Neutrino Factory: Physics and R&D Status

S. Geer, Fermilab

1. Introduction

In recent years exciting experimental discoveries have shown that neutrino flavors oscillate, and hence that neutrinos have nonzero masses and mixings. The Standard Model needs to be modified to accommodate neutrino mass terms, which require either the existence of right-handed neutrinos to create Dirac mass terms, and/or a violation of lepton number conservation to create Majorana mass terms. The observation that neutrino masses and mass-splittings are tiny compared to the masses of any of the other fundamental fermions suggests radically new physics, which perhaps originates at the GUT or Planck Scale, or perhaps indicates the existence of new spatial dimensions. Whatever the origin of the observed neutrino masses and mixings is, it will certainly require a profound extension to our picture of the physical world. The first step towards understanding this new physics is to pin down the measurable parameters, and address the first round of basic questions:

Are there only three neutrino flavors, or do light sterile neutrinos exist? Are there any other deviations to three-flavor mixing?

There is one angle θ_{13} in the mixing matrix which is unmeasured. Is it non-zero?

We don't know the mass-ordering of the neutrino mass eigenstates. There are two possibilities, the so-called "normal" or "inverted" hierarchies. Which is right?

There is one complex phase δ in the mixing matrix which is accessible to neutrino oscillation measurements. If both θ_{13} and $\sin\delta$ are non-zero there will be CP Violation in the lepton sector. Is $\sin\delta$ non-zero ?

What precisely is the value of the lightest neutrino mass and are neutrino masses generated by Majorana mass terms, Dirac mass terms, or both ?

All of these questions, with the exception of the last one, can in principle be addressed by accelerator-based neutrino oscillation experiments. However, getting all of the answers will not be easy, and will require the right experimental tools. A Neutrino Factory appears to be the ultimate tool for probing neutrino oscillations. Hence the interest in this new type of neutrino source.

2. The Neutrino Factory

New accelerator technologies offer the possibility of building, not too many years in the future, an accelerator complex to produce and capture more than 10^{20} muons per year. It has been proposed to build a *Neutrino Factory* [1,2] by accelerating the muons from this intense source to energies of several GeV, injecting the muons into a storage ring having long straight sections, and exploiting the intense neutrino beams that are produced by muons decaying in the straight sections. The decays: $\mu^- \rightarrow e^- \nu_\mu$ anti-ν_e & $\mu^+ \rightarrow e^+$ anti-ν_μ ν_e offer exciting possibilities to pursue the study of neutrino oscillations and neutrino interactions with exquisite precision.

To create a sufficiently intense muon source, a Neutrino Factory requires an intense multi-GeV proton source capable of producing a primary proton beam with a beam power of 1~MW or more on target. This is just the proton source required in the medium term for Neutrino Superbeams. Hence, there is a natural evolution from Superbeam experiments to Neutrino Factory experiments.

Neutrino Factory designs have been proposed in Europe [3], the US [4], and Japan [5]. Of the three designs, the one in the US is the most developed, and we will use it as a first example. The Neutrino Factory consists of the following subsystems:

i) **Proton Driver**. Provides 1-4 MW of protons on a pion production target.
ii) **Target , Capture and Decay**. A high-power target sits within a 20T superconducting solenoid, which captures the pions. The high magnetic field smoothly decreases to 1.75T downstream of the target, matching into a long solenoid decay channel.
iii) **Bunching and Phase Rotation**. The muons from the decaying pions are bunched using a system of rf cavities with frequencies that vary along the channel. A second series of rf cavities with higher gradients is used to rotate the beam in longitudinal phase-space, reducing the energy spread of the muons.
iv) **Cooling.** A solenoid focusing channel with high-gradient 201 MHz rf cavities and either liquid-hydrogen or LiH absorbers is used to

reduce the transverse phase-space occupied by the beam. The muons lose, by dE/dx losses, both longitudinal- and transverse-momentum as they pass through the absorbers. The longitudinal momentum is replaced by re-acceleration in the rf cavities.

v) **Acceleration.** The central momentum of the muons exiting the cooling channel is 220 MeV/c. A superconducting linac with solenoid focusing is used to raise the energy to 1.5 GeV. Thereafter, a Recirculating Linear Accelerator raises the energy to 5 GeV, and a pair of Fixed-Field Alternating Gradient rings using quadrupole triplet focusing accelerate the beam to 20 GeV.

vi) **Storage Ring**. A compact racetrack geometry ring is used in which 35% of the muons decay in the neutrino beam-forming straight section.

This scheme produces of order 2×10^{20} useful muon decays per operational year. The European Neutrino Factory design is similar in general to the US design, but differs in the technologies chosen to implement some of the subsystems. The Japanese design is very different, and uses very large acceptance accelerators rather than a system that reduces the phase-space occupied by the muons so they fit within the more limited acceptance of a more normal acceleration scheme.

3. Neutrino Factory Physics Program

Neutrino factories are attractive because, when compared with conventional neutrino beams, they yield higher signal rates with lower background fractions and lower systematic uncertainties. These characteristics enable neutrino factory experiments to be sensitive to values of θ_{13} that are beyond the reach of any other approach. Detailed studies [6] (see Fig. 1) have shown that a non-zero value of $\sin^2 2\theta_{13}$ could be measured for values as small as $O(10^{-4})$. In addition, both the neutrino mass hierarchy and CP violation in the lepton sector could be measured over this entire range. Even if $\theta_{13} = 0$ the probability for $\nu_e \leftrightarrow \nu_\mu$ oscillations in a long-baseline experiment is finite, and a Neutrino Factory would still make the first observation of $\nu_e \leftrightarrow \nu_\mu$ transitions in an appearance experiment, and put a sufficiently stringent limit on the magnitude of θ_{13} to suggest perhaps the presence of a new conservation law. The great strength of Neutrino Factories is that they provide a new sort of neutrino beam containing both electron-type neutrinos and

muon-type neutrinos. The experimental data samples can be divided into sub-samples tagged by the presence of (i) a "right-sign" muon, (ii) a "wrong-sign" muon, (iii) an electron or positron (assuming the charge cannot be measured), (iv) a positive tau-lepton, (v) a negative tau-lepton, or (vi) the absence of any lepton. The measurements can be made with positive muons stored in the Neutrino Factory, and with negative muons stored. Thus, there are 12 measured differential spectra that can be simultaneously fit to obtain the oscillation parameters. This provides neutrino factory experiments with a wealth of measurements that, in addition to offering exquisite precision, also offer the flexibility to exploit surprises that may turn up along the way.
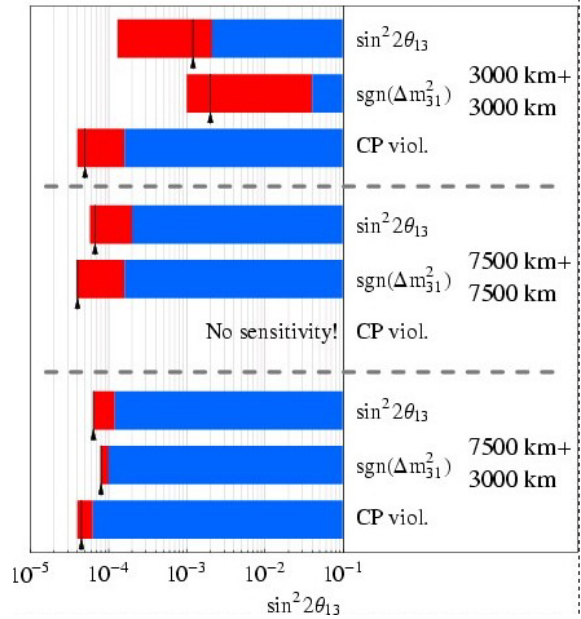

Figure 1: The sensitivity reaches as functions of $\sin^2 2\theta_{13}$ for $\sin^2 2\theta_{13}$ itself, the neutrino mass hierarchy, and maximal CP Violation ($\delta_{CP} = \pi/2$) for each of the indicated baseline combinations. The bars show the ranges in $\sin^2 2\theta_{13}$ where sensitivity to the corresponding quantity can be achieved at the 3σ CL. The dark (red) bars show the variation in the result as Δm^2_{21} is varied within its present uncertainty. Figure from Ref. [6].

4. Neutrino Factory R&D

An impressive Neutrino Factory R&D effort has been ongoing in Europe, Japan, and the U.S. over the last few years, and significant progress has been made towards optimizing the design, developing and

testing the required accelerator components, and significantly reducing the cost. To illustrate progress in cost reduction, the cost estimate for a recent update of the US design [7] is compared in Table 1 with the corresponding cost for the previous "Study II" US design. It should be noted that the Study II design cost was based on a significant amount of engineering input to ensure design feasibility and establish a good cost basis. This engineering step has not yet been done for the updated design, but the new cost estimate is based on experience from the Study II work. The conclusion is that the latest design ideas are expected to lead to very significant cost reductions, although more work must be done to establish a reliable new cost estimate.

Table 1: Comparison of unloaded Neutrino Factory costs estimates for the US Study II design and for the latest updated US design. Costs are shown including or not including the Proton Driver and Target station in the estimates. The New design cost estimate has not yet benefited from the level of engineering effort included in the Study II work. Table from Ref. [7].

	All (M$)	No PD (M$)	No PD & No Target (M$)
Study II	1832	1641	1538
New / Study II (%)	67	63	60

Neutrino Factory R&D has reached a critical stage in which support is required for two key international experiments (MICE and Targetry) and a third-generation international design study. If this support is forthcoming, a Neutrino Factory could be added to the Neutrino Physics roadmap in about a decade.

5. Prospects

The scientific case for pursuing Neutrino Factory R&D is strong. The encouraging technical progress in Neutrino Factory R&D over the last few years has been matched by progress in building the level of international collaboration needed for the next step, and preparing proposals for the critical R&D experiments. All of this has been accomplished with very limited funding. The next steps require an increase in funding, but to a level which is still modest considering the nature of the enterprise. If a Neutrino Factory is to remain a viable option for the future it is important that MICE, the Targetry experiment, and a third-generation international

design study are supported. If this is the case, we have much to look forward to.

References

[1] S. Geer, Phys. Rev. D57, 6989 (1998);
[2] A. De Rujula, M.B. Gavela, P. Hernandez, Nucl. Phys. **B547**:21-38,1999.
[3] B. Autin, A. Blondel, J. Ellis (Eds.), CERN yellow report 99-02.
[4] M.M. Alsharo'a et al., Phys. Rev. ST Accel. Bemas 6, 081001 (2003).
[5] NufactJ Working Group (Eds. Y. Kuno and Y. Mori) "A Feasibility Study of a Neutrino Factory in Japan", see
http://www-prism.kek.jp/nufactj/index.html
[6] P. Huber and W. Winter; Phys. Rev. **D68**, 037301(2003); hep/ph-0301257.
[7] *Neutrino Factory and Beta Beam Experiments and Developments*, (Eds. S. Geer and M. Zisman), Report of the Neutrino Factory and Beta Beam Working Group, APS Multi-Divisional Study of the Physics of Neutrinos, July 2004.