

INTERNATIONAL DESIGN STUDY OF A NEUTRINO FACTORY*

J. Scott Berg; Brookhaven National Laboratory; UPTON, NY 11973-5000; USA

Abstract

By providing an extremely intense source of neutrinos from the decays of muons in a storage ring, a neutrino factory will provide the opportunity for precision measurements and searches for new physics amongst neutrino interactions. An active international collaboration is addressing the many technical challenges that must be met before the design for a neutrino factory can be finalized. An overview of the accelerator complex and the current international R&D program will be presented, and the key technical issues will be discussed.

INTRODUCTION

Experiments have demonstrated that neutrinos have non-zero masses, and that the neutrino flavor eigenstates are different from their mass eigenstates (see [1] for a recent review). The clearest manifestation of this is in “neutrino oscillations”: neutrinos produced as one flavor (electron, muon, or tau) are detected as having a different flavor. This is the sole evidence of physics beyond the Standard Model of particle physics. A minimal model for the behavior of neutrinos is parametrized by two mass squared differences Δm_{21}^2 and Δm_{31}^2 (really three masses, but only the mass squared differences can be measured in experiments discussed here), three mixing angles θ_{12} , θ_{23} , and θ_{13} , and a CP-violating phase δ (ignoring Majorana phases). If θ_{13} were zero, then there would be no CP violation and δ would be irrelevant.

A neutrino factory is an accelerator complex for studying neutrino physics. A neutrino factory accelerates a beam of muons to high energy and allows them to decay in a decay ring with long straight sections. The decay ring is tilted downward so that the resulting neutrino beam will hit a detector several thousand km away. The neutrino spectrum is well-defined, and contains both ν_μ and $\bar{\nu}_e$ (for the decay of μ^+). The detector distinguishes between the products of these source neutrinos by determining the sign of the produced leptons.

Currently $\sin^2 \theta_{13}$ has only an upper bound of 0.053 at 3σ [2]. Of existing and proposed experiments, a neutrino factory has sensitivity to the smallest values of θ_{13} [1]. Furthermore, should θ_{13} be found to be non-zero, a neutrino factory can obtain the most precise values for the mixing parameters over much of the parameter range [1, 3].

Getting this muon beam into the decay ring requires a number of subsystems (see Fig. 1). One begins with a high-power proton accelerator (the “proton driver”), producing

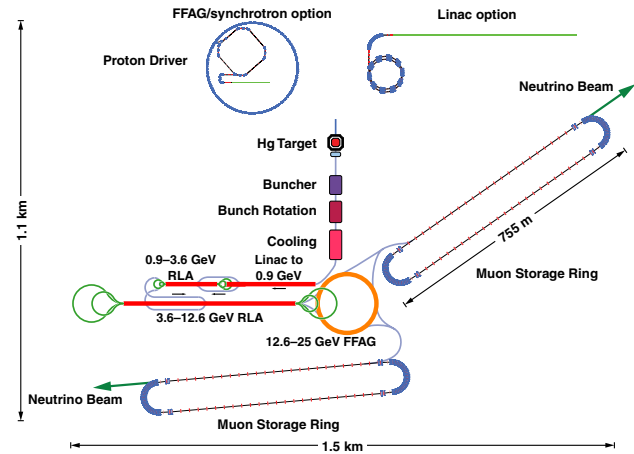


Figure 1: The accelerator facilities for the neutrino factory.

an intense pulsed proton beam that hits a target. Pions are produced in that target, and a system of solenoids maximizes the number of these pions within a useful energy range that are captured in the forward direction. The pions decay into muons, which have a large energy spread. That muon beam is manipulated into a train of muon bunches which have a reduced energy spread. The transverse emittance of this beam is reduced through ionization cooling, then the resulting muon beam is accelerated to the final energy through a number of stages.

The International Scoping Study of a Future Neutrino Factory and Superbeam Facility produced a design for an accelerator facility [4] which served as a starting point for the International Design Study of the Neutrino Factory (IDS-NF). The IDS-NF will complete an intermediate design report (IDR) at the end of 2010, and a reference design report (RDR) at the end of 2012. This paper describes recent progress in studies of the neutrino factory accelerator facility, much of which was presented in a recent progress report [5] and at the April 2010 plenary meeting of the IDS-NF (see <https://www.ids-nf.org/>).

RECENT UPDATES

Proton Driver

The proton driver must produce a 4 MW pulsed proton beam for pion production. To keep the proton bunch currents reasonable while keeping the RF duty factor in the neutrino factory low, the proton driver will accelerate 3 bunches at 50 Hz. The bunches should be 1–3 ns long (production decreases beyond 1 ns [6]). The three bunches should be separated by at least 80 μ s. This provides suffi-

* Work Supported by the United States Department of Energy, Contract No. DE-AC02-98CH10886.

cient time for the superconducting cavities accelerating the muon beam to have their stored energy replaced.

The proton energy should be in the range of 5–15 GeV, since the muon production from a heavy metal target is maximized in that range. Recent simulations have in fact indicated that for mercury, the optimal production is highly peaked in the lower part of this range, with a maximum near 8 GeV [7]. However, analyses of the HARP data [8, 9] point to a peak at slightly lower energy and less of a reduction in production at lower energies (though the analyzed data may not correspond well to the pions ultimately used in a neutrino factory). Lower energies require higher proton currents and make forming a short bunch more difficult, but lower energies can be achieved with smaller rings and less RF voltage.

There are two general types of proton drivers contemplated. One is based on a linac followed by accumulator and compressor rings. Such designs have been contemplated at Fermilab [10, 11, 12] and CERN [13]. These designs generally have lower energies, since going to higher energies requires adding expensive RF to a single-pass linac (though one could contemplate accelerating in a ring after the linac). Alternatively, one could consider a sequence of synchrotrons or other circular accelerators [14].

The choice of the proton driver will depend on the existing infrastructure at the laboratory where the neutrino factory is built. It is nonetheless important to understand the cost associated with proton facility upgrades to understand the cost of a neutrino factory. Therefore, individual laboratories that are interested in the possibility of a neutrino factory will contribute sections to the design reports describing what will be required to upgrade their proton accelerator complex to support a neutrino factory.

Target

A liquid mercury jet was chosen as the baseline for the target to avoid damage to the target from the intense proton beam. The MERIT experiment [15] built such a target and tested it with a proton beam from the CERN PS. Not only did the experiment demonstrate that such a target was operable, but it showed that the target would work with a proton beam pulse with energy comparable to what would be used for a neutrino factory. It also showed that if two bunches hit the target in rapid succession, there was no loss in particle production for the second bunch when the bunches were spaced by 350 μ s or less. Therefore there will be no difficulty having multiple proton bunches in succession with sufficient time between to refill the superconducting cavities that accelerate the muons.

Work is continuing on the design of the target station infrastructure (see Fig. 2). The target is inside solenoids that generate a 20 T magnetic field that tapers to lower values downstream. Energy deposition into the superconducting magnets is being studied to determine if the current design for shielding and geometry is acceptable. Fluid dynamics simulations of the nozzle and mercury delivery system are

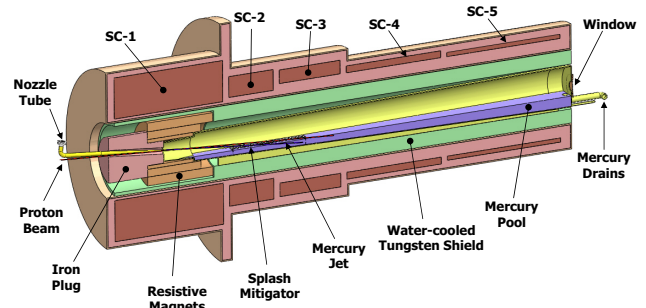


Figure 2: Neutrino factory target region showing the beam, mercury jet, solenoid magnets (SC- n are superconducting), and shielding.

being performed to understand and optimize the jet dynamics. Design is beginning on the mercury flow loop. The optimal location in the target area from which to drain the mercury is being studied. Fluid dynamics of the mercury pooling in the target area is also being studied, since that pool will also act as a beam dump.

While a mercury jet target is our baseline solution, concerns about mercury as a hazardous substance by itself or as yet undiscovered problems that might be found with the mercury circulation system have led some groups to consider using solid targets. Authors have considered tungsten rods which are rapidly rotated into place with each beam pulse [16] or a jet of fluidized tungsten powder [17]. Experimental work is currently being carried out on both these options.

Front End

The purpose of the front end of the neutrino factory is to take the pions coming off of the target, which soon decay into muons, and manipulate the phase space of the muons to be more suitable for acceleration and circulation in the storage ring. This involves reduction of the large energy spread of the muons produced by the pion decays, and reduction in the transverse phase space area.

Reduction in the energy spread is accomplished with a so-called Neuffer bunching and phase rotation system [18]. Ionization cooling [19, 20] is then used to reduce the transverse beam emittance.

The difficulty with these systems as designed is that experimental studies have found that in a magnetic field, the maximum gradient of room-temperature RF cavities is significantly reduced [21]. The precise cause and dependence on field configuration and cavity properties is not completely understood. Some theoretical models have been proposed ([22, 23] and references therein). Experimental studies of this phenomenon are continuing [24]. In particular, studies are beginning on a cavity where the external magnetic field can be oriented either perpendicular or parallel (and small angular deviations from these) to the cavity's electric field. In particular this will allow the study of "magnetic insulation," wherein a magnetic field paral-

lel to a cavity surface with a high electric field prevents emitted electrons from accelerating significantly and potentially damaging a different surface of the cavity from where they are emitted. Studies are also continuing on pressurized gas-filled RF cavities [25]. Filling the cavity with pressurized gas allows the cavity to achieve its maximum gradient even in the presence of magnetic fields [26]. Effects of surface material composition have been included in these studies, and will continue in a more extensive study of whether beryllium has benefits over copper on preventing breakdown [27].

Based on the experimental results, there are several options to mitigate the effects of breakdown. One could have reduced RF gradient which would result in a reduction in performance [4, 28]. One could reduce the magnetic fields on the cavities, either by increasing the distance between the coils and the cavities, adding bucking coils to reduce the fields far from the solenoids, or increasing shielding on the solenoids [29]. One could create a “magnetically insulated” lattice where the cavity surfaces follow the magnetic field lines in regions where the electric fields are significant. One could make the inside of the cavity entirely out of beryllium. Finally, one could fill the RF cavities with pressurized hydrogen gas (which would also act as the absorber for ionization cooling) [30].

Since the experimental work is still in progress, it is currently unknown to what extent the RF gradients will be limited by the magnetic fields. We will therefore use the design with the best performance for our baseline for the reports. This will be the design described in [31], with a more compact and efficient buncher and phase rotation section [32]. At least one alternative scenario will be considered to provide an idea of the penalty and cost of a strategy to mitigate any RF breakdown problems.

Low Energy Acceleration

The IDS-NF will accelerate muons to 25 GeV. This is done in four of stages to optimize the system cost by maximizing the efficiency at each stage. Efficiency is generally increased by increasing the number of passes through the RF cavities. The four stages can be seen in Fig. 1. A solenoid focused linac first accelerates the beam to 0.9 GeV total energy. Then two dogbone geometry recirculating linear accelerators (RLAs) with FODO cells accelerate the beam to 12.6 GeV [4]. The final stage is an fixed field alternating gradient (FFAG) accelerator, accelerating the beam to 25 GeV total energy, described in the next subsection. All accelerating cavities are 201.25 MHz superconducting cavities, the design of which is described in [33].

The lattices for accelerating to 12.6 GeV have been designed, including transition lines. Magnet error tolerances are reasonable. Magnet designs have begun, and tracking has started using more realistic magnet end fields.

As an alternative to this design, a group has been studying the use of a scaling FFAG to accelerate from 3.6 GeV to 12.6 GeV. The currently proposed design [5] accelerates

in 6 turns using 1.8 GV of 201.25 MHz RF. The larger number of turns compared to the RLAs (6 vs. 4.5) and the single (large aperture) arc in the FFAG vs. multiple arcs in the RLAs may provide a cost advantage. Acceleration is accomplished by creating an RF bucket which encompasses the full energy range and making a half synchrotron oscillation near the outside edge of the bucket. The main ring magnets will have fields of at least 4 T. Tracking simulations have been performed showing good performance. Injection and extraction systems have also been designed. An eventual goal will be to make a cost comparison between this design and the RLA design.

Final FFAG Acceleration

The final acceleration stage is a linear non-scaling FFAG. The magnet apertures in this type of machine are small for an FFAG, while still permitting a large number of turns to maximize acceleration efficiency. At higher energies earlier estimates have shown them to be significantly more cost effective than RLAs.

The primary downside of linear non-scaling FFAGs is that for the large transverse emittances in a neutrino factory, there is a significant dependence of the time of flight on transverse amplitude [34], which can lead to an effective longitudinal emittance growth. This can be mitigated by correcting the chromaticity in the lattice and increasing the average accelerating gradient. Chromaticity correction has the downside of reducing the transverse dynamic aperture.

Based on the need for some more space for injection, extraction, and other hardware, lattice designs presented in [35] were updated [5]. Multiple cell types were under consideration, but we have settled on a triplet lattice with 3 m drift lengths and two-cell RF cavities. The beam can make 11.8 turns in the lattice, a significant improvement over what could be achieved in an RLA. The longer drift lengths make injection and extraction more feasible [5], and the two-cell RF cavities that the longer drifts give a larger average accelerating gradient, reducing the effect of the time of flight dependence on transverse amplitude.

Injection and extraction will be the most challenging aspect of the FFAG. Magnets in the injection and extraction regions will need to be somewhat larger than the main ring magnets to take into account the beam oscillation in those regions. Preliminary simulations have indicated that the resulting symmetry breaking has a tolerable effect on the orbits [36].

Since more passes are made through the cavities in this FFAG than in any other subsystem, the maximum energy extracted from the cavities per bunch train occurs here. This energy must be restored between bunch trains, but the rate at which power can be restored is limited. Assuming that each cavity cell has a 1 MW input coupler (the design in [33] assumed 1 MW for a two-cell cavity; a second input coupler could be added if necessary), the restoration of the power extracted requires 80 μ s. This drives the specification for how long the proton driver must delay the extrac-

tion of individual bunches.

Storage Ring

The IDS-NF design specifies two racetrack-shaped storage rings pointed toward detectors 3000–5000 km and 7000–8000 km away respectively. The simultaneous use of both baselines allows degeneracies to be resolved and generally improves the sensitivity of the machine [1]. A design has been produced for a storage ring [37], and tracking studies have confirmed that the machine's dynamic aperture is more than sufficient for the beam [38].

To reduce the systematic uncertainty in the neutrino flux, certain non-standard diagnostics are useful to have in the storage ring [39]. First, one would like to measure the muon polarization. Not only is the polarization itself important to know since the neutrino flux depends strongly on it, but the time dependence of the polarization is also a measure of the beam energy and energy spectrum. One can measure the polarization by measuring the decay electron spectrum. The most straightforward place to do this, requiring minimal modification to magnet designs, would be with a detector perpendicular to the beam direction in a long straight section within the matching section from the arc to the production straight. There is a weak bend near the production straight to steer the beam in the matching section away from the far detector, and decay electrons passing through that magnet can be steered toward a detector. Simulations will be done to ensure that the detector can be placed so as to avoid the muon beam but still accomplish the electron spectrum measurement.

One would also like to measure the angular divergence of the beam in the production straight. An accurate measurement of the divergence will reduce the flux uncertainty at the far detector. An in-beam helium gas Cerenkov detector was proposed for this [40]. The concern is that multiple scattering or energy straggling would result in beam loss. Multiple scattering was estimated to be small in the helium gas, but the effect of the windows containing the gas was not considered. Studies will determine the maximum tolerable window thickness with respect to beam loss, and we will determine whether the Cerenkov detector can be made with these windows. Another option to measure angular divergence may be a second “near” detector which is significantly further away than the existing near detector.

LOW ENERGY NEUTRINO FACTORY

Especially if θ_{13} turns out to be large, a lower-energy neutrino factory (around 4 GeV) could be competitive in its physics reach with a high-energy neutrino factory [41]. A design for such a low-energy neutrino factory has been proposed [42], which is essentially a copy of the design described here up to the beginning of acceleration, then replacing the acceleration with a linac and a single RLA going up to 4 GeV. This is followed by a single 4 GeV decay ring. This design will be included in the IDS-NF reports as an alternative.

Authors have discussed the physics from a three stage neutrino factory facility [43]. The first stage is the aforementioned low-energy neutrino factory. The second stage upgrades the energy to 25 GeV but only uses a single decay ring. The third stage either adds a second storage ring with a longer baseline, making the neutrino factory described in the earlier sections, or increases the detector mass. The choice for what to do in the third stage depends on the results from the earlier two stages.

ACKNOWLEDGMENTS

This paper describes the work of all the members of the International Design Study of the Neutrino Factory. More details can be found in the references and at <https://www.ids-nf.org/>.

REFERENCES

- [1] A. Bandyopadhyay *et al.*, Rep. Prog. Phys. **72** (2009) 106201.
- [2] M. C. Gonzalez-Garcia, Michele Maltoni, and Jordi Salvado, JHEP04(2010) 056.
- [3] Patrick Huber, Manfred Lindner, and Walter Winter, JHEP05(2005) 020.
- [4] The ISS Accelerator Working Group *et al.*, JINST **4** (2009) P07001.
- [5] The IDS-NF collaboration, IDS-NF-017 (2010). <https://www.ids-nf.org/>
- [6] Juan C. Gallardo, NFMCC-doc-340 (2006). <http://nfmcc-docdb.fnal.gov/>
- [7] X. Ding, D. Cline, H. Kirk, and J. S. Berg, “OPTIMIZED PARAMETERS FOR A MERCURY JET TARGET” [44].
- [8] The HARP Collaboration, Eur. Phys. J. C **51** (2007) 787.
- [9] M. G. Catanesi *et al.*, Phys. Rev. C **77** (2008) 055207.
- [10] Charles Ankenbrandt *et al.*, in *Proceedings of LINAC08, Victoria, BC, Canada* (2008) 76.
- [11] Charles Ankenbrandt and Rolland P. Johnson, in *Proceedings of Hadron Beam 2008, Nashville, Tennessee, USA* (2008) 410.
- [12] Valeri Lebedev and Sergei Nagaitsev, in [45] 274.
- [13] M. Aiba, CERN-AB-Note-2008-048 BI (2008).
- [14] J. Pasternak, M. Asleninejad, K. Long, and J. Pozimski, “FEASIBILITY OF A COMMON PROTON DRIVER FOR A NEUTRON SPALLATION SOURCE AND A NEUTRINO FACTORY” [44].
- [15] K. T. McDonald *et al.*, “THE MERIT HIGH-POWER TARGET EXPERIMENT AT THE CERN PS” [44].
- [16] G. P. Skoro *et al.*, “SOLID TARGET FOR A NEUTRINO FACTORY” [44].
- [17] C. J. Densham *et al.*, “THE POTENTIAL OF FLUIDISED POWDER TARGET TECHNOLOGY IN HIGH POWER ACCELERATOR FACILITIES” [44].
- [18] D. Neuffer and A. Van Ginneken, in *Proceedings of the 2001 Particle Accelerator Conference, Chicago*, P. Lucas and S. Webber, eds. (IEEE, Piscataway, NJ, 2001) 2029.

- [19] A. N. Skrinskiĭ, V. V. Parkhomchuk, Sov. J. Part. Nucl. **12** (1981) 223. Russian original Fiz. Elem. Chastits At. Yadra **12** (1981) 557.
- [20] David Neuffer, Part. Accel. **14** (1983) 75.
- [21] A. Moretti *et al.*, Phys. Rev. ST Accel. Beams **8**, 072001 (2005).
- [22] A. Hassanein *et al.*, Phys. Rev. ST Accel. Beams **9**, 062001 (2006).
- [23] R. B. Palmer, R. C. Fernow, Juan C. Gallardo, and Diktys Stratakis, Phys. Rev. ST Accel. Beams **12**, 031001 (2009).
- [24] D. Huang *et al.*, “RF STUDIES AT FERMILAB MUCOOL TEST AREA” [44].
- [25] M. BastaniNejad *et al.*, “RF BREAKDOWN OF METALLIC SURFACES IN HYDROGEN” [44].
- [26] P. Hanlet *et al.*, in *Proceedings of EPAC 2006, Edinburgh, Scotland* (EPAC, European Physical Society Accelerator Group, 2006) 1364.
- [27] Diktys Stratakis, Juan C. Gallardo, and Robert B. Palmer, in [45] 303.
- [28] C. T. Rogers and G. Prior, “MUON IONISATION COOLING IN REDUCED RF” [44].
- [29] C. T. Rogers, in [45] 298.
- [30] Juan C. Gallardo and Michael S. Zisman, in [45] 308.
- [31] J. S. Berg *et al.*, Phys. Rev. ST Accel. Beams **9**, 011001 (2006).
- [32] David Neuffer, “Studies toward a Candidate IDS Neutrino Factory Front-End Configuration,” NFMCC-doc-546 (2010). <http://nfmcc-docdb.fnal.gov/>
- [33] S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo, “Feasibility Study-II of a Muon-Based Neutrino Source,” BNL-52623 (2001).
- [34] J. Scott Berg, Nucl. Instrum. Methods A **570** (2007) 15.
- [35] J. Scott Berg and Shinji Machida, “FFAG DESIGNS FOR THE INTERNATIONAL DESIGN STUDY FOR THE NEUTRINO FACTORY” [44].
- [36] J. Pasternak *et al.*, “FEASIBILITY OF INJECTION/EXTRACTION SYSTEMS FOR MUON FFAG RINGS IN THE NEUTRINO FACTORY” [44].
- [37] C. R. Prior, “MUON STORAGE RINGS FOR A NEUTRINO FACTORY” [44].
- [38] M. Apollonio, M. Aslaninejad, and J. Pasternak, “BEAM DYNAMICS STUDIES FOR A NEUTRINO FACTORY DECAY RING” [44].
- [39] The ISS Detector Working Group *et al.*, JINST **4** (2009) T05001.
- [40] Rodolphe Piteira, *Conception et simulation d'un système optique mesurant la divergence d'un faisceau de muons de 50 GeV*, report of “stage de recherche,” Magistère Interuniversitaire de Physique, Ecole Normale Supérieure, Paris (2001).
- [41] Enrique Fernández Martíne, Tracey Li, Silvia Pascoli, and Olga Mena, Phys. Rev. D **81**, 073010 (2010).
- [42] C. Ankenbrandt *et al.*, Phys. Rev. ST Accel. Beams **12**, 070101 (2009).
- [43] Jian Tang and Walter Winter, Phys. Rev. D **81**, 033005 (2010).
- [44] To appear in the proceedings of PAC09, Vancouver, BC, Canada (2009).
- [45] M. C. Goodman, D. M. Kaplan, and Z. Sullivan, eds., *Neutrino Factories, Superbeams and Beta Beams, 11th international Workshop* (AIP, Melville, NY, 2010).