R&D TOWARD A NEUTRINO FACTORY AND MUON COLLIDER*

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Abstract

There is considerable interest in the use of muon beams to create either an intense source of decay neutrinos aimed at a detector located 3000–7500 km away (a Neutrino Factory), or a Muon Collider that produces high-luminosity collisions at the energy frontier. R&D aimed at producing these facilities has been under way for more than 10 years. This paper will review experimental results from MuCool, MERIT, and MICE and indicate the extent to which they will provide proof-of-principle demonstrations of the key technologies required for a Neutrino Factory or Muon Collider. Progress in constructing components for the MICE experiment will also be described.

INTRODUCTION

The U.S. Neutrino Factory and Muon Collider Collaboration (NFMCC) is a grass-roots organization dedicated to exploring techniques for producing, accelerating, and storing intense muon beams for particle physics experiments. In the near term, a 25 GeV muon storage ring could serve as a source of well-characterized neutrinos (a Neutrino Factory, NF) for long baseline (~3000–7500 km) experiments. Ultimately, we envision a Muon Collider (MC) where counter-rotating beams of μ^- and μ^+ collide. Such a collider could be a Higgs Factory operating at a few hundred GeV or an energy-frontier machine operating at several TeV. The MC studies are carried out jointly with the Fermilab Muon Collider Task Force (MCTF) group.

FACILITY DESCRIPTION

Both a NF and a MC comprise a number of major subsystems. For a NF, these include:

- a Proton Driver that provides ~4 MW of beam to a production target,
- a Target, Capture, and Decay section where pions are created, captured, and allowed to decay into muons,
- a Bunching and Phase Rotation section, where the beam is bunched at 201 MHz and is manipulated in longitudinal phase space such that its energy spread is reduced and the bunch train is lengthened,
- an Ionization Cooling section, where the transverse emittance of the beam is reduced,
- an Acceleration section, where the beam energy is increased from 130 MeV to 25 GeV,
- a Decay Ring having long straight sections aimed at distant detectors.

The MC includes the same basic features, though the requirements are different. The collider requires both transverse and longitudinal cooling, the acceleration requires more stages to reach an energy of ~1 TeV, and the storage ring has a collider configuration with counter-rotating beams and a low-beta interaction region. A schematic layout of the MC is shown in Fig. 1.

MUON ACCELERATOR ADVANTAGES

Muon beam accelerators could address several of the key outstanding questions in particle physics. In the neutrino sector, a NF provides well-characterized beams of high-energy (above τ threshold) electron neutrinos or anti-neutrinos. Oscillations $\nu_e \rightarrow \nu_\mu$ give events with "wrong-sign" muons; this very clear signature permits study of CP violation and mass hierarchy with unmatched sensitivity.

For the MC, the muon (a point particle) makes the full beam energy available for production of new particles. In addition, the muon, being much heavier than the electron, emits almost no synchrotron radiation, resulting in a beam energy spread much narrower than at an e^--e^+ collider, and making it practical to build a circular collider that uses the expensive RF equipment efficiently and fits on the site of an existing laboratory. Finally, the heavier muon allows s-channel Higgs production.

MUON BEAM CHALLENGES

First and foremost, muons are created as a tertiary beam ($p \rightarrow \pi \rightarrow \mu$), which results in a low production rate and a beam with a very large energy spread and transverse phase space. These features necessitate a target that can handle a multi-MW proton beam, a solenoidal channel to focus in both planes simultaneously, and a technique to reduce the transverse phase space occupied by the beam.

In view of the 2.2 μs lifetime of the muon, only the ionization cooling process [1] is sufficiently rapid. Moreover, the short lifetime requires rapid beam manipulations, and thus favors high-gradient RF cavities that, in the cooling section, must operate in a high magnetic field. This has proved very difficult, as will be discussed below.

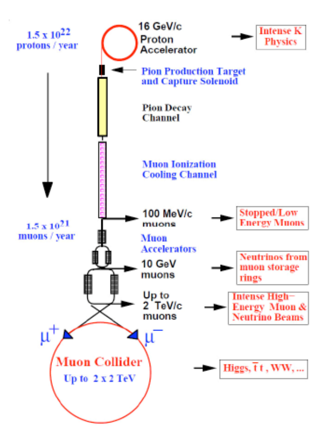

Figure 1: Schematic of MC subsystems.

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As a final challenge, electrons from muon decay create a substantial heat load in the mid-plane of superconducting decay- or collider-ring magnets and give rise to significant backgrounds in the collider detector.

The R&D program described here is aimed at addressing these challenges and finding the means to deal with them.

R&D OVERVIEW

The ongoing NFMCC R&D program includes the following components:

- simulation and theory
- development and testing of high-power target technology ("Targetry")
- development and testing of cooling channel components ("MuCool").

In addition, we participate in several major system tests as an international partner. These include MERIT [2], a high-power Hg-jet target test; MICE, the Muon Ionization Cooling Experiment [3]; and EMMA [4], the first test of an electron model of a non-scaling fixed-field, alternating gradient (FFAG) ring, which may lead to a cost-effective muon acceleration scheme.

MUCOOL R&D

The MuCool R&D program [5] develops and tests cooling channel components. The activities take place in a purpose-built area at Fermilab, the MuCool Test Area (MTA). The MTA is located at the end of the Fermilab 400 MeV linac, and is designed to permit beam tests of selected components.

In recent years, the prime thrust of the MuCool program has been to understand—and look for means to mitigate—the observed degradation in allowable RF gradient in the presence of a strong axial magnetic field. Figure 2 shows our 201-MHz test cavity in the MTA, located in the fringe field of our 5-T solenoid. A summary of the data is shown in Fig. 3. There is considerable degradation in performance when the cavity is operated in a magnetic field, as needed for a cooling channel.

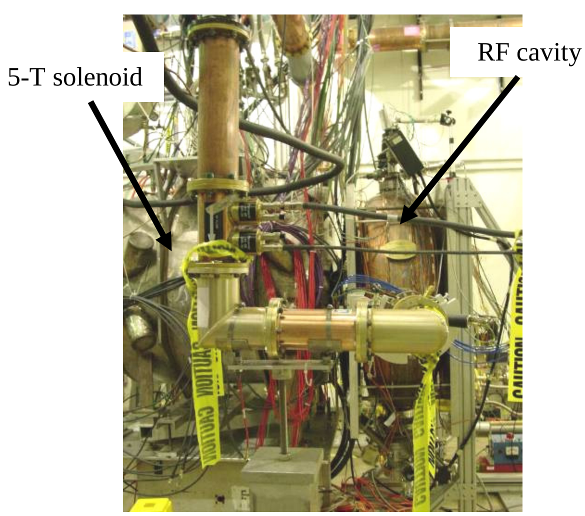

Figure 2: 201-MHz test cavity in the MTA.

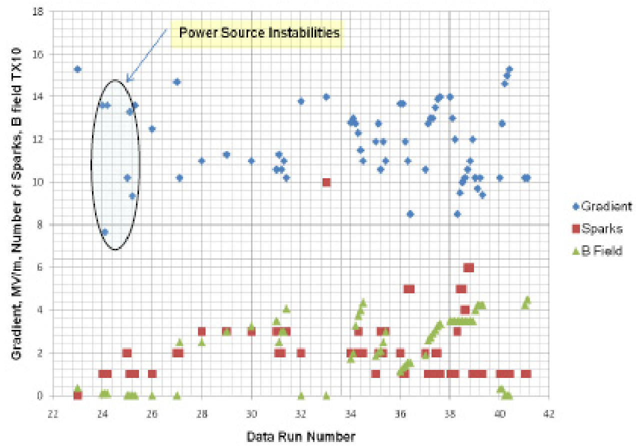

Figure 3: History of sparking during MTA magnetic field studies.

Studies by the MCTF and Muons, Inc. of an 805-MHz cavity filled with high-pressure hydrogen gas do not show such a degradation with magnetic field [6], which is encouraging. Our plan is to test such a cavity in the MTA with beam from the linac, to see if beam ionization of the gas affects cavity behavior. Work on 6D cooling apparatus, such as magnets for a helical cooling channel, is also under way at Fermilab, in collaboration with Muons, Inc. [7].

TARGETRY R&D

Design specifications for either a NF or a MC call for a proton beam power of about 4 MW. Developing a target system to handle such a beam is a substantial challenge. Schemes based on solid or powder targets have been investigated by various groups [8, 9]. Our approach, based on a Hg-jet target, is the basis of the successful MERIT experiment [2]. This experiment, which tested a Hg-jet system in a 15-T solenoid at the CERN PS, was carried out by the NFMCC in collaboration with scientists from CERN and RAL.

The target concept that formed the basis of the MERIT experiment is illustrated in Fig. 4. At a jet velocity of 20 m/s, a fresh target is available for each 50-Hz beam pulse. The experiment was run in the fall of 2007 and data analysis is currently under way [2].

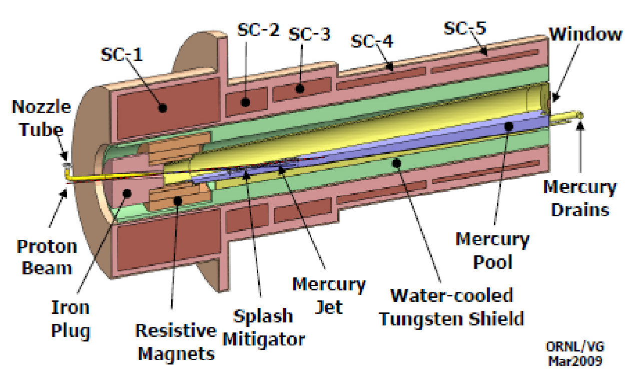

Figure 4: Hg-jet target concept studied in MERIT.

MERIT Results

MERIT results to date have looked at three main aspects of the jet behavior—determining the disruption length, estimating the velocity of dispersed filaments, and looking at the time-dependence of pion production.

Disruption length (defined as $v_{jet} \times$ duration of disruption) was monitored by means of optical diagnostics, using a fast camera [10]. It was found (see Fig. 5) that there is no evidence for disruption for proton beam pulses with an intensity below ~2 Tp. Above this value, modest disruption is observed, but appears to saturate at high magnetic fields. Other optical results indicate a maximum filament velocity of about 60 m/s at high magnetic field. It remains to be determined whether this velocity can damage the surface of the containment vessel.

Pion production was studied with particle detectors placed downstream of the target vessel. Pump-probe experiments, in which the following (probe) pulse could be delayed by nearly 1 ms, were performed. Initial results [2] indicate no significant decrease in production for a 350 µs delay, and about a 5% loss for a 750 µs delay.

MERIT conclusions

From the disruption results in Fig. 5, we can conclude that, for a jet velocity of 20 m/s, a disruption length of 28 cm would imply a maximum acceptable repetition rate of 70 Hz. As a 30 Tp beam pulse represents 115 kJ impinging on the target, the total acceptable power level would be 8 MW. Thus, our present baseline design value of 4 MW (corresponding to 80 kJ per pulse at a 50 Hz rate) seems comfortable. On this basis, the experiment has successfully demonstrated the proof-of-principle for the Hg-jet target design.

There remain target issues to study, however. First, as already mentioned, we must look for damage to the containment vessel from the 60 m/s Hg filaments. Second, we need to develop techniques to mitigate splashes (initiated by both the beam and the spent Hg jet) in the Hg pool that serves as a beam dump. Finally, we must develop the techniques to produce a continuously flowing Hg jet at the required velocity. All of these issues can be studied without the use of a beam.

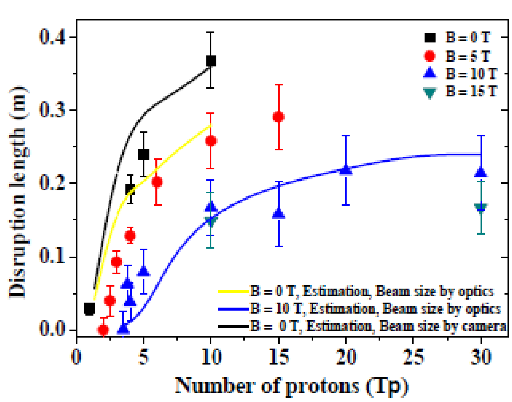

Figure 5: Disruption length *vs*. proton intensity.

MICE

A high performance NF that produces ~10^{21} ν_e per year aimed at a far detector depends on ionization cooling. Although the physics of this process is straightforward, its technical implementation is not. A MC depends even more heavily on ionization cooling. The MICE experiment [3] aims to:

- design, engineer, and build a section of cooling channel capable of giving the desired performance for a NF;
- place this apparatus in a muon beam and measure its performance *in a variety of modes of operation and beam conditions*.

Getting actual cooling channel components fabricated and tested will provide valuable information on both the cost and the complexity of a muon cooling channel. The reason for emphasizing a variety of configurations is to validate the simulation codes, which serve as our primary design tool. While it is unlikely that the specific MICE channel will be adopted for a future NF or MC design, once we have verified their accuracy, we can use the simulation codes with confidence to assess the performance of any new design.

MICE Status

Much of the MICE Hall infrastructure (including the muon beam line elements) is already installed, as can be seen in Fig. 6. The area is being prepared for the arrival this summer of the initial element of the cooling channel (see Fig. 7), the first of two spectrometer solenoids [11]. All of the other main components of MICE, the Coupling Coils, the RF cavities (Fig. 8), the Focus Coils, and the liquid-hydrogen absorbers are now in fabrication. One of the thin aluminum windows for the absorber is shown in Fig. 9.

Figure 6: View of the MICE Hall, looking upstream. The wall separating the Hall from the ISIS vault is in the background of the photo, and the final quadrupole (blue) of the muon beam line is in the center. All of the remaining MICE components will be installed downstream of the quadrupole and upstream of the muon beam dump visible in the foreground.

Figure 7: Spectrometer Solenoid being cooled down at Wang NMR. The first magnet will be delivered to RAL this summer.

Figure 8: Cavity half-shell being prepared at Acme Metal Spinning Company.

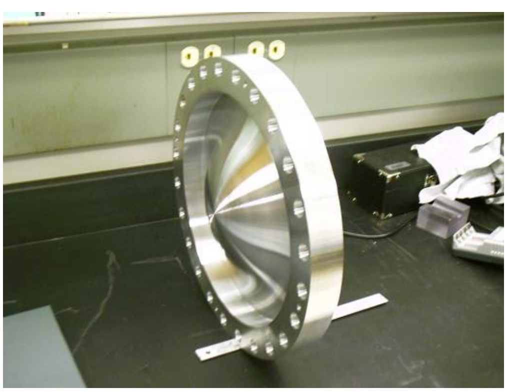

Figure 9: Thin aluminum window used for liquid-hydrogen absorber. The window and flange are machined at the University of Mississippi from a single disk, whose thickness in the center is reduced to 175 µm.

The experiment has formally begun with the commissioning of the muon beam line at RAL. We have demonstrated the ability to safely run parasitically to the ISIS neutron users, which involves being able to plunge a titanium target into the proton beam halo and remove it within a 20 ms ISIS beam cycle. The muon intensity is presently well below what we desire, but this situation is expected to improve greatly when our 5-m long, 5-T decay solenoid, donated to the experiment by PSI, becomes operational later this year.

The present MICE schedule, shown in Fig. 10, calls for the completion of Step 4 during 2010. The remaining steps of the experiment will be carried out after the long ISIS shutdown, currently planned for the latter part of 2010. Final experimental results are anticipated in 2012.

5-YEAR R&D PLAN

In order to pursue the tasks required for the designs of both a NF and a MC in a timely manner, the NFMCC and Fermilab's MCTF have developed and submitted to the Department of Energy (DOE) a 5-year muon beam R&D proposal. Main ingredients of the plan are indicated in Fig. 11. We anticipate that international plans for the next steps in particle physics will begin to take shape in the 2013–2014 time frame, and we would like the MC and NF capabilities and costs to be well enough understood at that time for these facilities to receive serious consideration as future options for the field.

The main deliverables for the R&D program include:

- a MC Design Feasibility Study, which is intended to be a high-end feasibility study that includes physics and detector studies and sufficient engineering to develop a component-level cost estimate;
- a NF Reference Design Report, provided in collaboration with our international colleagues under the auspices of the International Design Study of a Neutrino Factory (IDS-NF) [12];
- a demonstration of key MC technologies; and
- a down-selection of MC cooling channel approaches to identify the most promising ones, in preparation for planning a 6D cooling experiment in the period after the 5-year plan is completed.

As the required effort to accomplish this plan in the out-years exceeds by a significant margin the present staffing levels, we look forward to recruiting new institutions to participate in this endeavor, both from the U.S. and elsewhere.

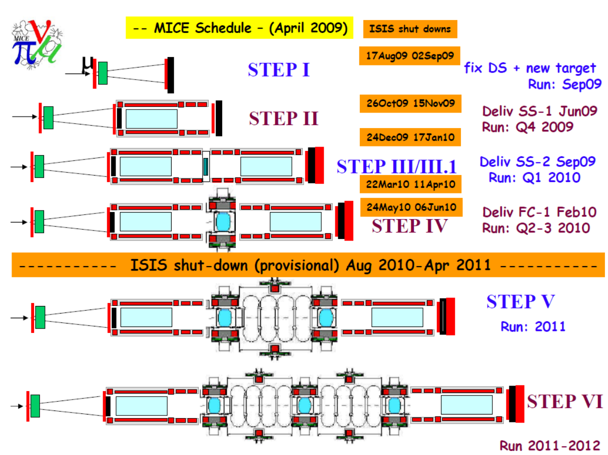

Figure 10: Provisional MICE experimental schedule. The experiment is carried out in discrete steps to minimize the influence of systematic errors on the measurements.

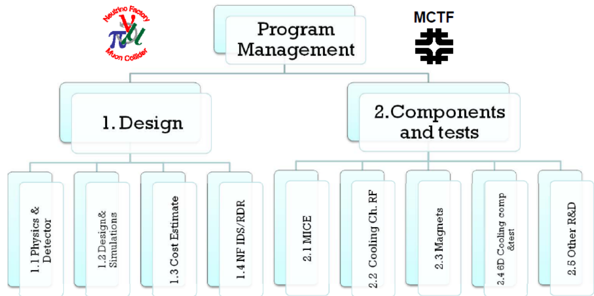

Figure 11: Elements of the joint NFMCC-MCTF R&D plan. The Design portion includes not only MC machine studies and cost estimates, but a study of the physics reach and detector aspects. The Components and tests portion includes ongoing commitments for MICE and MuCool, along with new efforts focused on MC components.

SUMMARY

R&D effort aimed at a Neutrino Factory and/or a Muon Collider has been under way for more than 10 years now, and is making steady progress.

The MERIT high-power target experiment has been completed and its analysis is well along. This work has established the ability of a Hg-jet target to withstand a proton beam power of at least 4 MW.

The MICE experiment is also progressing well. The preparation of the experimental hall is nearly complete and major technical components are all in production at various locations throughout the world. This effort will provide information on both the performance and the cost of cooling channel hardware. We are looking forward to having the first measurements of muon ionization cooling in the next several years.

MuCool R&D efforts are continuing, focusing primarily on understanding and mitigating the deleterious effects of a magnetic field on RF cavity gradient.

To make progress on the design effort for both the NF and MC in a timely way, significantly increased resources are needed. A proposal for the required 5-year R&D effort has been submitted to DOE, and we hope for a favorable funding decision soon. This R&D effort must be pursued aggressively if the MC and NF are to be given serious consideration as future particle physics facilities when new directions for the field are set in about 5 years.

Muon-based accelerator facilities offer great scientific promise for particle physics, and their development is thus a worthy—and challenging—goal to pursue.

ACKNOWLEDGMENTS

I would like to thank my colleagues in the NFMCC, the MCTF, and the MICE and MERIT collaborations for carrying out the R&D efforts described here. Their enthusiasm and dedication make the R&D in pursuit of a Neutrino Factory and a Muon Collider an extremely exciting and worthwhile activity.

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