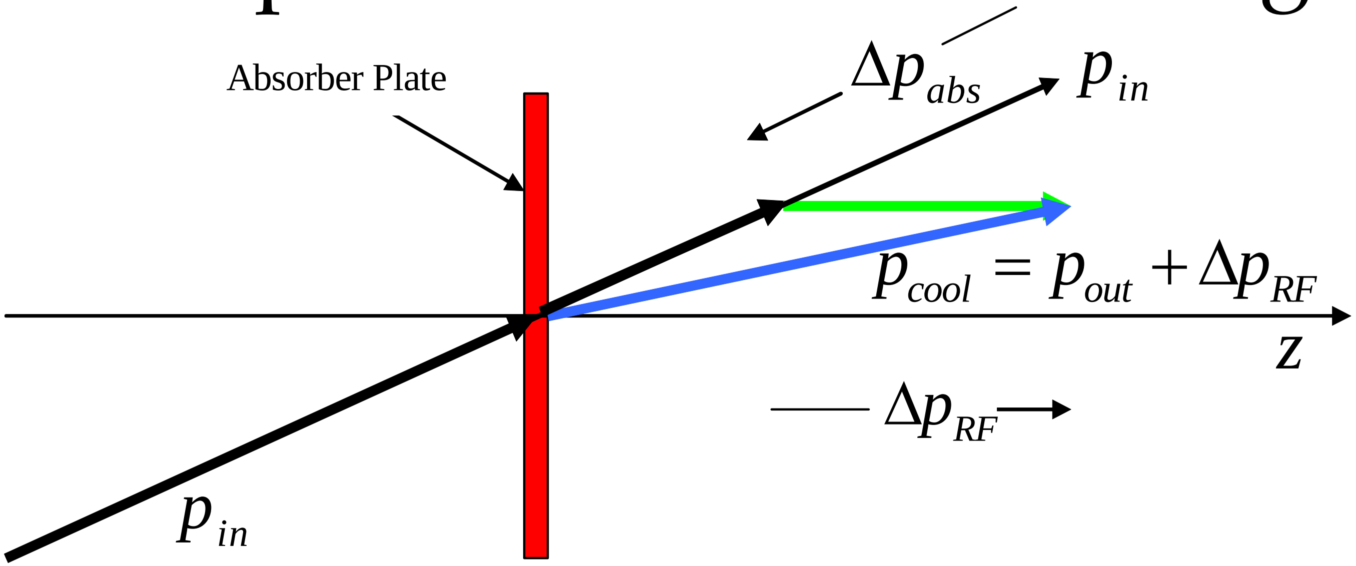
Ionization Cooling

Rolland P. Johnson
Muons, Inc.

Please visit "Papers and Reports" and
"LEMC Workshop" at
http://www.muonsinc.com/

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 is the muon energy in GeV, dE_μ/ds and X_0 are 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.

I. C. Figure of Merit

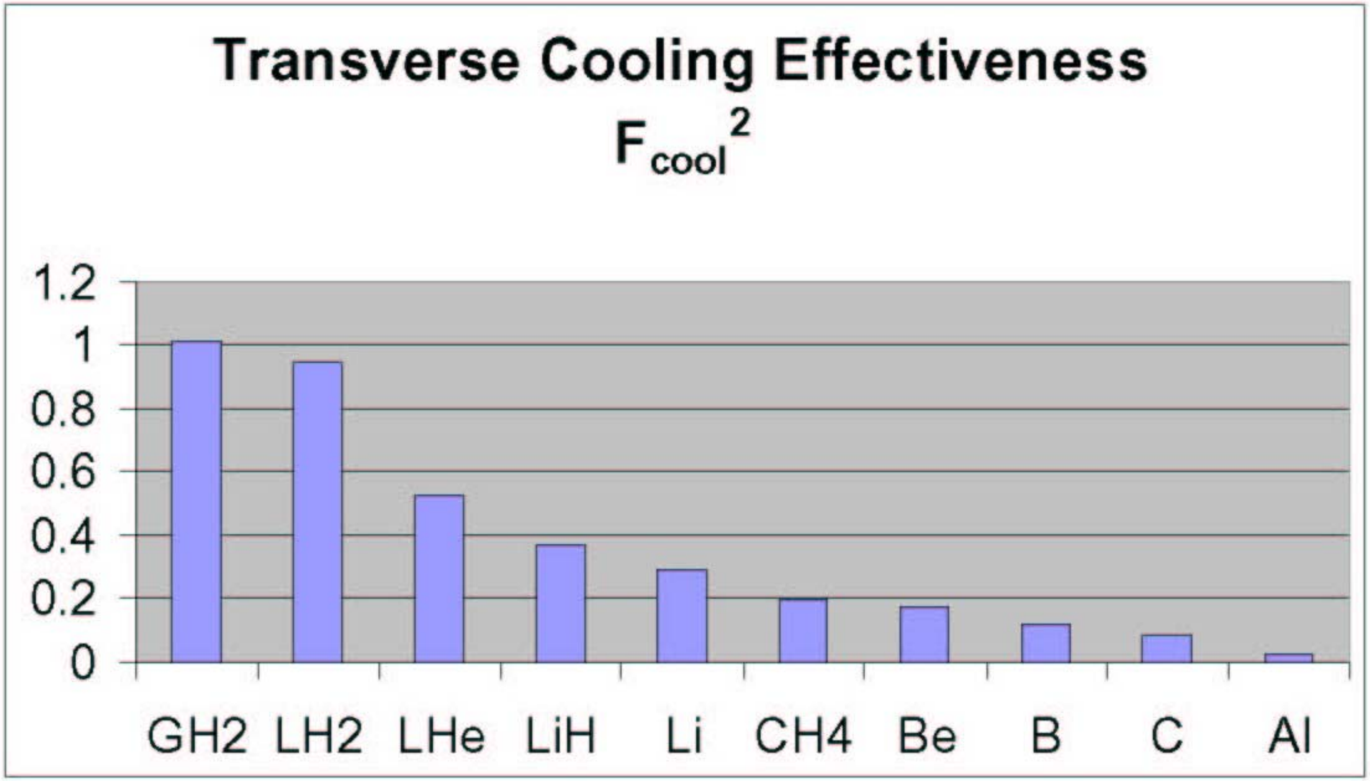
- Setting the heating and cooling terms equal defines the equilibrium emittance:

$$\varepsilon_n^{(equ.)} = \frac{\beta_\perp (0.014)^2}{2\beta m_\mu \frac{dE_\mu}{ds} X_0} \quad , where\ \beta_\perp \approx \frac{p_Z}{B_Z}$$

Small emittance means large X_0, dE/ds, B_z, and small p.

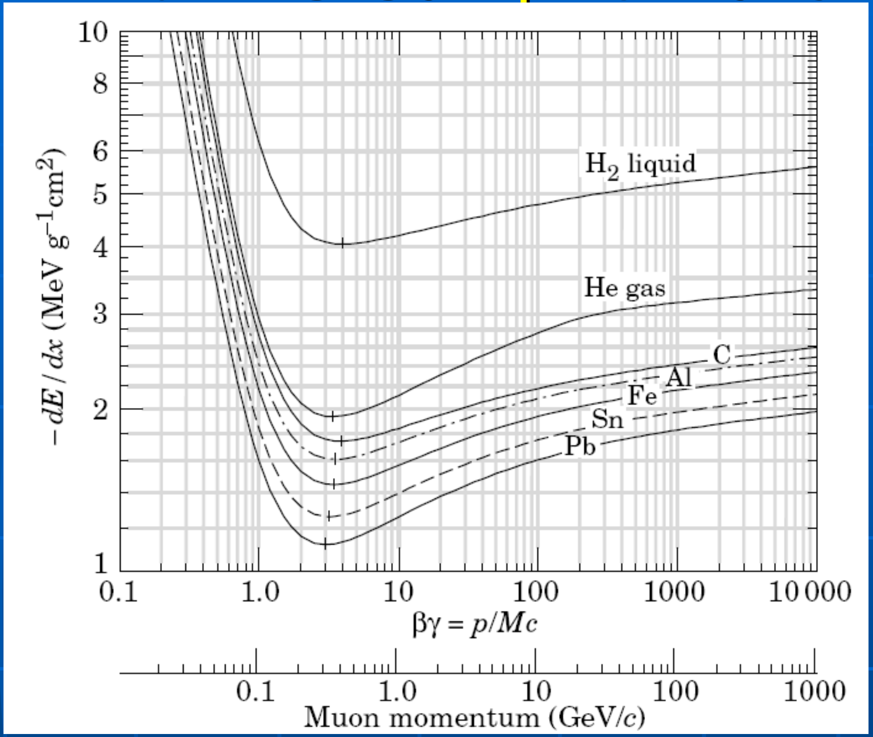
A cooling factor ($F_{cool} = X_0 dE_\mu/ds$) can be uniquely defined for each material, and since cooling takes place in each transverse plane, the figure of merit is F_{cool}^2. For a particular material, F_{cool} is independent of density, since energy loss is proportional to density, and radiation length is inversely proportional to density.

Comparison of Absorber Materials



(because of density and mechanical properties, Be is best for some cooling applications like PIC and REMEX)

A few IC Complications



Slope of dE/dx too small for longitudinal cooling if p>300

-also channel gets too long to cool at high p since 1/e folding is ΔE/E

Want $\beta_\perp \approx p/B$ as small as possible:

Reducing p difficult as the slope of dE/dx implies longitudinal heating for p<300.

-Synchrotron motion then makes cooling channel design more difficult.

-Can compensate with more complex dispersion function or absorber shape

Increasing B means new technology

Wedges or Continuous Energy Absorber for Emittance Exchange and 6d Cooling

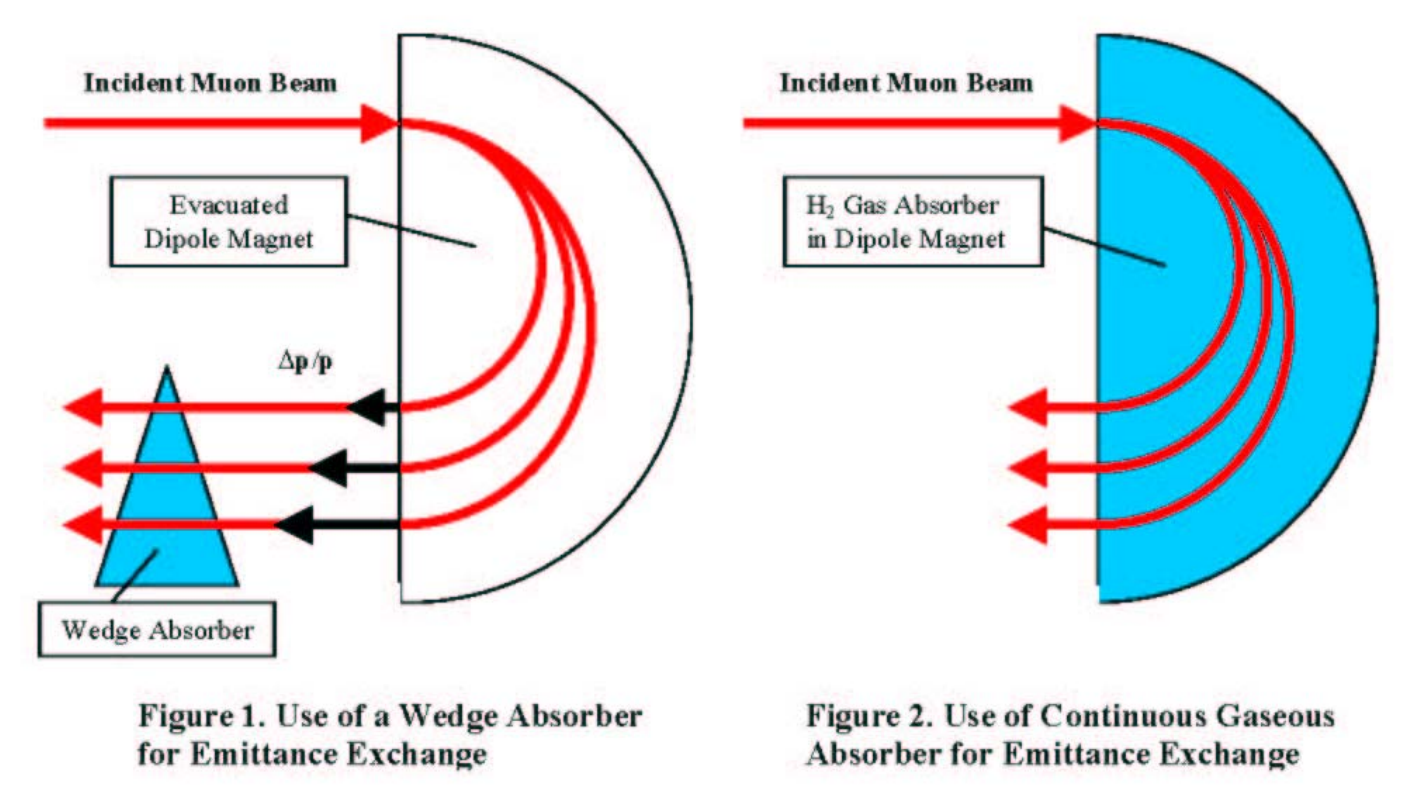


Figure 1. Use of a Wedge Absorber for Emittance Exchange

Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Ionization Cooling is only transverse. To get 6D cooling, emittance exchange between transverse and longitudinal coordinates is needed.

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	HTS Magnets	$795,000	FNAL TD
2005-8	Reverse Emittance Exch.	$850,000	JLab
2005-8	Capture, ph. rotation	$850,000	FNAL AD
2006-9	G4BL Sim. Program	$850,000	IIT
2006-9	MANX 6D Cooling Demo	$850,000	FNAL TD
2007-8	Stopping Muon Beams	$100,000	FNAL APC
2007-8	HCC Magnets	$100,000	FNAL TD
2007-8	Compact, Tunable RF	$100,000	FNAL AD
		$6,785,000 ($3,285,000 COOL05)	

[†] Not continued to Phase II

DOE 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 11 PAC07 papers on progress)

Ultimate Goal: High-Energy High-Luminosity Muon Colliders

- precision lepton machines at the energy frontier
- possible with new inventions and new technology
  - can take advantage of ILC advances
- achieved in physics-motivated stages
  - stopping muon beams
  - neutrino factory
  - Higgs factory
  - Energy-frontier muon collider

Basic Ideas

- A six-dimensional (6D) ionization cooling channel based on helical magnets surrounding RF cavities filled with dense hydrogen gas is the basis for one plan to build muon colliders.
- This helical cooling channel (HCC) has solenoidal, helical dipole, and helical quadrupole magnetic fields, where emittance exchange is achieved by using a continuous homogeneous absorber.
  - (Andy Sessler as Bob Palmer will talk about a wedge-based scheme)
- Momentum-dependent path length differences in the hydrogen energy absorber provide the required correlation between momentum and ionization loss to accomplish longitudinal cooling.
  - Recent studies of an 800 MHz RF cavity pressurized with hydrogen, as would be used in this application, show that the maximum gradient is not limited by a large external magnetic field, unlike vacuum cavities.
  - Crucial radiation tests of HP RF will be done at Fermilab next year.
- New cooling ideas, such as Parametric-resonance Ionization Cooling and Reverse Emittance Exchange, will be employed to further reduce transverse emittances to a few mm-mr to allow high luminosity with fewer muons.
- Present concepts for a 1.5 to 5 TeV center of mass collider with average luminosity greater than 10^{34}/s-cm^2 include ILC RF to accelerate positive and negative muons in a 10-pass RLA.
- a new precooling idea based on a HCC with *z* dependent fields is being developed for MANX, an exceptional 6D cooling experiment.

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

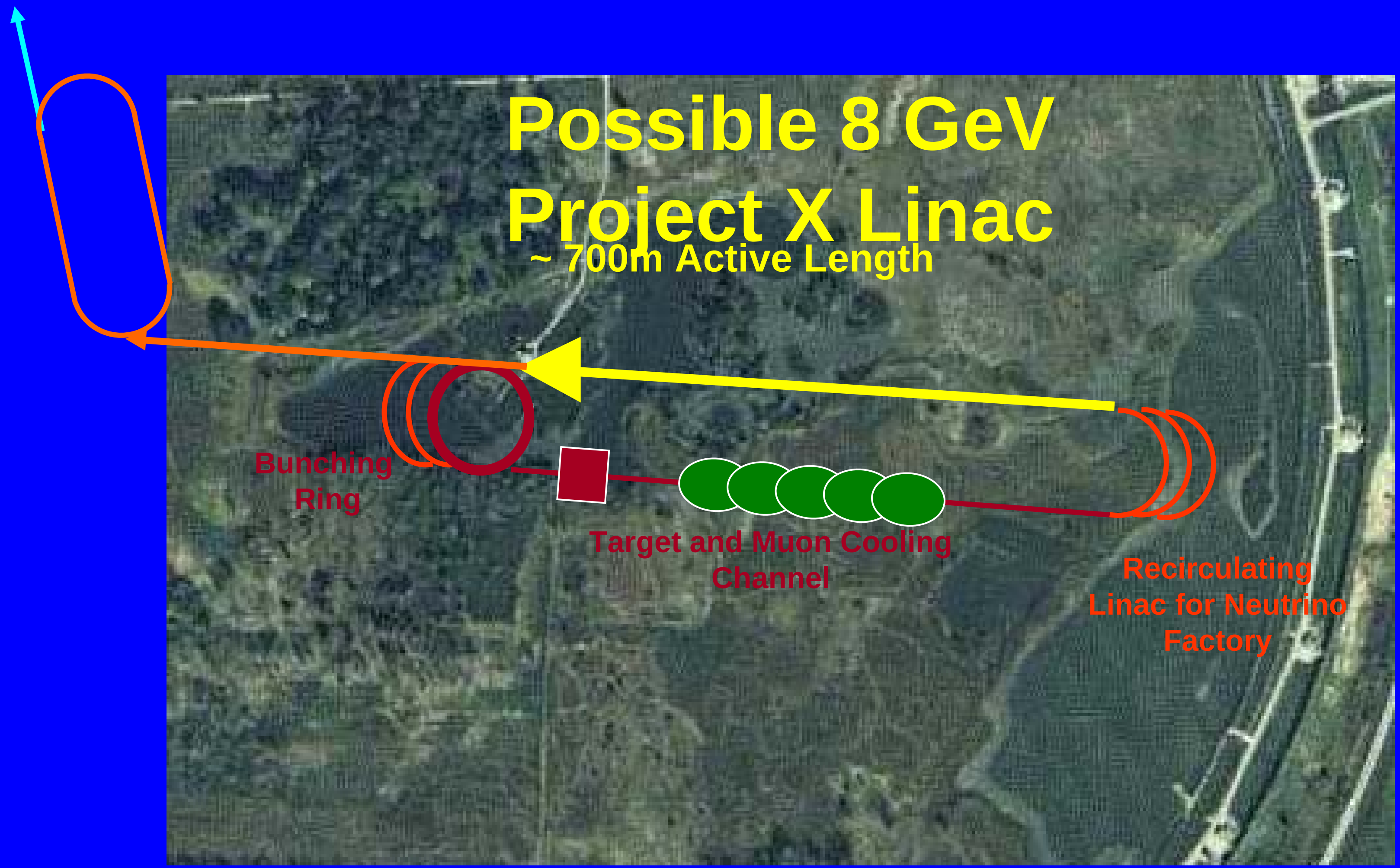
- A low-emittance high-luminosity collider
  - high luminosity with fewer muons
  - First LEMC goal: E_{com}=5 TeV, <L>=10^{35}
  - Revised goal is 1.5 TeV to complement the LHC

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

Muons, Inc.

Neutrino Factory use of 8 GeV SC Linac

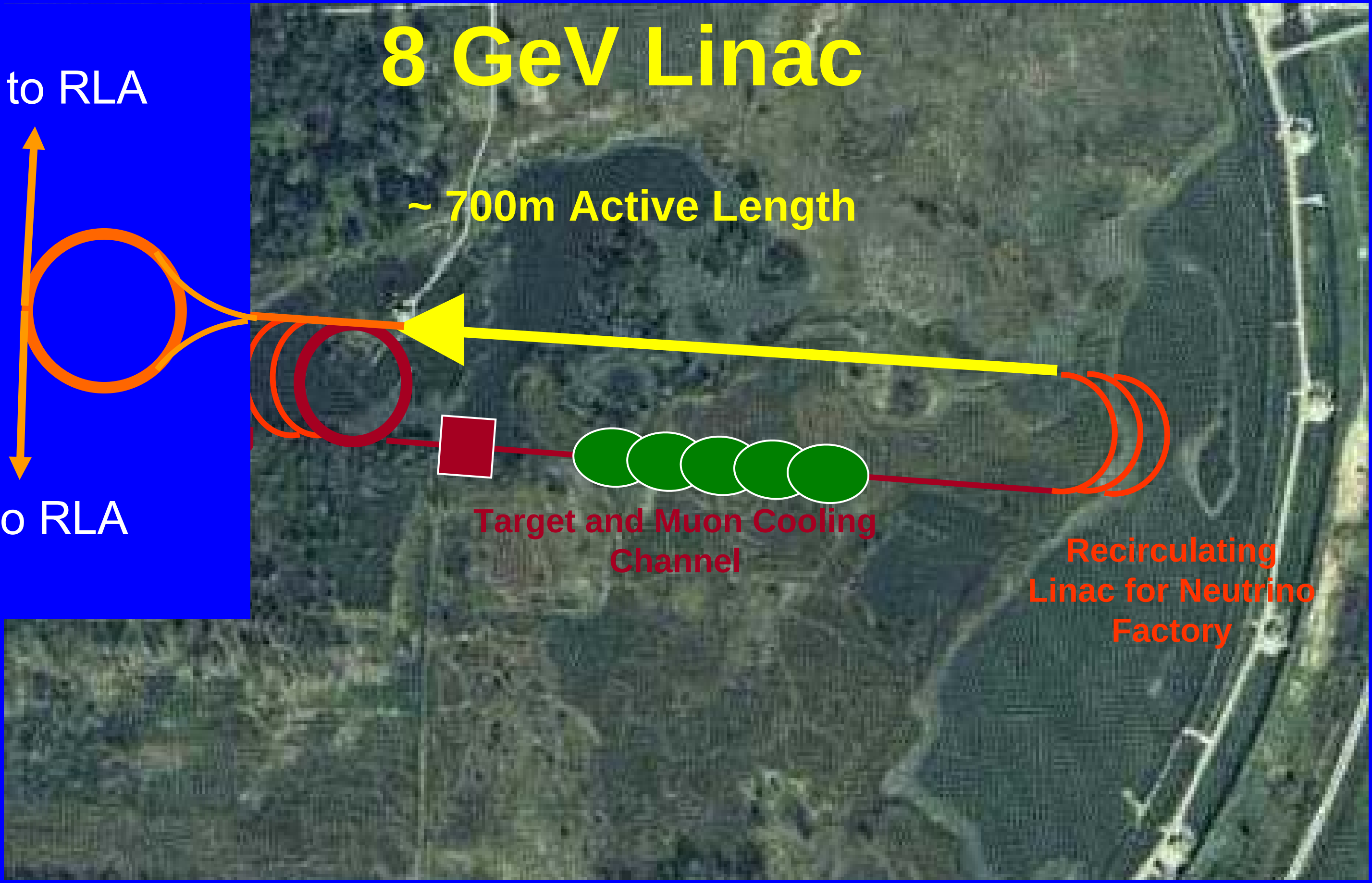
Beam cooling allows muons to be recirculated in the same linac that accelerated protons for their creation, Running the Linac CW can put a lot of cold muons into a small aperture neutrino factory storage ring.



Muons, Inc.

Muon Collider use of 8 GeV SC Linac

Or a coalescing ring (also new for COOL07) can prepare more intense bunches for a muon collider



5 TeV ~ SSC energy reach

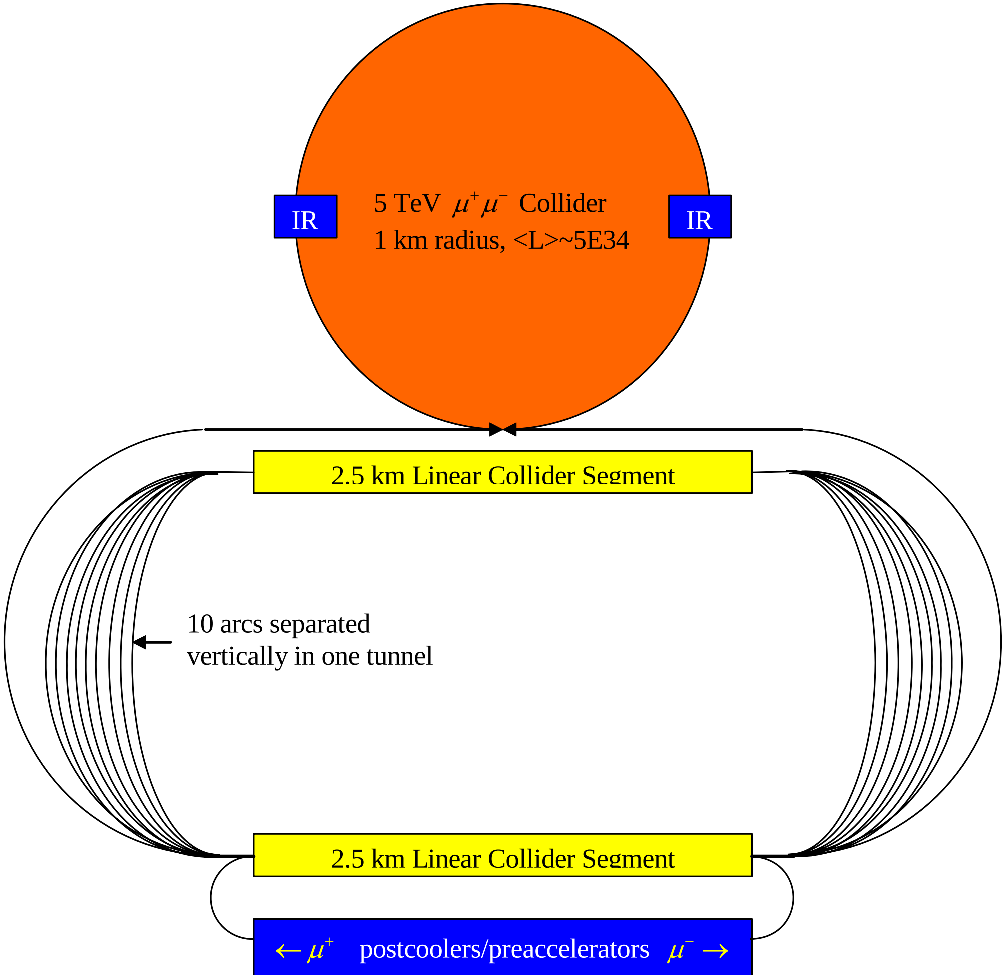
~5 X 2.5 km footprint

Affordable LC length (5 km), includes ILC people, ideas

More efficient use of RF: recirculation and both signs

High L from small emittance!

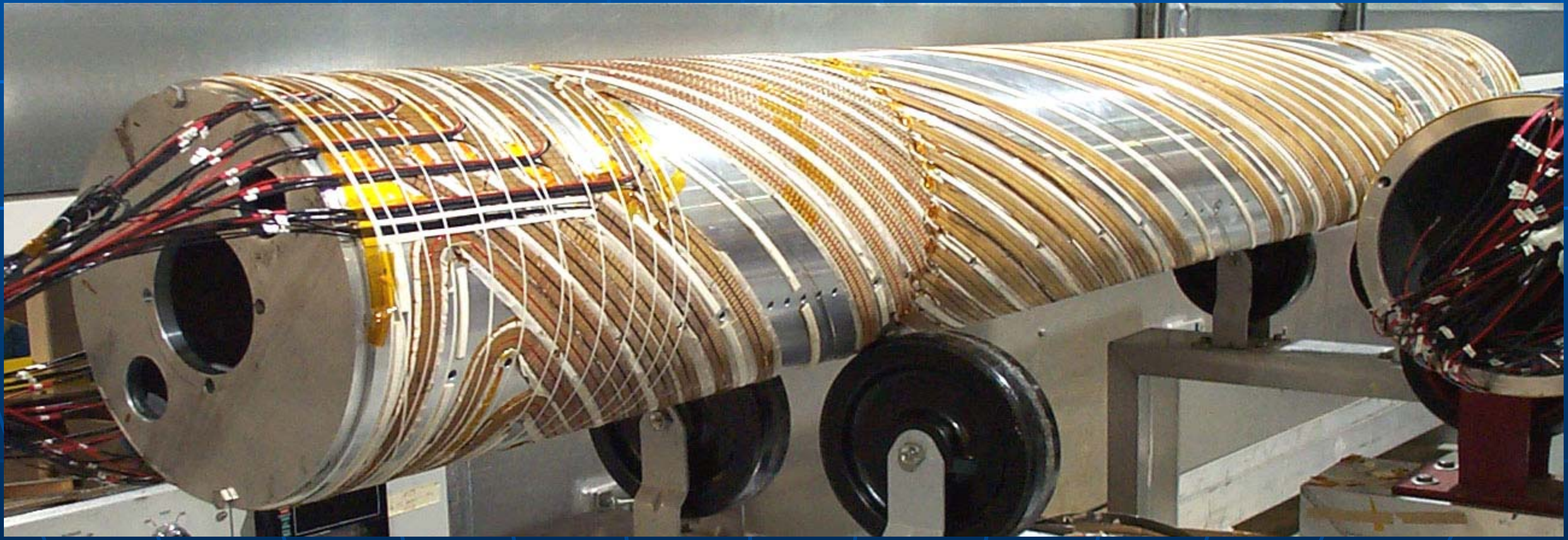
with fewer muons than originally imagined:
a) easier p driver, targetry
b) less detector background
c) less site boundary radiation



Beams from 23 GeV Coalescing Ring

Helical Cooling Channel

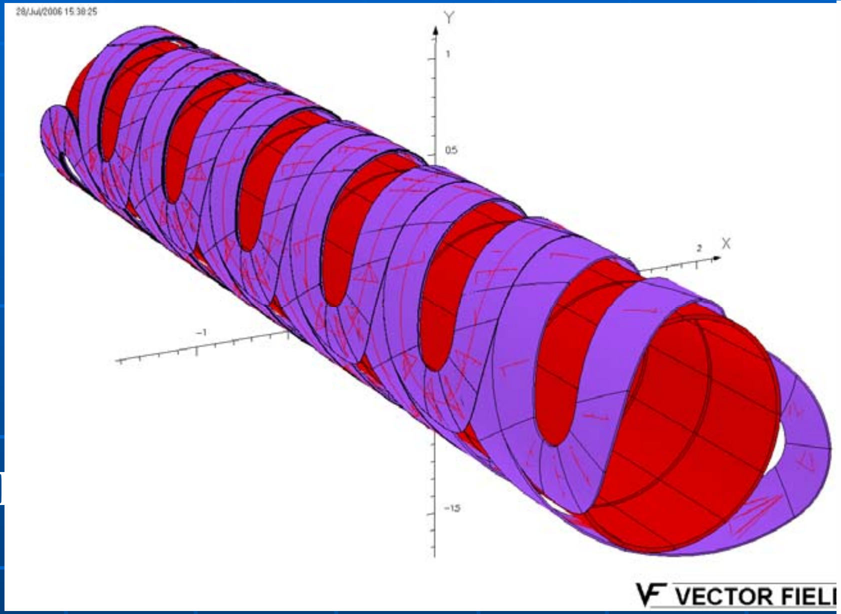
Continuous, homogeneous energy absorber for longitudinal cooling
Helical Dipole magnet component for dispersion
Solenoidal component for focusing
Helical Quadrupole for stability and increased acceptance



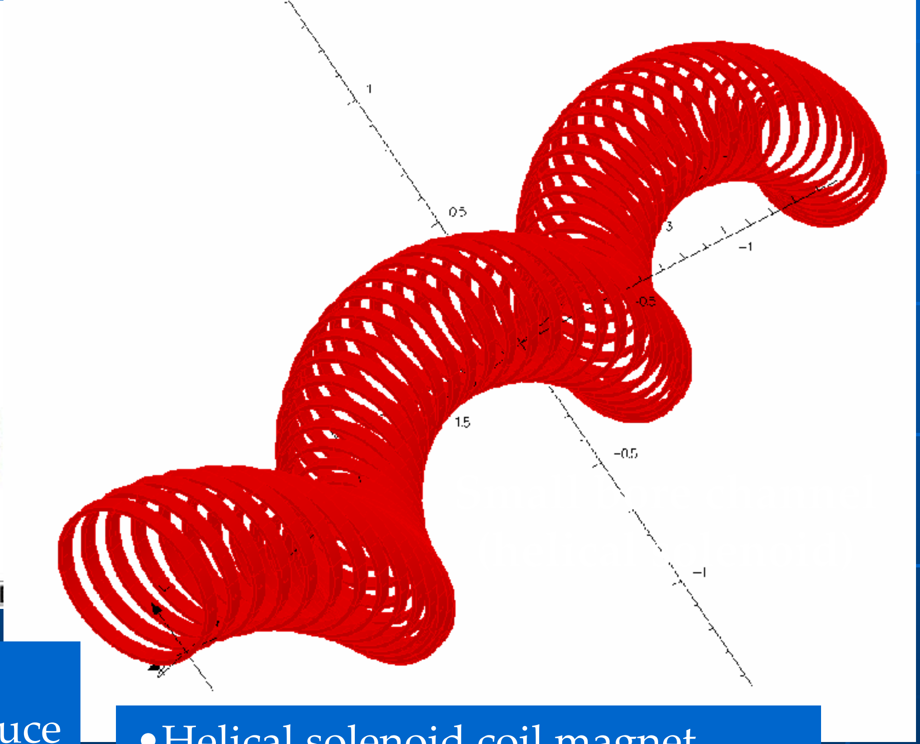
BNL Helical Dipole magnet for AGS spin control

Two Different Designs of Helical Cooling Magnet

Great new for COOL07 innovation!



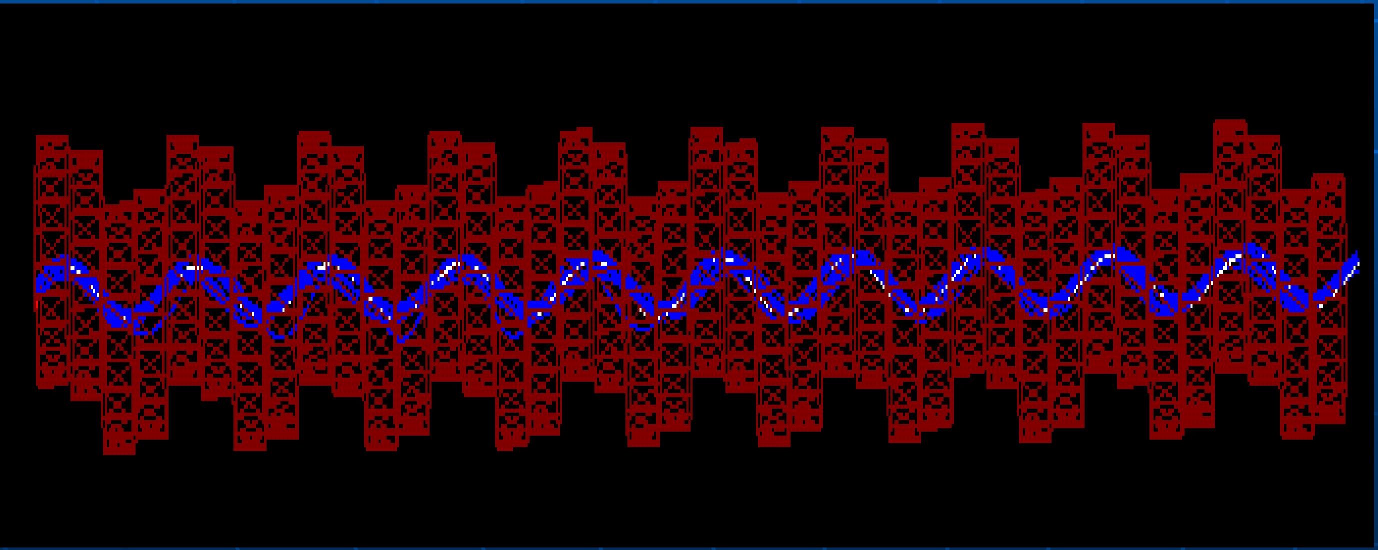
- Siberian snake type magnet
- Consists of 4 layers of helix dipole to produce tapered helical dipole fields.
- Coil diameter is 1.0 m.
- Maximum field is more than 10 T.

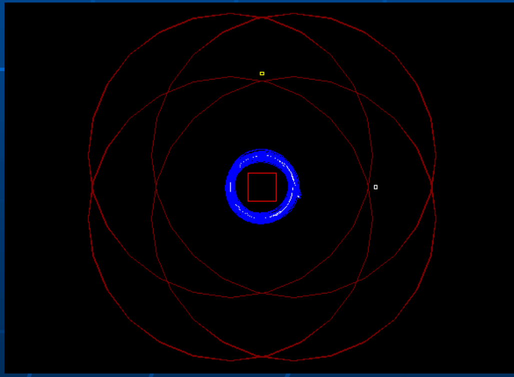


- Helical solenoid coil magnet
- Consists of 73 single coils (no tilt).
- Maximum field is 5 T
- Coil diameter is 0.5 m.

6-Dimensional Cooling in a Continuous Absorber

- Helical cooling channel (HCC)
  - Continuous absorber for emittance exchange
  - Solenoidal, transverse helical dipole and quadrupole fields
  - Helical dipoles known from Siberian Snakes
  - z- and time-independent Hamiltonian
  - Derbenev & Johnson, Theory of HCC, April/05 PRST-AB
    - http://www.muonsinc.com/reports/PRSTAB-HCCtheory.pdf

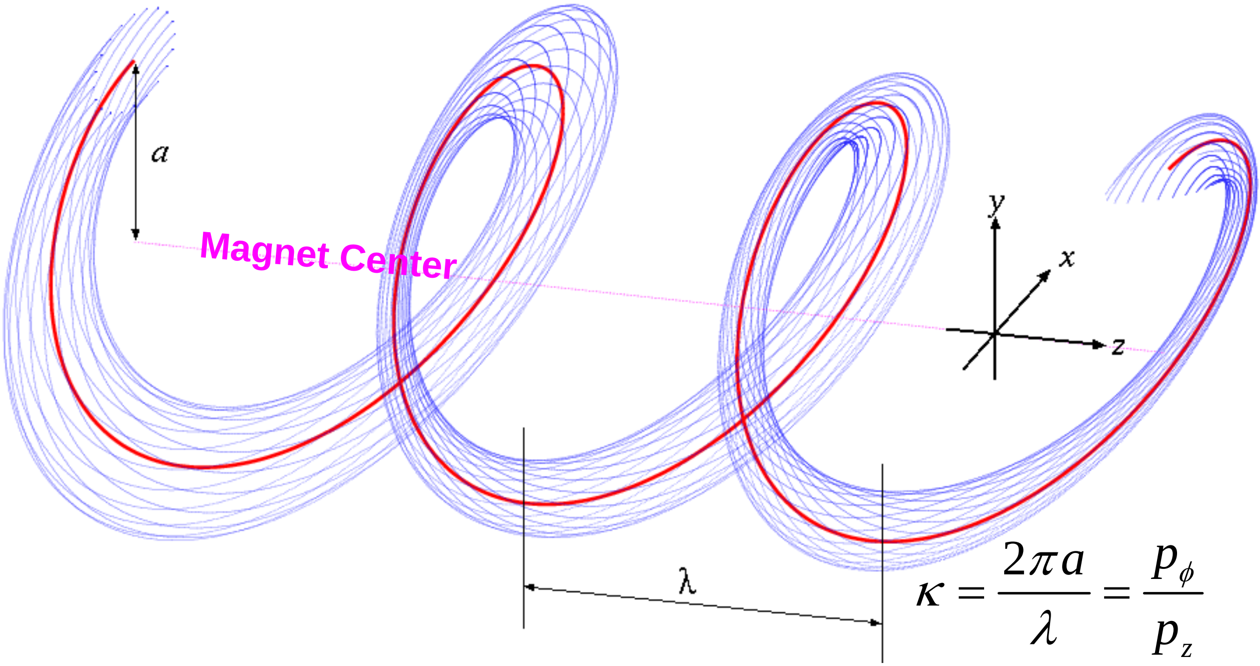




Particle Motion in a Helical Magnet

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

$$q \equiv \frac{k_c}{k} - 1 = \beta\sqrt{\frac{1+\kappa^2}{3-\beta^2}} \qquad k_c = B\sqrt{1+\kappa^2}/p$$

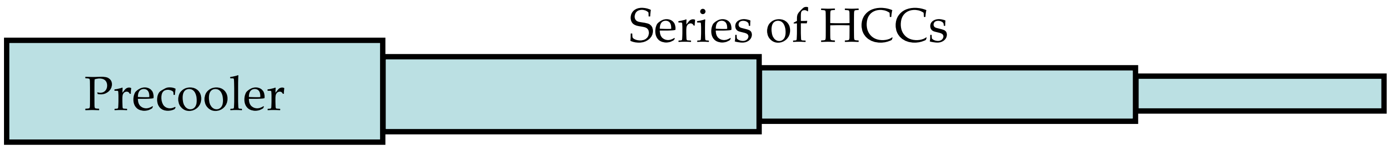
Longitudinal cooling only

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

~Momentum slip factor

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

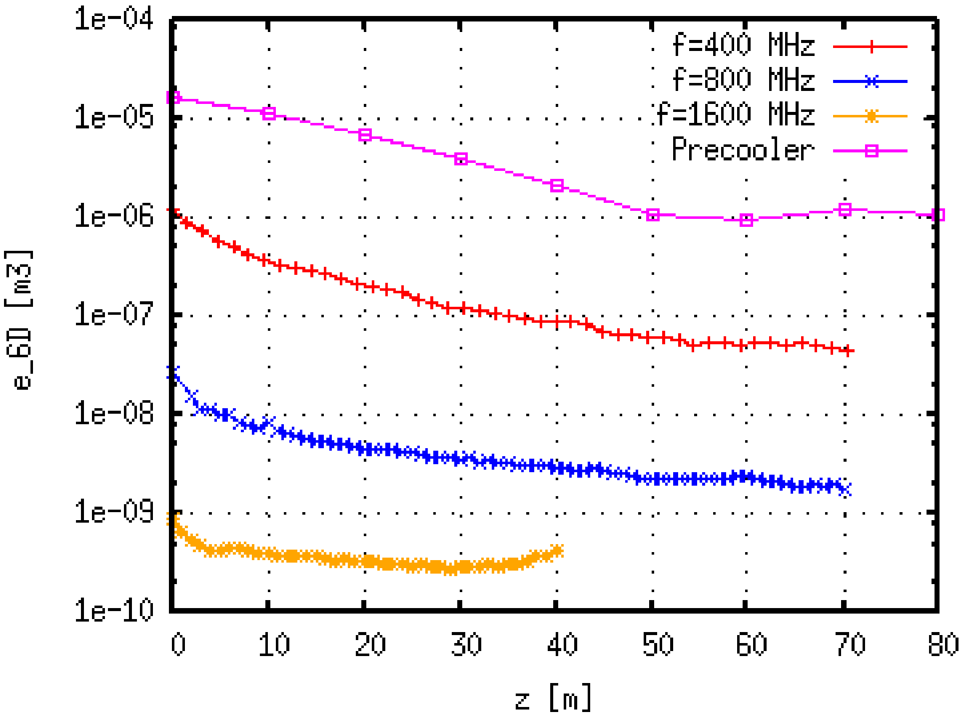
Precooler + HCCs
With first engineering constraints



Series of HCCs

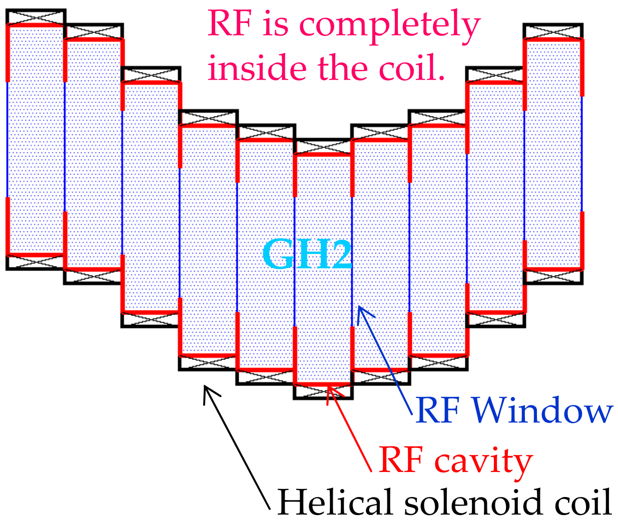
Precooler

Solenoid + High Pressurized RF



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

Engineering HCC with RF



- Use a pillbox cavity (but no window this time).
- RF frequency is determined by the size of helical solenoid coil.

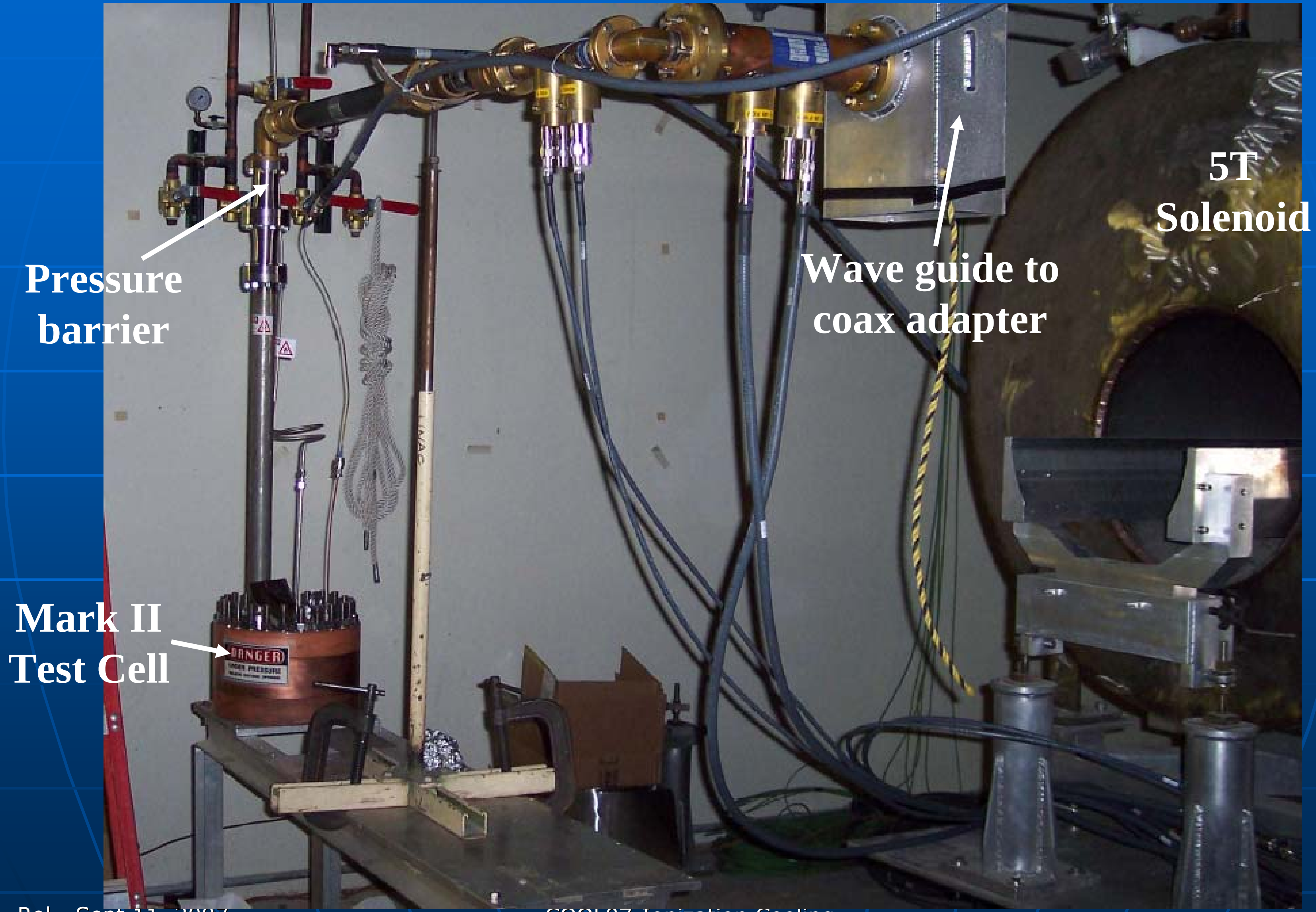
→Diameter of 400 MHz cavity = 50 cm
→Diameter of 800 MHz cavity = 25 cm
→Diameter of 1600 MHz cavity = 12.5 cm

- The pressure of gaseous hydrogen is 200 atm at room temp to adjust the RF field gradient to be a practical value.

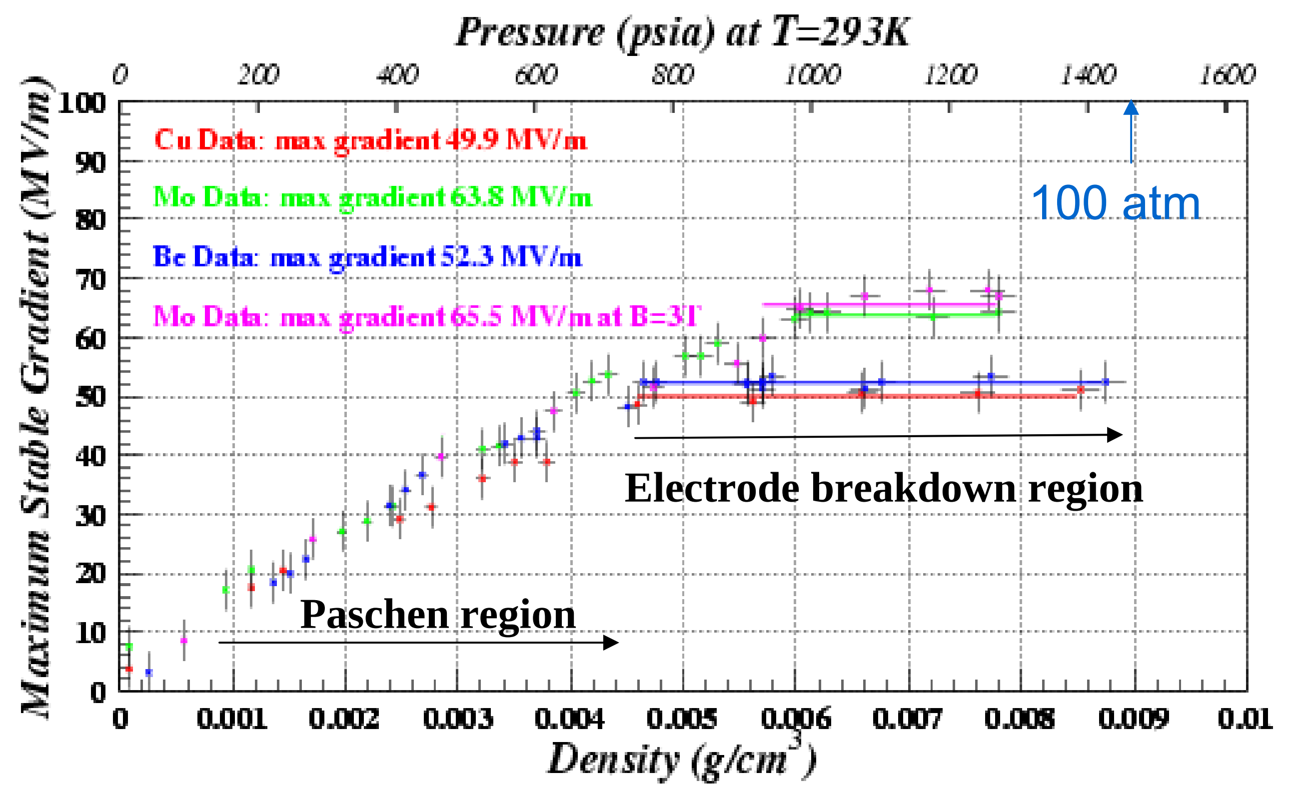
→The field gradient can be increased if the breakdown would be well suppressed by the high pressurized hydrogen gas.

parameters	λ	κ	*Bz*	*bd*	*bq*	*bs*	*f*	*Inner d of coil*	*Expected Maximum b*	*E*	*RF phase*
unit	*m*		*T*	*T*	*T/m*	*T/m2*	*GHz*	*cm*	*T*	*MV/m*	*degree*
1st HCC	*1.6*	*1.0*	*-4.3*	*1.0*	*-0.2*	*0.5*	*0.4*	*50.0*	*6.0*	*16.4*	*140.0*
2nd HCC	*1.0*	*1.0*	*-6.8*	*1.5*	*-0.3*	*1.4*	*0.8*	*30.0*	*8.0*	*16.4*	*140.0*
3rd HCC	*0.5*	*1.0*	*-13.6*	*3.1*	*-0.6*	*3.8*	*1.6*	*15.0*	*17.0*	*16.4*	*140.0*

MuCool Test Area (MTA)



HPRF Test Cell Measurements in MTA



- Paschen curve verified
- Maximum gradient limited by breakdown of metal.
- Cu and Be have same breakdown limits (~50 MV/m), Mo(~63MV/m), W(~75MV/m).
- Results show no B dependence, much different metallic breakdown than for vacuum cavities.
- **Need beam tests to prove HPRF works.**

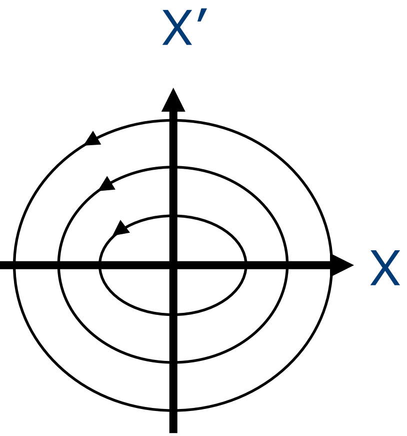
Parametric-resonance Ionization Cooling

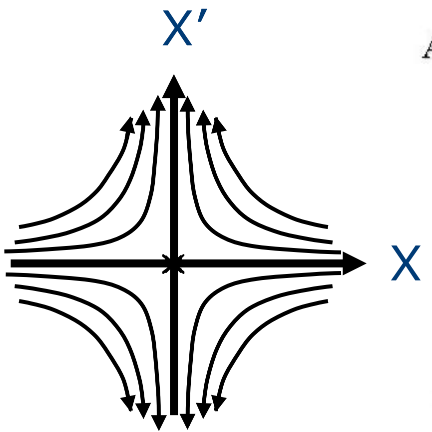
Excite ½ integer parametric resonance (in Linac or ring)

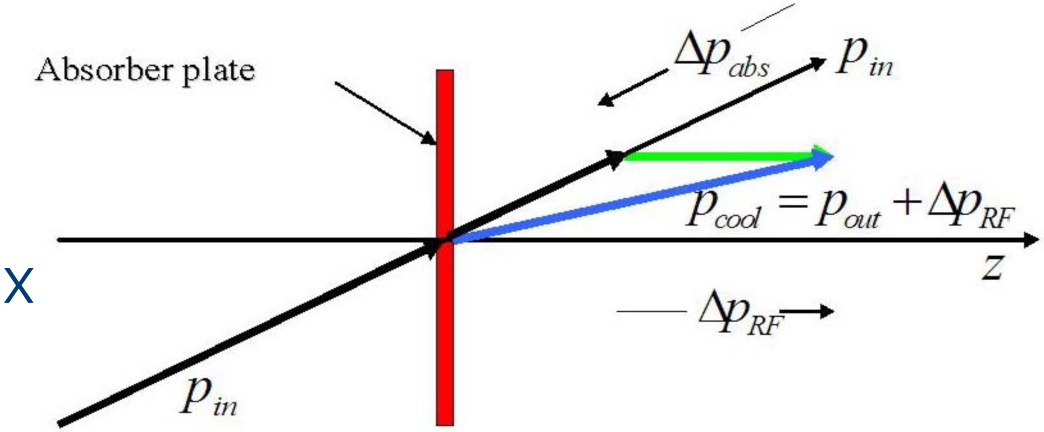
- Like vertical rigid pendulum or ½-integer extraction
- Elliptical phase space motion becomes hyperbolic
- Use xx'=const to reduce x, increase x'
- Use IC to reduce x'

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

Smaller beams from 6D HCC cooling essential for this to work!



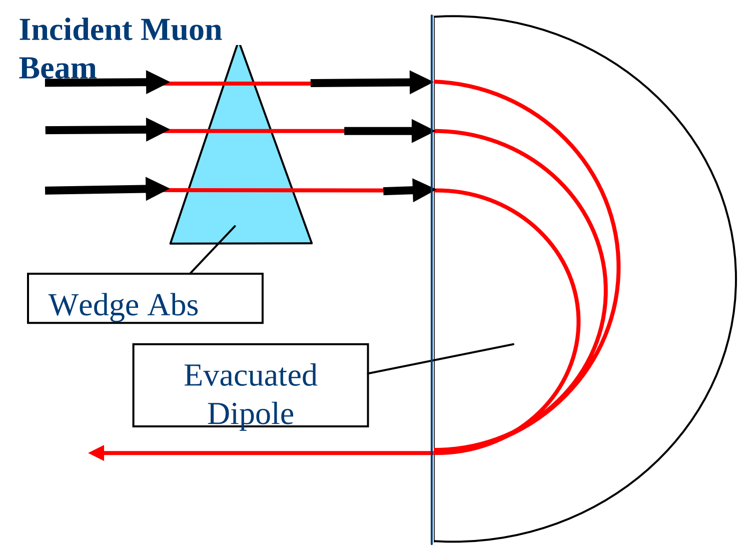




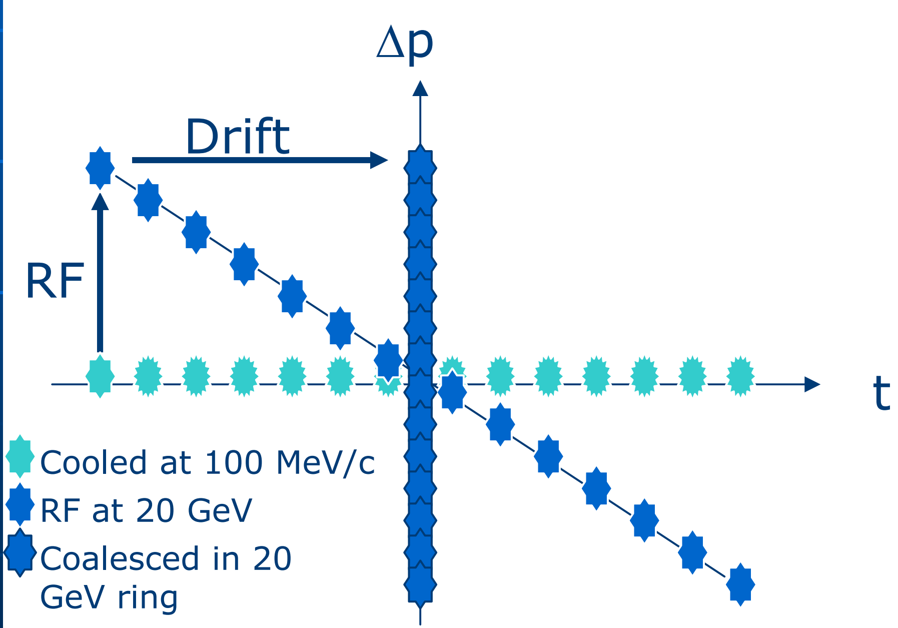
Muons, Inc.

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
- Allow bunch length to increase to size of low beta
- Low energy space charge, beam loading, wake fields problems avoided
- 20 GeV Bunch coalescing in a ring Neutrino factory and muon collider now have a common path



Concept of Reverse Emittance Exch.



1.3 GHz Bunch Coalescing at 20 GeV

Muon Collider Emittances and Luminosities

After:	ε_N tr	ε_N long.
Precooling	20,000μm	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

Many things get easier as muon lifetime increases!

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

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

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

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

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

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

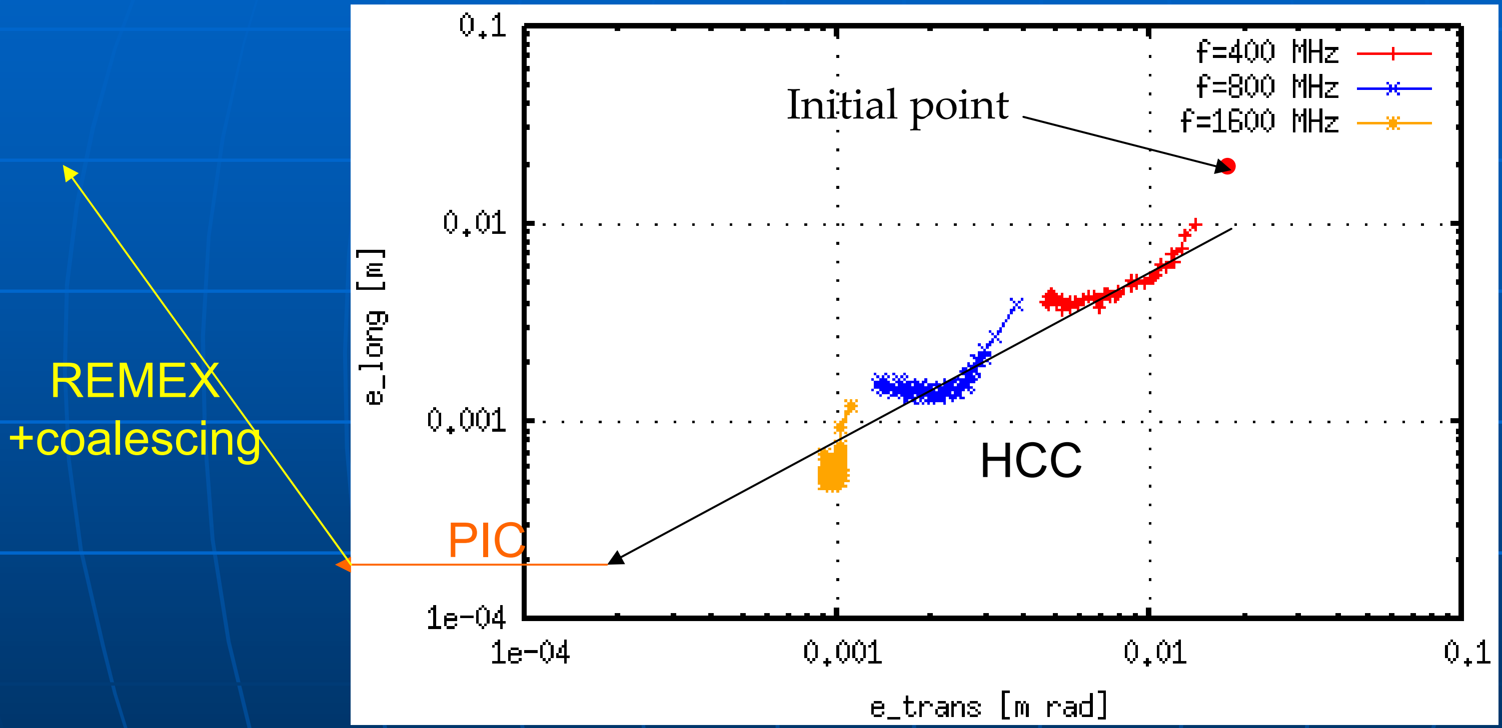
20 Hz Operation:

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

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

$0.3\mu^\pm / p$

Fernow-Neuffer Plot



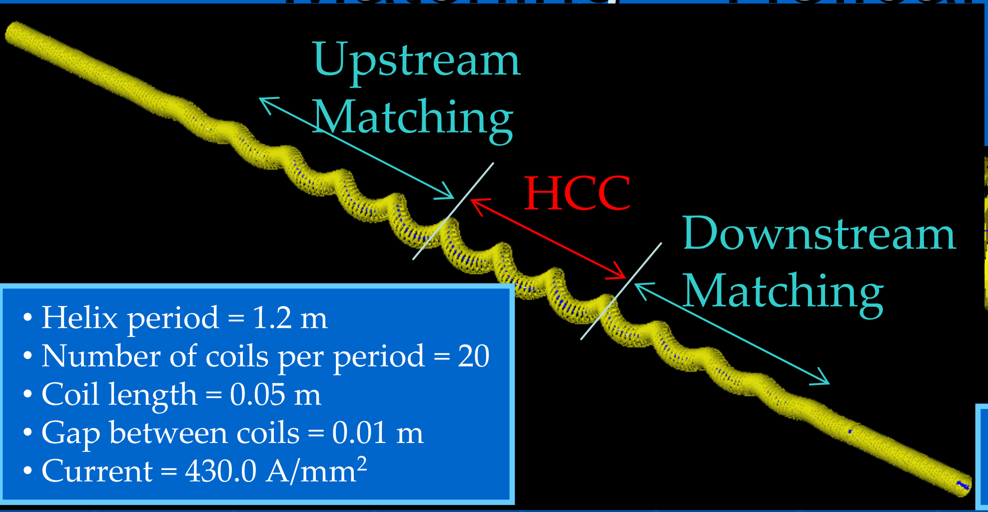
Cooling required for 5 TeV COM, 10^{35} Luminosity Collider.
Need to also look at losses from muon decay to get power on target.
Higher magnetic fields from HTS can get required HCC performance.

new ideas under development:

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

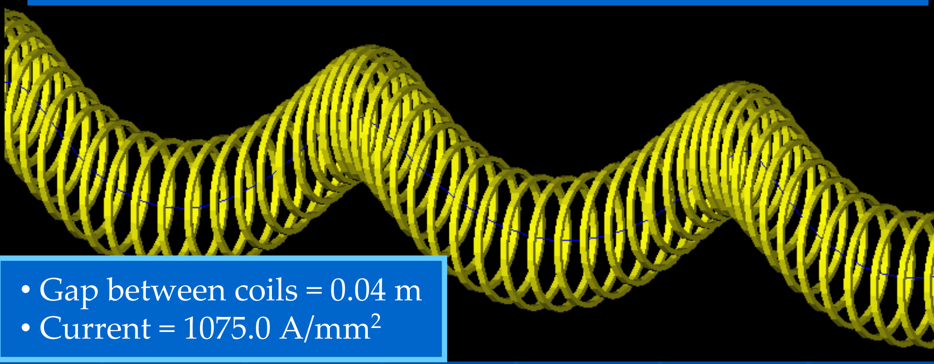
Besides these SBIR-STTR supported projects, note that Bob Palmer, Rick Fernow, and Steve Kahn have another path to low emittance.

Matching + Helical Cooling Magnets

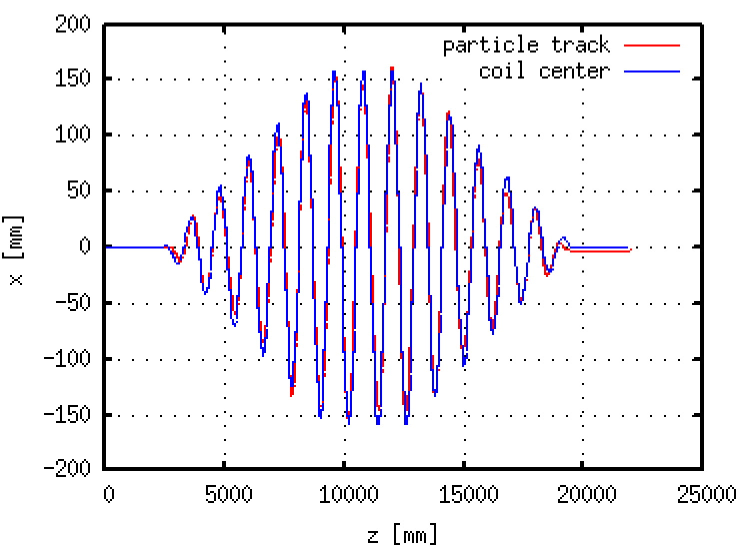


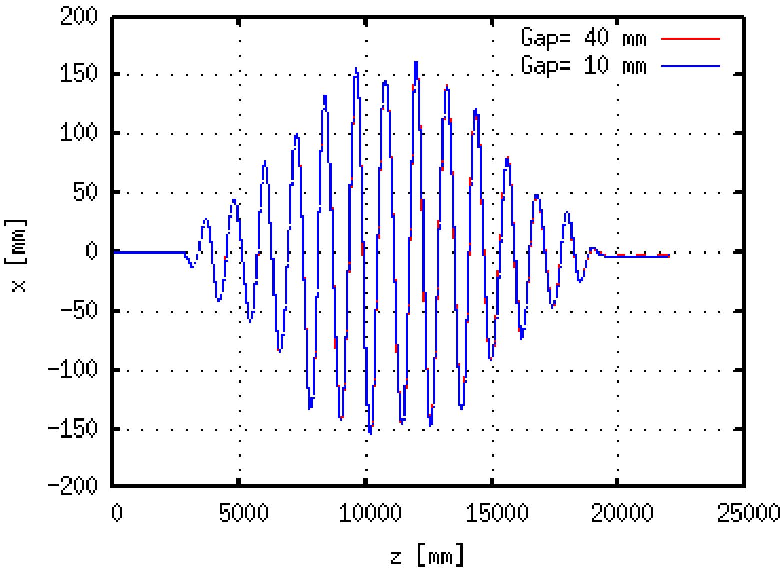
- Helix period = 1.2 m
- Number of coils per period = 20
- Coil length = 0.05 m
- Gap between coils = 0.01 m
- Current = 430.0 A/mm^2

Increase gap between coils from 10 to 40 mm

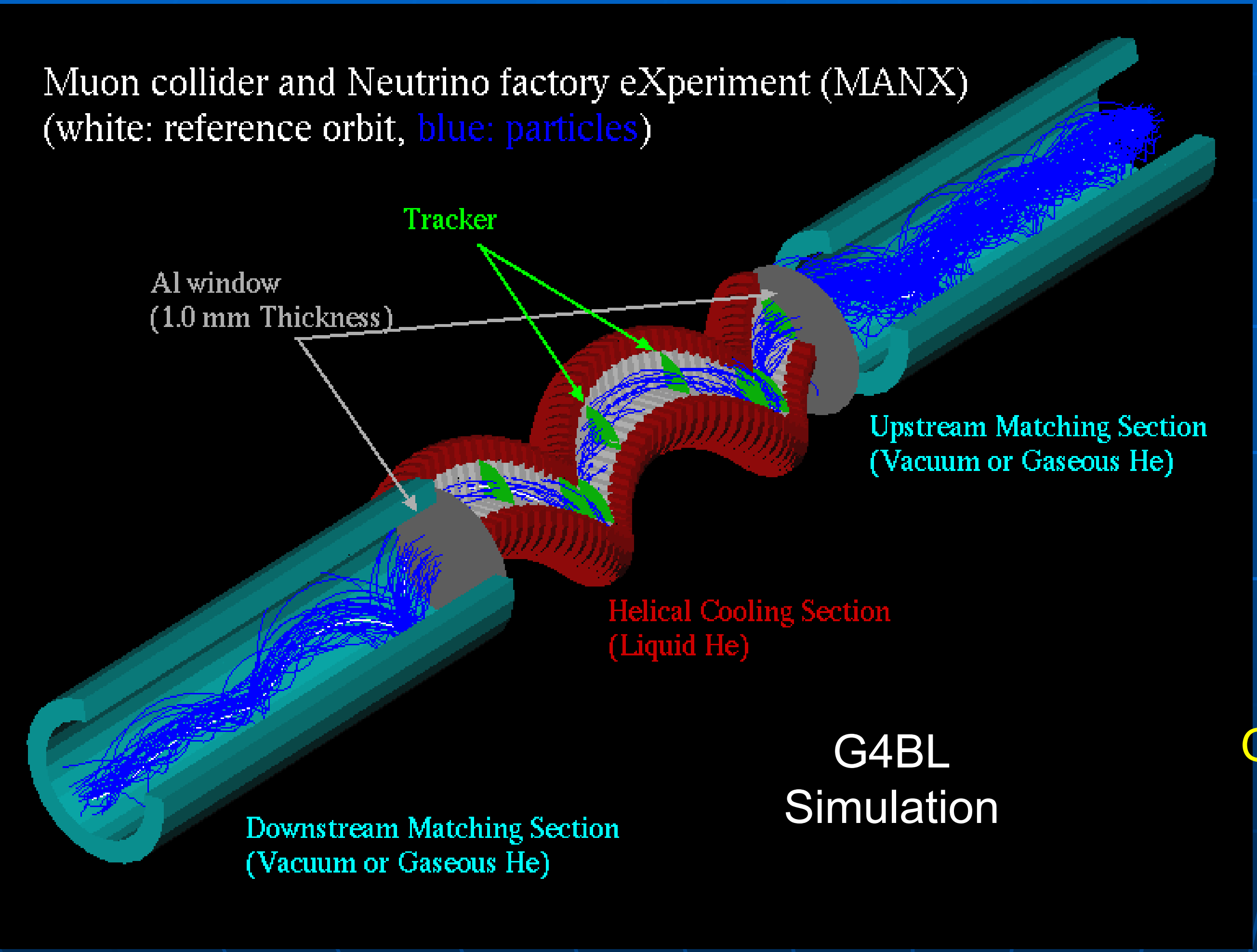


- Gap between coils = 0.04 m
- Current = 1075.0 A/mm^2





Overview of MANX channel



Muon collider and Neutrino factory eXperiment (MANX)
(white: reference orbit, blue: particles)

G4BL
Simulation

- Use Liquid He absorber
- No RF cavity
- Length of cooling channel: 3.2 m
- Length of matching section: 2.4 m
- Helical pitch κ: 1.0
- Helical orbit radius: 25 cm
- Helical period: 1.6 m
- Transverse cooling: ~1.3
- Longitudinal cooling: ~1.3
- 6D cooling: ~2

Most Simulations use
G4Beamline (Muons, Inc.)
and/or ICOOL (BNL)

Updated Letter of Intent to Propose

MANX, A 6D MUON BEAM COOLING EXPERIMENT

Robert Abrams[1], Mohammad Alsharo'a[1], Charles Ankenbrandt[2], Emanuela Barzi[2], Kevin Beard[3], Alex Bogacz[3], Daniel Broemmelsiek[2], Alan Bross[2], Yu-Chiu Chao[3], Mary Anne Cummings[1], Yaroslav Derbenev[3], Henry Frisch[4], Stephen Geer[2], Ivan Gonin[2], Gail Hanson[5], Martin Hu[2], Andreas Jansson[2*], Rolland Johnson[1*], Stephen Kahn[1], Daniel Kaplan[6], Vladimir Kashikhin[2], Sergey Korenev[1], Moyses Kuchnir[1], Mike Lamm[2], Valeri Lebedev[2], David Neuffer[2], David Newsham[1], Milorad Popovic[2], Robert Rimmer[3], Thomas Roberts[1], Richard Sah[1], Vladimir Shiltsev[2], Linda Spentzouris[6], Alvin Tollestrup[2], Daniele Turrioni[2], Victor Yarba[2], Katsuya Yonehara[2], Cary Yoshikawa[2], Alexander Zlobin[2]

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

---

[*] Contact, rol@muonsinc.com, (757) 870-6943
[*] Contact, jansson@fnal.gov, (630) 840-2824

Important Developments Since COOL05

- ILC delays are inspiring muon cooling and muon collider research
    - Accelerator Physics Center formed at Fermilab, MCTF
    - New SBIR projects
- RF cavities pressurized with dense hydrogen under development
    - Support surface gradients up to 70 MV/m even in large magnetic fields
- Helical Solenoid magnet invention will simplify HCC designs
    - Prototype section SBIR funded for design, construction, and testing
    - New HTS materials look promising for very large fields
- MANX is close to being a supported 6D demonstration experiment
    - Collaboration being formed, experimental proposal drafted
    - Looking for collaborators!