2nd Annual Low Emittance Muon Collider workshop: Progress and Issues

Rolland Johnson,
Muons, Inc.

In February, Muons, Inc. and the Fermilab TD sponsored the <u>second</u> annual low-emittance muon collider workshop at Fermilab (~85 participants). Muon Colliders are looking more feasible. Synergies with the ILC and Neutrino Factories can be important.

Several of the techniques to cool muon beams have been invented and are under development supported by DOE Small Business Innovation Research and Small business Technology Transfer Research grants.

Papers can be found at http://www.muonsinc.com
workshop link is at http://www.muonsinc.com/mcwfeb07/ also see
http://www.muonsinc.com/mcwfeb06/presentations/LEMCWorkshop.pdf

Amazing progress since LEM06

- Muons, Inc. success-2 Phase II and 2 Phase I STTR Grants
  - Includes G4BL and MANX Support
- Technology success
  - HPRF in magnetic field
  - HTS potential recognized
  - Muon Bunch Coalescing for NF and MC Synergy
- Increased Fermilab involvement
  - MANX Fermilab LOI
  - Fermilab Muon Collider Task Force
  - Accelerator Physics Center
- NFMCC renewed interest in Muon Colliders

Alternative technological paths to a LEMC are emerging

- 6-d Cooling – (first 6 orders of 6D cooling)
  - HCC with imbedded High-Pressure RF (original),
  - MANX HCC segments alternating with RF, and/or
  - Guggenheim Helix

- Extreme Transverse Cooling – (2 orders)
  - Parametric-resonance Ionization Cooling,
  - Reverse Emittance Exchange REMEX,
  - High-Temperature Superconductor for high B, and
  - Ring designs using clever field suppression for RF

Renewed HEP Theoretical Interest

- Chris Quigg
  - CLIC studies relevant
  - Something has to happen
- Kong
  - Muon collider resolution may be important handle on dark matter, extra dimensions
- Dobrescu and Skands (2006)
  - Muons as members of 2^{nd} generation of particles have new possibilities
- Lively discussions, interesting talks
  - Need to come up with killer need for a muon collider

From 2006 Workshop (red = new)

- An implementation plan with affordable, incremental, independently-fundable, sequential, steps:
- (RoI WAG $M)

1. attractive 6D Cooling experiment (MANX!) (5)
2. double-duty PD Linac (HINS!) (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 (mu2e!)
5. Higgs factory (~300 GeV com) (2000)
   Add more cooling, RLA, coalescing & collider rings, IR
6. energy frontier muon collider(5 TeV com) (2000)
   More RLA, deep ring, IRs (1.5 TeV study an intermediate step)

MCTF Charge

- **Charge**

  i) **Cooling Channel and Collider Design Concept**.
  Taking into account recent developments in muon cooling ideas, develop a plan to form a design and simulation study group that will develop a coherent concept for a Muon Collider with a center-of-mass energy of 1.5 TeV, based upon a low emittance parameter set. The group's focus should be to outline the general scheme, the parameter choices, and the 6D ionization cooling channel requirements to support a usable luminosity, and in addition identify the primary design challenges beyond the 6D cooling systems. Progress should be documented in reports in September 2007 and September 2008. The initial plan for creating the study group should include an estimate of the required Fermilab effort and the expected contributions from outside of Fermilab, and should be documented in a brief report in September 2006.
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  ii) **Cooling Channel R&D**.
- Prepare a one year study plan to (a) evaluate the technical feasibility of the components (rf cavities, magnets, absorbers, etc) needed for a muon collider class 6D cooling channel as identified in i), (b) identify the technical issues that must be addressed before a 6D cooling channel could be built, and (c) formulate a plan for the associated component R&D and 6D cooling tests that must be performed to establish basic viability of the cooling channel. The study plan should be documented in a short report in September 2006. The results of the one year study should be documented in a more detailed report in September 2007.
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Charge (cont.)

- iii) **Component Development and Testing.**
- (a) Prepare a plan to implement, in FY07, the beam and experimental setup required to test the high-gradient operation of a high-pressure gas-filled rf cavity operated in a multi-Tesla magnetic field and exposed to an ionizing beam. The implementation plan should be documented in a short report made available in September 2006. This plan should include a description of the measurements to be made, should be formulated in collaboration with Muons Inc, and should document the connection between these activities and charge elements i) and ii)
- b) Design, and prepare a plan to build, a helical solenoid suitable for a 6D cooling channel section test. The implementation plan should be described in a short report made available in September 2006, developed in collaboration with Muons Inc. and documenting the connection between this activity and charge elements i) and ii). A complete prototype design and fabrication plan should be described in a concise report in September 2007.
- c) Prepare an R&D plan to explore the feasibility of building a very high field (~50Tesla) high-Tc superconducting solenoid suitable for the final stages of a muon cooling channel for a Muon Collider. The R&D plan should be documented in a short report made available in September 2006, including documenting the connection between this activity and charge elements 1) and ii).

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Muons, Inc. SBIR/STTR Collaboration:

- Fermilab:
  - Victor Yarba, Emanuela Barzi, Ivan Gonin, Timer Khabiboulline, Gennady Romanov, Daniele Turrioni, Katsuya Yonehara,
  - Dave Neuffer, Chuck Ankenbrandt, Al Moretti, Milorad Popovic, Jim Griffin
  - Mike Lamm, Vadim Kashikhin, Vladimir Kashikhin, Sasha Zlobin
  - MCTF-APC, V. Shiltsev, S. Geer, A. Jansson, M. Hu, D. Bromelsiek, Alexehin,…

- IIT:
  - Dan Kaplan, Linda Spentzouris

- JLab:
  - Yaroslav Derbenev, Alex Bogacz, Kevin Beard, Yu-Chiu Chao, Robert Rimmer

- Muons, Inc.:
  - Rolland Johnson, Bob Abrams, Mohammad Alsharo'a, Mary Anne Cummings, Stephen Kahn, Sergey Korenev, Moyses Kuchnir, David Newsham, Tom Roberts, Richard Sah, Cary Yoshikawa (underlined are new-3 are from Lucent)

- Plus new proposals for 2007 with
  - ANL- Sasha Vaniachine
  - BNL- Ramesh Gupta
  - LBNL- Derun Li

First named are subgrant PI.

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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

See Fernow lattice with magnetic field suppression for vacuum RF

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, $\langle L \rangle = 10^{35}$
  - 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-STTR funding)

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 (discussed later)
- 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?

Pressurized High Gradient RF Cavities (IIT, Dan Kaplan)

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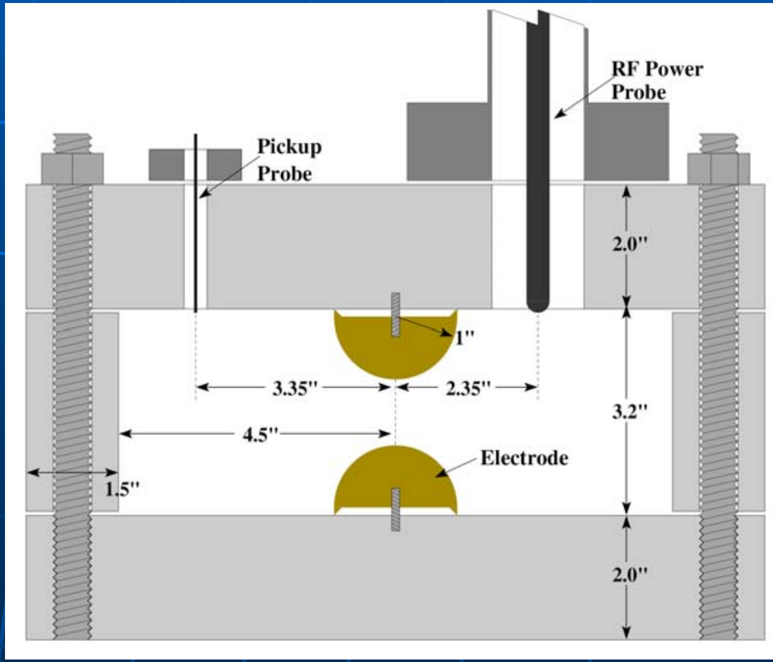
- Copper plated, stainless-steel, 800 MHz test cell with GH2 to 1600 psi and 77 K in Lab G, MTA
- Paschen curve verified
- Maximum gradient limited by breakdown of metal
  - fast conditioning seen, no limitation by external magnetic field!
- Cu and Be have same breakdown limits (~50 MV/m), Mo ~28% better



MuCool Test Area (MTA)

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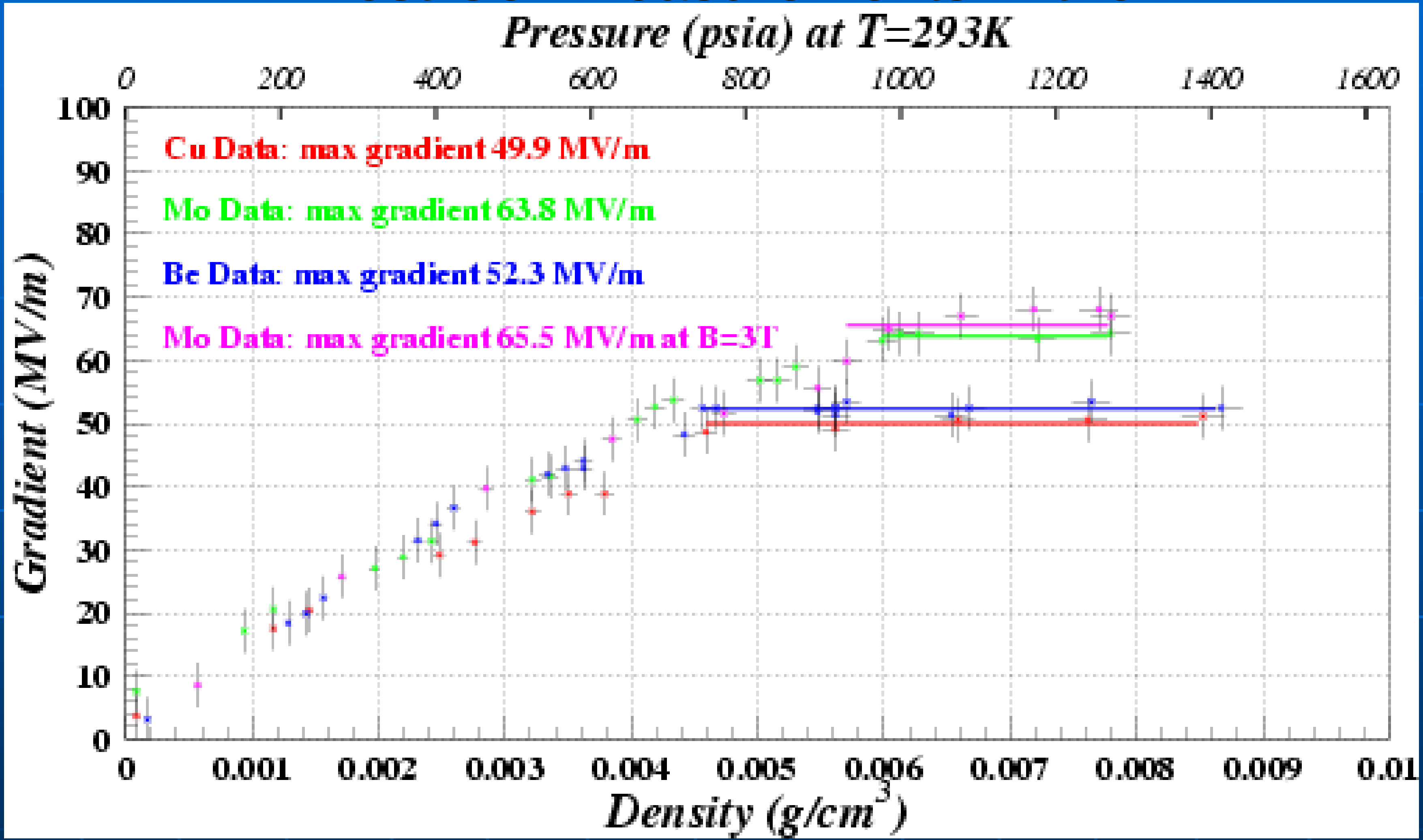
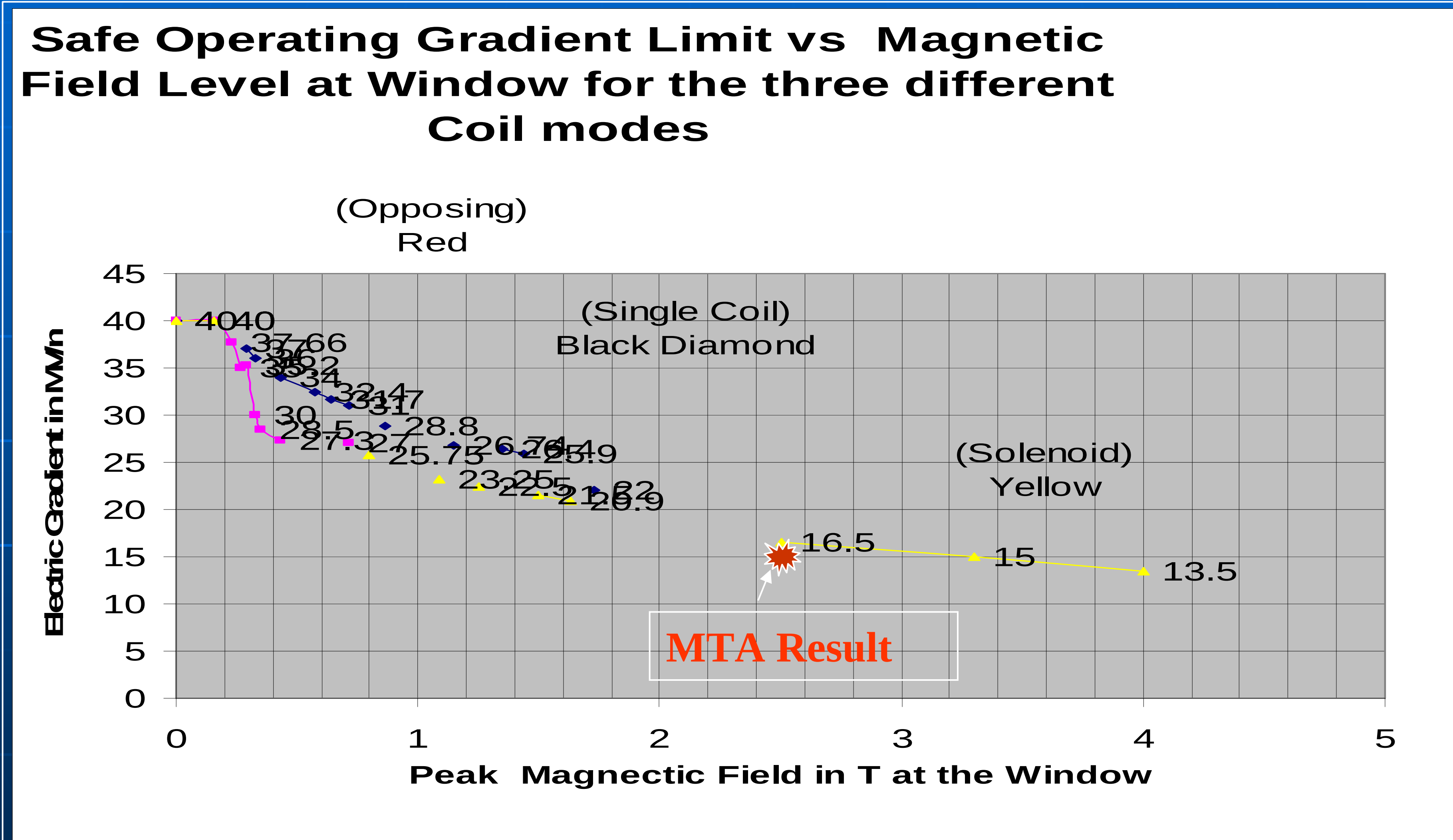
HPRF Test Cell Measurements in the MTA



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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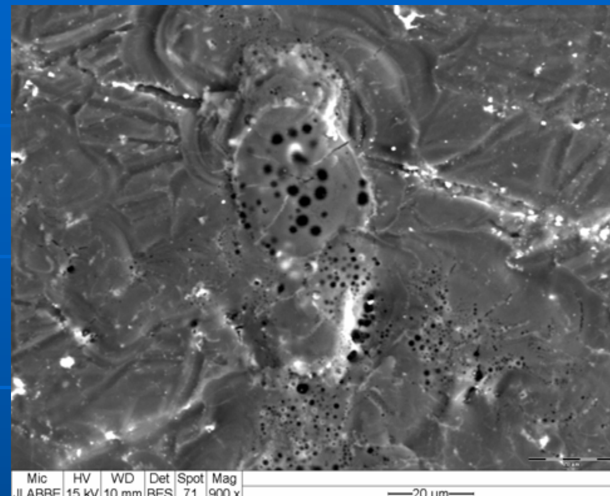
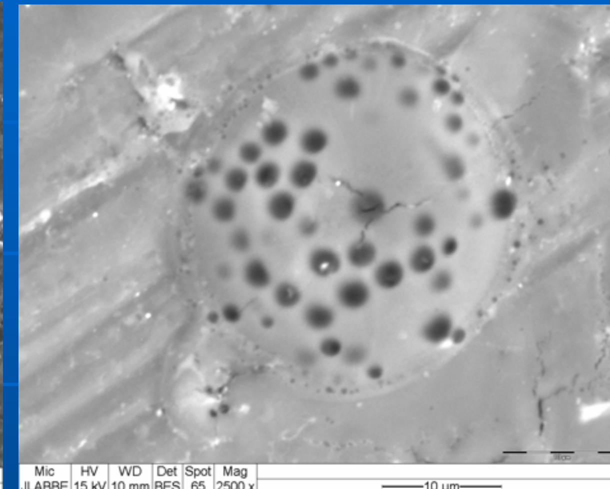
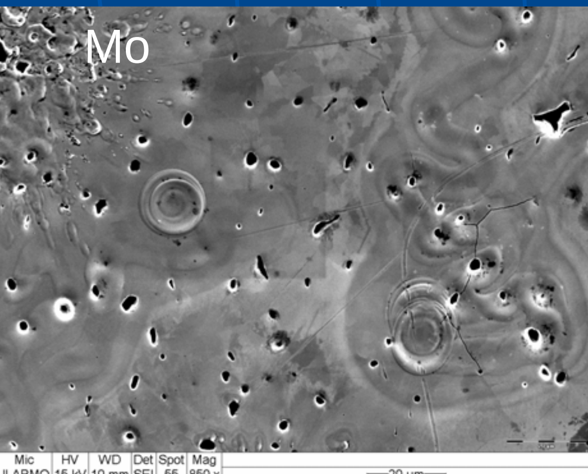
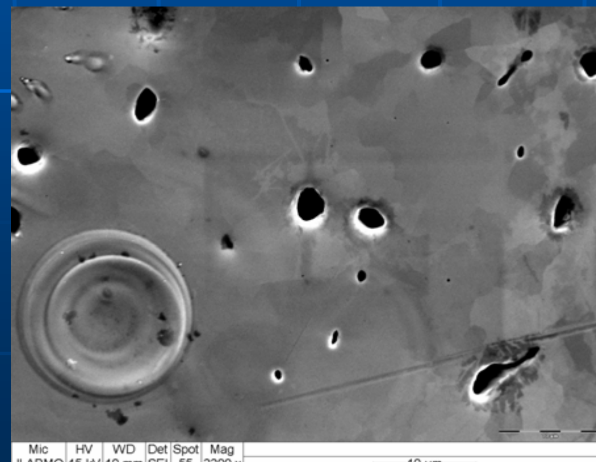
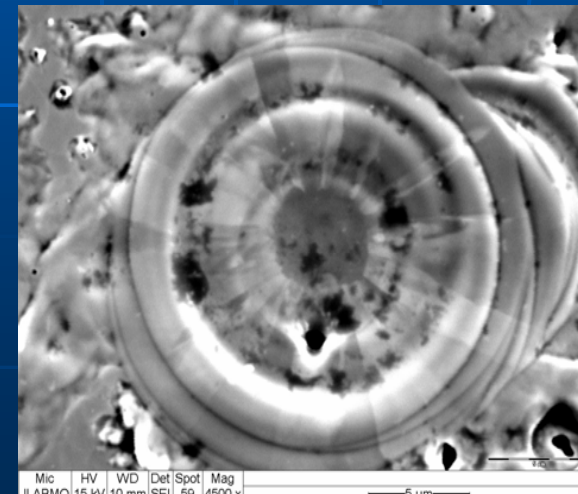
Understanding RF Breakdown in High Pressure Cavities: Scanning Electron Microscope Pictures of HP Electrodes











See Mahzad and Mageed poster

Technology Development in Technical Division

HTS at LH2 shown, in LHe much better

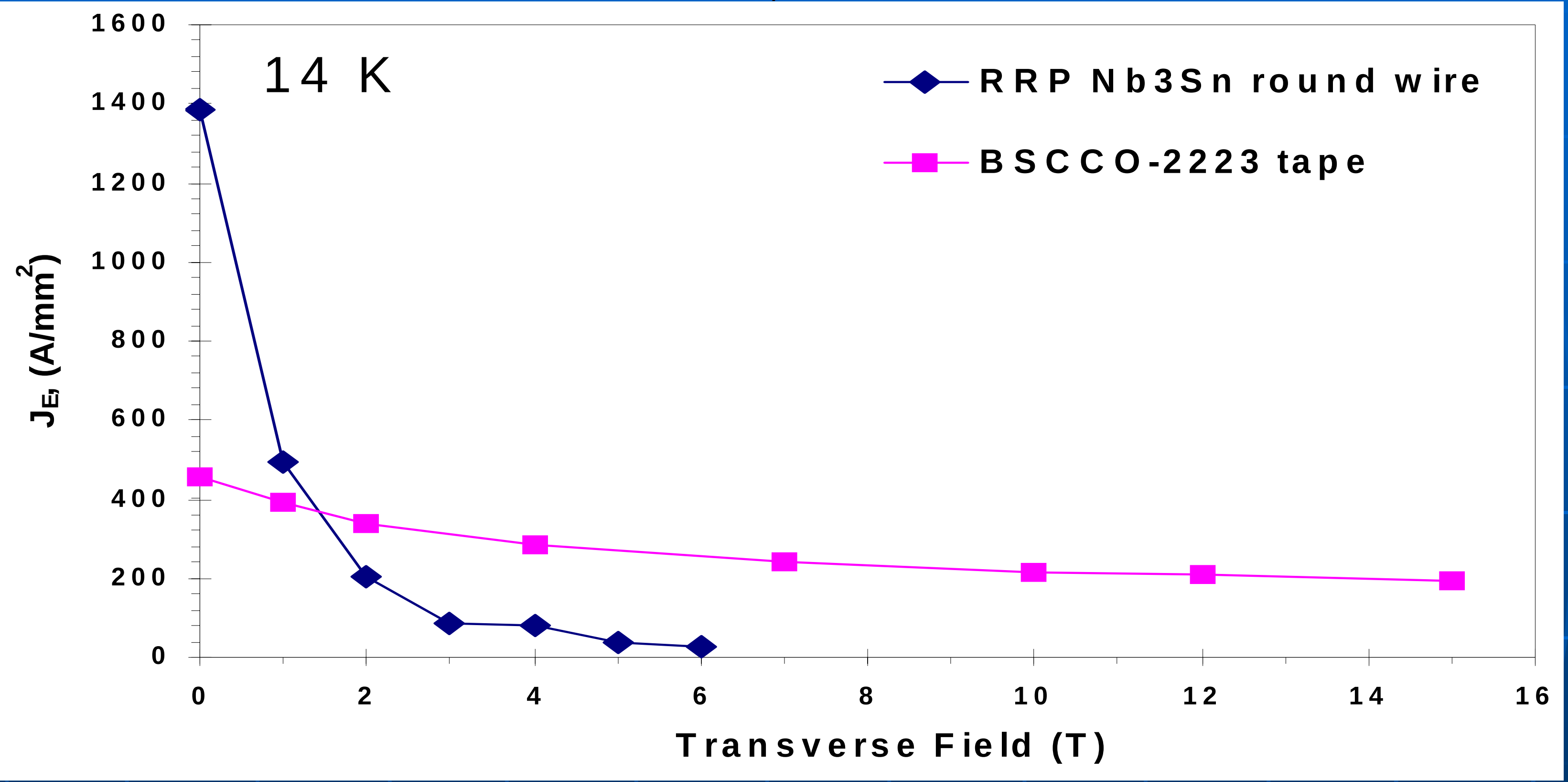


Fig. 9. Comparison of the engineering critical current density, J_E, at 14 K as a function of magnetic field between BSCCO-2223 tape and RRP Nb_3Sn round wire.

Emanuela Barzi et al., Novel Muon Cooling Channels Using Hydrogen Refrigeration and HT Superconductor, PAC05

50 Tesla HTS Magnets for Beam Cooling

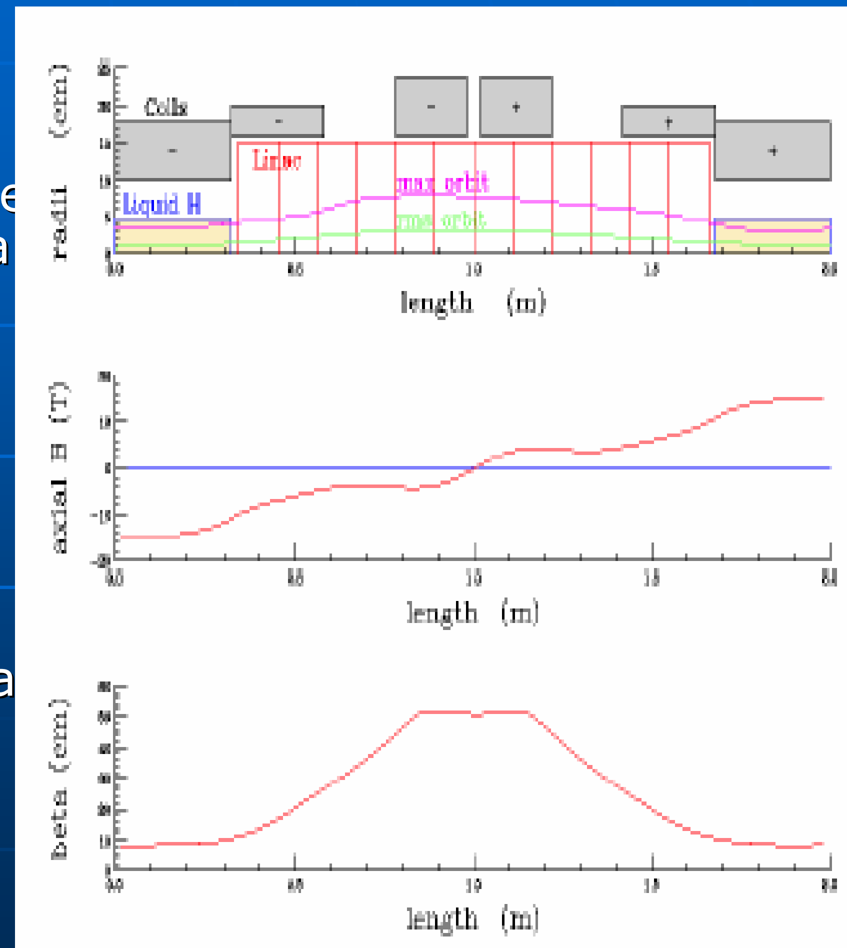
- We plan to use high field solenoid magnets in the near final stages of cooling.
- The need for a high field can be seen by examining the formula for equilibrium emittance:

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

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

- The figure on the right shows a lattice for a 15 T alternating solenoid scheme previously studied.

See Palmer, Kahn, Fernow



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Simulation study of helical cooling channel with continuous rf cavities

K. Yonehara
Fermilab

Target in Yonehara talk

- *Discuss the possibility of incorporating RF cavities into a helical cooling magnet.*
- *For simplicity, a 200 MHz cavity has been installed in a series of helical cooling channel.*
  - *Transverse phase space matching between two HCCs has been investigated in this channel.*
- *Now more practical design of HCCs is started.*
  - *Mount the higher frequency RF cavities in HCC is required to make a quick acceleration.*
  - *However, the absorber density is a constant in this presentation. So, the acceleration gradient is almost the same even in the high frequency cavity.*

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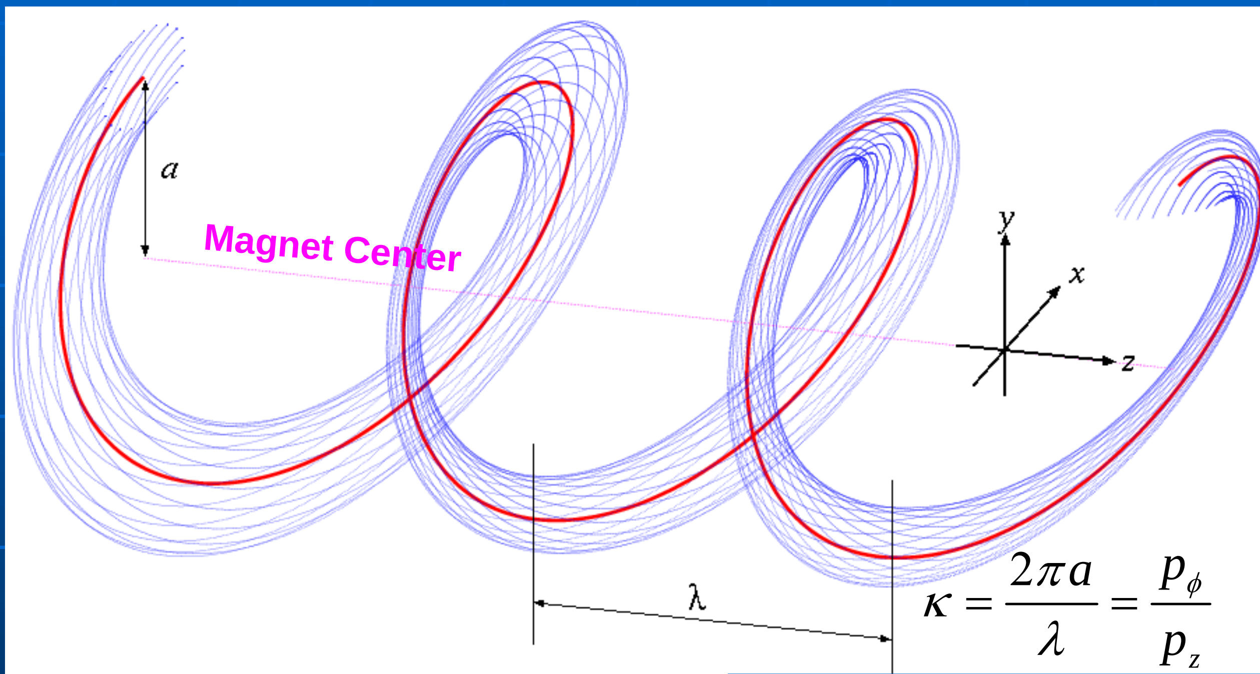
Particle Motion in Helical Magnet

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 particle and shorter path length for lower momentum particle.

$f_\uparrow \propto b_\varphi \cdot p_z$	Repulsive force
$f_\downarrow \propto -b_z \cdot p_\varphi$	Attractive force

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

terms have opposite signs.

RF cavity to compensate ionization energy loss

Continuous acceleration is more effective.

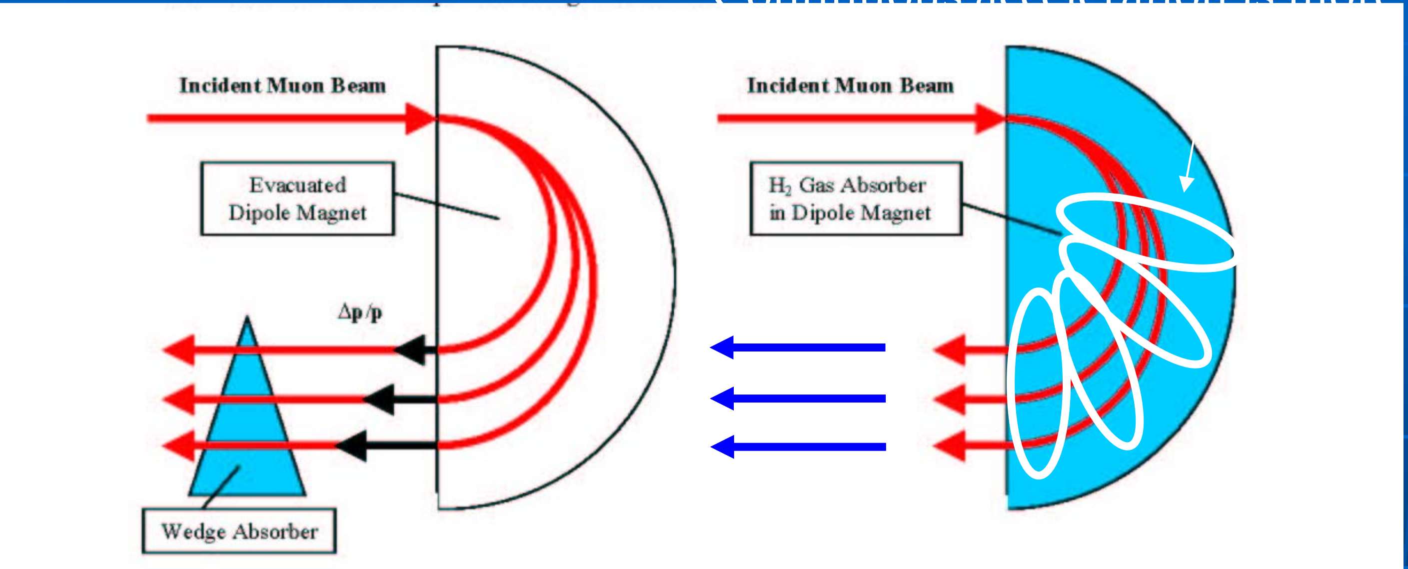


Figure 1. Use of a Wedge Absorber for Emittance Exchange

Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

RF cavity is needed to compensate ionization energy loss.

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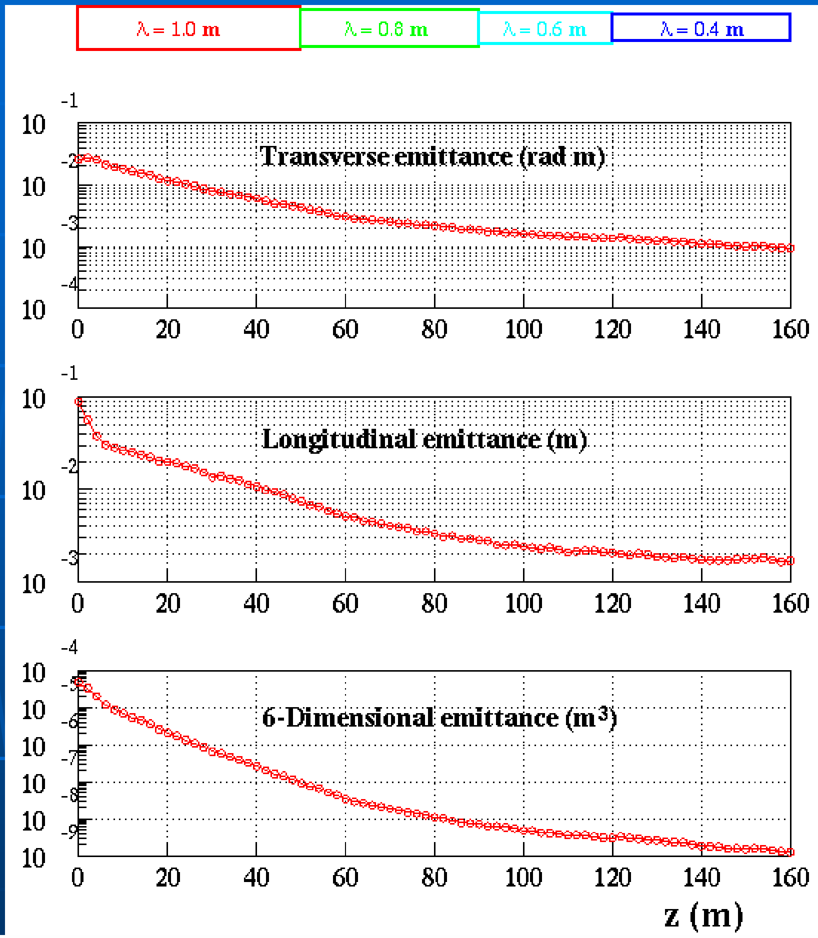
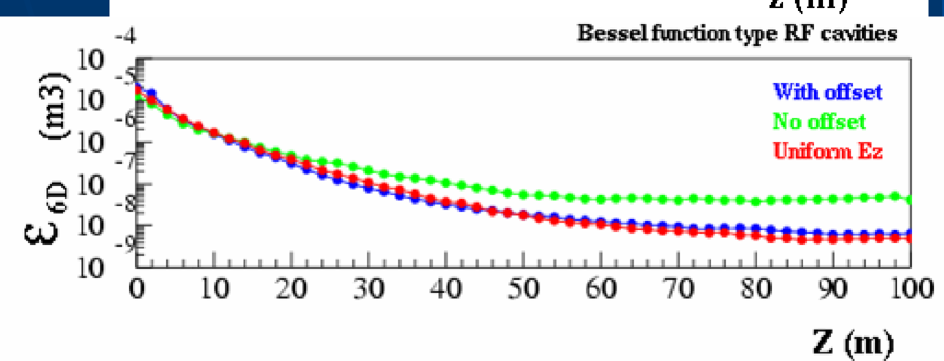
Emittance in series of HCC



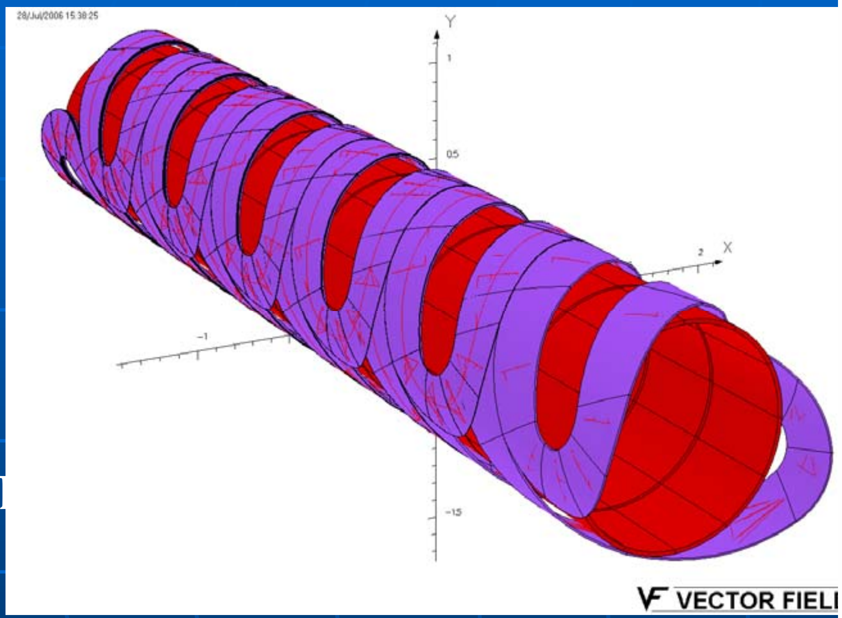


- Use continuous 200 MHz cavity in a whole channel.
- E=31 MV/m in 400 atm GH2.
- 6D cooling factor in the series of HCC is ~50,000.
- The realistic RF field is tested in the single helical cooling channel (bottom plot).
- This test is proved the predicted cooling performance in the Slava and Rol’s paper.
- However, this design requires a very large magnetic field.

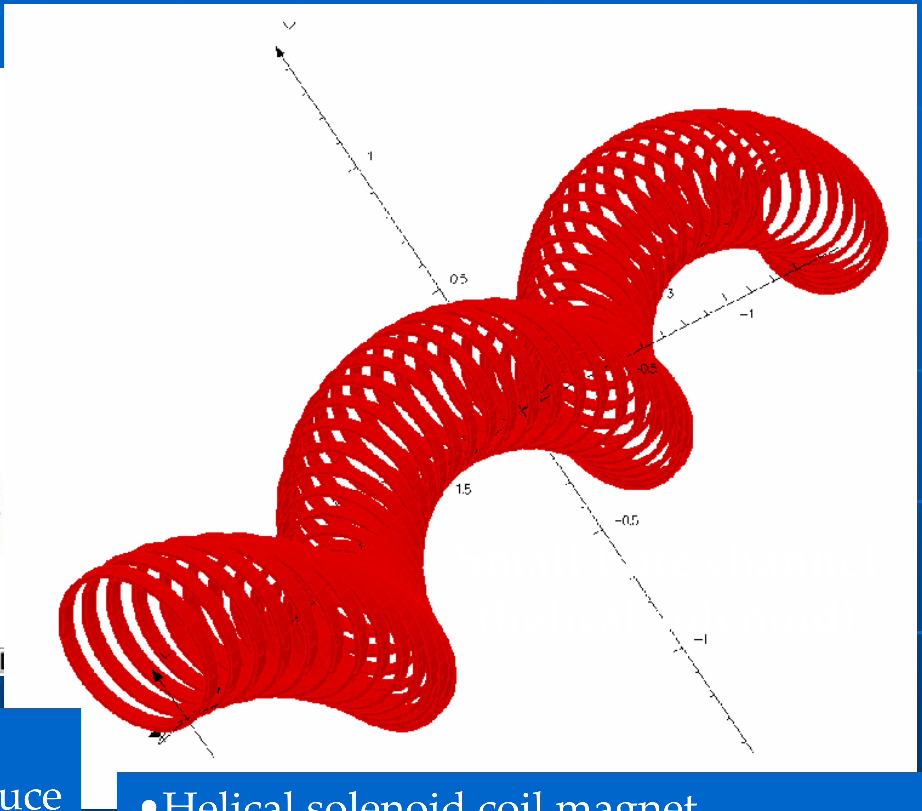
We need to solve this question.

New great innovation!

Two Different Designs of Helical Cooling Magnet

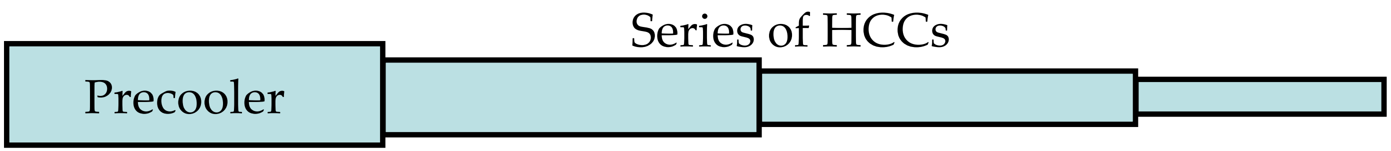


- Siberian snake type magnet
- Consists of 4 layers of helix dipole to produce tapered helical dipole fields.
- Coil diameter is 1.0 m.
- Maximum field is more than 10 T.

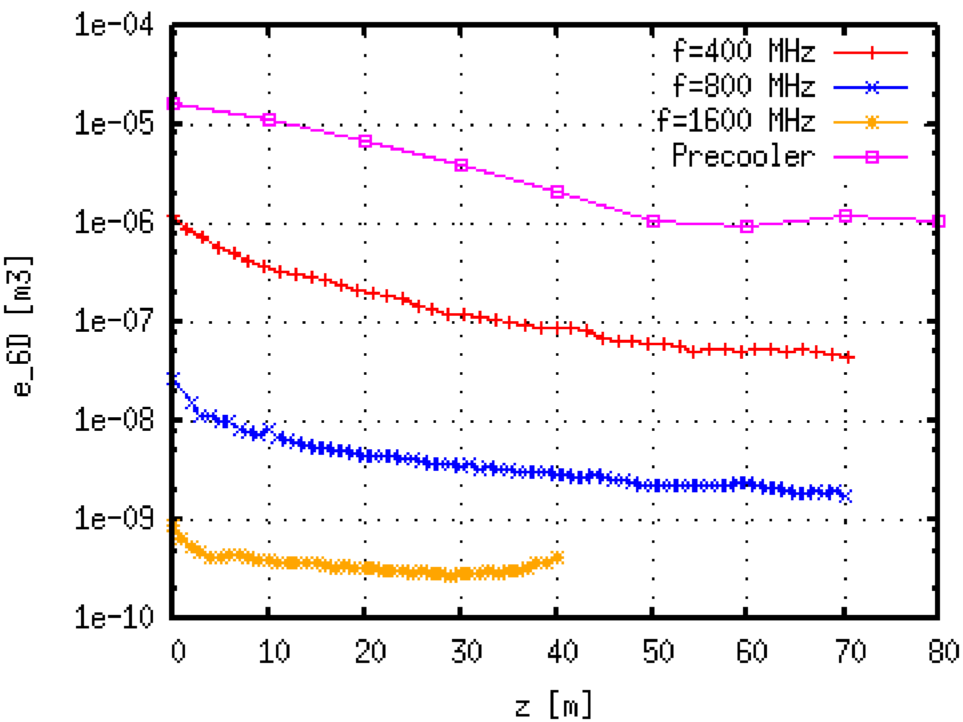


- Helical solenoid coil magnet
- Consists of 73 single coils (no tilt).
- Maximum field is 5 T
- Coil diameter is 0.5 m.
- Flexible field by adding a correction coils.

Precooler + HCCs



Solenoid + High Pressurized RF



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

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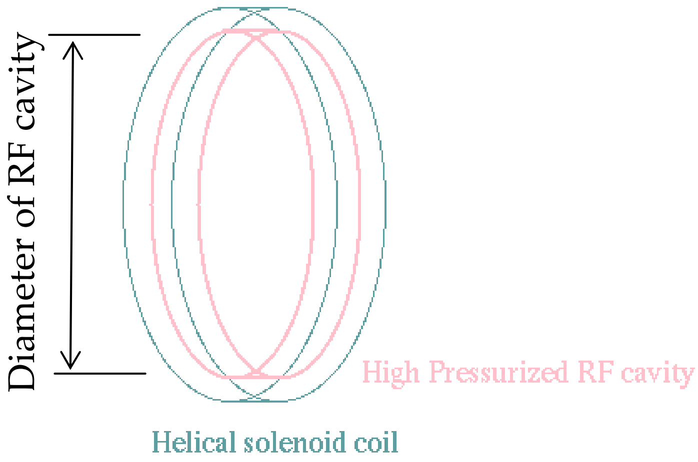
Incorporate RF cavity in helical solenoid coil



- 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 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.

parameters	*λ*	*κ*	*Bz*	*bd*	*bq*	*bs*	*f*	*Inner d of coil*	*Maximum b*	*E*	*rf phase*
unit	*m*		*T*	*T*	*T/m*	*T/m2*	*GHz*	*cm*	*Snake | Slinky*	*MV/m*	*degree*
1st HCC	*1.6*	*1.0*	*-4.3*	*1.0*	*-0.2*	*0.5*	*0.4*	*50.0*	*12.0 | 6.0*	*16.0*	*140.0*
2nd HCC	*1.0*	*1.0*	*-6.8*	*1.5*	*-0.3*	*1.4*	*0.8*	*25.0*	*17.0 | 8.0*	*16.0*	*140.0*
3rd HCC	*0.5*	*1.0*	*-13.6*	*3.1*	*-0.6*	*3.8*	*1.6*	*12.5*	*34.0 | 17.0*	*16.0*	*140.0*

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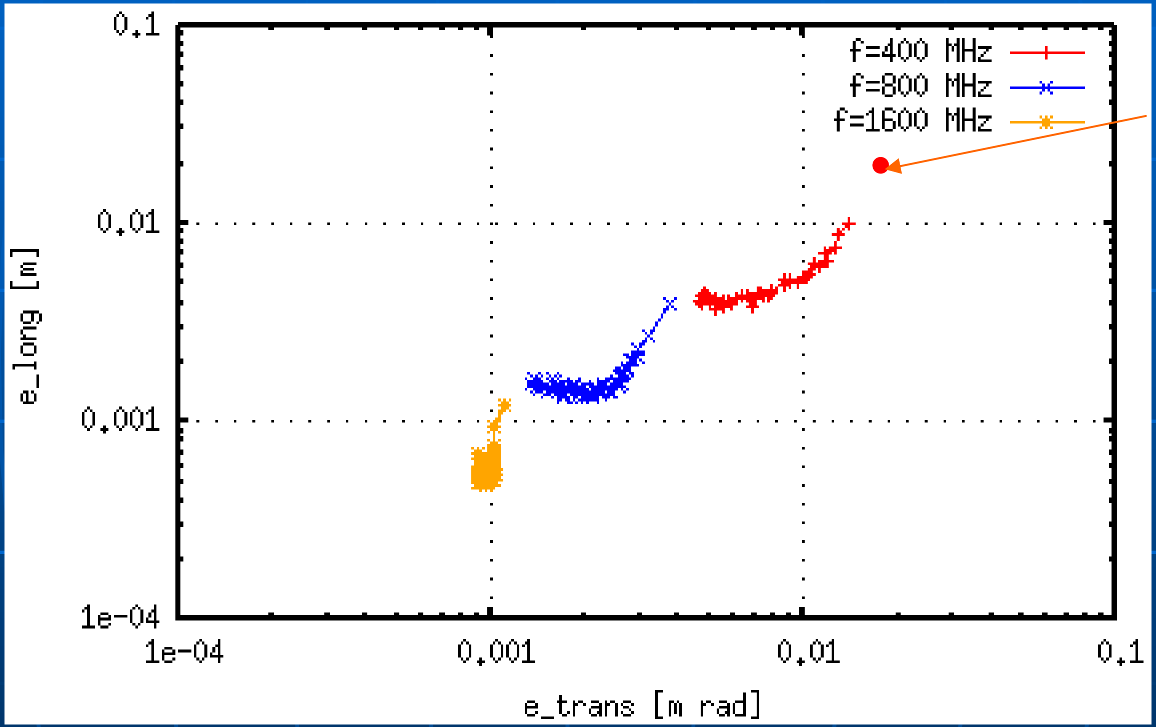
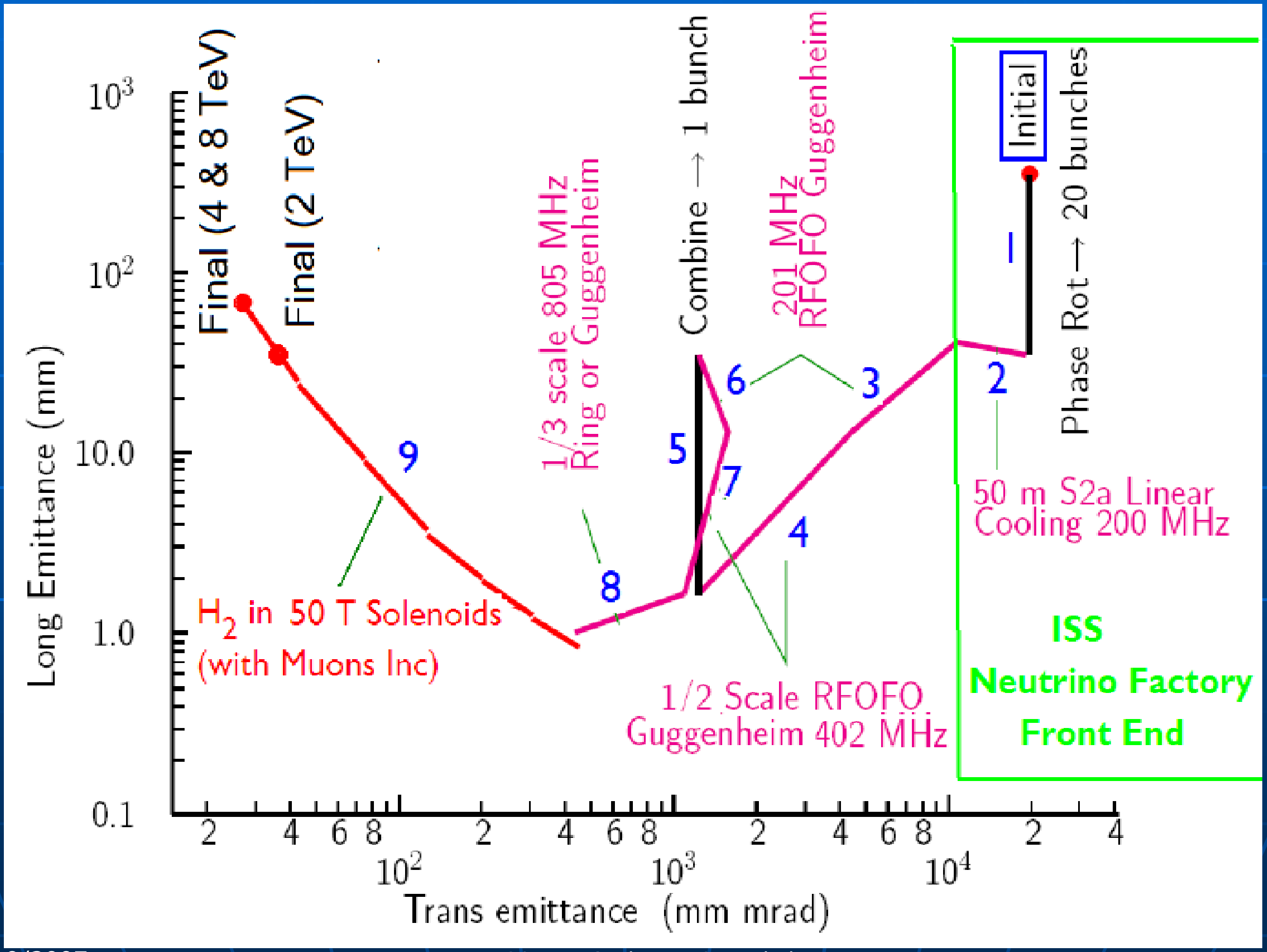
Yonehara HCC Fernow-Neuffer Plot



Initial point

Palmer's Fernow-Neuffer Plot



PIC and REMEX Progress

- The PIC and REMEX concepts have been invented and developed to provide the crucial final beam cooling in a muon collider. Their use can greatly reduce the final beam emittance and can permit the construction of a high-luminosity collider that requires fewer muons.
- Significant progress has been made in the design of these cooling channels and in the corresponding particle-tracking simulations
- Reflection symmetry in the cooling channel design can be used effectively to cancel the largest geometric aberration in the beamline optics

Palmer cooling cell classifications

- **1. Continuous or long cells**
  - **• 50 T Solenoids, Balbakov Rings, Li Lenses, Helical between mini-linacs**
  - **• Resonances not excited by adiabatic or designer matching**
  - **• Last 50 T simulated including match**
  - **• Gas helix ok at low frequencies**
- **2. Periodic focus in short un-chromatically corrected cells**
  - **• SFOFO, RFOFO, Super-Fernow, Helical + gaps for rf, Garren/Kirk rings**
  - **• Cells short so that Δp between resonances gives momentum acceptance**
  - **• Helical simulated but not yet with gaps for rf**
  - **• RFOFO simulated but with field on rf**
- **3. Periodic focus in longer chromatically corrected cells**
  - **• PIC, Rees rings, Wedge Reverse emittance Exchange**
  - **• Resonances avoided by correcting phase advance vs. momentum**
  - **• Complicated by transverse aberrations at large angles**
  - **• Complicated by significant space charge tune shifts**
  - **• Very hard and no example yet simulated**

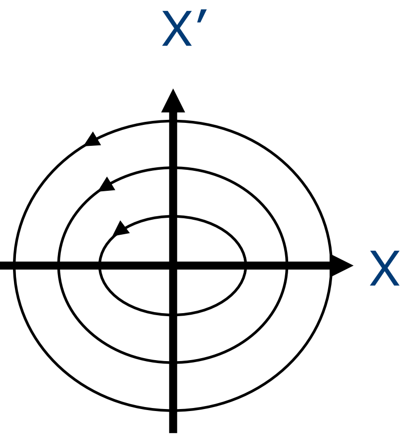
Parametric-resonance Ionization Cooling

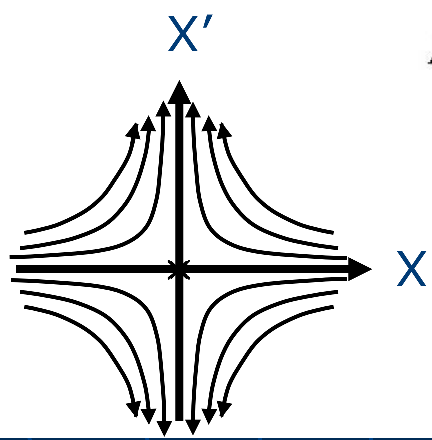
Excite ½ integer parametric resonance (in Linac or ring)

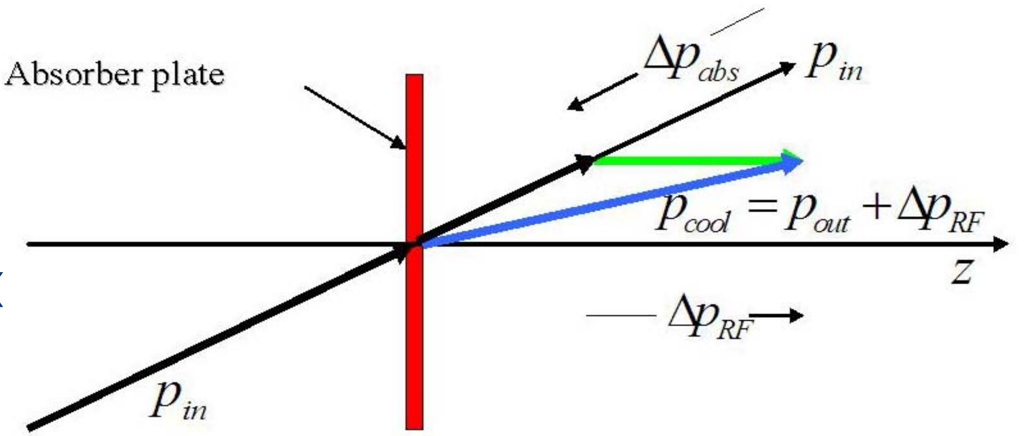
- Like vertical rigid pendulum or ½-integer extraction
- Elliptical phase space motion becomes hyperbolic
- Use xx’=const to reduce x, increase x’
- Use IC to reduce x’

Detuning issues being addressed (chromatic and spherical aberrations, space-charge tune spread). Simulations underway. New progress by Derbenev.

See Sah, Newsham, Bogacz







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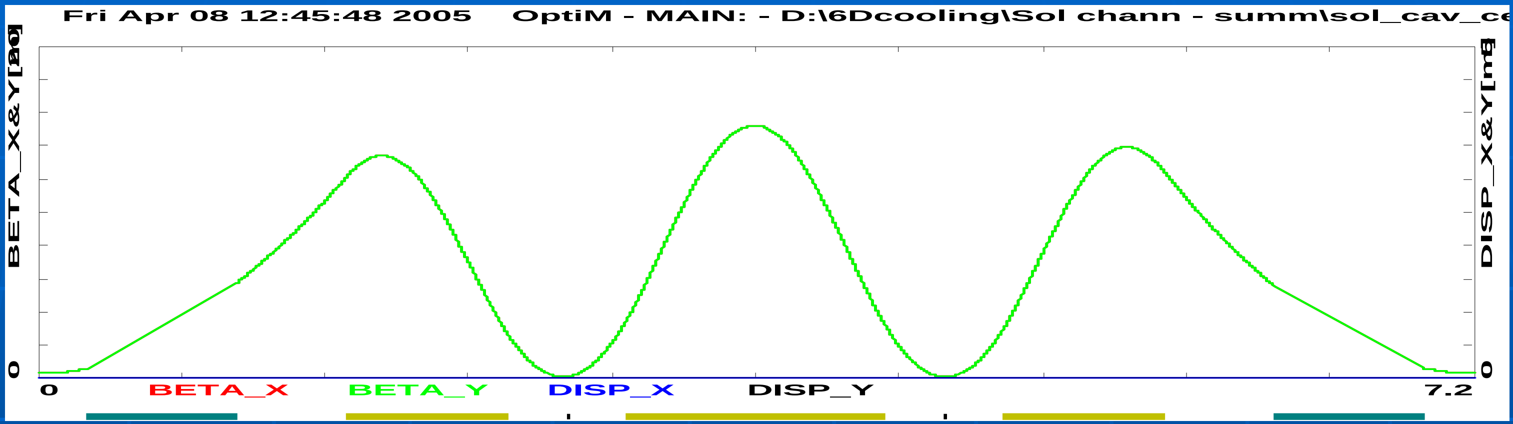
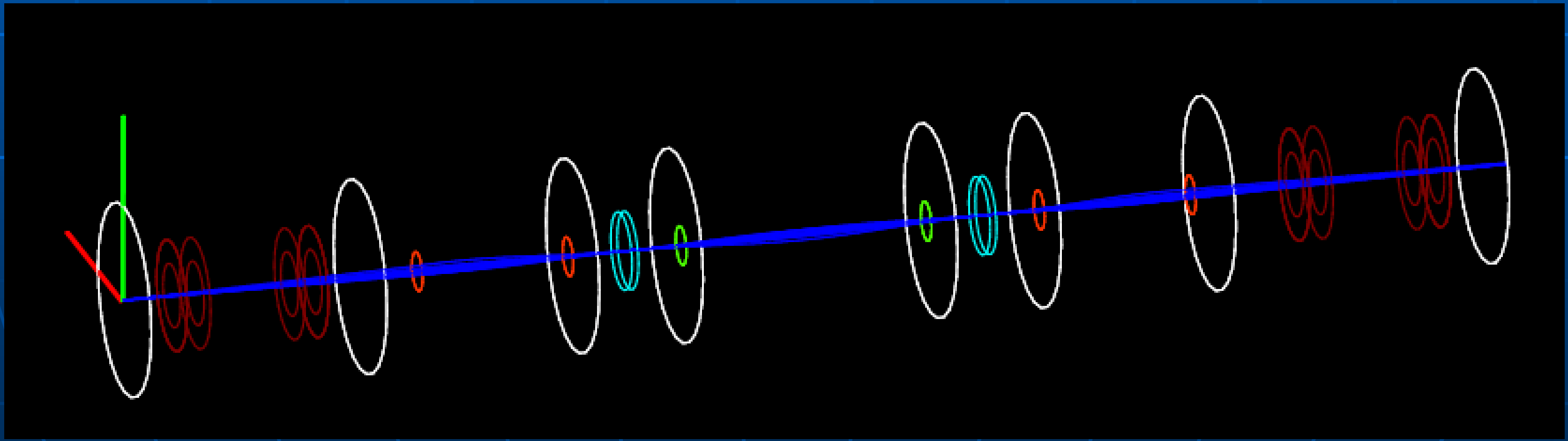
Example of triplet solenoid cell on ½ integer resonance with RF cavities to generate synchrotron motion for chromatic aberration compensation.



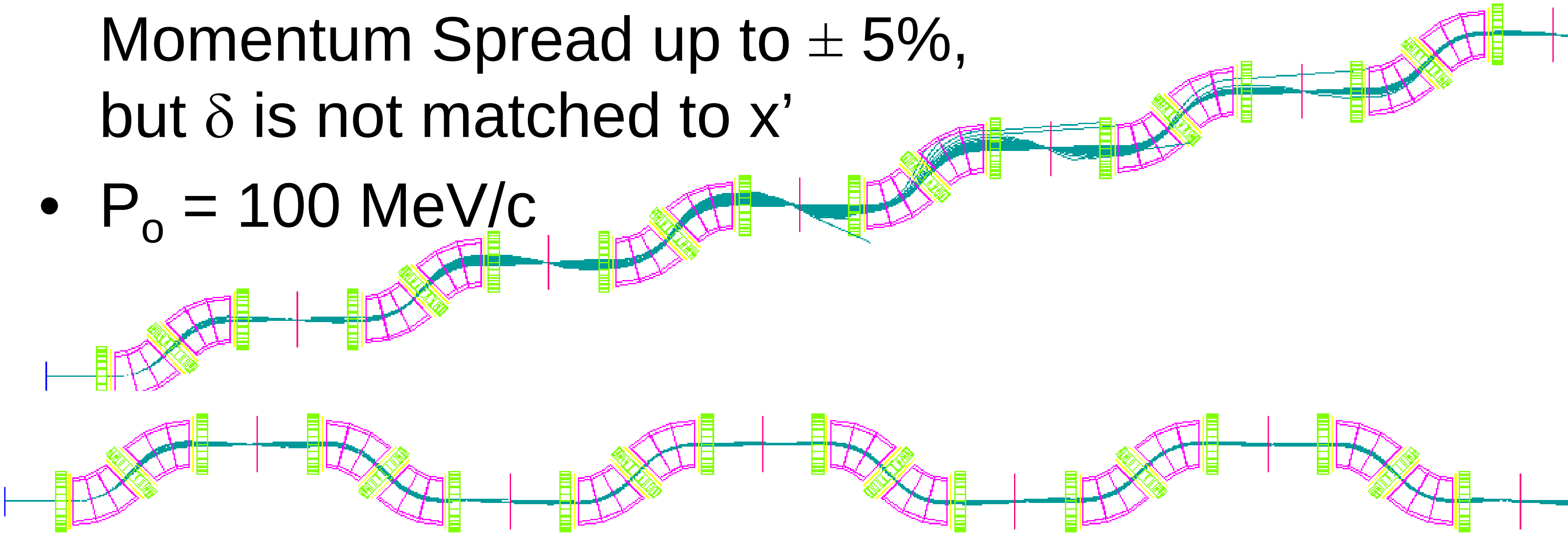
P-dependent focal length is compensated by using rf to modulate p.



OptiM (Valeri Lebedev) above and G4beamline (Tom Roberts) below.

Dispersion Prime

- Initial beam at $x = x' = y = y' = 0$
- 100 trajectories with Momentum Spread up to $\pm$ 5%, but δ is not matched to x'
- P_o = 100 MeV/c



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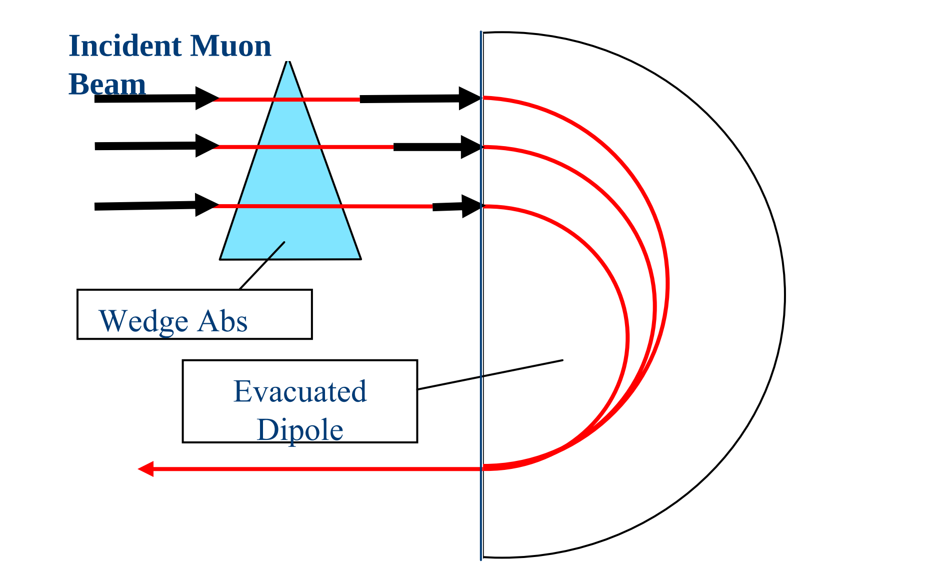
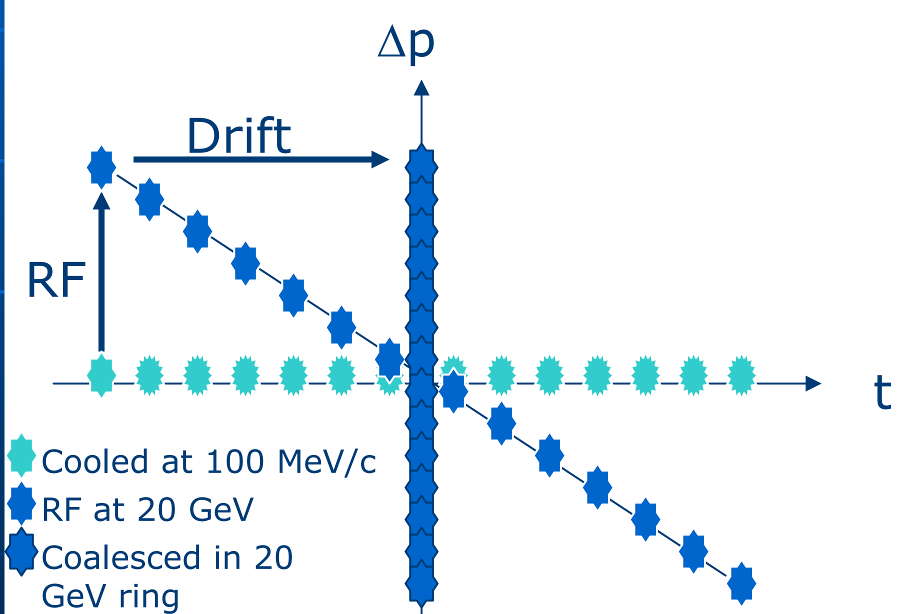
Reverse Emittance Exchange, Coalescing
see Derbenev, Ankenbrandt, Bhat

- p(cooling)=100MeV/c, p(colliding)=2.5 TeV/c => room in Δp/p space
- Shrink the transverse dimensions of a muon beam to increase the luminosity of a muon collider using wedge absorbers
- 20 GeV Bunch coalescing in a ring a new idea for ph II
- Neutrino factory and muon collider now have a common path

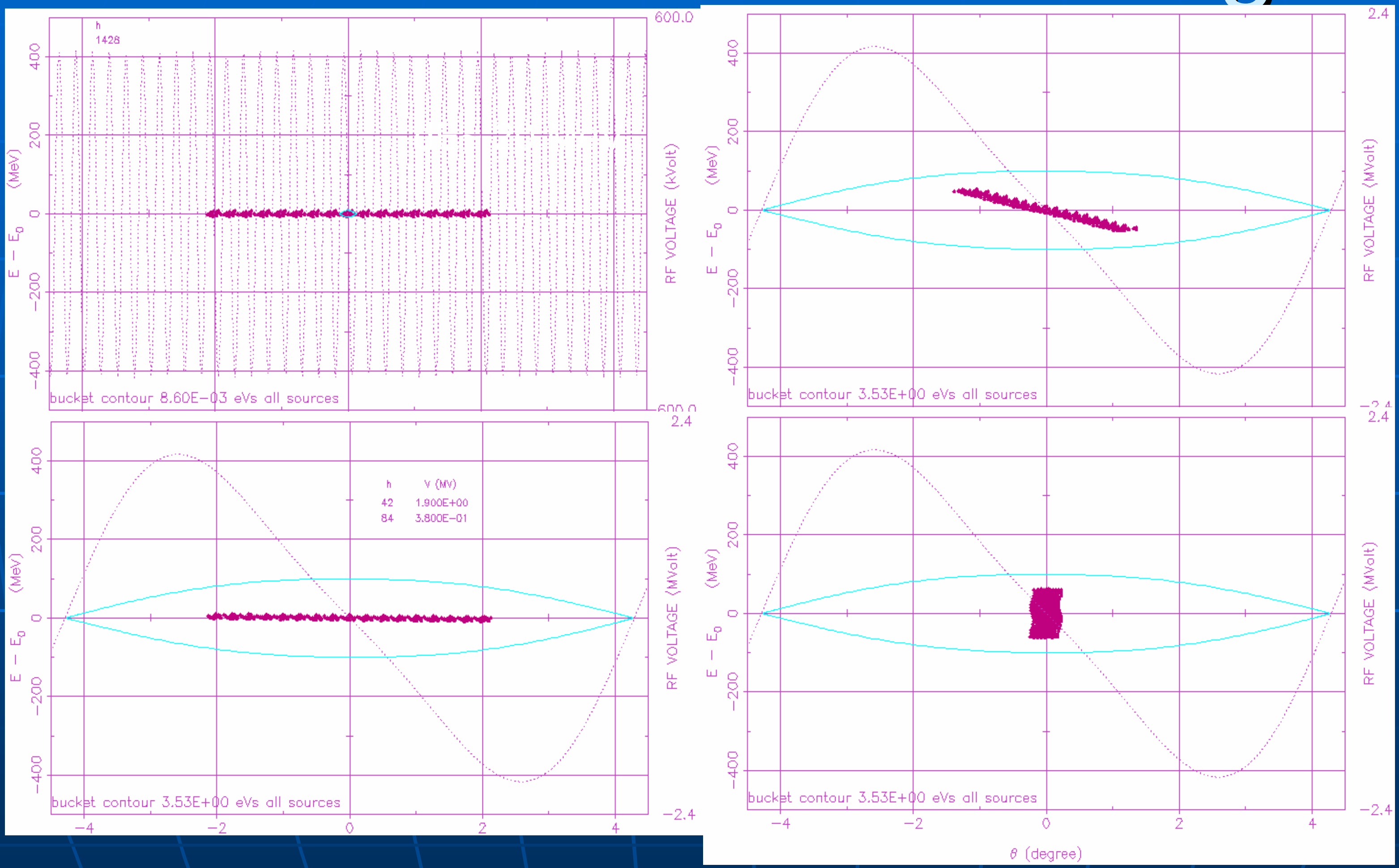


Concept of Reverse Emittance Exch.



1.3 GHz Bunch Coalescing at 20 GeV

Bhat et al. Coalescing

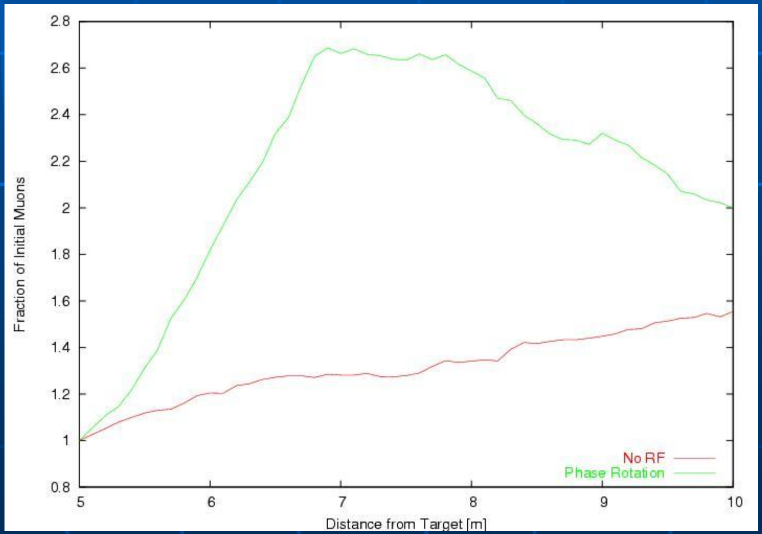


20 GeV muons in a 100 m diameter ring

Muons, Inc.

Capture, Bunching, and Precooling using HP GH2 RF

- Simultaneous muon capture, RF bunch rotation, and precooling in the first stage of a muon beam line
- Phase rotation and beam cooling will be simulated
- Continuation of the HP RF development in the MTA with high magnetic field and high radiation environment



Increase in muons captured when 2 m of bunch rotation RF is applied starting 5 m from target.

Progress on new ideas 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 Bob Palmer's talk shows another path to low emittance that looks promising due to him, Rick Fernow, and Steve Kahn.)

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

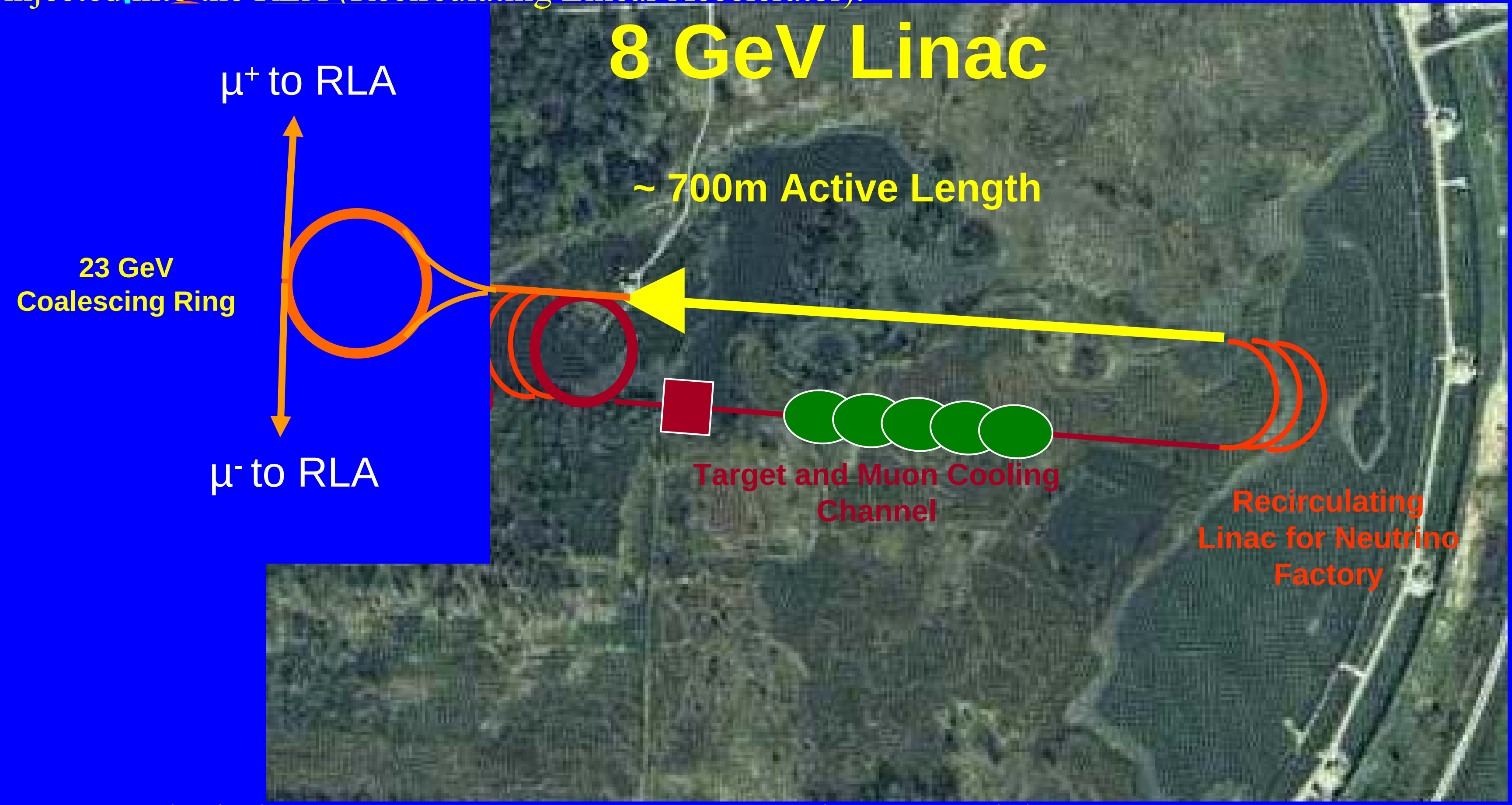
New Phase II grant

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 10x1.6 10^{10} muons/bunch become 10 bunches of 1.6x10^{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

5 TeV ~ SSC energy reach

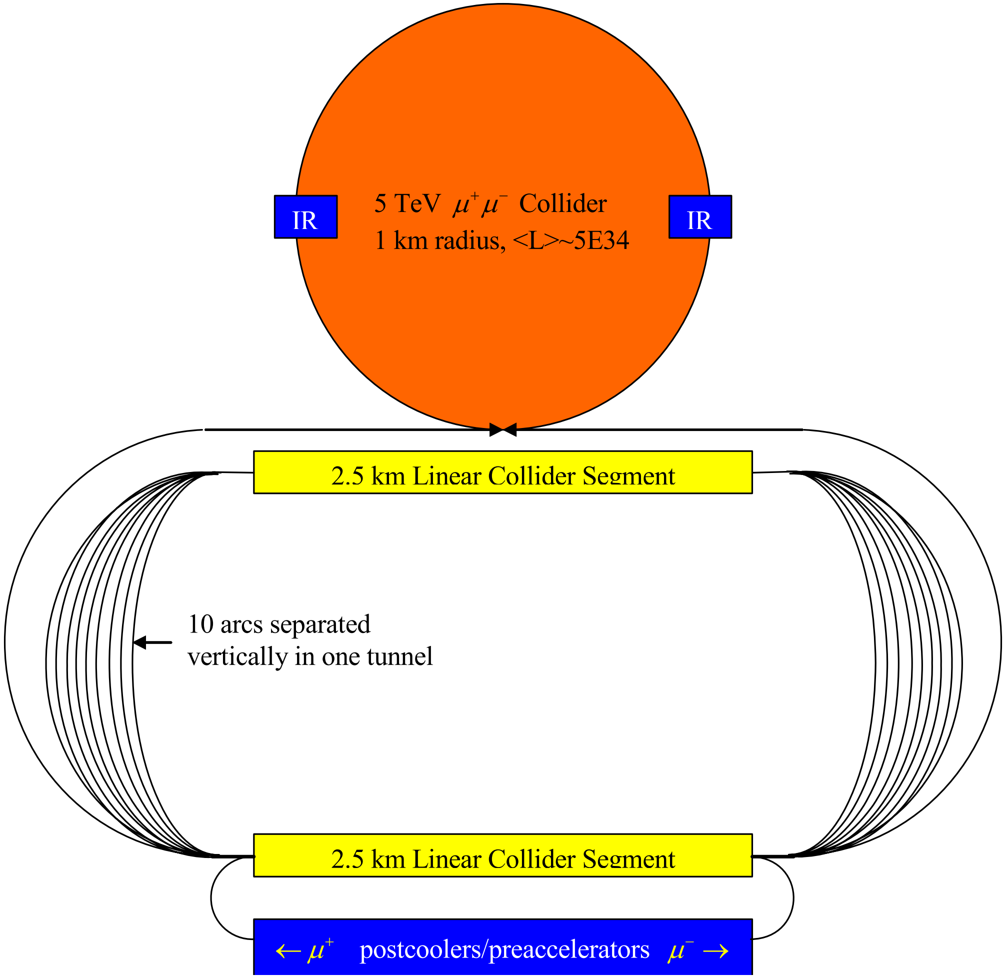
~5 X 2.5 km footprint

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

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

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

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

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

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

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

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

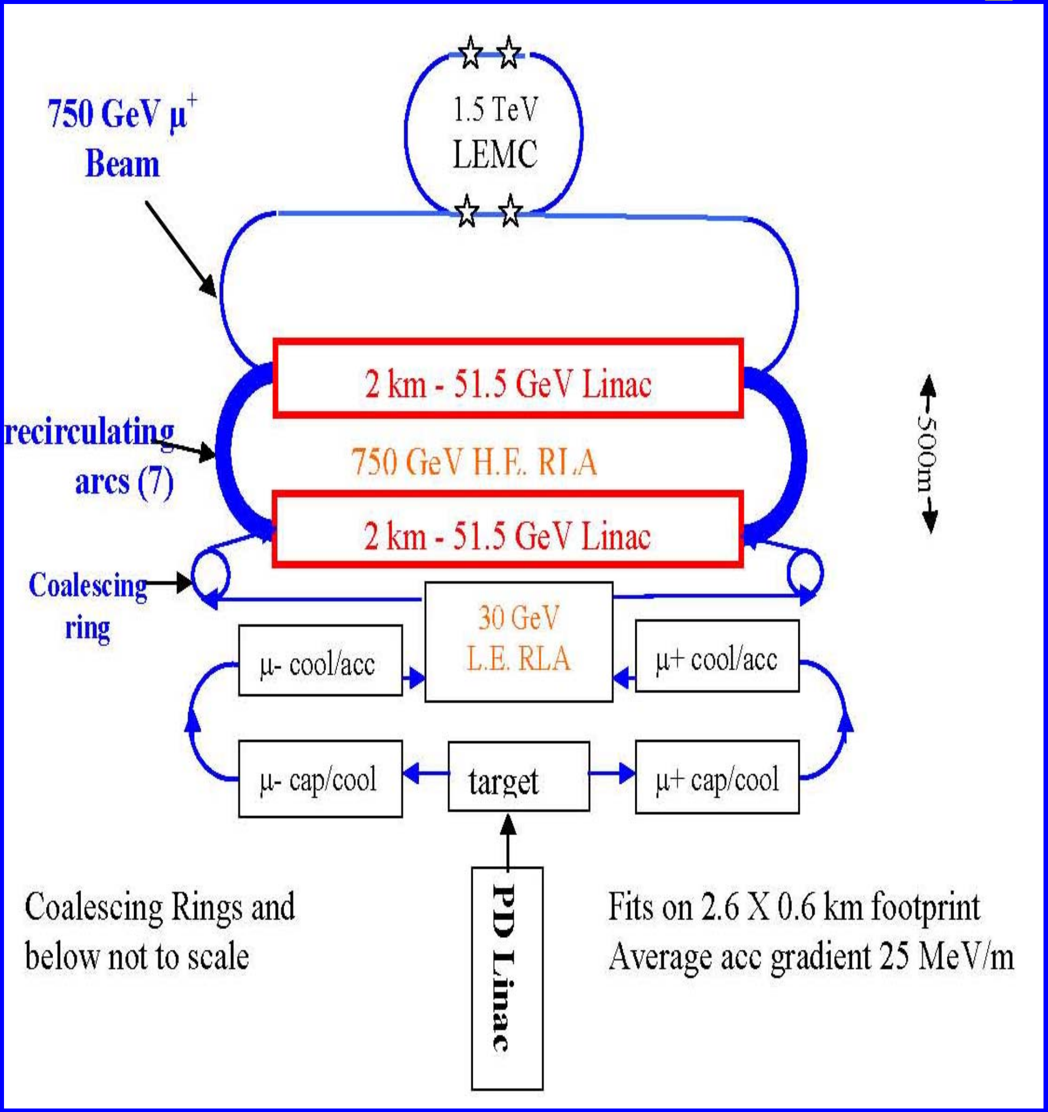
20 Hz Operation:

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

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

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

1.5 TeV COM Example



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.

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

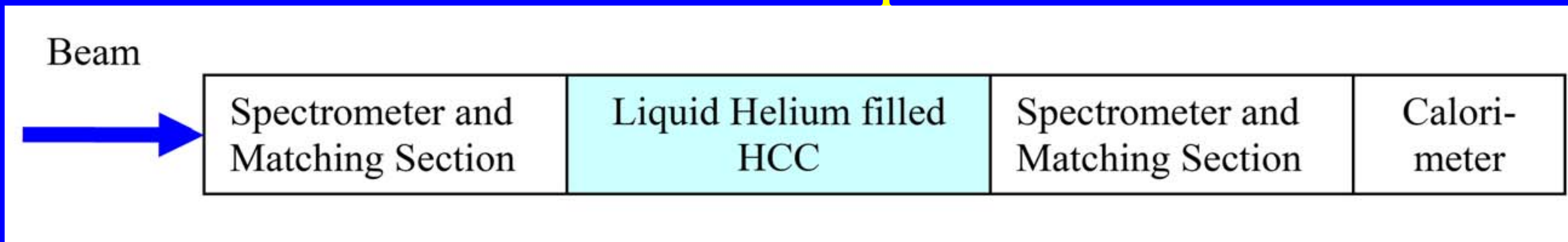
Muons, Inc.

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
    - 6D emittance reduction with HCC sections of absorber alternating with (SC?) RF sections.
  - New technology

MANX parts



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)

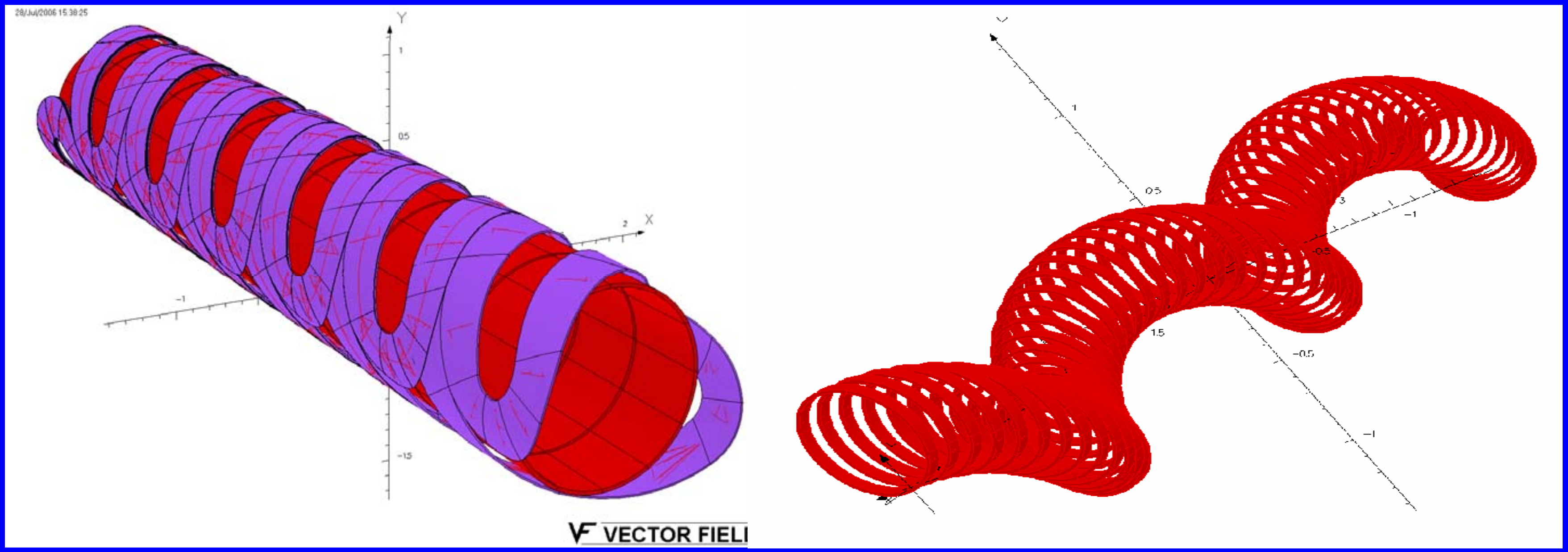
LHe instead of LH2 for safety concerns

Use ~300 MeV/c muon beam wherever it can be found
with MICE collaboration at RAL or at Fermilab

Present Efforts: Designing/building 3-coil helical solenoid prototype
Simulating the experiment with G4MANX with scifi
Improving the matching sections
Sweating the phase II proposal

Possible MANX magnet designs

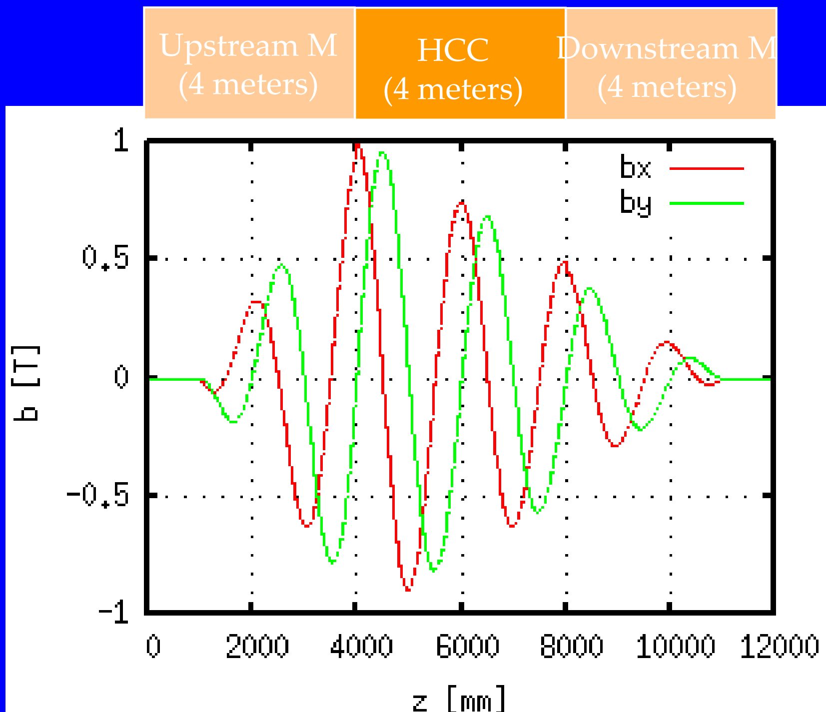
See Kashikhin



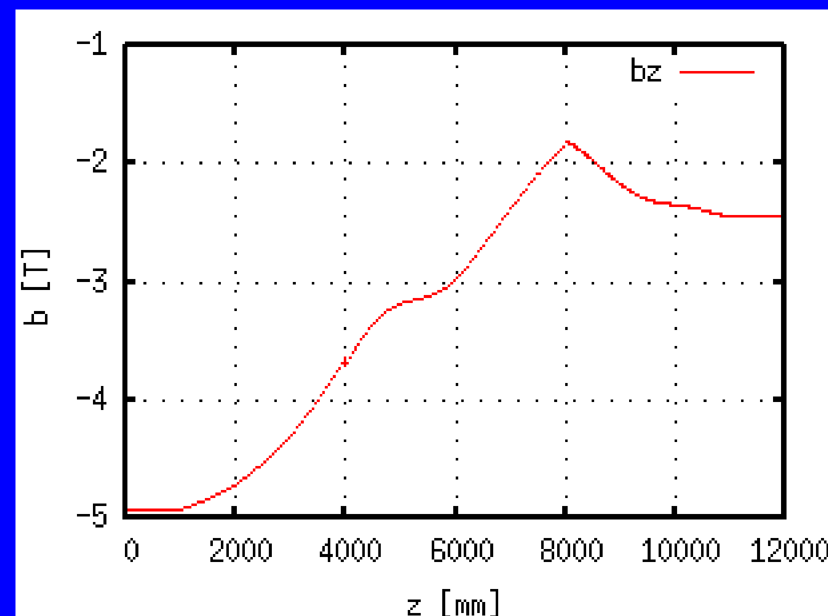
- Snake type MANX
- Consists of 4 layers of helix dipole
- Maximum field is ~7 T (coil diameter: 1.0 m)
- Field decays very smoothly
- Hard to adjust the field configuration

- 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



See Yonehara



Use linear function for first trial

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

b_0: Amplitude of initial helical dipole magnet

α: Ramping rate

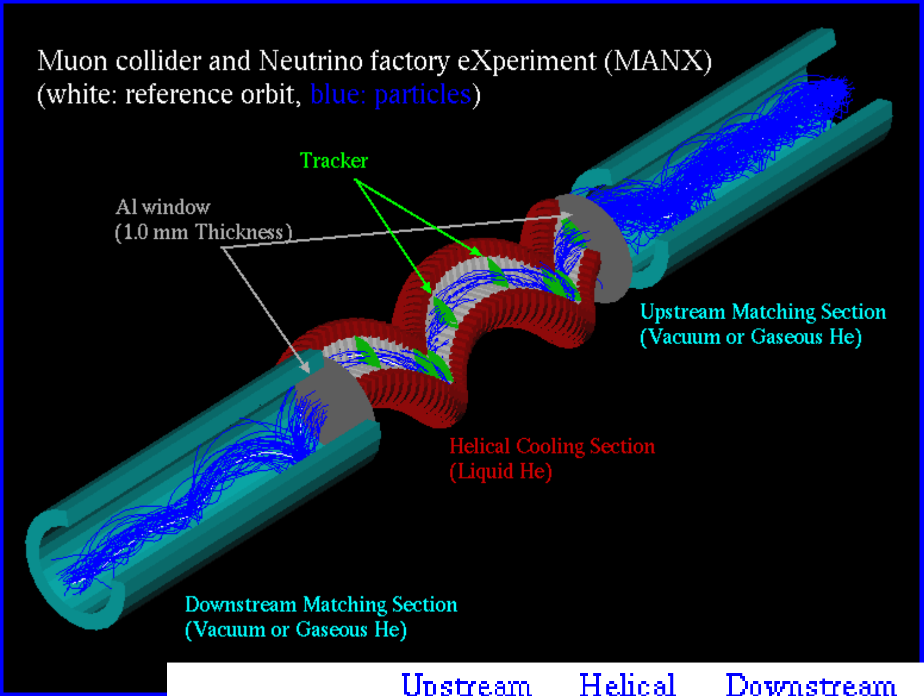
Adjust solenoid strength to connect to a proper helical orbit.

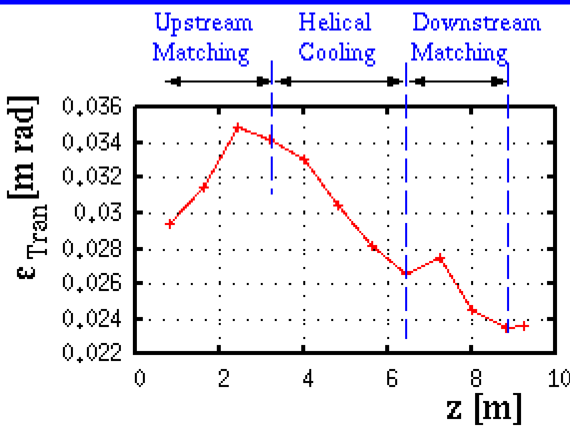
Katsuya's Simulation study

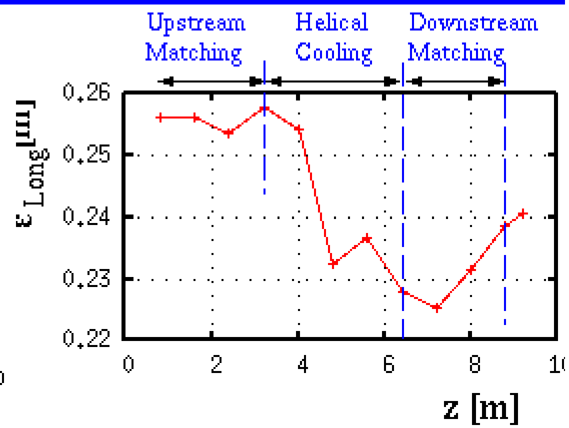
Initial beam profile

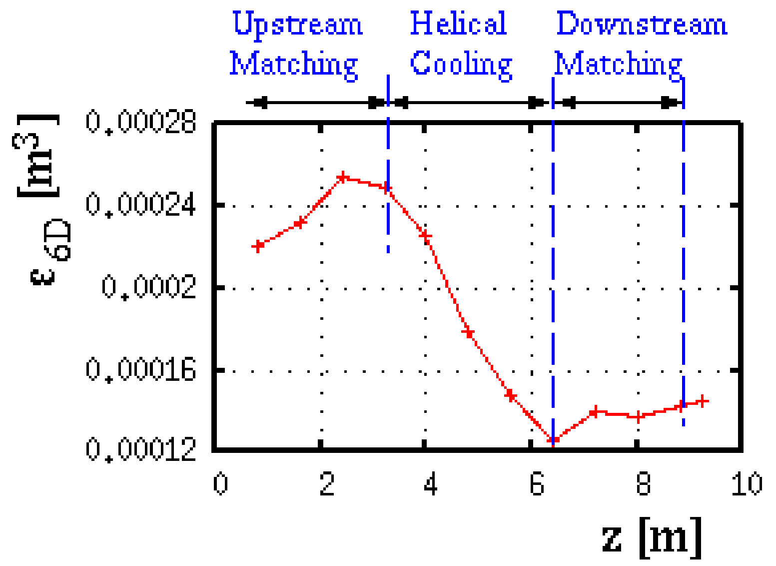
- Beam size (rms): ± 60 mm
- $\Delta p/p$ (rms): ± 40/300 MeV/c
- x′ and y′ (rms): ± 0.4

- Obtained cooling factor: ~200%
- Transmission efficiency: 32%
- But is matching necessary?!!









Where to put MANX?

- Several options studied, 3 discussed at this LEMC workshop:
  - MTA new beamline
  - Meson Lab test beam
  - Using recycler to transfer 8 GeV beam to a debuncher or accumulator stretcher ring
  - MICE Phase III

Phase II Proposals submitted April 13

- G4BL
  - More user support, e.g use processor farms, join GEANT4 collaboration
  - Finish upgrades (runs on Linux, XP, MacOS)
  - Phase II plans (polarization, space charge, low E)
- MANX
  - Fermilab Experimental Proposal
  - G4MANX, 3-coil HCC prototype

Low Emittance Muon Collider Prospects: we are getting close!

- A detailed plan for at least one 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, HCC magnet design
- And a really good 6D cooling demonstration experiment proposed to Fermilab

Discussion at the LEMC workshop

Memo: Muon Collider R&D Status

Date: Feb 21, 2007

To: P. Oddone

From:

A.Tollestrup, M. Zisman, S. Geer, A. Sessler, V. Shiltsev, R. Johnson, R. Palmer

During the Low Emittance Muon Collider Work shop, we had a discussion session on the status of the muon collider R&D and the overall understanding of the problems connected with the ultimate construction of such a machine. A summary of this discussion follows.

General Conclusion

If the present R&D effort, as defined by: (1) the ongoing NFMCC program, (2) the proposed MCTF program, and (3) the ongoing work of Muons, Inc. is successful, then the consensus was that it should be possible to develop a realistic design for a muon collider with a c.m. energy of 1.5 TeV, or greater and a luminosity of the order of 10^{34} cm^2/sec.

Key Elements of an R&D Program

An exciting and innovative program has been proposed that if funded and pursued vigorously would allow, in two or possibly three years, a feasibility study similar to that carried out for the neutrino factory (i.e., a rather detailed conceptual design and a rough estimate of the cost of the facility). Such a study is crucial for establishing the feasibility of a muon collider. Generating a coherent design will pull together the diverse and innovative ideas being presently pursued and indicate the direction of additional work.

LEMC workshop Muon Collider R&D Status Memo continued:

The proposed R&D Program

The proposed R&D Program has four key elements. They are:

1. An experimental study of the behavior of gas filled and vacuum RF cavities in a beam and with a strong axial magnetic field. This is dependent on getting a proton beam to MTA expeditiously.
   (1st STTR with IIT, present STTR ph II project with Fermilab)

2. The development of suitable conductor, a material properties data-base for materials used in high field magnets, and a model magnet program aimed at developing 20 to 50 T HTS solenoids.
   (1st STTR with Fermi TD, New SBIR ph I proposal with BNL)

3. Fabrication and testing of a model helical cooling magnet, provided the study described in the MCTF charge validates its use in a cooling channel.
   (New SBIR ph II proposal, with wonderful phase I results)

4. Theoretical studies, both analytic and numerical simulation, on how to actually incorporate the new ideas into a coherent design for a collider.
   (Several SBIR-STTR projects at JLab, Fermilab, and IIT underway and proposed)

Muons, Inc. Project History

Year	Project	Expected Funds	Research Partner
2002	Company founded		
2002-5	High Pressure RF Cavity	\$600,000	IIT
2003-7	Helical Cooling Channel	\$850,000	JLab
2004-5†	MANX demo experiment	\$ 95,000	FNAL TD
2004-7	Phase Ionization Cooling	\$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*	G4Beamline Simulation	\$100,000	IIT
2006-7*	MANX 6D Cooling Demo	\$100,000	FNAL TD
2006-7	10 ph I proposals submitted		ANL, BNL, FNAL, JLab

* Submitted for phase II for +\$750,000 and +2 years

† 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 \$750,000 for 2 years (see 13+3 PAC07 papers on progress)

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**

Comparison of ICOOL and G4BL

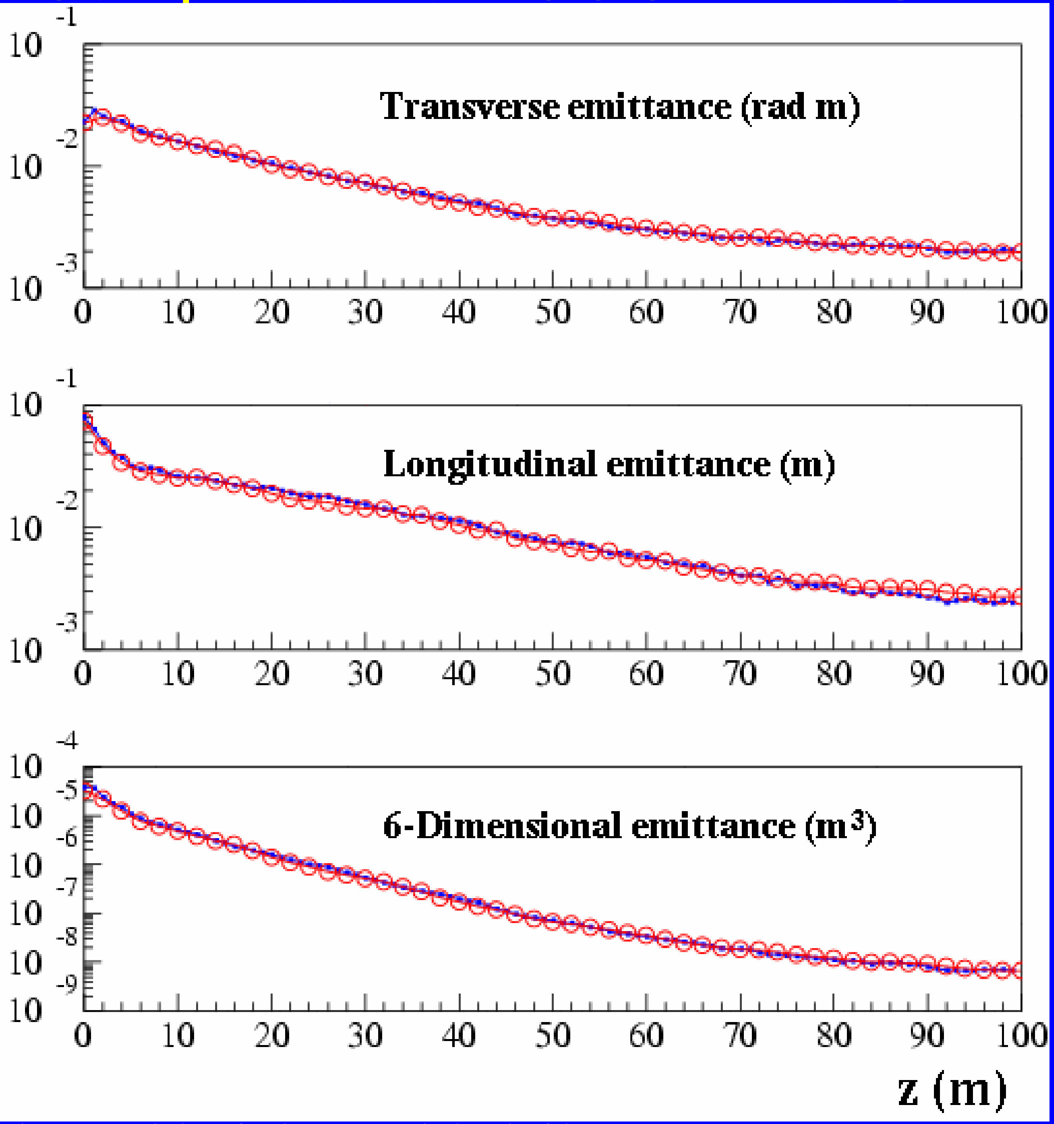


Figure 1: Evolution of emittance over the length of the 100 meter HCC.
Results in red are from G4Beamline and blue from ICOOL.
The six-dimensional emittance is reduced by a factor of 4800 in this simulation result.