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The U.S. Effort in Neutrino Factories *

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Abstract

We discuss the physics case for a neutrino factory and present the status of the effort in the U.S in making the neutrino factory a reality. We present the results from the two feasibility studies done on the factory and describe the R&D activities in collecting, cooling and accelerating muons. A staged scenario in which a neutrino factory is realized step by step is presented.

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1 Introduction

The concept of colliding muons was first proposed by Budker [1] and by Skrinsky [2] in the 60s and early 70s and the idea of ionization cooling was developed by Skrinsky and Parkhomchuk [3]. The ionization cooling approach was expanded by Neuffer [4] and Palmer [5], which led to the formation of the Muon Collider Collaboration [6, 7] in 1995. With the first evidence for neutrino oscillations from the SuperKamiokande atmospheric data [8], it was realized that a storage ring [9, 10] of muons collected and cooled using concepts developed for the muon collider would act as an intense collimated source of neutrinos which could be used to study neutrino oscillation phenomena in detail. The Collaboration was renamed the Muon Collider and Neutrino Factory Collaboration (MC) in 1998 and became engaged in designing a Neutrino Factory as a first stage towards realizing the Muon Collider.

In the fall of 1999, Fermilab undertook a Feasibility Study ("Study-I") of an entry-level Neutrino Factory [11] and a physics study on the potential of neutrino factories [12]. More recently, Fermilab initiated a study to compare the physics reach of a Neutrino Factory with that of conventional neutrino beams [14] powered by a high intensity proton driver, which are referred to as "superbeams".

Study-I was followed by a Brookhaven National Laboratory-organized follow-on study ("Study-II") [13] on a high-performance Neutrino Factory sited at BNL. Study-II was recently completed. Both study I and study II found that a neutrino factory was feasible, with study II improving on the study I performance and parameters considerably.

2 Physics Case for a Neutrino Factory

We outline briefly the physics case for a neutrino factory. The literature on this is quite extensive, and we touch here only on the salient points. A muon storage ring with a μ^- beam will produce an intense beam of muon neutrinos ν_μ and $\bar{\nu}_e$ at their point of origin. These undergo oscillations into other flavors and detectors placed at a distance from the storage ring will detect a different flavor content in the beam due to oscillations induced by the existence of non-zero mass differences and mixings. Recent data from the SNO detector [15] taken together with SuperK data [8] lend considerable credence to the model in which the three known species of neutrinos ν_e, ν_μ, ν_τ oscillate amongst themselves. The large mixing angle solution (LMA) is favored, though other solutions still cannot be excluded for the mixing matrix.

2.1 Neutrino Oscillation Formalism

We describe here the neutrino oscillation formalism consistent [16] with atmospheric and solar oscillation data. There are three electroweak-doublet neutrinos and the mixing matrix is described by

$$U = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - s_{13}c_{12}c_{23}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix} K' \quad (1)$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, and $K' = diag(1, e^{i\phi_1}, e^{i\phi_2})$. The phases ϕ_1 and ϕ_2 do not affect neutrino oscillations. Thus, in this framework, the neutrino mixing relevant for neutrino oscillations depends on the four angles θ_{12}, θ_{13}, θ_{23}, and δ, and on two independent differences of squared masses, $\delta m^2_{atm.}$, which are $\delta m^2_{32} = m(\nu_3)^2 - m(\nu_2)^2$ in the favored fit, and $\delta m^2_{sol.}$, which may be taken to be $\delta m^2_{21} = m(\nu_2)^2 - m(\nu_1)^2$. In the three-species-oscillation, that includes both matter effects and CP violation, the signs of the δm^2 quantities enter and can be measured.

In the absence of any matter effects, the probability that a weak neutrino eigenstate ν_a becomes ν_b after propagating a distance L is

$$\begin{aligned} P(\nu_a \to \nu_b) &= \delta_{ab} - 4\sum_{i>j=1}^{3} Re(K_{ab,ij}) \sin^2\Big(\frac{\delta m^2_{ij} L}{4E}\Big) + \\ &+ 4\sum_{i>j=1}^{3} Im(K_{ab,ij}) \sin\Big(\frac{\delta m^2_{ij} L}{4E}\Big) \cos\Big(\frac{\delta m^2_{ij} L}{4E}\Big) \end{aligned} \quad (2)$$

where

$$K_{ab,ij} = U_{ai}U^*_{bi}U^*_{aj}U_{bj} \quad (3)$$

and

$$\delta m^2_{ij} = m(\nu_i)^2 - m(\nu_j)^2 \quad (4)$$

In most cases there is only one mass scale relevant for long-baseline neutrino oscillations, $\delta m^2_{atm} \sim$ few $\times 10^{-3}$ eV^2, and one possible neutrino mass spectrum is the hierarchical one

$$\delta m^2_{21} = \delta m^2_{sol} \ll \delta m^2_{31} \approx \delta m^2_{32} = \delta m^2_{atm} \quad (5)$$

With the hierarchy (5), the expressions for the specific oscillation transitions are

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{23}) \cos^4(\theta_{13}) \sin^2\Big(\frac{\delta m^2_{atm} L}{4E}\Big) \quad (6)$$

$$P(\nu_e \to \nu_\mu) \;=\; \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\Big(\frac{\delta m^2_{atm} L}{4E}\Big) \qquad (7)$$

$$P(\nu_e \to \nu_\tau) \;=\; \sin^2(2\theta_{13})\cos^2(\theta_{23})\sin^2\Big(\frac{\delta m^2_{atm} L}{4E}\Big) \qquad (8)$$

Further, the quantity "$\sin^2(2\theta_{atm})$" often used to fit the data on atmospheric neutrinos with a simplified two-species mixing hypothesis, is, in the three-generation case,

$$\sin^2(2\theta_{atm}) \equiv \sin^2(2\theta_{23})\cos^4(\theta_{13}) \qquad (9)$$

The SuperK experiment finds that the best fit to their data is to infer $\nu_\mu \to \nu_\tau$ oscillations with maximal mixing, and hence $\sin^2(2\theta_{23}) = 1$ and $|\theta_{13}| << 1$. The various solutions of the solar neutrino problem involve quite different values of δm^2_{21} and $\sin^2(2\theta_{21})$: (i) large mixing angle solution, LMA: $\delta m^2_{21} \simeq$ few $\times\, 10^{-5}$ eV^2 and $\sin^2(2\theta_{21}) \simeq 0.8$; (ii) small mixing angle solution, SMA: $\delta m^2_{21} \sim 10^{-5}$ and $\sin^2(2\theta_{21}) \sim 10^{-2}$, (iii) LOW: $\delta m^2_{21} \sim 10^{-7}$, $\sin^2(2\theta_{21}) \sim 1$, and (iv) "just-so": $\delta m^2_{21} \sim 10^{-10}$, $\sin^2(2\theta_{21}) \sim 1$. The SuperK experiment favors the LMA solutions [8, 17]

By the time the neutrino factory turns on, $|\delta m^2_{32}|$ and $\sin^2(2\theta_{23})$ would be known at perhaps the 20 % level. The neutrino factory will significantly improve precision in these parameters, as can be seen from figure 1 which shows the error ellipses possible for a 30 GeV muon storage ring. It is possible to adjust the energy of the stored beam in the neutrino factory to give the maximum precision for a detector at a given baseline, once the parameters are known to 20%.

2.2 Matter effects

With a neutrino factory, the distances at which one can place detectors are large enough so that for the first time matter effects [18] can be exploited in accelerator-based oscillation experiments. The matter effects are the matter-induced oscillations which neutrinos undergo along their flight path through the Earth from the source to the detector. Given the typical density of the earth, matter effects are important for the neutrino energy range $E \sim O(10)$ GeV and $\delta m^2_{32} \sim 10^{-3}$ eV^2, values relevant for the long baseline experiments. Depending on the value of $\sin^2 2\theta_{13}$, it should be possible to observe the appearance of wrong-sign muons due to the oscillation $\nu_e \to \nu_\mu$ with a stored μ^+ beam and the charge conjugate channel with a stored μ^- beam. For a positive sign δm^2_{32} a resonant enhancement will be seen for a μ^+ stored beam and for a negative sign for a μ^- stored beam.

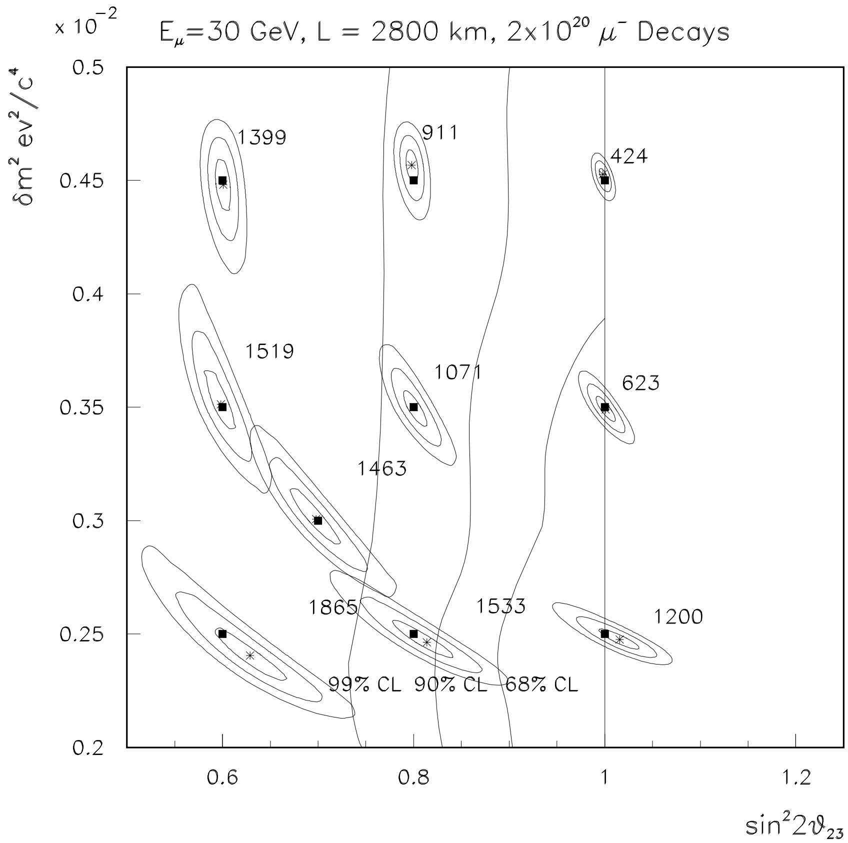

Figure 1: *Fit to muon neutrino survival distribution for $E_\mu = 30$ GeV and $L =$ 2800 km for 10 pairs of $\sin^2 2\theta$, δm^2 values. For each fit, the 1σ, 2σ and 3σ contours are shown. The generated points are indicated by the dark rectangles and the fitted values by stars. The SuperK 68%, 90%, and 99% confidence levels are superimposed. Each point is labelled by the predicted number of signal events for that point.*

Figure 2 [19] shows the wrong-sign muon appearance spectra as function of δm^2_{32} for both μ^+ and μ^- beams for both signs of δm^2_{32} at a baseline of 2800 km. The resonance enhancement in wrong sign muon production is clearly seen in Fig. 2 (b) and (c).

By comparing these (using first a stored μ^+ beam and then a stored μ^- beam) one can determine the sign of δm^2_{32} as well as the value of $\sin^2(2\theta_{13})$. Figure 3 [19] shows the difference in negative log-likelihood between a correct and wrong-sign mass hypothesis expressed as a number of equivalent Gaussian standard deviations versus baseline length for muon storage ring energies of 20, 30, 40 and 50 GeV. The values of the oscillation parameters are for the LMA scenario with

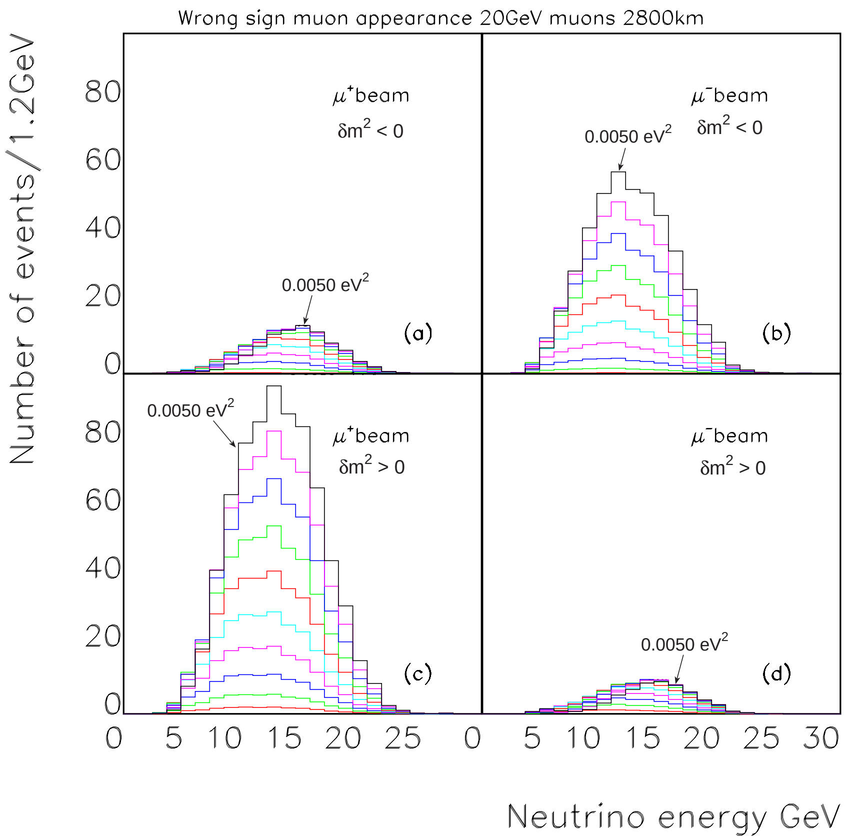

Figure 2: *The wrong sign muon appearance rates for a 20 GeV muon storage ring at a baseline of 2800 km with 10^{20} decays and a 50 kiloton detector for (a) μ^+ stored and negative δm^2_{32}, (b) μ^- stored and negative δm^2_{32}, (c) μ^+ stored and positive δm^2_{32}, (d) μ^- stored and positive δm^2_{32}. The values of $|\delta m^2_{32}|$ range from 0.0005 to 0.0050 eV^2 in steps of 0.0005 eV^2. Matter enhancements are evident in (b) and (c).*

$\sin^2 2\theta_{13} = 0.04$. Figure 3(a) is for 10^{20} decays for each sign of stored energy and a 50 kiloton detector and positive δm^2_{32} , (b) is for negative δm^2_{32} for various values of stored muon energy. Figures 3 (c) and (d) show the corresponding curves for 10^{19} decays and a 50 kiloton detector. An entry-level machine would permit one to perform a 5σ differentiation of the sign of δm^2_{32} at a baseline length of $\sim$2800 km if $\sin^2 2\theta_{13} = 0.04$ or greater.

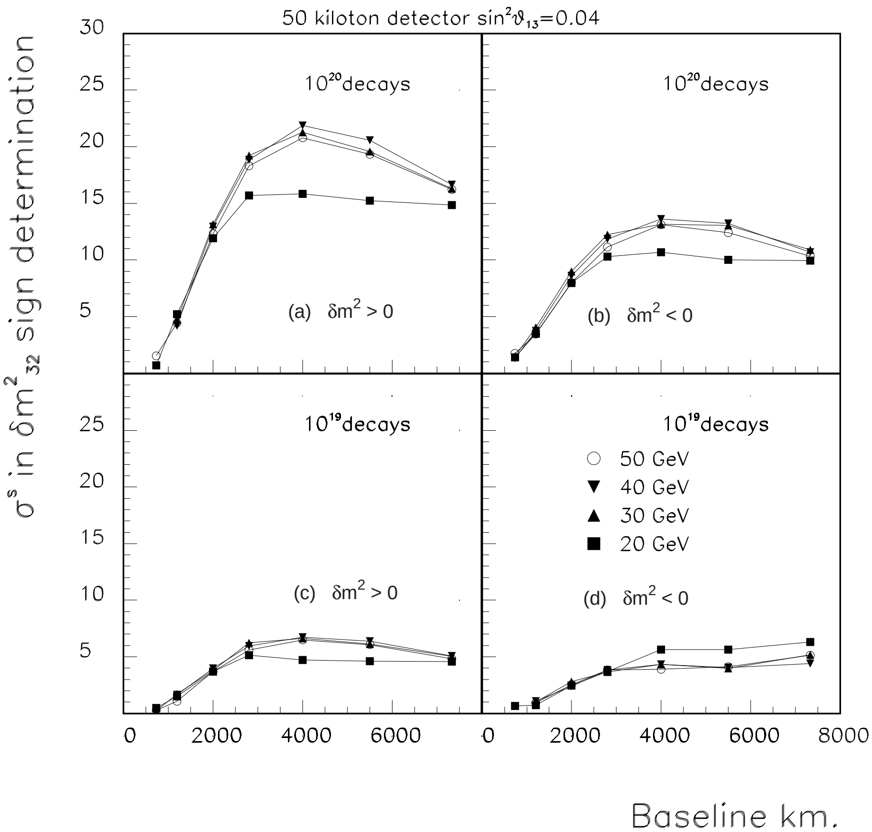

Figure 3: *The statistical significance (number of standard deviations) with which the sign of δm^2_{32} can be determined versus baseline length for various muon storage ring energies. The results are shown for a 50 kiloton detector, and (a) 10^{20} μ^+ and μ^- decays and positive values of δm^2_{32}; (b) 10^{20} μ^+ and μ^- decays and negative values of δm^2_{32}; (c) 10^{19} μ^+ and μ^- decays and positive values of δm^2_{32}; (d) 10^{19} μ^+ and μ^- decays and negative values of δm^2_{32}.*

2.3 CP Violation

CP violation is proportional to the Jarlskog invariant

$$J = \frac{1}{8}\sin(2\theta_{12})\sin(2\theta_{13})\cos(\theta_{13})\sin(2\theta_{23})\sin\delta \tag{10}$$

A promising asymmetry to measure is $P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e - \bar{\nu}_\mu)$. In the absence of matter effects,

$$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu) = -16J\sin\phi_{32}\sin\phi_{13}\sin\phi_{21} \tag{11}$$

where

$$\phi_{ij} = \frac{\delta m^2_{ij} L}{4E} \tag{12}$$

The Neutrino Factory provides an ideal set of controls to measure CP violation effects since we can fill the storage ring with both μ^+ and μ^- particles and measure the ratio of the number of events $\overline{\nu}_e \rightarrow \overline{\nu}_\mu / \nu_e \rightarrow \nu_\mu$. Figure 4 shows this ratio for a Neutrino Factory with 10^{21} decays and a 50 kilo-ton detector as a function of the baseline length. The ratio depends on the sign of δm^2_{32}. The shaded band around either curve shows the variation of this ratio as a function of the CP violating phase δ. The number of decays needed to produce the error bars shown is directly proportional to $sin^2\theta_{13}$, which for the present example is set to 0.004. Depending on the magnitude of J, one may be driven to build a Neutrino Factory just to understand CP violation in the lepton sector, which could have a significant role in explaining the baryon asymmetry of the Universe [21].

3 Neutrino Factory Parameters

The Muon Collaboration conducted two studies, Study I [11] which worked out the parameters for a 50 GeV muon storage ring sited at Fermilab. This was followed by Study II [13] which was for a 20 GeV muon storage ring with $\approx$ 10 times the number of stored muons than study I, for a Megawatt of protons on target. Study II examined the feasibility of siting such a Neutrino Factory at Brookhaven National Laboratory. A summary of the two studies can be found in [22]. Here we summarize a Neutrino Factory design as of Study II. A schematic of the layout is shown in Fig. 5.

3.1 Proton Driver

The proton driver considered in Study-II uses the existing BNL Alternating Gradient Synchrotron (AGS) and upgrades it to 1 Megawatt of beam power. The existing booster is replaced by a 1.2-GeV superconducting proton linac. and the AGS repetition rate is increased from 0.5 Hz to 2.5 Hz. A possible future upgrade to 2×10^{14} ppp and 5 Hz could give an average beam power of 4 MW. At the higher intensity, a superconducting bunch compressor ring would be needed to maintain the rms bunch length at 3 ns.

The Fermilab option consists of a newly constructed 16-GeV rapid cycling booster synchrotron [23]. The initial beam power would be 1.2 MW, and a future upgrade to 4 MW is possible. The design parameters for both BNL and FNAL options are included in Table 1. A less ambitious and more cost-effective 8-GeV proton driver option has also been considered for FNAL [23].

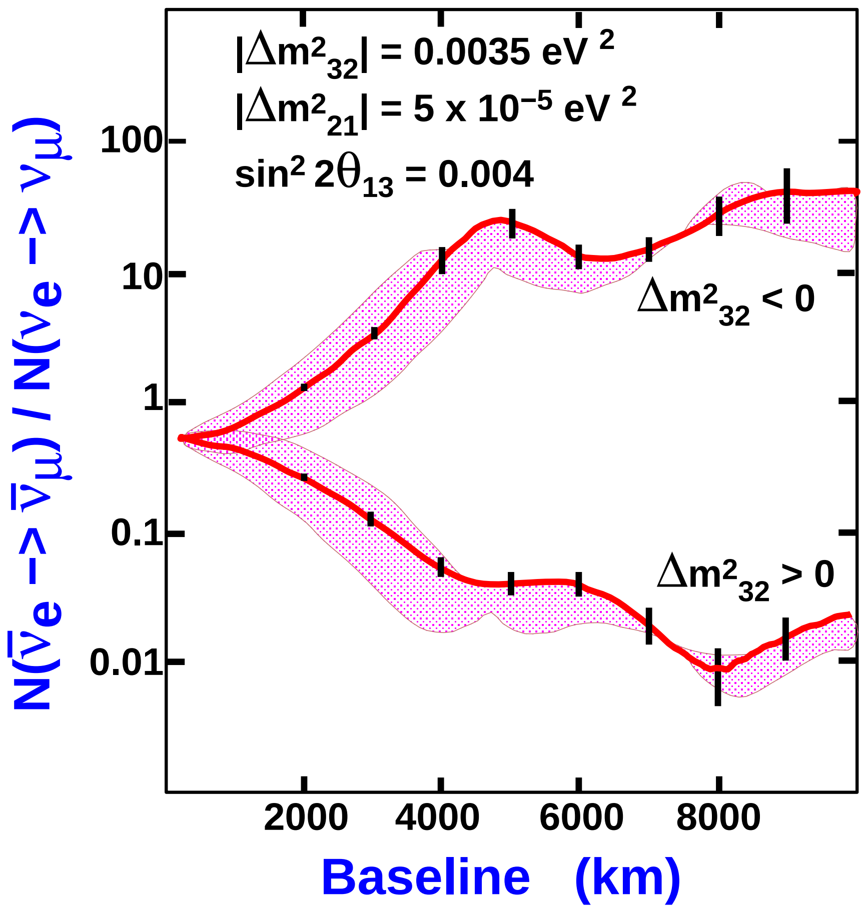

Figure 4: *Predicted ratios of wrong-sign muon event rates when positive and negative muons are stored in a 20 GeV neutrino factory, shown as a function of baseline. A muon measurement threshold of 4 GeV is assumed. The lower and upper bands correspond respectively to negatve and positive δm^2_{32}. The widths of the bands show how the predictions vary as the CP violating phase δ is varied from $-\pi/2$ to $\pi/2$, with the thick lines showing the predictions for δ=0. The statistical error bars correspond to a high-performance neutrino factory yielding a data sample of 10^{21} decays with a 50 kiloton detector. Figure is based on calculations presented in* [20]

3.2 Collecting and cooling muons

In Study II, a mercury jet target of the type shown in figure 6 is used to produce pions. A pool of mercury serves as the beam dump. Pions from the target are captured and focused in the decay channel by a solenoidal field of 20 T at the target center that changes over 18 m to a periodic (0.5m) superconducting solenoidal channel (1.25 T) that continues through the phase rotation system to the start of bunching. In Study -I a solid carbon target was considered. The pions and the decay muons are generated over a wide range of energies but in a short pulse of 1-3

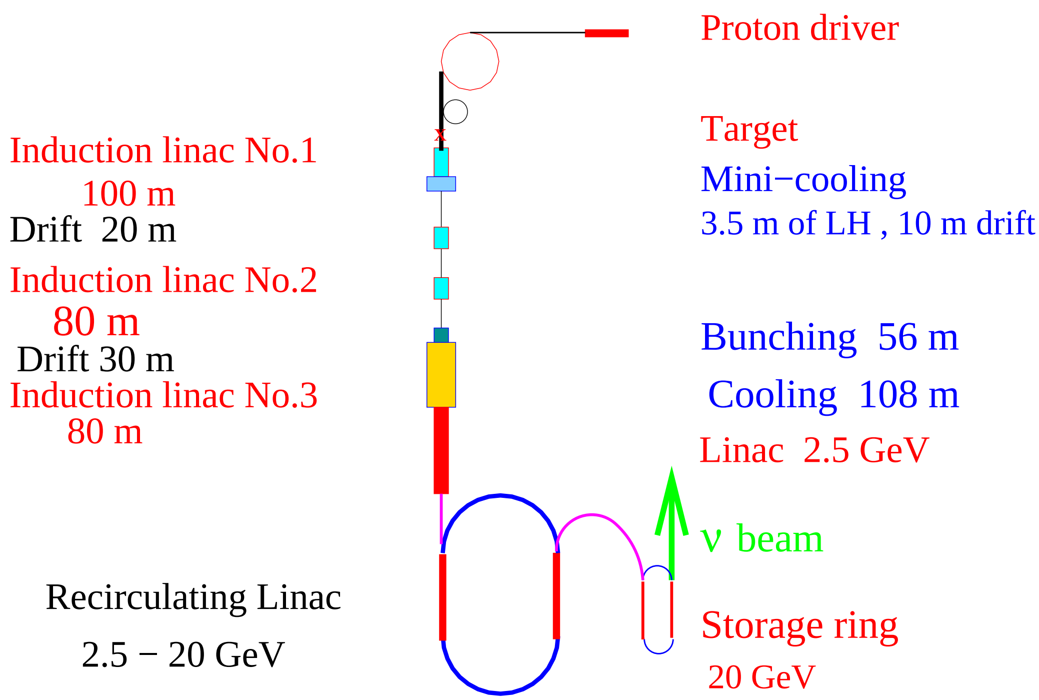

Figure 5: *Schematic of the neutrino factory-Study II version.*

ns wide. The muons first drift and spread out in time after which the induction linacs in the phase rotation system decelerate the early ones and accelerate the later ones. Three induction linacs (with lengths 100,80 and 80 m) are used to produce the phase-rotated bunch.

The cooling channel consists of liquid hydrogen absorbers that remove energy from the muon bunch. Both transverse and longitudinal momentum are reduced in the absorbers. The longitudinal momentum is replaced by 200 MHz rf cavities, which results in a reduction in transverse emittance of the beam. The beam is maintained in a focused state by solenoidal fields of alternating sign [24]. The absorbers are placed at locations where the beam size is smallest and beam divergence greatest so as to reduce the effects of multiple scattering on the beam. Figure 7 shows the transverse and longitudinal emittances of the beam as a function of channel length.Transverse cooling is is evident whereas the longitudinal emittance of the beam will eventually increase, due to straggling.

Table 1: Proton driver parameters for BNL and FNAL designs.

	BNL	FNAL
Total beam power (MW)	1	1.2
Beam energy (GeV)	24	16
Average beam current (μA)	42	72
Cycle time (ms)	400	67
Number of protons per fill	1×10^{14}	3×10^{13}
Average circulating current (A)	6	2
No. of bunches per fill	6	18
No. of protons per bunch	1.7×10^{13}	1.7×10^{12}
Time between extracted bunches (ms)	20	0.13
Bunch length at extraction, rms (ns)	3	1

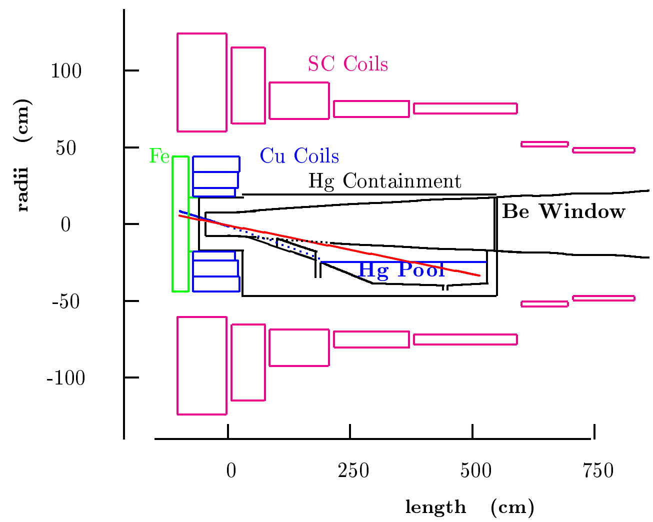

Figure 6: *Target, capture solenoids and mercury containment.*

3.3 Accelerating and storing muons

After the cooling section, the cooled muons (transverse emittance reduced by a factor of ≈ 100) are accelerated to 20 (50)GeV energy in Study II (Study I) using a system of recirculating linacs [11, 13]. The accelerated muon bunch is stored in a muon storage ring with long straight sections pointing towards detectors placed at baselines of typical length 3000 km. Approximately 30 % of the muons decay in the straight section pointing towards a far detector. Half the muons decay after

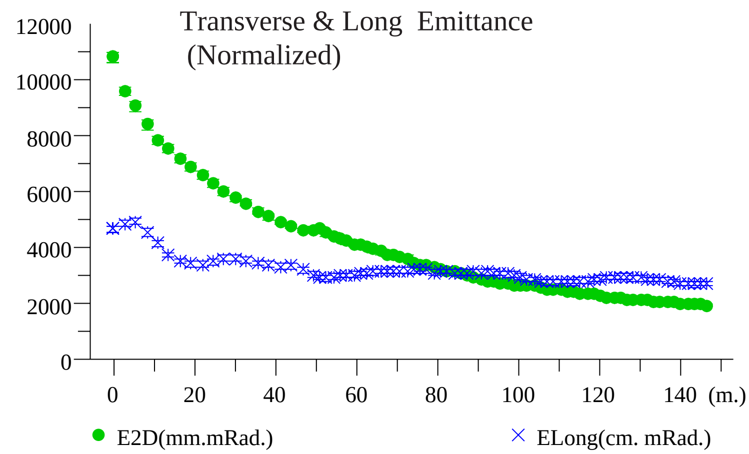

Figure 7: *The longitudinal and transverse emittances, obtained with the Geant4 simulation code, as a function of channel length. The last lattice (2,3) was extended by ≈20 m to investigate the ultimate performance of the cooling channel.*

circulating ≈ 100 turns.

4 Status of R&D Efforts

A Neutrino Factory consists of the following systems: Proton Driver, Target and (Pion) Capture Section, (Pion-to-Muon) Decay and Phase Rotation Section, Bunching and Matching Section, Cooling Section, Acceleration Section, and Storage Ring. The R&D program outlined here is designed to answer the key questions needed to embark upon a Zero'th order Design Report (ZDR) after three years. After completion of the full five-year program, it is expected that a formal Conceptual Design Report (CDR) can be realized. This set of R&D goals will also benefit the Muon Collider, since there is a significant degree of commonality between the Neutrino Factory and the Muon Collider in the Collection, Cooling and Acceleration phases.

A brief summary of the key physics and technology issues for each major system is given below.

Proton Driver

- Production of intense, short proton bunches, e.g., with space-charge compensation and/or high-gradient, low frequency rf systems

Target and Capture Section

- Optimization of target material (low-Z or high-Z) and form (solid, moving band, liquid-metal jet)
- Design and performance of a high-field solenoid ($\approx$20 T) in a very high radiation environment

Decay and Phase Rotation Section

- Development of high-gradient induction linac modules having an internal superconducting solenoid channel

Bunching and Matching Section

- Design of efficient bunching system

Cooling Section

- Development and testing of high-gradient normal conducting rf (NCRF) cavities at a frequency near 200 MHz
- Development and testing of efficient high-power rf sources at a frequency near 200 MHz
- Development and testing of LH_2 absorbers for muon cooling
- Development and testing of candidate diagnostics to measure emittance and optimize cooling channel performance
- Design of beamline and test setup (e.g., diagnostics) needed for demonstration of transverse emittance cooling
- Development of six-dimensional analytical theory to guide the design of the cooling section

Acceleration Section

- Optimization of acceleration techniques to increase the energy of a muon beam (with a large momentum spread) from a few GeV to a few tens of GeV (e.g., recirculating linacs, rapid cycling synchrotrons, FFAG rings) for a Neutrino Factory, or even higher for a Muon Collider

- Development of high-gradient superconducting rf (SCRF) cavities at frequencies near 200 MHz, along with efficient power sources (about 10 MW peak) to drive them
- Design and testing of components (rf cavities, magnets, diagnostics) that will operate in the muon-decay radiation environment

Storage Ring

- Design of large-aperture, well-shielded superconducting magnets that will operate in the muon-decay radiation environment

Detector

- Simulation studies to define acceptable approaches for both near and far detectors at a Neutrino Factory and for a collider detector operating in a high-background environment
- Develop ability to measure the sign of electrons in the Neutrino Factory detectors

5 A Staged Scenario for Realizing a Neutrino Factory

The attraction of a Neutrino Factory lies in the fact that it can be realized in stages each of which costs less than $1B. New physics opportunities are opened up at the end of each stage. The five stages we envisage in the development of a Neutrino Factory and Muon collider are:

Stage 1: $250–330M (1 MW) or $330–410M (4 MW)

This consists of a Proton Driver and a Target Facility. The Driver could have a 1 MW beam level or be designed from the outset to reach 4 MW. The Target Facility is built initially to accommodate a 4 MW beam. A 1 MW beam would provide about 1.2×10^{14} μ/s (1.2×10^{21} μ/year) and a 4 MW beam about 5×10^{14} μ/s (5×10^{21} μ/year) into a solenoid channel. Using this driver conventional neutrino beams can be upgraded ("superbeams") to measure the neutrino oscillation parameters with increased precision.

Stage 2: $660–840M

This stage would produce a muon beam that has been phase rotated and transversely cooled with a central momentum of about 200 MeV/c, a transverse (normalized) emittance of 2.7 mm-rad and an rms energy spread of about 4.5%. The intensity of the beam would be about 4×10^{13} μ/s (4×10^{20} μ/year) at 1 MW, or 1.7×10^{14} μ/s (1.7×10^{21} μ/year) at 4 MW. The *incremental* cost of this option is $840M, based on the cooling channel length adopted in Study-II.

Stage 3: $220–250M

A pre-acceleration Linac would be used to raise the beam energy to roughly 2.5 GeV. The incremental cost of this option is about $220M. At this juncture, it may be appropriate to consider a small storage ring, comparable to the $g-2$ ring at BNL, to be used, perhaps, for the next round of muon $g-2$ experiments. Electric dipole moment of the muon could be measured in a ring of smaller energy.

Stage 4: $550M (20 GeV) or $1250–1350M (50 GeV)

This would produce the world's first Neutrino Factory. For a 20 GeV beam energy, the incremental cost of this stage, which includes the RLA and the storage ring, is $550M. If it were necessary to provide a 50 GeV muon beam for physics reasons, an additional RLA and a larger storage ring would be needed. The incremental cost would then increase by $700–800M.

Stage 5

This would produce an entry-level Muon Collider to operate as a Higgs Factory. No cost estimate has yet been prepared for this stage. The emittance exchange muon cooling problem has to be solved for this stage to become a reality.

6 Conclusions

We have described the present state of work in the U.S. to build Neutrino Factories. The physics motivating us in this direction has been outlined. A staged scenario for achieving the neutrino factory has been described, the first stage of which would be an intense proton source, also known as a proton driver. The attraction of the stged approach is the physics is available after each stage, each costing less the $1B. The physics case for studying neutrino oscillations has become compelling, especially after the recent results from the SNO collaboration. Results expected in the immediate future from SNO and KamLand collaborations are likely to make this case even stronger and should lead to the construction of a neutrino factory before the end of the decade.

7 Acknowledgements

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