6D Muon Ionization Cooling with an Inverse Cyclotron

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Low Emittance Muon Collider Workshop

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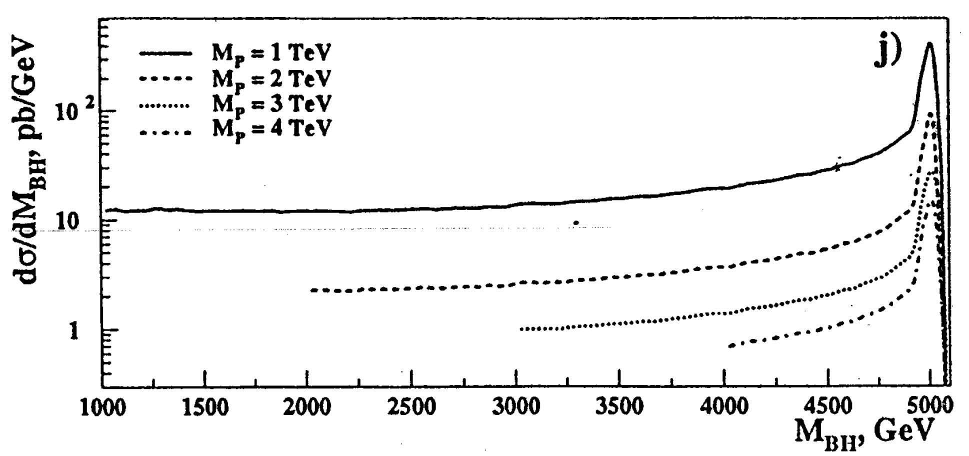
Introduction

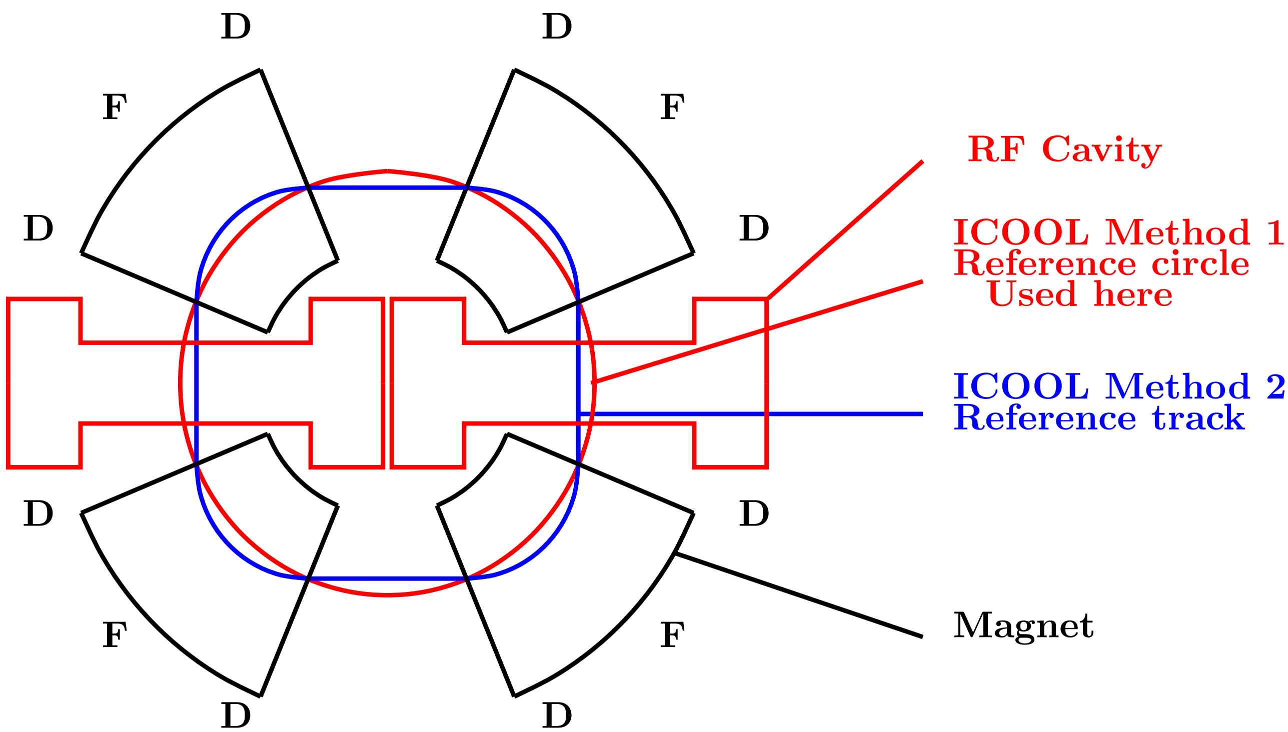
- **Ionization cooling is useful for ν factories ($\mu^- \to e^- \bar{\nu}_e \nu_\mu$ and $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$) and required for muon colliders.**
- **A muon collider needs 10^6 in cooling.**
- **50$\times$ 6D Muon Cooling. Palmer et al., "RFOFO Ionization Cooling Ring," Phys. Rev. ST Acc. Beam 8 (2005) 061003.**
- **Muon Collider Physics.**
  Scanning and splitting A^0/H^0 Higgs.
  Energy Frontier.
  Precision Black Hole Production.

Physics with Black Hole Systems of Known Mass at a Muon Collider

- **Only $\mu^+\mu^-$ might produce black holes/ initial gravitons of known mass.**
- **Known mass could be critical in measuring: Quantum Black Hole Remnants, Scanning production turn on, Initial/final gravitons as missing energy.**
- **The ILC e^+e^- energy is too low.**
- **CLIC e^+e^- suffers from beamstrahlung. 5 TeV spectrum from Greg Landsberg.**

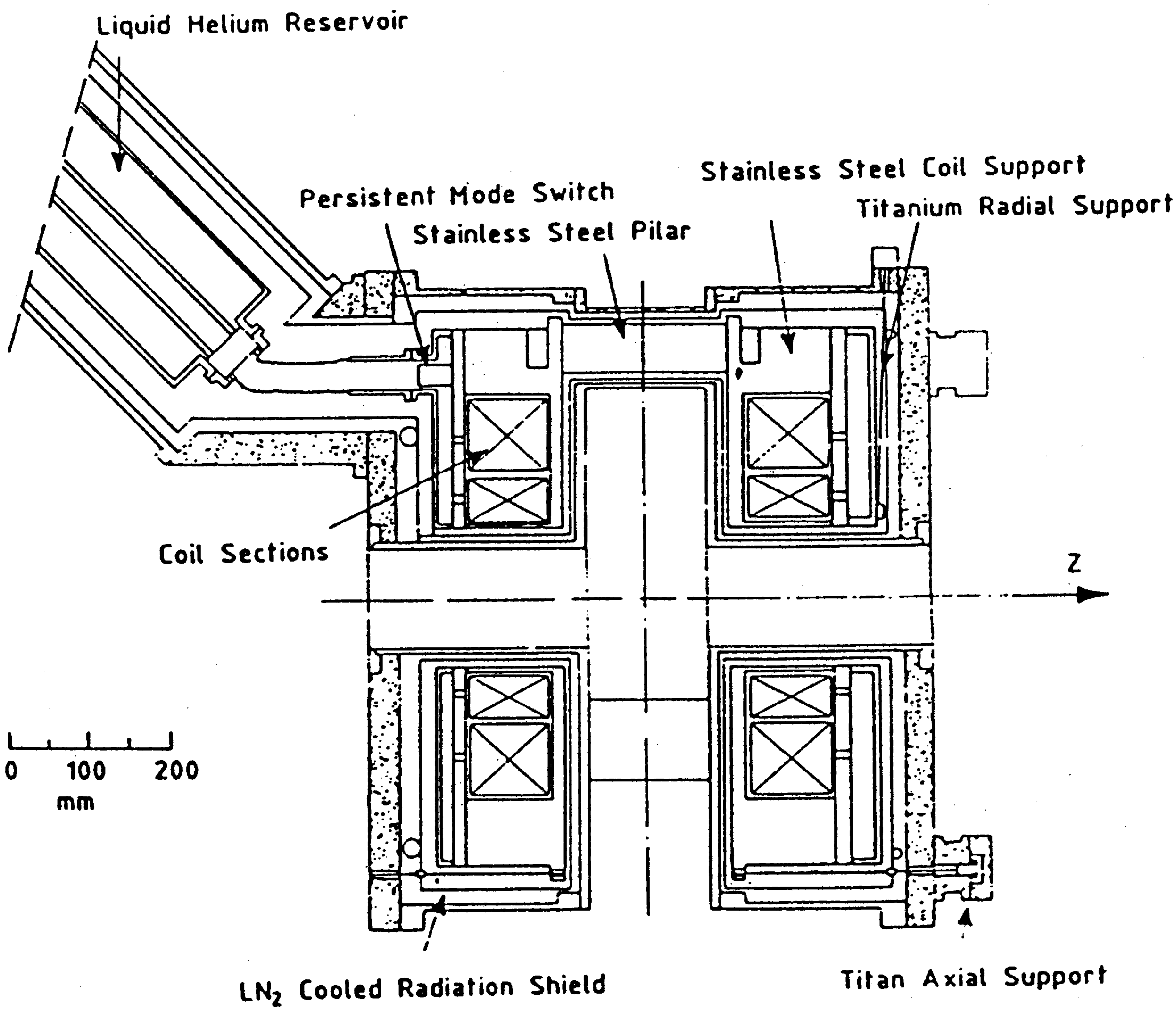


Large Admittance Sector Cyclotron



- **COOL 05: A. Garren, H. Kirk, S. Kahn, "6D Cooling of a Circulating Muon Beam."**

LEAR $\bar{p}$ Azimuthally Symmetric 3 Tesla Cyclotron



- NIM A278 (1989) 368.

LEAR $\bar{p}$ Azimuthally Symmetric 3 Tesla Cyclotron

- **dE/dx Injection radius = 120 mm, p = 105 MeV/c, 0.3 mbar hydrogen**
- **$\bar{p}$ adiabatically spiral to the center.**
- **Swarm: KE = 2 keV; r,h = 15,40 mm**
- **20 microsecond spiral time for 0.3 mbar**
- **1 microsecond spiral time for 10 mbar**
- **Pulsed axial electric kicker**
  80 ns pulse, 20 ns rise, 500 V/cm
  Anti-protons moves 32 cm in 500 ns
  Lighter muons will go farther (F=ma)
- **A bunch train is coalesced into a swarm.**

Halliday and Resnick

- **Cyclotron frequency**
  $\mathbf{f} = \omega/2\pi = \mathbf{qB}/2\pi\mathbf{m}$

- $\mathbf{f}_{\bar{p}}$ / $\mathbf{f}_{\mu}$ = **938/106 = 8.8**
  1 μS spiral $\rightarrow$ 0.11 μS spiral

LEAR→PSI: NIM A394 (1997) 287

- **A New Method to Produce Negative Muon Beam of keV energies**
- **Foil: 3 nm of nickel (3 μg/cm^2) on Formvar 30 min. of sputtering – Franz Kottmann**

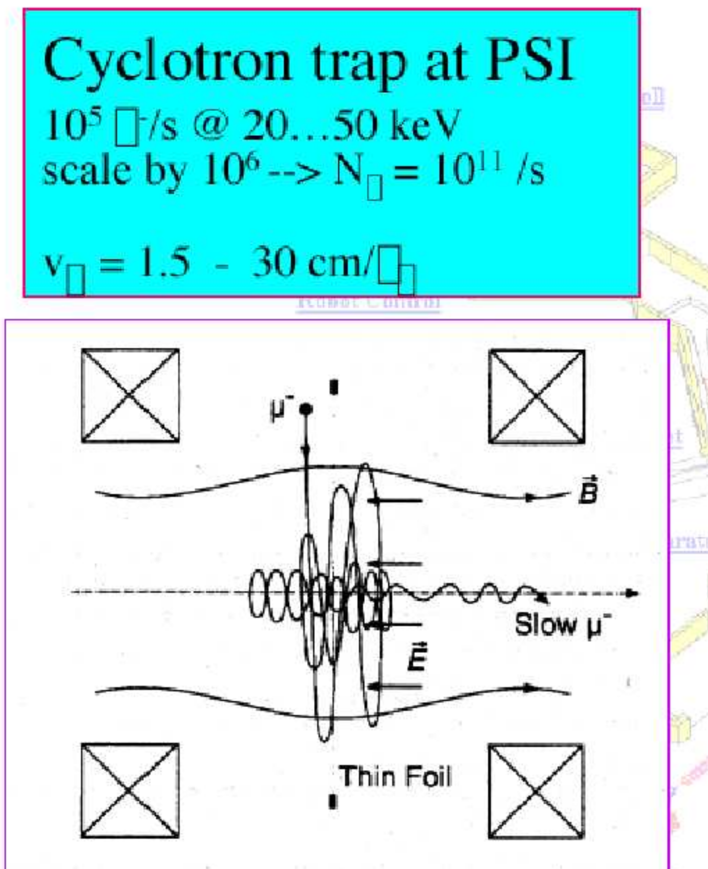
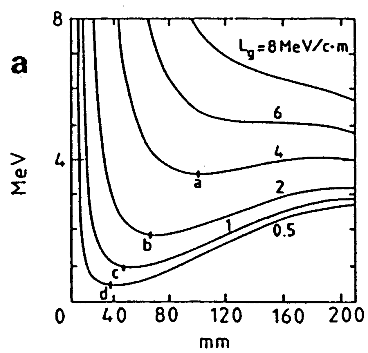
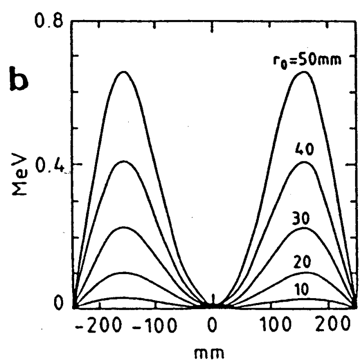


Fig. 2. Principle of the extraction method.

Damped Harmonic Oscillator

- **Generalized Angular Momentum**
  $\mathbf{L}_g = \mathbf{L}_z$ **- e r** $\mathbf{A}_\theta$**,** **NIM A278 (1989) 368**
- **Quasipotential Well,** η **= e/M**
  U(r,z) = V(r,z) - (1/2η**r**^{2}**) (L**$_g$**/M +** η **r A**$_\theta$**)**^{2}
- **(a) U′(r,0)[MeV] vs r [mm] for various L**$_g$
  a, b, c, and d are stable orbit radii
- **(b) [U′(r**$_O$**,z) - U′(r**$_O$**,0)] [MeV] vs z [mm] for various r**$_O$
- **Muons are ferried by the well to a central swarm.**





Space Charge

- **Put 10^{12} muons at a point**
  Take B = 1.0 Tesla
  $F = m\,v^2/r = qQ/4\pi\epsilon_0 r^2 + qvB$
  $r = [mv^2 \pm \sqrt{m^2v^4 - 4(qvB)(qQ/4\pi\epsilon_0)}]/(2qvB)$
  r(15 MeV/c, .14c) = 48 mm
  r(6 MeV/c, .06c) = 14 mm
  r(5 MeV/c, .05c) = imaginary

- **Ionized gas can automatically neutralize space charge! Phys. Rev. 72 (1947) 989, Lloyd Smith, W. Parkins, A. Forrester, "On Separation of Isotopes in Quantity by Electromagnetic Means."**

Avoid Slow Muon Capture

- **Slow muons like to stick to hydrogen**
- **Positive muons**

Helium gas to inhibit muonium formation.

- **Negative muons**

Deuterium gas. Fusion frees muons.

10% sticking factor.

$d + d \rightarrow {}^{3}He + n + 3.3\,\mathbf{MeV}$ **or** $t + p + 4.0\,\mathbf{MeV}$**.**

L. Ponomarev, Contemp. Phys. 31 (1990) 219

- **Lower gas pressure so muons won't range out before they spiral all the way in.**
- **Lower gas pressure so a lower electric field can kick a swarm out after it has built up.**

Avoid Slow Muon Capture

- **Slow negative muons like to stick to nuclei**
- **Slow negative muons used by**

Inverse Cyclotron, physics/0510034
Frictional Cooling, NIM A546 (2005) 356

- **Deuterium gas. Fusion frees muons.**

10% sticking factor.
$d + d \rightarrow {}^3He + n + 3.3\,\mathrm{MeV}$ **or** $t + p + 4.0\,\mathrm{MeV}$**.**
L. Ponomarev, Contemp. Phys. 31 (1990) 219

- 2×10^{12} **fusions @ 30 Hz** $\rightarrow$ **35 watts**

Maximum muon kinetic energy = 4 MeV
Maximum muon momentum = 29 MeV/c
r(29 MeV/c) = 49 mm for 2 Tesla
So the ejected muon stays in the swarm.

Busch's Theorem and Ejection

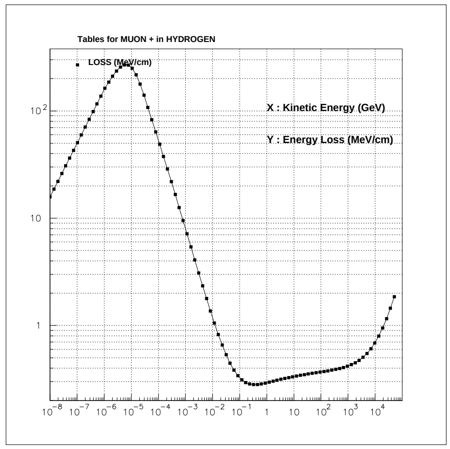
- **Accelerator Physics and Engineering**
  A. W. Chao and M. Tigner, page 101

- $\dot{\phi} = [\mathbf{e/2}\pi\,\gamma\,\mathbf{m\,r^2(s)}][\mathbf{\Phi(s) - \Phi_k}]$
  ϕ **is the azimuthal angle**
  r(s) is the radius of the beam edge
  $\Phi(s)$ **is the magnetic flux** $(\pi r^2 B_s)$ **at s**
  Φ_k **is the flux** $(\pi r^2 B_k)$ **at the cathode**

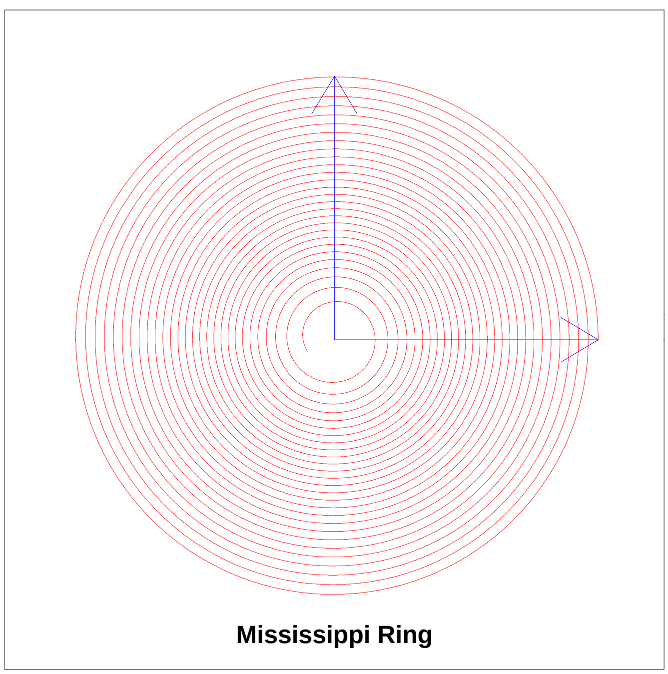
- $\mathbf{L_z = r^2}\gamma\,\mathbf{m}\,\dot{\phi} = \mathbf{-e\,B\,r^2/2 = xp_y - yp_x}$
- $\mathbf{L_z}$ **= 0.3 (0.5 Telsa) (0.05 m)**^{2} **/ 2 = .0002**
- $\mathbf{L_z}$ **= 200 MeV/c–mm**
- $\mathbf{L_z}$ **= 4 MeV/c** $\times$ **50mm**

- **An 4 MeV/c kick is moderately large.**
- **Accelerate, reverse/increase B, absorb** L_z**.**

Initial GEANT Simulations



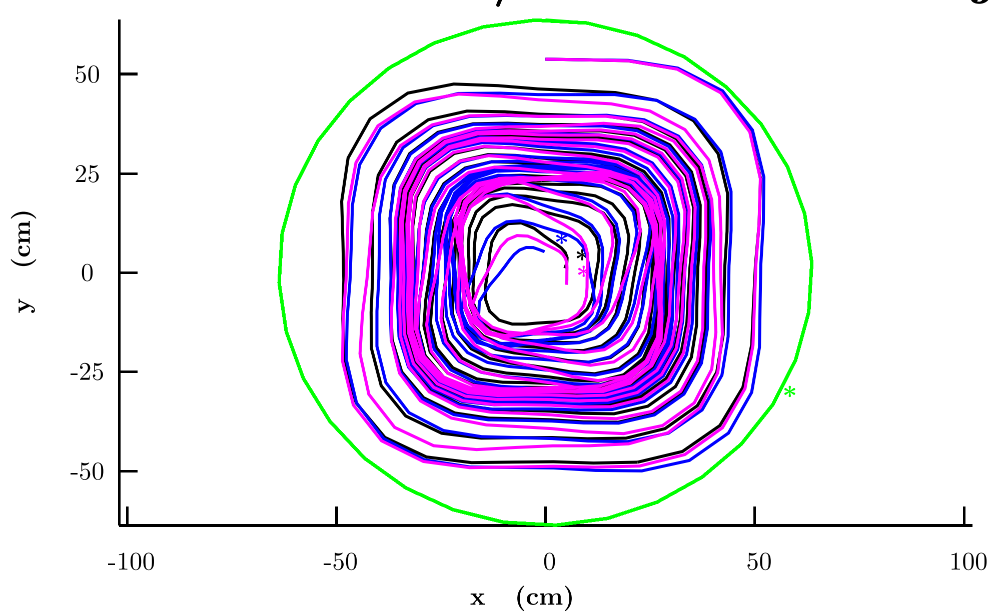
- μ^+ **dE/dx (MeV/cm) vs. KE (GeV) in** LH_2



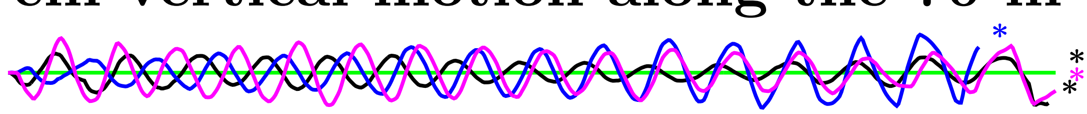
- **Muon spirals in 50 atm of** H_2**, uniform B**

Single Turn Energy Loss Injection

- **Four Magnet (1.8T) Sector Cyclotron.**
  Soft edged fields, ICOOL simulation.
  Multiple scattering and straggling on.
  Radial LiH wedges surrounded by hydrogen.
  Matter decreases adiabatically with radius.
  3 identical 172 MeV/c muons are injected.



- **± 5 cm vertical motion along the 70 m spiral**



- **Injection scaling relation: $\Delta p = .3\, B\, \Delta r$.**

Energy Dynamics

- **2 $\times 10^{12}$ muons arrived at 30 Hz**
  p = 172 MeV/c $\Longrightarrow$ KE = 96 MeV $\Longrightarrow$ 920 Watts beam power

- **Charged absorber foil rather than gas**
  Foil power dissipation = 100 Watts

- **Sector Cyclotron to magnetic bottle transition region = ECRIS**

Electron Cyclotron Resonance Ion Source

Emittance Reduction Goals

- **A muon collider needs 10^6 cooling.**
- $\epsilon = (\Delta p_x \, \Delta x) \, (\Delta p_y \, \Delta y) \, (\Delta p_z \, \Delta z)$
- Δp_x**: 30 MeV/c $\rightarrow$ 0.3 MeV/c**
- Δp_y**: 30 MeV/c $\rightarrow$ 0.3 MeV/c**
- Δp_z**: 30 MeV/c $\rightarrow$ 0.3 MeV/c**
- Δx**: 70 mm $\rightarrow$ 50 mm**
- Δy**: 70 mm $\rightarrow$ 50 mm**
- Δz**: 10000 mm $\rightarrow$ 50 mm**
- **In: 10$\times$ transverse cooler, physics/0411123.**
- **Out: "Frictional μ cooling," H. Abramowicz, A. Caldwell, R. Galea, and S. Schlenstedt, NIM A546 (2005) 356.**

Summary

- **Large admittance sector cyclotron.**
- **Tangential energy loss injection.**
- **Absorber ρ decreases smoothly with r.**
- **LiH wedges in low pressure gas.**
- **Muons ferried in well to center as $\Delta L \to 0$.**
- **As $p \to 0$, $\Delta p \to 0$.**
- **Helium gas inhibits $\mu^+ e^-$ formation.**
- **Deuterium gas frees μ^- via fusion.**
- **Central magnetic bottle holds muon swarm.**
- **A bunch train is coalesced.**
- **Axial ejection with an electric kicker.**