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MICE Close-Out Review:
Report of the Scientific and Technical Working Group

C. Whyte (Editor), M. Bonesini, A. Bross, C. Jamieson,
S. Peggs, R. Preece, C. Rogers, F.J.P. Soler, J. Tang, T. Taylor.

1. Introduction

The MICE Close-Out Review Panel met on 17th and 18th April 2018, to review the conditions of the MICE approval and to assess the way in which the MICE project was executed by the Collaboration and by the funding agencies, including any project oversight. The purpose of the review was to consider what went well and what did not go so well, with a view to capturing any lessons learnt that can be of help to similar projects in the future.

In addition to meeting in plenary sessions, the review panel broke into parallel sessions of two working groups: Management and Oversight; and Scientific and Technical. This public report from the Scientific and Technical working group complements the confidential report of the larger Close-Out Review panel.

The working group reflected on and considered the impact of decisions and assumptions made during the early phases of the project and on the operating challenges that arose in the later stages of the project. In doing so the group considered the following:

1. the processes and procedures from the start of the approval process which began in 2003;
2. whether the membership and expertise of the original approval panels covered all relevant aspects of the project;
3. the availability of suitable technical and engineering capabilities of all the international partners;
4. technical decision making, including the balance between developing and mature technologies;
5. the governance and reporting structures of the participating collaboration;
6. the interactions between the funding agencies;
7. the host laboratory's understanding of risks relating to hosting the project.

In this section of the report, the Panel reflects on some of the Scientific and Technical aspects of the project that motivate some of the final set of recommendations of the MICE Close Out Review.

2. MICE proposal and approval process

The aims of the MICE proposal to the Rutherford Appleton Laboratory (MICE-NOTE-021[1]) were:

- To show that it is possible to design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory;
- To place it in a muon beam and measure its performance in various modes of operation and beam conditions, thereby investigating the limits and practicality of cooling.

As a consequence, the MICE cooling channel design was based on the Neutrino Factory Design Study I, published in 2000[2]. The MICE cooling channel therefore included the very expensive and technically complicated coupling coils as well as eight RF cavities. By 2004, when the MICE proposal was approved, Neutrino Factory Study II and IIa had already completed. These studies concluded with the recommendation of a simpler lattice design[3,4]. A serious review of the lattice during the Gateway Review process should have identified these simpler lattice designs and challenged both the coupling coil design and the stray field assumptions. The review panel could have recommended a de-scope of the project, to simply demonstrate the physics of ionization cooling with a simpler design, leaving an engineering demonstration for a future phase. This could have made the experiment technically more feasible.

The working group felt that a realistic costing exercise, with fully engineered components and a resource-loaded schedule would have greatly increased the projected final cost and could have killed the project. The advantage of such an approach would have been that the financial, technical and schedule risks would have been better understood from the outset. A reasonable response to the full costing would have been an examination of de-scoping options which should have identified the less demanding lattice designs produced in subsequent iterations of the Neutrino Factory studies. Furthermore, the project team could have critically appraised whether there were any alternatives to 201 MHz RF cavities, which could have significantly reduced the size envelope of the experiment, and hence reduced the cost. The MAP collaboration[5] optimised their design for a Neutrino Factory, named NuMax, with 325 MHz cavities.

3. Beam line

The beam line consisted of a dipping titanium target intercepting circulating protons in the ISIS synchrotron ring and a conventional muon beam with nine quadrupoles, two dipoles and a superconducting decay solenoid to increase the capture efficiency and the pion decay length. A pneumatically operated diffuser system to increase the emittance of the muon beam was also delivered.

The quadrupole and the dipole magnets were recycled from an old accelerator at RAL (NIMROD), and required a full rebuild and test before use. New power supplies were

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[1] http://inspirehep.net/record/611532/files/MICE0021.pdf
[2] http://www.cap.bnl.gov/mumu/studyii/report/Feasibility-I/Feasibility-I-fnal.pdf
[3] http://www.cap.bnl.gov/mumu/studyii/
[4] http://www.cap.bnl.gov/mumu/study2a/
[5] https://map.fnal.gov

purchased for all the resistive magnets. There were few technical issues associated with the commissioning of the warm magnets into the new muon beam line, but some infrastructure issues arose, such as availability of an adequate cooling water supply for the magnets (water leaks were sometimes experienced) and an overall power demand that exceeded the installed capacity in the MICE Hall (a new power sub-station had to be built to cover the projected power demands of the completed Step VI configuration).

The superconducting decay solenoid that was donated to the experiment by the Paul Scherer Institute (PSI) required a significant amount of effort to re-commission. Furthermore, a new refrigeration plant, power supply and quench protection system had to be purchased. The decay solenoid refrigerator and power supply had issues throughout their operation, particularly in the commissioning phase, due to the service agreements with the Linde refrigeration plant. The working group considered whether a new decay solenoid would have been a better investment. On balance it seems that the decay solenoid delivered the performance required at a smaller integrated cost, but at increased risk.

The dipping target, developed from an initial concept by Sheffield university, was a significantly challenging and innovative sub-project of MICE. It required a linear magnetic motor to deliver 80 g acceleration over a distance of about 20 mm, with sub-millimetre precision. The development and implementation was a collaborative effort between university staff from Sheffield, Oxford and Imperial College with further mechanical input from RAL TD. ISIS technical staff were involved throughout. The first prototype, which delivered only 10 g acceleration, was tested successfully at ISIS. A human operational error during operation resulted in the target being “parked” in the beam for longer than required, causing the target to melt.

The first target system to deliver 80 g acceleration produced a small amount of dust from wear and tear and heating of materials. This target was significantly redesigned. The final version operated with a lifetime measured in tens of millions of actuations. A replica system was built to demonstrate to ISIS the safe operation of the target and as a hot-swappable spare. Sheffield University took ownership of this project, but it suffered initially from lack of technical expertise and dedicated engineering effort. However, over the final three years of the MICE project, the target was extremely successful and is seen as a technical achievement of the experiment.

The diffuser system, which was designed and built at Oxford, was also considered to be a technical success. The diffuser included a pneumatically controlled system to insert varying amounts of material in the beam line to change the emittance of the muon beam in a controlled manner. Since it operated in the vicinity of the high stray magnetic fields of the spectrometer solenoids, it could not use any magnetic motors. The whole system operated with a pneumatic system that could be controlled from the MICE control room. The diffuser operated smoothly throughout the data taking, except for a few minor issues. It enabled fast turn-around of beam conditions.

4. Detector systems

Due to their background in experimental particle physics, all the detector teams were very experienced in the design, construction, installation, commissioning and operation of particle detector technologies. The detectors delivered included an ambitious scintillating fibre tracker, a state-of-the-art Time-of-Flight (TOF) system, a Cherenkov detector with aerogel radiators, a pre-shower detector labelled KL and an Electron-Muon-Ranger (EMR). Institutional responsibilities for all the MICE detectors and other systems in MICE are found in Table 1.

All detectors worked to specification and were built and commissioned successfully, due to the experience and diligence of the detector teams. Furthermore, sufficient resources were made available to the various detector teams to build and operate the detector systems. All the sub-systems ran very smoothly, with few issues, and achieved their technical performance goals. As an example, the fibre tracker group, in addition to the motivated physicists, had the necessary mechanical, electrical and cryogenic engineering resources (along with appropriate drafting effort) to support the design and construction work. This paradigm was not available to all aspects of the MICE program.

MICE System	Responsibility
Muon beam line	STFC (initially CCLRC)
Infrastructure and integration	STFC (initially CCLRC)
Luminosity monitor	Glasgow
Diffuser	Oxford
Scintillating fibre tracker	Imperial, Brunel, Liverpool, FNAL, Osaka
Time-of-Flight (TOF)	INFN
Cherenkov	Louvain (Belgium) and then Mississippi
KLOE-Light (KL)	INFN, Sofia
Electron-Muon Ranger (EMR)	Geneva
RF cavities	LBNL
RF power systems and waveguides	Strathclyde, STFC, Mississippi
Spectrometer Solenoids (SSU and SSD)	LBNL
Focus coils	Oxford, STFC
Coupling coils	LBNL, Harbin
Hydrogen system	KEK, STFC
DAQ	Geneva
Online control	IIT, Chcago
Target	Sheffield

Table 1: Summary of institutes with MICE system responsibilities.

5. Superconducting magnets

The conceptual design of the three superconducting magnet types (spectrometer solenoids, focus coils and coupling coils) was done by LBNL, driven in large measure by a desire to save money. The designs suffered, resulting in the propagation of significant design flaws which a suitably qualified review should be expected to identify and challenge.

Flaws included

- Reliance on an internal (instead of external) support mandrel, as per usual practice for this type of solenoid. This problem would have been identified had there been a proper thermo-mechanical analysis. An experienced review team would have demanded this analysis, to correct the thermo-mechanical deficiencies, prior to procurement.
- Poor dimensioning and routing of bus-work linking the windings in the SS magnets.
- Insufficient temperature margin. The cost of the superconductor is small compared with that of constructing a single or a small series of magnets, so it is good practice to use conductor with a generous cross-section to provide a good margin.
- The problem of return magnetic field shielding should have been addressed at the design phase, and local magnetic shielding included in the original design. The shielding walls that were constructed did not address the influence of magnetic fields in the equipment in the hall. As a consequence, further magnetic shielding, in the form of the partial return yoke (PRY), was required, at great expense and causing more delays.

When a company wins a bid to supply a magnet, there must be a professional follow-up and, if necessary, the company should be given technical assistance to fulfill the contract. Once the contract is placed, it is in the interest of both vendor and client that the contract is fulfilled.

- The vendor chosen (Wang NMR inc, Livermore USA) for the spectrometer solenoids required extensive support. Follow-up and quality control in the manufacturing of the spectrometer solenoid magnets resulted in deficient practices and quality control measures, which ultimately proved fatal.
- The spectrometer solenoids had to be disassembled and re-built. Ultimately, a quality control failure resulted in the loss of the matching coil in one of the solenoids. The cost and schedule consequences of the required remedial work had a profound impact on the experiment. This ultimately resulted in the decision not to proceed beyond Step IV.
- The first coupling coil cold mass was tested to full current but was never installed into a cryostat.
- The focus coils also suffered from problematic thermal behavior. One of the magnets did not achieve the design specification current. There is some evidence that this may be due to overly tight clearances for the thermal insulation, which caused squeezing of the superinsulation layers.

More effort should have been put into finding ways to fund a larger cryogenic refrigeration plant to cool all the superconducting magnet systems, instead of using cryo-coolers for the spectrometer solenoids and focus coils. The decision to use cryo-coolers resulted in significant delays to the magnet program many of which would have been effectively mitigated by the increased cooling power available from a cryo-refrigeration plant. Low cooling margin also contributed to increased down-time during data-taking operations as the magnets had to be finessed during ramping operations. Lastly, the use of cryo-coolers placed increased load on the water-cooling plant, forcing operation into a temperature regime for which it was not well designed.

If some of these issues had been identified and corrected at the project approval stage, many of the delays and cost over-runs would have been avoided. The assumption that LBNL could provide working spectrometer solenoids and coupling coils proved to be naive.

6. RF cavities and power

The RF systems sub-project suffered from a number of changes throughout the project. Design of the RF cavities and the coupling coils was carried out at LBNL. However, significant cost and schedule over-runs, and increased risk to the project, led to a cancellation of MICE Step VI, which was envisaged as two Coupling Coils with eight RF cavities. A project review in 2014 deemed that a simplification to the design of the experiment, with only two RF cavities and without the Coupling Coil, could still demonstrate ionization cooling albeit with reduced accelerating gradient. This type of simplification of the project design, if carried out much earlier at the approval and scoping phase of the MICE project, could have led to a significant reduction in cost, schedule and risk. Consequently, resources were wasted in the procurement of superconducting cable, the follow-up of manufacture of the coupling coil and the development of the RF systems.

After the failure of the matching coil of the downstream spectrometer solenoid, a UK-based cost-to-completion review concluded that the project should complete Step IV (with just the spectrometers and the absorbers), adding extended data taking but not proceeding to the Step VI RF accelerating phase. At this point, all RF cavity and power supply effort stopped. The RF cavities were manufactured by LBNL, but were never put into operation. The RF power system designed and largely completed in the UK, which was shown to operate up to 1 MW, was never deployed in MICE. Again, this cancellation resulted in wasted resources and effort. It was extremely demoralizing for the members of personnel that had been working on the RF systems for many years. Furthermore, new institutes (IHEP and Sizchuan in China, Belgrade and Novi Sad in Serbia and UNIST in South Korea) that joined the collaboration on the basis of participation in the RF project were not able to complete their contributions. This led to a loss of reputation and to disappointment that the final demonstration of ionization cooling with reacceleration was never achieved.

7. Software, data acquisition, controls and computing

The simulation and reconstruction package, MAUS, ultimately met the requirements of the experiment and in the final years was a key resource enabling the collaboration team on several occasions to re-design the experiment and verify the projected performance of the design for presentation to the reviewing committees. The initial G4MICE framework had too many external dependencies and reconstruction paradigms, which were impossible to debug and lacked operational flexibility. Data serialisation also proved to be an issue, leading to a redesign of the framework into MAUS. The data format, based on ASCII JSON files, was very slow. A format change and a programme to increase the data flow led to improvements in the speed of the simulation and reconstruction. More experienced oversight of the project could have helped prevent some wrong turns along the way. However, in the end, MAUS was extremely efficient and very fast. Data collected was available for analysers within an hour of data taking, which led to a fast turnaround during the final phase of the experiment.

Overall, the data acquisition (DAQ) was able to successfully and reliably read out all the experimental systems, meeting most specifications. The DAQ did not meet the specification for required rate (600 muons per second), both for the tracker and the other detectors, but other factors (such as beam loss in the ISIS synchrotron) also limited the rate of data taking, so this did not strongly affect data collection. The DAQ developers were not local to RAL. The lack of on-site support caused some additional down-time, but local expertise was recruited to overcome some of these problems.

The controls software had many technical issues that impeded data taking. A local team of experts should have been put in place to implement the controls software. However, lack of experienced software personnel, exacerbated by a lack of line management for the individuals involved, added significantly to the problems. This was made worse by the remote nature of many of the collaborators who were contributing to the controls sub-system. A restructuring of the controls team at the end of MICE led to significant improvements that allowed the final data taking push in the final months of the project.

The computing infrastructure (websites, batch processing, and MICE control room) was generally reliable. Significant issues with the RAL networking support for visitors to the laboratory impeded work on the experiment. Permits for non-STFC users and access to some basic computing services, such as wireless, printing and email, led to frustration amongst some of the external collaborators.

Summarizing some of the issues encountered:

- There was insufficient oversight, neither on a line management level nor on a project management level, in some aspects of the software and computing. This was exacerbated by the distributed nature of the project, where workers and line managers were often on different sites and sometimes in different countries.
- The collaboration could not provide local on-call support for equipment, resulting in additional maintenance downtime.
- The laboratory networking infrastructure was not sufficiently reliable.
- The temporary nature of PDRA staff and PhD students led to significant overhead in training.
- STFC staff turnover led to significant extra overhead in training. Staff were often pulled to other STFC projects that had higher priority

Lessons learned include:

- A stronger senior management team should have been assembled with more direct buy-in to the project.
- Collaboration members should be required to provide local on-call support for equipment and projects for which they have responsibility.
- The RAL networking infrastructure should improve support for visitors (this was subsequently implemented).

8. Host infrastructure

The MICE hall Infrastructure (power, cooling water, air conditioning, electrical services, and personnel protection systems) was an on-going issue throughout the experiment. These capabilities are best dealt with by the host laboratory. Rarely, elsewhere, are they the responsibility of the experiment, except in limited cases related to specific equipment. A better understanding of the responsibilities of the host laboratory to the experiment would have helped streamline the provision of services and the supply of infrastructure. An assessment of the overall infrastructure and long-term maintenance needs should have been assembled by the host and then developed (in partnership with the MICE collaboration) into a detailed plan describing how these needs would be met.

9. Legacy

An indirect result of the evolution of the MICE experiment, and the well-publicised technical and financial difficulties of the project, leave a poor legacy for the development of future Neutrino Factories or Muon Colliders. MICE is perceived outside the collaboration as a technically very difficult project, so MICE is often cited to support the argument that Neutrino Factories or Muon Colliders are technically difficult and costly. It has been heard at particle physics community meetings and conferences that 'if MICE could not make a realistic ionization cooling channel work then Neutrino Factories or Muon Colliders are not practical propositions for the future'. This continues to impact research into Muon Storage Rings for neutrino physics and as a Higgs factory.

One of the lasting technical achievements of MICE is that it demonstrated that single-particle physics diagnostic techniques could be applied to accelerator physics measurements. The single-particle approach allows more precise measurements of beam parameters than more conventional diagnostic devices and provides data to explore some of the beam properties in greater detail. The collaboration's strength in detector design produced an excellent diagnostic instrument despite limited availability of national-lab expert technical staff.

Continuity of PDRA staff over the duration of the experiment was key. Students and PDRAs had ample opportunities to deliver conference contributions (313 delivered) but the number of peer-reviewed journal publications was small in comparison with other experiments. The number of MICE publications was not sufficient for PDRAs to compete effectively for academic posts at universities and research laboratories. However, it is expected that the number of high-profile publications will increase over the next year as the high-quality data is analysed. A detailed plan to deliver those publications is under construction.

RAL PPD research staff were never fully engaged with MICE, and the experiment suffered as a result, since it did not have local champions to promote the physics goals. Had MICE been owned and driven by PPD, it may have been possible to uplift the availability of ISIS capability to cover MICE requirements for electrical, water and air-conditioning, warm magnets and cryogenics. Having ISIS as an equal partner would also have been highly desirable.

The working group qualitatively considered the legacy and impact of each individual components of the MICE experiment in terms of both the innovation and originality, and also the technical execution by the collaboration team. The innovation and originality of some of the technical components were considered to be achievable, but the scale of the project and the integration of all of these components into a coherent experiment proved to be challenging. The general execution improved dramatically as the project progressed: as the team became more technically competent and as more professional project structures were adopted.

10. Technical and scientific successes

Although many sub-projects were delayed, in some cases significantly, the many technical and scientific successes that were achieved go beyond the published legacy of the MICE experiment. For example:

- The suite of diagnostic detectors produced state-of-the-art results, running flawlessly over an extended high-pressure data taking period to record over 1×10^8 triggered events for analysis. All detector systems operated (and exceeded) their performance expectations.
- MICE developed a core team of physicists and engineers over the long term that developed expertise in both accelerator and particle physics techniques, with novel applications of particle detectors for accelerator diagnostics.
- The final version of the target operated reliably at a peak acceleration of 80 g, dipping into the ISIS beam with a precision of 0.1 mm, and with up to 2×10^7 actuations between services.
- The MAUS simulation and reconstruction software suite in its final implementation was fast and accurate. MAUS served the Collaboration's demands for swift re-design of the experiment at short notice on several occasions, providing renewed opportunities. The MAUS application includes sophisticated software tools that can be used to develop future accelerator design opportunities.
- The Partial Return Yoke was designed, delivered and installed to schedule. Magnetic field measurements taken after data taking verified the robustness of the design.
- The liquid hydrogen absorber was designed and delivered to specifications, the first such installation of a liquid hydrogen system at a UK laboratory in decades. The system was delayed only by the liquid hydrogen supply system, the final implementation of which operated flawlessly.
- When data analysis is completed, the scientific legacy of MICE will include a first experimental demonstration of ionization cooling, with prospects for applications in future muon accelerators. MICE data will also produce state-of-the-art measurements of multiple Coulomb scattering and energy loss in low-Z materials, such as lithium hydride and liquid hydrogen.
- The inclusion of wedge absorbers in the final data-taking phase will lead to the first demonstration of emittance exchange, paving the way for six-dimensional ionization cooling required in a Muon Collider.
- New emittance measurement techniques, and the delivery of an engineering demonstrator for a cooling channel, have also been achieved. While there have been technical challenges associated with the development of MICE, it has conclusively shown that ionization cooling is a valid technique to realise a Neutrino Factory or a Muon Collider, and that it is feasible to engineer a cooling channel for a future facility.