Revised Completion Plan for the Muon Ionization Cooling Experiment (MICE) at Rutherford Appleton Laboratory

Submitted to the US Department of Energy by the US Muon Accelerator Program in response to the DOE program review on August 12–14, 2014

Report Date: September 15, 2014
Revised: September 25, 2014

1. Introduction

This report has been generated in response to the Technical and Management review of the US Muon Accelerator Program conducted by the US Department of Energy Office of High Energy Physics on August 12–14, 2014. As stated in the review charge, the review was carried out…

> *in response to the US Particle Physics Project Prioritization Panel (P5) Report*[1] *which recommended to:*
>
> > *Reassess the Muon Accelerator Program (MAP). Incorporate into the GARD program the MAP activities that are of general importance to accelerator R&D, and consult with international partners on the early termination of MICE.*
>
> *In particular, the panel recommends to "realign activities in accelerator R&D with the P5 strategic plan. Redirect muon collider R&D and consult with international partners on the early termination of the MICE muon cooling R&D facility."*

A key outcome of the review was the action item:

> ***Present to DOE a detailed plan for Step 3π/2 by 15 September 2014.***

This report describes that plan, which aims for the completion of MAP-supported participation in the Muon Ionization Cooling Experiment (MICE) with a demonstration of the full cooling process, including RF re-acceleration, on the 2017 timescale. It also targets a ramp-down of the other elements of the MAP research effort over roughly the next year with the goal of providing a suitable transition period for our early career researchers. We believe this plan will result in a successful demonstration of the muon ionization cooling process while fitting within the constraints specified by the US DOE.

[1] "*Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context*", http://science.energy.gov/~/media/hep/hepap/pdf/May%202014/FINAL_P5_Report_053014.pdf

2. Overview

2.1 Historical Overview

The Muon Ionization Cooling Experiment proposal[2] defined a staged deployment of the ionization cooling channel elements to support an experimental program in 6 steps (see Figure 1) at the Rutherford Appleton Laboratory (RAL). The lattice was based on the 201 MHz RF SFOFO cooling channel that was developed as part of the US Feasibility Study II[3]. Table 1 summarizes the key top-level experimental deliverables to be provided by each step, as originally envisioned.

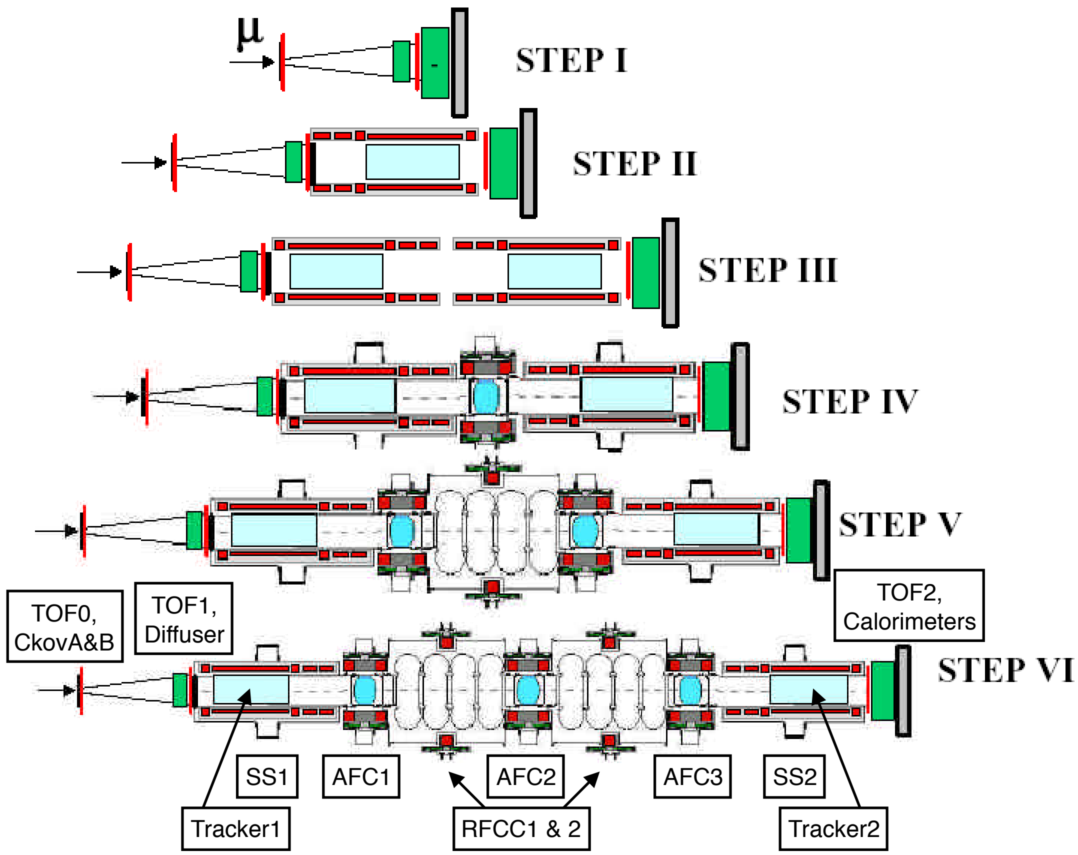

Figure 1: The six experimental steps as envisioned in the MICE proposal. Step I was completed in 2011. Due to the challenging fabrication schedule of the magnets, Steps II and III have been skipped with Step IV to begin commissioning early in calendar 2015. In the original proposal, Step V would have provided a demonstration of emittance cooling with RF re-acceleration while Step VI would provide a full cell of the cooling channel envisioned for the neutrino factory design of the US Feasibility Study II.

Due to challenges with the construction schedule, primarily associated with fabrication of the superconducting magnets, the collaboration subsequently opted for a more streamlined experimental plan. As of the November 2013 MICE Project Board review and the February 2014 DOE review of MAP, this revised plan comprised the following sequence:

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[2] "*An International Muon Ionization Cooling Experiment (MICE)*," Proposal to Rutherford Appleton Laboratory, http://mice.iit.edu/micenotes/public/pdf/MICE0021/MICE0021.pdf

[3] "*Feasibility Study-II of a Muon-Based Neutrino Source*," S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo, eds., BNL-52623, June 2001, http://www.cap.bnl.gov/mumu/studyii/FS2-report.html

- Step I (by then already complete),
- Step IV operations during the 2015–16 timeframe, and
- Step VI operations starting sometime in 2019.

Table 1: Key experimental deliverables of the 6 steps originally envisioned for the MICE Experiment.

Deliverable	Step I	Step II	Step III	Step IV	Step V	Step VI
Characterization of TOF and PID systems and muon beam	✓					
Characterization of Spectrometer Solenoid and Tracker Performance		✓	✓	✓		
Measurement of Material Properties that Determine Ionization Cooling Efficacy: Energy Loss and Multiple Scattering				✓		
Demonstration of Emittance Cooling with RF Re-acceleration					✓	✓
Characterization of SFOFO Cooling Channel Optics (based on Study II) with canonical momentum control and full optics flexibility						✓

However, in mid-April 2014, revised budget guidance from the DOE Office of High Energy Physics forced reconsideration of an experimental program extending through Step VI. At its April 29-30 review, the MICE Project Board endorsed development of a revised plan that would conclude at Step V, while still preserving the critical demonstration of the full ionization cooling process including RF re-acceleration.

The following month, the (May 2014) P5 Report recommended negotiating an "early termination" of the MICE experiment. In response, a DOE review was convened in August 2014 to evaluate whether a 3-year plan could accommodate Step IV and/or Step V.

2.2 Summary and upshot of August 2014 DOE review

The MAP position on the MICE experiment is that a demonstration of the full ionization cooling process (i.e., emittance cooling combined with RF re-acceleration) must be completed for the MICE experiment to be concluded successfully. As shown in Table 1, in the original sequence of MICE Steps, this would correspond to carrying out the experiment through at least Step V. Given both the budget profile now proposed by DOE (which would severely restrict US experimental support) and the 3-year timeframe prescribed (which would likely result in very limited US laboratory support being available for Step V operations), the members of the August 2014 DOE review committee indicated extreme skepticism that Step V could be completed successfully. The committee also expressed concerns whether the remaining R&D risks associated with the RF–Coupling Coil (RFCC) module could be adequately managed within the 3-year timeframe specified by the US DOE. Taking these concerns into consideration, during the August review the MICE team carried out a preliminary assessment of whether a demonstration of emittance cooling with RF re-acceleration could instead be provided with components already largely in hand, and within the aforementioned 3-year timeframe. The resulting concept has been (temporarily) labeled MICE Step $3\pi/2$. Over the course of the last month, this concept has been evaluated in greater detail as described below.

2.3 Overview of the Step $3\pi/2$ plan

The MICE Step $3\pi/2$ plan aims to utilize the complement of magnets presently available for the experiment, consisting of two spectrometer solenoids delivered by the US team and two focus coils provided by the UK team, as well as the hardware for 2 re-accelerating RF cavities, which is already largely in hand. This eliminates the US risks associated with assembly of the RFCC module, the UK effort required to modify the MICE Hall at RAL to accommodate the RFCC, and the required magnetic shielding which would have surrounded it in the Step V configuration. Figure 2 shows the generalized layout that has been defined in order to evaluate the relevant beam line optics. It should be noted that this generalized configuration actually has closer resemblance to the optics of "modern" neutrino factory cooling channel designs being considered by the IDS-NF study[4] as well as by the Muon Accelerator Staging Study (MASS) within MAP. The revised configuration will require an alternative design for a Partial Return Yoke (PRY) for the beam line to be developed – a relatively straightforward engineering exercise and significantly less expensive than the Step V configuration. Although additional absorbers may need to be procured in order to successfully execute the plan, they offer negligible project risk and budget impact.

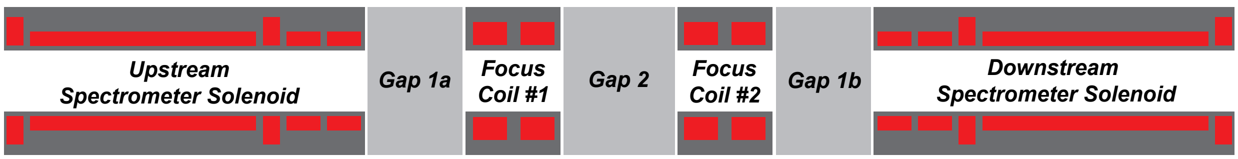

Figure 2: A generalized layout of the proposed cooling channel showing the position of the coils in each of the spectrometer solenoid and focus coil magnets. The three gaps shown provide space to match the lattice parameters for the cooling demonstration and for inclusion of the necessary RF and absorber elements.

The following sections describe the optics and project impacts of executing this Step as the conclusion of the MICE demonstration. Our evaluation indicates that a successful demonstration of the ionization cooling process can be achieved with this configuration within the timeframe mandated by the DOE budget profile for concluding the MAP effort.

3. MICE Optics Summary

As mentioned, in order to reduce the R&D risks associated with completion of MICE, the MICE optics team has focused on Step $3\pi/2$ options that make use of existing designs and hardware. The upshot is that such options are suitable for the key MICE deliverable: the demonstration of muon ionization cooling with RF re-acceleration.

3.1 Optics in the MICE Channel With and Without the RFCC Module

In the original design of Step V (shown schematically in Figure 3), an RFCC module containing four RF cavities is placed between two Absorber–Focus Coil (AFC) modules, each housing absorbers made of either liquid hydrogen (LH_2) or lithium hydride (LiH). The cavities are surrounded by the Coupling Coil magnet (CCM), which immerses them in a multi-tesla magnetic field.

The CC magnet allows the transverse betatron function in the solenoidal channel to be matched between two waists with small beta function (42 cm in the baseline Step V case) located within the absorbers inside the upstream and downstream AFC modules, while simultaneously limiting the maximum value of beta inside the cavities to the acceptable limits set by the cavity aperture. This effectively means that there is a maximum of the beta function near the center of the CC magnet, as indicated in Figure 4.

If the CC magnet is not present, it is no longer possible to have a maximum of the beta function between the two AFC modules. This also means that, assuming the symmetry of the beta function in the MICE channel, the maximum beta is now located at the AFC coils. Efficient ionization cooling requires that the beta function be as small as possible at the absorber positions, therefore the absorbers are no longer

[4] IDS-NF "*Interim Design Report*," http://arxiv.org/abs/1112.2853

ideally positioned within the AFC module and should be placed at other locations with sufficiently small beta values.

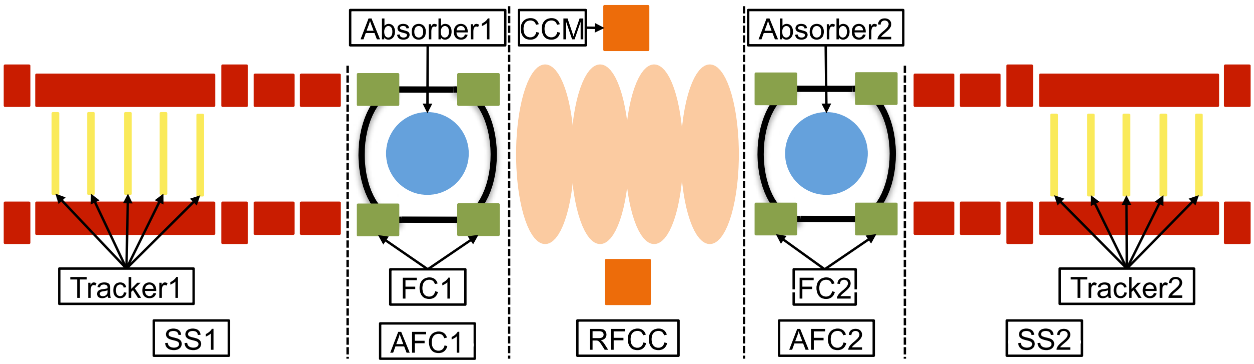

Figure 3: The conceptual layout of MICE at Step V, including upstream and downstream Spectrometer Solenoids (coils indicated in red), two AFCs (green) housing absorbers, and central RFCC with four RF cavities surrounded by the CC magnet (orange).

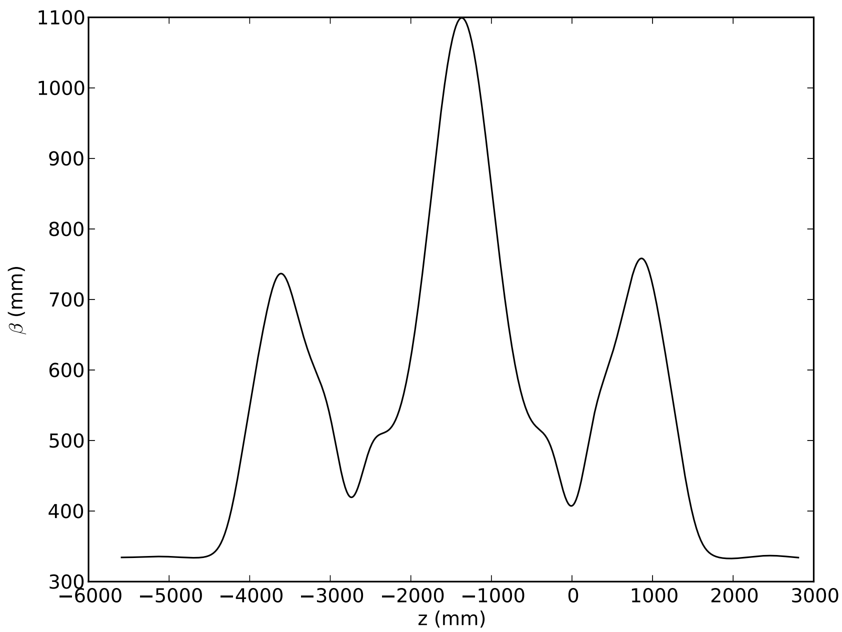

Figure 4: The optics in the MICE Step V Channel.

As shown in Figure 2 and as a starting point for developing suitable lattice solutions for Step 3π/2, a general layout has been considered consisting of two Spectrometer Solenoids at the upstream and downstream ends of the MICE Channel and two AFC magnets in between with three additional drift regions. Absorbers and RF cavities could be placed in these drift regions.

Two lattice options have been identified, which will allow MICE Step 3π/2 to successfully accomplish the proof-of-principle demonstration of ionization cooling with RF re-acceleration. Only the first option will be discussed in this document since it performs better and is simpler from an engineering point of view. In the following, we will refer to it as the "Reference Lattice design for Step 3π/2." Final optics specifications will be made on the basis of further assessment of the performance and engineering constraints.

3.2 Reference Lattice design for Step 3π/2

The Reference Lattice design for Step 3π/2 (Figure 5) is realized by centering the main absorber in the drift space between the two AFC magnets, where a low-beta region naturally arises (see Figure 6), and placing single RF cavity modules in the drift regions between the AFCs and the SSs. The distance between the AFCs was set so that it could accommodate an LH_2 absorber module, although the default option is to use the LiH disk absorber that is already on hand. It should be noted that two additional short absorbers may be necessary in order to shield the two Tracker detectors from dark current induced radiation. These absorbers would ideally be made of LiH, however plastic can also be considered. Figure 5 shows the conceptual layout of the Reference Lattice as well as how it looks in the MAUS Geant 4 simulation.

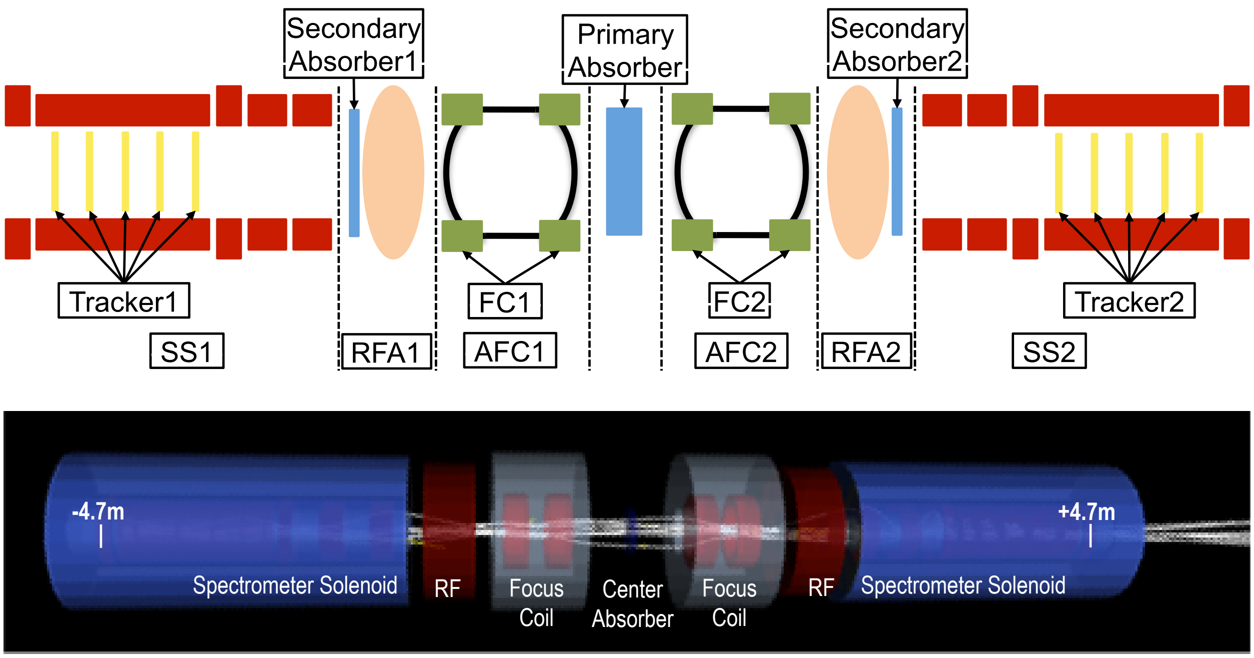

Figure 5: The layout of the Reference design for Step 3π/2 illustrating the focusing system consisting of two Spectrometer Solenoids (SS) and two Absorber-Focus Coil (AFC) modules, with one primary absorber (center) and two secondary absorbers along with RF cavities (RFA). (top) schematic, (bottom) 3D model.

The optics in the Reference Lattice solution allows matching of the beta function to relatively low values in the main absorber (42 cm at 140 MeV/*c*, 55 cm at 200 MeV/*c,* and 70 cm at 240 MeV/*c*) while maintaining large acceptance through the channel. At present the most thoroughly investigated AFC magnetic field polarity configuration is "+,–,–,+" (i.e., the solenoidal magnetic field is oriented along the beam axis in the outer two AFC coils and opposite the beam axis in the inner two coils), which allows smaller values of the beta function (both at the absorber and at the AFC) than the "+,+,–,–" case. The beta functions for different momentum and polarity settings are shown in Figure 6 and the corresponding magnetic fields in Figure 7.

The Reference Lattice requires one main absorber, and two single cavity modules, of which a prototype is already in operation at the Fermilab MTA. The Reference Lattice has sufficient flexibility in the choice of optical settings to allow a successful demonstration of ionization cooling.

3.2.1 RF in the Reference Lattice

The principle of ionization cooling requires that the energy lost in the absorbers be restored in RF accelerating cavities. In this way, the process can be iterated many times, with the many small emittance reductions accumulating into a substantial reduction by the end of the cooling channel. In the MICE

Step V lattice this is accomplished by means of four RF cavities each receiving 1 MW of power and producing an accelerating gradient of 8 MV/m.

In the Step 3π/2 Reference Lattice design, two single-cavity RF modules are incorporated into the lattice. In order to provide the same overall acceleration as the Step V RF system, each cavity would need to operate at a gradient of 16 MV/m with 4 MW of input power. At present, two RF stations, each capable of providing 2 MW of power at 201 MHz, can be fully commissioned within the 3-year time frame required for Step 3π/2. The resulting maximum accelerating gradient, nominally 12 MV/m, must be derated to about 10.3 MV/m in order to account for needed tuning headroom and RF losses in the distribution system. As seen below, this is sufficient for a partial restoration of the energy lost in the absorber, which readily suffices for a demonstration of the principle of ionization cooling.

While we feel the above operating configuration is clearly sufficient for the MICE demonstration, ensuring the ability to operate the cavities at the higher gradient of 16 MV/m remains desirable since the overall performance of any real cooling channel will be limited by the maximum attainable RF gradient. Components for two additional 2 MW RF stations, originally planned for MICE Step VI, are already in hand and could provide the necessary RF power. Furthermore, sufficient RF power is available in the MTA to characterize the Single Cavity Test System (SCTS) with 16 MV/m gradients in the magnetic field provided by the MTA magnet. Thus, while our baseline plan does not aim for full energy restoration, we intend to conduct the necessary testing and planning to preserve the option of operating the RF cavities at the higher gradient.

3.2.2 Tracking studies

Detailed tracking studies have been performed using two independent software simulation codes, with promising results. Both studies use the nominal MICE input beam parameters of 200 MeV/c and 6π mm·rad RMS normalized 4D beam emittance. Some small differences in implementation of the beam line exist, but both simulations show consistent performance of MICE Step 3π/2.

One study was performed using the MICE-standard code MAUS (MICE Analysis User Software). It performs stepwise tracking through the non-linear magnetic field of the magnets and EM fields of the RF cavities, including such details of the lattice geometry as aperture limitations and effect of materials (absorbers, Tracker planes, RF and safety windows), using realistic models of the relevant physics processes (energy loss, straggling and multiple scattering). The evolution of muon energy as the beam traverses the channel based on the Reference Lattice is shown in Figure 8. The two accelerating cavities, operating with simulated gradients of 10.3 MV/m, partially restore the energy lost in the main LiH absorber. These effects can be clearly seen in Figure 8 together with the small effects due to additional materials in the beam path.

The evolution of transverse emittance shown in Figure 9 indicates a clearly measurable emittance reduction. The amount of cooling will be marginally increased by adding absorbers outboard of the RF cavities, in order to shield the Tracker detectors against dark current induced radiation. This study was performed using the Reference Lattice with "+,–,–,+" polarity using an asymmetric matching to take into account the asymmetric energy profile (shown in Figure 8), with input beam momentum of 200 MeV/*c* and input normalized 4D emittance of 6π mm·rad. Other beam configurations are also being studied with encouraging results.

A second tracking study of the Reference Lattice was performed utilizing ICOOL/G4beamline and carried out by members of the US MAP cooling group. ICOOL was used to generate the input particle distributions, and G4beamline for the actual tracking. Stochastic effects such as multiple scattering and energy straggling were taken into account. The aperture limitation was set to a radius of 20 cm everywhere in the channel. In contrast to the MAUS study, no other materials besides the central LiH absorber (of 65 mm thickness) were included. The missing materials would include, in particular, the scintillating fiber Tracker planes in the spectrometer solenoids as well as RF and absorber windows.

Figure 10 shows the magnetic field on axis and resulting beta values. As in the MAUS study, the ICOOL/G4beamline study shows good cooling performance, which, as seen in Figure 11, is measurable in MICE with high significance. The study also indicates good beam transmission (Figure 12) for the MICE-nominal 6π mm·rad input emittance.

These two tracking studies, carried out with independent codes by two independent teams, and obtaining similar results, verify that the Step 3π/2 optics design is robust. Further detailed comparisons will be carried out in the coming weeks in order to refine our understanding of Step 3π/2. However, even at this early stage of lattice optimization, the results from these two independent simulations support the conclusion that MICE Step 3π/2 will achieve its goals.

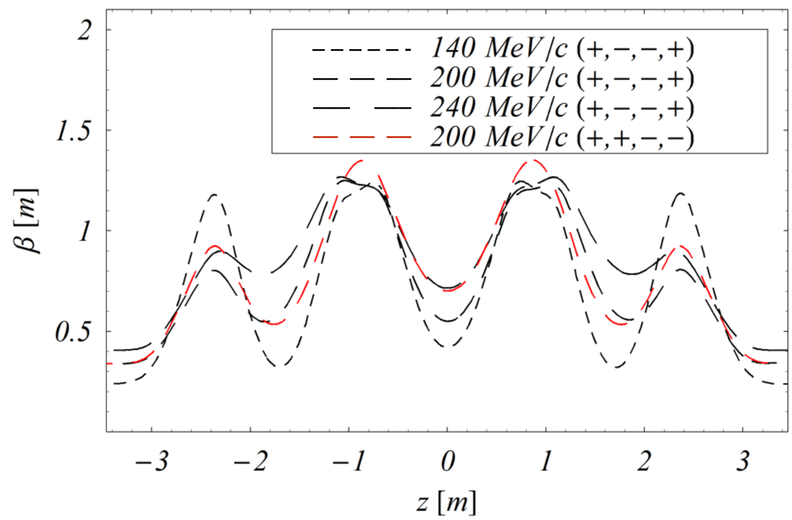

Figure 6: Betatron functions in the MAUS simulation of the Reference Lattice for "+,–,–,+" polarity for 140, 200 and 240 MeV/c settings (shown in black) and for "+,+,–,–" polarity for 200 MeV/c (red dashed curve).

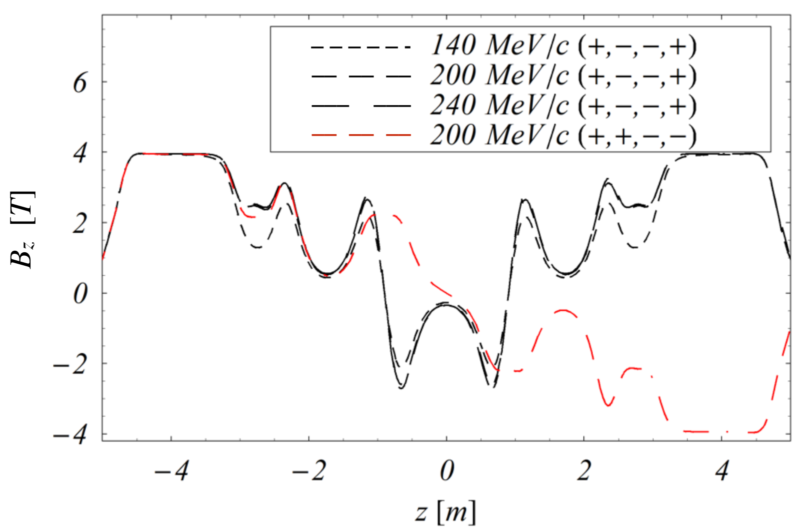

Figure 7: Magnetic field on axis in the MAUS simulation of the Reference Lattice for "+,–,–,+" polarity and settings for 140, 200 and 240 MeV/c (shown in black) and for "+,+,–,–" polarity for 200 MeV/c (red dashed curve).

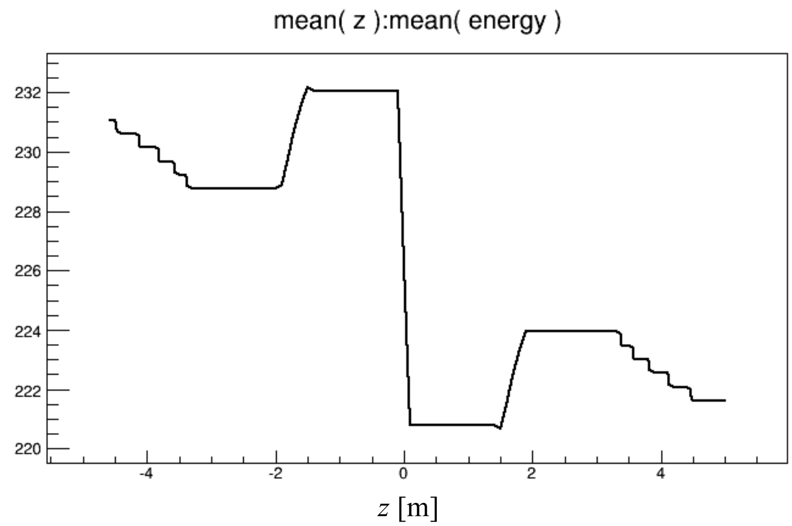

Figure 8: The evolution of mean total energy (in MeV) in the MAUS simulation along the length (in m) of the MICE Step 3π/2 channel using the Reference Lattice configuration.

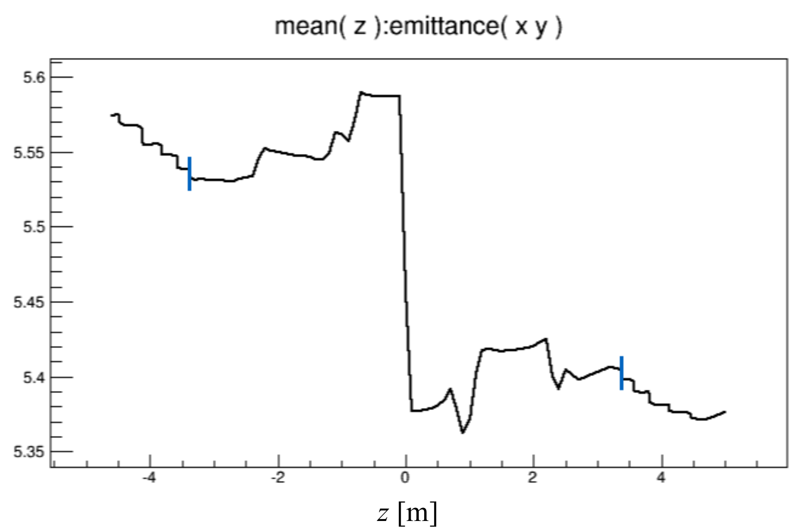

Figure 9: The evolution of 4D normalized RMS emittance (in π mm·rad) in the MAUS simulation along the length (in m) of the MICE Step 3π/2 channel in the Reference Lattice configuration, with "before" and "after" error bars indicated in dark blue (at the "Tracker Reference Plane" locations, z = ±3.4 m). The measurable emittance reduction is clearly visible. Some emittance growth is seen to occur at ±2.5 m (where Figure 6 shows the greatest chromaticity of the betatron function) and at ±1 m (where the maximum beta values occur). While optics optimization studies are ongoing, these initial results indicate more than adequate performance for the ionization cooling demonstration.

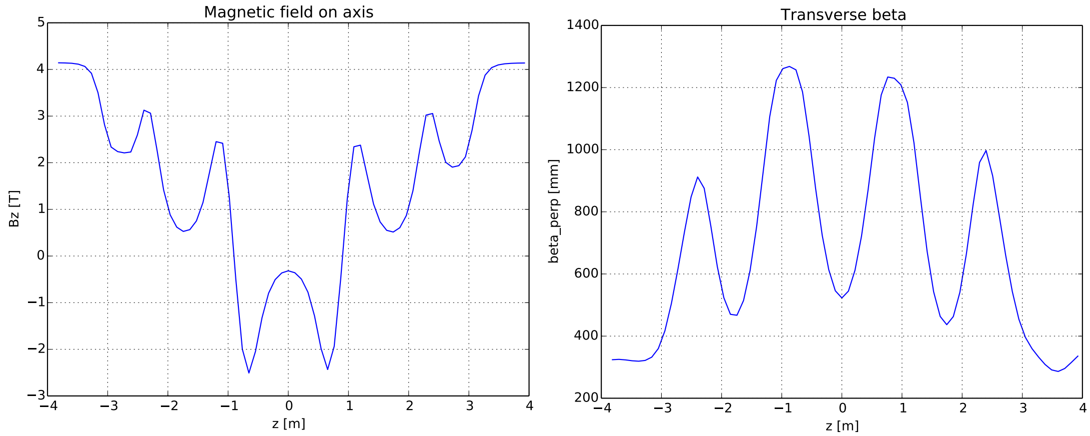

Figure 10: (left) longitudinal magnetic field on-axis and (right) transverse betatron function vs. z in ICOOL/G4beamline tracking study of Reference Lattice with beam parameters as given in text.

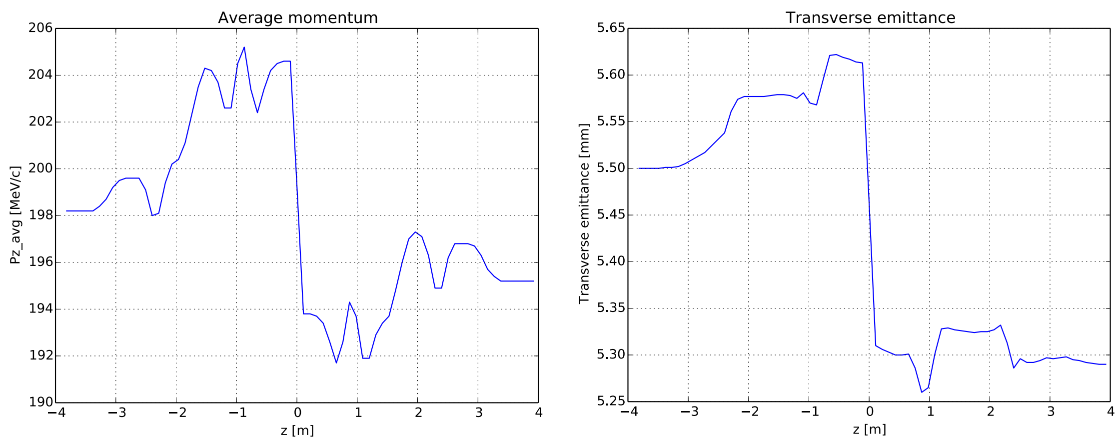

Figure 11: (left) average longitudinal momentum and (right) normalized transverse emittance vs. z in ICOOL/G4beamline tracking study of Reference Lattice with beam parameters as given in text.

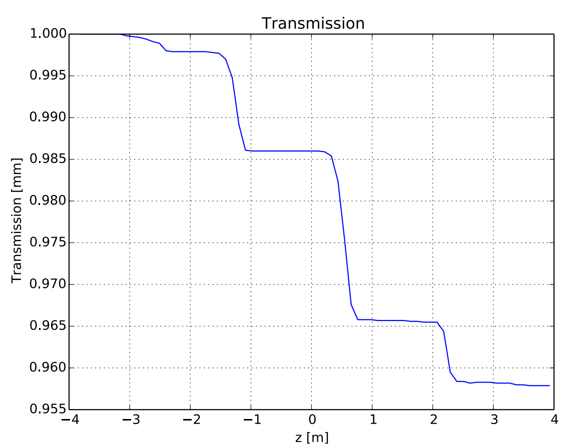

Figure 12: Muon transmission efficiency vs. z in ICOOL/G4beamline tracking study of Reference Lattice with beam parameters as given in text.

3.3 Conclusions

Two candidate lattices for Step 3π/2 have been studied in some detail. The Reference solution, which has been described in this Section, offers greater flexibility in beta function choice at the absorber position, and potentially offers engineering simplifications as well in that it uses the already-designed single RF cavity modules, of which one has already been built. However, both solutions are in principle suitable for use at Step 3π/2 for the demonstration of sustainable ionization cooling of muon beams. Optics studies will continue, with final specifications to be reported at the next (24–25 November 2014) MICE Project Board review.

4. The Revised MICE Project Plan

The changes from the Step V arrangement of the MICE experiment to the proposed Step 3π/2 are significant. Major changes in the hardware required have reduced the timescale for deploying the final MICE configuration and have greatly reduced the costs and risks for both the US and UK programs.

4.1 Summary of Modifications to UK Project Plan

The following sections identify the main activities that have been reduced or removed from the project's scope with a short description of the resulting changes in effort and timescale. The primary UK schedule drivers that remain are also identified.

4.1.1 Installation of the RFCC

In the Step 3π/2 configuration, the US-supplied RFCC module is eliminated. The assembly of the RFCC represented a very large and complex activity. Experience gained from the assembly of the Single Cavity Test System at the Fermi National Accelerator Laboratory, has provided insight into the amount of work required to assemble the full RFCC system at RAL. Major required activities would have included:

- Changes to the roadway outside the experimental hall at RAL as well as substantial modifications to the hall itself;
- Installation of extensive support services for the RFCC in the experimental hall.

Thus the elimination of the RFCC dramatically reduces the budget, timescale and risk required for implementing the final MICE configuration.

4.1.2 Installation of the Second Liquid Hydrogen System

The proposed Reference Lattice design for Step 3π/2 utilizes lithium hydride (LiH) as the main absorber material in place of the originally scoped liquid hydrogen (LH_2) absorber system. As discussed in Section 3.1, the second LH_2 system will no longer be required. The timescale and cost savings are not just in the hardware and effort associated with the construction of the hydrogen panel, control systems and contained exhaust system, but also in the extensive safety requirements in the design, construction and operation of the hydrogen system.

4.1.3 Schedule Drivers

The analysis of the proposed schedule to deploy Step 3π/2 shows that the main driver for the project's critical path is now the installation and commissioning of the two 201 MHz RF systems, each with 2 MW of output power, required to achieve 10.3 MV/m from the two RF cavities in the new layout. The work in advance of the installation is being carried out at the Daresbury Laboratory (DL), Warrington, where the buildup and initial testing to 2 MW, into a dummy load, will be completed. The first of the amplifier systems was successfully tested at DL to 2 MW and in the MICE Hall at RAL to a power of 500 kW into dummy loads. Following the power tests, the control racks and the model 4616 amplifier were removed and transferred back to DL for commissioning of the second TH116 amplifier system. Because these activities now represent the critical path, the Reference design assumes that two additional RF stations, for which components are in hand, will not be deployed.

In the plan leading to MICE Step V, the DL effort (from the Electrical Engineering department) was fully focused on Step IV implementation through mid-2015 with work for Step V following in series. With the expedited schedule proposed to complete the MICE demonstration, this is no longer possible and the DL electrical group has been requested to fully detail a new plan to complete, in parallel, the electrical installation work at RAL and electrical preparation work for the RF systems at Daresbury.

4.1.4 Schedule Assumptions

The critical path (see Table 2 and Figure 13) has been constructed by changing the amount of data taking in the Step IV arrangement to utilize all slack up to the completion of the Step 3π/2 arrangement. The slack is created due to the delivery and subsequent installation of the RF systems, RF system 2 being the last part delivered and installed on-site at RAL. Following the RF system installation the low and high power testing can commence and the commissioning of the whole channel can follow.

This analysis specifies the absolute latest date for delivery of the RF cavities and associated chambers, as well as of the PRY South and North frames and plates.

From the schedule analysis the following dates have been found:

Construction and Commissioning (taking ALL slack in the schedule)

- Step IV Construction complete – 25th May 2015
- Step IV Commissioning complete – 3rd August 2015
- Step IV De-commissioning start – 2nd June 2016
- Step 3π/2 Construction complete – 27th March 2017
- Step 3π/2 Commissioning complete – 3rd May 2017

Data-taking periods (taking ALL slack in the schedule)

- Step IV data taking – 3rd August 2015 to 2nd June 2016
- Step 3π/2 data-taking period – 3rd May 2017 to 31st March 2018 (end of the UK financial year)

Latest date for Step 3π/2 equipment delivery to RAL (taking ALL slack in the schedule)

- RF Cavities and associated chambers – 1st November 2016
- South PRY Frame – 15th October 2016
- South PRY Plates – 26th October 2016
- North PRY Frame – 1st January 2017
- North PRY Plates – 10th January 2017

All tasks in the schedule have 35% time contingency added.

Interface dates defined for the planned delivery of the Step 3π/2 equipment – Arrival at RAL

- RF Cavities and associated chambers – 26th April 2016
- South PRY Frame – 29th March 2016
- South PRY Plates – 29th March 2016
- North PRY Frame – 29th March 2016
- North PRY Plates – 29th March 2016

Thus all US deliverables should arrive with at least 6 months of slack before their scheduled installation dates at RAL.

As already stated the schedule has removed all slack to define the latest dates for delivery of the RF cavities and chambers and the Partial Return Yoke. The period for data taking will be discussed by the collaboration to ascertain the correct and required length of data taking. Even with a shortened data-taking period there will still be a substantial period of data taking available.

The data-taking period for the Step 3π/2 arrangement will terminate at the end of the UK 17/18 (March 18) financial year.

4.1.5 Possible expediters

The RF-system installation is found to be the main driver of the critical path. The initial buildup and test of the second amplifier system at the Daresbury Laboratory must be carried out before delivery to RAL. It is at this stage that resource limitations impact the schedule. During this period additional staff applied to the tasks would shorten the duration of each activity. Any technical expertise that could be brought to bear from collaborating institutes in the Electrical and RF disciplines would expedite the schedule. It has been estimated that two electrical technicians and two RF experts would be required to expedite the schedule and bring forward the completion date. Additional analysis of the RF-work-package resource-loaded schedule and discussions with senior management at the Daresbury Laboratory must take place to fully validate these estimates.

4.1.6 Risks

As noted previously, the elimination of the RFCC module along with the second liquid hydrogen system significantly reduces the risks associated with the UK effort. Table 3 shows the UK project risk assessment before and after implementation of the Step 3π/2 plan. A dramatic reduction in the major UK risks is clearly shown.

4.1.7 Conclusion

The project plan proposed here has many cost-and-schedule advantages and also offers some advantages for the experimental effort. The plan as proposed shows the very latest dates for the completion of the sub-projects. It can be seen that a data-taking period of 10 months in the Step IV arrangement is possible. This run will allow significant knowledge of the operation of the magnets in a lattice to be gained and will provide data with liquid-hydrogen and lithium-hydride absorbers. The experience of operating the lattice can be applied directly to Step 3π/2 and will therefore reduce risks associated with commissioning and operating Step 3π/2. The operational period shown for Step 3π/2 will terminate at the end of UK financial year 2017/18.

Table 2: Critical path

WBS	Name	Finish Date	Risks_Level	Risk_Impact	Risk Level Duration	Probability	Delay due to risk	Sequencial Delay
6.1.1.1.3.1.8	RF System #2 Delivered to RAL	31/08/2016	(RISK)-(R5)	Late delivery	5	0.5	02/09/2016	2.5
6.1.1.1.3.1.9	Install 4616 Amplifier	09/09/2016	(RISK)-(R4)	Unable to access the hall or shipping area	10	0.25	14/09/2016	5
6.1.1.1.3.1.10	Install 20kV HV Rack	13/09/2016	(RISK)-(R4)	Unable to access the hall or shipping area	10	0.25	20/09/2016	7.5
6.1.1.1.3.1.11	Install Auxiliary Rack	14/09/2016	(RISK)-(R4)	Unable to access the hall or shipping area	10	0.25	24/09/2016	10
6.1.1.1.3.1.12	Terminate 4616 Amplifier cables	19/09/2016					29/09/2016	10
6.1.1.1.3.1.13	Terminate HV Rack cables	23/09/2016					03/10/2016	10
6.1.1.1.3.1.14	Terminate Auxiliary Rack cables	29/09/2016					09/10/2016	10
6.1.1.1.3.2.8	Install Auxiliary Rack	30/09/2016	(RISK)-(R4)	Unable to access the hall or shipping area	10	0.25	12/10/2016	12.5
6.1.1.1.3.2.9	Install / Terminate HV Rack cables	07/10/2016	(RISK)-(R4)	Unable to access the hall or shipping area	10	0.25	22/10/2016	15
6.1.1.1.3.2.10	Install / Terminate Auxiliary Rack cables	21/10/2016	(RISK)-(R4)	Unable to access the hall or shipping area	10	0.25	07/11/2016	17.5
6.1.1.1.3.2.11	Install / Terminate TH116 Amplifier cables	28/10/2016	(RISK)-(R4)	Unable to access the hall or shipping area	10	0.25	17/11/2016	20
6.1.1.1.3.2.12	Prepare TH116 Dummy Load	07/11/2016	(RISK)-(R4)	Unable to access the hall or shipping area	10	0.25	29/11/2016	22.5
6.1.1.1.3.2.13	Commission Electrical system	24/11/2016	(RISK)-(R3)	Expert Personnel not available	20	0.5	26/12/2016	32.5
6.1.1.1.1.1.3	Install control rack	28/11/2016	(RISK)-(R5)	Expert Personnel not available	5	0.25	31/12/2016	33.75
6.1.1.1.1.1.4.1	Terminate controls cables	02/12/2016					04/01/2017	33.75
6.1.1.1.1.1.4.2	Commission system in MICE Hall - RF System#1	08/12/2016	(RISK)-(R4)	Expert Personnel not available	10	0.25	13/01/2017	36.25
6.1.1.1.1.1.5.1	Terminate controls cables	14/12/2016					19/01/2017	36.25
6.1.1.1.1.1.5.2	Commission system in MICE Hall - RF System#1	20/12/2016	(RISK)-(R4)	Expert Personnel not available	10	0.25	27/01/2017	38.75
6.1.1.1.1.1.6.1	Terminate controls cables	26/12/2016					02/02/2017	38.75
6.1.1.1.1.1.6.2	Commission system in MICE Hall - RF System#1	30/12/2016	(RISK)-(R4)	Expert Personnel not available	10	0.5	11/02/2017	43.75
6.1.1.1.1.1.7.1	Terminate controls cables	05/01/2017					17/02/2017	43.75
6.1.1.1.1.1.7.2	Commission system in MICE Hall - RF System#1	11/01/2017	(RISK)-(R4)	Expert Personnel not available	10	0.5	28/02/2017	48.75
6.1.1.1.3.2.14	Commission RF with Dummy Load	17/02/2017	(RISK)-(R4)	Expert Personnel not available	10	0.5	11/04/2017	53.75
6.1.1.1.3.2.15	RF System #1 and #2 - Amplifier 4616 & TH116 available for operation	17/02/2017					11/04/2017	53.75
10.3.4	LLRF Tests	24/02/2017	(RISK)-(R3)	Additional testing time required	20	0.5	28/04/2017	63.75
16	MICE step V installation complete	24/03/2017	(RISK)-(R2)	Delay due to currently non-critical items reaching critical path	40	0.5	15/06/2017	83.75
11.1	HPRF tests	24/03/2017	(RISK)-(R3)	Additional testing time required	20	0.5	25/06/2017	93.75
17.1	Cooling Channel magnet Commissioning	02/05/2017	(RISK)-(R2)	Commisioning of the channel is an unknown	40	0.25	13/08/2017	103.75
17.2.1	Test and condition cavities, with B field, 1MW	02/05/2017	(RISK)-(R2)	Additional testing time required - testing in the MTA	40	0.5	02/09/2017	123.75
17.2.2	RF cavity testing complete	02/05/2017					02/09/2017	123.75
18	Combined magnet and operational tests complete	02/05/2017	(RISK)-(R2)	Delay due to currently non-dritical items reaching critical path	40	0.5	22/09/2017	143.75

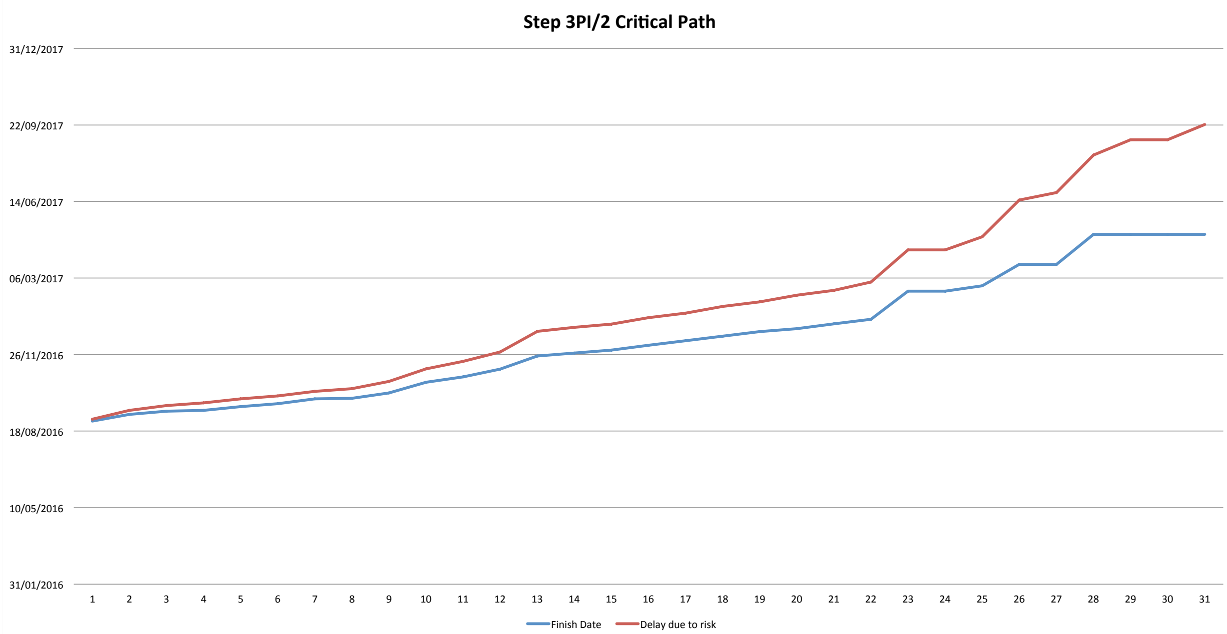

Figure 13: Critical path chart

Table 3: UK Risk Register. Risk scores on the left correspond to the Step V configuration, while the scores on the right show the reduction in risk associated with the Step 3π/2 implementation.

ID	Risk Description	Potential impact on project	Risk score			Ownership	Proposed Action	Post-action risk score			Comment / Conclusion	Cost of mitigation		Likely retirement of requirement
			L	I	LxI			L	I	LxI		Staff years	Non-staff (£k)	
MICE 3	Magnetic field effecting operation of electrical equipment relating to the continued operation of the cooling channel magnet systems and detectors.	Inability to operate the cooling channel	5	5	25	MICE - UK / MAP	Installation of a partial return yoke has mitigated the major risk. Movement of the control and power supply equipment to a dedicated room outside of the magnetic field.	1	4	4	Much work has been completed and provision of additional rack room has enabled the majority of the sensitive equipment to be moved away from the hall. The PRY has not yet been installed and so has not been tested, the residual risk still applies. Significant investment from UK and US to mitigate risk.	2	100	End of project
MICE 4	Extended period of re-training for the lattice of magnets for Step IV - SS1/AFC/SS2.	Timescales for the training period, cost of the amount of LHe required to carry out the training the availability of the Lhe. Expert personnel required to be available for magnet operations over a protracted period of time.	4	5	20	MICE-UK / MAP	Discussions with BOC (or supplier) to agree delivery timescales and availability during heavy use periods. Magnet integration task force to define commissioning method to keep schedule and cost to a minimum.	4	4	16	Each re-cool and fill of the Spectrometer Solenoid can take upto 500l LHe, AFC around 100L. Each full lattice quench could cost in the region of £7K. Initial investigations with BOC show that the predicted amount of LHe will be available during the commissioning period.	1	100	End step IV
MICE 5	AFC Module #2 has the same type of fault as AFC module #1	Extended delay and uncertain cost burden.	4	5	20	MICE - UK	Bring forward test of module #2. Shorter timescale for training runs. Purchase of additional Lhe if required to shorten timescale	2	4	8	Testing of the second Focus Coil has been successful. Some thermal performance required investigation	0.2	15	End Sept 14 after final soak test.
MICE 7	VAT payable on the delivery of all equipment imported from the non-UK collaborators	Budgetary constraints resulting in reduced work force and installation activities being carried out.	4	5	20	MICE UK	Escalation of the issue to the legal department of the STFC	2	4	8	At the moment it is unknown if the cost can be mitigated. STFC to bear the cost burden, 20% of the value of each item imported. With the shipping of the RFCC removed very large amounts are no longer possible.	0.1	100	Impacts final step
MICE 8	Resourcing issues	inability to complete significant sections of work on agreed time or cost scales.	4	5	20	MICE - UK / MAP	Escalation of the issue to the STFC and DOE.	2	4	8	Project scope has changed leading to a different labour profile required to complete the project.	2		Impacts Step IV and all other steps.
MICE 9	Senior management of the MAP collaboration / MICE-US changes.	Leadership and direction of the construction team unfocused.	4	5	20	MAP		n/a	n/a	n/a				End of Step 3PI/2
MICE 10	Late delivery of the PRY and / or Cavities for Step 3PI/2 after advanced scheduling.	Standing army cost for period after hall preparations are complete and receipt of the PRY materials / Cavities	3	5	15	MICE-UK / MAP	Interaction with the MICE-US construction team.	2	5	10	Cost will need to be borne as releasing and then re-forming the team will be difficult with an unknown timescale.	£90k / Month		End of Step 3PI/2
MICE 11	US budget cuts changing magnet manufacture, commissioning and delivery	Halting project installation and subsequent data taking. Loss of key personnel from the project. Inability to continue with full cooling program.	4	5	20	MAP	Discussion with senior STFC management.	2	4	8	DOE has assigned a budget profile of 9 / 6 / 3 for the next 3 US finacial years.			Impacts Step IV and Step 3PI/2
MICE 12	RF Power systems are not available for cavity testing	The critical path items following the RF system installation will extend in time. Testing of the cavities with and without B field. Commissioning of the channel and gaining data for the final step	4	5	20	MICE UK	Discussions with UK senior management to gain sufficient staff to carry out the work required on the RF systems and controls. Additional technical staff from collaborating institutes for installation work.	2	5	10	Successful completion of the RF power system installation will result in delays leading to the US collaborators being unable to contribute to the data taking period for Step 3PI/2.	2	75	End of Step 3PI/2
MICE 13	Focus Coil 1 extended timescale for repairs to gain full operating current.	Repairs enabling the Focus Coil 1 to operate at the nominal currents for the experiment are not completed in time for installation and operation in the Step 3PI/2	4	5	20	MICE UK	Scientific substantiation for the need to run at the higher current. Discussions with the manufacturing company to gain realistic timescales and cost. MICE project interaction with the manufacturing company senior management and supply technical effort to expedite the repairs.	2	5	10	Following scientific substantiation there may not be the need to make repairs to the Focus Coil 1. This would remove the risk of late delivery back to the experiment. The current analysis for Step 3PI/2 uses the current rating that has already been achieved.	1	100	Decision point 15th November.

4.2 US Construction Project Modifications

Modifications in the US plan include major changes to the originally planned magnet, partial return yoke (PRY) and RF systems.

4.2.1 Magnets

With the adoption of the new Step 3π/2 configuration, the US construction project has dropped further construction effort on the Coupling Coil (as well as the RFCC module of which it was a part). Thus all MICE magnets for which the US is responsible have been delivered to Rutherford Appleton Laboratory, having passed all acceptance criteria at the vendor prior to shipment. The only remaining US construction project magnet task is commissioning of the two Spectrometer Solenoids in the MICE hall.

4.2.2 Magnetic Mitigation - Partial Return Yoke (PRY)

The orders for the steel and the component fabrication for the Step IV PRY configuration are in the hands of the vendors. Fabrication of the framework parts is proceeding on schedule at Keller Technology with the south side framework already completed. The 50 mm thick steel plates from JFE Steel Corporation in Japan are complete. The heat treatment for the 100 mm plates has started and they are expected to be complete by the end of September 2014. Design work on the PRY extension for Step 3π/2 will begin as soon as the lattice layout is finalized. We plan to utilize the same vendors (for steel and fabrication) for the Step 3π/2 PRY extension.

4.2.3 RF

As shown in the Step 3π/2 lattice configuration (see Figure 5, top), the RF part of the RFCC module is being replaced by two single cavity 201 MHz RF modules. Each module will contain one cavity and one absorber disk (LiH or plastic). The Single Cavity Test System (SCTS) currently operating in the MuCool Test Area (MTA) at Fermilab (see Figure 14) has demonstrated the engineering design of the RF modules required for MICE Step 3π/2.

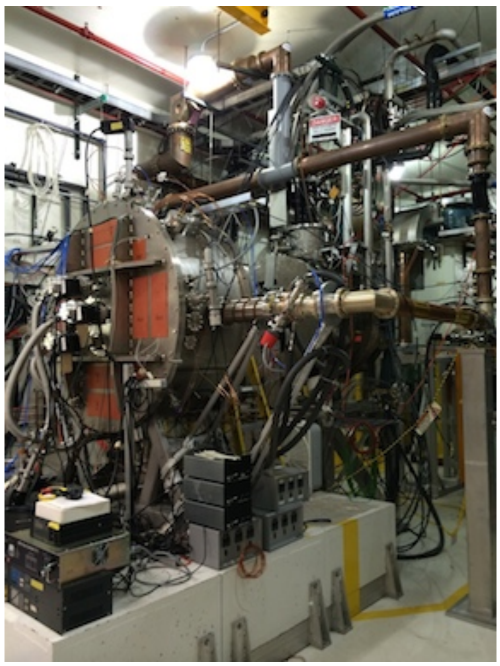

Figure 14: SCTS in the MTA

The production prototype cavity has already reached 8 MV/m (the original MICE specification) in the absence of an external magnetic field. Once the Step 3π/2 lattice configuration has been finalized, design modification of the existing SCTS vacuum vessel will begin. The cavity bodies, tuners, windows and RF power ceramic windows exist. Four new RF power couplers and 12 tuner actuators will have to be fabricated. We have production designs for the actuators and RF power couplers (for SCTS tests), but will wait for the results from the SCTS tests with *B* field before launching full production. Component fabrication can begin as soon as funds are available.

4.3 US Construction Overview

In response to the May 2014 P5 Report and the August 2014 DOE review, the US MAP program received DOE approval to execute a 3-year ramp-down plan which supports completion of the MICE cooling demonstration at RAL. The US MAP program has been redefined to conclude the design and simulation efforts, now called Advanced Muon and Neutrino Sources, at the end of FY15 and to conclude the studies of the operation of Vacuum and High Pressure RF Cavities by the middle of FY16. These ramp-down timescales were chosen to allow the early career researchers to complete the studies started in prior years. In addition, operations of the MuCool Test Area (MTA) are maintained through the middle of FY16 to ensure its availability for the testing and characterization of the MICE RF components. The US MICE Experimental Effort will be supported through the end of FY17, and US MICE Construction will continue through FY17 for installation and commissioning after delivery of the remaining major US supplied systems:

- Step IV Partial Return Yoke (PRY) Magnetic Shielding – March 2015
- Step 3π/2 PRY – March 2016
- RF Modules #1 and #2 – April 2016.

4.4 Key Project Evaluation Criteria

We distinguish R&D Risk from Contingency. Contingency is the typical project construction contingency based on incomplete specifications or design, and uncertainty in the cost estimate or in the time that will be required to perform a given task. Typically, this US MICE estimate includes a 30% contingency in the cost estimate and 40% contingency in US$ for labor. There is also an overall time contingency added to the time required to do a related series of tasks. This appears in the US MICE Project Plan as the difference between the "Required" (with time contingency) and the "Ready" (without time contingency) dates.

R&D Risks are different in nature. They are cost and time estimates of what might be needed to mitigate the unknown problems that might be encountered in performing a new type of task for the first time. While the contingency is included in the baseline MICE Project Plan cost estimate and schedule, the R&D Risk is not. It is tabulated and added separately. As the MICE construction project has progressed and the definition of the MICE program has matured, many of the original R&D Risks considered through MICE Step VI have either been faced and overcome or "retired," sometimes accruing part of the Risk estimated cost, or have been removed as the MICE program has changed from Step VI to Step V to Step 3π/2. In November 2013, the initial Risk Register consisted of 21 identified R&D Risks, and an estimate to mitigate or respond to a realized Risk was provided. As a first order estimate, we assumed that only ½ of these Risks would be realized, so provided a Risk allowance of 50% the estimate. Since then, we added another Risk, and retired 10 of the Risks at a ratio of accrued to estimate of 31% (compared to our 50% assumption).

The decision to limit MICE to Step 3π/2, using only two single RF cavity modules, has greatly reduced the US MICE cost, complexity, and R&D Risks. Thus we have re-evaluated the US Risk Register for Step 3π/2 obtaining 9 identified risks. It is important to note that the risk rankings of the identified risks are generally in the low to moderate range with no severe risks remaining. The elimination of the Coupling Coil Magnet (CCM) has removed the risks of cryostating, testing, integrating and commissioning the CCM, while also greatly reducing the scope and risk of the Partial Return Yoke (PRY) magnetic shielding from that of Step V. Now the PRY Step 3π/2 design is a straightforward extension of that for PRY Step IV. Thus the fabrication and installation plans and experience of PRY IV are directly applicable to PRY 3π/2 with minimum risk. Moreover, the elimination of the CCM means that the RF cavities will operate in fields quite similar to those generated by the Focus Coil (FC) magnets. The Single Cavity Test System (SCTS), using the prototype 201 MHz RF cavity, couplers, actuators, etc., is currently operating in the MuCool Test Area (MTA), and will be tested in the field of the MTA magnet, which was the prototype for the FC. Therefore the MTA test will validate a close approximation of the RF components and configuration to be operated at RAL (except without the PRY magnetic shielding of the couplers), hence reducing the overall risk.

The updated active Risk Register for Step IV and Step 3π/2 is shown in Table 4. In this plan, all of the US construction risks are now in the low to moderate risk range and *no high-risk items remain*. The identified R&D Risks are of three types: system integration, SCTS testing, and RF Module production and assembly. The SCTS has successfully operated up to 8 MV/m and 1 MW power. The Step 3π/2 baseline configuration requires 10.3 MV/m. Although testing in the magnetic field has not been done yet, testing with a similar prior RF cavity in this magnetic field has indicated that no problems should be anticipated. The successful assembly and operation of the SCTS using prototype MICE RF Module components has already been demonstrated. The system integration Risks will only be faced when the components are delivered, installed, and commissioned at RAL. The questions here will be whether the pieces fit together properly and whether there are unforeseen interactions between the Spectrometer Solenoid, AFC, RF Modules, and PRY systems. These will have to be addressed by sending engineers to RAL to assess and possibly make local field modifications, so a relatively large $ Risk estimate is retained.

A waterfall Gantt Chart of key construction project deliverables is shown in Table 5. Key dates for delivering US hardware to RAL are:

March 2, 2015 – completion of partial deliveries of Partial Return Yoke (PRY) for Step IV
March 29, 2016 – delivery of Partial Return Yoke (PRY) for Step 3π/2
April 26, 2016 – delivery of MICE RF Module #1 and Module #2

Table 4: US MICE Active Risk Register. The risk scores correspond to a new evaluation for Step 3π/2 for which no high-risk items appear. Furthermore, the proposed mitigations are expected to be effective as demonstrated by the low post-action risk scores.

				Risk Score					Post-Action							
ID	MAP WBS	Risk Description	Potential Impact on Project	L	I	L×I	Ownership	Proposed Action	L	I	L×I	Comment/Conclusion	Estimated Mitigation Duration (Working Days)	Estimated Mitigation Probability (%)	Targeted Retirement Date	Status (Active or Retired)
1	3.2.9.11	Additional magnetic issues found with design and surface treatment of MICE 201 MHz Couplers. Note, original prototype cavity showed no adverse B-field impact, so this risk is restricted to the coupler design.	Delay of readiness of MICE Step 3pi/2 production coupldors and full RF module.	2	4	8	MAP	Analyze adverse behavior, evaluate and implement coupler design and surface treatment changes required.	1	3	3	Given that the original prototype tested to ~10MV/m in Lab G magnet field, the likelihood of having an effect that adversely impacts the minimal operating configuration is considered very modest since significant design improvements to the coupler/window design have been implemented and fully simulated.	80	30%	4/16/15	Active
2	5.1.1.6.1.9	RF Module #1 & #2 Assembly	Likely impact is a months-scale delay due to module fit-up issues	2	2	4	MAP	Execute design and/or fabrication corrections at LBNL.	1	1	1	Design now directly derives from the SCTS prototype so all assembly issues fully tested.	40	30%	3/29/17	Active
3	5.3.1.1.1.31	Step IV Partial Yoke Shielding Integration problems.	Likely impact is a few week delay due to need to re-machine large parts.	1	2	2	MAP	Execute design and/or fabrication corrections at vendor.	1	1	1		40	10%	12/30/14	Active
4	5.3.1.2.2.7	MICE 3pi/2 Magnetic Shielding 2 Week Review Window	Delay in constuction and delivery of MICE Step 3pi/2 shielding.	3	1	3	MAP	Update design to satisfy requirements of MICE Step 3pi/2 operating configuration and then launch fabrication. Impact would be of order 1 month of re-engineering.	1	2	2	Minimal impact anticipated in Step 3pi/2 construction schedule due to significant slack in shielding construction schedule.	20	50%	4/14/15	Active
5	5.3.1.2.3.6	Step 3pi/2 Partial Yoke Shielding Integration problems.	Likely impact is a multi-month delay due to need to re-machine large parts.	1	2	2	MAP	Execute design and/or fabrication corrections at vendor.	1	2	2		40	10%	3/29/17	Active
6	5.5.2.1.3	RF Module #1 & #2 Integration Issues at RAL.	May require design changes or corrections. Potentially results in months-scale field engineering delays.	2	4	8	MAP	Correct all identified issues (eg, vacuum performance) in the field.	1	2	2	SCTS test in the MTA helps to define the necessary operation specifications and allow them to be dealt with in advance.	80	30%	3/29/17	Active
7	5.5.2.2.3	Spectrometer Solenoid integration and commissioning issues at RAL.	Delay of MICE Step IV commissioning and experimental operations.	3	4	12	MAP	Assess failure and repair magnet (s). Likely delay of > 3 months in commissioning schedule.	1	3	3	Magnets have been fully tested in a range of configurations in the US. The principal concern is that damage might have occurred during shipping. However, shock sensors and monitoring did not indicate any shipping issues.	80	50%	8/3/15	Active
8	5.5.2.3.3	Step IV Partial Yoke Shielding Fit-Up Issues at RAL	Likely impact is a multi-month delay due to need to re-machine large parts.	1	4	4	MAP	Re-do integration engineering for partial yoke solution in MICE Hall.	1	3	3	Decision to do full fit-up of components prior to shipping to UK largely mitigates this risk.	80	10%	8/3/15	Active
9	5.5.2.4.3	Step 3pi/2 Partial Yoke Shielding Integration problems.	Likely impact is a multi-month delay due to need to re-machine large parts.	1	4	4	MAP	Re-do integration engineering for partial yoke solution in MICE Hall.	1	3	3	Decision to do full fit-up of components prior to shipping to UK largely mitigates this risk.	80	10%	3/29/17	Active

Legend:		
Sym	Definition	Range
L	Likelihood	1-5
I	Impact	1-5

Likelihood Translation:	
Rank	Prob (%)
1	10%
2	30%
3	50%
4	70%
5	90%

Impact Translation:	
Rank	Work Days
1	1-20
2	21-40
3	41-80
4	81-120
5	>120

Table 5: US MAP Milestones ("Waterfall Plot") (rotated for ease of viewing).

14-09-12-MAP-RampDown-GanttChart-Milestones

WBS	Task Name	Status Date	% Complete
	L1 Milestones		
1.02.05	L1 - End of Advanced Concepts for Muon and Neutrino Sources	9/30/15	0%
1.03.04	L1 - End of MuCool Test Area Support (MTA)	3/31/16	0%
1.01.03	L1 - End of Program Management	9/29/17	0%
1.04.02	L1 - End of Muon Ionization Cooling Experiment (MICE)	9/29/17	0%
1.05.06	L1 - End of MAP/MICE	9/29/17	0%
1.05.07	L1 - End of UK Effort	3/30/18	0%
	L4 Milestones		
1.05.04.01.02.01.04	L4 - [Required] - MICE-US LiH Disk Fabrication	4/30/14	100%
1.05.04.01.02.02.01	L4 - MICE-US LiH Disk Shipping Approval by DOE	8/15/14	100%
1.05.03.01.01.01.08	L4 - [Required] - MICE Step IV Magnetic Shielding Procurement and Fabrication - SOUTH FRAME - Complete	9/10/14	100%
1.05.03.01.02.01.04	L4 - [Required] - MICE Step 3pi/2 Magnetic Shielding Conceptual Design Studies	9/30/14	0%
1.05.03.01.01.02.04	L4 - [Required] - MICE Step IV Magnetic Shielding Shipped to RAL - SOUTH FRAME - Complete	10/15/14	0%
1.05.02.01.02.01.03	L4 - Cold Mass #2 Arrives at LBNL	11/4/14	0%
1.05.03.01.01.01.17	L4 - [Required] - MICE Step IV Magnetic Shielding RAW Material Procurement - SOUTH WALL - Complete	11/5/14	0%
1.05.03.01.01.01.19	L4 - [Required] - MICE Step IV Magnetic Shielding RAW Material Procurement - NORTH WALL - Complete	11/5/14	0%
1.05.03.01.01.01.10	L4 - [Required] - MICE Step IV Magnetic Shielding Procurement and Fabrication- NORTH FRAME - Complete	12/18/14	0%
1.05.03.01.01.01.23	L4 - [Required] - MICE Step IV Magnetic Shielding Fabrication - SOUTH WALL - Complete	12/30/14	0%
1.05.03.01.01.01.27	L4 - [Required] - MICE Step IV Magnetic Shielding Fabrication - NORTH WALL - Complete	12/30/14	0%
1.05.03.01.01.01.30	L4 - [Required] - MICE Step IV Magnetic Shielding FRAME and WALL Fit-Up - Complete	12/30/14	0%
1.05.01.01.04.01.04	L4 - [Required] - 201 MHz Production Cavity Body Preparation Tooling (Production)	1/5/15	0%
1.05.03.01.01.02.12	L4 - [Required] - MICE Step IV Magnetic Shielding Shipped to RAL - NORTH FRAME - Complete	2/6/15	0%
1.05.01.01.04.01.08	L4 - [Required] - 201 MHz Production Cavity Body Preparation (Production)	2/17/15	0%
1.05.01.01.04.01.09	L4 - 201 MHz Production Cavity Body Preparation - Complete (Production)	2/17/15	0%
1.05.01.01.06.01.04	L4 - [Required] - RF Module#1 & RF Module#2 - Purchase & Assemble Components	2/24/15	0%
1.05.03.01.01.02.08	L4 - [Required] - MICE Step IV Magnetic Shielding Shipped to RAL - SOUTH WALL - Complete	3/2/15	0%
1.05.03.01.01.02.16	L4 - [Required] - MICE Step IV Magnetic Shielding Shipped to RAL - NORTH WALL - Complete	3/2/15	0%
1.05.03.01.01.02.17	L4 - MICE Step IV Magnetic Shielding Received at RAL	3/2/15	0%
1.05.03.01.01.04	L4 - MICE IV Magnetic Shielding - Complete	3/2/15	0%
1.05.01.01.05.01.04	L4 - [Required] - RF Vacuum Vessel Fabrication	3/18/15	0%
1.05.03.01.02.02.04	L4 - [Required] - MICE Step 3pi/2 Magnetic Shielding Detailed Engineering	3/31/15	0%
1.05.03.01.01.03.05	L4 - MICE Step IV Magnetic Shielding Installation at RAL - NORTH FRAME (Constraint Start Date Supplied by RAL)	4/10/15	0%
1.05.03.01.02.02.09	L4 - MICE Step 3pi/2 Magnetic Shielding Detailed Engineering	4/14/15	0%
1.05.03.01.01.03.08	L4 - MICE Step IV Magnetic Shielding Installation at RAL - NORTH WALL (Constraint Start Date Supplied by RAL)	4/22/15	0%
1.03.02.09.06	L4 - [Required] - MICE 201MHz Cavity Run 5 (Other Testing)	4/29/15	0%
1.05.05.01.01	L4 - UK - Step IV Construction Complete	5/25/15	0%
1.05.05.01.02	L4 - UK - Step IV Commissioning Start	5/25/15	0%
1.05.01.01.04.03.04	L4 - [Required] - 201 MHz Actuator Fabrication (Production Units)	6/10/15	0%
1.05.01.01.05.02.04	L4 - [Required] - RF Vacuum Vessel Assembly & Test	6/12/15	0%
1.05.01.01.05.02.05	L4 - RF Vacuum Vessel Assembly & Test (Complete)	6/12/15	0%
1.05.01.01.04.02.04	L4 - [Required] - 201 MHz Cavity Electro-polished (Production)	6/18/15	0%
1.05.01.01.04.06.03	L4 - All RF Parts (Except Couplers) for RF Modules Ready	6/18/15	0%
1.03.02.09.09	L4 - [Required] - MICE 201MHz Cavity Run 5 (Other Testing)	7/29/15	0%
1.05.05.01.03	L4 - UK - Step IV Commissioning Complete	8/3/15	0%
1.05.05.01.04	L4 - UK - Step IV Data Taking Start	8/3/15	0%
1.05.05.02.02.05	L4 - MICE-US SS Component Integration - Complete	8/3/15	0%
1.05.02.01.01.02	L4 - SS#1 & SS#2 Spectrometer Solenoids Ready for Operations	8/10/15	0%
1.05.01.01.04.04.08	L4 - [Required] - 201 MHz Coupler Fabrication (Production Units) - Complete	9/24/15	0%
1.05.01.01.03.01.06	L4 - [Required] - 201 MHz SCTS Coupler Tests - Complete	10/12/15	0%
1.05.01.01.06.01.08	L4 - [Required] - RF Module#1 & RF Module#2 RF to Vacuum Vessel Fit-up - Complete	1/7/16	0%
1.05.01.01.06.01.11	L4 - RF Module#1 & RF Module#2 Ready to Ship to RAL	1/7/16	0%
1.05.03.01.02.03.05	L4 - [Required] - MICE Step 3pi/2 Magnetic Shielding Parts - Completed	1/29/16	0%
1.05.01.01.06.02.04	L4 - [Required] - RF Module#1 & RF Module#2 Preparation for Shipment to RAL	2/15/16	0%
1.05.03.01.02.04.04	L4 - [Required] - MICE Step 3pi/2 Magnetic Shielding Shipped to RAL	3/29/16	0%
1.05.03.01.02.04.05	L4 - MICE Step 3pi/2 Magnetic Shielding Received at RAL	3/29/16	0%
1.05.01.01.06.03.03	L4 - [Required] - RF Module#1 & RF Module#2 Shipment to RAL	4/26/16	0%
1.05.01.01.06.03.04	L4 - MICE RF Module#1 & RF Module#2 Arrives at RAL (UK Desired by 04/04/16)	4/26/16	0%
1.05.04.01.02.03.04	L4 - [Required] - MICE-US Extra LiH Disk Fabrication	4/29/16	0%
1.05.05.01.05	L4 - UK - Step IV Data Taking Complete	6/2/16	0%
1.05.05.01.06	L4 - UK - Step IV Decommissioning Start	6/2/16	0%
1.05.05.01.07	L4 - UK - Step 3pi/2 Constructioin Start	6/2/16	0%
1.05.01.01.06.04.01	L4 - UK NEED by: RF Module#1 & RF Module#2 (Constraint Supplied by RAL)	11/1/16	0%
1.05.03.01.02.06	L4 - MICE 3pi/2 Magnetic Shielding - Complete	12/29/16	0%
1.05.05.01.08	L4 - UK - Step 3pi/2 Construction Complete	3/27/17	0%
1.05.05.01.09	L4 - UK - Step 3pi/2 Commissioning Start	3/27/17	0%
1.05.01.01.06.04.04	L4 - RF Module#1 & RF Module#2 Installation & Commissioning at RAL - Complete	5/3/17	0%
1.05.05.01.10	L4 - UK - Step 3pi/2 Commissioning Complete	5/3/17	0%
1.05.05.01.11	L4 - UK - Step 3pi/2 Data Taking Start	5/3/17	0%
1.05.05.01.12	L4 - UK - Step 3pi/2Data Taking Complete	3/30/18	0%

5. Conclusion

In response to the recommendations and action item identified by the August 2014 DOE review Committee, the Muon Accelerator Program (MAP), the MICE International Project Office (MIPO) and MICE Experimental Management Office (MEMO) have prepared a plan to complete the demonstration of the muon ionization cooling process, i.e., the demonstration of emittance cooling along with RF re-acceleration of the muons, on the 2017 timescale. An alternative to the MICE Step V layout and optics configuration (the temporarily named Step 3π/2 layout), which has acceptable performance to complete this demonstration, has been developed. The baseline schedule for the expedited plan envisions:

- Assembly and commissioning of MICE Step IV through July 2015;
- MICE Step IV Running from August 2015 to June 2016;
- Assembly and commissioning of the MICE Cooling Demonstration (i.e., the so-called 3π/2 configuration) through April 2017;
- Start of the Cooling Demonstration in May 2017.

The more rapid deployment of the experimental steps has been achieved by focusing on the innovative use of hardware that is in hand or which is ready for assembly, thus minimizing further component design and construction activities. ***Our conclusion is that this plan will achieve the necessary performance goals while fitting within both the time and budget constraints specified by DOE and the review committee for the successful conclusion of the MICE demonstration and the ramp-down of all MAP effort.***

It should be noted that the above plan for the early completion of the MICE demonstration has been assembled quite rapidly – from April to August 2014. Modifications were made to the MICE baseline plan to conclude the experiment with the Step V configuration in lieu of the originally envisioned Step VI. The present exercise, which has spanned roughly one month, has led to further very substantial changes in both the construction and experimental plan. While we consider our conclusions about the acceptability of the plan to be *strongly justified*, further design optimization and a thorough review of the updated construction and experimental plans, including a detailed review of the proposed intermediate milestones required to evaluate progress, are required. Thus the MAP, MIPO and MEMO intend to solicit comments from the members of the MICE collaboration through the time of the next MICE collaboration meeting (MICE CM40, October 26–29, 2014) and to prepare a *final* version of the plan for review by the MICE Project Board and Resource-Loaded Schedule review Committees at their next scheduled review (November 24–25, 2014 at RAL).

In light of the dramatic modifications embodied in this plan with the aim to successfully conclude the MICE ionization cooling demonstration, a recapitulation that summarizes the major choices, trade-offs, and potential areas for further discussion is in order.

In particular, the plan aims for a "good enough" demonstration leading to a number of baseline choices intended to expedite and simplify the remaining construction effort:

- Key choices for the US plan:
    - Eliminate the use of the RFCC module, thus eliminating the majority of the remaining construction project risks for magnets;
    - Proceed with fabrication of two single-cavity RF modules (in lieu of a multi-cavity module), which differ only marginally from the Single Cavity Test System (SCTS) currently operating in the MTA;
    - Execute the next-generation PRY design (i.e., without the Coupling Coil magnet) utilizing key design elements of the Step IV PRY design which is presently in fabrication;
    - Prepare to run RF cavities in magnetic field at higher operating gradients for MICE (potentially as high as 16 MV/m). This requires an updated experimental plan for tests of

the SCTS in the MTA, which, with contingency, should fit within an 18 month operating window for that facility.

- Key choices for the UK plan:
    - Eliminate extensive MICE Hall infrastructure modifications required to accommodate the RFCC module and associated Partial Return Yoke;
    - Eliminate integration activities required to accommodate the RFCC module;
    - Eliminate plans for fabricating and commissioning a second LH_2 system.

Overall these modifications significantly reduce the both the cost and time required to achieve the cooling demonstration for both the US and UK efforts.

Risks associated with this plan have been dramatically reduced by eliminating the construction of any further novel hardware and adapting the cooling channel optics to utilize only components for which either prototypes and/or final production hardware already exist. In terms of the risks that remain, we note that the Reference optics requires operation of the RF cavities at higher fields than planned for the MICE Step V configuration. However, the RF operating environment is reasonably approximated by the test configuration in the MTA and the higher gradients required are readily tested in the MTA. This results in a clear emphasis in the US plan to complete the MICE 201 MHz RF characterization in the MTA over the next approximately 12 months (18 months with contingency). Overall, the US effort now much more closely matches the configuration of a "typical" construction project in that the R&D risks are largely retired and the principal focus is on fabrication, assembly and delivery of well-understood components. Similarly, the focus of the UK effort shifts towards integration and exploitation of each of the key experimental configurations.

In conclusion, a plan has been prepared which we believe will result in a successful demonstration of the muon ionization cooling process, and which will support a productive ramp-down of the other elements of the MAP research effort, while fitting within the constraints specified by the US DOE. MAP efforts are now pivoting towards the execution of this plan.

GLOSSARY

#:

4616: Tetrode vacuum tube used to drive the 2 MW TH116 in 201 MHz RF power amplifier

C:

CCM: Coupling Coil Magnet (also referred to as "CC magnet")
Ckov: MICE aerogel-radiator threshold Cherenkov counter

D:

Diffuser: Discs made of movable brass and tungsten "petals" that can be interposed into the beam path in order to prepare beams with a range of input emittance.
DL: Daresbury Laboratory, Warrington, UK
Dollar: U.S. currency denomination, approximately equivalent to 0.6 British Pounds.

E:

Emittance: Generalized beam size in 6-dimensional phase-space, or a sub-space thereof.

F:

FC: Focus Coil, 2-coil magnet pair of the AFC module

G:

G4beamline: Particle-tracking simulation code based on Geant 4 developed and maintained by Muons, Inc.

I:

ICOOL: Particle-tracking simulation code developed and maintained by BNL muon cooling group
Ionization cooling: Process of reducing beam emittance via ionization energy loss in low-*Z* absorbers intermingled with RF re-acceleration.

L:

LH_2: liquid hydrogen
LiH: lithium hydride

M:

MAP: U.S. Muon Accelerator Program
MASS: Muon Accelerator Staging Study
MAUS: MICE Analysis User Software
MICE: Muon Ionization Cooling Experiment
MICE Steps: Partial implementations of MICE on the way to the planned, full implementation.
MIPO: MICE International Project Office
MEMO: MICE Experimental Management Office
MTA: MuCool Test Area (at Fermilab)
Muon: Elementary lepton, "2^{nd}-generation electron."

N:

Normalized emittance: Geometrical emittance scaled by relativistic factor $\beta\gamma$ in order to compensate for apparent increase or decrease of beam size in a focusing channel when energy is decreased or increased.

P:

PRY: Partial Return Yoke, used to suppress fringe fields from the MICE magnetic channel that might otherwise affect the performance of electrical and electronic equipment in the MICE Hall.

R:

RAL: Rutherford Appleton Laboratory, Oxfordshire, UK
RF: radio frequency
RFA: RF–Absorber module
RFCC: RF–Coupling Coil module

S:

SFOFO: "Super-FOFO" cooling-channel lattice employing a double-resonance scheme in order to reduce the betatron function value at the absorber locations.
SS: Spectrometer Solenoid
SCTS: Single-Cavity Test System

T:

TH116: Thomson power triode providing 2 MW output power in 201 MHz RF power amplifier
TOF: Time-of-Flight scintillation-counter hodoscope
Tracker: MICE 5-station scintillating-fiber track measurement system