\varphi)$$

Transforming to the frame of the rotating helical dipole leads to a time and z –independent Hamiltonian, can form relation:

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



Red: Reference orbit

Blue: Beam envelope

Manipulate values of parameters to change performance

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

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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

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

Simulation study of HCC for Muon Collider (MC)

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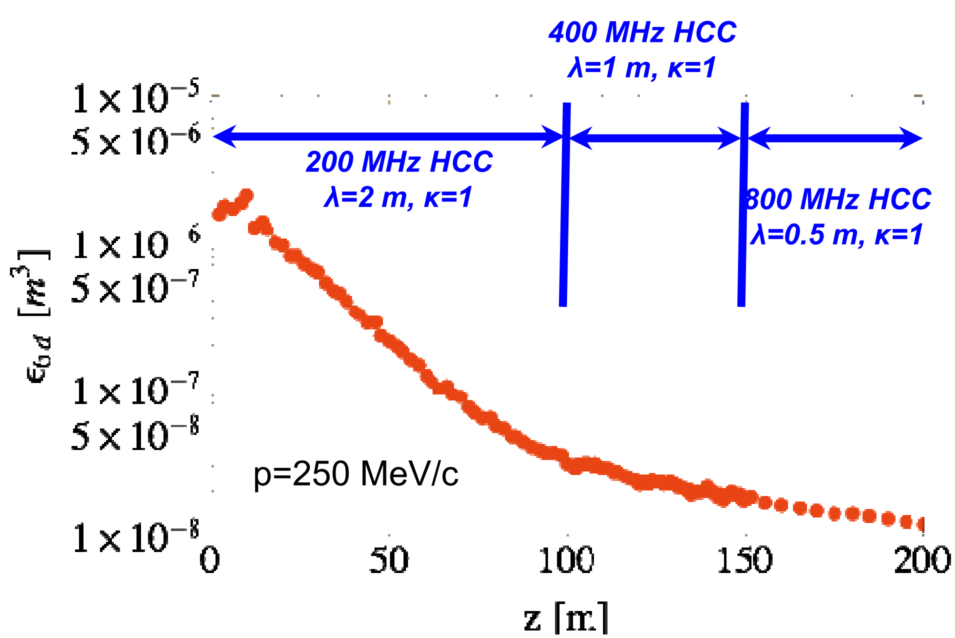

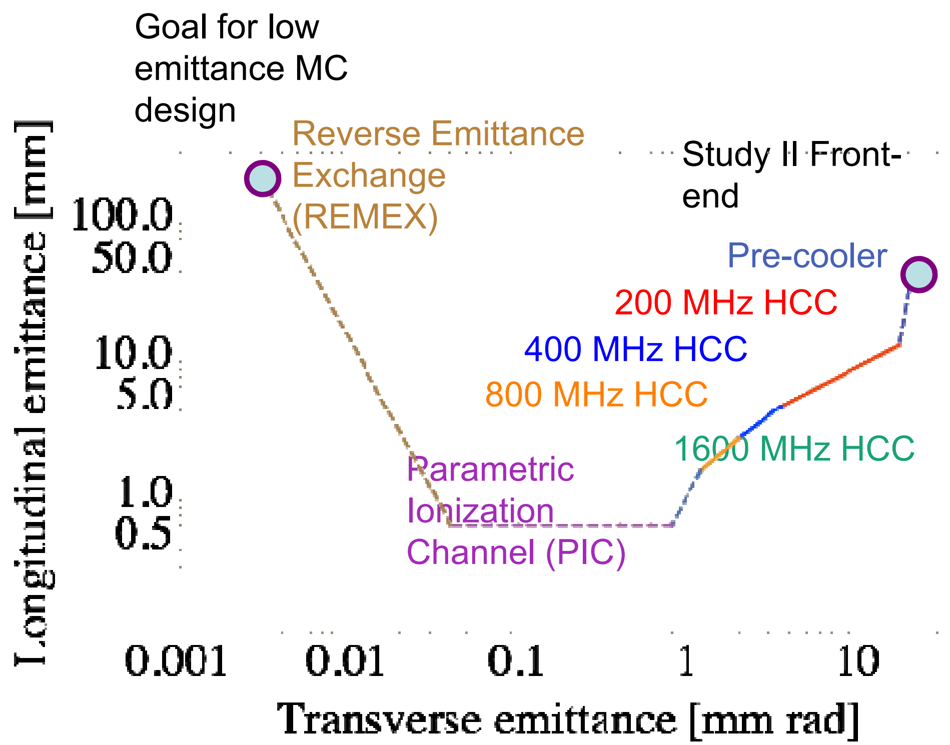

6D Phase space evolution in current HCC, by Katsuya Yonehara

Phase space evolution for Muon Collider

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

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
  - Reducing the 6D emittance by a million implies a long channel

Many uses for muon beams

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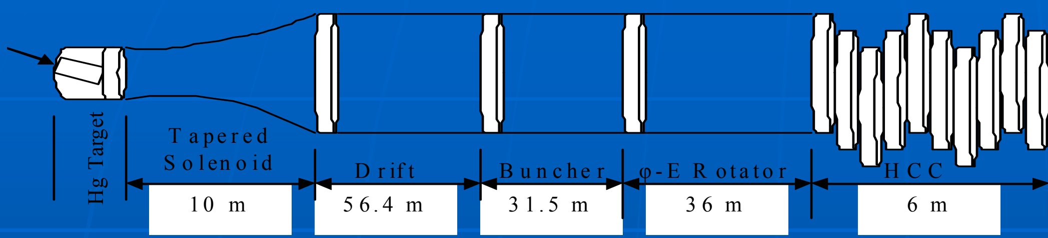
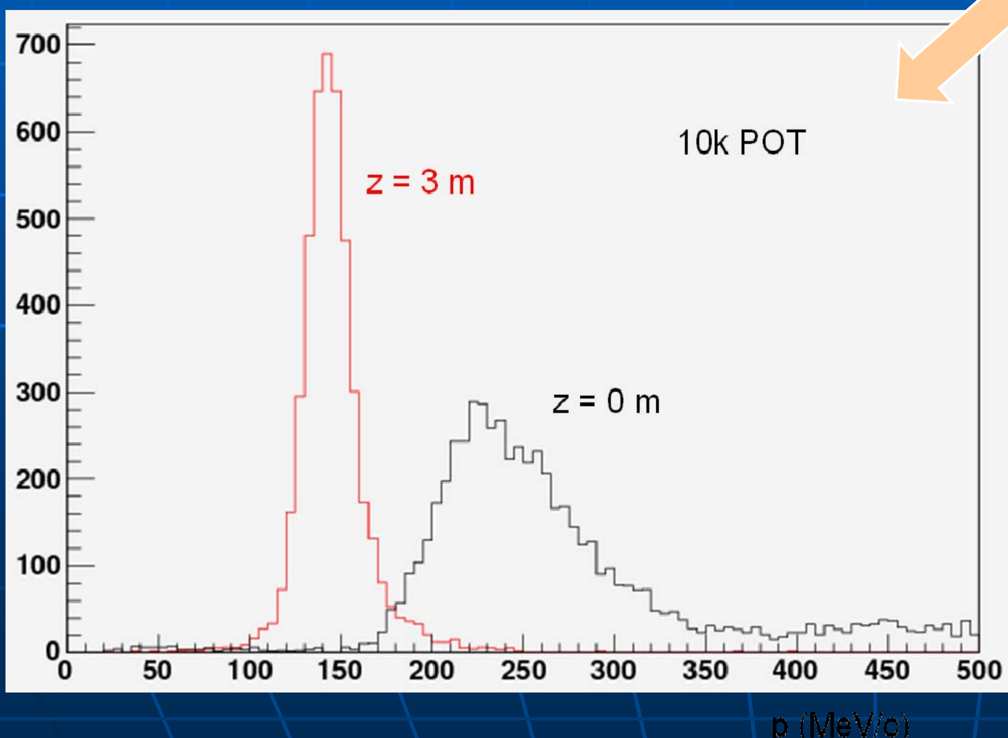
MC or NF Factory Front Ends

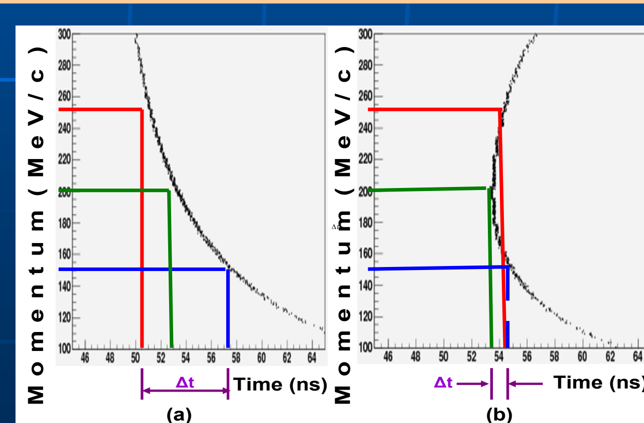
Work with David Neuffer of Fermilab



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.



"quasi-isochronous" pion decay HCC channel



Intense Stopping Muon Beams

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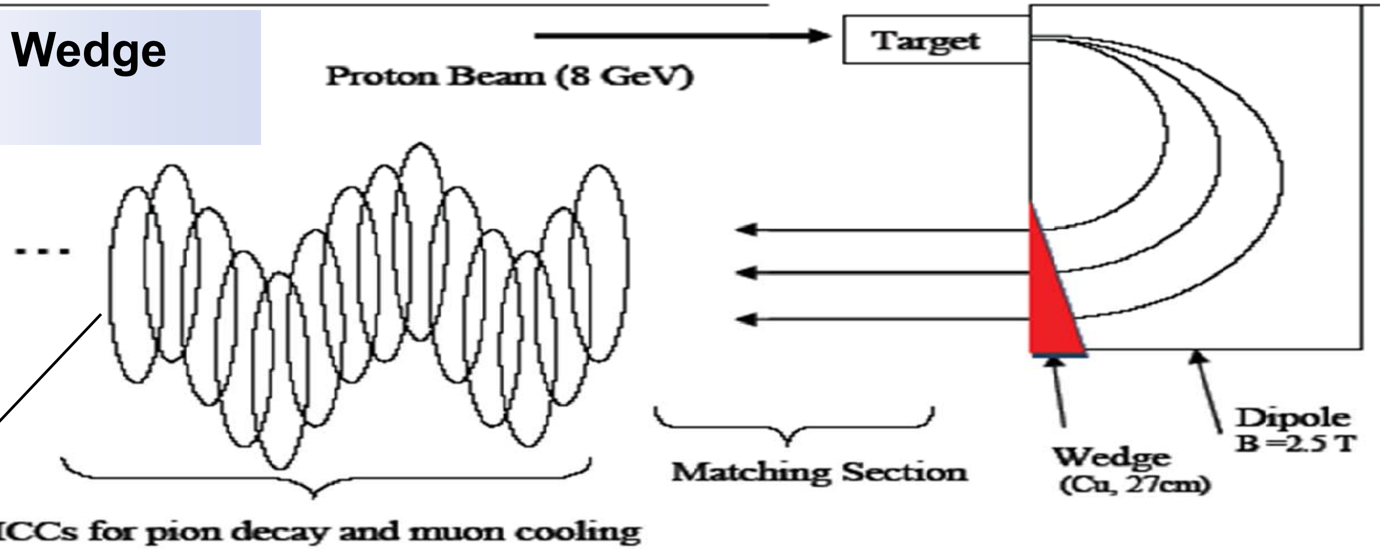
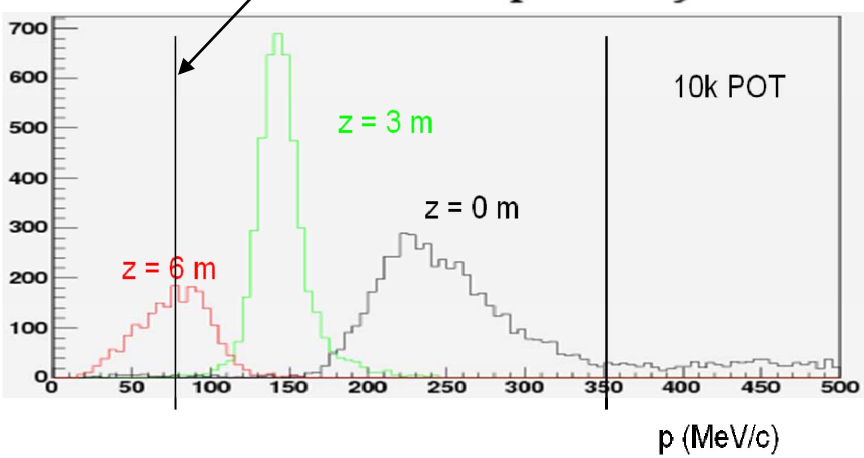
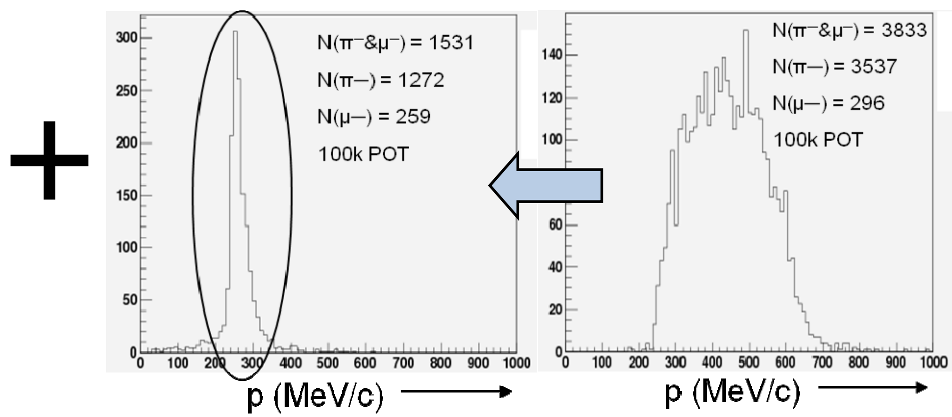
Dipole and Wedge Into HCC







Matching into the HCC which degrades muons to stop in target

Wedge narrows P distribution

Stopping Muon Beams for Mu2e

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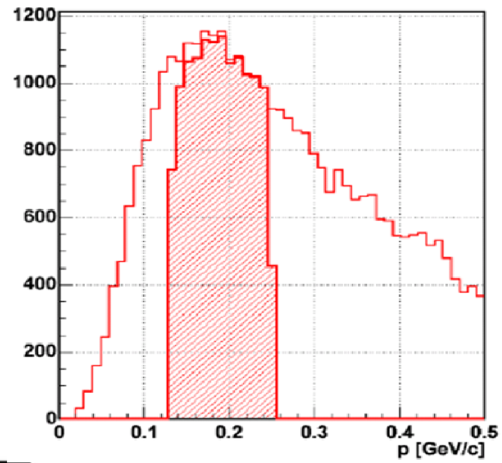
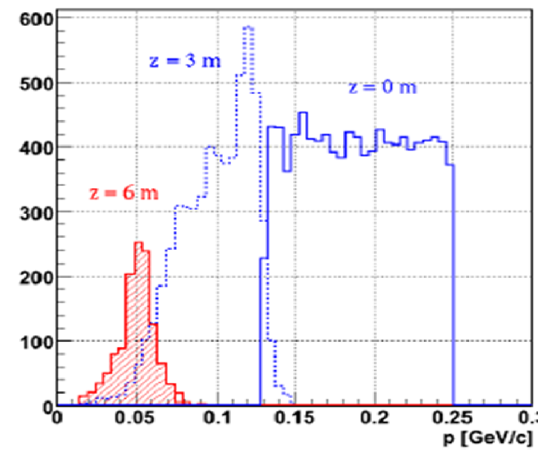
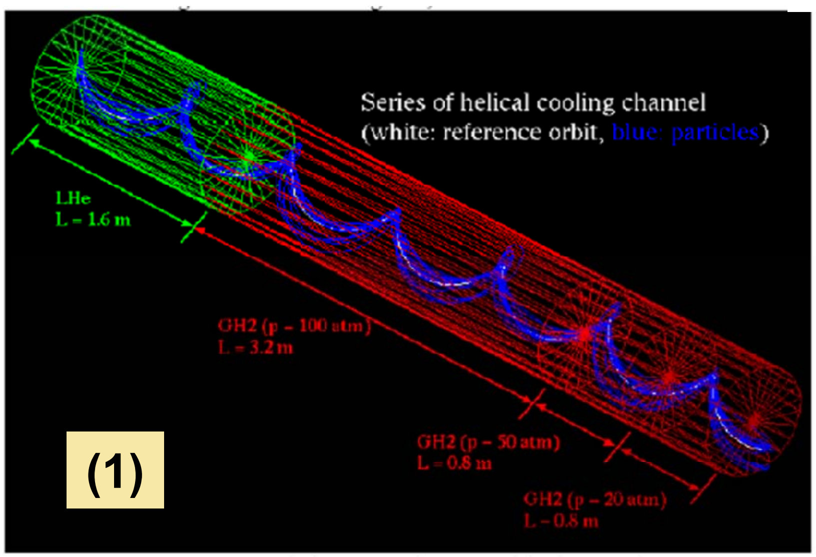
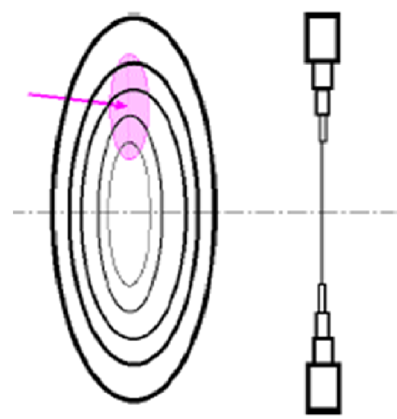
Using an HCC to reduce the energy spread of the secondary pion beam which produces the muons, decrease backgrounds and increase mu/p production.

Mu/p production can be optimised by capturing pions at the production peak. Cooling brings down the mean momentum low enough to stop in the detector target.









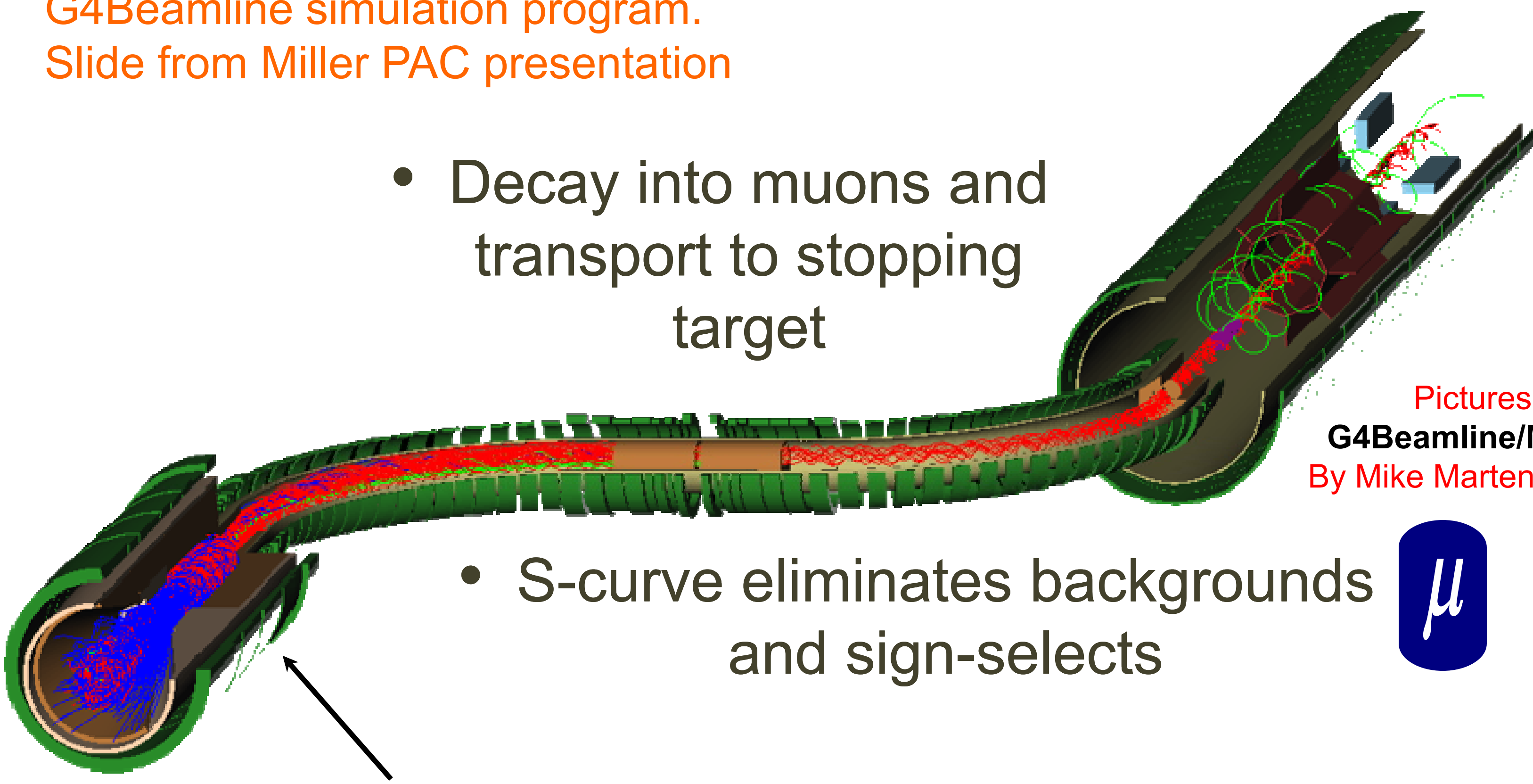
(2)

“Tapered-density” absorber HCC channel: “concept” study (1), and a element of a realistic absorber (2), a thin radial LiH wedge. Density is decreased by increased wedge spacing.

Mu2e: Detector and Solenoid Simulations

Major Muons, Inc. Product:
G4Beamline simulation program.
Slide from Miller PAC presentation

- Tracking and Calorimeter
- Decay into muons and transport to stopping target



- S-curve eliminates backgrounds and sign-selects

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- Production: Magnetic mirror reflects π's into acceptance

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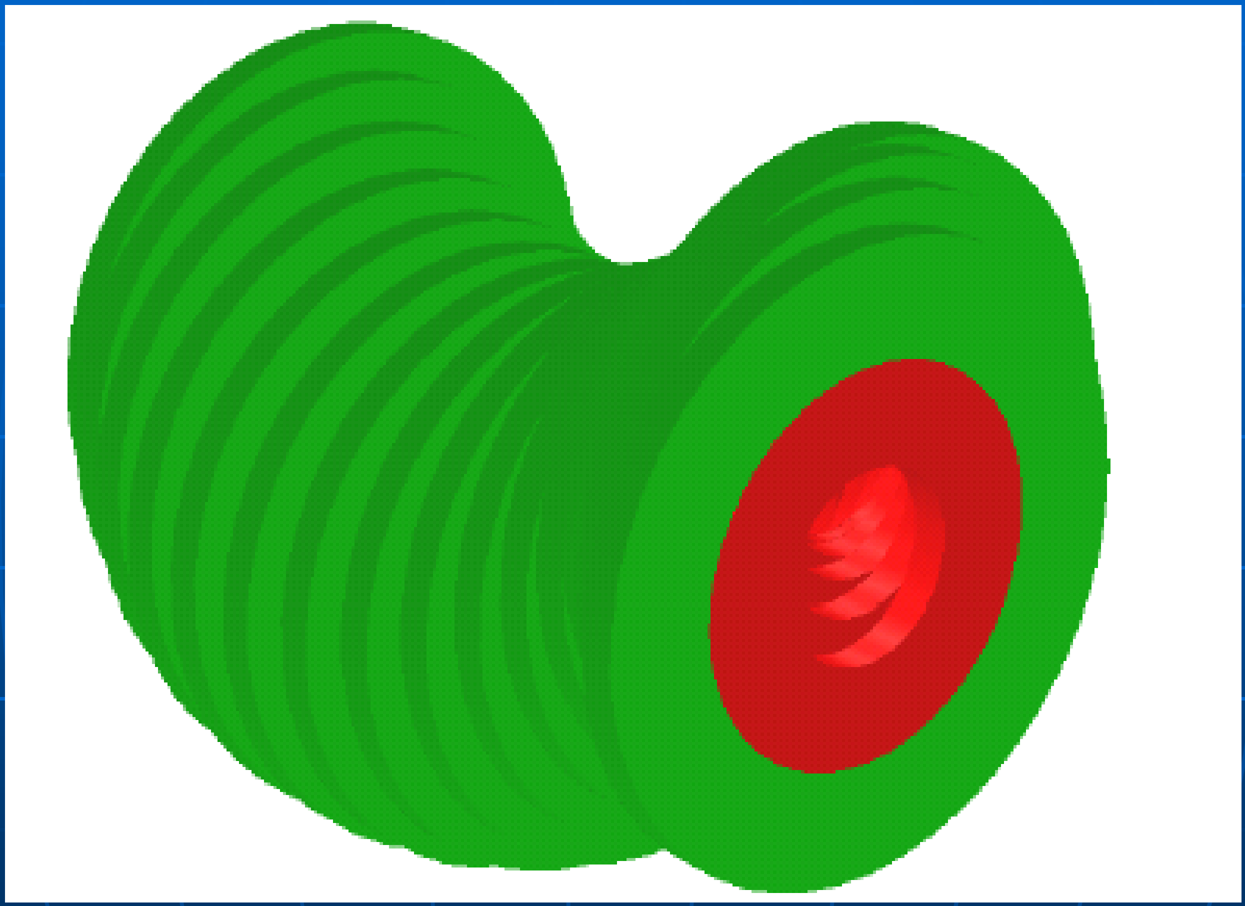
HCC HS Magnets using HTS



*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 is underway. Here a hybrid magnet of Nb3Sn (green) and HTS (red) could provide up to 30 T in an HCC design. Subject of a HS HCC Magnet STTR grant with Fermilab TD and **Sasha Zlobin**, with many contributions from **Emanuela Barzi**, **Valdimir Kashikhin**, and many others.*

Bi2212 HTS development with FSU using 1mm Au-coated Fiber Optic sensor

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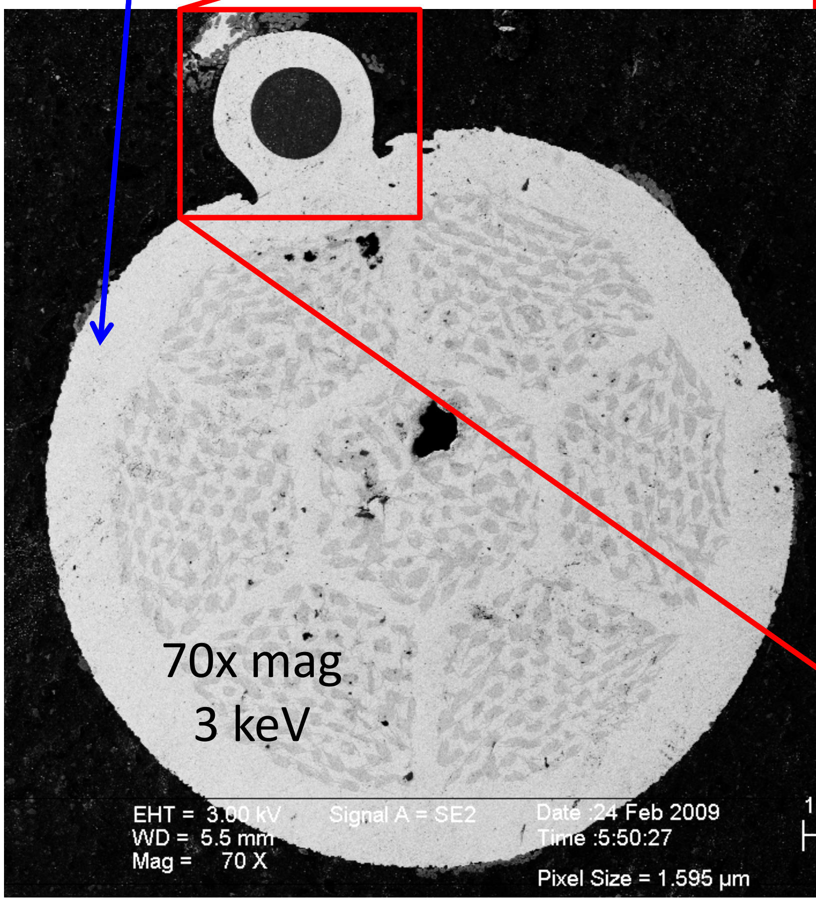
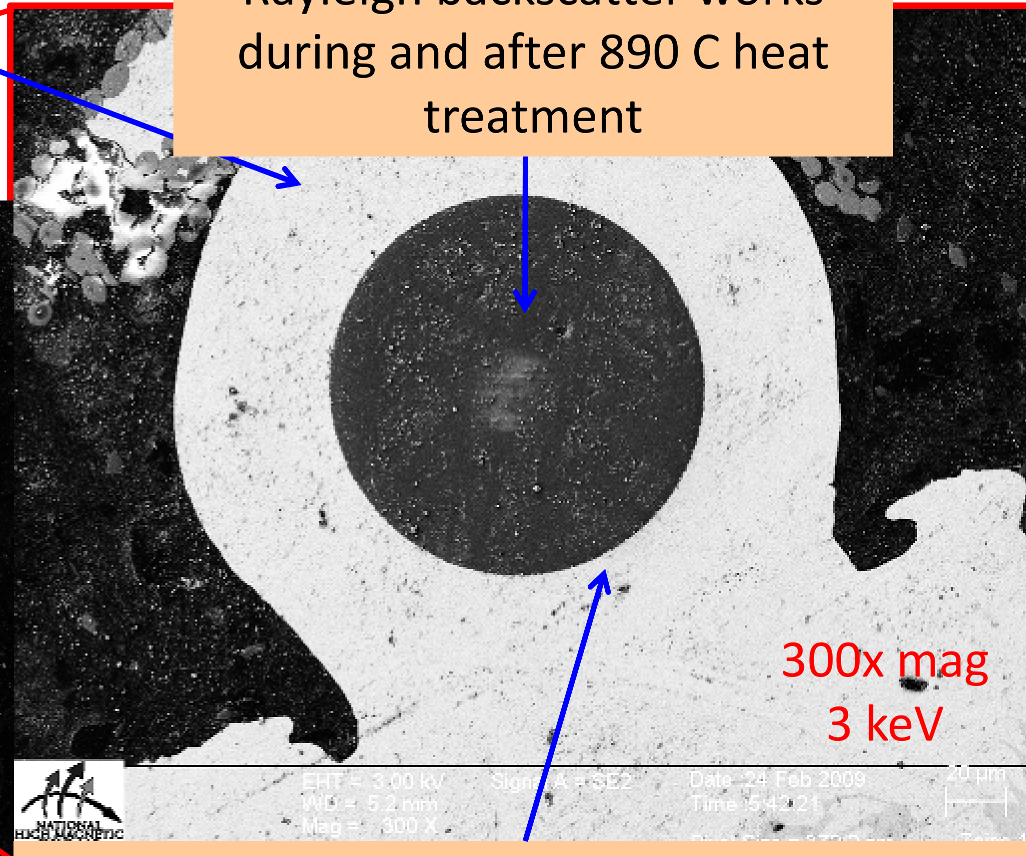
Au-coated optical fiber

Bi2212 Ag matrix

Rayleigh backscatter works during and after 890 C heat treatment





No visible change between Au and Ag: indicates diffusion during heat treatment

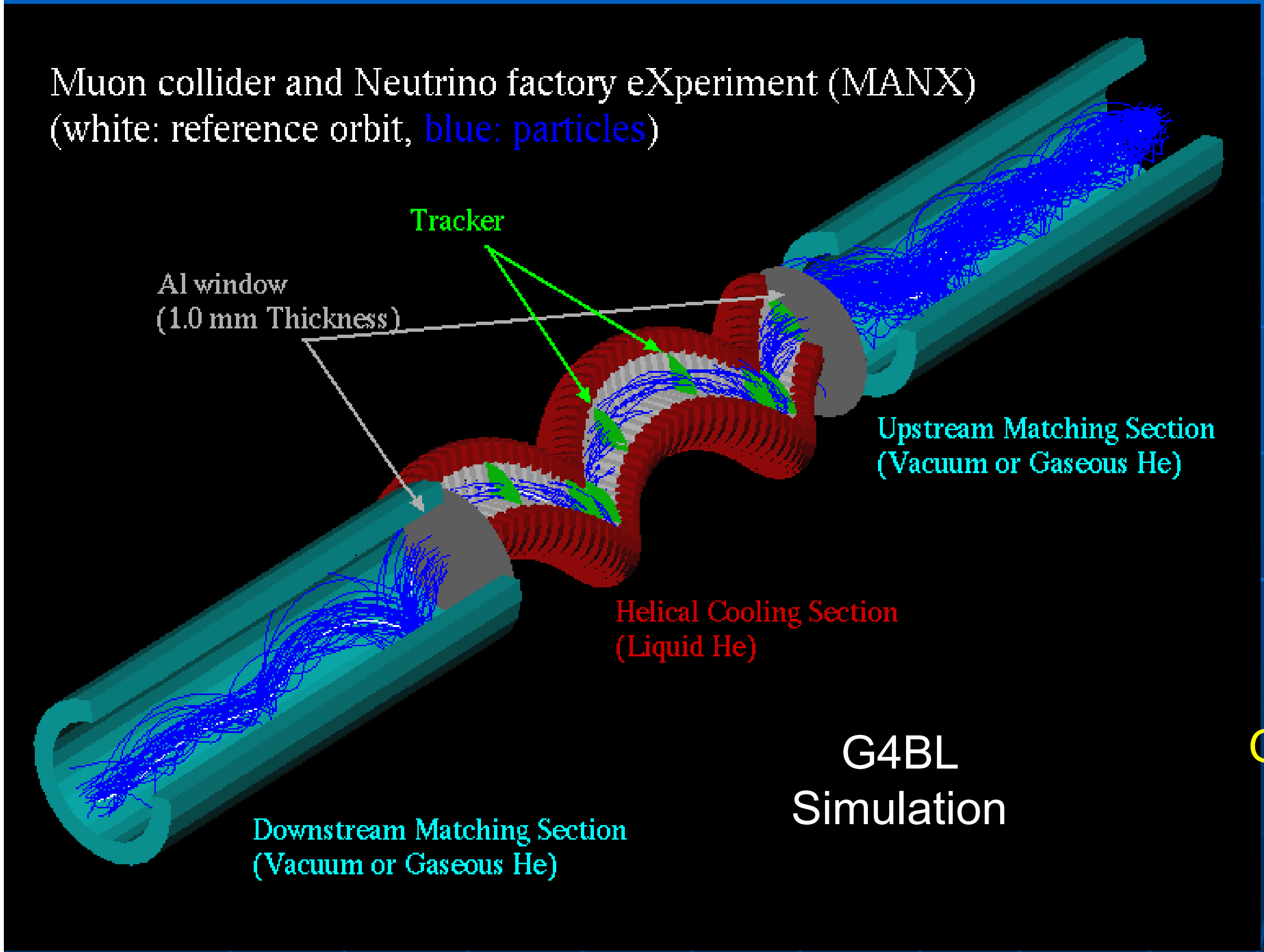
MANX, A 6D MUON BEAM COOLING EXPERIMENT

Robert Abrams[1], Mohammad Alsharo'a[1], Andrei Afanasev[1], Charles Ankenbrandt[1], Emanuela Barzi[2], Kevin Beard[1], Alex Bogacz[3], Daniel Broemmelsiek[2], Yu-Chiu Chao[3], Linda Coney[4], Mary Anne Cummings[1], Yaroslav Derbenev[3], Henry Frisch[5], Ivan Gonin[2], Gail Hanson[4], David Hedin[6], Martin Hu[2], Valentin Ivanov[1], Rolland Johnson[1], Stephen Kahn[1], Daniel Kaplan[7], Vladimir Kashikhin[2], Moyses Kuchnir[1], Michael Lamm[2], James Maloney[6], Michael Neubauer[1], David Neuffer[2], Milord Popovic[2], Robert Rimmer[3], Thomas Roberts[1], Richard Sah[1], Pavel Snopok[4], Linda Spentzouris[7], Melanie Turenne[1], Daniele Turrioni[2], Victor Yarba[2], Katsuya Yonehara[2], Cary Yoshikawa[1], Alexander Zlobin[2]

[1]*Muons, Inc.*
[2]*Fermi National Accelerator Laboratory*
[3]*Thomas Jefferson National Accelerator Facility*
[4]*University of California at Riverside*
[5]*University of Chicago*
[6]*Northern Illinois University*
[7]*Illinois Institute of Technology*

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

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 6D Cooling Demonstration

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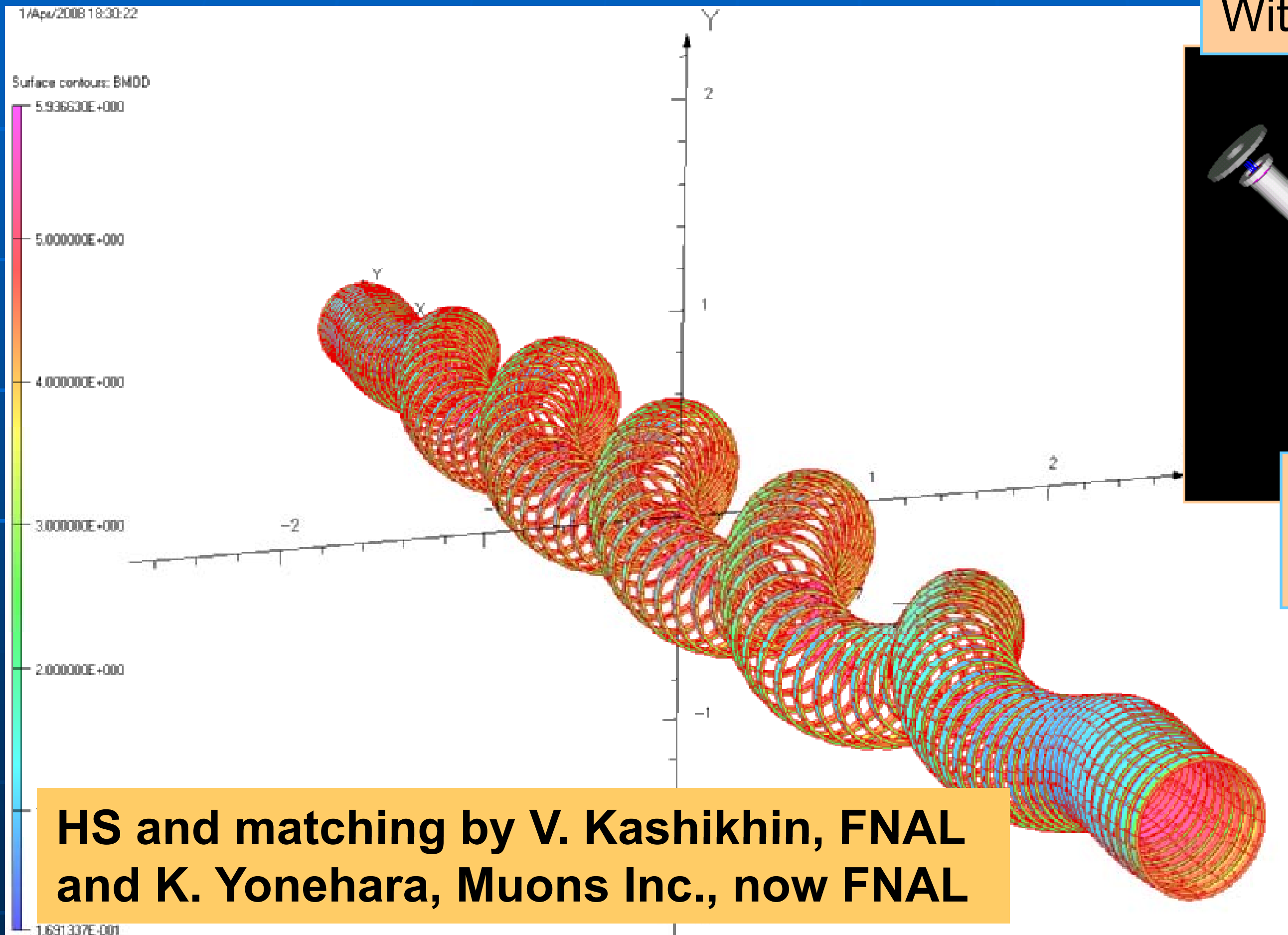
Goals: cooling demonstration, HS technology development

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



HS and matching by V. Kashikhin, FNAL and K. Yonehara, Muons Inc., now FNAL

With MICE spectrometers:

Without matching – requires transverse displacement of downstream spectrometer

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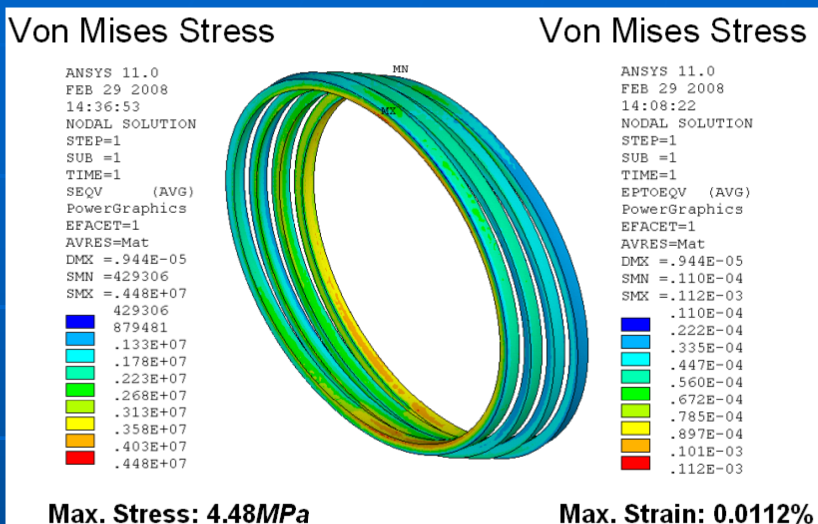
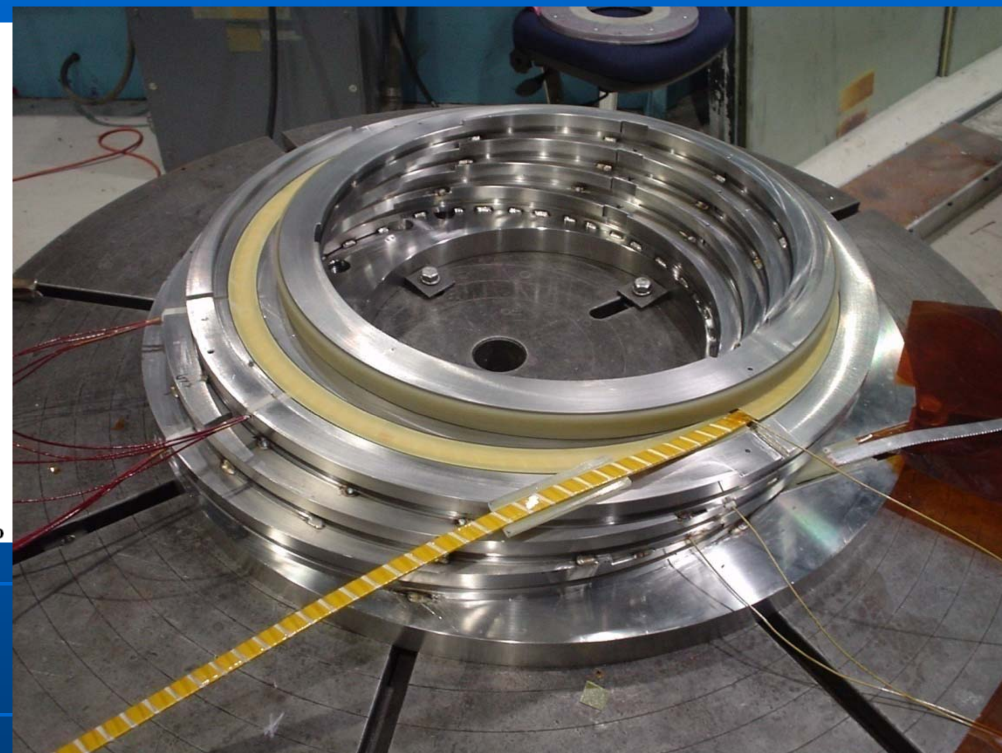
HCC Magnets for MANX





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. Work done in Fermilab TD under an STTR with ***Mike Lamm****,* ***Vladimir Kashikhin****,* ***Sasha Zlobin****,* ***Mauricio Lopes****,* ***MiaoYu*** *and many others.*

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

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Summary: Muons, Inc. R&D

- Muons, Inc. R&D with SBIR-STTR research partners is growing
  - relevant to most stages of MC/NF and
  - Project X physics (mu2e, g-2, CW RF)
- MTA HP RF beam tests are about to start
  - Fermilab priority: seeded with SBIR-STTR funds
- HCC theory/use is being simulated and refined, e.g.:
  - Epicyclic Parametric-resonance Ionization Cooling
  - Dielectric-filled RF for smaller radial size and HS compatibility
  - HCC HS 4-coil tests a start on practical engineering
  - Stopping muon beams
- Many parallel projects working on engineering challenges
  - HTS magnets, HPRF, RF windows/couplers, RLAs, ...
  - Consistent with and complimentary to the 5-year plan in critical cooling channel component testing, primarily through additional SBIR-STTR funds
- Awaiting Fermilab and APC guidance after AAC presentations...
  - About MANX at RAL
  - About Mu2e upgrade for Project-X
- Intend to participate in 5 Year Plan, if approved
- Awaiting SBIR-STTR award announcements
  - 19 Phase I, 5 Phase II

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Coming up….