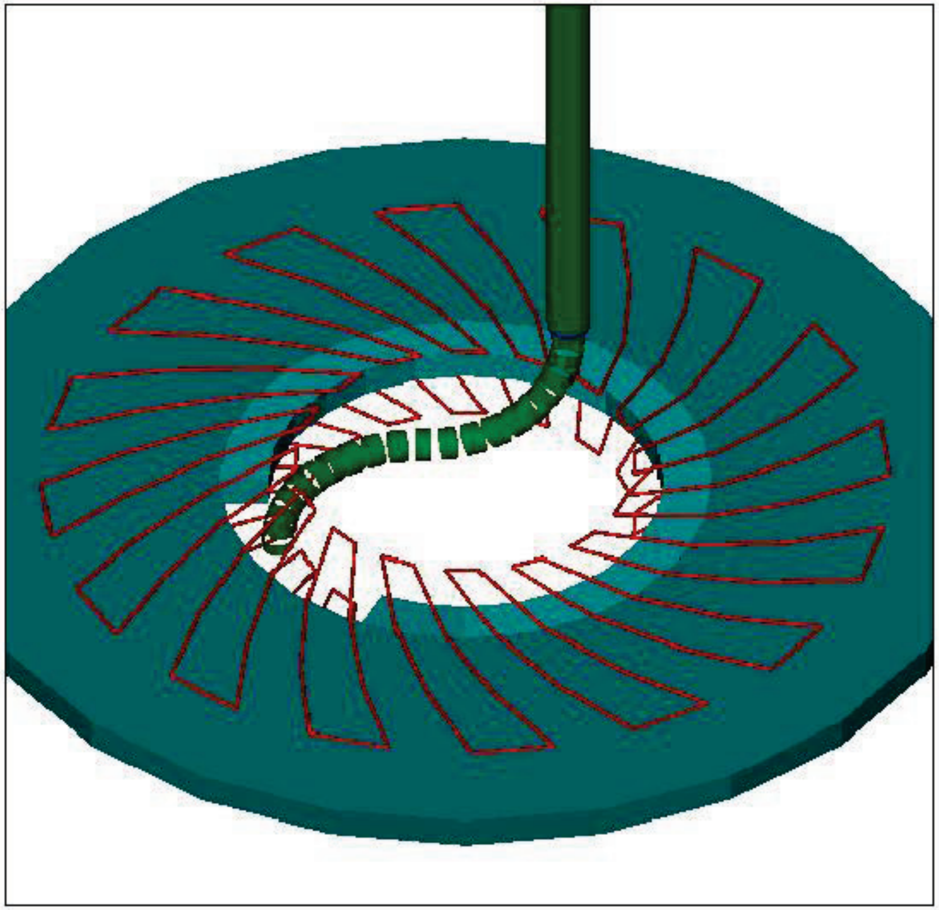
An Inverse Cyclotron For Muon Cooling



- Muons as Experimental Probes
- Muon Cooling
- The Inverse Cyclotron
- Simulation Results
- Summary and Plans

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Cyclotrons'13,
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September 16, 2013

Muons as Particle Physics Probes

- Muons *elementary* unlike protons
  - In proton colliders, collision energy taken up by “spectator” quarks and gluons.
  - LHC has only about 2 of 14 TeV center-of-mass energy, $E_{c.m.}$, part of primary quark-quark collision
  - Muon collisions cleaner than proton collisions.

- Muons much more *massive* than electrons ($m_\mu = 207\ m_e$)
  - Radiation losses limit energy, size of circular electron colliders

$$\Delta E, P \propto \left(\frac{E_{c.m.}}{m}\right)^4 \frac{1}{r}$$

  - At LEP with max. $E_{c.m.}$ = 209.2 GeV, r = 4.2 km
    - ΔE, energy loss per turn = 2.5 GeV
    - P, radiation power = 15 MW

Challenges of Muons for Particle Physics

- Muon production from 8 – 40 GeV protons on target
  - Roughly scales with beam power
  - Requires 1 - 4 MW proton beam for suitable luminosity
  - Production target also challenging

- *Muons produced with a large phase space or emittance which must be reduced for suitable beam.*
  - *K.E. ~ 100 MeV*
  - $\varepsilon_{TR,N}$ *~ 20 mm*
  - $\varepsilon_{L,N}$ *~ 40 mm*

- Muon lifetime = 2.2 μs so beam needs to be prepared quickly.
  - *Emittance reduction (cooling)*
  - Acceleration

Standard Model Tests For Experiments Using Muons as Probes

- Physics Questions
  - Higgs boson properties
  - Neutrino properties
  - Supersymmetric particles, new physics
  - $\mu \rightarrow e\gamma$ decay (lepton flavor violation)
  - (g – 2) anomalous magnetic moment

$$\vec{\mu} = g\left(\frac{e}{2m_{\text{muon}}}\right)\vec{S}$$

- Potential Facilities Using Muon Beams
  - Higgs Factory
  - Neutrino Factory
  - Muon Collider

Muon Cooling R&D

- Most muon cooling designs are single-pass structures requiring strong RF gradients and strong transverse focusing for rapid cooling.

- Multi-pass synchrotron ring structures would be more economical, but are limited by injection difficulties.

- ***Inverse cyclotron: a cyclotron in which particles***
  - ***are injected at large radius***
  - ***lose energy by passing through a moderator material***
  - ***spiral toward center***

Muon Cooling With Inverse Cyclotron

- For Neutrino Factory and Muon Collider, 6D normalized emittances need to be reduced by factors of ~ 10^3 and 10^6, respectively.
- An inverse cyclotron could potentially replace part of sequence of single-pass muon cooling devices.
- *This simulation of inverse cyclotron will test energy reduction to lowest energies, from about 300 keV → 30 keV.*
- *30 keV muons approach low energies at which frictional cooling can reduce energy spread to about 2 keV.*

Inverse Cyclotron

- When muons lose energy passing through moderator, different energy muons will take different number of turns to spiral in to common radius and corresponding energy.

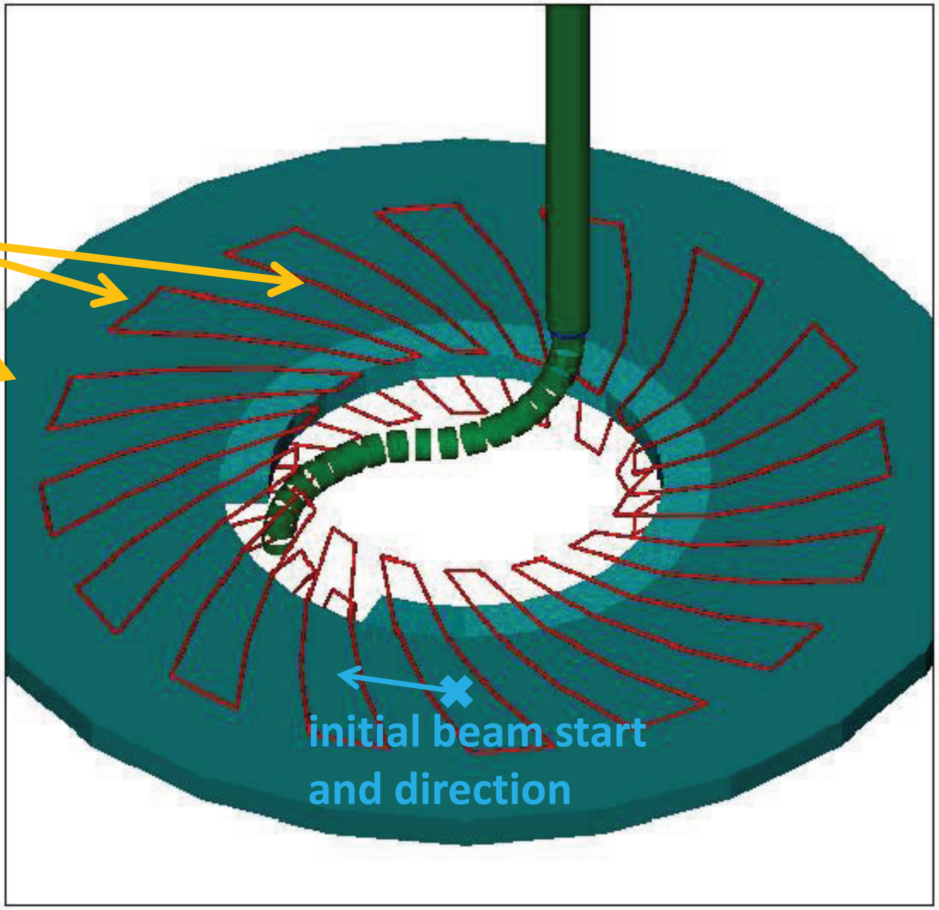
- Turn period doesn't have to be synchronous with RF cycle

- ***Inverse cyclotron can accept beam with initial K.E. and large energy spread and bring beam to lower final K.E. and smaller energy spread.***

Inverse Cyclotron Structure

Three sections

- **Cyclotron field with helium**
  - 16 sector field from 32 spiral coils (red)
  - 0.0001 mg/cm^3 helium (aqua)



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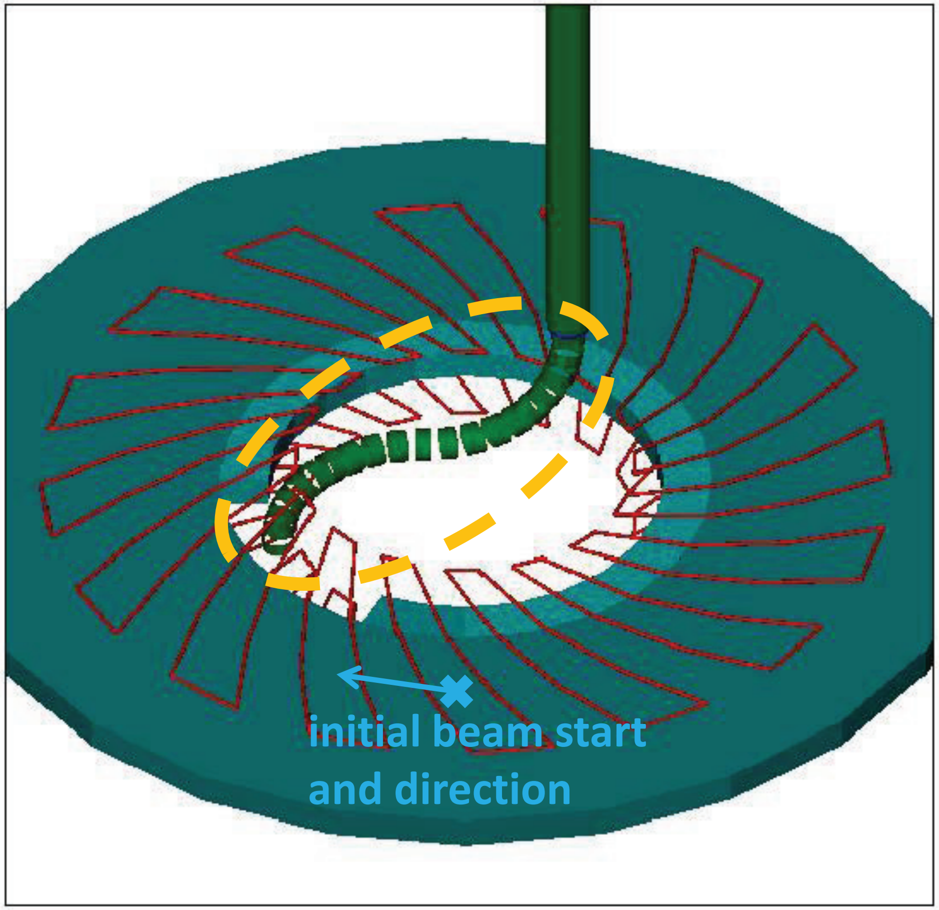
- **Extraction Section**
  - Two arcs of coils (green) transporting beam out of cyclotron plane upward



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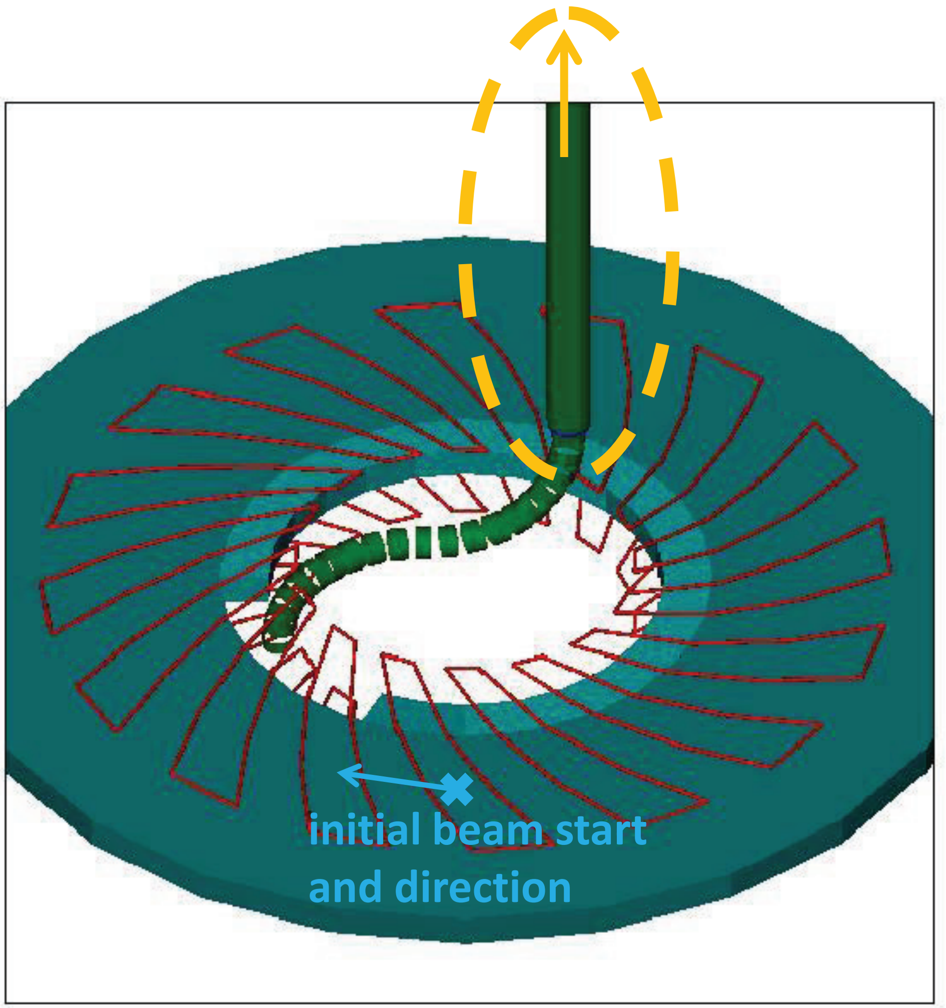
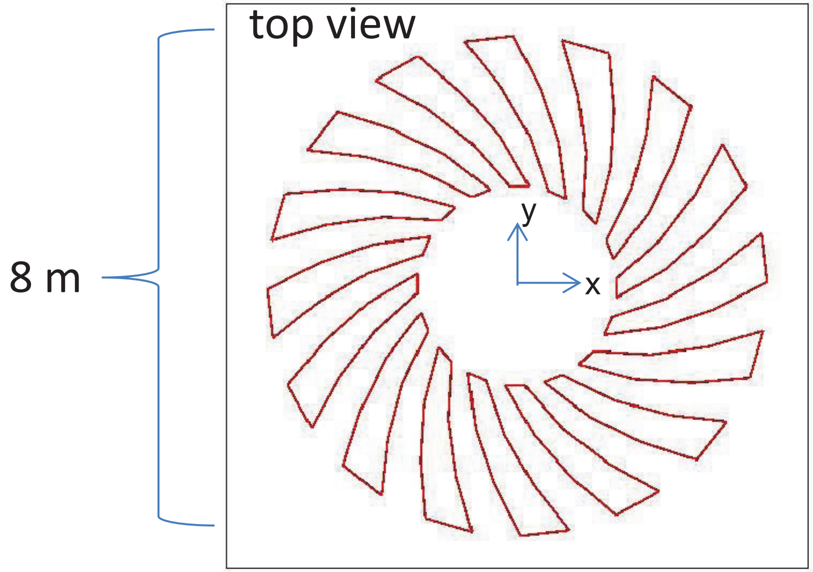
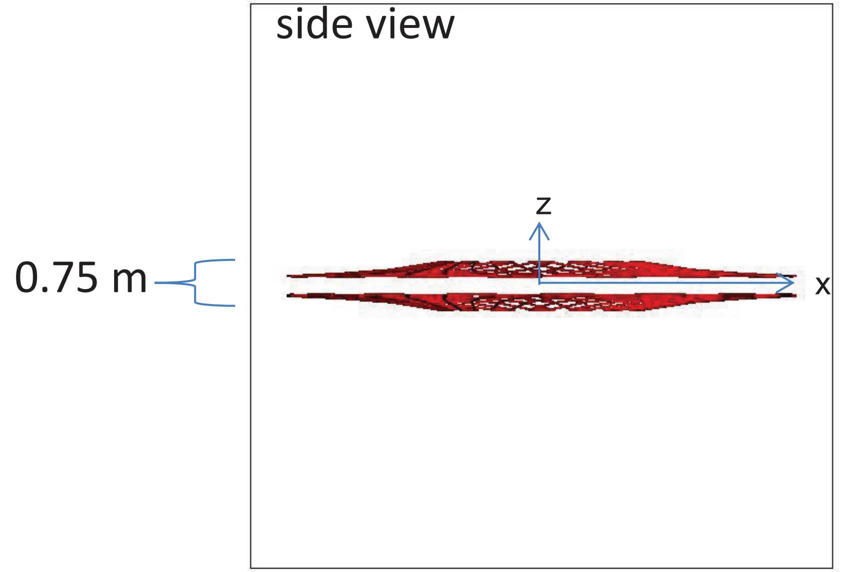
- **Longitudinal Modulation (reduce K.E., trap muons)**
  - Long solenoid (dark green) contains
    - Static opposing E_z to slow muons
    - Series of traps with time varying E_z to trap beam



Cyclotron Magnetic Field

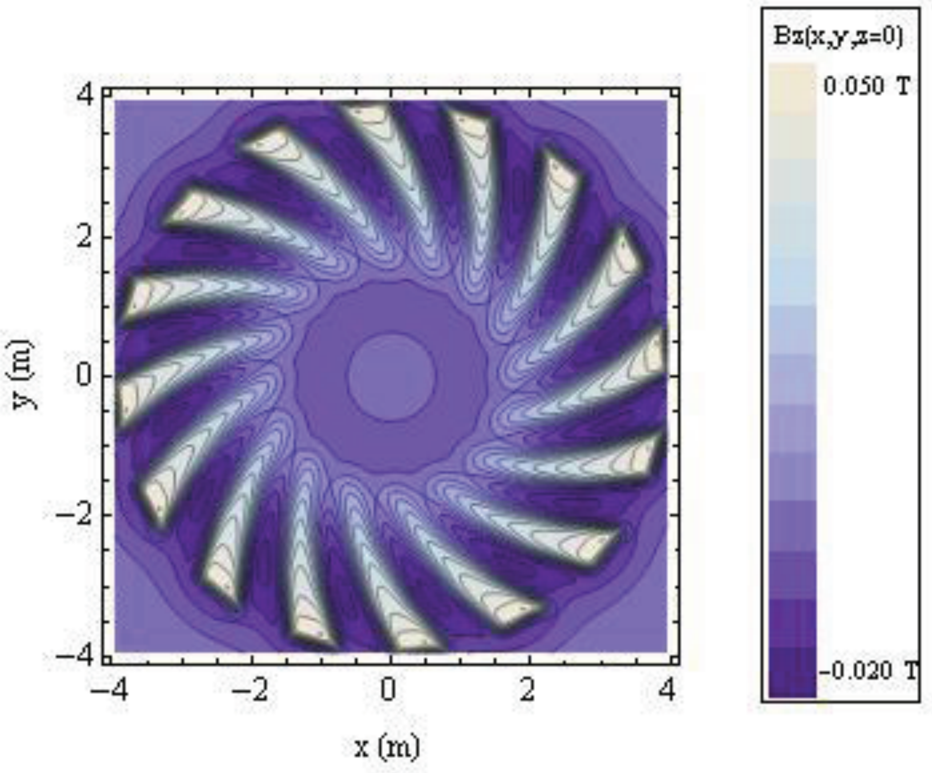


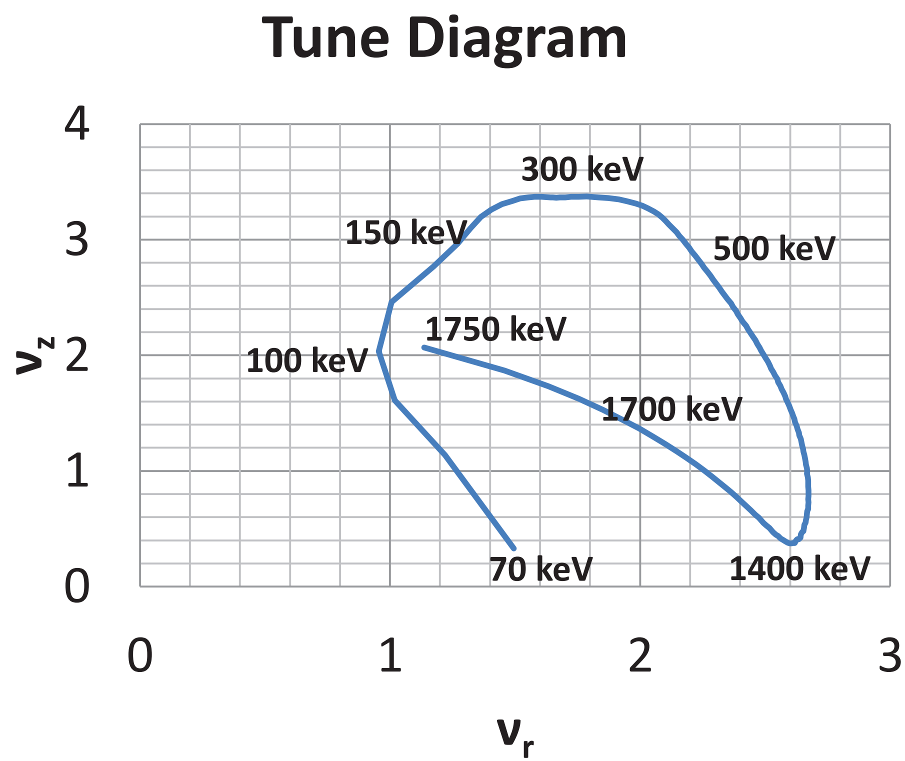


32 coils form 16 sector **B** field

- Each coil carries 21.3 kA
- Each coil has radial extent (1.6 m < r < 4.0 m), makes 30° spiral
- Coil follows $z = 0.6\ m^2/r$
  - Coils get closer together as radius increases
  - $\langle B_z \rangle$ increases with r → strong radial focusing

Cyclotron $B_z(z = 0)$ and Tune Diagram

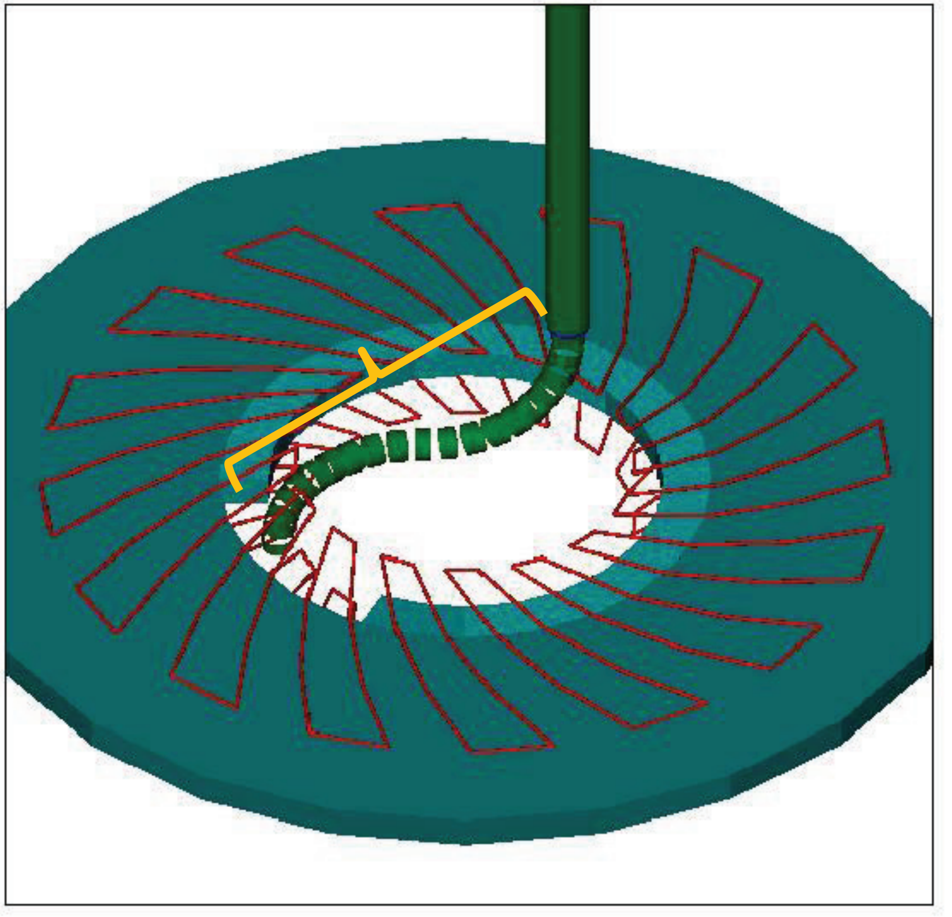




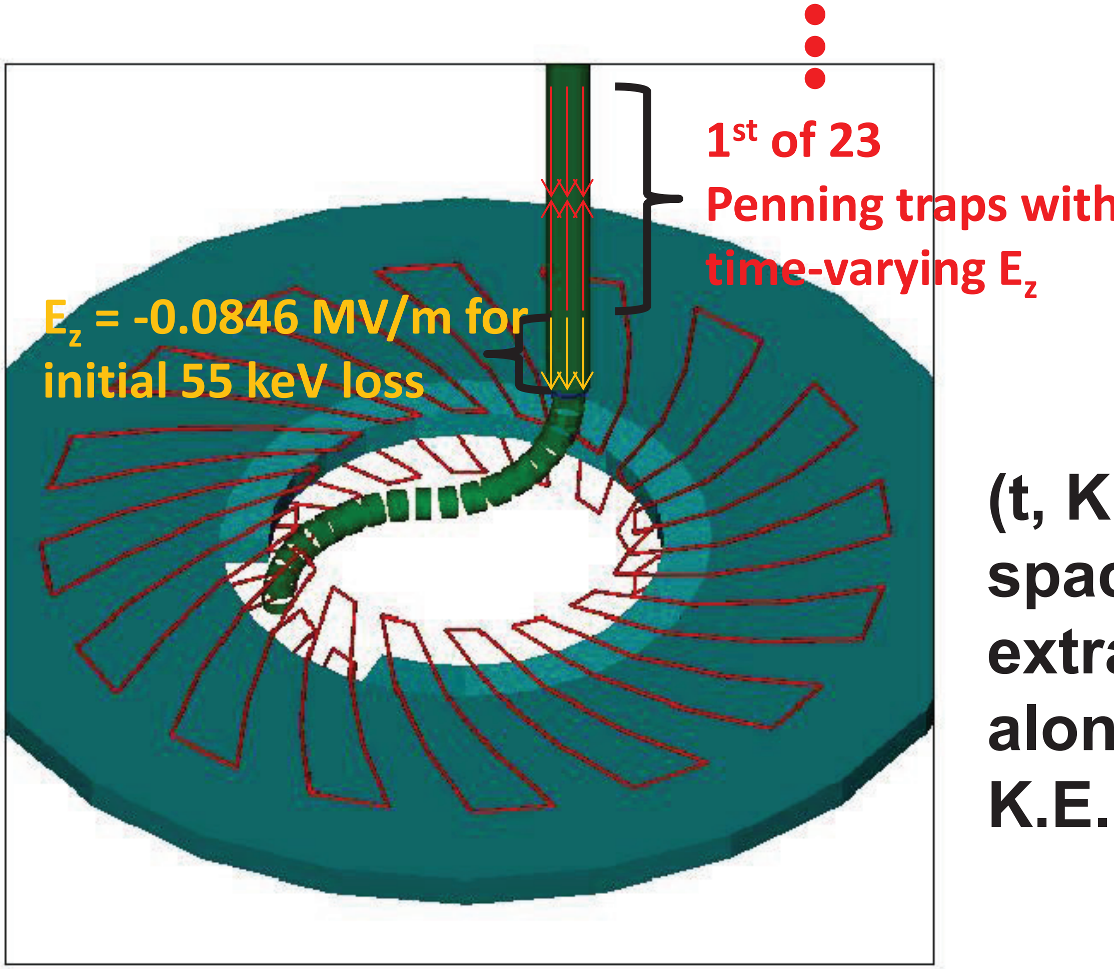
- $\langle B_z \rangle$ rises with r for strong radial focusing; 30° spiral angle, large flutter for axial focusing
- 16 sectors keeps phase advance per sector < 90° keeps aperture large with high (ν_r, ν_z)

Extraction Channel

- Take muon orbit out of (x, y) plane with (x, y) and (y, z) arcs of equal curvature.
- Arcs made up of coils with alternating current direction necessary for beam transport.
- **B** along coil = 0.1 T and alternates direction from coil to coil
- Primitive design: refinements may require coil tilts or putting coils off-center of central beam path.



Longitudinal Manipulation



(t, K.E.) phase space manipulation after extraction to trap muons along sequence of traps at K.E. ~ 10 keV.

Single Trap

$|E_z|$ increases from 0 MV/m to 0.005 MV/m in 300 ns

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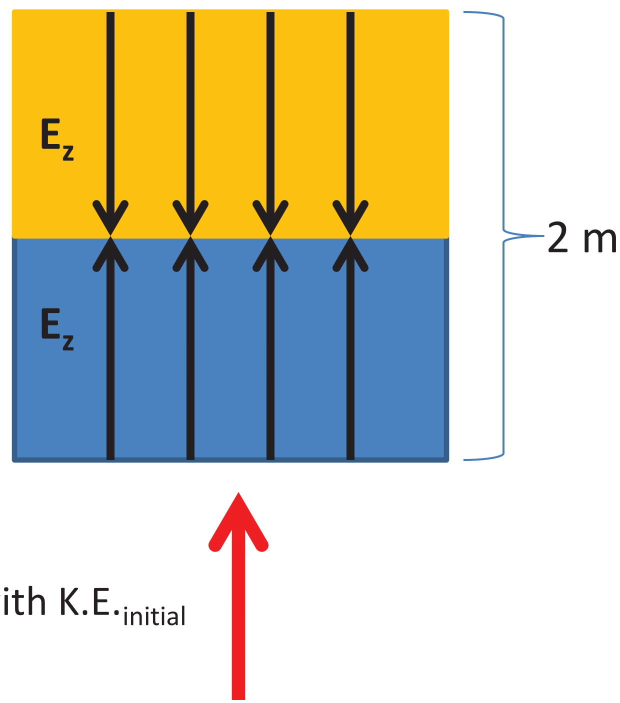


Muon with $K.E._{initial}$

Possibilities for muon in trap

1) Muon trapped, has K.E. with ***(0 < K.E. < $K.E._{max}$) with $K.E._{max}$ > $K.E._{initial}$***
2) Muon exits from top of trap and slowed with K.E. < $K.E._{initial}$
3) Muon exits top of trap with K.E. = $K.E._{initial}$ if E_z doesn't change while muon in trap

Place 23 traps along muon beam direction +z

Times when traps are turned on set so that 50 keV muon at mean time at start of traps is trapped In last (23^{rd}) trap with K.E. < 5 keV.

Simulation Specifics

Use G4Beamline, a GEANT4-based particle tracking simulation program

- Muon decay processes turned off
  - Orbit times >> muon lifetime
  - Focus on lowest energy portion using small helium density for orbits with many turns
- No single-turn injection for now

Input Muon Beam

Mean values, Gaussian spreads
(beam started at fixed azimuth ϕ)

$r = (3289 \pm 50)$ mm
$\theta_r = (0.00 \pm 0.04)$ rad

$z = (0 \pm 15)$ mm
$\theta_z = (0.00 \pm 0.02)$ rad

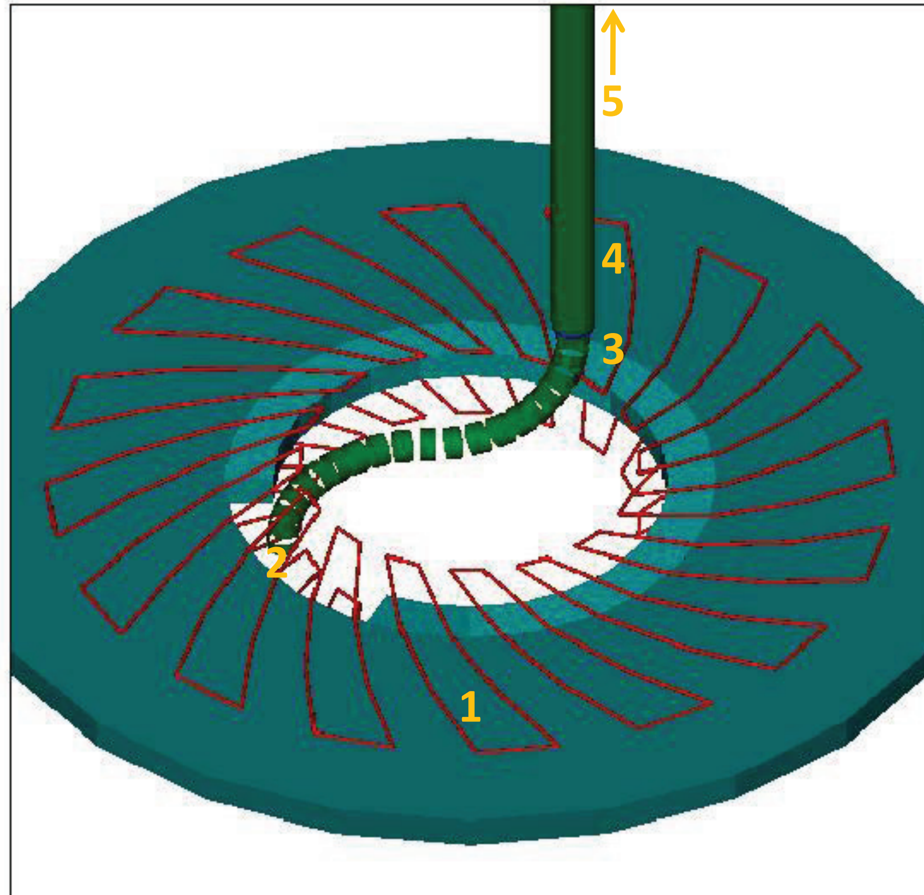
$t = (1 \pm 98)$ ns
K.E. = (305 ± 75) keV

For (r, θ_r, z, θ_z, and K.E.), used special runs with wide uniform spread in one quantity and no spreads in other quantities.

Checked quantity spread of subset of beam that went through entire inverse cyclotron to set input beam spreads.

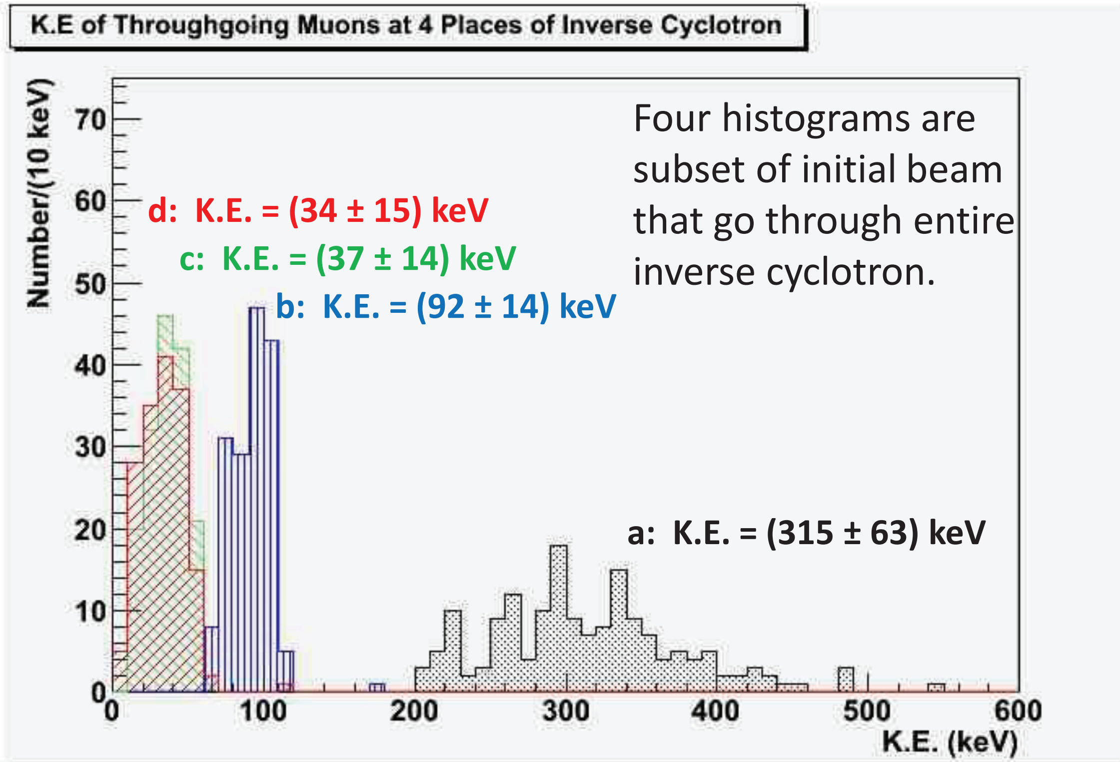
Beam Losses (Decay Losses Turned Off)

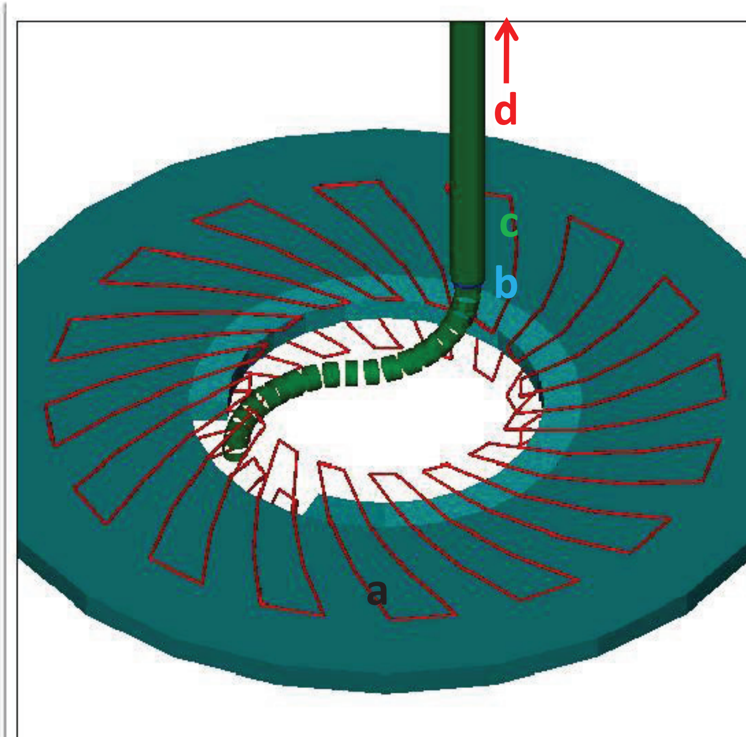
Location	Beam Fraction Remaining
1) Beam start at (r, z) ~ (3300, 0) mm	1.000
2) Extraction start at (r, z) ~ (2200, 0) mm	0.310
3) Extraction end at z = 1470 mm	0.024
4) After ΔK.E. = -55 keV at z = 2120 mm	0.017
5) After electric traps at z = 50,000 mm	0.016



- Main losses are while losing energy in helium and during extraction
- 1.6% of initial beam reaches end. ***Evaluate this throughgoing beam at different locations of inverse cyclotron.***

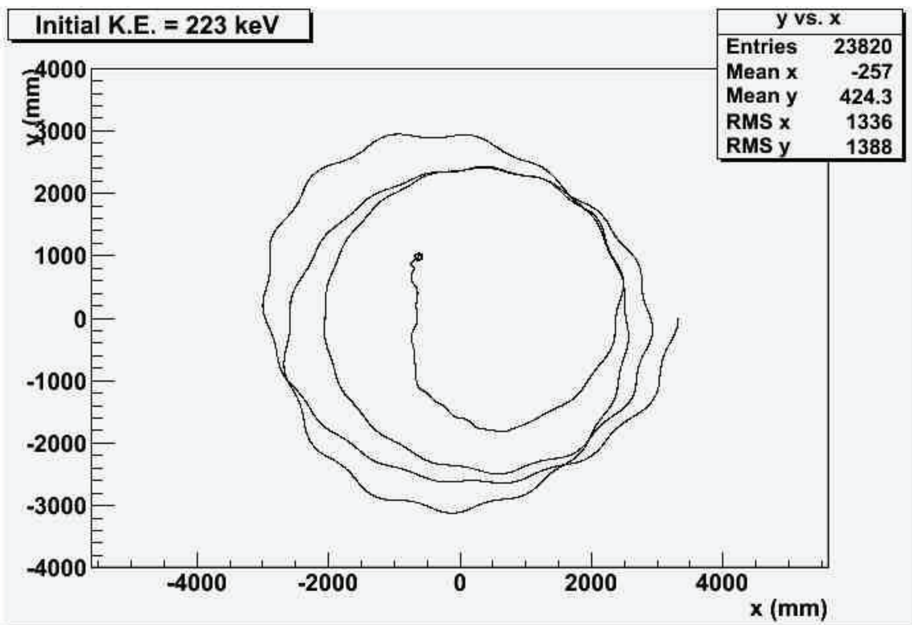
Reduction in K.E. and K.E. Spread



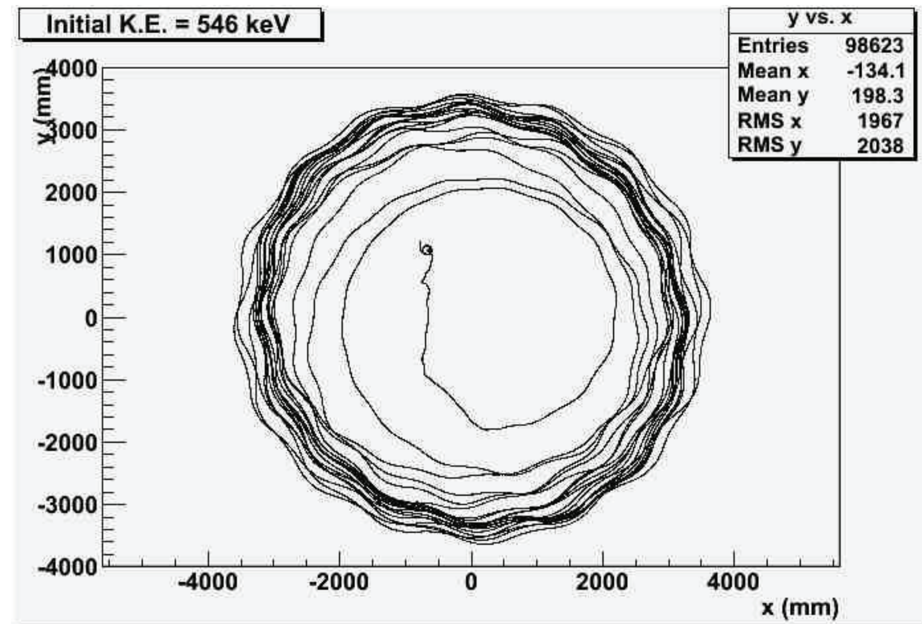


- **a**: beam start
- **b**: end of extraction with reduction in average K.E. and K.E. spread
- **c**: end of 650 mm long section with E_z = -0.0846 MV/m with 55 keV K.E. reduction
- **d**: end of series of electric traps with small change in K.E. and K.E. spreads

Orbits of Low and High Energy Muons



223 keV → 95 keV in 3150 ns, 3 turns



546 keV → 90 keV in 16,500 ns, 18 turns

- This shows that in a cyclotron field with moderator, muons with different initial energies can adjust orbit length to lose enough energy to reach common, final K.E.

- ($0.9 < \nu_r < 2.5$) for (90 keV < K.E. < 600 keV): strong radial focusing through large field index $k = (r/\langle B_z \rangle)(d\langle B_z \rangle/dr)$

Other Kinematic Spreads

- Increase in time spread from 100 ns → 2300 ns from injection to extraction
  - Large time spread increase because initial σ_t (100 ns) << turn period (~ 1000 ns)
  - Scaling up p_i, ρ_{He}, **B** by common factor would yield same orbits, shorter turn period
  - For instance, with 25-fold increase, 120 MeV muons would have ~ 40 ns turn period so that initial 100 ns time spread wouldn't increase much
- Beam size, angular spreads increase as muon beam loses energy
  - Initial transverse emittance acceptance < equilibrium transverse emittance
  - Mismatch largest at low energy
  - Improved cyclotron design, larger energies could improve transverse performance

Summary

- Energy and energy spread of part of muon beam reduced by passage through helium in strong-focusing cyclotron field; transverse spreads increased
- Part of beam extracted perpendicular to plane of cyclotron
- Initial attempt at modulation of longitudinal phase space for further reduction of energy and energy spread

Plans

- Turn on muon decay processes, incorporate G4Beamline space charge

- Introduce variation of moderator density for
  - Reducing overall time
  - Increasing initial energy
  - Single-turn injection

- Improve extraction channel to transport large extracted beam

- Optimize electric trap sizes, $|E_z|$ ramp-up times and turn-on timings for low energy (t, K.E.) manipulation

- Explore use in different energy regions to see if there's optimal emittance range for effective muon cooling with inverse cyclotron