Muon Colliders and Muon Storage Rings as a Source of Neutrino Beams

(For the Neutrino Factory and Muon Collider Collaboration)

presented by

Andrew M. Sessler

1. Muon Collider Physics [Raja]
2. Neutrino Physics [Shaevitz]
3. Proton Source
4. Targeting, Capture and Decay
5. Cooling
6. Acceleration
7. Collider Ring or Storage Ring
8. Example: The PJK Neutrino Factory
9. Detector and Background [Raja]
10. Neutrino Radiation Hazard
11. R and D: Theory, Mucool, Target Experiment, Other Experiments

History of Muon Colliders

Muon Collider mentioned {
- Tinlot (1960)
- Budker (1969)
- Skrinsky (1971)
- Neuffer (1979)

Ionization Cooling
{Skrinsky & Parkhomchuk (1981)

High Luminosity {Neuffer(1985) & Palmer(1994)

Collaboration Formed (1995)

Charles M. Ankenbrandt et al. (Muon Collider Collaboration) Phys. Rev. ST Accel. Beams 2, 081001 (1999) (73 pages)

Future

Collaboration Home Page
http://www.bnl.gov/~cap/mumu/mu_home_page.htn

Physics Potential of Muon Colliders, San Francisco, Dec. 15-17, 1999

Collaboration Meeting, Catalina, May 17-19, 2000

History of Muon Storage Rings as a Neutrino Source

1. Concept proposed: DeRujula,A., S.L. Glashow, R.R. Wilson, G. Charpak, Phys. Rev. **99**, 341 (1983).

2. Quantified: Geer, S. Phys. Rev. D **57**, 6989 (1998).

3. Workshop on Front End Physics of a Muon Collider, Fermilab, 1997:

4. Workshop on the Potential for Neutrino Physics at Future Muon Colliders, Brookhaven, 1998.

6. Meeting in Berkeley, April, 1999.

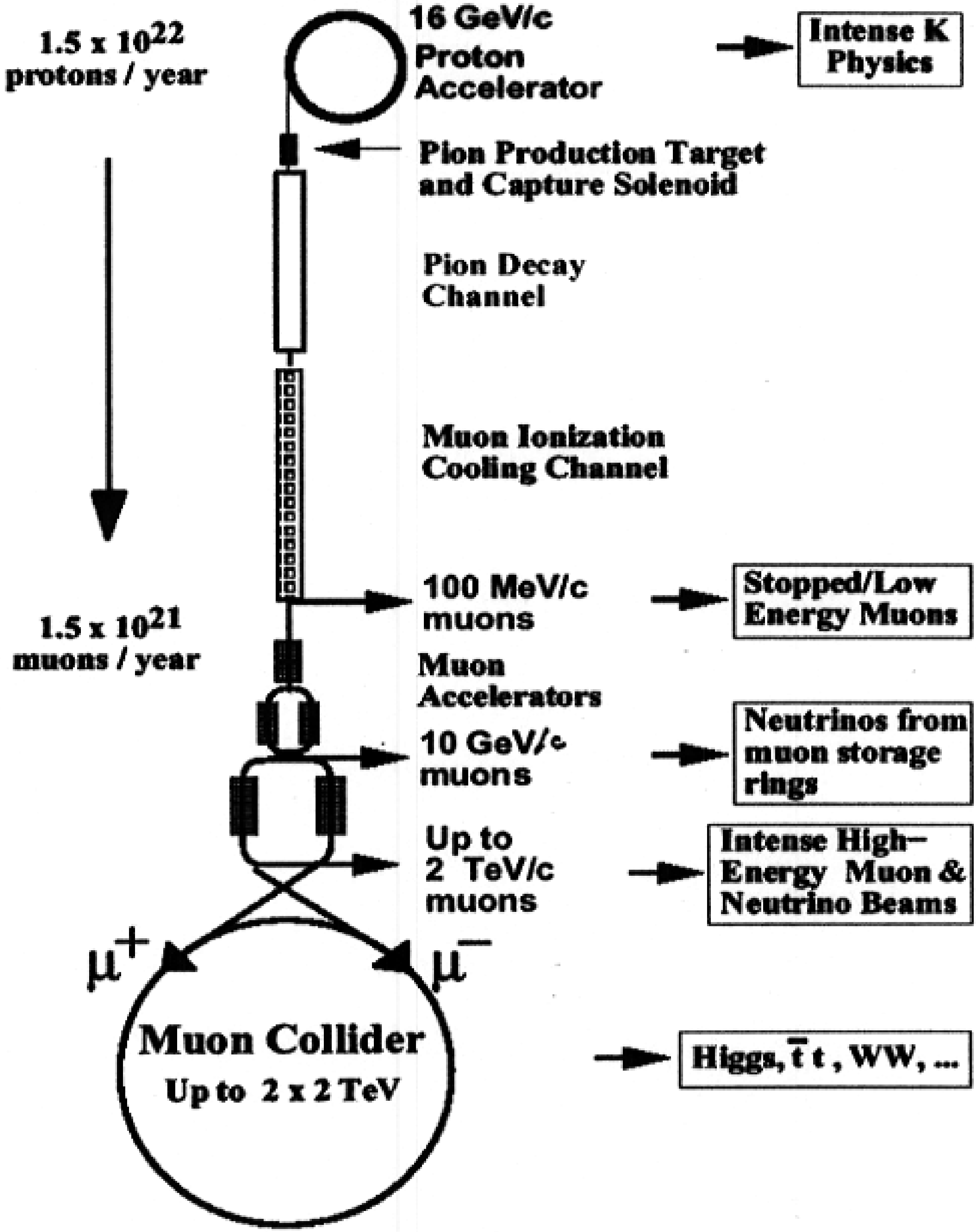
6. Discussion at St. Croix, May, 1999.

7. ICFA/ECFA Workshop,NUFACT99, Lyon, July 5-9, 1999. (http://lyopsr.in2p3.fr/nufact99/)

Future

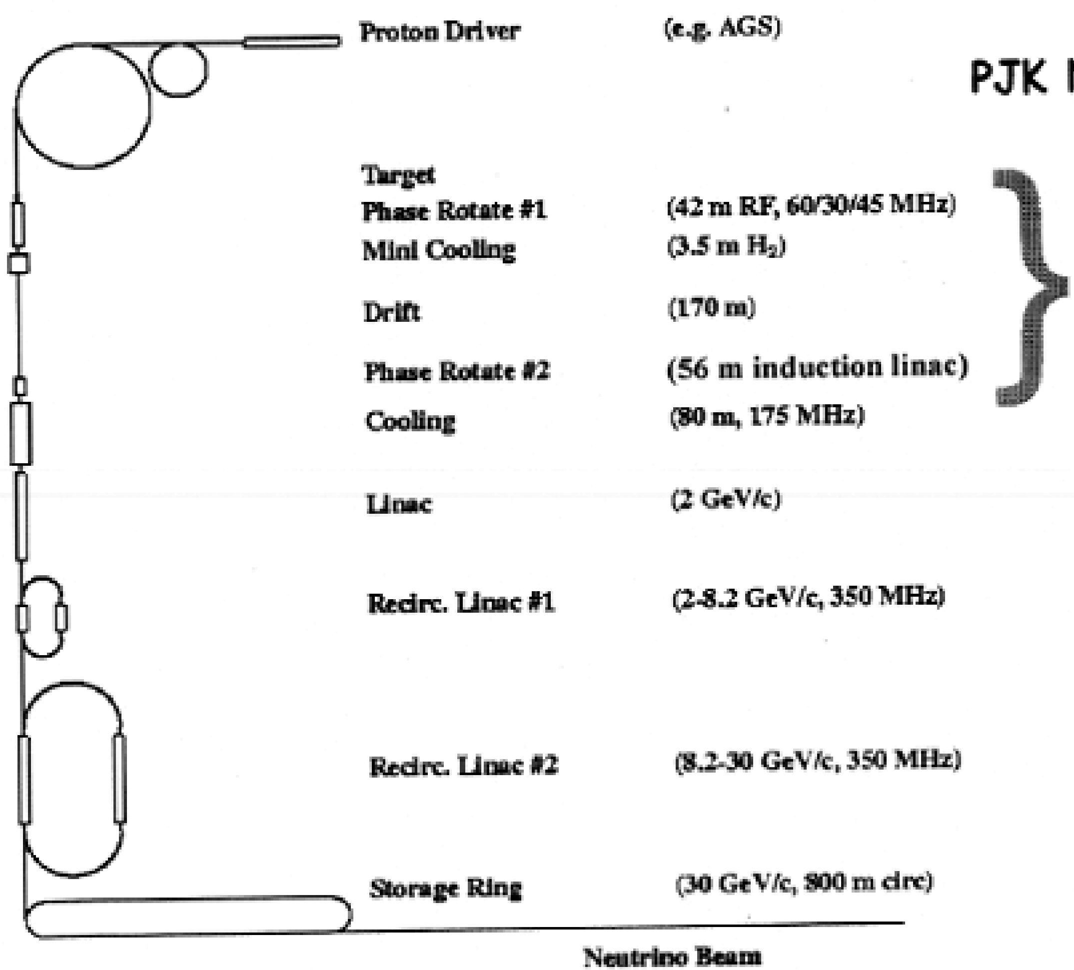
NuFACT00, Monterey, May 22-26, 2000

Muon Collider Schematic



Overall Layout of a Neutrino Factory

PJK Neutrino Factory Layout



Low frequency capture region

Basic Facts $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

$$\frac{d^2N_{\nu_\mu}}{dx\,d\Omega} = \frac{2x^2}{4\pi}[(3-2x)-(1-x)\cos\vartheta]$$

$$\frac{d^2N_{\nu_e}}{dx\,d\Omega} = \frac{12x^2}{4\pi}[(1-x)-(1-x)\cos\vartheta]$$

$$\cos\vartheta = \hat{P}_\nu \bullet S_\mu \qquad x = \frac{2E_\nu}{m_\mu c^2}$$

$$\sigma_{\nu n} = 0.67 * 10^{-38} E_\nu(\text{GeV})\text{cm}^2$$

$$\sigma_{\nu n} = 0.34 * 10^{-38} E_\nu(\text{GeV})\text{cm}^2$$

OSCILLATIONS

$$P(\nu_1 \rightarrow \nu_2) = \sin^2(2\vartheta)\sin^2\frac{1.27(\Delta m^2)L}{E}$$

ϑ = Mixing angle

$\Delta m_2 = m_1^2 - m_2^2$ in $(\frac{eV}{C^2})^2$

L in km

E in GeV

MIXING PARAMETERS

Assume only three neutrinos

$$\vartheta_{12},\ \vartheta_{13},\ \vartheta_{23},\ \Delta^2 m_{12},\ \Delta^2 m_{23},\ \delta$$

ϑ_{ij}: $\nu_e \rightarrow \nu_\mu$, etc.

$$\sigma:\ \text{CP}\quad \nu_e \rightarrow \nu_\mu \overset{?}{=} \bar{\nu}_e \rightarrow \bar{\nu}_\mu$$

$$\text{T}\quad \nu_e \rightarrow \nu_\mu \overset{?}{=} \nu_\mu \rightarrow \nu_e$$

$$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \overset{?}{=} \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

If 3 θ's don't sum to π then sterile neutrino

$$\text{CPT}\quad \nu_e \rightarrow \nu_\mu \overset{?}{=} \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$\nu_\mu \rightarrow \nu_e \overset{?}{=} \bar{\nu}_e \rightarrow \bar{\nu}_\mu$$

In general, a 3x3 matrix, characterized by 6 parameters, describes the oscillation of the 3 neutrinos.

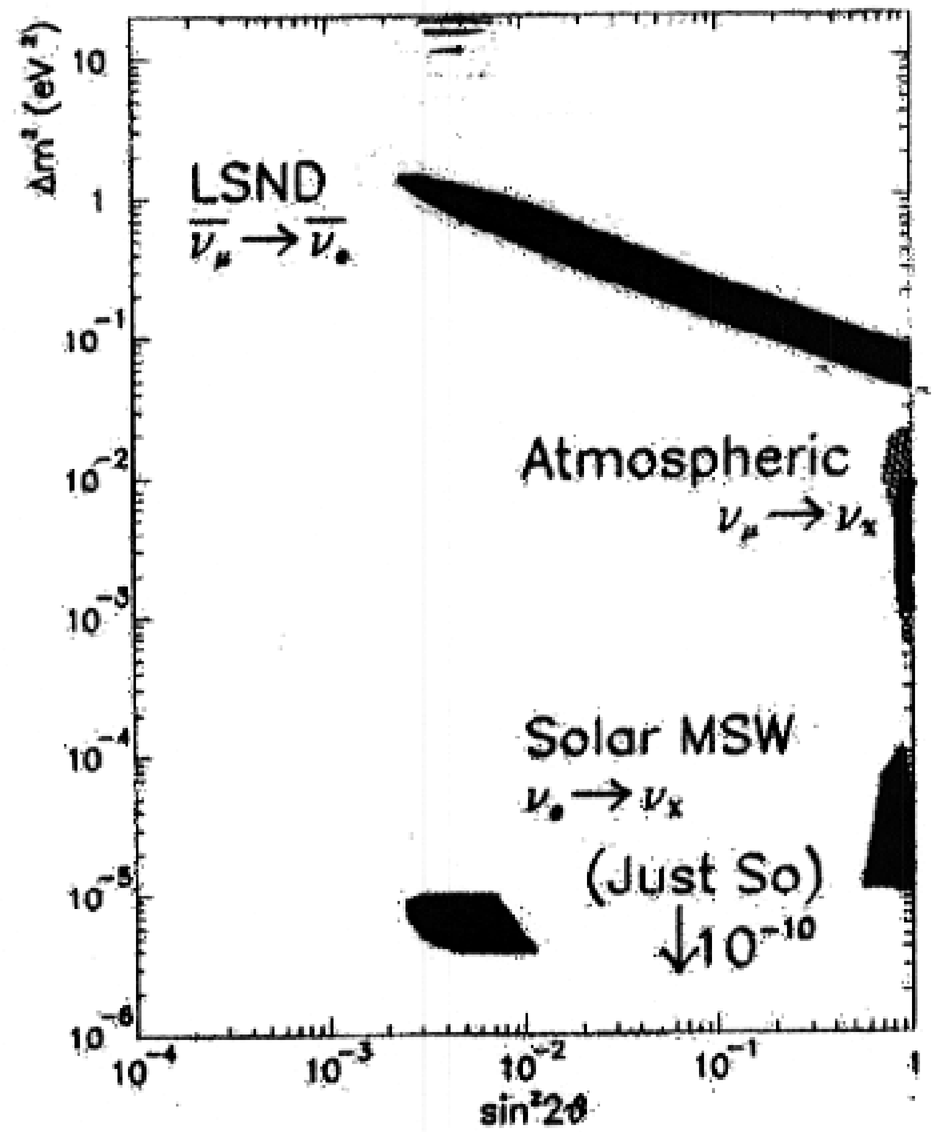
For $\delta = 0$:

$$P(\nu_e \rightarrow \nu_\mu) \sim \sin^2(\vartheta_{23})\sin^2(2\vartheta_{13})\sin^2\left(\frac{\Delta m^2{}_{13} L}{4E}\right)$$

$$P(\nu_e \rightarrow \nu_\tau) \sim \cos^2(\vartheta_{23})\sin^2(2\vartheta_{13})\sin^2\left(\frac{\Delta m^2{}_{23} L}{4E}\right)$$

$$P(\nu_\mu \rightarrow \nu_\tau) \sim \cos^4(\vartheta_{13})\sin^2(2\vartheta_{23})\sin^2\left(\frac{\Delta m^2{}_{23} L}{4E}\right)$$

3 different mass-scales



From J. Conrad hep-ex/9811009

QUESTIONS

- Is a ν factory feasible?
- At what cost?
- How soon?
- What R&D is needed?
- What do we want to know about neutrino masses and mixings

  now... in 5 years... in 10 years?
- Is a ν factory the best (only) way to answer these questions?
- What range of beam parameters should the ν factory provide?
- What detectors are needed to carry out the ν factory physics program?

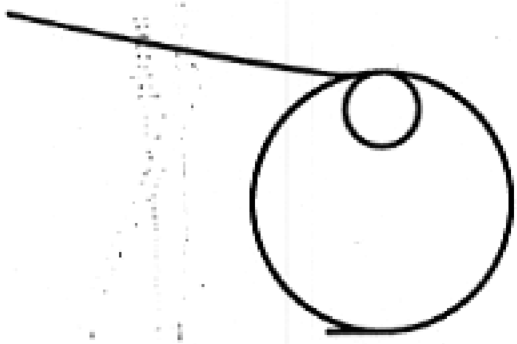
Probably known:
θ_{12} & θ_{23}
Δm^2_{23} Δm^2_{12}

Left to learn:
1) θ_{13} 2) δ
3) Sign of Δm^2

Neutrino souces and muon colliders

- Requires high power proton source/target and efficient capture, but many other parts are easier, and some are different.
  - No N_{μ}^2 dependence from luminosity-- bunches less intense, higher-frequency rf.
  - Transverse cooling factor 100 (vs 10^4), no longitudinal cooling.
  - Accelerator chain and storage ring must have large acceptance to minimize cooling requirements (but no small beta sections)
  - The ring may have unusual bow tie or triangle shape--and be tilted.

PROTON SOURCE



NEED:

- **Proton Beam Power 2-4 MW**
- **Very short bunch: rms 1-2 nsec**

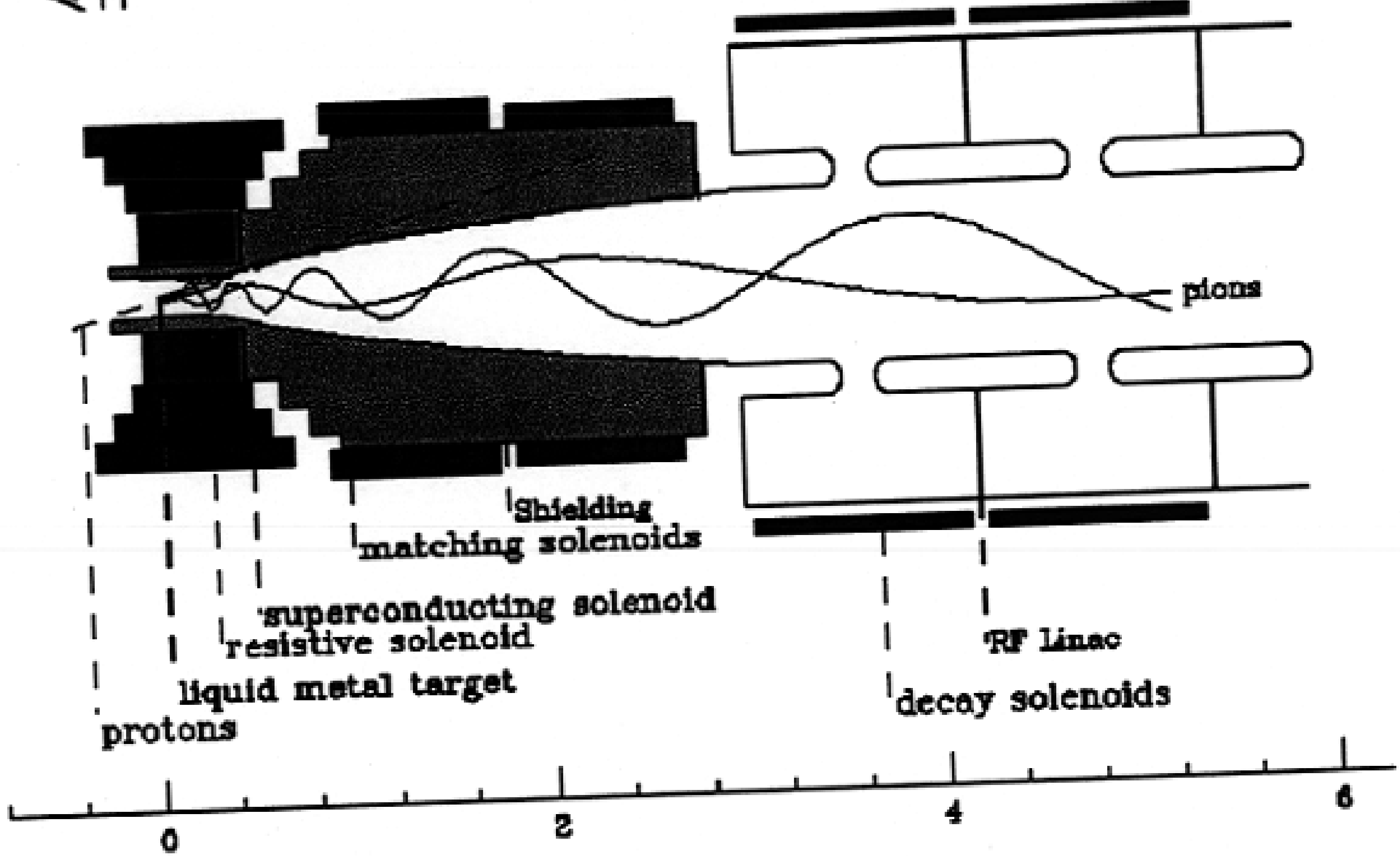
FNAL PROPOSAL: 4 MW S. Holmes FNAL

- **Upgraded linac (.4 → 1 GeV)**
- **Higher field operation in Booster**
- **New Pre-Booster** (16 GeV)

BNL PROPOSAL: 2 MW T. Roser BNL

- **Upgraded linac (.2 → .6 GeV)**
- **Increased AGS rep rate: 2.5 Hz**
- 1 MW if 10^4 @ 2.5 Hz

Target and Capture



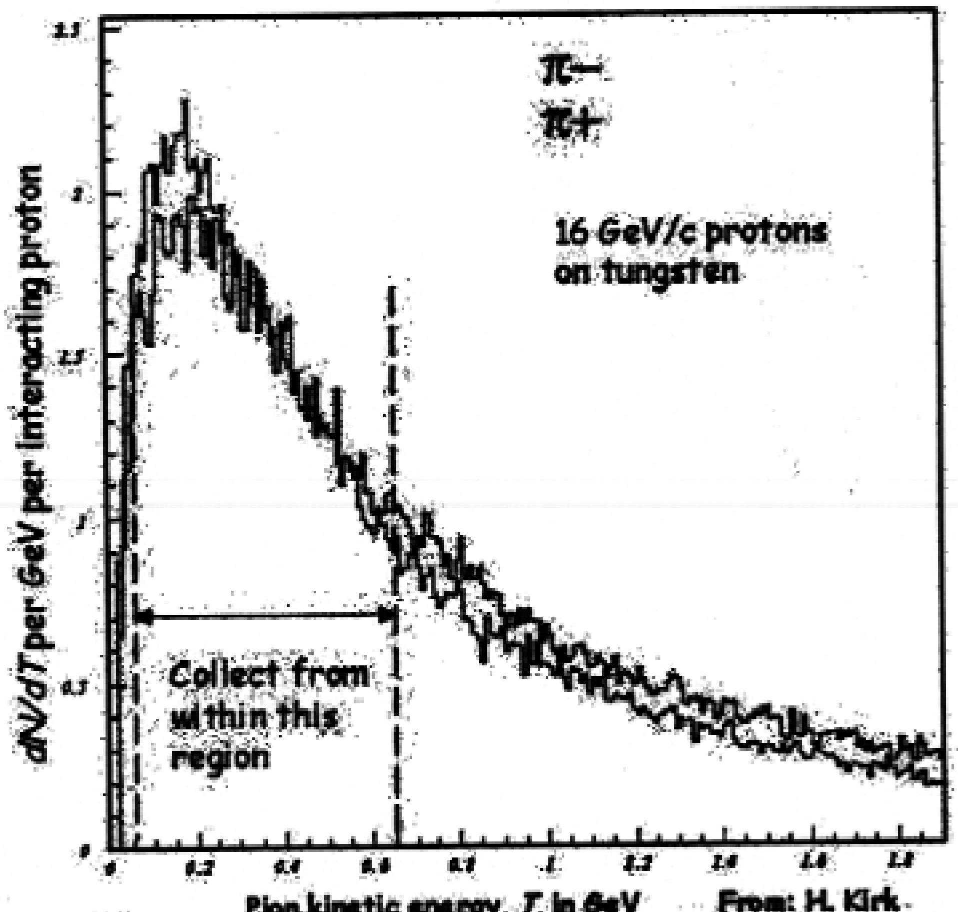
4MW,16 GeV proton beam hits liquid metal target in 20T solenoid
Pions and (then muons) captured in decay channel

Target and Production

We aim to collect and deliver to the first phase rotation channel 0.6 pions of each sign per proton of 16 GeV/c.

In the region of low kinetic energy shown opposite this can be achieved by immersing the production target in a 20 T solenoid field of 75 mm radius. Pions of both signs having transverse momentum of up to 225 *MeV/c* are focused into the decay channel via the matching channel.

Note that the pion velocity varies from 0.68 to 0.98



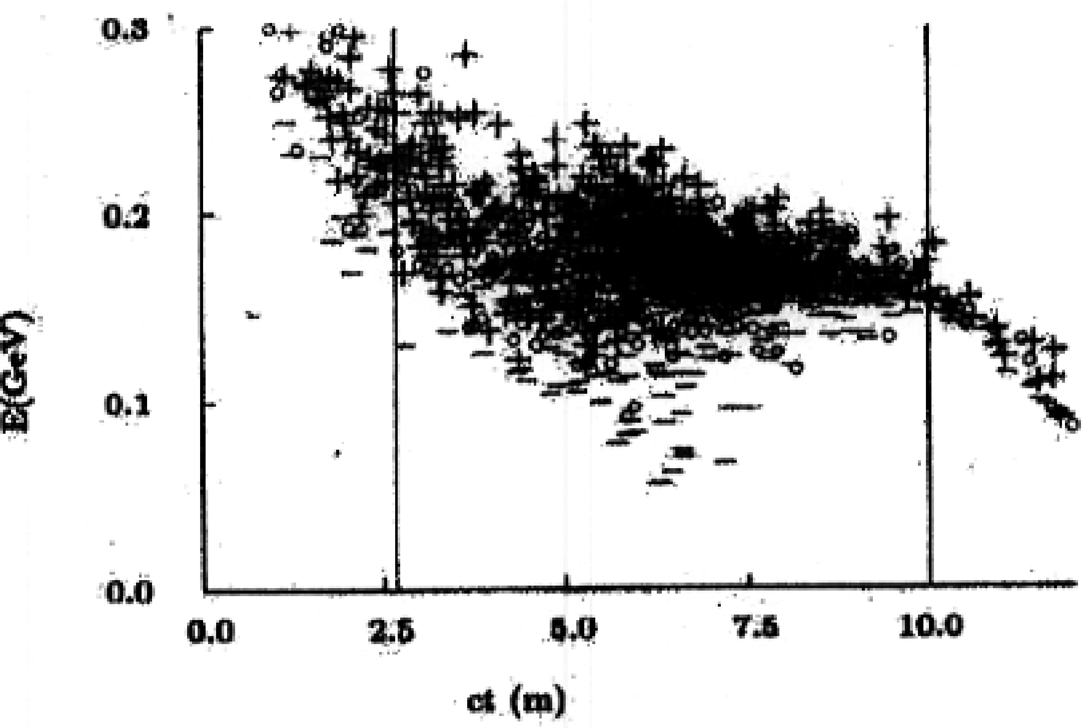
Simulations of Capture and phase Rotations

Color and symbols indicate Polarization:

red +	P > .3
green o	.3 > P > -.3
black −	-.3 < P

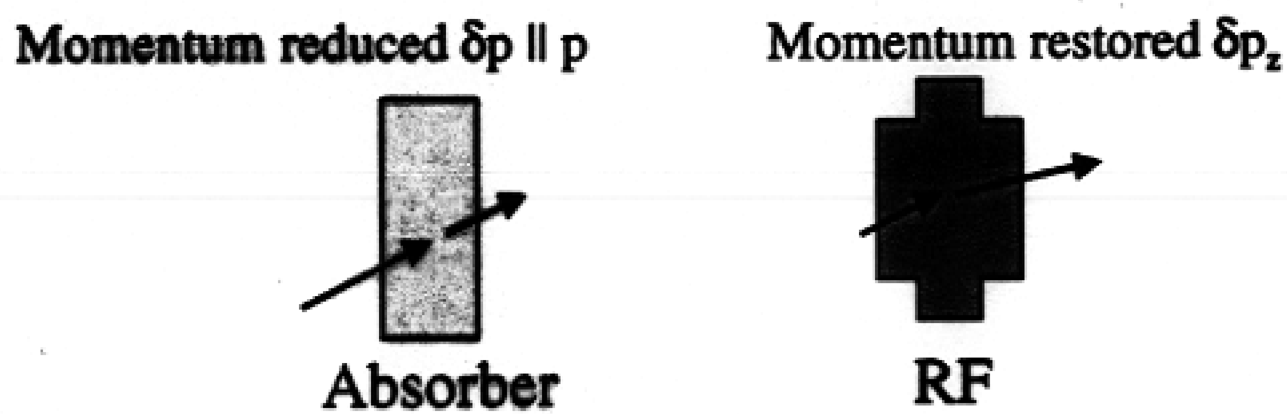
After First Phase Rotation:

$\mu/\pi \approx 0.3$ $\delta_p \approx 15\%$



Cooling of 6-D phase space

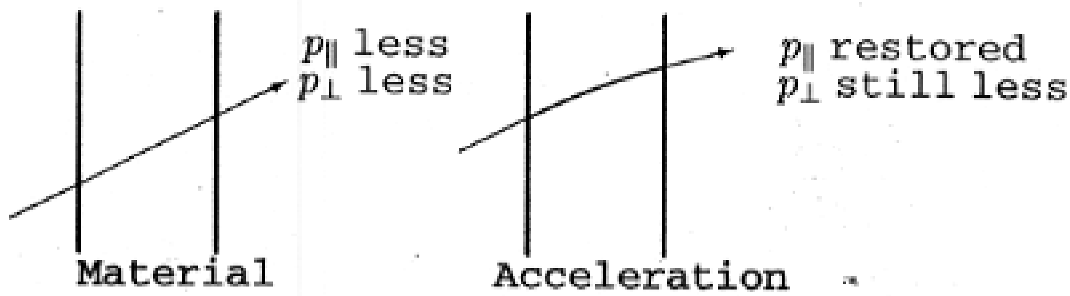
- Muons from the target are initially captured into a 6-D phase space volume that must be decreased by 10^6 before collision
- Cooling time must be of order τ_μ --distance of order $c\tau_\mu$~660m.
- Ionization cooling (Skrinsky&Parhomchuk,81). Basic Idea



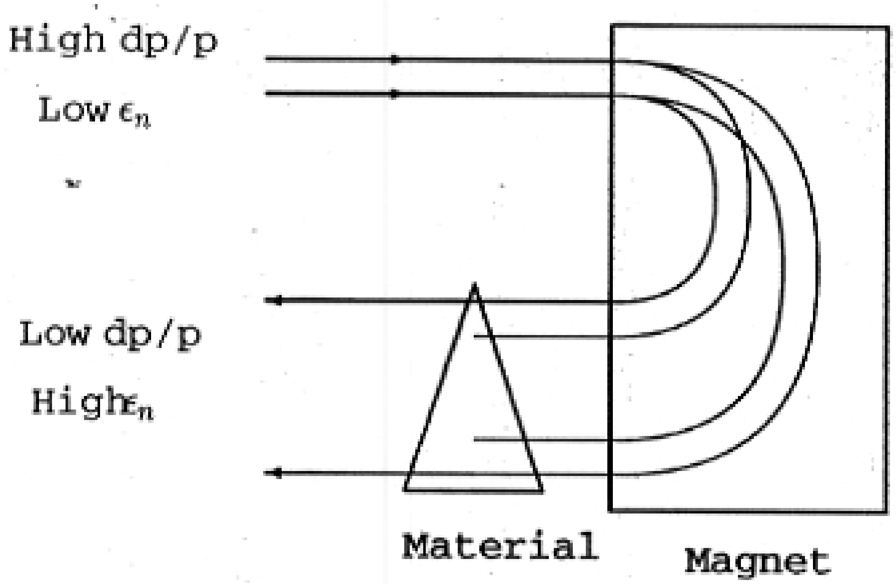
Need to fight multiple scattering and longitudinal blowup

IONIZATION COOLING

- TRANSVERSE



- LONGITUDINAL COOLING



†

- Emittance rate of change

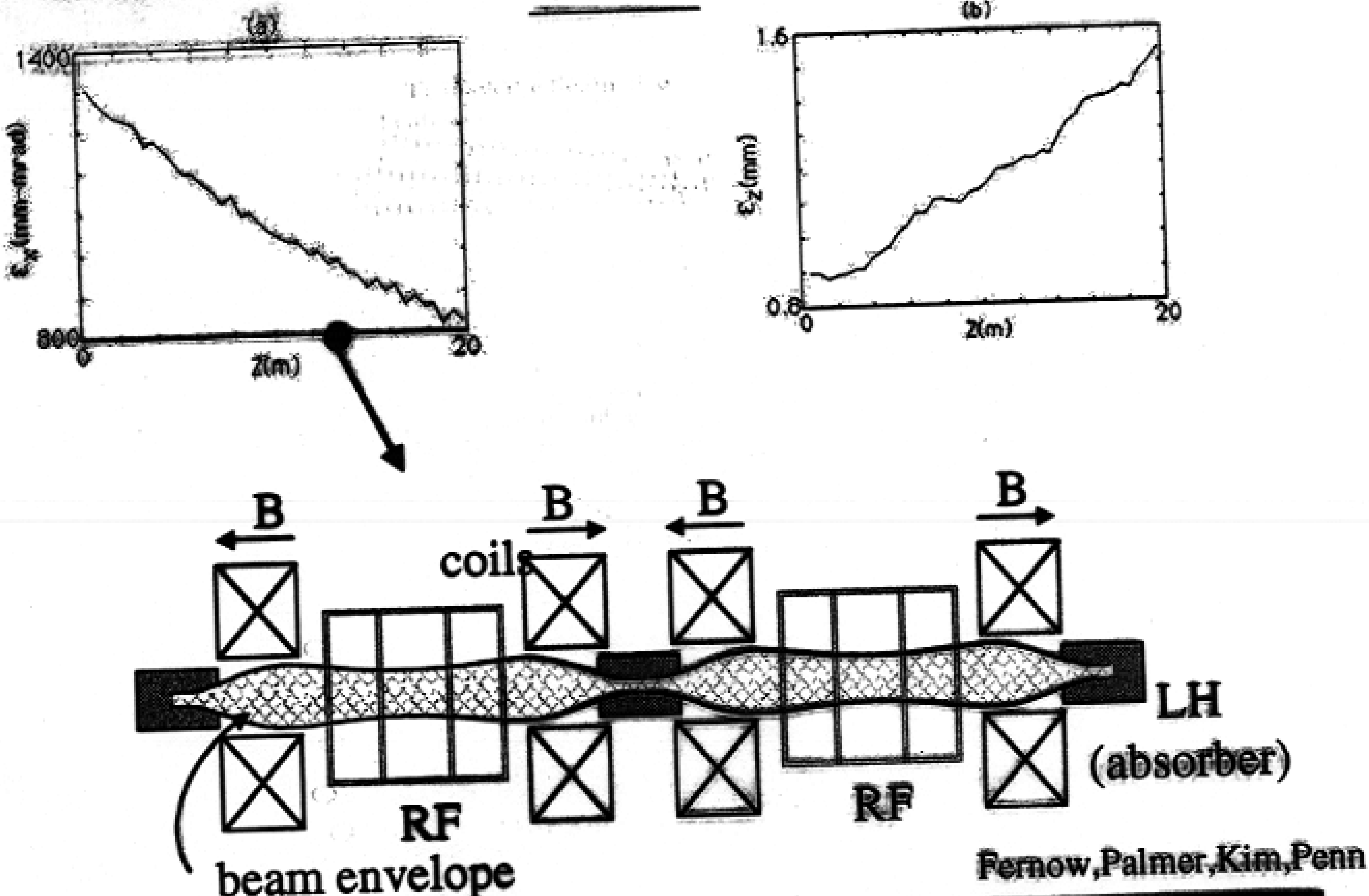
$$\frac{d\epsilon_n}{dz} = -\frac{\epsilon_n}{E\beta^2}\left\|\frac{dE}{dz}\right\| + 0.5\beta\gamma\frac{d<\theta^2>}{dz}$$

- MINIMUM EMITTANCE

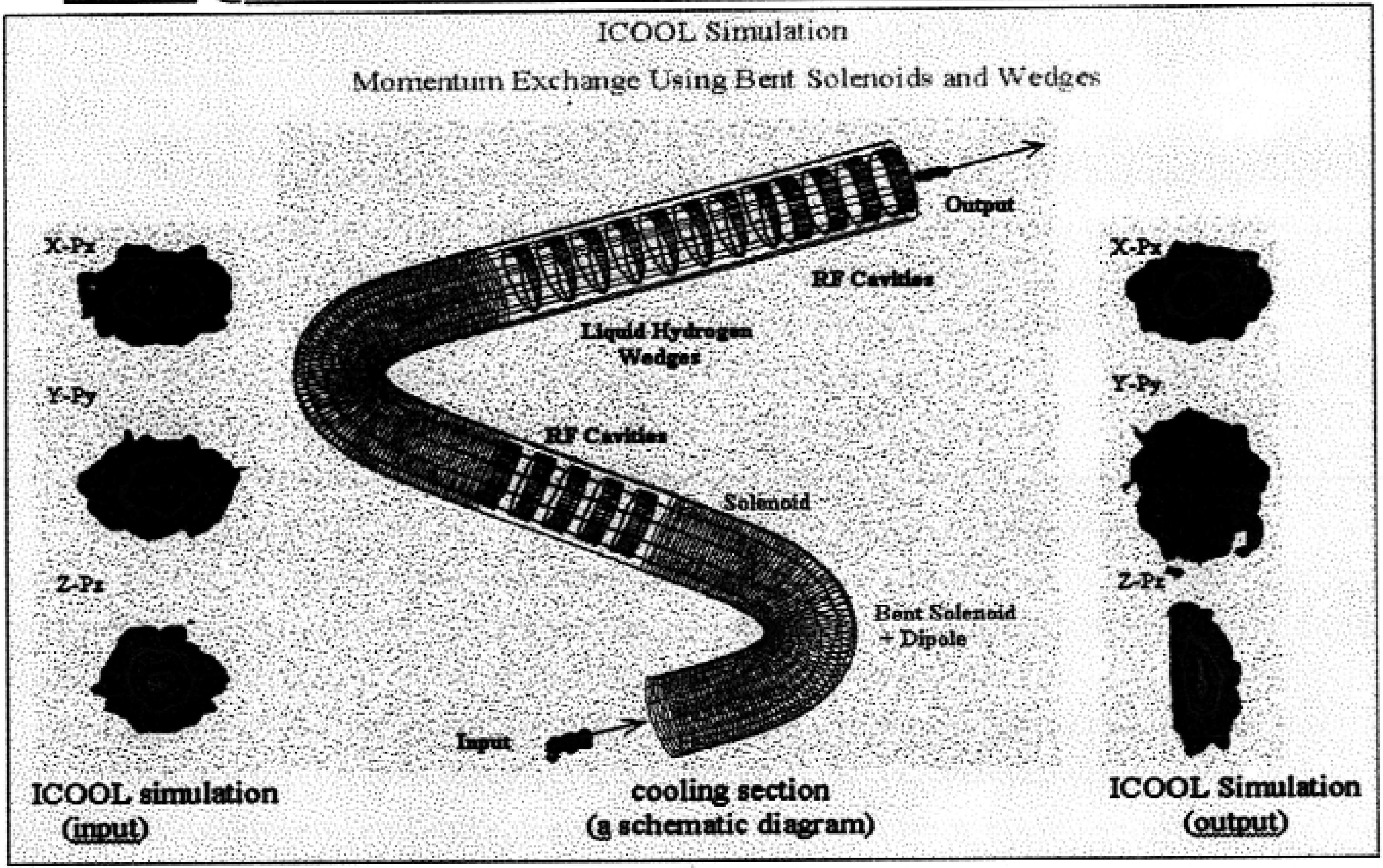
$$\epsilon_n \approx \frac{0.5E_s^2}{m_\mu c^2}\frac{\beta_\perp}{\beta}\left(L_R\|dE/dz\|\right)^{-1}$$

- Best material for cooling, Li, LiH, Be, H_2

Transverse Cooling Simulation



Emittance exchange is crucial



- Scenarios

1. Sequence of linacs (VERY EXPENSIVE)

2. Recirculating linacs with multiple arcs (similar to CEBAF) (RELATIVELY EXPENSIVE)

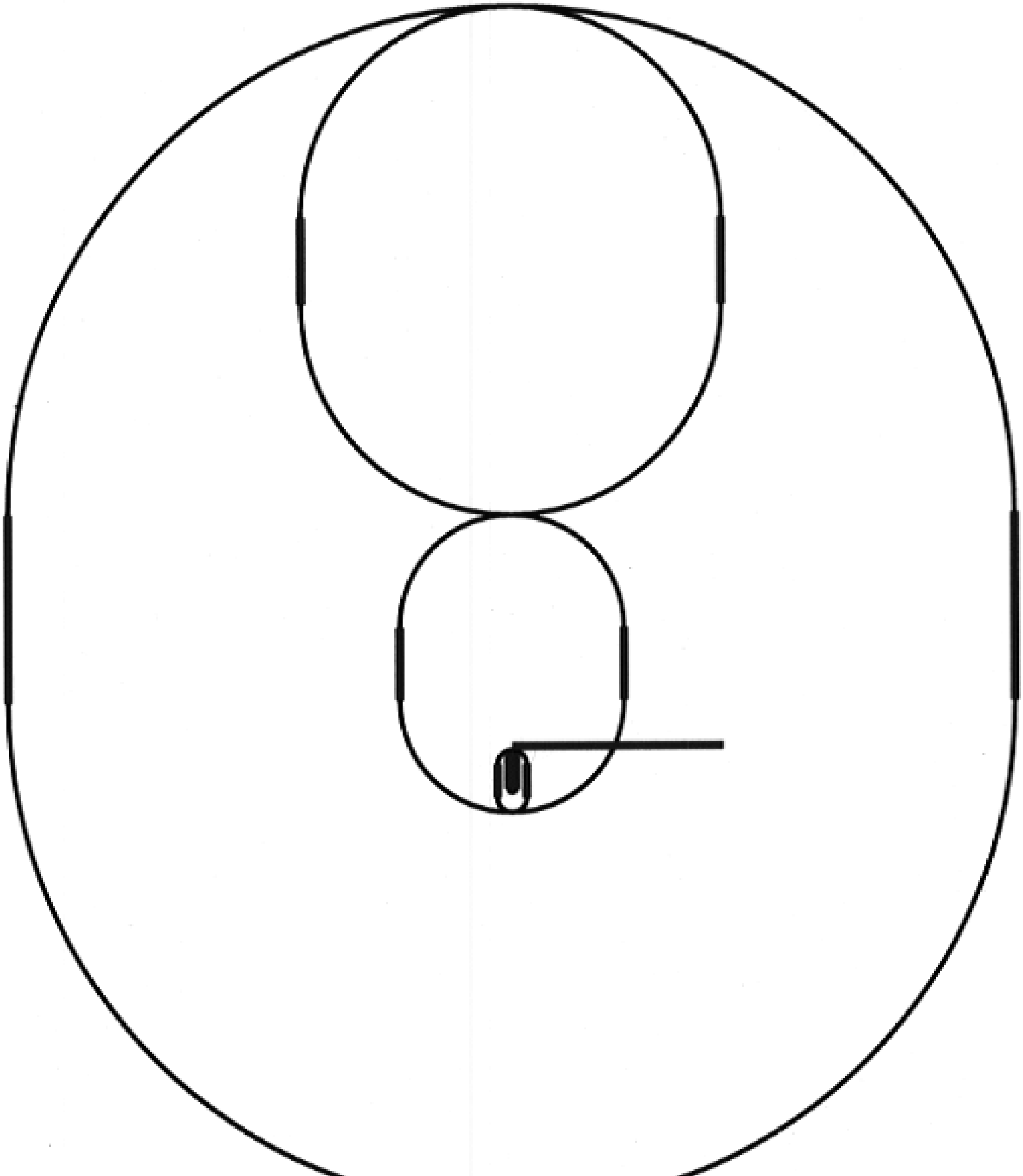
3. Synchrotrons with fast pulsed magnets with long SC linacs (MORE ECONOMICAL)

4. (250 GeV) 4 T pulsed magnets (t=1 msec)

5. (2 TeV) Interlace of fixed 8 T SC dipole magnets with ±2 T pulsed magnets

6. FFAG

†



Recirculating Linacs

E. Keil

Frequency:	352.209 MHz	
Energy(GeV):	2-8	8-30
Number of Passes:	4	4
Accelerating Linac Voltage (MV)	1.5	5.5
Length of Half Cell (m):	3.4	14.9
β (Max) (m)	11.3	49.6
$\mu/2\pi$	0.21	0.21
Acceptance (mm) (normalized)	16.5	15.0

FFAG Accelerating Ring Green

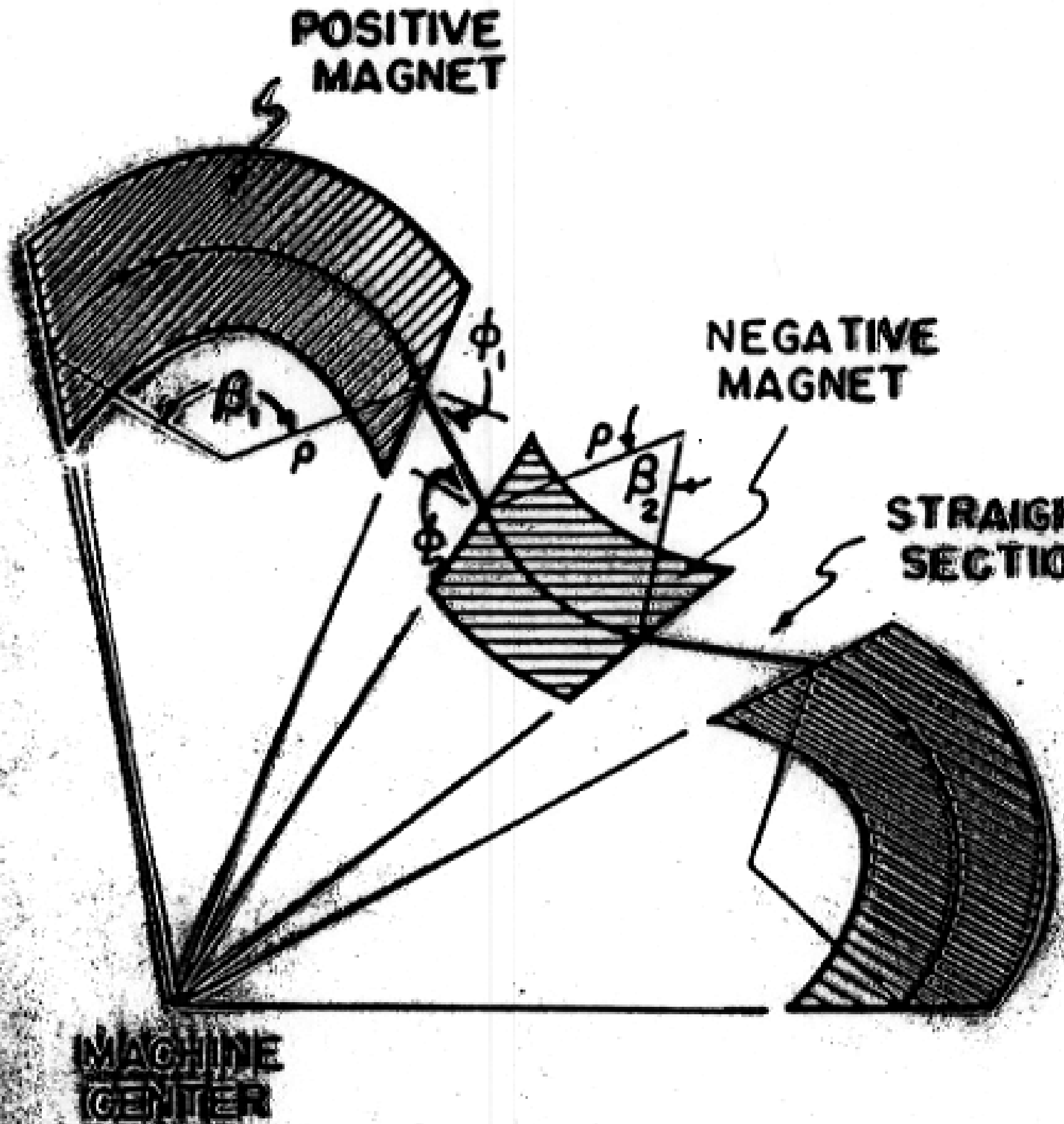


Fig. 17. Equilibrium orbit notation for radial sectors with straight sections.

COLLIDER RING :*

3 TeV × 3 TeV

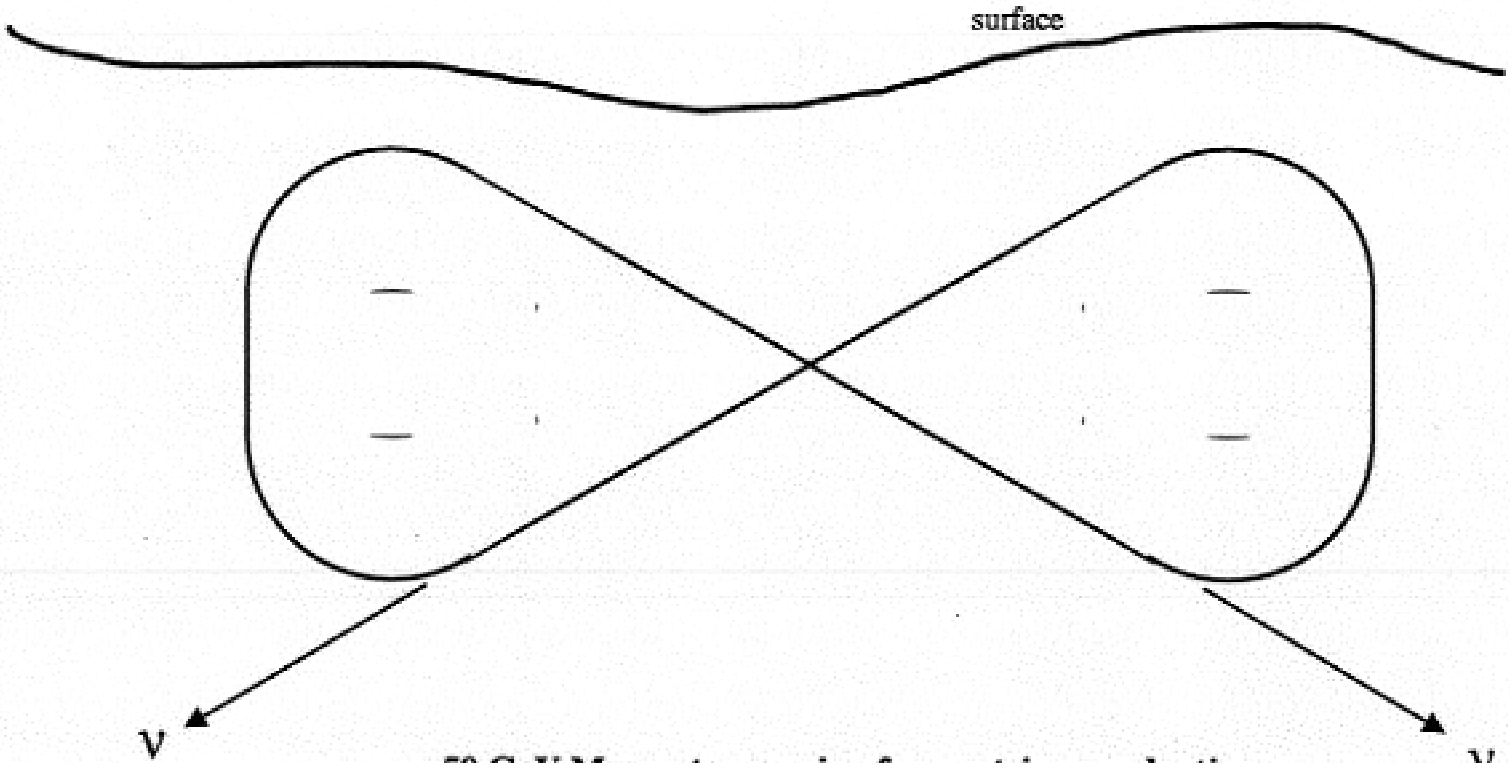
- Highest possible bending magnet to maximize No. of turns in the ring before decay

β^*	$3\ mm$
σ_z	$3\ mm$
ϵ_n	$50\ \pi\ mm - mrad$
$\delta = \frac{\Delta p}{p}$	0.12%
No. of turns	1000
No. muons	2×10^{12}
No. bunches	2
beam − beam tune shift	0.05

- Isochronous lattice

- IP Local Chromatic Correction is essential

$\mu^+\mu^-$ COLLIDER



50 GeV Muon storage ring for neutrino production

Circumference 1150 m; 400 m total length of straight sections that produce low-divergence neutrino beams.

Ring lies in a tilted plane so that the neutrinos travel through the earth to two distant detectors.

Arcs contain superconducting dipoles at 5.3 T and quadrupoles.

Muon Budget for a Neutrino Factory

All numbers are μ/p

Initially	0.66
After Phase Rotation #1	0.3
After Phase Rotation #2	0.21
After RF Capture	0.15
After Cooling	0.13
After Acceleration	0.1

For a 1.5 MW proton source, this would be 4 x 10^{20} muons per year decaying. (A year is taken as 2.5 x 10^7 seconds.) About 25 % are pointing in a direction to hit a detector, so the number of decays will be 10^{20} per year in any one detector. (Probably two detectors are illuminated.)

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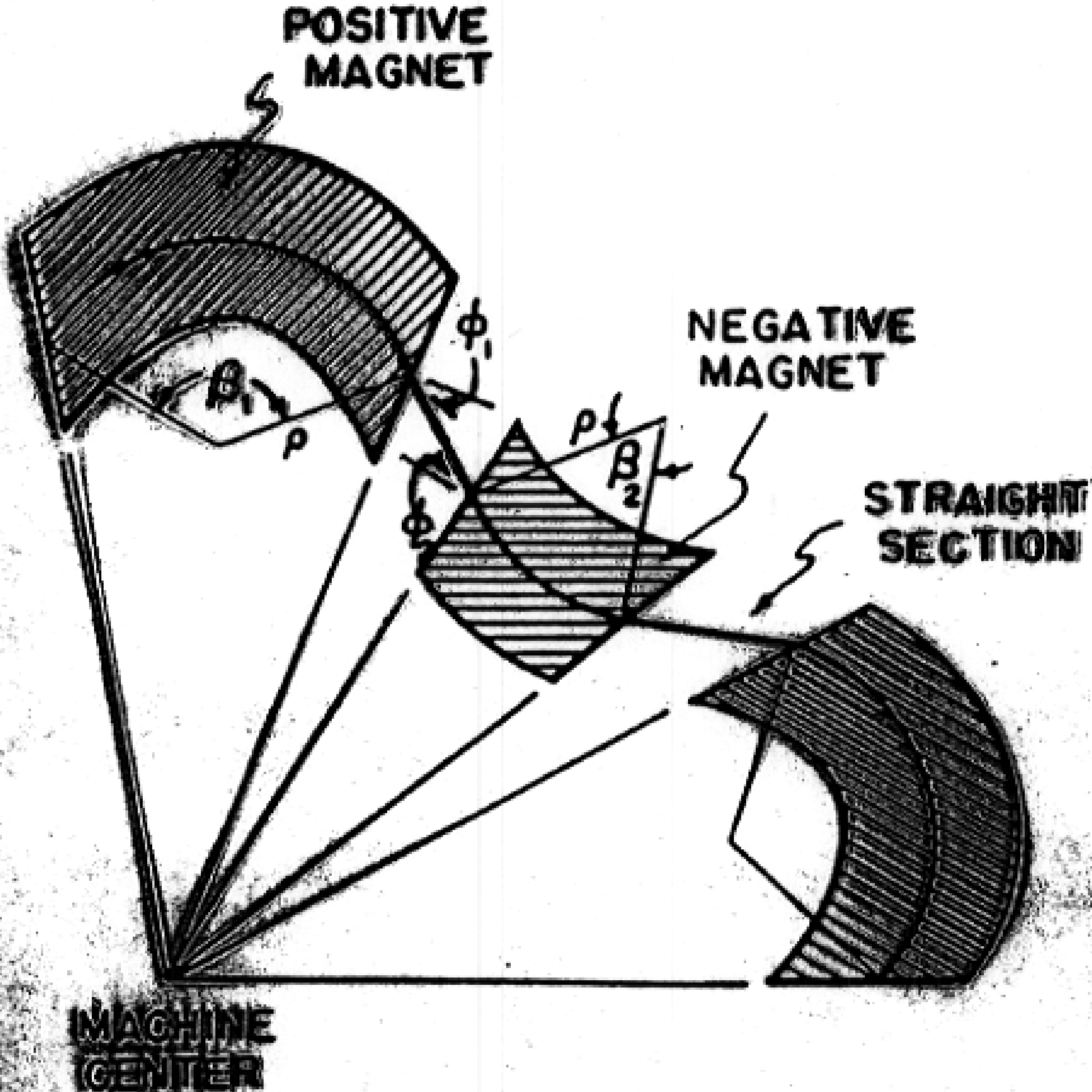

FIG. 7. Equilibrium orbit notation for radial sectors with straight sections.

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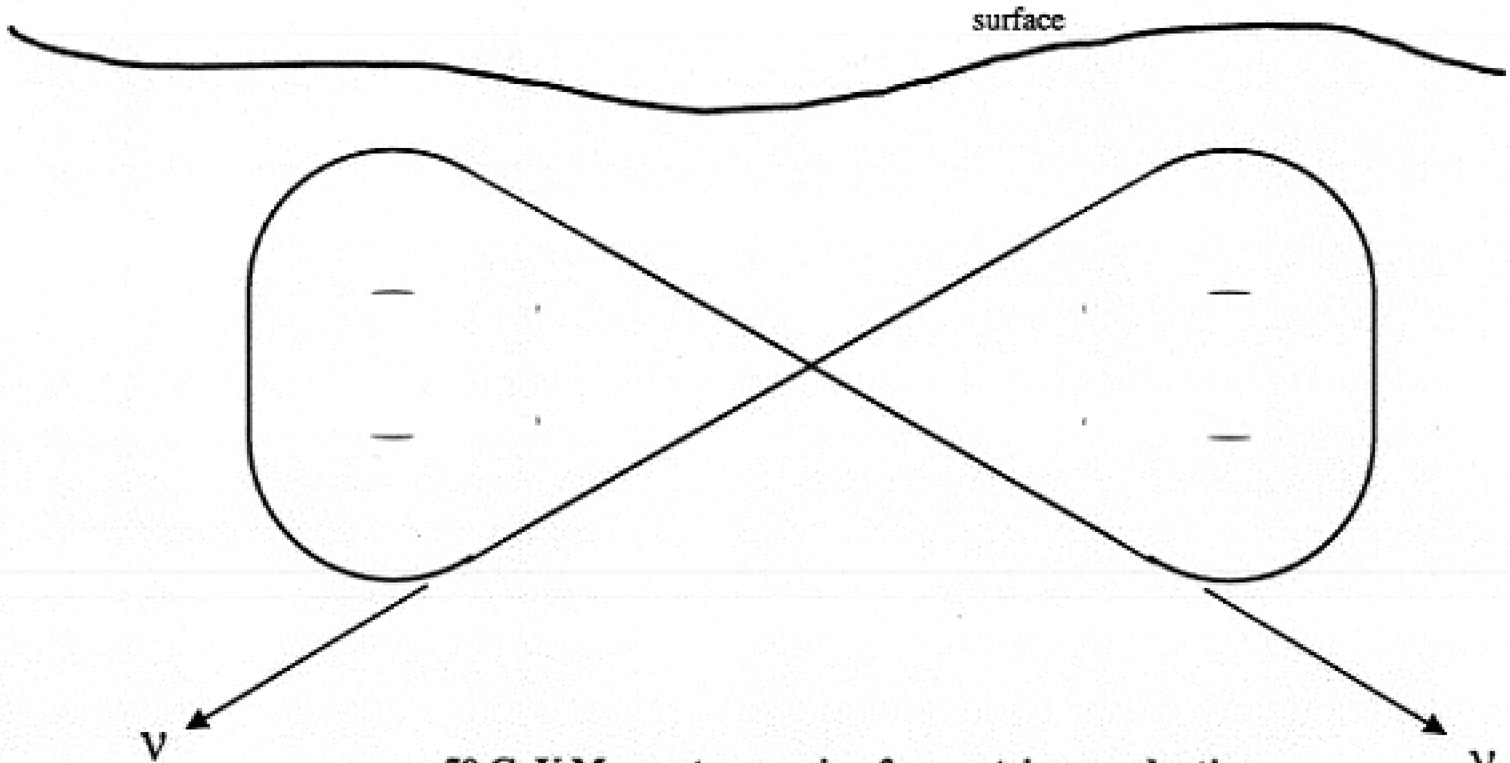

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Linacs

p_{min} GeV/c	p_{max} GeV/c	f MHz	V MV/m	ϕ °	L_{lin} m	loss %	σ_E MeV	σ_τ ps
.186	.67	50	7.5	71-33	145	6.4	19-44	1231-541
.67	2.1	200	15	65-33	213	2.9	85-176	283-136
2.1	4	800	30	65-45	166	0.9	336-511	71-47

Recirculators

p_{min} GeV/c	p_{max} GeV/c	f MHz	V MV/m	ϕ °	L_{arc} m	L_{lin} m	n_{turn}	P_{peak} MW	loss %	σ_E MeV	σ_τ ps
4	16	800	30	29	28	88	4	1246	1.7	350	77
16	64	800	30	29	112	83	17	696	3.0	343	79
64	250	1600	42	25	873	178	21	405	5.0	792	34
250	625	1600	42	24	1637	213	35	278	4.9	842	32
625	1500	1600	42	18	3930	464	36	266	4.9	1097	25

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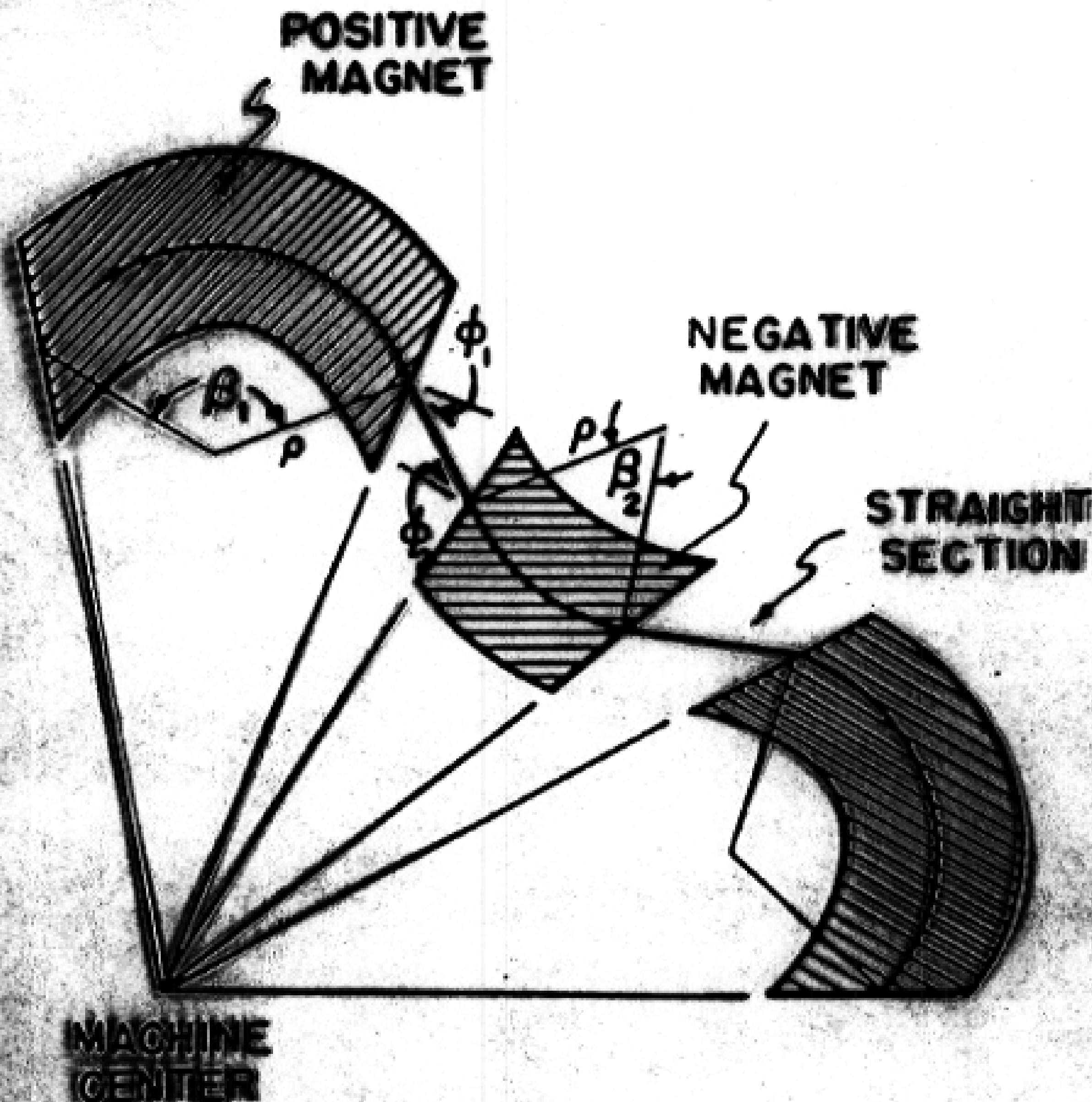
FFAG Accelerating Ring   Cameron



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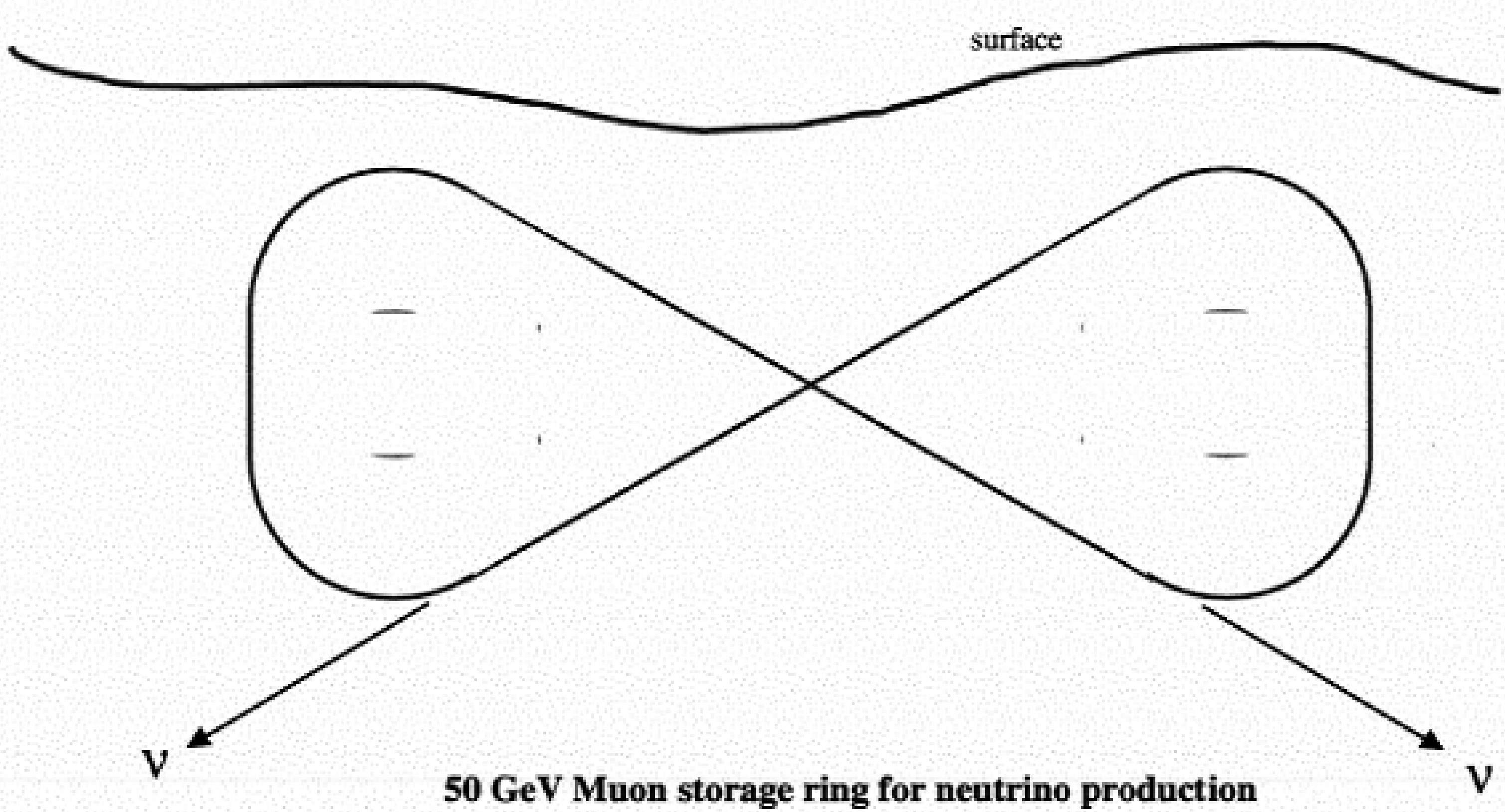

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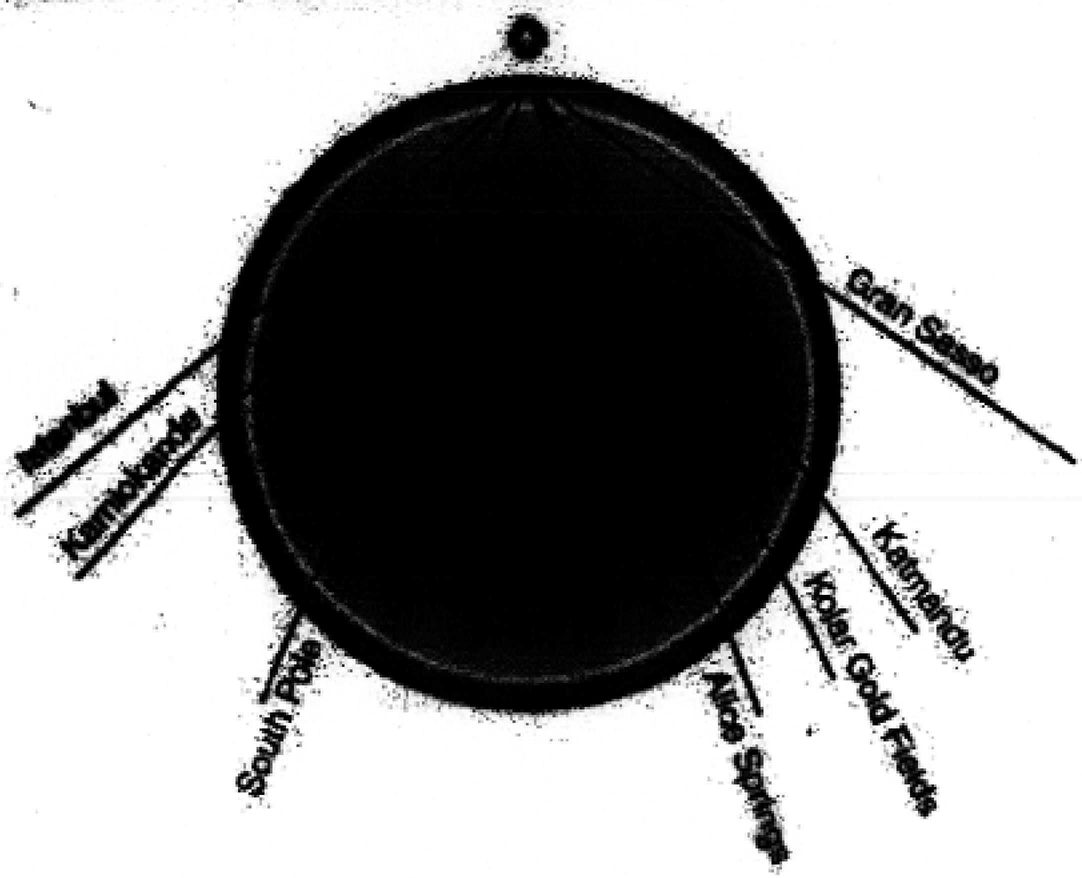
The Ultimate International Collaboration?



Expected Event Rate

Rate is calculated for $E_\mu = 50$ GeV and 10^{20} muon decays per year pointing to the detector (1.5 MW driver), and oscillations are calculated assuming (the Super-K result) of $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2/c^4 and $\sin^2 2\theta = 1$. The detector is 1kT-year (and would surely be larger and run longer).[One kT of water is $(33\ ft)^3$]

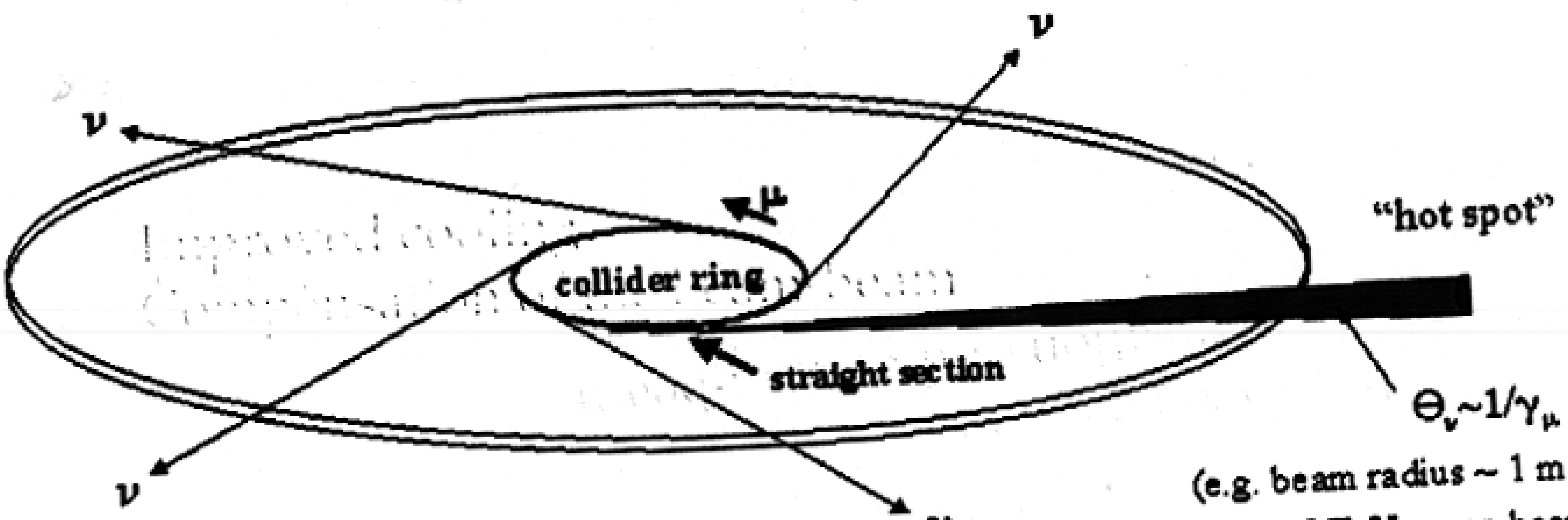
Consider (just one example) Fermilab to Gran Sasso: 7332 km

L → 2L
E → ½E

$\nu_\mu \rightarrow \nu_\tau$ 410 → disentangle CP &
$\nu_\mu \rightarrow \nu_\mu$ 490 (If no oscillations) matter effects

Compare to Fermilab to Soudan (750 km), Minos, where the oscillations, $\nu_\mu \rightarrow \nu_\tau$ are expected to be about 30 events per year. For this source the rate is 1.4×10^5.

Neutrino Production at Muon Colliders



(e.g. beam radius ~ 1 m at 50 km from 5 TeV muon beam)

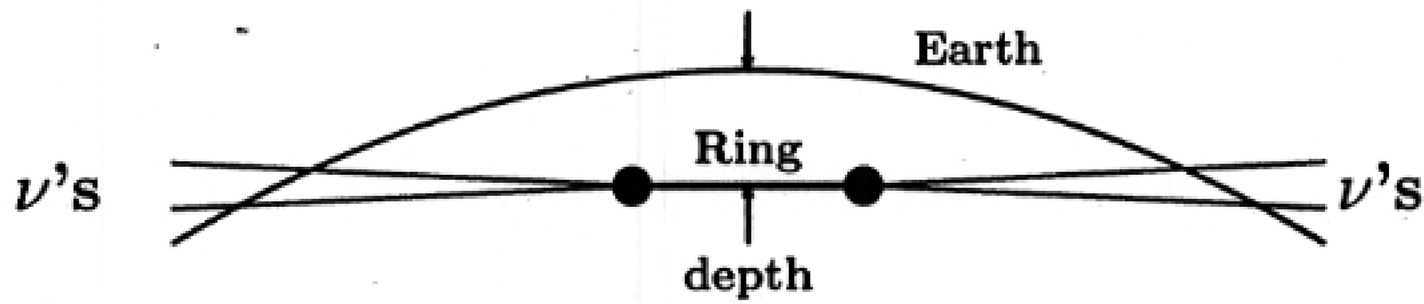
ν beam stronger at str. sections: e.g. even <u>0.1 m</u> str. section is ~ <u>twice</u> disk average

Neutrino Background: Critical problem as energy increases

- Radiation ~ $(\text{Energy})^3/\text{length}^2 \sim (\text{Energy})^3/\text{depth}$
- Need to either wiggle beam to dilute effect, or build collider in isolated area, or
- Improved cooling— optical stochastic cooling? Compensation of the beam-beam interaction in the collider ring (lithium, plasma). Lowers average power and neutrino radiation.
- This and numerous other problems: Workshop on 10-100TeV muon colliders (**27/9-1/10 1999, details at: http://pubweb.bnl.gov/people/bking/heshop/**
- *If technology works, 100TeV muons could share VLHC tunnel with 100TeV protons.*

B King
BNL

NEUTRINO RADIATION



- Radiation $\propto$ $E^3/length^2$ $\propto$ $E^3/depth$
- Use: 1/10 Federal limit = 10 mR/year ≈ 3% of Natural Rad

THEN

- Negligible problem at 1.5 TeV
  - ≈ 1 mR/year
- E = 3 TeV ok at 300 m depth
  - ≈ 10 mR/year
- E > 3 TeV Requires:
  - Beam wobbles, and/or
  - Special Locations, and/or
  - Better Cooling(Optical Stochastic?)

M. Zolotorev

THE MOST
CRITICAL ISSUES

- **Target**
  - **Heating → liquid metal?**
  - **Splash?**
  - **Motion in Magnet**

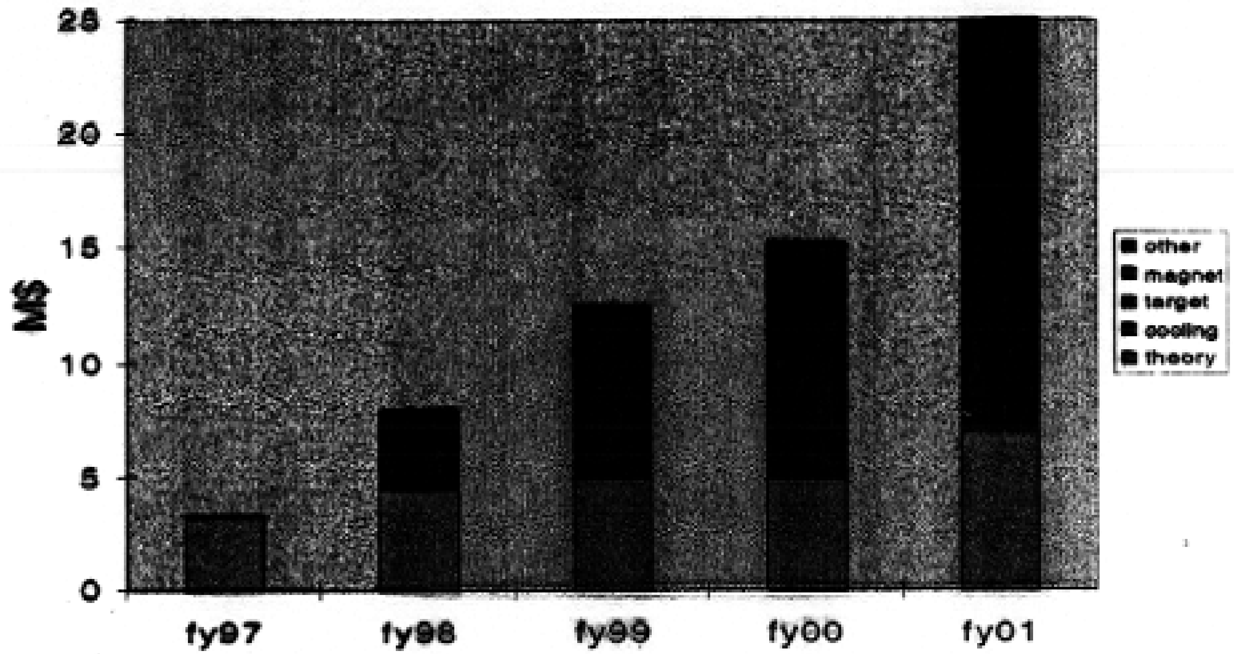
- **Capture RF**
  - **Low Frequency (30-90 MHz)**
  - **High Gradient (3-6 MV/m)**
  - **High Radiation**

- **Cooling RF**
  - **Higher Frequency (800 MHZ)**
  - **Very High Gradient (36 MV/m)**

- **Cooling Demonstrations**
- Target

Short term funding needs

- These numbers are a first estimate. They do not include contingencies or EDIA.
- Fiscal year 01 is very approximate, but indicates that increased funding will be needed.



The Grand Scheme of Things

(As seen by muon beam enthusiasts)

1. Lots of R and D
   (Started: 1996)
   (Needed: 2000 + 5 to 10 years)

2. Build a Neutrino Factory
   (200X)

3. Build a Higgs Factory Collider
   (200X + 5 years = 20YY)

4. Build a Few TeV Collider
   (20YY + 10 years = 20ZZ)

5. Build a 10-100 TeV Collider
   (????)

(This should keep even our grandchildren's grandchildren busy)

Conclusions

For a Neutrino Factory:

1. Most interesting physics
   (We know almost nothing about the neutrino sector)
2. Seems likely to "work"
3. Cost should not be "excessive"
   (by US Congress criteria)
4. Within (say) 5 years the R and D should be sufficiently advanced that a serious proposal can be made.

For a Muon Collider:

1. Interesting physics even for a low energy machine (S coupling to a Higgs and a low dE/E can be achieved (3×10^{-5}))
2. Easier tolerances than linear colliders
3. A high energy (multi-TeV range) can be achieved without QED confusion
4. Perhaps the cost ($/TeV) is not excessive
5. A fair amount of R and D is needed