

# DESIGN AND EXPECTED PERFORMANCE OF THE MUON BEAM LINE FOR THE MUON IONISATION COOLING EXPERIMENT

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## Abstract

It is proposed to install a Muon Ionisation Cooling Experiment (MICE) at the ISIS facility, at Rutherford Appleton Laboratory (RAL). This experiment will be the first demonstration of ionisation cooling as a means to reduce the large transverse emittance of the muon beam produced during the early stages of a Neutrino Factory. In order to permit a realistic demonstration of cooling, a beam of muons must be produced, possessing particular qualities, notably in emittance and momenta. This paper describes the current design for the muon beamline, outlining issues particular to the needs of the MICE experiment, and discusses its expected performance.

## INTRODUCTION

A Neutrino Factory based on a muon storage ring is the ultimate tool for studying neutrino oscillations. One of the challenges posed is the control of the large emittances possessed by muons produced from pion decay at the proton driver target. Ionisation cooling is a proposed mechanism to reduce this on a suitably short timescale, and the MICE collaboration has designed an experiment [1] in which a section of cooling channel is exposed to a muon beam, which would demonstrate and explore this technique for the first time in practice.

The ISIS facility is an intense pulsed neutron source, and the synchrotron accelerates a high intensity proton beam from 70 to 800MeV at 50Hz. To provide muons for MICE, an internal target will be installed, which will provide a source of pions for a pion-muon decay channel, and thereby provide muons for MICE. The muon beamline makes use of existing dipole and quadrupole magnets, together with a superconducting solenoid contributed by PSI in Switzerland.

This paper describes the evolution of the beamline design since the previous description in [2]. Much work has focussed on estimating its performance, through target physics simulations and particle tracking using a new Geant4 [3] based code. This work is also described here.

## BEAMLINE FUNCTIONS

The MICE experiment requires a muon beam with particular qualities in momenta, emittance, muon purity and rate. MICE is designed for reference momenta 140-240MeV/c, with a  $\pm 10\%$  momentum acceptance, and to allow for energy loss in material along the beamline, muon momenta of up to 300MeV/c must be supplied.

The MICE apparatus is designed to cool muon beams to a normalised transverse rms equilibrium emittance of  $2.5\pi$  mm rad. To explore the cooling performance, a range

of beams with emittances from  $\sim 1\pi$  mm rad up to  $\sim 12\pi$  mm rad are desirable. In order to cool effectively, the muon beam must also be well matched into the experiment.

Finally, a suitably high flux must be supplied, with background contamination less than 0.1%. Particle identification detectors are present to strengthen this discrimination, and their effect on the beam must be accounted for in the optical design.

## OVERVIEW OF DESIGN

The basic structure of the beamline has been described before [2], however it is in essence based on a conventional pion-muon decay channel, similar to those used for condensed matter research [4]. The beamline thus splits into three parts: a pion capture and selection section, a pion-muon decay section and a transport line to convey muons to MICE. The last section also hosts a thick lead scatterer, and serves to generate the large emittances and match the beam into the experiment.

A schematic of the current beamline layout is shown in Figure 1. The synchrotron is shown to the left, and the upstream MICE spectrometer solenoid and end coils are visible on the right.

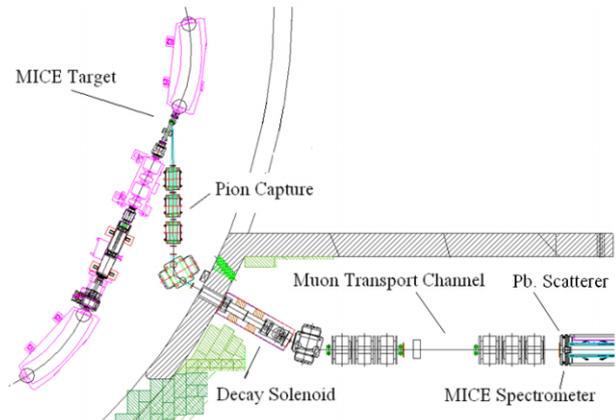


Figure 1: Current layout of MICE muon beamline.

The codes TRANSPORT and DECAY TURTLE [5] have been used to design the basic beamline optics.

## Target

A thin titanium target will be dipped into the ISIS proton beam just before extraction at 800MeV, to supply the initial source of pions. Some of the target physics simulation is described later in this paper.

## Pion Injection and Decay Section

The first section of the beamline is designed to capture as large a pion acceptance as possible from the target, and to momentum select the pions into the decay section. The decay solenoid then serves to accumulate as large a flux of muons as possible. A notable development since [2] has been to select high momentum pions, such that the muons are derived from backward decay in the pion rest frame. This has advantages in terms of the final muon flux and purity.

The half-widths of the pion beam profile for the first two sections are illustrated in Figure 2.

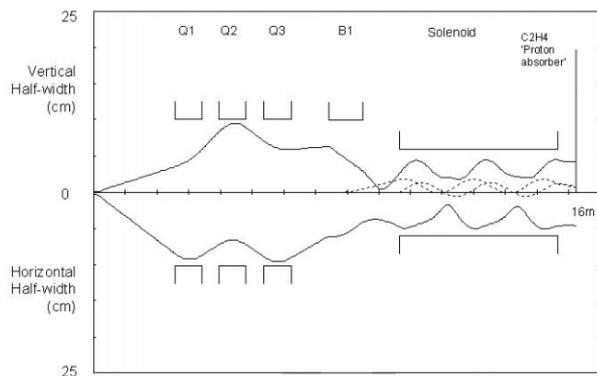


Figure 2: TRANSPORT beam profile for the pion injection and pion-muon decay section.

Almost all emittance and momentum tunes of the beamline plan to use the same pion optic shown above. The main tuning will involve scaling the fields for different pion momentum settings.

A polyethylene absorber, used to remove the proton background from the target, can be seen in the above figure. Materials have now been explicitly included in design of the beamline. These have been modelled consistently in both codes, and their properties derived from a Geant4 [3] based representation of these elements.

## Muon Extraction

This section consists of a large aperture dipole, to select muons of the desired momentum, and two sets of large aperture quadrupole triplets to transport the muon beam towards the experiment.

The transport line includes the upstream MICE detector system: a Cherenkov detector (Ckov1) and two time-of-flight counters (TOF0 and TOF1). The layout has been influenced by the needs of TOF particle identification, and the detector materials themselves have a significant impact on the beam in terms of energy loss and scattering.

One of the functions of the muon transport section is to provide a particular beamsize and focus just before the scatterer, which is specific to each emittance and momentum case. The details of this are described more in the following section. To achieve this in the presence of the detector materials, has required careful application of the design codes TRANSPORT and TURTLE.

The beam profiles for this section are shown in Fig. 3. This shows the rms beam profiles for the nominal  $7\pi$  mm

rad, 200MeV/c case. Profiles are for those muons which reach the scatterer, subject to a momentum bite of  $\pm 10\%$ .

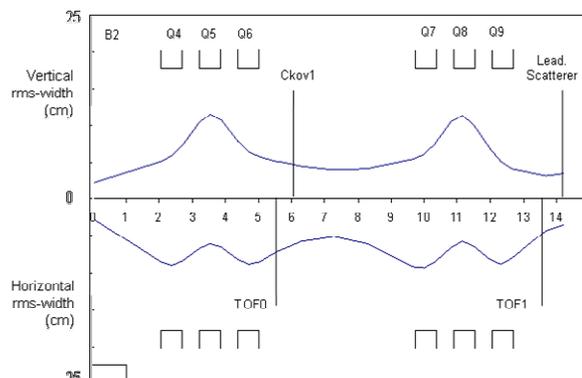


Figure 3: TRANSPORT beam profile for muon extraction. (nominal  $7\pi$  mm rad, 200MeV/c setting).

Consideration has also been given to beam steering and correction schemes for this section. Studies show that displacements and angles of  $\pm 5$ mm and  $\pm 1$ mrad can be corrected using two steering magnets per plane.

## Emittance Generation & Matching

The transport line typically supplies a normalised emittance of  $\sim 3\pi$  mm rad, and to supply the large emittances for MICE, a thick scatterer is used. Matching this beam into MICE involves a combination of focussing to a specific beamsize and choosing a suitable thickness of lead to stretch the beam into a specific angular spread.

Extensive study has indicated that in order to generate the largest emittances, the optimum position for the lead is inside the solenoid bore. A mechanism to support and change the lead plates within the bore of the MICE solenoid has been designed [6].

## EXPECTED PERFORMANCE

To provide the greatest likelihood of success in designing the beamline, and to provide data to guide the MICE detector design, we have simulated the beamline performance using particle production codes for the target and performed particle tracking using the code G4beamline [7]. The G4beamline program is based on the Geant4 toolkit [3], as used extensively in the high energy physics community; it includes for example, field maps for the magnetic elements and accurately models stochastic processes. This simulation work is significantly more detailed than is usually performed during beamline design.

## Target Physics Simulation

In the absence of direct measurements, quantifying the pion production from the target is a challenge, and we have chosen to use three different programs for this: LAHET [8], MARS [9], and Geant4 [3]. One important output is the available pion momentum spread, which informs for the settings of the beamline. An example of

the pion spectrum as calculated with Geant4 is shown in Figure 4.

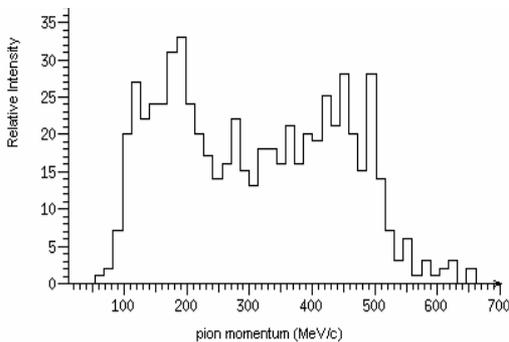


Figure 4. Pion momentum spectrum from the target.

These codes can also be used to calculate absolute particle rates, however the largest uncertainty is in the number of protons intersecting the target. A number of reasonable assumptions have been made [10], however factors such as target heating and tolerable beam loss will set practical upper limits. The in-beam test of the prototype target in Winter 2006 will provide valuable data for this [11].

### Detector Beam Rates & Particle ID

The upstream detectors are essential to improve the muon discrimination and to provide triggering for MICE. Beamline design choices have been taken to minimise the rates seen by these detectors, and together with limits on the MICE DAQ system of  $\sim 0.6$  MHz, we may also limit the proton current intercepted by the target. Current estimates of detector beam rates are given in Table 1.

Table 1. Beam particle rates of upstream detectors.

	Singles Rate (MHz)
TOF0	2.40
CKOV1	2.31
TOF1	0.87
Tracker1 (1 <sup>st</sup> plane)	0.84
'Good' muons	0.60

The beamline itself has a non-muon contamination of less than 0.5%, but using the upstream Cherenkov and the two TOF devices in their current layout, together with the tracker, easily ensures the necessary discrimination can be made.

### Emittance and Twiss Parameters

The emittance and Twiss parameters of the beam are calculated in the MICE upstream tracker, with a beam cut of  $\pm 10\%$  about the reference momentum. Using G4beamline, the 4D normalised emittance for this design is calculated to be  $11.7\pi$  mm mrad. Beta and alpha functions average close to the match values, although there still exists scope for convergence.

To better tune the generated-emittance and also the quality of the match into MICE, an optimiser is under

development. The optimiser uses G4beamline for tracking, the MICE analysis software [12], and links to various external packages and Perl scripts. Presently, the Minuit ROOT libraries are used to minimise the difference between the tracked beta and the target beta by altering the final six matching quadrupole currents.

## SUMMARY AND FUTURE PLANS

The current design for the MICE beamline has been described, together with an overview of its estimated performance. The work has been illustrated here with reference to the  $7\pi$  mm rad, 200MeV/c beamline design. In general, the performance of all current beamline designs meet their goals in terms of muon beam rates and purity. The final beam emittances and the quality of the match however need further study, and a plan for optimisation is underway. A correction scheme is also under study for the muon transport line. This work has fed into the design of the MICE detectors and other critical systems.

Future plans include evaluating the beamline with the full MICE lattice, and then exploring the other emittance, momentum cases. The upcoming test of the prototype MICE target will provide important insights for removing one of the main uncertainties, specifically muon flux and purity. The MICE schedule envisages the beamline will be available for commissioning in September 2007.

## ACKNOWLEDGEMENTS

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