MICE bimonthly project update $\sharp$6

1 Introduction

This, the sixth bimonthly progress report, presents the status of the project at the end of July 2016. The updated project dashboard may be found at `http://micewww.pp.rl.ac.uk/dashboard/`. The response to the feedback from the MICE Project Board (MPB) and the Resource Loaded Schedule Review (RLSR) panel may be found at [1].

The highlights of progress over the past three months include:

Commissioning: The MICE Muon Beam is in routine operation and all the MICE instrumentation has been recommissioned and is routinely used for data taking.

A Magnet Readiness Review, chaired by O. Kirichek (RAL/ISIS), took place on the 28th June 2016 [2]. The review concluded that the magnet system, including the upgraded quench-detection/quench-protection system for the spectrometer solenoids was ready for operation [3]. The review panel recommended a conservative approach to magnet commissioning and that the operation of the second match coil (M2) in the downstream solenoid (SSD) be postponed until later in the Step IV programme when some physics data had been taken.

It was decided to operate in solenoid mode during ISIS User Cycle 2016/02 (28th June to 29th July 2016). The focus coil (FC) was run up to 90 A without quench. The maximum operating current in solenoid mode is 86 A. The focus coil is now in routine operation for data taking.

The upgraded quench-detection/quench-protection system for the spectrometer solenoids has been commissioned. The end and centre coils of both solenoids have been operated at full current. Transients were observed on the quench-detection voltage signals in both magnets and an effort was made to understand the origin of the transients. To simplify the circuit, and to remove a possible source of noise, the trim power supplies on both the upstream and the downstream spectrometer solenoids were removed from the circuit. Subsequent operation was limited to the end and centre coils of each magnet; i.e. each magnet was operated such that the E1, C and E2 coils were operated at the same current (referred to as the ECE configuration). Measurements of the stability of the power supplies, the quench-detection signals, the movement of the PRY and the movement of the magnets themselves were then carried out. While the cause of the transients has not been understood, it has been possible to establish stable operation of each of the magnets for periods of many hours.

On Wednesday 20th July 2016 the upstream and downstream spectrometer solenoids were operated together for the first time. Stable operation was established at a current of 140 A in each magnet; corresponding to a field in the tracking volume of ~ 2 T and data were taken for a period of approximately six hours.

The commissioning of the full magnetic channel, i.e. both solenoids in the ECE configuration and the focus coil, began on Tuesday 26th July 2016. Stable operation was established with the ECE coils in both spectrometer solenoids operating at 140 A (approximately 2 T in the tracking volume) and the focus coil at an appropriately chosen current. Data were taken at a muon-beam central momentum of 140 MeV/c and the FC current was varied by $\pm 10\%$ around the optimal current of 44.7 A. The data are now being analysed to understand the optics of the empty channel in detail.

Operation: The plan for User Cycle 2016/02 was to commission the superconducting magnets in solenoid mode. As described above, stable operation of both solenoids and the focus coil was achieved. Data taking for mechanical and magnetic alignment and for calibration was interleaved with magnet commissioning. Data taking has been routine, more details are given in section 3 below;

Absorber: The impact of thermal contraction on the indium seals between the liquid-hydrogen-absorber bodies and the windows has been tested by subjecting the vessels to a number of thermal cycles. The tests demonstrate that the indium seal is not compromised by thermal cycling. The wiring modifications required for operation of the cryocooler that will be used to condense hydrogen have been completed. The safety "end-caps", which must be fitted to the absorber/focus-coil module in R9 before tests commence, was delivered in the last week of July 2016. The module is now being assembled to allow tests to start in August.

Installation of the absorber/focus-coil module in the MICE Hall followed by commissioning of the magnet and hydrogen system can not be completed in less than 5 weeks. The November 2016 shutdown, of 2-weeks duration, is too short. Planning is therefore underway to initiate the installation in advance of the Christmas 2016 break so that the time during the Christmas shutdown can be used to evacuate and cool the hydrogen vessel. It is expected that the absorber/focus-coil module can be transferred from R9 to the Hall while it is still cold.

Formal approval of Step IV and the cooling demonstration: The MICE-UK cost-to-completion (CtC) review took place on the 24th April 2016. The review panel found that MICE had made good progress in the execution of Step IV. The scientific importance of the Step IV programme and the seminal nature of the demonstration of ionization cooling were recognised.

The 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 exploits existing equipment, minimises risk and substantially reduces the cost of the programme to the STFC.

Following the CtC review, work began to define the minimum viable programme by which a quantitatively-compelling demonstration of ionization cooling could be delivered [4]. Options that require one solenoid only were 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 (PRY) 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 [4]. Initial studies of the performance of the single-solenoid option 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.

The STFC Executive Board met on the 23rd May 2016. It endorsed the recommendation that the Step IV programme be executed and therefore decided that funding should be provided for an extended period of Step IV operation to August 2017. The STFC EB did not recommend that a proposal for a descoped cooling demonstration be invited.

The project team and the collaboration note that the STFC Executive Board decision was made "... *because of the current financial situation and the financial pressures.*" Since receiving news of the STFC EB's decision, therefore, the spokesman has been working within the international collaboration to understand the degree to which it remains committed to delivering the cooling demonstration and the extent to which new resources from outside the UK can be raised to support the cooling demonstration. The results of this consultation are that:

- All of the present members of the collaboration remain committed to delivering a demonstration of ionization cooling;

- New groups from Korea (UNIST) and Serbia (Novi Sad) continue to seek to join the collaboration to carry out the cooling demonstration and to exploit the Step IV data; and
- Commitments to seek significant new resources to support the execution of the cooling demonstrations have been given by Bulgaria, China, Korea and Serbia. While willingness to negotiate additional contributions in kind have been received from China, Serbia, the Netherlands and Switzerland.

The DOE also holds resources previously allocated to the ramp down of the Muon Accelerator Program against the contingency that the downstream spectrometer solenoid may need to be recovered.

The project team and the collaboration is clear that stable operation, for physics, of the Step IV configuration needs to be demonstrated before a revised proposal for a cooling demonstration can be brought forward. Once confidence has been established in the capability to deliver the extended Step IV programme, the collaboration will seek to discuss once more the conditions under which a configuration capable of demonstrating ionization cooling can be proposed. This approach was endorsed by the Collaboration Board when it met on the 29th July 2016.

2 Schedule

The MICE programme has been subject to an extensive series of reviews over the first half of 2016. The outcomes of these reviews are:

STFC MICE-UK Oversight Committee, 21st *March 2016* noted that the MICE project requires a solution to the funding shortfall currently impeding the US recovery of the downstream spectrometer solenoid. The OsC requested that MICE management provide a costing for a "Step IV only" program that would maximise the scientific return from Step IV. This was to be presented to the STFC MICE-UK Cost to Completion review. A schedule by which the full emittance/momentum "matrix" could be measured was developed, with running extending to August 2017;

RLSR and MPB, 5th *and* 6th *April 2016*: the MICE Resource Loaded Schedule Review (RLSR) panel noted that the plan to move the procurement of a replacement for the downstream solenoid from the US to the UK, with a transfer of funds from the DOE to the STFC, could potentially lead to lower overall costs and a viable route forward. The MICE Project Board (MPB) noted the excellent progress in operations, software and analysis and commended the collaboration on the high quality of the physics papers presented;

STFC MICE-UK cost-to-completion review, 26th *April 2016*: recommended that:

- MICE should not proceed with the procurement, through RAL, of a replacement for the downstream solenoid due to the risks attendant on such a programme and the possibility that the replacement would not be in operation before the next long ISIS shutdown;
- MICE-UK should be funded for Step IV as a "base level"; and
- MICE-UK should be invited to prepare, on a three-month timescale, a proposal for a "de-scoped" cooling demonstration for evaluation by a new panel of accelerator scientists. This proposal should provide for the cooling-measurement programme to complete before the ISIS long shut-down that is anticipated to be in 2019; and
- MICE-UK continue preparations for the cooling demonstration pending the result of the review of the de-scoped proposal; and

STFC Executive Board meeting, 26th *May 2016* decided that MICE-UK be funded for an extended Step IV run that would allow the full emittance/momentum matrix to be measured. The Executive Board declined to invite a proposal for a de-scoped cooling demonstration as recommended by the cost-to-completion review panel.

Following the advice of the MICE-UK Oversight Committee and the RLSR panel, by the time of the CtC review, the project team had prepared an almost complete data-pack for the procurement of a replacement for the downstream solenoid (SSD). This work was stopped following the recommendations of the Cost to Completion review.

At this point effort was focused on preparing and analysing a number of possible de-scope options for presentation to a future review committee. Two options using only one spectrometer solenoid were evaluated. A configuration that would allow a cooling demonstration to be completed, albeit with a degraded momentum resolution downstream of the cooling cell and a modest reduction in transmission, was developed [4]. One option using both solenoids but with SSD rotated such that the match coils were not required was also evaluated. This option provided the best transmission, but with increased risk and with the requirement for an increased civil engineering program compared to the alternative single-solenoid options. The output from these investigations was prepared in less than a month and provided to the STFC to inform the STFC Executive Board's deliberations. Following the STFC Executive Board decision to fund an extended Step IV and not to pursue the review schedule recommended by the Cost to Completion review panel, the project team issued instructions to stop all work not directly related to Step IV. This chiefly affects the mechanical work package which has reduced effort by 50%. No reduction in booking has yet occurred in the RF program, discussions are ongoing with Daresbury Laboratory senior staff with a view to resolving the situation.

Following the decision of the STFC Executive Board not to invite a proposal for a de-scoped cooling demonstration, the tracking milestones were revised. Only Milestones related to the Step IV programme are retained. Figure 1 shows the revised project dashboard and figure 2 shows the revised milestone slip chart.

The "Step IV only" schedule fully exploits all ISIS Cycles up to and including 2017/02 which will end in late July 2017. Magnet-string commissioning started in June 2016 and stable running of the end and centre coils of both spectrometer solenoids at a nominal field of 2 T together with the focus coil was achieved on the 26th July 2016. Data-taking was continuous to the end of the Cycle. Data have been taken at 140 MeV/c with ±5% and ±2.5% variations made to the focus-coil current.

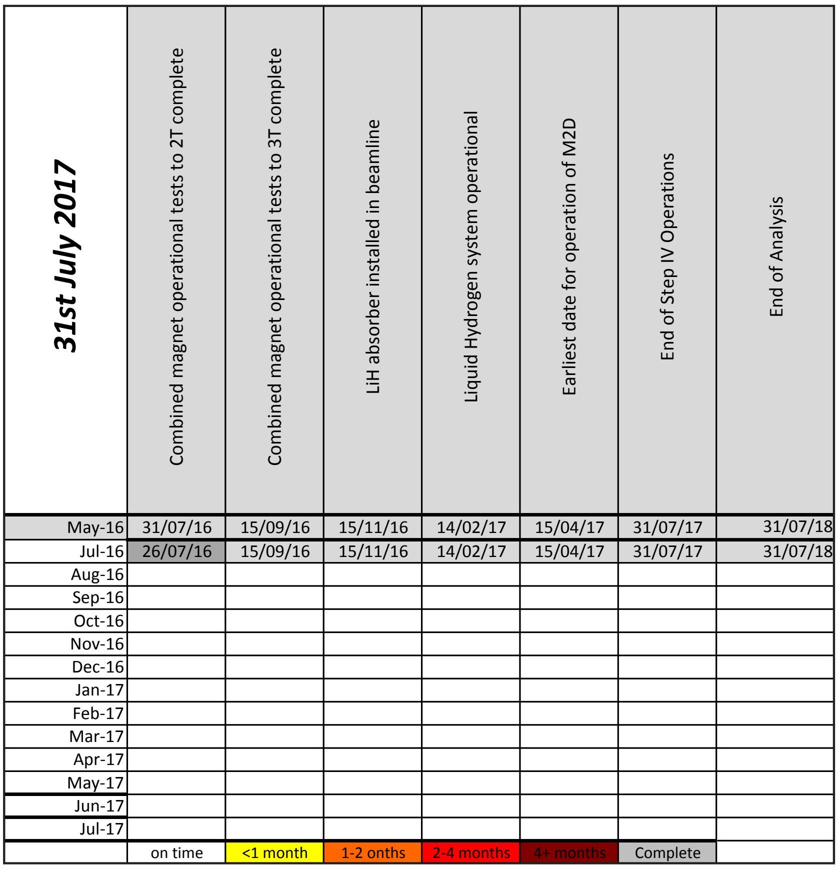
The "Magnet Readiness Review" took place on the 28th June 2016 at RAL [2]. The panel was composed of magnet and electrical experts drawn from Daresbury Laboratory and ISIS. The review was chaired by O. Kirichek (RAL/ISIS). The review panel recommended that data be gathered on a lowest-risk-to-magnets basis—i.e. data should be taken at beam-line settings with the lowest interaction forces between magnets first and without match coil 2 in SSD (M2D) [3]. Only once a complete data set with both liquid hydrogen and LiH has been gathered will data be taken with M2D; this is not expected to be before spring 2017.

The liquid-hydrogen system will be tested "off-line" in R9 over the 2016 ISIS summer shutdown. Vacuum "end caps" will be used to ensure testing is carried out under the pressure conditions that replicate those that will pertain in the MICE experiment. The earliest possible date when the system can be ready is September 2017; this projection makes no allowance for contingency. It has been decided to schedule the first use of liquid hydrogen after ISIS Cycle 2016/04. This will allow use of the Christmas/New Year shutdown to start to cool the hydrogen cell.

The critical milestones that remain in the Step IV programme are:

- Data-taking complete: August 2017; and
- Analysis complete: June 2018.

The de-scoped cooling-demonstration work undertaken earlier in the year showed that a cooling cell could be demonstrated without the extensive Hall modifications envisaged in the original program. The reduction in performance was small using an option with one spectrometer solenoid placed upstream of the cooling cell. This option offers the best compromise of performance and short installation time. A critical factor in any future cooling demonstration is the long ISIS shutdown, which is expected to begin no earlier than the start of 2019 and may not occur before the start of financial year 2019/20. Assuming Step IV runs until the end of July



31st July 2017	Combined magnet operational tests to 2T complete	Combined magnet operational tests to 3T complete	LiH absorber installed in beamline	Liquid Hydrogen system operational	Earliest date for operation of M2D	End of Step IV Operations	End of Analysis
May-16	31/07/16	15/09/16	15/11/16	14/02/17	15/04/17	31/07/17	31/07/18
Jul-16	26/07/16	15/09/16	15/11/16	14/02/17	15/04/17	31/07/17	31/07/18
Aug-16							
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Jul-17							
	on time	<1 month	1-2 onths	2-4 months	4+ months	Complete	

Figure 1: MICE project dashboard. Following the national and international reviews of the project that took place in the spring and early summer of 2016, only those milestones pertaining to the Step IV programme have been retained. In future, changes in the projected milestone-completion dates are indicated using the colour code defined in the legend. Completed milestones are shaded grey.

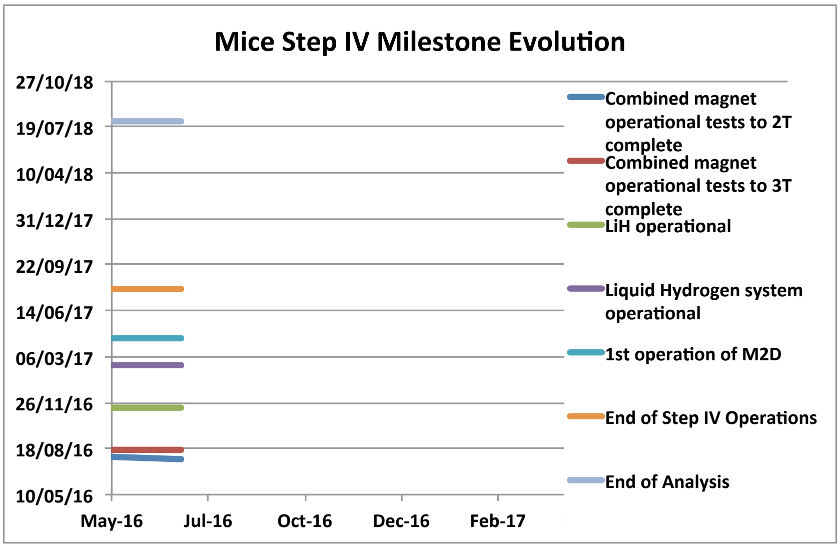

Figure 2: MICE milestone-slip chart. Following the national and international reviews of the project that took place in the spring and early summer of 2016, only those milestones pertaining to the Step IV programme have been retained.

2017 and that a minimum of 3 ISIS Cycles would be required (with data-taking complete before the end of 2018), were a cooling demonstration to be mounted, construction would have to complete in 11 months. There would be further benefit should it prove possible to compress the construction timetable to 8 months, such that it could be implemented before ISIS Cycle 2017/01. Initial indications are that this may be feasible. Factors that help to accelerate the timetable include:

- A significant reduction in mechanical work required in the MICE Hall;
- The cooling cell can be assembled off-line in R9;
- Only minor modifications are required to the PRY—these can be effected by water jet cutting locally;
- The single-cavity modules are currently being assembled at LBNL;
- The RF controls are largely complete, only installation now being required; and
- Collaborators are willing to provide precision manufacturing assistance (such as the reconfiguration of the downstream tracker).

It therefore seems reasonable to consider an extension to the Step IV program to leverage the investment to date. A substantial increase scientific return can be gained for a small incremental cost.

3 Data taking and analysis

3.1 Operations

ISIS have completed User Cycles 2015/04, 2016/01 and 2016/02 since the last report. In 2015/04 MICE operated a 16-hour per day shift cycle. One hundred and ten shifts were offered to the collaboration. All were allocated. The majority of time during this User Cycle was devoted to taking straight-track data with an empty channel and with the LiH absorber to study the validity of models of multiple scattering of muons. A complete data-taking campaign was planned and carried out with an impressive MICE up-time of more than 95%.

User Cycle 2016/01 was set aside to complete the installation and commissioning of the quench-detection/quench-protection systems for the spectrometer solenoids. Preparations for the separation of the demineralised and inhibited water systems were also made.

During Cycle 2016/02 data taking was interleaved with the commissioning of the spectrometer solenoids. date were taken with straight tracks for the purposes of calibration and detector alignment. The focus coil, with no absorber, was stable in operation for periods of many days. date were taken with the focus coil in solenoid mode at 50 A to map the orientation and alignment of the magnetic field. Finally, at the end of the Cycle, 3 days of date were taken with both spectrometers and the focus coil in simultaneous operation.

The data taken during these user cycles, to date, is summarised in table 1 below.

Date	**Description**	**Data sample (particle triggers)**
February 23rd	1. Pion reference run without DS 2. TOF1 Calibration	50K 503K
February 24th	1. Detector alignment studies	580K
February 25th	1.Pion reference run without DS 2. Detector alignment studies	30K 250K
February 26th	1.Pion reference run without DS 2. Detector alignment studies	30K 180K

February 26th	1.Pion reference run without DS 2. Detector alignment studies	30K 200K
February 27th	1.Pion reference run without DS 2. Detector alignment studies	35K 184K
February 28th	1.Pion reference run without DS 2.Studies on the effect of the proton absorber	35K 302K
February 29th	1.Pion reference run without DS 2.Zero absorber data	56K 108K
March 1st	1.Pion reference run without DS 2.Zero absorber data	40K 170K
March 5th	1.Pion reference run with DS 2.Zero absorber data	110K 250K
March 6th	1.Pion reference run with DS 2.Zero absorber data	50K 540K
March 7th	1.Pion reference run with DS 2.Zero absorber data	50K 483K
March 8th	1.Pion reference run with DS 2. Rate studies	52K 281K
March 11th	1.Pion reference run without DS 2. LiH absorber without DS	70K 153K
March 12th	1.Pion reference run without DS 2. LiH absorber without DS 3. Rate studies	51K 522K 141K
March 13th	1.Pion reference run with DS 2. LiH absorber with DS	115K 727K
March 15th	1.Pion reference run with DS 2. LiH absorber with DS	603K 518K
March 16th	1.Pion reference run with DS 2. LiH absorber with DS	51K 475K
March 17th	1.Pion reference run with DS 2. LiH absorber with DS	34K 477K

March 18th	1.Pion reference run with DS	50K
	2. LiH absorber with DS	487K
March 19th	1.Pion reference run with DS	11K
	2. LiH absorber with DS	356K
March 20th	1.Pion reference run with DS	25K
	2. LiH absorber with DS	319K
March 21st	1.Pion reference run with DS	32K
	2. LiH absorber with DS	417K
March 22nd	1.Pion reference run with DS	12K
	2. LiH absorber with DS	826K
March 23rd	1.Pion reference run with DS	70K
	2. LiH absorber with DS	486K
March 24th	1.Pion reference run with DS	38K
	2. LiH absorber with DS	776K
July 7th	1.Pion reference run with DS	27K
	2. TOF calibration	547K
July 8th	1.Pion reference run with DS	33K
	2.Detector alignment	33K
July 9th	1.Pion reference run with DS	11K
	2.Detector alignment	633K
July 10th	1.Pion reference run with DS	16K
	2.Detector alignment	1207K
July 14th	1.Pion reference run with DS and FC @ 50 A solenoid mode	25K
	2. 200 MeV muon beam with DS and FC @ 50 A solenoid mode	704K
July 15th	1.Pion reference run with DS and FC @ 50 A solenoid mode	36K
	2. 300 MeV muon beam with DS and FC @ 50 A solenoid mode	246K
	3. 400 MeV muon beam with DS and FC @ 50 A solenoid mode	54K
July 16th	1.Pion reference run with DS	20K
	2. 300 MeV muon beam with DS alignment	452K
	3. 200 MeV muon beam with DS alignment	258K
	4. 400 MeV muon beam with DS alignment	90K

July 17th	1.Pion reference run with DS	32K
	2. 140 MeV muon beam with different proton absorber thicknesses	83K
	3. 170 MeV muon beam with different proton absorber thicknesses	223K
	3. 240 MeV muon beam with different proton absorber thicknesses	300K
	4. 200 MeV muon beam with different proton absorber thicknesses	232K
July 18th	1.Pion reference run with DS	12K
	2. 240 MeV muon beam with different proton absorber thicknesses	150K
July 19th	1.Pion reference run with DS	12K
	2. 400 MeV pions with SSD @ 2T	282K
	3. 400 MeV pions with SSD off	725K
July 20th	1.Pion reference run with DS	12K
	2. 200 MeV pions with SSU and SSD @ 2 T	363K
	3. 140 MeV pions with SSU and SSD @ 2 T	97K
	4. Pion reference run with DS	12K
	5. 140 MeV muon beam with different proton absorber thicknesses	298K
July 21st	1.Pion reference run with DS	11K
	2. 240 MeV muon beam with different proton absorber thicknesses	20K
	3.Pion reference run with DS	23K
	4. Focus coil magnetic field alignment	1112K
	5.Pion reference run with DS	12K
July 22nd	1.Pion reference run with DS	12K
	2. 140 MeV D2 tuning run	21K
	3. Focus coil magnetic field alignment	51K
July 23rd	1.Pion reference run with DS	44K
	2. 140 MeV D2 tuning runs	92K
	3. 300 MeV FC alignment @ -50 A solenoid mode	275K
	4. 400 MeV FC alignment @ -50 A solenoid mode	115K
	5. 200 MeV FC alignment @ -50 A solenoid mode	159K

Table 1: Data taken in February 2016 (ISIS User Cycle 2015/04) and June 2016 (ISIS User Cycle 2016/02). Abbreviations used: decay solenoid, DS; time-of-flight, TOF; Cherenkov, Ckov; Electron Muon Ranger, EMR; dipole 2, D2; centre of mass, CM; SSU (SSD), Upstream (downstream) spectrometer solenoid.

The commissioning of the magnetic channel is now in full swing. In line with the recommendations of the Magnet Readiness Review Panel, the decision was taken to commission the channel “piece-wise”, data being taken with the experiment in each configuration as stable operation is established. Data have been taken with each magnet (the upstream solenoid, SSU, SSD and FC) energised individually and with all magnets operating together. The magnetic forces on the the magnet supports and other equipment depend on which magnets are in operation and can be significant. The following steps were taken to establish stable operation in solenoid mode of the end and centre coils of SSU and SSD together with the focus coil:

- The end and centre (ECE) coils in the upstream solenoid were ramped to 140 A, generating a field of approximately 2 T in the tracking volume;
- The FC was ramped to 44.7 A. The focus coil couples the magnetic fields of the two spectrometers. Therefore, the ramp of the FC was done in steps so that the force between SSU and the FC and its effect on the stability of the magnets could be observed; and finally
- The ECE coils in the downstream solenoid were ramped to 140 A.

At this point, date were taken with all magnets in operation.

The next step in the magnet-channel commissioning will be to investigate the instabilities in the end-coil power supplies and establish stable operation of the ECE combination of SSU and SSD 210 A, corresponding to a magnetic field in the tracking volume of of 3 T. The decision to run the ECE combination at 3 T (rather than the nominal 4 T) is in line with the recommendations of the Magnet Readiness Review panel. A significant program of magnet-current tuning and beam-optics investigations has been defined to ensure that the channel is fully understood and optimised before physics data is taken. This program will include:

- Taking magnetic-field alignment data with each magnet powered on its own;
- Changing the current of SSU and SSD by -5% and -10% from the nominal with the focus coil unpowered;
- Investigating the effect on the beam input emittance of different diffuser settings at the nominal settings of SSU and SSD; and
- Changing the currents of SSU and SSD by -5% and -10% and the FC by $\pm5\%$ and $\pm10\%$ from the nominal values when the magnets are operated together..

It is expected that a significant part of user cycle 2016/03 will be devoted to these studies. The rest of the Cycle will be used to take physics data with no absorber.

Following the characterisation of the channel and the collection of zero-absorber data, the materials program will be carried out. Cycle 2016/04 will be devoted to materials measurements with a LiH absorber. Between the end of this user cycle and the New Year, the LH_2 absorber vessel and focus coil will be cooled down and LH_2 added before the first Cycle of 2017, which runs from mid-February to late March 2017. At the end of this user cycle, the decision on whether to power the M2D coil will be made and the measurement program adjusted according to the result of this decision.

3.2 Analysis

Three papers are being prepared for publication:

- The measurement of multiple Coulomb scattering using data taken in the winter and spring of 2016;
- The measurement of beam emittance using the upstream spectrometers; and
- The optimisation of the lattice for the demonstration of ionization cooling that was adopted as the baseline for the experiment in November 2014.

Preliminary results from each analysis were presented at ICHEP 2016, which took place in Chicago from the 4^{th} to the 10^{th} August 2016. The draft of the paper detailing the November 2014 baseline configuration of the ionization-cooling demonstration lattice has been circulated to the collaboration for comment.

Analysis continues on beam commissioning data taken in July 2016.

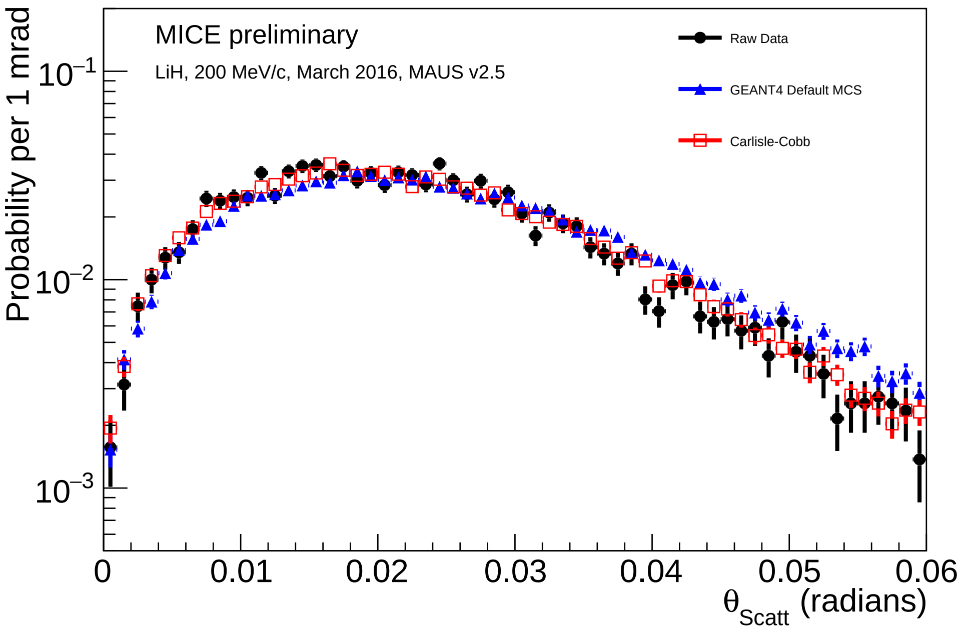

Figure 3: Measured scattering distribution of muons in lithium hydride (filled circles). The convolution of the empty-channel data with Geant4 is shown as the solid blue triangles and the convolution of the empty-channel data with the Cobb-Carlisle model is shown as the open red squares.

3.2.1 Papers in progress

Measurement of multiple Coulomb scattering

To prepare for the measurement of multiple Coulomb scattering (MCS) in Step IV, the collaboration took data in December 2015 with the hydrogen-absorber body filled with helium gas (negligible scattering) and with xenon gas. In the spring of 2016, data were taken both with and without the lithium-hydride absorber. The particle trajectories upstream and downstream of the scattering medium were measured.

The measured distribution of scattering angle can be unfolded to determine the underlying multiple-Coulomb-scattering distribution. Scattering due to windows and other material in the beam can be determined by measuring the trajectories of muons in the absence of an absorber. The scattering distribution due to the material of the absorber is then determined by:

- Convoluting the empty-channel data with Geant4 and, separately, convoluting it with an implementation of a model of MCS developed by J. Cobb (Oxford) and T. Carlisle (Oxford). The result of this convolution can then be compared directly to the data;
- Determining the underlying scattering distribution using a Bayesian-deconvolution approach; the Geant4 and Cobb-Carlisle scattering models are each used independently to deconvolute the data; and
- Determining the scattering distribution using Gold's algorithm [5], which is a model-independent method of deconvolution.

The measured scattering distribution using the Bayesian-deconvolution technique is shown in figure 3. The scattering distribution produced by Geant4 and the Cobb-Carlisle model are also shown. The Cobb-Carlisle model shows better agreement with the data.

The convolution and Bayesian-deconvolution analyses have been completed. Deconvolution using Gold's

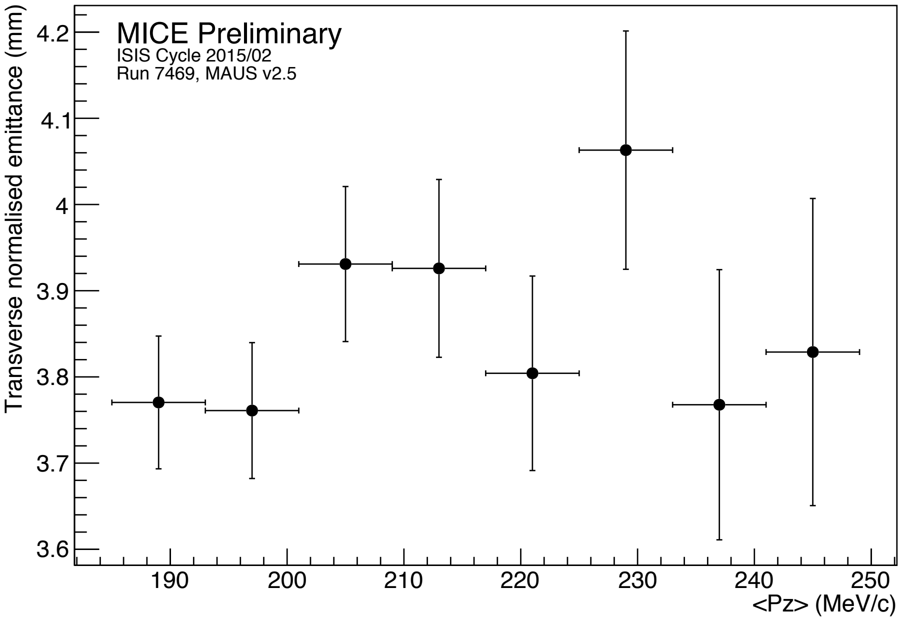

Figure 4: Measured beam emittance in the MICE upstream diagnostics system in different momentum bins. Errors shown are statistical errors arising due to sampling of the input beam distribution.

algorithm is under way. The estimation of systematic uncertainties is still in progress.

Measurement of upstream beam emittance

Data taken during October 2015 with a field of 4 T in the tracking volume of the upstream spectrometer solenoid is being prepared for publication to demonstrate the single-particle emittance-reconstruction technique. Tracks measured in the upstream tracker have been used to reconstruct the emittance. The measured emittance at the tracker is shown in figure 4. The emittance is calculated separately in the different momentum bins so that the effect of dispersion on the emittance calculation is suppressed.

The emittance reconstruction has been validated by extrapolating tracks from the tracker, through the spectrometer-solenoid fringe field and associated windows, to TOF1. The extrapolated momentum has been compared with that determined using TOF0 and TOF1. The momentum measured in the tracker is consistent with that reconstructed using TOF0 and TOF1 to within $\sim 0.4\%$. There is a slight mis-match between the position of the measured beam distribution at TOF1 and that of the tracks extrapolated to TOF1 from the tracker. Analysis is underway to improve the agreement between beam position measured at TOF1 and that obtained by back-extrapolating the beam measured in the tracker to the TOF1 reference plane.

Demonstration of Ionisation Cooling

The paper documenting the design of the lattice for the demonstration of ionization cooling has now been distributed to the collaboration for comment. This is the final internal review before submission of the paper to the arXiv and to a journal.

3.2.2 Analysis of beam-line commissioning data

Data to commission the magnetic channel was taken in July 2016. The analysis of this data is underway. Data were taken with each of the magnet modules powered individually; SSU and SSD powered; and all three modules powered together in solenoid mode. By analysing data with many different combinations of magnets, it will be possible to determine the magnetic alignment of individual modules and isolate effects due to the combined operation of modules.

The collaboration is validating the magnetic model and transport through the lattice. This is achieved by making a direct measurement of the transfer matrix between the upstream and the downstream diagnostics and by projecting individual tracks between the upstream and the downstream instrumentation and minimising the residuals between the detectors. In addition, studies of the combined analysis of the upstream and the downstream diagnostics are underway. These studies seek to demonstrate the validity of the MICE emittance-change analysis-model by, for example, demonstrating emittance conservation between the upstream and the downstream diagnostics.

References

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