LEMC Scenario

(More of a Goal)

Rolland Johnson,
Muons, Inc.

Muons, Inc. Philosophy

- Nothing designed today will be used exactly as imagined now
  - Better ideas always come along
- Muon Colliders need an existence-proof design
  - To get support (more attractive is better)
- Innovation is our contribution
  - Push ideas, technology
  - Source of our income

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14 2008 DOE Ph I Proposals

Working Title	Inst.	PI	subPI	DOE topic/office
Achromatic low beta for colliders	JLab	Johnson	Derbenev	49a HEP
RF Breakdown Studies	LBNL	Sah	Li	50a HEP RF
GUI for Radiation Simulations	Jlab	Roberts	Degtiarenko	3a BES
HTS High Field Magnets	FSU	Kahn	Schwartz	51a HEP HTS
High Power SRF coupler	JLab	Johnson	Rimmer	3b BES
Hydrogen Filled RF Cavities	FNAL	Johnson	Yonehara	50a HEP RF
Multi-Pixel Photon Counters	FNAL	Abrams	Deptuch	52a HEP Det
Multi-purpose Fiber Optic for HTS	FSU	Johnson	Schwartz	51b HEP HTS
Novel Muon Collection	FNAL	Johnson	Ankenbrandt	49a HEP
Plasma Lenses	BNL	Kahn	Hershcovitch	49b HEP
Pulsed-focusing RLA	Jlab	Johnson	Bogacz	49a HEP
Rugged Ceramic Window	Jlab	Johnson	Rimmer	36a NP
Ultra-pure Metallic Deposition	FNAL	Kuchnir	Wu	36a NP
User-Friendly Detector simulations	Uchi	Roberts	Frisch	45b nonprolif

(all are related to Muon Colliders)

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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

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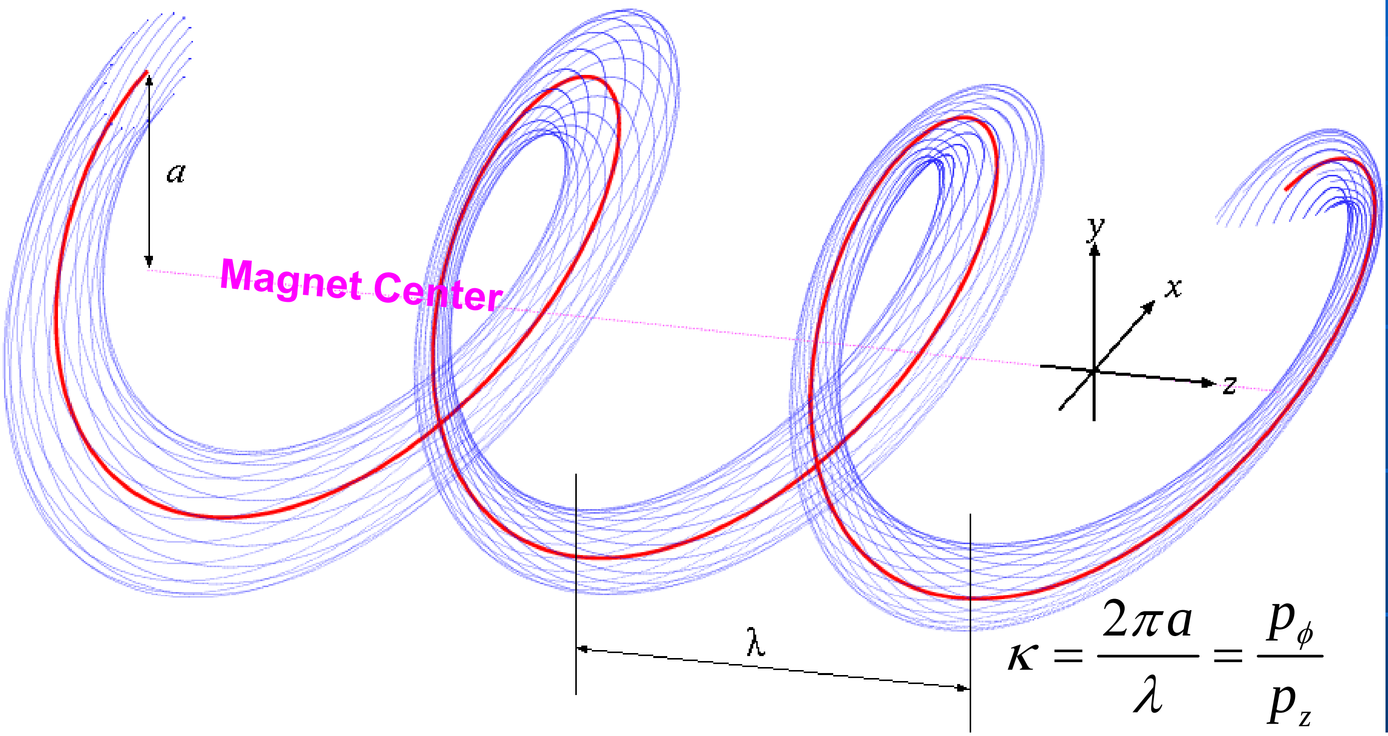
Alternative technological paths to a LEMC are emerging

- Muon Capture and Precooling in HCC
- 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
- Acceleration in ILC structures
  - Dogbone RLA with pulsed quads

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

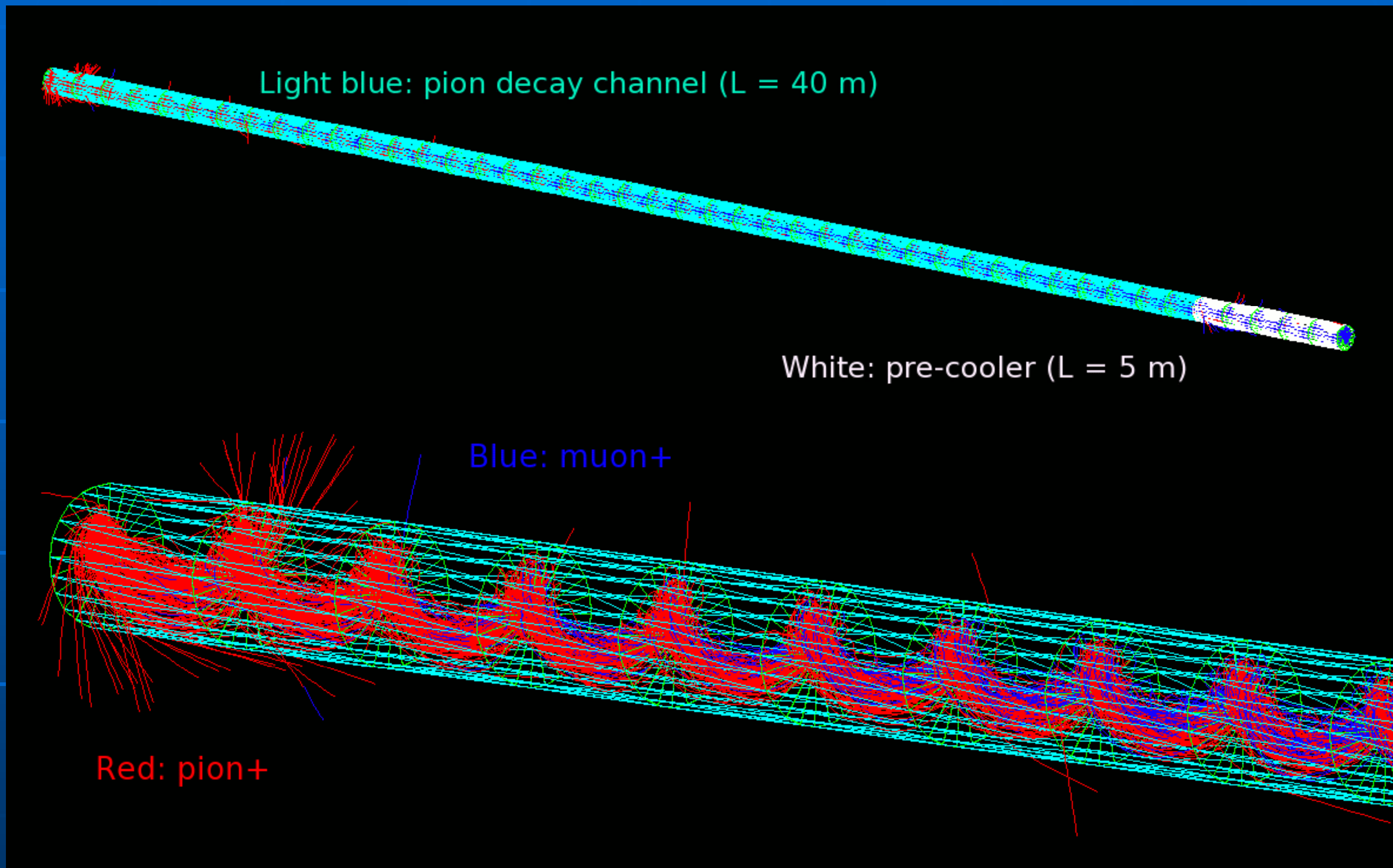
Hamiltonian Solution
$$p(a)=\frac{\sqrt{1+\kappa^2}}{k}\left[B-\frac{1+\kappa^2}{\kappa}b\right] \qquad k=2\pi/\lambda \qquad \kappa=ka$$

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

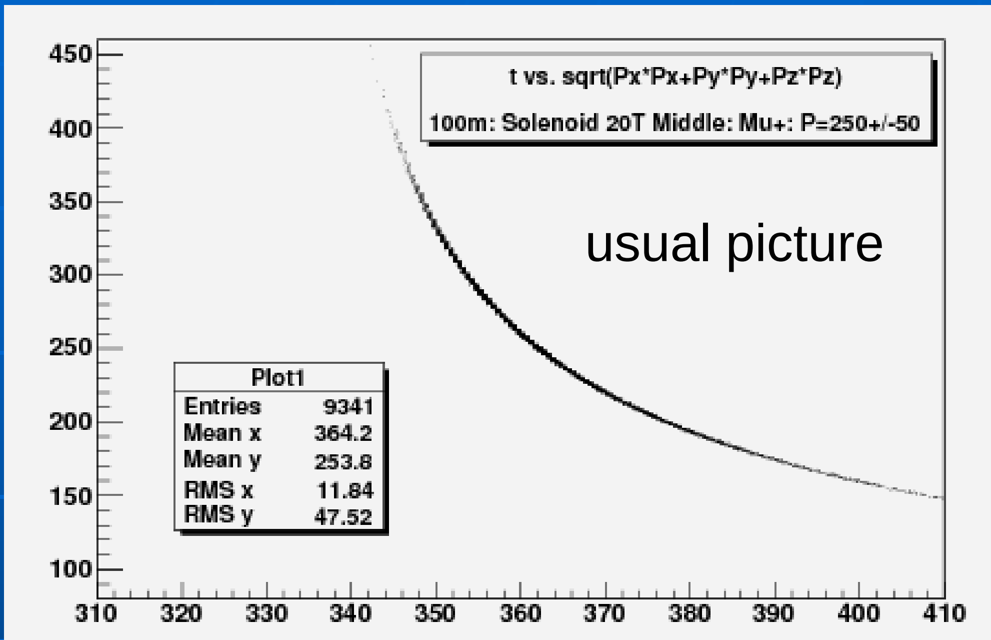
~Momentum slip factor
$$\eta=\frac{d}{d\gamma}\frac{\sqrt{1+\kappa^2}}{\beta}=\frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left(\frac{\kappa^2}{1+\kappa^2}\hat{D}-\frac{1}{\gamma^2}\right) \qquad \frac{\kappa^2}{1+\kappa^2}\hat{D}\sim\frac{1}{\gamma^2_{transition}}$$

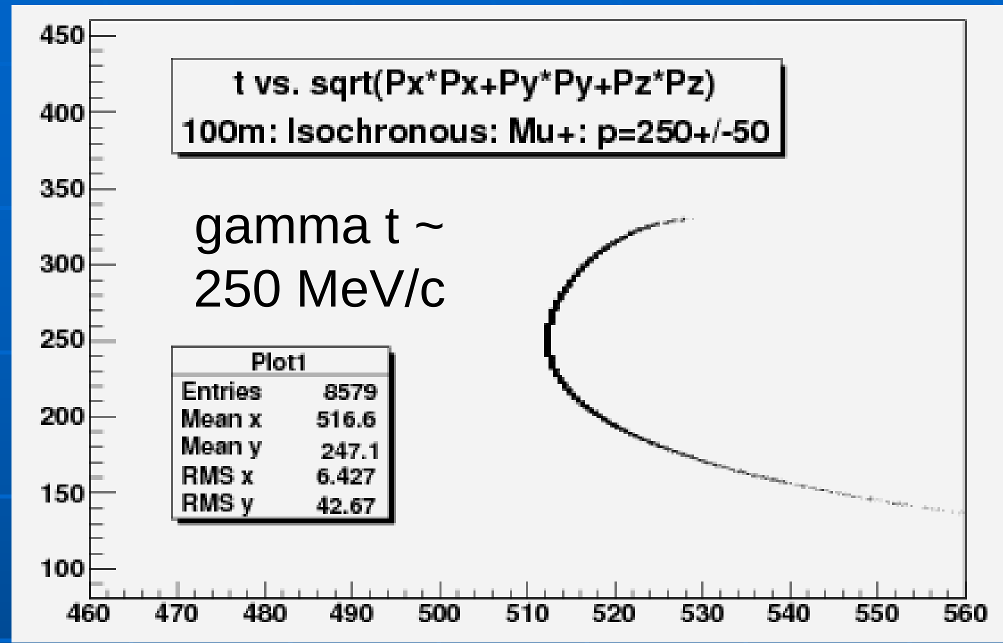
HCC as Decay Channel



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

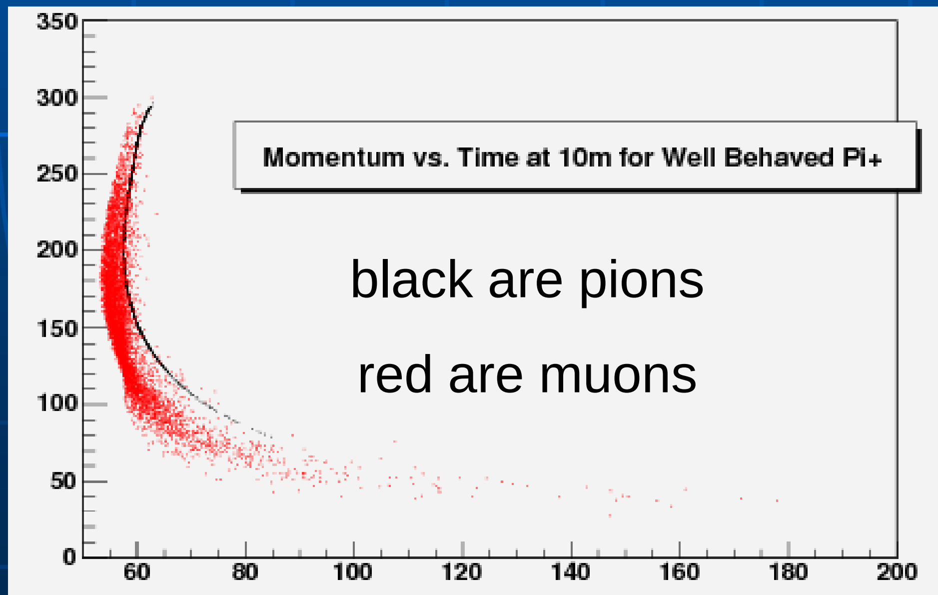
Adjusting gamma t to get a short muon bunch





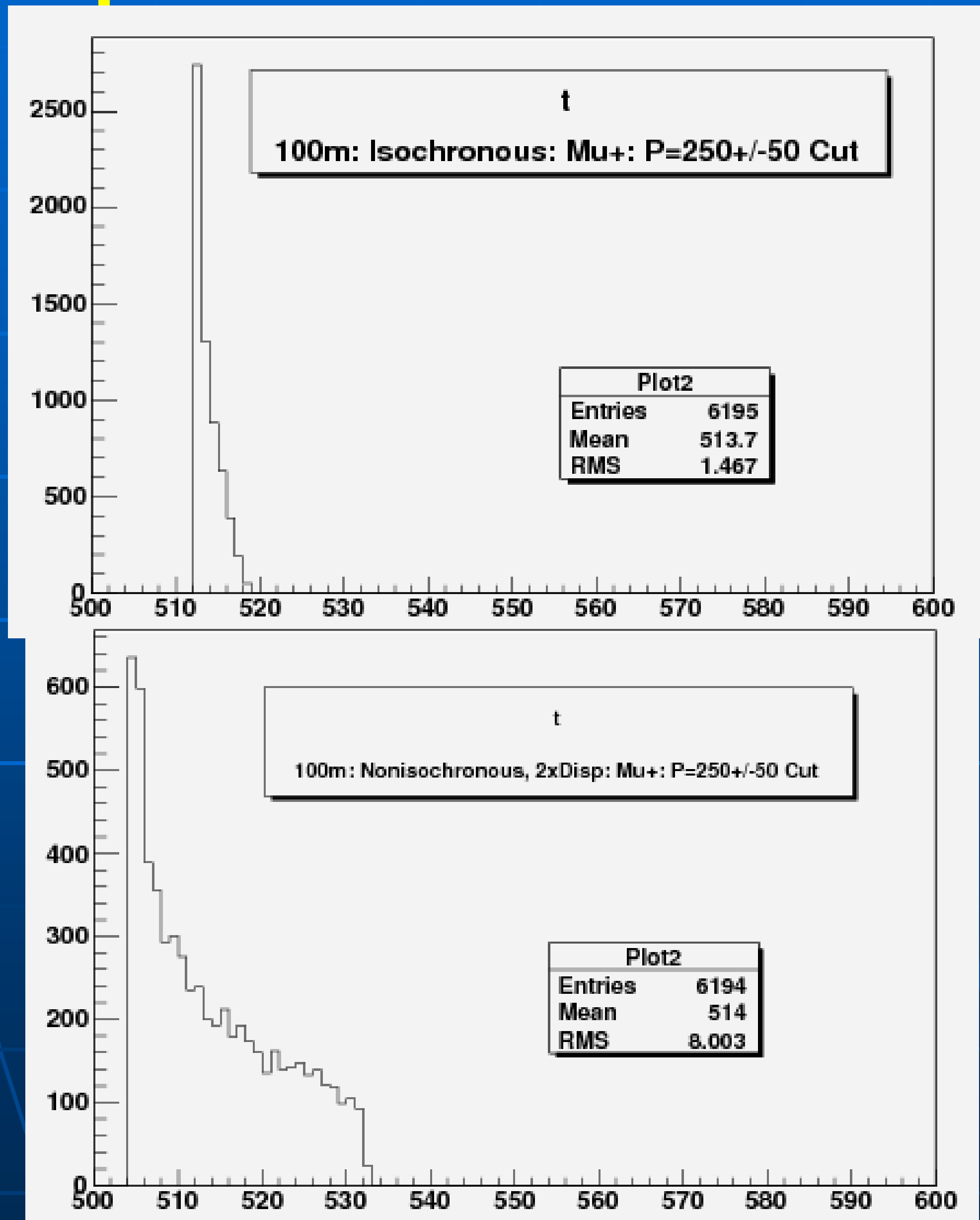
abscissa is time (ns)

ordinate is p (MeV/c)

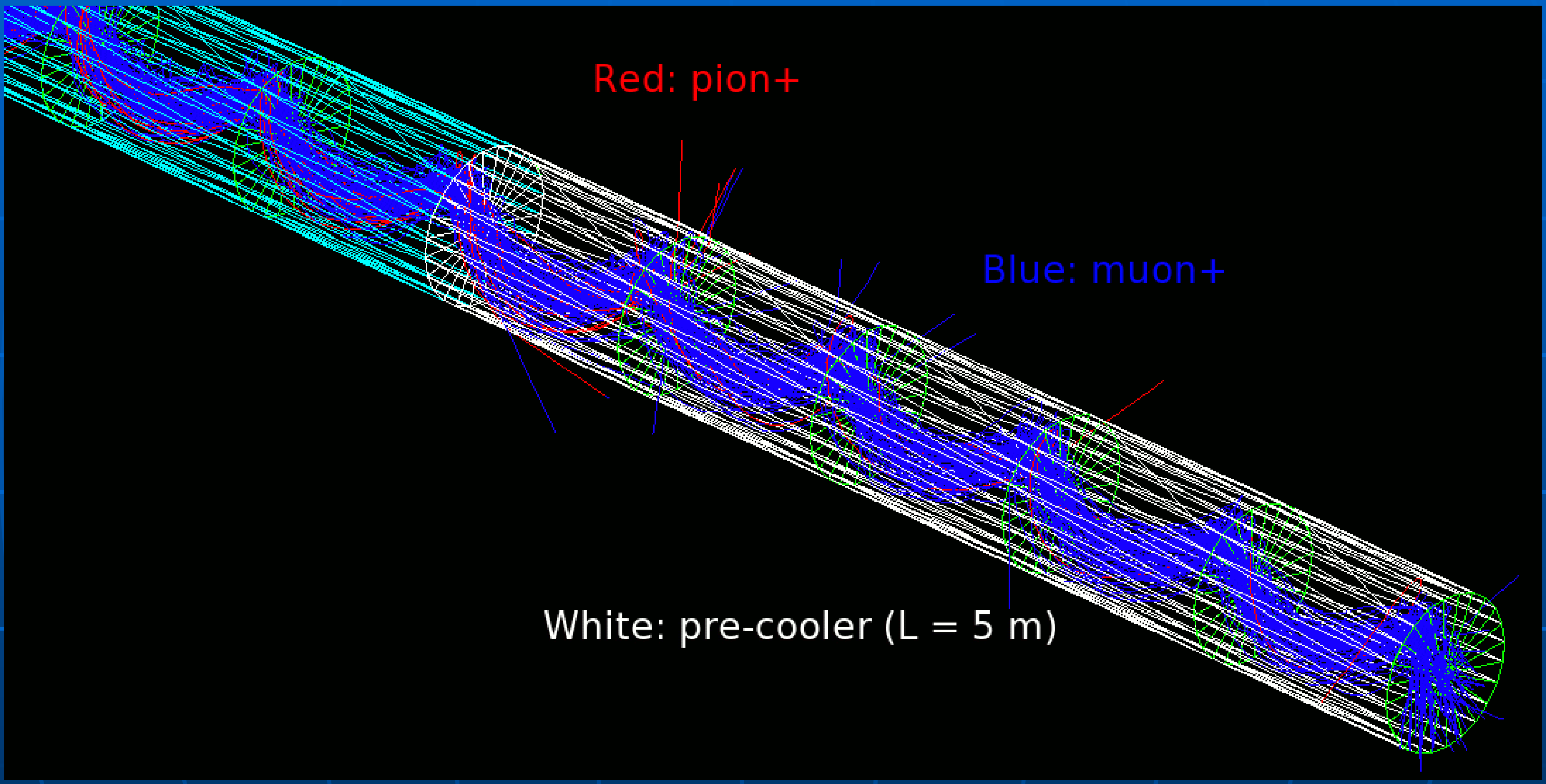


work in progress by Yoshikawa, Neuffer, and Ankenbrandt

compressed muon bunch



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.

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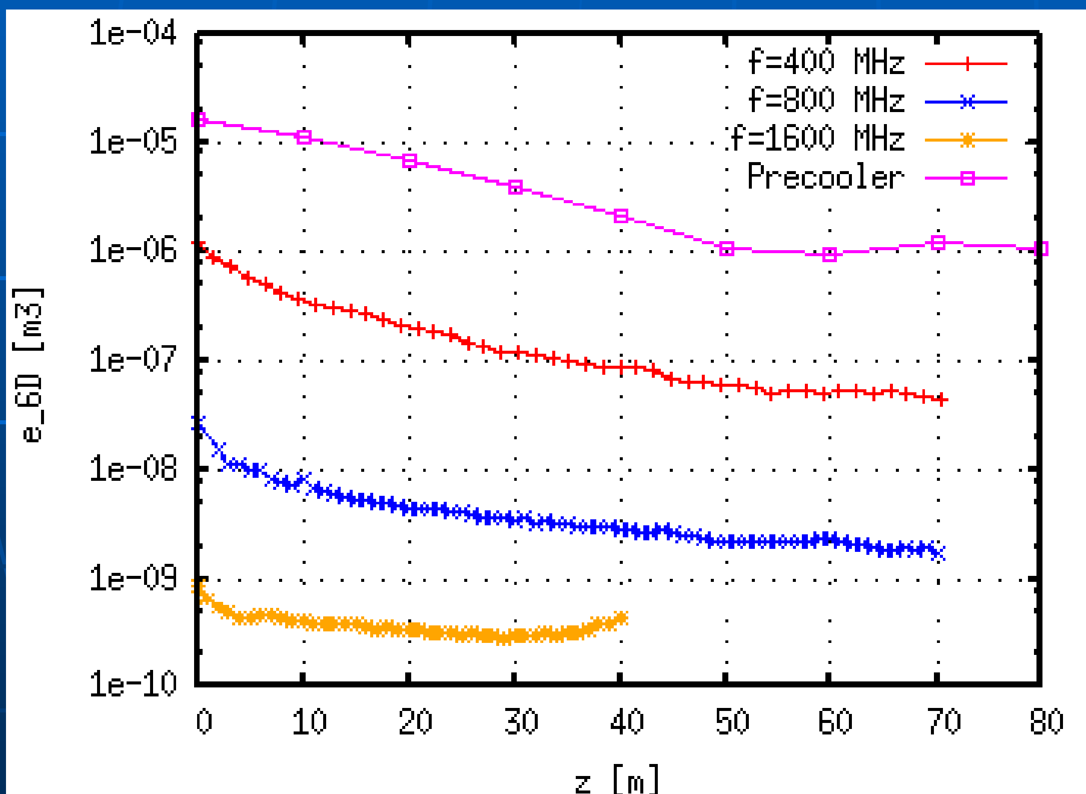
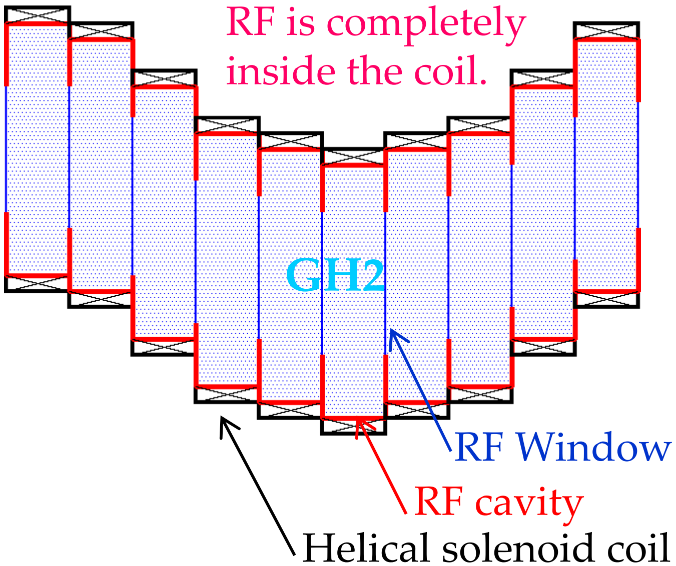
Precooler + HCCs
With first engineering constraints

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.

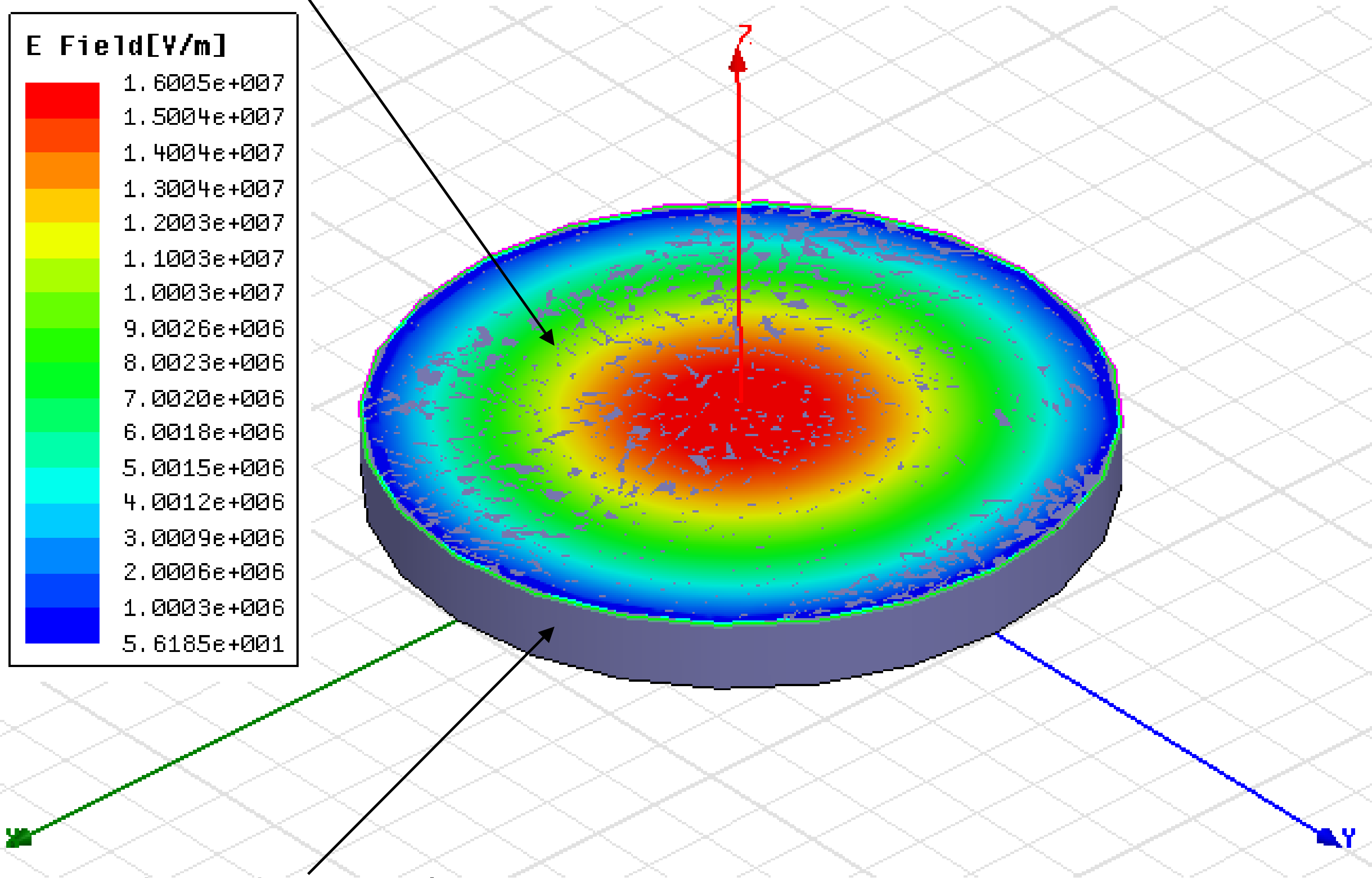
parameters	λ	κ	Bz	bd	bq	bs	f	Inner d of coil	Expected Maximum b	E	RF phase
unit	m		T	T	T/m	T/m2	GHz	cm	T	MV/m	degree
1st HCC	1.6	1.0	-4.3	1.0	-0.2	0.5	0.4	50.0	6.0	16.4	140.0
2nd HCC	1.0	1.0	-6.8	1.5	-0.3	1.4	0.8	30.0	8.0	16.4	140.0
3rd HCC	0.5	1.0	-13.6	3.1	-0.6	3.8	1.6	15.0	17.0	16.4	140.0

Simple pillbox of Al at 400 MHz and LN2 temperature, resistivity 0.4 E-6 Ohm cm
HFSS results

154 kW, on one side of 1 foil

Upeak = 800 kV, for crossing with betaparticle infinity (transit factor = 1)

$\varepsilon_{rel} = 1.32$



Radius = 0.25 m
Height .= 0.05 m

Q = 26630

W = 3 Joule/pillbox

R/Q =(Upeak)^{2}/2ωW
= 42.5 Ohm
circuit convention

63 kW on inner mantle

371 kW total/pillbox during passage of trains,
~6 kW average

Note that for a given Ez, and scaled dimensions R/Q remains unchanged: the 1.6 GHz pillbox has the same R/Q as the 400 MHz one.

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MuCool Test Area (MTA)

HPRF Test Cell Measurements in MTA

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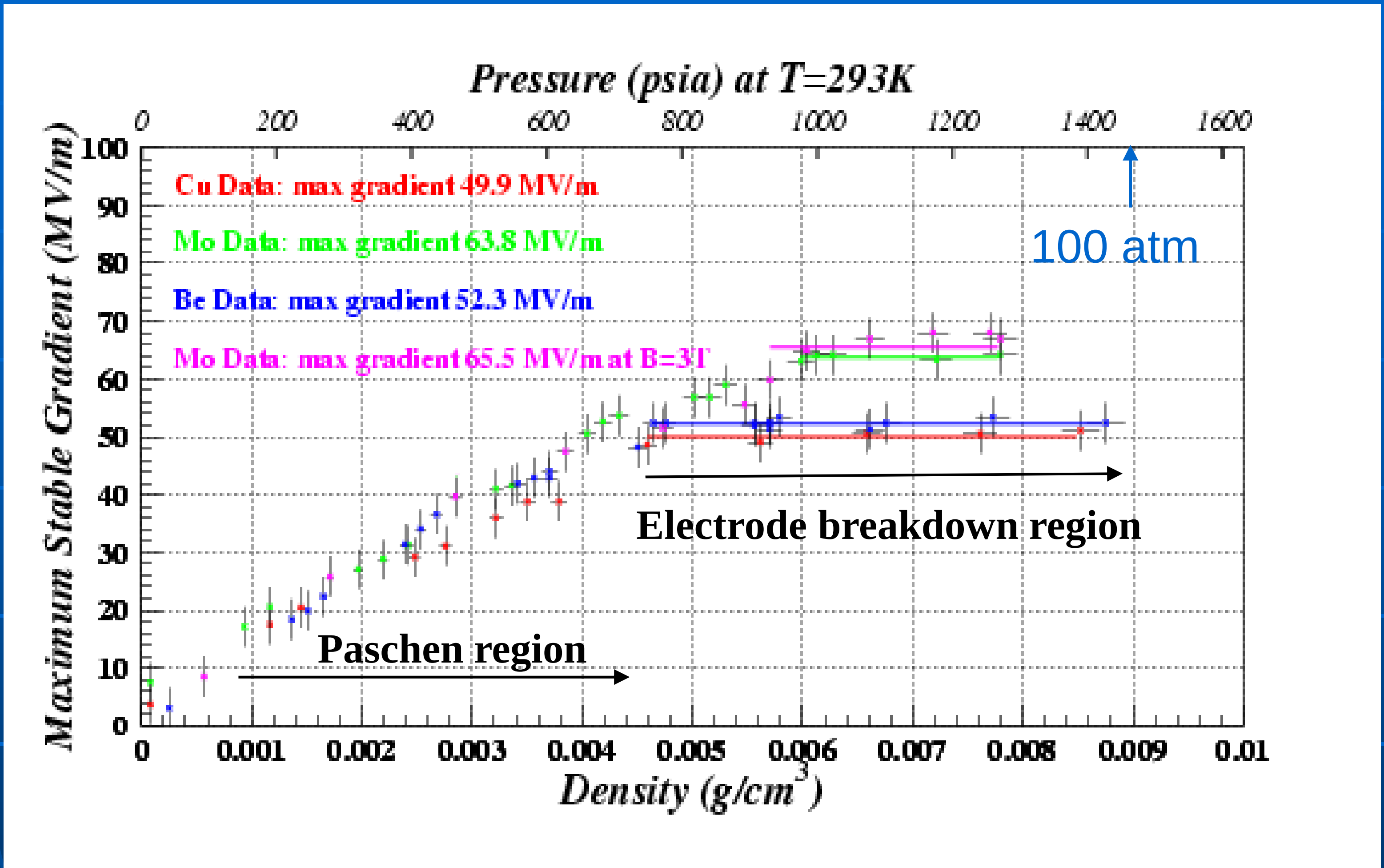


- Paschen curve verified
- Maximum gradient limited by breakdown of metal.
- Cu and Be have same breakdown limits (~50 MV/m), Mo(~63MV/m), W(~75MV/m).
- Results show no B dependence, much different metallic breakdown than for vacuum cavities.
- **Need beam tests to prove HPRF works.**

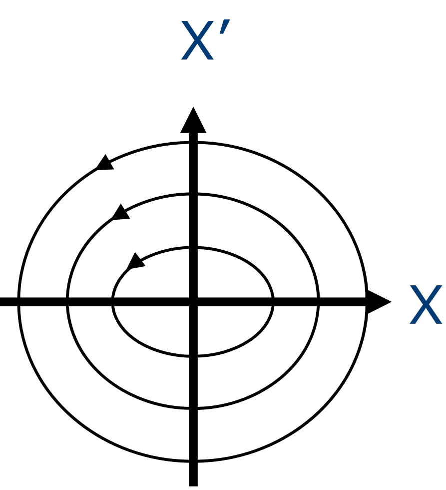
Parametric-resonance Ionization Cooling

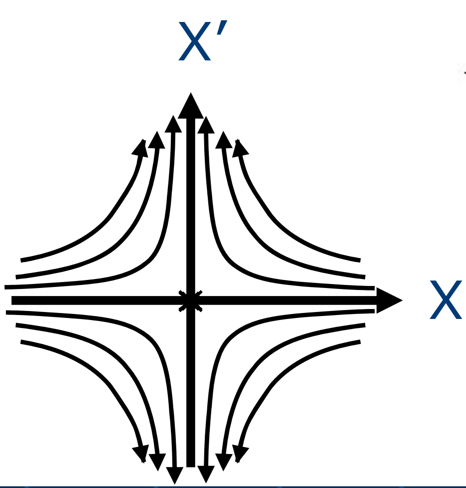
Excite ½ integer parametric resonance (in Linac or ring)

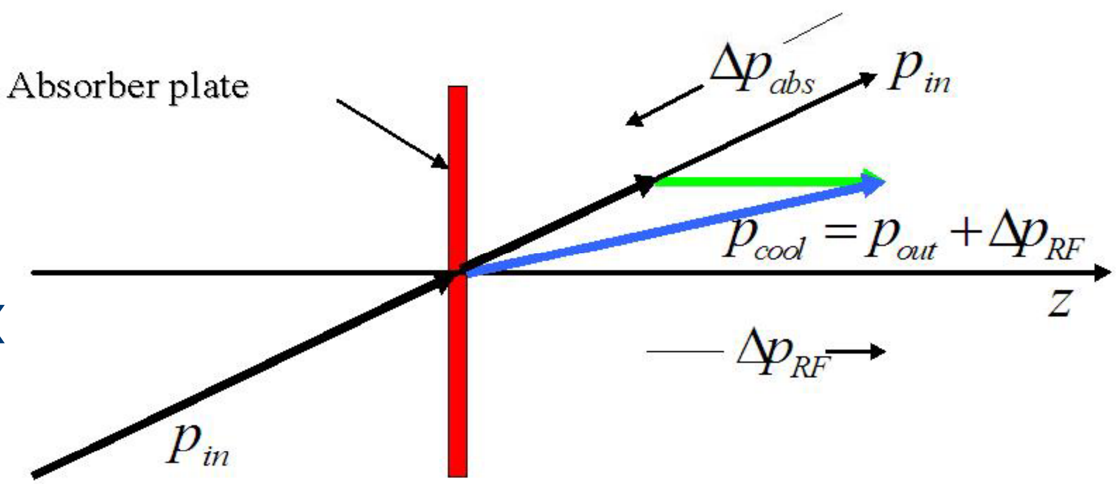
- Like vertical rigid pendulum or ½-integer extraction
- Elliptical phase space motion becomes hyperbolic
- Use xx’=const to reduce x, increase x’
- Use IC to reduce x’

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!

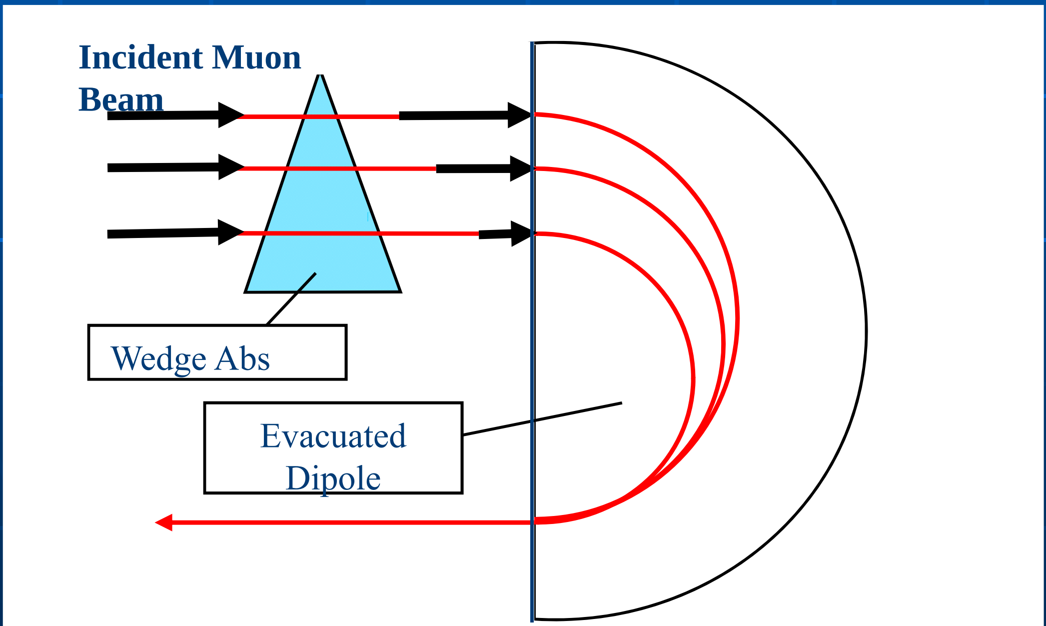




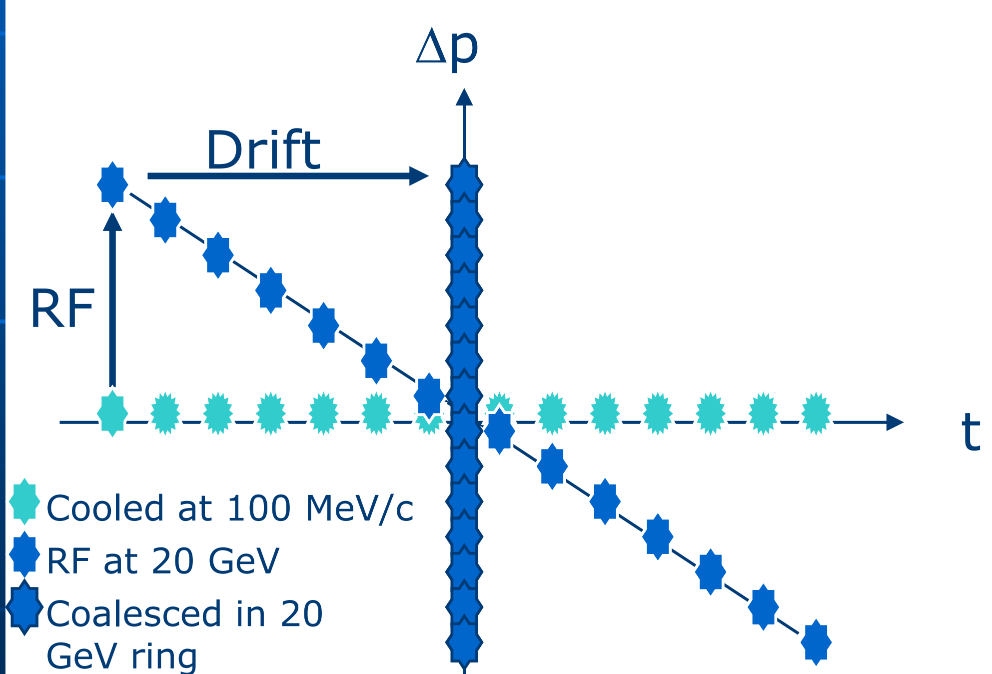


Reverse Emittance Exchange, Coalescing

- 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

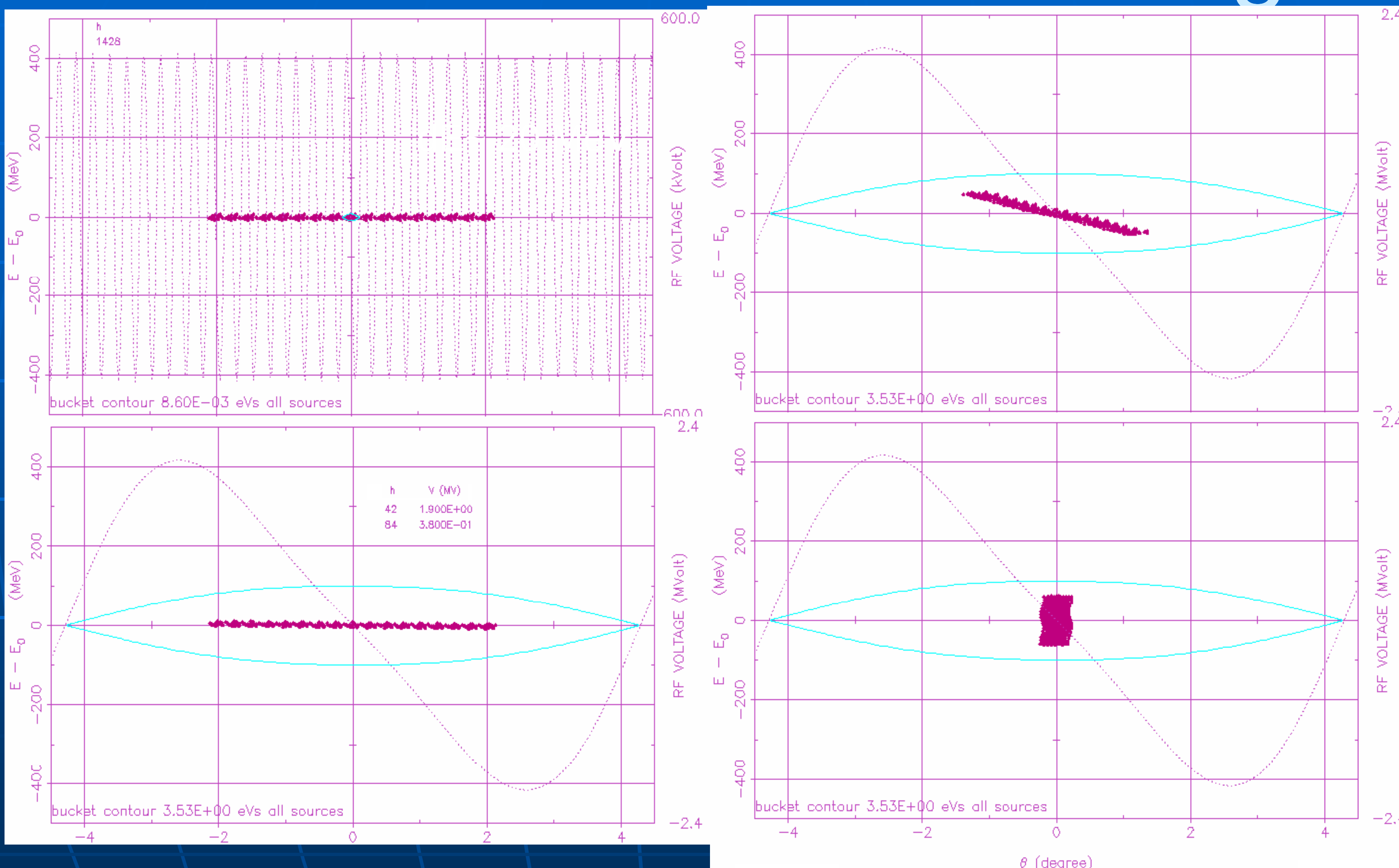


Concept of Reverse Emittance Exch.



1.3 GHz Bunch Coalescing at 20 GeV

Bhat et al. Coalescing



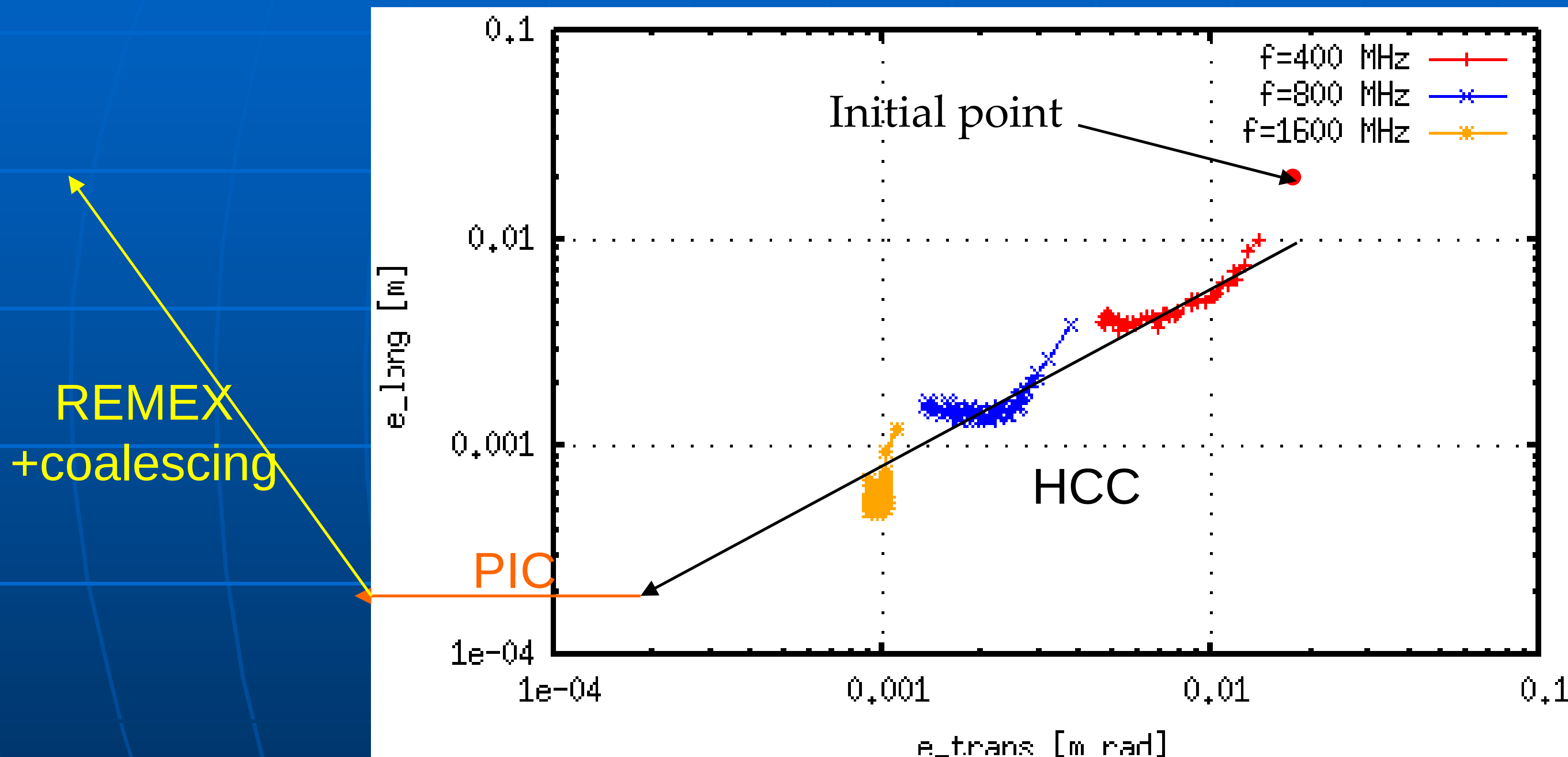
20 GeV muons in a 100 m diameter ring

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

Detailed theory in place, simulations underway.

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.

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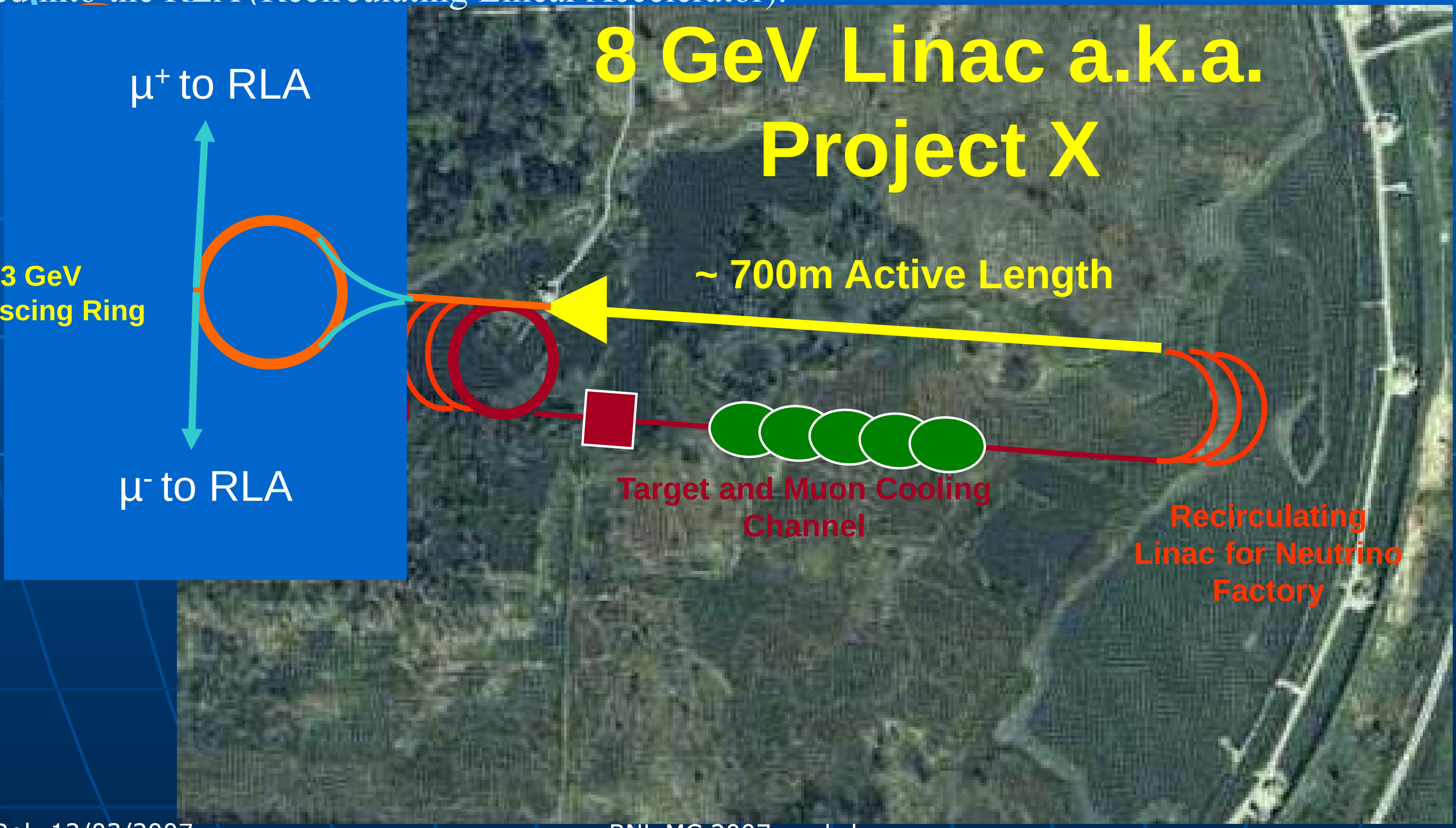
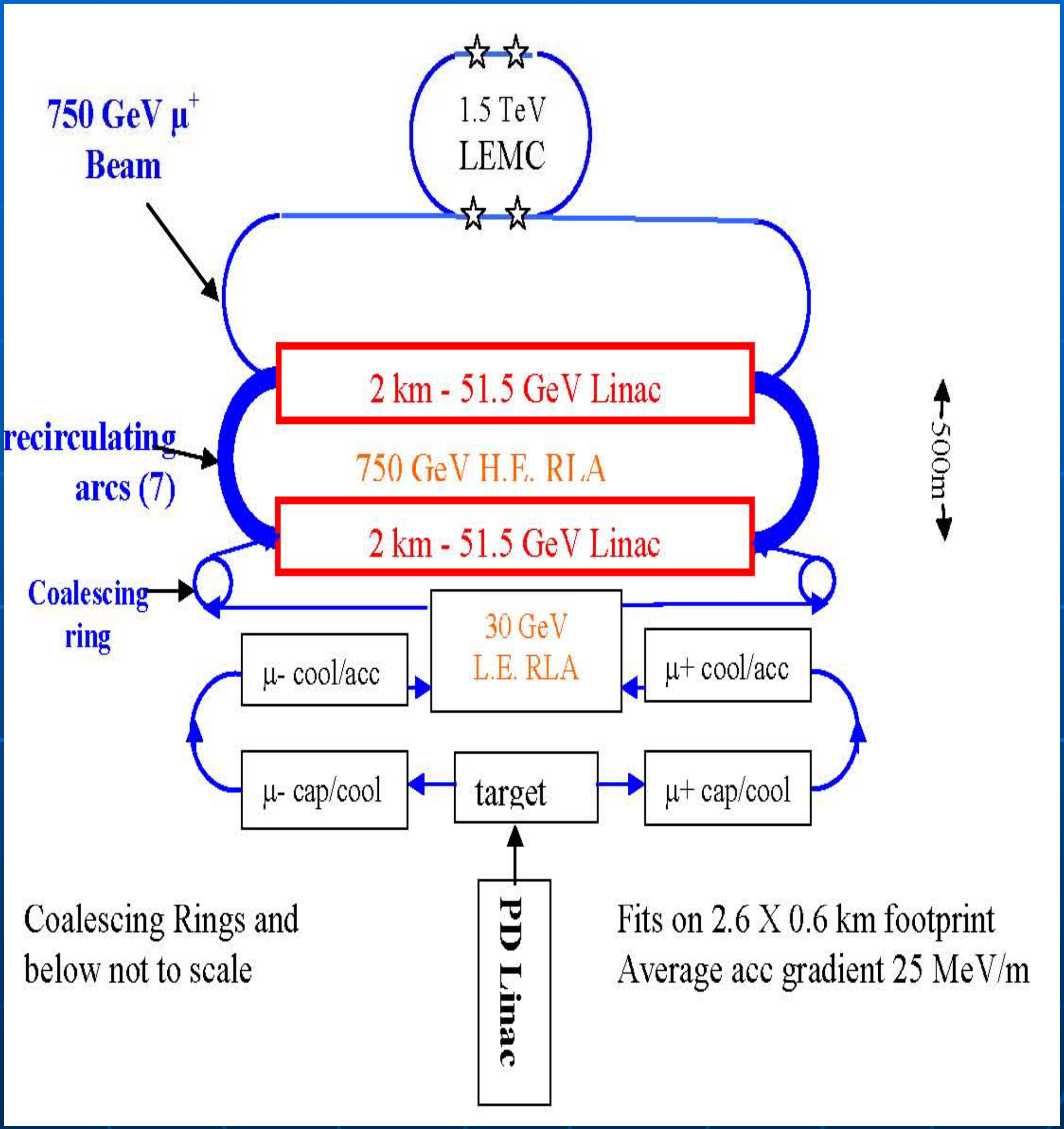
Muon Collider use of 8 GeV SC Linac

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 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).



1.5 TeV COM Example



5 TeV ~ SSC energy reach

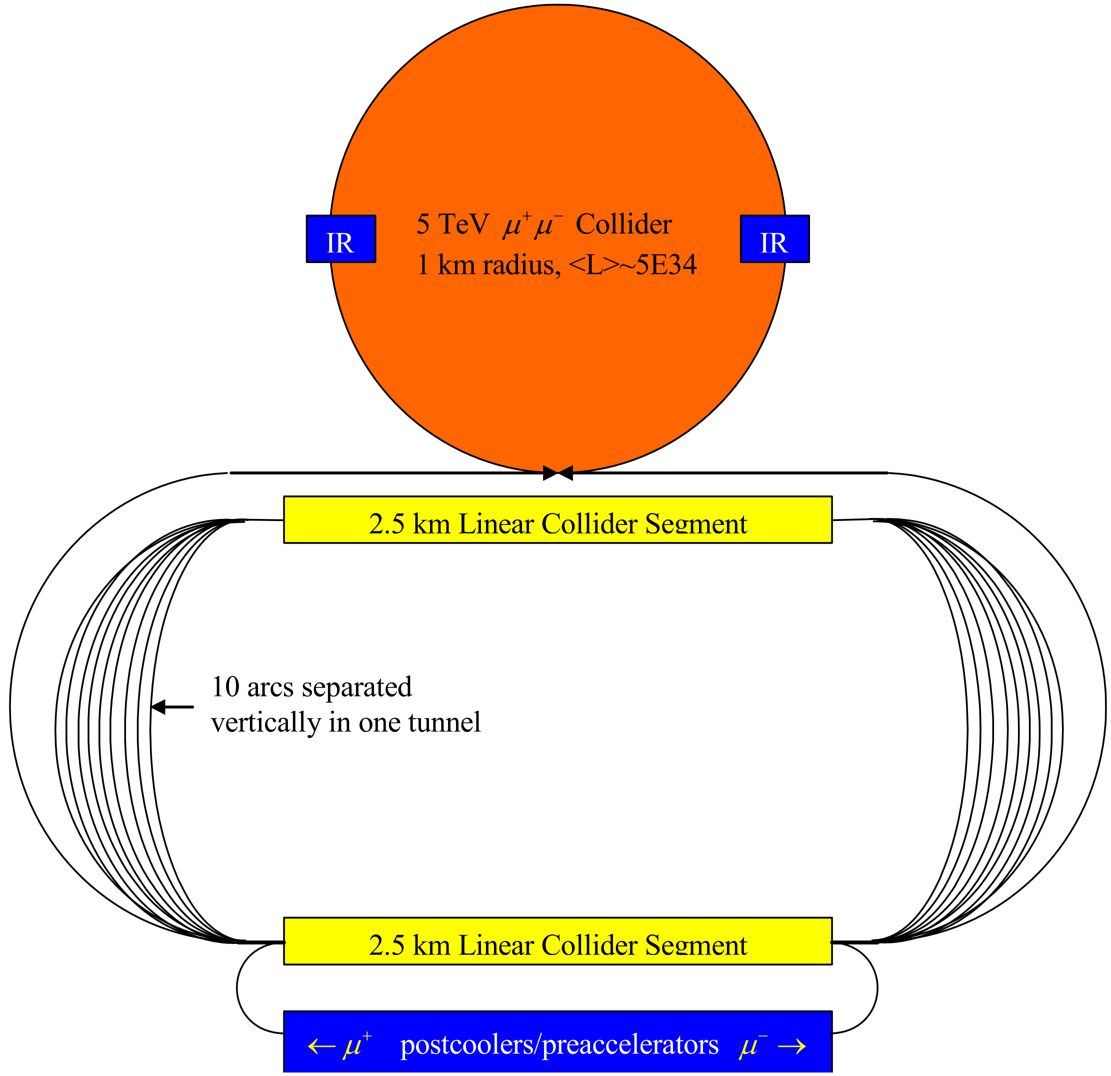
~5 X 2.5 km footprint

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

Many things get easier as muon lifetime increases!

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

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

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

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

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

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

20 Hz Operation:

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

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

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

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Parameter Spreadsheet

- On workshop web page
- A working document to connect pieces
- Consistent beginning to end connections
    - Example: change collider E, see P on target change
- Will become basis for design report
- Includes play pages for "what-if" scenarios
- See Mary Anne or me with suggestions for additions and improvements e.g. Site boundary radiation levels, wall-plug power, linac wakefield and beam loading parameters, cost, etc.

Important Recent Developments

- Anticipated LHC discoveries are inspiring muon cooling and 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
    - p beam line available soon for next tests
- 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!

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]

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[6]*Illinois Institute of Technology*

http://www.muonsinc.com/tiki-download_file.php?fileId=230

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6DMANX demonstration experiment

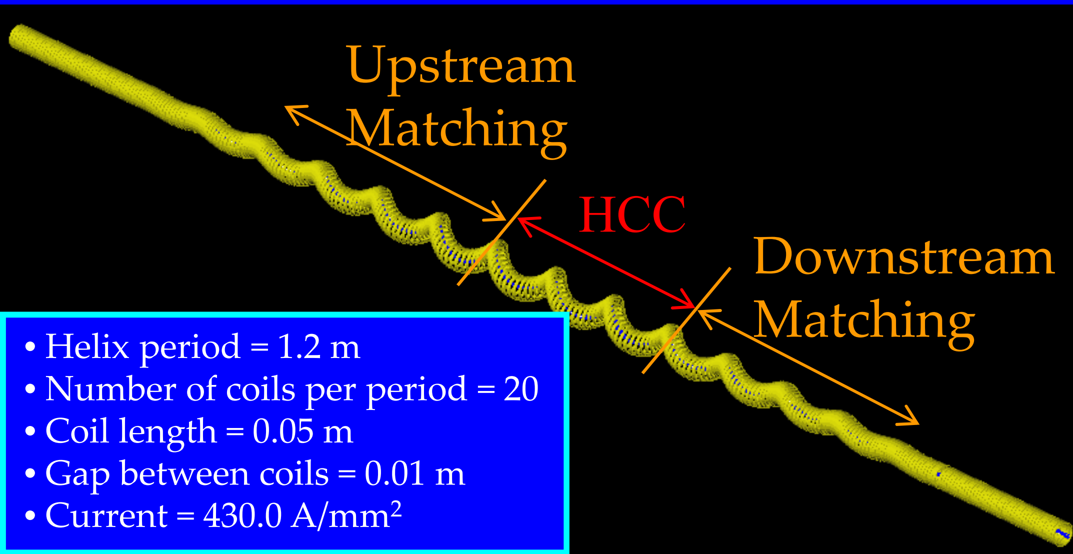
Muon Collider And Neutrino Factory eXperiment

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

Uses for a HCC

- Decay channel
- Precooler
- MANX 6D cooling demo
- Stopping muon beam cooler
  - can add RF for even better cooling (path to a MC)
- Fast 6D Emittance reduction
  - new approach to neutrino factory (path to a MC)
- Preliminary to extreme cooling (needed for a MC)
  - Parametric Ionization Cooling
  - Reverse Emittance Exchange and muon bunch coalescing

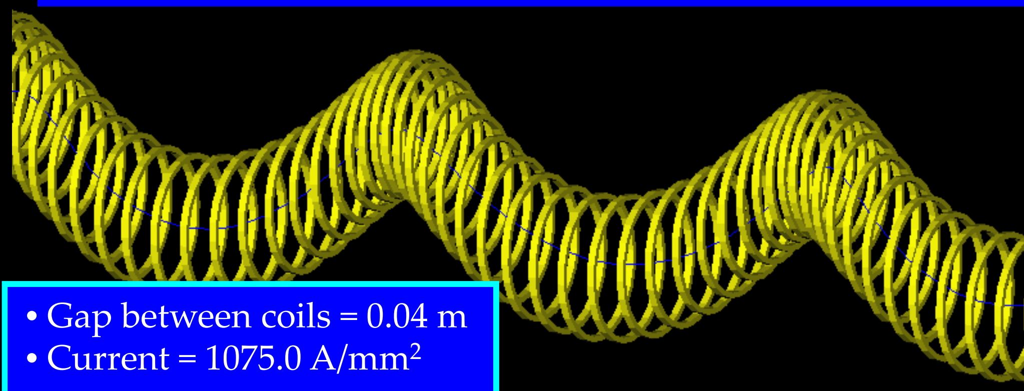
Design of HCC Magnet



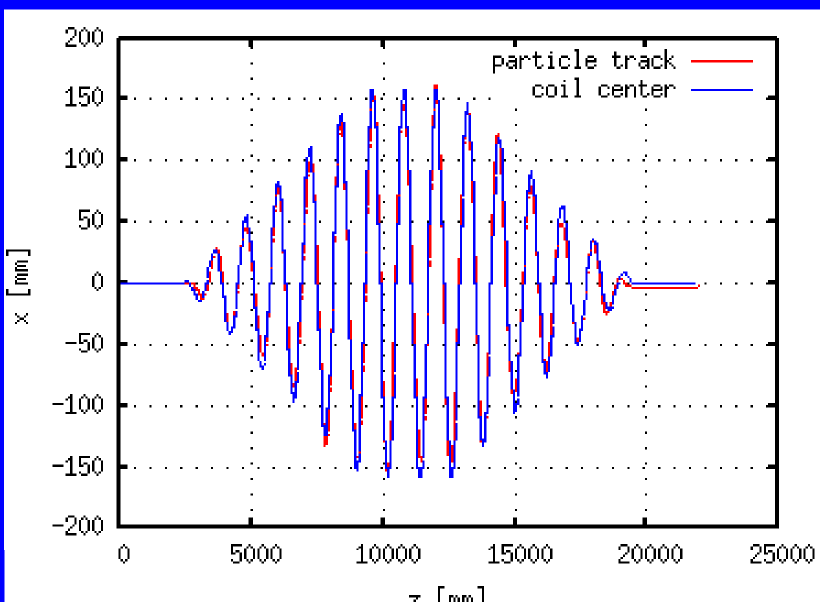
- Helix period = 1.2 m
- Number of coils per period = 20
- Coil length = 0.05 m
- Gap between coils = 0.01 m
- Current = 430.0 A/mm²

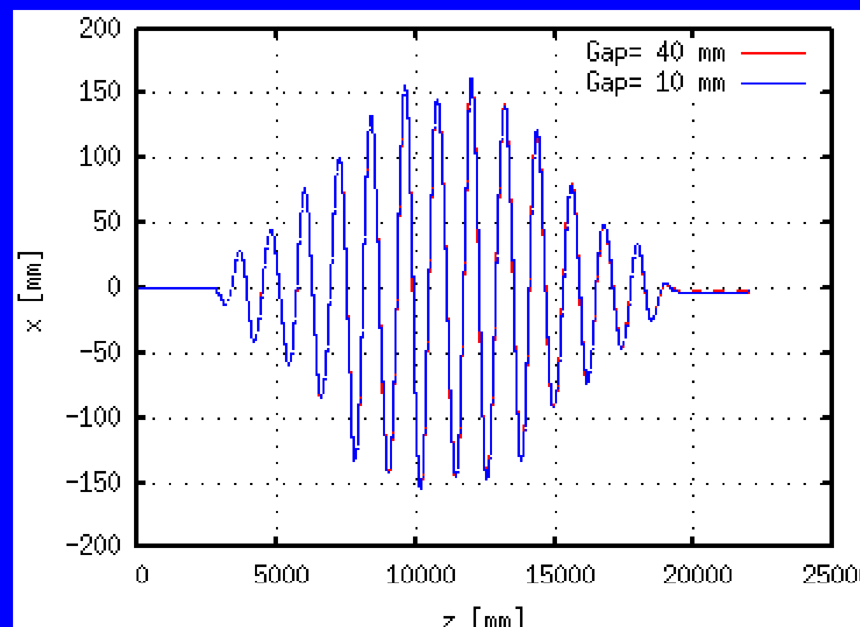
Cooling Magnets

Increase gap between coils from 10 to 40 mm



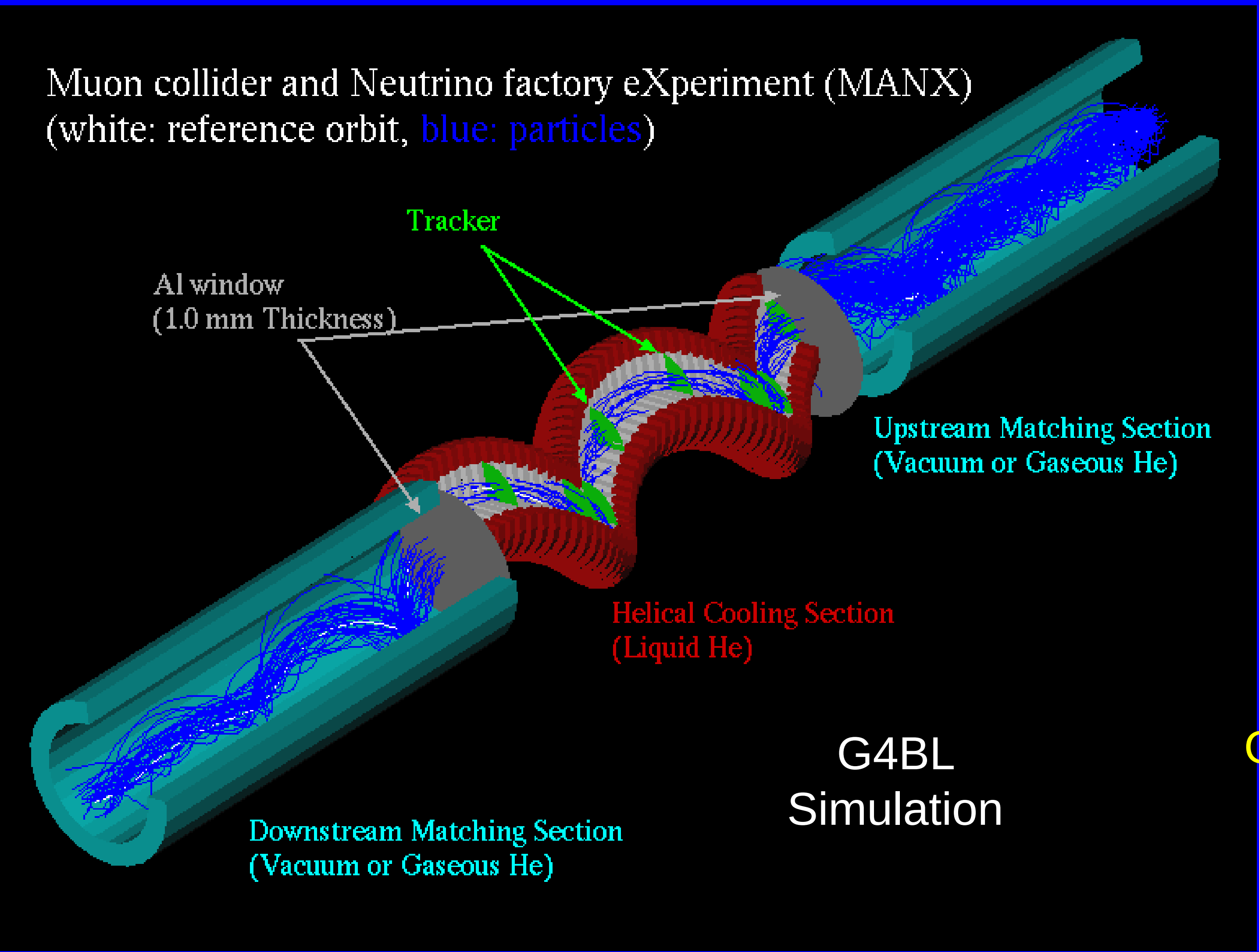
- Gap between coils = 0.04 m
- Current = 1075.0 A/mm²





MANX

Overview of MANX channel



- 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)