# Magnet and Beam Commissioning at Step IV

## 1 Introduction

The international Muon Cooling Experiment (MICE) [1] aims to demonstrate, for the first time, the ionization cooling necessary for future facilities based on stored muon beams; the Neutrino Factory, the Muon Collider and next generation muon experiments. In the full demonstration of ionization cooling it is necessary to pass the muon beam through an absorber material ($LH_2$, LiH, etc.) and to re-accelerate the beam in RF cavities. At Step IV the beam passage through the absorber will be studied. At Step V re-acceleration will also be demonstrated.

Several important experimental goals will be achieved at Step IV:

- The observation of a decrease of normalised emittance;
- The test of phase-space reconstruction using single muons;
- The study of optics in the MICE Step IV channel; and
- The measurement of muon stopping/straggling and multiple scattering.

In order to achieve these goals it is necessary to commission the magnets that make up the MICE channel efficiently and successfully. It us also necessary to ensure that the optimum beam can be provided by the MICE Muon Beam (MMB) and satisfactory matching conditions can be achieved between the MMB and the MICE experiment for each of the numerous operating conditions. Moreover, the optical properties of the Step IV channel must be verified experimentally.

This note describes the MICE magnet-commissioning procedure established by the MICE Magnets Integration Task Force (MMITF) for individual magnets and for all magnets in the Step IV cooling channel together. In addition, the procedures by which it is proposed to commissioning the Step IV MICE channel with beam will be described.

## 2 MICE Channel at Step IV

The MICE channel at Step IV will use three superconducting-magnet modules: two spectrometer solenoids (SS) in which the trackers are installed and one focus-coil (FC) modules in which the absorber is installed. The Step IV magnetic channel consists of 12 coils, of which 11 can be powered independently. The SS consists of the long “central coil” between two “end coils” which, together, produce a uniform field in the regions where the trackers sit. The SS also includes two “matching coils”, which are used to perform beam-optics adjustment between the SS and the FC. It is planned to operate the central coil and end coils with current values close to the nominal ones with only small adjustments in end coil 1. However, the currents in matching coils and in the FC will vary considerably between different momentum and optical settings. The Step IV configuration is shown in figure 1. In addition to various momentum and optical settings, MICE can be operated in “flip” and “solenoid” modes. These modes differ in the magnetic field direction in the upstream and downstream halves of the experiment. In flip mode the field reverses sign in the centre of the FC module while in solenoid mode the field does not reverse. By comparing the transmitted phase space distributions between the two modes it will be possible to examine the behaviour of the beam envelope and canonical angular momentum.

The coils in the MICE channel are of large aperture so that they are able to provide strong focusing of the large beam emittance. In addition, with the exception of the long central coil, the coils in the MICE Channel are short and are positioned close to one other. These conditions result in strong magnetic coupling. This can

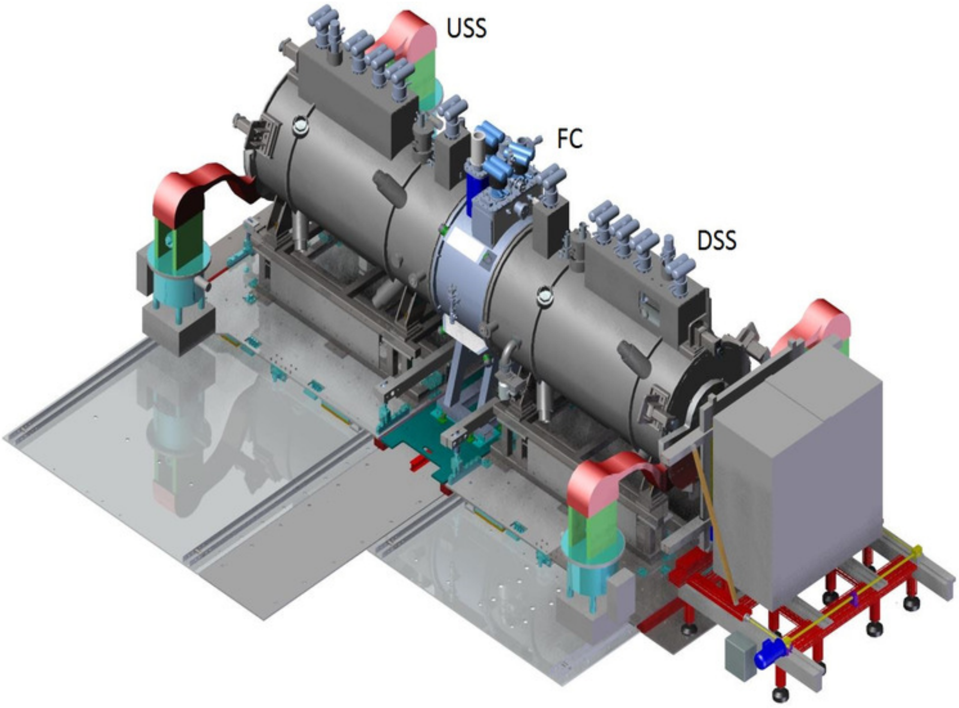

Figure 1: The layout of MICE at Step IV consisting of upstream and downstream Spectrometer Solenoids (USS and DSS) and the FC.

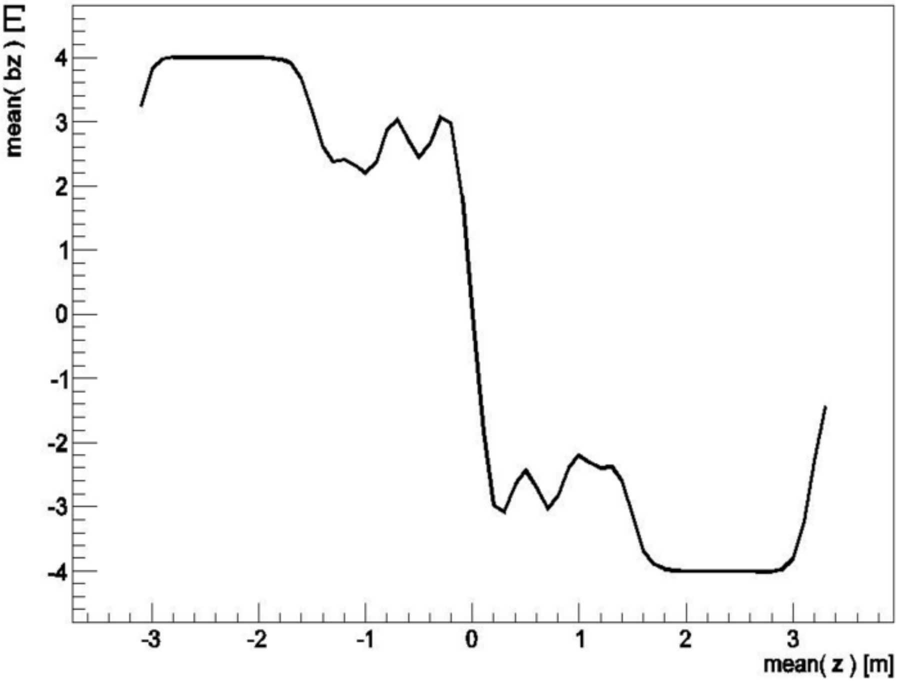

Figure 2: The magnetic field in the baseline ”flip” configuration.

clearly be seen in figure 2 in which the complete overlap of the magnetic field between the various modules may be observed. This overlap results in an alteration of the distribution of forces acting on the individual coils. In the event of a quench, since the coils are inductively coupled, eddy currents are induced in neighbouring coils and in their aluminium mandrels. These phenomena need to be taken into account when planning the commissioning and operation of the MICE magnetic channel.

Both the SSs and the FC have been trained in isolation and the magnetic fields that they produce have been mapped. The training behaviour of the SSs and the FC differs significantly;

- The SSs do not remember their training after a thermal cycle and require about 15 quenches to reach the nominal operating currents; while
- The FC remember its training after a thermal cycle and when changing between flip and solenoid mode.

The training histories for SSs and the FC are shown in figure 3 and figure 4 respectively.

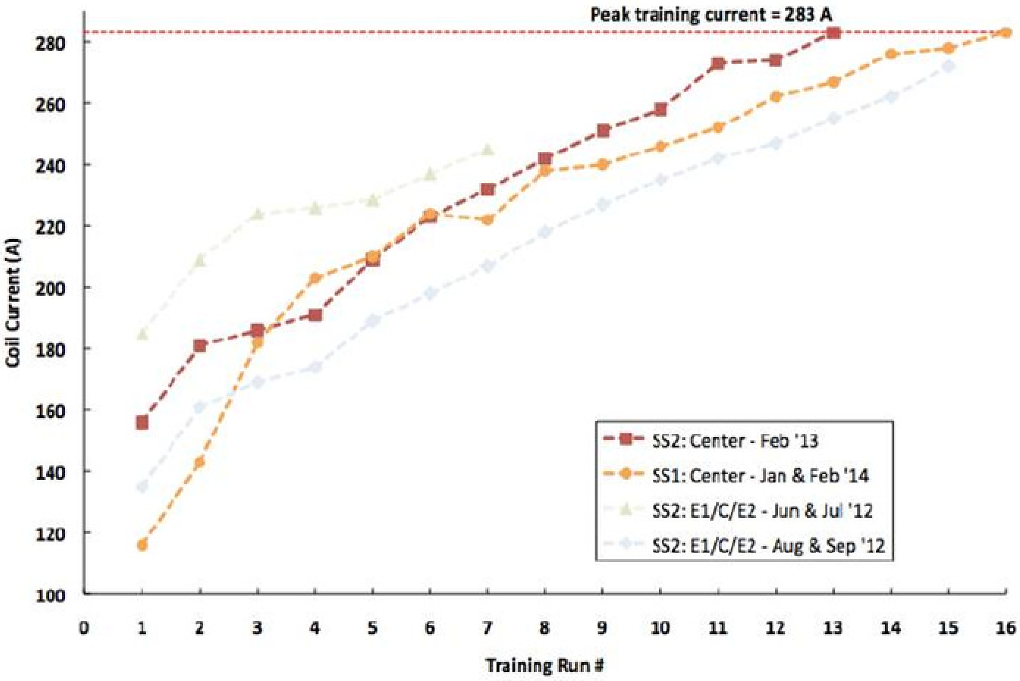

Figure 3: Training for SS solenoids. The figure shows no significant difference between attempts requiring about 15 quenches to reach nominal currents each time.

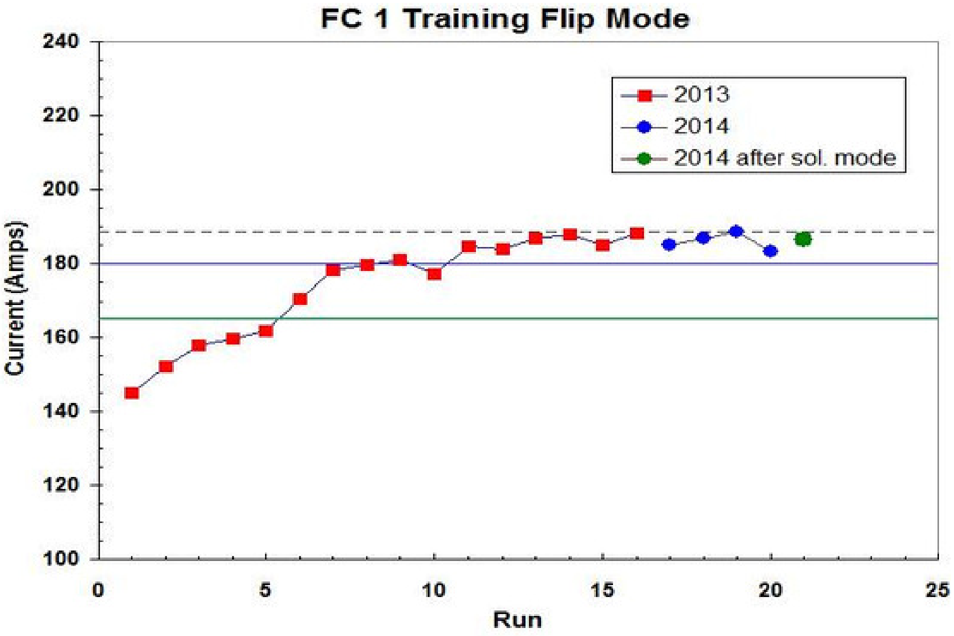

Figure 4: Training for the FC magnet in the flip mode. After relatively long initial training the magnet remembers its training even after changing the modes and returning to the flip mode again.

## 3 Quench propagation in MICE Step IV Channel

Quench propagation in the MICE channel at Step IV has been carefully considered. The first mechanism examined was eddy-current induced heating in the aluminium mandrels of the coils adjacent to a coil which quenches, the phenomenon known as "quench back". The as-built magnet geometry was simulated using

COMSOL [2], which allowed for a coupled, multi-physics analysis (using the electromagnetic and thermal solvers). The detailed material properties were taken into account and magnet switch-off times of 3s and 5s for the FC and SS respectively were assumed. The temperature increase in the aluminium mandrels of the matching coils induced by a quench of the FC magnet is shown in figure 5. The temperature reached clearly exceeds the temperature which will trigger a quench-back event. A similar effect can be seen in figure 6 which shows the temperature increase in both the coils in the FC module caused by a quench event in the SS. The conclusion of the study is that as soon as the FC magnet is powered, a quench will propagate through the entire Step IV channel. However, if the FC is not powered the eddy-current heating induced by a quench of the SS is unable to trigger a quench in the second SS module.

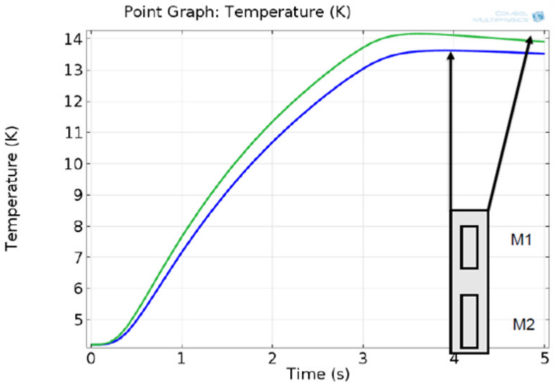

Figure 5: The temperature increase in the Aluminium mandrels of the Matching Coils induced by the quench of the FC magnet.

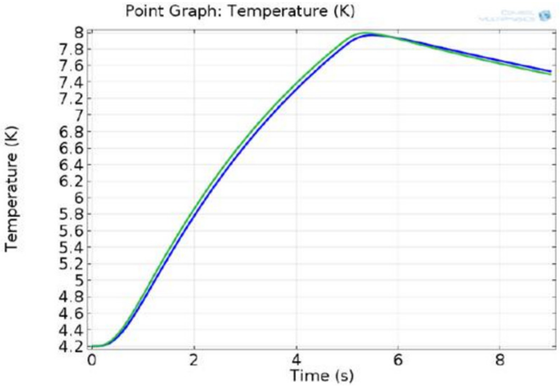

Figure 6: The temperature increase in the Aluminium mandrels in the FC induced by the quench of the SS magnet.

The second phenomenon examined was the voltage signal induced in neighbouring coils by a quench through the inductive coupling. The induced voltage is proportional to $\frac{dI}{dt}$. In order to estimate this effect, the inductance matrix was evaluated. The results show that a quench event in one of the SS will induce a voltage of about 4.9 V in the second matching coil of the “other” SS. This is similar to the thresholds set in the Quench Detection (QD) system. Therefore, a quench will most likely be triggered by the QD system and, given the quench-back effect discussed above, this will induce a quench in the full channel.

In summary a single quench event in any of the coils in the MICE Step IV channel is likely to result in the quenching of the full channel. The commissioning procedure has been developed based on this assumption.

## 4 Magnet commissioning procedure

Commissioning of the superconducting (SC) magnets in the MICE Channel will follow the successful completion of the construction phase and will be necessary to allow for routine data taking. Stable conditions are needed in all operational modes with sufficient margin in the matching coils to tune for a match between the SSs and the FC. The commissioning will also set the standards and the knowledge required for operation procedures such as switching on and off the magnets, changing their settings and tuning the Step IV channel.

The experience gained in training the FC indicates that this magnet should achieve the nominal currents in solenoidal mode when operated in the MICE channel. However in flip mode, a conservative assumption has been made for the de-rating of the operating current that will be necessary to accommodate the forces acting on coils from the SS modules. The establishment of these experimental limitations is one of the key goals of the magnet commissioning phase.

The MITF has examined several scenarios for magnet commissioning taking into account the cost (including requirements for liquid helium and manpower), the duration of the commissioning period, the level of complexity and the efficiency of the operations. These considerations have led to the conclusion that the commissioning procedure should proceed as follows:

1. Electrical and control tests of the power supplies and quench detectors both individually and as part of the full Step IV channel;
2. Sufficient supplies of LHe will be secured. It is recommended that each magnet be equipped with its own Dewar for easy and fast refilling after a quench using the individual transmission lines prepared for each magnet;
3. Vacuum will be established and magnets will be cooled down;
4. SSs will be trained in parallel, but, only one magnet will be ramped at any one time. Assuming one quench per magnet per day and two quenches per day in 24/7 training operations, it is expected that this phase will take up to three weeks (including a time contingency of 40%) as about 15 quenches per magnet are required. As the FC remembers its training it is expected that the magnet will achieve its nominal individual current after only one or two quenches. However, the minimum time to recover from a quench of the FC is 48 hours. This dictates the timetable for the training of the FC;
5. Once all magnets reach their nominal settings in independent training, the nominal current will be set in each of the SSs and the current will start to be ramped in the FC. Either the nominal current will be reached or a quench will be observed. By detecting which coil quenches first it will be possible to assess the situation and inform decisions on the next steps in the training sequence.

Depending on experimental findings this procedure may be followed by trying to train the FC with SS currents fixed at nominal values (repeating the same procedure), by de-rating currents in SSs or by switching to combined training. The combined training assumes ramping all magnets simultaneously at approximately 2.5 quench per week (once again including a time contingency of 40%). It is currently assumed that training will first take place in solenoid mode since the maximum operating current in the FC is lower in this mode. This will be followed by commissioning of the flip mode.

A system to measure displacements in the Partial Return Yoke (PRY) induced by magnetic forces will be installed. During training this system will be used to ensure that the displacements agree with calculation and are always acceptable.

## 5 Beam commissioning

The object of commissioning with beam is to:

- Verify the optical properties of the MICE Muon Beam which delivers beam from the pion-production target on ISIS to the MICE experiment;
- Verify the matching conditions into the MICE channel including the effect of the diffuser that will allow the manipulation of the value of the input emittance; and
- Verify the properties of optics in the Step IV channel.

Discussion of the commissioning with beam is separated into phases:

- Pre-commissioning of the MMB and the MICE channel;
- Full commissioning of the MMB and the MICE channel; and
- Commissioning of the MICE channel.

## 5.1 Beam line pre-commissioning

This part of the beam commissioning aims to test the new MMB settings required for Step IV operations with the diffuser. In addition, a dedicated optics is required for tracker commissioning without magnetic field in which the particle flux is maximised, especially to the downstream Tracker.

The pre-commissioning phase will also test the beam line hardware which will not have been used for many months. The required hardware includes the target, all beam-line quadrupole magnets, the decay solenoid and the proton absorber. The beamline instrumentation, especially the time-of-flight hodoscopes TOF0 and TOF1 will be required. The tomography-like phase-space reconstruction developed and tested in Step I operations will allow the matching condition at TOF0 to be measured and compared with Monte Carlo (MC) predictions for the new settings [3]. Some of the settings used at Step I may be repeated to cross-check with the updated MC simulations and, in addition, to ensure that no accidental changes have been introduced to the beam line during Step IV construction. It will be necessary to collect $\sim 10k$ good triggers per setting.

A "physics block" assumes data taking at each of three momenta and three different input emittance settings. This requires that nine matching conditions be tested. With the addition of one "old" setting from Step I and one new setting for tracker commissioning without magnetic field a total of at least 11 settings need to be commissioned. This will require at least 110k useful triggers to be collected, which will take about an hour of data taking assuming rates extrapolated from Step I operations [4]. However, including the time required for calibration of the TOFs and assuming that the procedure will need to be repeated, it is estimated that the beam line pre-commissioning will require about 8 shifts. It is important to note, that this pre-commissioning does not require the SC magnets and may be performed before, or interleaved with, the magnet commissioning described above. In addition, the beam time may be shared with the data taking required to commission and align the trackers without magnetic field.

## 5.2 Beam line commissioning

The incoming muon beam line will pass through the diffuser, which will define the muon-beam emittance at the input to the Step IV channel. The diffuser thickness will need to be set to a value appropriate for each of the nine emittance/momentum settings for a particular physics block. The beam must be matched to the channel in order to maximise the number of good muons available for analysis. In addition to the hardware required for pre-commissioning, the diffuser and the upstream tracker with magnetic field will be required. This will allow the Twiss parameters $\beta$ and $\alpha$ and the emittance to be reconstructed at each of the five tracker planes. By studying the evolution of $\beta$ along the tracker it will be possible to establish the degree to which the MMB is matched to the channel.

For each of the nine settings corresponding to one physics block, $\sim$ 90k useful triggers will be needed. This corresponds to $\sim$ 10 h of operation. The useful-muon rate in the tracker is expected to be about one order of magnitude lower than that in TOF0 [4]. Taking into account that the procedure will need to be repeated, it is estimated, that about 15 shifts are needed including a contingency of 30%. This part of beam commissioning can only be performed once the upstream SS and the upstream tracker have been commissioned and the phase-space reconstruction has been established.

### 5.3 Beam commissioning of Step IV Channel

The beam optics in the Step IV Channel needs to be assessed before data taking for physics will begin. Firstly, the trajectory through the channel will be measured. The mean positions and divergence are expected to be close to zero assuming the elements of the beam line have been aligned with sufficient precision. Secondly, the $\alpha$ and $\beta$ functions and the emittance will be measured at all 10 tracker planes. This will allow the transfer matrix through the channel to be calculated and the predicted evolution of the $\beta$ function to be measured. The measurements will be compared with the MC predictions as it will be necessary to understand the beam optics in the channel by confronting it with the simulation and potentially allowing for retuning. This phase requires that all of the channel's magnets to have been commissioned and that TOF0, TOF1 and both the downstream and the upstream trackers are available. These requirements imply that this phase of the beamline commissioning may take place once the full magnet commissioning has been accomplished.

The baseline, symmetric setting at 200 MeV/c with an intermediate emittance and with an empty absorber should be used for this assessment and 10k useful triggers ($\sim$ 1 h of useful beam) will be sufficient to assess the optics. However, it may be decided to make a precision measurement at this stage in which case 100k useful triggers, the equivalent of 10h of the useful beam time, will be required.

These considerations lead to an estimated requirement of approximately 3 shifts per setting, including magnet tuning, MMB setting etc. The chromatic behaviour of the Step IV channel may be investigated by performing these measurements on all three momentum settings. This will add up to nine, 8 h long, shifts in total. However at present very little is known about the time it will take to go from one setting of the channel to another. Realistically, this can only be estimated once the magnet commissioning is successfully concluded. Including an additional time for calibration runs, for extra tuning and including contingency the estimated number of shifts is $\sim$ 21 for assessing all three momentum settings.

This phase of the beamline commissioning will allow knowledge and confidence to be built up before the start of the real physics with the absorber filled begins.

## 6 Conclusions

The procedure for magnet commissioning has been defined by the Magnet Integration Task Force. The commissioning procedure is designed to minimise the number of SC-magnet quenches and the associated requirement for liquid Helium, to minimise the required cost and time duration using to the maximum the experience gained in operating MICE magnets to date. It will allow the challenges related to the strong coupling between the magnets to be assessed quickly and will inform decisions on the next steps of the commissioning process. Although the operation of the channel will be challenging due to the strong coupling, there is confidence that commissioning will be accomplished successfully allowing the experience required for operations to be developed. In a worst case scenario magnets would be operated with derated currents that will still allow the successful conclusion of the Step IV programme [5].

The principal phases of beam commissioning have been identified. The required hardware has been listed and the number of shifts needed has been estimated. The process consists of beamline pre-commissioning followed by beamline commissioning. Beamline commissioning includes the commissioning of the diffuser, matching the MMB into the channel and finally the commissioning of the Step IV Channel. The shift requirements are summarised in Table 1. Beam commissioning is required to optimise the input beam, to perform the proper matching into the channel and to ensure that the expected optical conditions are met.

Table 1: Summary of shift requirements for various beam commissioning phases.

| Beam commissioning phase | Number of 8h sifts |
|---|---|
| Beam line pre-commissioning | 8 |
| Beam line commissioning | 15 |
| Mice Channel commissioning | 21 |

## References

[1] `http:mice.iit.edu`

[2] COMSOL Multiphysics web page: www.comsol.com

[3] D. Adams *et al.*, Characterisation of the muon beams for the Muon Ionisation Cooling Experiment, Eur. Phys. J. C (2013) 73:2582 DOI 10.1140/epjc/s10052-013-2582-8

[4] S.Boyd and V.Blackmore, Planning the MICE Data Campaign, document prepared for this review.

[5] C. Hunt, Measuring Muon Beam Emittance in MICE Step IV, talk at MICE collaboration meeting CM39 in Oxford, June 26, 2014.