The MICE luminosity monitor

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Abstract. The MICE experiment will provide the first measurement of ionisation cooling, a technique suitable for reducing the transverse emittance of a tertiary muon beam in a future neutrino factory accelerator facility. MICE is presently in the final stages of commissioning its beam line. The MICE luminosity monitor has proved an invaluable tool throughout this process, providing independent measurements of particle rate from the MICE target, normalisation for beam line detectors and verification of simulation codes.

1. Introduction

Substantial research and development work has justified the neutrino factory as the facility of choice for cataloguing the parameter space of neutrino oscillations [1]. No other proposed facility provides a more promising venue for the discovery of leptonic CP violation over as great a range of values of the θ_{13} oscillation angle, or greater precision in measuring the oscillation parameters than the neutrino factory.

A significant cost driver of such an accelerator facility is the cooling channel, which must reduce the phase space volume of the muon beam to within the acceptance of the downstream acceleration system. In an ionisation cooling channel, muons undergo energy loss in low density absorbers and the longitudinal momentum is restored in accelerating Radio Frequency (RF) cavities.

The Muon Ionisation Cooling Experiment (MICE) seeks to provide a first ever demonstration of ionisation cooling [2]. Whilst the physics of the process is not in doubt, significant engineering challenges exist in realising a cooling channel in practice. The goal of MICE is to measure a fractional change in emittance of order $\sim 10\%$ to an error of 1% with two scintillating fibre trackers at the entrance and exit of the channel (see figure 1). MICE has reached its first major milestone: a high purity muon beam line capable of providing sufficient muons for precision measurement of emittance.

2. Luminosity monitor and beam loss

The MICE target operates parasitically to the host proton synchrotron ISIS, dipping into the halo of the beam in the last few milliseconds of the acceleration cycle. This produces beam loss, which is measured by a series of 3 and 4 metre argon gas ionisation tubes along the synchrotron, approximately 2-3 m from the beam. The beam loss experienced by ISIS, and consequently the muon rate in MICE, will vary depending upon beam conditions and target control parameters, such as dip depth and the time of injection in the beam. In order to characterise the beam line ahead of future analyses, it is essential that MICE can both measure and predict particle rate.

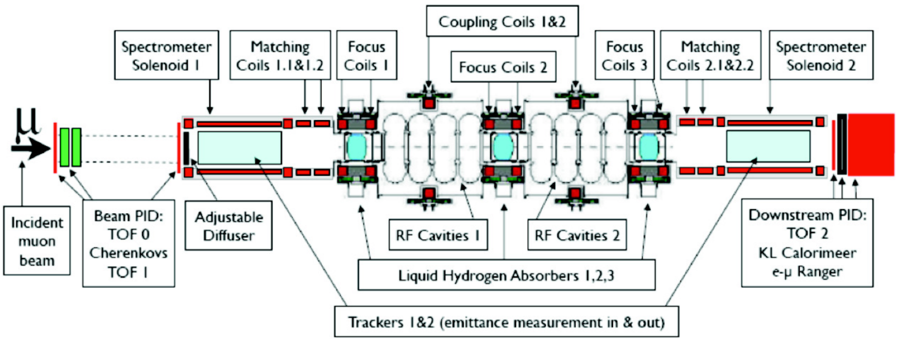


Figure 1. The full MICE cooling channel with absorbers and RF cavities braced by scintillating fibre trackers and particle identification detectors.

The luminosity monitor (LM), shown in figure 2, provides a means to measure particle rate independently of the host accelerator beam loss monitors. Two pairs of scintillators are read out through low noise photomultiplier tubes and the coincidence of hits in each pair (C12 and C34), as well as the four-fold coincidence (C1234), are recorded in data. Placed 10 m from the target at a similar polar angle to the MICE beam line, the LM allows for normalisation of all detectors along the beam line as well as verification of physics models and simulation codes [3].

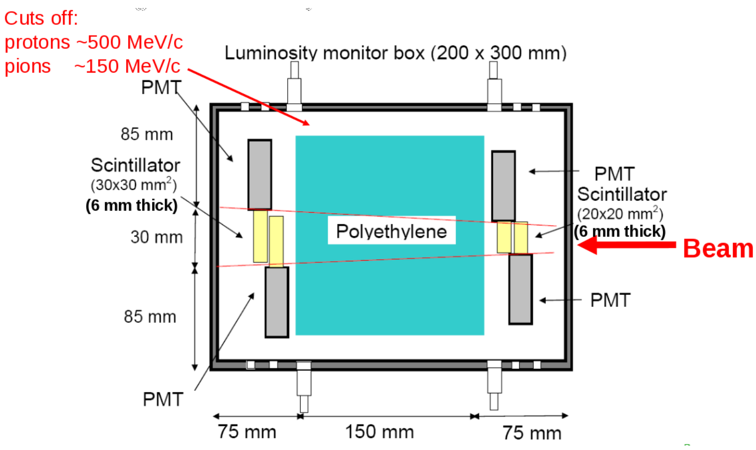


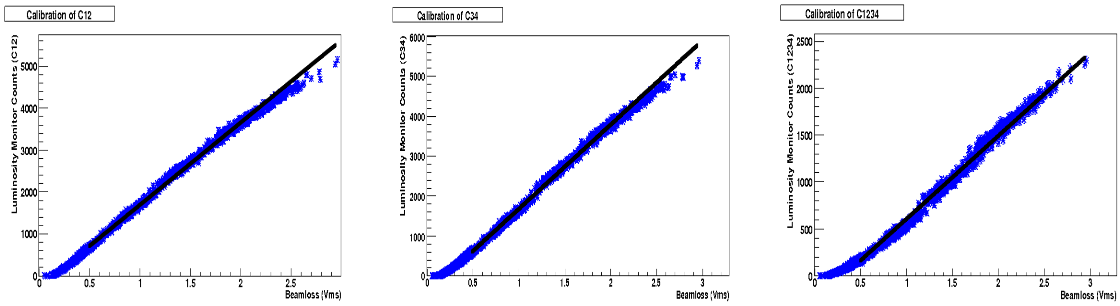
Figure 2. The luminosity monitor consists of two pairs of scintillators read out through low noise photomultiplier tubes. The second set is shielded by 15 cm of polyethylene which acts as a filter stopping low energy protons and pions.

LM commissioning (figure 3) has demonstrated an expected linear relationship between counts in each of the LM channels and beam loss. Predefined beam loss conversions can then be applied to convert counts to protons on target.

3. Simulations and results

The geometry of the luminosity monitor and target were modelled in G4Beamline, a general purpose simulation program based on GEANT4 [4]. In order to increase statistical accuracy, the area of the scintillator planes and plastic were increased by a factor of 100 and 2×10^9 protons on target were simulated using Grid resources. This simulation was successful in producing a reasonable rate at the first set of scintillators (C12). A second set of simulations with the actual experimental geometry was created to study the particle transmission rate and to determine the rates in the downstream scintillators (C34 and C1234) with respect to C12.

The number of protons on target that interact with the target and create beam loss in the ISIS ring depend upon the target thickness and geometry. At present, MICE employs a titanium



(a) (b) (c)

Figure 3. First data from the luminosity monitor showing a direct relationship between luminosity and beam loss on all three scaler output channels. Graphs show counts for coincidences of signals for PMTs (a) 1,2 (b) 3,4 and (c) 1,2,3 and 4. The straight lines indicate a linear fit to the data between 0.5 Vms and 3 Vms, since the method for calculating beam loss is unreliable below 0.5 Vms.

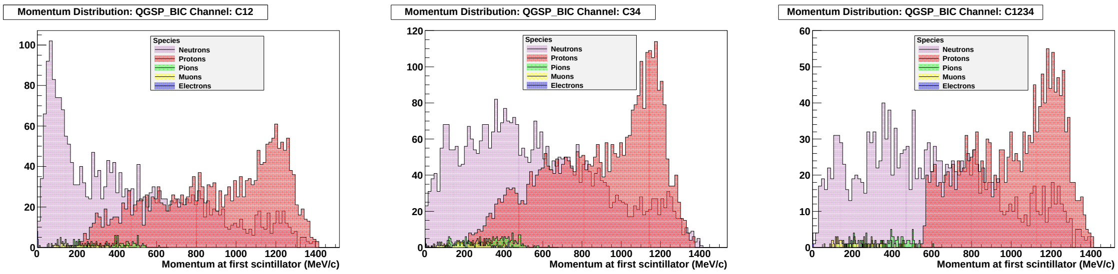
cylindrical target with inner radius 2.3 mm and outer radius 3 mm. As a consequence of the geometry, protons encounter a variable thickness of titanium. To study this effect, a rectangular target with cross-section 1×1 mm^2 and length 10 mm was also simulated. This target is similar to that previously employed by MICE in early data taking. The ratio of the counts produced from the cylindrical target to the long and thin rectangular target (the geometry factor) was found to be $\eta = 0.169 \pm 0.001$.

The geometry factor can be understood qualitatively by considering the mechanisms in which a proton is lost in the beam when it encounters the target. This was studied with the Objective Ring Beam and Injection Tracking code (ORBIT) [5], which is a particle tracking software package for accelerator rings, including space-charge effects. ORBIT simulations with the correct dimensions of the target were compared to other simulations in which the target was 10 mm long and 1 mm wide (long and thin). Preliminary results from these simulations show that the ratio of protons from the ISIS beam lost in the target area compared to those lost in the downstream collimators, is 5.4 for the long and thin target and 2.1 for the cylindrical MICE target [6]. This suggests that this ratio is 2.5 times larger in the long thin target than in the MICE cylindrical target. In the G4beamline simulation it was found that there is a factor of $1/\eta = 5.9$ times more beam loss in the long thin target than the cylindrical target. While the two independent calculations do not agree numerically, it does suggest that targets with a greater average material thickness do suffer more local beam loss than thinner targets. The beam loss mechanisms along the ISIS ring can be due to a mixture of scattering, which deflect the protons from their ideal trajectory, and from energy loss in the target.

Five hadronic physics models in GEANT4 were studied: QGSP_BIC, the default physics model in MICE, QGSP_BERT, QGSC, QGSC_CHIPS and LHEP [7]. Momentum distributions for QGSP_BIC are shown in figure 4. For each model, the yield (number of particles per proton-on-target, POT, per cm^2) was calculated as follows:

$$\mathrm{Y} = \frac{\mathrm{LM\ Counts}}{\mathrm{POT} \times \mathrm{Area}} \times \frac{1}{\eta} \tag{1}$$

The results are shown in table 1, finding close agreement with data. The errors in the data are dominated by the unknown uncertainty in the calibration of the host accelerator beam loss monitors from which we infer the number of protons interacting with the target.



(a) (b) (c)

Figure 4. The momentum distributions at (a) the first, (b) second and (c) both sets of scintillators using the QGSP_BIC hadronic model.

4. Conclusions

A luminosity monitor has been designed, built and installed at the ISIS synchrotron, performing well as a beam line tool, as MICE reaches the final stages of commissioning its beam line. It has also provided an excellent device for studying the validity of simulation codes, with QGSP_BIC, QGSP_BERT and QGSC_BERT the most consistent with MICE data. As the experiment moves forward, the LM will be useful for normalising particle rate in all the MICE detectors and to independently measure beam loss from ISIS. Simulations of proton interactions in the MICE target compared to ORBIT simulations show some differences in the expected local beam loss, probably since ORBIT takes into account disruptions in the proton trajectory in the ISIS ring.
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Table 1. Response of the luminosity monitor as a function of hadronic model. Each simulation has an identical geometry description and is given the same set of functional parameters, including 2×10^9 protons on target. Errors in data are dominated by the 30% estimated error attributed to the beam loss calibration whilst errors in the simulation are statistical.

	Yield $\left(10^{-8}\frac{\text{counts}}{\text{POT cm}^2}\right)$		
Model	C12	C34	C1234
Data	1.72 ± 0.52	0.82 ± 0.25	0.79 ± 0.24
QGSP_BIC	1.67 ± 0.01	0.84 ± 0.03	1.06 ± 0.04
QGSP_BERT	1.80 ± 0.02	0.81 ± 0.03	1.05 ± 0.04
LHEP	1.03 ± 0.01	0.25 ± 0.01	0.29 ± 0.02
QGSC_CHIPS	0.74 ± 0.01	0.37 ± 0.02	0.49 ± 0.03
QGSC_BERT	1.80 ± 0.02	0.84 ± 0.03	1.06 ± 0.04

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