Low Emittance Muon Colliders

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.

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

Related Muon Work at PAC07

MOPAS012 - **Magnets for the MANX Cooling Demonstration Experiment**
V. Kashikhin...

MOPAN117 - **Magnet Systems for Helical Muon Cooling Channels**
S. A. Kahn...

MOPAN118 - **High Field HTS Solenoid for Muon Cooling**
S. A. Kahn...

WEPMS071 - **Evidence for Fowler-Nordheim behavior in RF Breakdown**
M. BastaniNejad...

THPAN103 - **G4BeamLine Program for Matter-dominated Beam Lines**
T. J. Roberts...

THPMN096 - **Stopping Muons Beams**
M. A. C. Cummings...

THPMN110 - **Design of the MANX 6D Demonstration Experiment**
K. Yonehara...

THPMN094 - **Simulations of Parametric-resonance Ionization Cooling**
D. Newsham...

THMN095 - **Muon Bunch Coalescing**
R. P. Johnson...

THPMN106 – **Use of Harmonic RF Cavities in Muon Capture for NFs or MCs**
D. Neuffer...

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, lower cost
  - Each cavity used 10 times for both muon charges
  - Potential 20x efficiency wrt ILC approach offset by
    - Muon cooling
    - Recirculating arcs
    - Muon decay implications for detectors, magnets, and radiation
- A low-emittance high-luminosity collider
  - high luminosity with fewer muons
  - First LEMC goal: E_{com}=5 TeV, <L>=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)

Muons, Inc. SBIR/STTR Collaboration:

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

- 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)

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 (HCC)
    - Effective 6D cooling (simulations: cooling factor >50,000 in 160 m)
  - Momentum-dependent Helical Cooling Channel
    - 6D Precooling device (e.g. stopping muon beams)
    - 6D cooling demonstration experiment (MANX)
  - 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 very high field magnets
    - Faster cooling, smaller equilibrium emittance

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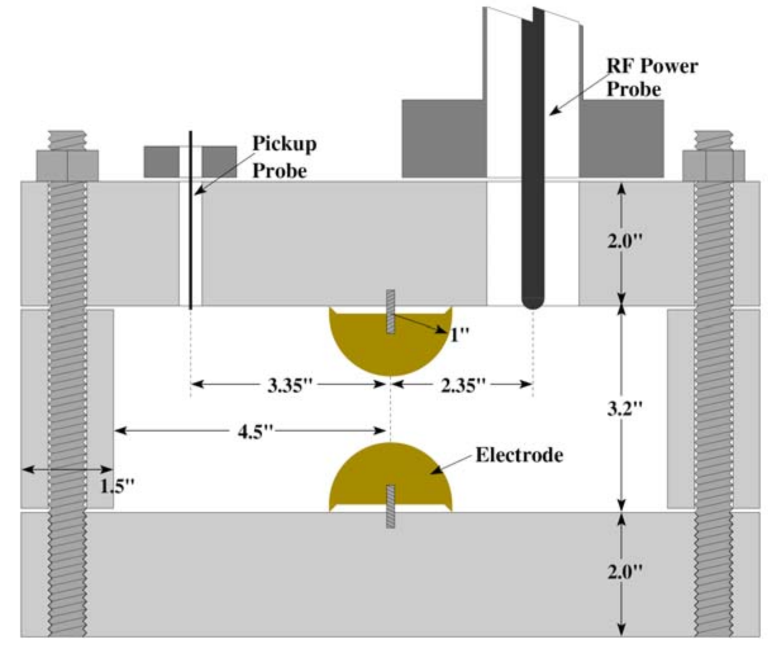
Pressurized High Gradient RF Cavities

- 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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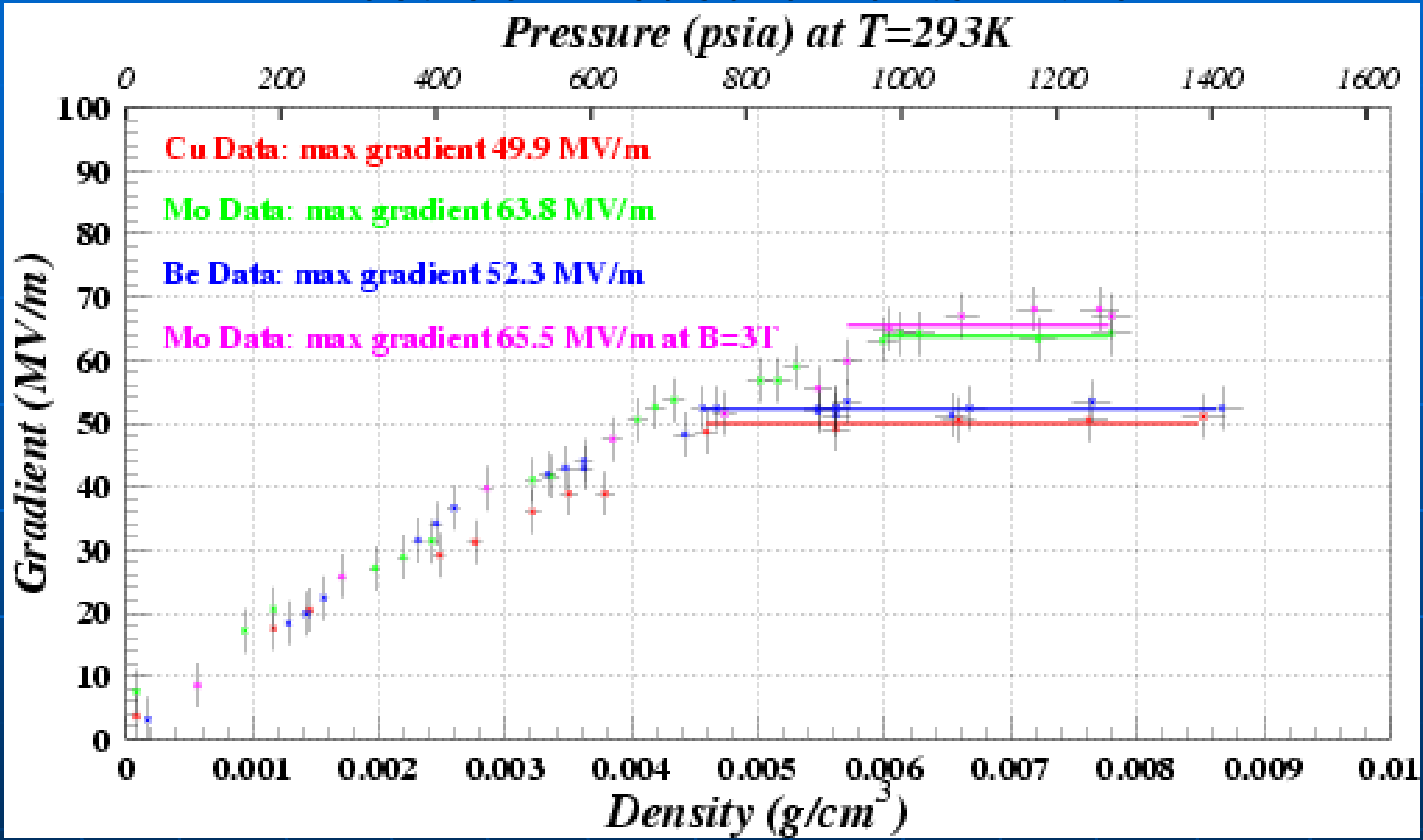
HPRF Test Cell Measurements in the MTA



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

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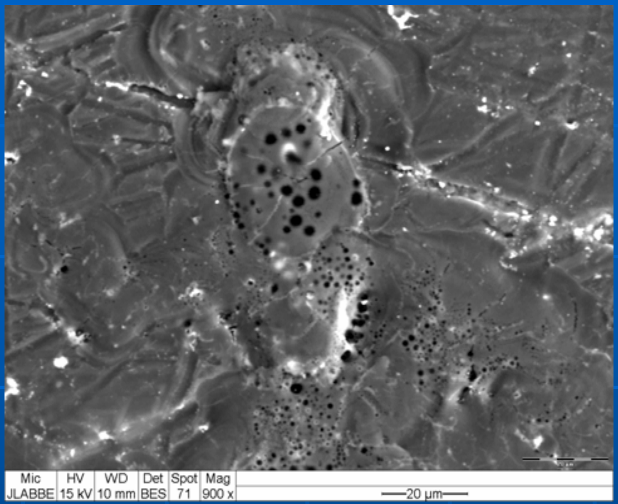
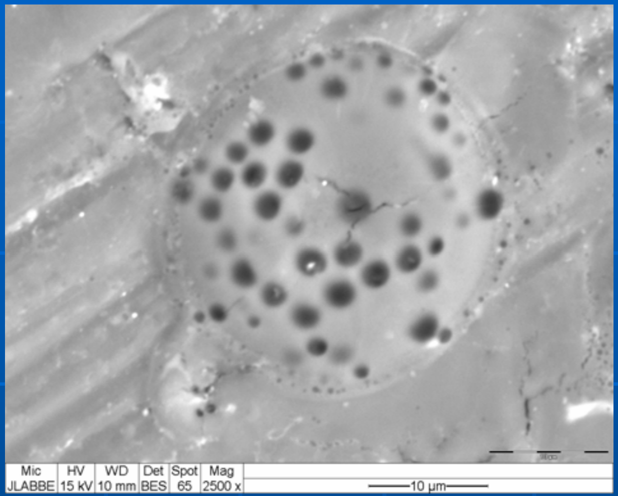
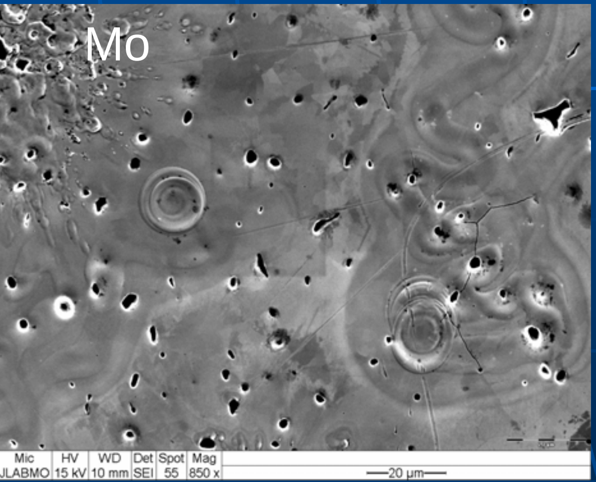
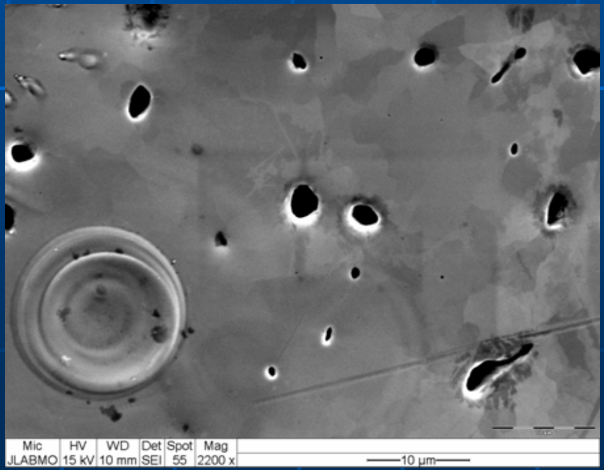
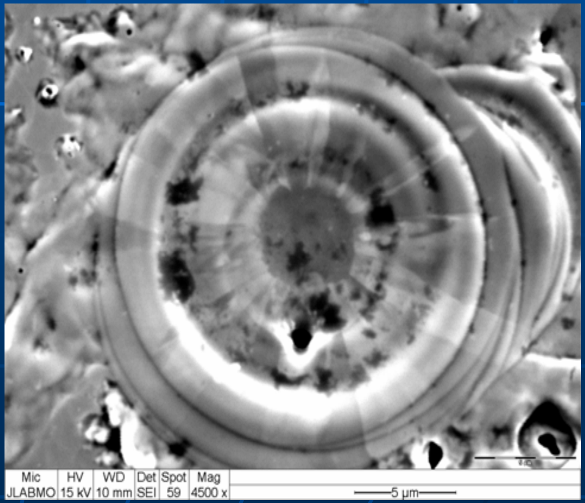
Understanding RF Breakdown in High Pressure Cavities: Scanning Electron Microscope Pictures of HP Electrodes











See WEPMS071 - Evidence for Fowler-Nordheim behavior in RF Breakdown

Technology Development in Technical Division

HTS at LH2 shown, in LHe much better

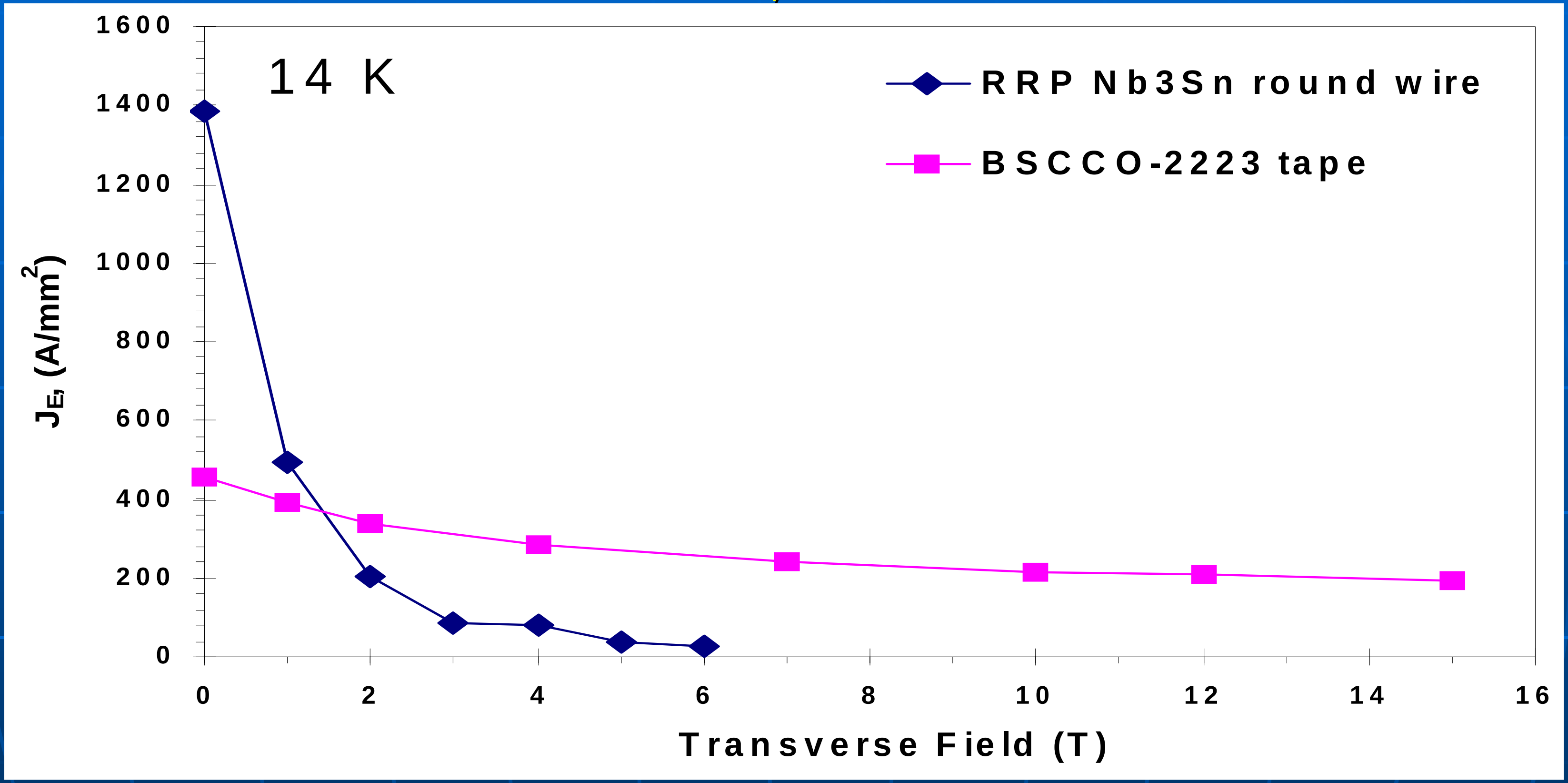
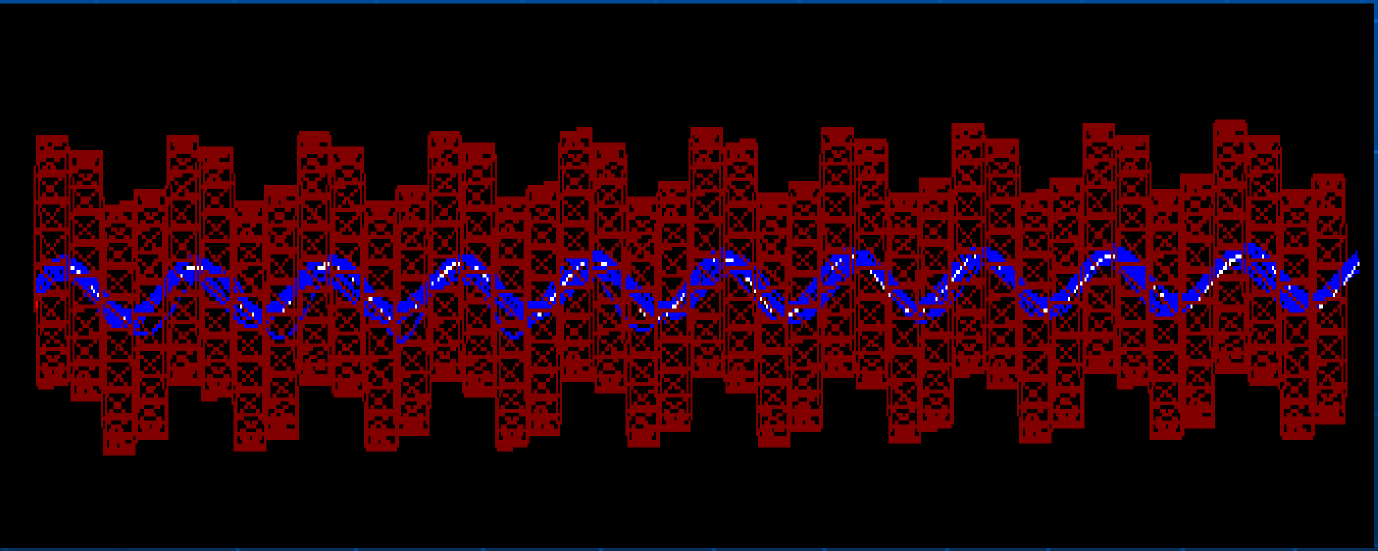


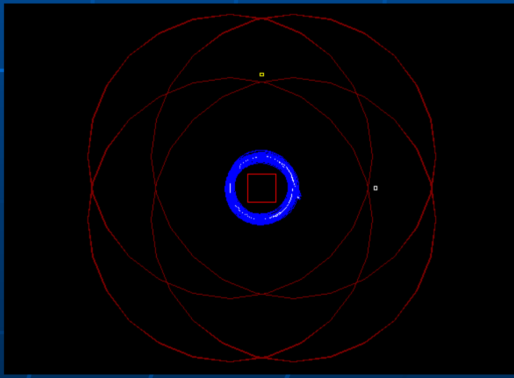
Fig. 9. Comparison of the engineering critical current density, J_E, at 14 K as a function of magnetic field between BSCCO-2223 tape and RRP Nb_3Sn round wire.

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

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

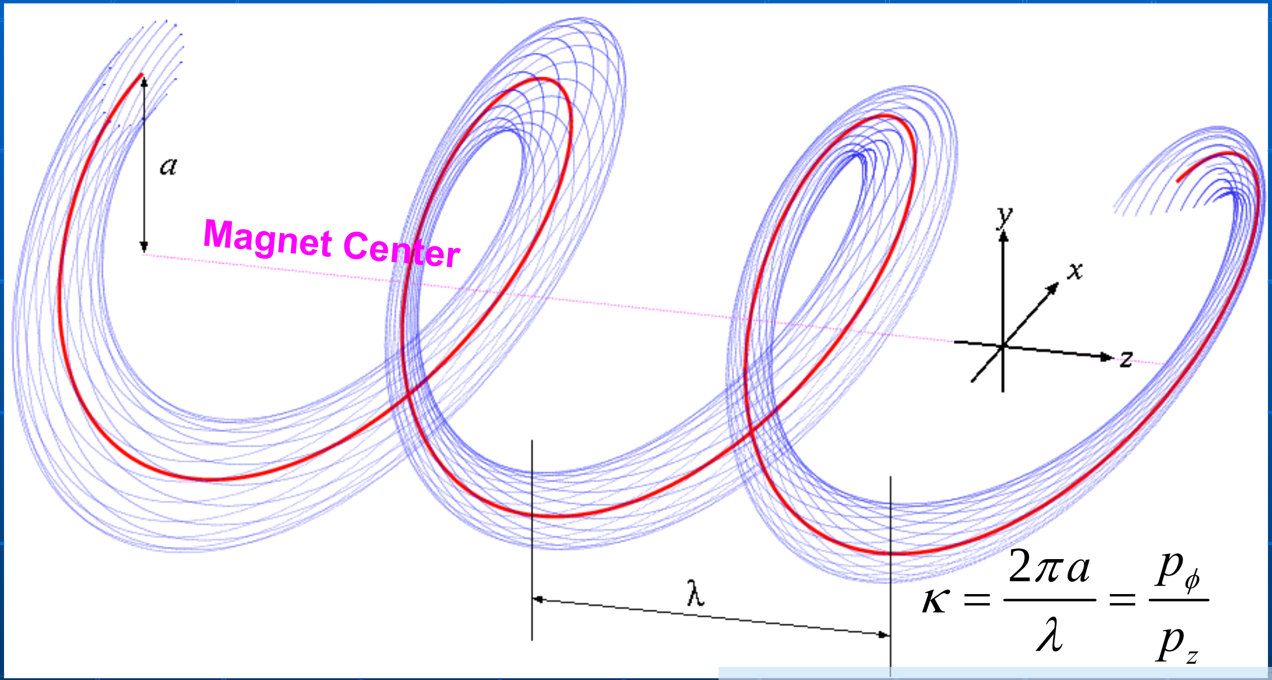




Particle Motion in Helical Magnet

Combined function magnet (invisible in this picture)

Solenoid + Helical dipole + Helical Quadrupole



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 sign

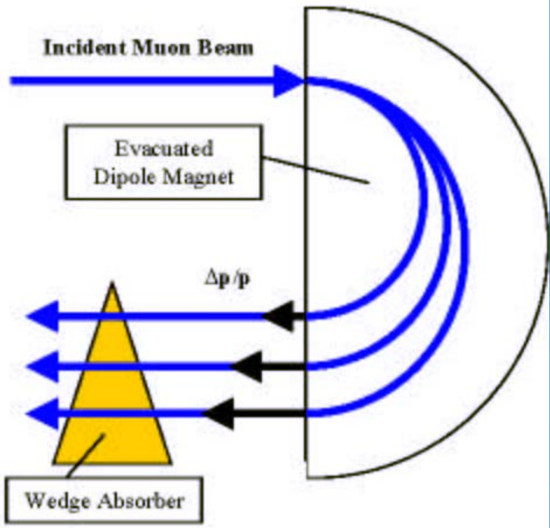


Figure 1. Use of a Wedge Absorber for Emittance Exchange

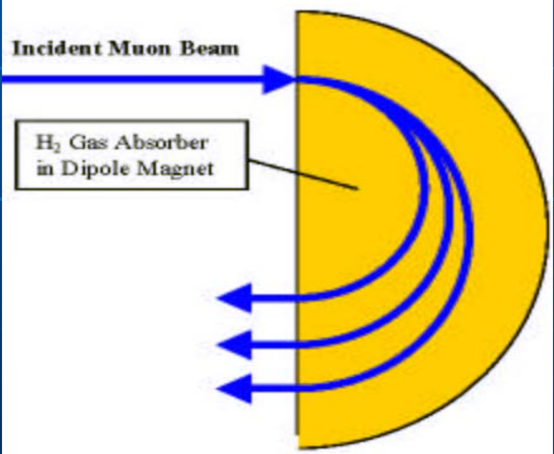
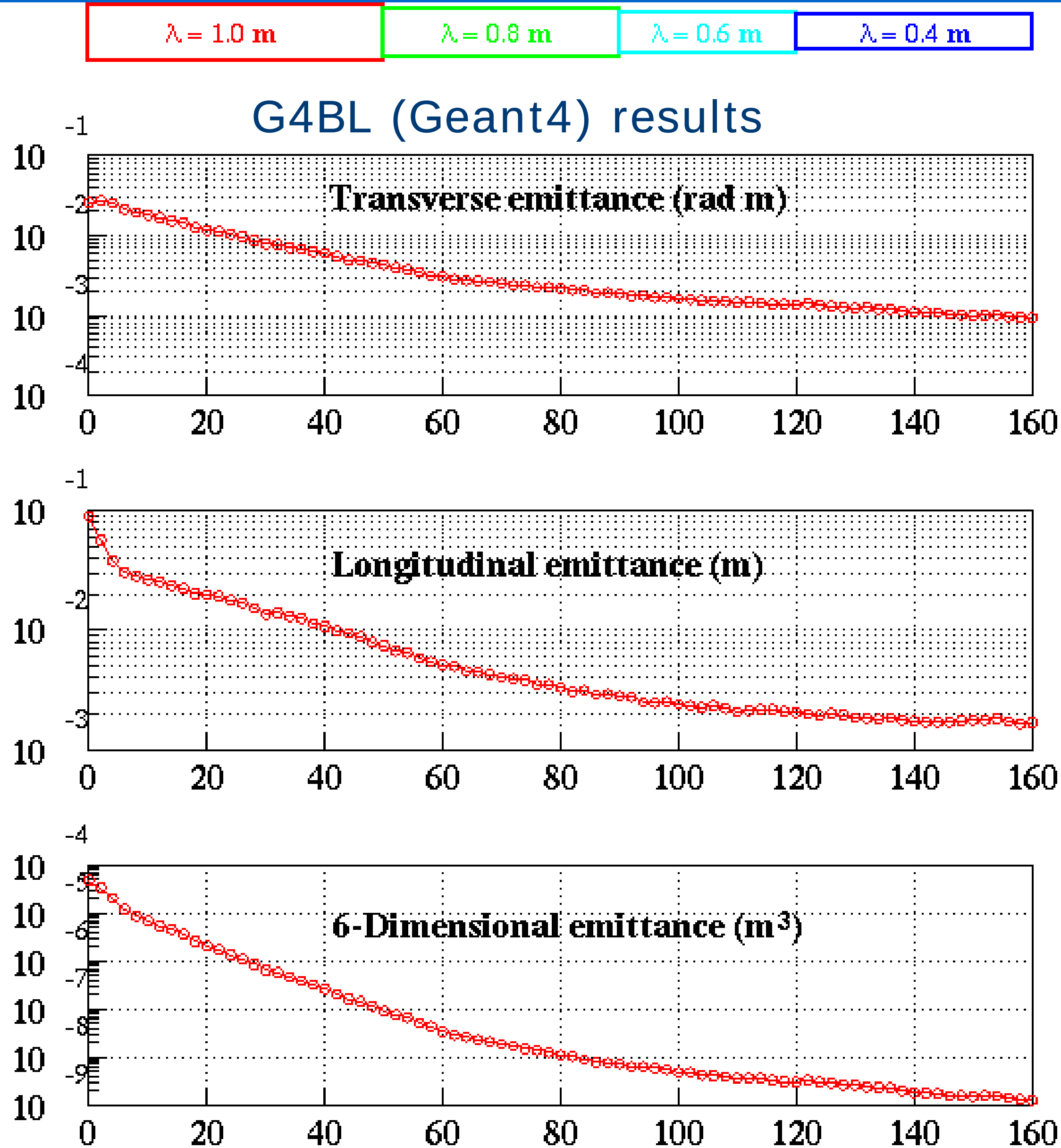


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

G4BL (Geant4) results



6D Cooling factor ~ 50,000

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Hydrogen Cryostat for Muon Beam Cooling

Technology for HCC components:

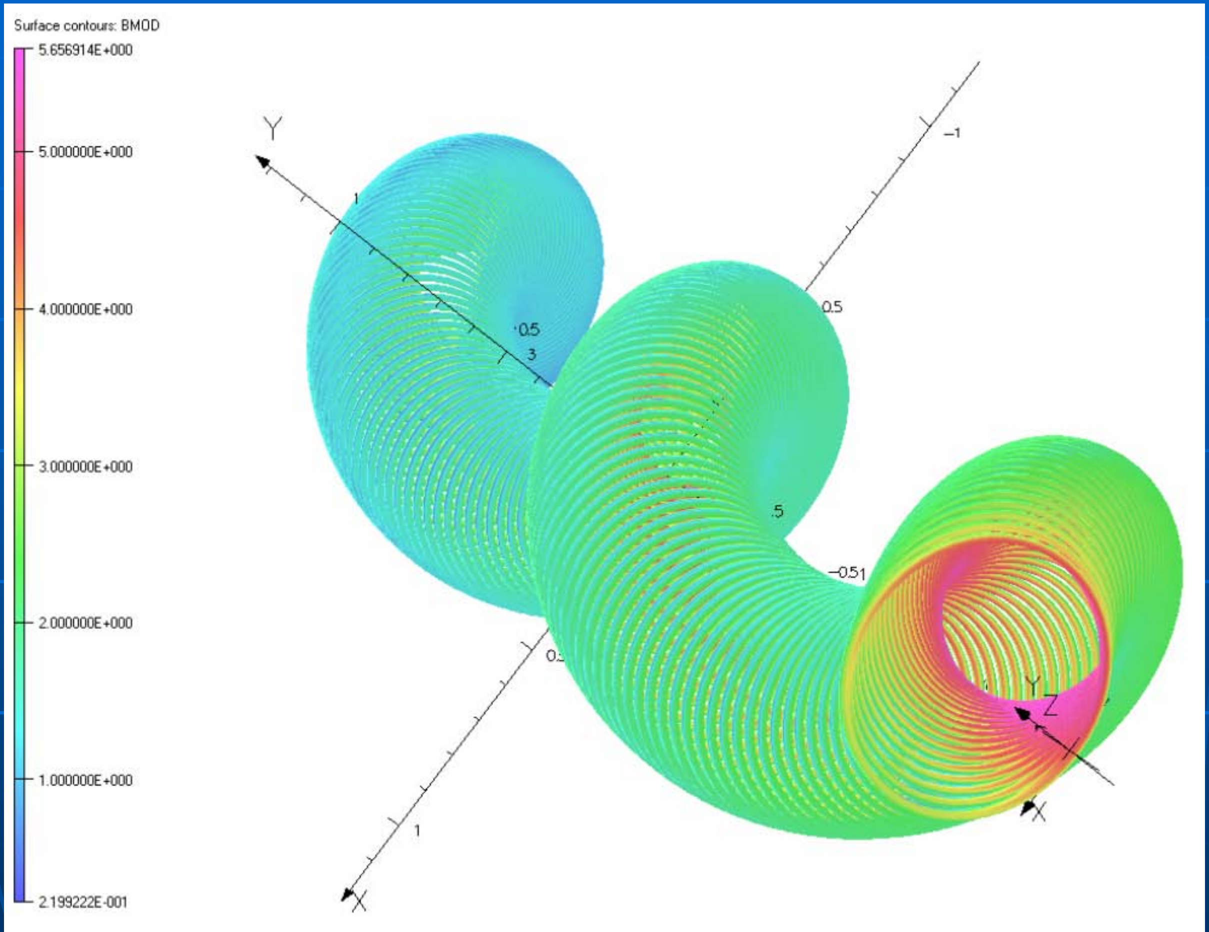
HTS (nice BSSCO data from TD Ph I), Helical magnet design,

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

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.

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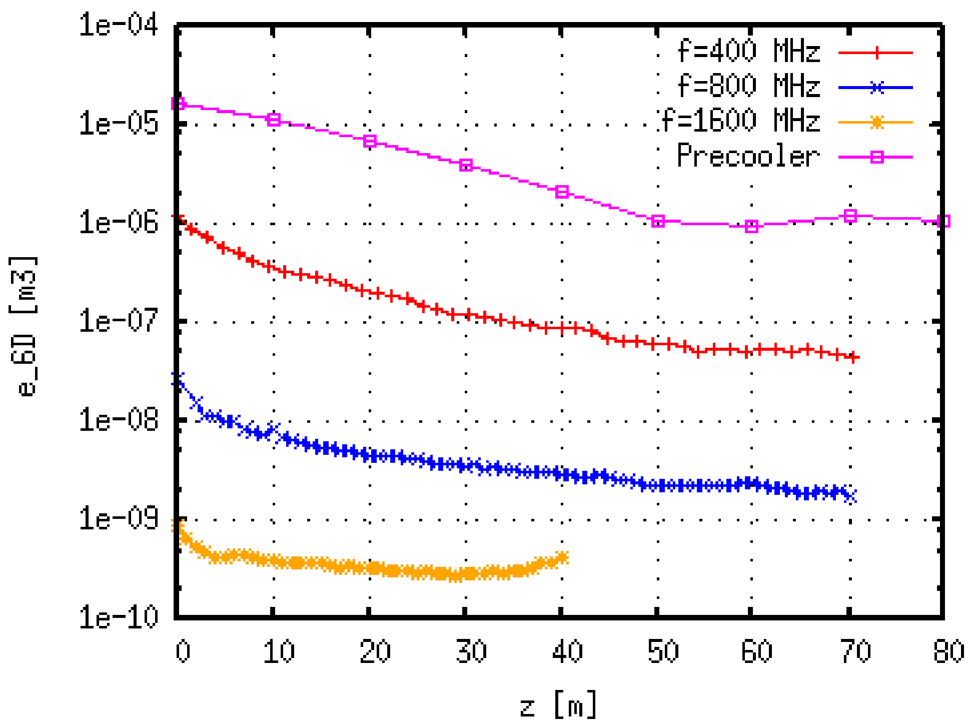
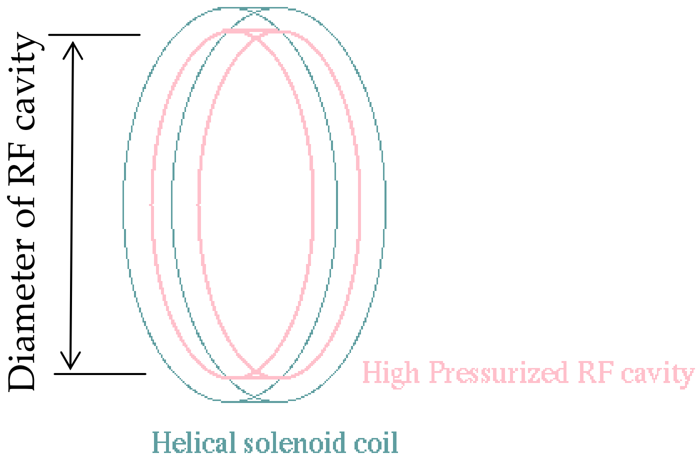
Precooler + HCCs



- 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*

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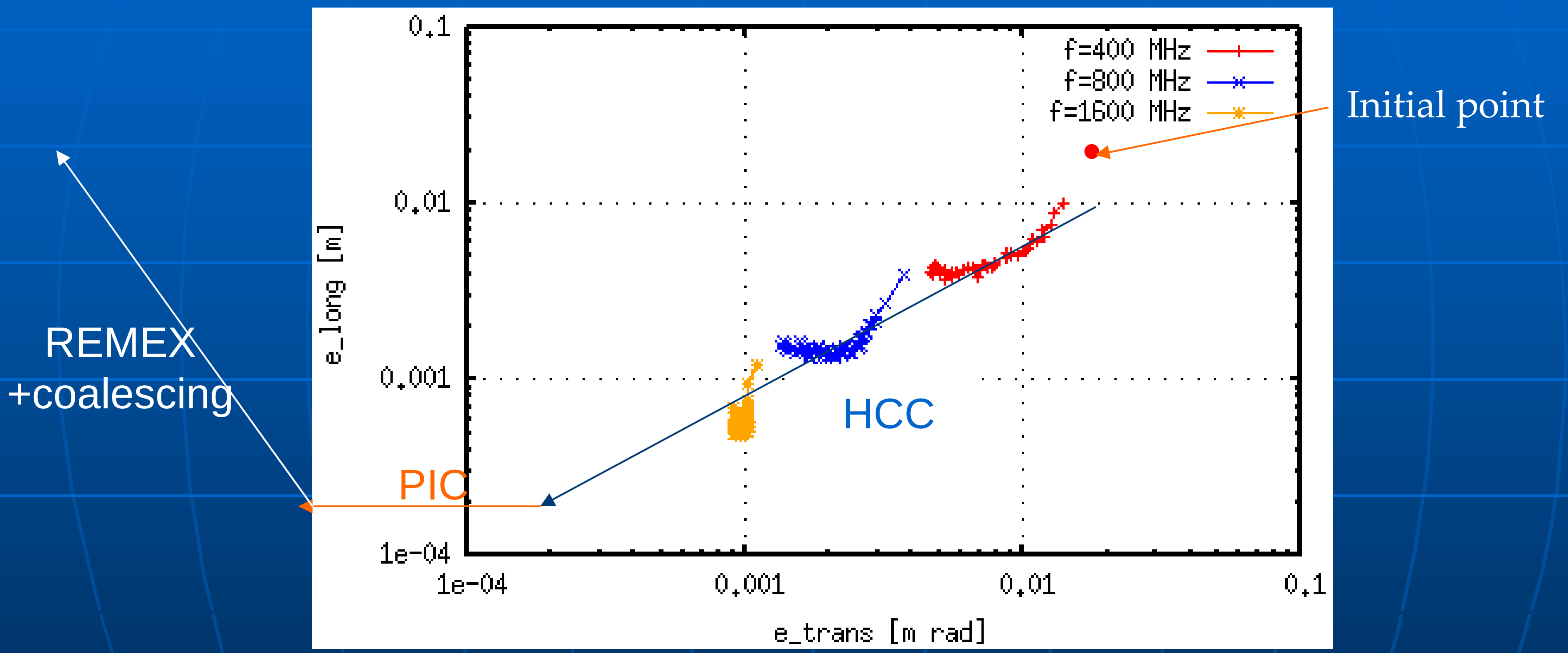
Yonehara HCC Fernow-Neuffer Plot



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.

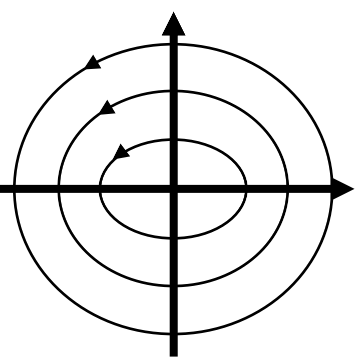
Parametric-resonance Ionization Cooling

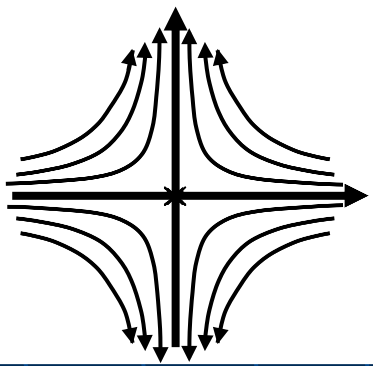
Excite ½ integer parametric resonance (in Linac or ring)

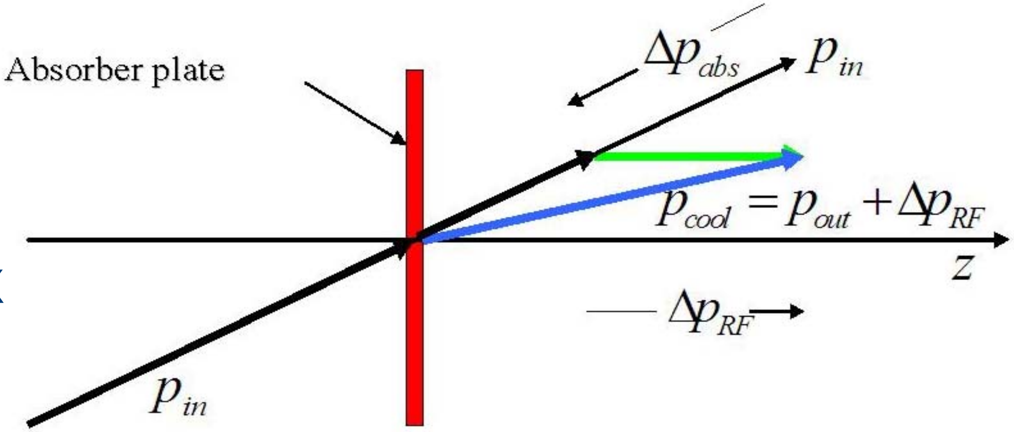
- Like vertical rigid pendulum or ½-integer extraction
- Elliptical phase space motion becomes hyperbolic
- Use xx'=const to reduce x, increase x'
- Use IC to reduce x'

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

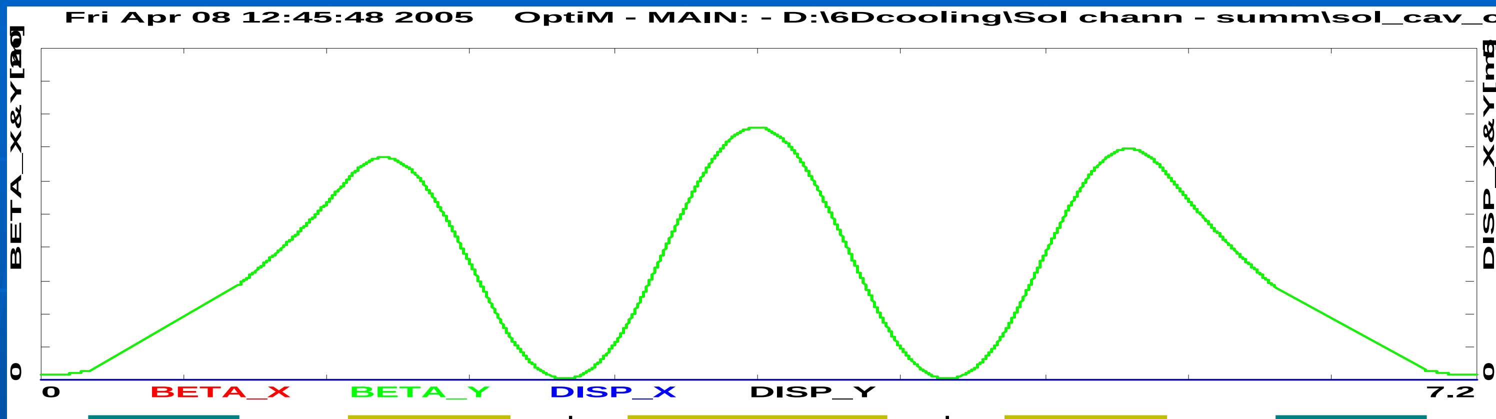
See Sah, Newsham, Bogacz



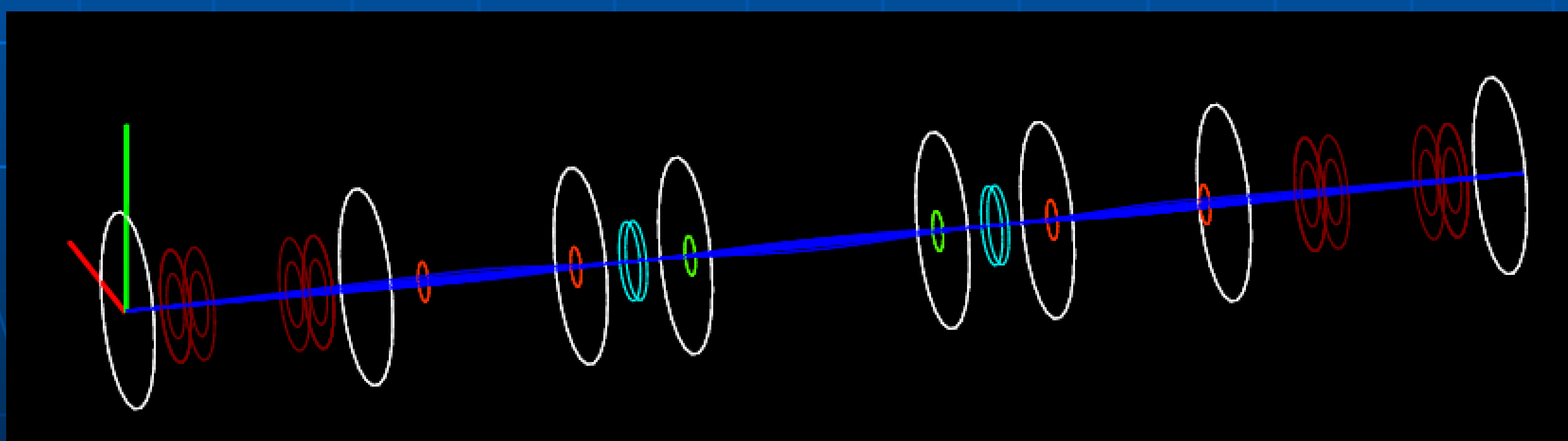




Example of triplet solenoid cell on ½ integer resonance with RF cavities to generate synchrotron motion for chromatic aberration compensation.



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



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

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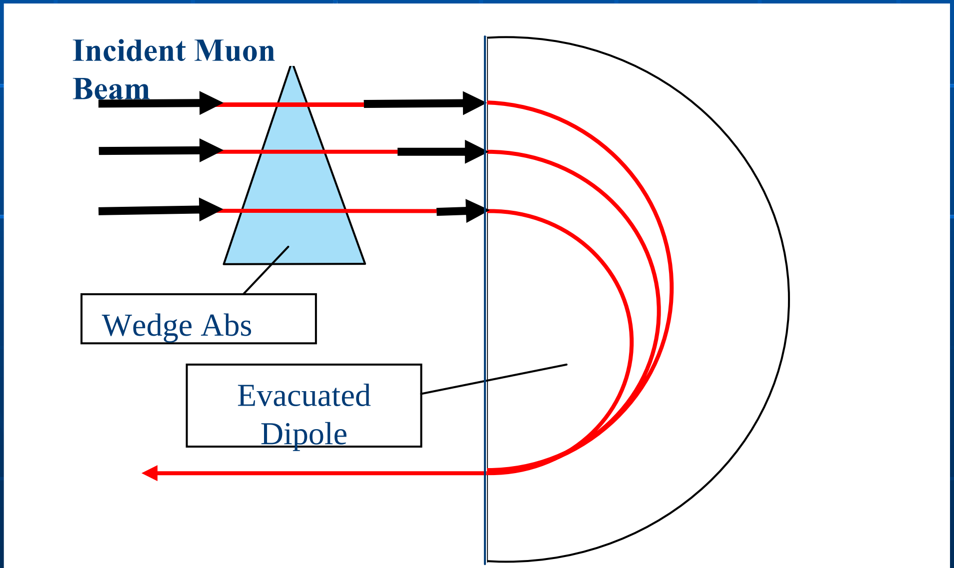
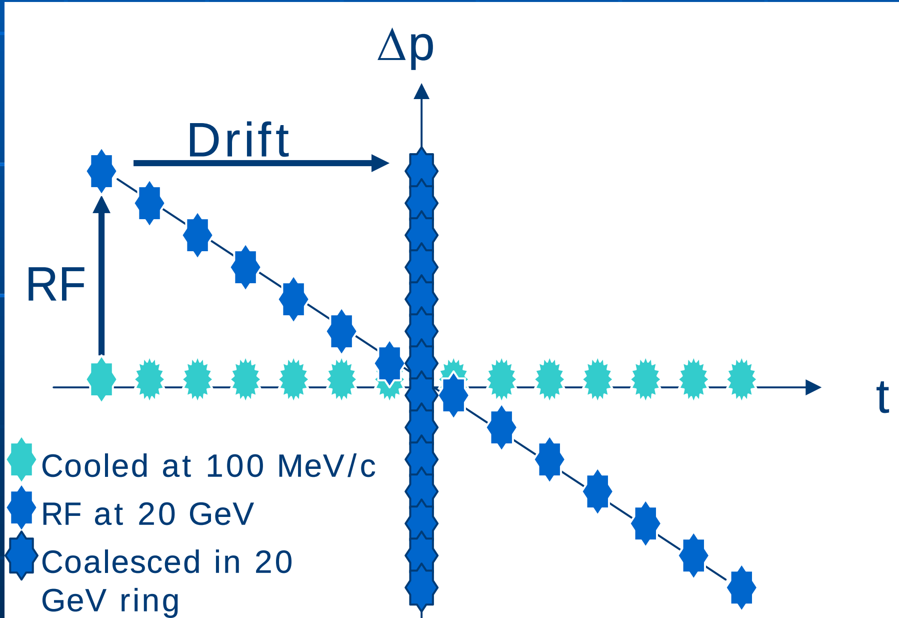
Reverse Emittance Exchange, Coalescing

- 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

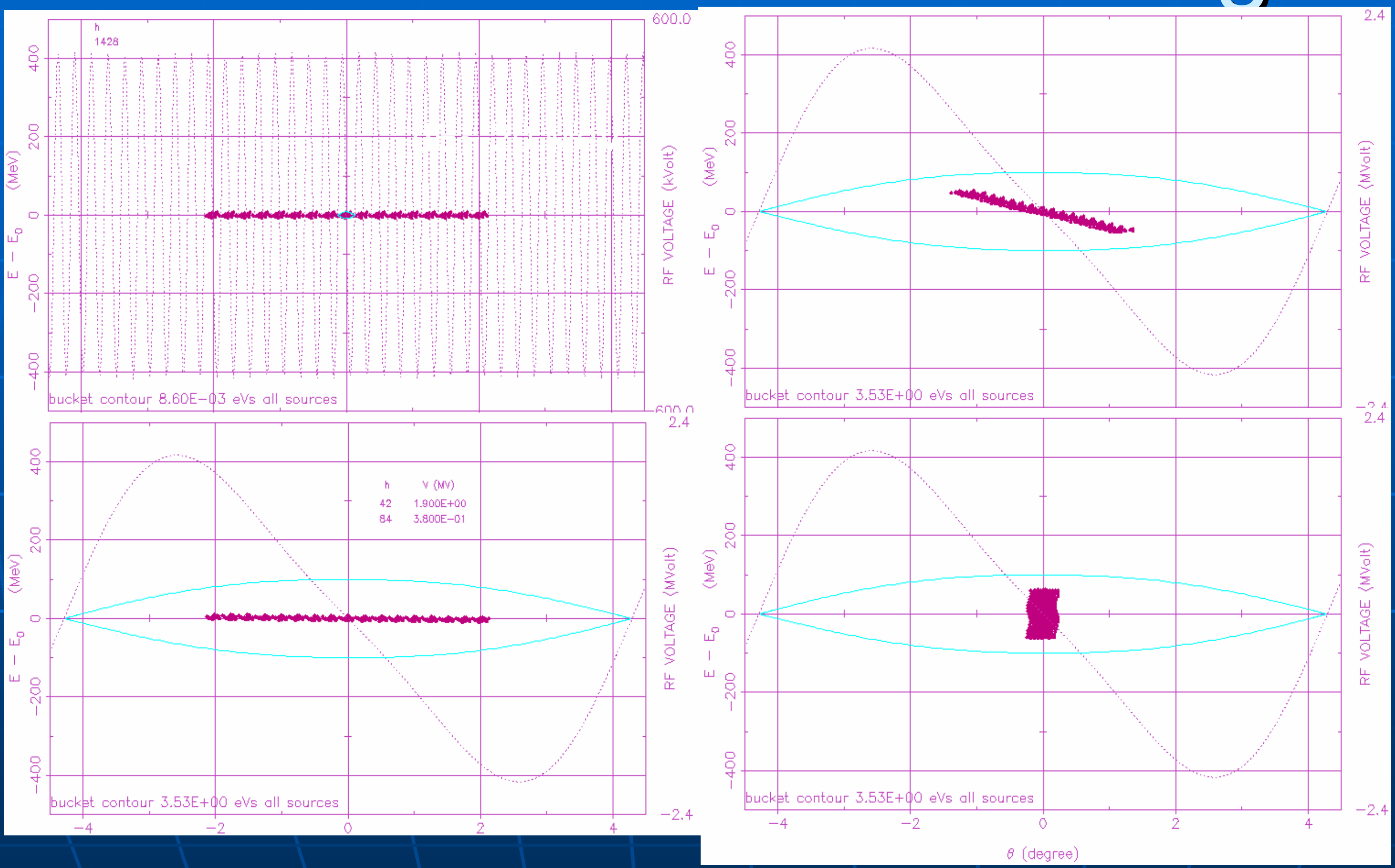


Concept of Reverse Emittance Exch.



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

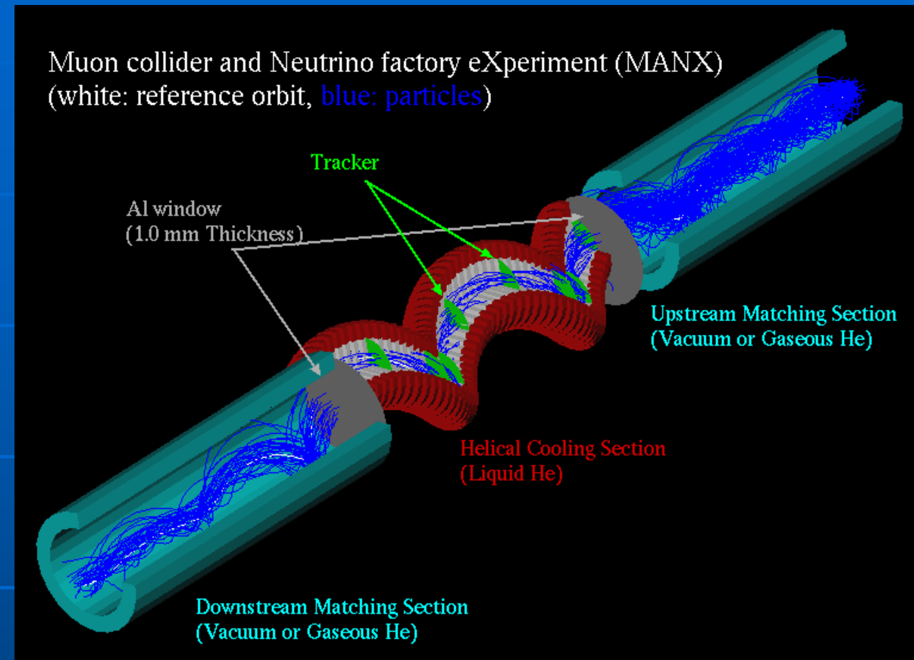
- To Demonstrate
  - Longitudinal cooling
  - 6D cooling in cont. absorber
  - Prototype precooler
  - Helical Cooling Channel
  - Use for stopping muon beams
  - New technology

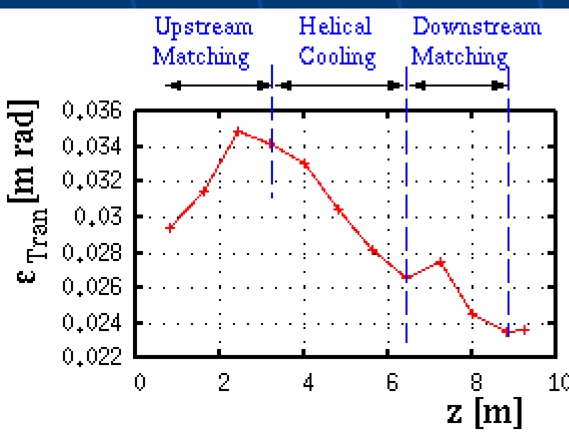
Katsuya's Simulation study

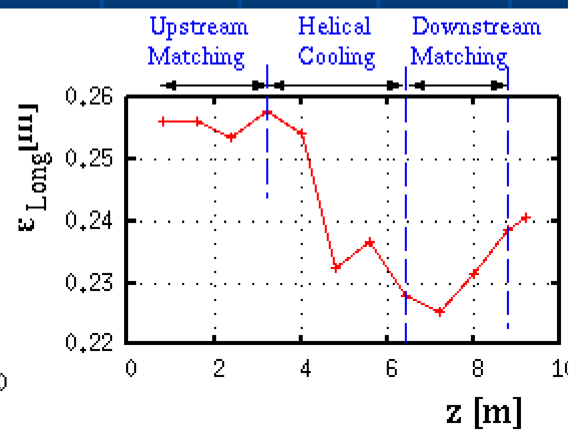
Initial beam profile

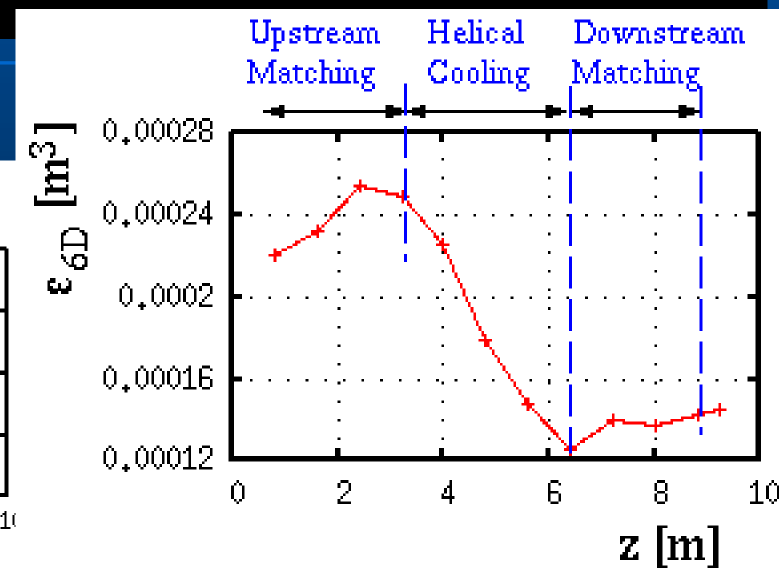
- Beam size (rms): ± 60 mm
- $\Delta p/p$ (rms): ± 40/300 MeV/c
- x′ and y′ (rms): ± 0.4

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









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

(For other paths to LEMCs, see
THPMS090 A Complete Scheme of Ionization Cooling for a Muon Collider, - Palmer et al., and
THPMS082 Muon Acceleration to 750 GeV in the Fermilab Tevatron Tunnel for a 1.5 TeV mu+ mu- Collider - Summers et al.)
.

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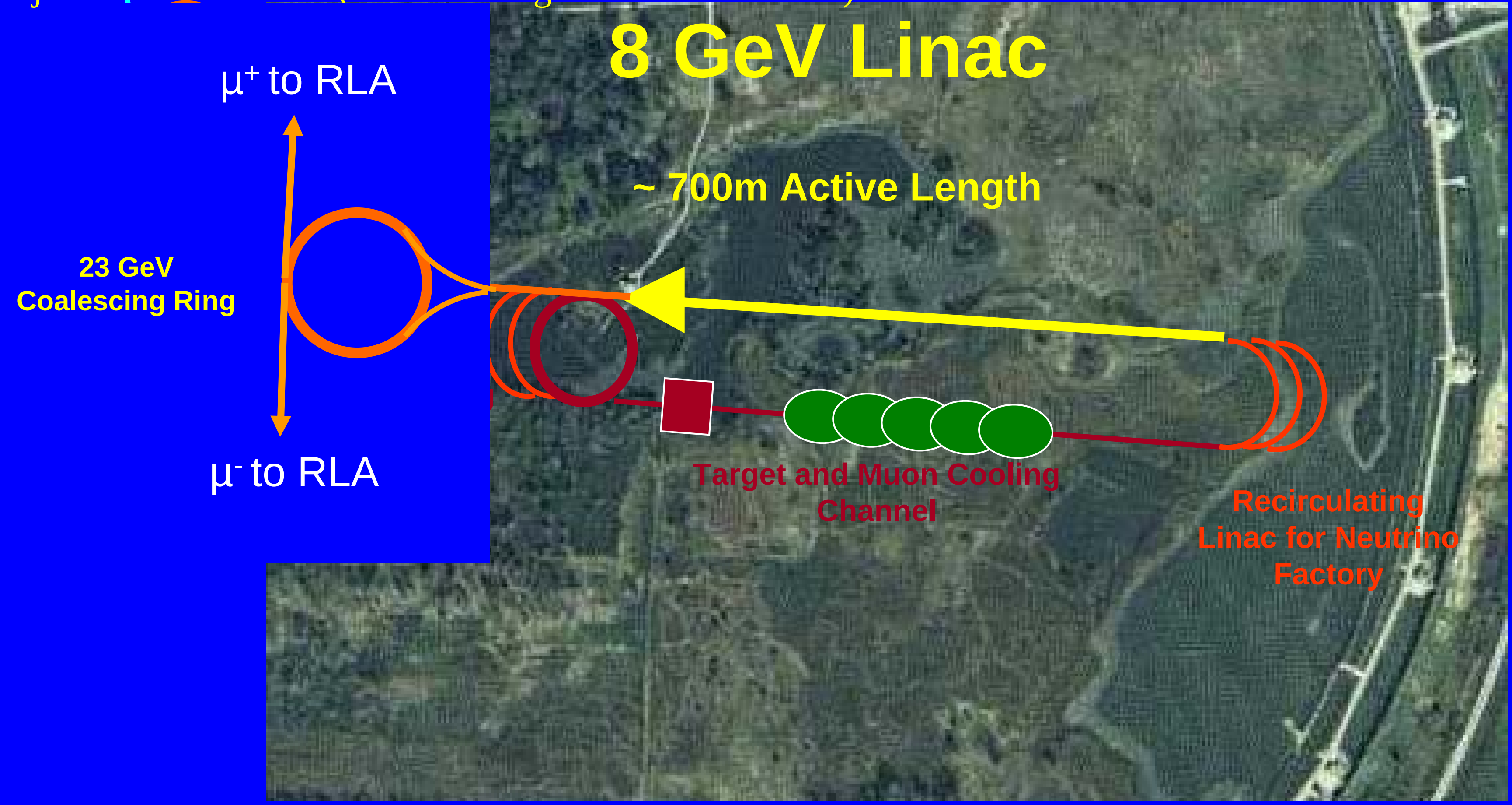
Muon Collider use of 8 GeV SC Linac

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

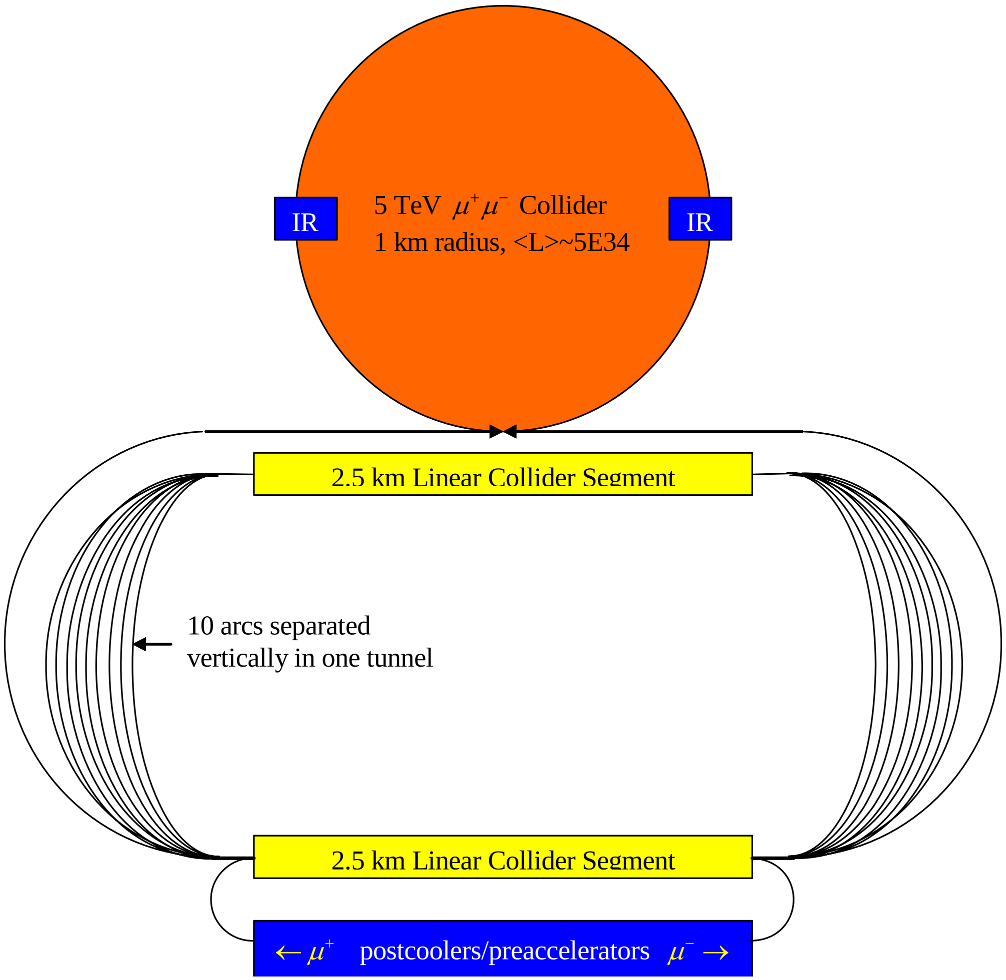
~5 X 2.5 km footprint

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

Muon Collider Emittances and Luminosities

	ε_N tr	ε_N long.
• After:		
– 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

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

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

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

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

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

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

20 Hz Operation:

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

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

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

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.

See the LEMC Workshop web page. And please come to the next workshop in February, 2008!

Low Emittance Muon Collider Next Steps: 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

High-Energy High-Luminosity Muon Colliders

- Are precision lepton machines at the energy frontier
- Are possible and affordable with new inventions and new technology
- Can take advantage of ILC advances
- Can be achieved in physics-motivated stages
- Require more effort from DPB and DPF communities
  - Please join in!