Report on the MICE Optics Review

Held 14-15 January 2016, Abingdon, Oxfordshire, U.K.

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Intro

A review of the beam-dynamics analyses anticipated for the Muon Ionization Cooling Experiment (MICE) being conducted at the STFC Rutherford Appleton Laboratory was carried out on 14-15 January 2016. The reviewers were asked to *(taken from the* Terms of Reference *for the meeting)*:

1. Consider the data reduction, analysis, data-curation techniques and the beam-optics and simulation methodology adopted by the collaboration;
2. Identify areas in which improved techniques or methodologies should be developed to improve the analysis or to expedite its completion;
3. Consider the Step IV programme in the light of the loss of the M1D coil in the downstream-spectrometer solenoid, comment on the degree to which the Step IV programme can be executed using the configurations presented by the collaboration and advise on improved strategies to maximise the physics output of Step IV; and
4. Advise on strategies by which the impact and clarity of the results of the experiment can be presented to the accelerator–and experimental–physics communities.

The reviewers heard presentations from the MICE collaboration that led to many fruitful and interesting discussions over the two days. The collaboration was very well prepared and responded timely to the over-night "assignments" asked for by the committee. In what follows, findings by the committee are listed as well as recommendations spurred by the guidance to the committee found above.

Overall, the MICE instrumentation and measurement performance found from simulations and from initial data from the system were presented and the arguments indicate sufficient resolution and sensitivity for Step IV and cooling demo measurements. In the pages that follow findings from the Review are presented as well as a list of recommendations for the collaboration to consider.

Date: 15 February 2016

Findings

A large set of well-prepared presentations covered in great detail lattice optimization for the final cooling ionization demo, development of an alternative scenario following the M1D failure (and M2 running at 60% of its capacity), description of data analysis and phase space reconstruction from experimental data, data logging system, physics of the interaction of the muon beam with materials (energy loss and multi-Coulomb scattering), RF phase identification and selection, magnetic field characterization, operational planning.

The committee understands that the MICE project team has explored the possibility to rearrange the existing hardware to ease mitigation of the M1D failure. In particular, moving S2 closer to S1 or even rotating S2 by 180 degrees, so that the working coil in S2 will be placed closer to the centre, would likely make optics reconfiguration, with failed M1D, easier. However, the MICE project team has found that such reconfiguration of the existing hardware is quite difficult, due to, for example, mismatch of various cable and cryogenic connections with the penetrations in the magnetic shielding. Therefore, the MICE project team considers only the option of optics reconfiguration without moving hardware around. The Committee agrees with this decision. If unexpected difficulties with optics and beam analysis are encountered, or if the process of M1D repairs meets unexpected delays, the option of reconfiguration of the existing hardware may need to be revisited and explored in more detail.

Physics goals of the experiment

Status of MICE. A separate Muon Accelerator Program Director's review was held at FNAL on 3-4 December 2015, whereby it was recommended and subsequently agreed to manufacture a new cold mass in parallel to the Step IV measurements of MICE in order to move toward a full Cooling Demonstration in roughly one-year's time. Thus, the present committee fully expects the successful repair of the M1D coil and sufficient functionality for the cooling demo. The Step IV measurements are to be performed over the next year, with a newly developed optics scheme that does not require the inoperable coil. The cooling demonstration is to follow the subsequent year.

Expected performance. The primary goals of the Step IV measurements are to characterize and verify the expected multiple Coulomb scattering and associated *dE/dx* through the relevant material in the MICE apparatus and cooling channel. For Step IV, the system without M1D as presented should perform adequately to provide the necessary measurements of scattering and energy loss.

The MICE instrumentation and measurement performance found from simulations and from initial data from the system were presented and the arguments indicate sufficient resolution and sensitivity for Step IV and cooling demo measurements. If the M1D coil were not in the final configuration, the final expected performance would indeed be in doubt for the cooling demo. For Step IV, the re-tuning of the optics allows for meaningful measurements of the intended parameters.

Materials characterization

Scattering discussion. The committee found that the presentation and ensuing discussion of the material-physics measurements to be performed over Step IV provided a strong and relevant physics case. In addition to being important for the proper interpretation of the cooling demo measurements, the Step IV measurements are themselves of high importance to the general understanding of particles (muons in particular) passing through low-Z materials at these energies.

Single Particle Simulations

Lattice optimization. The linear optics for the Step IV configuration and for the Cooling Demonstration was optimized originally using standard software packages. Meanwhile, new software tools were also generated that allow for powerful optimization of the system using genetic algorithms. Having these tools available and tested at the time the M1D coil failure occurred has enabled the collaboration to find new settings of the optical elements allowing for Step IV to continue during the upcoming year while the new M1D coil and downstream solenoid package can be repaired. The collaboration has mastered a full suite of simulation tools that will provide simulations and data analyses (see below) that can cover the wide range of conditions present in the experiment.

Data Analysis

The committee was presented information on the MICE computing framework, database and user software. An impressive amount of effort has gone into the development of a data and database management system for MICE. The MICE Analysis User Software (MAUS) provides a robust interface between the data and user to enable quick and efficient data visualization and analysis. The system is up and running and has provided initial "beam" data for analysis. The initial data, taken during the 7th October 2015 run and amounting to over 14,000 muon events delivered from ISIS, were presented and continue to be analyzed by the team.

An impressive plot of the phase space of the ~14000 muons tracked was presented. This is probably the first phase space evolution of a beam reconstructed from measured particle-by-particle data and perhaps the first 'direct' emittance measurement, i.e. based on the statistical definition of emittance (with the disclaimer that the 'beam' in this case is also an off-line collection of muons that actually went through the detector at different times).

The particle ID system is working well, and a system for particle timing via RF phase determination will be implemented and tested over the coming year (important for the final cooling demonstration). Initial scattering angle measurements are beginning to unfold, critical for both Step IV and the cooling demo. Methods for analyzing emittances of particle distributions were presented and widely discussed between the presenters and the committee. In particular, the interpretation of results in the presence of dispersion was discussed in full, leading to new insights into ways to admit more particle measurements into the final analyses thus, perhaps, enhancing the measurement or reducing the overall necessary measurement times.

Measurements

Detectors. The general characteristics of the particle detectors have been well established. Very detailed simulations are being performed to continue to scrutinize the system, especially with regards to alignment and calibration. Now that relevant particle (beam) data is beginning to appear, iterations will continue to take place to flush out the various systematics.

Magnets. A large amount of data has been taken on the magnetic fields of the tracker solenoid system as well as several magnet surveys. The magnetic axes of the modules have been determined to <0.3 mm and are within 1mm of the module flange centers. The SSC module has a large pitch that is going be addressed.

Physics. With a re-optimized optics, increasingly understood detectors and magnets, and robust data management and analysis tools, the program is well positioned to begin first runs toward physics measurements over the next year for Step IV.

Overall, the committee appreciates the set of powerful simulation tools and advanced technical skills displayed by the collaboration. The team appears to have all the means to fully assess the physics outcome of Step IV, as well as fully exploit the potential of the MICE Step IV despite the failure of the M1D coil. And, with a fully functional system for the Cooling Demonstration expected, this yields confidence in the group's ability to succeed in the final goals of the demonstration.

A successful matching of the measured evolution of the tracked muons with the simulated one is essential to build the trust in the reconstruction methods which will allow the identification of the emittance reduction in the final ionization cooling demo. The particle-by-particle trajectory measurement that MICE offers is also a unique opportunity for accelerator physicists to check and benchmark the various well-established single-particle tracking codes. The success in fully reconstructing the data using the advanced modeling tools that have been described in several talks is a crucial step already at this stage (Step IV).

Recommendations

1. Continue to work on bridging the HEP and AP communities. Language (jargon) for example: bunch vs. single particle, amplitude vs. area, tracking vs. trackers vs. … even “cooling” gets used differently at times. Perhaps most importantly, as the experiment is searching for small changes in the emittance it has to find a robust way of defining `emittance'.
    a. The RMS definition does not satisfy this, as it is subject to losses and to filamentation effects. The collaboration is generally aware of the first and accommodates it by considering only the initial particles that are also selected as final particles, but not of the second. Hence several plots shown had increases and decreases in emittance which taken at face value would clearly violate Liouville's theorem. A definition in terms of `particle amplitudes' – though that name is unfortunate – is used in some of the talks presented: it needs to be widely adopted.
    b. Lost muons are typically removed from initial distribution and not taken into account for emittance analysis. Since lost particles in upstream end of beam line are the major contributor in final emittance, it is possible that this cut artificially reduces final emittance more than initial one. This effect needs to be analyzed.
2. Test understanding by using the same data reconstruction algorithms and tools on both simulated (tracking) data and real data (simulation data could be saved in the same file format as the on-line data, in order to be processed by the same software, etc.).
3. Further optimize resources. A reshuffling of resources and ideally seeking new recruitment might be in order now that data taking is near.
4. Move toward an integrated end-to-end (from TF1, say; excluding the target) muon tracking simulation completing the currently missing parts (e.g., partial return yoke and solenoid misalignment).
    a. Run the genetic-algorithm optimization with SSU and SSD as **independent** degrees of freedom. (The aim of the optimization is to find how SSD can cope with the lack of M1D. Adding a new degree of freedom might help.)
    b. Although the present mismatch could be due to the non-uniform solenoid field, which is so far not included in the model, an effort should be made to fully explain this case.
5. Better ascertain the implications of taking data over several days or several weeks. Are you sure all relevant parameters (incl. hall temperatures, phase of the moon, etc.) will be data-logged?

6. Building upon all the above, improve and test the data reconstruction algorithm to assess the precision of the emittance measurement and its

sensitivity to the effects of **static** and ***dynamic*** imperfections. This should be performed on the simulated data.

   a. Check the reconstruction algorithms on simulations of an ideal setup.
   b. Assess the impact of imperfections on the measurements precision of emittance and scattering angle.
   c. Demonstrate, using simulations, how well emittance can be measured both with and without the M1D magnet. Then the vital question of whether changes in emittance can be measured can be more readily established. (Or, perhaps, how long one would need to take data to do this, and then whether it is realistic to run for this period without changes in conditions.)

7. To maximize the physics output the experiment should exploit all the muons. In this sub-sampling exercise, minimize the number of muons that are thrown away. Explore optimization of upstream optics (e.g., dispersion, beta matching) to increase muon acceptance.
   a. Continue to analyze data in ways to include dispersion effects so as to be able to include more of the data set in the analyses and to better understand systematics. Initial distribution with small energy spread is beneficial to reduce dispersion effects of lattice, but will require more time to collect required number of muons in re-constructed phase space. Analyze dispersion effects to optimize acceptable energy spread in initial distribution.
   b. Continue studies of chromatic beta function, effects of solenoid alignment, nonlinearities, etc.
   c. Be sure that after installation in beam line, magnetization of all environmental material does not affect field map. This should be taken into account in all simulations and track reconstruction algorithms. Compare performance of the system for ideal fields and perfectly aligned system vs. realistic parameters.
   d. Find out what region of the input phase space maximizes the transmission and try to match the input beam to that (including modifying the upstream optics if necessary).
   e. Material Physics of absorber (losses and multiple scattering) is not well known. Check how emittance reduction value is sensitive to details of models, as presented in R.Soler talk in this review.

8. Some general remarks that could help in the future to better structure a review that targets an audience mainly made of accelerator physicists:

   a. Start from a general explanation of the experimental set up from the extracted beam from ISIS up to the end of the ionization channel. Introduce how the final beam of muons/pions/electrons is created and reaches the entry point of the ionization channel, and what phase space is expected at that point. It is this initial condition together with the magnet settings in the ionization channel that will then determine the optical properties (beta functions) of the channel itself. With this approach, the presence of a correlation between the transverse phase space and the longitudinal momentum at the entrance would be directly taken into consideration in the construction of the downstream optics, with its dispersive and chromatic effects.

b. Provide an overview on all the tools used for the optics and particle tracking through the ionization channel. Describe the underlying models and their level of completeness/robustness (which probably was partly done at this review, just that the talks could have been given in a different order and better cross-referenced).
c. Explain and fully justify upfront the approach to construct a 'beam' as an ensemble of muons going through the channel over a certain acquisition time span and not necessarily all together as a real beam (e.g. particles are not interacting with each other in the transport, i.e. space charge can be assumed to be negligible, but are there other ensemble dependent effects we might be neglecting e.g. in the cooling through the absorber material?).
d. List clearly at some point all the criteria that lead to particle selection for the creation of the final 'beam' to be analyzed. An optimization goal should be in fact also to limit this particle selection as much as possible and therefore increase the efficiency of the experiment. The aim should be kept around not dismissing large amounts of data that could be potentially used and not requiring running much longer than needed in order to collect the needed statistics.
e. Since the emittance reduction that the experiment seeks to measure seems still rather small compared with other emittance changes along the ionization cooling channel, it is essential that an error analysis based on different scenarios is conducted and shown in detail as a dedicated topic.
f. Provide some simulation results illustrating the various terms of the basic cooling equation; perhaps show results of a "cooling channel" and emphasize that MICE is a basic unit.
g. Example presentation: start with original linear lattice, then without M1D, then how to optimize (using genetic algorithms), leading to "today's" final solution.
h. Good to show that there is still a lot to learn about multiple scattering and energy loss (nice presentation); bring this in earlier in the discussion. The nature of the data is such that an unfolding procedure is required. This should be considered seriously. We recommend two methods, possible SVD decomposition and Iterative Bayesian. Consult Tim Adye and Fergus Wilson (both at RAL).