U.S. Department of Energy
Field Work Proposal

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	0	August 9, 2002

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Neutrino Factory and Muon Collider Collaboration	KA-04-03-01-2

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Begin:: (mm dd yy) End:: (mm dd yy) OPEN	NO

8. NAME *(Last, First, MI)* *(FTS Number)* HEADQUARTERS/OPERATIONS OFC PROGRAM MANAGER	11. HEADQUARTERS ORGANIZATION	14. DOE ORGANIZATION CODE:
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10. CONTRACTOR WORK PROPOSAL MANAGER Andrew Sessler, Spokesperson 510-486-4992 Michael Zisman, Project Manager 510-486-5765	13. CONTRACTOR NAME: Neutrino Factory and Muon Collider Collaboration	16. CODE:

17. WORK PROPOSAL DESCRIPTION *(Approach, anticipated benefit in 200 words or less)*

PRINCIPAL INVESTIGATORS: A. SESSLER, M. ZISMAN, S. GEER, R. RAJA, K. McDONALD, R. FERNOW, R. PALMER, A. TOLLESTRUP

One of the most important discoveries in high-energy physics in the past few years is evidence for neutrino oscillations (implying non-zero neutrino mass). A complete study of this new physics will require an accelerator-based neutrino beam to be directed at a detector thousands of kilometers away. A high-intensity muon storage ring is the ideal source of such neutrinos. In the longer term, it is expected that building a Neutrino Factory is a key step toward a Muon Collider (where counter-rotating beams of positively and negatively charged muons collide). Advantages of a Muon Collider over other colliders are: *i*) it has the same physics reach as a proton collider of ten times higher energy, *ii*) it is more strongly coupled to the Higgs than is an electron by the square of the mass ratio, making it an ideal probe for Higgs studies, and *iii*) the heavier muons emit little or no synchrotron radiation, making a high-energy circular Muon Collider energetically and economically feasible. Because muons are unstable, such a facility offers many unique and exciting technical challenges. Funds are requested here for the investigation of physics and technology issues critical to the development of both a Neutrino Factory based on a muon storage ring and a Muon Collider. These studies will be carried out by members of the Neutrino Factory and Muon Collider Collaboration (MC), an organization sponsored by three DOE laboratories, BNL, FNAL, and LBNL. Present activities focus on targetry (development and testing of high-power targets to produce an intense muon beam), muon cooling ("MUCOOL," development and testing of components required for a cooling channel, such as high-gradient rf cavities, strong solenoids, and liquid-hydrogen absorbers), emittance exchange (study of longitudinal emittance reduction in rings or other cooling channels), and simulations. We are also participating in the preparation of a proposal for an International Muon Ionization Cooling Experiment, MICE, which we expect to be hosted by Rutherford Appleton Laboratory in the UK.

18. CONTRACTOR WORK PROPOSAL MANAGER	19. OPERATIONS OFFICE REVIEW OFFICIAL
(Signature) *(Date)*	*(Signature)* *(Date)*

20. DETAIL ATTACHMENTS *(See Attachments)*

[ ] a. Facility requirements	[X] d. Background	[ ] g. Future accomplishments	[ ] j. Explan. of milestones
[ ] b. Publications	[ ] e. Approach	[ ] h. Relationships to other projects	[ ] k. ZBB detail
[X] c. Purpose	[X] f. Technical progress	[ ] i. Environment and Safety	[X] l. Other (Specify): Personnel

Work Proposal Requirements for Operating Equipment Obligations and Costs

MC Funding

CONTRACTOR NAME	WORK PROPOSAL NUMBER	REV. NO.	DATE PREPARED
NEUTRINO FACTORY AND MUON COLLIDER COLLABORATION		0	08-09-2002

21. STAFFING (*in staff years*)	PRIOR YEARS	BY-1	BY REQUEST	BY AUTHORIZED	BY+1	BY+2	TOTAL TO COMPLETE
a. Scientific		2	4		5		
b. Other Direct							
c. Total Direct		2	4		5		
22. OPERATING EXPENSE (*in Thousands*)		2805	3000		3500		
a. Total Obligations							
b. Total Costs		2805	3000		3500		
23. EQUIPMENT (*in Thousands*)			1500		1000		
a. Equipment Obligations							
b. Equipment Costs			1500		1000		

24. MILESTONE SCHEDULE (Tasks)	PROPOSED	BUDGET YEAR AUTHORIZED	PROPOSED	SCHEDULE AUTHORIZED
Submit MICE technical proposal	December 2002			
Test 201 MHz superconducting cavity at design gradient (NSF funded)	December 2002			
MTA construction complete	March 2003			
Design of high power 201 MHz test cavity	March 2003			
Design 4-T solenoid for 201 MHz cavity test	July 2003			
Test convection-cooled absorber in MTA	September 2003			
Test high-speed Hg jet system	September 2003			
Fabrication of 201 MHz cavity complete	July 2004			
Test Hg-jet and solid targets at full design intensity of AGS beam	September 2004			
Test 201-MHz rf cavity with solenoid and absorber at FNAL	June 2005			
Integrated target tests with high intensity beam and test solenoid	September 2005			
Identify key physics and technology challenges for the feasibility of a Muon Collider, especially longitudinal cooling	Ongoing			

Base Program Funding

CONTRACTOR NAME	WORK PROPOSAL NUMBER	REV. NO.	DATE PREPARED
NEUTRINO FACTORY AND MUON COLLIDER COLLABORATION		0	08-09-2002

21. STAFFING (*in staff years*)	PRIOR YEARS	BY-1	BY REQUEST	BY AUTHORIZED	BY+1	BY+2	TOTAL TO COMPLETE
a. Scientific		16.6	20		20		
b. Other Direct		0.5	12		12		
c. Total Direct		17.1	32		32		
22. OPERATING EXPENSE (*in Thousands*)		2134	3500		3500		
a. Total Obligations							
b. Total Costs		2134	3500		3500		
23. EQUIPMENT (*in Thousands*)		50					
a. Equipment Obligations							
b. Equipment Costs		50					

24. MILESTONE SCHEDULE (Tasks)	PROPOSED	BUDGET YEAR AUTHORIZED	PROPOSED	SCHEDULE AUTHORIZED
See previous page for milestones				

CONTRACTOR NAME NEUTRINO FACTORY AND MUON COLLIDER COLLABORATION	WORK PROPOSAL TITLE: Intense Muon Beam Accelerator Research		
	WORK PROPOSAL NO.	REVISION NO. 0	DATE PREPARED: August 9, 2002

20c. Purpose

The purpose of this FWP is to support Neutrino Factory and Muon Collider Collaboration, "MC," participation in research and development for a high intensity Neutrino Factory and, potentially, a future Muon Collider. (Although the HEP base programs at the three "sponsoring" National Laboratories, BNL, FNAL and LBNL, support their respective scientific staffs, a significant and growing program in muon-beam R&D is supported by MC funds. Universities in the MC also play a vital role in providing staff for our R&D program.) Constructing a Neutrino Factory would shed light on important topics in high-energy physics concerning neutrino masses and neutrino mixing. Moreover, muons have important benefits compared with either electrons or protons when considering a possible next step for a high-energy physics facility. Since synchrotron radiation by muons is highly suppressed compared with electrons, it is feasible to consider a relatively compact circular collider in the TeV energy range. Also, the muon, like the electron, is a point particle and therefore can explore the same physics regime as would protons having approximately ten times higher energy. Accordingly, the idea of someday building a Muon Collider has attracted increasing interest over the last few years, which ultimately led to the formation of the MC. More recently, the NSF has become interested in the possibility of a Neutrino Factory and has become an active participant in the MC, primarily via Cornell University. Since the muon is an unstable particle, there are many new facets of accelerator physics and technology that need to be examined before construction of such a facility could begin. A Muon Collider feasibility study submitted to the Snowmass '96 conference was a first step and a full-fledged R&D program began at National Laboratories and universities throughout the U.S. A major goal of the work is to establish the case for the Neutrino Factory as a recognized piece of the U.S. high-energy physics program. Specific tasks for the Neutrino Factory include designs of the entire complex, theoretical and simulation studies of beam behavior, and design and testing of components, for example, superconducting magnets, liquid-hydrogen (LH_2) absorbers, and high-gradient rf structures. The MC is also centrally involved in the planning for an International Muon Ionization Cooling Experiment ("MICE") that includes members from the U.S., the EU, and Japan.

If a muon-based accelerator is built anywhere in the world, the MC desires—and would expect—to have a strong role in both its construction and the physics program that it enables.

In the recent past a number of workshops (NUFACT99, NUFACT00, NUFACT01, NUFACT02) have been devoted to discussions of the Neutrino Factory concept. A "Neutrino Factory and Muon Collider Collaboration" of more than 100 accelerator and detector experts, led by participants from three sponsoring DOE National Laboratories, BNL, FNAL, LBNL, along with Cornell University, has been formed. This group is somewhat unique in being a grass-roots effort of both the particle physics and accelerator physics communities. The MC has also been very successful in establishing cordial and effective working relations with other groups working on these topics, both in Europe and in Japan. The Collaboration initially produced a feasibility study report that was presented to a wide audience at the 1996 DPF/DPB Summer Study "New Directions for High Energy Physics" held in Snowmass, Colorado. The rationale for pursuing a Muon Collider and the status of current research are discussed at length in this document. Compared with familiar proton and electron collider concepts, a Muon Collider is complementary and offers some attractive advantages, mostly due to low radiation (synchrotron, beamstrahlung, and bremsstrahlung) combined with having the full collision energy available for production of new particles. The 2+2 TeV Muon Collider studied at Snowmass would have an energy reach beyond the LHC but be compact enough to fit on the existing DOE sites at BNL or FNAL. Current work on Ring Coolers suggests that the cooling required for a Muon Collider may be achievable. The pace of activity has increased markedly in the last few years, seeded by the growth of MC-funded R&D activities. The recent evidence for neutrino oscillations led, in 1999, to a change in focus by the MC to the more immediate, and technically simpler, Neutrino Factory. There have been two Neutrino Factory feasibility studies completed, one sponsored by FNAL and one by BNL, and this work has been presented at the 2001 DPF/DPB Summer Study "The Future of Particle Physics" held in Snowmass, Colorado. Technically feasible designs capable of providing the required intensity of $1–4 \times 10^{20}$ neutrinos per 10^7-s year have been developed. To validate the concepts on which the feasibility studies are built, component development must be undertaken to demonstrate the specified operating parameters. Most of the work in the next few years will aim at a Neutrino Factory design, which serves as a key first step toward the eventual possibility of constructing a Muon Collider. Encouraging progress in designing Ring Coolers for longitudinal emittance exchange is spurring simulation effort in that area as well, with potentially substantial cost and performance benefits for either a Neutrino Factory or a future Muon Collider.

In addition to the project management structure of the MC itself (comprising a Spokesperson, three Associate Spokespersons, a Project Manager, an Executive Board and a Technical Board), R&D program oversight is provided by a Muon Collaboration Oversight Group (MCOG) comprising senior technical managers at the sponsoring Labs and an international Muon Technical Advisory Committee (MUTAC) that reviews the program annually and submits a report to MCOG. At present, the Spokesperson is A. Sessler (LBNL), the Associate Spokespersons are M. Tigner (Cornell), R. Palmer (BNL), and A. Tollestrup (FNAL), the Project Manager is M. Zisman (LBNL), the MCOG members are S. Holmes (FNAL), T. Kirk (BNL), and P. Oddone (LBNL), and the Chairperson of MUTAC is H. Edwards (FNAL).

There are several major technical challenges to be faced when using muons in an accelerator:

1. They are hard to produce (requiring a high-power proton beam on target).

2. They are created, through pion decay, into a diffuse phase space and this phase space cannot be reduced rapidly enough by conventional stochastic or radiation cooling. For a Neutrino Factory, the phase space can be sufficiently reduced by ionization cooling. For a Muon Collider, the parameters are more severe and cooling is considerably more challenging.

3. They decay, in their rest frame, with a lifetime of 2.2 μs. This problem is partially overcome by rapidly increasing the energy of the muons, and thus taking advantage of their relativistic gamma factor. At high energies, the muon lifetime suffices for roughly 500 storage ring turns. One consequence of the muon decay is that the decay products heat the magnets of the storage ring or collider, and also potentially create backgrounds in a collider detector.

4. For a collider, the luminosity requirements and the limits on muon production require the acceleration, storage, and collision of intense bunches (2×10^{12} particles) in a bunch length of 3 mm and transverse dimensions of about 10 microns at the interaction point. For a Neutrino Factory, the bunch length and number of circulating bunches are not critical parameters, which greatly eases the beam preparation requirements.

Dealing with these challenges, primarily in the context of a Neutrino Factory, has been undertaken by the MC, augmented by base program support for the scientists from the sponsoring National Laboratories and Cornell. In a muon accelerator complex, a high intensity proton beam is bunch compressed and focused on a target. The pions generated are captured by a high-field solenoid and transferred to a solenoidal decay channel followed by either a low-frequency linac or a suitably designed rf and drift system. Either of these serves to reduce, by phase rotation, the momentum spread of the muons into which the pions decay. Subsequently, the muons are cooled by a sequence of ionization cooling stages. Each stage consists of energy loss and acceleration. (While not an absolute requirement, it would be advantageous if the longitudinal phase space of the beam were also reduced, in which case we would require emittance exchange in energy-absorbing wedges in the presence of dispersion.) Once they are cooled, the muons must be rapidly accelerated to minimize decay losses. This can be done in recirculating linear accelerators (RLAs) (e.g., like that at Jlab) or possibly in rapid-cycling synchrotrons or fixed-field, alternating gradient (FFAG) machines. Finally, the beam is injected into a storage ring with one or more long straight sections aimed at detectors nearby as well as thousands of kilometers away. Muon decays in the straight sections produce beams of neutrinos for the remote detectors.

Work on a Neutrino Factory can be separated into the following areas: Target and Capture Section, Decay and Phase Rotation Channel, Bunching and Cooling Section, Acceleration Section, and Storage Ring. The first three areas are collectively referred to as the “Front End.” This is the broad area that is presently the main focus of MC activity. The target must tolerate a very high power proton beam (1–4 MW) with reasonable lifetime and good pion yield. Both solid and mercury-jet targets are being designed and studied with intense beams from the AGS at BNL. All the Front-End systems require high-gradient radio frequency (rf) systems operating at relatively low frequency (a few hundred MHz) and superconducting solenoids operating at fields of about 5 T. In addition, the cooling channel requires LH_2 absorbers having very thin, but very strong, entrance and exit windows and excellent heat-removal properties. Design of the Front End system requires considerable expertise in complex physics simulations, and both Laboratory and university physicists play lead roles here.

A Muon Collider, while having unique technical and physics advantages, is a new and untried concept. Though we have been working on its technical challenges for some years, our efforts to understand it fully still have a long way to go. Because studies aimed toward an eventual Muon Collider have the potential to define a new and productive direction for high-energy physics at the energy frontier, this effort is very worthwhile. MC scientists will continue to look at the problems relevant to a Muon Collider as they work toward the design of a first technological step in that direction, the Neutrino Factory.

The scientists and engineers in the MC have unique expertise to contribute to this endeavor. We have considerable experience at designing superconducting magnets of all types, including dipoles, quadrupoles, and solenoids. We also have considerable experience in the design of high-power rf cavities. Finally, we have significant experience in the simulation tools and underlying physics needed to design the Front End of a Neutrino Factory as well as in the overall design of complex facilities, e.g., the Low-Energy Ring of the PEP-II B Factory, presently the world's highest current positron storage ring, or the Tevatron, presently the world's highest energy collider. This research was strongly endorsed by the recent Barish-Bagger HEPAP Subpanel, who stated: *"We support the decision to concentrate on the development of intense neutrino sources, and recommend continued R&D near the present level of $8M per year. This level of effort is well below what is required to make an aggressive attack on all of the technological problems on the path to a neutrino factory."*

The R&D program outlined here corresponds to the funding level recommended by HEPAP.

FY 2002

During FY2002 the MC is utilizing its scientific and engineering staff, experienced in accelerator physics and design, to continue component design and testing efforts. The Collaboration conducts a regular schedule of video conferences, workshops, and semiannual Collaboration Meetings. Some of the MC work is theoretical or conceptual, and some involves design and fabrication of hardware components. Topical workshops are held to stimulate the work and provide a forum for discussion. MC members also play a central role in the organization of the International Muon Ionization Cooling Experiment (MICE), as discussed below.

At BNL, work is continuing on simulating each of the Neutrino Factory component systems in greater detail. Monte Carlo simulations aimed at developing a complete, self-consistent scenario for building a Higgs Factory and for building multi-TeV Muon Colliders have likewise continued. Studies continued on examining possible paths for upgrading a Neutrino Factory facility to a Higgs Factory. Possible scenarios and parameter lists for accelerating the muon beams to high energy were developed further. Work continued on the design of transverse ionization cooling channels based on lattices of alternating solenoids.

The emphasis in the cooling studies shifted to emittance exchange, which is required to reduce the longitudinal emittance of a muon beam. The simulation code ICOOL continued to be upgraded for these studies. Analysis began on several types of cooling rings, including designs based on quadrupole channels and on modifications of the transverse cooling lattice. Theoretical analyses were made of ideal emittance exchange systems. A three week long workshop studied in detail the possibility of using emittance exchange to control the growth of longitudinal emittance at a Muon Collider.

Work at BNL continued on experiments relevant to the Neutrino Factory or Muon Collider. (*i*) Experiment E-951 (with Princeton) for the study of targetry, production, and collection issues had its first run at the AGS. Single bunches were extracted from the AGS on-demand with intensities of up to 4×10^{12} protons. The integrity of various window materials was examined. The stress in solid targets, measured with strain gauges, agreed qualitatively with simulations. Carbon-carbon composites were shown to have less stress than graphite targets. A high-speed optical camera system was used to study the effect of the proton beam on static mercury sitting in a trough and on a 2 m/s mercury jet. First evidence of beam-induced disturbances in the jet did not occur until 40 µs after the arrival of the beam pulse. The velocity of mercury droplets leaving the disturbed jet was measured. Theoretical studies were made of the issues involved in using liquid-metal-jet and rotating-solid targets in a 1-MW proton beam. A stress analysis was made of possible window materials. Design work continued on a lower-cost 15-T pulsed solenoid magnet system for a later stage of the experiment. (*ii*) Work continued on the muon cooling (MUCOOL) program at FNAL to demonstrate components suitable for ionization cooling of a diffuse muon beam. In particular, we are pursuing a more realistic magnetic field design for a possible ring cooler system. (*iii*) Analysis was completed on the pion production data from Experiment E-910 at the AGS. Final results of acceptance-corrected pion yields for Be, Cu, and Au targets at 12 and 18 GeV incident proton energies were written up and published in February 2002. Results from the experiment were used to benchmark the simulation code MARS. (*iv*) We have become involved with the MICE collaboration to demonstrate ionization cooling of a diffuse muon beam. Simulations were made of possible configurations for the demonstration experiment that would produce a significant effect for modest cost.

Work at FNAL focused primarily on preparing a design for Phase-II of the MUCOOL Test Area (MTA), at the exit of the 400 MeV proton linac. Designs were completed and a bid package was prepared for the remaining construction activities. The MTA will be completed during FY2003 in preparation for beginning filling tests of the first LH_2 absorber. Work on Fermilab E-907, an experiment to measure particle production yields in the energy range spanning the FNAL Main Injector and the BNL AGS, is also under way.

The Neutrino Factory will require several different rf systems to bunch, cool, and accelerate the beam. With such a multitude of rf structure and systems designs, critical work is required at an early stage to assess the viability of different options. For the experimental R&D program, rf structures and systems are being designed and developed at frequencies of 201 MHz and 805 MHz by LBNL. To obtain the high gradients required in these applications, novel and technically challenging designs are needed. FNAL completed testing this year of its open-cell 805-MHz cavity in Lab G. In parallel, LBNL designed a pillbox cavity with beryllium foils, through which the muon beam would pass, that maximizes the accelerating field on axis. The cavity was fabricated at the University of Mississippi and shipped to Lab G at Fermilab for high-power testing under LBNL supervision, with the goal of evaluating high-gradient cavity performance in a high-field solenoid. In initial tests without a magnetic field, the cavity has reached a gradient of 34 MV/m, exceeding its design value of 30 MV/m. The breakdown rate was acceptably low. In order to carry out dark-current measurements, the cavity windows have just been replaced with thinner ones. The internal surfaces of the cavity were inspected for damage when the windows were replaced and found to be undamaged. This inspection will be redone after the cavity has been operated in the magnetic field at high gradient. Continued work on formulating future 805 MHz cavity development is proceeding. This frequency permits more compact and less expensive structures to be built, which makes the development program more cost-effective than if all work were done at 201 MHz. Handling of high-power in the input coupler, and the cooling channel cavities themselves, is critical, and multipactor and surface preparation will be studied to avoid problems. Design studies began for a grid of hollow tubes for the high-gradient 201-MHz cavities. This design approach serves as an alternative to the baseline approach of using Be foils to terminate the cavity fields.

The LBNL-designed 5-T solenoid is being used this year at FNAL to test the pillbox cavity referred to above. This magnet has a novel design with two independently powered coils that can be operated with the same polarity (“solenoid mode”) or opposite polarity (“gradient mode”). The solenoid was installed and commissioned in Lab G at FNAL last year and used to test the open-cell 805 MHz cavity designed and built by FNAL.

Thin windows for liquid-hydrogen absorbers have been successfully tested in collaboration with the ICAR universities (particularly IIT and Northern Illinois University), and the cryogenics plant required to fill an absorber is at an advanced design stage. Flow simulations have been carried out at Oxford University. A new window shape that is expected to be stronger and more suitable for the cooling flow has been developed. This design will be fabricated and tested next year. An R&D program to develop and test promising instrumentation types will continue, making use of the component test setup in the MTA once it is operational. All of this work involves a partnering of National Laboratory and university groups in a very effective way—one of the strengths of the MC R&D program.

In the context of the MICE collaboration, a letter of intent has been presented at Paul Scherrer Institute (PSI) in Zurich, Switzerland and at the Rutherford Appleton Lab (RAL) in Chilton, England. Based on the encouraging response from RAL, a formal MICE collaboration is being set up, with the goal of submitting a full technical proposal to RAL by the end of 2002. The MC has an important role in rf design and fabrication for the anticipated MICE experiment. The approach of using beryllium foils to increase the shunt impedance (thus reducing the power requirements for these high-gradient cavities) was developed at LBNL and is taken as the present basis for the cooling channel design. Initial results suggest that foil deformation will be acceptable if the power dissipated is 50 W or less. LBNL is now well along on the design of a 201-MHz cavity suitable for the cooling channel of a Neutrino Factory. We have evaluated both two-cavity and four-cavity module designs having Be foil windows of up to 25 cm radius. When the first cavity is completed (expected toward the end of FY2004, depending on availability of funds), it will be tested at high power at FNAL.

Simulations of the cooling process remain a key component of the MC effort. This year, a main focus will be to study various approaches to emittance exchange. To this end, the MC has already hosted workshops on emittance exchange at BNL in September 2000 and at LBNL in October 2001, and plans to hold another workshop at Fermilab in November 2002. Several options are being evaluated, including the dipole-plus-solenoid cooling ring concept developed by Balbekov, the tilted-solenoid ring proposed by Palmer, and the quadrupole ring proposed by Garren and Kirk. A quadrupole-based linear cooling channel, as opposed to our "standard" solenoid-based approach, is also being investigated by Johnstone and Errede. In addition to these studies, there is effort being put into developing a better understanding of FFAG rings. The Japanese approach to a Neutrino Factory is based exclusively on this type of ring and we need to understand the performance and cost trade-offs compared, say, with the Study-II design approach. FFAG designs also play a potential role in the acceleration system, where such a ring might replace the baseline RLA. A two-week workshop on FFAG designs will be sponsored by the MC in October 2002; a follow-on workshop will be organized by our Japanese colleagues in 2003. This activity is another good example of close collaboration between National Lab (BNL, FNAL) and university groups (U-Miss, UCLA, MSU, and a number of ICAR institutions). We continue to explore options to reduce the cost and/or enhance the performance of our Study-II Neutrino Factory Front-End design, such as the "adiabatic buncher" concept proposed by Neuffer. Improving our simulation tools is another important MC activity. We have added a new integrator into the ICOOL code to improve accuracy and increase calculation speed. In addition, we continue to evaluate ICOOL with an eye toward converting it to run on the NERSC parallel processors. This would greatly increase its power as a design tool. We are likewise developing GEANT into a tool for muon cooling simulations. Efforts to evaluate Ring Coolers using this tool are under way and a package for simulating the full MICE environment is under development. (The baseline MICE design is based on a few cells of the Study-II cooling lattice.) Another valuable simulation tool, not directly related to muon cooling, is the nonlinear dynamics code COSY. Incorporating realistic solenoid fields and including the effects of magnet fringe fields in Ring Cooler simulations are the present focus of the COSY effort at MSU and UIUC.

Another simulation effort unrelated to cooling involves studying the behavior of the Neutrino Factory target, which in the present vision is a jet of mercury injected into the field volume of a strong solenoid (up to 20 T) surrounding the target area. This year, we will apply our efforts to the assessment of magneto-hydrodynamics effects for a mercury jet in a magnetic field.

In an effort to provide scientific choices for the particle physics community, we continue our involvement with "community" activities. MC members are involved in the organizing committee for the NUFACT workshops. The past ones, in Lyon (1999), Monterey (2000), Tsukuba (2001), and London (2002), were very successful, and the next one is now scheduled for New York in June 2003. We also played a significant role in the organization of Snowmass 2001 by co-leading the M1 group (Sessler and McDonald). The MC provided information on muon accelerators for the Barish-Bagger Subpanel of HEPAP this year, and we were successful at convincing them to recommend an ongoing funding commitment at the present level. We may not be successful, however, in turning this recommendation into action, since our current budgetary guidance from DOE is to expect a severe budget cut in FY2003. Finally, as noted earlier, we have become involved in the organization of the MICE experiment.

FY2003

The 2001 HEPAP Subpanel recommended a roughly constant level of support for Neutrino Factory R&D, and this recommendation was subsequently endorsed by HEPAP. Unfortunately, in the past few years funding for the MC has decreased significantly, and the present budget guidance for this year represents a further and dramatic decrease. The recent MUTAC report, transmitted to the DOE with a strong endorsement from MCOG, praises the technical progress made by the MC, and also recommends increased support for the development of the Neutrino Factory components in general, and cooling channel components in particular. These components consist of: (*i*) high-gradient 201-MHz cavities, (*ii*) liquid-hydrogen absorbers, (*iii*) high-field solenoids within which the absorbers and rf cavities are located, and (*iv*) instrumentation required to monitor and operate a cooling channel. In addition, MUTAC recommended that our ongoing simulation effort be strengthened to be able to study the performance of a cooling channel in full detail. A substantial effort is needed to determine all of the required engineering tolerances, and to identify all of the issues that must be addressed by the R&D program. Another critical demand for simulations, likewise endorsed by MUTAC, is the need to provide adequate guidance for the MICE experiment.

It is vital to the health of the R&D program that support for continued high-gradient NCRF development at 201 MHz be pursued, that the MUCOOL test area be completed, and that the activities of the design and simulation group continue to be effectively focused on advanced cooling channel designs and the design of the MICE experiment. The present FY2003 guideline represents a factor of two reduction in the level of support compared with FY2002, a level that is inadequate to carry out the proposed R&D program. At the anticipated level of funding it will not be possible to develop all of the components for a cooling channel within a reasonable number of years.

It is important to note that the rapidly evolving research on muon storage rings and colliders requires numerous workshops and meetings for the participants from the three sponsoring laboratories to interact and coordinate their efforts. This is especially true for the Collaboration Spokesperson, who must be available for meetings, workshops, talks, briefings to the funding agencies and the like. Likewise, the Project Manager must be able to visit the various R&D sites to assess and monitor the ongoing work on a regular basis. These latter costs are expected to be borne by base program funds, but these are woefully inadequate to satisfy present needs.

The technical tasks covered by this FWP in FY2003 *should* include the following activities. With the requested supplemental funds, and assuming there is AGS running for HEP this year, we expect to carry out all of the tasks listed below. In the absence of supplemental funds, the scope of the MC program in FY2003 would be greatly reduced. Substantial progress would be made only on the 805-MHz rf work, the MTA construction, beam simulations, and target development.

1. RF Structures
High-power testing of full-scale prototype structures is essential to develop confidence with state-of-the-art systems. We will continue such experiments at FNAL, where existing high-power rf infrastructure is available. The focus in Lab G will be continued understanding of dark currents and causes of breakdown

and on developing means to suppress them. This will likely involve tests of alternative processing techniques and/or tests of coatings or alternative materials. Initial tests will be carried out in Lab G with 805-MHz cavities, in preparation for testing the most promising approaches on the 201-MHz cavity. Development of a second test setup (the MUCOOL Test Area, MTA) to accommodate the 201-MHz equipment is under way at FNAL. Fabrication work on a 201-MHz cavity to test there will commence at LBNL this year, funds permitting. Experiments will continue on Be-window technology, focusing mainly on tests at room-temperature. For this work to progress in a timely way, we must acquire a moderate power CW 201-MHz rf power source, costing $50K in equipment funds. If the simulation, electromagnetic, and thermal calculations look encouraging, a grid structure for terminating the cavity fields will be fabricated and tested. First tests would be carried out at 805 MHz to serve as a proof-of-principle for the approach. If these are successful, a test in the 201-MHz cavity would be planned for FY2005. Alternative tuner and coupler concepts will also be developed and tested as needed.

Testing of the 201-MHz SCRF cavity will continue at Cornell (funded by NSF). Plans this year include testing the bare cavity to its design gradient of 17 MV/m. Designs for the various ancillary devices (tuner, input coupler, HOM loads) will be carried out, with the aim of a full systems test in the next few years. Because this is the first 201-MHz cavity that will be available for testing, we envision using it to test the behavior of proposed MICE detectors in the vicinity of a high-gradient 201-MHz cavity. Though not all detectors lend themselves to such tests, the Scintillating Fiber ("SciFi") readout can be evaluated. In addition, measurements of the x-ray spectrum and flux will permit an evaluation of the performance of other detectors by using the data as input to our simulation codes.

We will provide design support as required for the rf components of MICE. The baseline scenario for this international experiment includes the 201-MHz design developed for Feasibility Study-II. It is expected that the 201-MHz cavities will be one of the U.S. responsibilities for MICE. This task would be carried out at LBNL.

2. LH_2 Absorbers

Work will continue on fabricating a test device to use in the MTA facility. Dimensions of the absorber will be chosen to make it compatible with the existing Lab G solenoid magnet. The magnet will ultimately be transferred to the MTA from Lab G for this purpose. Window design, in collaboration with engineers at Oxford University, has progressed well in the past year. A new window shape has been developed that promises to be stronger than our present torispherical shape. This would permit using less material in the window, with concomitant reduction in multiple scattering (an emittance increasing effect that degrades the performance of a cooling channel). The new shape also looks better from the viewpoint of heat transfer, as it gives a better flow pattern for the LH_2, thus avoiding possible dead zones that would result in hot spots within the absorber. Tests to qualify the original window design for the FNAL safety committee have been completed successfully. However, the new design will require that a number of new windows be fabricated and the testing protocol repeated. This effort will be carried out by the ICAR universities in collaboration with FNAL. Safety implications are a key design constraint and we are working closely with the appropriate FNAL staff to make sure our absorber test protocol satisfies the applicable rules. When the MTA is available, we anticipate initial tests on a convection-cooled absorber assembly. This device has been designed and fabricated by our collaborators at KEK in Japan and will be available for testing with

LH_2 as soon as the MTA is deemed ready for such tests. To test the absorber as part of the MICE setup means likewise satisfying the RAL safety guidelines and this effort is part of our ongoing design process. Design of the LH_2 cryogenics plant is well along, and assembly of the system will begin this year if funding permits.

3. Superconducting Magnets

Several of the more challenging magnet systems required for a Neutrino Factory were studied in FY2001 and FY2002, and these efforts will continue in FY2003. Magnet systems work aimed at the specific Neutrino Factory requirements will be performed. The magnet tasks include support for near-term experiments as well as conceptual design work on proposed storage ring and collider designs. Designs for the high-field solenoid sections of the beam cooling system are being studied, with an eye toward cost reduction. Several conductor and magnet approaches are being evaluated in order to select a cost-effective option for these magnets, which represent a significant fraction of the cost of the cooling system. Similar design tradeoff studies will ultimately be done for the storage ring, since this represents a challenge to design high-field magnets that can operate in a high-radiation environment. Alternative magnet designs, using Nb_3Sn superconductor, will be evaluated.

To accommodate the larger size required for a 201-MHz cavity, we will begin the design of a new large-bore "coupling" solenoid. This device, which will begin fabrication in FY2004, will ultimately be sent to FNAL for testing with the cavity. The magnet will be needed to explore the behavior of the cavity in a magnetic field. Because the influence of the magnetic field on our 805-MHz open-cell cavity tested in Lab G was substantial, it is critical to do these tests at 201 MHz as well before "declaring success" for the cavity R&D program. Funding limitations are determining the pace of this activity. An improved design concept for the focusing coils has been developed. By integrating the absorber body with the coil support a considerable reduction in stored energy results, with a corresponding reduction in magnet cost.

4. Muon Cooling and Beam Dynamics Studies

Work will concentrate on studying options that increase the performance and lower the cost of a future facility, leading eventually to a complete self-consistent scenario for a more cost-effective Neutrino Factory. The front-end simulation efforts will continue, with the goal of developing detailed designs for all the component systems. Studies will be made of kickers suitable for injection and extraction from small bunch-compression and cooler rings. Beam dynamics studies of the RLA and FFAG accelerators and storage ring will continue, including studies of the effects of error fields. A two-week workshop on FFAG design issues will be held at LBNL from October 28–November 8, 2002. This workshop will explore the use and relative merits of FFAGs both for acceleration (in place of Recirculating Linear Accelerators, RLAs) and for capture (in place of a solenoid channel scheme). It will involve Japanese FFAG experts in addition to their U.S. and European counterparts. A follow-on workshop is contemplated in Japan, where a 150 MeV proton FFAG is being readied for commissioning in mid-2003.

Possible solutions to the problem of emittance exchange will continue to be investigated. The design of future Muon Colliders, especially the Higgs Factory, will be investigated further. Studies will be made of realistic magnetic fields and lattice designs for use in a possible ring cooler demonstration experiment. A second workshop on this topic will be held at Fermilab in November 2002. It is our intention, funding permitted, to recruit several post-doctoral physicists to participate in these studies. The applications will be reviewed by a combined Laboratory and university panel, and placements could be made at either type of institution as mutually agreed upon by the candidate and his or her sponsor.

Collaboration on the MICE experiment will continue. Simulations will be made of the most cost-effective experimental arrangement to demonstrate ionization cooling in a piece of a real cooling channel. Our goal is to prepare a full technical proposal to be submitted to RAL by Q1 of FY2003. Funding for the U.S. portion of the experiment will be requested jointly from DOE and NSF.

Our Monte Carlo programs will be further refined, leading hopefully to a complete scenario for ionization cooling in a Muon Collider. In past years, we have developed an analytic formulation of the solenoid channel optics, analogous to the Courant-Snyder formalism for quadrupole focusing channels. This approach, implemented in transverse phase space, is in agreement with simulations that require 2–3 orders of magnitude more computational resources. The formulation has been incorporated into the ICOOL simulation code, written at BNL, as a means to facilitate its use as a design tool. Other improvements to ICOOL, such as an improved integrator, have also been provided. We intend to use the code to study and optimize individual sections of the cooling channel. For example, initial studies of error sensitivity could be quickly done with this technique, and incorporation of engineering constraints could be evaluated easily. In the future, the analytic code will be extended to include longitudinal emittance exchange and compared with multi-particle simulations. The work on longitudinal cooling via emittance exchange in ring coolers has been reinvigorated, and we expect our simulation tools, in particular GEANT and COSY, to play a role in that activity. These tools are likewise being applied to the design of the MICE experiment, which we expect to be carried out at RAL.

In the two recent feasibility studies, a number of possible alternative technical approaches were identified but not studied in detail. We anticipate evaluating the most promising of these and carrying them to the point where they can either be rejected or incorporated into our baseline design. Examples of such alternatives include FFAG acceleration schemes, simultaneous rf phase rotation and bunching (“adiabatic bunching”), double-flip cooling channels, and helical channels to provide some longitudinal cooling.

A new idea, being explored this year for the first time, is to examine a cooling channel in which the discrete LH_2 absorbers are replaced by a continuous absorber. In this concept, funded by a DOE STTR grant, the high-gradient normal-conducting rf cavities would be operated with high-pressure gaseous hydrogen inside them rather than being under vacuum. At high pressure, the gas serves not only as the absorber medium but to inhibit electrical breakdown, just as it does in a high-voltage electrostatic accelerator (a Van de Graaff). If the initial exploration looks promising, follow-on funding will be sought to actually test such a system.

We have made considerable progress in the past year on the design of a cooling ring. The motivation for this work is twofold: First, we hope to develop a practical method for longitudinal cooling (really, emittance exchange between the longitudinal and transverse planes), and second, we hope to develop a more cost-effective cooling channel by “reusing” components (that is, by making several passes through the same components in a ring geometry). As noted earlier, several different rings are under study. Present effort focuses on developing realistic lattices having Maxwellian fields and practical component specifications. We are also developing means to compare the performance with a suitably defined figure-of-merit. We are using TOSCA to design a realistic magnet and then incorporating the fields into GEANT for evaluating cooling performance. Concepts for a suitable full-aperture kicker are also being developed. This component is critical to the success of the ring cooler concept.

5. Targetry

Data from FNAL E-907 will add to our understanding of particle production cross sections in a wider energy range than was covered in the E-910 experiment at BNL. Both these experiments serve to test and calibrate our predictions using the MARS code. Additional data concerning the interaction of the AGS proton beam with various targets will be obtained from experiment E-951 if AGS beam time is available to us this year. Modifications of the AGS extraction system should produce more intense proton bunches, and these will ultimately be used to test both Hg-jet and solid targets at roughly the single-bunch intensity specified in Feasibility Study-II, that is 1.6×10^{13} protons per pulse. Design and construction of a new mercury nozzle and a new high-speed (≈20 m/s) liquid metal jet assembly will take place. Construction of a 10–15 T pulsed solenoid collection magnet will begin.

<u>FY2004</u>

This year will see the completion of the 201-MHz high-power rf cavity at LBNL. This prototype 201-MHz cavity will subsequently be delivered to the MUCOOL Test Area at Fermilab. Also in FY2004, a prototype forced-flow liquid-hydrogen absorber will be completed and filled with LH_2 in the newly constructed MTA. The 5 T magnet in Lab G will be moved to the new area, enabling absorber operation to be tested within the solenoid. The cavity-absorber system with its associated solenoids will ultimately be tested as a unit. In preparation for this, high-power test capability for 805 MHz and 201 MHz cavities will be implemented in the MTA during FY2004. Fabrication of the coupling solenoid coil that surrounds the 201-MHz cavity will be carried out this year, supervised by LBNL. This is a large diameter coil (1.3 m warm bore) with high stored energy (nearly 6 MJ) and is costly to fabricate. It will be integrated with the cavity and absorber during FY2005. It is our expectation that a 400 MeV proton beam from the Fermilab linac will eventually be made available in the MTA, enabling high intensity engineering beam tests. Beyond the MUCOOL test R&D program, the MTA will be used as a facility to test components required for the MICE experiment, which will demonstrate cooling channel operation in a muon beam.

Depending on the results of the tests at 805 MHz, both Be foil and grid schemes will be fabricated and tested. Based on these tests and calculated performance, a choice will be made between beryllium foil cavity windows designed at LBNL and the alternative gridded design being developed at FNAL. The most effective mitigation techniques from the 805 MHz dark-current studies will be implemented in the 201-MHz cavity and tested at 201 MHz to understand the scaling and to demonstrate an acceptable result on the actual cavity type being considered for the MICE experiment. Depending on the test results, it is possible that a second, improved, cavity might need to be fabricated. If so, engineering for this would begin late this year or early in FY2005.

Work will continue on the SCRF cavity. Effort this year will focus on developing a fully operational cryostat configuration with all required items. When complete, this system will be tested up to full design gradient. While this work may be carried out at Cornell under NSF sponsorship, there is a good possibility that this phase of the SCRF R&D program will become a DOE responsibility. In this circumstance, the natural candidate for carrying out the program is Jlab. They are already involved in the MC program to some degree and would likely be willing to increase their role to accommodate this activity.

In parallel with our rf cavity design effort, impedance assessment and collective effects studies will be required to ensure that the rf systems, and other components, do not cause excessive beam instability. We propose to study the impedance of machine components using state-of-the-art electromagnetic design codes, first in two dimensions and later with full three-dimensional modeling, both time domain and frequency domain. We will eventually produce an impedance budget, analysis of collective effects, and conceptual designs of feedback systems, if they are required.

The simulation effort will continue to concentrate on producing a complete self-consistent, detailed scenario for a cost-effective Neutrino Factory. Realistic simulations of the complete Front End will be carried out, including all errors and all known engineering constraints to ensure design of a channel that can be fabricated. Solutions to the problem of emittance exchange will be incorporated into the design, if possible. A main thrust of the effort will be to identify schemes that could potentially be incorporated into an improved Neutrino Factory design. As an example, it is clear that a successful ring cooler design would have the benefit of reducing the beam longitudinal emittance, potentially reducing the cost of the downstream acceleration system significantly. Detailed simulations of bunching and acceleration will continue. Geological and environmental issues in siting the storage ring will be studied. If these simulations lead to promising results (in terms of cost reductions and/or performance gains), we would anticipate co-sponsoring a Feasibility Study-III afterward, probably during FY2005. Designs of future Muon Colliders, especially the Higgs Factory, will be explored further. Exotic cooling techniques, which could greatly enhance the performance of a Muon Collider, will continue to be investigated. The Monte Carlo programs will continue to be refined. This work will make extensive use of post-doctoral fellows that we anticipate hiring during FY2003 and FY2004.

Work will continue on improvements to the AGS extraction system required to get more intense proton pulses at the target. Assuming that AGS running for HEP is available this year, we anticipate tests with the AGS operating at the full Neutrino Factory proton intensity of 1.6×10^{13} protons per pulse. The cost to the MC for AGS operation depends on whether we are able to take advantage of operating parasitically to the *g*–2 experiment at BNL. If the running is not parasitic, the MC would be required to pay a substantial charge for AGS operation. If the target magnet fabrication is completed, first results from the interaction of an AGS proton beam with targets in a 10–15 T pulsed solenoid field will be obtained from experiment E-951. Measurements will be taken with the new nozzle and with the new high velocity liquid-metal-jet target assembly. Simulations in support of the target program will continue at BNL. These sophisticated 3D magneto-hydrodynamics calculations will be compared in detail to the observed behavior of the target to ensure that we have an adequate grasp of the key physics concepts. This will qualify the model thus developed for use in designing an actual Neutrino Factory at a later date.

In addition to completing the design of a solenoid magnet and rf cavity for the 201-MHz test program at FNAL, we will prepare for fabrication of additional components that can be used in the international MICE experiment, presently envisioned to get under way in this time frame. It is expected that construction of U.S.-contributed components for the experiment will begin in earnest during FY2004. These are anticipated to include 201 MHz rf cavities, one or more of the cooling channel solenoids, and some of the detector equipment. Other MICE-related work will focus on development of a solid absorber, e.g., LiH, that could be used initially as a simpler alternative to the final LH_2 absorber system. Simulations this year will focus on the starting experimental configuration for MICE, and will contain as much realism as we are able to include in the code at this stage, including the systematic errors resulting from imperfect detector response and reconstruction uncertainties. We expect to send physicists to RAL to participate in the initial experiments when they begin, and to play a role in the data analysis as well.

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