

NEUTRINO FACTORY AND MUON COLLIDER COLLABORATION R&D ACTIVITIES

Michael S. Zisman[†]
Center for Beam Physics
Accelerator & Fusion Research Division
Lawrence Berkeley National Laboratory, Berkeley, CA 94720 U.S.A.

for the Neutrino Factory and Muon Collider Collaboration

Abstract

The Neutrino Factory and Muon Collider Collaboration (MC) comprises about 140 U.S. and non-U.S. accelerator and particle physicists. The MC is carrying out an R&D program aimed at validating the critical design concepts required for the construction of such machines. We are committed to encouraging international cooperation and coordination of the R&D effort. Main activities of the MC include a Targetry program, a MUCOOL program, a component development program, and a theory and simulation effort. Moreover, the MC has participated in several feasibility studies for a complete Neutrino Factory facility, with the aim of identifying any additional R&D activities needed to prepare a Zeroth-order Design Report (ZDR) in about two years and a Conceptual Design report (CDR) about two years thereafter. In this paper, the R&D goals in each area will be indicated, and the present status and future plans of the R&D program will be described.

1 INTRODUCTION

For the past two years, the MC effort has focused primarily on Neutrino Factory R&D topics, though Muon Collider issues have not been ignored. (Examples include an Emittance Exchange Workshop at BNL [1] and a Higgs Factory Collider Workshop at UCLA [2].) In addition to the more traditional R&D activities undertaken by the MC, we have engaged in two “feasibility studies” of a Neutrino Factory facility.

In Study-I [3], done with FNAL, technical feasibility of an entry-level 50-GeV facility was established (assuming the component specifications are met), and an outline of a scientifically-productive staged approach to a full facility was given. It was shown that a carbon target is viable for an entry-level machine. Cost drivers for the facility were identified, with the result that R&D on cost-effective designs is now part of the overall program.

[†]Supported by the U.S. Department of Energy, Division of High Energy Physics, under contract DE-AC03-76SF00098.

Study-II, done jointly with BNL [4, 5], was aimed at a higher performance design. The front-end systems (capture, phase rotation, bunching, and cooling) were treated in an integrated way. Improved understanding of the physics requirements led to a 20 GeV beam energy.

2 COLLABORATION R&D GOALS

About one year ago, the MC created a long-range R&D plan to cover a 5-year period. The plan was based on a “technology-limited” schedule, that is, a schedule that assumes adequate funding would be available. At the end of the 5-year period (i.e., 4 years from now), the MC expects to be ready to begin a formal Conceptual Design Report (CDR) for a Neutrino Factory. Reaching this stage implies that we are ready to design, and do a detailed cost estimate, for most required components. This implies that:

- all optics designs are completed and self-consistent
- all validation experiments are completed, or at least well along
- concepts for all hardware are defined
- prototypes for the technically challenging items are completed, or at least designed

As a milestone along this path, we envision preparing a ZDR in about two more years. Thus far, our assumption on funding availability has not been entirely fulfilled but, for now, we have been able to make sufficient progress to roughly maintain our technology-limited schedule.

3 R&D PROGRESS

R&D activities of the MC are organized along the following lines:

- Beam simulations and theory (organized by J. Wurtele, UCB/LBNL)

- Targetry experiments (organized by K. McDonald, Princeton)
- MUCOOL experiments (organized by S. Geer, FNAL)
- Component development

In the last category are topics such as the development of 201.25-MHz superconducting RF (SCRF) cavities at Cornell, design of induction linacs for phase rotation at LBNL, design of a 20-T solenoid at BNL and MIT, and development of muon beam diagnostics, both those needed for a cooling demonstration experiment and those needed later for facility operation.

It is worth noting here that significant resources in the past two years have been invested in the two feasibility studies mentioned above. These efforts have drawn other groups into the R&D program and have made a strong case that a Neutrino Factory can be built.

3.1 Targetry

The goal of the targetry program is to demonstrate the performance of MW-level targets in a high field solenoid, and, in particular, to demonstrate the lifetime of both solid and liquid targets. Plans also call for verifying pion and neutron yields.

Considerable progress has been made in the past year. We are just beginning the E951 experimental program at BNL after more than a year of preparation. In the first round of experiments, a carbon target and one or more mercury targets (see Fig. 1) will be exposed to a 24 GeV proton beam from the AGS. Strain monitors and a high-speed camera will be the primary diagnostic devices. Simulations to assess target mechanical behavior are under way [6]. It is worth commenting here that initial tests of a mercury jet in a high-field solenoid magnet are being prepared by our colleagues at CERN, and we look forward to seeing their results. Engineering of a pulsed 20-T solenoid for the E951 experiment is now commencing; this device will be used in a subsequent phase of the program.



Figure 1: Initial Hg target test apparatus.

3.2 MUCOOL

The MUCOOL program goals are to build component prototypes for a cooling cell and bench test a complete cell. The ultimate goal for this program is to test the complete cooling cell in a muon beam and eventually to carry out an experimental demonstration of ionization cooling. Though the present cooling channel designs are based on 201.25-MHz RF components, initial component tests, to be done this year, utilize 805-MHz components.

Normal conducting (NC) RF cavities are required to operate at very high gradients. To improve the shunt impedance and maximize the accelerating field on axis, we have explored the use of Be foils to close off the cavity apertures. Thermal deformation tests have been completed [7] with encouraging results. In addition, finite-element calculations have been carried out [8] to validate the model and reproduce the observed foil deformation. One result of this work has been the use of stepped windows to aid in heat conduction while reducing the material thickness near the beam axis. This approach is the baseline for the Study-II design [4,5].

The Lab G facility at FNAL has been prepared for carrying out high-power tests of the RF components [9]. This facility includes a 5-T solenoid having independently powered coils and thus capable of operation in either a standard solenoid or a gradient mode [10]. Two different cavities will be tested there in the coming months, a 6-cell open aperture cavity (Fig. 2) and a pillbox cavity with Be windows. Studies with the first cavity will examine high-gradient limitations and studies with the second will permit the evaluation of Be window behavior and multipactor issues. Either cavity can be immersed in the 5-T solenoidal field that represents a realistic cooling channel environment.

A new area is presently being constructed at FNAL to test the 201.25-MHz cavities now being designed. This area, which will serve initially as the site for LH₂ absorber



Figure 2: Open cell 805-MHz cavity at FNAL being tuned to final operating frequency in preparation for high-power testing.

tests, is located at the end of the linac and will later give access to the beam for component tests. It has convenient access as well for 201.25-MHz RF power.

Absorber tests are now being readied by the Illinois Consortium for Accelerator Research (ICAR) to occupy the area. Pressure tests of the windows will be first, followed eventually by thermal tests of a full system. Very sophisticated thermal modeling is required for the absorber design. Both internal and external heat exchanger concepts are being investigated, the former as a joint R&D activity funded by U.S.-Japan funds.

3.3 Theory and Simulations

The goal for the beam simulation group is to complete end-to-end simulations for a complete facility (target, capture, bunching, cooling, acceleration, storage ring), including the effects of errors. Developing analytical tools for understanding front-end performance is another key activity, as is developing tools and techniques to study full 6D cooling (“emittance exchange”). Such techniques are required for the design of an eventual muon collider and would be helpful as well for improving the performance of a Neutrino Factory. The simulation group also provides support for the design of a demonstration experiment of cooling. As described in Ref. 4, considerable progress has been made at developing an integrated front-end design. Analytical tools for the transverse cooling have been developed [11] and work on a more generalized approach is in progress. Simulations and tracking for the acceleration and storage ring have also been undertaken. Due to the large beam size and energy spread, these efforts require a very detailed description of the magnetic fields.

3.4 Component Development

An important R&D area is the development of 201.25-MHz SCRF cavities capable of high gradients and with adequate mechanical stiffness to avoid microphonics. Though SCRF is by now a well-developed art, cavities at the frequency required for muon acceleration have not been produced. In addition to a technical demonstration of such devices, cost-effective fabrication methods must be developed and tested. A test facility for this R&D program (Fig. 3) is being built at Cornell. It will include an enlarged clean room and high-pressure water rinsing facility suitable for the 201.25-MHz cavity work.

Fabrication of the first 201.25-MHz SCRF test cavity, a Nb-coated-copper design, has begun at CERN. In addition, tests have begun at INFN-Legnaro to produce a spun cavity, thus eliminating the welding step. The first trial will be at 500 MHz; if successful a 201.25-MHz version will be built. Improving the quality of sputtered Nb films is being studied at Beijing University using DC



Figure 3: Test facility for 201.25-MHz SCRF cavities under construction at Cornell.

bias sputtering as opposed to the magnetron technique used at CERN.

Study of induction linac technology for the phase rotation section is another MC R&D activity. In Study-I, the challenge was to provide multiple pulses for the cores on a microsecond time scale. For Study-II, the time separation between pulses, 20 ms, is more standard for this technology. However, the ability to combine multiple pulse waveforms in a common core, and the identification of the most cost-effective core material require R&D. Plans for this are being developed. It is worth noting here that, though large, induction linac cores of this general size have already been successfully produced (Fig. 4) for the DARHT project [12].

4 R&D PLANS

For the targetry program, the next steps will include measurements of neutron and pion yields as part of the E951 experiment. Completing the design and then the fabrication of a pulsed 20-T solenoid is also a priority.

As mentioned, the MUCOOL program will shift emphasis to the larger 201.25-MHz component development. Developing Be windows or grid tubes for the large aperture cavity is an R&D task in its own right. A new solenoid for testing the RF cavities will be required and must be designed and fabricated. Finally, developing plans for a cooling demonstration experiment is part of the mandate of this program.

There are several component development activities to be pursued. For the SCRF cavities, the near-term plan is to fabricate a cavity with adequate mechanical stiffness and then demonstrate high-power pulsed operation at design gradients of 15–20 MV/m. Design of a power source for the RF systems is another important R&D item. The favored approach is a multibeam klystron, possibly



Figure 4: Induction linac cores fabricated at LBNL for the DARHT project; these are representative of the cores that would be used in a Neutrino Factory.

having 19 beams. Multibeam klystrons have been built previously, but not at this frequency. Development of diagnostics suitable for transporting, characterizing, and maintaining the muon beam during cooling, acceleration, and storage must be developed. Such work has implications as well for the anticipated cooling demonstration, though different devices may well be needed for the experiment.

Beam simulation work will focus on optimization to improve cooling channel performance and exploration of alternative approaches that have the potential for being more cost effective. Error studies aimed at defining component specifications will continue. Analytic work on 6D cooling and study of efficient emittance exchange techniques will also be pursued.

5 R&D SCHEDULE

The schedule for the next several years R&D activities is reasonably well understood. As noted, however, the schedule outlined below is based on obtaining adequate funding support, which is certainly not guaranteed.

5.1 FY02 (October 2001–September 2002)

During this period, we anticipate the following major activities:

- Begin (π , n) yield measurements to benchmark the MARS production code
- Construct a prototype carbon target
- Test LH_2 absorber with beam
- Test 201.25-MHz SCRF cavity (CW and pulsed)

- Begin fabrication of high-power NCRF cavity and suitable test solenoid
- Design prototype high-power 201.25-MHz RF power source
- Complete acceleration and storage ring simulation studies, including errors and fringe fields

5.2 FY03 (October 2002–September 2003)

During this period, major activities are expected to be:

- Test target with solenoid at 10^{14} ppp (~6 weeks parasitic beam)
- Complete pion yield tests (~6 weeks parasitic beam)
- Begin high-power tests of 201.25-MHz NCRF components
- Begin beam tests of diagnostics devices
- Integrate simulations end-to-end (target to storage ring) with realistic errors and component specifications

6 SUMMARY

The MC R&D program is vigorous and healthy at present, though funding levels have fallen below what had been anticipated. We have clear directions to proceed on all R&D fronts. Long-range planning of the required R&D program has been done. We anticipate being ready to begin a ZDR in about 2 years and a CDR about two years thereafter. MC membership is at a healthy level; the Collaboration is a grass-roots effort of both particle and accelerator physicists. Though we have sufficient manpower to carry out our program, additional groups could be attracted to participate if support were available. We are particularly fortunate to be joined now in this endeavor by several NSF institutions; these university groups are a potential source of students to participate in this interesting R&D program. The involvement of international institutions, while not formalized, is very beneficial, and we hope to continue this positive trend. We intend to provide detailed information to the community at Snowmass'01 that will permit them to consider and evaluate the physics potential, technical efficacy, and R&D requirements of a Neutrino Factory. The R&D program we are following will give the high-energy physics community the opportunity to carry out frontier experiments in a relatively unexplored sector—an opportunity that should not be missed.

ACKNOWLEDGMENTS

The work described here represents the efforts of many MC members. The leaders of the major R&D efforts deserve much of the credit for guiding their programs and making the work happen. Support from the U.S. DOE and NSF make the work reported here possible. The special help from FNAL and BNL managements for Study-I and Study-II, respectively, has gone a long way toward making the concept of a Neutrino Factory real. Lastly, the close interactions and cooperation with our colleagues in Europe and Japan have done much to enrich the effort of the MC. I am grateful for helpful comments from A. Sessler and M. Tigner in preparing this paper.

REFERENCES

- [1] Emittance Exchange Workshop, BNL, September 11–29, 2000, R. Fernow and G. Hanson, Organizers. <http://www.cap.bnl.gov/mumu/exchange/> (see links to presentations included).
- [2] Higgs Factory Workshop, UCLA, February 28–March 1, 2001, D. Cline and G. Hanson, Organizers, <http://www.physics.ucla.edu/conferences/HIGGS/higgs.html>.
- [3] “A Feasibility Study of a Neutrino Factory Based on a Muon Storage Ring,” ed. N. Holtkamp and D. Finley, available at http://www.fnal.gov/projects/muon Collider/nu/study/report/machine_report/
- [4] R. Palmer, S. Ozaki, and M. Zisman, “A Second Feasibility Study of a Muon Storage Ring Neutrino Source, these proceedings.
- [5] M. S. Zisman, S. Ozaki, and R. Palmer, “Technical Implementation of the Feasibility Study-II Design, these proceedings.
- [6] R. Samulyak, “Muon Collider Target Simulation: Effects of the Proton Energy Deposition and Magnetic Field,” see http://www.cap.bnl.gov/mumu/studyii/editor_meeting/roman_study.pdf.
- [7] D. Li, J. Corlett, N. Hartman, S. Skar, M. Leung, and D. Lozano, “Be Window Studies at Room Temperature,” see <http://www-mucool.fnal.gov/mcnotes/muc0110.ps>.
- [8] N. Hartman, D. Li, and J. Corlett, “Thin Beryllium Windows—Analysis and Design Status,” see <http://www-mucool.fnal.gov/mcnotes/muc0180.pdf>.
- [9] J. N. Corlett, et al., “Status report on the R&D of High-Gradient Normal-Conducting RF Structures for the Neutrino Factory and Muon Collider Collaboration,” these proceedings.
- [10] M.A. Green, “A Test Report for the MUCOOL RF Solenoid,” see <http://www-mucool.fnal.gov/mcnotes/muc0163.pdf>, LBNL-45148.
- [11] C.-x. Wang and K.-J. Kim, “Formulas for Transverse Ionization Cooling in Solenoidal Focusing Channels,” *Phys. Rev. Lett.* **85**, 760 (2000); G. Penn and J. Wurtele, “Beam Envelope Equations for Cooling of Muons in Solenoidal Fields,” *Phys. Rev. Lett.* **85**, 764 (2000).
- [12] M. J. Burns, *et al.*, “DARHT Accelerators Update and Plans for Initial Operation,” in *Proc. 1999 Particle Accel Conf.*, p. 617; 1999; <http://accelconf.web.cern.ch/accelconf/p99/PAPERS/FRA R4.PDF>.