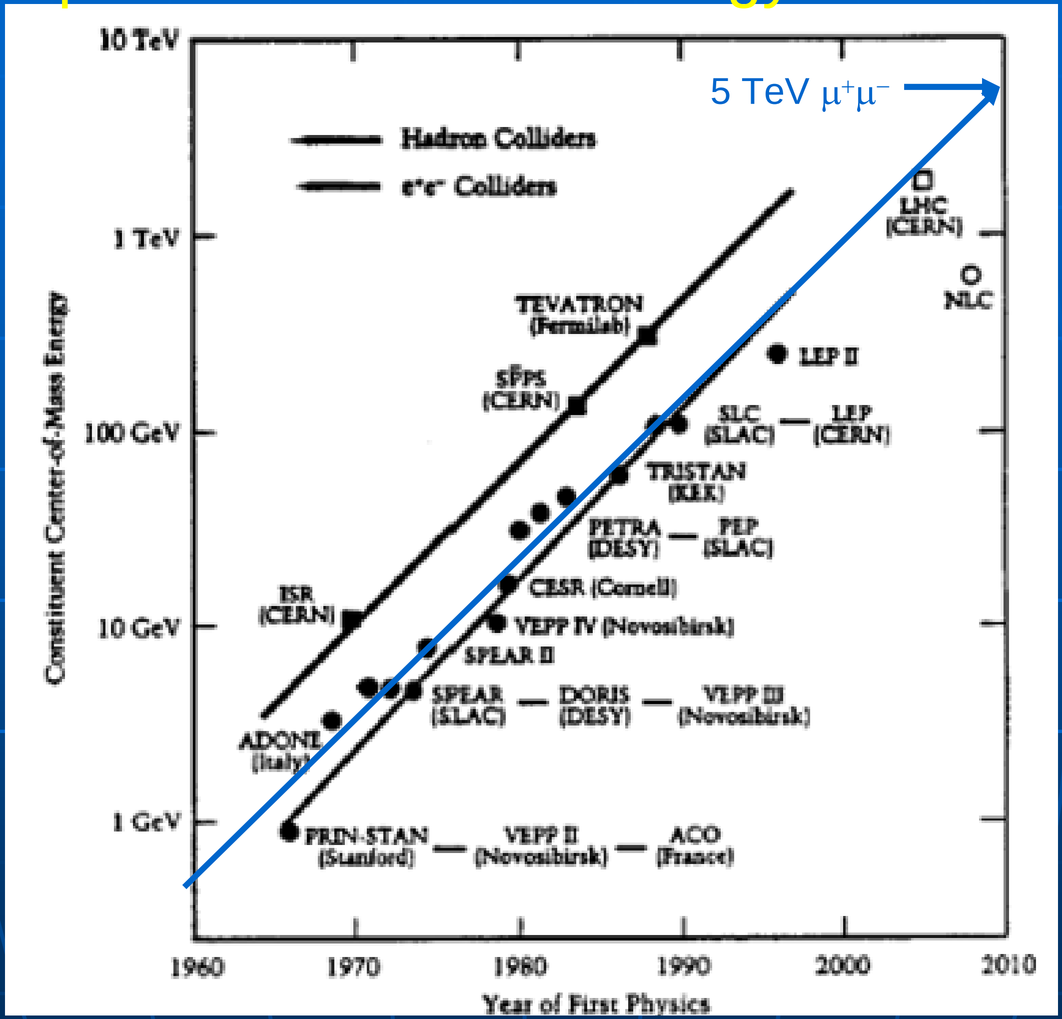
The Low Emittance Muon Collider Workshop

http://www.muonsinc.com/mcwfeb06

Goals:

- Merge several new ideas with older ones into a self-consistent muon collider (MC) design with new parameters
  - Many essential JLab contributions from Derbenev and Bogacz
- Make a Fermilab-site specific baseline MC design based on ILC RF technology
  - Using proposed proton driver Linac to also accelerate muons
- Create a staged plan to get to the energy frontier, where each step is a funding package with an exciting experimental physics goal
  - Implies an exceptional neutrino factory as an intermediate step

Muon Colliders: Back to the Livingston Plot
A lepton collider at the energy frontier!



Modified Livingston Plot taken from: W. K. H. Panofsky and M. Breidenbach, Rev. Mod. Phys. 71, s121-s132 (1999)

Workshop Desirables

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

1. attractive 6D Cooling experiment (5)
2. double-duty proton driver Linac (400)
3. exceptional neutrino factory (23 GeV) (1000)
   P buncher, target, cooling, recirculation, PDL upgrade, decay racetrack
4. intense stopping muon beam (100)
   Experimental hall, beamlines
5. Higgs factory (~300 GeV com) (2000)
   Add more cooling, RLA, coalescing & collider rings, IR
6. energy frontier muon collider(5 TeV com) (2000)
   More RLA, deep ring, IRs

New inventions, new possibilities

- Muon beams can be cooled to a few mm-mr (normalized)
  - allows HF RF (implies Muon machines and ILC synergy)

- Muon recirculation in ILC cavities: high energy for lower cost
  - Affordable neutrino factory, which by coalescing, becomes
  - A muon collider injector for

- A low-emittance high-luminosity collider
  - high luminosity with fewer muons
  - LEMC goal: E_{com}=5 TeV, <L>=10^{35}

- Many new ideas in the last 5 years. A new ball game!
  - (many new ideas have come from DOE SBIR funding)

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.

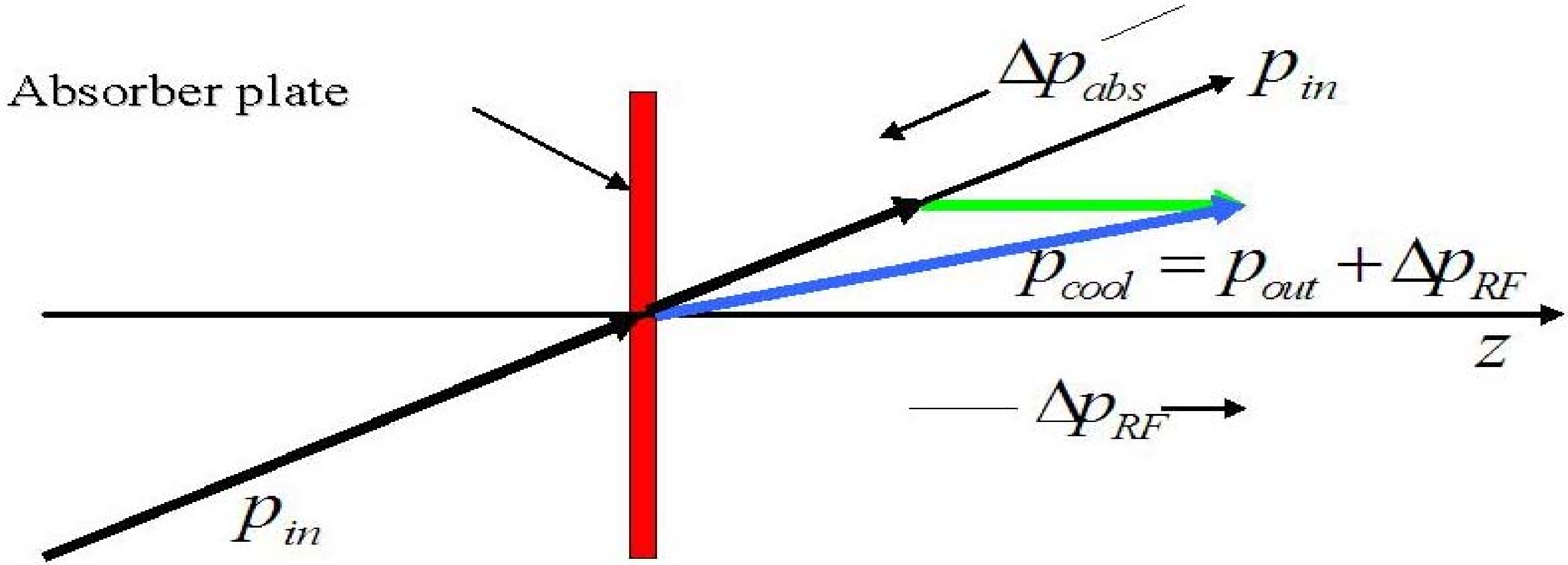
Smaller emittance also:

- 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.

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 150 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
  - High Temperature Superconductor for up to 50 T magnets
    - Faster cooling, smaller equilibrium emittance

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



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

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

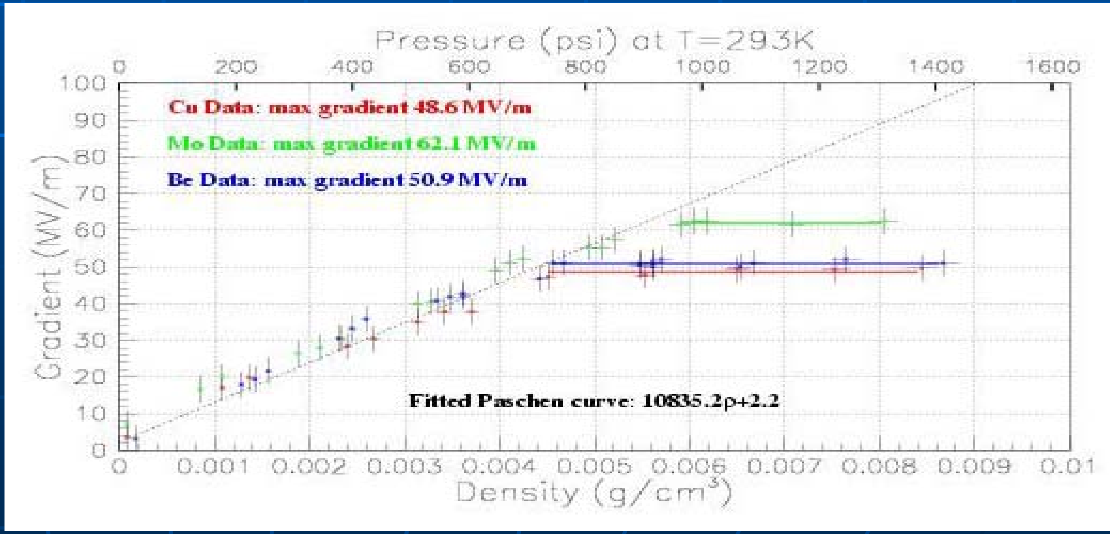
Fast enough for muons

Only works for muons

Pressurized High Gradient RF Cavities

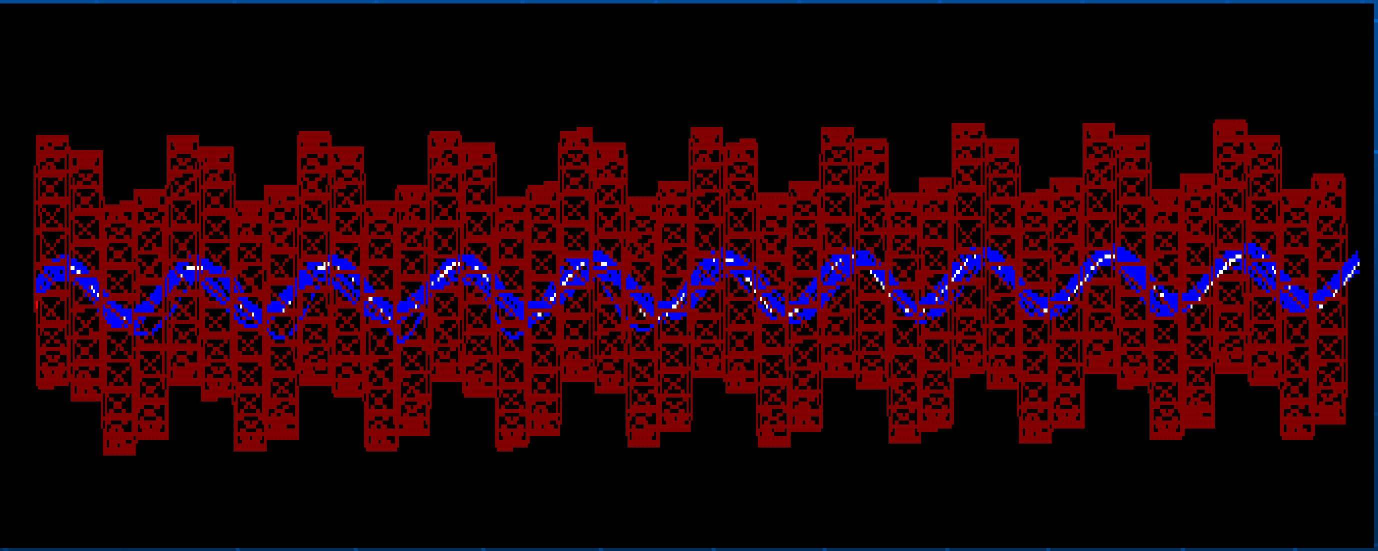
see Kaplan, Popovic, Moretti, Johnson, Paul, Neuffer, Hanlet

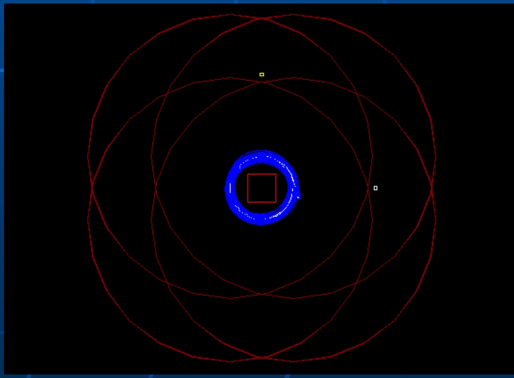
- 800 MHz test cell with GH2 to 1600 psi and 77 K in Lab G, MTA
- Paschen curve verified
- Maximum gradient limited by breakdown of metal
  - fast conditioning seen
- Cu and Be have same breakdown limits (~50 MV/m), Mo ~20% better



6-Dimensional Cooling in a Continuous Absorber
see Derbenev, Yonehara, Johnson

- Helical cooling channel (HCC)
  - Continuous absorber for emittance exchange
  - Solenoidal, transverse helical dipole and quadrupole fields
  - Helical dipoles known from Siberian Snakes
  - z-independent Hamiltonian
  - Derbenev & Johnson, Theory of HCC, April/05 PRST-AB





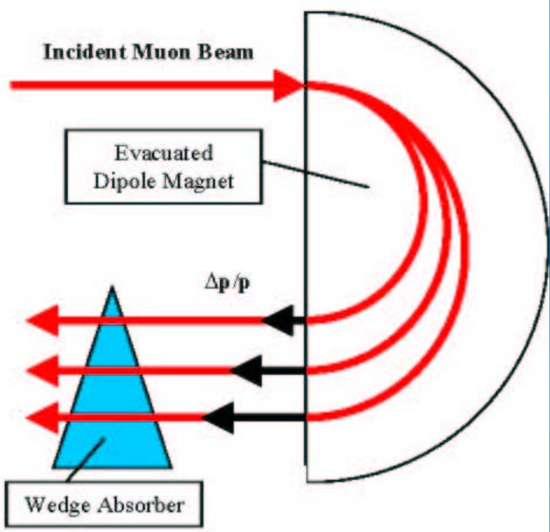


Figure 1. Use of a Wedge Absorber for Emittance Exchange

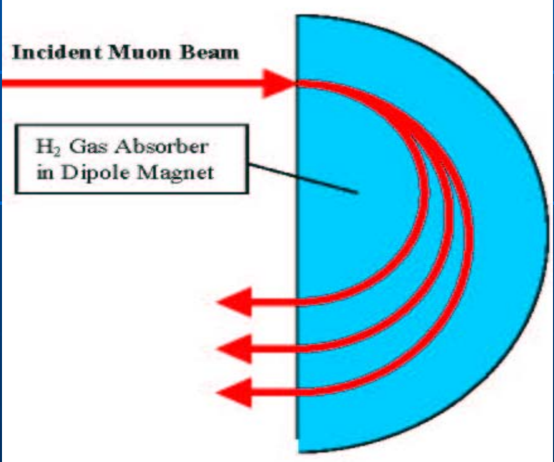
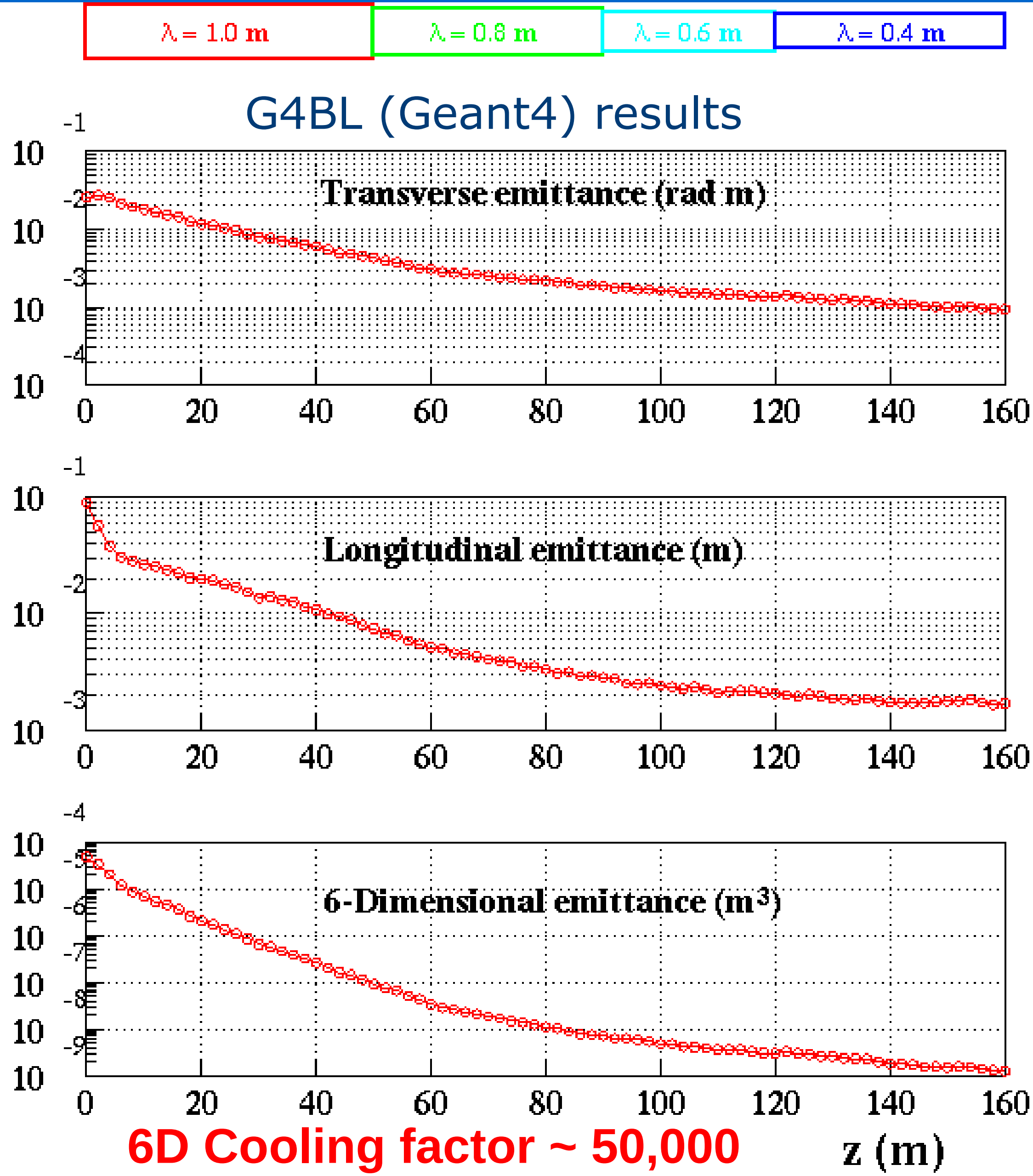


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange



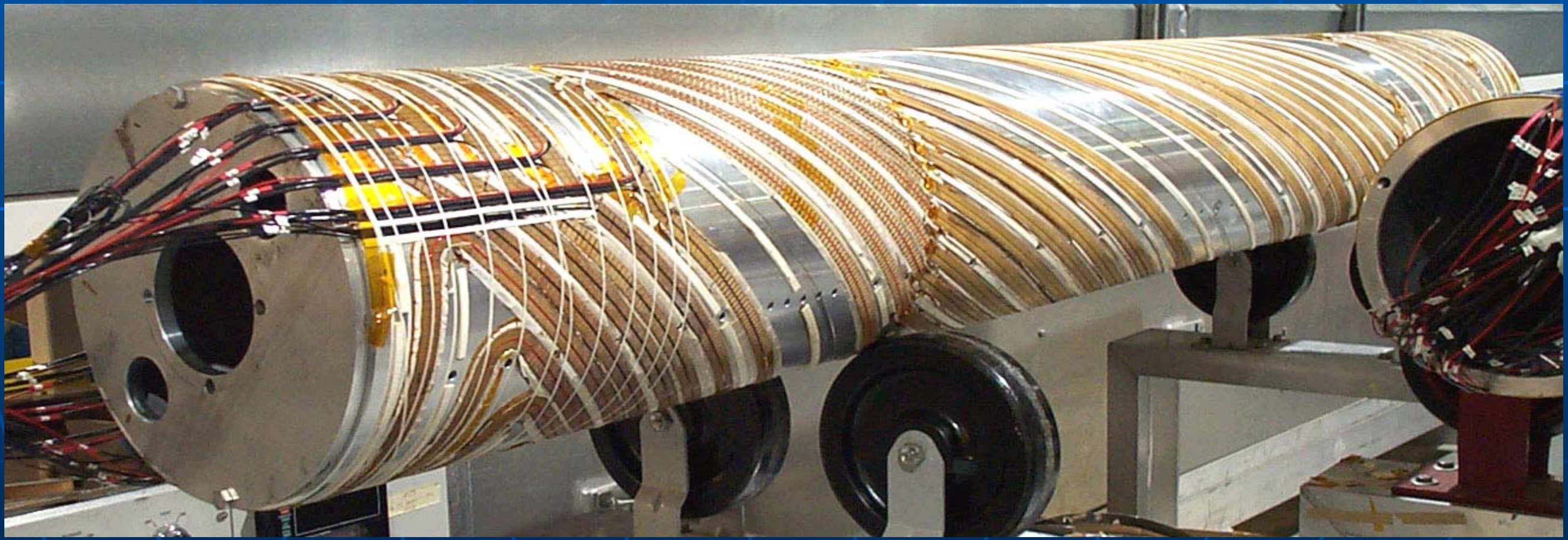
Hydrogen Cryostat for Muon Beam Cooling
See Kashikhin, Yonehara, Kuchnir, Yarba

Technology for HCC components:

HTS (nice BSSCO data from TD Ph I), Helical magnet design,

low T Be or Cu coated RF cavities, windows, heat transport, refrigerant

Cryostat for the 6DMANX cooling demonstration experiment (proposal 7)

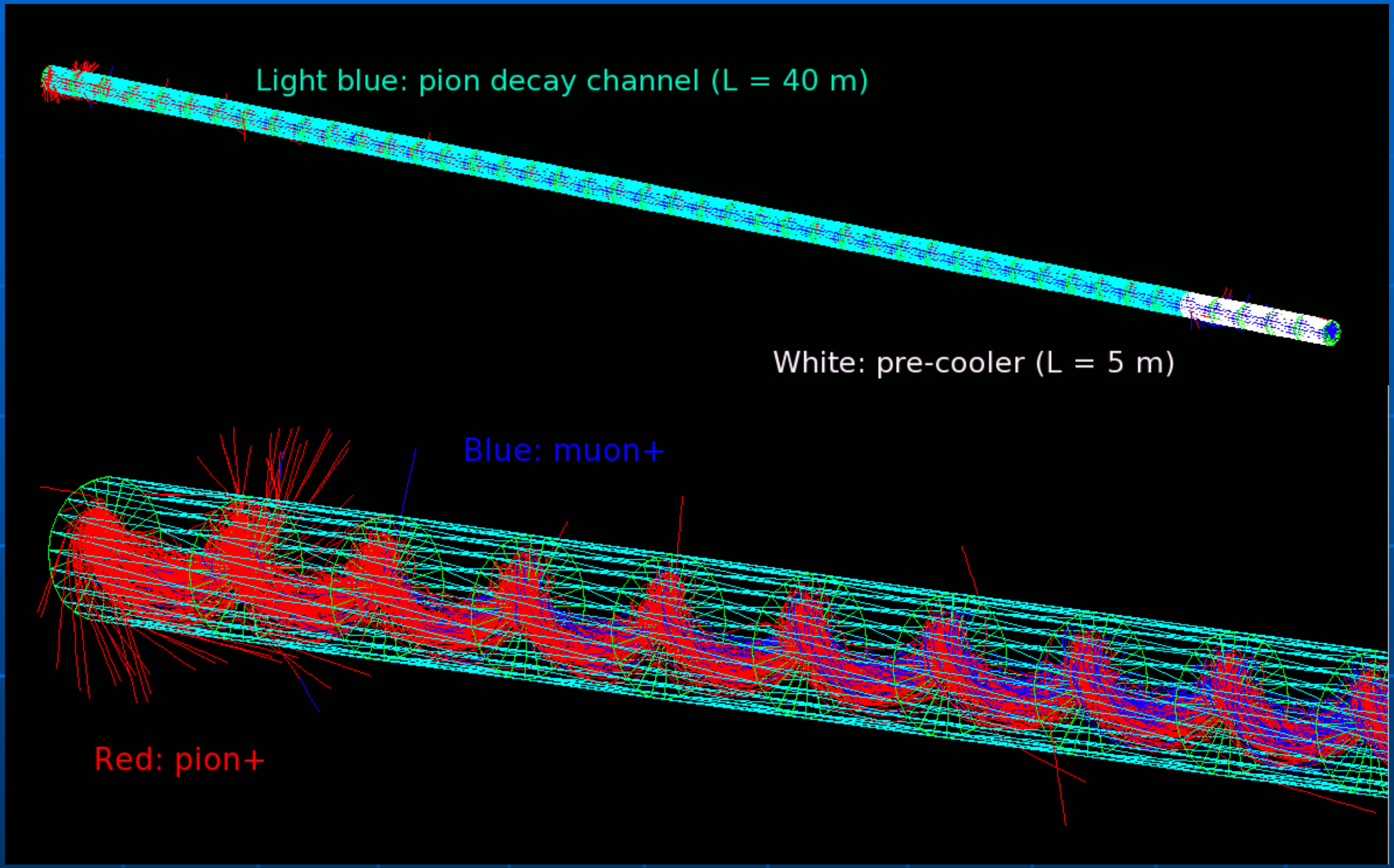


BNL Helical Dipole magnet for AGS spin control

MuCool Test Area (MTA)

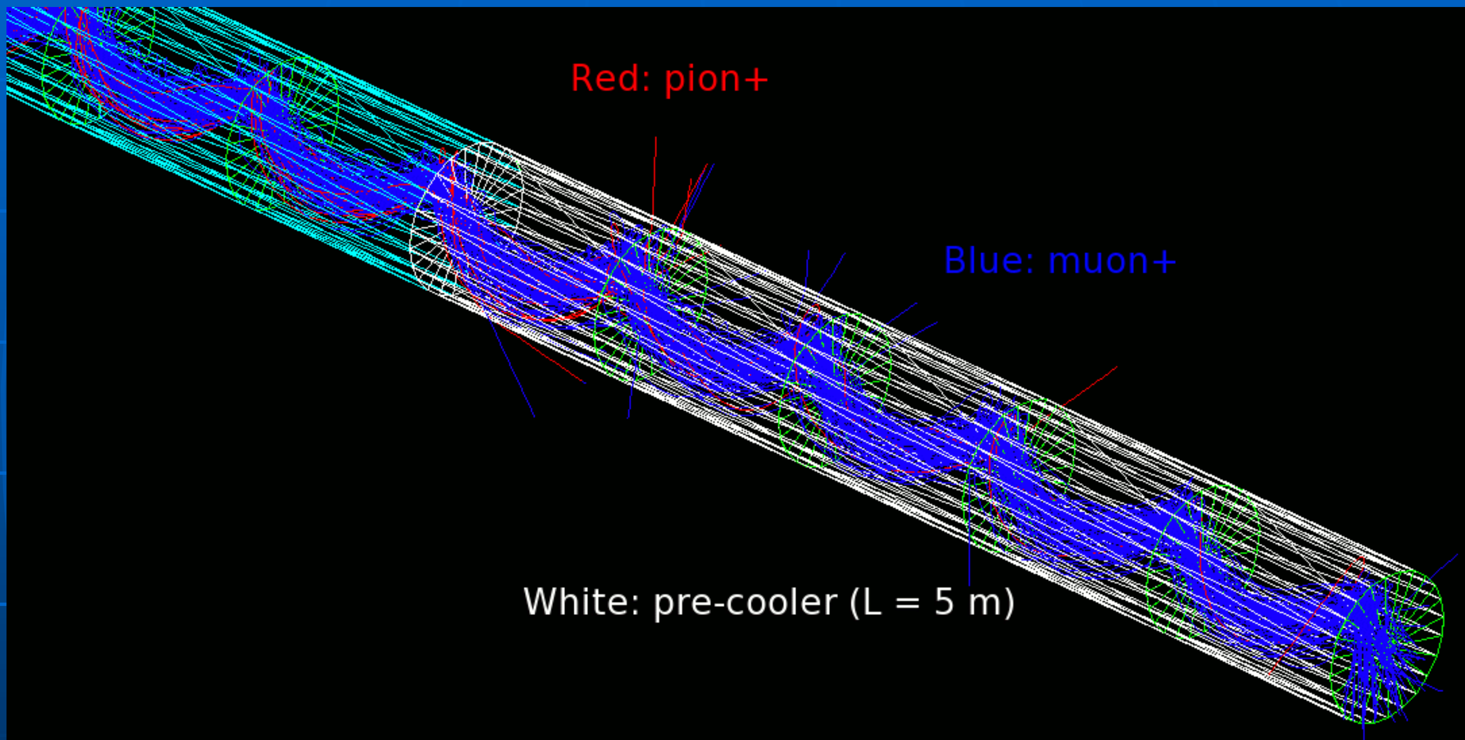
HCC with Z-dependent fields

see Yonehara, Paul, Derbenev



40 m evacuated helical magnet pion decay channel followed by a 5 m liquid hydrogen HCC (no RF)

5 m Precooler and MANX



New Invention: HCC with fields that decrease with momentum. Here the beam decelerates in liquid hydrogen (white region) while the fields diminish accordingly.

First G4BL Precooler Simulation

see Yonehara, Roberts

Equal decrement case.

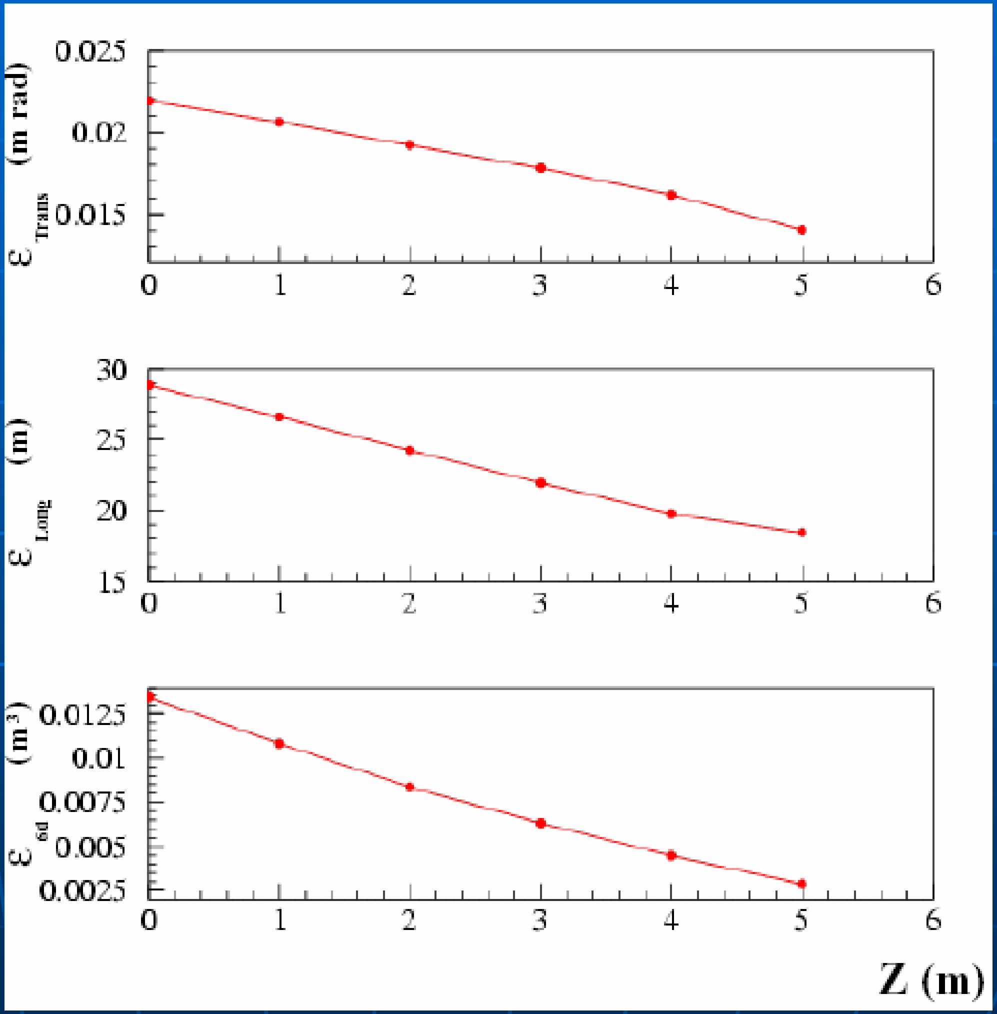
~x1.7 in each direction.

Total 6D emittance reduction ~factor of 5.5

Note this would require serious magnets: ~10 T at conductor for 300 to 100 MeV/c deceleration

MANX results with B <5.5 T will also work!

below show LHe absorber



MANX 6-d demonstration experiment

Muon Collider And Neutrino Factory eXperiment

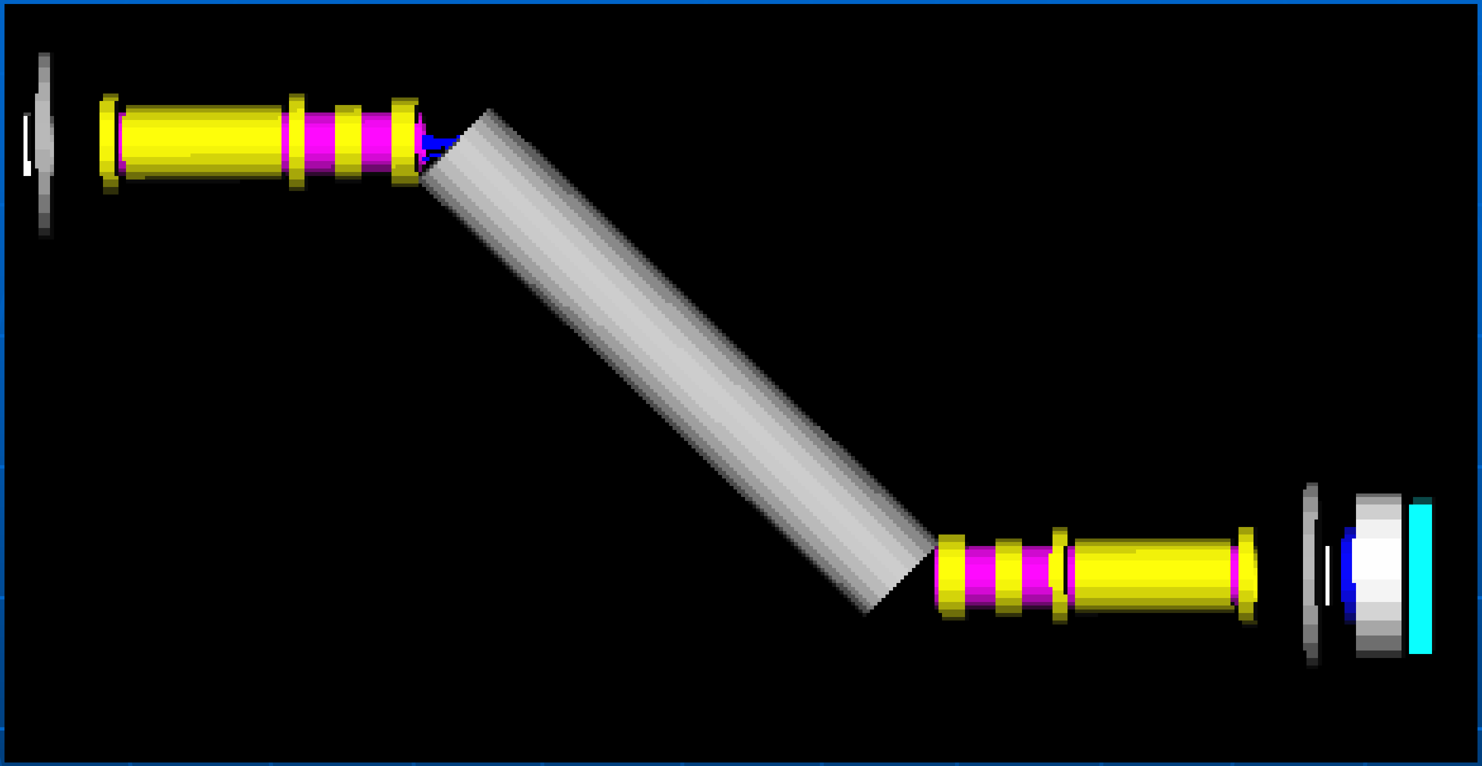
see Roberts, Yonehara, Derbenev

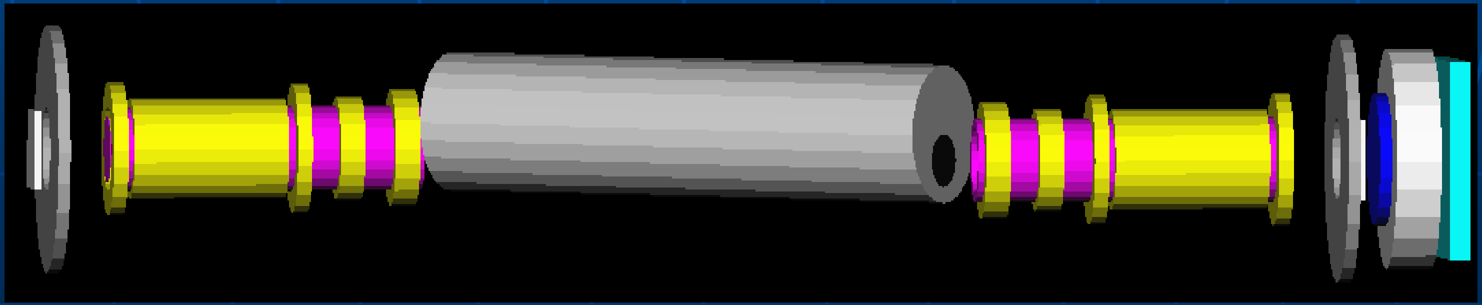
NEED EXPERIMENTERS!!!

- To Demonstrate
  - Longitudinal cooling
  - 6D cooling in cont. absorber
  - Prototype precooler
  - Helical Cooling Channel
  - Alternate to continuous RF
    - 5.5^8 ~ 10^6 6D emittance reduction with 8 HCC sections of absorber alternating with (SC?)RF sections.
  - New technology

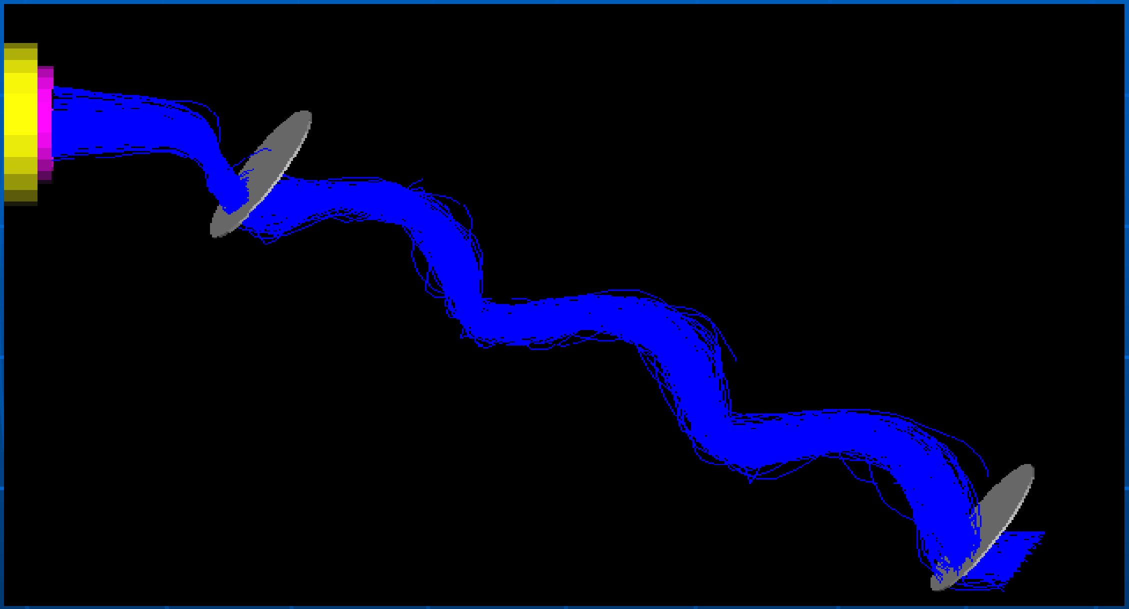
Thomas J. Roberts et al., A Muon Cooling Demonstration Experiment, PAC05

G4BL MANX with MICE spectrometers



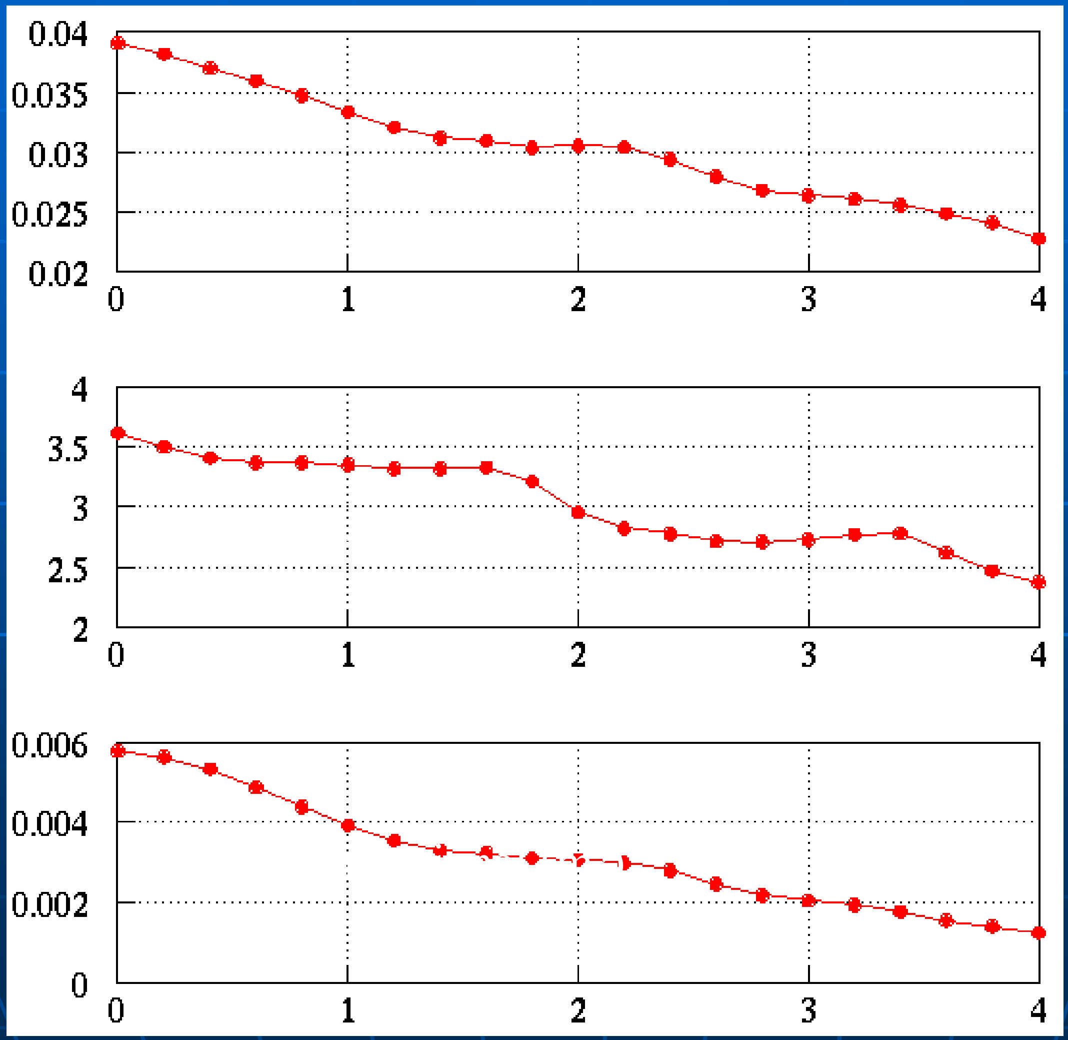


Muon Trajectories in 3-m MANX



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

Emittance evolution in LHe HCC



Z (m)

LHe MANX Summary

- Maximum field can be less than 5.5 T at r = 35 cm.
- Cooling factor is ~500%.
- Studying matching of emittance between MANX and spectrometers.
- Really great opportunity for HEP people to get involved. Maybe use spectrometers stored in meson lab.

Technology Development in Technical Division
see Kashikhin, Kuchnir, Yonehara

HTS at LH2 shown, in LHe much better

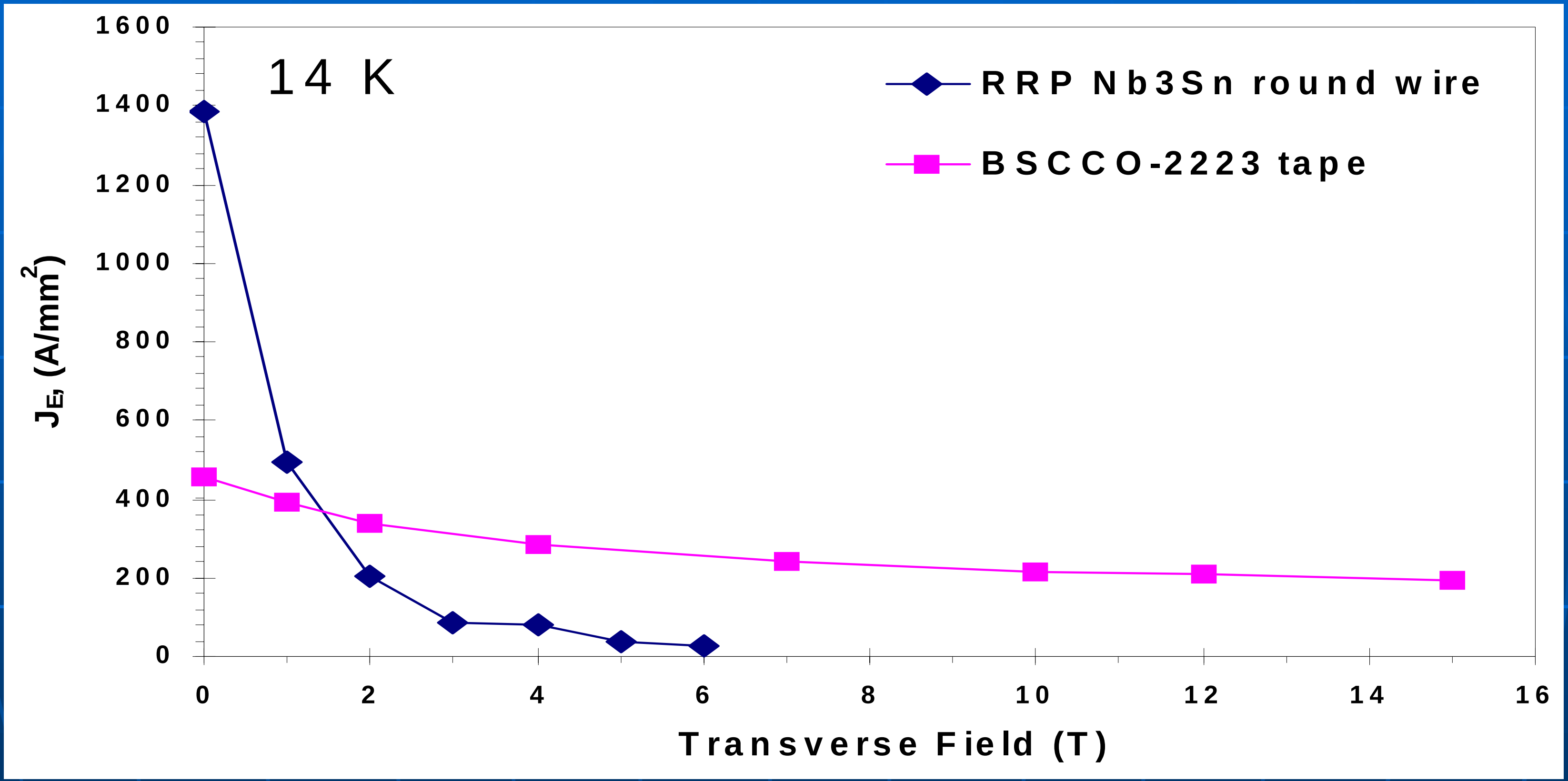
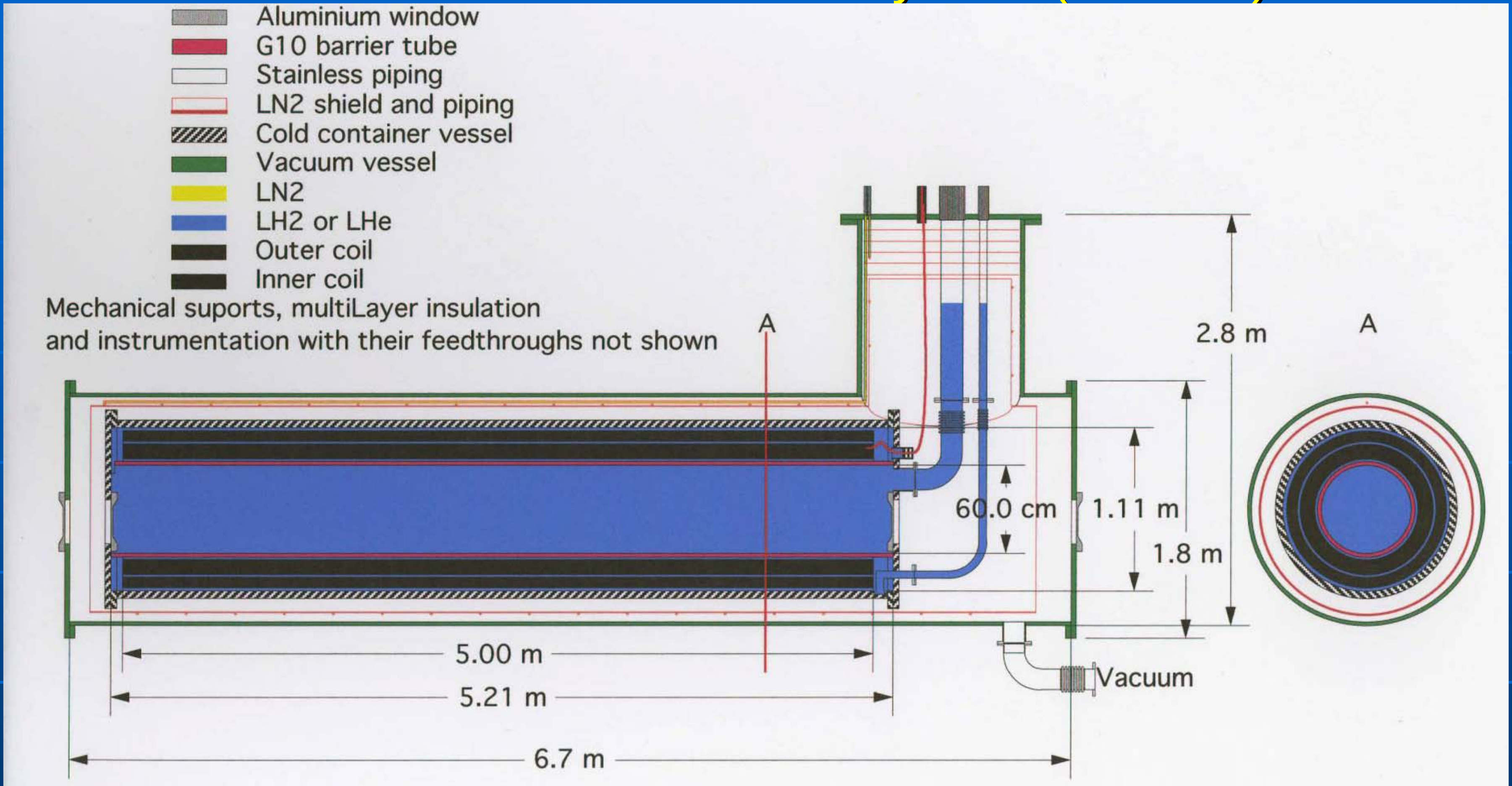


Fig. 9. Comparison of the engineering critical current density, J_E, at 14 K as a function of magnetic field between BSCCO-2223 tape and RRP Nb_3Sn round wire.

Licia Del Frate et al., Novel Muon Cooling Channels Using Hydrogen Refrigeration and HT Superconductor, PAC05

MANX/Precooler H2 or He Cryostat (Kuchnir)



Five meter long MANX cryostat schematic.

The use of Liquid He at 4 K is possible, with Nb3Sn or NBTi magnets.

Thin Al windows designed for MICE will be used (see Cummings).

50 Tesla HTS Magnets for Beam Cooling

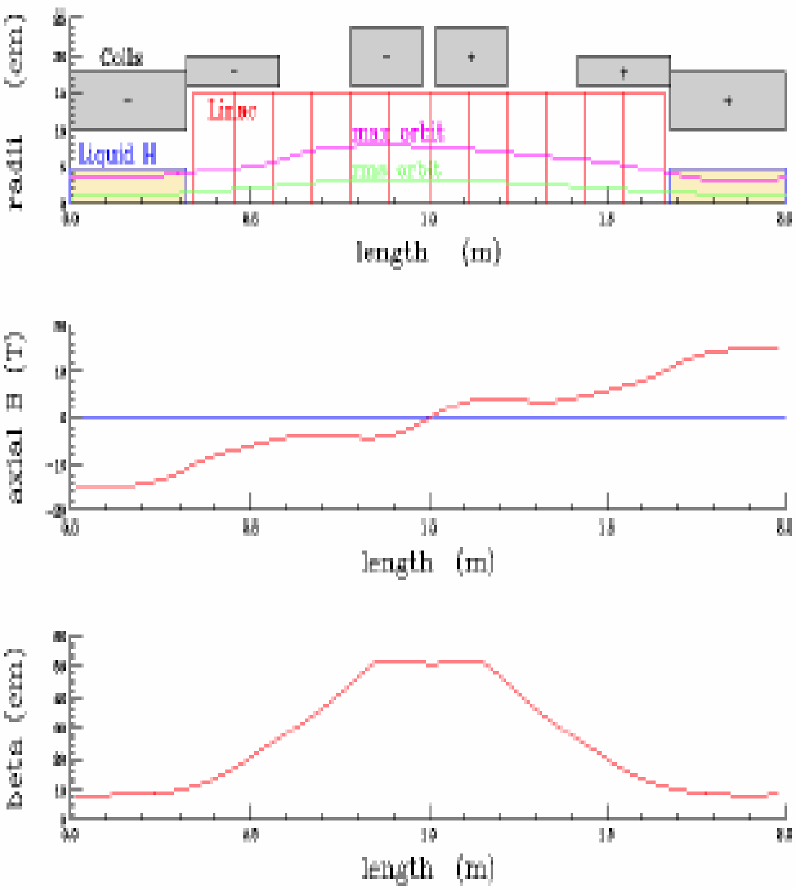
See Kahn, Palmer, Kuchnir

- 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:

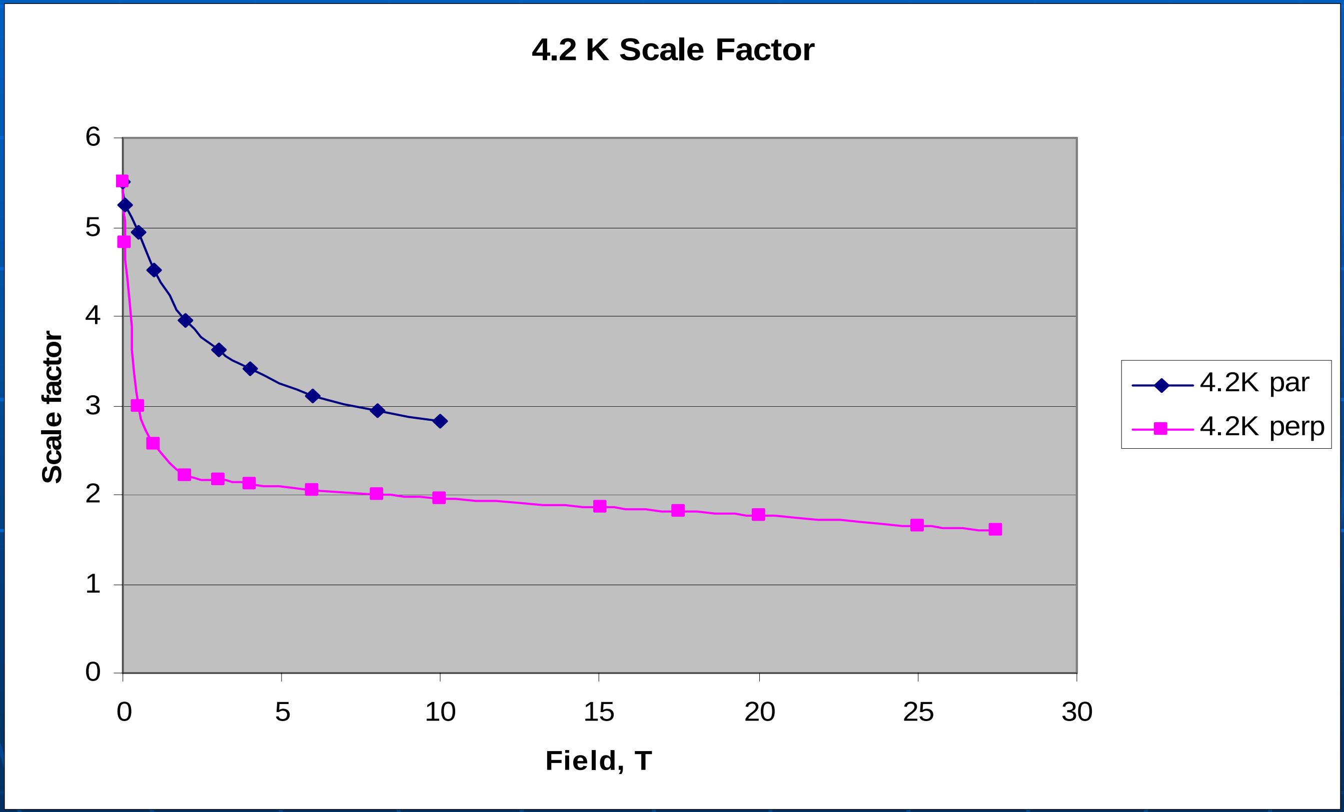
$$\min\ \epsilon_{xN} = \frac{\beta_{\perp} E_s^2}{2\beta m c^2 L_R \left|\frac{dE}{dz}\right|}$$

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

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



Current Carrying Capacity for HTS Tape in a Magnetic Field
Scale Factor is relative to 77ºK with self field

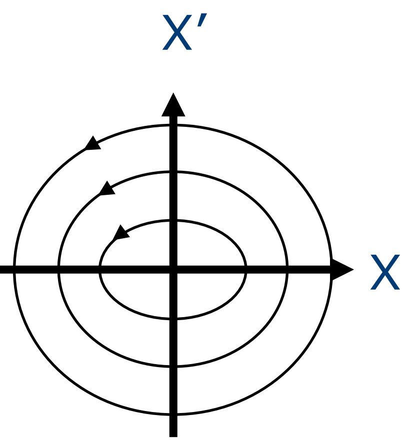


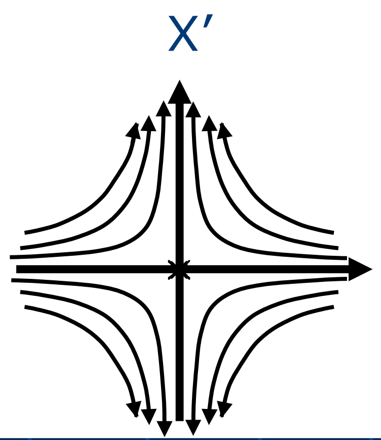
Parametric-resonance Ionization Cooling
see Derbenev, Johnson, Beard

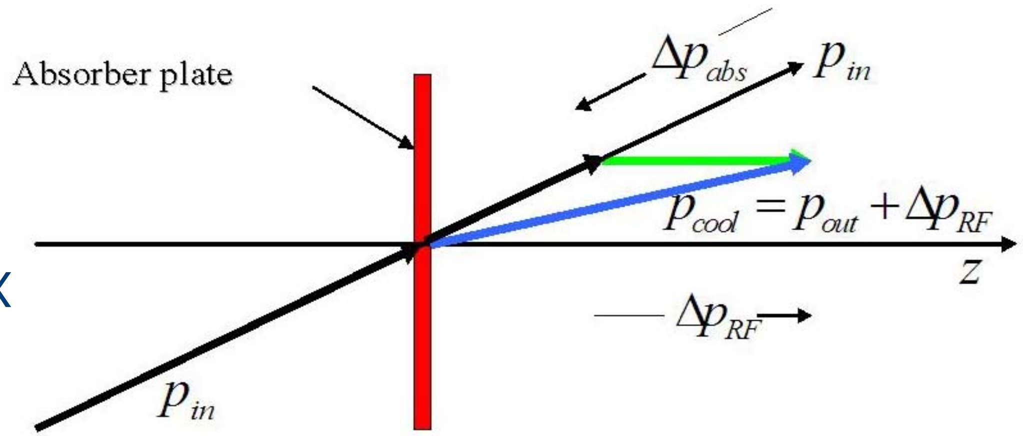
Excite ½ integer parametric resonance (in Linac or ring)

- 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′

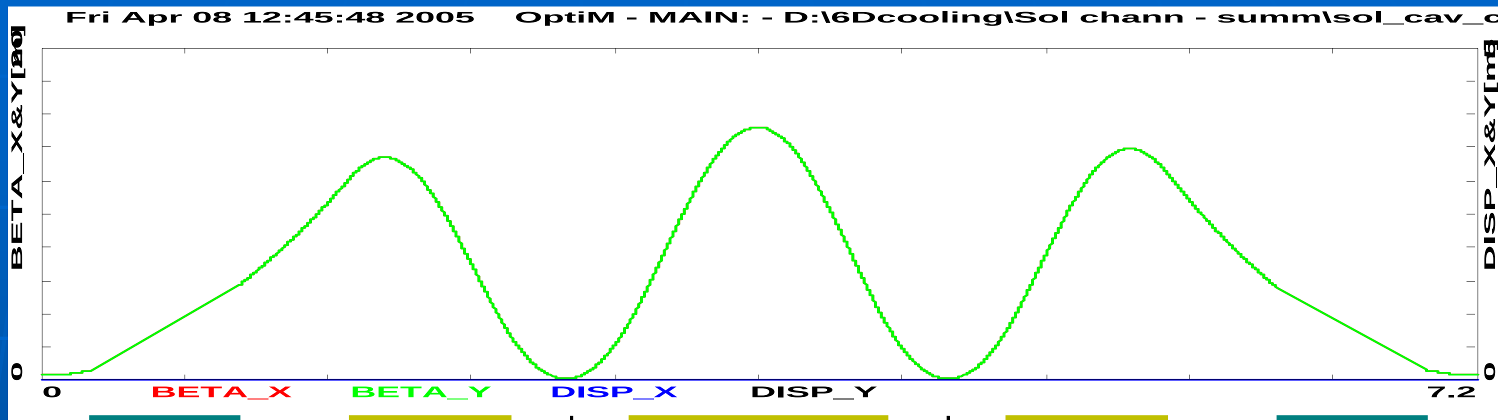
Detuning issues being addressed (chromatic and spherical aberrations, space-charge tune spread). Simulations underway. New progress by Derbenev.



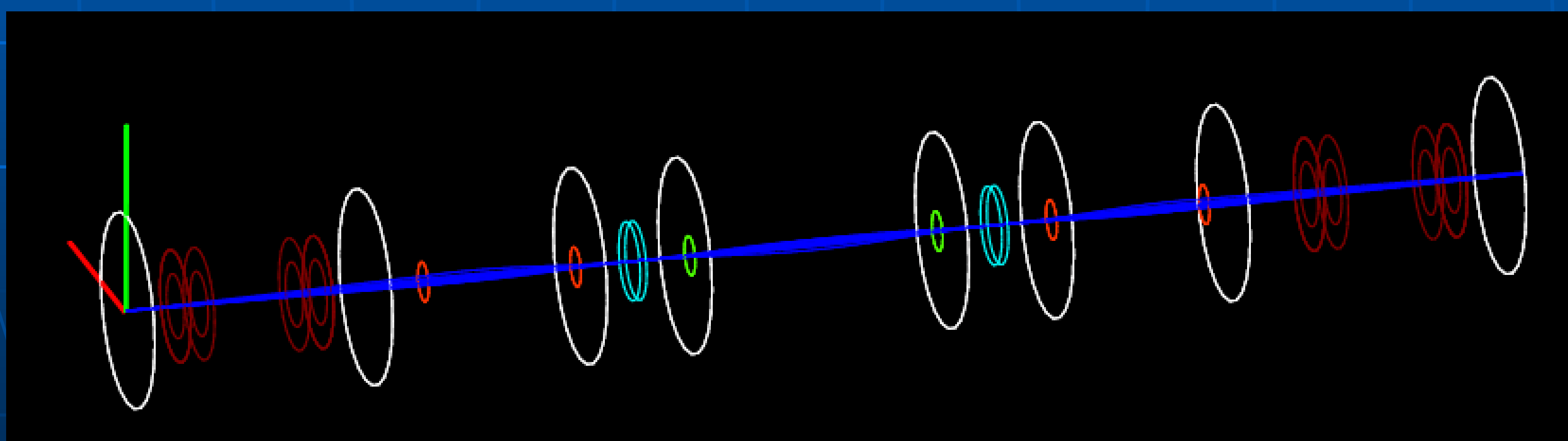




Example of triplet solenoid cell on ½ integer resonance with RF cavities to generate synchrotron motion for chromatic aberration compensation.



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



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

Evolution of transverse and longitudinal phase space through 8 triplet solenoid cells, without (left) and with (right) RF cavities. Alex Bogacz

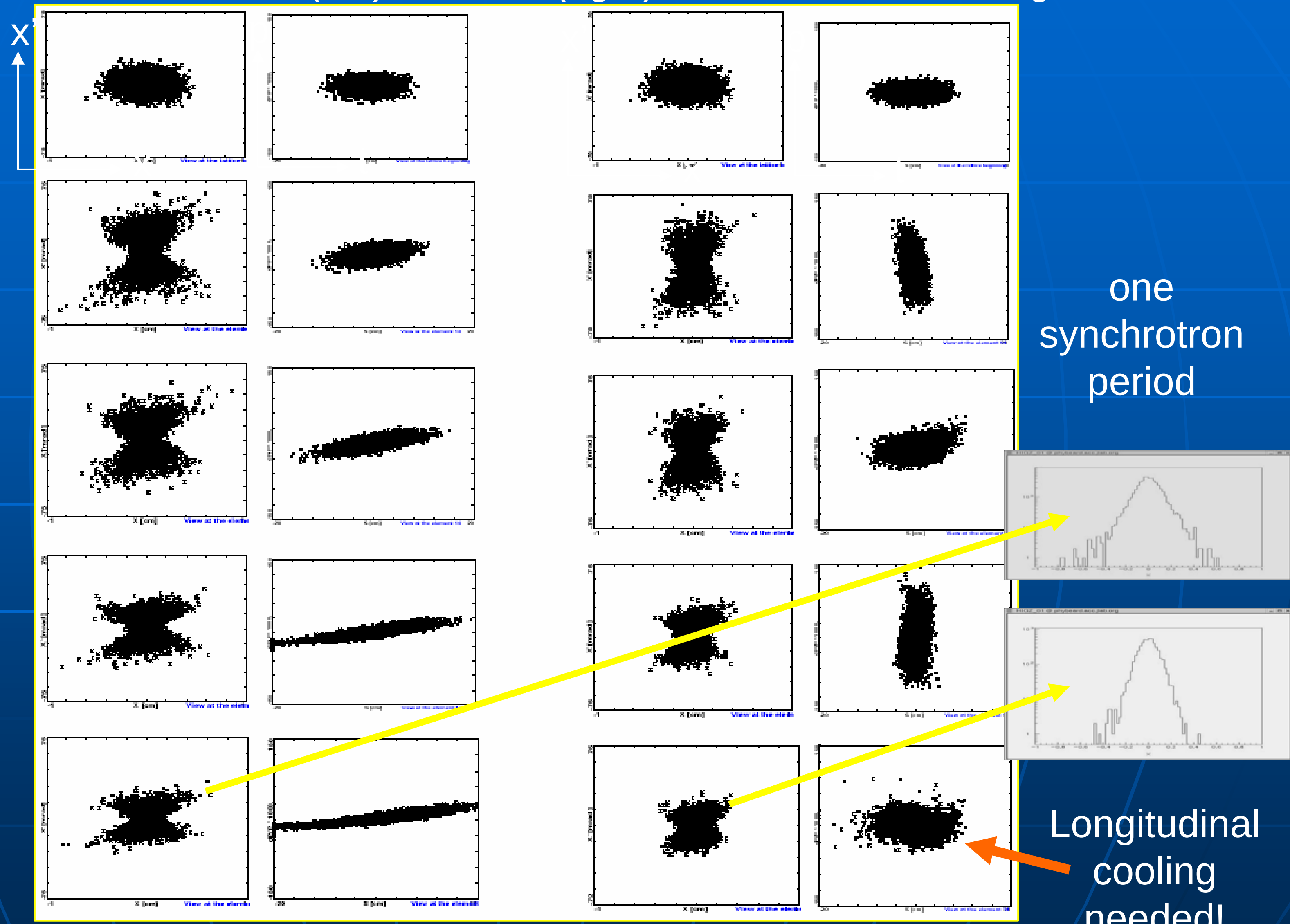
start

After 2 cells

After 4 cells

After 6 cells

After 8 cells

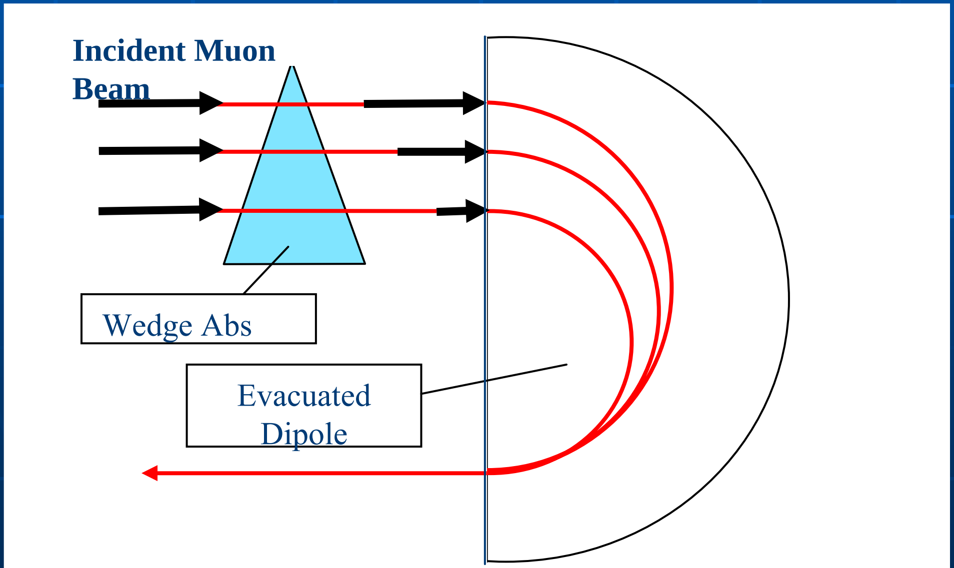


one synchrotron period

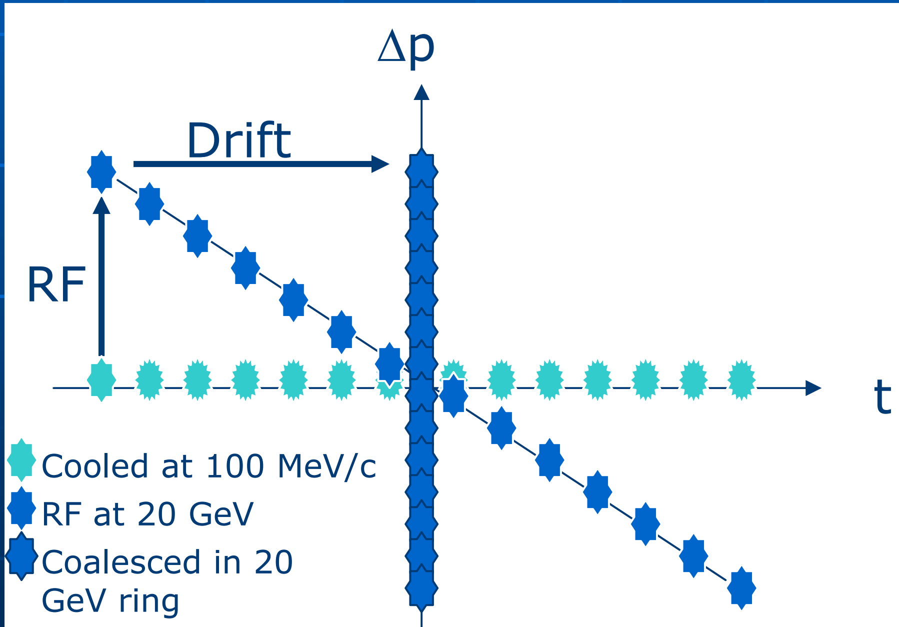
Longitudinal cooling needed!

Reverse Emittance Exchange, Coalescing
see Derbenev, Ankenbrandt

- 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.

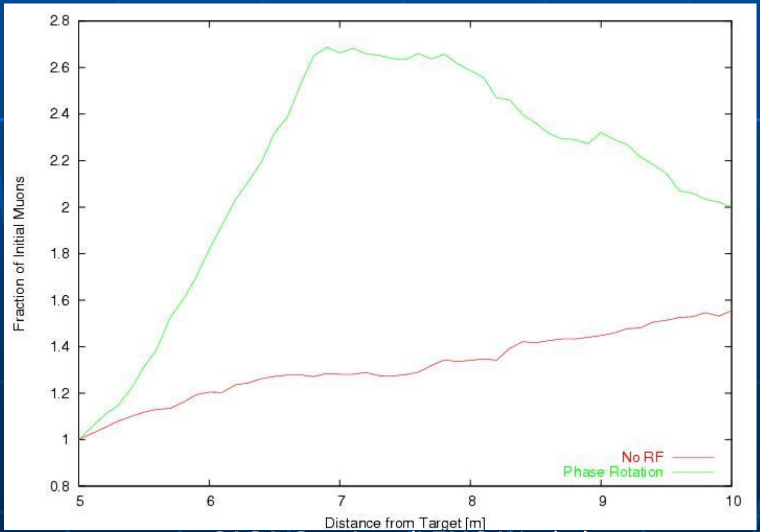


1.3 GHz Bunch Coalescing at 20 GeV

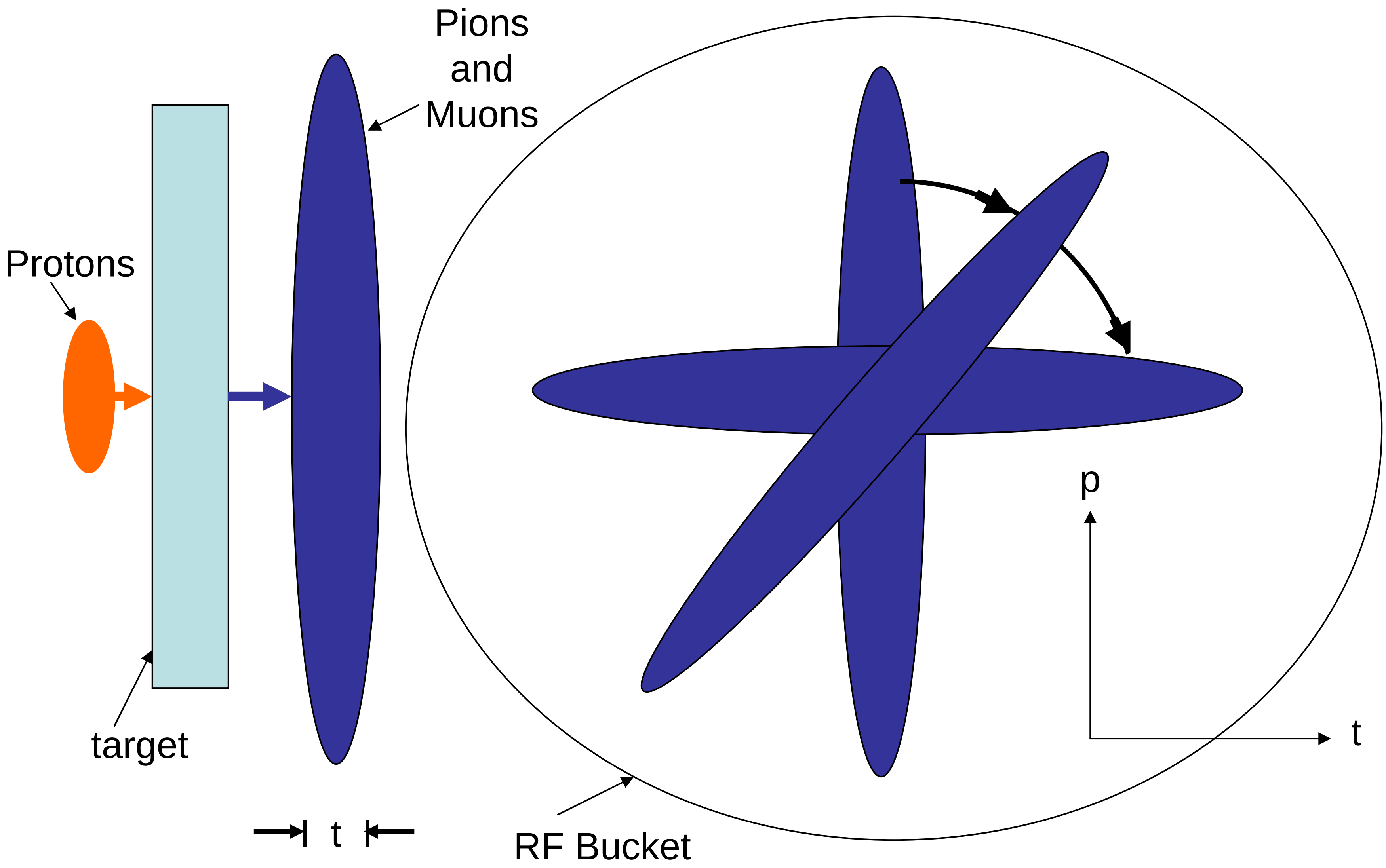
Capture, Bunching, and Precooling using HP GH2 RF
see Neuffer, Paul, Hanlet

- 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

- **We need data from the MTA with the LBNL solenoid and the promise of the MTA beamline for a strong Phase II proposal**



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


Pions
and
Muons
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RF Bucket
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Simulations of RF phase rotation

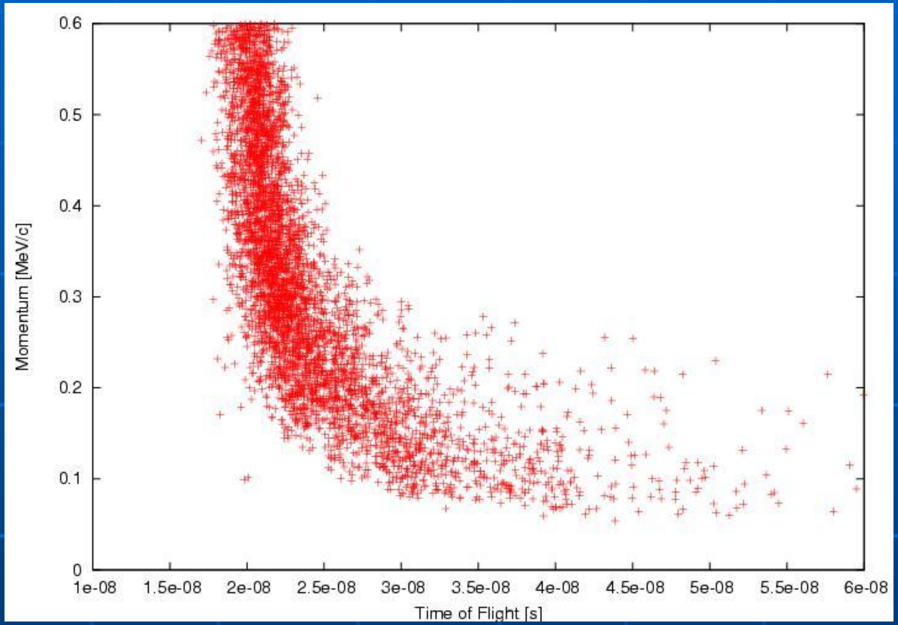


Figure 1. Momentum versus time of flight of muons 5 meters from the production target. Before phase-energy rotation.

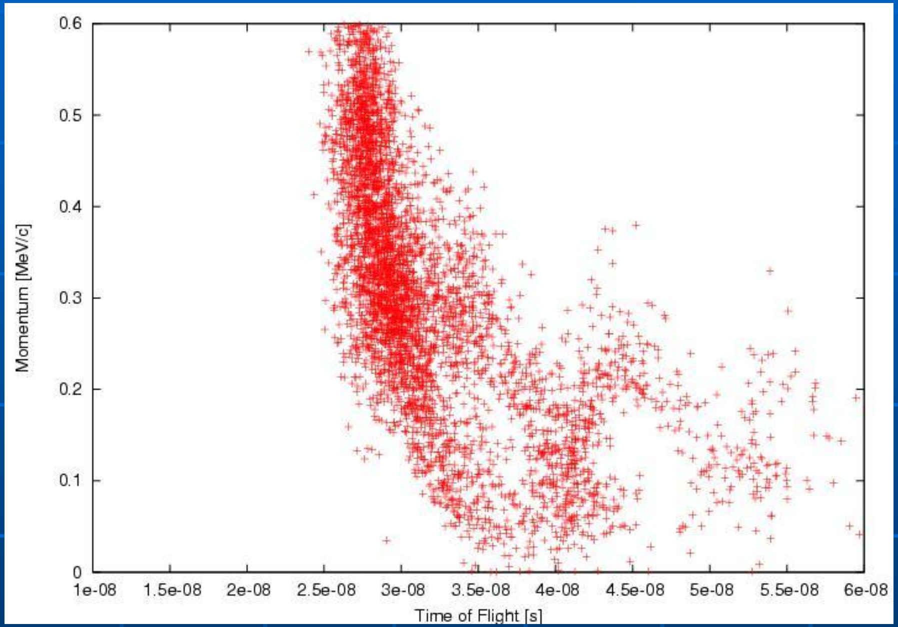


Figure 2. Momentum versus time of flight of muons 7 meters from the production target, after passing through 2 meters of high-gradient phase-energy rotation RF cavities

Simulations of phase rotation to improve muon capture rate

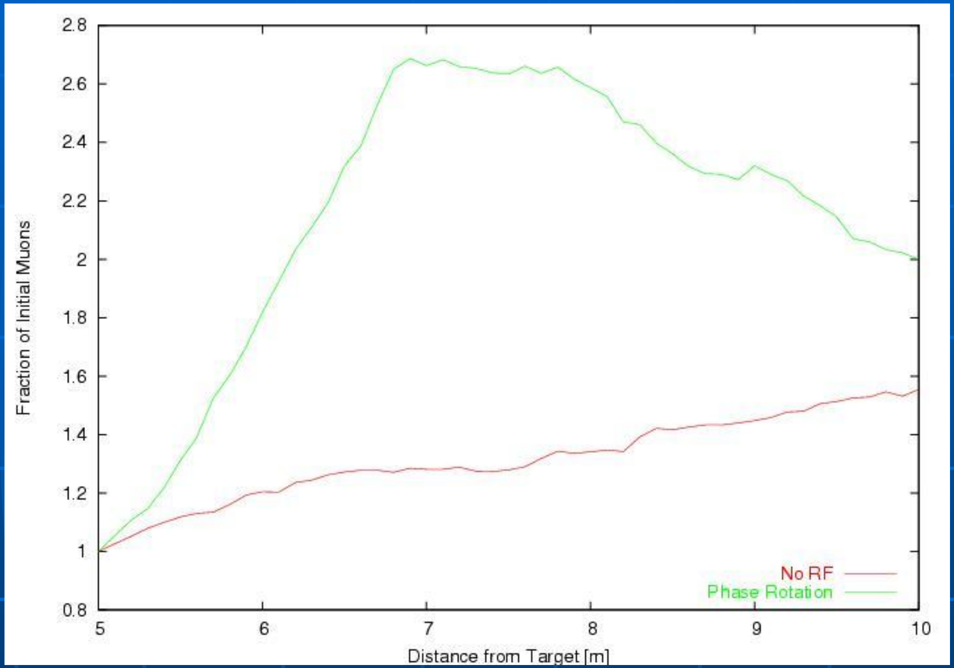
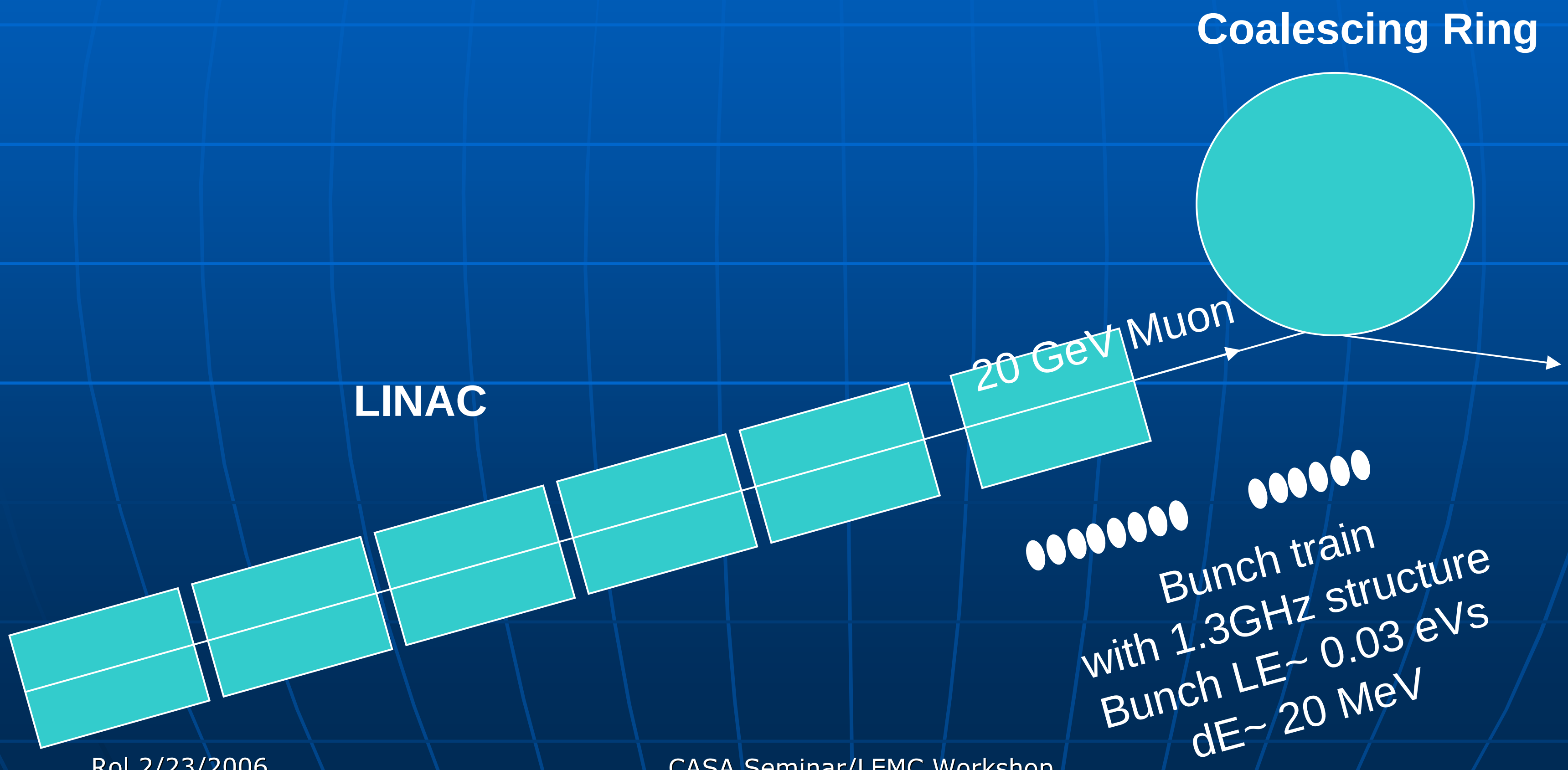


Figure 3. Fraction of muons within the 200 to 300 MeV/c momentum range as a function of distance from the target for the case of the phase rotation RF on or off.

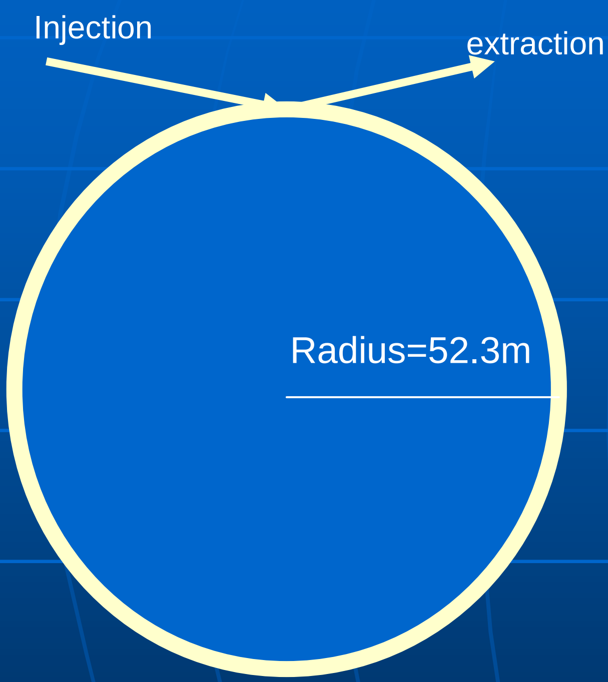
Schematic of the LINAC+Coalescing Ring

Chandra Bhat



Muon Coalescing Ring.

Based on the information given to Bhat by Chuck Ankenbrandt following parameters are derived for the Coalescing Ring (also see Bogacz ring)



Injection beam : 1.3GHz bunch structure
# of bunches/train = 17

Ring Radius = 52.33m; Revolution period= 1.09μs
Energy of the muon = 20 GeV (gamma = 189.4)
gamma_t of the ring = 4

If we assume
Ring-Radius/rho (i.e., fill factor) = 2, then B-Field = 2.54T
(This field seems to be reasonable)

h for the coalescing cavity = 42, 84
Number of trains/injection = less than 37
(assuming ~100ns for injection/extraction)
RF voltage for the coalescing cavity = 1.9 MV (h=42)
= 0.38 MV (h=84)

fsy ~ 5.75E3Hz
Tsy/4 = 43.5us
Number of turns in the ring ~40

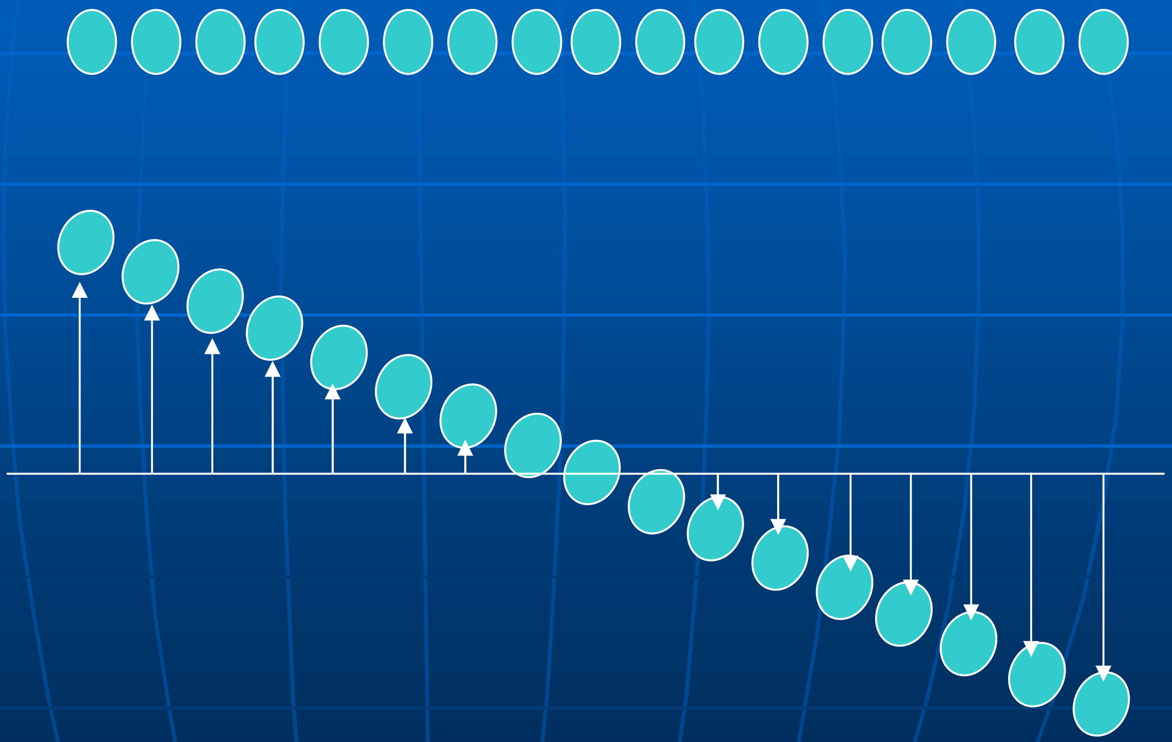
Constraints:
Muon mean-life = 2.2us (rest frame)
Muon half-life in lab = 288us for 20 GeV beam
Time (90% survival) = 43.8us

2nd Scenario

- A pre-linac to give a tilt in the Longitudinal Phase-space

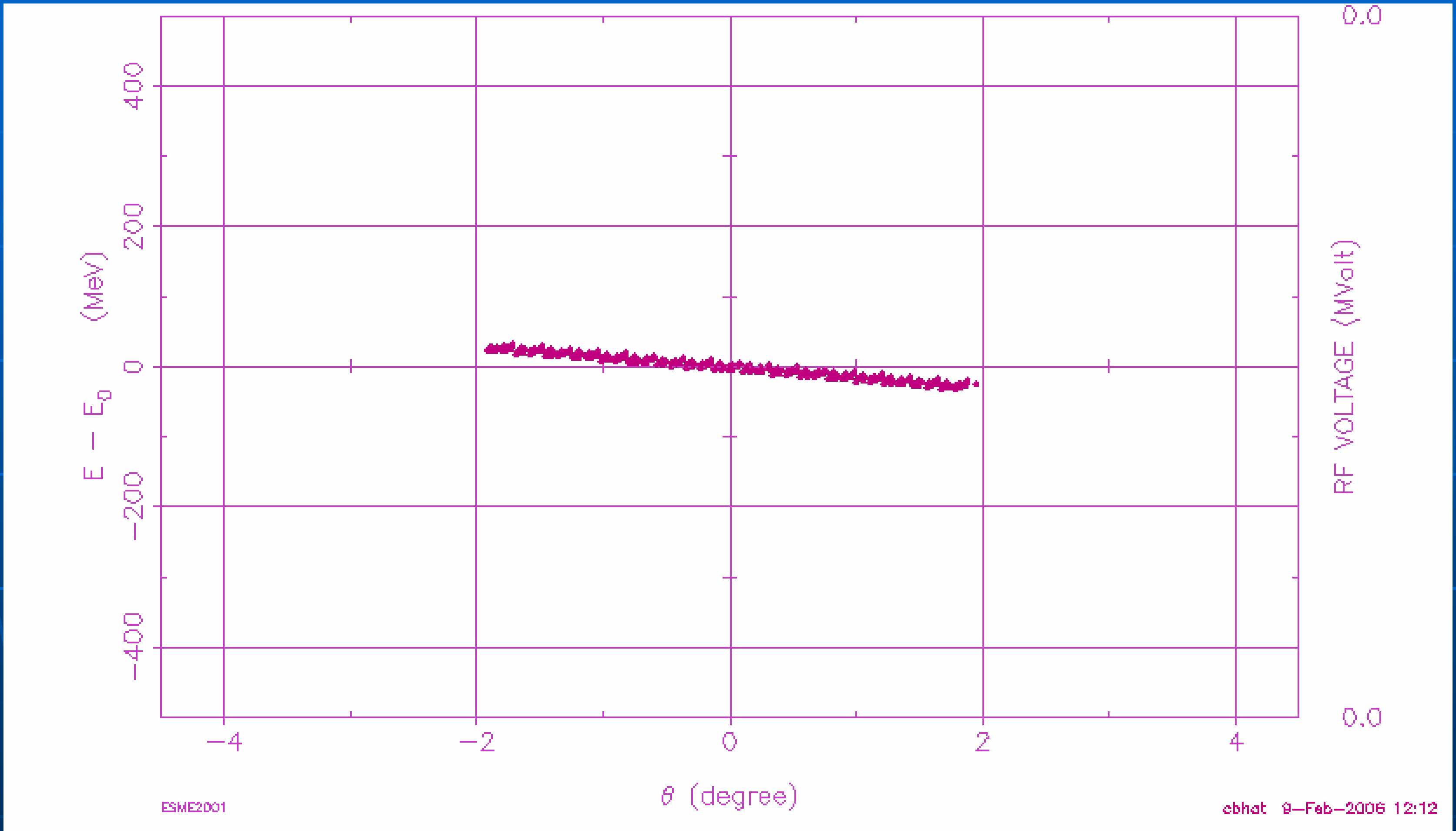
Bunch train before the special purpose pre-linac

Muon Bunches after pre-linac

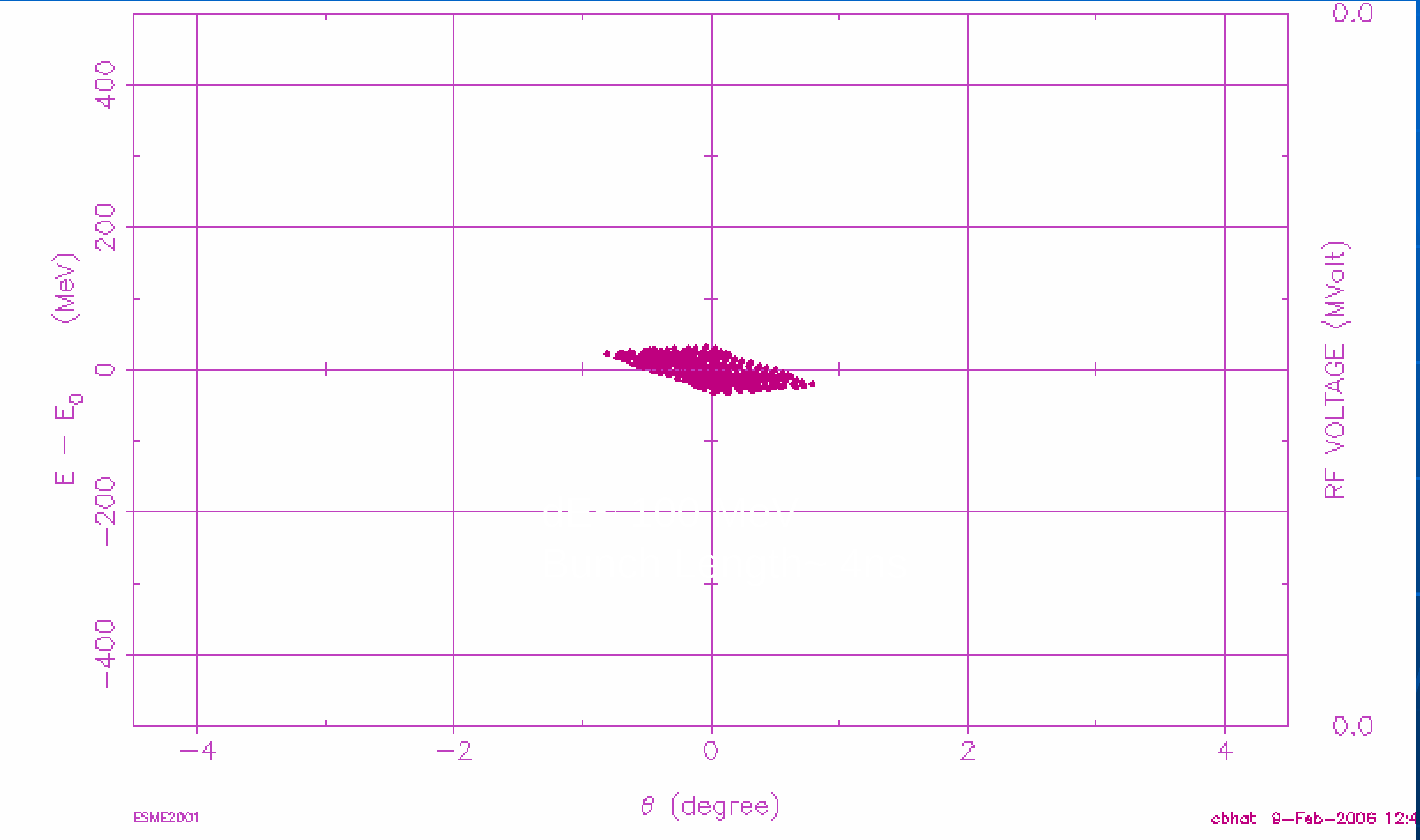


- And next inject the beam into the **Coalescing Ring**

Muon Bunch train in the Coalescing Ring
T=0 sec



Muon Bunch train in the Coalescing Ring
T=46 μsec



End of survey of some new ideas
Now discuss their use at Fermilab

- H_2-Pressurized RF Cavities
- Continuous Absorber for Emittance Exchange
- Helical Cooling Channel
- Z-dependent HCC
- MANX 6d Cooling Demo
- Parametric-resonance Ionization Cooling
- Reverse Emittance Exchange
- RF capture, phase rotation, cooling in HP RF Cavities
- Bunch coalescing

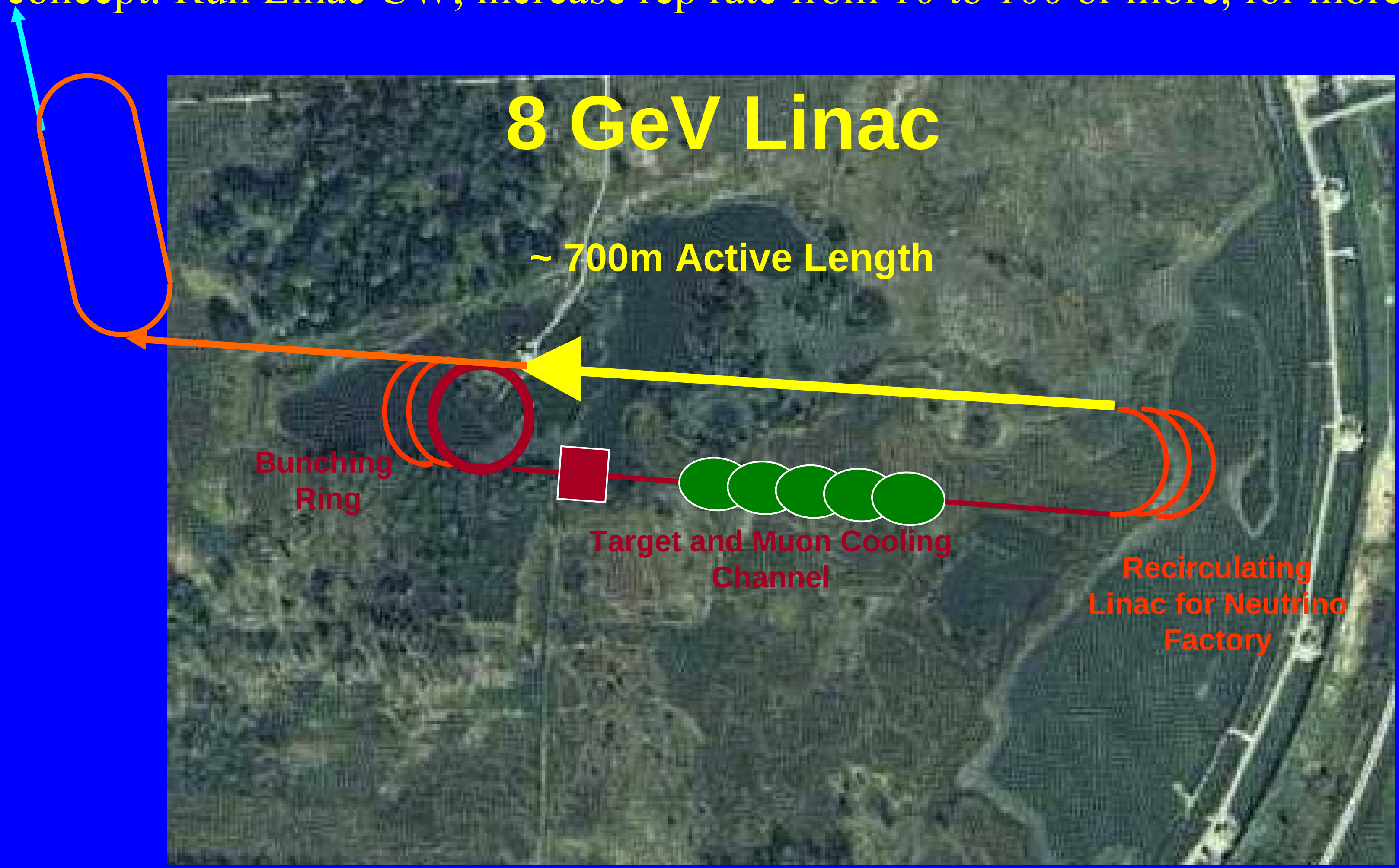
The Fermilab/ILC Neutrino Factory

see Popovic, Foster

- neutrino factory based on
  - extreme muon cooling
  - ILC RF
  - Muon recirculation through p-driver Linac
  - High rep rate capability (See Foster)

Neutrinos from an 8 GeV SC Linac

Muon cooling to reduce costs of a neutrino factory based on a storage ring.
Cooling must be 6D to fit in 1.3 GHz SC RF, where the last 6.8 GeV of 8 GeV are β=1.
New concept: Run Linac CW, increase rep rate from 10 to 100 or more, for more νs.



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 during this 700 m cooling sequence
- Then recirculate to 23 GeV, inject into racetrack NF storage ring

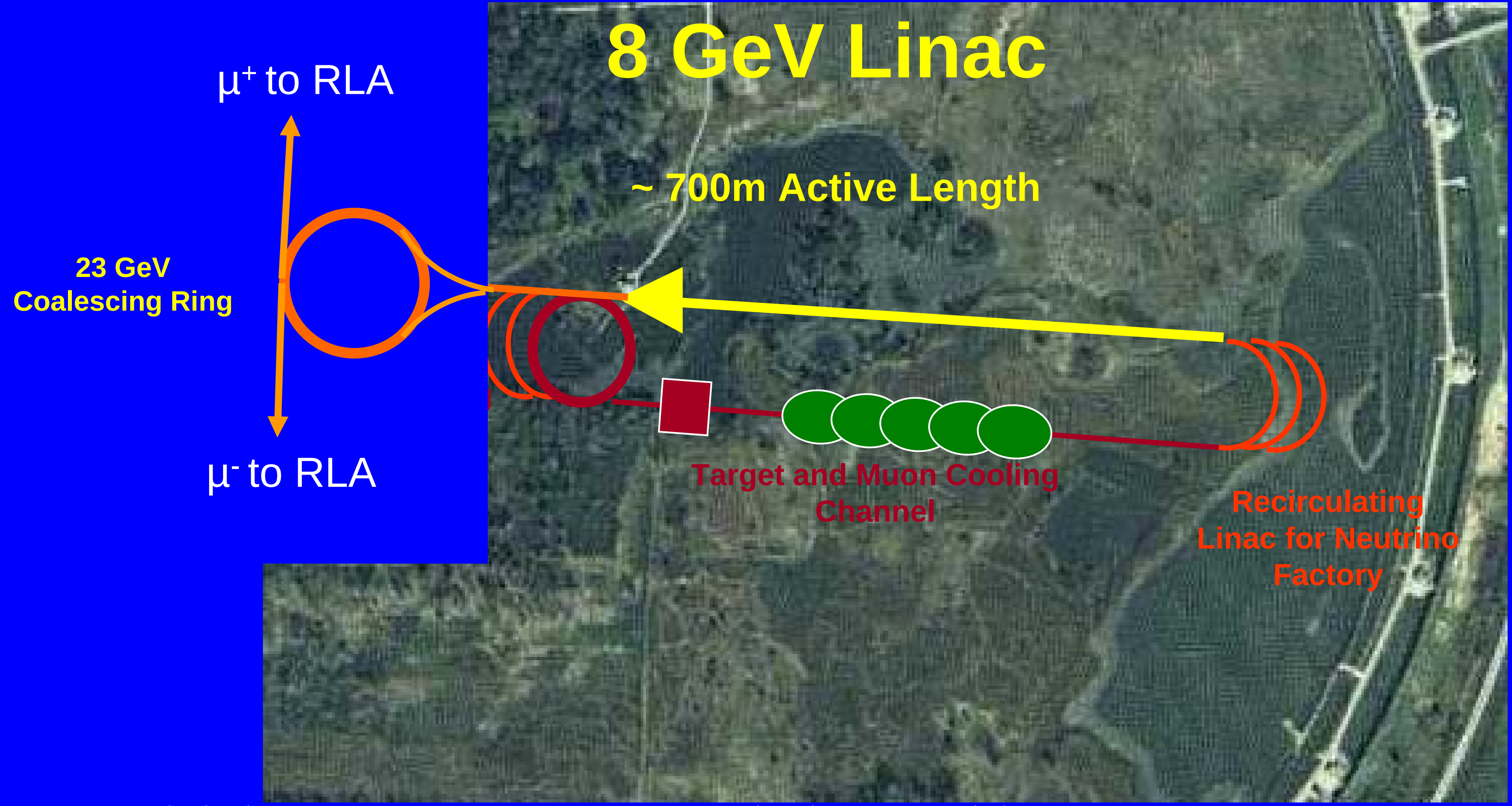
Detailed theory in place, simulations underway.

The Fermilab/ILC Muon Collider

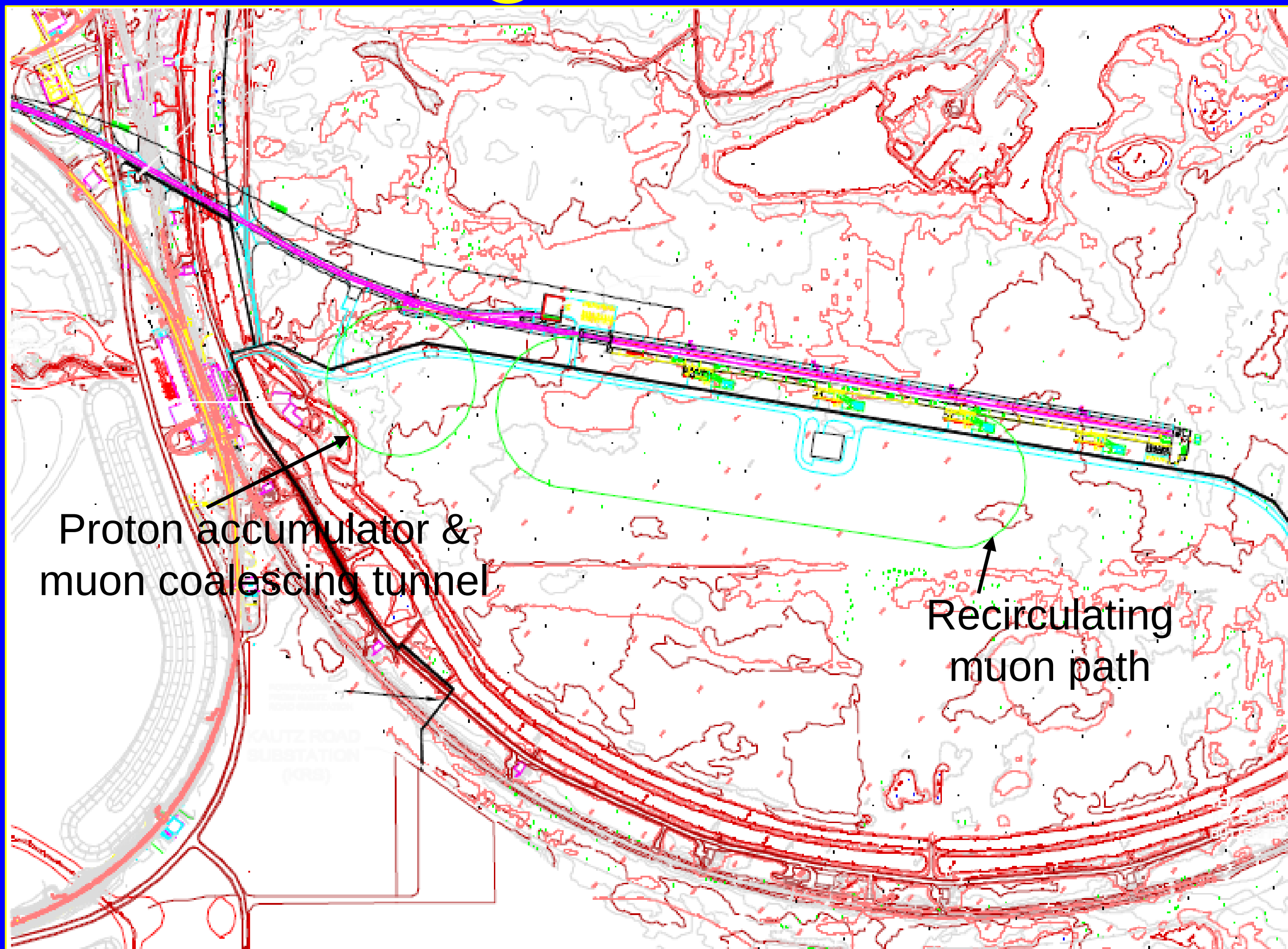
- After three passes through the PDL the muons reach 2.5+3x6.8=22.9 GeV
- RF cavities operating off-frequency at the end of the Linac create a momentum-offset for the bunches in each batch
- Positive and negative muons are injected into a 23 GeV storage ring
- Waiting for ~50 turns, the bunches in a batch are aligned and recaptured in a 1.3 GHz bucket

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 $10 \times 1.6\ 10^{10}$ muons/bunch become 10 bunches of 1.6×10^{11}/bunch. Plus and minus muons are coalesced simultaneously. Then 10 bunches of each sign get injected into the RLA (Recirculating Linear Accelerator).



Recirculating muons in the PDL



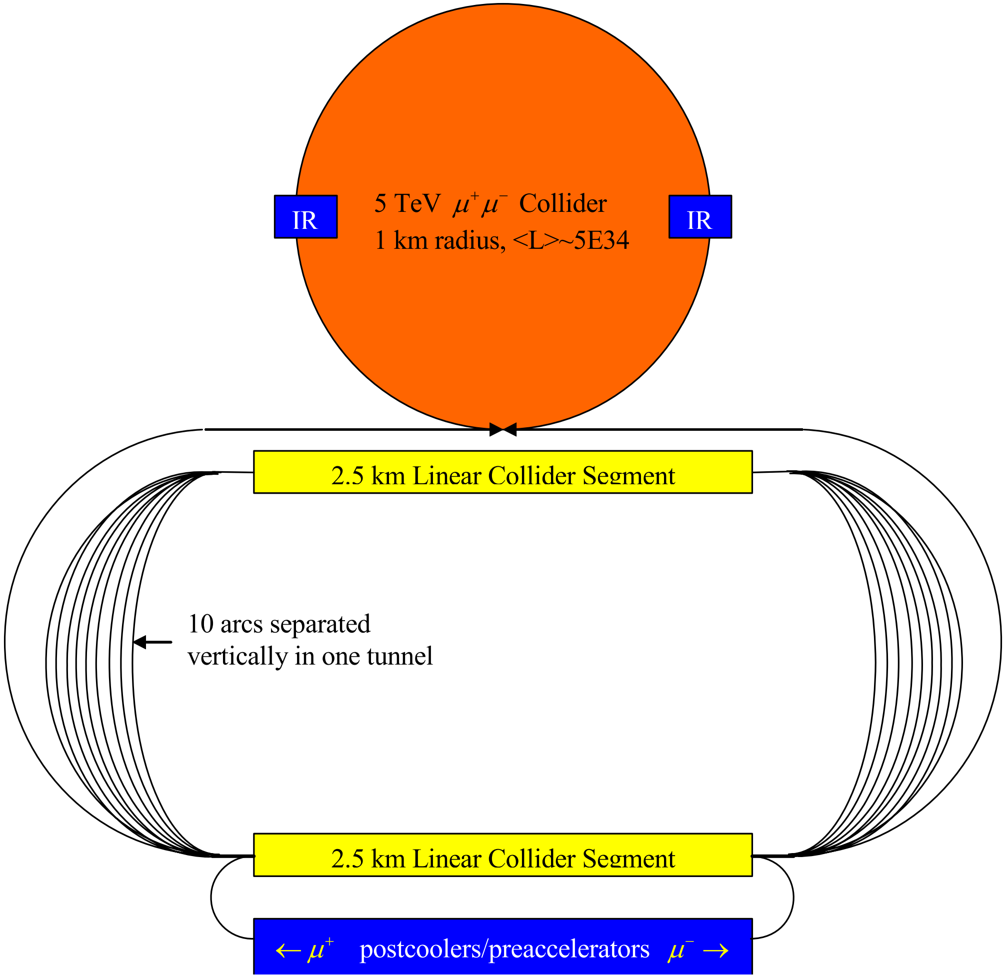
5 TeV ~ SSC energy reach

~5 X 2.5 km footprint

Affordable LC length (half of baseline 500 GeV ILC), includes ILC people, ideas

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 (parameters & calculations need updating)

- After:
  - Precooling
  - Basic HCC 6D
  - Parametric-resonance IC
  - Reverse Emittance Exchange

	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

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

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

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

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

$\sigma_z = 3 mm$ $\Delta\gamma / \gamma = 3 \times 10^{-4}$

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

20 Hz Operation:

$$\langle L \rangle \approx 4.3 \times 10^{34} / cm^2 - s$$

$$Power = (26 \times 10^9)(6.6 \times 10^{13})(1.6 \times 10^{-19}) = 0.3 MW$$

$0.3 \mu^\pm / p$

My interpretation of Theory talks

- If the LHC shows no interesting physics to be explored in the reach of the ILC
  - An energy frontier muon collider is needed
  - ILC R&D is only useful for a low emittance muon collider
- If the LHC indicates interesting physics in the reach of the ILC
  - A muon collider to do precision measurements is needed since the beams in an ILC are not so precise
  - An energy frontier muon collider is needed for the higher mass states that must be above the reach of the ILC
- The energy frontier is always the way to go and muons may have a special advantage

First Annual Low Emittance Muon Collider Workshop

- By next year we should have a complete cooling scheme with end-to-end simulations to support the analytical theory that has been developed

- And a really good 6D cooling demonstration experiment designed and proposed to Fermilab