Planning the MICE Step IV Data Campaign

1 Introduction

The foundation for the smooth operation of MICE during Step IV rests on understanding the details of the commissioning and data-taking plans well in advance of running. The commissioning plans are described elsewhere. This document discusses the data-taking campaign needed to satisfy the physics goals. Using the observed data rates from Step I, an estimate for the time required to take the core physics data is made in Section 2. This is then used as a basis for the data-taking plan discussed in Section 3.

2 Expected Step IV particle rate

The expected number of particle triggers collected during Step IV can be approximated from the rate of triggers collected during Step I. The estimated rate depends on the following assumptions,

- particle rate is independent of the accepted beam line momentum
- particle rate scales linearly with beam loss (Section 2.1)
- the beam line magnet currents, as designed for Step I, can be re-tuned to accommodate recent changes to the diffuser (Section 2.3)

For the purpose of this study, an "analysable" muon is defined as a particle with a time-of-flight between TOF0 and TOF1 of $26.2 \leq t_\mu \leq 32\,\text{ns}$, which is contained within a matched ellipse at the upstream tracker reference plane of $\varepsilon_N = 6\,\pi$.mm.rad, $\beta = 333.34\,\text{mm}$ and $\alpha = 0$. In addition, the longitudinal momentum of the muon must belong to a Gaussian distribution with mean $p_z = 200\,\text{MeV}/c$ and $\sigma_{pz} = 10\,\text{MeV}/c$ at the tracker reference plane[1]. This satisfies the requirements that (a) the total muon beam is matched in the upstream tracker, and (b) the beam has a Neutrino Factory-like momentum spread.

2.1 Beam loss and particle rate

The total particle flux through the beam line depends on the target dip depth into the ISIS proton beam. Increasing the target dip depth has the unwanted side-effect of increasing the beam loss observed by ISIS in nearby sectors. Hence, the total particle flux through MICE depends crucially on the allowable beam loss observed by ISIS.

During Step I of MICE, the allowed beam loss was 1.0 V.ms whereas during In Step IV it will be nominally 4.0 V.ms. Beam loss fluctuates spill-to-spill, however, and it has been observed in previous runs that the average beam loss expected at a nominal 4.0 V.ms setting is closer to 2 V.ms. The variation of beam loss with particle rate was studied by A. Dobbs [1]. The total particle rate in the beam line, as a function of beam loss, was measured using the scalar hits provided by GVA1, BPM1 and 2, TOF0 and 1. Figure 1 demonstrates that the particle rate varies linearly with beam loss from 0.5–4.7 V.ms.

Figure 2 shows the accepted muon rate as a function of beam loss, where muon tracks are reconstructed according to their time of flight in the TOF detectors ($26.2 \leq t_\mu \leq 32\,\text{ns}$). At low beam loss (top), the average number of muon tracks per spill varies approximately linearly. However, at greater than 4 V.ms beam loss

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[1] Canonical angular momentum acquired when crossing the diffuser is neglected for this study; future studies should include its effect

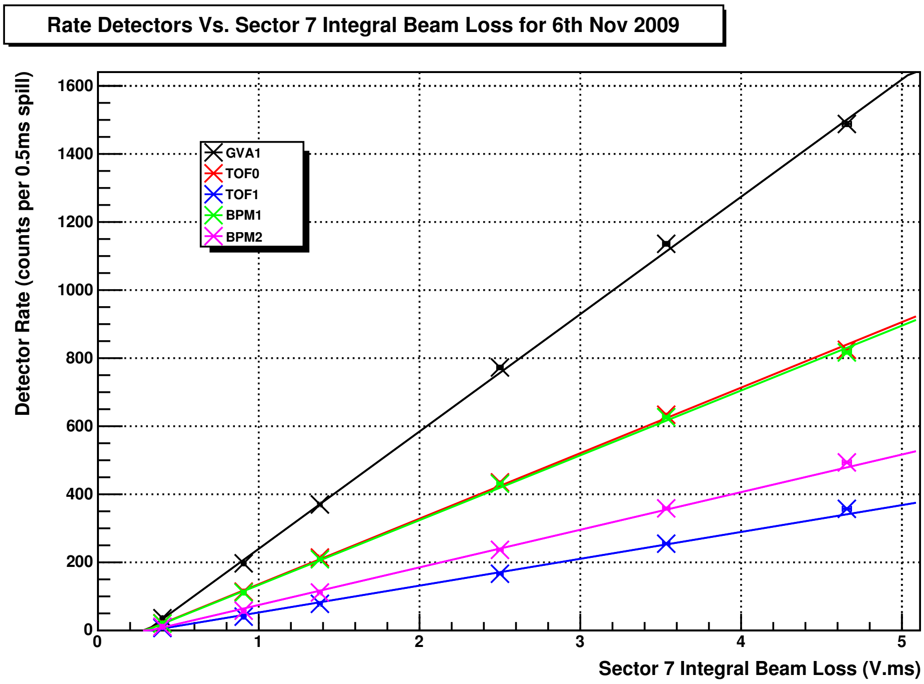

Figure 1: Total particle rate as recorded in GVA1, BPM1 and 2, TOF0 and 1, as a function of beam loss in ISIS sector 7 (MICE) [1].

Table 1: Summary of beam loss studies [1], with an assumed spill gate of 3.2ms.

Polarity	Triggers per spill (per V.ms)	Muons per spill (per V.ms)
Positive	53	26
Negative	6	3

(bottom) the average muon rate reaches a plateau, due to dead time in the DAQ [1]. A further complication is that the tracker readout imposes non-negligible dead-time on the experiment. Figure 3 shows the number of accepted triggers as a function of trigger requests from a test of the tracker readout systems. Table 1 summarises the number of triggers and muon tracks per V.ms of beam loss per spill for both positive and negative muon beams. With zero dead time, the expected number of particle triggers per spill for a positive beam during Step I (at 1 V.ms beam loss) was 53 and during Step IV is approximately 212, corresponding to 26 and 104 μ/spill respectively. The negative particle rate is $\approx 12\%$ of the positive particle rate.

The tracker deadtime is non-linear. The number of muons expected to be recorded for beam loss between 1 V.ms and 4 V.ms are shown in Table 2.

Table 2: Effect of tracker deadtime on muon rate

Nominal Beam loss	Positive	Negative
1 V.ms	19	3
2 V.ms	33	5
3 V.ms	45	8
4 V.ms	55	10

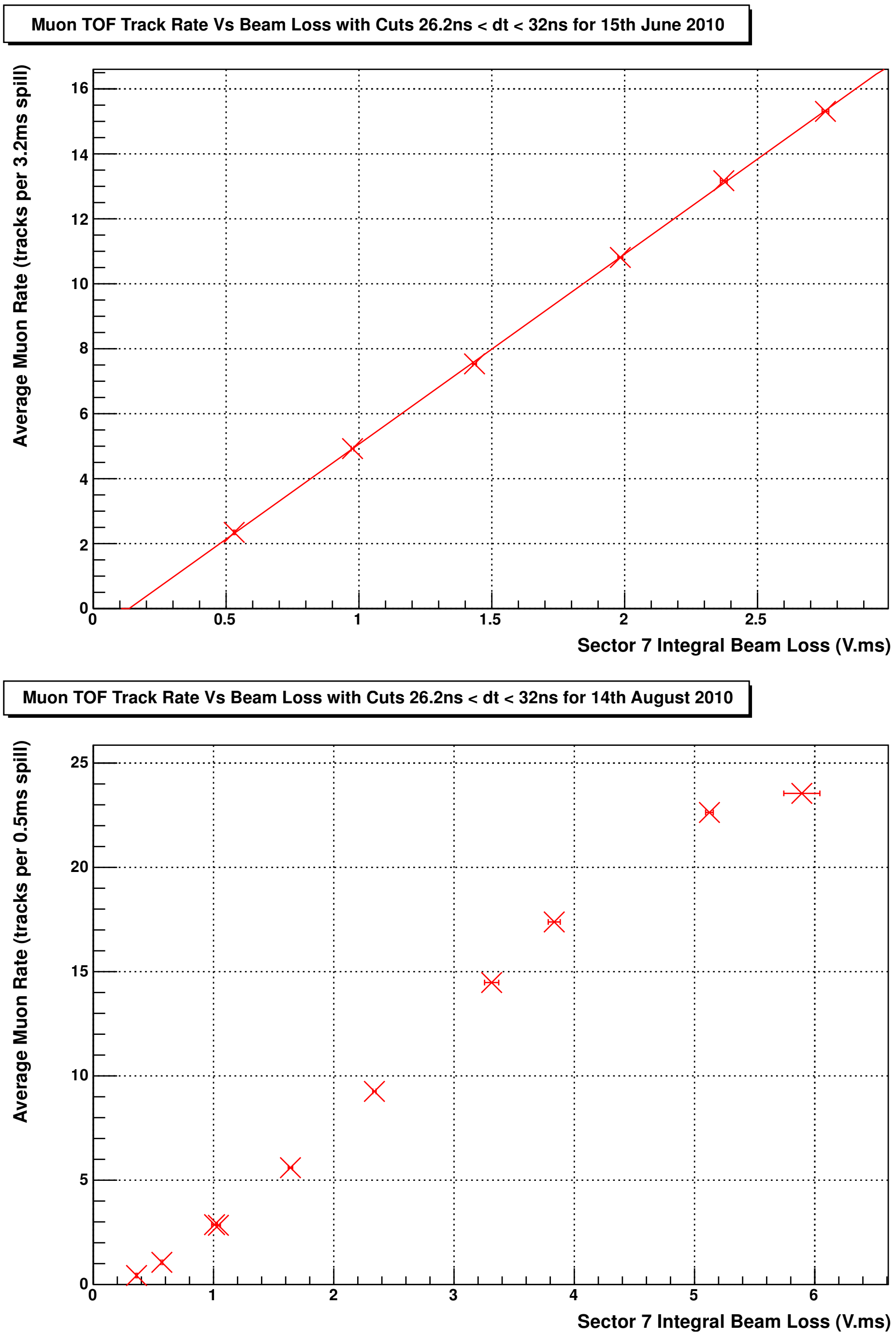

Figure 2: Average muon rate per spill from reconstructed TOF tracks as a function of beam loss in ISIS sector 7 (MICE). At low beam loss the rate is linear, however, at higher values the rate plateaus due to effects such as DAQ dead time. [1]

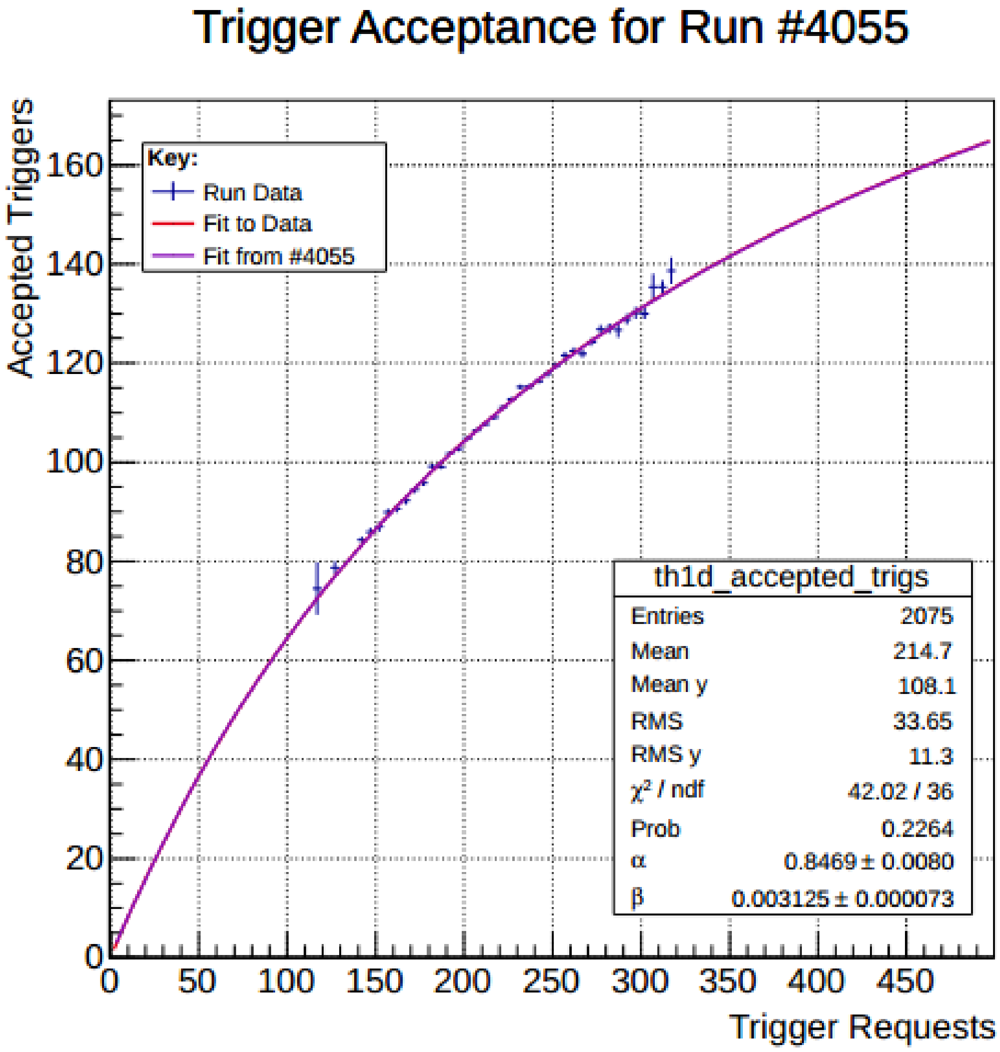

Figure 3: Effect of tracker deadtime on the accepted trigger rate as a function of requested trigger rate.

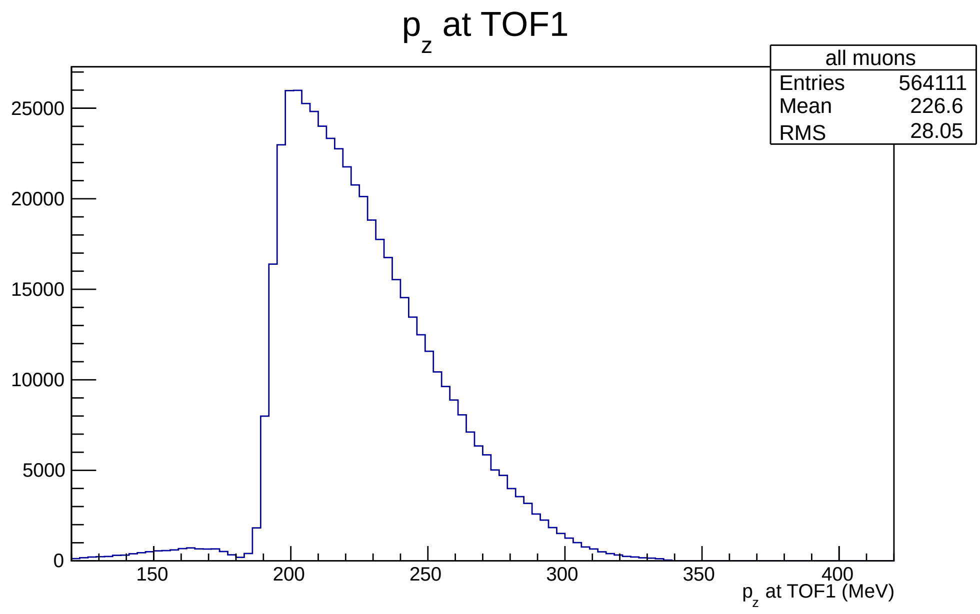

Figure 4: Longitudinal momentum distribution of all muons at TOF1, selected by time-of-flight, in the baseline beam Step I data.

2.2 Characterised beams at TOF1 and initial momentum selection

The MICE muon beams were characterised during Step I with TOF0 and TOF1 [2] using the technique documented in [3]. The characterisation allowed the determination of (x, y, p_x, p_y, p_z) for each individual muon[2]. Hence, it is possible to estimate how these real, measured muons will propagate through to the upstream tracker reference plane.

The data sets used in this study correspond to the baseline (*i.e.* "6, 200") beam as listed in [3]. Data were taken at a mean beam loss of 1.3 V.ms (*c.f.* 4 V.ms in Step IV), at a mean rate of 38.8 triggers/spill at TOF1. In total, 800,013 particle triggers were recorded at TOF1. The number of muons at TOF1, based on their time-of-flight, was 564,111 (70.5%).

Figure 4 shows the longitudinal momentum distribution of all accepted muons at the upstream face of TOF1. Note that the mean momentum of the beam is not 200 MeV/c, since the beam must still pass through TOF1 and the diffuser (see Section 2.3). This beam was designed to pass through 7.5 mm of lead, losing approximately 25 MeV of longitudinal momentum between TOF1 and the tracker reference plane.[3].

A gaussian momentum selection is performed at TOF1 so that identical beams can be propagated through different diffuser designs and a fair comparison of their efficiency made. During Step IV operation, this selection would ideally be made at the upstream tracker reference plane. Figure 5 shows the result of this selection at TOF1, reducing the number of analysable muons to 154,799. This represents 19.35% of the original recorded triggers.

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[2] A small correction is necessary to fully account for multiple scattering in the air between TOF0 and TOF1, however, the statement is sufficent for this estimate

[3] Plus some small amount of energy loss in the tracker planes.

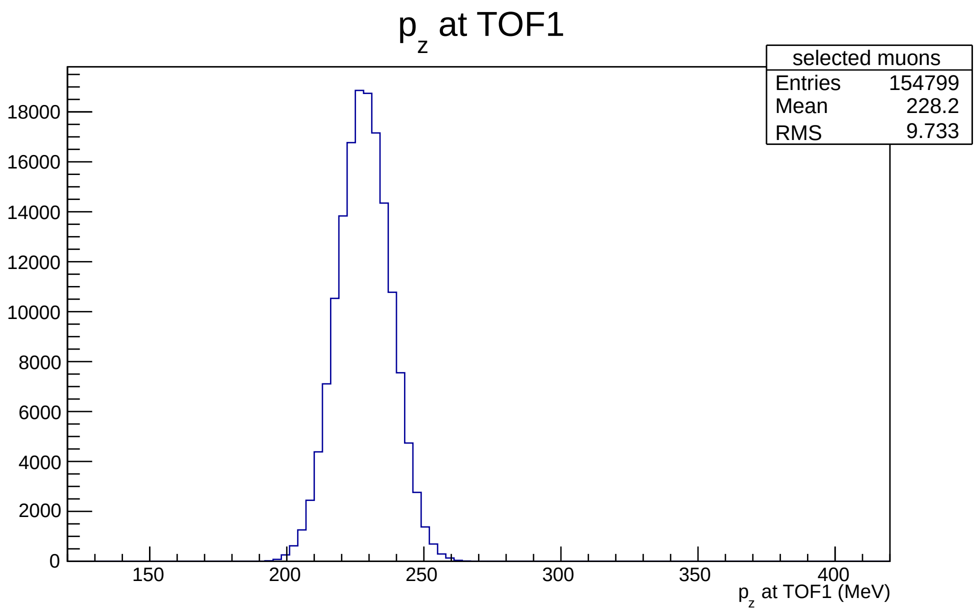

Figure 5: Longitudinal momentum distribution of muons at TOF1 after a Gaussian selection with $\langle p_z \rangle = 228\,\mathrm{MeV}/c$ and $\sigma_{pz} = 10\,\mathrm{MeV}/c$

2.3 Beam line configurations and the diffuser

The initial beam line design was made using the TURTLE beam transport code and then optimised with G4Beamline [2]. This design sets the quadrupole and dipole currents of the muon beam line, but cannot produce the wide range of emittance beams required by MICE to demonstrate ionisation cooling. The beam is passed through a variable thickness of high-Z material, known as the “diffuser”, which inflates the beam emittance before it reaches the upstream tracker reference plane.

The beams measured during Step I assumed that the diffuser would consist of several interchangeable lead discs, with a 7.5 mm thick disc required for the baseline beam ($\varepsilon_N = 6\,\pi$.mm.rad, $\langle p_z \rangle = 200\,\mathrm{MeV}/c$). For mechanical reasons the diffuser design was changed to four “irises” that can be opened and closed, consisting of brass (3 mm, 6 mm) and tungsten (3 mm, 6 mm). The irises were chosen to provide a range of radiation lengths of material, from 0–3 X_0 in $0.2X_0$ steps, so as to replicate the function of the lead diffuser. Nevertheless, the change in material means that muons will lose more energy crossing the diffuser than previously desired.

The muon rate used to design the data campaign uses simulation results made with the brass-tungsten design. Re-optimised beams using brass and tungsten are in progress, but will not be used for the purposes of this document.

It is assumed throughout that the muon rate scales linearly with momentum, and so the additional energy lost when passing through the brass-tungsten diffuser is ignored at this stage. This part of the estimate will be studied once the re-optimisation of the beam line has been completed.

To estimate the effect of the cooling channel on an initial muon beam, $\approx 10,000$ Step I muons were propagated through a G4MICE simulation containing TOF1, a diffuser, and the magnetic fields of the Step IV cooling channel. The number of analysable muons are therefore presented as a percentage, for consideration in combination with Section 2.2. Further studies are desirable, particularly with respect to optimising the beam through the brass-tungsten diffuser.

Figure 6 shows the longitudinal momentum of the selected muons after passing through $1.2\,X_0$ of the brass-tungsten diffuser, as seen at the tracker reference plane. Note that the momentum lost when passing through

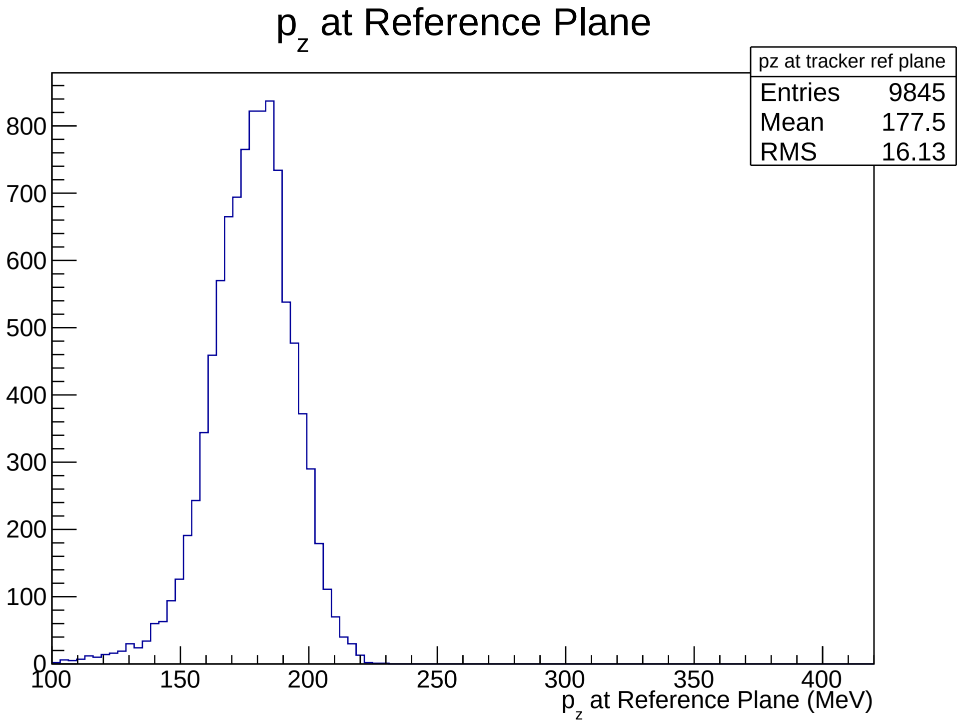

Figure 6: Longitudinal momentum distribution, after the brass-tungsten diffuser, at the tracker reference plane.

Requirement	% TOF1 triggers remaining brass-tungsten diffuser
Triggers at TOF1	100
Is a muon	70.51
Gaussian p_z selection	19.35
Phase-space selection	8.37

Table 3: Proportion of Step I analysable triggers (*i.e.* muons) in the baseline beam.

this diffuser is much greater than for lead, and so it will be mis-matched with respect to the cooling channels momentum acceptance. Correcting for this is beyond the scope of this estimate, and instead it is assumed that the “correct” mean momentum in this instance is 177.5 MeV/c.

The unselected (x, p_x) and (y, p_y) phase space of the beam is shown in Figure 7. A matched beam would occupy an ellipse described by $\varepsilon_N = 6\,\pi$.mm.rad, $\beta = 333.34$ mm and $\alpha = 0$. Requiring that an individual muon’s amplitude lies within the matched (baseline) ellipse gives Figure 8, resulting in a reduction in the number of analysable muons of 43.3% (or 8.4% of the initial triggers). The longitudinal momentum distribution of this “matched” beam is shown in Figure 9.

The proportion of muons contained within a phase space ellipse of $\varepsilon_N = 6\,\pi$.mm.rad, $\beta = 333.34$ mm and $\alpha = 0$ at the upstream tracker reference plane has been summarised in Table 3. Using the data in Table 2 the estimated number of spills required to generate 100,000 analysable muons [4] is 66,700 at 1 V.ms beam loss, and 22,700 at 4 V.ms beam loss. Given a target dip rate of 0.8 Hz (*i.e.* 1 dip per 1.25 s) this corresponds to 22.0 and 8 hours respectively. The time required for a similar negative run of equal statistics is at least a factor of 5 larger.

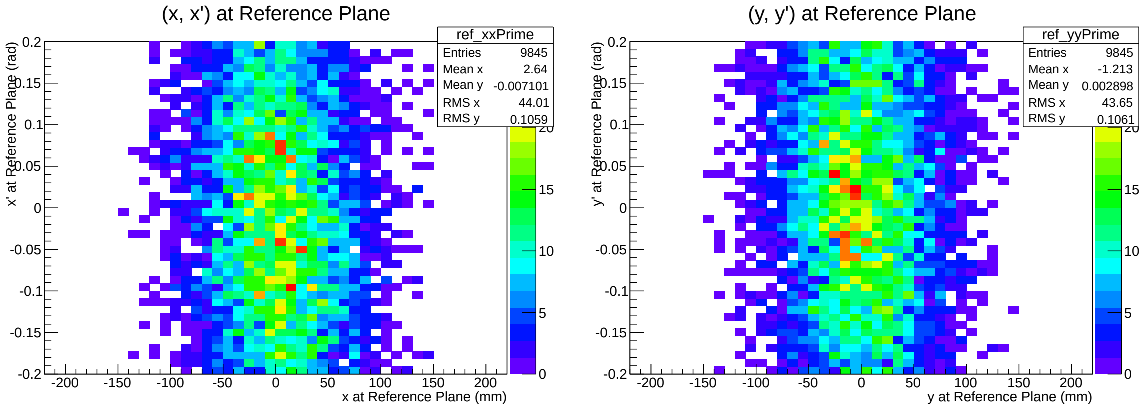

Figure 7: Transverse phase space, of an unselected beam, at the tracker reference plane. Left: Horizontal phase space, right: vertical phase space

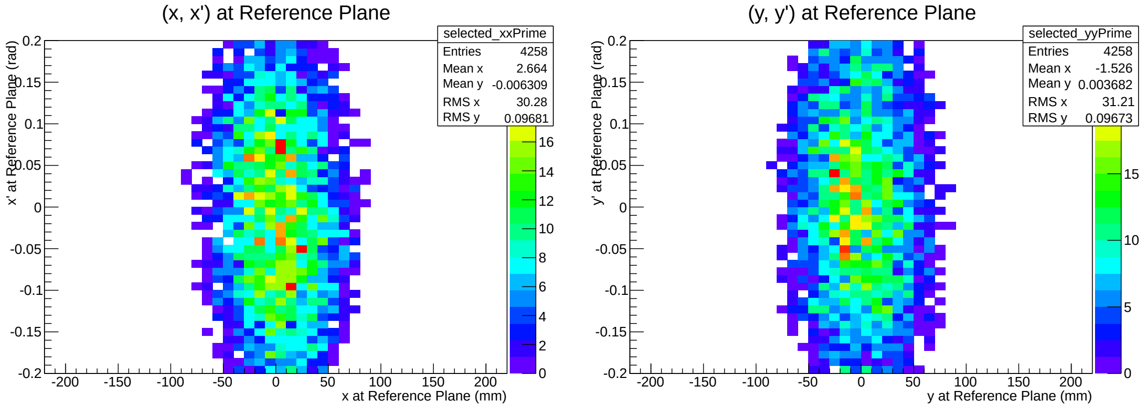

Figure 8: Transverse phase space of a selected "matched" beam at the tracker reference plane. Left: horizontal phase space, right: vertical phase space

Polarity	Beamloss (V.ms)	Analysable μ/spill	Number of spills for 100k μ / 1k	Time (hours)
Positive	1.0	1.5	66.7	22
	2.0	2.6	38.5	13
	3.0	3.6	27.8	9
	4.0	4.4	22.7	8
Negative	1.0	0.2	500.0	166
	2.0	0.4	250.0	83
	3.0	0.6	166.7	55
	4.0	0.8	125.0	42

Table 4: Expected postively charged muon rate in Step IV given Table 3.

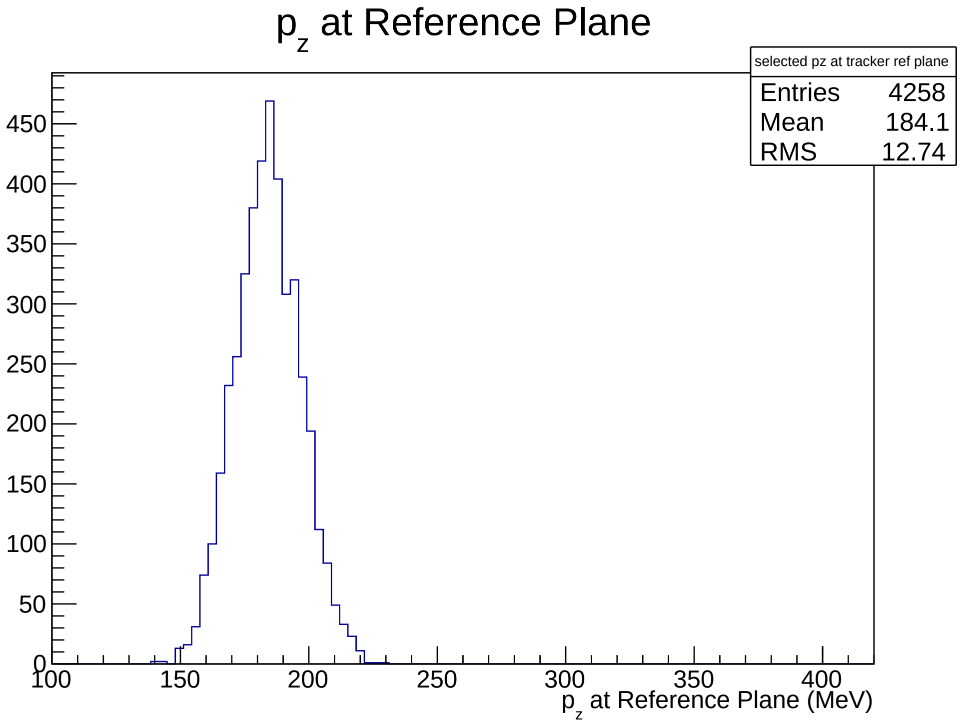

Figure 9: Longitudinal momentum distribution of a selected "matched" beam after the brass-tungsten diffuser, at the tracker reference plane.

User Period	Start Date	End date	Run length (days)
1	17/3/2015	24/4/2015	33
2	2/6/2015	24/7/2015	54
3	8/9/2015	16/10/2015	38
4	3/11/2015	18/12/2015	45

Table 5: Provisional ISIS run plan for 2015.

3 The data campaign

With an estimate for the time required to take sufficient data for a given MICE configuration in hand, the data-taking campaign can start to be developed. A provisional ISIS run plan for 2014/2015 has been made available showing how many days are available in which to take data. Using this, some scenarios for the data-taking plan can be defined.

3.1 ISIS Provisional Run Plan

A provisional ISIS run plan for 2015/2016 is available for planning purposes. In 2015/2016 there will be four user runs with dates and length as shown in Table 4. The 2016/2017 ISIS user period plan has not been developed yet. Currently, Step IV operations must cease in late May to prepare for construction of the next phase. Given this we assume that the first user run period in 2016 will be available for data-taking and that it will have the same length as that in 2015.

The construction program will be handover to Operations in late May, 2015. The exact starting date of the commissioning program is currently uncertain. The bulk of the first available user run, User Period 2, will be used for cooling channel commissioning. Technical runs, yielding calibration and alignment data will also take place in this period. Pre-commissioning tests of control room operations are expected to take place in January 2015. Step IV data-taking will begin in the third User Run period.

After user run periods 1 and 2, there are a total of 143 days for commissioning and data-taking in 2015 and 2016.

3.2 Assumptions

The focus for the data-taking campaign is to first ensure that all the data required to carry out the physics program for the STEP IV is taken. Other running configurations will be carried out if there is time. The core program involves

- the nominal 9 measurement points in muon momentum and post-diffuser emittance. The muon momentum points are 140, 200 and 240 MeV/c, and the emittance settings are 3, 6 and 10 mm. In addition, at each (momentum, emittance) point, investigation of the betatron function at each of the tracker planes and the center of the absorber is also envisaged. Here we assume 4 betatron function measurement points per (momentum, emittance) point. In the discussion in Section 3.3 these 36 measurement points will be denoted as the *physics grid.*
- four possible absorber options : an empty run, LH_2, LiH and, if possible, the wedge absorber.
- two settings of the focus coil currents : flip, and solenoid modes.
- MICE will run with double target dip rate (0.8 Hz), and at 4 V.ms nominal beam loss.

In addition, data should be taken with both positive and negative polarity beams. It is not envisaged that equal statistics of positive and negative polarity beams can be taken for each measurement point, especially as the running time for negative beams is approximately a factor of 10 larger than for positive beams. In the discussion below we assume that full negative polarity samples are recorded for one (momentum, emittance) point only for each current and absorber setting. Calibration and monitoring runs will also be required. These are less well known as the stability of the cooling channel and detectors during standard running is less well-understood and contingency for these runs has been added into the run plan discussed in Section 3.3.

3.3 Data-taking Campaign

We assume here that the beam will run with an average beam loss of 3 V.ms to allow for beam problem and other delays. A basic run block can be defined assuming 9 hours of data-taking is required for one point in the physics grid for positive polarity beam settings and 55 hours for a negative polarity run. The run block includes calibration and monitoring runs which are assumed to require 30 minutes of running per (momentum,emittance) setting, a full pass through the physics grid, and a further contingency of approximately 25%, for an individual configuration of absorber, and current setting. This is shown in Table 5 for both positive and negative polarity beams. It is assumed that experiment shifts will last eight hours and that there will be three shift sessions per day.

3.4 Run Scenarios

Using the run blocks a number of run scenarios can be tensioned against the ISIS run schedule. The underlying assumptions of the following scenario are that

1. minimal changes to the setup are made between run blocks.

Run type	Positive polarity	Negative polarity
Calibration and Monitoring	4.5 hours	4.5 hours
Physics grid	14 days	2.5 days
Contingency	4 days	0.5 day
Total	18 days	3 days

Table 6: Basic run block for STEP IV data campaign plan, assuming positive and negative polarity beams. The total runtime assuming a 3 shift / day operations mode is shown.

User run period	Run type	Absorber	Focus coil mode	Beam polarity	Run time (days)	Total
2	Commissioning				33	
3	Physics	Empty	Solenoid	+	18	
	LH_2 Fill				2	
	Physics	LH_2		+	18	38
4	Calibration/Setup			+	7	
	Physics	Empty	Flip	+	18	
	LH_2 Fill				2	
	Physics	LH_2		+	18	45
1	Calibration/Setup			+	7	
	Physics	LiH	Flip	+	18	
	Physics		Solenoid	+	18	36

Table 7: Run scenario for Step IV for a full set of data using positive beams.

2. the core program must be carried out as a matter of priority
3. user run period 2 is used solely for commissioning work.
4. the first week of a user run are reserved for setup, calibration and other startup issues.
5. installation of a solid absorber is likely to take a significant amount of time, as access through the PRY is required. We assume that such installation will take place between user runs.

We assume that we start with an empty absorber to provide a baseline for comparison with data taken with the other absorber options. The decision has been made to start data-taking in solenoid mode is currently under study. Starting in flip mode will require that the cooling channel must be commissioned in flip mode before user run period 3. In fact, the time at which this commissioning step is performed has little effect on the run plan as the time required to fill the physics grid naturally accommodates a change to flip mode between runs 3 and 4.

Table 3.4 assumes that the cooling channel was commissioned in flip mode before user run period 2. In this plan, we are able to take all necessary data for empty and LH_2 absorbers for solenoid and flip mode in the same run period allowing early analysis of the effect of the absorber on a beam. The magnet modes are swapped and data taken for the LiH absorber in the first run period of 2016. There is no time in this schedule either to run with a negative beam or unallocated for other studies.

4 Operations Planning

4.1 Structure of the Operations Group

As the MICE experiment moves from it's construction and installation phase to data-taking, oversight of operations will shift to the new Operations Group. The responsibility of the Operations Group is to ensure the smooth operation of the MICE Muon Beam, instrumentation and cooling cell, and to ensure that all data necessary for the delivery of the physics goals are taken and archived for analysis. The Operations Group covers the range of MICE activities. The group itself is in the final stages of construction with the intent that the activities and modes of operation of the group will be in place and understood well before Step IV running begins.

4.1.1 Support for MICE operations form the ISIS Operations Group

The smooth operation of MICE will depend on timely access to sufficient personnel with the technical expertise necessary to address problems to complex systems when the arise. The ISIS Operations Group, which is led by Z. Bowden, carried out a review of the technical-staff support that MICE will require in steady-state operation. The review considered the support required in the following disciplines: RF; vacuum; superconducting magnets; cryogenics; mecanical and electrical engineering; ancillary plant; accelerator physics; controls; logistics and survey. It recommended 6 FTEs of effort should allocated within the ISIS teams to support MICE operations for Steps IV and V. This effort has been allocated and comes into effect at the start of FY 2014/15.

4.1.2 Expert and Operational Shifts

MICE is a complex experiment, reliant on a number of inter-dependent subsystems to achieve its physics goals. Experts responsible for each system are required to be available during each data-taking period. The ISIS support team will be available, through the Hall Manager, to deal with problems in the support systems. However it is important that experts in the subdetectors, the data acquisition and online systems and the near-online software framework also be available if something goes wrong during data taking. To this end, the experiment now maintains an expert list, divided into two parts; a responsibilites list and a contact list. The Operations group is responsible for the responsibilites list, with the MOM and Operations Co-ordinator ensuring that each subsystem provides a list of one or more experts. The MICE Admin group then ensure that all of the listed experts (as well as other key roles, such as Collaboration Spokesperson or Project Manager) have entered their personal contact details in the ISIS database. On a monthly basis, they will produce updated lists which are kept in the MICE Local Control Room, for the use of the MOM or shifters during data taking, and on the secure Operations page of the micemine website, accessible to all confirmed MICE collaborators.

Data taking runs during commissioning and stable running need to be monitored and the data being taken needs to be checked as it is sent to archive. This will be carried out in shifts, with the members of the collaboration acting as the shifters. A shift allocation policy has been drafted and agreed by the Collaboration Board. Shifts will be allocated to each institute in proportion to the number of PhD holders and students who will sign the Step IV papers. A set of shift duties has been defined, although this will change as different parts of the MICE channel come online and are commissioned. Shift signup and tracking will be accomplished using an online shift allocation tool, as used in a number of experiments. The requirements for this tool are being defined. Shifts allocation and status will be overseen by a shift co-ordinator (P. Kyberd).

5 Conclusion

The length of a standard data collection run has been derived from Step I data and Monte Carlo studies. For positve polarity beams, it is possible to accumulate a full physics grid for specific magnet mode/absorber configuration in 5 days. This can be used, along with the ISIS schedule, to devise possible running scenarios. It has been shown that it is possible to take data on all four absorbers, with positive and negative beams, in the 2015 ISIS run, as long as the cooling channel is commissioned in flip mode before user run period 2. If this is not the case, then the installation time of the solid absorbers limits what can be done. Priority will be given to the core program involving the empty, LH_2 and LiH absorbers, with the wedge absorber included if possible. It is important to note, however, that it may also be possible to run in early 2016 as well, which would help expand the schedule and allow all necessary configurations as well open physics runs to be explored.

References

[1] Particle Rate and Host Accelerator Beam Loss on the MICE Experiment, A. J. Dobbs, PhD Thesis, Imperial College London, 2011

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