Report from The Snowmass 2001 Working Group M1: Muon Based Accelerators

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I. INTRODUCTION

Recent results from the SNO collaboration [1] coupled with data from the SuperK collaboration [2] have provided convincing evidence that neutrinos oscillate and that they very likely do so among the three known neutrino species. Experiments currently under way or planned in the near future will shed further light on the nature of neutrino mixing and the magnitudes of the mass differences between them. Neutrino oscillations and the implied non-zero masses represent the first experimental evidence of effects beyond the Standard Model, and as such are worthy of our utmost attention.

This working group reviewed the international effort on establishing an ongoing program of research in accelerator and experimental physics that can be implemented in an incremental fashion. At each step, one opens up new physics vistas, leading eventually to a Neutrino Factory and a Muon Collider. One of the first steps toward a Neutrino Factory is a proton driver that can be used to provide intense beams of conventional neutrinos in addition to providing the intense source of low energy muons from pion decay that must be cooled to be accelerated and stored. While the proton driver is being constructed, one could simultaneously engage in R&D on collecting and cooling muons. A source of intense cold muons can be immediately used to do physics on such items as measuring the electric and magnetic dipole moments of the muon to higher precision, muonium-antimuonium oscillations, rare muon decays and so on. Once the capability of cooling and accelerating muons is developed, the storage ring for such muons will be the first Neutrino Factory. Its precise energy and its distance from the long-baseline experiment will be chosen using the knowledge of neutrino oscillation parameters gleaned from the present generation of solar and accelerator experiments (Homestake, Kamiokande, SuperKamiokande, SAGE, GALLEX, K2K, SNO), the next generation experiments (MiniBooNE, MINOS, CNGS, KamLAND, Borexino), and the high-intensity conventional beam experiments that would already have taken place.

A Neutrino Factory provides intense beams of both ν_μ and $\overline{\nu}_e$ from stored μ^- beams, and their charge conjugate beams for stored μ^+ beams. In addition, it provides beams having smaller divergence than conventional neutrino beams of comparable energy. These properties permit the study of non-oscillation physics at near detectors and the measurement of structure functions and associated parameters in non-oscillation physics to unprecedented accuracy. They also permit long-baseline experiments that can determine oscillation parameters. Depending on the value of the parameter $\sin^2 2\theta_{13}$ in the three-neutrino oscillation formalism, one can expect to measure the oscillation $\nu_e \to \nu_\mu$. By comparing the rates for this channel with its charge-conjugate channel $\overline{\nu}_e \to \overline{\nu}_\mu$, one can determine the sign of the leading mass difference in neutrinos, Δm^2_{32}, by making use of their passage through matter in a long-baseline experiment. Such experiments can also shed light on the CP violating phase, δ, in the lepton mixing matrix and enable us to study CP violation in the lepton sector. It is known that CP violation in the quark sector is insufficient to explain the baryon asymmetry of the Universe. Perhaps the lepton sector CP violation played a crucial role in creating this asymmetry during the initial phases of the Big Bang.

While the Neutrino Factory is being constructed, R&D can be performed to make the Muon Collider a reality. This would require orders of magnitude more cooling than the Neutrino Factory. Muon Colliders, if realized, provide a tool to explore Higgs-like objects by direct s-channel fusion, much as LEP explored the Z . They also provide a means to reach higher energies (3–4 TeV in the center of mass) using compact collider rings.

These concepts and ideas have aroused significant interest throughout the world scientific community. In the U.S., a formal collaboration of some 140 scientists, the Neutrino Factory and Muon Collider Collaboration (MC) [3], has undertaken the study of designing a Neutrino Factory, along with R&D activities in support of a Muon Collider design.

II. HISTORY

The concept of a Muon Collider was first proposed by Budker [4] and by Skrinsky [5] in the 60s and early 70s. However, there was little substance to the concept until the idea of ionization cooling was developed by Skrinsky and Parkhomchuk [6]. The ionization cooling approach was expanded by Neuffer [7] and then by Palmer [8], whose work led to the formation of the Neutrino Factory and Muon Collider Collaboration (MC) [3] in 1995 [29].

The concept of a neutrino source based on a pion storage ring was originally considered by Koshkarev [12]. However, the intensity of the muons created within the ring from pion decay was too low to provide a useful neutrino source. The physics potential of neutrino beams produced by muon storage rings was investigated by Geer in 1997 at a Fermilab workshop [13, 14], where it became evident that the neutrino beams produced by muon storage rings needed for the Muon Collider were exciting on their own merit. The Neutrino Factory concept quickly captured the imagination of the particle physics community, driven in large part by the exciting atmospheric neutrino deficit results from the SuperKamiokande experiment.

As a result, the MC realized that a Neutrino Factory could be an important first step toward a Muon Collider and the physics that could be addressed by a Neutrino Factory was important to pursue. With this in mind, the MC shifted its primary emphasis toward the issues relevant to a Neutrino Factory. There is also considerable international activity on Neutrino Factories, with international conferences held at Lyon in 1999 [15], Monterey in 2000 [16], Tsukuba in 2001 [17], another planned for London in 2002, and one planned in the U.S. in 2003.

In the fall of 1999, Fermilab undertook a Feasibility Study ("Study-I") of an entry-level Neutrino Factory [18]. One of the aims of Study-I was to determine whether the Fermilab accelerator complex could be made to evolve into a Neutrino Factory. Study-I answered this question affirmatively. Simultaneously, Fermilab launched a study of the physics that might be addressed by such a facility [19]. More recently, Fermilab initiated a study to compare the physics reach of a Neutrino Factory with that of conventional neutrino beams [20] powered by a high intensity proton driver, which are referred to as "superbeams". The aim was to compare the physics reach of superbeams with that of a realistic Neutrino Factory. It was determined that a steady and diverse stream of physics will result along this evolutionary path, *i.e.*, that a superbeam addresses fundamental neutrino physics beyond that available using a conventional beam, and that a Neutrino Factory can go even further.

More recently, BNL organized a follow-up study ("Study-II") on a high-performance Neutrino Factory sited at BNL. Study-II was recently completed [21]. An important goal of Study-II was to evaluate whether BNL was a suitable site for a Neutrino Factory; that question was answered affirmatively. Figure 1 shows a comparison of the performance of the neutrino factory designs in Study I and Study II [19]. Both Study-I and Study-II were carried out jointly with the MC [3], which has over 140 members from many institutions in the U.S. and abroad.

Complementing the Feasibility Studies, the MC carries on an experimental and theoretical R&D program, including work on targetry, cooling, rf hardware (both normal conducting and superconducting), high-field solenoids, LH_2 absorber design, theory, simulations, parameter studies, and emittance exchange [23].

III. FEASIBILITY STUDIES

Our present understanding of the design of a Neutrino Factory and results for its simulated performance are summarized here. Specific details can be found in the Study-II report [21]. A schematic layout is shown in Fig.2.

As noted, one aim of Study-I was to assess the extent to which the Fermilab accelerator complex could evolve into a Neutrino Factory. Study-I showed that such an evolution was clearly possible. The performance reached in Study-I, characterized in terms of the number of muon decays aimed at a detector located 3000 km away from the muon storage ring, was $N = 2 \times 10^{19}$ decays per "Snowmass year" (10^7 s) per MW of protons on target.

Likewise, an important goal of Study-II was to evaluate whether BNL was a suitable site for a Neutrino Factory. Study-II answered that question affirmatively. A second goal of Study-II was to examine various site-independent means of enhancing the performance of a Neutrino Factory. Based on the improvements in Study-II, the number of muons delivered to the storage ring per Snowmass year from a 1-MW proton driver would be:

$$\begin{aligned}\mu/\text{year} &= 10^{14}\ \text{ppp} \times 2.5\ \text{Hz} \times 10^{7}\ \text{s/year} \times 0.17\ \mu/\text{p} \times 0.81 \\ &= 3.4 \times 10^{20}\end{aligned}$$

where the last factor (0.81) is the estimated efficiency of the acceleration system. For the case of an upgraded 4 MW proton driver, the muon production would increase to $1.4 \times 10^{21}\ \mu$ /year. (R&D to develop a target capable of handling this beam power would be needed.)

The number of muons decaying in the production straight section per Snowmass year would be 35% of this number, or 1.2×10^{20} decays for a 1 MW proton driver (4.8×10^{20} decays for a 4 MW proton driver; *i.e.* 24

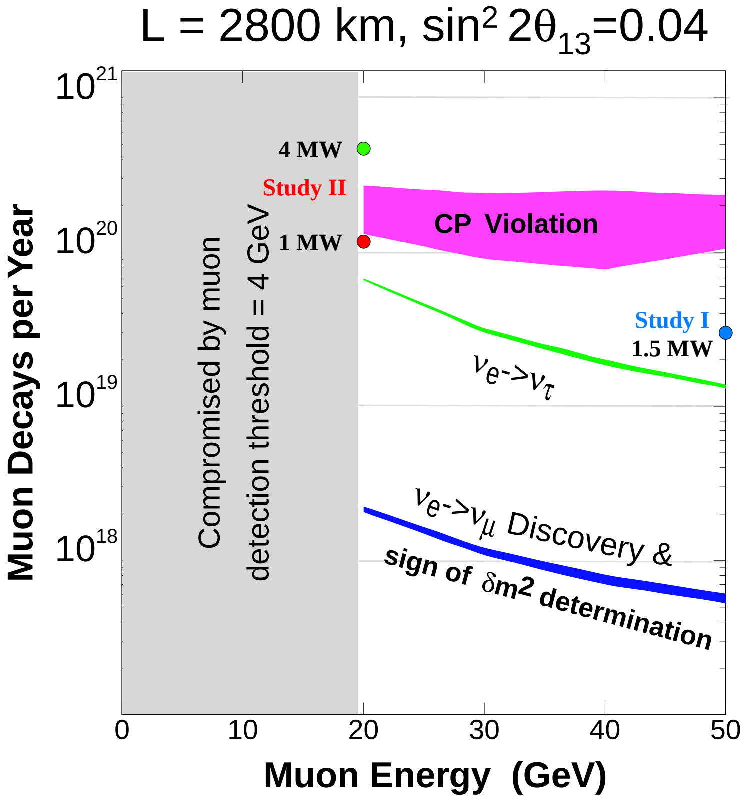

FIG. 1: Muon decays in a straight section per 10^7 s *vs.* muon energy, with fluxes required for different physics searches assuming a 50 kT detector. Simulated performance of the two studies is indicated.

times the Study-I yield). Though these neutrinos are potentially available for experiments, in the current storage ring design the angular divergence at both ends of the production straight section is higher than desirable for the physics program. This can be improved in a straightforward manner and we are confident that storage ring designs allowing 30–40% of useful muon decays are feasible.

Both Study-I and -II are site specific in that each has a few site-dependent aspects; otherwise, they are generic. In particular, Study-II uses BNL site-specific proton driver specifications corresponding to an upgrade of the 24-GeV AGS complex and a BNL-specific layout of the storage ring, which is housed in an above-ground berm to avoid penetrating the local water table. Study-I uses a new Fermilab booster to achieve its beam intensities and an underground storage ring. The primary substantive difference between the two studies is that Study-II is aimed at a lower muon energy (20 GeV), but higher intensity (for physics reach). Taking the two Feasibility Studies together, we conclude that a high-performance Neutrino Factory could easily be sited at either BNL or Fermilab.

It is worthwhile noting that a μ^+ storage ring with an average neutrino energy of 15 GeV and 2×10^{20} useful muon decays will yield (in the absence of oscillations) $\approx 30,000$ charged-current events in the ν_e channel per kiloton-year in a detector located 732 km away. In comparison, a 1.6 MW superbeam [20] from the Fermilab Main Injector with an average neutrino energy of 15 GeV will yield $\approx$13,000 ν_μ charged-current events per kiloton-year. However, a superbeam has a significant ν_e contamination, which will be the major background in $\nu_\mu \to \nu_e$ appearance searches. In addition, there is a significant background in the detector from π^0s that are produced by ν_μs being mis-identified as electrons. It is thus much easier to detect the oscillation $\nu_e \to \nu_\mu$ from muon storage rings than the oscillation $\nu_\mu \to \nu_e$ from conventional beams, and the experimental systematics are far better.

IV. NEUTRINO FACTORY DESCRIPTION

The muons that are used result from decays of pions produced when an intense proton beam bombards a high-power production target. The target and downstream transport channel are surrounded by superconducting solenoids to contain the pions and muons, which are produced with a larger spread of transverse and longitudinal

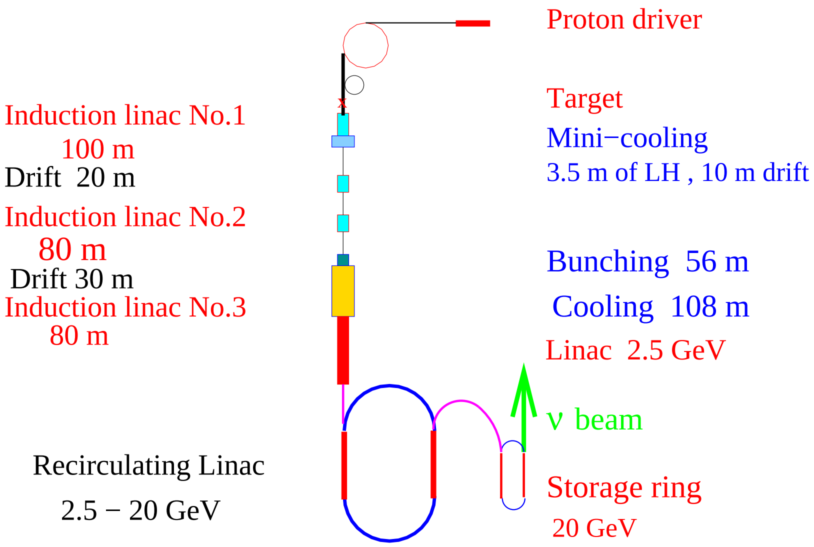

FIG. 2: Schematic of the Neutrino Factory-Study II version.

momenta than can be conveniently transported through an acceleration system. To prepare a beam suitable for subsequent acceleration, one first performs a *phase rotation*, during which the initial large energy spread and small time spread are interchanged using induction linacs. Next, to reduce the transverse momentum spread, the resulting long bunch, with an average momentum of about 250 MeV/c, is bunched into a 201.25-MHz bunch train and sent through an ionization cooling channel consisting of LH_2 energy absorbers interspersed with rf cavities to replenish the energy lost in the absorbers. The resulting beam is then accelerated to its final energy using a superconducting linac to make the beam relativistic, followed by one or more recirculating linear accelerators (RLAs). Finally, the muons are stored in a racetrack-shaped ring with one long straight section aimed at a detector located at a distance of roughly 3000 km.

A list of the main ingredients of a Neutrino Factory is given below. Details of the design described here are based on the specific scenario of sending a neutrino beam from Brookhaven to a detector in Carlsbad, New Mexico. More generally, however, the design exemplifies a Neutrino Factory for which the two Feasibility Studies demonstrated technical feasibility (provided the challenging component specifications are met), established a cost baseline, and established the expected range of physics performance.

- **Proton Driver:** Provides 1–4 MW of protons on target from an upgraded AGS (Fig. 3); a new booster at Fermilab [24] (Fig. 4) would perform equivalently.
- **Target and Capture:** A high-power target immersed in a 20-T superconducting solenoidal field to capture pions produced in proton-nucleus interactions.
- **Decay and Phase Rotation:** Three induction linacs, with internal superconducting solenoidal focusing to contain the muons from pion decays, that provide nearly non-distorting phase rotation; a "mini-cooling" absorber section is included after the first induction linac to reduce the beam emittance and lower the beam energy to match the cooling channel acceptance.
- **Bunching and Cooling:** A solenoidal focusing channel, with high-gradient rf cavities and liquid-hydrogen absorbers (Fig. 5), that bunches the 250 MeV/c muons into 201.25-MHz rf buckets and cools their transverse normalized emittance from 12 mm·rad to 2.7 mm·rad.
- **Acceleration:** A superconducting linac with solenoidal focusing to raise the muon beam energy to 2.48 GeV, followed by a four-pass superconducting RLA to provide a 20 GeV muon beam; a second RLA could optionally be added to reach 50 GeV, if the physics requires this.

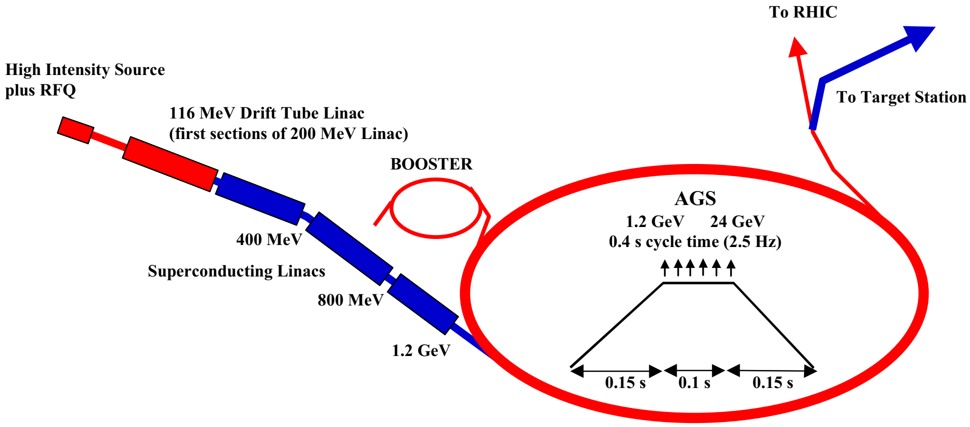

FIG. 3: Schematic of a proton driver at BNL.

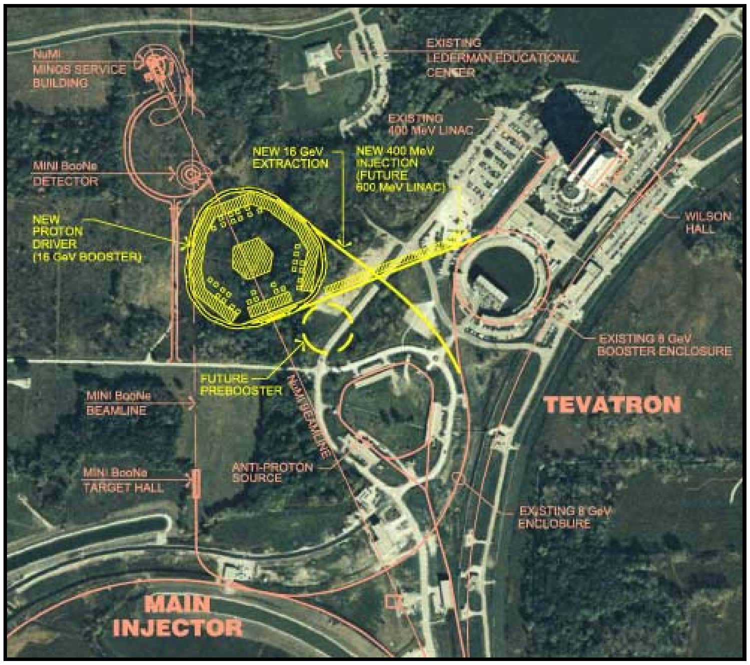

FIG. 4: Fermilab proton driver on the Fermilab site.

- **Storage Ring:** A compact racetrack-shaped superconducting storage ring in which ≈35% of the stored muons decay toward a detector located about 3000 km from the ring.

V. DETECTOR

The Neutrino Factory plus its long-baseline detector would have a physics program that is a logical continuation of current and near-future neutrino oscillation experiments in the U.S., Japan and Europe. Moreover, detector facilities located in experimental areas near the neutrino source would have access to integrated neutrino intensities 10^4–10^5 times larger than previously available (10^{20} neutrinos per year compared with 10^{15}–10^{16}).

Specifications for the long-baseline Neutrino Factory detector are rather typical for an accelerator-based neutrino experiment. However, because of the need to maintain a high neutrino rate at these long distances ($\approx$ 3000 km), the detectors considered here are 3–10 times more massive than those in current neutrino experiments.

Several detector options are possible for the far detector:

- A 50 kton steel–scintillator–proportional-drift-tube (PDT) detector. The PDT detector would resemble

MINOS. A detector with dimensions 8 m × 8 m × 150 m (Fig. 6) would record up to 4×10^4 ν_μ events per year.

- A large water-Cherenkov detector, similar to SuperKamiokande but with either a magnetized water volume or toroids separating smaller water tanks. This could be the UNO detector [25], currently proposed to study both proton decay and cosmic neutrinos. UNO would be a 650-kton water-Cherenkov detector segmented into a minimum of three tanks. It would have an active fiducial mass of 440 kton and would record up to 3×10^5 ν_μ events per year from the Neutrino Factory beam.
- A massive liquid-argon magnetized detector [26] that would attempt to detect proton decay, detect solar and supernova neutrinos, and also serve as a Neutrino Factory detector.

For the near detector, a compact liquid-argon TPC (similar to the ICARUS detector [27]) could be used. It would be cylindrically shaped with a radius of 0.5 m and a length of 1 m, would have an active volume of 10^3 kg, and would provide a neutrino event rate $O(10\ \text{Hz})$. The TPC could be combined with a downstream magnetic spectrometer for muon and hadron momentum measurements. At these neutrino intensities, it is even possible to envision an experiment with a relatively thin Pb target ($1\ L_{rad}$), followed by a standard fixed-target spectrometer containing tracking chambers, time-of-flight and calorimetry, with an event rate $O(1\ \text{Hz})$.

VI. R&D PROGRAM

Successful construction of a muon storage ring to provide a copious source of neutrinos requires many novel approaches to be developed and demonstrated. To construct a high-luminosity Muon Collider is an even greater extrapolation of the present state of accelerator design. Thus, reaching the full facility performance in either case requires an extensive R&D program.

Each of the major systems has significant issues that must be addressed by R&D activities, including a mix of theoretical, simulation, modeling, and experimental studies, as appropriate. Component specifications need to be verified. For example, the cooling channel assumes a normal conducting rf (NCRF) cavity gradient of 17 MV/m at 201.25 MHz, and the acceleration section demands similar performance from superconducting rf (SCRF) cavities at this frequency. In both cases, the requirements are beyond the performance reached to date for cavities in this frequency range. The ability of the induction linac units to coexist with their internal SC solenoids must be verified, and the ability of the target to withstand a proton beam power of up to 4 MW must be tested. Finally, a cooling demonstration experiment must be undertaken to validate the implementation of the cooling channel.

To make progress on the R&D program in a timely way, the required support level is about \$15M per year. At present, the MC is getting only about \$8M per year, so R&D progress is less rapid than it could be.

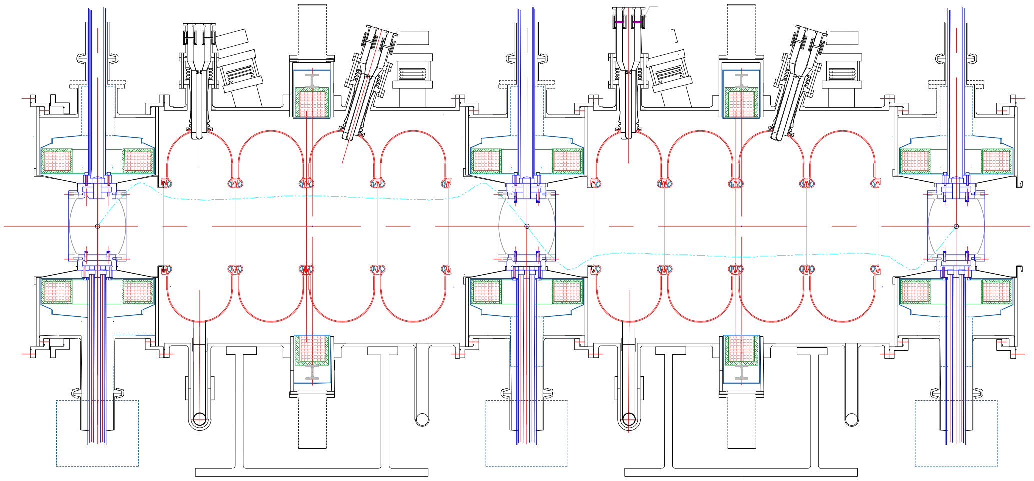

FIG. 5: Two typical cells of an ionization cooling channel.

VII. COST ESTIMATE

The Study-II team has specified each system in sufficient detail to obtain a "top-down" cost estimate for it. Clearly this estimate is not the complete and detailed cost estimate that would come from preparing a full Conceptual Design Report (CDR). However, there is considerable experience in designing and building accelerators with similar components, so they had a substantial knowledge base from which costs could be derived. With this caveat, they find that the cost of such a facility is about \$1.9 B in FY01 dollars. This value represents only direct costs, not including EDIA, overhead, contingency allowances or escalation. A breakdown by system is shown in Table I.

It should be noted that the current design has erred on the side of feasibility rather than costs. Thus, they do not yet have a fully cost-optimized design, nor one that has been reviewed from the standpoint of "value engineering." In that sense, there is hope that a detailed design study will *reduce* the costs compared with what is indicated here.

VIII. STAGING SCENARIO

If desired by the particle physics community, a fast-track plan leading directly to a Neutrino Factory could be executed. This would be done by beginning now to create the required Proton Driver (see Stage 1 below), using well-understood technology, while working in parallel on the R&D needed to complete a CDR for the Neutrino Factory facility. It is estimated that, with adequate R&D support, one could complete a CDR in 2006 and be ready for construction in 2007. On the other hand, the Neutrino Factory offers the distinct advantage that it can be built in stages. This could satisfy both programmatic and cost constraints by allowing an ongoing physics program while reducing the annual construction funding needs. Depending on the results of our technical studies and the results of ongoing searches for the Higgs boson, it is hoped that the Neutrino Factory is really the penultimate stage, to be followed later by a Muon Collider (e.g., a Higgs Factory). Below we list possible stages for the evolution of a muon beam facility and give an indication of incremental costs. These cost increments represent only machine-related items and do not include detector costs.

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

We envision 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

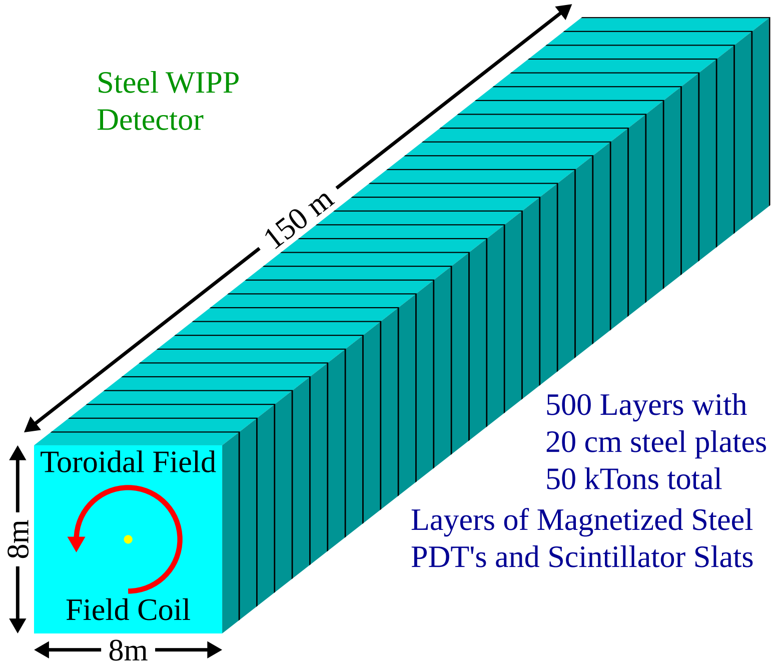

FIG. 6: A possible 50-kton steel-scintillator-PDT detector at WIPP.

TABLE I: Summary of construction cost totals for Study-II Neutrino Factory. All costs are in FY01 dollars unless otherwise noted.

System	Sum (\$M)	Others[a] (\$M)	Total (\$M)
Proton Driver	168.0	16.8	184.8
Target Systems	92.0	9.2	101.2
Decay Channel	4.6	0.5	5.1
Induction Linacs	319.0	31.9	350.9
Bunching	69.0	6.9	75.9
Cooling Channel	317.0	31.7	348.7
Pre-accel. linac	189.0	18.9	207.9
RLA	355.0	35.5	390.5
Storage Ring	107.0	10.7	117.7
Site Utilities	127.0	12.7	139.7
Totals	1,747	175	1,922

[a] Others is 10% of each system to account for missing items, as was used in Study-I.

5×10^{14} μ/s (5×10^{21} μ/year) into a solenoid channel. Costs for this stage depend on site-specific choices, e.g., beam energy. This stage could be accomplished within the next 4–5 years if the particle physics community considers it a high priority.

Stage 2: \$660–840M

We envision a muon beam that has been phase rotated and transversely cooled. This provides a muon beam 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 taking the cooling channel length adopted in Study-II. If more intensity were needed, and if less cooling could be tolerated, the length of the cooling channel could be reduced. Accepting twice the transverse emittance would reduce the incremental cost by about \$180M. At this stage, physics with intense cold muon beams can start and continue to the stage when the muons are accelerated.

Stage 3: \$220–250M

We envision using the pre-acceleration Linac to raise the beam energy to roughly 3.1 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. No cost estimate has been made for this ring, but it would be expected to cost roughly \$30M.

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

We envision having a complete 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

We envision an entry-level Muon Collider to operate as a Higgs Factory. No cost estimate has yet been prepared for this stage, so we mention here only the obvious "cost drivers"—the additional cooling and the additional acceleration. Future work will define the system requirements better and permit a cost estimate of the same type provided for Studies-I and -II.

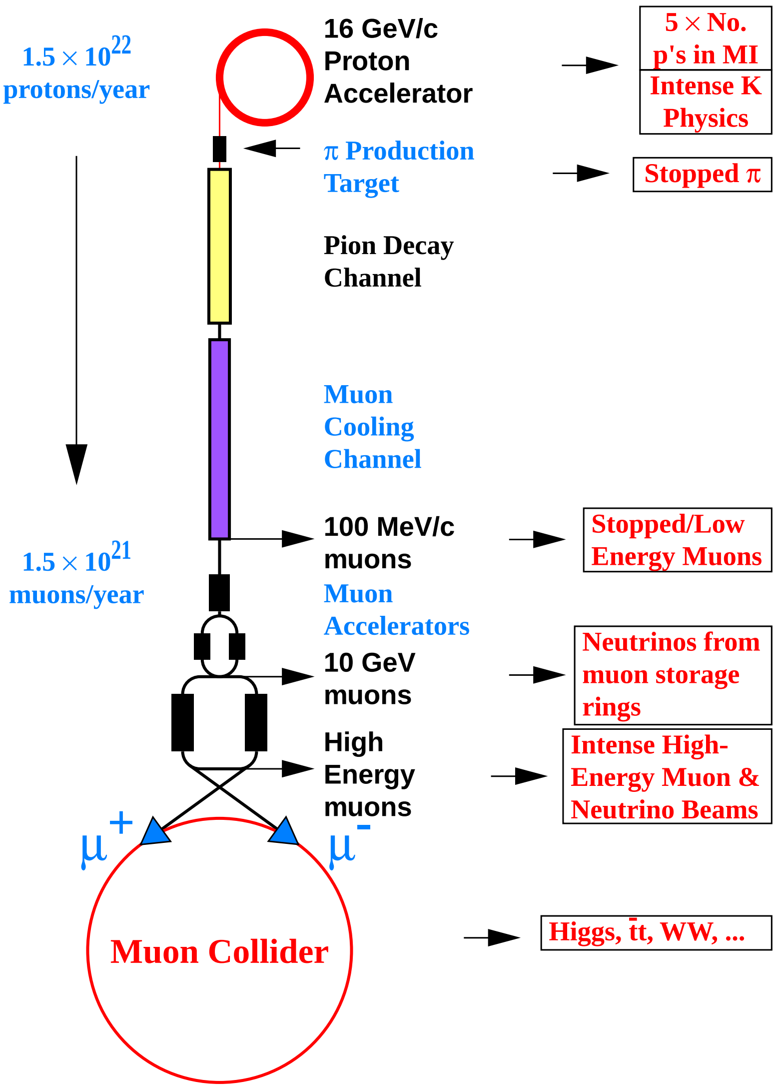

FIG. 7: Schematic of a muon collider.

IX. SUPERBEAMS

The first stage of a Neutrino Factory is a proton driver that could be immediately used as a source for a neutrino superbeam. Such a beam is of considerable physics interest; its physics case has been carefully explored in Working Group E1. Our group is strongly in favor of building a driver in the U.S., either at Fermilab or at BNL.

X. MUON COLLIDER

As is clear from the above discussion, a Neutrino Factory facility can be viewed as a first critical step on the path toward an eventual high-energy Muon Collider. Figure 7 shows a schematic of such a muon collider, along with a depiction of the possible physics that can be addressed with each stage of the facility [23]. Such a collider offers the potential of bringing the energy frontier in particle physics within reach of a moderate sized machine. The very fortuitous situation of having an intermediate step along this path that offers a powerful and exciting physics program in its own right presents an ideal opportunity; it is hoped that the particle physics community will have the resources to take advantage of it.

To reach the feasibility study stage, we must find robust technical solutions to longitudinal emittance cooling, issues related to the high bunch charges, techniques for cooling to the required final emittances, and the design of a nearly isochronous and a very low β^* collider ring. We are confident that solutions exist along the lines we have been investigating. The MC is eager to advance to the stage of building a Muon Collider on the earliest possible time scale. However, for that to happen there is an urgent need to increase support for muon R&D so that the MC can address the vital issues. Unless and until we obtain such support, it is hard to predict how long it will take to solve the longitudinal emittance cooling and other collider-specific problems.

XI. INTERNATIONAL ACTIVITIES

Work on Neutrino Factory R&D is being carried out both in Europe and in Japan. Communication between these groups and the MC is good. In addition to having members of the MC Executive Board from these regions, there are annual NUFACT workshops held to disseminate information. These meetings, which rotate through the three regions, have been held in Lyon (1999), in Monterey (2000), and in Tsukuba (2001); the next meeting will be held in London, followed the next year with one in the U.S.

Activities in Europe are centered at CERN but involve many European universities and labs. Their concept for a Neutrino Factory is analogous to that of the MC, but the implementation details differ. The European Proton Driver is based on a 2.2-GeV superconducting proton linac that makes use of the LEP rf cavity infrastructure. Phase rotation and cooling are based on rf cavities operating at 44 and 88 MHz, along with appropriate LH_2 absorbers. R&D on the rf cavities is in progress. CERN has mounted the HARP experiment to measure particle yields in the energy regime of interest to them (about 2 GeV). The CERN group is participating actively in the E951 Targetry experiment at BNL, and has provided some of the mercury-jet apparatus that was tested successfully. European groups are also heavily involved in the MUSCAT experiment at TRIUMF, where they play a lead role.

Activities in Japan have concentrated on the development of Fixed-Field Alternating Gradient (FFAG) accelerators. These have very large transverse and longitudinal acceptance, and thus have the potential of giving a Neutrino Factory that does not require cooling. They are pursuing this scheme. A proof-of-principle FFAG giving 500-keV protons has already been built and tested, and plans exist for a 150 MeV version. A 50-GeV 1-MW Proton Driver is approved for construction in Japan, with a six-year schedule. A collaboration with the MC on LH_2 absorber design is under way, using U.S.-Japan funds.

On a global note, the three regions are in the process of developing a joint proposal for an international Cooling Demonstration Experiment that could begin in 2004. A Steering Committee has been set up for this purpose, with representatives from all three regions (see section A).

XII. ACTIVITIES

Primarily, the M1 Group had joint meetings with other groups as can be seen from the Agenda in Section B. Also in this Section is the charge to the M1 Group and a list of participants in the M1 Group.

The purpose of the many joint meetings was to reach out to physicists not presently involved in muon activities. From the Technical Groups we profited from the many experts on particular technologies. Hopefully, we also interested them in working on some of our problems. In our interaction with experimental physicists, the E Groups (in particular the E1 group), we primarily worked on the staging concept. Here the interaction was intense as we supplied them with beam parameter lists, and they suggested to us some modifications that would be advantageous. An example is the linac energy, which we have had at 2.87 GeV: a change to 3.1 GeV would be advantageous for $g-2$ work.

Turning to the *Charge*, we believe that essentially all of the points raised have been discussed in other Sections of this document. However, to summarize:

- The accelerator aspects of a Neutrino Factory and a Muon Collider have been delineated. A Muon Collider requires all of the elements needed for a Factory (Driver, target, decay and capture section, longitudinal manipulation of particles and transverse cooling of particles, and acceleration). The racetrack-shaped storage ring from the neutrino factory will be replaced by a circular collider ring for the collider. In addition, the Collider requires very much more cooling and emittance exchange, and a collider ring that is nearly isochronous. Also there are space-charge effects associated with the intense bunches needed for a Collider. The major issue, beyond those encountered in a Factory, is longitudinal cooling (emittance exchange).

- The Factory is an important step towards a Collider. The various aspects of a Factory (as described above), aside from the storage ring, would all have to be achieved experimentally prior to initiating a Collider.

- The required R&D is described in Section VI, and described in much more detail by the MC. Realizing that program will require around $15M per year in funding.
- Various international activities are described in Section 11. It should be noted that the Japanese have already initiated construction of a proton driver. They will have a superbeam (at the 1 MW level) by 2007.
- Cooling experiments are needed. MUSCAT, a scattering experiment, and HARP, a production experiment, have been initiated by our European colleagues (but we are involved also). In addition, there is a production experiment proposed (FNAL-P907) in the Meson laboratory at Fermiab which will measure particle spectra with nearly complete acceptance and particle identification over the energy range 5 GeV/c to 120 GeV/c for various beam species that is also of interest to us[28]. Tests of components are under way at Fermilab; a string test (3 sections of the cooling channel) is the long-term goal. In addition, an international cooling demonstration experiment is being explored as described in Appendix A (Section A).
- It is premature, in our judgment, to make comparisons of a Muon Collider and a Linear Collider either in performance or a required R&D program.

XIII. CONCLUSIONS

In summary, the working group has assessed the present knowledge and ability to create, manipulate, and accelerate muon beams. Their R&D program will position the HEP community such that, when it requires a Neutrino Factory or a Muon Collider, we shall be in a position to provide it. A staged plan for the deployment of a Neutrino Factory has been developed that provides an active neutrino and muon physics program at each stage. The requisite R&D program, diversified over laboratories and universities and having international participation, is currently supported at the $8M level, but requires of the order of $15M per year to make progress in a timely way.

APPENDIX A: AN INTERNATIONAL AGREEMENT

1. Towards an International Muon Cooling Experimental Demonstration

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Dan Kaplan, Michael Zisman
June 15, 2001

a. Motivation

Ionization cooling of minimum ionizing muons is an important ingredient in the performance of a neutrino factory. However, it has not been demonstrated experimentally. We seek to achieve an experimental demonstration of cooling in a muon beam. In order to achieve this goal, we propose to continue to explore, for the next six months or so, at least two versions of an experiment based on existing cooling channel designs. If such an experiment is feasible, we shall then select, on the basis of effectiveness, simplicity, availability of components and overall cost, a design for the proposed experiment.

On the basis of this conceptual design, we will then develop detailed engineering drawings, a schedule and a cost estimate. The costs and responsibilities will be broken down by function (e.g. magnets, RF, absorbers, diagnostics, etc.) and also by laboratory and region. A technical proposal will be developed by Spring 2002, and will be used as the basis for detailed discussions with laboratory directors and funding agencies.

The aim of the proposed cooling experimental demonstration is

- to show that we can design, engineer and build a section of cooling channel capable of giving the desired performance for a neutrino factory;

- to place it in a beam and measure its performance, i.e. experimentally validate our ability to simulate precisely the passage of muons confined within a periodic lattice as they pass through liquid hydrogen absorbers and RF cavities.

The experience gained from this experimental demonstration will provide input to the final design of a real cooling channel.

The signatories to this document volunteer to organize this international effort. It is expected that the membership of this group, referred to in this document as the Muon Cooling Demonstration Experiment Steering Committee (MCDESC) will evolve with time. It is proposed that the Chair of this group should be Alain Blondel for the first year.

b. Organization

- The overall organization and coordination of the activity shall be the responsibility of the MCDESC.
- The MCDESC shall assemble members of a technical team to develop the proposal. The members of this technical team should represent at least two geographical regions in each of the following aspects

1. Concept Development and Simulation
2. Absorbers
3. RF Cavities and Power Supplies
4. Magnets
5. Diagnostics
6. Beamlines

- It is expected that the MCDESC will work mainly by telephone conference and e-mail, but should meet, typically, twice each year, preferably in association with other scheduled meetings. These meetings should rotate around the regions. The technical team should organize its activities as appropriate.

c. Schedule

The goal is to carry out a first experiment in 2004, in the expectation that this could develop into more sophisticated tests, including possibly the demonstration of longitudinal cooling. In order to achieve this ambitious schedule, it will be necessary to make proposals to laboratory directors and funding agencies in 2002. *Therefore*,

1. A short document (of order ten pages) making key technology choices (including the choice of version of the experiment and location) should be presented by Dec 15th 2001.
2. This conceptual design should be developed into a full technical proposal by June 2002. This technical proposal would need engineering drawings, schedules and costs, and distribution of responsibilities. This would include the cost breakdown by component (RF, magnet, absorber, diagnostics, beam) and by country and/or laboratory.

It is the responsibility of the technical team to provide the technical evaluations of the alternative approaches, in order for the MCDESC to be able to make the required technology choices in the Fall of 2001.

APPENDIX B: CHARGE, AGENDA AND PARTICIPANTS OF WORKING GROUP M1

1. Charge

Intense muon sources have been discussed as a starting point for very high energy colliders and even more in recent years as a source of very intense and well-collimated neutrino beams. This working group should identify, but clearly distinguish, the main accelerator physics aspects of both the Muon Collider and the Neutrino Source. Even more, it is crucial to understand for the high energy physics community, how much a neutrino Source represents a first step to a muon collider and what are the additional burdens. Given the variety of technologies that require R&D makes it necessary to have the group present a risk assessment of the various subcomponents, their R&D goals and the time scale on which the R&D could be realized. The more recent refocus of the collaboration towards Neutrino Sources should reflect in the main topics of the discussion. The different approaches: CERN, KEK-JAERI, and the Muon Collaboration (including the Fermilab and Brookhaven locations) should be compared in performance, risk and (if possible) schedule. A discussion on whether a Muon Cooling experiment is necessary and/or viable is absolutely required and should be presented by the group. For the Muon colliders, the technical performance, especially for a low energy (Higgs collider) machine should be addressed. Technical performance (power consumption, risk assessment, luminosity, etc.) should be compared to linear colliders in the same energy range. Input here will be required from the High Energy physicists to define the measure of performance for these two concepts (MC, LC). For the long-term R&D the advantages compared to electron-positron accelerators should be worked out and quantified as much as possible.

2. Agenda

The M1 working group covered several topics, including

- Overviews of neutrino factory machine issues and physics (E1)
- Higgs factories (E1)
- Intense muon sources from intense proton beams (E1, E5, M6)
- Targetry (T4)
- Staging scenarios (E1)
- Cooling dynamics (T5)
- Codes for cooling simulations (T7)
- Muon beam diagnostics (T9)
- FFAG rings (T5)
- Cooling experiments
- Magnets (T2)
- RF structures (T3)
- High energy muon colliders (multi-TeV)
- Muon colliders based on linear colliders (M3)

Many of our sessions were joinly convened with another of the working groups; groups that we met with are indicated in parentheses after the topic.

TABLE II: Participants in the M1 working group.

M. Aoki	IPNS/KEK	K. Hoffman	U. Chicago	B. Parker	BNL
V. Balbelkov	FNAL	A. Jackson	LBNL	Z. Parsa	BNL
W. Barletta	LBNL	C. Johnstone	FNAL	G. Penn	UC Berkeley
J.S. Berg	BNL	C.-K. Jung	SUNY Stony Brook	B. Pope	MSU
M. Berger	Indiana U.	S. Kahn	BNL	R. Raja	FNAL
M. Berz	MSU	Y. Kamyshkov	U. Tennessee	P. Reimer	ANL
A. Blondel	U. Geneve	D. Kaplan	IIT	T. Roser	BNL
A. Bogacz	TJNAL	E. Keil	CERN	R. Ryne	LBNL
E. Buckley-Geer	FNAL	B. King	BNL	R. Samulyak	BNL
M. Campanelli	ETH/IFT	H. Kirk	BNL	J. Sato	KEK
D.B. Cline	UCLA	E. Kinney	U. Colorado	P. Schwandt	Indiana U.
L. Coney	Columbia U.	Y. Kuno	Osaka U.	A. Sessler	LBNL
F. DeJongh	FNAL	D. Krop	Indiana U.	M. Shaevitz	FNAL
M. Diwan	BNL	J. Learned	U. Hawaii	M. Sharp	Columbia U.
V. Elvira	FNAL	P. Lebrun	FNAL	N. Simos	BNL
R. Fernow	BNL	Z. Li	BNL	M. Sokoloff	U. Cincinnati
D. Finley	FNAL	S. Lidia	LBNL	P. Spentzouris	FNAL
B. Fleming	Columbia U.	S. Machida	KEK	I. Stumer	BNL
J. Formaggio	Columbia U.	K. Makino	U. Illinois	D. Summers	U. Miss.
Y. Fukui	UCLA	W. Marciano	BNL	K. Takayama	KEK
J.Gallardo	BNL	S. Martin	Juelich	V. Telnov	Budker INP
A. Garren	UCLA	K. McDonald	Princeton U.	P. Tenenbaum	SLAC
S. Geer	FNAL	K. McFarland	U. Rochester	M. Tigner	Cornell U.
M. Goodman	ANL	P. McIntrye	Texas A&M	A. Tollestrup	FNAL
A. Green	Iowa SU	E. McKigney	Imperial C.	Y. Torun	IIT
J. Gunion	UC Davis	F. Mills	FNAL	C.-X. Wang	ANL
J. Griffin	FNAL	N. Mokhov	FNAL	H. Weerts	MSU
R. Gupta	BNL	J. Monroe	Columbia U.	R. Weggel	BNL
J. Hansen	CERN	Y. Mori	KEK	M. Witherell	FNAL
G. Hanson	Indiana U.	P. Murray	UC Davis	S. Wojcicki	Stanford U.
D. Harris	FNAL	D. Neuffer	FNAL	J. Wurtele	LBNL
H. Haseroth	CERN	J. Norem	ANL	K. Yoshimura	KEK
M. Hebert	UC Irvine	M. Oreglia	U. Chicago	J. Yu	FNAL
S. Henderson	Cornell U.	R. Palmer	BNL	M. Zisman	LBNL

3. Participants

Table II gives the participants in the M1 working group along with their institutions. This was compiled from the list of those who indicated in their registration that they would be participating in the M1 working group, plus those who were known to have participated in the working group.

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