Response to feedback from the MICE Optics Review

The MICE collaboration welcomes the feedback from the MICE Optics Review panel following the meeting on the 14th and 15th January 2016. This document provides the collaboration's response to each of the panel's 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".**

   The collaboration will continue to address this issue. In particular, the collaboration seeks to report its work in journals and at conferences serving each community seeking, in this way, to expose the experiment to experts from both fields.

   1.a. **The RMS definition does not satisfy this [i.e. is not a robust definition of emittance], 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.**

   The collaboration is actively seeking to improve its presentation and understanding of filamentation effects. In addition to the studies of amplitude, the collaboration is studying measures of estimating the phase-space volume occupied by the beam; the Kernel Density Estimator technique [1] and tessellation of phase space [2] using measured particle phase-space coordinates are both under study. An example of the phase space of the beam reconstructed using the Kernel Density Estimation technique is shown in figure 1.

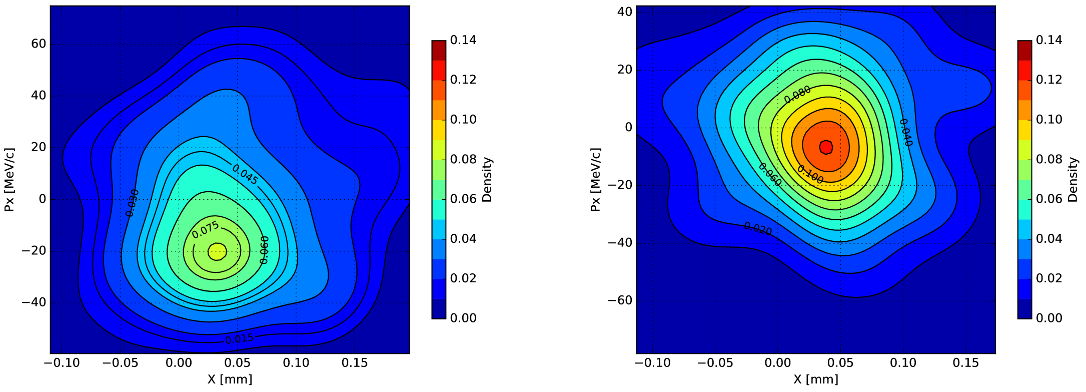

Figure 1: Density estimation of a simulated beam passing through the MICE lattice, calculated using the Kernel Density Estimation (KDE) technique [1]. The (x, p_x) space is shown at the reference surface of the upstream tracker (left panel) and at the reference surface of the downstream tracker (right panel).

The collaboration is also studying the effects that drive filamentation. Flexibility in the MICE magnetic lattice may make it possible to examine the effect of varying parameters that can drive optical

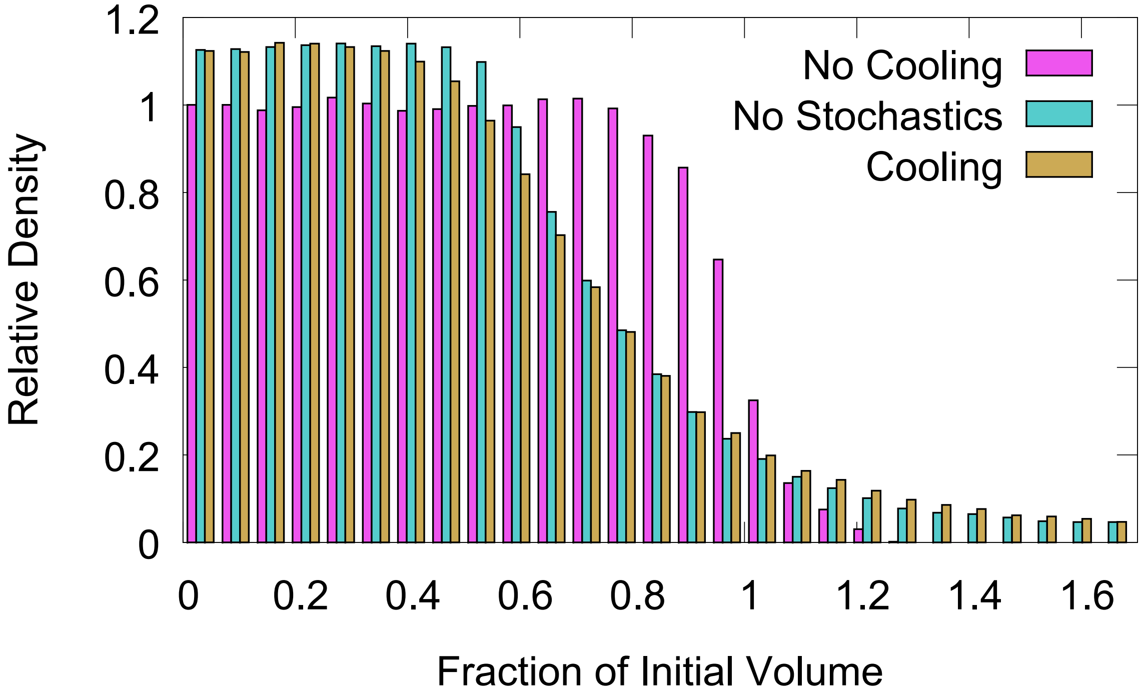

Figure 2: Particle count in histogram bins relative to what would be expected for a linear system with no cooling. Horizontal axis corresponds to $(J_x + J_y)/J$. 262144 particles were launched with $J = 1.0\,\mathrm{MeV.s}$. Runs are with either no absorbers, only the average energy loss included, or a full simulation with energy loss, energy straggling, and multiple scattering included.

emittance-growth (for example adjusting the focusing strength of magnets) and to measure the associated emittance-growth in detail.

1.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 analysed.**

The collaboration has performed an analysis in which the initial phase space, measured in the upstream tracker, is sliced into concentric volumes of equal size. Volumes of lower amplitude have a larger particle count. The distribution of particles within the phase-space volumes defined in this way gives an approximation to phase-space density. Similar concentric volumes of the same size are defined for the final phase space measured in the downstream tracker. If there are volumes in the final phase space with a higher particle count than that of the initial phase-space volumes, an increase in phase-space density will have been observed, indicating cooling.

The analysis has been applied to the Step IV lattice using simulated data; example results were presented at the review by A. Liu (see page 5 of [3]). Figure 2 shows the increase in phase space density for a sample of muons in such a Step IV lattice. A paper on the technique was published in the IPAC 2015 proceedings [4].

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.).**

The software framework and data structure are designed such that the outputs from simulation and real data are identical in format, allowing the same reconstruction and analysis programs, without modification, to be run on both simulated and real data. When data are simulated, the reconstruction operations are identical to those performed on real data. It is routine practice to compare the results of data analysis to the simulation to gain an understanding of detector effects and the underlying accelerator physics.

3. **Further optimize resources. A reshuffling of resources and ideally seeking new recruitment might be in order now that data taking is near.**

   The collaboration is actively seeking to recruit additional members. Groups from China and Serbia have recently joined the collaboration. Discussions are underway with Korean groups to enhance the collaboration further. The collaboration routinely considers (and reconsiders) carefully the distribution in the light of pressures on its construction, simulation and analysis activities and in the light of recommendations from its various review and oversight bodies.

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).**

   The end-to-end simulation of MICE is achieved using a combination of simulation codes. Work is in hand to streamline the generation of particle distributions generated using G4beamline [5] at TOF0, which is the most time-consuming step. At present, the distribution at TOF1 is being validated to ensure that it represents the measured distributions obtained using the MICE Muon Beam. Consideration is also being given to the need to increase the speed of execution of the simulation of the experiment. In parallel, the effect of the partial return yoke (PRY) on muons passing through the experiment is being taken into account using a field map generated using OPERA that accounts for the soft iron of the PRY. The necessary infrastructure to add magnet misalignments is also being developed.

   4.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.)**

   The upstream and downstream spectrometer solenoids are each treated as independent elements during the optimisation of the Step IV lattice (see for example [3]).

   4.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.**

   The MICE collaboration makes full simulations of the lattices including realistic 3D field maps generated using the as-built geometries of all the coils. Particle trajectories are calculated by integrating the Lorentz force law through the field maps. The 3D field maps have a correct fringe-field model. The trajectories of particles traversing these fringe fields are calculated with micron-level precision, including non-uniformities in the field maps.

   There are two sources of mismatch in the MICE Step IV lattice. Limitations in the MICE Muon Beam can lead to a mismatch on entry to the MICE lattice due to dispersion and chromatic effects generated by the tight focusing required in the cooling cell for beams with relatively large emittance. Beam selection upstream of the cooling cell will be used to diminish the particle density in overdense regions of phase space to improve the match into the cooling cell.

   Downstream, in the absence of match coil 1 in the downstream spectrometer solenoid (SSD), there is insufficient focusing to catch the beam as it leaves the focus-coil region. In a conventional accelerator, one might loosen the focusing in the focus-coil region, reducing the requirement for focusing in the SSD match coils. Unfortunately, in MICE this would degrade the cooling performance of the lattice. In Step IV, it is planned to allow some degree of mismatch as this appears to result in limited emittance growth that is only present downstream of the measurement planes in the SSD region.

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?**

Though data are taken over several days and weeks, individual data sets are broken into "runs" that span approximately two hours. This makes it possible to understand variations run-to-run in a systematic manner. The Hall and detector environments are monitored constantly and logged to an archiver. Further work is underway to store the Hall-probe readings from the magnets in the raw-data stream. Following the committee's feedback we shall take stock of the parameters that are currently being logged and check once more that the list is comprehensive.

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.**
   6.a. **Check the reconstruction algorithms on simulations of an ideal setup.**
   Reconstruction of individual detectors has been validated using simulations using idealised geometry and with "infinitely-precise" instrumentation. Further tuning and optimisation of track reconstruction and particle identification is underway.
   6.b. **Assess the impact of imperfections on the measurements precision of emittance and scattering angle.**
   As noted in (4), batch simulation efforts are underway to study this and to validate the reconstruction in the presence of imperfections in the magnetic field and detector (mis-)alignment.
   6.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.)**
   The absence of match coil 1 (M1) in the downstream spectrometer solenoid does not affect track reconstruction as the field remains acceptably uniform in the tracking volume. This has been demonstrated in the analysis of the data taken on the 7th October 2016 with the end and centre coils of the upstream solenoid at full current and with both match coils off. The effect of the loss of M1 on matching and transmission will be studied using dedicated Monte Carlo simulations in various cooling-cell configurations.
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.**
   The collaboration thanks the committee for this recommendation. The collaboration is studying how to improve the upstream optics and sample the beam in an appropriate manner.
   7.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.**
   Following discussion at the optics review, the collaboration has identified a means to provide a beam with smaller momentum spread but larger pion impurity. The collaboration expects that pion rejection will be possible at the required level using the existing detector infrastructure. Monte Carlo simulations have been undertaken following the optics review and data has been taken to confirm the simulated beam distributions.

   The collaboration will continue to study the effect of dispersion in this context.
   7.b. **Continue studies of chromatic beta function, effects of solenoid alignment, nonlinearities, etc.**
   The collaboration will continue its study of the effects of non-linearities and misalignment on the lattice.

7.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.**

MICE has studied the tolerance of Step IV beam dynamics to the following parameters:

- Magnet currents;
- Magnet alignment;
- Input beam alignment and matching; and the
- Effect of the Partial Return Yoke, including misalignment.

Tolerance studies on the diagnostics performance have not been performed in detail.

The collaboration has undertaken a full tolerance analysis of the demonstration-of-ionisation-cooling lattice. This analysis is presently underway.

7.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).**

The collaboration notes that cooling performance depends not only on transmission but also on momentum spread at the absorber and optical "heating" of the beam. Maximising transmission is of interest for material physics studies.

7.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 P.Soler talk in this review.**

The effect of multiple scattering on the cooling performance of MICE as well as the precision with which multiple Coulomb scattering can be measured has been studied [6]. Part of this work was presented at the review by P. Soler. For example, the equilibrium emittance has been studied for different multiple scattering models (see for example table 5.2 in [6]). Discrepancies in the equilibrium emittance of up to 50% in liquid hydrogen can be observed for different models.

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

The collaboration thanks the committee for this and following recommendations and will carefully consider future presentations for such an audience.

References

[1] D. Scott, *Multivariate Density Estimation: Theory, Practice, and Visualization*. John Wiley & Sons, 1992.

[2] C. T. Rogers, "Phase Space Tessellation to Estimate Non-Linearities in the MICE Lattice." slides at MICE collaboration meeting 44.

[3] A. Liu, "MICE Step IV Lattice Design." slides at MICE optics review.

[4] J. S. Berg, "Phase Space Density as a Measure of Cooling Performance for the International Muon Ionization Cooling Experiment," in *Proceedings, 6th International Particle Accelerator Conference (IPAC 2015)*, p. WEPJE025. 2015.

[5] T. Roberts *et al.*, "G4beamline, A Swiss Army Knife for Geant4, optimized for simulating beamlines." `http://www.muonsinc.com/muons3/G4beamline`.

[6] T. Carlisle, *Step IV of the Muon Ionization Cooling Experiment (MICE) and the multiple scattering of muons*. PhD thesis, Oxford U., 2013.