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# From Super Beams to Neutrino Factories

Alan Bross

*Fermi National Accelerator Laboratory, Batavia, IL 60510 US*
*for the US Neutrino Factory and Muon Collider Collaboration*

**Abstract.** The Neutrino Factory, which produces an extremely intense source of flavor-tagged neutrinos from muon decays in a storage ring, arguably gives the best physics reach for CP violation, as well as virtually all parameters in the neutrino oscillation parameter space. I will briefly describe the physics capabilities of the baseline Neutrino Factory as compared to other possible future facilities (β-beam and super-beam facilities), give an overview of the accelerator complex and describe in detail the current international R&D program.

**Keywords:** neutrino oscillation, neutrino factory.
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## INTRODUCTION

It has been over 10 years since the discovery that neutrinos have mass and can oscillate [1] and we now understand that most experimental data are well described by the 3ν mixing model [2]. Many parameters in this model have now been measured, but there are still unknowns: whether neutrinos are Dirac or Majorana particles (are they their own antiparticle?), the neutrino mass ordering (are there two light neutrinos and one heavy neutrino, normal hierarchy, or two heavy and one light, inverted hierarchy?), what is the absolute neutrino mass scale, the value of the unknown mixing angle $\theta_{13}$, and is CP violation present in the leptonic sector? In order to measure these unknowns, experiments with unprecedented sensitivity are needed. The systematics of the neutrino beam determine, to a large degree, the ultimate sensitivity of a neutrino oscillation experiment. In order to address the precision needed for future neutrino oscillation experiments, the Neutrino Factory was proposed by Geer [3]. In the Neutrino Factory, the neutrino beam is generated from muons which decay along the straight section of a race track-like decay ring and since the decay of the muon is well understood, the systematic uncertainties associated with a neutrino beam produced in this manner are very small. In addition since the muon (anti-muon) decays produce both muon and anti-electron neutrinos (anti-muon and electron neutrinos), many oscillation states are accessible from a Neutrino Factory and the reach in the oscillation parameter space is extended. In the so-called "golden" channel, $\nu_\mu \rightarrow \nu_e$, the experimental signature in the neutrino detector is the presence of a muon with the "wrong" sign — a muon with the opposite sign to that which is stored in the decay ring. This requires that the neutrino detector be magnetized, but for Neutrino Factories with stored muons with energy of approximately 25 GeV, this represents standard neutrino detector technology [4]. It has been shown [5] that for a "magic" baseline of approximately 7500 km, the "golden" channel offers unprecedented sensitivity for the determination of the unknown mixing angle $\theta_{13}$ and the mass hierarchy. As we shall see, a Neutrino Factory that points beams to 2 detectors, one at the magic baseline and one at a baseline of 4000 km, offers the best sensitivity over the full neutrino-oscillation parameter space

## THE INTERNATIONAL SCOPING STUDY

Over the last decade there have been a number of studies [6-9] that have explored the physics reach of Neutrino Factories to measure $\theta_{13}$, determine the mass hierarchy and determine the CP violating phase, $\delta$. The most recent study to be completed, the International scoping study of a future Neutrino Factory and super-beam facility (ISS) [10], studied the physics capabilities of various future neutrino facilities: super-beam, β-Beam and Neutrino Factory. Within the study, the accelerator working group developed a full concept specification for the Neutrino Factory accelerator facility based on the physics

requirements and detector performance parameters developed within the study. See Figure 1.

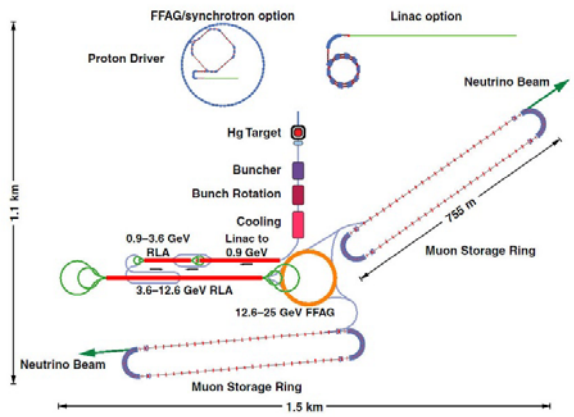


**FIGURE 1.** ISS Neutrino Factory facility baseline.

The facility consists of: a 4 MW proton driver, a Liquid Hg jet target station, a 201 MHz capture and phase rotation section, approximately 70m of transverse muon ionization cooling, acceleration using a linac and recirculating linear accelerators (RLAs) with superconducting RF, followed by a fixed-field alternating-gradient accelerator, FFAG, accelerating the muons to a final energy of 25 GeV and finally two decay rings.

## The ISS Physics Study

The ISS physics study [11] set out as a goal "to establish the strong physics case for the various proposed facilities and to find the optimum parameters of the accelerator facility and detector systems from a physics point of view." The study looked at super-beam facilities, a β-beam facility and the Neutrino Factory.

*The ISS Neutrino Factory Baseline Detectors*

The Neutrino Factory detectors need to be magnetized and for the 25 GeV muon storage ring in the ISS; a more or less conventional detector is all that is required. For the ISS, the primary detector is the magnetized iron neutrino detector (MIND) which produces a toroidal magnetic field in iron and uses scintillator strip readout following the example of the MINOS detector [12]. A schematic of MIND is shown in Figure 2. In addition at the shorter baseline, the ISS detector configuration includes a Magnetized Emulsion Cloud Chamber (MECC) for the detection of the "silver channel" ($\nu_\tau$ appearance) .

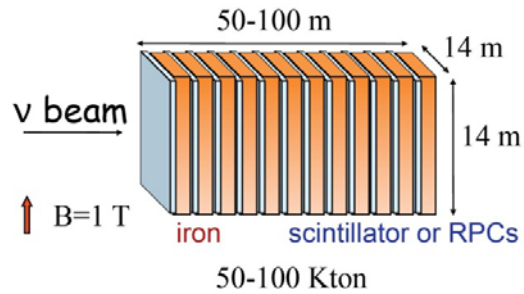


**FIGURE 2.** ISS Neutrino Factory facility baseline.

*Comparison of sensitivity in the ν oscillation parameters*

Within the ISS physics study, 5 facilities were studied. They were: a 4 MW facility at CERN (SPL) pointing to a 1 megaton water Cerenkov detector at a baseline of 130 km (super-beam), a 4 MW facility at JPARC (T2HK) pointing to a 1 megaton water Cerenkov detector at a baseline of 295 km (super-beam), a 2 MW facility at FNAL (WBB) pointing to a 1 megaton water Cerenkov detector at a baseline of 1300 km (super-beam), a high-energy β-beam facility (BB350) pointing to a 1 megaton water Cerenkov detector at a baseline of 730 km and the 4 MW Neutrino Factory pointing to two 50 kT MIND detectors at baselines of 4000 and 7500 km plus a 10 KT MECC at 4000 km.

The results of the study for the discovery reach in $\theta_{13}$ and the CP violating phase, $\delta$, are shown in Figures 3a and 3b where 3σ exclusion contours are shown (best-case scenario for each facility).

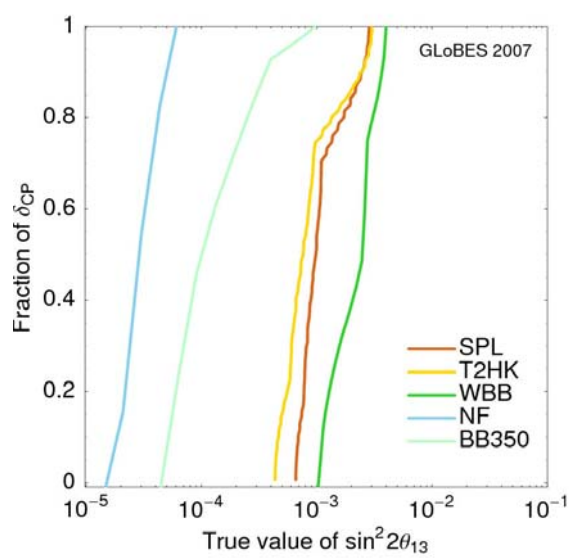


**FIGURE 3a**: Discovery reach for $\theta_{13}$.

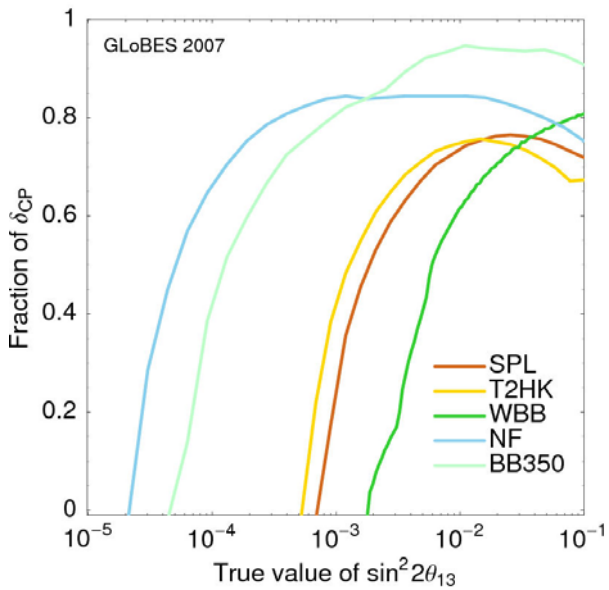


**FIGURE 3b**: Reach in the CP phase $\delta$.

As can be seen from the data in Figures 3a and 3b, the Neutrino Factory offers the best possible reach for measuring a non-zero $\theta_{13}$ and gives the best capability for determining the CP violating phase for small $\theta_{13}$. The executive summary of the ISS physics report states: "Studies so far have shown that the Neutrino Factory, an intense high-energy neutrino source based on a stored muon beam, gives the best performance over virtually all of the parameter space; its time scale and cost, however, remain important question marks."

### *The Case For A Neutrino Factory If $\theta_{13}$ Is Large*

One can ask what is the case for a Neutrino Factory if $\theta_{13}$ is possibly measured before the final technical case for the facility can be made and its costs are better determined. One scenario being considered within the IDS-NF is a Low-Energy Neutrino Factory (LENF) [13]. At a baseline of the order of 1300 km, a LENF utilizing stored muons of energy of ≈ 4 GeV produces a neutrino oscillation pattern that is very rich, and with an appropriate detector, the $\theta_{13}$ reach can extend down to approximately $10^{-4}$ ($\sin^2 2\theta_{13}$). A detector with low neutrino event energy threshold and excellent event energy resolution is required, but a concept that uses a totally active scintillator detector in an air-core solenoid [13] shows very interesting possibilities. The baseline is that of Fermilab to DUSEL, so studies of the LENF are synergistic with the ongoing work studying a wide-band super-beam to DUSEL [14].

## MOVING FORWARD WITH THE NEUTRINO FACTORY

As can be deduced from the above discussion, the outstanding questions regarding the Neutrino Factory are not in its capability to do the ν oscillation physics, but in the uncertainty with regard to its technical feasibility, cost and time scale. The larger the technical risk, the larger the cost of the final facility is likely to be. This will undoubtedly lengthen the time scale in which such a facility might become operational. In order to mitigate the risk associated with building a Neutrino Factory, there is an on-going international R&D program that is studying all the technical aspects of the facility. The International Design Study for a Neutrino Factory (IDS-NF) has set as a goal to deliver a Reference Design Report (RDR) in which the physics performance of the Neutrino Factory is detailed and the specification of each of the accelerator, diagnostic, and detector systems that make up the facility is defined. It is envisioned that the RDR will be delivered in the 2012—2013 time frame and could present the engineering basis for moving the Neutrino Factory into the project phase. The major technical challenges facing the NF design are the design of a high power proton source, a pion production target system that can handle multi-MW beam power, efficient pion capture and phase rotation, the ionization cooling channel and rapid acceleration.

## CURRENT R&D PROGRAM

Many of the key technologies and components for the Neutrino Factory are currently under study. The MERIT experiment [15] has successfully tested the concept of the liquid Hg jet target and it has shown very promising results which indicate that this type of target system can operate at a power level of 4 MW and above. A schematic of the MERIT experiment is shown in Figure 4. To date key results from the experiment have shown: a) Jet surface instabilities and radial filament formation are reduced by jet containment in a high magnetic field, b) He jet disruption is also mitigated by the magnetic field and with a jet velocity of 20m/s, a proton beam-pulse rate of 70 Hz is sustainable with a single pulse power of 115 kJ and c) Pion production remains stable up to 350μs after previous beam impact.

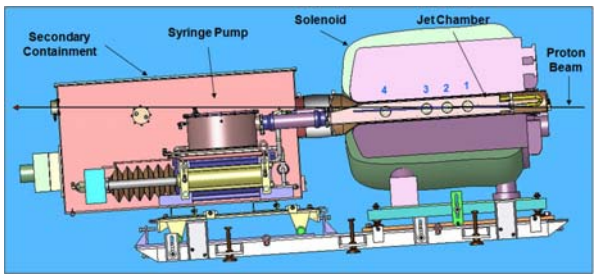


**FIGURE 4.** Schematic of the MERIT experiment

The Muon Ionization Cooling Experiment, MICE [16], is preparing to perform a demonstration and engineering test of 4D muon ionization cooling utilizing 201 MHz RF and liquid hydrogen absorbers. An engineering drawing of the MICE cooling channel is shown in Figure 5.

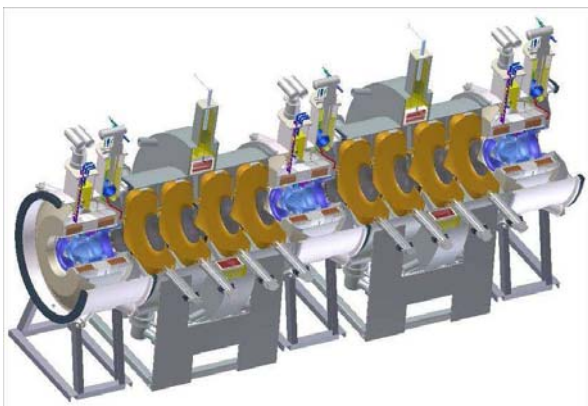

**FIGURE 5.** Engineering section view of the MICE cooling channel

The MICE cooling channel reduces the incoming emittance by 10% and the experiment is designed to measure this effect with 1% precision.

The MuCool [17] program is investigating operation of vacuum RF cavities in the presence of high magnetic fields, has made preliminary studies on liquid hydrogen absorbers and will also be studying the use of LiH absorbers as an alternative to using liquid hydrogen in the muon cooling channel. The MuCool program focuses on component R&D and, in addition to the capability to test RF components at high power, will have the capability to test cooling channel components with a high-intensity proton beam from the Fermilab linac.

Of all the underlying accelerator technologies that are required for the Neutrino Factory complex, it can be argued that RF technology is the single most important "Limiting-Technology." It is of fundamental importance for these facilities in that it is needed in: 1) Muon capture, bunching and phase rotation; 2) Muon Cooling; and 3) Acceleration. Both normal conducting RF (front-end: 1 and 2 above) and superconducting RF (acceleration) are required.

A crucial challenge for the Neutrino Factory front-end design and cooling channel is the operation of high-gradient normal-conducting RF (NCRF) in the presence of high magnetic field. This problem has been the primary focus of the MuCool program. What has been observed in MuCool is that the safe operating gradient limit degrades significantly when a NCRF cavity is operated in magnetic field, Figure 6.

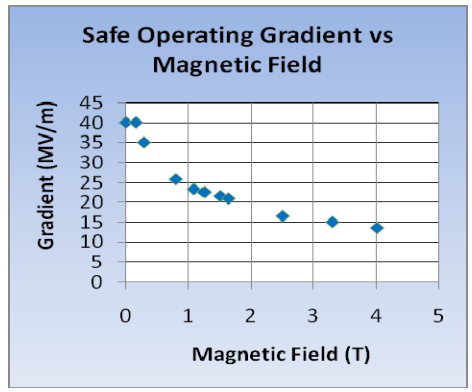


**FIGURE 6:** Maximum safe operating gradient v. magnetic field.

The data shown in Figure 6 are for an 805 MHz pillbox test cavity. The maximum stable gradient degrades quickly with increasing B field. There are a number of models that have been developed that attempt to describe this phenomenon, but all involve field emission from emitters (surface field enhancements in the regions of high gradient) in the cavity. The interaction of the field emission with the magnetic field can cause surface imperfections on the cavity to break off which then produces a plasma under bombardment by the field emission current. The plasma then initiates a breakdown. In order to address this problem, three approaches are being investigated.

The first is to eliminate field emission by processing the NCRF copper cavities using superconducting RF (SCRF) or more advanced techniques. A 201 MHz copper cavity (prototype for MICE) was processed using SCRF techniques and tested in the MuCool program. This cavity reached a stable operating gradient of 21 MV/m (the design gradient was 16 MV/m) in the absence of B field. Tests at low magnetic field did show a significant drop off in stable operating gradient, but the cavity behaved very differently from the 805 MHz pillbox with respect to X-ray emission [18]. Other processing techniques include coating the cavity utilizing the Atomic Layer Deposition process [19]. Other possible approaches to

eliminating the magnetic field effect are to operate the cavities filled with high-pressure $H_2$ gas [20] and to investigate fabricating the cavities with materials other than copper.

The acceleration systems for the Neutrino Factory must accelerate the muons rapidly in order to minimize decay losses. The current scheme for accomplishing this includes a superconducting linac, a pair of recirculating linear accelerators with "dog bone" arcs and finally a non-scaling fixed-field alternating gradient (FFAG) accelerator to bring the muons to their final energy of 25 GeV. The Electron Model with Many Applications (EMMA) [21] experiment which is being carried out at the Daresbury Laboratory in the UK will study the properties of a non-scaling FFAG. The overall schematic of the acceleration system for the Neutrino Factory is shown in Figure 1.

## IDS-NF TIMELINE

As was mentioned above, the goal of the IDS-NF is to have a reference design document ready in the time frame of 2012—2013. The IDS-NF community feels that this is an extremely important time frame in that by this time there will be many new results from existing and soon to turn on neutrino experiments (MINOS, OPERA, Double Chooz, Daya Bay, T2k, NOνA) which will give physicists new insights on the requirements for future neutrino facilities. Figure 7 shows the "aspirational" timeline that was presented at NuFact07 and is the goal of the IDS-NF.

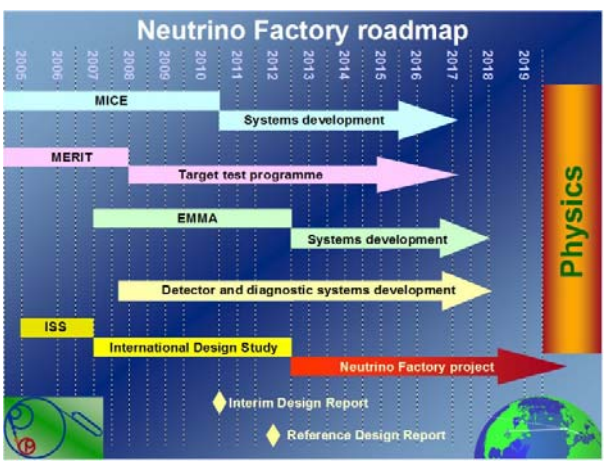


**Figure 7:** Aspirational timeline for a Neutrino Factory leading to a Neutrino Factory Project circa 2013.

## ACKNOWLEDGMENTS

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