Ionization Cooling and Muon Colliders*

Rolland Johnson,
Muons, Inc.

New inventions are rapidly improving the prospects for high luminosity muon colliders for a Higgs factory 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 machines to be built, where each one is a precursor to the next, with its own unique experimental and accelerator physics programs. The ultimate machine is an energy-frontier muon collider.

In about 4 years, the LHC and Tevatron will tell us the desired energy of the next lepton collider. At that time we must understand the needed technology and be ready to design, cost, and build the appropriate muon collider.

***Supported by US DOE HEP SBIR-STTR Grants**

Muon-Related EPAC08 Papers

Supported by DOE Small Business Innovation / Technology Transfer Research Grants:

MOPP071 Intense Stopping Muon Beams, Cummings…
MOPP073 Plasma Lenses for Muon and Neutrino Beams, Kahn…
MOPP080 Studies of Breakdown in Pressurized RF Cavities, Bastaninejad
MOPP090 Incorporating RF into a Muon Helical Cooling Channel, Kahn…
MOPP105 Compact, Tunable RF Cavities, Popovic…
TUPD036 G4Beamline Simulations for Detector Development, Roberts…
WEPD013 4-Coil SC HS Model for Muon Beam Cooling, Kashikhin…
WEPD014 Magnets for the MANX 6-D Demonstration Experiment, Kashikhin…
WEPD015 Designs of Magnet Systems for Muon Helical Cooling Channels, Kashikhin…
WEPD022 High Field Superconductor for Muon Cooling, Schwartz…
WEPD023 Multi-purpose Fiber Optic Sensors for HTS Magnets, Schwartz…
WEPP028 Flexible Momentum Compaction Return Arcs for RLAs, Trbojevic…
WEPP048 Recirculating Linear Muon Accelerators with Ramped Quadrupoles, Bogacz…
WEPP117 Muon Bunching and Phase-energy Rotation for a NF and MC, Neuffer…
WEPP118 A Complete Scheme of Ionization Cooling for a Muon Collider, Palmer…
WEPP120 G4Beamline Particle Tracking in Matter-dominated Beam Lines, Roberts…
WEPP123 Isochronous Pion Decay Channel for Enhanced Muon Capture, Yoshikawa…
WEPP147 Aberration-free Transport Line for Extreme Ionization Cooling, Afanasev…
WEPP149 Advances in Parametric-resonance Ionization Cooling, Derbenev…
WEPP153 Status of the MANX Muon Cooling Experiment, Yonehara…

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Neutrino Factory Papers

MERIT

MOPC087 The MERIT High Intensity LHgTarget Experiment at CERN PS, Efthymiopoulos…
WEPP169 The MERIT High-power Target Experiment at the CERN PS, Kirk…
WEPP170 A 15-T Pulsed Solenoid for a High-power Target Experiment, Kirk…

MICE

MOPD028 RFPower Sources for the Muon Ionisation Cooling Experiment, Orrett…
MOPP098 A 201-MHz Normal Conducting RF Cavity for the MICE Experiment, Li…
MOPP099 MICE RF System, Moss…
MOPP106 Electron Emission in RF Cavities Embedded in Magnetic Field, Sandstrom …
TUPC012 Mice Diagnostic Systems, Bross…
TUPC088 Analysis of MICE: a Single Particle Accelerator Experiment, Rogers…
WEPP108 The MICE Diffuser System, Apollonio…
WEPP109 Status of the International Muon Ionization Cooling Experiment, Blondel …
WEPP110 Design and Operational Experience of the MICE Target, Smith…
WEPP122 Commissioning Status of the MICE Muon Beamline, Tilley…

New inventions, new possibilities

- Muon beams can be cooled to a few mm-mr (normalized transverse emittance)
  - allows HF RF (implies <u>Muon machines and ILC research synergy</u>)
- Synchrotron radiation power loss $(m_e/m_\mu)^{-4}$
  - Muon recirculation in HF RF cavities => high energy, lower cost
  - Each cavity used >10 times for each muon species
  - Potential >20x efficiency wrt ILC approach offset by
    - Muon cooling
    - Recirculating arcs
    - Muon decay implications for detectors, magnets, and radiation
- A <u>low-emittance high-luminosity collider</u>
  - high luminosity with fewer muons
  - First LEMC goal: E_{com}=5 TeV, $\langle L \rangle = 10^{35}$
  - ~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)

New Inventions/Developments

- **New Ionization Cooling Techniques**
  - Emittance exchange with continuous absorber for longitudinal cooling
  - Helical Cooling Channel (HCC) Derbenev
  - Momentum-dependent Helical Cooling Channel
    - 6D Precooling device, muon stopping beam (mu2e) Yonehara
    - 6D cooling demonstration experiment (MANX) Cummings
  - Ionization cooling using a parametric resonance (PIC) Derbenev
- **Methods to manipulate phase space partitions**
  - Reverse emittance exchange using absorbers (REMEX) Derbenev
  - Bunch coalescing (NF and MC can share injector) (mucoal) Bhat
- **Technology for better cooling**
  - Pressurized RF cavities (HPRF) Johnson
  - Helical Solenoid (HS) Kashikhin
  - Higher Fields (HTS) Zlobin, Schwartz
  - Simulation programs (G4BL) Roberts

- **BNL inventions/extensions to earlier work** Palmer
  - Big Helix (Gugenheim)
  - Cooling channel ideas (super Fernow)
  - Low energy emittance exchange in high B (HTS)

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

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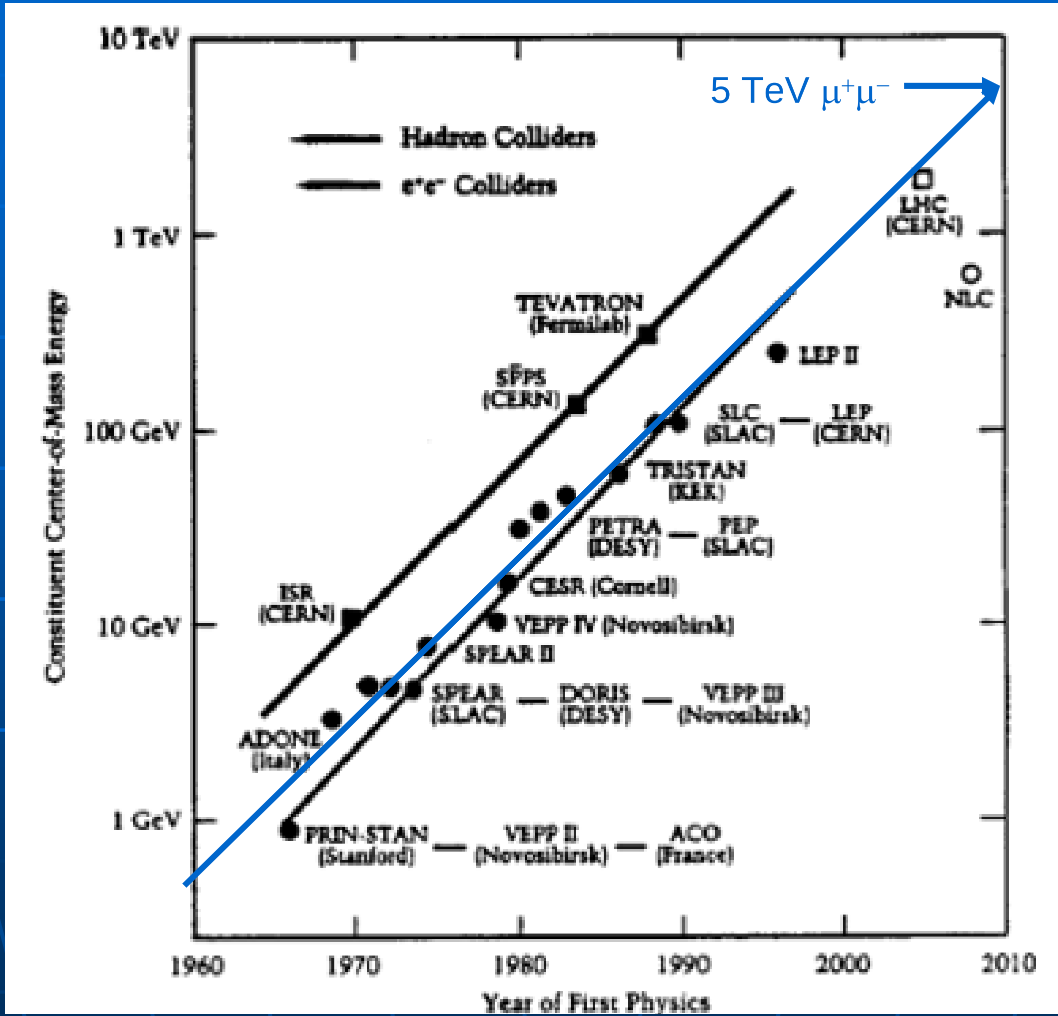
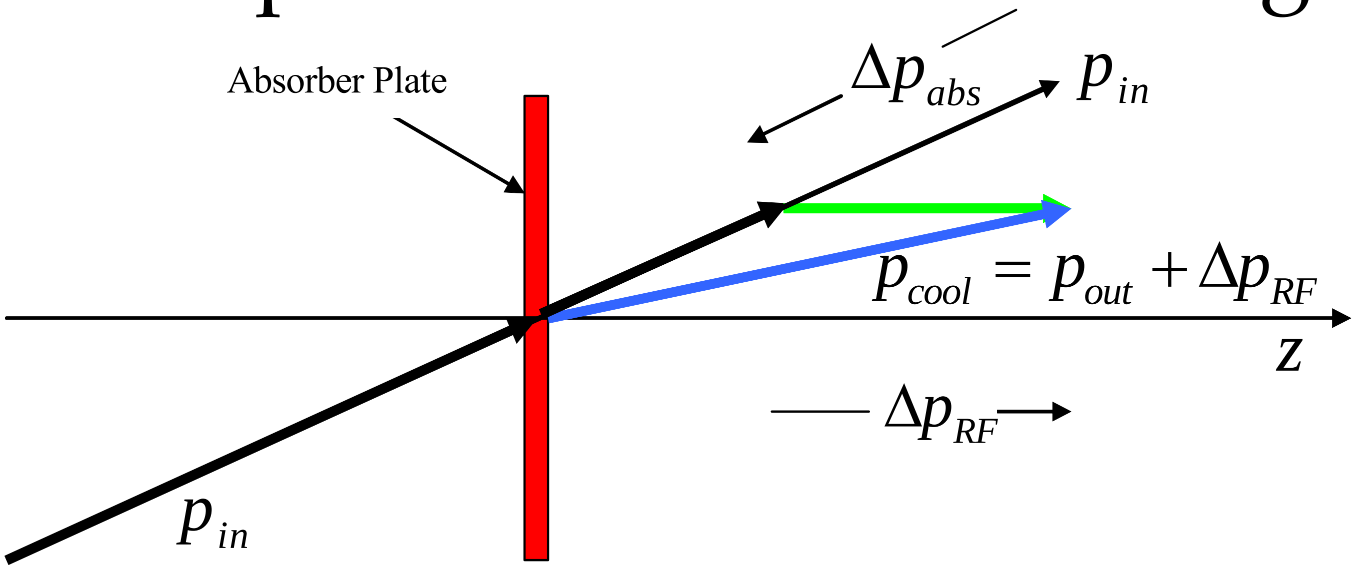


Modified Livingston Plot taken from: W. K. H. Panofsky and M. Breidenbach, Rev. Mod. Phys. 71, s121-s132 (1999)

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 the muon energy in GeV, dE_μ/ds and X_0 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.
- Ionization cooling is only transverse (4D).
- To add momentum cooling (6D), you need to exchange longitudinal and transverse emittances.

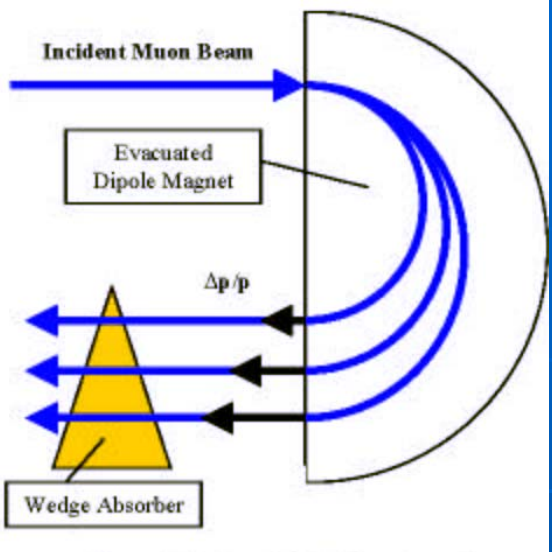


Figure 1. Use of a Wedge Absorber for Emittance Exchange

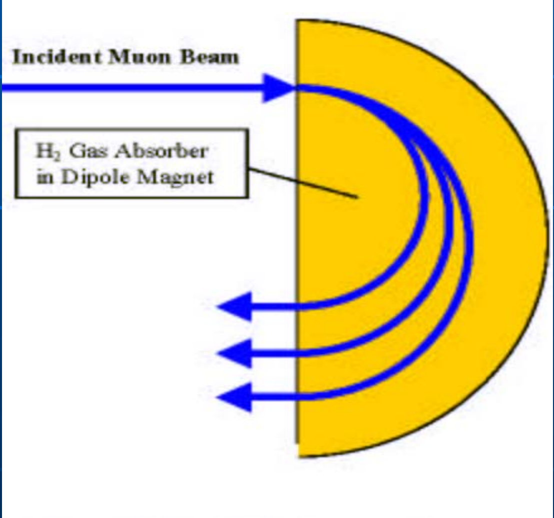
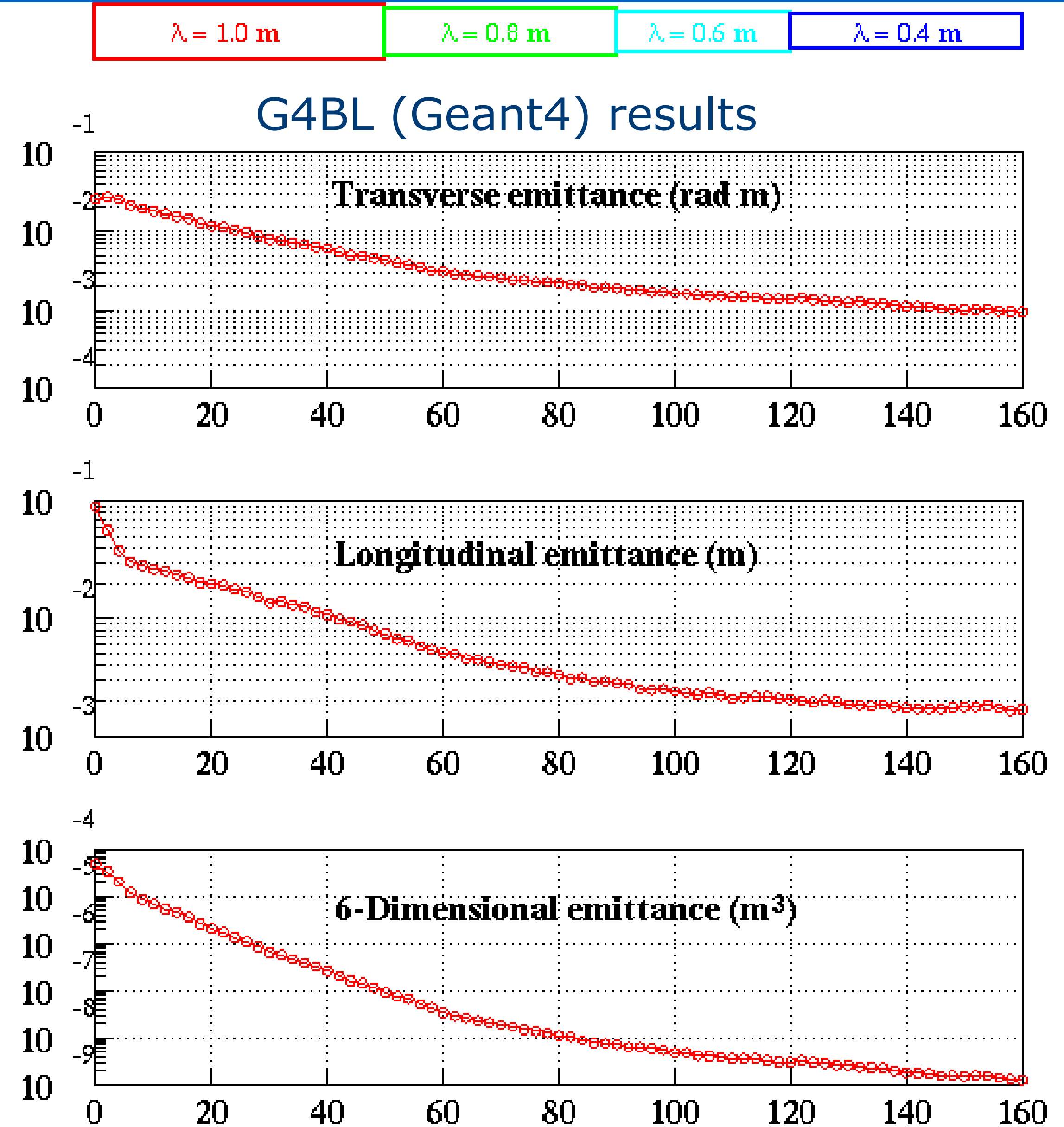


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

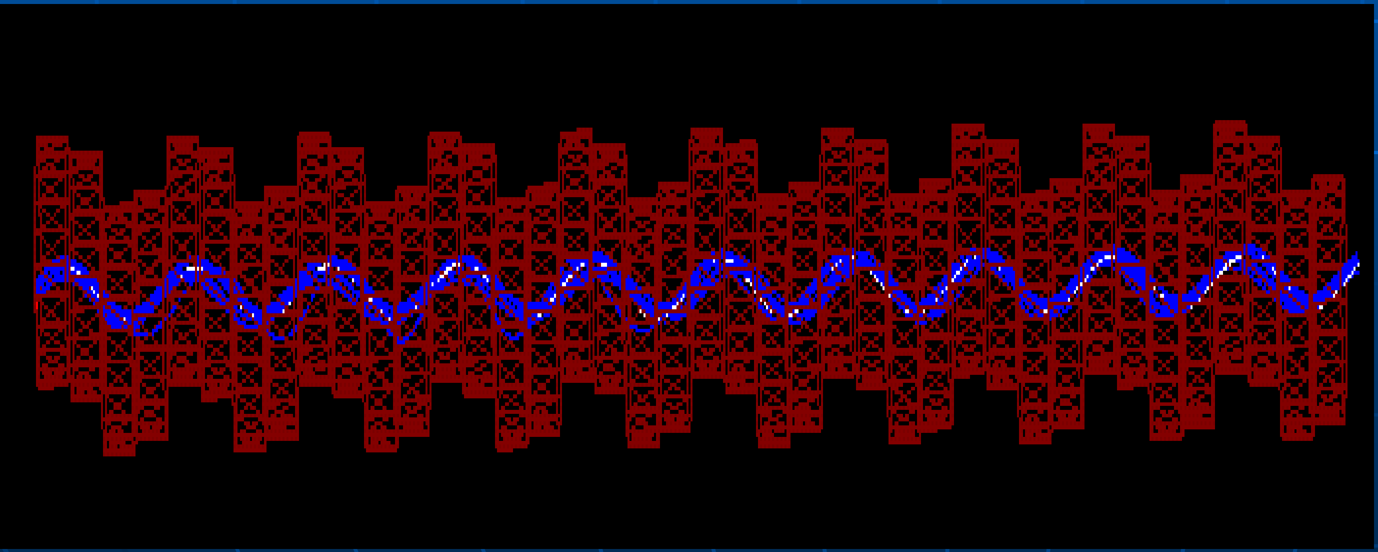


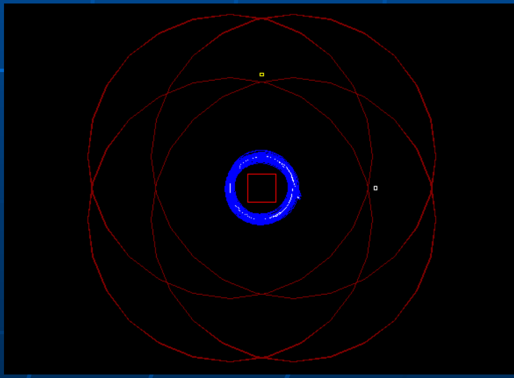
6D Cooling factor ~ 50,000

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

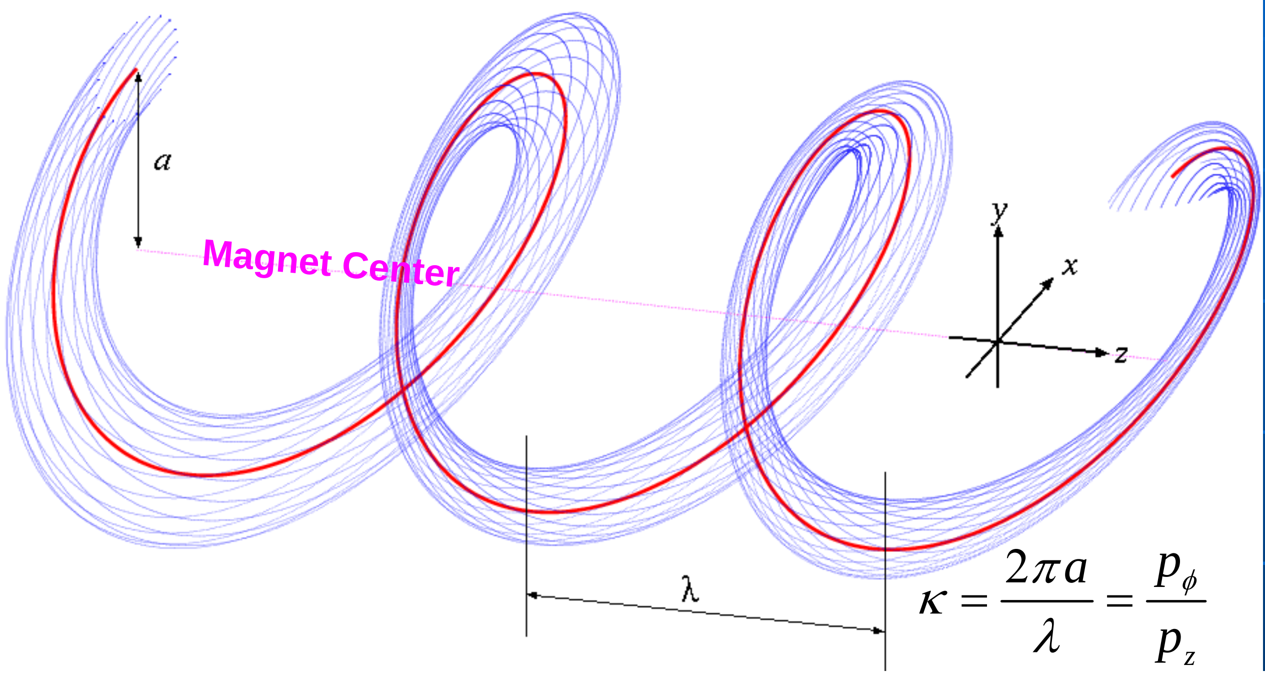




Particle Motion in a Helical Magnet

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

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

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

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

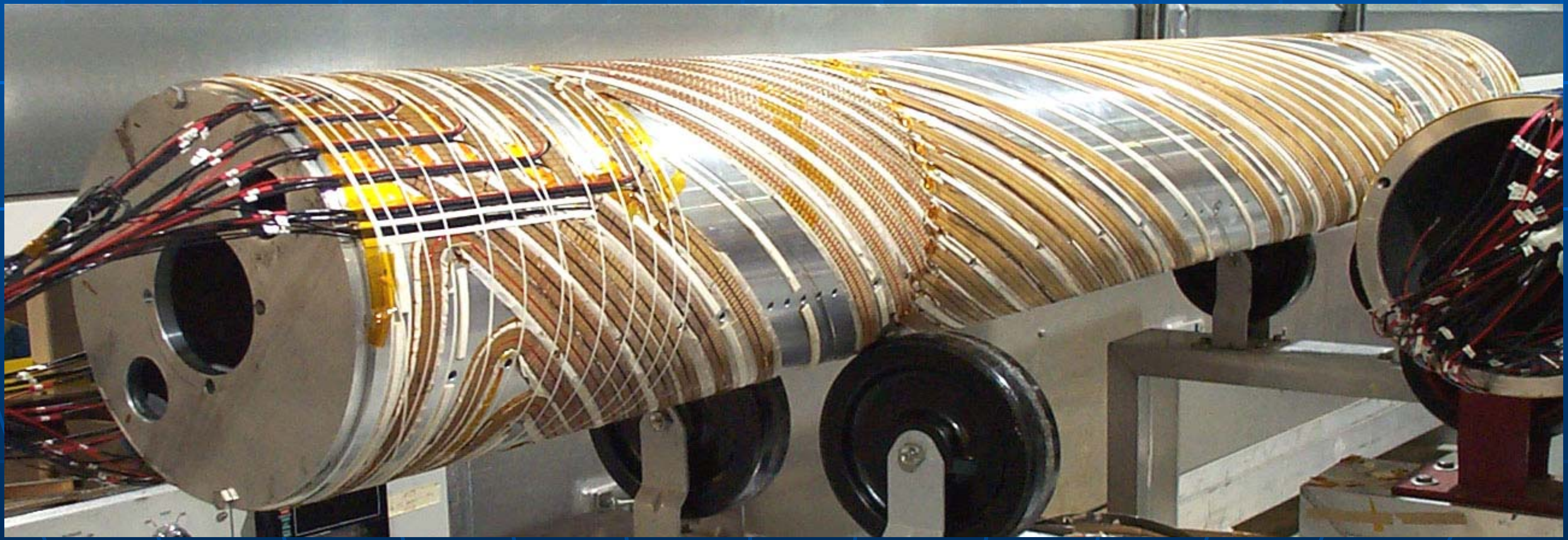
$$\hat{D} \equiv \frac{p}{a}\frac{da}{dp} = 2\frac{1+\kappa^2}{\kappa^2} \qquad q = 0$$

~Momentum slip factor

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

WEPP117, WEPP120, WEPP123

BNL Helical Dipole Siberian Snake magnet for AGS spin control



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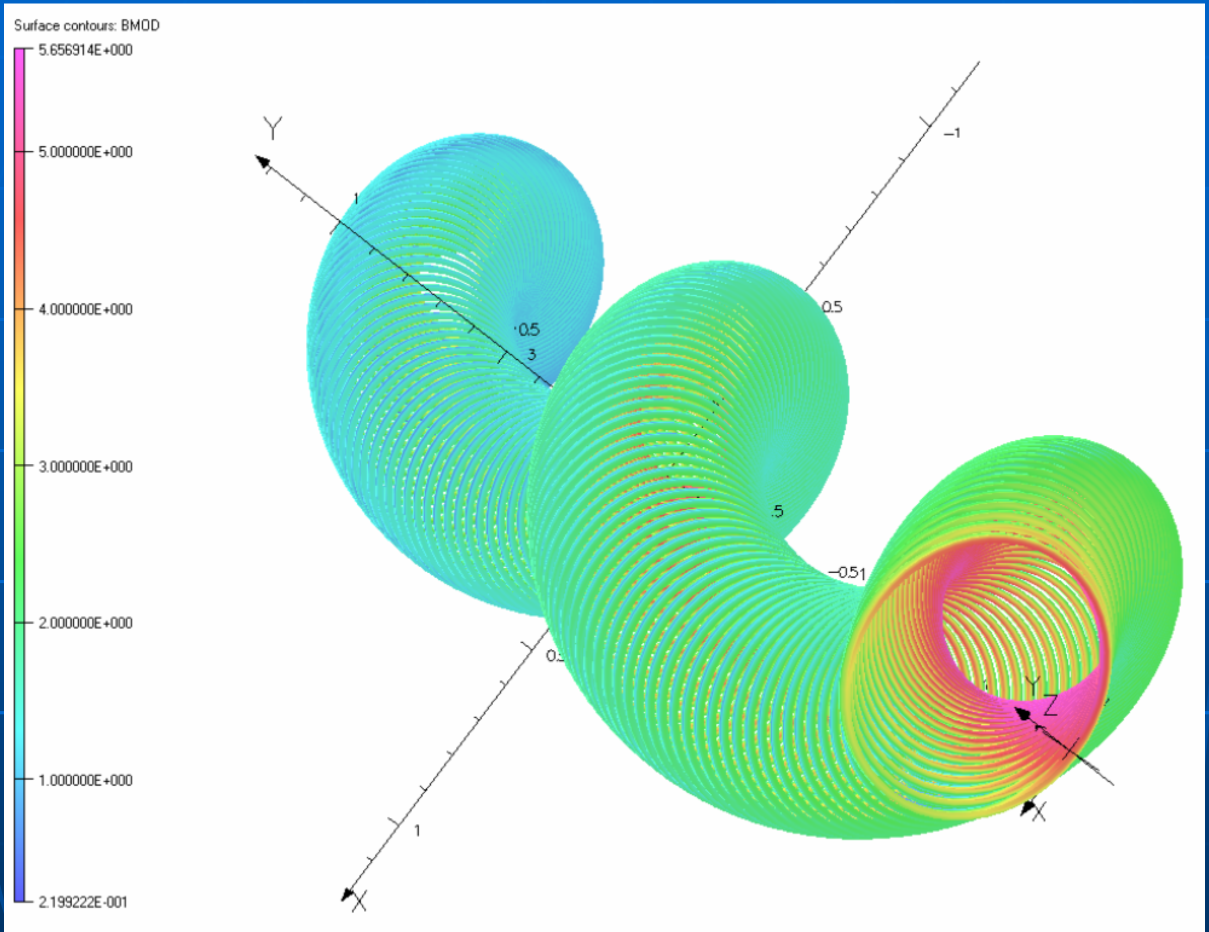
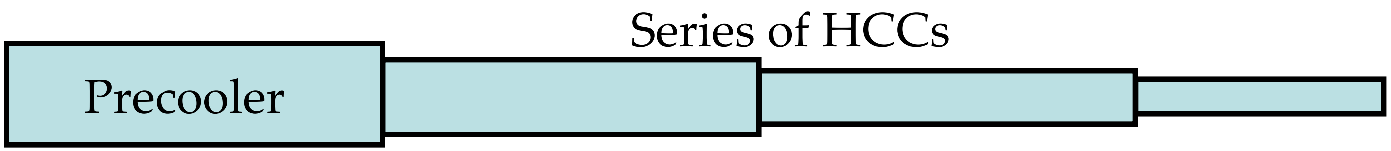
Helical Solenoid Magnet for HCCs



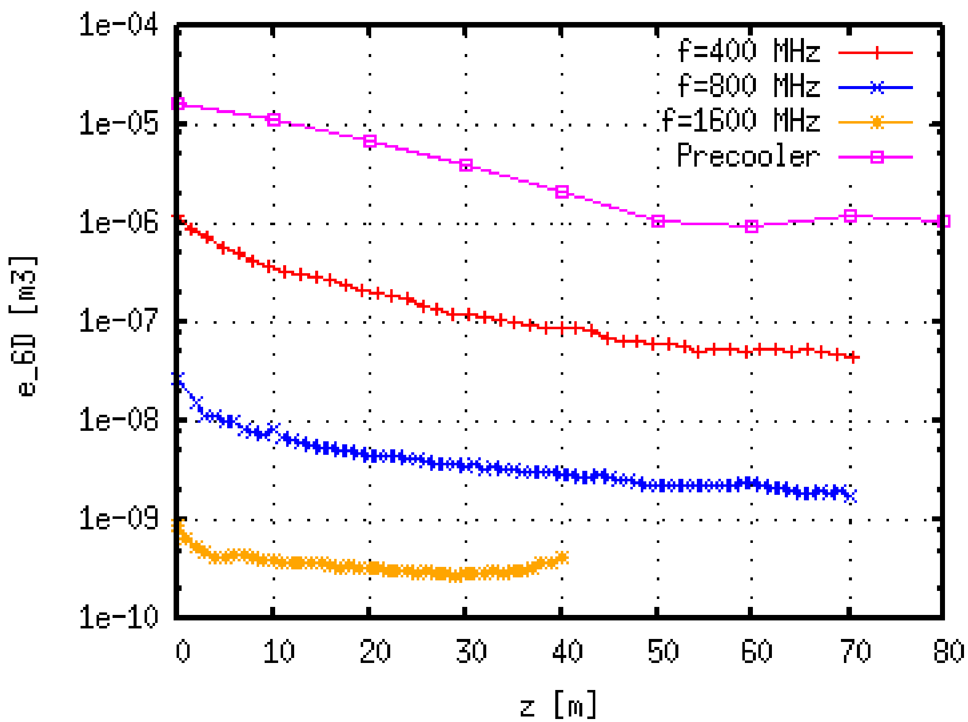
Simple concept simultaneously provides solenoidal, helical dipole, and helical quadrupole fields needed for HCC. Also provides momentum-dependent HCC.

See Kashikhin et al.

Precooler + HCCs

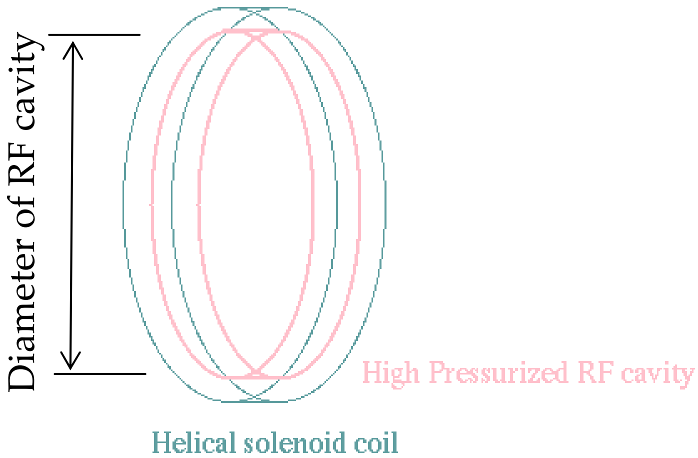


Solenoid + High Pressurized RF



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

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.

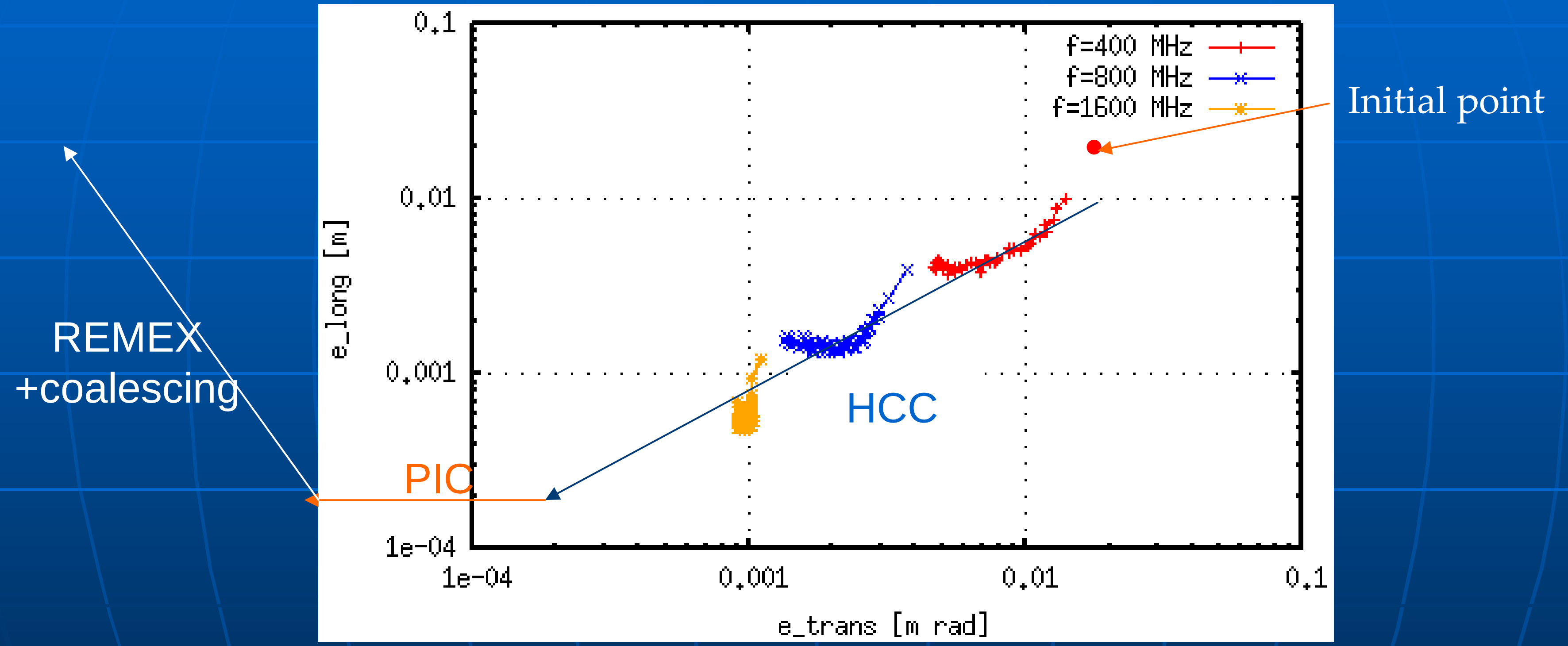
→Diameter of 400 MHz cavity = 50 cm
→Diameter of 800 MHz cavity = 25 cm
→Diameter of 1600 MHz cavity = 12.5 cm

- 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*

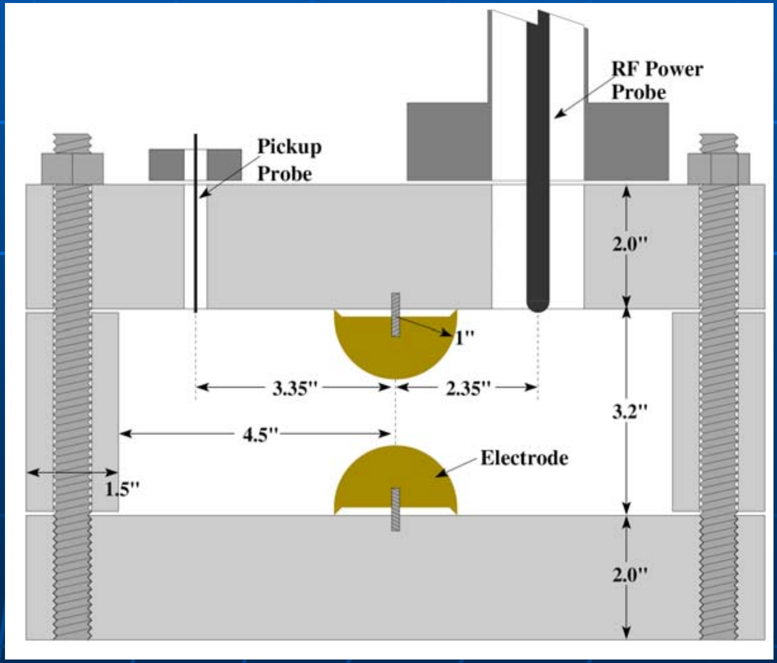
Yonehara HCC Fernow-Neuffer Plot



Cooling required for 5 TeV COM, 10^{35} Luminosity Collider, shown later.
Need to also look at losses from muon decay to get power on target.
Higher magnetic fields from HTS can get required HCC performance.

Pressurized High Gradient RF Cavities

- 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 ~60, W ~70



MuCool Test Area (MTA)

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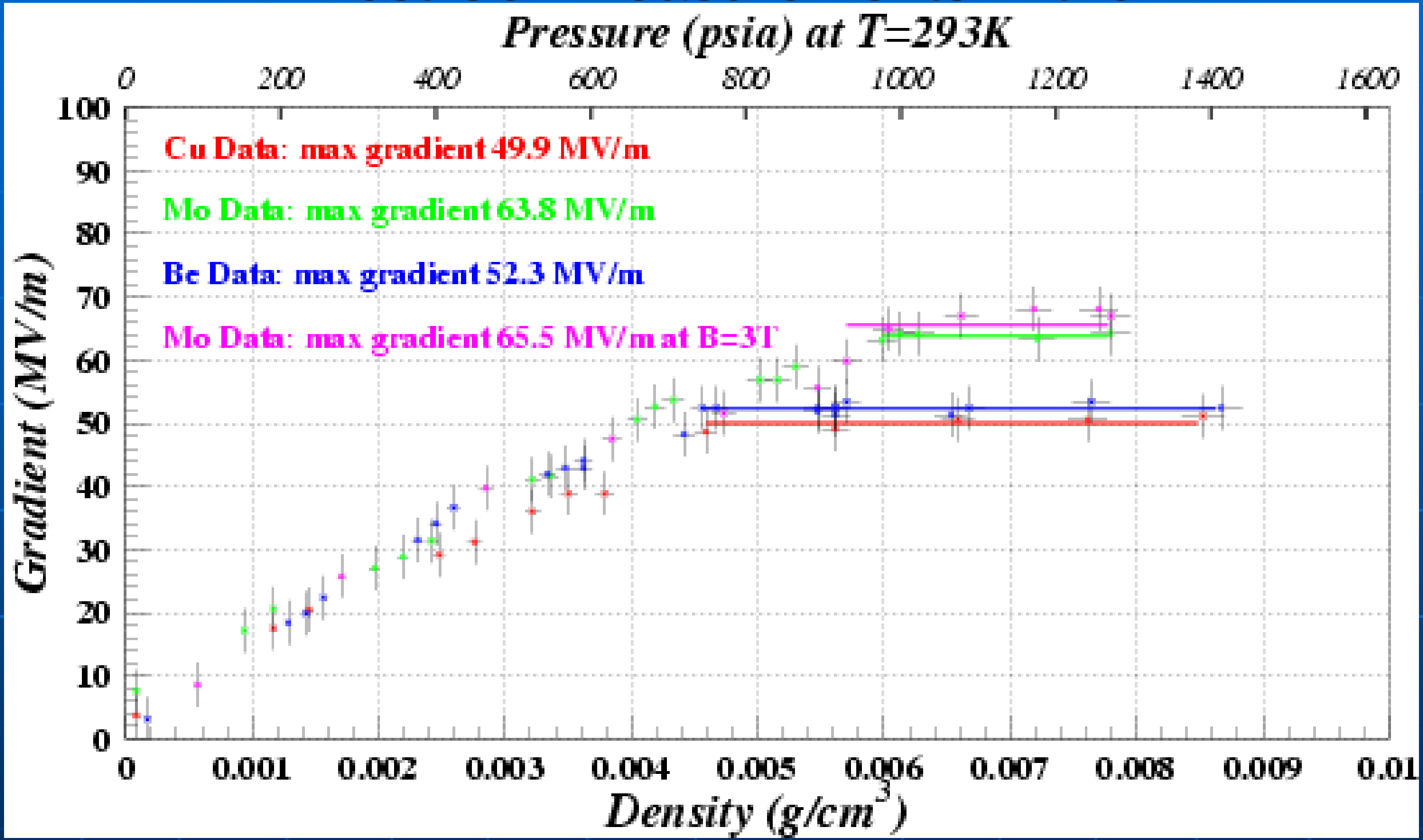
HPRF Test Cell Measurements in the MTA



Results show no B dependence, much different metallic breakdown than for vacuum cavities. **Need beam tests to prove HPRF works.**

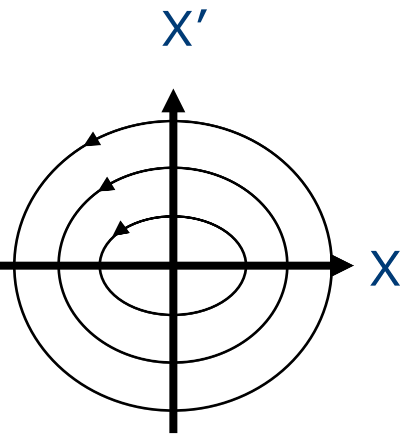
Parametric-resonance Ionization Cooling

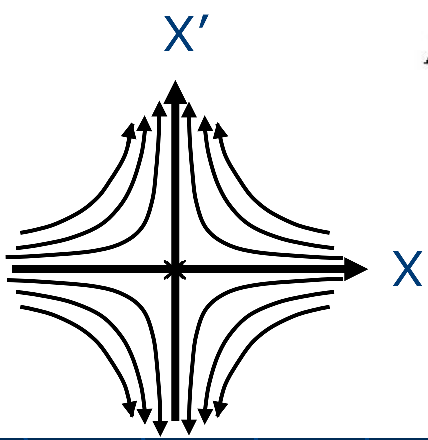
Excite ½ integer parametric resonance (in Linac or ring)

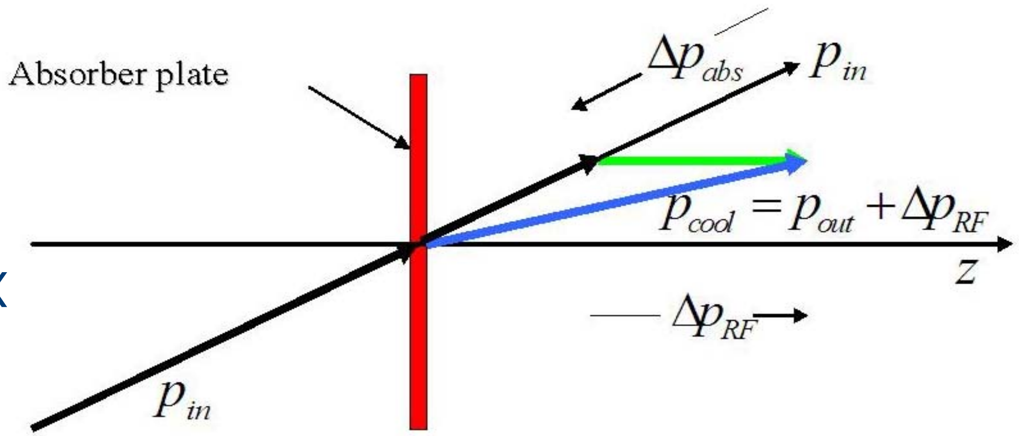
- Like vertical rigid pendulum or ½-integer extraction
- Elliptical phase space motion becomes hyperbolic
- Use xx'=const to reduce x, increase x'
- Use IC to reduce x'

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

See Sah, Newsham, Bogacz

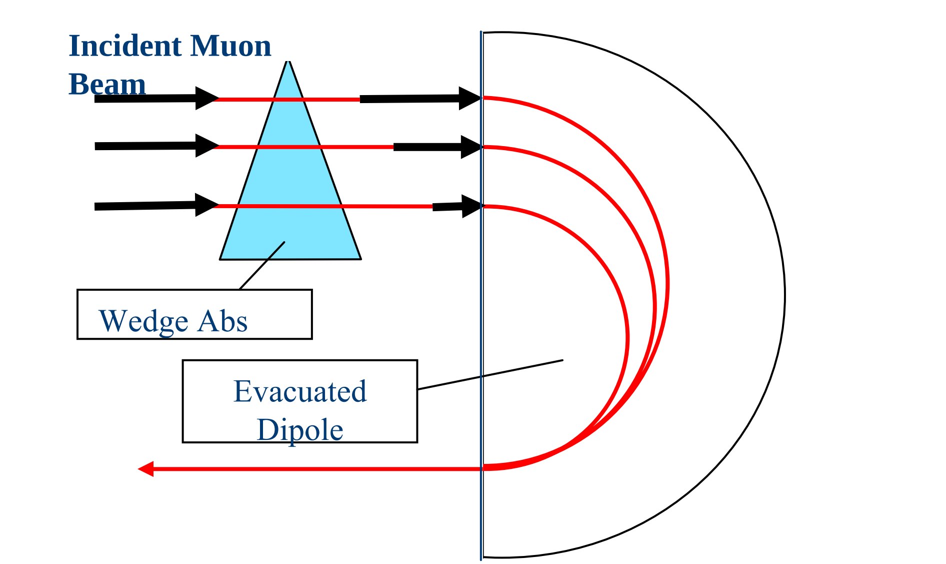




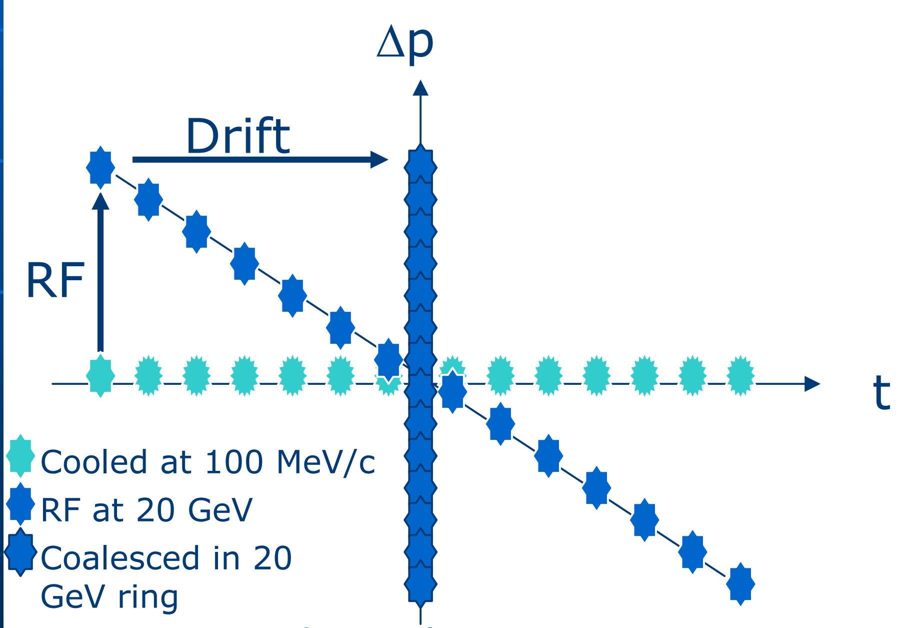


Reverse Emittance Exchange, Coalescing

- 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

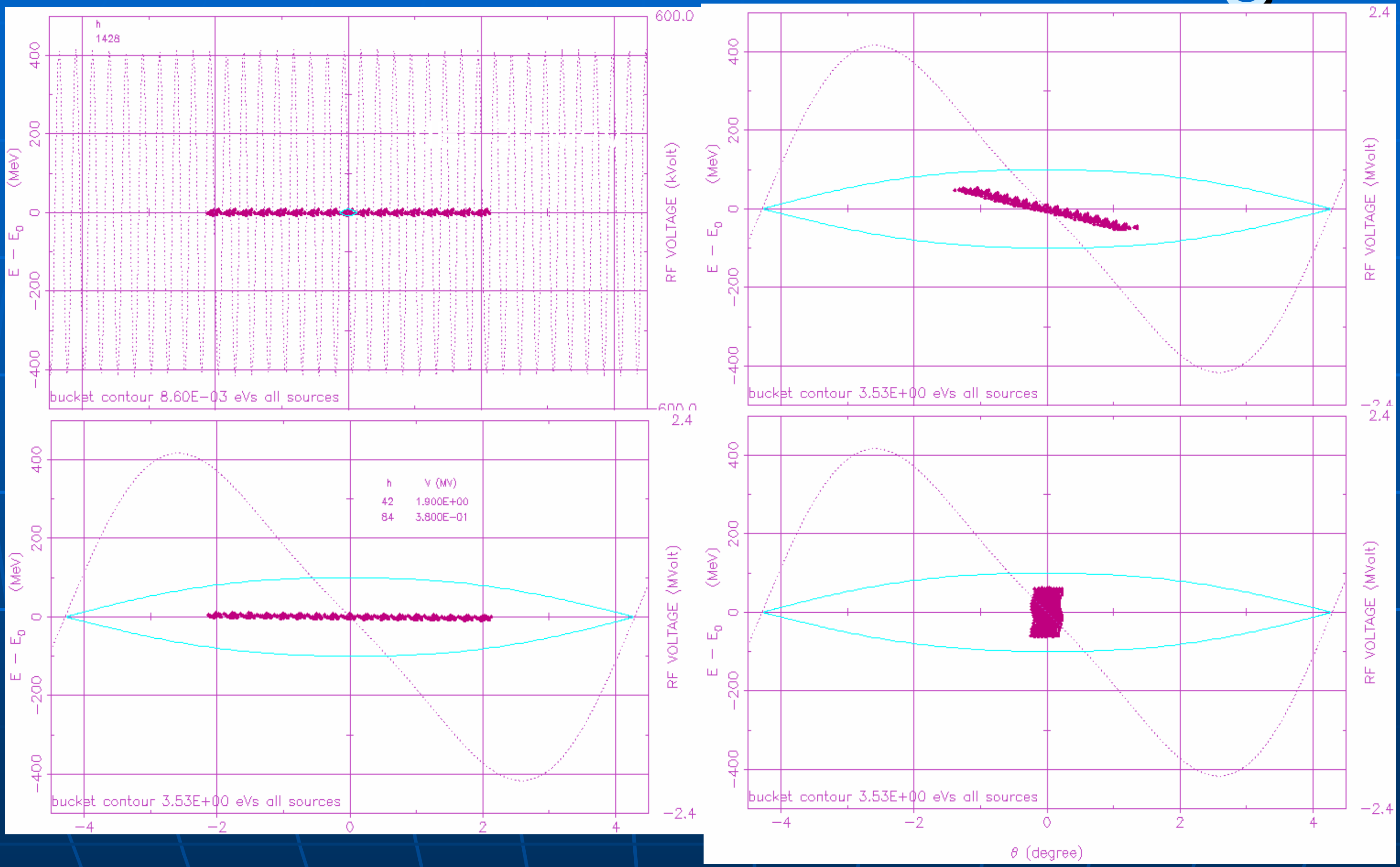


Concept of Reverse Emittance Exch.



1.3 GHz Bunch Coalescing at 20 GeV

Bhat et al. Coalescing



20 GeV muons in a 100 m diameter ring

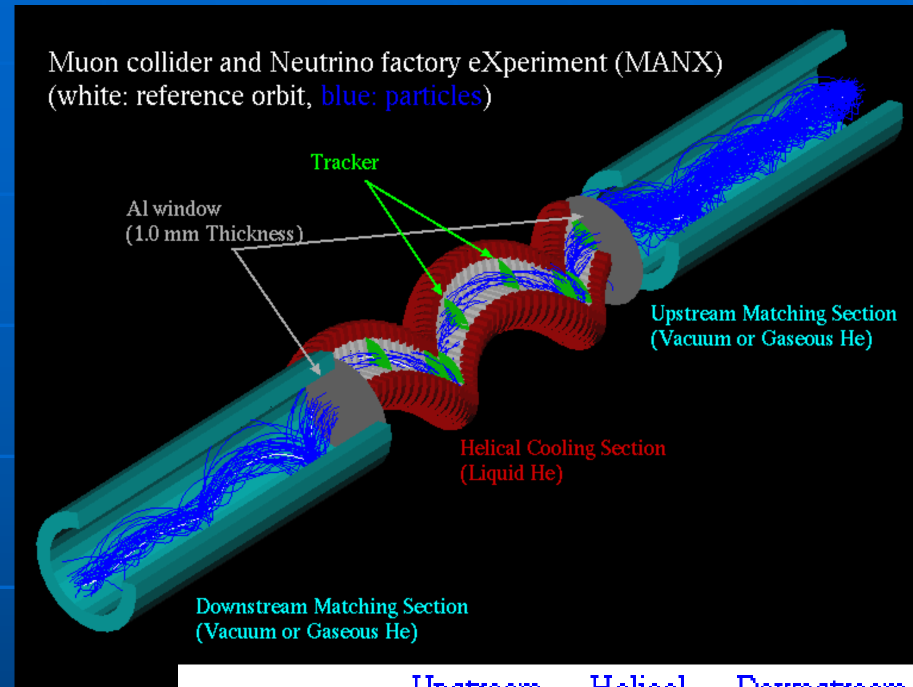
6DMANX demonstration experiment

Muon Collider And Neutrino Factory eXperiment

See Kashikhin, Yonehara, Cummings

- To Demonstrate
  - Longitudinal cooling
  - 6D cooling in cont. absorber
  - Prototype precooler
  - Helical Cooling Channel
  - Use for stopping muon beams
  - New technology

Katsuya's Simulation study

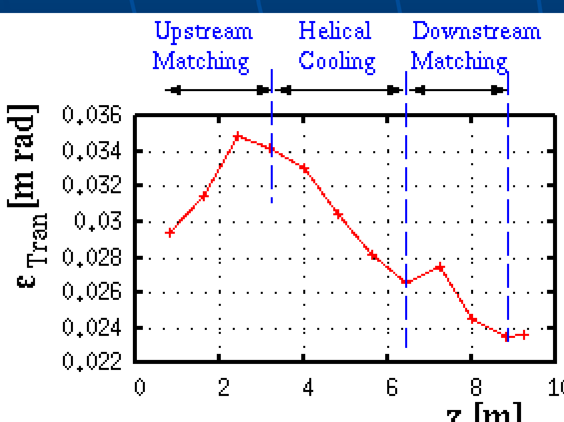


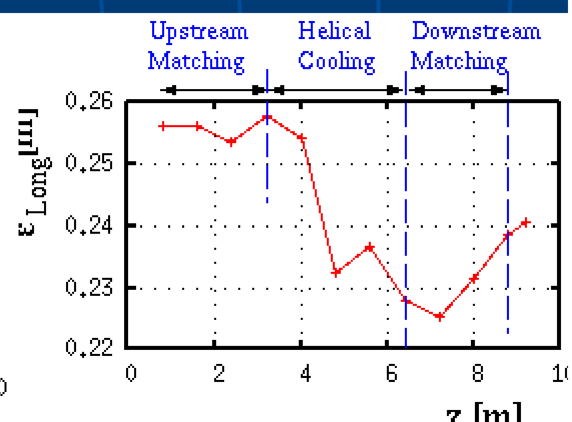
Initial beam profile

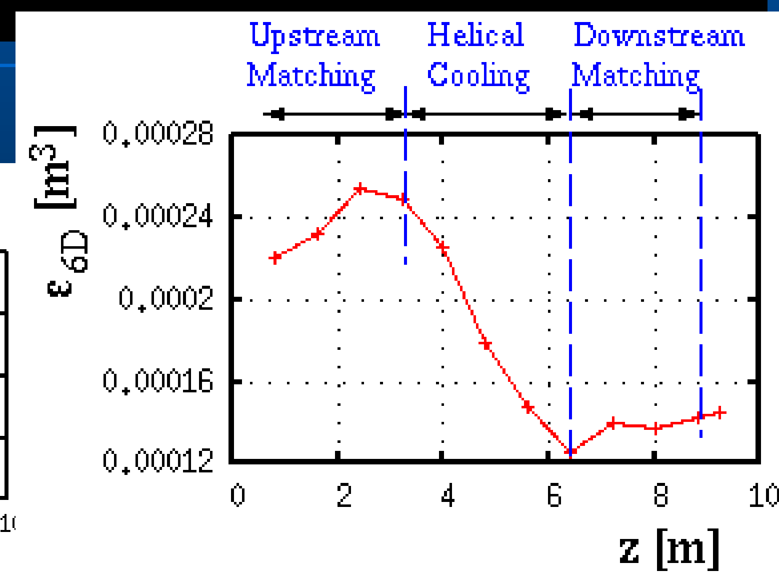
- Beam size (rms): ± 60 mm
- $\Delta p/p$ (rms): ± 40/300 MeV/c
- x′ and y′ (rms): ± 0.4

↓

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





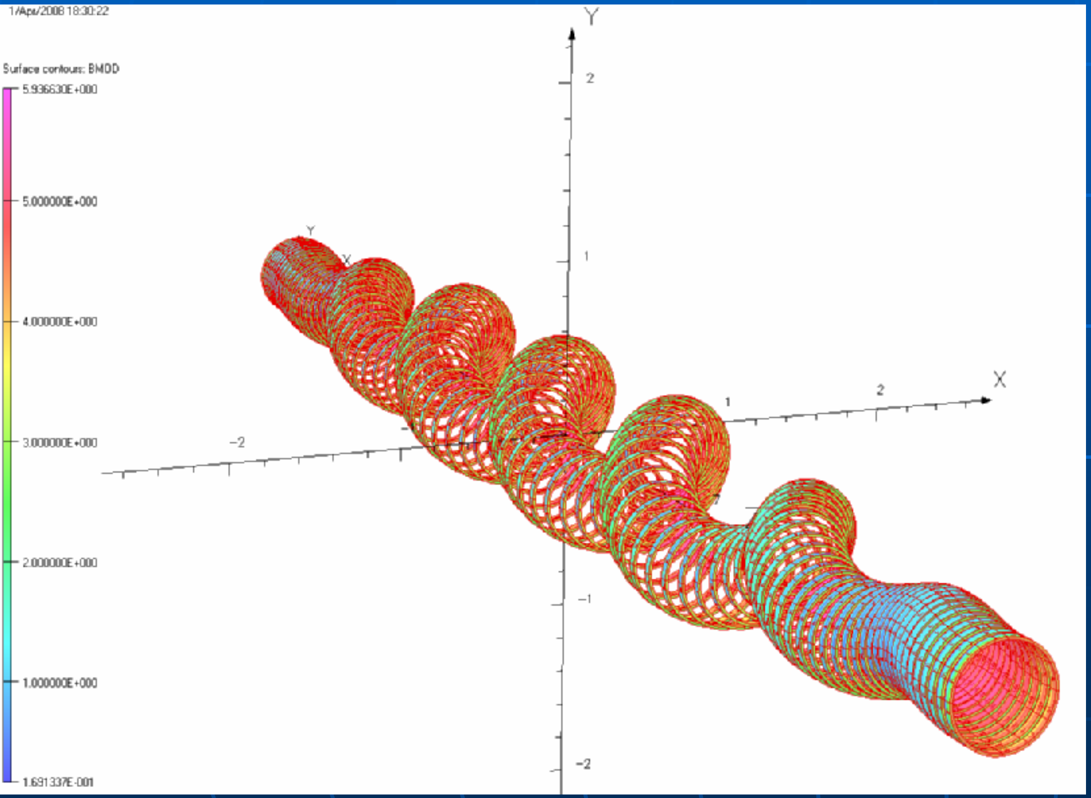


HS for Cooling Demonstration Experiment

V. Kashikhin, A. Zlobin, M. Lamm, S. Kahn, M. Lopes

Goals: cooling demonstration, HS technology development

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



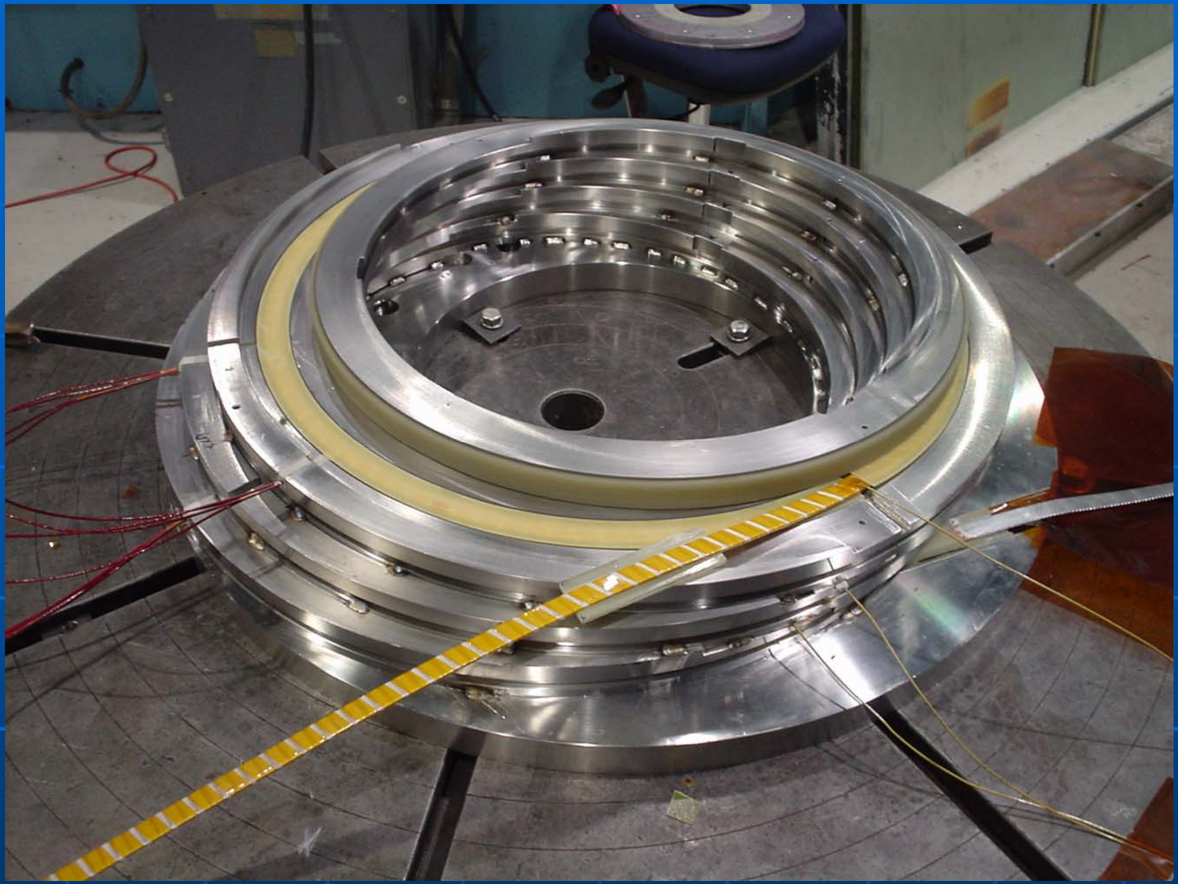
Status: conceptual design complete

- solenoid
- matching sections

Next: engineering design

- mechanical structure
- field quality, construction tolerances
- cryostat
- powering and quench protection

4-Coil Prototype HCC test



The 4-Coil Helical Solenoid model is capable of reproducing the same level of stresses in superconductor and support structure as in long solenoids, fabrication is now in progress, tests planned for the summer of 2008.

WEPD013 ,WEPD014, WEPD015 WEPD022 WEPD023

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Technology Development in FNAL Technical Division

HTS at LH2 shown, in LHe much better

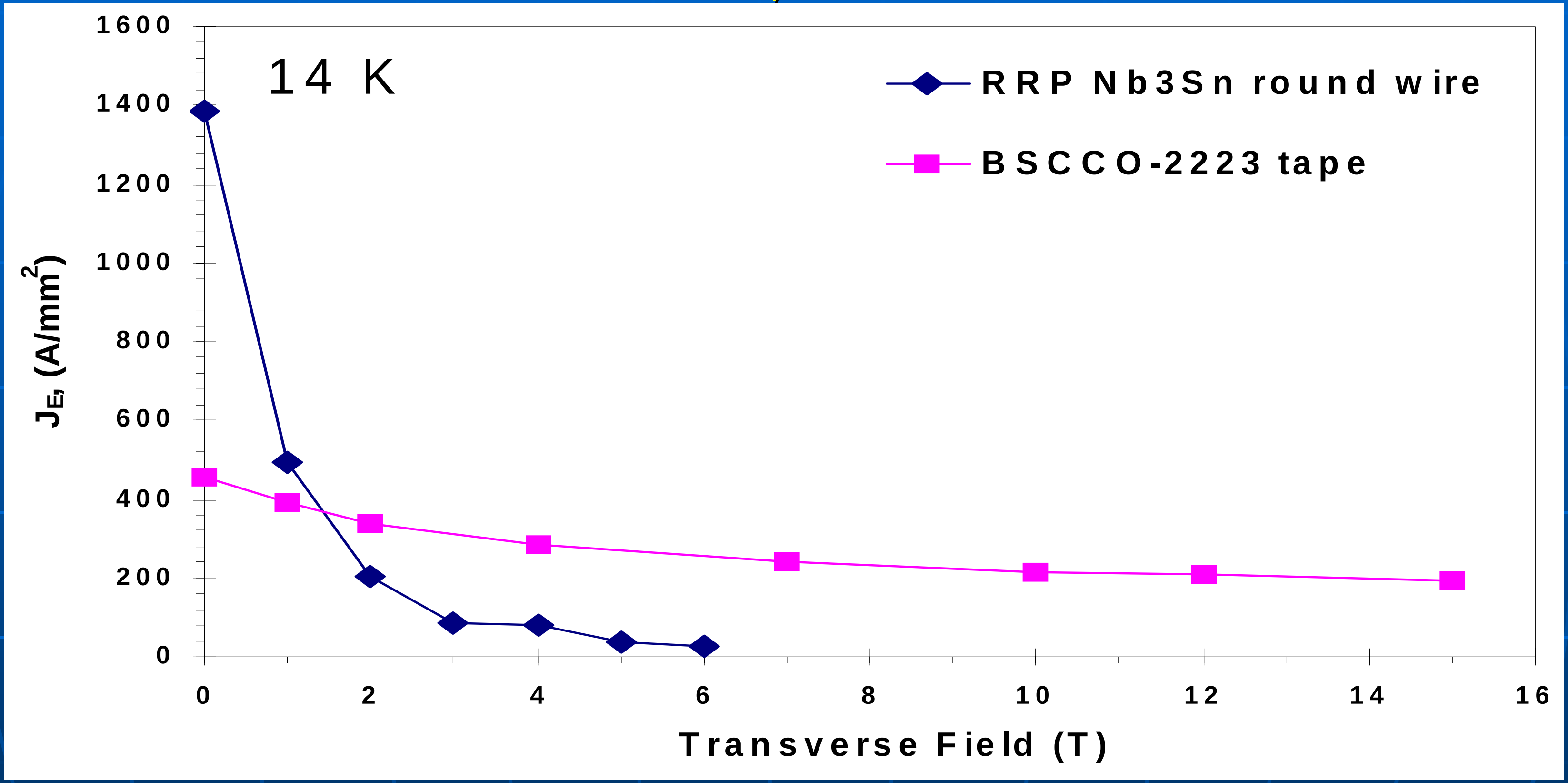


Fig. 9. Comparison of the engineering critical current density, J_E, at 14 K as a function of magnetic field between BSCCO-2223 tape and RRP Nb_3Sn round wire.

WEPD015, WEPD022, WEPD023

Progress on new ideas described:

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

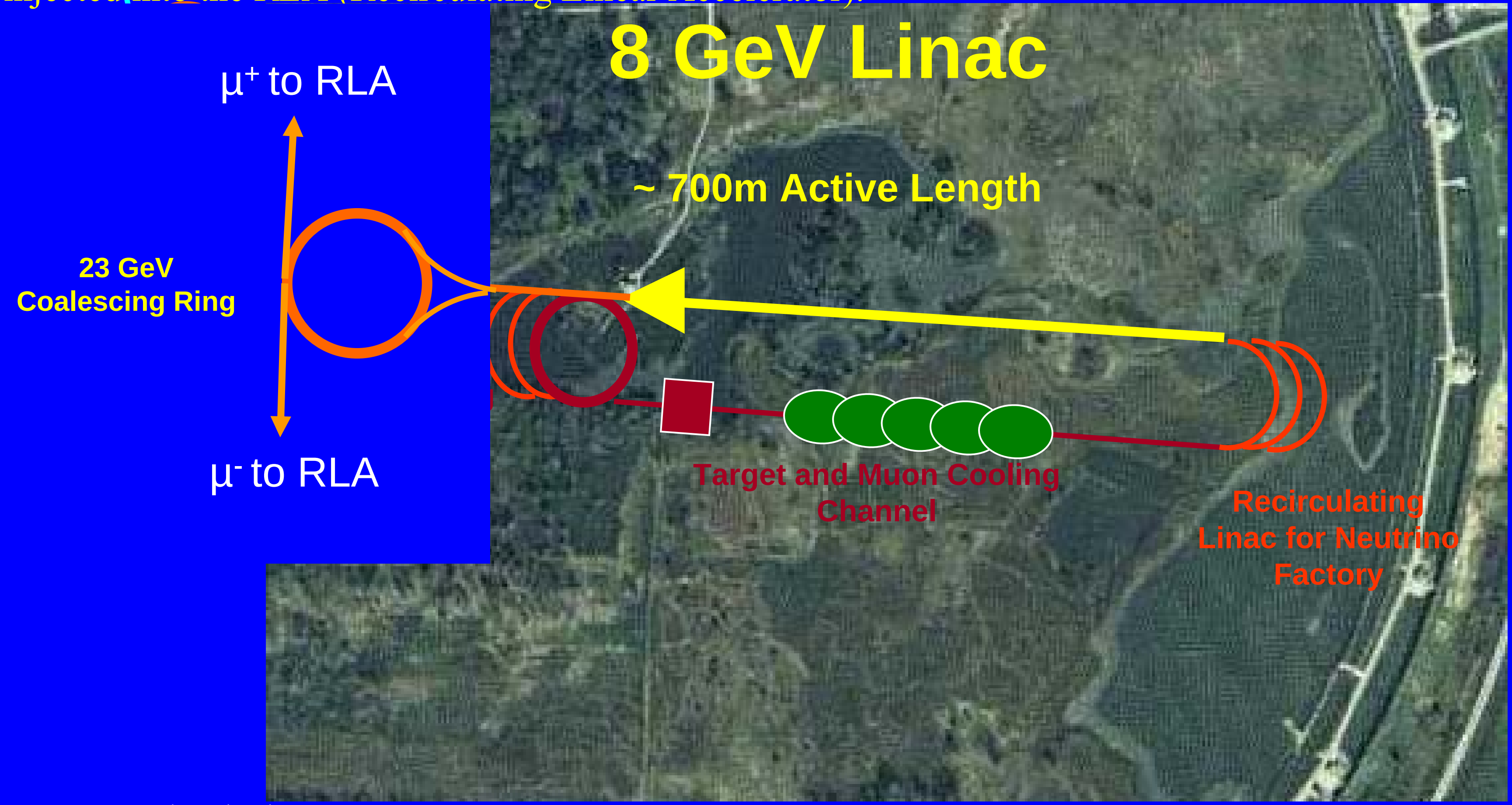
(For other paths to LEMCs, see
Related experiments motivated by neutrino factories and useful for muon colliders:

The MICE experiment at RAL is to demonstrate 4-D

The Merit experiment at CERN to demonstrate 4 MW targetry on Hg

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).



5 TeV ~ SSC energy reach

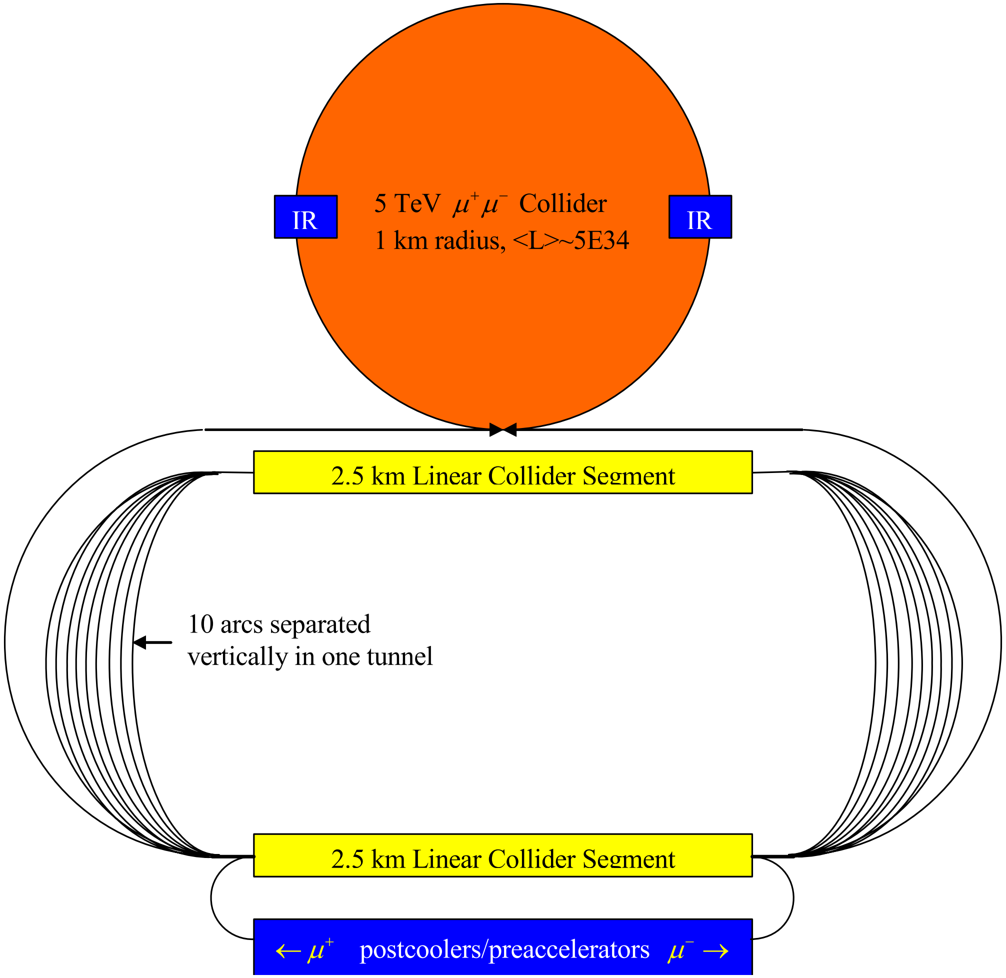
~5 X 2.5 km footprint

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

More efficient use of RF: recirculation and both signs

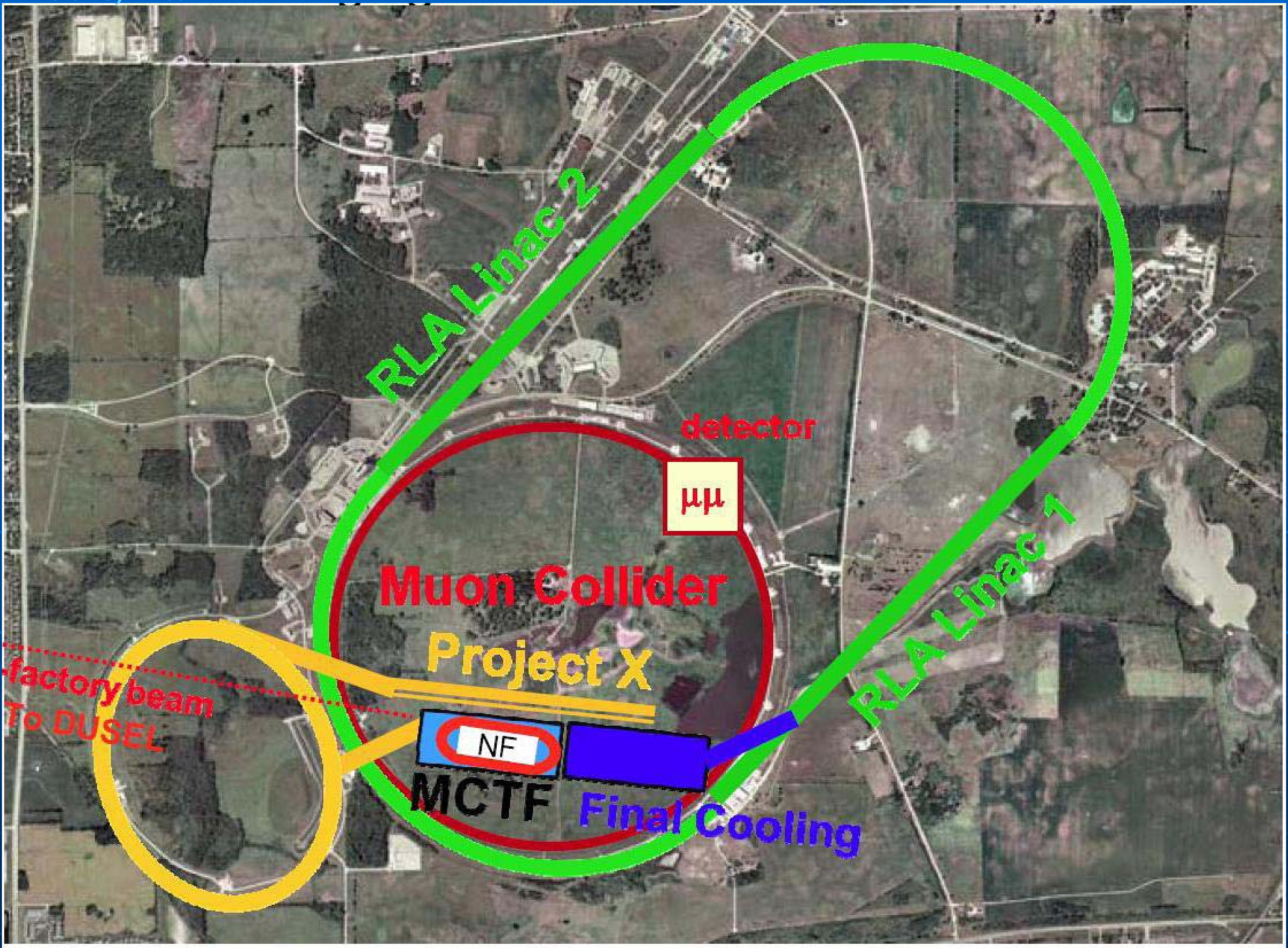
High L from small emittance!

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

1-4 TeV MC from Pier Oddone's P5 presentation



Muon Collider Emittances and Luminosities

- 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

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

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

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

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

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

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

20 Hz Operation:

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

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

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

High-Energy High-Luminosity Muon Colliders

- precision lepton machines at the energy frontier
- possible with new inventions and new technology
- achievable in physics-motivated stages
  - Project-X
  - stopping muon beams (e.g. mu2e experiment)
  - neutrino factory
  - Higgs factory
  - Z' factory (lower luminosity, perhaps LHC inspired)
  - Energy-frontier muon collider
- next meetings:
  - MANX Collaboration Meeting July 14-15 Fermilab
  - Muon Collider Design Workshop Dec. 1-5 BNL or Jlab

(for info on either, email MACC@muonsinc.com)