# *Status of Research on Neutrino Factories in the U.S*

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# *Format of Talk*

- Brief History of Muon Colliders, Neutrino Factories
- Review physics of Neutrino Oscillations and the physics case for neutrino factories
- Ionization Cooling, Ring Coolers,Emittance Exchange.
- The 4 stages needed in getting to a neutrino factory
- Motivate Stage 5- A muon collider
- Status of R&D on cooling hardware
- The Muon International Cooling Experiment-MICE –Status
- Conclusions

# *Brief History of Muon Collider/Neutrino Factory effort*

- An old idea.. Muon colliders mentioned by Tinlot(1960), Budker(1969), Skrinsky(1971), Neuffer(1979)
- A key concept for a high luminosity muon collider is ionization cooling: Skrinsky and Parkhomchuk(1981).
- The realization that a high luminosity muon collider might be feasible (Neuffer&Palmer) resulted in a series of workshops. After the Sausalito workshop in 1995, Fermilab and BNL joined in an effort to study the concept and publish a report. The muon collider collaboration grew -->26 institutions and ~ 100 Physicists.
- -->$\mu^+\mu^-$ collider: A feasibility study, Snowmass (1996): Fermilab-conf-96/092-->feasibility of a 2x2 TeV Collider.

# *Brief History*

- Although many questions were left open in the Snowmass report, no show stoppers were identified… and the muon collider collaboration has continued to develop the concepts.
- Workshop on Physics at the first Muon Collider and the front end of the muon collider- Nov 97- AIP proceedings S.Geer, R.Raja eds.
- Status of Muon Collider Research and future plans **Phys.Rev.ST Accel.Beams 2:081001,1999**
- Interest in Neutrino factories (Muon storage rings) grew after the discovery of neutrino oscillations by Super-K and the realization of their potential in investigating the lepton sector.(S.Geer, Barger et al papers, host of others…)
- NUFACT series of conferences. Next one is NUFACT03 in Columbia University in June.
- Status of Neutrino Factory and Muon Collider Research and future plans– Submitted to PRSTAB-2003.

# Neutrino masses and oscillations - Brief review

Pattern of neutrino masses

Absolute neutrino masses not known . Relative mass differences are measurable using neutrino oscillations. Tritium end point measurements needed to make absolute measurements. The sign of the mass differences is not known currently. $\delta m^2_{32}$ is known as the atmospheric neutrino mass difference and is measured by superK to be ~2-3 $10^{-3}$ $eV^2$.
$\delta m^2_{12}$ is known as the solar mass difference and is known to be ~6-8 $10^{-5}$ $eV^2$. The mixing angles $\theta_{23}$ and $\theta_{12}$ are near maximal but the angle $\theta_{13}$ is not measured yet and is known to be small. We need a non-zero $\theta_{13}$ for neutrino factories to realize their full potential.

# *Review of SNO and SuperK results taken together(Snowmass 2001)*

- Recent SNO results show that

Using the reaction

$\nu_e$+p+n → $e^-$ +p+p (charged current, only sensitive to $\nu_e$) from the sun

And the reaction (from SuperK)

$\nu$ +$e^-$ → $\nu$ + $e^-$ (elastic scattering, sensitive to $\nu_e$+1/6($\nu_\mu$+$\nu_\tau$) that there is a depletion of $\nu_e$ from the sun, and that the deficit is made up by an unknown combination of $\nu_\mu$+$\nu_\tau$. I.e sterile neutrino solution is unlikely. This means a)Clear demonstration of FIRST effects beyond the standard model. b)Large mixing angle solution still in the running-I.e.large mixings!

There should be a feeding frenzy to investigate this.

# *Review of SNO and SuperK results taken together(Snowmass 2001)*

- $\nu_e$ CC flux from SNO

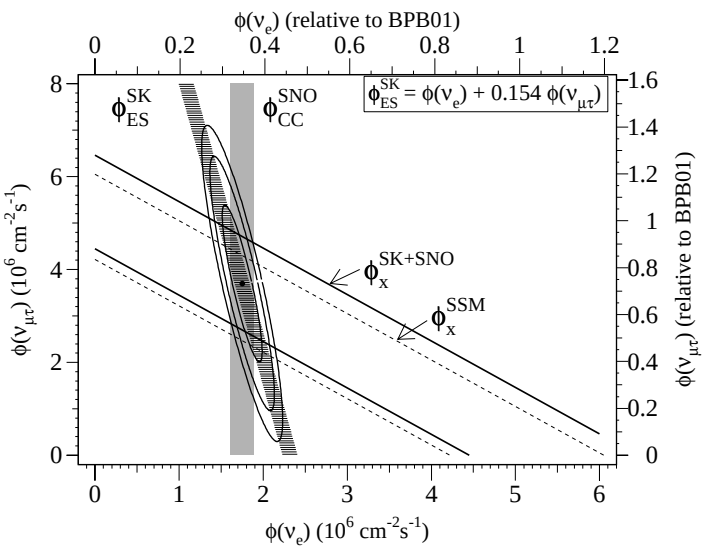
  $= 1.75 \pm 0.07(\text{stat.})\ ^{+0.12}_{-0.11}(\text{sys.}) \pm 0.05(\text{theor}) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$

- $\nu_x$ flux from SNO (elastic scattering)

  $= 2.39 \pm 0.34(\text{stat.})\ ^{+0.16}_{-0.14}(\text{sys.})\ \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$

  $\nu_x$ flux from SuperK (elastic scattering)

  $= 2.32 \pm 0.03(\text{stat.})\ ^{+0.08}_{-0.07}(\text{sys.})\ \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$




$\nu_{\mu\tau} = 3.69 \pm 1.13 \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$

(3.3s)

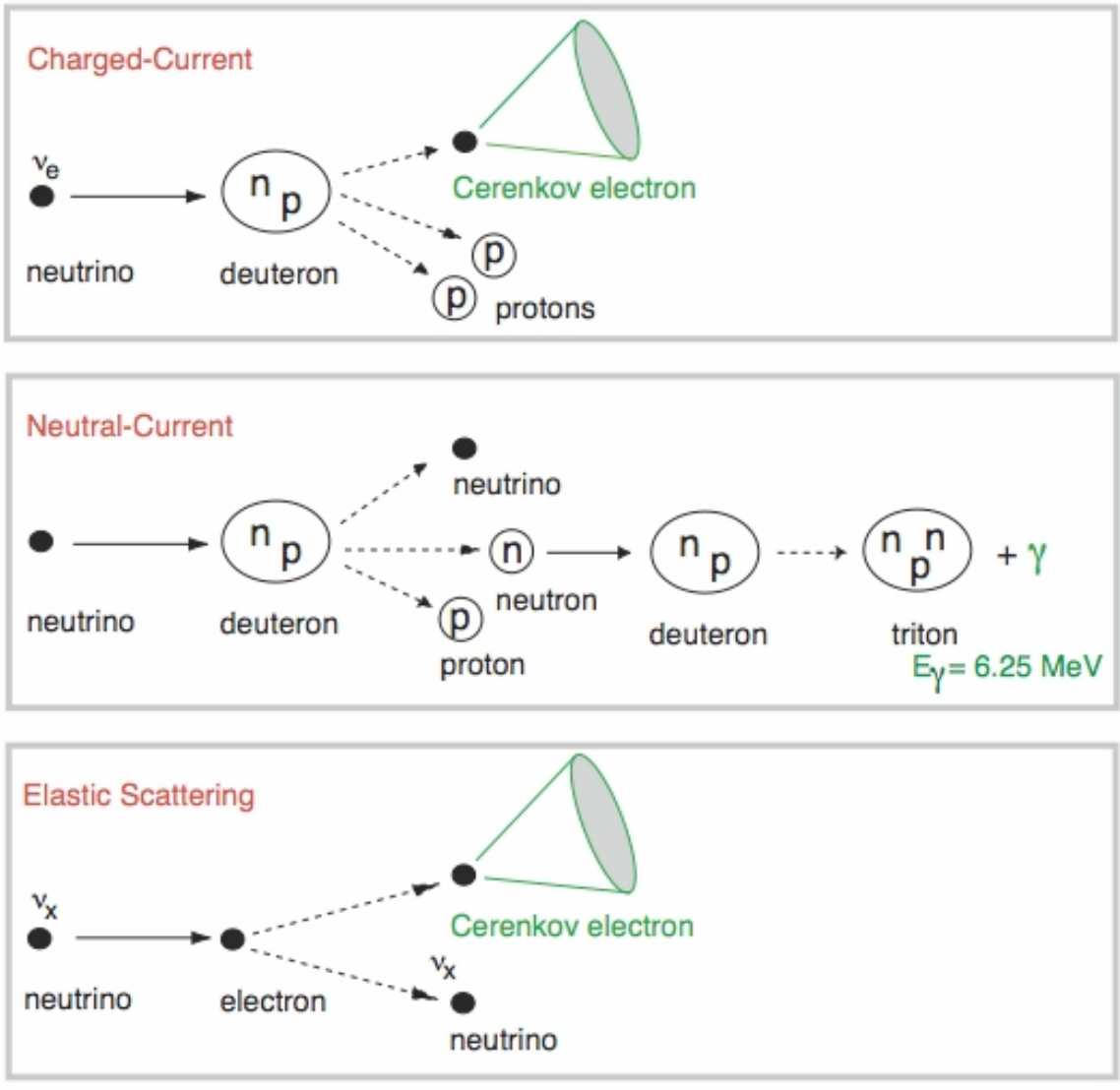
Total flux of $^8$B neutrinos=

$5.44 \pm 0.99 \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$

Total flux of $^8$B Solar model=

$5.05 \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$ (Bahcall et al)

# Neutrino Interactions on Deuterium- K.Hager, Moriond2003



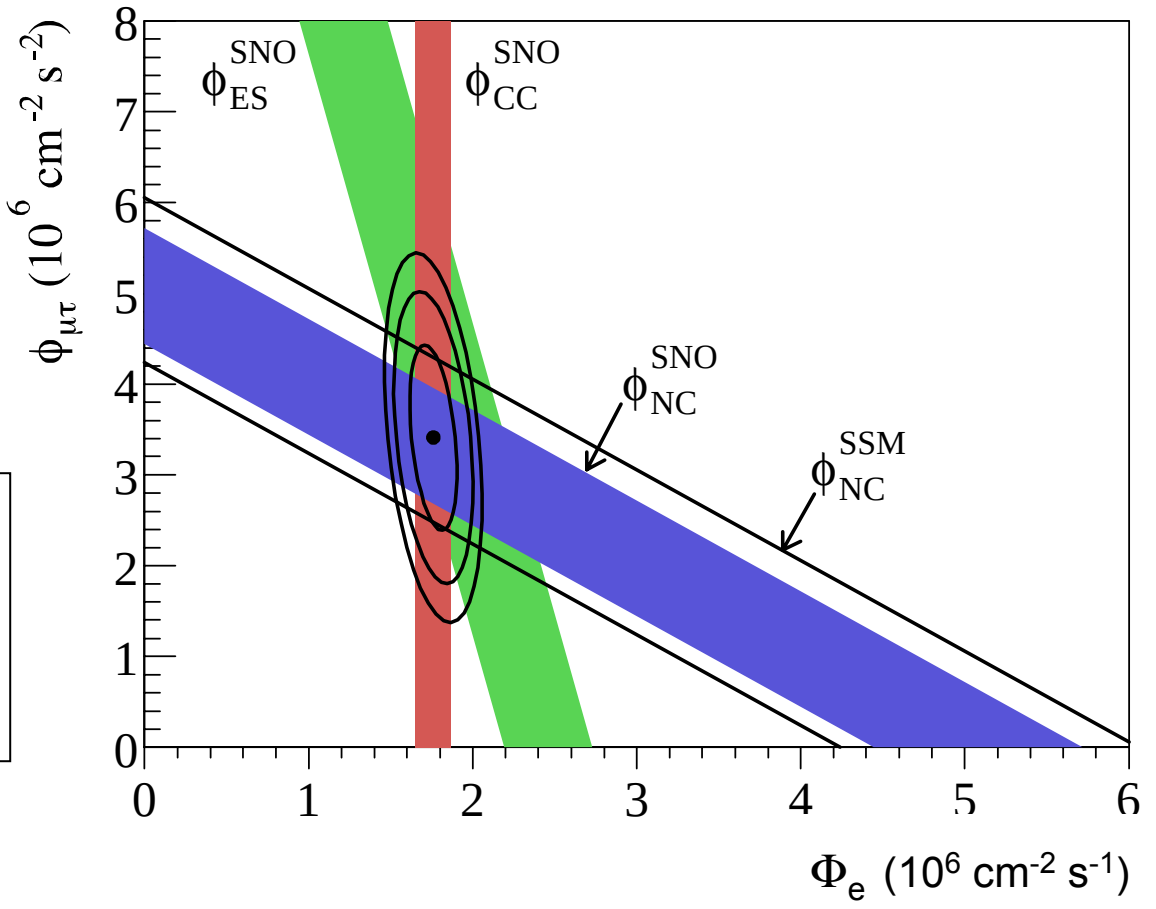
# Flavor Content of the Solar $^8$B Neutrino Flux

2/3 of initial solar $\nu_e$ are observed at SNO to be $\nu_{\mu,\tau}$

Standard Solar Model predictions for total $^8$B flux in excellent agreement!

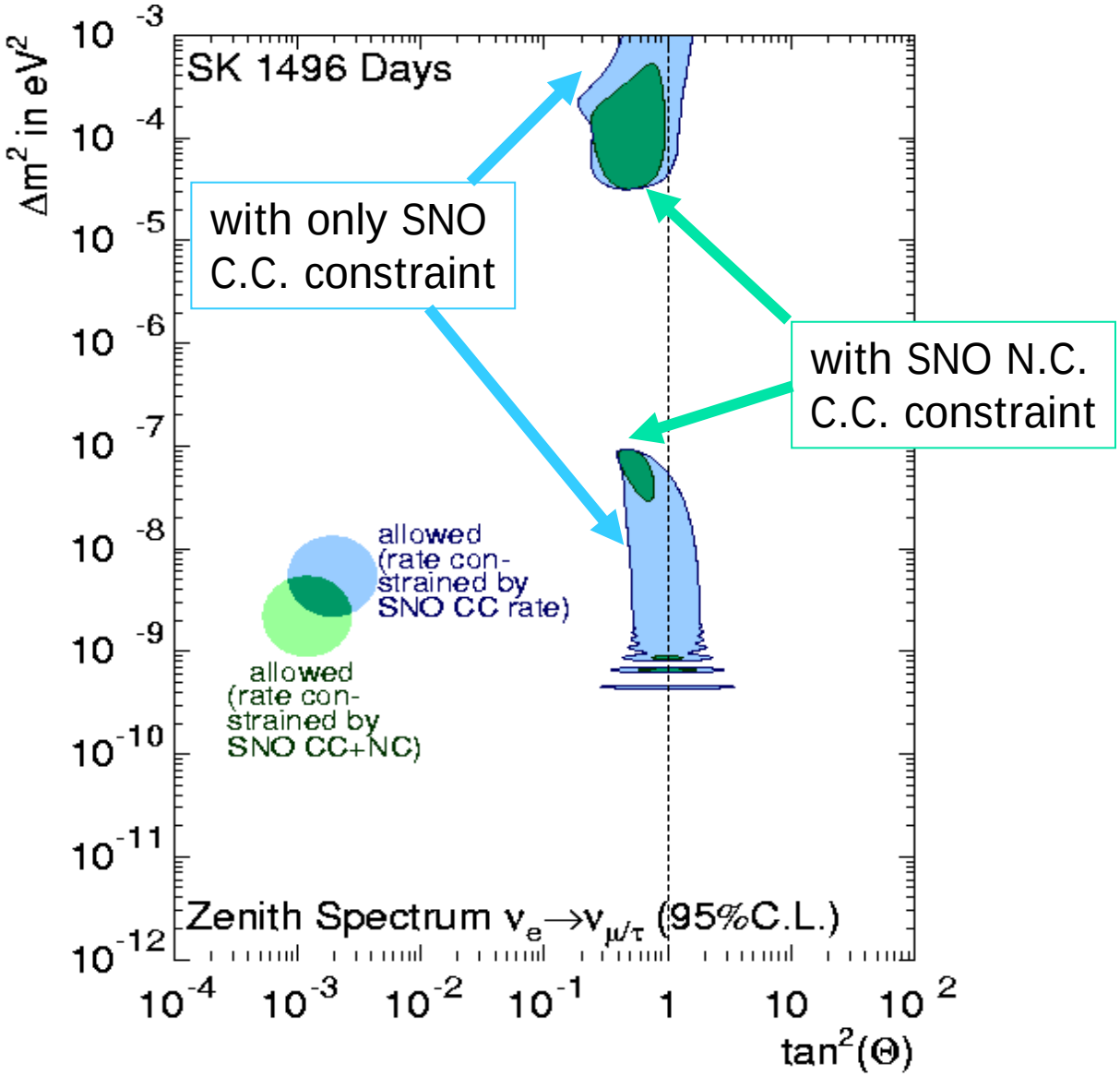
$$\Phi^{8B}_{SSM} = 5.05 \; {}^{+1.01}_{-0.81}$$

$$\Phi^{NC}_{SNO} = 5.09 \; {}^{+0.44}_{-0.43} \; {}^{+0.46}_{-0.43}$$

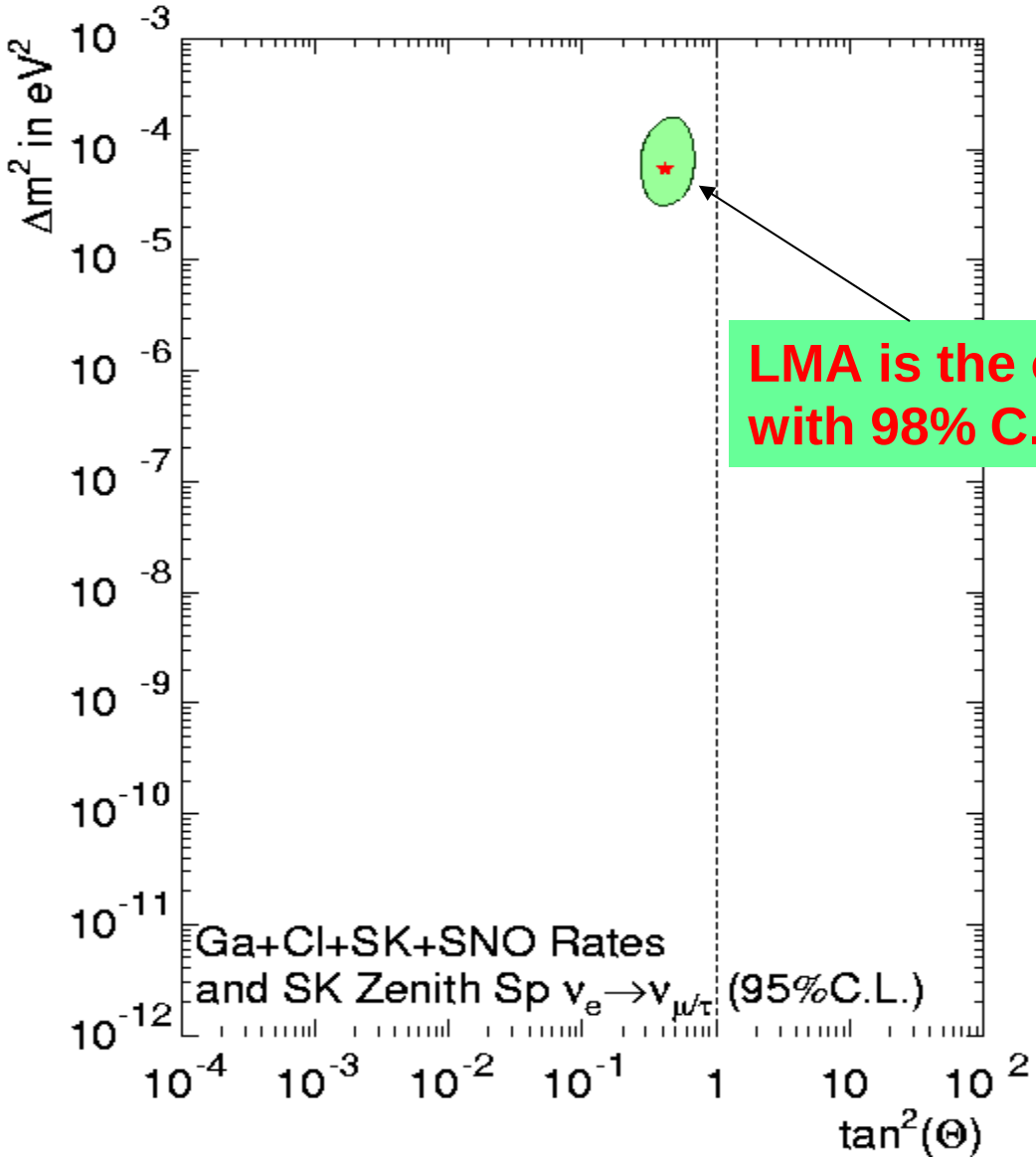


# Combined fits-Y.Koshio

From SK and SNO results

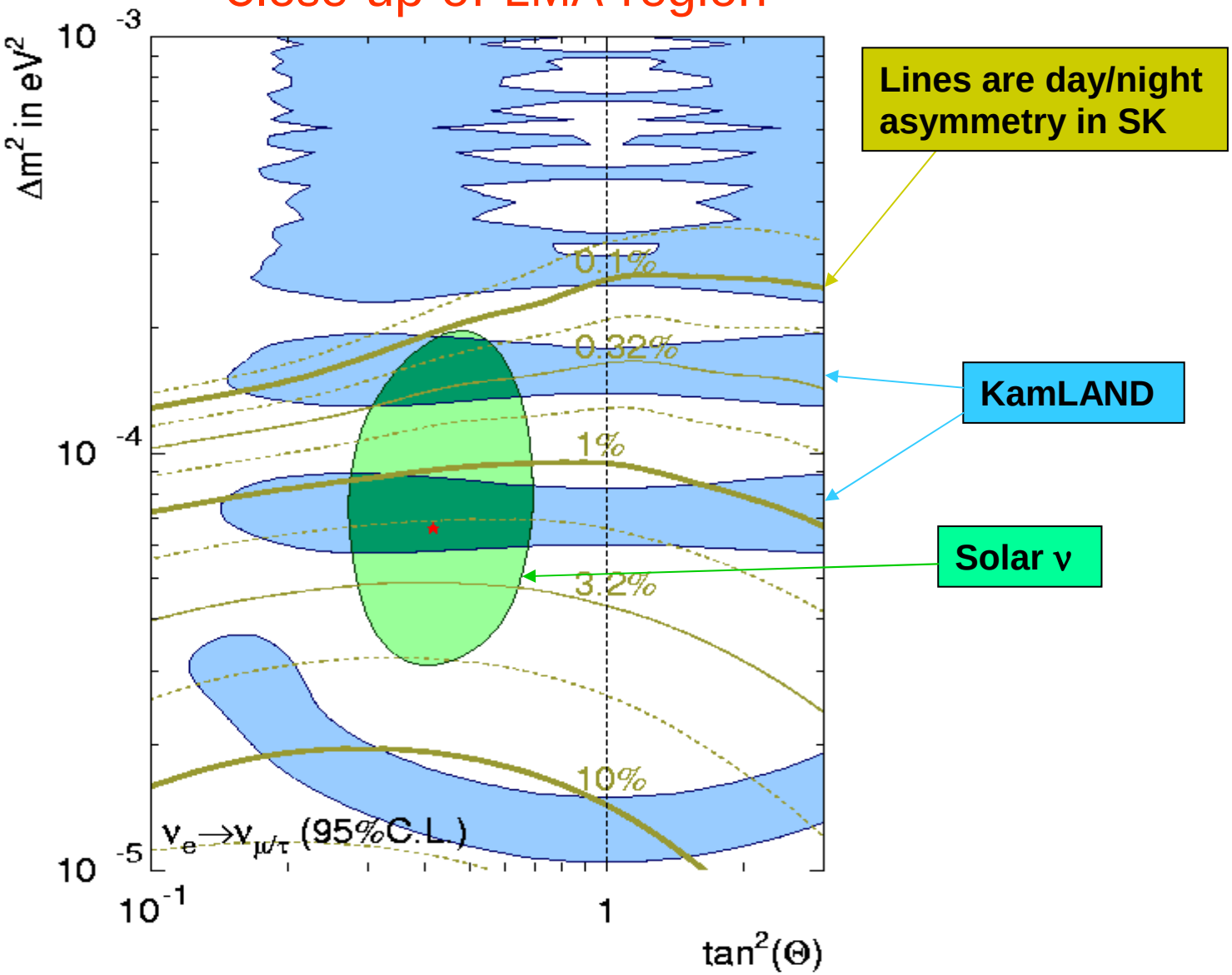


# with all solar neutrino experiments




**LMA is the only solution with 98% C.L.**

# Close up of LMA region



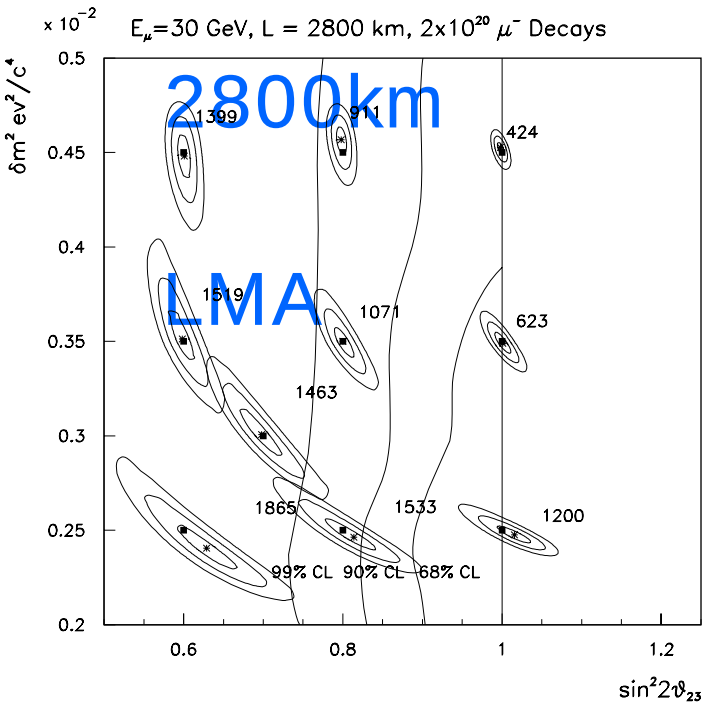
# *Neutrino Factory Physics Potential*

- Determination of $\delta m^2_{32}$ $\sin^2 2\theta_{23}$ with high accuracy
- Matter effects and sign of $\delta m^2_{32}$
- Observation of CP violation in the lepton sector. Measurement of the phase $\delta$. Importance of CP violation in the lepton sector to baryon asymmetry in the early universe.
- Non-oscillation physics.

# *Neutrino factory determination of oscillation parameters*

V.Barger,S.Geer,R.Raja,K.Whisnant,

Phys.REVD62,013004(2000)



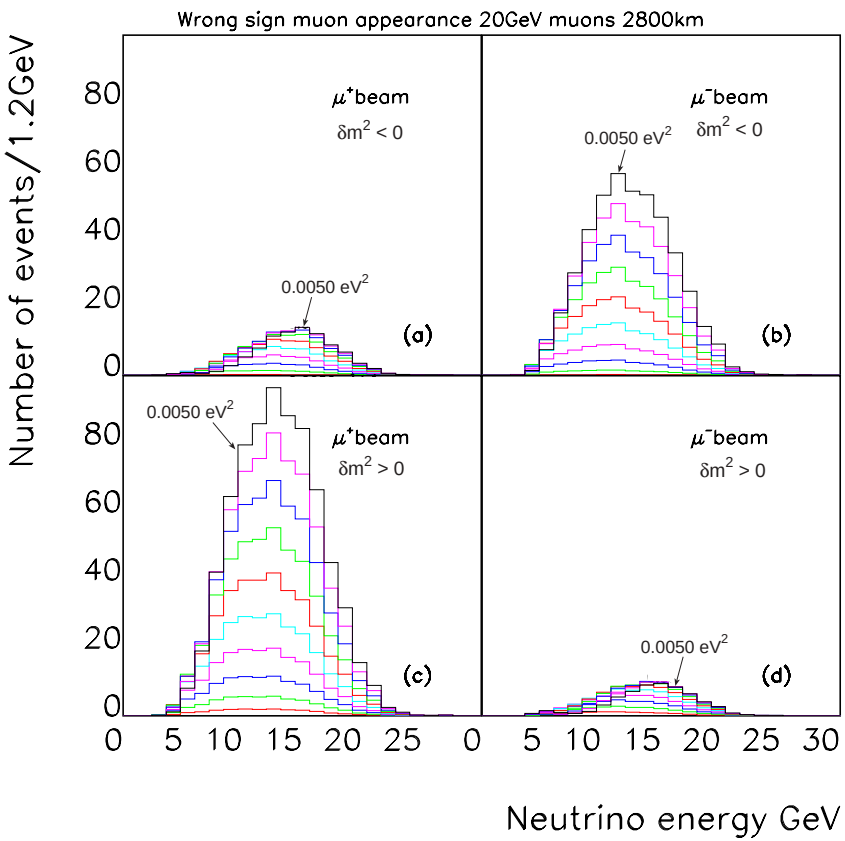

Predictions for

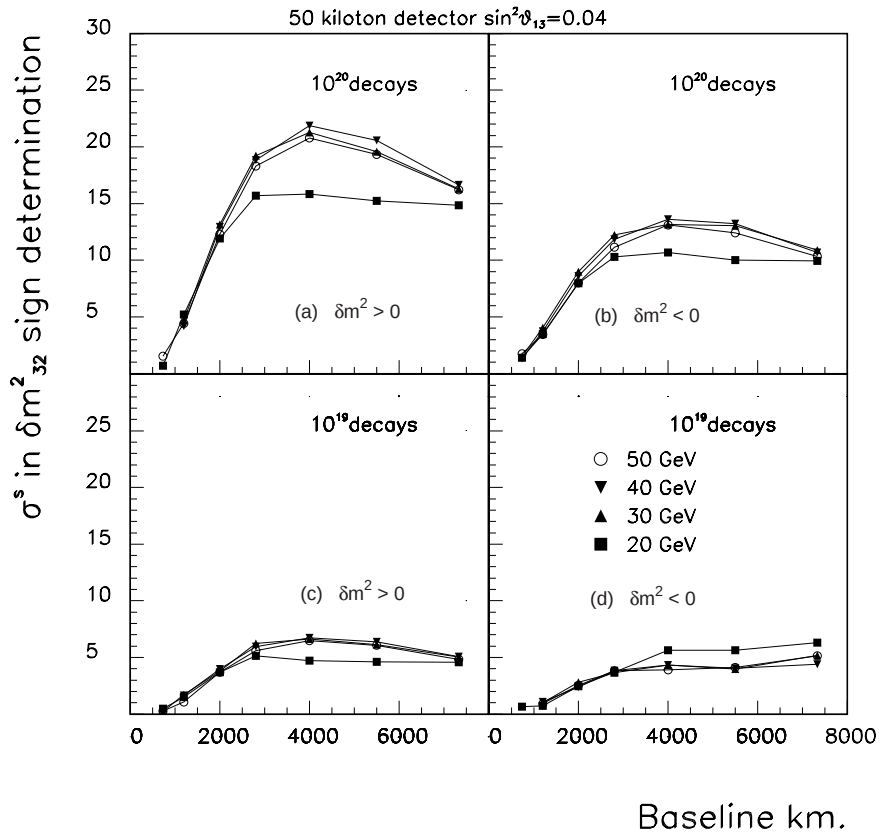
$2x10^{20}$ muon decays.

solution assumed.

# Neutrino Factory Determination of $\delta m^2_{32}$ Sign

- V,Barger,S.Geer,R.Raja,K.Whisnant, Phys.Lett.B485(2000)379



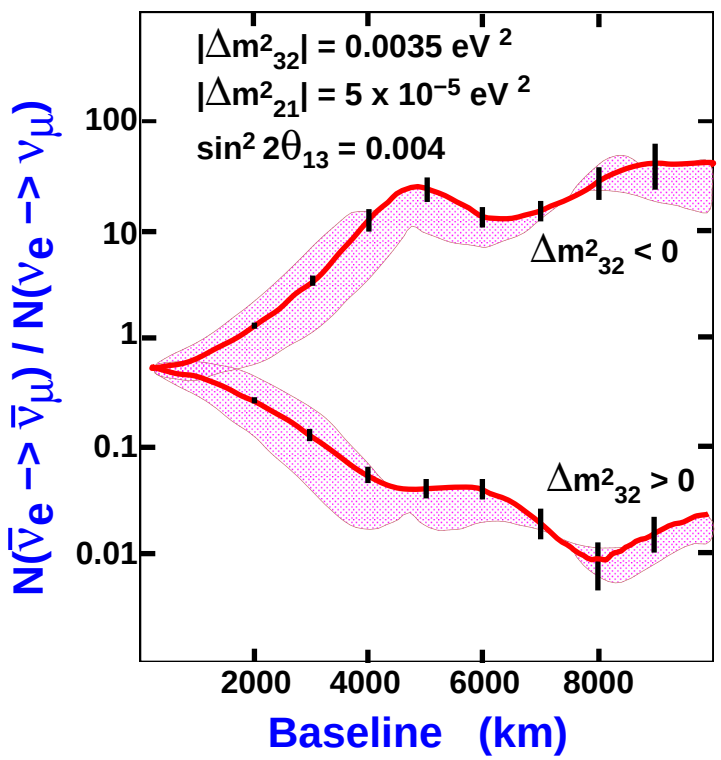

20GeV m 2800km $10^{20}$ decays

50k-ton detector

# *CP Violation in Neutrino Factories*

- All mixings and mass differences need to be non-zero for CP violation to be observed in the lepton sector. If LMA is correct, then $\sin^2 2\theta_{13}$ has to be non-zero for neutrino CP violation to be observed.

  V.Barger,S.Geer,R.Raja,K.Whisnant,Phys Rev D62,073002(2000)




50kiloton detector, $10^{21}$ decays

Leptonic CP violation maybe important in explaining the baryon asymmetry of the Universe.

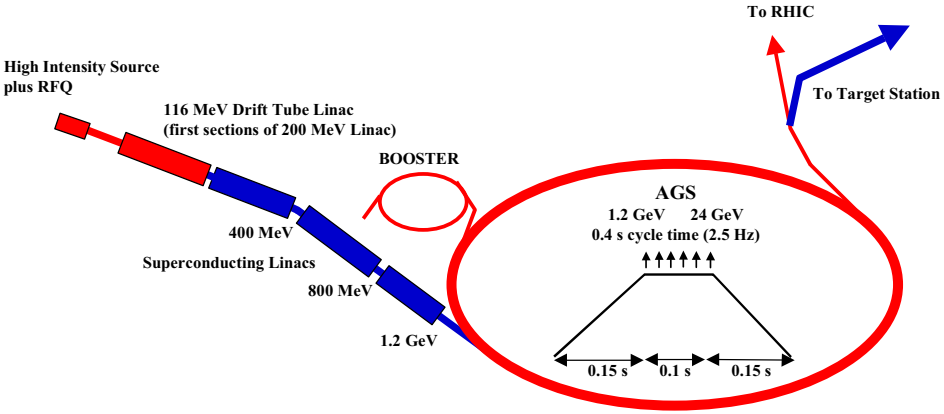
# *Non-oscillation Physics*

- M.L.Mangano et al CERN-TH/2001-131,hep-ph/0105155
- Parton densities x>0.1, best accessible with 50GeV muon beams. Knowledge would improve by more than one order of magnitude. Individual quark and gluon components are measured with relative accuracies of 1-10% 0.1<x<0.6. Higher twist corrections accurately determined. Theoretical systematics in extracting $\alpha_s$ from sum rules and global fits reduced.
- Polarized parton densities measurable. Few percentge accuracy for up and down. Requires a-priori knowledge of polarized gluon density. Polarized DIS experiments at CERN and DESY and RHIC will provide this.
- $\sin^2\theta_W$ at the neutrino factory can be determined with error ~ $2 \times 10^{-4}$
- Permits usage of hydrogen targets. Nuclear effects can be bypassed.
- Rare lepton flavor violating decays of muons can be tagged with the appearance of wrong sign electrons and muons or of prompt taus.

# Stage-1 Proton Driver

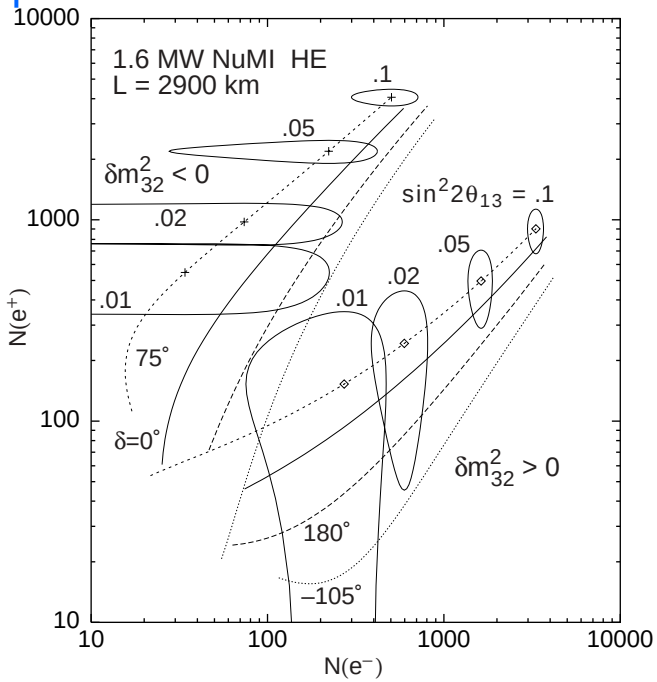
- Costs $250M-330M (1MW), $330M-410M(4MW)
- FNAL scheme

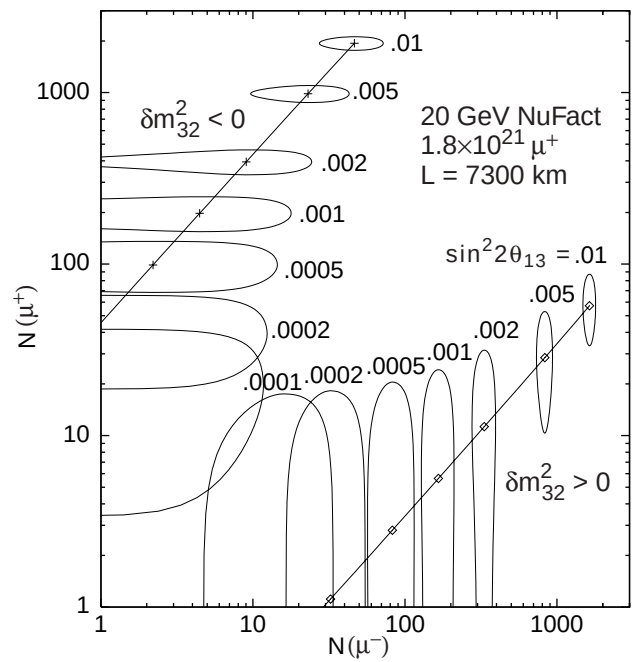
BNL scheme



# Superbeams

- .77 MW JHF, CERN super Linac are also contenders.
- V.Barger et al, Fermilab-FN-703,hep-ph/0103052.
- V.Barger,S.Geer,R.Raja,K.Whisnant **Phys.Rev.D63:113011,2001**
- These reports conclude that superbeams will extend the current limits in oscillation parameters, but that "The sensitivity at a neutrino factory to CP violation and the neutrino mass heirarchy extends to values of the parameter $\sin^2 2\theta_{13}$ that are one to two orders of magnitude lower than at a superbeam"



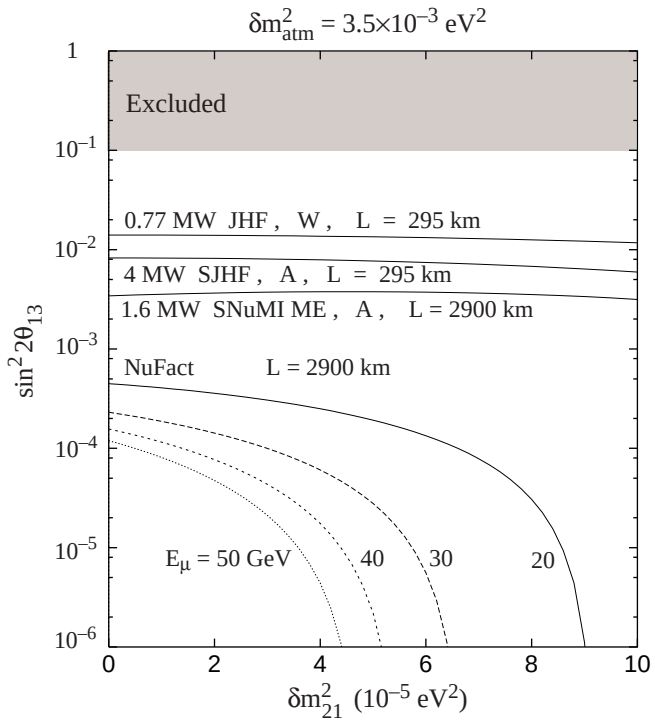



# *Superbeams vs neutrino factories*

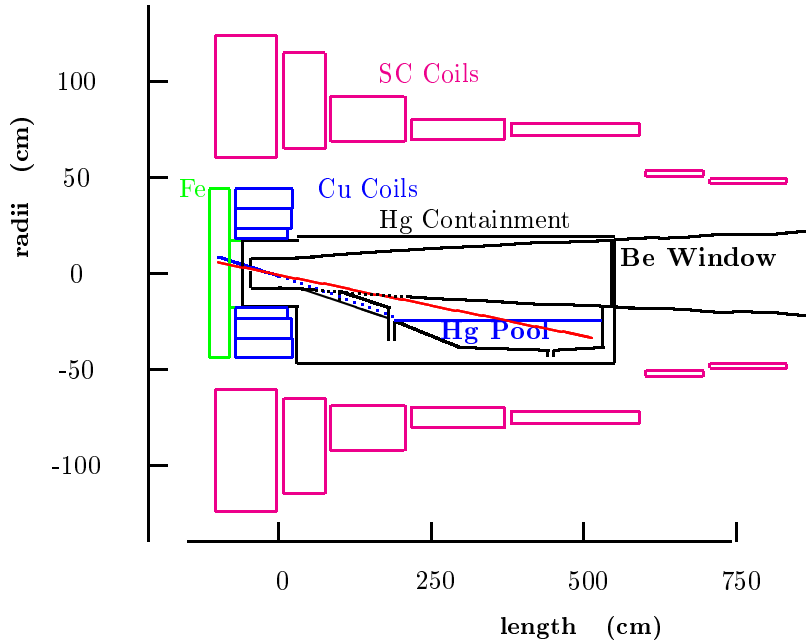
- Superbeam plot on previous page assumes 1.6MW proton driver,liquid argon detector at 2900km, 3 years of running with neutrinos and 6 years of running with antineutrinos.
- Neutrino factory plot assumes 20GeV muons. $3.6\times10^{21}$ muon decays and $1.8\times10^{21}$ antimuon decays, 50kt detector L=7300km.
- Rare K decays
- Measurement of

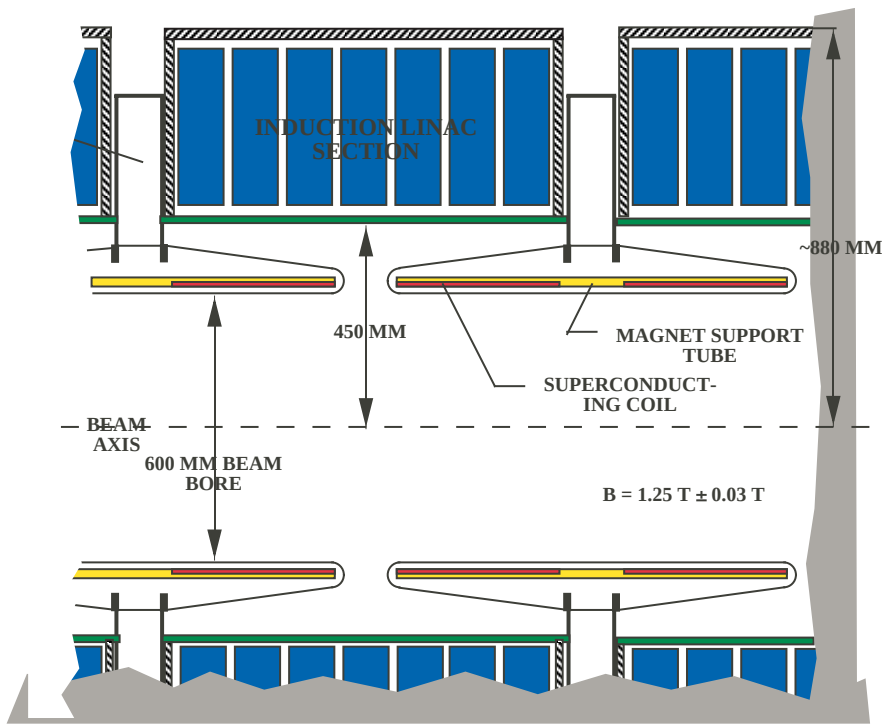
$\delta m^2_{32} \sin^2 2\theta_{23}$ is done quite well by superbeams.

Plot at right $2\times10^{20}$ muon decays



# Stage 2 collection , phase rotation



# *Ionization Cooling*

- In a Hamiltonian system, a particle's motion along the beam direction may be specified by a set of 6 canonical variables $(x,p_x),(y,p_y),(z,p_z)$ or $(x,p_x),(y,p_y),(E,t)$ . Let us define a 6-vector $X_i$ ,(i=1,6), which refers to the above set. Over an ensemble of particles, let us define a 6-vector Y such that $Y_i=X_i-\langle X\rangle_i$
- Then the error matrix

  $E_{ij} = \langle Y_i Y_j\rangle$
- Then the 6-Dimensional emittance $\varepsilon_6$ is defined as

  $(\varepsilon_6)^2$= determinant(E)/$(m_\mu c)^6$
- In a Hamiltonian system, the 6-vector X' at a later time is given by a linear transformation U such that

  X' = U X, leading to $E' = UEU^T$
- I.e. Det(E') = Det(E), emittance is preserved if Det(U)=1. Such transformations are known as Symplectic transformations. Liouville's theorem.
- Cooling is a non-Hamiltonian transformation with Det(U)<1, leading to emitance reduction.

# *Ionization Cooling*

- In the special case where correlations between x,y and z sets of variables can be neglected, the 6-dimensional emittance can be written as

$$(\varepsilon_6) = (\varepsilon^x{}_n)(\varepsilon^y{}_n)(\varepsilon^z{}_n)$$

where $\varepsilon^x{}_n$ is the normalized emittance in the x direction etc. The x and y emittances are referred to as the transverse emittance and the z emittance is known as the normalized emitance.

When angles wrt beam direction are small, it can be trivially shown that

$$(\varepsilon^x{}_n)^2 = \{\langle x^2\rangle\langle\theta^2\rangle - \langle x\theta\rangle^2\}\gamma^2\beta^2$$

- The term in the {} is known as the (unnormalized) emittance.
- Defining E as the particle energy, as the beta function, $\beta\gamma$ as the usual Lorentz factors and $L_R$ as the radiation length of cooling material, and $m_\mu$ as the mass of the muon, leads to the following expressions.

# Ionization Cooling

- We can show
  - » rate of cooling decreases as emittance decreases
  - » Effects due to multiple scattering are ameliorated by placing absorbers at points where angular divergence of beams is large so that the additional angular spread due to MS is not a large increase in emittance. This translates to areas of small beta function.

$$\text{Differentiating,}$$

$$\frac{d\varepsilon_N^x}{dz} = \varepsilon^x \frac{d(\beta\gamma)}{dz} + \beta\gamma \frac{d\varepsilon^x}{dz}$$

$$\text{----cooling --heating --}$$

$$\frac{d\varepsilon_N^x}{dz}(\text{cool}) = -\frac{1}{\beta^2}\frac{\varepsilon_N^x}{E}\left|\frac{dE}{dz}\right|$$

$$\frac{d\varepsilon_N^x}{dz}(\text{heat}) = \frac{\beta\gamma}{2\varepsilon_x}\left\{ < x^2 > \frac{d < \theta^2 >}{dz} + < \theta^2 > \frac{d < x^2 >}{dz} - 2 < x\theta > \frac{d < x\theta >}{dz} \right\}$$

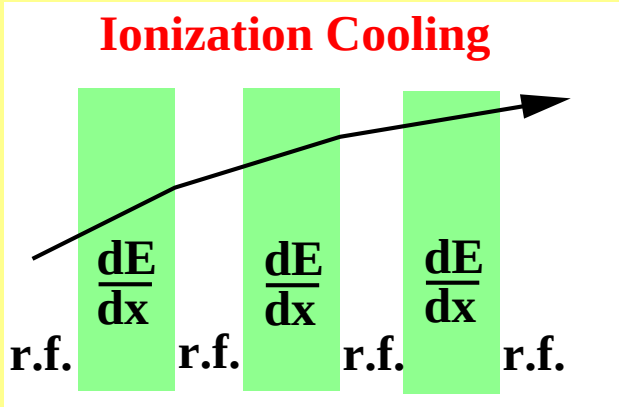
$$\text{--neglecting --correlations --}$$

$$\frac{d\varepsilon_N^x}{dz}(\text{heat}) = \beta\gamma \frac{\beta_\perp}{2}\frac{d < \theta^2 >}{dz} \text{--multiple --scattering}$$

$$\text{leading --to}$$

$$\frac{d\varepsilon_N^x}{dz} = -\frac{1}{\beta^2}\frac{\varepsilon_N^x}{E}\left|\frac{dE}{dz}\right| + \frac{\beta_\perp}{2\beta^3 E m_\mu L_R}(0.014)^2$$

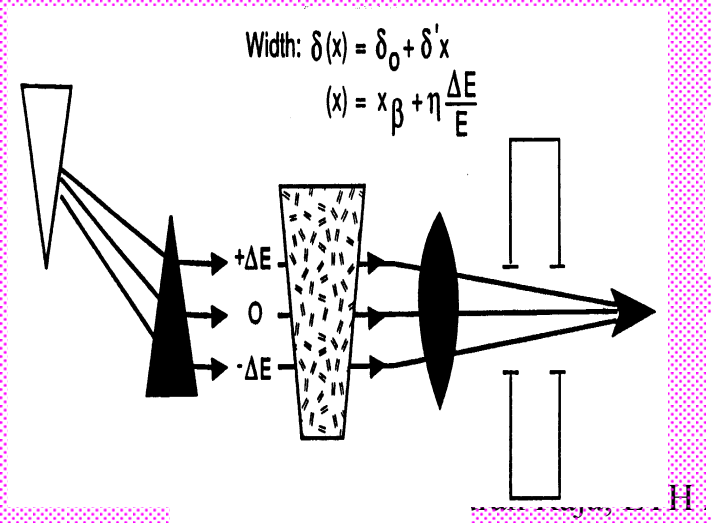
# Ionization Cooling




**Transverse Cooling**

**Muons lose energy by dE/dx and longitudinal momentum replaced by r.f.**

- **To Minimize heating from Coulomb Scattering:**
  - **Small $\beta_\perp$ (strong focusing) : High−field solenoids or Lithium Lenses**
  - **Large $L_R$ (low−Z absorber) : Liquid $H_2$**

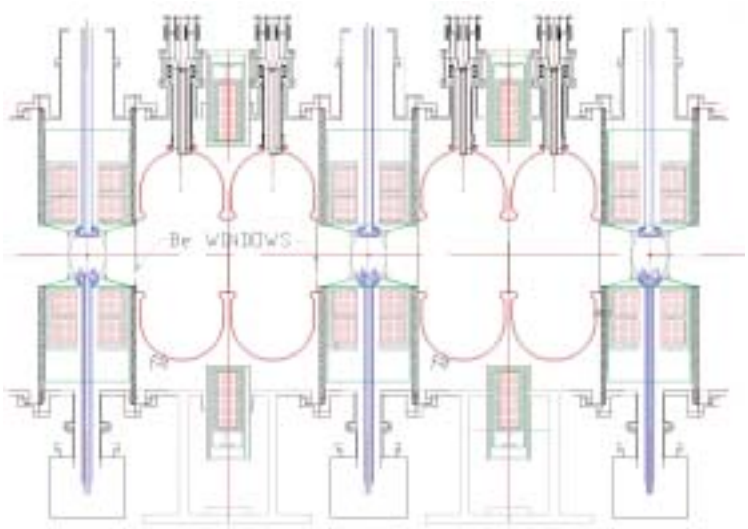


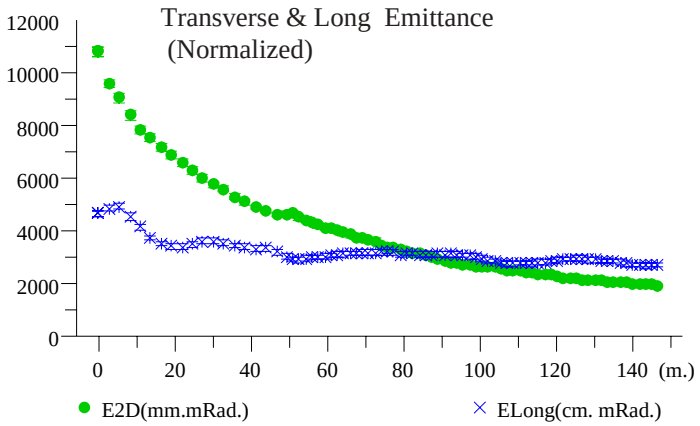

**Energy "Cooling"**

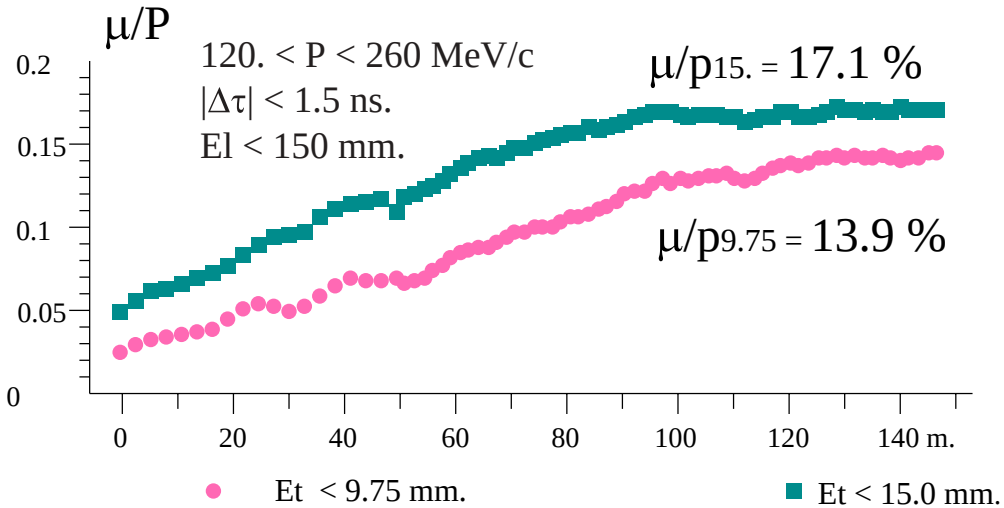
**Ionization cooling using a wedge plus dispersion.**

**Exchanges emittance between transverse & longitudinal directions**

# Stage 2 Cooling



# Stage 2

- Price tag $660M-$840M. Muon beam is phase rotated and transversely cooled. Central momentum 220MeV/c, transverse normalized emittance of 2.7 mm-rad and an rms energy spread of ~4.5%. 4x $10^{20}$ muons per year.
- Cold muon physics can start.

Table 3.2: Some current and future tests for new physics with low-energy muons (from [73], [80], and [81]). Note that the "Current prospects" column refers to anticipated sensitivity of experiments currently approved or proposed; "Future" gives estimated sensitivity with Neutrino Factory front end. (The $d_\mu$ measurement is still at the Letter of Intent stage and the reach of experiments is not yet entirely clear.)

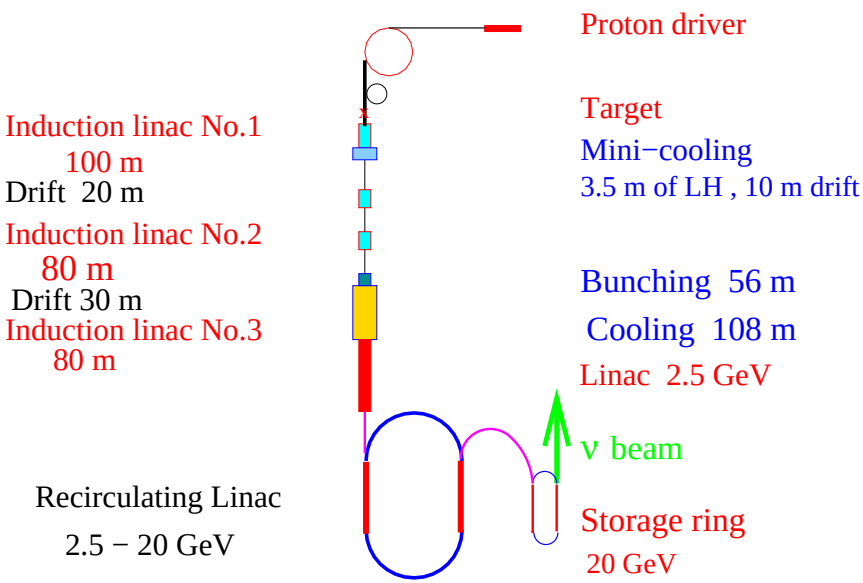
| Test | Current bound | Current prospects | Future |
|---|---|---|---|
| $B(\mu^+ \to e^+\gamma)$ | $< 1.2 \times 10^{-11}$ | $\approx 5 \times 10^{-12}$ | $\sim 10^{-14}$ |
| $B(\mu^-\mathrm{Ti} \to e^-\mathrm{Ti})$ | $< 4.3 \times 10^{-12}$ | $\approx 2 \times 10^{-14}$ | $< 10^{-16}$ |
| $B(\mu^-\mathrm{Pb} \to e^-\mathrm{Pb})$ | $< 4.6 \times 10^{-11}$ | | |
| $B(\mu^-\mathrm{Ti} \to e^+\mathrm{Ca})$ | $< 1.7 \times 10^{-12}$ | | |
| $B(\mu^+ \to e^+e^-e^+)$ | $< 1 \times 10^{-12}$ | | |
| $d_\mu$ | $(3.7 \pm 3.4) \times 10^{-19}\, e{\cdot}\mathrm{cm}$ | $10^{-24}\, e{\cdot}\mathrm{cm}$? | ? |

Table 3.3: Some examples of new physics probed by the nonobservation of $\mu \to e$ conversion at the $10^{-16}$ level (from [73]).

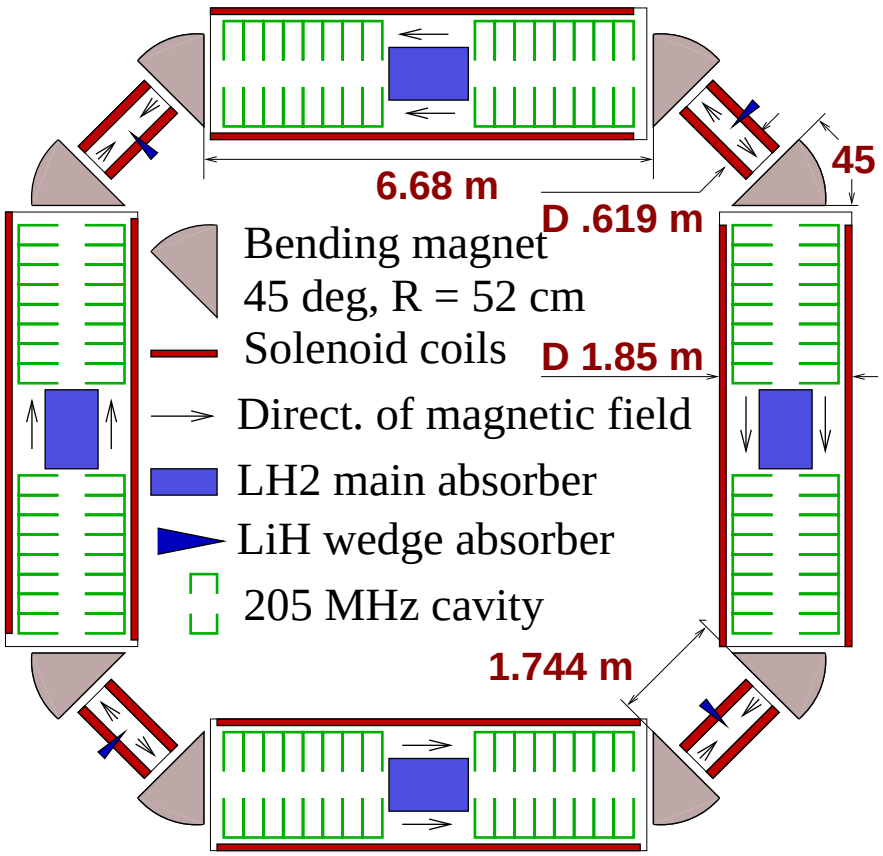
| New Physics | Limit |
|---|---|
| Heavy neutrino mixing | $\lvert V^*_{\mu N} V_{eN}\rvert^2 < 10^{-12}$ |
| Induced $Z\mu e$ coupling | $g_{Z_{\mu e}} < 10^{-8}$ |
| Induced $H\mu e$ coupling | $g_{H_{\mu e}} < 4 \times 10^{-8}$ |
| Compositeness | $\Lambda_c > 3,000\,\mathrm{TeV}$ |

# Stage 3, Stage 4

- Stage 3-Accelerate muons to 2.5GeV. $220-250Million.
- g-2, edm of muons can start. (needs 3.1 GeV magic momentum)
- Stage 4- Full neutrino factory 20GeV version costs $550M. 50GeV version costs $1250-1350M.



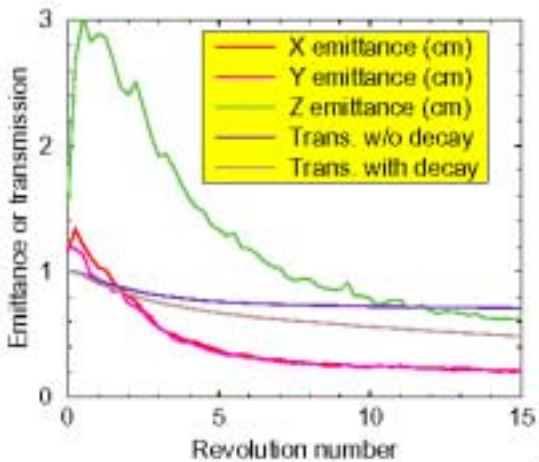
# Ring Coolers




| | |
|---|---|
| Circumference | 36.963 m |
| Nominal energy at short straight section | 250 MeV |
| Bending field | 1.453 T |
| Norm. field gradient | 0.5 |
| Max. solenoid field | 5.155 T |
| rf frequency | 205.69 MHz |
| Accelerating gradient | 15 MeV/m |
| Main absorber length | 128 cm |
| LiH wedge absorber | 14 cm |
| Grad. of energy loss | 0.75 MeV/cm |

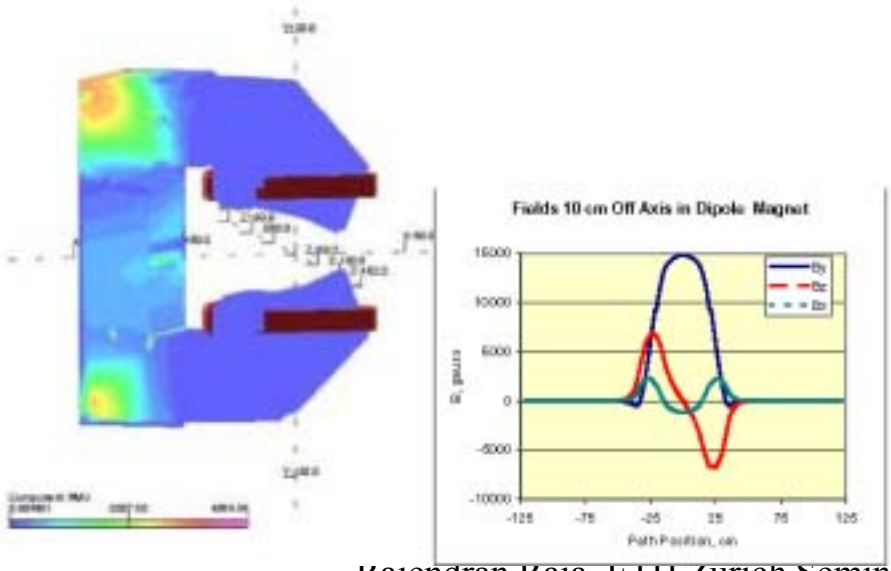
FIG. 34: Layout and parameters of the solenoid based ring cooler

# Ring Cooler performance

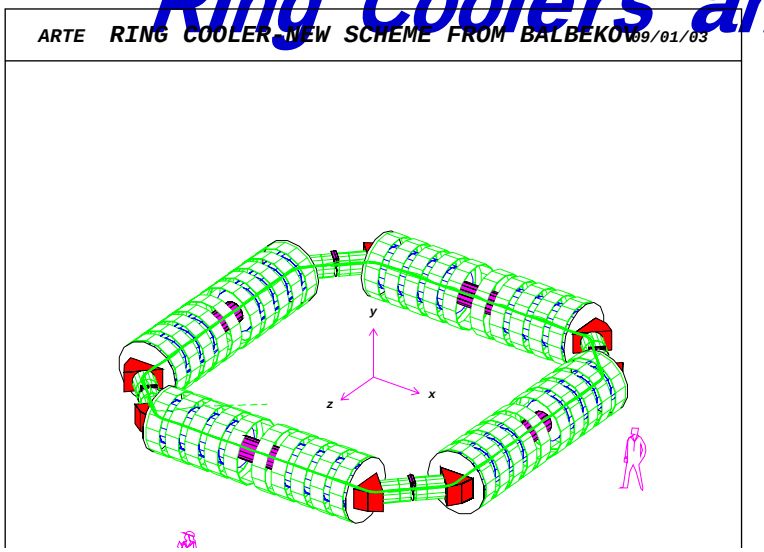


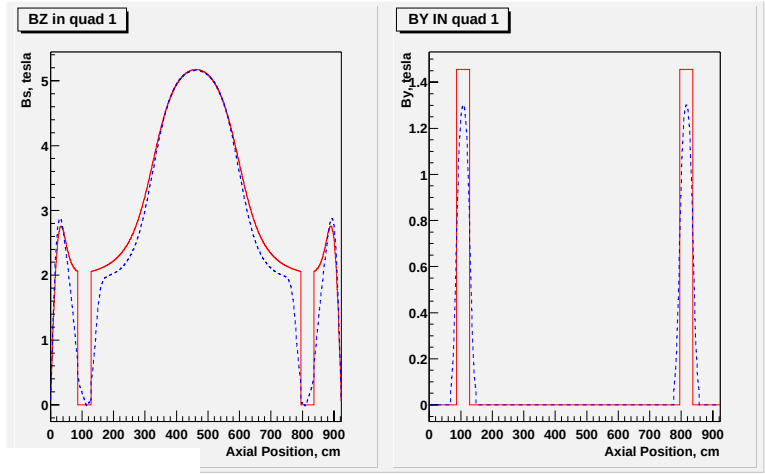

| Number of turns | 0 | 10 | 15 |
|---|---|---|---|
| $x$ emittance (cm) | 1.2 | 0.24 | 0.21 |
| $y$ emittance (cm) | 1.2 | 0.24 | 0.21 |
| $z$ emittance (cm) | 1.5 | 0.79 | 0.63 |
| 6-D emitttance ($cm^3$) | 2.2 | 0.045 | 0.028 |
| 6-D cooling factor | 1 | 49 | 79 |
| Trans. w/o decay | 1 | 0.72 | 0.71 |
| Trans. with decay | 1 | 0.56 | 0.48 |
| Merit factor | 1 | 27 | 38 |

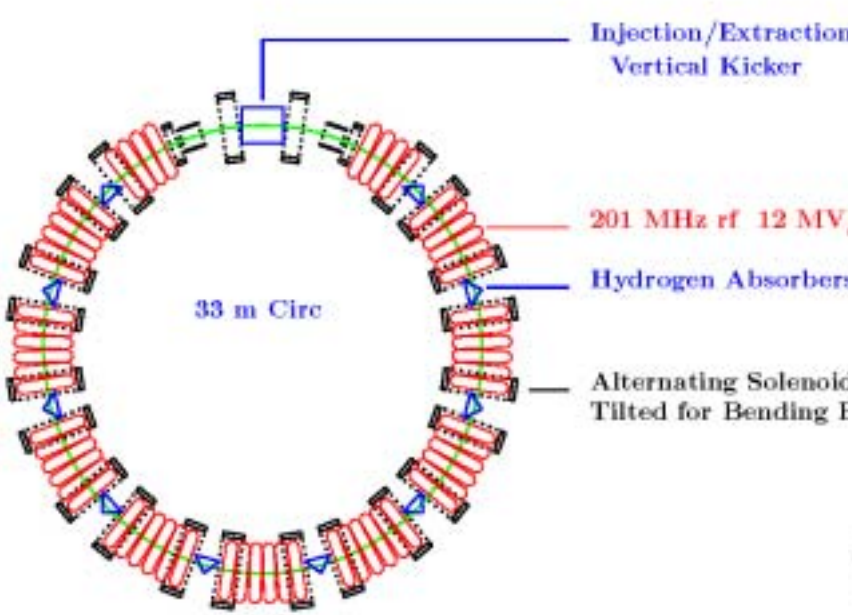
FIG. 35: Evolution of the beam emittance/transmission at the ring cooler.



# Ring Coolers and Emittance Exchange



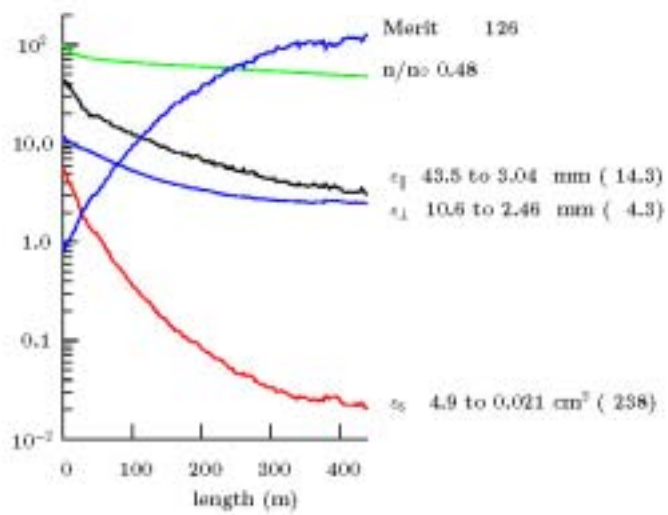




FIG. 39: Transmission, normalized transverse emittance, normalized longitudinal emittance, normalized 6-dimensional emittance, and the merit factor, as a function of distance.

# Performance of Tetra ring coolers

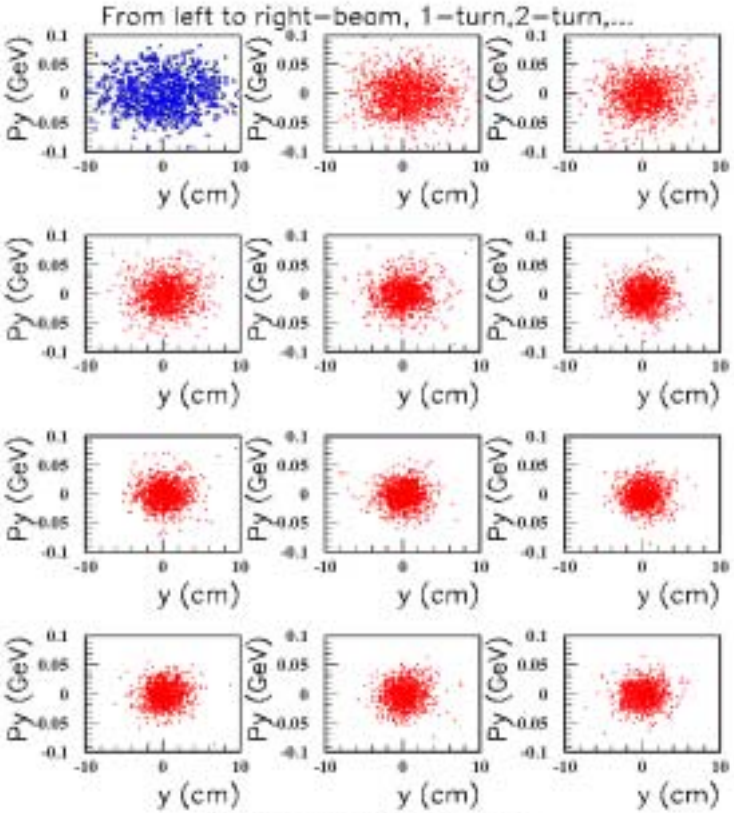



Figure 4: $Y - P_Y$ distribution turn by turn.

6

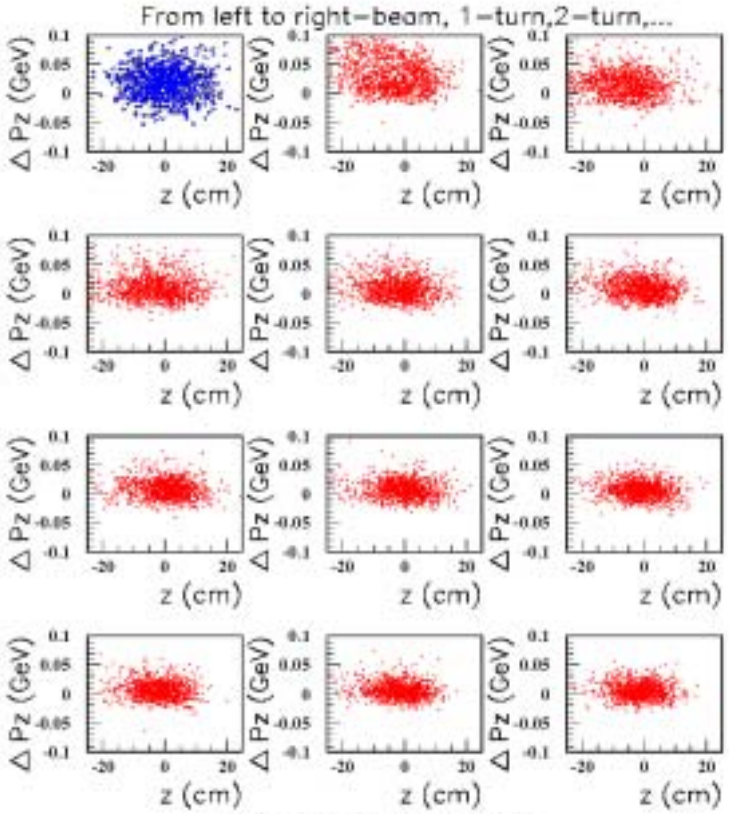



Figure 5: $Z - P_Z$ distribution turn by turn.

7

# Quadrupole/Dipole ring coolers

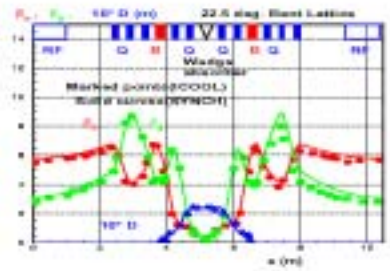


FIG. 41: The $\beta_x$, $\beta_y$, and $D$(dispersion) in a 22.5° bending cell. SYNCH calculations(solid curves) and beam parameters from an ICOOL simulation(marked points) are compared.

FIG. 42: Top view of a sixteen cell muon cooling ring.

# *Geant3 modified*

- Electric fields added
- dE/dx, multiple scattering done well in Geant3
- Electromagnetic showers and hadronic interactions done well
- Arbitrarily complex geometry shapes available by nesting Geant3 shapes
- One can feed in 3D magnetic fields that are realistic.
- We hope to study the problem of injection/extraction into ring coolers using these tools.

# Equations of motion in presence of electric and magnetic fields

$\vec{p}$, $E$ is the particle 4 vector, $\vec{u}$ is the tangent to the trajector y, s the arc length,
v the velocity, $\eta$ is the Lorentz factor
c the velocity of light,
$m_0$ the particle mass, q the charge
$\vec{\varepsilon}$ is the electric field, $\vec{B}$ is the magnetic field

$$\frac{d\vec{p}}{dt} = q\,(\vec{\varepsilon} + \vec{v} \times \vec{B})$$

$$\frac{d\vec{p}}{dt} = \frac{d\vec{p}}{ds} \times \frac{ds}{dt} = v\,\frac{d\vec{p}}{ds}$$

$$\vec{p} = \vec{u}\, m_0 c\, \eta$$

$$p\,\frac{dp}{ds} = \vec{p} \circ \frac{d\vec{p}}{ds} \Rightarrow \frac{dE}{ds} = q\,(\vec{\varepsilon} \circ \vec{u}) \qquad (1)$$

$$\frac{d\vec{u}}{ds} = \frac{d^2\vec{x}}{ds^2} = \frac{q}{p}\left(\vec{u} \times \vec{B} + \frac{\vec{\varepsilon}}{v} - \frac{\vec{\varepsilon} \circ \vec{u}}{v}\vec{u}\right) \qquad (2)$$

$$\frac{dt}{ds} = \frac{1}{v} \qquad (3)$$

# Runge-Kutta Equations

Runge-Kutta is performed on 3 equations simultaneously.Nystrom algorithm

$$y'' = f(y', y, x)$$

solves to

$$y(x+h) = y(x) + hy'(x) + (h^2/6)(K_1 + K_2 + K_3) + O(h^5)$$

$$y'(x+h) = y'(x) + (h/6)(K_1 + 2K_2 + 2K_3 + K_4) + O(h^5)$$

$$K_j = f(y'_j, y_j, x_j) \text{ for } j = 1,2,3,4$$

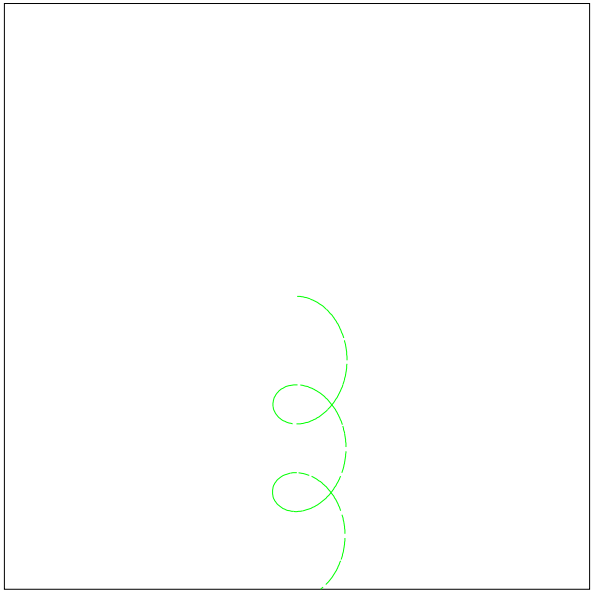
$$x_1 = x, x_2 = x_3 = x + h/2, x_4 = x + h$$

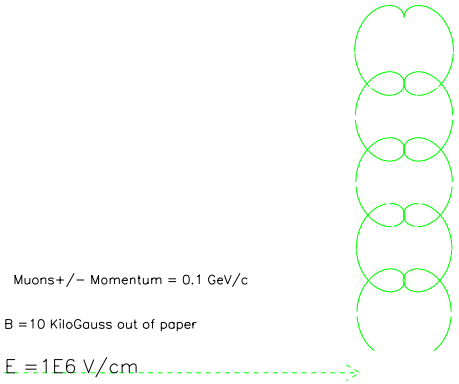
$$y_1 = y(x), y_2 = y_3 = y(x) + (h/2)y'(x) + (h^2/8)K_1$$

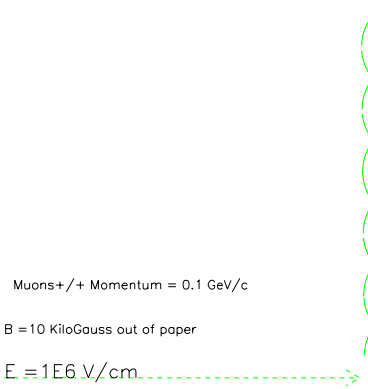
$$y_4 = y(x) + hy'(x) + (h^2/2)K_3$$

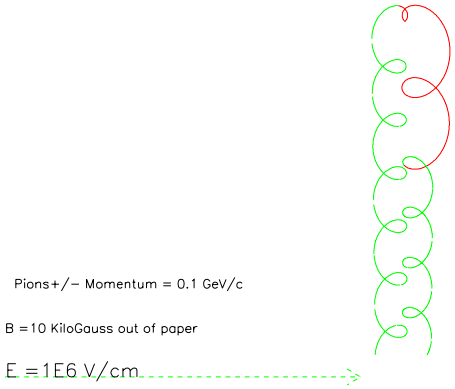
$$y'_1 = y'(x), y'_2 = y'(x) + (h/2)K_1, y'_3 = y'(x) + (h/2)K_2,$$

$$y'_4 = y'(x) + hK_3$$

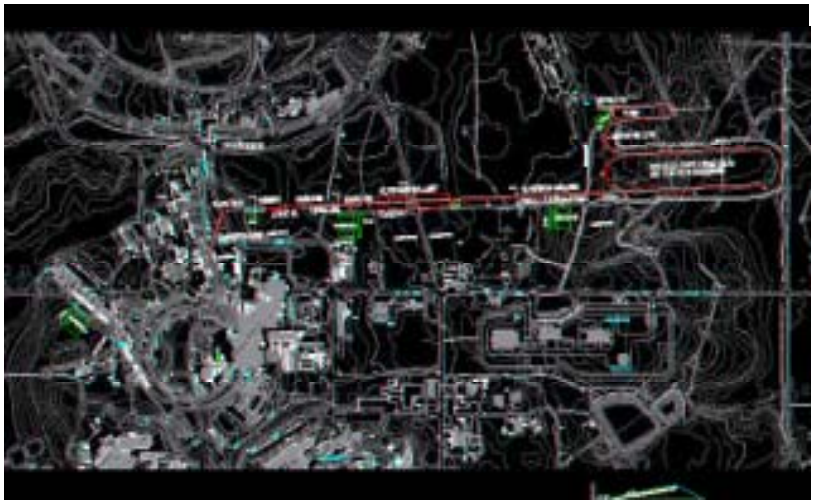


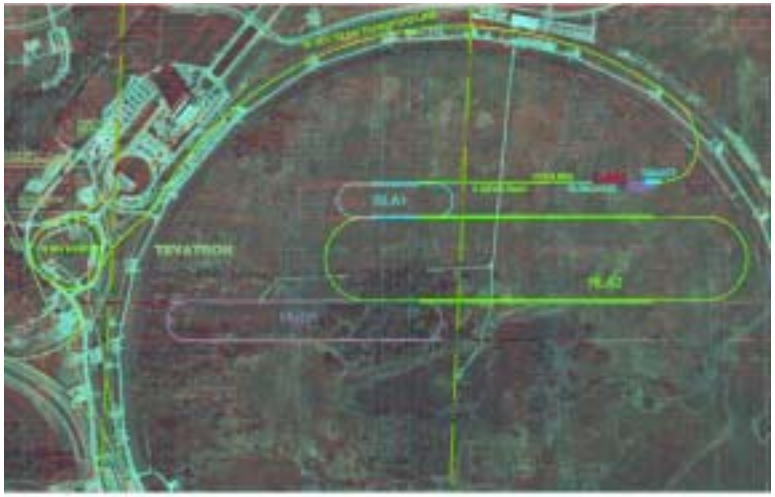

Muons+/− Momentum = 0.1 GeV/c
B =10 KiloGauss out of paper
E =1E6 V/cm


Muons+/+ Momentum = 0.1 GeV/c
B =10 KiloGauss out of paper
E =1E6 V/cm


Pions+/− Momentum = 0.1 GeV/c
B =10 KiloGauss out of paper
E =1E6 V/cm

# *Neutrino factory placements at BNL,FNAL*



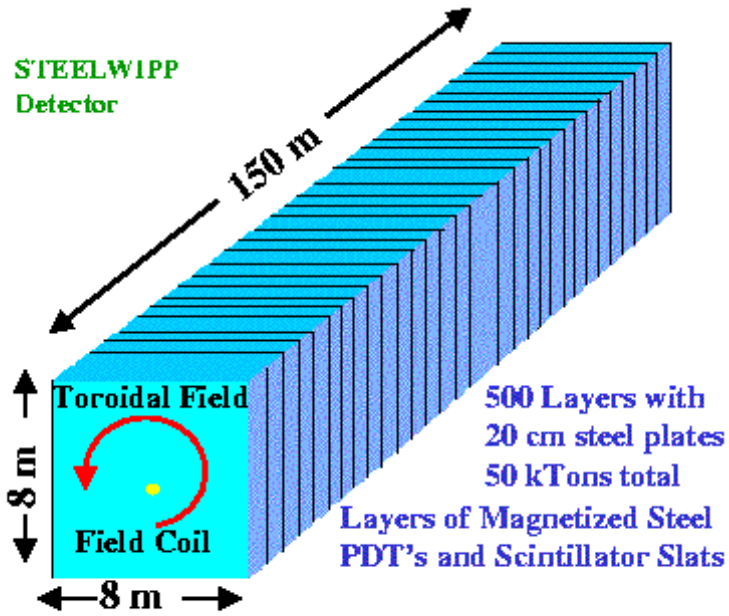


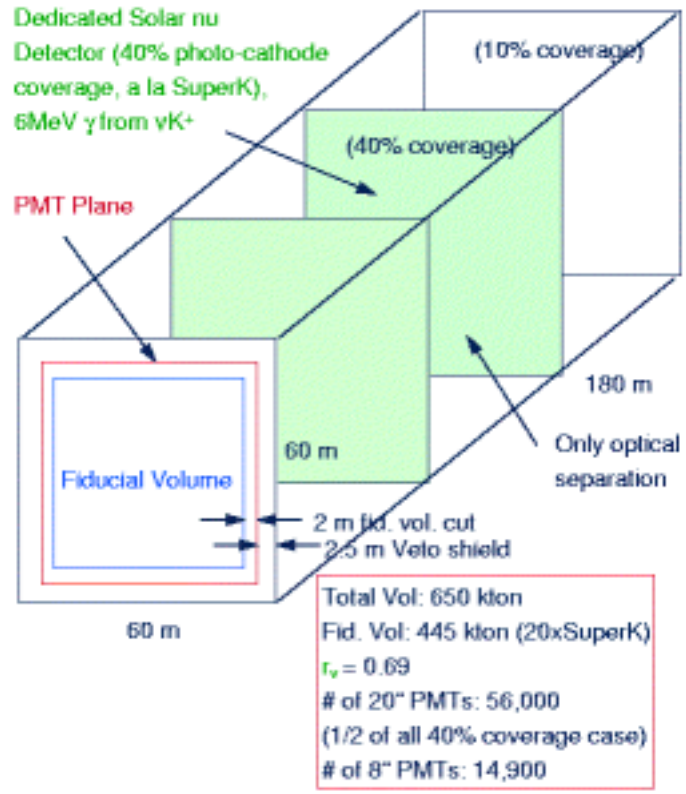
# *Near detector*

- Compact Liquid Argon TPC
- Hydrogen targets.
- Thin lead target followed by standard fixed target spectrometer with tracking chambers. Silicon targets?

# Far Detetctor

- 50kiloton steel scintillator at WIPP, Carlsbad Caverns.
- UNO 650kiloton water Cherenkov detector

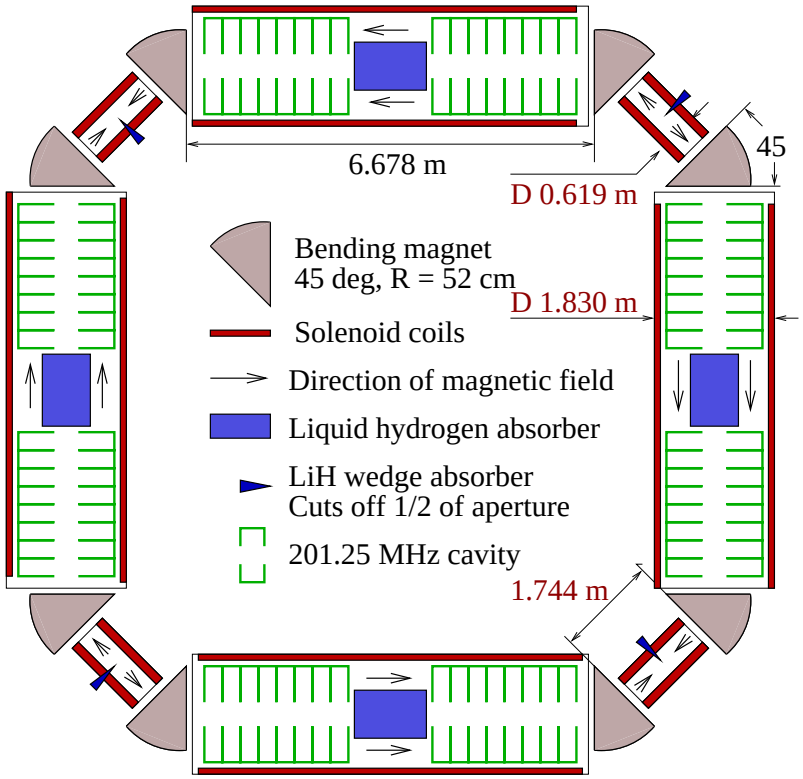


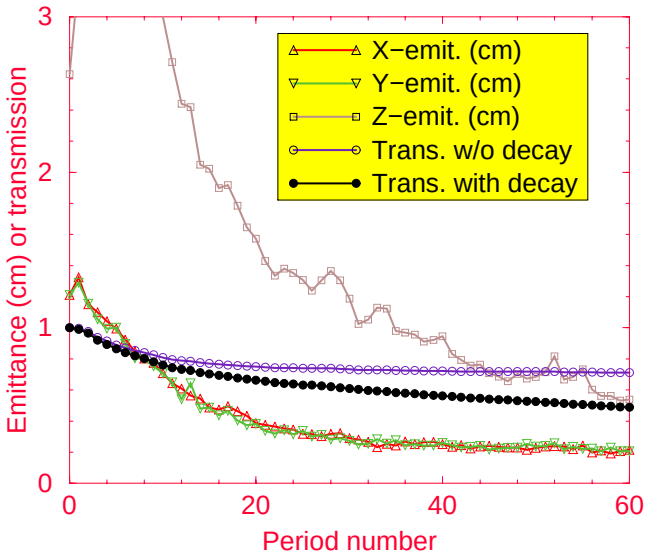




- LANDD-Magnetized massive liquid argon detector that would do supernovae, proton decay and solar neutrinos.

# Stage 5- Muon Collider

- Need to solve emittance exchange problem.
- Ring coolers are a possibility. Injection/extraction, equilibrium emittance are problems.



# Physics with Higgs factory/Muon Collider

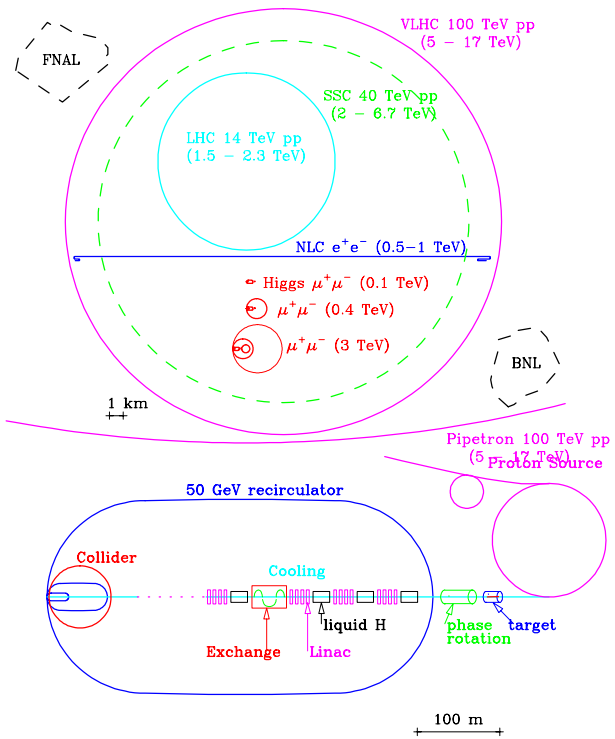
## *Muon Colliders*

- Muon colliders are attractive because they are compact. Muon is 200 times heavier than electron, so Higgs like objects will have 40,000 more cross section in s-channel
- First Muon Collider/Higgs Factory can be used to scan a narrow Higgs of mass 115GeV and width 2-3 MeV. This is possible since we can measure the energy of the muon bunches to 1 part per million using g-2 spin precession as described in

  R.Raja and A. Tollestrup, Phys. Rev.D58(1998)013005
- Emittances need to be cooled by $10^6$ for FMC to be a reality. However, if this is done (Emittance Exchange is a must), then higher energy colliders become feasible.
- W and top thresholds can be scanned and W mass and top quark mass measured very well.
- $H^0/A^0$ Higgs of the MSSM can be resolved in the s-channel using an MC if they are degenerate as in the 'decoupling limit' of the theory.
- Muon Colliders of 3-4 TeV can fit on existing lab sites.
- Backgrounds can be brought under control in detector regions using clever shielding ideas.

6/29/01 Andrew M Sessler, Snowmass 2001

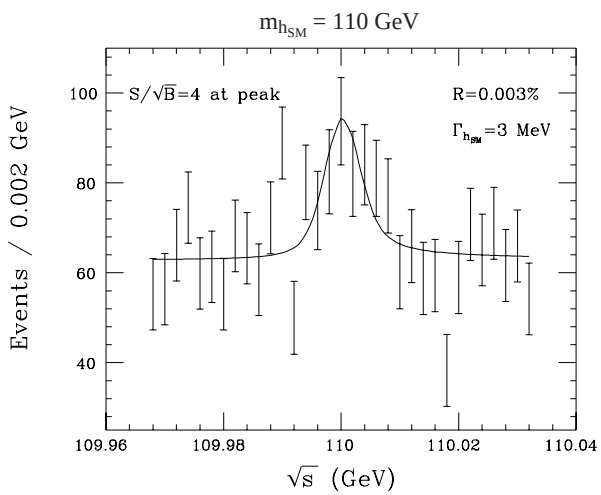
## *Schematic of Muon Collider*




6/29/01 Andrew M Sessler, Snowmass 2001

# Higgs Factory/Muon Collider

## *Scanning the Higgs peak using the muon collider*




6/29/01 Andrew M Sessler, Snowmass 2001

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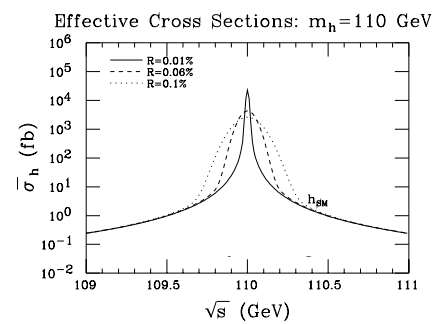
## *Light Higgs Resonance Profile*

Convolve $\sigma_h$ with Gaussian spread

$$\bar{\sigma}_h\left(\sqrt{s}\right) = \int \sigma_h\left(\sqrt{\hat{s}}\right) \frac{\exp\left[-\left(\sqrt{\hat{s}}-\sqrt{s}\right)^2\right] d\sqrt{s}}{\sqrt{2\pi}\,\sigma_{\sqrt{s}}}$$




Need resolution $\sigma_{\sqrt{s}} \sim \Gamma_h$ to be sensitive to the Higgs width

### Light Higgs width

$80 \leq m_h \leq 120$ GeV

$\Gamma_h \approx 2$ to 3 MeV if $\tan\beta \sim 1.8$

$\Gamma_h \approx 2$ to 800 MeV if $\tan\beta \sim 20$

6/29/01 Andrew M Sessler, Snowmass 2001

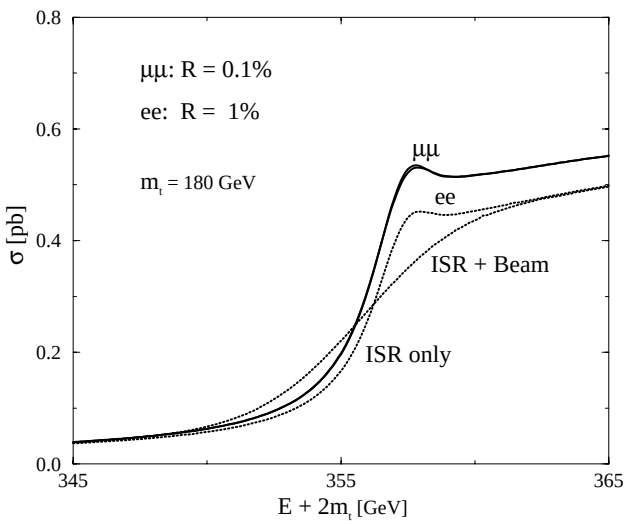
# Higher energy Muon Colliders

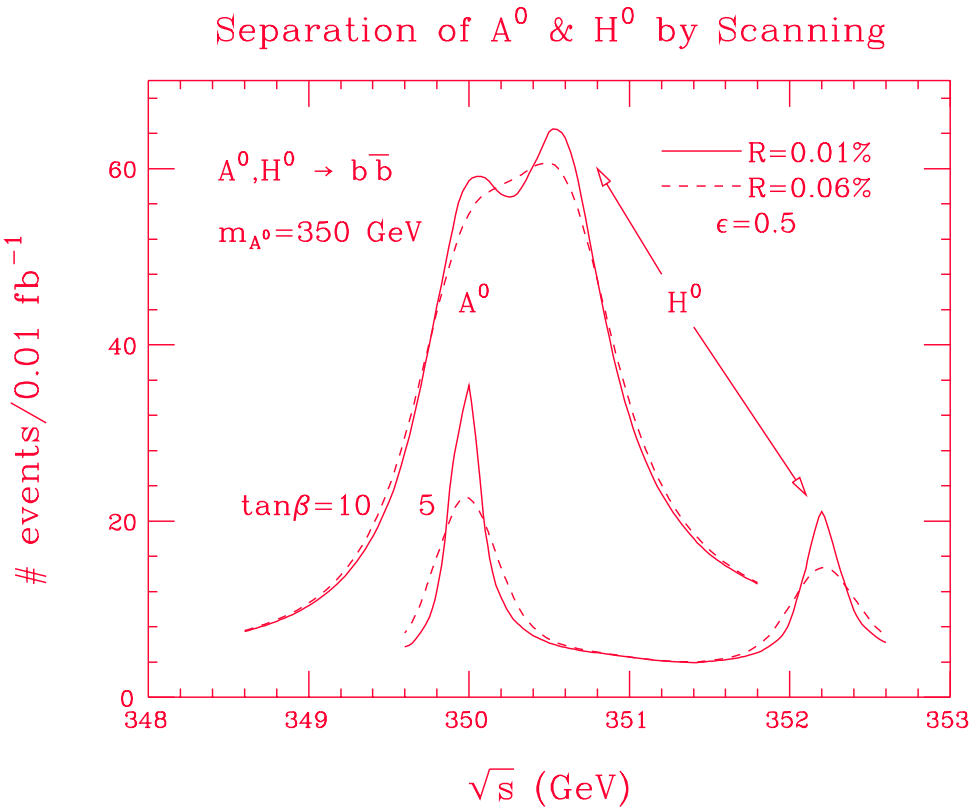
- 3TeV center of mass

Will not cause neutrino Background problems.

More exotic cooling, Exotic locations etc.

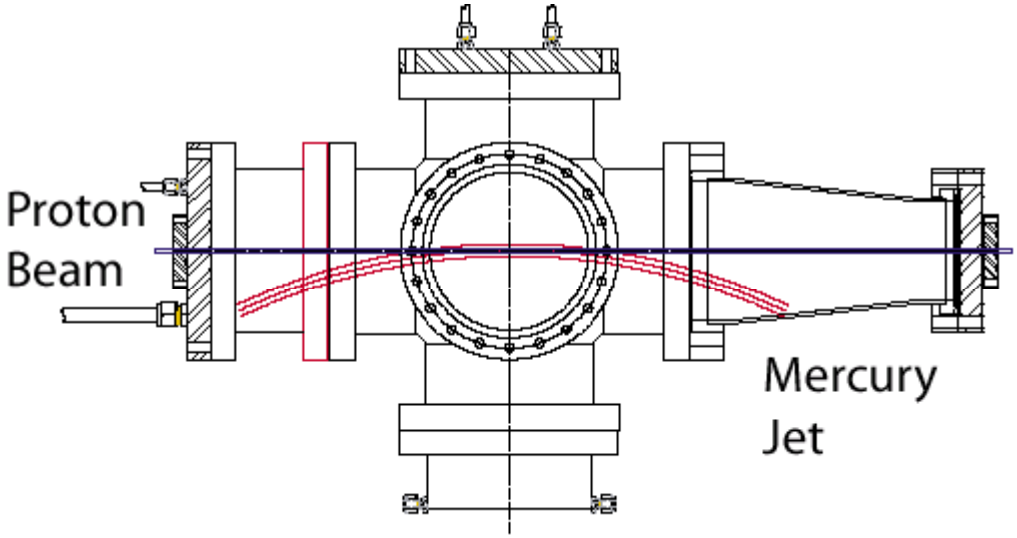
***Top quark threshold- ISR and beam effects***



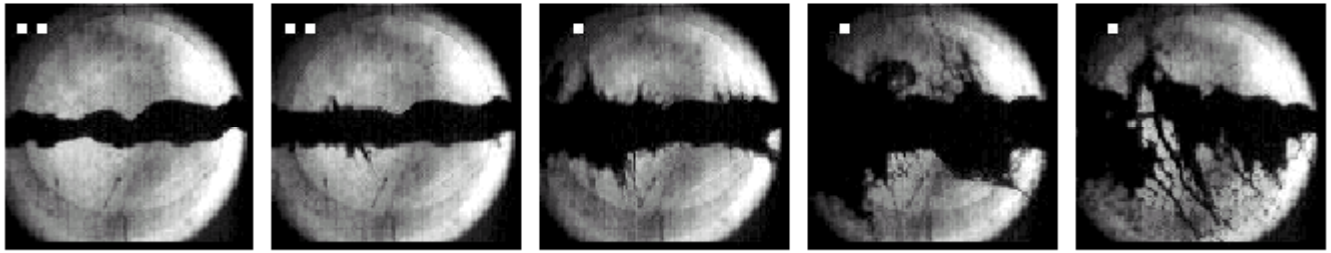



# *Targetry R&D*

- • **Mercury-jet target tested at BNL**
- 
- 

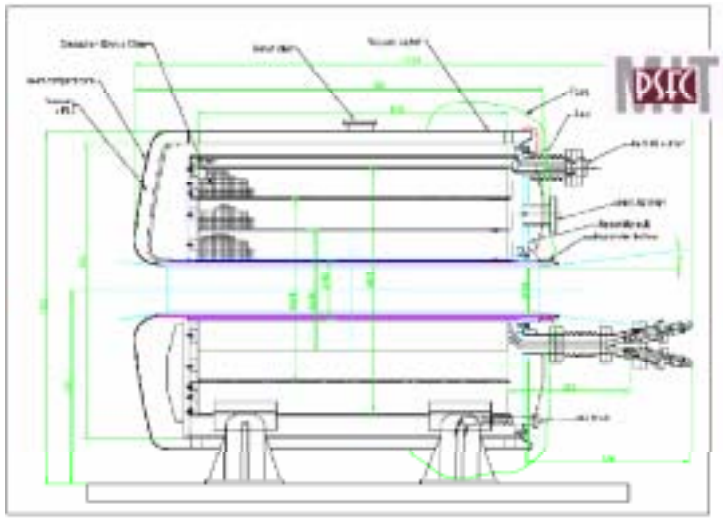



1-cm-diameter Hg jet in 2e12 protons at $t = 0, 0.75, 2, 7, 18$ ms.



# Solenoid R&D

**Concept for test target solenoid (5, 10, 14.5 T capability)**



| | Units | Case#1 | Case #2 | Case #3 |
|---|---|---|---|---|
| Peak on-axis field | T | 5.0 | 10.0 | 14.5 |
| No. of 0.54 MVA power supplies | - - | 1 | 4 | 4 |
| Mode of ganging supplies | - - | none | 2 x 2 | 2 x 2 |
| Initial temperature | K | 84 | 74 | 30 |
| Number of turns utilized | - - | 1200 | 1200 | 1800 |
| Charge time | sec | 7.2 | 6.3 | 15.3 |
| Temperature rise at end of pulse | K | 5.8 | 21.7 | 48.3 |
| Cumulative heating at end of pulse | MJ | 2.7 | 9.1 | 15.2 |

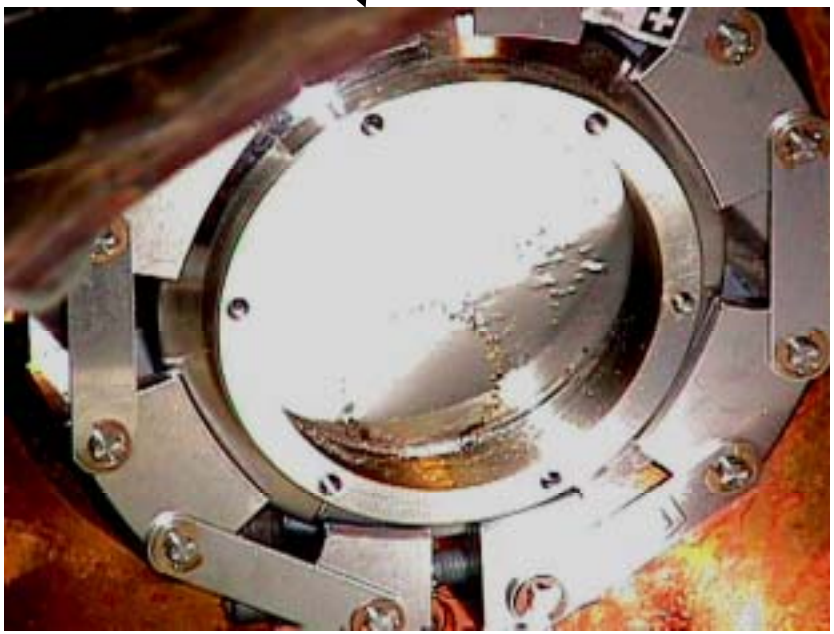
# Cooling R&D

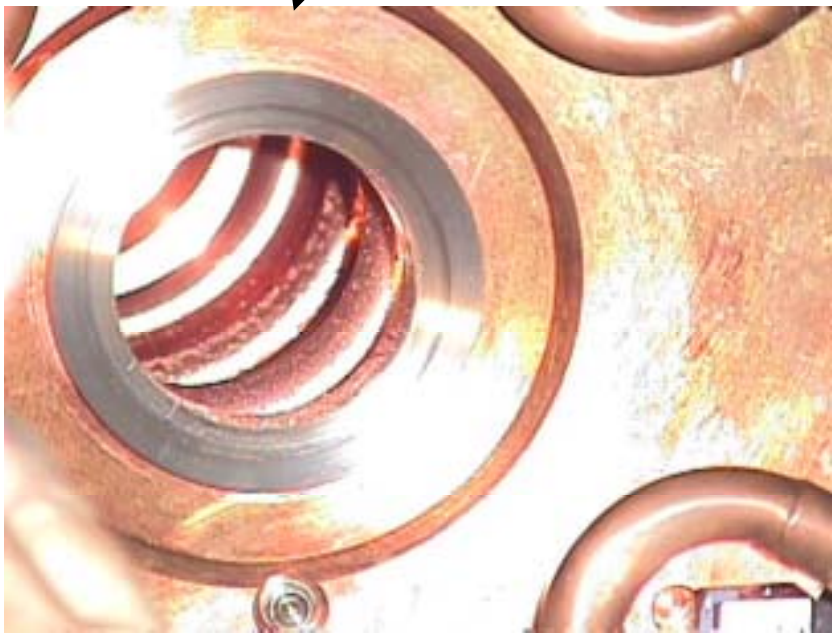
- — includes hardware R&D on rf cavities, absorbers, solenoids
- 
- — rf work to date done at 805 MHz; 201 MHz cavity designed now
- 
- o issue: limits to gradient (breakdown; dark current suppression)
- 
- — absorber work going on in Illinois (ICAR supported) and Japan (U.S.-Japan funding)
- 
- o focus is on development and testing of large, thin windows
- 
- o consideration of hydrogen safety implications is well along
- 
- – proximity of $LH_2$ to "ignition source" requires additional containment windows seen by beam
- 
- – solutions being developed initially in the context of MICE
- 
- — solenoid work is aimed mainly at cost and reliability issues
- 
- o unable to begin fabrication due to funding limitations
- 

# 805 MHZ RF R&D

**Initial tests of 805 MHz cavity in magnetic field showed damage**

**— "rings" on window (image of irises) and iris damage**

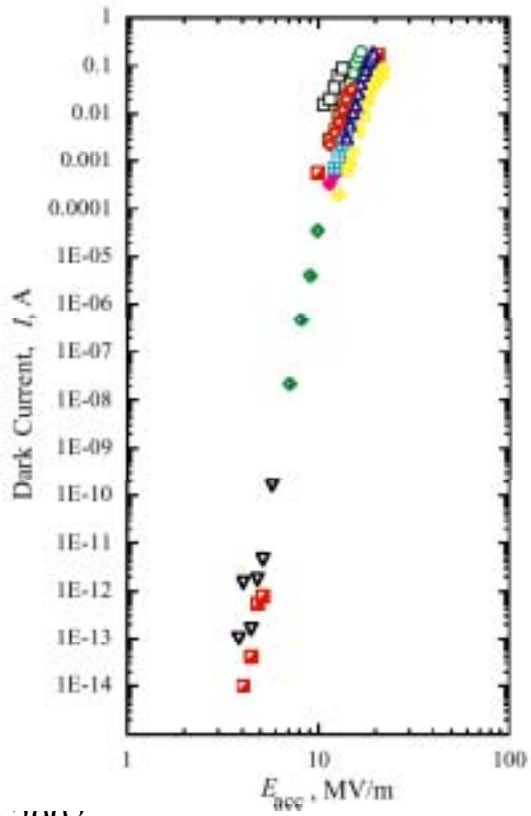


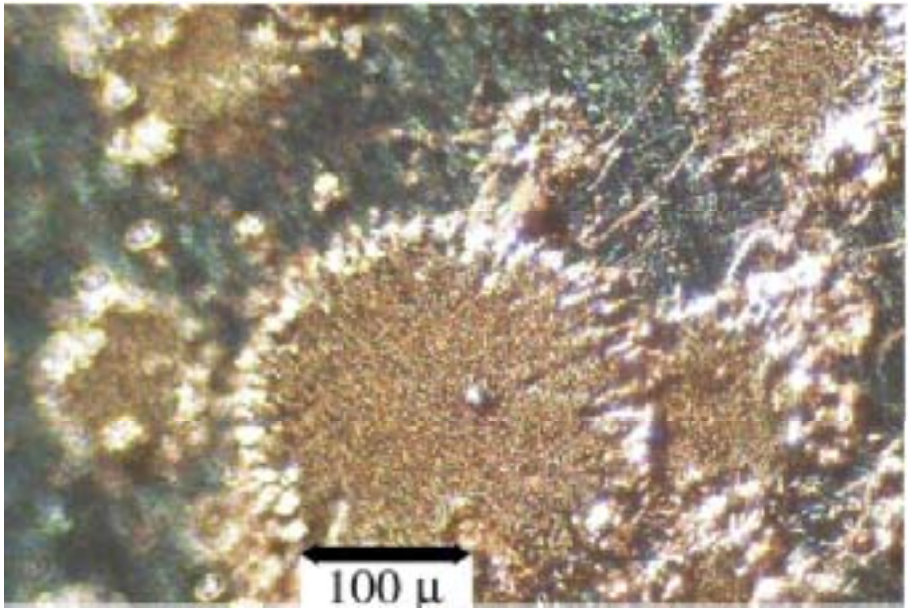


# *Dark Currents*

**Dark currents found to be very large ($\propto E^{10}$) (Norem)**

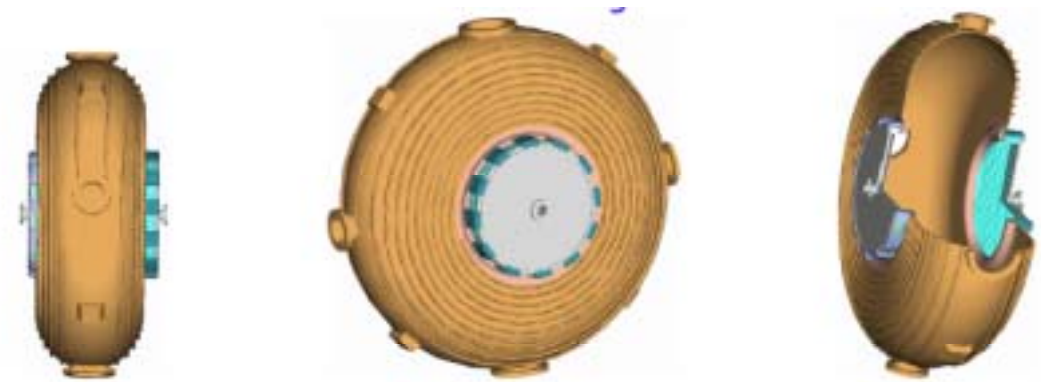
**— copper splashes appear on window when solenoid field present**



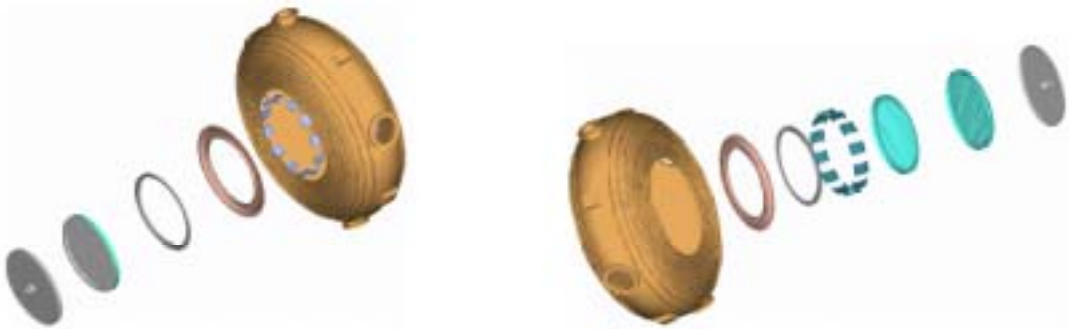



# *205MHZ design*

**201 MHz rf cavity design is well along**



201.25 MHz cavity conceptual design



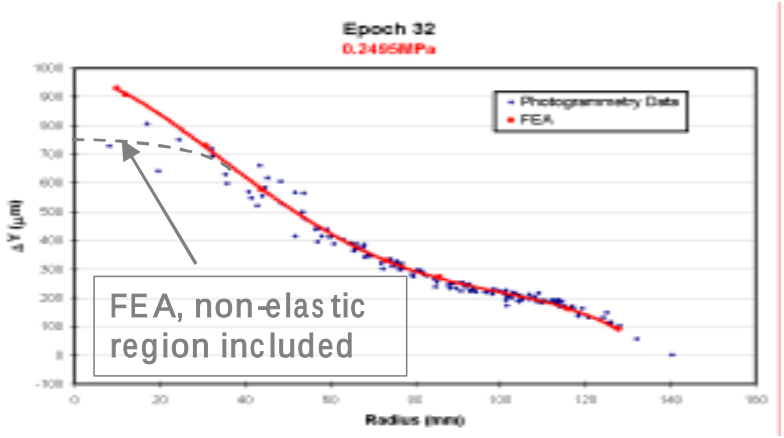
Exploded views showing foil and grid mounting hardware

**— options for either Be windows or grids are available**

# *Absorber Work*

**Absorber work focusing mainly on developing strong, thin windows**

- **windows as thin as 125 μm machined from solid Al**
- **destruction tested at NIU (performance satisfactory)**
  - **125 μm window broke at 44 psi (3 atm), 340 μm window at 120 psi (8 atm)**
- **use photogrammetry to characterize window behavior**
  - **goal is to verify FEA calculations ($LH_2$ safety requirement)**



# *MUCOOL test Area at Fermilab*

**To test hardware, building MUCOOL Test Area at Fermilab**

- **absorber, solenoid, and 201 MHz rf cavity will be integrated here**

**Original area**

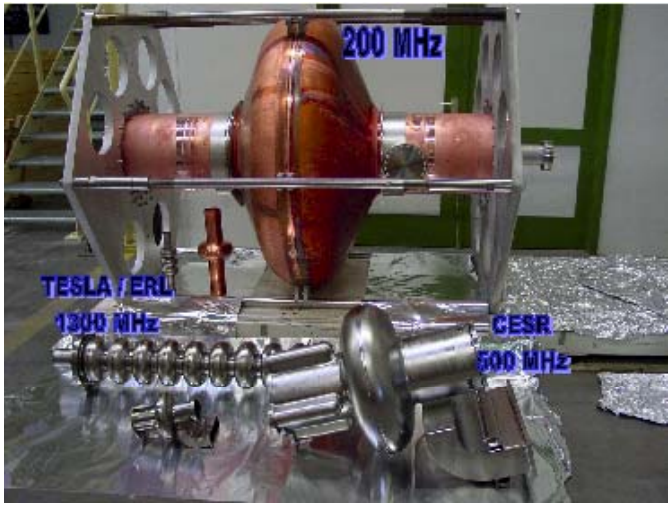
**Stage 2 construction area**

**What it will look like when completed**

# *200MHZ Superconducting R&D*

**Work on 201 MHz SCRF cavity for the acceleration system made good progress (NSF funded)**

- **focusing on achieving gradient, *Q*, mechanical stability**
  - **reached 11 MV/m after re-cleaning cavity**
  - **low-power $Q = 10^{10}$**
- **developing designs for ancillary items (input coupler, HOM coupler, tuner) based on existing experience, e.g., KEKB**



# MICE

**Motivation for MICE**

- **— straightforward physics, but not experimentally demonstrated**
- **— prudence dictates demonstration of key principle for expensive facility, *O*($1B)**

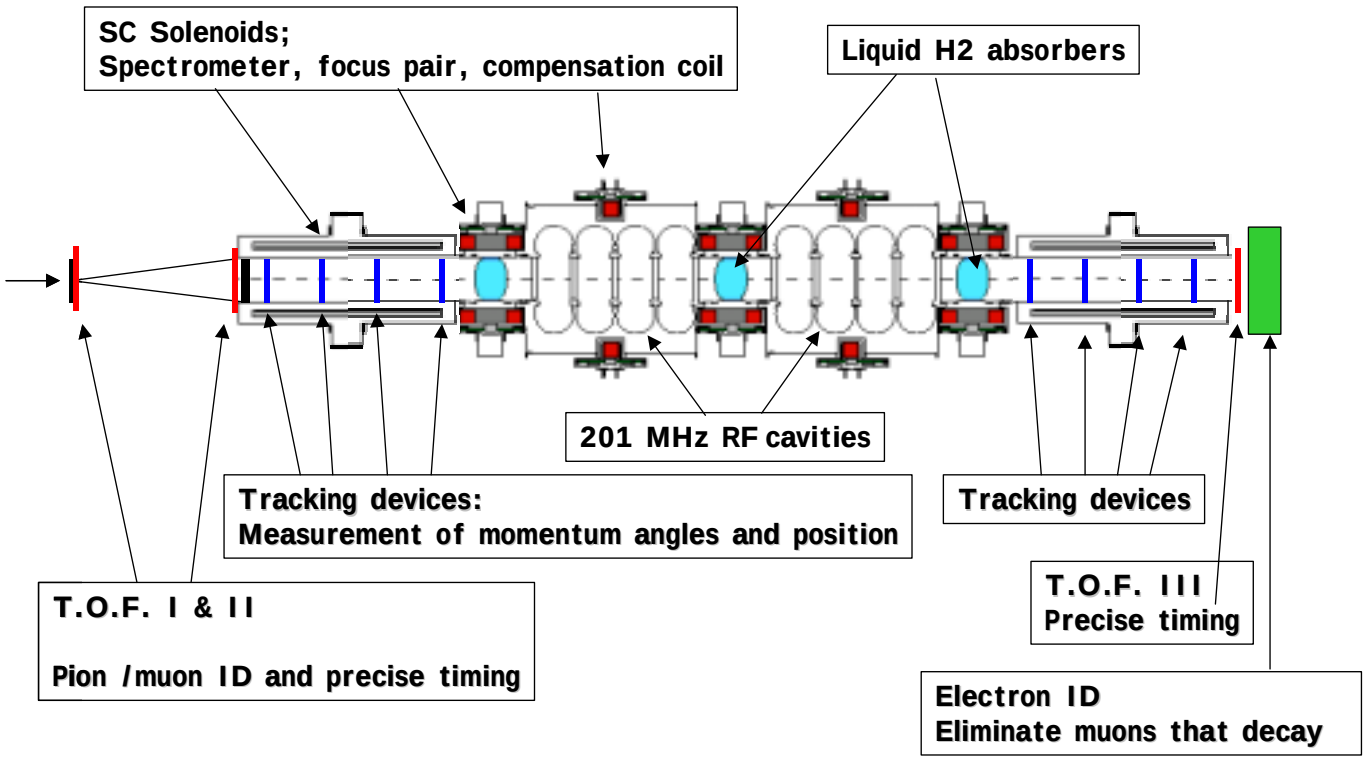
- **MUTAC + MCOG strongly recommended MICE last year (and this year)**
  - **— experiment considered "crucially important demonstration"**
- **MC participating in planning and organization of (international) MICE**

- **Why should we move forward expeditiously?**
  - **— we have a motivated collaboration, an enthusiastic host lab, and a solid experiment design ⇒ the time to begin is now**
  - **— experiment forces us to deal with operational and cost issues early**

# MICE

**Basic ingredients of MICE experiment:**

- **absorbers** to give energy loss ($LH_2$ capable of handling 100–300 W)
- **rf cavities** to restore lost energy (up to 17 MV/m at 201 MHz)
- **solenoid magnets** to contain the muons (up to 5 T)
- **diffuser** to create large emittance sample
- **upstream diagnostics section** to define initial emittance
- **downstream diagnostics section** for final emittance and particle ID



# MICE Anticipated Schedule

— **anticipated schedule (depends on availability of support)**

| | Milestone | Start date |
|---|---|---|
| 1 | Characterization of muon beam | Q1 2004 |
| 2 | Commissioning of spectrometer detectors | Q1 2005 |
| 3 | Commissioning of first spectrometer | Q3 2005 |
| 4 | Commissioning of both spectrometers | Q1 2006 |
| 5 | Measurements with one absorber | Q3 2006 |
| 6 | Measurements with two absorbers and one RF cavity | Q1 2007 |
| 7 | Measurements with the full version of MICE | Q2 2007 |

- **Hardware cost estimate (preliminary)**

| Item | Estimated cost | U.S. | Japan | Europe | UK |
|---|---|---|---|---|---|
| Cooling section | 13.9 | 6.3 | 0.3 | 3.7 | 3.6 |
| Spectrometer section | 7.5 | 2.1 | 0.7 | 3.0 | 1.7 |
| Ancillary items | 3.8 | 0.1 | 0.0 | 0.5 | 3.2 |
| Total | 25.2 | 8.5 | 1.0 | 7.2 | 8.5 |
| | | (34%) | (4%) | (29%) | (34%) |

# *Conclusions*

- The proposed approach is intellectually challenging and will engage the best minds in both Accelerator R&D and HEP.
- It is incremental. One does not need to wait for all the money to be spent before realizing physics.
- It enhances the base program- It IS the base program, due to the staging. Construction the Neutrino factory will not bring other physics to a halt. On the contrary, it causes more physics to be done.