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Review of North American Neutrino Factory R&D

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Abstract

We report here on the R&D program of the U.S. Neutrino Factory and Muon Collider Collaboration. Our effort includes work on targetry, muon ionization cooling, simulation work, and development of superconducting RF cavities. In addition, we are involved in the international effort toward a Muon Ionization Cooling Experiment (MICE). Recent activities in all these areas will be described.

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1. INTRODUCTION

In recent years, the Neutrino Factory and Muon Collider Collaboration (MC) has been attacking the R&D topics associated with a Neutrino Factory on a broad front, while continuing to pursue Muon Collider R&D issues as well. As a practical matter, the distinction between the two sets of topics is largely illusory; the distinction often has more to do with the scientific motivations of the persons doing the R&D than it does with the R&D topic itself. For the purposes of this paper, the term "North American" will be interpreted to encompass only the work of the MC R&D program. This choice simply reflects pragmatism on the part of the author.

From the MC perspective, a lot has happened since the last Neutrino Factory Workshop, NuFact01, held in Japan. Of most significance, there was an in-depth review of U.S. high-energy physics plans carried out by a Subpanel of the High Energy Physics Advisory Panel (HEPAP). The Subpanel, co-chaired by Jonathan Bagger and Barry Barish (hence referred to colloquially as the "B&B" Subpanel), met with representatives of the MC on two occasions to discuss our R&D program, our concept for constructing a Neutrino Factory and subsequent Muon Collider, and our R&D support needs to carry out the program envisioned. There was support for the MC R&D program expressed by the B&B Subpanel in its report [1], though our activity was accorded lower priority than the e^-e^+ Linear Collider (LC) R&D program. In terms of their primary recommendations, the Subpanel's Recommendation 5 was: *"We recommend that vigorous long-term R&D aimed toward future high-energy accelerators be carried out at high priority within our program."* They commented elsewhere in the report that *"We give such high priority to accelerator R&D because it is absolutely critical to the future of our field."*

In the Subpanel report, two scenarios for the LC were discussed, one in which it is constructed in the U.S. ("onshore") and one in which it is constructed elsewhere ("offshore"), with substantial U.S. involvement. In either scenario, the Subpanel envisioned that U.S. scientists would be involved in neutrino science. In the onshore case, they anticipated significant U.S. participation in the worldwide neutrino program, possibly including use of a new proton decay detector. In the offshore case, they anticipated that there would be a major new neutrino facility in the U.S., with significant international participation, as part of the worldwide neutrino program, and that this facility might be coupled with a new proton decay detector. Based on these statements, it is fair to characterize the Subpanel report as supportive of accelerator R&D in general, and muon-related accelerator R&D in particular. From the MC perspective, this is a very positive development.

Another important event for the MC was our annual review by MUTAC, the Muon Technical Advisory Panel. This review was very favorable for the MC, and MUTAC noted that our progress in the past year was excellent.

In broad view, the programs in hardware development remain the major focus—and major expense—for the MC. However, the simulation work we carry out is also very important to our overall progress. As examples of this, the completion of Feasibility Study-II [2] was important, and did us a lot of good, both at the MUTAC review and at Snowmass. The new work we have embarked upon aimed at ring coolers has also been valuable. Such studies have the potential for improving the design and lowering the cost of a Neutrino Factory. In the past year, activities related to the international Muon Ionization Cooling Experiment (MICE) have increased, and are becoming a significant part of the MC R&D activity.

In what follows, the current activities and recent progress of the MC R&D program are summarized. Section 2 describes the Targetry program activities, and Section 3 discusses Cooling R&D, including RF cavity studies, absorber studies, and solenoid magnet studies. Section 4 covers the simulation activities, presently related mainly to the subject of emittance exchange. Interest in this topic has led to the formation of a new R&D group* within the MC devoted to the subjects of ring coolers and emittance exchange. In Section 5, we describe our work on superconducting RF cavities at 201 MHz. Section 6 summarizes the status of our MICE activities, which extend beyond the boundaries of the MC, as MICE is an international group. Finally, Section 7 provides a brief summary.

2. TARGETRY R&D

In the past year, initial beam tests of both solid and liquid targets were completed. These tests made use of the 24 GeV proton beam from BNL's Alternating Gradient Synchrotron (AGS).

The solid material studied was in the form of carbon rods. Carbon was the target material on which Feasibility Study-I [3] was based. In addition to standard graphite, rods of a carbon-carbon composite were tested. The expectation was that the low coefficient of thermal expansion (CTE) of this material would result in lower mechanical stress when the proton beam impinges on the target. This concept was borne out, and it appears that such materials may be acceptable from a stress perspective even up to 4 MW of proton beam power. However, this is not the whole story in terms of target performance. Sublimation of the target material at high temperatures and radiation damage (which could drastically affect material properties, such as the CTE) remain issues to explore. Initial sublimation tests performed in vacuum at ORNL [4] lead to a prediction of a one month target lifetime under bombardment with a 1.2 MW proton beam. It is expected that placing the carbon rod in a helium atmosphere will limit sublimation and thus increase the lifetime. Tests of this idea are under way at ORNL.

Initial results with the mercury-jet [5] have been very encouraging. Photographs of the interaction between the mercury jet and a 24-GeV proton beam from the AGS demonstrate that the dispersal occurs well after the proton pulse. Mercury droplets dispersed by the interaction with the beam have modest velocities, a few tens of meters per second, which should not cause damage to the containment vessel.

One open question in the targetry program concerns the nonlinear jet dynamics associated with higher proton intensity. Present tests have been carried out with about 4×10^{12} protons per pulse, compared with a design intensity of 1.6×10^{13} protons per pulse. To reach this higher intensity in the A3 beam line at the AGS already requires an effort to upgrade the AGS extraction line and perform RF manipulations (bunch merging) in the synchrotron. The second open question concerns the behavior of the target jet and beam when they collide in a strong solenoidal field of about 20 T. To test this aspect, we are designing, in collaboration with MIT, a pulsed target test magnet (see Figure 1) capable of operating at 5, 10, or 14.5 T. The magnet will be cryogenically cooled, but will not be superconducting. Parameters for magnet operation are summarized in Table 1. In addition, because the present jet velocity, about 2.5 m/s, is well below the 20–30 m/s velocity specified in Study-II, work on an improved jet system is under way at BNL and Princeton.

3. COOLING R&D

3.1 Overview

Much of our activity in muon cooling comes under the MUCOOL program. This effort includes R&D work on RF cavities, liquid-hydrogen (LH_2) absorbers, and high-field solenoids. We also have a separate program to study so-called “ring coolers.”

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[*] Led by Rajendran Raja from Fermilab.

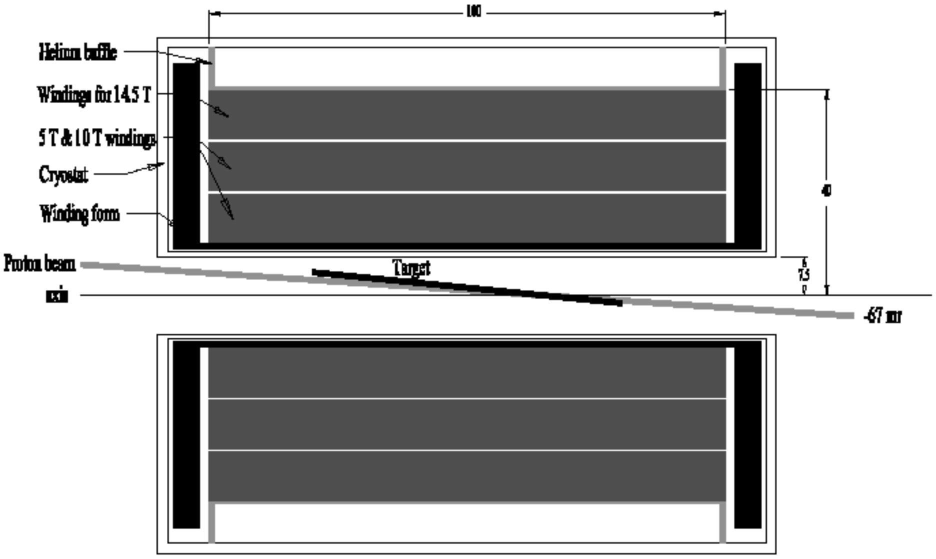

Figure 1. Schematic of pulsed target test solenoid, showing three nested coils. Only the two inner coils are used at field levels up to 10 T; to reach 14.5 T, the outer coil is also energized.

Table 1. Design parameters for target test magnet at various fields.

Peak field on-axis (T)	5	10	14.5
No. of 0.54 MVA power supplies	1	4	4
Mode of ganging supplies	none	2 × 2	2 × 2
Initial temperature (K)	84	74	30
No. of turns	1200	1200	1800
Charging time (s)	7.2	6.3	15.3
ΔT at end of pulse (K)	5.8	21.7	48.3
Cumulative heating at end of pulse (MJ)	2.7	9.1	15.5

Our experimental RF work to date has focused on 805-MHz cavities.[*] Based on our initial tests of an 805-MHz open-iris 6-cell cavity, it was clear that the key issues for high-gradient operation of normal-conducting (NC) cavities are suppression of breakdown and dark currents. It is these phenomena that limit the usable gradient.

Absorber development work is ongoing in Illinois, supported by funds from the Illinois Consortium for Accelerator Research (ICAR), and also at KEK, supported by U.S.-Japan funding. In the U.S., the focus is on development and testing of thin windows, engineering of fluid flow (aided by University of Oxford), and cryogenics design. Hydrogen safety is another critical R&D issue. Because of the proximity of the absorber to an “ignition source” (i.e., the RF cavities), it is likely that additional containment windows will be needed, and these too are necessarily in the beam path. An important goal of this R&D effort is to test an absorber in a solenoid magnet in about 1 year.

Solenoid work is aimed mainly at cost and reliability issues. In general, the designs we require are challenging, but not beyond the state of the art.

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[*] We have nearly completed the design for a 201-MHz cavity, but fabrication has not begun due to funding limitations.

At the present time, we are testing components in the Lab G area at Fermilab. However, this area is not suitable for testing hydrogen absorbers, nor is it suitable for powering a 201-MHz cavity. For these reasons, a new MUCOOL Test Area (MTA) is being developed at Fermilab. This area, situated at the end of the injector linac building, will ultimately be equipped to carry out beam tests with the 400 MeV proton beam from the linac. Although the proton beam is unsuitable for demonstrating cooling, it will permit operating the cooling channel components in a radiation environment equivalent to what would occur in an actual cooling channel. This will permit a "blast test" to verify that the components can operate at their rated specifications in this harsh environment. In the initial phase, to be completed in 2003, the MTA will be readied for component tests without beam. Beam capability, designed in from the outset, will be made available later, probably 2004 or 2005.

Complementary to these experimental programs, is a strong program in beam simulations. A main thrust here is to examine ways to optimize the performance, and reduce the costs, of a Neutrino Factory. For example, we are exploring an RF bunching and phase rotation scheme that would replace the induction linac approach that Study-II was based on. The other main thrust is to work on the design of a "ring cooler" that would serve to reduce 6D emittance, that is, it would combine emittance exchange to reduce longitudinal emittance with "standard" ionization cooling to reduce transverse emittance. Lastly, we are participating in simulation studies in support of MICE. These simulations will serve as the benchmark for interpreting the results of the experiment and are key to our demonstrating that we can build a channel to cool a muon beam.

3.2 RF R&D Activities

This year, we completed our studies on the 805-MHz open-iris cavity. This cavity was conditioned to 24 MV/m accelerating field, corresponding to a peak surface field of 53 MV/m. With the magnetic field on, we observed considerable pitting of the irises (Figure 2, left), and copper was found deposited on the titanium end window of the cavity (Figure 2, right). Measurements made with this cavity [6] showed a high level of dark current activity, which scaled as roughly the tenth power of the gradient. Because of the current interest in this problem, we anticipate having a workshop at Fermilab sometime next year to share knowledge among the world's experts. This issue likewise has significant implications for MICE. During the next year, we plan to study cleaning and coating techniques that might mitigate the problem. Initially this will be done using replaceable windows to modify the properties of the existing 805-MHz pillbox cavity (see below).

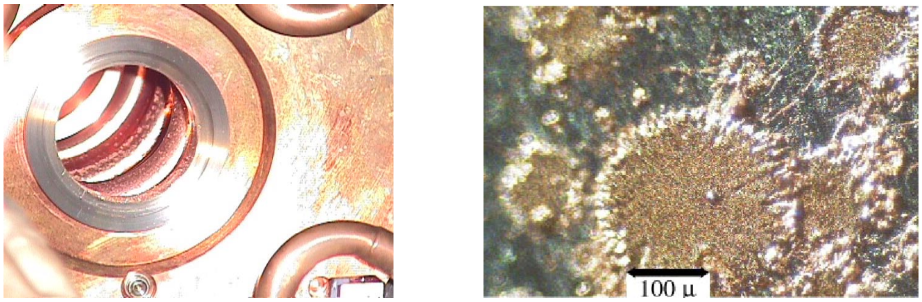

Figure 2. Damage observed in open-iris cavity at Lab G after operation at high gradients in a solenoidal field. Left, view of copper irises, showing pitting; right, copper "splashes" on titanium vacuum window.

At present we are focusing our efforts on an 805 MHz pillbox cavity (Figure 3) having replaceable windows. Initially we have installed copper windows, though we intend eventually to use beryllium windows (possibly TiN coated). This cavity reached a gradient of 34 MV/m in tests without a solenoidal field. Because the end windows were thick, it was not possible to carry out dark current measurements. To permit these, we have now replaced the end windows with thinner ones, again using copper. Visual inspection of the cavity during the window replacement showed no evidence for damage, an encouraging result. The cavity is now being reconditioned without magnetic field in preparation for testing with a solenoidal field.

Our work on the design of a 201-MHz cavity for MUCOOL is well along. The concept being explored is illustrated in Figure 4. The initial design will have options for using either stepped beryllium foils or aluminum grid tubes. Both concepts are shown in the exploded views in Figure 4. The cavity shown here is also the design basis for the MICE experiment, which is discussed in Section 6.

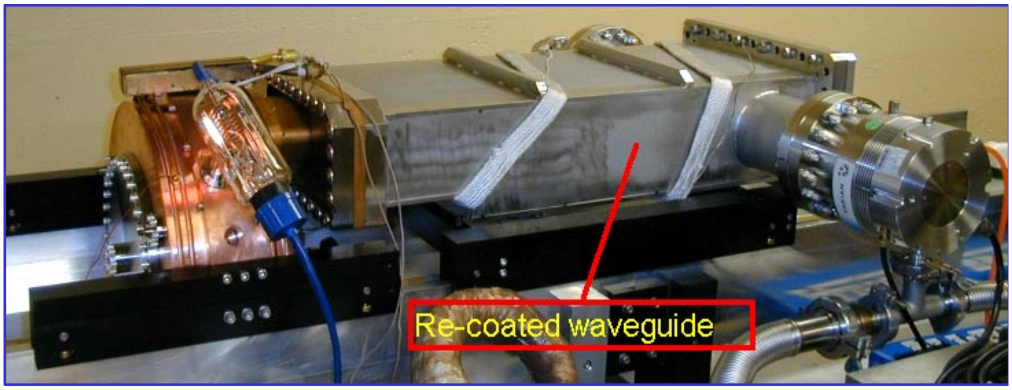

Figure 3. 805-MHz pillbox cavity (to left in picture) along with its waveguide. The cavity is being studied at high power in the Lab G test facility at Fermilab.

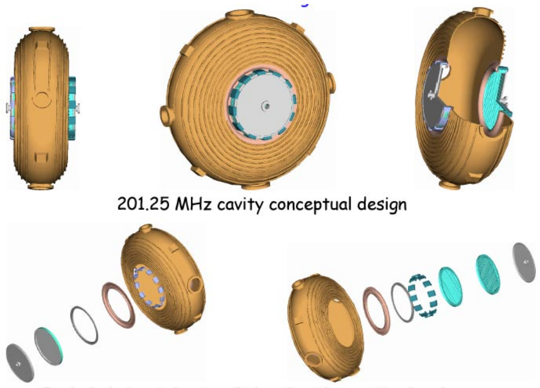

Figure 4. Conceptual design of 201-MHz cavity. The exploded views illustrate the mounting of either a beryllium foil or a series of crossed aluminum grid tubes. The design can accommodate either option, with the choice to be based on our R&D results.

3.3 Absorber R&D Activities

Absorber work focused initially on development of very thin aluminum windows. We have succeeded in machining windows as thin as 125 μm, with an integral flange, from solid pieces of aluminum. To qualify the design for use in a liquid-hydrogen system, we have tested [7] a number of windows to destruction using a pressurized water system. Our results showed that a 125 μm window bursts at about 3 atm, and a 340 μm window at about 8 atm. The latter thickness is realistic, in the sense of being representative of what the Study-II cooling channel assumed. The strength demonstrated is enough to satisfy Fermilab's stringent requirements for hydrogen safety. We have carried out finite-element calculations to predict the window strength, and find good agreement between these and our observations.

Two different types of liquid-hydrogen absorber are being studied in the MUCOOL program. The first is a convection-cooled design, being developed at KEK, and the second is a more conventional flow-through design (Figure 5) with external heat-exchanger, being developed by the ICAR universities in collaboration with Fermilab. The first approach has the advantages of a more compact structure with less hydrogen volume, but is likely to be more limited in its power dissipation ability. The second approach—more typical of today's hydrogen targets—is bulkier and has more hydrogen volume, but should be able to handle higher beam power levels. The first flow-through absorber is being designed to operate in our existing Lab G solenoid to permit tests under realistic conditions. This solenoid will be relocated to the new MTA facility when the Lab G program ends. The advantages of the convection-cooled design make it a natural choice for MICE (see Section 6), where the beam power is negligible. It is not yet clear whether the convection design will be suitable for a full intensity cooling channel.

3.4 Solenoid R&D Activities

Since the completion of Study-II, the main effort has been on optimizing the design of the focusing coils that surround the absorber. Compared with the concept considered in Study-II, the new idea is to make the absorber body an integral part of the focusing coil assembly. This implementation will permit the coil diameter to be reduced, lowering both the stored energy in the coil and the forces between the two opposite polarity coils. Other items that need to be better understood are mainly those relating to mechanical engineering and operational issues. An evaluation of off-normal conditions, such as quench effects on the magnets themselves and devices inside them, is getting under way in the context of evaluating the MICE experiment.

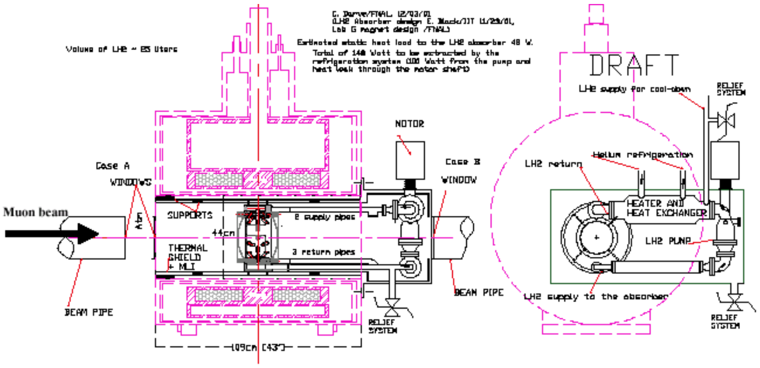

Figure 5. Engineering drawing of flow-through liquid-hydrogen absorber installed in the bore of the Lab G solenoid.

4. Simulation R&D Activities

As mentioned earlier, in the past year the MC has created a new group dedicated to the study of emittance exchange for longitudinal cooling. The group is focusing most of its effort on the study of “ring coolers,” that is, cooling channels arranged in a ring geometry. These devices, if they can be implemented, offer potentially significant payoff for a Neutrino Factory, and even more for a Muon Collider. By “reusing” the cooling channel components via multiple orbits, cost savings may accrue. In addition, a reduction of longitudinal emittance is beneficial for increasing the transmission of a cooling channel, since the losses from the RF bucket are significant even at the high gradients presently specified for the cooling channel RF system.

An example of a ring cooler layout [8] is shown in Figure 6. In this case, the dipole field required to create the circular trajectory (and the dispersion) for the muons is generated by tilted solenoids. Wedge-shaped absorbers, located in the dispersive regions, are arranged to give more energy loss for the higher energy particles, thus reducing the energy spread of the muon beam.

The highest priority is to develop a technically feasible design. For the dipole-based concept, the design of the short, large aperture dipoles is an issue. For all ring coolers, the design of the large aperture injection and extraction magnets is a challenge, as is the design of the wedge absorbers, which necessarily must dissipate more power than in a single-pass system. A concept for a full-aperture injection kicker has been proposed [9] that appears feasible, though quite expensive.

5. Other Hardware R&D Activities

In addition to the normal conducting RF activities described in Section 3.2, we[*] are also embarked upon a program to develop and test a high-gradient superconducting (SC) cavity at 201 MHz. Such a cavity cannot be used in a cooling channel, owing to the presence of the strong magnetic field, but it is perfectly suitable for the acceleration portion of a Neutrino Factory facility, for example, to serve in the linac portion of the Recirculating Linear Accelerator. The size of this cavity, constructed by Cornell in collaboration with CERN, dwarfs the more standard SCRF devices, as can be seen in Figure 7.

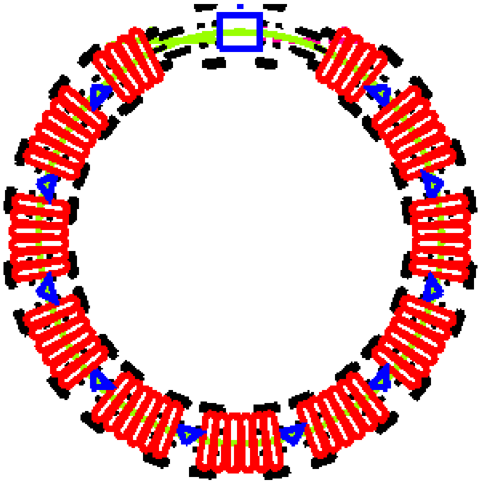

Figure 6. Schematic diagram of cooling ring based on tilted solenoids. The wedge absorbers (small triangles) are located between the RF cavities and solenoids. Injection and extraction take place at the top of the diagram.

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[*] This effort is led by the SCRF group at Cornell University, supported by NSF funds.

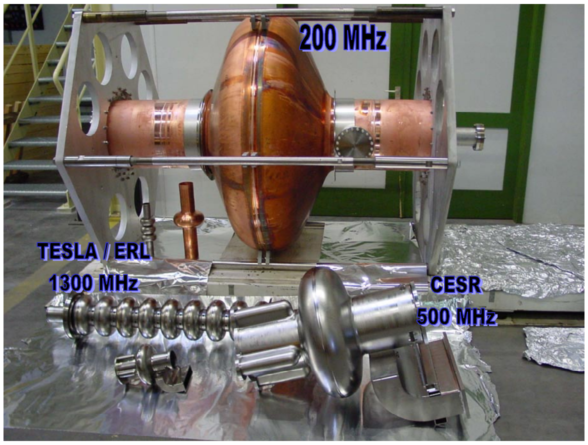

Figure 7. Photograph of 200 MHz SCRF cavity at Cornell, with its smaller siblings.

In the first test of the cavity it reached a gradient of 3 MV/m, limited by the failure of the input power cable due to an arc. A low-field Q of 10^{10} was observed, typical of other SC cavities. In addition to testing the cavity, we will develop designs for the required ancillary devices (input coupler, higher-order-mode coupler, and tuner) based on existing concepts, e.g., the cavities at KEKB.

6. MICE Activities

It is clear that ionization cooling will be required in order to build a high-performance Neutrino Factory. (By “high-performance,” we envision a facility capable of providing $\approx 4 \times 10^{20}$ ν_e aimed at a far detector per 10^7 s year.) A Muon Collider would demand even higher performance. While we are confident that the physics associated with ionization cooling is straightforward, the process has not been experimentally demonstrated. It follows, then, that it is prudent to demonstrate this key principle. This is the motivation for carrying out MICE.

At the October, 2001 review of the MC R&D program by our Muon Technical Advisory Committee (MUTAC), the committee made a strong recommendation on MICE. They consider the experiment as a “crucially important demonstration” and they encouraged the MC to take an international approach to setting up the experiment. The MICE organization has been fully international from the outset, consistent with what MUTAC recommended to us. The MICE organization is listed in Tables 2 and 3. The MC has four members on the MICE Steering Group and provides eight of the technical conveners.

Table 2. MICE steering committee.

A. Blondel, Chair	Geneva University
R. Edgecock	Rutherford Appleton Laboratory
S. Geer	Fermilab
H. Haseroth	CERN
D. Kaplan	Illinois Institute of Technology
Y. Kuno	Osaka University
Y. Torun, Secretary and Webmaster	Illinois Institute of Technology
M. Zisman	Lawrence Berkeley National Laboratory

Table 3. MICE technical conveners.

Concept development	A. Lombardi (CERN)	R. Palmer (BNL)
Experiment simulations	G. Catanesi (CERN)	Y. Torun (IIT)
Absorbers	M. Cummings (NIU)	S. Ishimoto (KEK)
RF cavities and power supplies	H. Haseroth (CERN)	D. Li (LBNL)
Magnet systems	M. Green (LBNL)	J-M. Rey (Saclay)
Detectors	A. Bross (Fermilab)	V. Palladino (Naples)
Beamline	P. Drumm (RAL)	
RF radiation	E. McKigney (ICL)	J. Norem (ANL)
Engineering integration	E. Black (IIT)	I. Ivaniouchenkov (RAL)

Carrying out a cooling demonstration involves the following tasks:

- Development and testing of individual components having challenging operating specifications
- Showing that these components can function properly in close proximity
- Showing that a system of realistic components can reduce the emittance of muons

(Of these tasks, the first one is being carried out as part of the MUCOOL program, and is thus "outside" of MICE.) The remaining task for MICE is to show that our design tools, i.e., our simulation codes, are in agreement with experimental observations. This is a rather critical goal, as it gives us confidence in our ability to optimize someday the design of an actual facility. It is unlikely that any cooling channel design we test now would be exactly what might be selected later for a facility design, but having a validated simulation tool will permit us to proceed with certainty.

The baseline configuration for MICE [10] uses 201-MHz RF cavities. With that in mind, anticipated U.S. contributions to MICE would include the RF cavities, absorber windows, one of the solenoid families, some detector components, and some of the simulation studies. As noted earlier, the 201-MHz cavity to be prepared for MUCOOL serves as the MICE prototype. Absorbers developed for MUCOOL are also directly applicable for MICE. The low beam power in MICE favors the choice of the convection-cooled absorber being developed in Japan.

Among the simulation studies we have carried out to date, it is worth noting one interesting result. The safety implications of using LH_2 motivated us to explore the merits of alternative absorbers for the initial phase of MICE. Palmer, Fernow, and Gallardo [11] evaluated both the MICE experiment and the original Study-II cooling channel performance for three different absorber systems, LH_2, LHe, and LiH (the last being a solid material). The liquid-helium case assumed the standard Study-II absorber configuration, suitably adjusted in length to give the same energy loss as hydrogen. The LiH was taken as uncoated material, again suitably adjusted in length to give the same energy loss. The liquid-hydrogen case was done by tripling the thickness of the absorber window, to represent the effect of the required containment windows that would reside at a location of higher beta function than does the normal absorber window. (The assumption used for the liquid hydrogen is probably somewhat pessimistic, since the secondary containment window need not be as thick as the primary window, and the assumption for the LiH is somewhat optimistic, since a thin protective coating to serve as a moisture barrier is likely to be needed.) With these assumptions, the results, summarized in Tables 4 and 5, were somewhat surprising. The performance of all three absorber systems was found to be nearly identical. As might be expected, LH_2 is the best choice, but not by very much. This result may not seem very intuitive, but is related to the fact that both the MICE beam line and the Study-II cooling channel operate far from the equilibrium emittance point. In this regime, the cooling is dominated by the damping term, which depends only on dE/dx.

7. Summary

In this report we have briefly summarized the program of the U.S. Neutrino Factory and Muon Collider Collaboration.[*] The MC program has made excellent progress on all fronts in the past few years, and there is strong enthusiasm in the U.S. to continue to build upon this success. The MC is part of a strong international effort for MICE. We expect to provide hardware for the experiment and participate in the supporting simulation effort. To do so, we need to identify funding beyond that presently available to the MC, and efforts to do so are already under way. The MC and its interaction with colleagues worldwide is believed to be a good example of how such major international efforts ought to operate. We expect that, together, we will be able to continue this good work.

Acknowledgments

I would like to thank the members of the MC for the high quality of their R&D effort, which is the basis of this paper. In particular, I appreciate the R&D group leaders, A. Blondel and D. Kaplan (MICE), R. Fernow (Simulations), S. Geer (MUCOOL), D. Hartill (SCRF), K. McDonald (Targetry), and R. Raja (Emittance Exchange and Ring Coolers) for their strong technical leadership. Lastly, I wish to thank outgoing Spokesperson A. Sessler for his yeoman efforts to maintain the MC as a focused and productive enterprise.

Table 4. MICE simulations for different absorber configurations (see text).

Configuration	Cooling rate (%/m)
FS-II	1.81
LH_2 + Containment	1.71
LHe	1.71
LiH	1.61

Table 5. Simulations of Study-II cooling channel performance for different absorber configurations (see text).

Configuration	Avg. μ/p ratio
FS-II	0.139 ± 0.04
LH_2 + Containment	0.127 ± 0.02
LHe	0.121 ± 0.02
LiH	0.121 ± 0.02

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[*] The MC home page can be found at http://www.cap.bnl.gov/mumu/mu_home_page.html, and the listing of current MC notes can be found at http://www-mucool.fnal.gov/notes/notes.html .

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