Injection, Extraction, and 6D Muon Cooling with an Anti–Cyclotron

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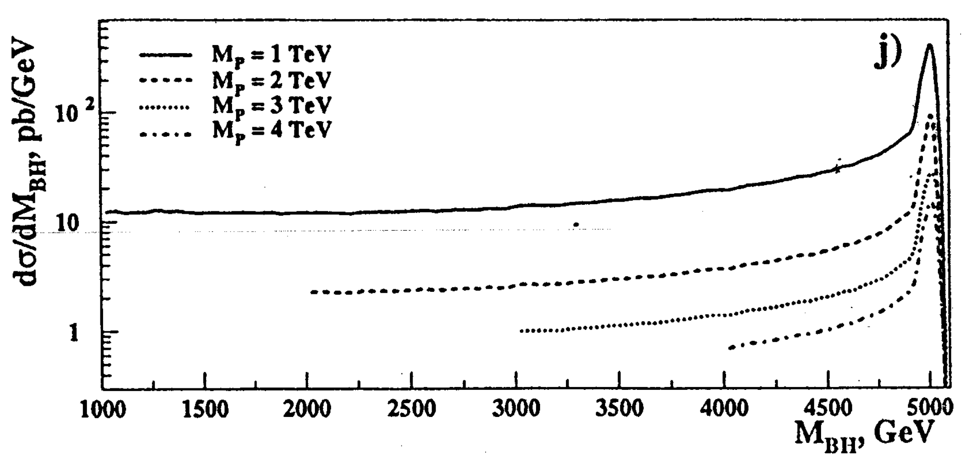
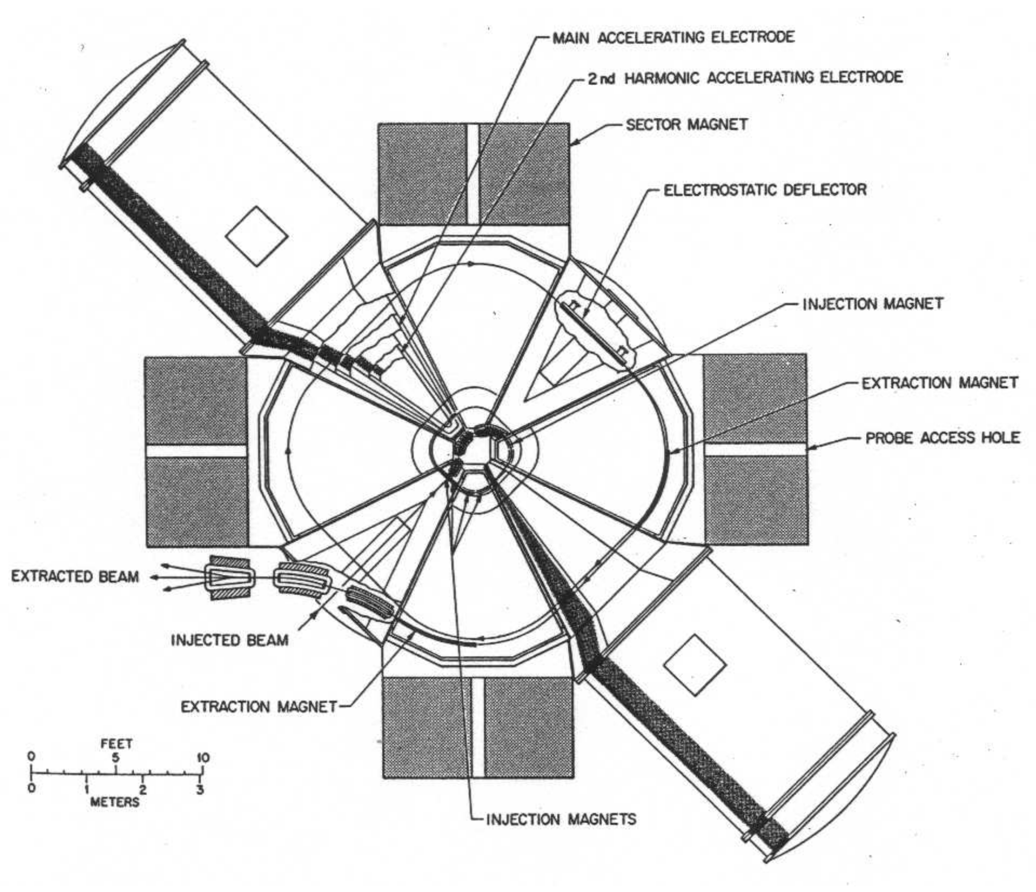
Physics with Black Hole Systems of Known Mass at a Muon Collider

- **Only the Muon Collider can produce black hole systems (black hole plus 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.**
- **CLIC e^+e^- suffers from beamstrahlung 5 TeV spectrum from Greg Landsberg**



Oak Ridge Sector Cyclotron, AIP 9 (1972) 54

Uranium energy (MeV/u)	10	Peak V, fundamental, kV	250
Relativistic Energy Limit	100	2nd Harmonic V, % fund.	26
Min. q/A (for 10 MeV/u)	0.15	Power, fundamental, kW	400
$B\rho_{max}$ (kG-cm)	3018	Power, 2nd harmonic, kW	100
E Constant, K (E = q^2/A)	440	Resonator Length, m	8.6
Max. magnetic field (kG)	16.0	Resonator dia. (max.), m	3.3
Magnet fraction (52^0 hills)	0.58	Amplitude Stability	1 in 10^4
Number of sectors	4	Phase stability, deg	$\pm$0.1
Injection E, U ion (MeV/u)	0.6	Energy Ratio (E_f/E_i)	9 – 19
Radius Ratio (R_f/R_i)	3 – 4.3	Injection $\overline{R}$, R_f/R_i=3 (m)	1.05
Extraction mean R (m)	3.15	RF freq., 10 MeV/u (MHz)	13.22
RF freq. range, (MHz)	6 – 14	Harmonic # (10 MeV/u U)	6
Magnet weight, tons	2300		



Tabletop 6D Cooling Rings with RF

- **6 Sector Dipole Ring**

  Weak edge focusing, B= 5.2 Tesla

  Add skew quads to mix x and y

  Radius = 30 cm, 250 MeV/c muons

  45 MeV/m 201 MHz RF

  100 atm H_2 everywhere

  Merit factor = 400 after 250 orbits

- **12 Cell FFAG Ring**

  Strong Focusing, B= 2.6 Tesla

  $+30^0$ and -15^0 Bends

  Radius = 96 cm, 250 MeV/c muons

  8 MeV/m 201 MHz RF

  100 atm H_2 everywhere

  Merit factor = 120 after 50 orbits

Tabletop 6D Cooling Rings with RF

- **Principles**

  Simulate with ICOOL and SYNCH

  Transverse ionization cooling

  Higher energy $\rightarrow$ Longer path

  $\rightarrow$ Emittance exchange

  $\rightarrow$ Longitudinal cooling

  Constant β allows H_2 everywhere

  High pressure H_2 inhibits RF breakdown

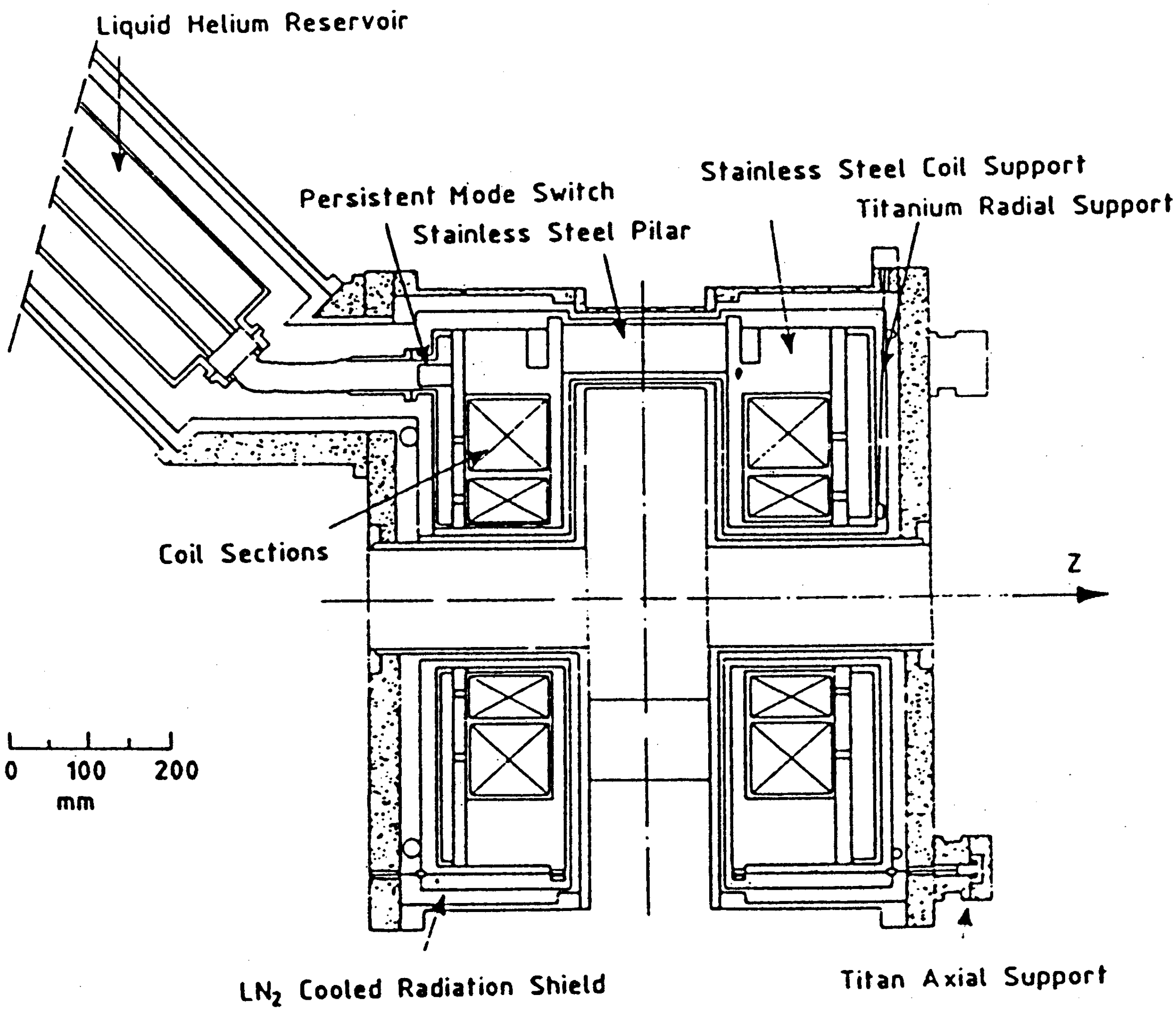
- **Immediate Goal**

  Build 6 sector Demonstration Ring

  1.5 Tesla

  Merit factor = 10

Anti–cyclotron, NIM A278 (1989) 368



B-Field

- **Magnet 3 Tesla**
  4 concentric coils
  Weak focusing
  Azimuthally symmetric field

- **dE/dx Injection radius = 120 mm,**
  p = 105 MeV/c, 0.3 mbar hydrogen

- **Anti-protons adiabatically spiral to the center. dE/dx cannot be too high.**

B-Field Continue...

- **Final anti-proton swarm. KE = 2 keV**
  r = 15 mm
  h = 40 mm

- **20 microsecond spiral time for 0.3 mbar**
- **1 microsecond spiral time for 10 mbar**

- **Pulsed electric kicker in Z**
  80 ns pulse, 20 ns rise
  500 V/cm kick
  Anti-protons moves 32 cm in 500 ns
  Lighter muons will go farther

- **A long bunch train is coalesced into one swarm**

Halliday and Resnick

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

- $\mathbf{f_{\overline{p}}\ /\ f_{\mu} = 938/106 = 8.8}$
  1 μS spiral $\rightarrow$ 0.11 μS spiral

Muon Swarm Size Estimate

- **Put 10^{12} muons at a point**
  Take B = 2.9 Tesla
  Set electric repulsion = Lorentz force
  Find radius
  Estimate, not orbit!!!
- **E = vB; v = qBr/m**
  $$10^{12}\ q\ /\ (4\pi\epsilon_0\ r^2) = q\ r\ B^2\ /\ m$$
  $$r = [10^{12}\ m\ /\ (4\pi\epsilon_0\ B^2)]^{1/3}$$
  $$= 6\text{mm}$$
- **Put a wire through the muon swarm**
  Neutralize the charge!
  10^{12} electrons move in a μS $\rightarrow$ 1 Amp

Beam Pipe

- **The central region of the anti–cyclotron may need an Al or Be beam pipe**
- **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.**

- **Slow muons like to stick to hydrogen**
- **Three positive muon solutions**

Positively charged foils instead of gas.
Helium gas to inhibit muonium formation.
Let muonium form. Laser disassociate.

- **Two negative muon solutions**

Negatively charged foils instead of gas.
Deuterium-Tritium gas. Fusion frees muons.

dE/dx Injection

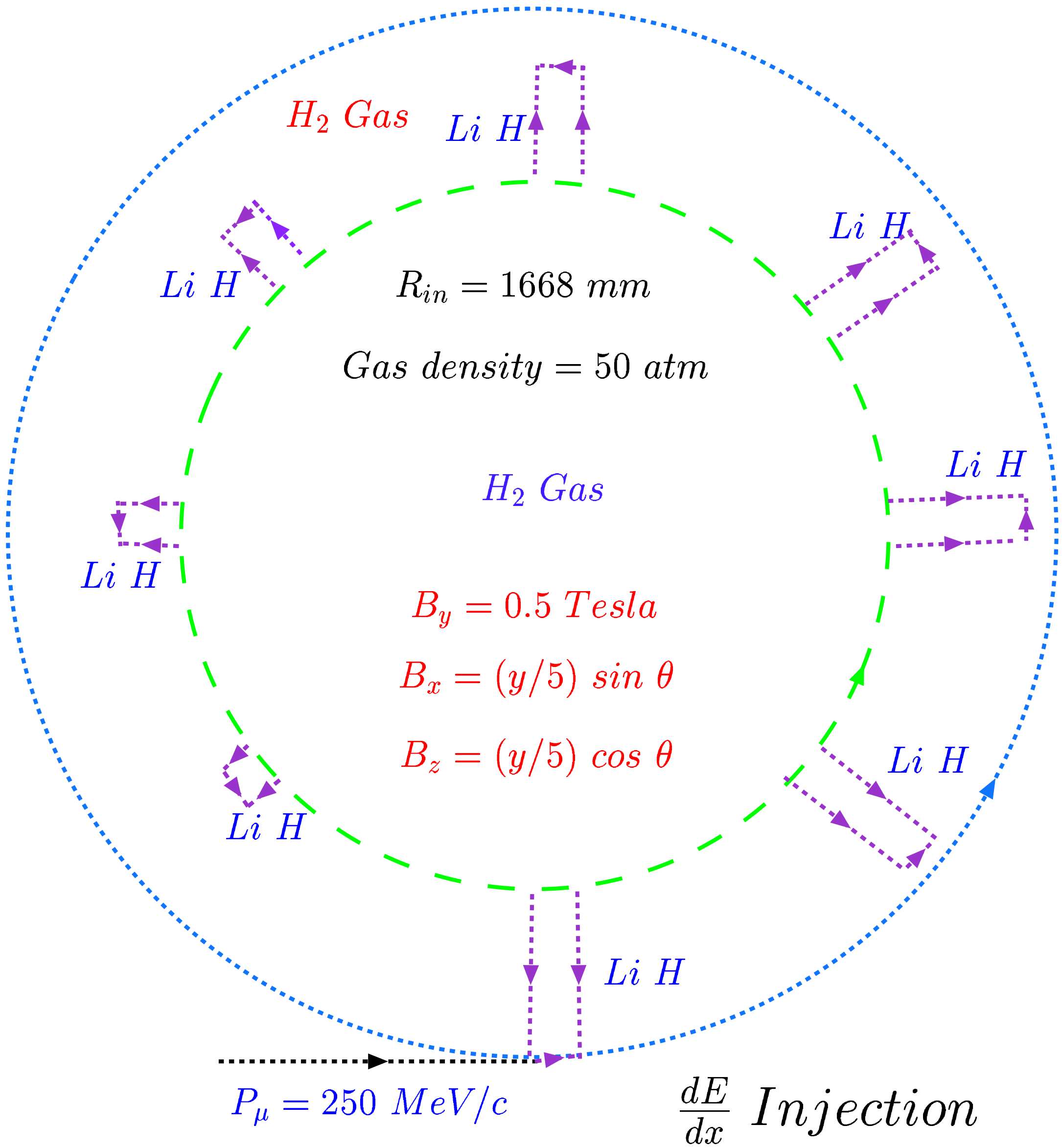
- **Imagine a 250 MeV/c muon entering an 0.5 Telsa ring tangent to a 1688 mm radius. A small kick gets it in.**

- **Now imagine that a swarm needs to spiral in 500 mm and lose 30% of its momentum in one orbit.**
- **KE loss needed = 67 MeV in 9000 mm**

- **http://www.cap.bnl.gov/mumu/conf/ MUTAC-040219/TALKS/Palmer1.pdf**
- **LiH absorbs 160 MeV/m $\rightarrow$ 420 mm**
- **LH_2 absorbs 30 MeV/m $\rightarrow$ 2300 mm**

- **So its worth simulating dE/dx injection.**

dE/dx Injection Layout



Busch's Theorem and Ejection

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

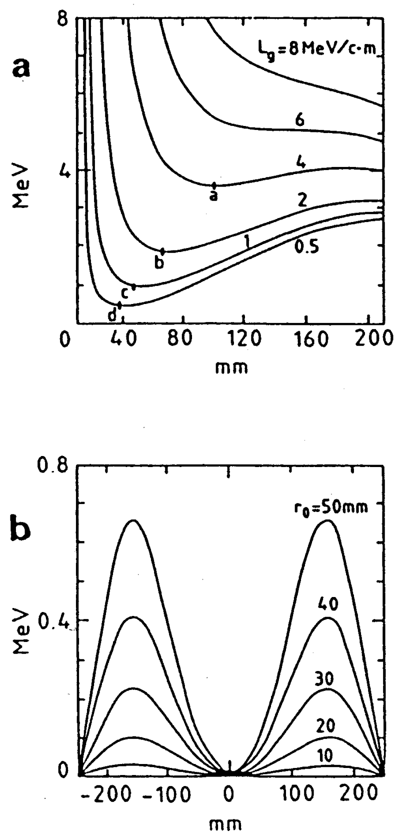
- $\dot{\phi} = [\mathbf{e}/\mathbf{2}\pi\,\gamma\,\mathbf{m}\,\mathbf{r^2}(\mathbf{s})][\mathbf{\Phi}(\mathbf{s}) - \mathbf{\Phi_k}]$
  ϕ **is the azimuthal angle**
  r(s) is the radius of the beam edge
  $\Phi(s)$ **is the magnetic flux** $(\pi r^2 B_s)$ **at s**
  Φ_k **is the flux** $(\pi r^2 B_k)$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

- $\mathbf{L_z} = \mathbf{r^2}\gamma\,\mathbf{m}\,\dot{\phi} = -\mathbf{e}\,\mathbf{B}\,\mathbf{r^2}/\mathbf{2} = \mathbf{xp_y} - \mathbf{yp_x}$
- $\mathbf{L_z}$ **= 0.3 (0.5 Telsa) (0.10 m)**^{2} **/ 2 = .0008**
- $\mathbf{L_z}$ **= 800 MeV/c–mm**
- $\mathbf{L_z}$ **= 8 MeV/c** $\times$ **100mm**

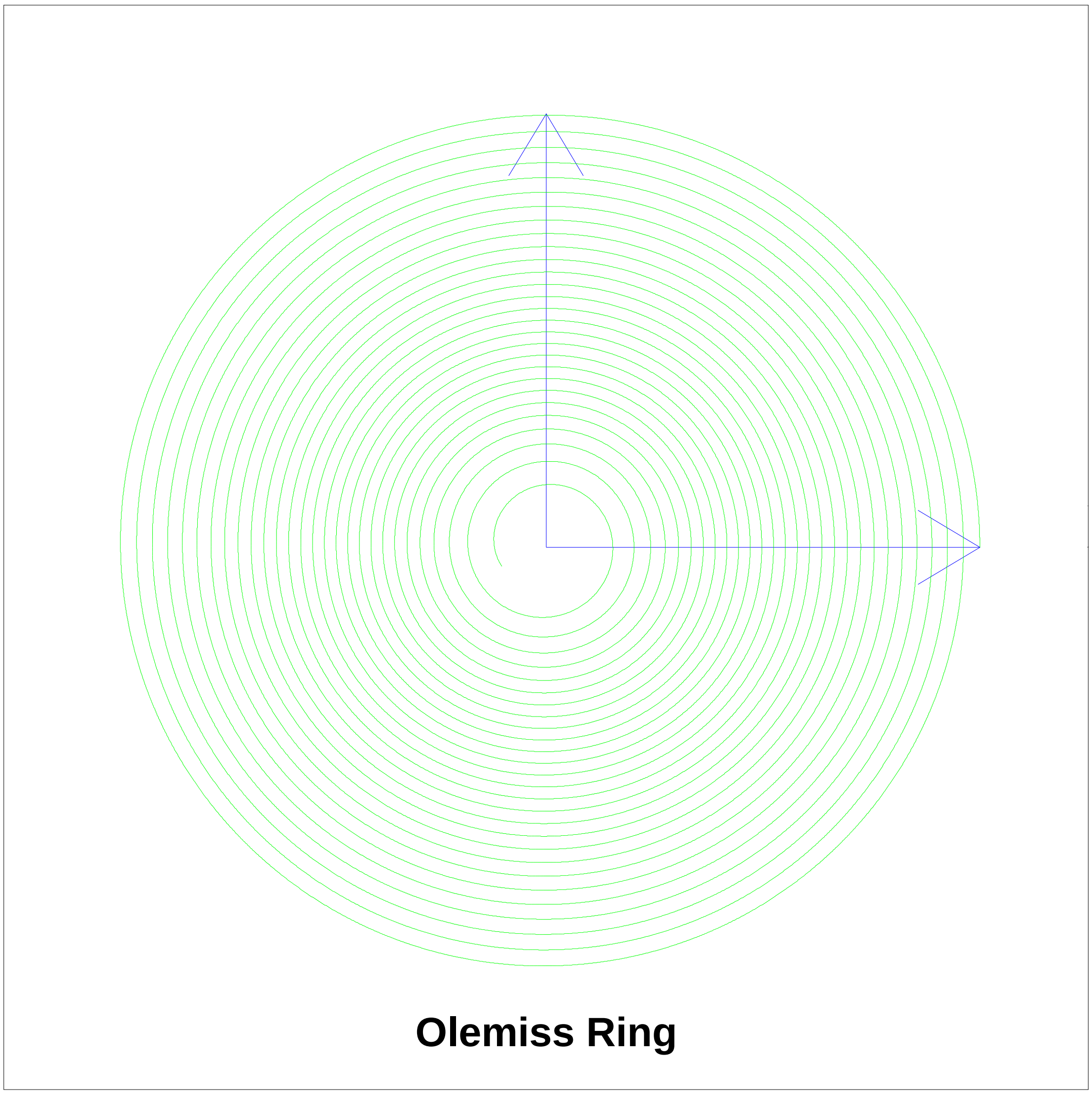
- **An 8 MeV/c kick is moderately large.**
- **So, maybe increase the mirror ratio...**

Damped Harmonic Oscillator

- **Generalized Angular Momentum**
  $L_g = L_z - e\,r\,A_\theta$, **NIM A278 (1989) 368**
- **Quasipotential Well,** $\eta = e/M$
  $U(r,z) = V(r,z) - (1/2\eta r^2)\,(L_g/M + \eta\,r\,A_\theta)^2$
- **(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**

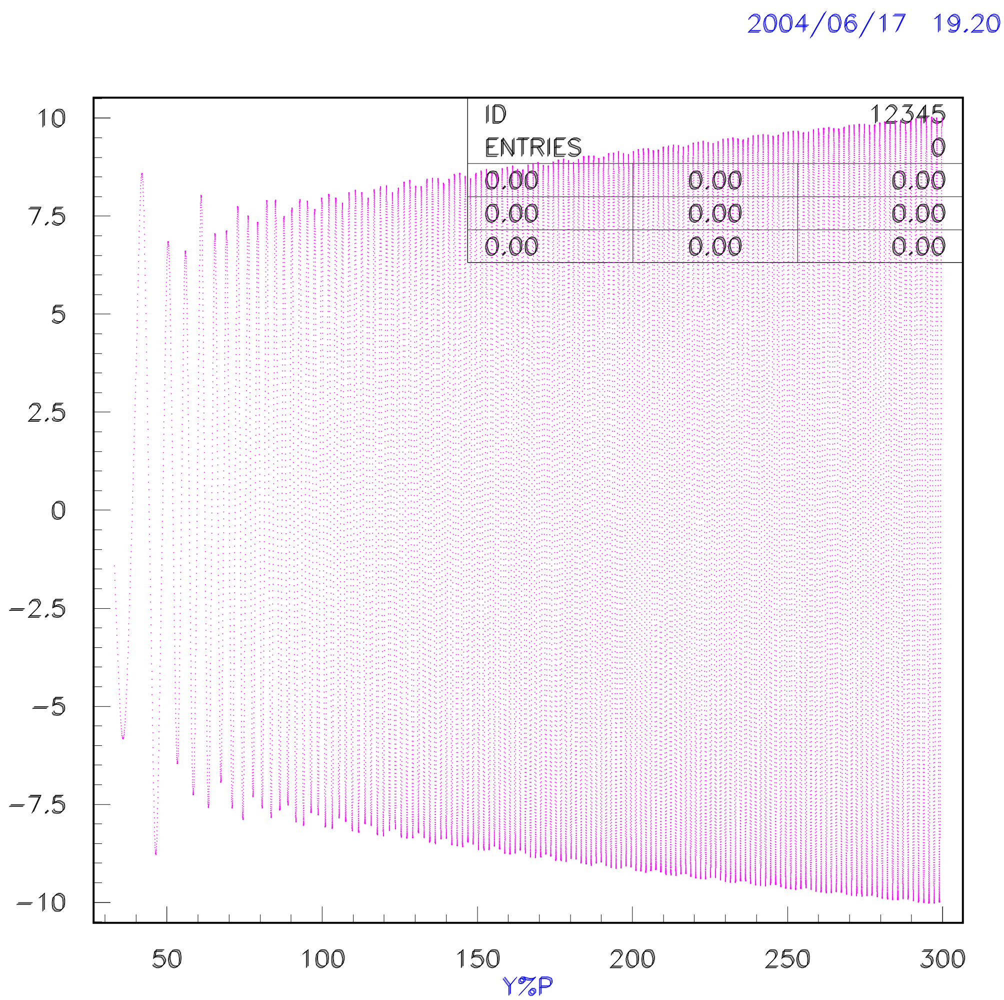


Initial GEANT Simulations



- **A muon spirals in 50 atm of H_2.**

Initial GEANT Simulations



- **Vertical damping from 10 to 7 cm as a 300 MeV/c muon spirals in (50 atm H_2) from 100 cm using non-Maxwellian fields. B(y,x,z) = (1, (y/5) sin θ, (y/5) cos θ) Tesla**

Data from PSI: NIM A394, 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

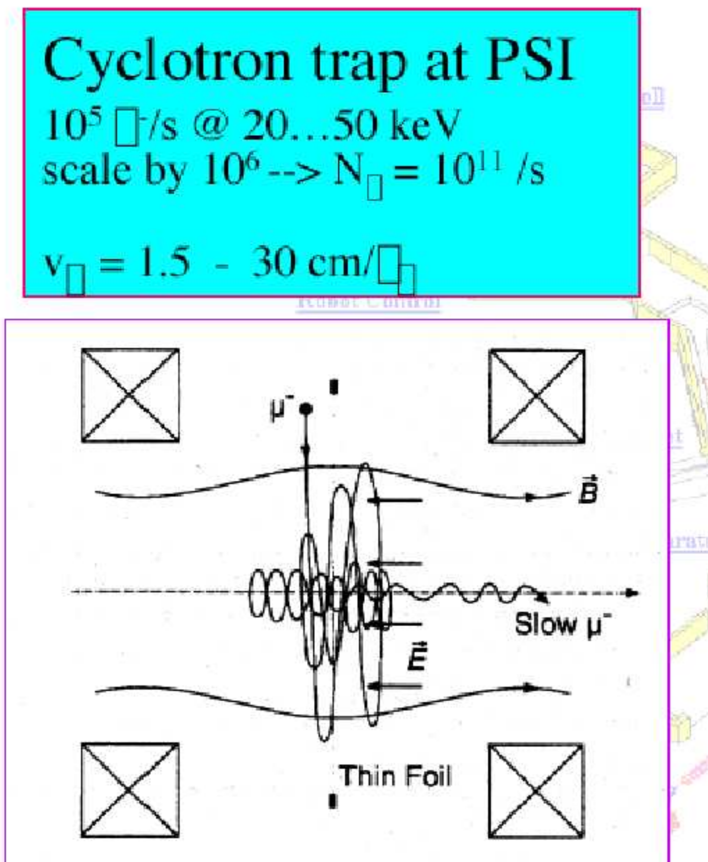


Fig. 2. Principle of the extraction method.

Emittance Reduction Goals

- $\epsilon = (\Delta p_x \, \Delta x) \, (\Delta p_y \, \Delta y) \, (\Delta p_z \, \Delta z)$
- Δp_x: **50 MeV/c $\rightarrow$ 1 MeV/c**
- Δp_y: **50 MeV/c $\rightarrow$ 1 MeV/c**
- Δp_z: **50 MeV/c $\rightarrow$ 1 MeV/c**
- Δx: **150 mm $\rightarrow$ 100 mm**
- Δy: **150 mm $\rightarrow$ 100 mm**
- Δz: **10000 mm $\rightarrow$ 100 mm**
- **Re-accelerate. Exchange Δp_x for Δx and Δp_y for Δy. Repeat Anti-Cyclotron**
- Δp_x: **15 MeV/c $\rightarrow$ 1 MeV/c**
- Δp_y: **15 MeV/c $\rightarrow$ 1 MeV/c**
- Δp_z: **1 MeV/c $\rightarrow$ 1 MeV/c**
- Δx: **50 mm $\rightarrow$ 30 mm**
- Δy: **50 mm $\rightarrow$ 30 mm**
- Δz: **100 mm $\rightarrow$ 30 mm**