

# 6D Ionization Muon Cooling with Tabletop Rings

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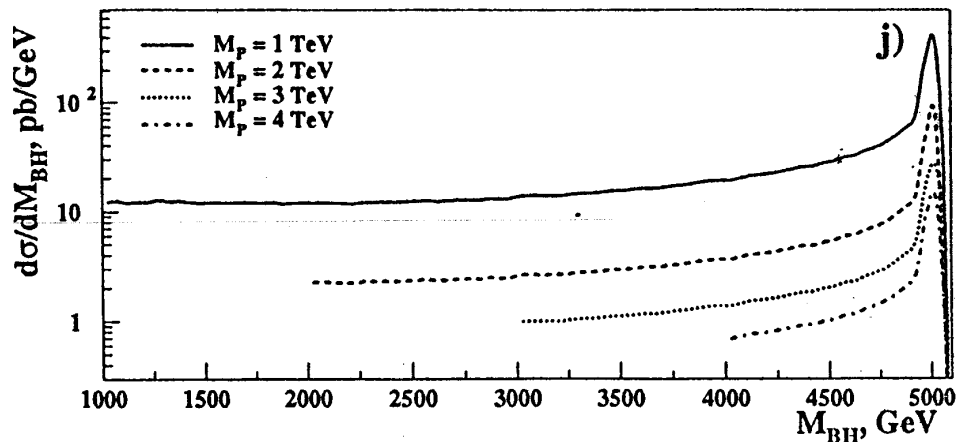
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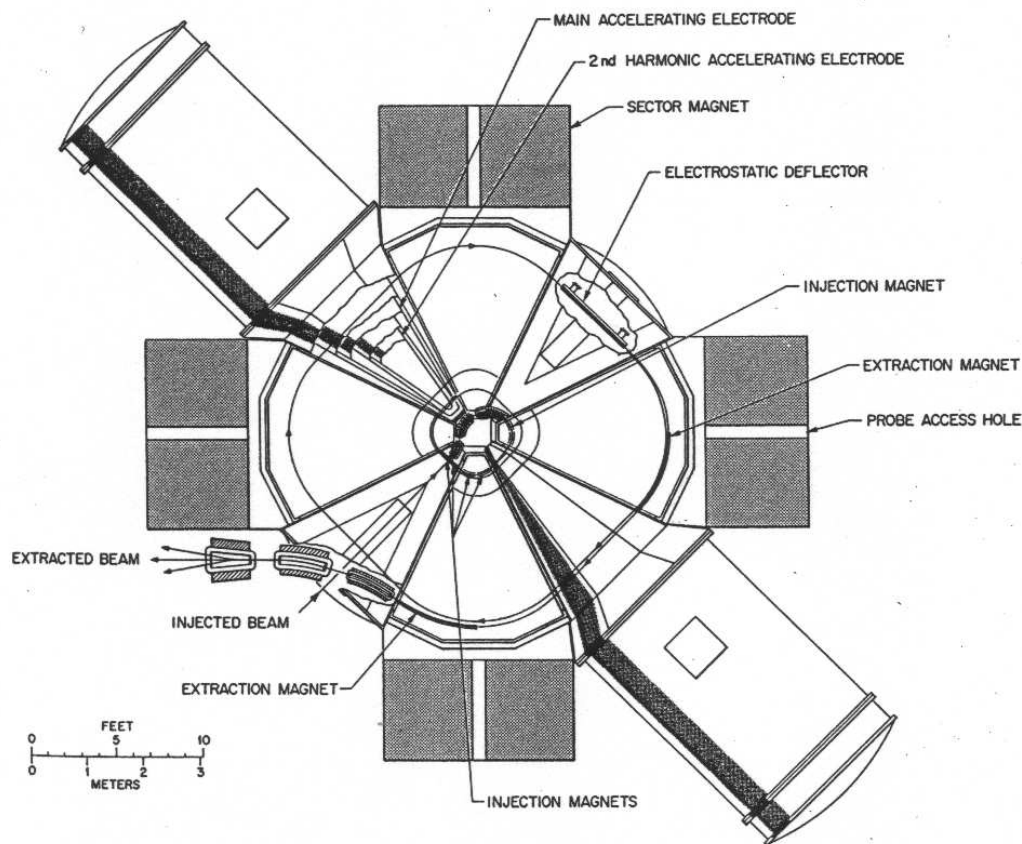
## Physics with Black Hole Systems of Known Mass at a Muon Collider

- 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 $\bar{R}$ , $R_f/R_i=3$ (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° and -15° 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 → Longer path

→ Emittance exchange

→ Longitudinal cooling

Constant  $\beta$  allows H<sub>2</sub> everywhere

High pressure H<sub>2</sub> inhibits RF breakdown

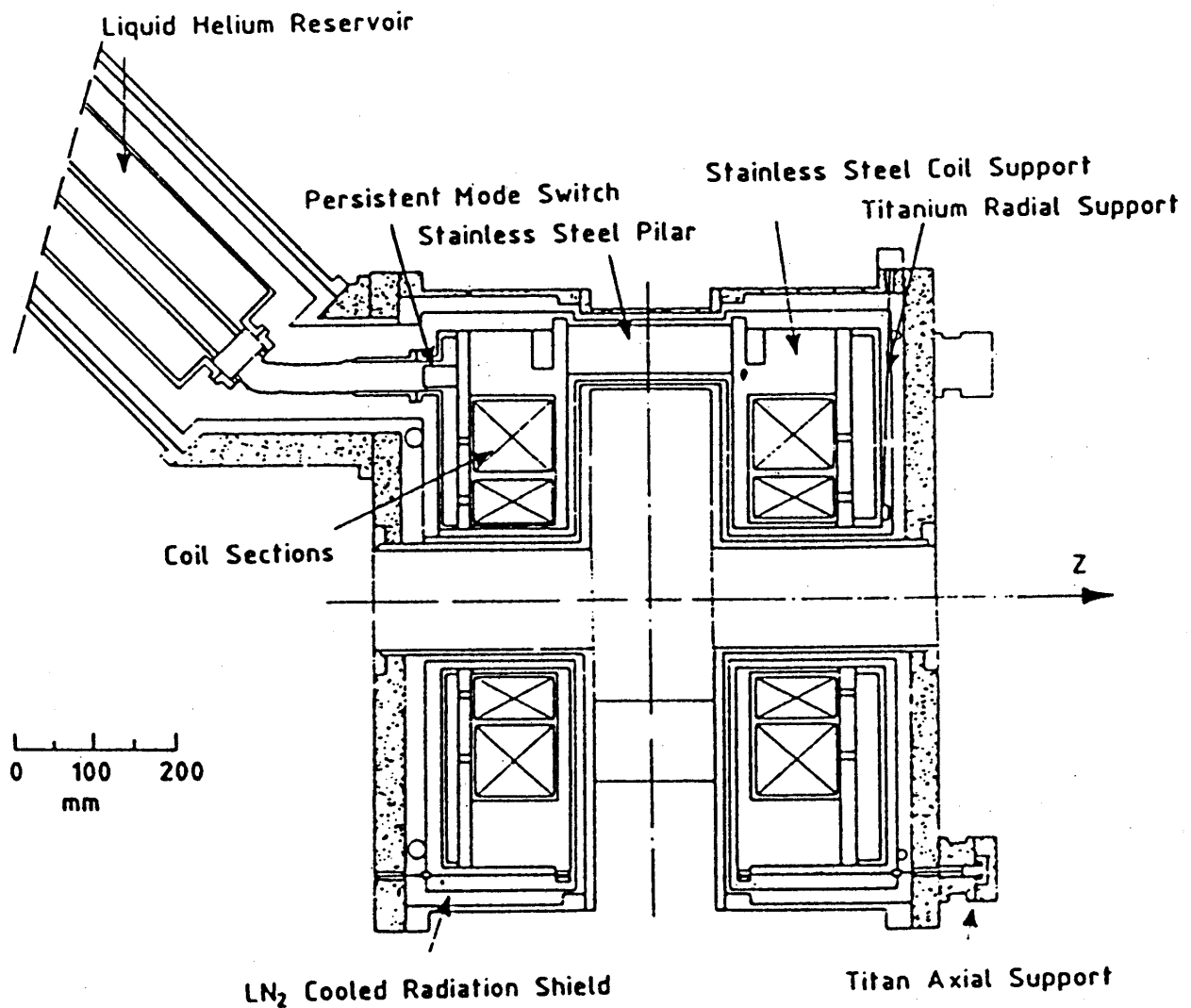
- Immediate Goal

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,  
 $p = 105 \text{ MeV}/c$ , 0.3 mbar hydrogen
- Anti-protons adiabatically spiral to  
the center.  $dE/dx$  cannot be too high.

## B-Field Continue...

- Final anti-proton swarm.  $KE = 2 \text{ keV}$   
 $r = 15 \text{ mm}$   
 $h = 40 \text{ mm}$
- 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

$$f = \omega / 2\pi = qB / 2\pi m$$

- $f_p / f_\mu = 938 / 106 = 8.8$

1  $\mu\text{S}$  spiral  $\rightarrow$  0.11  $\mu\text{S}$  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  $\mu\text{S} \rightarrow 1$  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
- Two positive muon solutions  
Positively charged foils instead of gas.  
Helium gas to inhibit muonium formation.
- 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 Tesla 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 → 420 mm
- LH<sub>2</sub> absorbs 30 MeV/m → 2300 mm
- So its worth simulating dE/dx injection.

## Busch's Theorem and Ejection

- Accelerator Physics and Engineering  
A. W. Chao and M. Tigner, page 101
- $\dot{\phi} = [e/2\pi \gamma m r^2(s)][\Phi(s) - \Phi_k]$   
 $\phi$  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  $s$   
 $\Phi_k$  is the flux ( $\pi r^2 B_k$ ) at the cathode
- $L_z = r^2 \gamma m \dot{\phi} = -e B r^2 / 2 = x p_y - y p_x$
- $L_z = 0.3 (0.5 \text{ Telsa}) (0.10 \text{ m})^2 / 2 = .0008$
- $L_z = 800 \text{ MeV}/c - \text{mm}$
- $L_z = 8 \text{ MeV}/c \times 100 \text{mm}$
- An 8 MeV/c kick is moderately large.
- So, maybe increase the mirror ratio...

## Damped Harmonic Oscillator

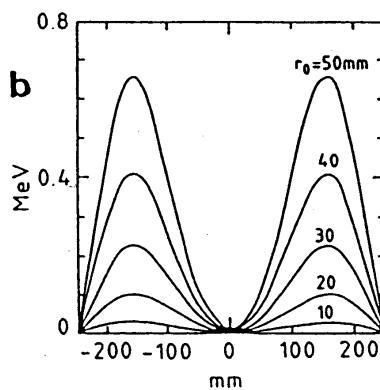
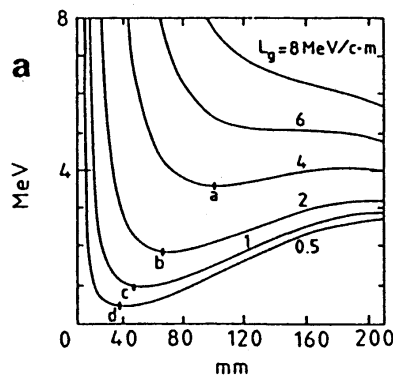
- Generalized Angular Momentum

$$L_g = L_z - e r A_\theta, \quad \text{NIM A278 (1989) 368}$$

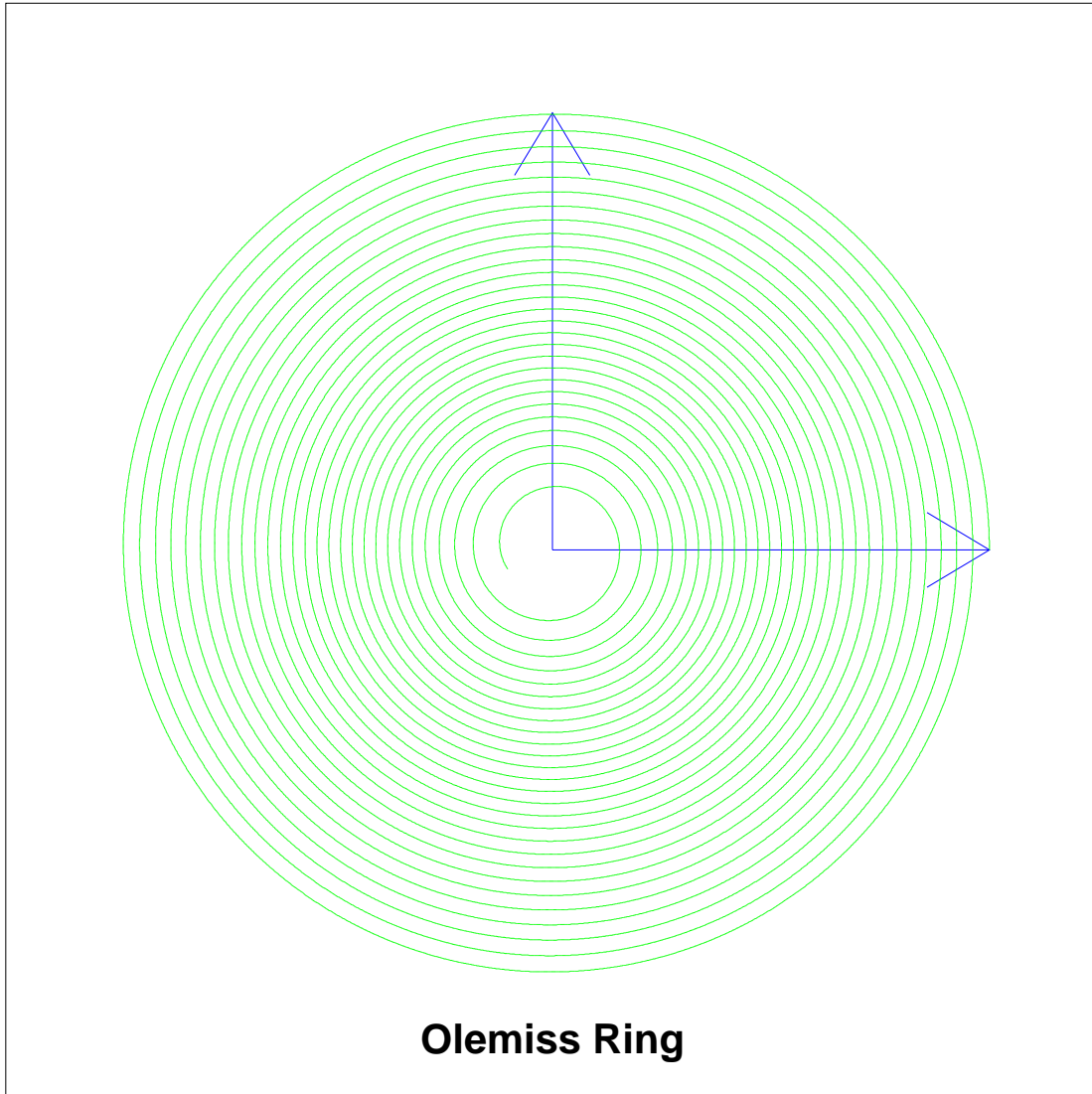
- Quasipotential Well,  $\eta = e/M$

$$U(r,z) = V(r,z) - (1/2\eta r^2) (L_g/M + \eta r A_\theta)^2$$

- (a)  $U'(r,0)$  [MeV] vs  $r$  [mm] for various  $L_g$   
a, b, c, and d are stable orbit radii
- (b)  $[U'(r_0,z) - U'(r_0,0)]$  [MeV] vs  $z$  [mm] for various  $r_0$



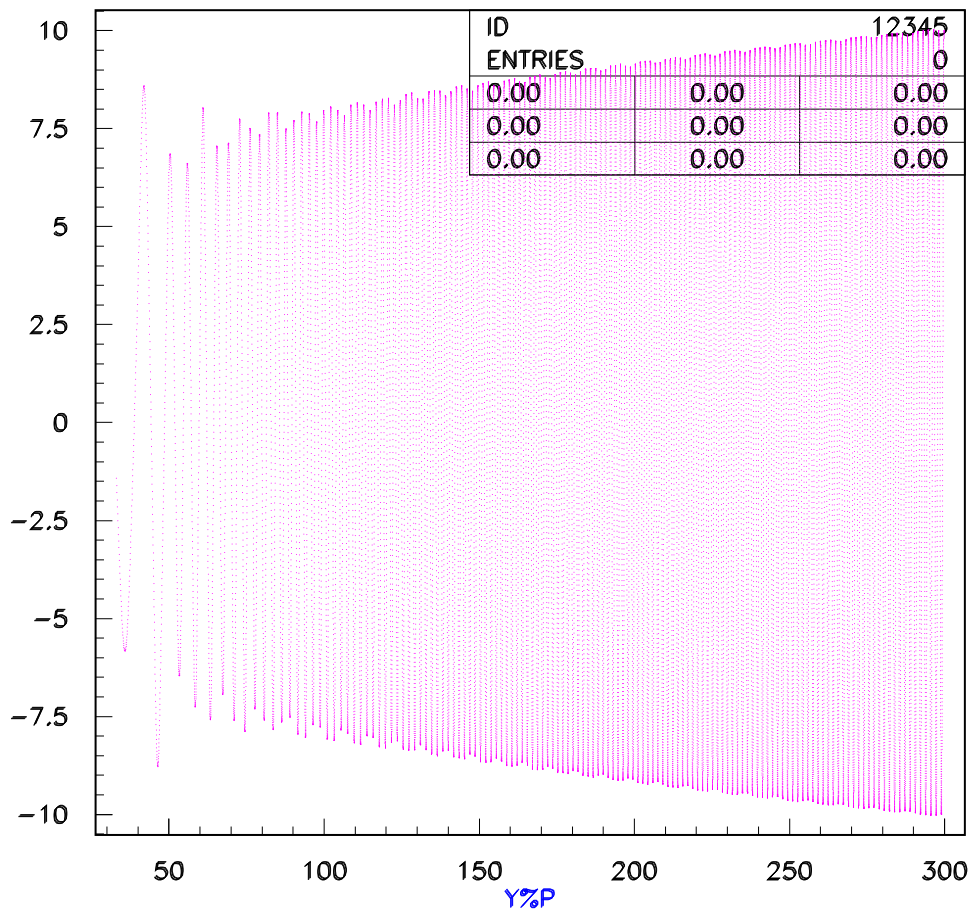
## Initial GEANT Simulations



- A muon spirals in 50 atm of H<sub>2</sub>.

# Initial GEANT Simulations

2004/06/17 19.20



- Vertical damping from 10 to 7 cm as a 300 MeV/c muon spirals in (50 atm H<sub>2</sub>) from 100 cm using non-Maxwellian fields.  
 $B(y,x,z) = (1, (y/5) \sin \theta, (y/5) \cos \theta)$  Tesla

## Emittance Reduction Goals

- $\epsilon = (\Delta p_x \Delta x) (\Delta p_y \Delta y) (\Delta p_z \Delta z)$
- $\Delta p_x$ : 50 MeV/c  $\rightarrow$  1 MeV/c
- $\Delta p_y$ : 50 MeV/c  $\rightarrow$  1 MeV/c
- $\Delta p_z$ : 50 MeV/c  $\rightarrow$  1 MeV/c
  
- $\Delta x$ : 150 mm  $\rightarrow$  100 mm
- $\Delta y$ : 150 mm  $\rightarrow$  100 mm
- $\Delta z$ : 10000 mm  $\rightarrow$  100 mm
  
- Re-accelerating and running through a 2nd sector anti-cyclotron may help  $\Delta x$ ,  $\Delta y$ , and  $\Delta z$ .
- Negative muons are now running in the PSI anti-cyclotron using a foil.  
See NIM A394, 287