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

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.

2. 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

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[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

Appleton Laboratory (RAL). The optics were 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 that would be provided by each step.

Due to challenges with the construction schedule, primarily associated with fabrication of the superconducting magnets, the collaboration opted for a streamlined experimental plan. As of the November 2013 MICE Project Board Review and the February 2014 DOE review of MAP, that plan envisioned Step I (already complete), Step IV operations during the 2015–16 timeframe, and Step VI operations starting sometime in 2019. In April 2014, revised budget guidance from the DOE Office of High Energy Physics forced reconsideration of this plan and the MICE Project Board endorsed development of a revised plan that could conclude at Step V, to save both money and time, while preserving the critical demonstration of the full ionization cooling process including RF re-acceleration. In May 2014, the P5 recommendation to negotiate a rapid conclusion of the MICE experiment appeared and the August DOE review was convened to evaluate whether a 3-year plan could accommodate Step IV and/or Step V.

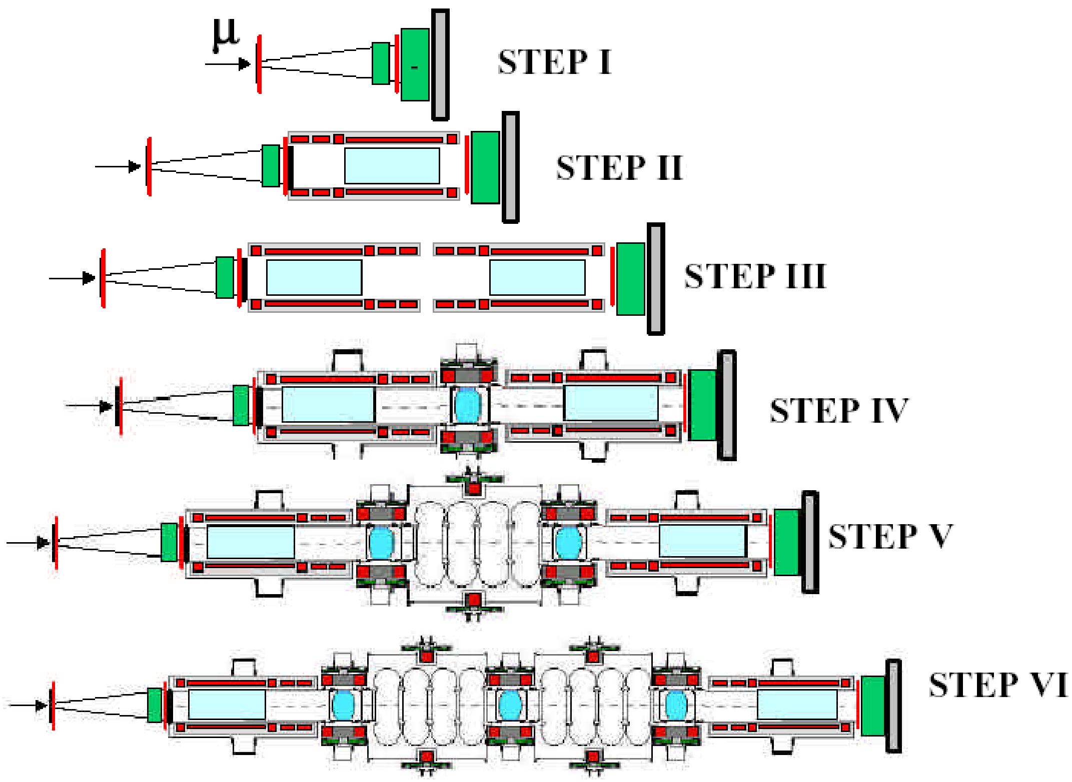

Figure 1: The six experimental steps as envisioned in the MICE proposal. Step I has been completed and due to the fabrication schedule of the magnets, Steps II and III have been skipped with Step IV to begin commissioning early in calendar 2015. The originally envisioned Step V would provide a demonstration 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.

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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

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						√

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 MICE to be concluded successfully. In Table 1, this corresponds to completion of Step V. However, the members of the August 2014 review committee indicated extreme skepticism that declining US support would allow this to be achieved with Step V given both the budget profile being 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 to be available for Step V operations). Finally, the committee expressed concerns that the remaining R&D risks associated with the RF-Coupling Coil (RFCC) module could be adequately managed within the 3-year timeframe. With these concerns, the MICE team at the review carried out a preliminary assessment of whether a demonstration of emittance cooling with RF re-acceleration could be provided with components already largely in hand and within the 3-year timeframe specified by the US DOE. 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.

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 RF cavities on the beam line which is already largely in hand. This eliminates the US risks associated with assembly of the RFCC module and the UK effort required to modify the MICE Hall at RAL to accommodate the RFCC and the required magnetic shielding which would surround it in the Step V configuration. Figure 2 shows the generalized layout that has been pursued 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 which is significantly less expensive than that of the Step V configuration. Furthermore, additional absorbers may need to be procured in order to successfully execute the plan. The additional absorbers offer negligible project risk and budget impact.

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

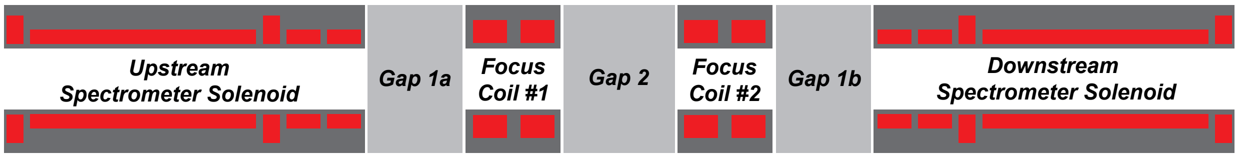

Figure 2: A generalized layout of the proposed cooling channel showing the position of the coils in each of the spectrometer solenoid and focus coil magnets. The three gaps shown provide space to match the lattice parameters for the cooling demonstration and for inclusion of the necessary RF and absorber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

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 indeed exist and 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 CC magnet, which immerses them in a multi-tesla magnetic field.

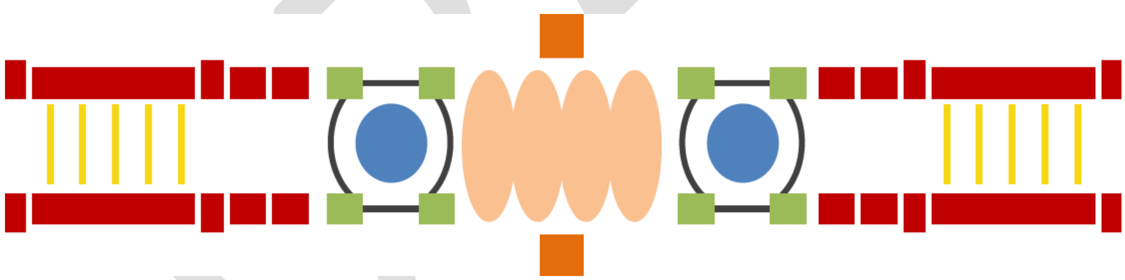

Figure 3: The conceptual layout of MICE at Step V, including upstream and downstream Spectrometer Solenoids (coils indicated in red), two AFCs (green) housing absorbers, and central RFCC with four RF cavities surrounded by the CC magnet (orange).

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

As the starting point for developing suitable lattice solutions for Step 3π/2, a geometry 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 as shown in Figure 5. Absorbers and RF cavities could be placed in these drift regions. Two lattice solutions 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. These solutions are briefly discussed in the following sections.

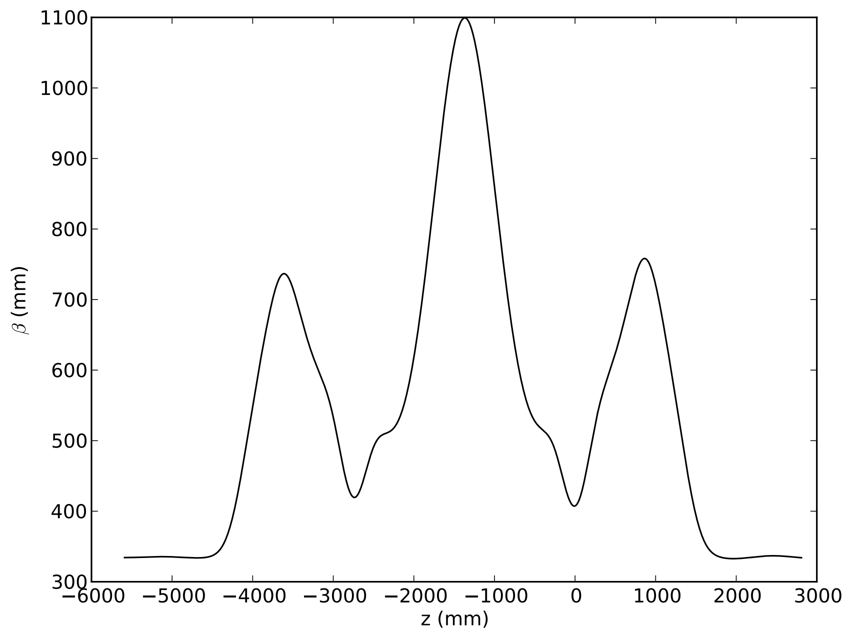

Figure 4: The optics in the MICE Step V Channel.

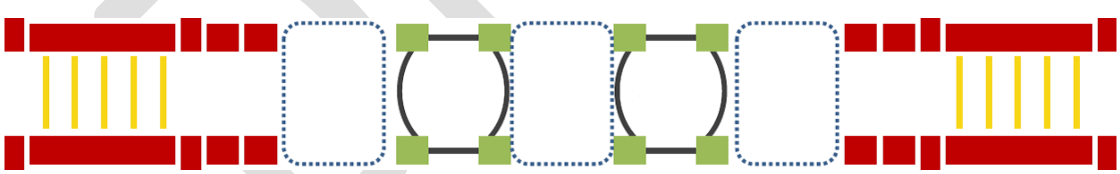

Figure 5: The preliminary geometry illustrating the focusing system of the potential Step 3π/2 consisting of SSs and AFCs, with dashed rounded rectangles indicating the available space for absorbers and RF cavities.

3.2 Reference lattice for Step 3π/2

The reference lattice solution for Step 3π/2 is realized by centering the main absorber in the drift space between the two AFC magnets, where a low-beta region naturally arises, and placing single RF cavity modules in the drift regions between the AFCs and the SSs. The distance between the AFCs was set so as to accommodate the LH_2 absorber. It should be noted that two additional short absorbers may be necessary in order to shield the two Trackers from dark current induced radiation. These absorbers would ideally be made of LiH, however plastic can also be considered. The layout of the reference lattice is shown in Figure **6**.

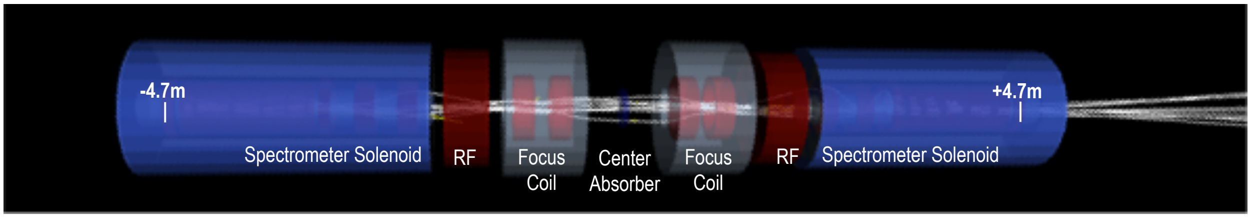

Figure 6: The layout of the reference lattice design for Step 3π/2.

The optics in the reference lattice solution allow 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 **7** and the corresponding magnetic fields in Figure **8**.

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. Detailed tracking studies have been started, with promising results. The 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, and 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 MICE Step 3π/2, channel based on the reference lattice, is shown in Figure **9**. The two accelerating cavities, operating with gradients of 10.3 MV/m, partially restore the energy lost in the main LiH absorber. These effects can be clearly seen in Figure **9** together with the small effects due to additional materials in the beam path. The evolution of transverse emittance shown in Figure **10** indicates a clearly measurable emittance reduction. The amount of cooling is marginally increased by adding absorbers outboard of the RF cavities. These absorbers will also 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 **9**), with 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.

An alternate lattice configuration has also been studied but appears to have less flexibility than the reference lattice. It assumes a two-RF-cavity module with space for an absorber between the cavities located at the center of the channel. Final optics specifications will be made on the basis of further assessment of the performance and engineering constraints.

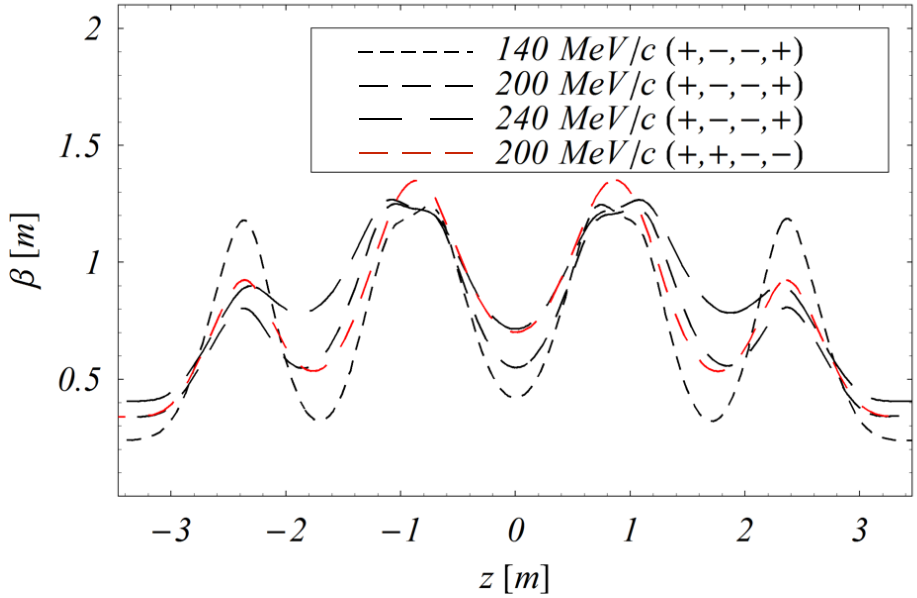

Figure 7: Betatron functions in the reference lattice for “+,–,–,+” polarity for 140, 200 and 240 MeV/*c* settings (shown in black) and for “+,+,–,–” polarity for 200 MeV/*c* (red dashed curve).

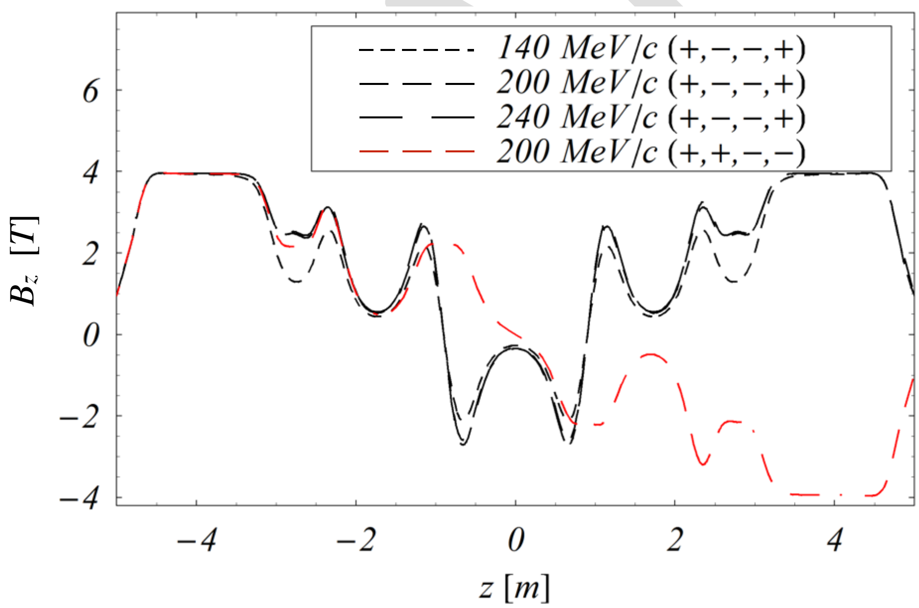

Figure 8: Magnetic field on axis in the reference lattice for “+,–,–,+” polarity and settings for 140, 200 and 240 MeV/*c* (shown in black) and for “+,+,–,–” polarity for 200 MeV/*c* (red dashed curve).

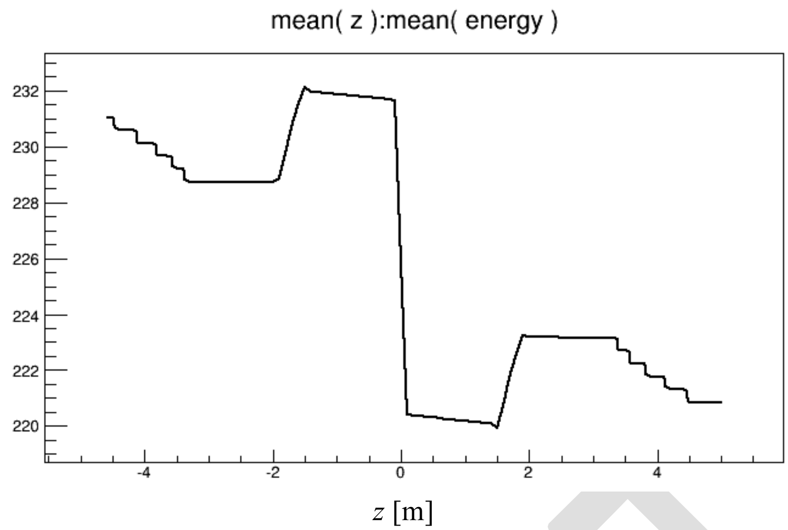

Figure 9: The evolution of mean total energy (in MeV) along the length (in m) of the MICE Step 3π/2 channel using the reference lattice configuration.

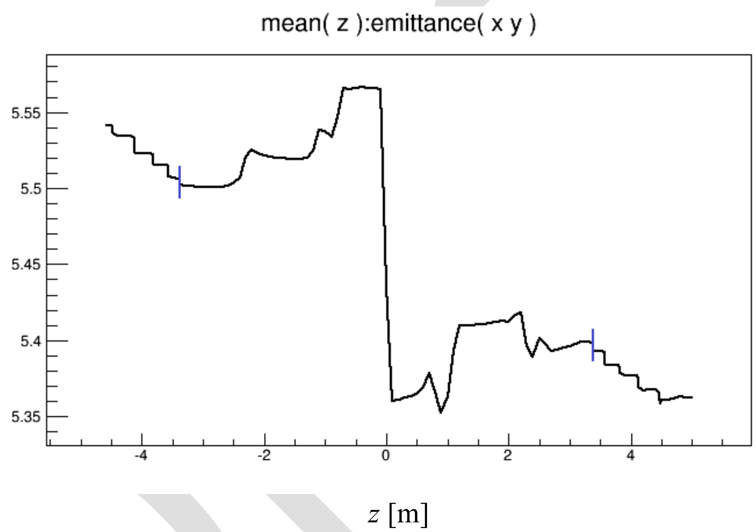

Figure 10: The evolution of 4D normalized RMS emittance (in π mm·rad) along the length (in m) of the MICE Step 3π/2 channel in the reference lattice configuration, with "before" and "after" error bars indicated in dark blue (at the "Tracker Reference Plane" locations, $z = \pm 3.4$ m). The measurable emittance reduction is clearly visible.

3.3 Conclusions

Two candidate lattices for Step 3π/2 have been studied in some detail. The reference solution offers greater flexibility in beta function choice at the absorber position, and potentially offers engineering simplifications as well (it uses only 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 first demonstration of sustainable ionization cooling of muon beams. Optics studies will continue, with final specifications to be reported at the next (25/26 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, gave an 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 as part of the MICE optics 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 Step 3π/2 arrangement of the MICE cooling channel utilizes lithium hydride (LiH) as the main absorber material in place of the originally scoped liquid hydrogen (LH_2) Absorber system. With this change in absorber medium 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 RF systems required to drive 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 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 testing with the second TH116 amplifier.

During the lead-up to completion of the construction of the Step IV arrangement of the experiment, the DL effort (from the Electrical Engineering department) was to concentrate on the current step. With the schedule as it was for the preparation and installation of Step V, work could be carried out sequentially: Step IV installation and then RF preparations and operations, followed by Step V preparation. With the expeditious nature of the schedule to complete the MICE project that is now proposed this is no longer the case and significant pressure is bearing on the electrical group to work both on 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 **3** and Figure **11**) 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.

In this analysis, the absolute latest date for delivery of the RF cavities and associated chambers can be found. The same is true for 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 needs to 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 **4** 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: UK budget summary

MICE UK Cost to Complete		2014/15	2015/16	2016/17	2017/18	Totals
		£k	£k	£k	£k	£k
	Staff totals	**2606.42**	**2422.18**	**2470.34**	**2137.72**	**9636.66**
	Non-staff totals	**917.56**	**843.91**	**846.65**	**650.17**	**3258.29**
Grand totals	(Cost with time contingency and risk)	**3523.98**	**3266.09**	**3316.99**	**2787.89**	**12894.95**
Grand totals	(Cost with time contingency)	**3378.98**	**3096.09**	**3136.99**	**2557.89**	**12169.95**

Table 3: 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

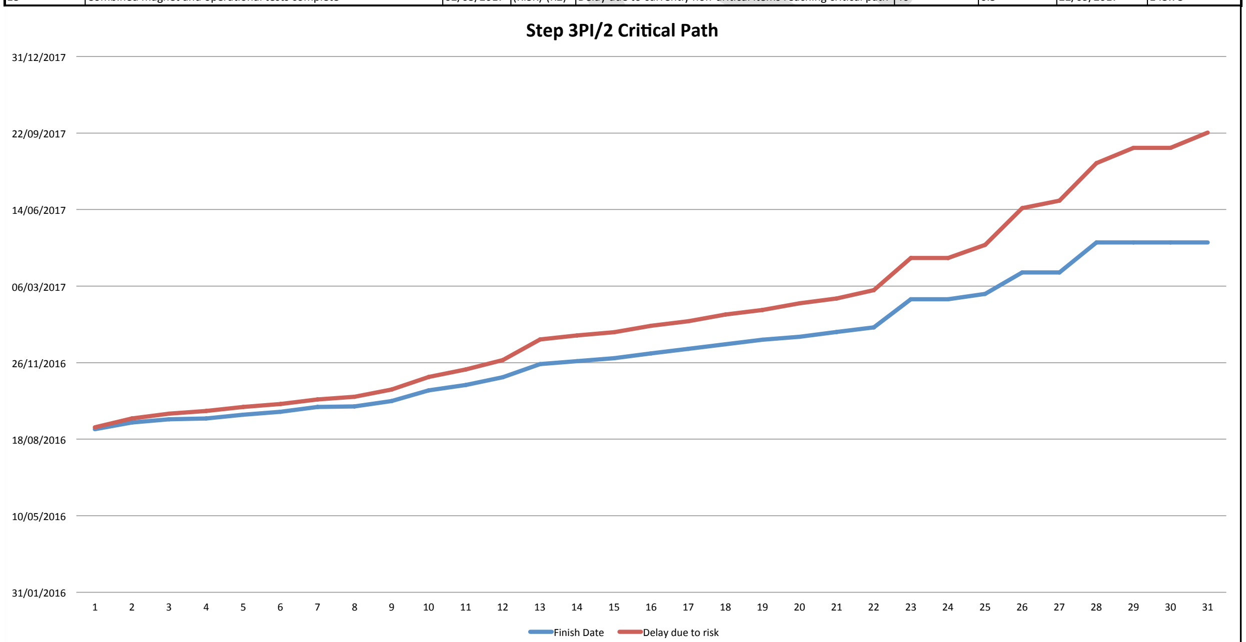

Figure 11: Critical path chart

Table 4: 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 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 plate 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 complete. 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 **6**), 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 **12**) is a very close approximation to what will be needed for MICE Step 3π/2.

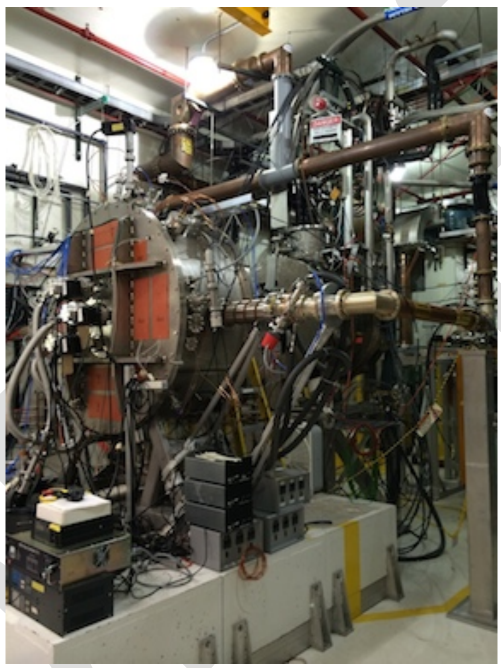

Figure 12: SCTS in the MTA

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 Budget Overview

In response to the May 2014 P5 Report and the August 2014 DOE Review, the US MAP program received DOE budgetary guidance to expect \$9M, \$6M, and \$3M in FY15, FY16, and FY17, respectively. US MAP 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. This new budgetary guidance maintains the operations of the MuCool Test Area (MTA) through the middle of FY16 to ensure its availability for the testing and characterization of the MICE RF components. In addition, these funds include support for US MICE Experimental Support through the end of FY17. 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 $3\pi/2$ PRY – March 2016
- RF Modules #1 and #2 – April 2016.

An R&D Risk of $537K (Risk Estimate × Probability of occurrence) is included in FY16. The total US MAP Budget for FY15 + FY16 + FY17 is under the three-year DOE guidance of $18M, but is ~2% above the FY15 guidance of $9M. A summary of the proposed US MAP Budget for FY15–17 is shown in Table **5**.

Table 5: US MAP Budget Summary for US FY15–17

New MAP Budget 12sept2014 - $ K	**FY15**	**FY16**	**FY17**	**Sum FY15-FY17**	**Comments**
1.01 Project Management	**1,115**	**774**	**148**	**2,037**	
1.02 Advanced μ & ν Sources	**2,173**			**2,173**	**end in FY15**
1.03 MuCool Test Area	**2,293**	**1,078**		**3,371**	**operate thru first half of FY16**
1.03.01 Facilities & Operations	1,292	627		1,919	**operate thru first half of FY16**
1.03.02 MICE Component Testing	300	124		424	**operate thru first half of FY16**
1.03.03 RF Cavities in Magnetic Field	701	328		1,029	**operate thru first half of FY16**
1.03.03.01 Vacuum RF Cavities	309	129		438	**operate thru first half of FY16**
1.03.03.02 High Pressure RF Cavities	392	199		591	**operate thru first half of FY16**
1.04 MICE Experimental Support	**1,070**	**1,093**	**1,176**	**3,339**	
1.05 MICE Construction	**2,547**	**1,881**	**888**	**5,316**	
1.05.01 RF Systems	1,365	904	270	2,539	
1.05.02 Magnet Systems	208			208	
1.05.03 Magnetic Shielding	656	330	101	1,087	
1.05.04 Detectors & LiH Absorbers	22	161	20	203	
1.05.05 US Component Integration	295	486	497	1,278	
total	**9,198**	**4,826**	**2,212**	**16,236**	**sum of 1.0x level estimates**
R&D RISK (Estimate x Probability)		**537**		**537**	**Expedited R4 - 13sept2014**
Grand Total	**9,198**	**5,363**	**2,212**	**16,773**	**slightly > goal in FY 15 but**
DOE IFP Guidance = goal	**9,000**	**6,000**	**3,000**	**18,000**	**< goal over FY15+16+17**

Does not assume or assign carry-over from FY14

US MICE Key Deliverables:	**Delivery at RAL**
Step IV PRY (complete)	**2-Mar-15**
Step 3π/2 PRY	**29-Mar-16**
RF Module #1 and #2	**26-Apr-16**

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, with an estimate of $10.4 M to mitigate or respond to a realized Risk. As a first order estimate, we assumed that only ½ of these Risks would be realized, so provided a Risk allowance of 50%*$10.4 M = $5.2 M. Since then, we added another Risk, and retired 10 of the Risks at an accrued cost of $973 K compared to a Risk estimate of $3.1 M, or 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 Risk Register for Step 3π/2 obtaining 9 identified risks with a total cost estimate of just over $1.6M (with a probability weighted impact of $537K). It is important to note that the risk ranking of the identified risks are generally in the low to moderate range with no severe risks remaining. The removal of the Coupling Coil Magnet (CCM) has removed the risks of cryostating, testing, and 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 PRY Step 3π/2 is only a 40% linear extension of the PRY Step IV and the design and installation plans and experience are of PRY IV are directly applicable to PRY 3π/2 with minimum risk. Moreover, the removal of the CCM means that the RF cavities will experience only the fields of the Absorber Focus Coil (AFC) magnets. The Single Cavity Test System SCTS, using the prototype 201 MHz RF cavities, couplers, actuators, etc., is currently operating in the MuCool Test Area (MTA), and will operate using the MTA magnet, which was the prototype for the AFC. Therefore the systems test with magnetic field of the SCTS at MTA will test a close approximation of the components and configuration (except without the PRY magnetic shielding of the couplers) as for the MICE production system and its operational conditions. The only difference between the SCTS and the production MICE RF Modules is in the vacuum end windows.

The updated active Risk Register for Step IV and Step 3π/2 is shown in Table **6**. 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. Step 3π/2 requires 12 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 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 **7**. 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 6: US MICE Active Risk Register (rotated for ease of viewing). 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 Risk Score				Estimated Cost of Mitigation				Estimated Mitigation Duration (Working Days)	Estimated Mitigation Probability (%)	Weighted Costs (K$)	Weighted Durations (Working Days)	Targeted Retirement Date	Status (Active / Retired)
ID	MAP WBS	Risk Description	Potential Impact on Project	L	I	L×I	Ownership	Proposed Action	L	I	L×I	Comment/Conclusion	SWF (K$)	M&S (K$)	OH (K$)	Total (K$)						
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 coupIders 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.	50	25	55.75	130.75	80	30%	39.23	24	4/16/2015	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.	25	50	36.5	111.5	40	30%	33.45	12	3/29/2017	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		10	0	10	20	40	10%	2.00	4	12/30/2014	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.	50	0	50	100	20	50%	50.00	10	4/14/2015	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		25	50	36.5	111.5	40	10%	11.15	4	3/29/2017	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.	150	75	167.25	392.25	80	30%	117.68	24	3/29/2017	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.	200	100	223	523	80	50%	261.50	40	8/3/2015	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.	25	50	36.5	111.5	80	10%	11.15	8	8/3/2015	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.	25	50	36.5	111.5	80	10%	11.15	8	3/29/2017	Active
												Totals for All Items (Active Risks Only)	560	400	652	1612			537.3	134		

Legend:

Symbol	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 7: 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 transverse 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 $3\pi/2$ 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 $3\pi/2$ 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 conclusion 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 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 comment from the members of the MICE collaboration through the time of the next MICE collaboration meeting (MICE CM40, October 26-29, 2104) 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 to successfully conclude the MICE ionization cooling demonstration, a recap is in order which summarizes the major choices, trade-offs, and potential areas for further discussion is in order.

In particular, the plan aims for a demonstration that is "good enough" 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 only differ 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.