R&D TOWARD A NEUTRINO FACTORY AND MUON COLLIDER*

Michael S. Zisman[†], LBNL, Berkeley, CA 94720, U.S.A.

Abstract

Significant progress has been made in recent years in R&D towards a neutrino factory and muon collider. The U.S. Muon Accelerator Program (MAP) has been formed recently to expedite the R&D efforts. This paper will review the U.S. MAP R&D programs for a neutrino factory and muon collider. Muon ionization cooling research is the key element of the program. The first muon ionization cooling demonstration experiment, MICE (Muon Ionization Cooling Experiment), is under construction now at RAL (Rutherford Appleton Laboratory) in the UK. The current status of MICE will be described.

INTRODUCTION

A muon-based storage ring or collider would be a powerful tool in the experimentalist's arsenal. A muon storage ring could serve as an intense source of electron and muon neutrinos, and a muon collider would permit exploration of the energy frontier with leptons, complementing the ongoing program at the Large Hadron Collider (LHC). Design and performance evaluations for such muon-based machines have been under way for more than a decade, carried out by the U.S. Neutrino Factory and Muon Collider Collaboration (NFMCC) [1] and Fermilab's Muon Collider Task Force [2]. At the behest of DOE-OHEP, these two organizations have now been merged to form MAP [3].

Recent interest by Fermilab management has spurred increased effort to develop particularly the muon collider design into a real option for the particle physics community.

MUON ACCELERATOR PROGRAM

MAP was set up to deliver, in a 5–7 year time frame:

- a Design Feasibility Study (DFS) for a muon collider. The DFS will include a realistic cost range for such a facility;
- a technology development program to inform the DFS and enable down-selection of suitable approaches;
- a neutrino factory Reference Design Report that will be prepared under the auspices of the International Design Study of a Neutrino Factory (IDS-NF) and will include a Fermilab site-specific design;
- a continued program of system tests, including participation in MICE and planning for a future 6D muon cooling experiment.

Table 1: MAP Deliverables.

Deliverable	Nominal schedule
MC DFS	
Interim	FY14
Final + cost range	FY16
MICE hardware completion	FY13
RF studies (down-select)	FY12
IDS-NF RDR	FY14
6D cooling definition	FY12
6D cooling section component bench test	FY16
6D demonstration proposal	FY16

Table 1 summarizes the proposed schedule for major deliverables, assuming the requested funding profile (~$15M per year) is reached. In addition to the MAP effort, a parallel Physics and Detector Study is being launched to ensure that the facility design will be responsive to user requirements.

MUON ACCELERATOR ADVANTAGES AND CHALLENGES

Muon beam accelerators can address several of the key accelerator-related particle physics questions. At the energy frontier, the fact that the muon is a point particle means that the full beam energy is available for particle production, and its heavier mass compared with the electron means it couples well to the Higgs sector. Compared with electrons of the same energy, muons experience negligible synchrotron radiation and beamstrahlung. The former feature permits use of a circular collider that can fit on an existing laboratory site (see Fig. 1), and the latter results in a narrow energy spread for the colliding beams (see Fig. 2).

For the neutrino sector, the spectrum from muon decay is well understood, and produces high-energy electron neutrinos (or anti-neutrinos) above the tau threshold. The oscillations from ν_e to ν_μ give rise to "wrong-sign" muons that are detectable with low backgrounds. A neutrino factory thus has unmatched sensitivity to CP violation, the neutrino mass hierarchy, and unitarity violation.

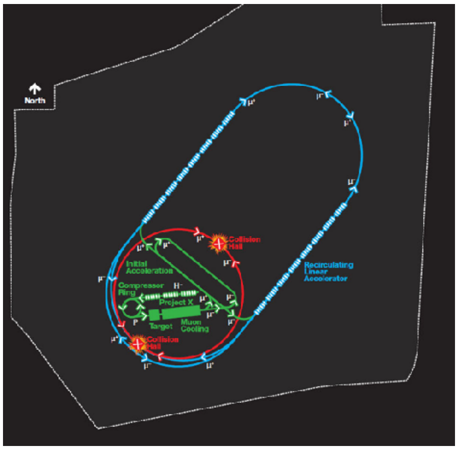

Figure 1: Footprint of muon collider on Fermilab site.

---

*Work supported by U.S. Dept. of Energy, Office of Science, under contract no. DE-AC02-05CH11231.

[†] mszisman@lbl.gov

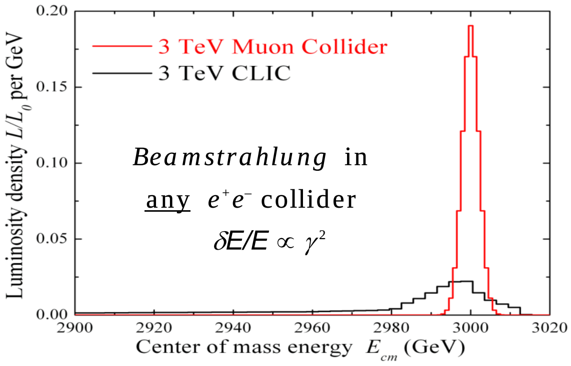

Figure 2: Luminosity density for 3 TeV e^+e^- and $\mu^+\mu^-$ colliders.

The challenges of muon beams stem from two features:

- muons are created as a tertiary beam (p → π→ μ);
- muons have a very short lifetime (2.2 μs at rest).

The first aspect implies a low production rate, and thus a target that can handle a multi-MW proton beam and a proton source that can provide it. It also results in a muon beam having a large energy spread and very large transverse phase space, which consequently requires some form of emittance cooling, in addition to high-acceptance acceleration and collider or decay rings. The second aspect means that there is a premium on rapid beam manipulations, which results in the need for high-gradient normal conducting rf cavities, the presently untested ionization-cooling technique, and a very rapid acceleration system. Decay electrons from the muon beam are a problem in their own right, giving a high heat load in decay ring or collider magnets and potentially severe backgrounds in the collider detectors.

MUON COLLIDER INGREDIENTS

Figure 3 illustrates a schematic layout for a muon collider, and Table 2 summarize its main parameters. It comprises a proton driver; a front end that includes the target, capture and decay section, bunching and phase rotation sections, and one or more ionization cooling sections that provide both transverse and longitudinal cooling; a multi-stage acceleration section to reach 1–2 TeV; and finally a collider ring.

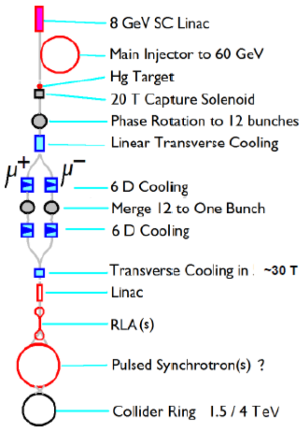

Figure 3: Schematic of muon collider systems.

Table 2: Example muon collider parameters.

Parameter	Value	
$E_{\text{c.m.}}$ (TeV)	1.5	3.0
Luminosity (cm^{-2}s^{-1})	1×10^{34}	4×10^{34}
Beam-beam tune shift	0.087	0.087
Muons per bunch	2×10^{12}	2×10^{12}
Beam stored energy (kJ)	480	960
Circumference (km)	2.6	4.5
Avg. dipole field (T)	6	8.4
Bunch length, rms (mm)	10	5
β^* (mm)	10	5
$\delta p/p$	0.001	0.001
f_{rf} (MHz)	805	805
V_{rf} (MV)	20	230
Repetition rate (Hz)	15	12
Proton beam power (MW)	~4	~4
$\varepsilon_{\perp}$, norm. (μm)	25	25
ε_{L}, norm. (mm)	72	72

A neutrino factory has a similar list of subsystems, and it is presently anticipated that the front end will be the same—or at least very similar—for both types of facility. However, a neutrino factory is a simpler device than a muon collider because it does not need longitudinal cooling, and needs much less acceleration to reach its operating energy of 25 GeV.

R&D PROGRAM

Overview

To address the technical challenges and validate the design choices, a substantial R&D program is under way within MAP. For the neutrino factory, the effort falls mainly under the auspices of the IDS-NF [4].

The MAP R&D effort has the following components:

- *simulation and theory* in support of muon collider and neutrino factory design;
- *technology development*, focused mainly on cooling channel components ("MuCool") and high-power target technology ("Targetry"); and
- *system tests*, in which we participate as an international partner.

The (completed) MERIT experiment [5], and the ongoing MICE activity [6], serve as examples of system tests. This activity will also include the evaluation of, and planning for, a possible 6D cooling experiment at some future time. However, it is not envisioned that such an experiment would be carried out during the initial phase of MAP.

Simulations

Considerable effort has been dedicated to optimization of the front end portion of the neutrino factory, as a MAP contribution to the interim design report (IDR) [7] for the IDS-NF. The bunching and phase rotation sections have been shortened, with a concomitant reduction in the length of the bunch train from 120 m to 80 m. As indicated in Fig. 4, the transmission of the optimized

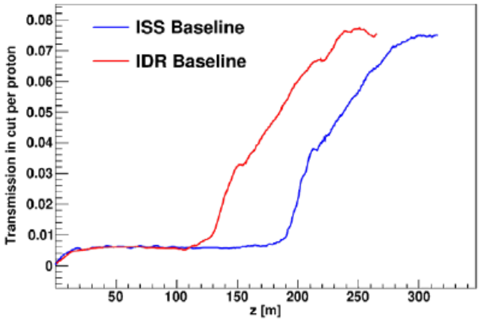

Figure 4: Comparison between optimized IDR front end transmission and original ISS performance.

system is identical to that of the earlier International Scoping Study (ISS) design [8].

The target area is also receiving attention. Recent studies [7] have indicated that the radiation dose and its associated heat load on the magnets are too high, and a reoptimization of the configuration to include more shielding is in progress.

Simulations in support of the muon collider design are also making continued progress. A new front end concept starting initially with 6D cooling is under study and looks promising [9], and a final cooling section with a solenoidal field of 30 T has been shown to work effectively [10].

MuCool

The MuCool program at Fermilab carries out R&D on cooling channel components, e.g., rf cavities and absorbers. In recent years, the focus has been mainly on rf issues [11], along with some development of LiH solid absorbers [12] for MICE. The experimental work takes place in the MuCool Test Area (MTA) at Fermilab (see Fig. 5). The MTA is situated at the end of the 400 MeV linac, and has recently been upgraded to permit proton-beam testing of components, such as a high-pressure gas-filled rf (HPRF) cavity [13].

The plan for MuCool is to continue assessment of alternative rf technologies, with the goal of identifying at least one approach that eliminates—or at least reduces to acceptable levels—the observed degradation in cavity performance seen [14] with an axial magnetic field. For vacuum cavities, the approach is to reduce or eliminate surface electric field enhancements, either by using superconducting rf processing techniques (electro-polishing followed by a high-pressure water rinse), by using atomic layer deposition (ALD) techniques to smooth the cavity surface with a conformal coating at the molecular level, or by identifying cavity materials resistant to damage. The HPRF approach has already demonstrated [15] the ability to suppress the performance degradation in a magnetic field, but the key question of whether such a cavity can operate with an intense beam traversing it remains unanswered. Such tests will be the first use of the newly available beam capability in the MTA.

Figure 5: MTA enclosure showing 5-T solenoid in foreground and 201-MHz cavity behind it.

Recent tests of our 201-MHz rf cavity in the fringe field of the MTA 5-T solenoid showed degradation in the maximum stable gradient. When the cavity was subsequently opened for inspection, its inner surfaces still looked pristine, but there was evidence for arcing at the coupling loop and, as shown in Fig. 6, there was a layer of copper deposited on the TiN-coated ceramic rf windows. The plan is to replace the windows and also to attempt to model the observed effects, which appear to be magnetic field related. We plan to test the cavity in a more "MICE-like" field configuration (Fig. 7) when the first large diameter coupling coil solenoid is delivered next year.

Figure 6: View of ceramic rf window after testing cavity in a magnetic field. A layer of copper was somehow deposited on the ceramic window during the test process.

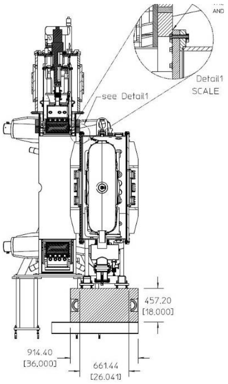

Figure 7: Drawing showing how the coupling coil (to the left) will be mounted adjacent to existing 201-MHz cavity (to the right) in the MTA.

Other activities in the MTA include the testing of a “box” cavity to assess the efficacy of the magnetic-insulation concept [16] in our application. The initial results, shown in Fig. 8, were somewhat disappointing in that, compared with the no-field performance of 50 MV/m, there was a degradation in gradient at 3 T for all angles tested.

System Tests

As mentioned earlier, MERIT [5] was our first successful system test. It demonstrated that the power handling capability of the target is adequate, and thus serves as a proof-of-principle for the mercury-jet target concept.

The ongoing system test effort is directed toward MICE [6]. MICE aims to:

- design, engineer, and build a section of cooling channel capable of giving the desired performance for a neutrino factory;
- place this apparatus in a muon beam and measure its performance in a variety of operating modes and beam conditions; and
- show that the simulation tools correctly predict the experimental observations.

Getting the required components fabricated and operating is itself a technical challenge, and is teaching us about both the complexity and the cost of constructing a muon cooling channel. Responsibilities for the various MICE components are indicated schematically in Fig. 9.

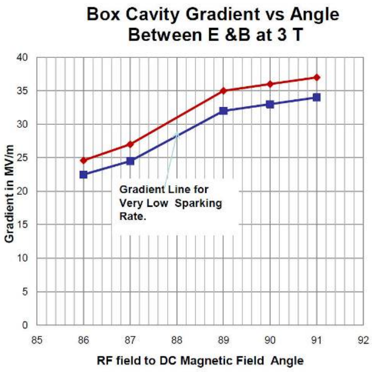

Figure 8: Maximum gradient reached in box cavity *vs.* angle between electric and magnetic field directions. Even at angles near 90° there was a loss compared with the 50 MV/m found in the no-field case.

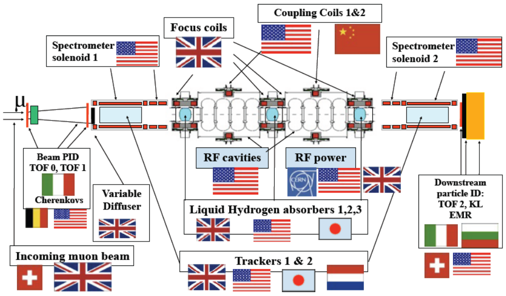

Figure 9: Schematic representation of MICE responsibilities.

MICE comprises one cell of the Feasibility Study 2 cooling channel [17], along with upstream and downstream detectors for particle identification and emittance determination. A layout of the experiment is shown in Fig. 10. The experiment is carried out using particle physics techniques to measure the muon properties particle-by-particle. The muons are produced as a tertiary beam from ISIS at RAL and transported in a purpose-built muon beam line to the MICE Hall. The upstream section of the beam line is shown in Fig. 11.

Commissioning of the beam line is essentially complete; its capability to provide the range of beams required has been verified and the installed detectors are working well. Figure 12 shows the purity of the muon beam when the second beam line dipole is adjusted to half the momentum of the first dipole. Figure 13 shows phase-space plots measured using timing information from the time-of-flight (TOF) counters compared with simulations. Although the TOF detectors were not designed with emittance measurement in mind, they nonetheless do a decent job—much better than their crude segmentation would suggest. The ability of the simulation code to reproduce the measured data is encouraging, and bodes well for the cooling measurements to follow.

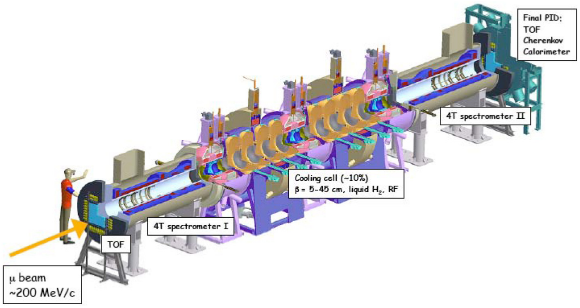

Figure 10: Cutaway view of MICE cooling and detector hardware.

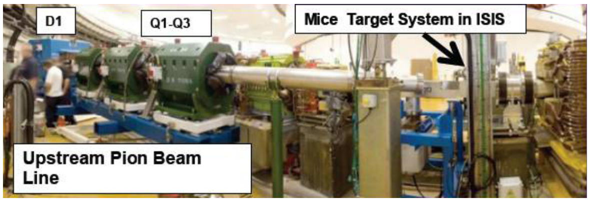

Figure 11: Upstream portion of MICE muon beam line. The ISIS ring is visible in the background.

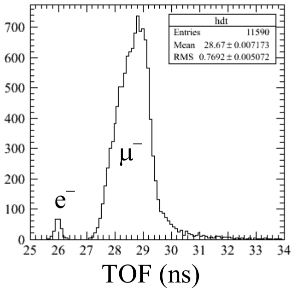

Figure 12: TOF spectrum showing clean muon separation.

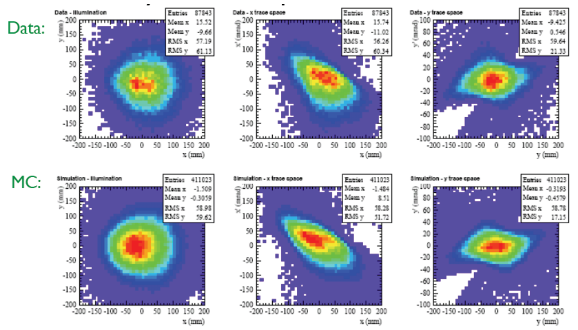

Figure 13: Plots of real-space (x,y) (left column), and phase-space (x,x′) (middle column) and (y,y′) (right column), distributions. The upper row shows measurements and the lower row shows the ability of Monte Carlo (MC) simulations to reproduce them.

The main components of the cooling channel—solenoids, rf cavities, and absorbers—are all under construction at various institutions and vendors throughout the world. These components should begin arriving at RAL starting late this year or early in 2012.

SUMMARY

The R&D toward a neutrino factory and muon collider is making steady progress. The MERIT experiment has been completed, and the MICE experiment is progressing well, with the beam line completed and all but one detector system ready. We are looking forward to making the first ionization cooling measurements soon.

In the U.S., the Muon Accelerator Program R&D plan is under way. Its main deliverables in the next 5–7 years include producing a Design Feasibility Study for a muon collider, completing the U.S. contributions to the IDS-NF Reference Design Report, making MICE a success, carrying out a technology assessment leading to a down-selection of suitable rf and magnet approaches for a neutrino factory and muon collider, and assessing the need for a future 6D cooling experiment.

A community-wide workshop on Muon Colliders, including physics, detectors, and accelerators, will be held in Telluride, Colorado from June 27–July 1, 2011. This will be an opportunity for interested scientists to learn about the exciting potential of such a facility, and the role it might play in Fermilab’s future.

It should be obvious that the development of muon-based accelerator facilities offers great scientific promise and remains a worthy, though challenging, goal to pursue.

ACKNOWLEDGMENTS

I would like to thank the members of MAP for the hard work that has led to the results shown here, and the funding agencies, DOE and NSF, for their unwavering support of these efforts. I would also like to thank my MICE colleagues for their continued dedication to making this important experiment a success. I am grateful for the well-focused and collegial effort that has been undertaken by the IDS-NF and looking forward to continued progress. Finally, I would like to thank Daniel Kaplan and Vittorio Palladino for their helpful comments on this paper.

REFERENCES

[1] See http://www.cap.bnl.gov/mumu/mu_home_page.html.
[2] See http://apc.fnal.gov/MUONRD/.
[3] See http://map.fnal.gov/.
[4] See https://www.ids-nf.org/wiki/FrontPage.
[5] H. G. Kirk *et al.*, in Proc. EPAC 2008, p. 2886.
[6] See http://mice.iit.edu/.
[7] IDS-NF note IDS-NF-020; see https://www.ids-nf.org/wiki/FrontPage/Documentation?action=AttachFile&do=get&target=IDS-NF-020-v1.0.pdf.
[8] M. Apollonio *et al.*, “Accelerator Design Concept for Future Neutrino Facilities,” JINST_4_P07001, see http://www.iop.org/EJ/abstract/1748-0221/4/07/P07001.
[9] R. Palmer and R. Fernow, “Six Dimensional Bunch Merging for Muon Collider Cooling,” paper MOP003, these proceedings.
[10] R. Palmer, “Muon Collider Final Cooling in 30–50 T Solenoids,’ paper THOBN2, these proceedings.
[11] Y. Torun *et al.*, “The MuCool Test Area and RF Program,” in Proc. of IPAC10, Kyoto, Japan, p. 3780; see http://accelconf.web.cern.ch/AccelConf/IPAC10/papers/thpea046.pdf.
[12] C. T. Rogers *et al.*, “Wedge Absorber Design and Simulation for MICE Step IV,” paper MOP060, these proceedings.
[13] K. Yonehara et al., “High Pressure RF Cavity Test at Fermilab,” paper MOP032, these proceedings.
[14] D. Huang et al., “RF Studies at Fermilab MuCool Test Area,” in. Proc. PAC09, Vancouver, BC, Canada, p. 888; see http://accelconf.web.cern.ch/AccelConf/PAC2009/papers/tu5pfp032.pdf.
[15] M. BastaniNejad *et al.*, “Studies of Breakdown in a Pressurized RF Cavity,” in Proc. EPAC’08, Genoa, June 2008, p. 736; see http://accelconf.web.cern.ch/AccelConf/e08/papers/mopp080.pdf.
[16] R. Palmer *et al.*, “RF Breakdown with External Magnetic Fields in 201 and 805 MHz Cavities,” Phys. Rev. ST Accel. Beams 12 (2009) 031002.
[17] S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo, eds., “Feasibility Study-II of a Muon-Based Neutrino Source,” BNL-52623 (2001); see http://www.cap.bnl.gov/mumu/studyii/final_draft/The-Report.pdf.