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

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1 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.

This working group reviewed the 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. In addition, the group continued with the efforts to establish and maintain strong international collaborations in several areas of R&D.

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 there is fully developed the capability for cooling and accelerating muons, 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 both ν_μ and $\overline{\nu}_e$ intense beams for stored μ^- beams and their charge conjugate beams for stored μ^+ beams. In addition, they have 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 $\nu_e \rightarrow \nu_\mu$. By comparing the rates for this channel with its charge-conjugate channel $\overline{\nu}_e \rightarrow \overline{\nu}_\mu$, 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 plays 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. 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.

2 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.*

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 interesting in its own right. 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 to what extent 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

*A good summary of the Muon Collider concept can be found in the Status Report of 1999 [9]; an earlier document [10], prepared for Snowmass-1996, is also useful reading. MC Notes prepared by the MC are available on the web [11] neutrino physics beyond that available using a conventional beam and, that a Neutrino Factory can go even beyond.

More recently, BNL organized a follow-on 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.

Studies I and II are site specific in that in each study there are a few site-dependent parts; otherwise, they are quite generic. In particular, Study-II uses BNL site-specific proton driver specifications and a BNL-specific layout of the storage ring, especially the pointing angle of the straight sections. Study-I uses an upgraded Fermilab booster to achieve the required beam intensity. 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). 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 [22].

3 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.

One aim of Study-I was to assess the extent to which the Fermilab accelerator complex could be made to 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.

As noted above, 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:

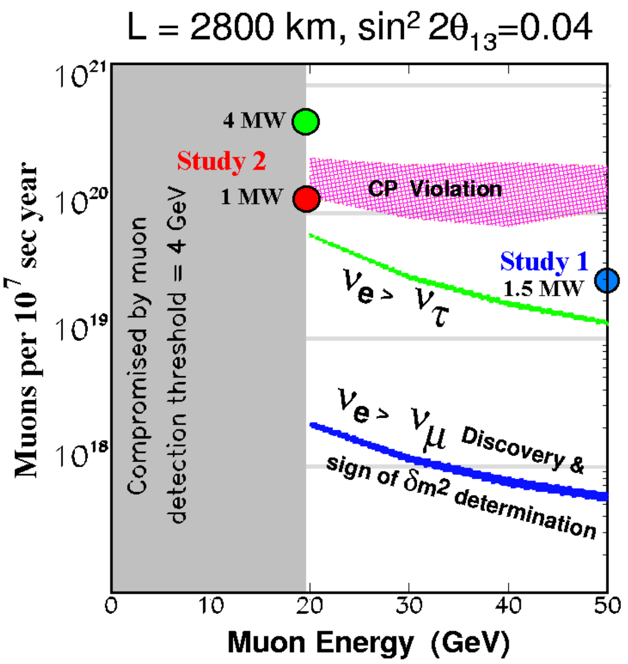

Figure 1: Muon decays in a straight section per 10^7 s *vs.* muon energy, with fluxes required for different physics searches assuming a 50 kT detector. Simulated performance of the two studies is indicated.

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

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 1.4×10^{21} μ /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 times the Study-I yield at 4 MW).

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

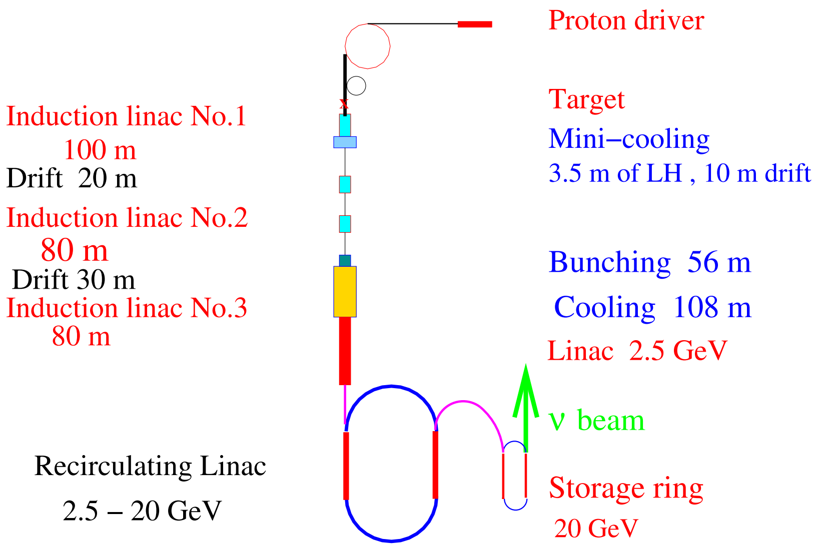

Figure 2: Schematic of the Neutrino Factory-Study II version.

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 ≈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. It is 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 neutrino beams, since the electron final state from conventional beams has significant background contribution from π^0's produced in the events.

4 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 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; a new booster at Fermilab 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, 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.

- **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.

5 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 (≈ 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 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 [23], 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 [24] 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 [25]) 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 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 Hz).

6 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. Alternative designs of some of the sections, which may have significant cost and/or performance advantages will also be explored. 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.

Table 1: 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.

7 Cost Estimate

The Study-II members have 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 scallation. A breakdown per components is shown in Table 1.

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.

8 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 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

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 and bunch stacking. Future work will define the system requirements better and permit a cost estimate of the same type provided for Studies-I and -II.

9 Superbeams

The first stage of a Neutrino Factory is a proton driver which, most properly, would 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.

10 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 3 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 [22]. Such a collider offers the potential of

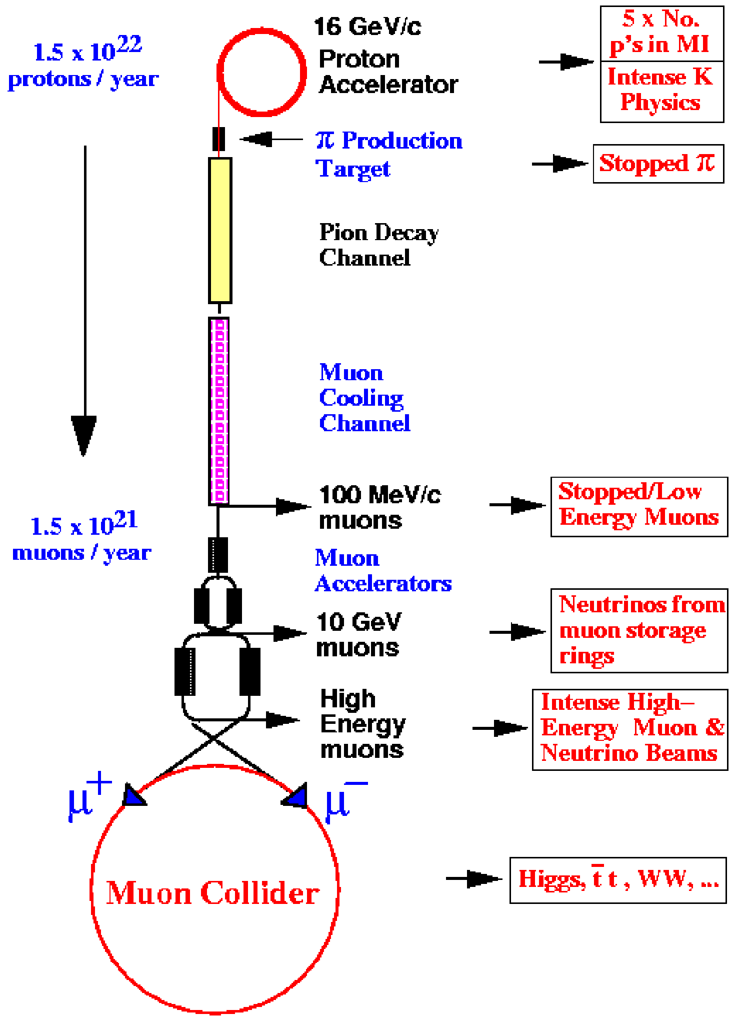

Figure 3: Schematic of a muon collider.

bringing the energy frontier in particle physics within reach of a moderate sized machine. The very fortuitous situation of having intermediate steps along this path that offer a powerful and exciting physics program in their 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 closely isochronous and a very low β^* collider ring. We are confident that solutions exist along the lines we have been investigating (bend and helical solenoids and ring coolers). 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.

11 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 laboratories. 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 14).

12 M1 Activities

Primarily, the M1 Group had joint meetings with other groups, as can be seen from the Agenda in Section 15. Also in 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. In the join meetings with the Technical Groups, we profited from the many experts on distintive technologies; in particular, the beam dynamics group (T5) has provided a number of insights toward the solution of the non-linear problems encounter in the cooling channel. In our interaction with experimental physicists, the E Groups, we mainly interacted on the staging concept and, primarily, with the E1 Group. 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 had been 2.87 GeV and 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). Only the storage ring is not needed. However, a Collider requires very much more cooling and emittance exchange, and a collider ring that is closely isochronous. In addition there are space charge effects associated with the intense bunches needed for a Collider. The major difficulty, 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), simply without a storage ring, would all have to be achieved experimentally prior to initiating a Collider.

- The required R&D is described in Section 6, and described in much more detail by the MC. It requires $15M a year for a healthy and directed program.

- 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 super beam by 2007.
- Cooling experiments are needed. MUSCAT, a scattering experiments, and HARP, a production experiment have been initiated by our European colleagues (but we are involved also). Test of components are underway at Fermilab, while 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 14).
- 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.

13 Conclusions

In summary, the working group has assessed the present knowledge and ability to create, manipulate, and accelerate muon beams. This 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.

14 Appendix-A: An International Agreement

Towards an International Muon Cooling Experimental Demonstration

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June 15, 2001

Motivation

Ionisation cooling of minimum ionising 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, schedule and a cost estimate. The costs and responsibilities will be broken out 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 organise 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.

Organisation

- The overall organisation 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 organise its activities as appropriate.

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.

15 Appendix-B: Charge, Agenda and Participants of Working Group M1

15.1 Charge

Snowmass 2001 Working Group M1:

Muon Based Accelerators

Working Group Conveners: K. McDonald (Princeton), A. Sessler (LBL)
Organizing Committee Contacts: N. Holtkamp (SNS), T. Roser (BNL)

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.

15.2 Agenda

Meet in Club (Silvertree Hotel) unless otherwise noted

M1 Working Group Schedule

(Everything not marked as	confirmed	might still change)

Day	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturda
Date	July 1	July 2	July 3	July 4	July 5	July 6	July 7
Morning [Session Convener]	Plenary	Plenary	**E&M #1 Overview of Neutrino Factories Joint with E1 [Raja]**	**E&M #2 Higgs Factory Muon Colliders Joint with E1 [Cline, Hanson]**	**P&T #3 E1/P1 Joint Session?**	**E&M #3 Intense Muon Sources Joint with E1 and E5 Intense Proton Sources Joint with M6 [McDonald]**	**E&M #4 Muon Collider with E > 1 TeV [King]**
Status	Confirmed	Confirmed	Confirmed	Confirmed		Confirmed	Confirme
Afternoon	Plenary	**P&T #1**	**P&T #2**	Holiday	Teach-in: Accelerator R&D	**P&T #4 Targetry Joint with T4 [Mokhov]**	**P&T #5**
Status	Confirmed			Confirmed	Confirmed	Confirmed	

Day	**Sunday**	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturd**
Date	July 8	July 9	July 10	July 11	July 12	July 13	July 1
Morning	Open	**E&M #5 Neutrino Factory Overview II / Staging Scenarios Joint with E1 [Geer]**	**P&T #7 Cooling Dynamics, 1 Joint with T5 [Wurtele]**	**E&M #7 Open (The E1 session is on underground experiments)**	Plenary	**E&M #8 Cooling Dynamics, 3 Joint with T5 [Fernow]**	**E&M # Open (The E session is staging**
Status	Confirmed	Confirmed	Confirmed	Confirmed	Confirmed	Confirmed	
Afternoon	Open	**P&T #6 Magnets Joint with T2?**	**E&M #6 Cooling Dynamics, 2 Joint with T5? [Kaplan]**	**P&T #8 Muon Beam Diagnostics Joint with T9 [Norem]**	Plenary	(Teach-in: Non Accelerator Experiments) **E&M #8a FFAG Ring Dynamics Joint with T5 [Johnstone]**	**P&T # Codes f Coolin Simulati Joint wit [Spentzou**
Status	Confirmed		Confirmed	Confirmed	Confirmed	Confirmed	Confirm

Day	**Sunday**	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**
Date	July 15	July 16	July 17	July 18	July 19	July 20	July 21
Morning	Open	**E&M #10 Cooling Experiment** **[Geer]**	**E&M #11 Electron - Muon Colliders Joint with M3 [King]**	**E&M #12 Summary [Sessler]**	Plenary	Plenary	Departure
Status	Confirmed	Confirmed	Confirmed	Confirmed	Confirmed	Confirmed	Confirme
Afternoon	Open	**P&T #10**	**P&T #11**	**P&T #12 Advanced RF Structures & Spinoffs [Padamsee]** **T3 Group**	Plenary	Plenary	Departure

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Created 11 April 2001 by K. McDonald, based on the M5 group page

15.3 Participants

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Last updated 06/15/01

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