Muon Collaboration

Neutrino Factory and Muon Collaboration
R&D Plan

August 26, 2000

Introduction

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. The breadth of R&D issues to be dealt with is beyond the resources available at any single national laboratory or university. For this reason, in 1995 interested members of the high-energy physics and accelerator physics communities formed the Neutrino Factory and Muon Collider Collaboration (*MC)* to coordinate the required R&D efforts nationally. The *MC* (see the Collaboration homepage, http://www.cap.bnl.gov/mumu/mu_home_page.html, for further details) comprises three sponsoring national laboratories (BNL, FNAL, LBNL) along with groups from other U.S. national laboratories and universities and individual members from non-U.S. institutions. Its task is to define and carry out R&D required to assess the technical feasibility of constructing initially a muon storage ring that will provide intense neutrino beams aimed at detectors located many thousands of kilometers from the accelerator site, and ultimately a $\mu^+\mu^-$ collider that will carry out fundamental experiments on the energy frontier in high-energy physics. The *MC* also serves to coordinate related R&D activities of the NSF-sponsored University Consortium (*UC*) and the state-sponsored Illinois Consortium for Accelerator Research (*ICAR*) and is the focal point for defining the needs of muon-related R&D to the managements of the sponsoring national laboratories and to the funding agencies (both DOE and NSF). Though the *MC* was formed initially to carry out R&D that might lead eventually to the construction of a Muon Collider, more recently its focus has shifted mainly, but not exclusively, to a Neutrino Factory. For those interested, there is a library of more than 140 Muon Collaboration Notes posted on the web at the URL http://www-mucool.fnal.gov/htbin/mcnote1LinePrint. A detailed report on the design of a Muon Collider was produced for the Snowmass ’96 meeting and this is also available on the web at URL http://www.cap.bnl.gov/mumu/pubs/snowmass96.html.

The *MC* maintains close contact with parallel efforts under way in Europe (centered at CERN) and in Japan (centered at KEK). Through its international members, the *MC* also fosters coordination of the international muon-beam R&D effort. Two major initiatives, a Targetry Experiment (E951) recently approved for operation at BNL and a Muon Cooling R&D program (MUCOOL), have been launched by the *MC*. In addition, the Collaboration, working in conjunction with the *UC* and *ICAR* in some areas, coordinates substantial efforts in accelerator physics and component R&D to define and assess parameters for feasible designs of muon-beam facilities.

The Collaboration elects a Spokesperson (now Andrew Sessler from LBNL) to be contact person for policy and planning with the funding agencies, with the management of the

M. Zisman
Project Manager

sponsoring national laboratories and universities, and with the Muon Collaboration Oversight Group (MCOG) and its Technical Advisory Committee (MUTAC). A Project Manager (now Michael Zisman from LBNL), appointed by MCOG, is responsible for overseeing the implementation of the *MC* R&D program and for reporting on the budget, schedule, and technical progress to MCOG and to the DOE. The Collaboration, through its Executive Board (http://www.cap.bnl.gov/mumu/info/executive_board.html gives the membership list) and Technical Board, (whose membership list can be found at http://www.cap.bnl.gov/mumu/info/technical_comm.html) reviews and approves funding for muon-related R&D activities. The Project Manager, in consultation with the *MC* Spokesperson, advises the sponsoring national laboratories, the *UC*, and the *ICAR*, about how best to use their muon-related resources in a complementary manner.

To coordinate the R&D program, the *MC* holds semiannual Collaboration Meetings where summaries of ongoing work are presented and proposals and plans for new activities are made. The Project Manager, with the help of the Collaboration Spokesperson, is responsible for preparing budget submissions to the DOE, and accounting for monies previously allocated. The Project Manager and Spokesperson also review plans, schedules, and budgets for the related work undertaken by the *UC* and the *ICAR*. *MC* R&D plans and progress are reviewed on a regular basis by MUTAC, made up from experts in the field. MUTAC members are appointed by, and report to, MCOG, which presently includes senior managers from the three sponsoring national laboratories. MCOG provides oversight for the Collaboration and, together with the Project Manager, represents the Laboratory viewpoint to the funding agencies.

Each year, Collaboration R&D plans are submitted to and reviewed by the *MC* Technical Board. Budgets are prepared by the R&D leaders and reviewed and approved by the Executive Board and the Project Manager prior to allocation of *MC* resources. A schedule with auditable milestones is required. Prior to committing major funds for component fabrication or substantial consulting activities, there is a Final Design Review organized by the Project Manager to validate the expenditure. The Project Manager is subsequently responsible for monitoring and reporting progress to the *MC*, MCOG, and the funding agencies.

R&D Goals

The approach taken by the *MC* to define the overall R&D program was to decide what we wished to accomplish in a five-year time span in each area and then “work backwards” to see what would be needed to reach that goal. For this exercise, we assumed a technology-limited schedule, that is, we assumed that the required financial resources and personnel would be available and considered how much time would be needed to achieve our technical goals. With this approach, we expect that a five-year technology-limited plan will result in:

- all optics designs being completed and self-consistent
- validation experiments being completed or well along
- all required hardware being defined
- prototypes of the most challenging and costly components being completed or well along, i.e., we would know how to build the "hard parts"
- being ready to begin the design of, and provide cost estimates for, most of the remaining components

At the end of the five-year period, the above goals would put the *MC* in position to begin a formal Conceptual Design Report (CDR) for a Neutrino Factory. It is expected that this CDR stage would take 1–2 years to complete. The CDR would document a complete and fully engineered design for the facility, including a detailed bottom-up cost estimate for all components. This document would form the basis for a full technical, cost, and schedule review of the construction proposal, subsequent to which construction could commence after obtaining government approval.

As an "intermediate milestone" we envision preparing a Zeroth-order Design Report (ZDR) after three years. The ZDR will examine the complete systems of a Neutrino Factory, making sure that nothing is forgotten, and will show how the parts merge into a coherent whole. While it will not present a fully engineered design with a detailed cost estimate, enough detail will be presented to ensure that the critical items are technically feasible and that the proposed facility could be successfully constructed and operated at its design specifications.

Even earlier, by Summer 2001, we expect to prepare a report for the community summarizing the status of Neutrino Factory R&D. This information will permit the high-energy physics community to consider and evaluate the physics potential of a Neutrino Factory and assess the R&D activities and resources necessary to prepare for project construction.

<u>R&D Program Issues</u>

A Neutrino Factory comprises the following major systems: Proton Driver, Target and (Pion) Capture Section, (Pion-to-Muon) Decay and Phase Rotation Section, Bunching and Matching Section, Cooling Section, Acceleration Section, and Storage Ring. These same categories remain for a Muon Collider, with the exception that the Storage Ring is replaced by a Collider Ring having a low-beta interaction point and a local detector. Parameters and requirements for these systems are generally more severe in the case of the Muon Collider, so a Neutrino Factory can properly be viewed as a scientifically productive first step toward the eventual goal of a collider. With this in mind, the Collaboration is concentrating most of its initial effort on the R&D activities that will lead to a design for a Neutrino Factory. As noted earlier, the R&D program described in this document is designed to answer the key questions needed to embark upon a Zeroth-order Design Report (ZDR) after three years. After completion of the full five-year program, it is expected that a formal Conceptual Design Report could begin. Longer-term activities related primarily to the Muon Collider are also supported and encouraged.

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. A brief summary of the key physics and technology issues for each major system is given below.

Proton Driver:

- Production of intense, short proton bunches, e.g., with space-charge compensation and/or high-gradient, low frequency RF systems

Target and Capture Section:

- Power dissipation in the target and beam dump (up to 4 MW of incident protons)
- Performance and pion yield of a liquid-metal jet target
- Performance and pion yield of a solid target
- Verification of predicted pion yield in the Capture Section
- Optimization of target material and geometry (low-*Z* or high-*Z*) by determination of production curves (number of particles vs. energy) for various choices
- Design and performance of a high-field solenoid (≈20 T) in a very high radiation environment
- Development of remote handling capability for target and capture system components

Decay and Phase Rotation Section:

- Design, and performance in a high-radiation environment, of high-gradient, low-frequency RF systems used in conjunction with an external or internal solenoid channel
- Development of efficient and cost-effective high-power sources (e.g., klystrons, tetrodes) for low-frequency RF systems
- Design and performance of high-gradient induction linac modules having an internal superconducting solenoid channel
- Identification and assessment of techniques for polarization preservation

Bunching and Matching Section

- Design and development of efficient bunching system
- Design of transverse matching optics into downstream cooling section

Cooling Section

- Design of transverse emittance cooling channel to reduce emittance by up to a factor of 10 in each plane
- Development and testing of high-gradient RF cavities at a frequency near 200 MHz
- Development and testing of efficient high-power sources at a frequency near 200 MHz
- Development and testing of absorbers (e.g., liquid hydrogen or LiH) for muon cooling
- Design of large-aperture high-field solenoids compatible with 201-MHz RF cavities
- Development and testing of candidate diagnostics to measure emittance and optimize cooling channel performance

- Assessment of the influence of multiple scattering and energy straggling predictions on cooling channel performance, including verification if necessary
- Design beamline and test setup (e.g., diagnostics) needed for demonstration of transverse emittance cooling (MUCOOL program)
- Demonstration of transverse emittance cooling (MUCOOL program)
- Design of longitudinal emittance cooling channel ("emittance exchange")
- Development of six-dimensional analytical theory to guide the design of the cooling section

Acceleration Section

- Design and performance of high-gradient linac at a frequency near 200 MHz (both normal conducting and superconducting versions are needed)
- Design of rapid and efficient acceleration techniques to increase the energy of a muon beam (with a large momentum spread) from a few GeV to a few tens of GeV (e.g., recirculating linacs, rapid cycling synchrotrons, fixed-field alternating-gradient rings) for a Neutrino Factory, or even higher for a Muon Collider
- Design of accelerator lattices to accommodate a muon beam with large momentum spread
- Development of high-gradient superconducting RF cavities at frequencies near 200 MHz, along with efficient power sources (about 10 MW peak) to drive them
- Design and testing of components (RF cavities, magnets, diagnostics) that will operate in the muon-decay radiation environment

Storage Ring

- Design of a storage ring with long straight sections aimed at suitable detectors far from the accelerator site

- Design of large aperture, well shielded superconducting magnets that will operate in the muon-decay radiation environment
- Design of superconducting RF cavities that will operate in the muon-decay radiation environment

Collider

- Cooling of 6-D emittance (x, p_x y, p_y, t, E) by up to a factor of 10^5–10^6
- Acceleration systems to reach an eventual muon beam energy of about 2 TeV
- Design of a collider ring with very low beta (a few mm) at the interaction point having sufficient dynamic aperture to maintain luminosity for about 1000 turns
- Study of muon beam dynamics at high beam-beam tune shifts
- Study of longitudinal space-charge phenomena

Detector

- Simulation studies to define acceptable approaches for both near and far detectors at a Neutrino Factory and for a collider detector operating in a high-background environment
- Develop ability to detect electrons in detector environment

<u>R&D Activities</u>

Fiscal Year 2000

During this year, simulations of an initial version of the Front End of a Neutrino Factory will be completed. The Front End simulations will follow the muons from their production (via pion decay) downstream of the target to the end of an example cooling channel comprising solenoid focusing, high-gradient RF cavities ($f \approx 200$ MHz), and absorbers of liquid hydrogen. Work on understanding and optimizing the Front-End design will continue throughout the year. Investigations of error sensitivity will commence. Additional simulations will be carried out to help define the MUCOOL demonstration. A three-week workshop focusing on emittance exchange, organized jointly by BNL and Indiana University, will be held at BNL toward the end of the year. Understanding this topic is critical for an eventual Muon Collider and even now offers promise to mitigate the effects of the large beam energy spread in the Neutrino Factory cooling channel. In addition, work is under way at Columbia's Nevis Laboratory to evaluate alternative strategies for obtaining a beam of cold muons, such as the moderation of the μ^+ energy in a thin solid rare-gas layer [E. Morenzoni et al., Phys. Rev. Lett. 72, 2793 (1994)] or laser ionization of muonium [K. Nagamine et al., Phys. Rev. Lett. 74, 4811 (1995)].

Work will continue on the targetry experiment, recently approved for operation at BNL. This year the primary emphasis will be on getting the A3 beam line at BNL ready for beam. Other effort will include refurbishing a 70-MHz RF power source at LBNL. This unit will be sent to BNL where it will power a 70 MHz RF cavity having a solenoid field, to be tested ultimately as part of the initial phase rotation channel (for both intensity improvement, in terms of muon to proton ratio, and polarization preservation). In addition to getting ready for experimental tests with the refurbished equipment, engineering studies of a 20-T pulsed solenoid magnet will begin. These will start to explore the hardware implications of operating a high-field solenoid magnet in a high-radiation area. Parallel studies will be carried out on the development of a 5 MW power supply for the pulsed magnet. Simulation studies of solid and liquid-metal targets will be continued to define an initial configuration to test.

Preparations for a muon cooling demonstration (as part of the MUCOOL effort) will continue. Work this year will focus on defining a time-phased set of experimental goals and on developing and testing the required hardware. To focus on the parameter regime appropriate for a Neutrino Factory, the Collaboration will concentrate mainly on the initial portion of the cooling channel where the incoming beam emittance is very large. Carrying out such experiments will require a muon beam line somewhere in the world. Identifying a site for this beam line will be an important goal, as the facility is clearly a long lead time item. To prepare for the experimental program, the first step is to develop components to test. For historical reasons, our initial components will operate at 805 MHz, so they serve as scale models of the actual components. Work is under way to prepare a facility at FNAL (Lab G) for cooling experiment component tests (without beam). This includes installation of refrigeration and power supplies for superconducting solenoids, and power supplies for a high-power 805-MHz open-cell test cavity being completed at FNAL. A 5-T solenoid that can operate in either a standard solenoid or a gradient-solenoid mode (with two coils of opposite polarity) has been completed at LBNL and shipped to FNAL for the tests in Lab G. Initial work will aim at issues associated with operating a high-gradient RF cavity in a strong solenoidal magnetic field. Fabrication of a high-power 805-MHz cavity having beryllium windows will also begin this year. Complementary studies at LBNL will address the behavior of liquid-nitrogen-temperature 5-mil (125-μm) beryllium windows under low-power RF heating to look for deformation effects and define a suitable operating regime. Work is under way at University of Mississippi, Princeton University, UCLA, and at several *ICAR* member institutions to investigate suitable diagnostics devices for the experiments, including Cerenkov detectors, fast-timing devices, TPCs and the like. Work is also proceeding at ANL to examine the x-ray flux from high-gradient RF cavities to evaluate this potentially significant source of backgrounds for a cooling demonstration experiment. Absorber cell development work will focus on development of strong, thin, low-*Z* containment windows. Safety verification of the design will be an important initial task. A test area, probably at FNAL, will be developed for this work, which will be led by the Illinois Institute of Technology and Northern Illinois University as part of the *ICAR* program.

Design work on a 201-MHz high-power normal conducting (NC) RF cavity has commenced. After fabrication, this device will be tested, first in Lab G and ultimately with a muon beam. As a follow-up to the first Feasibility Study (see below), design work is beginning at Cornell (as part of the *UC* program, funded by NSF) for low-frequency superconducting RF cavities. There are a number of technical issues to be addressed in the development of high gradient SCRF cavities at frequencies as low as 200 MHz. The niobium sputtering process must be well controlled over a large surface area, the mechanical structure must be free of low-frequency resonances, and the cavity shell manufacturing process must be efficient and reliable for cost reasons. Initial design work will focus on a single-cell cavity with input coupler port. ANSYS calculations will be done to determine the parameters (shape and wall thickness) necessary to ensure that mechanical resonances will be pushed to high frequencies. Alternative cavity fabrication techniques will also be studied. One approach will use a copper cavity spun as two half-cells and electron-beam welded, then sputtered with niobium, as was done for CERN cavities. A second approach will aim at a single-piece spinning from one sheet, or perhaps a tube, thus avoiding the welding process. This will involve collaboration with INFN in Italy and industry. The goal of this effort is to understand and improve the performance of SCRF cavities in this frequency regime to reach the required operating parameters.

The Collaboration also worked with FNAL staff in carrying out a Feasibility Study for an entry-level Neutrino Factory. This study served to flesh out many of the possible design options and identified potential cost drivers of such a facility. From this study has come the next round of design alternatives and some of the directions that the R&D program will need to take to aim for a proposal to construct such a facility at some future date. A second study of this type, focusing on a “high-end” facility, carried out jointly by BNL and the Collaboration, will commence toward the end of the year.

Fiscal Year 2001

Simulation studies this year will emphasize further optimization of the front-end design. Proper matching of the phase rotation and buncher sections will be studied. Analytic work that aids in understanding better the key design principles will also be done. Both efforts will feed into the second feasibility study, which will be completed during this year. Hardware constraints and limitations defined by the component R&D efforts will be incorporated into the simulations as they become available, in order to ensure that the design uses practically realizable components. Estimates will be made of polarization, to assess whether an initial phase rotation is able to significantly enhance the beam polarization and/or the μ/p (muon per incident proton) ratio delivered to the downstream acceleration section. Studies of emittance exchange techniques will continue at Indiana University and elsewhere, following up on ideas generated at the Emittance Exchange Workshop. Studies of alternative cooling schemes will continue at Columbia if a promising approach is identified. This year, the Front End simulation study will be extended to include the downstream portions of a Neutrino Factory—the acceleration chain and the storage ring itself. When completed, these extended simulation efforts will define a strawman design for a complete facility. Simulation studies for the specific parameters of a possible MUCOOL demonstration will also continue at FNAL, LBNL, ANL, Indiana University, and elsewhere, particularly to examine the influence of straggling and multiple scattering model parameters on the simulation results. Finally, simulations this year will focus more heavily on the downstream portions of the facility, the acceleration chain and the storage ring, paying particular attention to the “transition region” where the focusing changes from solenoidal to quadrupole. This will include detailed modeling of the accelerator magnets including multipole and strength errors and fringe-field effects, using tools such as COSY. During this year the results of the feasibility studies and the R&D program will be summarized for the HEP community as part of the preparations for the Snowmass ’01 meeting that will serve to define future directions for HEP nationally and perhaps internationally.

The targetry experiment A3 line at BNL will see first beam this year. After commissioning, it is expected that initial target tests will take about 6 weeks of (parasitic) beam time. Tests of a liquid-metal jet target in a high magnetic field will get under way at the National High Magnetic Field Laboratory in Florida. This work is a precursor to actual beam tests at BNL. Initial work on solid target R&D will also begin this year at ORNL and FNAL. Target geometries and cooling will be examined via simulations to evaluate steady-state and peak thermal stresses, the latter being important in the context of fatigue failure. The primary short-term goal is to determine the survivability of a passively cooled graphite target under the thermal and radiation conditions expected at a

Neutrino Factory. This will involve the following activities: *i*) evaluation of the properties of different grades of graphite, including carbon-carbon composites; *ii*) thermal tests to determine bending-creep and axial-creep effects on full-scale target rods for various support schemes; *iii*) investigation of non-uniform power distribution on full-scale rods to determine temperature and stress effects; *iv*) thermal shock tests on small scale samples; *v*) neutron irradiation tests to determine target survivability; *vi*) designing and testing of one or more water cooling schemes for the target support tube. Other activities will include investigation (by calculation and tests) of the impact of pressure shock-wave effects due to the very short duration beam spill, development of a design for a water-cooled graphite target if tests on the passively cooled target are unsuccessful (i.e., small-scale samples of graphite with cooling tubes would be fabricated and tested for thermal and radiation survivability), and evaluation of safety and environmental requirements and assessment of their impact on the target system design and operation. To provide a suitable test beam from the AGS, work to upgrade the extraction kicker system will begin. This year will see the start of fabrication of a 20-T test solenoid, its 5-MW pulsed power supply, and a test target for the A3 line. Diagnostics for studying the pion yield from the target will be fabricated. Results from the HARP experiment at CERN will be folded into our design and simulation effort as they become available; we will monitor the progress of this experiment and provide support if needed. Tests on radiation hardness of materials for the target station and its solenoid magnet will begin, with the ultimate goal of defining suitable materials and fabrication techniques for these components. This year's work will focus on structural tests of candidate materials to ensure suitable mechanical properties for magnet fabrication. This work, by a group comprising staff from MSU, LBNL, BNL, and the Environmental Measurements Lab, is anticipated to be partially supported by *UC* funds provided by NSF.

Systems studies related to safe handling of the irradiated targets in the final facility will begin this year. Over the next several years, we will develop full-scale mock-ups (using simulated components and substitute materials where possible) to demonstrate remote handling of key components. A partial mock up of the target region, complete with utility interfaces (electrical, cooling, instrumentation) will be fabricated. This setup will be used to demonstrate replacement of the target module, replacement of the Bitter coil, and replacement of the proton beam window. Finally, consequences of possible failure modes, e.g., of the beam isolation window, will be investigated to make sure the design is robust against such occurrences. We expect to benefit in this area from close collaboration with groups at existing facilities (or those now under construction) that have similar requirements for beam power on target.

Fabrication of components suitable for a cooling channel will begin this year. Design of a 201-MHz high-power NCRF cavity will be completed and design of a solenoid magnet to fit around it will begin. R&D on the corresponding superconducting solenoid will begin this year. This may involve scale models initially to explore the parameter regime of interest quickly. Achieving the required solenoid field strength on axis is reasonably straightforward technically, but will require substantial R&D to achieve it at acceptable cost. Moreover, achieving the exact field shape considering engineering constraints on current densities, on field on the coils, and on forces on the coils and supports, generally requires a number of iterations. Each coil configuration studied should have a maximum field on the coil below about 9 T. Common rules on the allowable hoop stress will be developed by the experts, to provide guidance to the simulation and design groups on what configurations are acceptable. Mechanical stability analysis for the magnets of the cooling channel, development of a mechanical scheme for the channel, and design of a mechanical support for coils and magnets in the cooling channel will be carried out, supported partially by *ICAR*. The design will be optimized to reduce the mechanical stress on the coil. Detailed analysis of quench behavior, including the mechanical stresses induced on the magnet coils, is also important. Another issue to evaluate is that of field quality. Based on engineering estimates of coil placement accuracy, we will assess the effects on the beam cooling and transport of the field imperfections that result from coil displacements and from edge-field effects. A prototype absorber will be fabricated. After completing safety tests, it will ultimately be tested in a proton or electron beam to verify its thermal design.

Studies of muon-beam instrumentation will commence at Northwestern University and University of Chicago this year, supported by NSF and *ICAR*. Although measurements of muon beams have been done for years, the issues associated with the cooling channel will make the required measurements difficult. Measurement requirements include: *i*) initial matching of the cooling optics to the beam parameters, *ii*) maintaining this match down the length of the cooling channel, *iii*) producing and maintaining the physical alignment of beam components, *iv*) identifying and minimizing transverse and longitudinal loss mechanisms, and *v*) measurement of the emittance at various stages of cooling. Ideally, we wish to have high-precision measurements of the six-dimensional muon phase space at a variety of locations along the cooling channel and acceleration system, although the only experimentally available quantities are the transverse and longitudinal bunch profiles. Measurement of the muon emittance from a beam profile is complicated by possible mismatches in the cooling optics that could produce errors in the beta function and the calculated emittance. Measurements could also be complicated by pion and other backgrounds, particularly at the upstream end of the cooling channel. While many conventional accelerator diagnostics may be appropriate for some applications, it seems desirable to look carefully at secondary emission monitors (SEMs) and Faraday cups. The intense muon beams expected would produce large signals without amplification, and the short range of low-energy muons would permit the option of stopping the beam in a transmission line and looking at the electrical pulse directly.

Proton driver R&D will get under way this year. Included will be studies of the microwave instability below transition, prototyping and testing of high-gradient RF structures, and the design of inductive inserts for space-charge compensation. Such inserts will later be tested with beams at FNAL, BNL, and/or LANL. Studies and development of techniques for high-intensity bunch compression will begin, building on work already under way at BNL, FNAL, and CERN. Much of this work is motivated and supported by other interests, so the benefits to the *MC* are highly leveraged in this case.

Investigations on suitable high-efficiency and high-power RF sources will be done. An engineering design for an induction linac module, including an internal superconducting solenoid, will be made in preparation for fabricating a complete prototype cell. Fabrication of a 201-MHz SCRF cavity will be completed this year and processing will begin at Cornell.

Fiscal Year 2002

Simulations this year will focus on iterating the front-end channel design to be compatible with realizable component specifications. Studies of the acceleration system and the storage ring will include errors and fringe-field effects. From these studies will come component specifications for the acceleration system and storage ring components.

For the targetry experiment, fabrication of a pulsed 20-T solenoid and its 5-MW power supply will be completed. A selected target will be tested with beam this year, with the choice based on the studies carried out the previous year. An upgrade of the AGS extraction kicker to permit fast extraction of the entire beam will be done. Fabrication of a high-power, 70-MHz RF cavity will continue in preparation for beam testing, as will fabrication of instrumentation for pion detection. Late in the year, pion yield measurements will begin, to verify the MARS predictions on which the Neutrino Factory design is being based. Simulations in support of this measurement effort will continue. A prototype carbon target will be constructed. Radiation tests on selected coil materials will begin this year, to verify behavior prior to actual magnet fabrication. As part of this work, we will launch an effort to measure neutron yields from the target, to compare with predictions of the MARS code. Systems studies of the target facility will continue to identify and test key issues related to handling and remote maintenance.

Fabrication of all cooling channel components required for the initial phase of testing, including a high-power 201 MHz NCRF cavity, a test solenoid, and diagnostics that could be used for the experiment, will be completed. Upgrade of the Lab G test area at FNAL to accommodate the 201-MHz test equipment will commence this year. Preparatory work will be planned to minimize interference with any remaining 805 MHz testing. Simulation efforts in support of a cooling demonstration program will continue. Plans for beam testing will be finalized. Thermal tests of the absorber with a suitable electron or proton beam will commence.

Proton driver R&D this year will involve beam tests to produce the short bunches and high intensities needed for a Neutrino Factory. A test of inductive inserts to compensate for space-charge effects will be carried out at FNAL and/or BNL.

A prototype induction linac cell, designed to operate at ≈2 MV/m and including an internal superconducting solenoid with suitable dimensions and field strength, will begin fabrication. A prototype 201-MHz SCRF cavity will be tested. At high gradients, the input power coupler design must be tested and validated. Detuning issues associated with the pulsed RF system must also be evaluated. Finally, because of the large stored energy in a 201 MHz SCRF cavity, a reliable quench protection system must be designed and tested. Fabrication of prototype high-power RF sources will begin, based on the R&D studies carried out previously.

Fiscal Year 2003

For the targetry experiment, high intensity beam tests ($\approx 1 \times 10^{14}$ protons per pulse) will take place using a selected target and the 20-T capture solenoid; about six weeks of parasitic AGS beam time are envisioned. A second round of high-intensity tests, now including the high-gradient 70-MHz RF cavity, will be carried out later in the year, again needing about six weeks of parasitic beam time. Measurements of pion yield will be made using the diagnostics built last year. These will use a much lower beam intensity ($\approx 1 \times 10^{6}$ protons per pulse), also for 6 weeks of parasitic beam time. The tests of radiation hard materials will be completed and selected candidate materials will be used to begin manufacture of an actual (warm) solenoid coil for testing in a high-radiation environment. Target facility studies will progress to prototypes or full-size models of key components as needed to verify the design concepts.

High-power tests of the 201-MHz NCRF cavity will begin. A full cooling cell will be assembled and bench tested. After testing, it is anticipated that these components will be installed in a muon beam line and tested with beam. Upon completion of the integration tests, fabrication of additional components will begin; these will be added to the beam test line as available to demonstrate a more realistic segment of cooling channel with appreciable cooling.

Magnet designs suitable for the arcs of the recirculating linacs (RLAs) and the muon storage ring will be examined this year. Both conventional and superconducting designs will be compared where either is possible. With SC magnets, radiation heating becomes an issue and must be assessed and dealt with. Assessment of field error effects on the beam transport must be made to define acceptance criteria for the magnets. This will require use of sophisticated tracking codes like COSY that permit rigorous treatment of field errors and fringe-field effects. Because the beam circulates in each RLA for only a few turns, the sensitivity to magnet errors should not be extreme, though the large energy spread will serve to enhance it. Optimization of the RLAs in terms of the number of passes in each must be done. This depends on the details of the splitter and recombiner magnet designs and also on the beam energy spread coming from the cooling channel. Designs for these magnets must be developed and—depending on how nonstandard they are—prototypes will be built. Work on finalizing the optics design for the arcs must be done. Tests of a 201 MHz SCRF cavity will continue this year, including demonstration of the ability to shield nearby magnetic fields in a realistic lattice configuration.

The simulation effort this year will focus on understanding experimental results from the targetry experiment. Additional effort will be given to beam dynamics studies in the RLAs and storage ring, including realistic errors. In many ways, the storage ring is one of the most straightforward portions of a Neutrino Factory complex. However, beam dynamics is an issue here as the muon beam must circulate for many hundreds of turns. Use of a tracking code such as COSY is required to assess fringe field and large aperture effects. As with the RLAs, the relatively large emittance and large energy spread enhance the sensitivity to magnetic field and magnet placement errors. Suitable magnet designs are needed, with the main technical issue being the relatively high radiation environment. The storage ring optimization favors long straight sections and short arcs. However, it is advisable to leave some room in the arcs ("utility" straight sections) for presently unspecified elements; a lattice design that preserves this flexibility will be developed and tracked. Another lattice issue that must be studied is polarization preservation. In the initial implementation of a Neutrino Factory it is expected that polarization will not be considered, but it may be important in later phases. Investigation of what is involved in transporting a polarized beam through the entire accelerator chain will be completed.

The proton driver group will test a high-gradient, low frequency RF cavity in a ring, either at BNL or FNAL.

Fiscal Year 2004

For the targetry experiment, the work this year will focus on completing systems studies of the final target station, including issues of radiation handling and safety. A (normal conducting) test solenoid coil based on the materials tests in prior years will be completed and tested in a radiation environment.

The MUCOOL demonstration will proceed incrementally, adding cells to the beam line as dictated by financial resources and programmatic considerations. This process will continue until we have demonstrated the efficacy of cooling, possibly reaching an emittance reduction of 50%. Simulations in support of this effort will continue.

Work on the ZDR will commence this year. This activity will require about two years of effort, leading to a document that presents a description of all aspects of a Neutrino Factory, in sufficient detail to demonstrate technical feasibility of the full facility.

Required Budget

Table 1 summarizes the projected budget requirements for the activities described above. The numbers represent our estimate of the required resources from *all* sources, including direct DOE funding for the *MC*, DOE base program support from the sponsoring Laboratories, NSF support to the *UC*, state support for the *ICAR*, and possible contributions by foreign collaborators. The profile below corresponds to the technology-limited schedule we are considering. If the funds below were not available, the R&D work would proceed more slowly.

Table 1. Neutrino Factory R&D Budget Requirements.

R&D area	FY01 ($M)	FY02 ($M)	FY03 ($M)	FY04 ($M)	FY05 ($M)	Sum ($M)
MUCOOL	4.9	3.8	4.3	23.3	17.5	54
Targetry	5.7	5.2	4.4	3.7	2.1	21
Proton Driver	0.1	0.1	0.1	0.1	0.1	1
Beam Simulations	2.3	2.0	2.0	2.0	2.0	10
Acceleration/Storage Ring	0.9	0.6	0.6	0.6	0.6	3
Components	1.9	4.0	7.0	2.3	1.0	16
ZDR Preparation	—	—	—	10.0	10.0	20
TOTAL	16	16	18	42	33	125

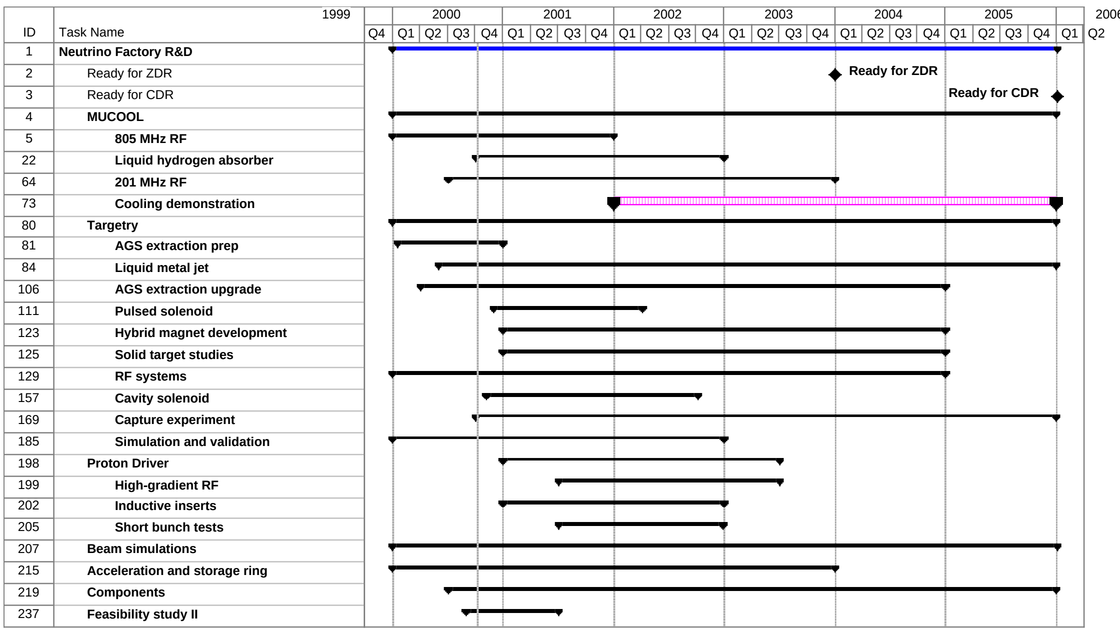
Muon Collaboration

Neutrino Factory and Muon Collaboration
R&D Plan

August 26, 2000

Schedule

A summary of the schedule described in this plan appears below. As noted, this schedule assumes a technology-limited program with no constraints on funding or level of effort.



M. Zisman
Project Manager