To: C. Jamieson (Programme Manager, STFC) May 18, 2016

From: K. Long (MICE spokesman), C. Whyte (MICE Project Manager) Final

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Progress in redefining the scope of the MICE cooling demonstration

Summary

Recent reviews of MICE have found that the collaboration has made strides in the publication of results and the execution of Step IV. The scientific importance of the Step IV programme and the seminal nature of the demonstration of ionization cooling continues to be recognised. The MICE-UK Cost to Completion (CtC) Review panel recommended that Step IV be executed. The panel did not recommend that the collaboration pursue the procurement necessary to recover the full functionality of the downstream solenoid, but recommended that the collaboration be asked to bring forward a proposal for a descoped cooling demonstration that minimises risk and substantially reduces the cost of the programme to the STFC.

Following the CtC review, work began to seek to define the minimum viable programme by which a quantitatively-compelling demonstration of ionization cooling could be delivered. Options that require one solenoid only have been considered as well as options that require both solenoids. One advantage of the single-solenoid options is that the cooling cell and the spectrometer solenoid can be accommodated within the Partial Return Yoke already installed for Step IV. This substantially reduces the cost, complexity and risk of the reconfiguration of the MICE Hall required to mount the cooling demonstration. The necessary compromise in the precision with which the muon momentum is measured results in an increase in the uncertainty on the emittance-reduction measurement. Initial studies of the performance of the single-solenoid options indicates that the emittance-change uncertainty will increase by a factor of $\lesssim \sqrt{2}$; i.e. a quantitatively-compelling measurement of ionization cooling can be made.

One of the single-solenoid options (option "A") was studied to obtain an indicative estimate of the cost, schedule and risks associated with the implementation of one of the descoped configurations. The initial analysis shows data-taking for physics in the cooling-demonstration configuration starting in March 2018 allowing a substantial period of data taking before the ISIS long shutdown. The incremental cost to the STFC of the programme, including data taking and analysis, is estimated to be £3.6M over the three financial years 2016/17 to 2018/19.

1 Context

Over the past six to eight weeks the MICE project has been reviewed by national[1] and international[2] panels. Each of the review panels concluded that:

- The collaboration had made strides in the commissioning and operation of Step IV, the preparation of its software and analysis frameworks and in the publication of its results;
- The Step IV science programme was important and must be completed, including operation with both LiH and LH_2; and that
- The cooling demonstration was important and should be completed.

With the Step IV measurement programme underway, the reviews also considered the plans put forward for the recovery of the full functionality of the downstream solenoid. The report of the MICE Project Board included the action that:

> *"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.*

Work started on the plan for the necessary procurement immediately. By the time of the STFC MICE-UK Cost to Completion (CtC) review (26^{th} April 2016) significant progress had been made and a large portion of the data necessary to launch an EU-wide tender in the Official Journal of the European Union had been entered in the UK SBS "Emptoris" data base.

The MICE-UK CtC review panel considered the schedule, financial and reputational risks associated with the procurement required to recover the downstream solenoid too large for them to recommend that STFC allow the collaboration to continue with the procurement. The CtC review panel therefore recommended:

- The full exploitation of the present (Step IV) configuration of the experiment; and
- That the collaboration be asked to bring forward a proposal for a descoped cooling demonstration that has a cost to STFC significantly below the flat-cash programme presented at the CtC review and that allows data taking in the descoped cooling-demonstration configuration before the next long ISIS shutdown. The date of the shutdown is not known, but, it is likely to be around 2019.

To maximise the scientific output from the investment of the STFC and its international partners, Step IV running will be extended to August 2017 if a descoped cooling demonstration does not go forward. The full exploitation of Step IV, including the extended running period, is now referred to as the "core" programme. The CtC review panel recommended that the collaboration be asked to submit a proposal for a descoped cooling-demonstration experiment within three months.

2 Cost of the core (extended Step IV) programme

The cost to the STFC of the extended Step IV programme (the core programme) over the four financial years 2016/17 to 2019/20 is estimated to be £4.9M. The core programme includes the extension of data taking in the Step IV configuration to August 2017, the analysis of the data and the preparation of the results for publication.

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[1] The MICE-UK Oversight Committee, 21^{st} March 2016.

[2] The MICE Project Board, 5^{th}–6^{th} April 2016, and the Resource Loaded Schedule Review, 5^{th} April 2016.

3 Descoped demonstration of ionization cooling

In line with the recommendations of the CtC panel, the collaboration has sought to identify the minimum viable programme that will deliver a quantitatively-compelling demonstration of ionization cooling. Configurations that use both spectrometer solenoids have been examined as have solutions that use only one solenoid. In each case solutions have been found that allow the cooling demonstration to proceed with construction completing late in calendar 2017 and with commissioning completing in time for data-taking to begin in the first ISIS User Cycle of 2018. Were one of the two-solenoid options to be adopted, there would be additional complication in that floor cutting and drilling operations as well as modifications to the structure of the south mezzanine would be required. This, coupled with the risks associated with operating with a critical component, the downstream solenoid, that is known to be damaged, mitigates against the two-solenoid options. Therefore, the paragraphs that follow will focus on the options that require only one spectrometer solenoid.

Two cost-effective, low-risk single-solenoid options have been identified that:

1. Decrease the risk and complexity of the reconfiguration of the MICE Hall necessary to mount the cooling demonstration;
2. Allow a significant data taking programme to be carried out before the next long ISIS shutdown (2019); and
3. Make best use of the equipment that has been supplied or is in production so as to maximise the return on the investment of the STFC and its international partners.

The two options, sketched in figure 1, differ principally in the position of the spectrometer solenoid. With the tracker upstream of the cooling cell (option A), the beam can be matched into the cell. With the spectrometer solenoid placed downstream of the cooling cell (option B), the beam can be matched into the tracking volume with the aim of ensuring good capture of the beam into the downstream instrumentation. The five planar scintillating-fibre stations from the unused spectrometer may be used to measure the beam emerging from the cooling cell (option A) or to improve the instrumentation of the beam line upstream of the experiment (option B).

Initial consideration of the layout of the experiment in the Hall (see figure 2) shows that the cooling cell and the single spectrometer-solenoid module fits within the existing Partial Return Yoke (PRY). This means that the work required to go from Step IV to the descoped cooling-demonstration configuration is minimised.

3.1 Initial study of performance

The performance of both option A and option B is being evaluated using the collaboration's simulation and reconstruction software. As an example, figure 3 shows the estimated emittance reduction for option A. An emittance reduction of $\sim 8\%$ is observed for an input emittance of 7.9 mm. This is to be compared with an emittance reduction of 7% for a beam of similar input emittance in the baseline configuration. The reduced acceptance of the downstream instrumentation in the descoped configuration causes a reduction in the transmission of the channel (the fraction of particles accepted by the instrumentation downstream of the cooling cell) from 91% in the baseline configuration to 85% in the descoped configuration. The study of the systematic uncertainty associated with transmission losses has been initiated. Given the modest decrease in transmission in going from the baseline to the descoped configuration, careful study of the beam dynamics and scraping within the experiment will allow the systematic uncertainty to be reduced to an acceptable level.

In option A, the performance of the instrumentation downstream of the cooling cell is compromised, while the performance of the upstream instrumentation is unchanged. Initial estimates of the resolution of the instrumentation downstream of the cooling cell indicates that the uncertainty in transverse and longitudinal momentum

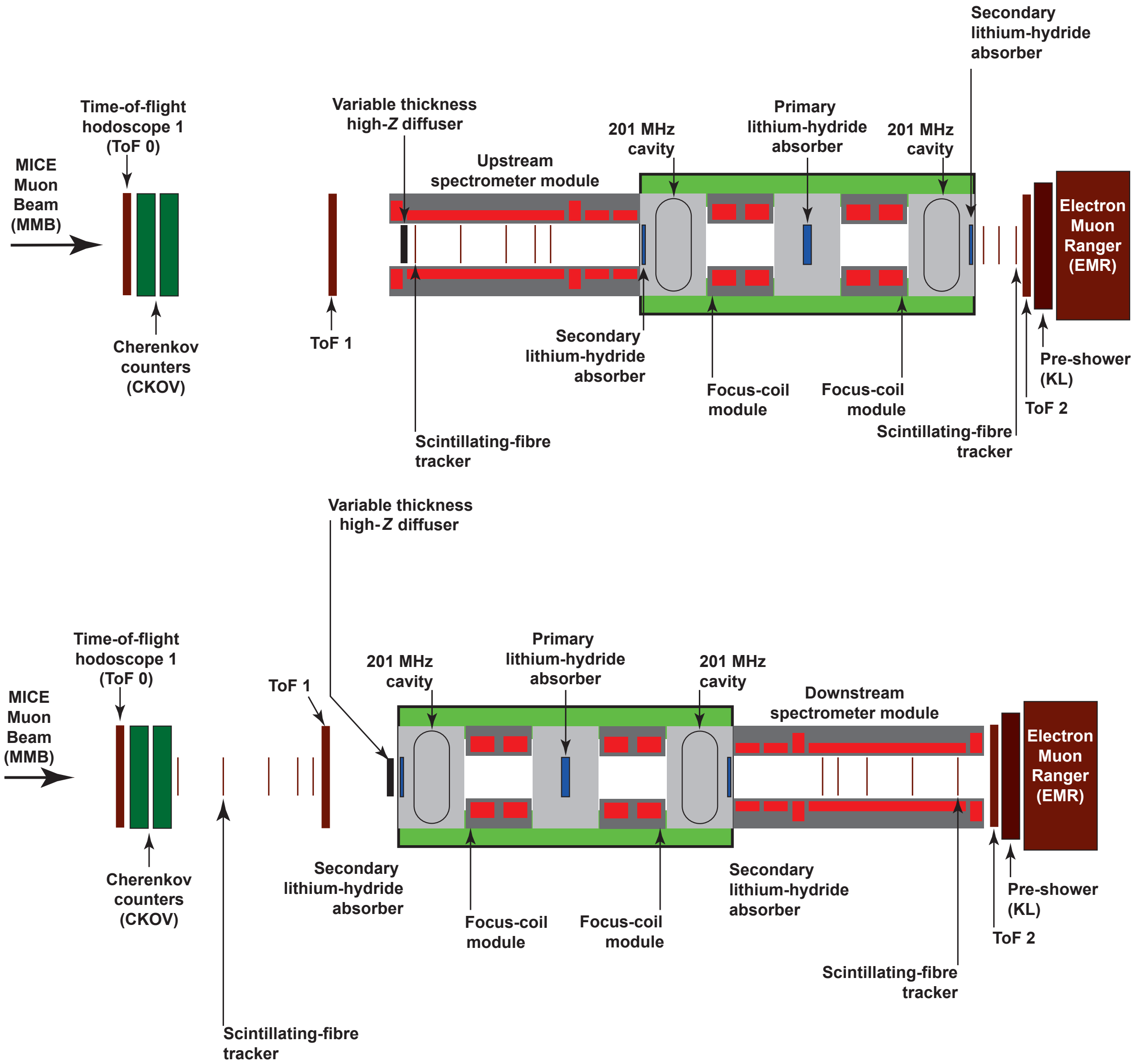

Figure 1: Schematics of configurations prepared to meet the constraints imposed by the reviews of the project in March and April 2016. Top: spectrometer solenoid placed upstream of the cooling cell. Bottom: spectrometer solenoid placed downstream of the cooling cell. In each case the cooling cell is highlighted in green.

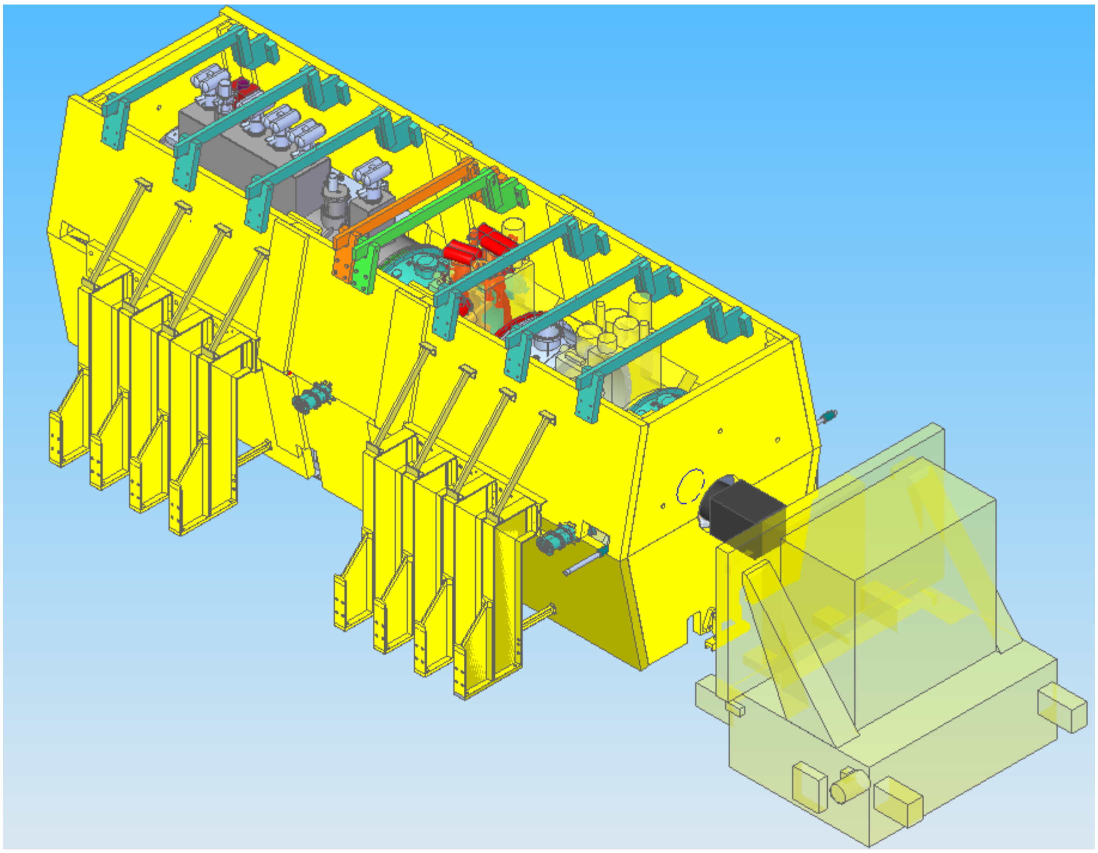

Figure 2: Layout of the descoped cooling-demonstration configuration (option A) in the MICE Hall. The figure shows the Partial Return Yoke (PRY) in yellow surrounding the cooling cell (two single-cavity modules, two focus-coil modules, primary and secondary absorbers) and the single spectrometer solenoid module. The down stream instrumentation is also shown.

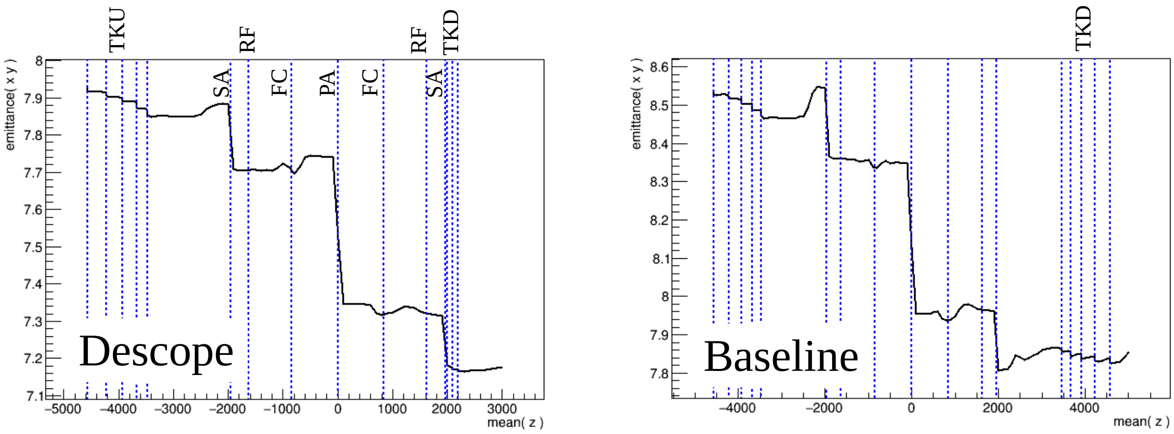

Figure 3: Left: cooling performance of the descoped demonstration of ionization cooling experiment. Right: cooling performance of the baseline cooling demonstration experiment. The vertical lines indicate the postion of components of the experiment: upstream tracker (TKU), secondary absorbers (SAs), RF cavities (RF), focus-coil modules (FC), principal absorber (PA) and downstream tracker (TKD).

is increased by a factor of ~ 1.4 and ~ 1 respectively. MICE plans to take data such that the statistical uncertainty on the relative change in emittance for a particular setting is 1%. The spectrometers were designed such that the track-reconstruction uncertainty would contribute at the $\sim 0.3\%$ level to an emittance-change measurement with a statistical precision of 1%; i.e. for such a measurement, the track-reconstruction uncertainty would be negligible. Detailed studies are underway, but, the initial studies presented here indicate that the track-reconstruction uncertainty for the downstream instrumentation in option A will now make a contribution less than or comparable to the 1% statistical uncertainty on the emittance-change measurement; this would result in an increase of only a factor $\lesssim \sqrt{2}$ in the emittance-change uncertainty. The study of option B is not as advanced as that of option A, however, similar conclusions are expected to hold. The initial indications are, therefore, that a quantitatively-compelling measurement of ionization cooling can be made with the descoped experiment. This would be the seminal measurement that the collaboration has been working towards.

3.2 Risk management

The decision not to recover the downstream solenoid has removed the principal risk of further delay and cost overrun. The re-use of the Step IV PRY implies that it is no longer necessary to modify the South Mezzanine, remove part of the concrete ramp adjacent to the south shield wall, move existing, and install new, PRY support legs and reconfigure the false floor; i.e. the reconfiguration project has been substantially simplified and streamlined. The work required to reconfigure the scintillating-fibre tracker is modest and well within the capability of the Tracker Group.

All magnets that will be used in the descoped cooling demonstration have been operated at full current in isolation. In the course of Step IV operation, experience will be gained in the combined operation of the magnets. This experience, together with the fact that the inter-magnet coupling in the cooling demonstration is lower than in Step IV, serves to mitigate the risk of unexpected behaviour of the magnets in the magnetic channel of the cooling demonstration.

A full re-analysis of the project risk register is underway. It is anticipated that the principal risks to the cooling-demonstration-construction project will relate to the installation, commissioning and subsequent operation of the RF system. These risks are mitigated by the fact that the first amplifier system has been operated in the MICE Hall and a second system has delivered 1 MW into a resistive load in a test rig at the Daresbury Laboratory. Integration of the single RF-amplifier system to be used in the descoped cooling demonstration with the single-cell cavities is scheduled to take place well before the systems are required. Commissioning and operation of the RF system will be supported by the experienced ASTeC RF-engineering team from DL and the US team that has successfully commissioned and operated the prototype of the MICE 201 MHz cavity in the MuCOOL Test Area (MTA) at FNAL.

In operation, the availability and maintainability of the experiment will benefit from the use as spares of the magnet power- and cryo-system components already commissioned for the failed spectrometer solenoid. The components purchased to build up the second RF-amplifier chain will also be kept as spares, further improving the availability and maintainability of the cooling demonstration.

3.3 Initial evaluation of the schedule for the implementation of the descoped cooling demonstration

To give an early indication of the cost and schedule for the implementation of one of the descope options outlined above, an initial project plan has been developed (see figure 4). Following the CtC recommendation not to recover the downstream solenoid allows the integration of the cooling-demonstration experiment to be

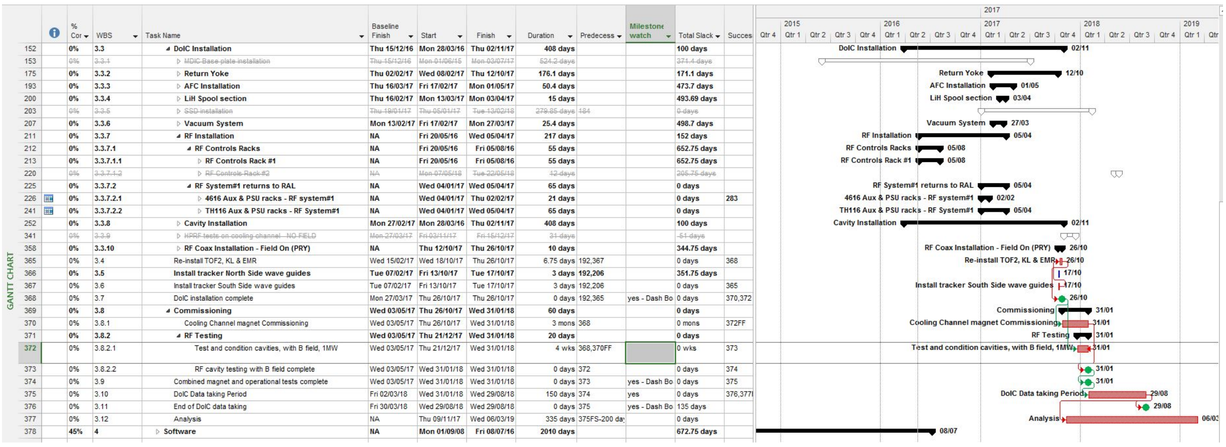

Figure 4: Gantt chart showing the major steps in the initial analysis of the descoped cooling-demonstration programme described in the text.

advanced by approximately 18 months. The critical path runs through the installation and commissioning of the RF system in the MICE Hall. The efforts made during financial year 2015/16 to strengthen the RF team will be of substantial benefit in executing the necessary programme.

Currently it is planned that Step IV will run until the end of 2016. There is some indication that this could be delayed until after the first ISIS User Cycle in 2017 (mid-February to end March) without delaying the completion of the descoped cooling-demonstration experiment. Taking this option would move the installation closer to the critical path but would have the benefit of allowing additional Step IV data to be taken. The benefit of an additional User Cycle in the Step IV configuration needs to be weighed against the increased pressure on the cooling-demonstration-integration timetable. At the present level of analysis of the schedule it appears that there is sufficient slack in the schedule to make the additional data-taking attractive.

There is significant engineering required to integrate the cooling cell within the Step IV PRY and to ensure all inter-magnet forces are appropriately controlled; the additional time provided by delaying the end of Step IV data-taking may usefully be applied to this problem. This decision does not need to be made at this point but can be resolved in the next few months once a broader understanding of the best solutions to the interface engineering have been developed.

3.4 Initial estimate of the cost of the descoped cooling demonstration

An initial estimate of the cost of delivering the demonstration of ionization cooling has been derived from the schedule presented in section 3.3 and is shown in table 1. The table shows that the seminal demonstration of ionization cooling can be delivered for a modest additional investment of £3.6M.

Table 1: The cost of the carrying out the descoped cooling-demonstration programme described in the text. The cost of mitigation of the risks to the programme is included in the totals.

(£k)	**2016/17**	**2017/18**	**2018/19**	**2019/20**	**Total**
Incremental cost above the core programme	480.5	1498.1	1643.9	0.0	3622.42

4 International perspective

The demonstration of ionization cooling remains the seminal measurement that is required to unlock the potential of high-brightness muon beams for particle physics. The work carried out in the short time since the CtC panel met indicates that there is a cost-effective, low-risk programme by which a quantitatively-compelling demonstration of ionization cooling can be delivered with equipment that is already available or that is already being manufactured.

Seeking to deliver the seminal demonstration of ionization cooling in this manner will maximise the scientific return on the substantial investments made in MICE by the STFC and its international partners.