
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.

Ionization cooling is achieved by reducing the muon-beam energy by passing it through an “absorber”, thereby decreasing the momentum parallel and perpendicular to the beam axis in equal proportions, and restoring the lost longitudinal momentum using RF cavities. The net effect of the energy-loss and acceleration processes is to reduce the volume of phase space occupied by the beam. The demonstration of ionization cooling therefore requires the beam to be accelerated.

Step IV is optimised for the study of the material properties that determine the ionization-cooling effect. It is only with the acceleration provided by the RF cavities in the cooling-demonstration configuration that ionization cooling can be achieved. The minimum-viable programme outlined in this note can demonstrate ionization cooling, albeit with a compromise in the precision with which the emittance reduction can be measured. The proposed descoped experiment is therefore a cost-effective means of delivering the principal scientific aims of the MICE collaboration.

1 Context

Over the past six to eight weeks the MICE project has been reviewed by national¹ and international² 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 lithium-hydride and liquid-hydrogen absorbers; 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 (26th 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 procurement necessary to recover the downstream solenoid was not recommended by the MICE-UK CtC review panel as it considered the schedule, financial and reputational risks to be too large. 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 the 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 £5.1M. 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.

¹The MICE-UK Oversight Committee, 21st March 2016.

²The MICE Project Board, 5th–6th April 2016, and the Resource Loaded Schedule Review, 5th 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 existing 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.

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 momentum is increased by a factor of ~ 1.4 and the uncertainty in the longitudinal momentum is unchanged. 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

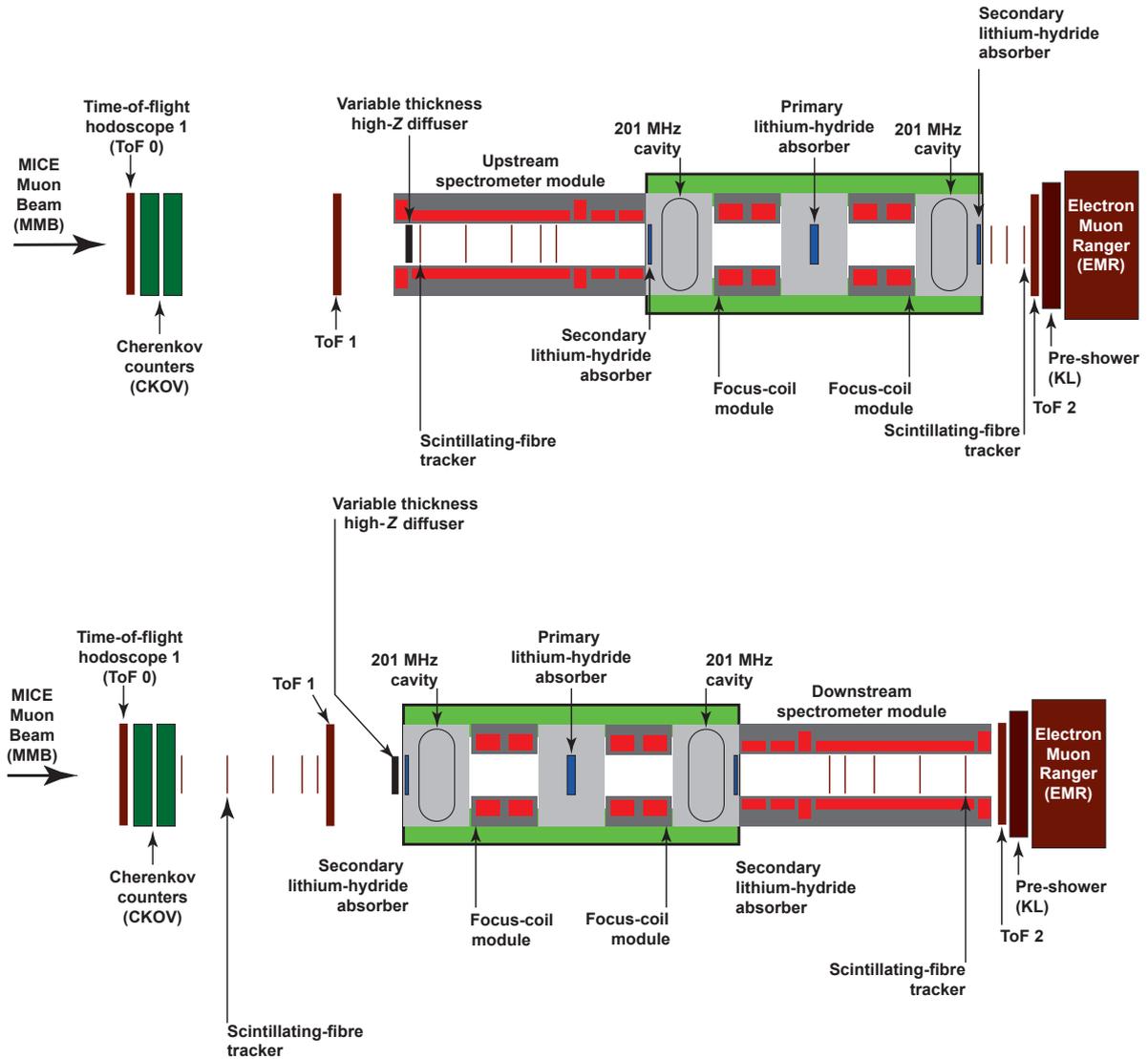


Figure 1: Schematics of configurations prepared to meet the constraints imposed by the reviews of the project in March and April 2016. Top: spectrometer solenoid placed upstream of the cooling cell. Bottom: spectrometer solenoid placed downstream of the cooling cell. In each case the cooling cell is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

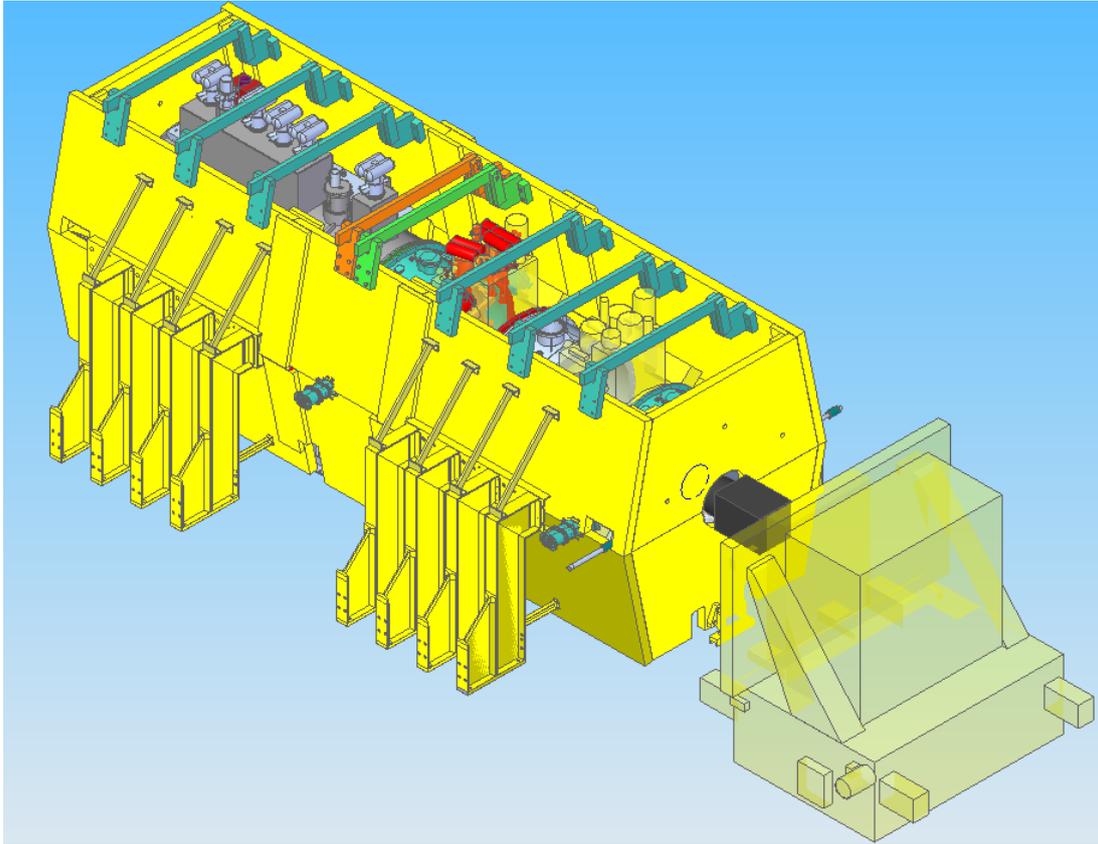


Figure 2: Layout of the descope cooling-demonstration configuration (option A) in the MICE Hall. The figure shows the Partial Return Yoke (PRY) in yellow surrounding the cooling cell (two single-cavity modules, two focus-coil modules, primary and secondary absorbers) and the single spectrometer solenoid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

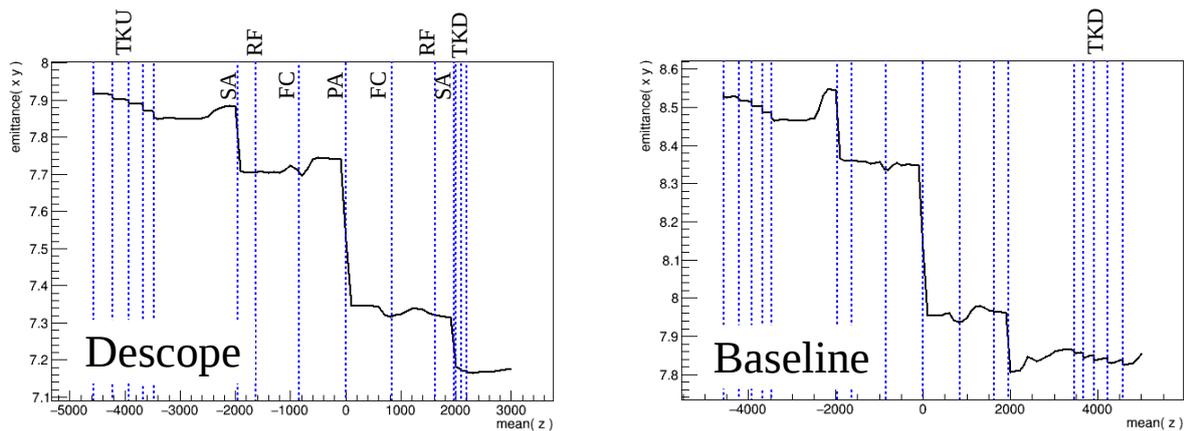


Figure 3: Left: cooling performance of the descope demonstration of ionization cooling experiment. Right: cooling performance of the baseline cooling demonstration experiment. The vertical lines indicate the position of components of the experiment: upstream tracker (TKU), secondary absorbers (SAs),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

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 (DL). 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 Fermilab.

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. Following the CtC recommendation not to recover the downstream solenoid allows the integration of the cooling-demonstration experiment to be 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. The initial analysis shows that the descoped experiment will be

ready for data-taking in March 2018, thereby allowing a significant period of data-taking before the long ISIS shutdown in 2019.

3.4 Initial estimate of the cost of the descoped cooling demonstration

An initial estimate of the cost to the STFC of delivering the demonstration of ionization cooling has been derived from the schedule outlined in section 3.3 and is shown in table 1. The cost of mitigating the risks associated with mounting the cooling demonstration are included in the figures. For comparison, the cost of the core programme, in which Step IV is operated until August 2017, is also shown. 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 carrying out the descoped cooling-demonstration programme described in the text is presented in the row labelled “Incremental cost of delivering the cooling demonstration”. The cost of mitigation of the risks to the programme is included in the totals. The cost of the core programme (i.e. the extended operation of Step IV) is shown for comparison in the row labelled “Core programme”.

(£k)	2016/17	2017/18	2018/19	2019/20	Total
Core programme (operation of Step IV to August 2017)	2797.0	1754.2	389.5	149.3	5089.0
Incremental cost of delivering the cooling demonstration	480.5	1498.1	1643.9	0.0	3622.4
Total	3277.5	3252.3	2033.4	149.3	8711.4

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.

Ionization cooling is achieved by reducing the muon-beam energy by passing it through an “absorber”, thereby decreasing the momentum parallel and perpendicular to the beam axis in equal proportions, and restoring the lost longitudinal momentum using RF cavities. The demonstration of ionization cooling therefore requires the beam to be accelerated.

Step IV is optimised for the study of the material properties that determine the ionization-cooling effect. It is only through the acceleration provided by the RF cavities in the cooling demonstration that ionization cooling can be achieved. The minimum-viable programme outlined in this note can deliver a quantitatively-compelling demonstration of ionization cooling, albeit with a compromise in the precision with which the emittance reduction can be measured. The proposed descoped experiment is therefore a cost-effective means of achieving the principal scientific objective of the MICE collaboration; the demonstration of ionization cooling. Delivering 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.