The MAP System Tests R&D Program

August 16, 2010

Abstract

This document describes the *Systems Tests* activity within the MAP program, its goals and objectives, and its relation to the other components of the MAP plan.

1. INTRODUCTION

As the name suggests, the goal of the *Systems Tests* part of the MAP program is to test relevant new technology at the system level. In many cases, such a systems test is a natural follow up to, and builds upon, the component development in the *Technology Development* part of the plan. In the recent past, a system test of a muon production target (MERIT) was successfully carried out. For the duration of the current MAP proposal, the focus will be on cooling channels.

Since the prospect of muon colliders depends critically on ionization cooling, it is imperative to demonstrate that such cooling channels can be built and operated as designed before any construction decision can be made. The *Systems Tests* section of the MAP plan addresses this need.

For practical reasons, including cost, any demonstration will be made with a relatively small section of cooling channel. There are two aspects of demonstration that can be accomplished, with increasing levels of difficulty:

1) Show that the cooling channel design can be implemented in practice, and operated within its design parameters. For this, the cooling channel section must be long enough that each individual component is integrated and operated in its design environment. For example, enough magnets must be included that cavities are being operated in the design field. No beam is needed for such a "bench test" demonstration.
2) Show that the cooling channel can cool a suitable muon beam by a measurable amount. For this, the channel must be long enough to provide a significant cooling effect, and sensitive instrumentation must be added to measure the muons before and after the channel. A further extension to this goal is to demonstrate that the simulations of the cooling channel performance agree with the measurements to a sufficient degree that simulations of a long cooling channel can be trusted. This requires a more sophisticated analysis than simply measuring a cooling decrement, and may also require either a longer channel or more precise measurements of the beam particles (or both). It also implies a detailed and accurate model of all cooling channel hardware.

Previous work as part of Feasibility Study 2 [1] for a Neutrino Factory identified a suitable candidate cooling channel for initial transverse cooling, which is being tested in the MICE experiment. The US contribution to MICE, which was launched under the auspices of the US Neutrino Factory and Muon Collider Collaboration (NFMCC), will continue as part of the MAP plan. MICE is intended to address both aspects of demonstration listed above.

For a Muon Collider, cooling is needed in all six dimensions of phase space. Although several designs for 6D cooling channels exist, they all depend to some degree on untested technology, the main issue being how to address the observed limitations on the RF gradient when operating in a strong axial magnetic field. These issues will be addressed by R&D at the component level (e.g., RF cavities and magnets), in the *Technology Development* section of the MAP plan. It is anticipated that in about two years the results from that R&D program will allow us to choose a baseline candidate for a 6D cooling channel.

Beyond making sure that the components are individually feasible, the 6D cooling channel must also be able to work as a system. Demonstrating this is a main objective of the *Systems Tests* activity. To carry it out, we plan to build a section of the chosen baseline cooling channel and test it on the bench. We also plan to develop a proposal for a beam test, which due to its likely expense would be carried out as a follow-up to the current 7-year MAP plan.

2. MERIT

The requirements for a Muon Collider/Neutrino Factory call for a target capable of intercepting and surviving a 4-MW-class proton beam. The concept for a target system capable of sustained operation in such an unprecedented environment involves a ~1-cm-diameter free mercury jet intercepting an intense proton beam within the confines of a high-field (~20-T) solenoid. At inception, this target concept represented an unproven approach and the MERIT experiment [2] was conceived and executed as a proof-of-principle demonstration that this basic concept is viable and that the core of such a target can sustain the required level of beam power. Thus, the MERIT experiment, designed to test target concepts, was actually the first system-level test of new technology for a muon collider.

The MERIT experiment ran successfully in the fall of 2007 at the CERN PS. The experiment benefited from the intensity of the beam pulses (up to 30 x 10^{12} ppp) and the flexible beam structure available for the extracted PS proton beam. Key experimental results include demonstration that:

- the magnetic field of the solenoid greatly reduces both the extent over which the mercury is disrupted and the velocity of the ejected mercury after interception of the proton beam;
- the magnetic field suppresses surface instabilities of the mercury jet;
- the delivery of subsequent proton beam pulses separated by up to 350 μs can be sustained without impacting the efficiency of pion production;
- two beam pulses separated by more than 6 μs interact with the mercury jet as independent beam interceptions;
- the 20 m/s mercury jet can support up to a 70 Hz operational rate;
- individual beam pulses with intensities up to 115 kJ can be safely accommodated.

3. MICE

The Muon Ionization Cooling Experiment (MICE) [3], which is hosted at Rutherford Appleton Laboratory in the UK, has been designed and is being constructed, commissioned, and operated by an international collaboration in which MAP institutions play a crucial role, contributing to every aspect of the experiment.

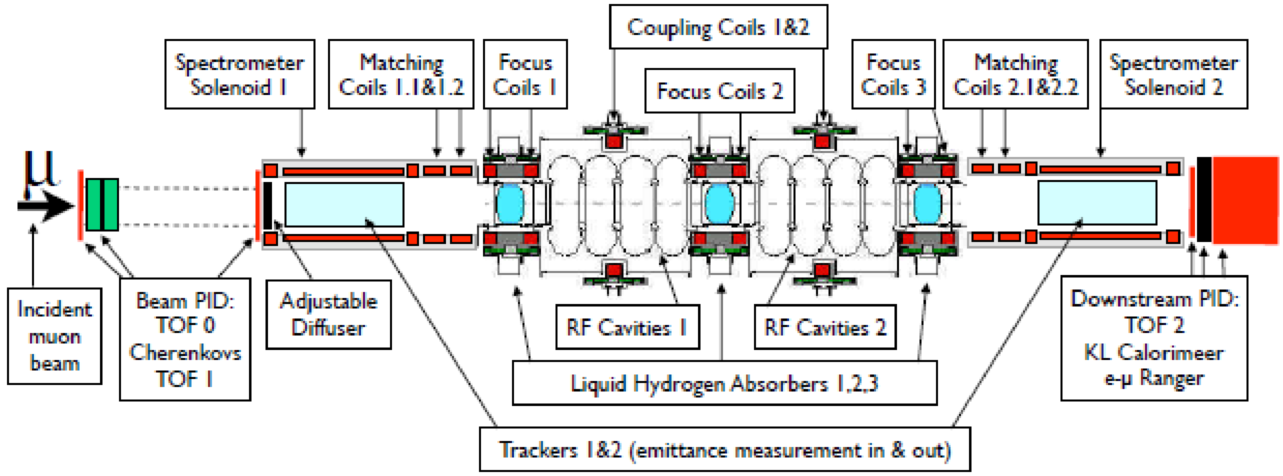

Figure 1: Layout of MICE.

The MICE apparatus is shown schematically in Fig. 1. It consists of an upstream instrumentation section to precisely measure incoming muons, a short cooling channel section consisting of absorbers and RF cavities in a solenoid lattice, and a downstream instrumentation section to precisely measure the outgoing muons. The ionization cooling lattice cell comprises eight superconducting coils that can be variously powered to create "super-FOFO" [4] (field direction alternating each half-cell) or solenoid-type (field direction constant) optics, and the currents can be tuned to characterize cooling performance with a variety of beta functions.

The main goals of MICE are to

- Demonstrate that a section of transverse cooling channel can be built and operated as designed. This is a technical challenge, from which the lessons learned can be applied to future cooling channel designs.
- Demonstrate cooling (emittance reduction) of a muon beam in such a channel. The challenge here is to be able to measure the individual muons with high enough precision, as well as to properly select and weight the individual tracks to form a virtual beam. This work is well under way.
- Build confidence in the simulation codes.

The MICE channel is designed to provide a ≈10% transverse cooling decrement (depending on beam momentum and initial emittance), and the spectrometers on either side of the channel are designed to measure the emittance of the beam entering and exiting the channel to 0.1%. MICE will be built and executed in steps (see Fig. 2). The first step, which is essentially a test of the incoming beam line, is running now.

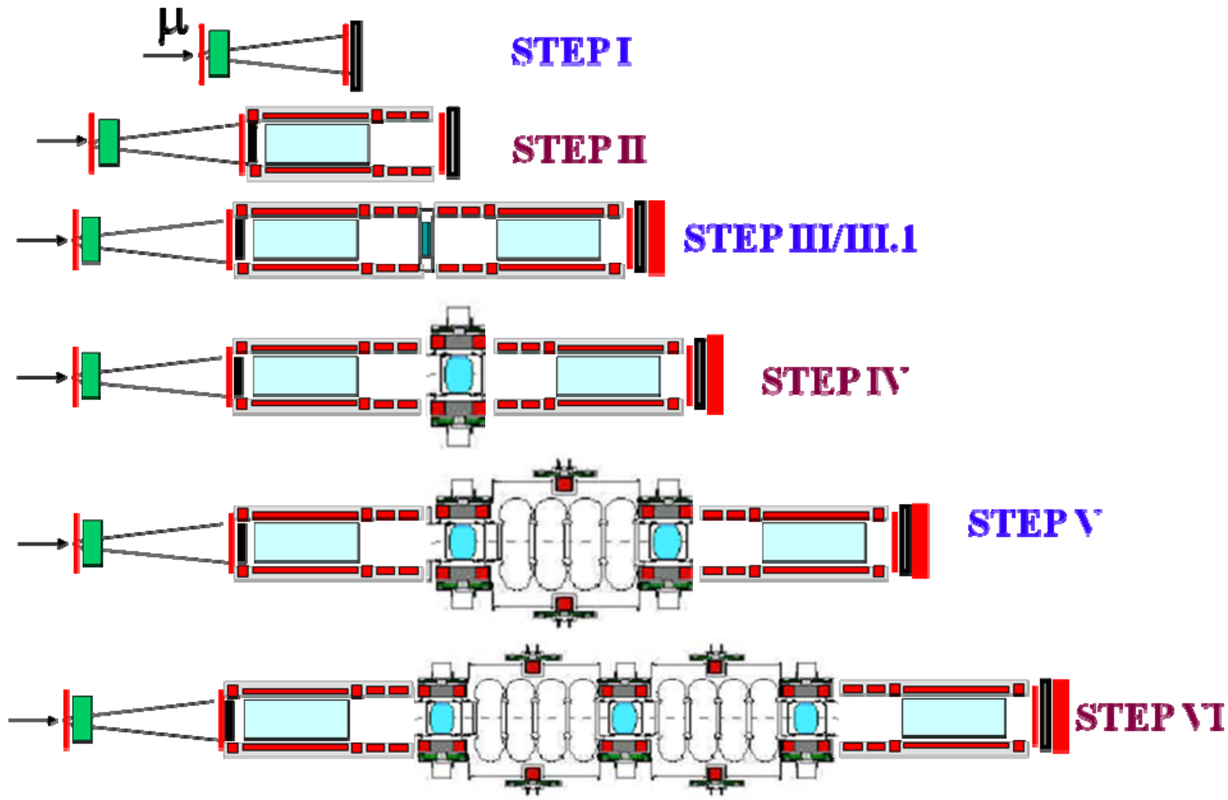

Figure 2: MICE steps.

To date, the US contribution to MICE has been coordinated and largely funded through the NFMCC. Many of the US deliverables have already been completed, including

- Assembly of scintillating-fiber planes (15) for fiber-tracking spectrometers;
- AFE-IIt readout boards, VLPCs, and VLDS interface modules for fiber tracking readout;
- Design, fabrication, and commissioning of VLPC cryostats (4) for fiber tracking spectrometers;
- Fiber-tracking readout system integration and commissioning;
- Fabrication, installation, and commissioning of two Cherenkov counters;
- Scintillating-fiber beam position/profile monitors (4 planes);
- Beam line optimization.

Other contributions are still in progress, and will continue to be supported through MAP. These include

- Spectrometer solenoids (2), including engineering, fabrication, testing, and field-mapping;
- RFCC modules (2), each comprising 4 RF cavities and 1 coupling coil;
- Design and fabrication of LiH absorbers;
- Participation in MICE operations and analysis.

The goals, timeline and requirements for each of these will be discussed in more detail below.

3.1 MICE Spectrometer Solenoids

The MICE instrumentation will incorporate a pair of Spectrometer Solenoid superconducting magnets. Each magnet consists of five coils wound on a common aluminum mandrel. Cooling of the radiation shield and cold mass is provided by a set of two-stage cryocoolers. Liquid helium is maintained within the cold mass by means of a recondensation circuit. To date, both of the magnets have been fully assembled, tested, and partially trained in the fabrication vendor's facility. The goal of the training runs is to reach a current of 275 A in all five coils. The first magnet reached a training current of 196 A before being disassembled, primarily to modify the recondensing circuit, which was prone to blockage. The second magnet was completed with a modified recondensing circuit and several other design enhancements. The second magnet reached a training current of 238 A when an HTS lead burned out due to inadequate cooling of the upper ends of the leads. A quench of the magnet during training is shown in Fig. 3.

Figure 3: Quenching of the magnet during training of the coils.

In view of the difficulties encountered in testing and training the Spectrometer Solenoids, two review committees have been convened to assess the design and assembly of the Spectrometer Solenoid magnets. In November 2009, a committee convened by the MICE project management developed a set of recommendations prior to the reassembly of Magnet #2 for a second round of testing. After evaluating the committee's recommendations, a single-stage cryocooler was incorporated to provide additional cooling to the shield and HTS leads (see Fig. 4). The addition of the single-stage cooler solved the HTS lead issue, and training continued. During the latest testing of Magnet #2, when a training current of 258 A was reached, one of the coil leads developed an open circuit. During this latest cool-down of the magnet, the performance of the magnet recondensing system was assessed through a series of boil-off measurements. It was determined that the existing three 2-stage cryocoolers plus the added single-stage cryocooler did not provide enough cooling power to maintain a closed LHe system. Since that time, Magnet #2 has been fully disassembled, including the cutting of an access panel into the cold-mass cover plate. The failed lead was found to be just inside the feedthrough where the coil leads enter the cold mass. Further expert analysis will be required to develop modifications that will prevent any of the leads from burning out in the future. Figure 5 shows the opened Magnet #2 cold mass with preparations for repair under way.

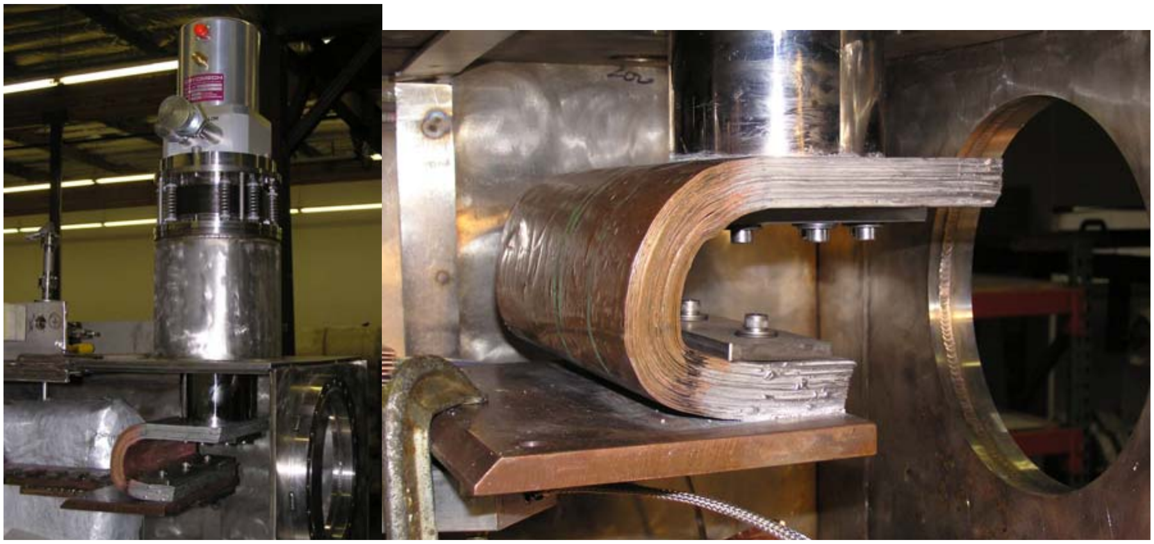

Figure 4: Added single-stage cryocooler and a close-up of the connection.

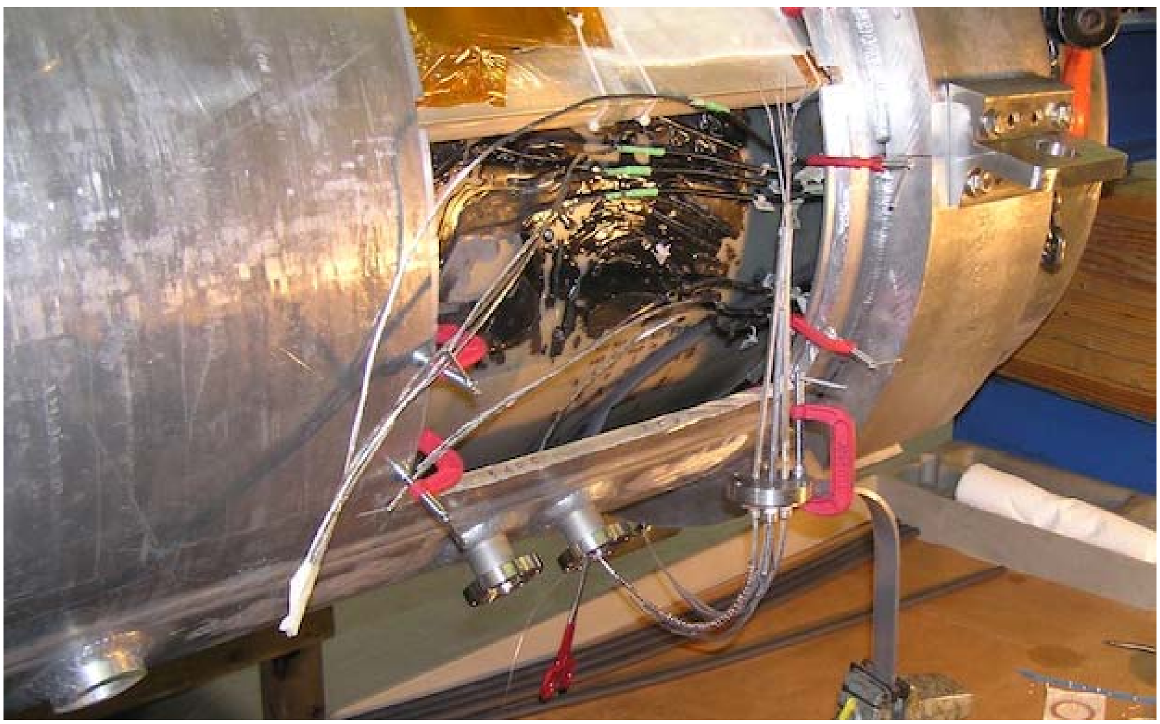

Figure 5: Opened cold mass of Magnet #2.

A second review committee consisting of three Fermilab magnet experts was convened at LBNL's request to review and assess both the lead failure and the helium boil-off issue. The committee's final report, which includes a series of recommendations, was recently provided to LBNL. A plan to institute several design changes and reassemble the magnets is currently being developed. The initial steps that must be completed prior to finalizing the design changes are listed below. These steps are expected to be complete by the middle of September, assuming the appropriate manpower is available.

- A complete set of drawings for the as-built magnet, including already-implemented modifications and proposed future modifications, is being compiled to allow accurate engineering calculations to be carried out.
- The heat-load calculations will be redone for the as-built magnet to ensure that the selected number of cryocoolers will be adequate to maintain liquid helium within the cold mass.

- All of the magnet-system electromagnetic calculations will be redone for both test and operational conditions.
- The instrumentation plan will be reviewed and changes implemented to ensure that the thermal and electromagnetic calculations can be confirmed during testing.
- Calculations and documentation will be completed to demonstrate that the mechanical support of the magnet, leads, piping, and other internal components is adequate, including effects due to motion upon cool-down.

A modification and assembly plan is being developed in parallel with the analysis effort. The main points of the plan will likely include the following: reduction of heat leaks to the cold mass, the addition of more cryo-cooling power, and modification of the leads in the area of the cold mass feedthroughs to prevent the recurrence of a burn-out. The plan is expected to be complete by the time of the next MICE collaboration meeting in early October. Once the final magnet configuration has been established, the first of the two magnets can be reassembled and ready for testing in approximately four months. The currently proposed plan is shown below. Note that this is a preliminary plan pending the outcome of the analyses.

- LBNL or other MICE-collaboration personnel will be present during all phases of the reassembly of both magnets in order to document and photograph the as-built design, fabrication methods, and assembly techniques.
- An improved vacuum pumping system and modifications to the radiation shield will be implemented to ensure there is adequate vacuum pumping between the shield and the cold mass. A cold-cathode gauge will be added to monitor the vacuum during the cooldown procedure.
- The entire surface of the 4K components will be covered by the actively cooled shield where possible. Any areas that cannot be completely covered will be analyzed to determine the magnitude of the resulting effect.
- Additional cryocoolers will be added to the system in order to increase the total cooling power available. The preliminary plan incorporates five 2-stage pulse-tube coolers and one single-stage cooler.
- The cold leads' thermal and mechanical stability will be improved by adding extra copper and superconductor in the area of the cold-mass feedthrough.
- The heat load for the following items will be evaluated and redesigned as necessary: the pass-through holes in the shield for the cold-mass supports, the intermediate cold-mass-support heat intercepts, and the shielding of the warm end of the supports.
- A detailed inspection of the superinsulation prior to sealing the magnet vacuum vessel will be specifically included in the QA plan.
- The individual leads will be wrapped with superinsulation.
- The vent lines will be reviewed for potential thermal acoustic oscillations and corrected as necessary.
- The heat load through the vent lines will be evaluated and reduced where possible.
- Any copper instrumentation wires will be replaced with CuNi to reduce the heat load. The cross-sectional areas of the wires may also be reduced, if practical.
- A fast DAQ system for continuous monitoring of the voltage-tap signals will be implemented.

3.2 MICE RFCC Modules

There are two RF and Coupling Coil (RFCC) modules in the MICE cooling channel. Each module (see Fig. 6) has four normal-conducting 201-MHz cavities with one superconducting solenoid magnet around the cavities. The cavity design features a rounded pillbox-like geometry with 41-cm-diameter open beam irises terminated by thin, curved beryllium windows, similarly to the 201-MHz prototype cavity for MuCool. Fabrication of the MICE cavities is based on techniques developed for the MuCool cavity.

Figure 6: 3D CAD view of a MICE RFCC assembly.

Fabrication of the first five MICE cavities is complete. Figure 7 (left) shows a photo of one of the MICE cavities, with beryllium windows installed, at LBNL; the second batch of five MICE cavities will be complete in September 2010 (Fig. 7, right). Low-power RF measurements of the first five cavities agreed well with the design parameters; measurement results are given in Table 1.

Figure 7: One of the completed MICE cavities at LBNL (left). Fabrication of the second batch of five MICE cavities is in progress (right) and will be complete in September 2010.

Table 1: Measurements of the first five MICE cavities.

Cavity No.	1	2	3	4	5 (spare)*
Freq. (MHz)	201.084	200.888	201.247	200.740	201.707

*no water cooling tubes brazed to the cavity body.

Auxiliary components of the MICE RFCC modules include beryllium windows, RF couplers and ceramic windows, tuners and supporting structures, and vacuum vessels. All these components are either in the final design phase or at the prototyping and fabrication stage. The following is a partial list of the current status of a few key components:

- Three completed beryllium windows with TiN coatings are at LBNL now. A total of 11 windows has been ordered, and we expect to receive the remaining eight windows before October 2010.
- RF-coupler fabrication is in progress.
- A purchase order for 10 ceramic RF windows has been placed.
- The tuner design is complete, and the first tuner prototype has been tested with satisfactory results. Six more tuners will be fabricated soon (48 are needed).

For the post-processing of the cavities, we have identified a vendor for electro-polishing (EP). Qualification of the vendor is in progress.

Design and fabrication of the MICE superconducting coupling coil magnets are being done in collaboration with the Institute of Cryogenics and Superconductivity Technology (ICST) of the Harbin Institute of Technology (HIT) in China. Design of the cold-mass is complete; fabrication of the magnets was contracted to a company in Beijing in March 2010. Cryostat design will be complete in September 2010, with participation of the Shanghai Institute of Applied Physics (SINAP), in collaboration with LBNL. The first-magnet coil winding started in late June 2010 and the first few layers of the conductor have been wound on the bobbin (see Fig. 8).

In order to test the cold-mass, the cryogenic test system at ICST must be modified and ready by November 2010. Testing of the first cold-mass will be conducted at ICST in early 2011.

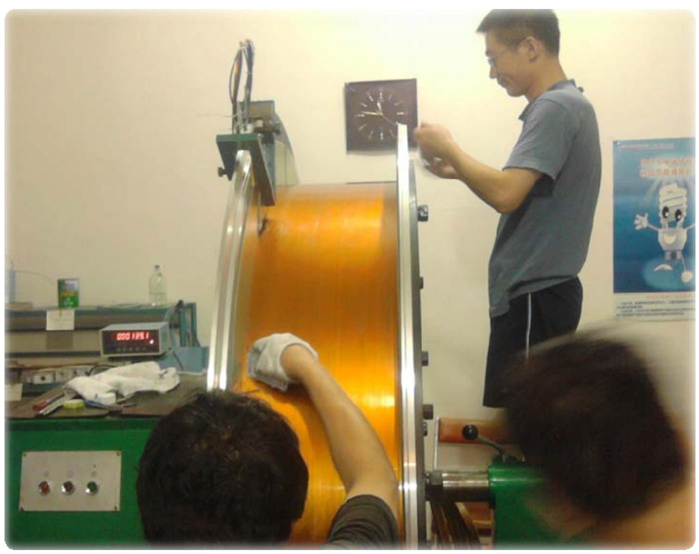

Figure 8: Work on the coupling coil for the RFCC.

3.3 MICE LiH Absorbers

As part of the approved MICE program, in step III.1 of MICE a lithium hydride (LiH) absorber will be tested. For this purpose, two LiH disks have been ordered from Y12 in Oak Ridge. A large (50-cm diameter, 6.5 cm thick) disk will be used for the MICE beam test, and a smaller disk (30-cm diameter, 4 cm thick) will be used for thermal tests (see Fig. 9). The latter will be fitted with a heater in the center and cooling tubes around the perimeter, as well as multiple thermocouples to measure the temperature distribution. This test is done to ensure that LiH is able to deal with the heat load from a high-intensity muon beam. For a similar reason, two small samples will be subjected to radiation tests to check material stability.

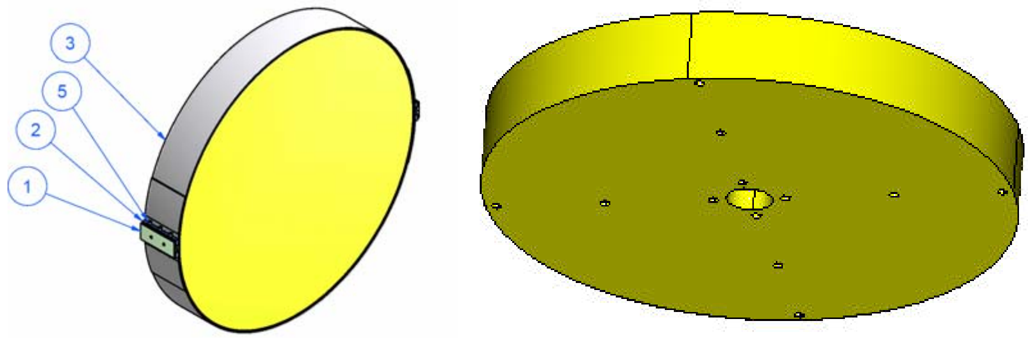

Figure 9: MICE LiH absorber (left) and thermal test model (right).

The disks are produced by hot isostatic pressing (30,000 psi at 150º C) in existing molds. The parts will be tested for chemical composition and purity, radiographed to ensure freedom from voids, then machined to size and coated with an epoxy to protect them from moisture. For practical reasons, the lithium used is the isotope ^{6}Li, which means that the parts are classified as nuclear material. This generates some extra paperwork, e.g., when shipping, but is not otherwise expected to be a problem.

Although MICE was conceived as a purely transverse cooling experiment, recently (and in part due to the MAP effort) it has been decided also to attempt a demonstration of emittance exchange (which is the key principle in 6D cooling) by inserting a LiH absorber wedge. This will be carried out in MICE step IV (spectrometers with focus coil + LiH wedge), selecting/weighting the initial beam to have a suitable dispersion at the wedge so as to generate emittance exchange. Besides demonstrating emittance exchange, this will also provide some practical experience in producing and handling LiH wedges, which could be a key component of a future 6D cooling channel. A schematic of the wedge design is shown in Fig. 10.

Polyethylene wedges may also be tested. The cooling performance of polyethylene is not as good as that of LiH, but testing a second material would provide an important cross-check. Also, since plastic wedges are significantly cheaper to manufacture, a variety of wedge angles could be cost-effectively explored.

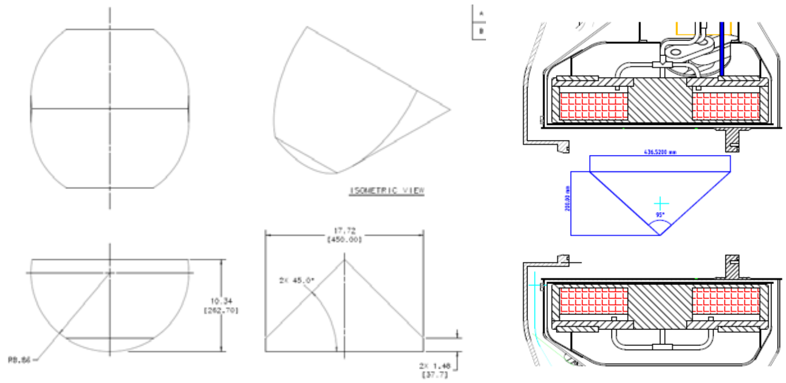

Figure 10: (left) Design of wedge absorbers for MICE; (right) indication of how wedge fits in Focus Coil module.

3.4 MICE Operation and Analysis

Personnel from US institutions are playing an important role in MICE operation and analysis. This involvement will continue under the MAP program. A concern here is that there is presently a shortfall of junior physicists and students to carry out these tasks. This has been ameliorated to some extent by the participation of NSF-supported university groups in MICE, but it remains an issue.

The technique employed in MICE is to measure individual muon tracks and then select and weight them into a virtual beam in post-processing. Conceptually, this is a simple method where, in principle, high precision can be achieved. However, many details remain to be studied, in particular when it comes to the systematic errors involved. Some issues that need further study include

- Finding the best track selection and weighting algorithm. Recently, significant progress has been made using Voronoi diagrams to determine the local phase-space density around a track and use this information to assign weights. However, this method may not scale well to a large data set.
- Studying the sensitivity to matching errors due either to field errors or imperfect track selection/weighting. A mismatched initial beam could generate either an artificial emittance increment or a decrement through nonlinearities in the optics, which could mask the cooling decrement.
- Developing a blinding scheme to avoid confirmation bias when analysis methods are developed and tuned after real data are available.

Besides being important to the success of MICE, the lessons learned here will be very useful in developing a follow-up 6D cooling experiment. Therefore, this is an area in which MAP has chosen to invest.

3.5 MICE Extensions

As part of the MAP effort, we plan to continue studying extensions of the MICE program that could possibly represent a viable alternative (or complement) to a separate, full-blown, follow-up 6D cooling experiment. As mentioned above, a LiH-wedge test has already been introduced into the official MICE program. Beyond that, one could consider alternative configurations and optics. In fact, as mentioned later, some 6D cooling channels (e.g., the FOFO snake) could conceivably be tested by rearranging and supplementing MICE hardware.

In addition, alternative analysis concepts beyond measuring the emittance decrement of a virtual beam will be studied. When muon tracks are bundled into a beam before comparing to simulations, details such as the scattering tails may be washed out, but these details could be important for the performance of a long channel. Analyzing individual tracks (or groups of tracks with a common origin) may be a more sensitive way of testing the simulation codes. This concept needs to be developed further.

4. 6D COOLING CHANNEL BENCH TEST

We anticipate that the combined efforts within the *Design and Simulations* and *Technology Development* sections of the MAP program will enable us to identify a suitable candidate for a baseline 6D cooling channel by the end of 2012.

The primary selection criterion for the cooling channel will be the simulated performance, when operating within the limitations (e.g., on cavity gradient) established by the *Technology Development* R&D program over the next few years. If there is more than one viable candidate, the secondary criteria will be estimated cost and technical risk (e.g., complexity).

Once selected, a section of the channel will be built and tested to make sure it works as expected. However, rather than moving directly to a beam-cooling experiment, as in the case of MICE, we plan to separate the integration demonstration from the cooling demonstration. The reason for this is twofold. First, a 6D cooling experiment would be a major undertaking, and it is unlikely that it could be carried out within the time frame and budget of the MAP 7-year plan. In addition, assuming that MICE is successful in demonstrating transverse cooling and emittance exchange, our assessment is that most of the remaining technical risk in 6D cooling will be related to whether the cooling channel can be implemented and operated as designed, rather than its performance with a muon beam. A bench test can be carried out, possibly in our MTA facility, within the time frame of the 7-year plan, and will give valuable feedback on the technical feasibility of the selected channel design.

The channel designs come in different versions depending on the stage of 6D cooling at which they will be used. Generally speaking, the late-stage 6D-cooling designs are the more challenging from an integration perspective, and are therefore prime candidates for a bench test.

4.1 Guggenheim Cooling Channel

The Guggenheim lattice comes in a few basic variants, depending on which RF technology is used. A Guggenheim channel employing magnetic insulation (Fig. 11) would be more complicated than a Guggenheim channel that uses, e.g., beryllium cavities (Fig. 12) to mitigate breakdown in magnetic fields. It has also been proposed that low-pressure gas (enough to provide protection against breakdown, but not to act as the main absorber) could be used along with absorber wedges. As such, the Guggenheim is a potential candidate regardless of which RF technology turns out to perform best in magnetic fields.

In all cases, the basic cell includes a liquid-hydrogen wedge absorber embedded in a strong (10–15 T) solenoid field, along with a string of cavities. The minimum logical section of Guggenheim to test on the bench is one such cell. Wedge absorbers, approximated by offset cylinders in current simulations, entail potential spatial-integration issues due to their proximity to nearby focusing coils, and would certainly be part of any Guggenheim bench test. Because thinner liquid-hydrogen wedges are less efficient, late-stage Guggenheim lattices use LiH wedge absorbers instead of liquid hydrogen. These are anticipated to be less challenging, and therefore the likely section to be tested would be a mid-stage cooling channel.

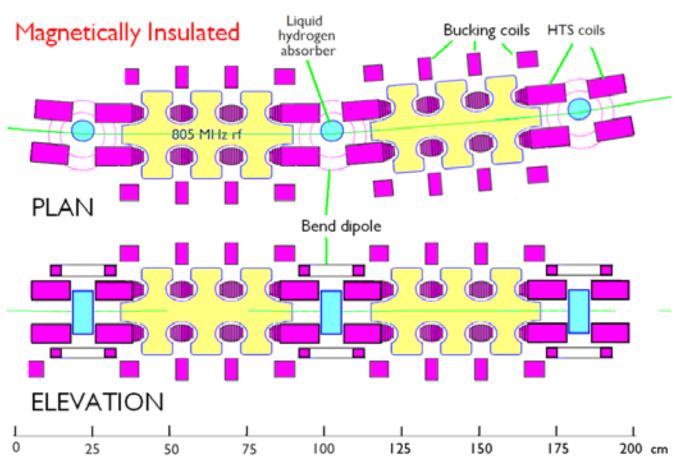

Figure 11: Guggenheim lattice employing magnetic insulation. The basic cell corresponds to the distance between two absorbers.

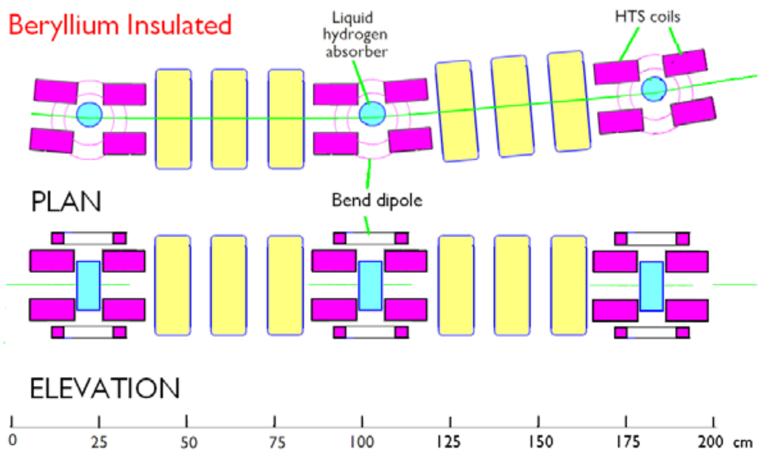

Figure 12: Guggenheim lattice using e.g. beryllium vacuum cavities to avoid breakdown when operating in magnetic field. The basic cell corresponds to the distance between two absorbers.

4.2 FOFO Snake

The helical FOFO snake is a relatively simple lattice of interleaved cavities and solenoids. Unlike the HCC or Guggenheim, the channel is straight which means it can accept muons of both charges. The solenoids are displaced or tilted to resonantly drive a helical dispersion function, which is needed for 6D cooling. LiH wedges or slabs are used as absorbers.

It is conceivable that a FOFO snake test could be made using rearranged MICE hardware (see Fig. 13). In addition to the hardware foreseen for MICE, one FOFO snake period would require: 4 more RF cavities, 4 additional coupling coils, and 6 new LiH absorbers. A full period would likely be required for a beam test. However, for a bench test a shorter section would likely be sufficient. It should be noted that, as of now, snake lattices exist only for the early stages of 6D cooling.

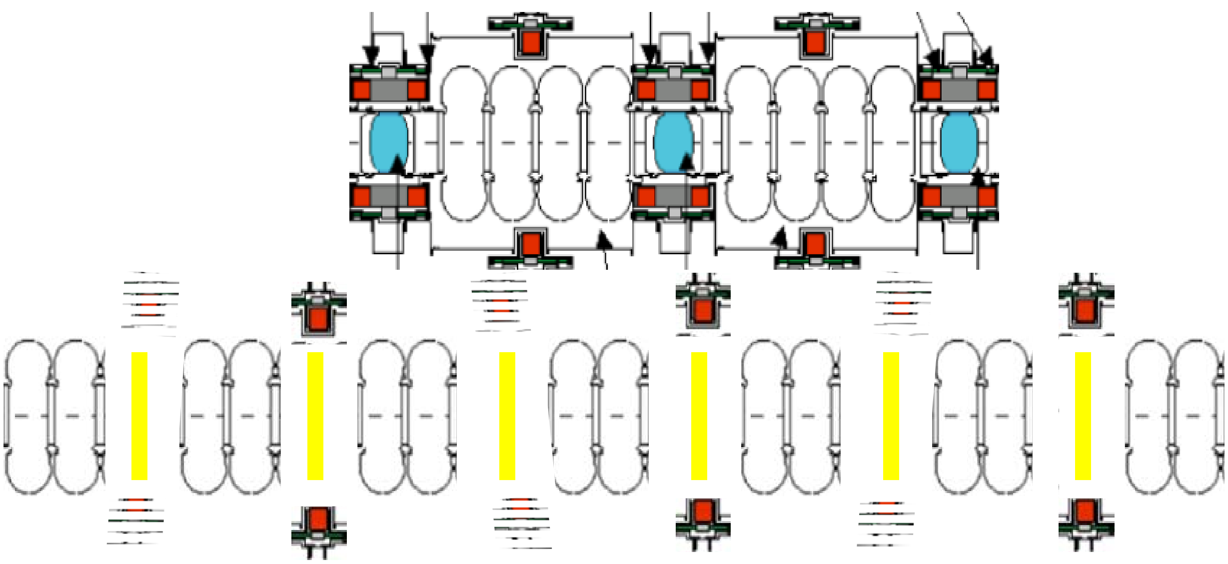

Figure 13: A FOFO snake lattice (bottom) could conceivably be implemented by reusing and supplementing parts from MICE (top).

4.3 Helical Cooling Channel

The most challenging cooling channel from an integration perspective is the Helical Cooling Channel (HCC). On the other hand, the potential payoff is a very compact channel. The HCC is based on a helical solenoid with RF cavities inside. The magnetic field in a helical solenoid is determined by the helix wavelength, helix pitch, and coil diameter. The optimal RF frequency is also linked to the helix wavelength, which makes the system over-constrained. Therefore, an overall compensation (anti-) solenoid may also be required in order achieve the correct field components with a coil inner aperture sufficient to house the cavities.

A bench test of an HCC will likely involve building one full period of the helical solenoid, since in this case the central field is a good approximation of that of a long HCC. Enough cavities should be installed to address all issues of spatial integration, which is one of the main challenges. This likely means at least 3 cavities are needed. However, for demonstration purposes, it may be sufficient to operate only one cavity at a time. Figure 14 shows a conceptual layout for a one-period HCC, indicating proposed locations of the RF feedthroughs. Figure 15 shows a small plastic rapid-prototype model of such a channel. Since the HCC concept is based on a continuous absorber, as provided by high-pressure hydrogen gas, an HCC bench test would likely be an option only after a successful demonstration of HPRF cavities in the presence of a beam of appropriate intensity.

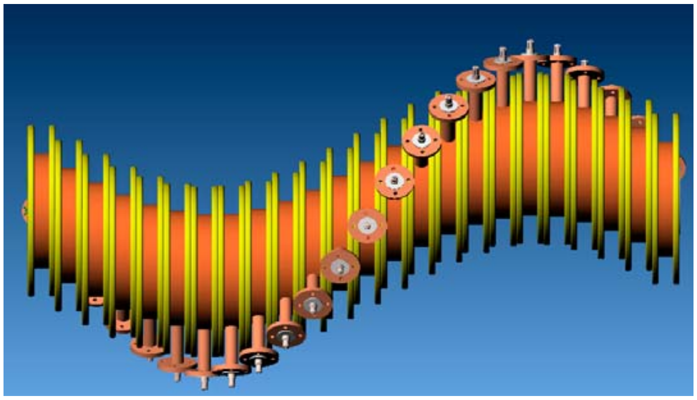

Figure 14: Conceptual HCC layout with cavities and RF feedthoughs (courtesy of Muons, Inc.).

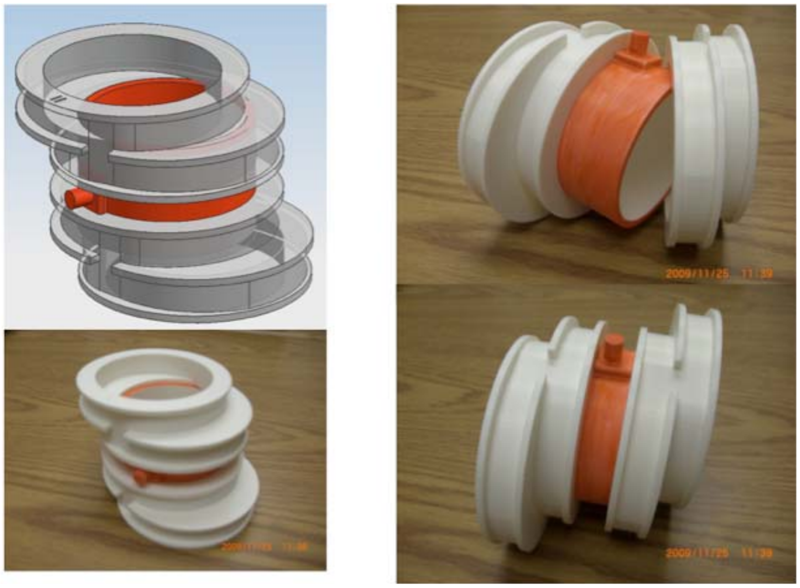

Figure 15: Rapid prototyping plastic models of a late stage HCC (Fermilab TD).

5. 6D COOLING EXPERIMENT

Although the execution of a 6D cooling experiment is not part of the plan, we intend to make preparations to carry out such an experiment as a follow-up to the current MAP 7-year program. The details of the experiment will necessarily depend on which 6D cooling channel is selected as the baseline, but it can be assumed that the experiment will be conceptually similar to MICE, in that it will have a section of the relevant channel sandwiched between upstream and downstream detectors to characterize the beam. To arrive at an optimal experimental setup, we need to carry out

- A simulation effort to understand what aspects of the cooling channel performance need to be tested, and to what precision. This will include determining the required length of cooling channel, the required beam parameters, and the analysis approach.
- A diagnostics/detector effort to determine how best to measure the muon beam to the required precision.
- A design/integration effort to specify, and define a layout for, the experiment. This will be coordinated with the bench-test activity, to ensure to the extent possible that the cooling channel hardware built for the bench test can also be used for a beam test. This will also include finding a suitable location and designing a muon beam line, unless the MICE hall can be reused for this purpose.

These efforts will be coordinated with the Cooling Channel Design effort within the Design and Simulation Activity, as well as the MICE effort. It is anticipated that much will be learned from the MICE analysis, both in terms of results and analysis methods, and therefore in the short run, the best way of preparing for a 6D cooling experiment is to concentrate on making MICE a success.

Based on the information from MICE, we will evaluate the incremental benefit of a 6D cooling experiment. A question that needs special attention is to what extent the results from a short section of 6D cooling channel can be extrapolated to a long channel. One of the main uncertainties in the simulations is the exact scattering and energy-straggling distributions, as well as correlations between them. These effects may be challenging to measure in a short cooling channel, since they affect mainly the equilibrium emittance rather than the cooling rate, and precise measurement of the equilibrium emittance may be affected by subtle beam-transport and matching effects. For example, in short sections of cooling channels, end effects may well dominate the result. Understanding the details of how track selection, matching, and nonlinearities affect the results from a short 6D-cooling-channel beam test will be critical to evaluating the incremental benefit of such a test. Incidentally, the same issues need attention in MICE.

In summary, the main purpose of this activity is to define the next step in cooling-channel beam measurements, given what can be learned from MICE and any extensions to the MICE program, in order to demonstrate that a 6D cooling channel is feasible. If it turns out that an additional experiment is needed to prove that 6D cooling is practical, the aim is to be ready to propose such an experiment at the end of the MAP 7-year plan. This includes both writing a proposal and beginning to form an experimental collaboration. One should keep in mind, however, that it is entirely possible that the outcome of the study will be that the combination of a successful MICE experiment and a bench test of a 6D cooling channel is sufficient to prove that 6D cooling is feasible.

6. TIMELINE AND MILESTONES

The *Systems Test* activity depends heavily on the other parts of the MAP plan. In particular, input from the other parts of the plan is required to determine which 6D cooling channel to build and test.

Therefore, with the exception of MICE, the bulk of the activity will only start in earnest a few years into the plan. The anticipated milestones are shown in Table 2.

Table 2. System test task milestones and deliverables.

Date	Milestone	Designation	Deliverables[a)]
FY10	Study possible minor extensions to MICE	ST10.1	DR
FY11	Deliver Spectrometer Solenoids to RAL	ST11.1	DR
FY12	Deliver first RFCC module to RAL	ST12.1	DR, MR
FY13	Initial specification of 6D cooling bench test	ST13.1	DR, MR
FY14	Finalize 6D cooling bench test specification	ST14.1	DR, MR
FY15	Initial component specifications for 6D cooling experiment	ST15.1	MR
FY16	Install 6D cooling bench test section in MTA	ST16.1	MR
	Prepare proposal for 6D cooling experiment	ST16.2	FR, ER

a) DR: design report (MAP technical note); ER: external review; FR: formal report; MR: MAP (internal) review.

7. SUMMARY

The aim of the Systems Test activity within the MAP plan is to demonstrate that key parts of the Muon Collider and Neutrino Factory designs work on a systems level. The focus is on cooling channels, since these currently represent the most significant technical risk. During the proposed 7-year program, the Systems Test activity will contribute to the completion of MICE, test a section of 6D cooling channel on the bench, assess the need for a follow up 6D beam-cooling experiment, and, if necessary, prepare the plans for such an experiment.

References

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