A. Grant, K. Long, C. Rogers, P. Soler C. Whyte April 25, 2016

Response to suplemmentary questions

On Thursday the 21st April 2016 eleven questions were received from the STFC in preparation for the MICE-UK cost-to-completion review. Answers to each of these questions are given below.

1. **If the project was to go beyond Step IV (without demonstrating cooling) what effect would this have on the risks and how much contingency funds would be needed?**
   Should it prove to be impossible to proceed to the cooling demonstration, the collaboration will seek to maximise the physics output from the Step IV configuration. The full Step IV programme was presented in [1, 2].
   The reconfiguration of the MICE Hall necessary to mount the cooling demonstration is scheduled to start in January 2017. The plan for data taking at Step IV that can now be accommodated before the reconfiguration begins is summarised in table 1. Each of the configurations will deliver a data sample just sufficient to deliver the associated, priority-one Step IV measurement. For each configuration, a "cross" in emittance/momentum space will be sampled, thereby reducing the number of points at which the phase-space is sampled and allowing the programme to fit within the available time. The table indicates that there is little or no contingency in the time available for Step IV data taking.

Table 1: Data-taking plan for Step IV running. The decision to power the second match coil in the downstream solenoid will be made based on an operational readiness review that will include consideration of the relevant risks and benefits that operation of the coil implies.

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ISIS Run	Activity	Absorber	Days	Total days per run	Available days per run
2016/02	Setup	None	1		
	Beam commissioning	None	15		
	No absorber	None	21	37	32
2016/03	Setup	LH_2	1		
	Physics without M2D	LH_2	9		
	Physics with M2D?	LH_2	21		
	Physics with M2D?	Empty	21	52	45
2016/04	Setup	LiH	1		
	Physics without M2D	LiH	15		
	Physics with M2D?	LiH	21	31	31

The run plan for the full exploitation of Step IV [2] is summarised in table 2. The plan provides for a systematic study of the full momentum/emittance space using both LiH and LH_2 absorbers. The plan was conceived to maximise the physics delivered at Step IV. To execute this plan will require data taking through to October 2017. Additional measurements with a wedge absorber to study emittance exchange have also been discussed.

If it proves not to be possible to mount the cooling demonstration and an extended Step IV programme is executed to maximise the physics output of the experiment, the dominant risk to completing the programme would be a further failure of the downstream solenoid (SSD). Two possible failure modes of SSD have been identified: further breakdown causes the loss of match coil 2 and a catastrophic failure of the feed-through that connects the helium-space to the insulating-vacuum space rendering the whole magnet

Table 2: Summary of run plan for the full exploitation of Step IV should it prove not to be possible to recover the downstream solenoid.

Run type	Absorber	Focus coil mode	Beam polarity	Run time (days)	Total
Commissioning				33	33
Physics	Empty	Solenoid	+	15	
LH_2 fill				2	
Physics	LH_2		+	15	
Physics			-	3	
Open				3	38
Calibration/Setup			+	7	
Physics	Empty	Flip	+	15	
LH_2 fill				2	
Physics	LH_2		+	15	
Physics			-	3	
Open				3	45
Physics	LiH	Flip	+	15	
Physics			-	3	
Physics		Solenoid	+	15	33

inoperable. The project team has begun to explore possible routes to recovery should such a catastrophic failure occur. In the first instance, contact has been made with experts from CERN (R. Venness and J.P. Tock) each of whom was involved in the recent repair of 2200 LHC magnets. Initial indications are that a "surgical" intervention may be possible, though it carries a substantial risk. The extensive experience of our CERN colleagues leads them to believe that, subject to satisfactory test on a mock-up model, they may be able to assist in devising a recovery procedure. In this regard MICE's status as a "recognised experiment" may prove invaluable. Investigation of this option has not gone beyond an initial discussion, however, it is the project team's intention to work with the experts at CERN to investigate the feasibility of such an intervention. As a minimum a warm up and retraining of the SSD would be required; the cost of liquid helium for this procedure will be in the region of £50k and an additional two months of effort will be required.

2. **If further funds were invested into the project, how confident is the Collaboration that cooling will be demonstrated?**

   The collaboration has every confidence in its ability to deliver the demonstration of ionization cooling successfully:

   - The full diagnostic chain has been operated successfully on the MICE beam line and the hardware has been shown to meet or exceed specifications;
   - The focus-coil modules have each been operated successfully and shown to operate stably at currents 25% above those which are required in the cooling-demonstration lattice;
   - A prototype RF cavity has been successfully operated at Fermilab and the performance has been shown to exceed the performance required in the cooling demonstration;
   - The fabrication of the two single-cavity modules proceeds on schedule; and
   - The first high-power RF amplifier has been operated at the required power and tested in the MICE Hall. The assembly and test of the second module is advanced at the Daresbury Laboratory.

   In addition, the upstream spectrometer solenoid has been successfully operated at full current. Therefore, assuming the functionality of the downstream solenoid is recovered successfully, the performance of the

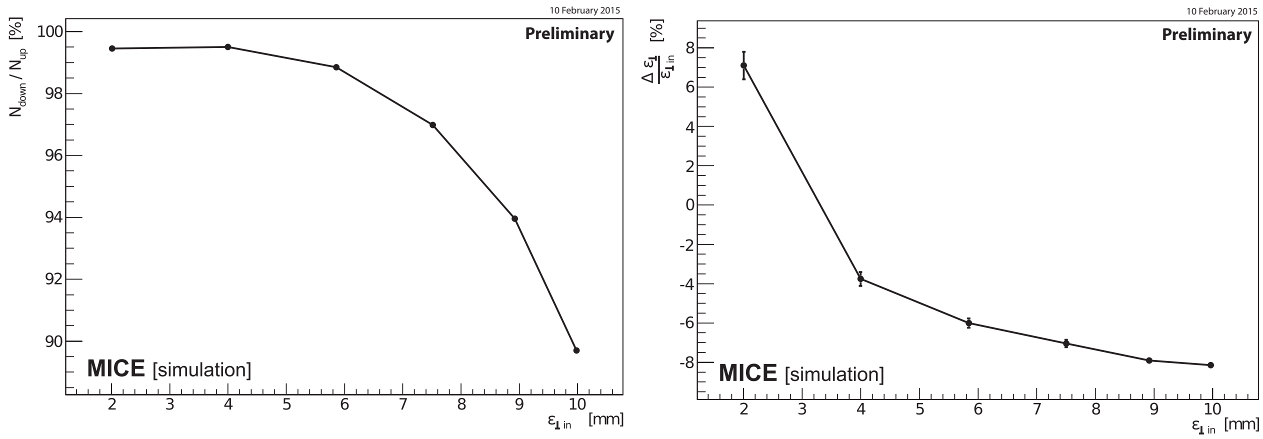

Figure 1: Transmission (left) and emittance reduction (right) as a function of input emittance for 200 MeV/c beams. The error bars correspond to $\sim$ 100k muons passing through the experiment.

hardware of the cooling demonstration will be that used in the Monte Carlo analysis of the performance of the experiment [3–7]. The cooling lattice has been extensively modelled and shown to have performance that significantly exceeds the precision with which the emittance-change measurement can be made. An example is shown in figure 1 where the transverse emittance and transmission of the cell is shown as a function of input emittance for a 200 MeV/c beam.

3. **If a new magnet is purchased, has the Collaboration considered the way forward if there are problems with the new magnet?**
The collaboration has considered two options for the procurement of the new magnet. If a full magnet is purchased then the responsibility for, and remedial action in the case of, "problems" will lie with the manufacturer. If the "cold-mass only" option is taken then the cold mass will arrive pre-tested and warrantied. It will then be necessary for the project team to build an expert team at the Rutherford Appleton Laboratory (RAL) to complete the cryostating. The project team will ensure that this team remains available until the magnet is fully integrated on the beam line. In this instance, any remedial action that may be required will be carried out by the RAL-based team. If neither of the above options resolves the "problems" we shall be forced to revert to consideration of the options that are presently being considered for the eventuality in which a replacement for SSD is not procured.
4. **What is the level of confidence that the new magnet will work and will not have any problems?**
The confidence level will be influenced by the method of procurement that is adopted. If a full magnet is purchased from one of the large, well-established manufacturers, one can have very high confidence in their ability to supply to specification and remediate in the unlikely event that any remediation is required. We now have access to magnet experts at RAL (J. Boehm, T. Bradshaw) with a deep knowledge of the superconducting-magnet market and able to provide informed opinion on supplier quality. We are also taking advice from colleagues at CERN and at other collaborating institutions to access their experience of international vendors. A cold-mass only option will necessarily carry higher risk. Assembling a team of industry experts in all the required disciplines for the cryostating is non-trivial. There is the additional complication that the design of SSD is not well aligned with state-of-the-art magnet-construction techniques. Industry experts are therefore unlikely to have direct experience of repairing magnets of this design.

5. **How will the UK ensure other deliverables within the project are still completed if the UK takes the lead on the new magnet?**

   The project schedule assumes completion of the single-cavity modules and the extension of the partial return yoke within the present US fiscal year (i.e. before September 2016). Our US colleagues current best estimate indicates that these items will be delivered with some time in hand. The associated costs, which fall within this US fiscal year, will be unaffected by any funds transfer.

   The additional work-load associated with the magnet procurement will be managed within the current resources, work on the focus coils is now largely complete, freeing resource to work on the SSD recovery. In the event that a cold-mass only procurement is chosen, contract effort will be retained to complete the expert team.

6. **Can the Collaboration explain why the US should not repair the damaged magnet?**

   The Resource Loaded Schedule Review (RLSR) panel and the MICE Project Board considered the options for the recovery of the downstream solenoid when they last met in April 2016. One of the Project Board's findings was:

   > *... that the total estimated cost (including contingency) of procuring a new magnet to replace SSD exceeds the funds available in the U.S.*

   Further, the Board recorded the action:

   > *STFC (RAL) should plan for the procurement of a new cold mass with an option for the supply of the enveloping cryostat. The vendor should be required to make the coil according to a detailed specification based on the knowledge of the previous magnets supplemented by any intervening studies. Report to STFC as soon as possible—about 6 months—in order to decide the course of action.*

   The collaboration's response to this action, and the other actions and recommendations from the recent review, may be found in [8].

   Preparations for the procurement of a replacement of SSD have been initiated. US manufacturers and US Laboratories will be invited to respond when the tender is issued.

7. **Can the Collaboration think about any possible descopes, for example, what would be the measure of success if:**

   (a) **there is only one RF system;**

   The collaboration has performed a first study of the effect of using only one RF-amplifier system to power both cavities. To first approximation this would reduce the available RF voltage by a factor $1/\sqrt{2}$. The mean energy recovered will be reduced from 6.6 MeV to 4.7 MeV, compared to the mean energy loss in the primary absorber of around 11 MeV. The RMS transverse emittance reduction (cooling) is reduced from 5.8% in the two-amplifier configuration to 4.8%. The resulting emittance reduction is shown as a function of position along the axis of the experiment in figure 2.

   (b) **stopping at Step IV and not demonstrating cooling;**

   The principal scientific deliverables of Step IV and the cooling demonstration are summarised in table 3 [5]. While it will be possible to complete the deliverables of Step IV, ionization cooling, which requires re-acceleration, will not have been demonstrated.

   (c) **having only one RF system and one magnet?**

   The absence of a magnet is considerably more detrimental to the experimental performance of the cooling demonstration than the loss of one RF amplifier. The cooling performance of the lattice is crucially dependent on the focusing performance of the MICE magnets.

   If SSD is not recovered, the collaboration will attempt to operate the cooling demonstration with SSD in the design position, without one or both downstream match coil(s). In order to mitigate the poor optical performance in the match-coil region, the collaboration will consider additional

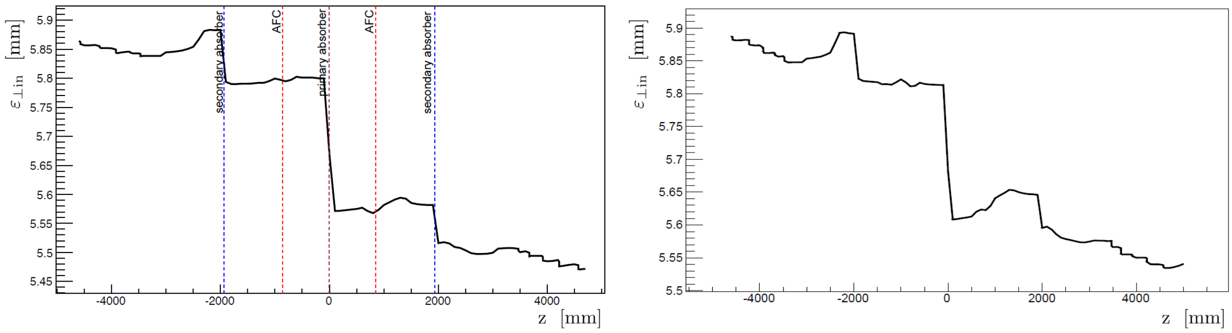

Figure 2: Emittance reduction with (left) two high-power RF amplifier (baseline condition) and (right) with only one RF amplifier available.

Table 3: MICE physics programme [5]. $\varepsilon_\perp^n$ denotes the normalised transverse emittance while $\varepsilon_\perp$ and $\varepsilon_{//}$ denote the transverse and longitudinal emittance respectively. The elements of the Step IV and cooling-demonstration programmes are listed in priority order.

Step IV:
Material properties of LH_2 and LiH that determine the ionization-cooling performance Observation of $\varepsilon_\perp^n$ reduction
MICE demonstration of ionization cooling:
Observation of $\varepsilon_\perp$ reduction with re-acceleration Observation of $\varepsilon_\perp$ reduction and $\varepsilon_{//}$ evolution Observation of $\varepsilon_\perp$ reduction and and angular momentum evolution

tracker stations upstream of the match coils, allowing the measurement of tracks upstream of the match coils. The transmission of such an arrangement will be relatively poor, an effect that is almost certain substantially to increase the systematic uncertainties of the measurement. Further studies will be required to demonstrate the feasibility of such an arrangement.

Two options have been identified in the event that a second spectrometer solenoid is not available beyond Step IV (see figure 3):

- An arrangement has been envisaged that would use the excellent reconstruction capabilities of the EMR detector to measure particle range and hence absolute momentum, together with tracker stations around the downstream focus coil that would measure particle position and angle. The aperture of the tracker is narrower than that of the focus-coil module, while the beam radius can be relatively large in this region; i.e. it may be that the beam envelope is larger than the acceptance of the tracker stations. Such an arrangement may prevent installation of the downstream RF cavity due to geometrical constraints and concerns of radiation damage to the downstream detectors. The overall resolution achieved in the downstream region would need to be studied; and
- In extremis, it may be possible to make some measurements using only the downstream tracker. The spectrometer solenoid that is presently upstream of the cooling cell would be placed downstream of the cooling cell. The emittance-reduction measurement would be achieved by comparing the beam emittance measured in the tracker with and without an absorber. Such an arrangement would require stability of the MICE Muon Beam on a timescale sufficient to permit emptying and filling of the absorber to enable the difference measurement. As sampling of the

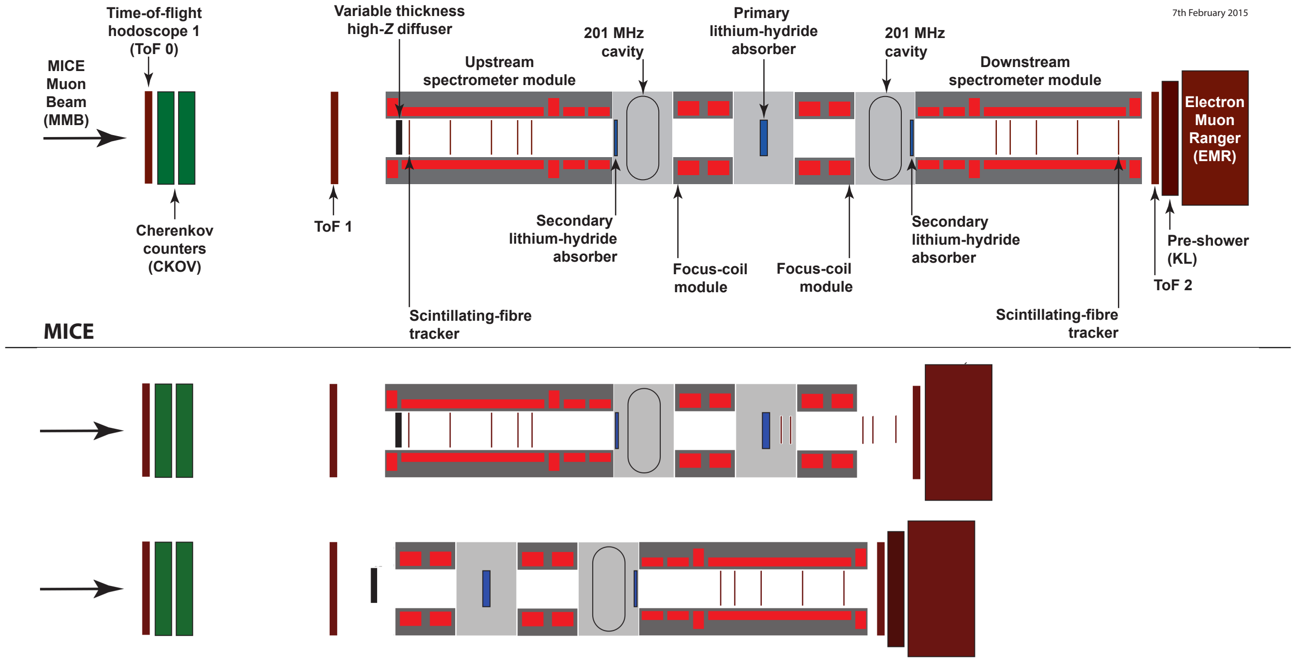

Figure 3: Top: schematic diagram of the cooling-demonstration configuration. Centre and bottom: schematics of the descope options discussed in the text that may be considered in the event that the downstream solenoid is not available.

beam upstream of the cooling apparatus is not possible, a very good match must be achieved between the MICE Muon Beam and the cooling channel.

The feasibility of the arrangements outlined above has not yet been demonstrated and the configurations have yet to be studied in detail.

8. **If the project has a maximum of £10M over the same time-frame, what would this mean and what would be descoped?**

An initial analysis has been carried out seeking a scenario by which damage to the scientific programme is minimised if the allocation is reduced below the flat-cash scenario that will be presented to the review committee. The result, summarised in table 4, should be regarded as a working model; further study will be required to determine the distribution of cuts that minimises damage to the scientific output of the programme.

To deliver the project within an allocation of £10M would require to descope to a single high-power RF-amplifier system and make significant further reductions in staff effort as listed below:

- Remove the ISIS support that has recently been brought into the project in financial years 2018/19 and 2019/20 (a reduction of $\sim$ 3 FTEs in Work Package 10, Operations and Analysis);
- Reduce PPD support for the duration of the project (a reduction of 1.75 FTEs in Work Package 10); and
- Cut two post-docs from the Operations and Analysis Work Package (a reduction of 8 FTEs over the course of the project).

The result of these cuts would be to decrease substantially the flexibility and resilience of the operations activity and to reduce the effectiveness of the UK's analysis activity. Such cuts will put the smooth operation of the experiment at risk and substantially reduce the ability of the UK to take the lead in delivering physics from the experiment.

Table 4: Summary of the cost profile per work package for a scenario in which the total allocation is reduced to £10M

	Work package	2016/17	2017/18	2018/19	2019/20	Total
Total staff and non-staff by work package						
MICE-UK						
1	Project management and project office	519.95	585.87	399.59	26.20	1531.62
2	Mechanical integration	250.50	345.36	258.51	47.96	902.33
3	Electrical Integration	264.91	256.82	206.08	69.19	796.99
4	Focus Coil	199.52	186.20	163.33	51.54	600.59
5	Hydrogn Delivery System	62.34				62.34
6	RF power	457.87	375.36	292.79	82.14	1208.17
7	Vacuum	98.01	62.59	40.24	5.92	206.76
8	Magnetic Mitigation	66.32	11.49	5.83		83.65
9	Software and computing	340.02	389.42	380.04	385.74	1495.22
10	Operations and analysis	770.15	890.73	863.70	659.44	3184.01
	Sub-totals	*3029.58*	*3103.84*	*2610.11*	*1328.13*	*10071.66*
MICE-UK	**Cost of risk mitigation**	**130.00**	**180.00**			**310**
	% above allocation	-6%	-4%	-19%	-61%	

9. **As the amount of money the US could transfer to the UK is currently unclear, can you provide some scenarios on the way forward depending on how much money is transferred from the US?**

   We are preparing costings for two magnet-recovery options. It seems likely that, before the cost of risk mitigation is taken into account, the cold-mass-only option will not be as expensive as the procurement of a full magnet. An initial assessment of the risks associated with the cold-mass-only option are included in the latest revision of the Risk Register. The cold-mass-only option may therefore be favoured if the resources transferred from the US fall short of the cost of the procurement of a full magnet. Were more money to be available, a full magnet procurement is of lower risk and is therefore preferred. It seems possible that, if executed from RAL, the cost of this option lies within the US budget for US fiscal year 2016/17.

10. **If there are any other failures will it curtail the experiment?**

    Depending on the specific failure, the resilience of the experiment may allow recovery. Currently only the failure of a large piece of equipment would test the project team. For example, we have recently recovered the failure of the Decay Solenoid power supply on time and on budget. Were the upstream solenoid (SSU) to fail, we might still hope to recover it, leveraging the work done to date on the SSD recovery—see below.

11. **What would be the impact if the other spectrometer solenoid should break/fail?**

    An upgrade to the quench-detection and quench-protection systems for the spectrometer solenoids is presently being installed. This system is designed to avoid a recurrence of the events that led to the failure of match coil 1 in the downstream solenoid. The system also provides a maximum of protection for both the upstream and the downstream solenoids.

    If, despite these precautions, a failure of SSU were to occur, the recovery options would be the same or similar to those presently being considered for SSD. Depending on the timing of any problems we might hope to have SSD available as a source of spares or an expert team in place to effect the required repairs. For this reason, if a replacement magnet is bought, the project team will consider an immediate autopsy on SSD to determine the cause of the failure and possibly to prepare the cold mass of SSD as a potential recovery route for SSU. In the response to 1 above, we outlined our work with CERN to investigate "surgical" recovery options—these options would be relevant to any SSU failure.

References

[1] The MICE Executive Board, "Actions and recommendations from the Resource Loaded Schedule Review panel and the MICE Project Board." http://micewww.pp.rl.ac.uk/attachments/2888/2014-11-10-ResponseToFeedback.pdf, 2014.

[2] S. Boyd and V. Blackmore, "MICE Step IV Commissioning and Operations Plan." http://micewww.pp.rl.ac.uk/documents/106, 2014.

[3] V. Blackmore *et al.*, "The MICE Demonstration of Ionisation Cooling: Technical Note." http://mice.iit.edu/micenotes/public/pdf/MICE452/MICE0452.pdf, 2014.

[4] MICE Executive Board, "MICE report to the MICE Project Board." http://micewww.pp.rl.ac.uk/documents/134, 2015.

[5] MICE Executive Board, "MICE report to the MICE Project Board." http://micewww.pp.rl.ac.uk/documents/159, 2015.

[6] K. Long *et al.*, "Review of the MICE beam-dynamics analysis, January 2016." http://micewww.pp.rl.ac.uk/projects/governance/wiki/2016-01-14-15-OpticsReview, 2015.

[7] MICE Executive Board, "MICE report to the MICE Project Board." http://micewww.pp.rl.ac.uk/documents/172, 2016.

[8] MICE Executive Board, "Response to feedback from the RLSR panel and the MPB." http://micewww.pp.rl.ac.uk/documents/176, 2016.