MUON IONIZATION COOLING EXPERIMENT (MICE)*

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Abstract

There is presently considerable activity worldwide on developing the technical capability for a "Neutrino Factory" based on a muon storage ring and, later, a muon collider. Muons are obtained from the decay of pions produced when an intense proton beam hits a high-Z target, so the initial muon beam has a large 6D phase space. To increase the muons' phase-space density (i.e., decrease the emittance), we use ionization cooling, which is based on energy loss in an absorber, followed by re-acceleration with high-gradient, normal-conducting RF cavities. A superimposed solenoidal focusing channel contains the muons. The international MICE collaboration will demonstrate ionization cooling in a short section of a realistic cooling channel, using a muon beam at Rutherford Appleton Laboratory (RAL). We will measure the cooling effects of various absorber materials at several initial emittance values using single-particle measurement techniques. The experiment layout and goals are discussed, as is the status of component R&D.

INTRODUCTION

It is now widely believed that a Neutrino Factory based on a muon storage ring will be the most effective tool to probe the physics of the neutrino sector. Depending on the values of presently unknown parameters, it may also offer the first means to observe charge-conjugation–parity (*CP*) violation in the lepton sector. Scientific results from a Neutrino Factory will test theories about neutrino masses and oscillation parameters, and thus provide important information for both particle physics and cosmology.

A high-performance Neutrino Factory—one capable of delivering roughly 4×10^{20} ν_e aimed at a remote detector in a 10^7 s "year"—depends on ionization cooling of the muon beam. As will be described below, this cooling process involves straightforward physics, but the technique has not been experimentally demonstrated. As a Neutrino Factory is expected to be an expensive facility, it is highly appropriate to carry out a demonstration of this key principle.

The cooling demonstration we propose 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

The experiment will verify that our design tools (simulation codes) agree with observations. This will give confidence that we can optimize the design of an actual facility. No matter what configuration we test today, it is likely that there will be changes made before construction of a Neutrino Factory facility actually begins. Validating the design tools will permit their use in someday developing a full proposal for a Neutrino Factory. It is important to note, however, that this approach depends on both the equipment being tested and the simulation codes being as realistic as possible. Thus, full engineering details of all components must be included in the simulations—a nontrivial task.

The main challenge of MICE is that, for cost reasons, we use only a single cell of a cooling channel, which means that the expected cooling effect is small, about 10%. We therefore wish to measure the emittance reduction to a precision of about 10^{-3}. Other challenges include:

- operating high-gradient RF cavities in a solenoidal field and with field terminations (windows or grids)
- safely operating LH_2 absorbers with very thin windows
- integration of cooling channel components while maintaining functionality

Fortunately, these challenges are being worked on via R&D activities that fall outside of MICE, mainly carried out by the U.S. Neutrino Factory and Muon Collider Collaboration (MC).

NEUTRINO FACTORY INGREDIENTS

A Neutrino Factory is a relatively complex facility. It starts with a proton driver capable of providing a MW-level beam directed at a production target, such as a Hg-jet. Pions from the interaction are captured into a solenoidal decay channel, where they decay to muons. The muon beam is then bunched and "phase rotated" to reduce its energy spread (effectively exchanging energy spread for bunch length). Thereafter, an ionization cooling channel is used to reduce the transverse emittance of the beam. This is the aspect that is the focus of this paper. After cooling, the muon beam is rapidly accelerated to its final energy by means of Recirculating Linear Accelerators (RLAs) or Fixed-Field Alternating Gradient (FFAG) machines. Finally, the muon beam is injected into a storage ring where it circulates for about 500 turns. A long straight section of the ring is oriented toward a neutrino detector located several thousand kilometers from the accelerator site.

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As should be obvious from this description, a Neutrino Factory is not an easy project, but no fundamental problems have been identified to date.

COOLING DESCRIPTION

Because the muon lifetime in its rest frame is quite short, 2.2 μs, it is necessary to cool the muons quickly. Standard cooling techniques, such as stochastic cooling, are far too slow to be useful. Instead we make use of ionization cooling, a technique tailor-made for the weakly interacting muons.

Ionization cooling is analogous to the familiar synchrotron radiation damping process in electron storage rings. In ionization cooling, the energy loss process corresponding to the synchrotron radiation energy loss is ionization energy loss, i.e., *dE/ds*, in an absorber medium, which reduces the momentum in all three planes (p_x, p_y, p_z). Energy gain is via RF cavities, which restore only the longitudinal momentum, p_z. Repeating this process many times reduces $p_{x,y}/p_z$, and thus transverse emittance.

Just as in the synchrotron radiation case, there is also a "heating" term. The equivalent to quantum excitation in our case is multiple scattering. There is a balance between heating and cooling that gives rise to an equilibrium emittance given approximately by:

$$\varepsilon_{x,N,equil.} = \frac{\beta_{\perp}(0.014\,\mathrm{GeV})^2}{2\beta\, m_{\mu}\, X_0 \left|\frac{dE_{\mu}}{ds}\right|} \tag{1}$$

where $\beta = v/c$. We see from Eq. 1 that the best cooling results from low $\beta_{\perp}$ (strong focusing), large radiation length, X_0, and large *dE/ds*. With this in mind, Table 1 summarizes the merit factor for various candidate MICE absorber materials, defined as $[X_0(dE/ds)]^2$, relative to liquid hydrogen (LH_2). LH_2 is the optimal material choice. In practice, an LH_2 absorber is extended in size (sampling more than the minimum beta function) and has aluminum windows. Together, these aspects degrade the performance of the absorber by about 30%, but LH_2 remains the best absorber choice.

The cooling channel operates at a typical momentum of about 200 MeV/c. This momentum, which corresponds to the ionization minimum, is roughly optimal from the viewpoint of capturing muons from the production target. Running below the ionization minimum results in a substantial increase in longitudinal emittance, since in this regime particles of lower energy have increased *dE/ds*. Running above the ionization minimum is disadvantageous, as it is more demanding on RF and magnet performance and gives rise to more energy straggling. Considering transverse cooling alone, momenta below the ionization minimum are preferable to those above.

Table 1: Merit factors for candidate MICE absorbers.

Material	$(dE/ds)_{min}$ (MeV g^{-1} cm^2)	X_0 (g cm^{-2})	Rel. merit
H_2 gas	4.103	61.28	1.03
H_2 liq.	4.034	61.28	1
He	1.937	94.32	0.55
LiH	1.94	86.9	0.47
Li	1.639	82.76	0.30
CH_4	2.417	46.22	0.20
Be	1.594	65.19	0.18

BENEFITS OF COOLING

The need for cooling results from the fact that the initial muon beam emittance is quite large, making it difficult to transport and accelerate efficiently. To do so would require very large magnets and RF cavity apertures. Both are possible in principle, but are expected to be very costly. Cooling typically increases the phase space density within a given acceptance by a factor of 4–10, depending on the size of the acceptance. (The smaller the downstream acceptance, the larger the gain from cooling, and vice versa.)

MICE will calibrate the cost and performance of actual cooling hardware and permit a quantitative evaluation of the trade-offs between cooling and acceleration. This is very important, as the cost of a typical acceleration stage can be $500M.

For many particle physicists, the Holy Grail of muon beam R&D is to build a muon collider, for which cooling is a necessity both transversely and longitudinally. Successful construction of a muon collider would provide an energy-frontier facility that would fit easily onto the site of an existing laboratory.

MICE IMPLEMENTATION

The layout of the MICE components, based on a single cell of the U.S. Feasibility Study II configuration [1] is shown in Fig. 1. Note that, in effect, the cooling channel is simply a linac to which absorber material has been added.

Simulations of MICE performance have been done using ICOOL [2] and Geant4 [3]. The former code is used primarily for matching the beam optics of the cooling channel, whereas the latter code contains the information on the detectors and permits evaluation of anticipated backgrounds and systematic errors. Representative parameters used in the simulations are summarized in Table 2. Figure 2 shows the predicted transmission and predicted cooling effect of the configuration shown in Fig. 1. As can be seen, the transmission is essentially 100% for input emittance below 6 mm rad. Above this value, there is significant particle loss, and the curves in the lower part of Fig. 2 represent emittance reduction due to "scraping" as well as due to cooling.

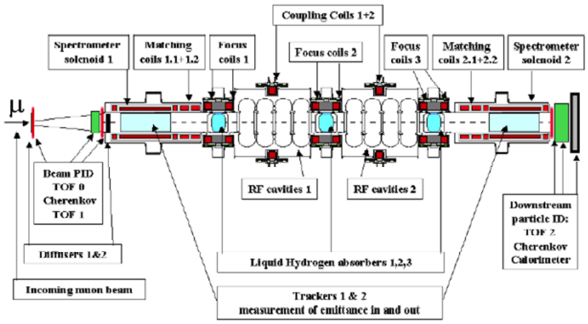

Figure 1: Layout of MICE, showing cooling channel components along with upstream and downstream spectrometers.

In addition to testing a baseline case corresponding to the Feasibility Study II optics, we plan to test alternative scenarios to verify that we can correctly scale our results using a simulation code. The variants to be studied will include some or all of the alternative absorber materials listed in Table 1, as well as different optics. Though our ability to produce a lower $\beta_\perp$ at the absorber is limited by the current density in the magnet coils, we expect to be able to reduce $\beta_\perp$ to about 250 mm at the nominal operating momentum of 200 MeV/c. Reducing the central momentum to 140 MeV/c should permit reaching $\beta_\perp \approx$ 60 mm. Other options to be studied include an optics configuration with no field flips at the absorbers and a configuration with higher RF gradients (by powering fewer cavities with the 8 MW of available RF power and/or by operating the cavities at liquid-nitrogen temperature to reduce the RF power dissipation).

COOLING HARDWARE

The basic ingredients of a cooling channel include:

- absorbers to give energy loss
- RF cavities to restore the lost energy
- solenoid magnets to contain and focus the muons as they traverse the channel

For MICE, we augment the cooling channel hardware with:

- a diffuser to create a large emittance muon sample
- an upstream diagnostics section including time-of-flight measurements, Cerenkov particle identification, and a tracker to measure incoming emittance

Table 2: Representative cooling simulation parameters.

Parameter	Value
Momentum (MeV/c)	200
Momentum spread (MeV/c)	±20
$\sigma_{x,y}$ [mm]	50
$\sigma_{x',y'}$ [mrad]	150
Solenoid field (T)	3
$\beta_\perp$ (mm)	420
RF phase (deg)	90 (on crest)

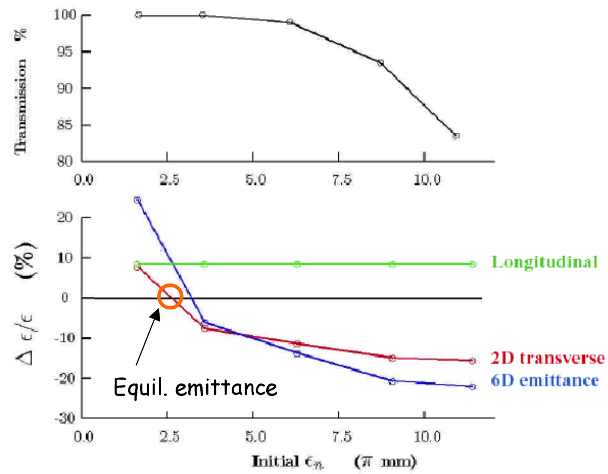

Figure 2: Result of "scan" over input emittance. The equilibrium emittance is given approximately by Eq. 1.

- a downstream diagnostics section having an electromagnetic calorimeter, another Cerenkov system, and an identical tracker to measure final emittance.

Two types of solenoid magnets are needed for the MICE cooling channel: focusing coils, which are integrated with the absorber and provide the low beta function at the absorber position, and coupling coils, which surround the RF cavities (see Fig. 1). In the baseline configuration, the focus coil modules have opposing polarities, resulting in the field profile shown in Fig. 3. For reasons of cost and simplicity, all magnets will use cryocoolers rather than conventional cryogens. As noted earlier, it is possible to power the focusing coils with the fields the same, referred to as a "non-flip" configuration.

The LH_2 absorber design makes use of internal convection cooling, as opposed to a more conventional forced-flow design with external heat exchanger. This choice is more than adequate for MICE, though the forced-flow approach might be preferred in a high-intensity Neutrino Factory. The absorber configuration, showing the surrounding focusing coils, is indicated in Fig. 4. This design, with a second set of thin windows for isolating the absorber from the rest of MICE, has been reviewed for safety by an international panel and found to be acceptable. The primary Al window has a 300 mm diameter and will be about 120 μm thick.

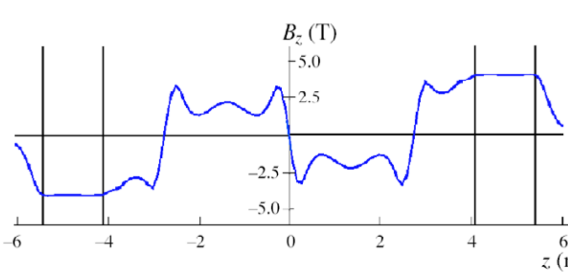

Figure 3: Baseline magnetic field configuration for MICE.

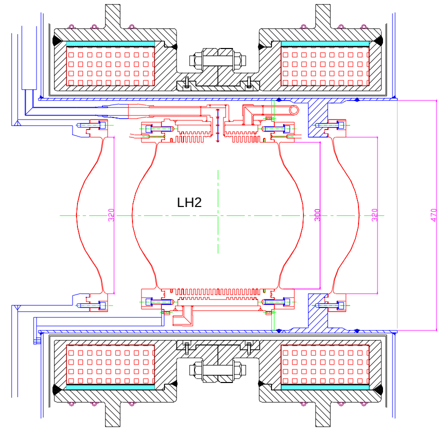

Figure 4: Liquid-hydrogen absorber assembly, showing inner absorber window, outer vacuum window, and surrounding focus coils.

The two RF modules for MICE each contain four separately powered 201 MHz cavities, 1.2 m diameter, with independent tuners. Each cavity iris is terminated with a pre-curved Be window of 420 mm diameter. The curvature makes the window resistant to thermal distortion. Furthermore, we orient the pair of windows for each cavity in a common direction, so any small deflection due to heating has only a minor effect on the cavity frequency.

MUCOOL R&D PROGRAM

The ability of MICE to achieve its goals is greatly enhanced by the hardware R&D programs under way worldwide. In particular, the MUCOOL R&D program [4] of the MC is developing prototypes of both the LH_2 absorber and the RF cavity needed for MICE. To promote this effort, a new facility, the MUCOOL Test Area (MTA), has been constructed by the MC at Fermilab to permit tests of the prototype components.

RF Cavity R&D

The main challenge for the RF cavity is to attain a high gradient in the presence of a strong magnetic field. In tests to date [5] using an 805 MHz pillbox cavity, we observed increased breakdown and dark currents as the magnetic field was increased. Continued R&D to test different materials and coatings to mitigate the observed effects will continue with the 805 MHz cavity, in preparation for the arrival of the prototype 201 MHz cavity later this year.

As shown in Fig. 5, the prototype 201 MHz cavity, being fabricated as a collaboration among LBNL, Jlab, and University of Mississippi, is now well along. In operation, the beam iris will be closed with a thin Be window.

Figure 5: 201 MHz cavity being fabricated at Jlab. The beam aperture is 420 mm in diameter, and the cavity body is about 1.2 m in diameter. The small hole visible on the side is a pilot hole for extruding one of the four required equatorial ports.

LH_2 Absorber R&D

The absorber R&D program [6] is being carried out at KEK and at various Illinois universities near Fermilab. The university effort has focused on developing the thin Al windows for LH_2 containment, working with the University of Mississippi for fabrication and with Oxford University in the UK for engineering design and analysis. Windows as thin as 120 μm have been machined from solid aluminum blanks. The most recent window was destruction tested and found to fail at 9.8 bar. This is some 44% higher than needed for safety, but was not in good agreement with predictions from the FEA code. The discrepancy is believed to be partially due to different material properties in the actual window compared with what was assumed for the FEA model, and partially due to a different thickness of the window. Unfortunately, several measurements of the window gave conflicting results for its thickness and this needs to be resolved.

The KEK effort is aimed at developing the absorber body, the required instrumentation for controlling the system, and the cryogenic seals. A prototype absorber (see Fig. 6), somewhat smaller than that specified for MICE, has been fabricated in Japan and—after meeting all of the appropriate safety requirements at Fermilab—was recently successfully test-filled with LH_2 at the MTA.

MICE INSTRUMENTATION

A parallel effort on the development and testing of the detectors for MICE is also under way [7], with much of the effort centered in Europe. Work on the upstream time-of-flight system, which aims for 70 ps resolution, is under way at Milan. This system will be used for particle identification, for timing with respect to the RF waveform, and for triggering the data acquisition system. The upstream Cerenkov detector, being developed by University of Mississippi, will be used for π/μ separation.

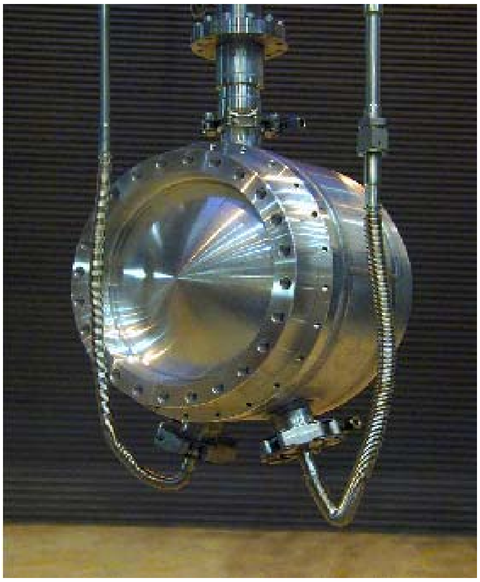

Figure 6: Prototype LH_2 absorber developed at KEK and successfully tested at the Fermilab MTA.

To provide downstream μ/e separation there will be an electromagnetic calorimeter (being developed by Rome III) and a Cerenkov detector (being developed by Louvain la Nueve). The tracker system, which will have identical units in both the upstream and downstream spectrometer solenoids, is based on a scintillating fiber detector. Five planar stations will be used to measure 6D emittance. This is a major effort for the particle physics members of the MICE Collaboration, involving groups from Bari, Brunel, CERN, Edinburgh, Fermilab, Geneva, IIT, Imperial College, KEK, Legnaro, Liverpool, Osaka, UCLA, and UC-Riverside. A prototype of the system has already been built and tested, and plans for a beam test at KEK are in progress.

Although not the baseline tracker option, considerable work, led by the Italian groups, has also been put into the development of a Time Projection Chamber with GEM readout, referred to as a "TPG." Assuming the R&D is completed successfully, this option could serve as a backup if major problems were to arise with the baseline tracker. (Given the present success with the baseline tracker, we do not anticipate the need for a fallback option, but prudence dictates extra caution on such a critical system.)

MICE STATUS

The MICE proposal [8] was submitted to RAL in January 2003. An international review panel, chaired by Alan Astbury, was convened in February 2003 and this group recommended to RAL management that the experiment be approved. Scientific approval from RAL was given in October 2003. As noted earlier, the absorber design concept has successfully undergone a preliminary safety review. A second review will be required before getting permission to operate the absorber at RAL, but there are no issues of principle remaining to be resolved.

We are now in the process of refining the cost estimate for the experiment and firming up funding commitments from the various countries involved. Our present estimate of the hardware costs for the experiment is £11M. The fully loaded cost, with effort, contingency, and tax included, is £25M. At present, we have commitments for more than half of the required funding and we are working diligently to find the remaining portion.

In the U.S., the technical advisory committee (MUTAC) and the oversight group (MCOG) for the MC program have both strongly endorsed our participation in MICE, deeming it a "crucially important demonstration." A proposal has been submitted to the NSF that is currently under review. Unfortunately, support for high-energy physics in the U.S. has been stagnant for some years, so new initiatives are finding it an uphill fight to secure funding.

SUMMARY

R&D on the various components required for MICE is already at an advanced stage. The first prototype absorber has been fabricated and filled with LH_2, and the fabrication of the prototype 201 MHz RF cavity is well along. A prototype tracker system has likewise been fabricated and tested with cosmic rays; a beam test at KEK is in the planning stages. MICE will assemble and test these components in a realistic beam environment and verify their operation. As new ideas mature, it is likely that MICE will be available to serve as a test-bed for additional cooling components. Clearly, MICE is a very challenging "linac R&D" program, and new collaborators would be most welcome to join.

The resultant demonstration of muon cooling will validate the key concept of a Neutrino Factory design, and will also put the idea of a muon collider closer to realization. The measured cooling performance will be compared quantitatively with our simulations, thus "calibrating" our design tools and permitting the optimization of both the cost and performance of a future Neutrino Factory. We strongly believe that there is no substitute to carrying out this program with an actual muon beam, which will be sensitive to all of the relevant physics issues—those we have included and those (if any) that we have forgotten.

REFERENCES

[1] S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo; eds.; http://www.cap.bnl.gov/mumu/studyii/final_draft/The_Report.pdf.

[2] R. Fernow, http://pubweb.bnl.gov/users/fernow/www/icool/readme.html.

[3] Geant4 homepage, http://geant4.web.cern.ch/geant4/.

[4] D. Kaplan, J. Phys. G 29, 1585 (2003).

[5] D. Li, *et al.*, J. Phys. G 29, 1683 (2003).

[6] M. Cummings, *et al.*, J. Phys. G 29, 1689 (2003).

[7] R. Edgecock, J. Phys. G 29, 1601 (2003).

[8] See http://mice.iit.edu/mnp/MICE0021.pdf.