PARTICLE TRACKING AND BEAM MATCHING THROUGH THE NEW VARIABLE THICKNESS MICE DIFFUSER

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Abstract

The Muon Ionisation Cooling Experiment (MICE) aims to demonstrate the transverse cooling of muons for a future Neutrino Factory or Muon Collider. The diffuser is an integral part of the MICE beamline. It aims to inflate the emittance of the incoming beam such that cooling can later be measured in MICE. A new diffuser design is in development at Oxford, consisting of a sequence of high density scatterers of variable radiation lengths. Simulations have been carried out in order to understand fully the physics processes involved with the new diffuser design and to enable a proper matching of the beam to the MICE cooling channel.

INTRODUCTION

A future neutrino factory requires a cooled muon beam for maximum acceptance into its downstream accelerators [1, 2]. This is especially important if the facility is to be the starting point for a muon collider, which requires cooling to reach its design luminosity. However, due to the short muon lifetime, conventional beam cooling methods are unsatisfactory.

Ionisation cooling was first explored many years ago [3] – [7]. The transverse phase space of the beam is reduced by passing it through a low Z medium such as liquid hydrogen to minimise multiple scattering. Ionisation losses in the material reduce the overall momentum of the beam, which is then re-accelerated to restore its longitudinal momentum. Although it is the most promising technique for cooling muon beams, ionisation cooling has not yet been demonstrated experimentally.

The Muon Ionisation Cooling Experiment (MICE) is a proof-of-principle device with two primary aims:

1. To design, engineer, and build one section of cooling channel suitable for a Neutrino Factory [8].

2. To measure the cooling performance of this channel under a variety of operating modes and beam conditions.

A muon beam is passed through a series of absorbers followed immediately by accelerating RF cavities, as described in [9]. This is expected to reduce the transverse emittance of the beam by 10%. The MICE experiment is currently under construction at the Rutherford Appleton Laboratory (RAL), UK.

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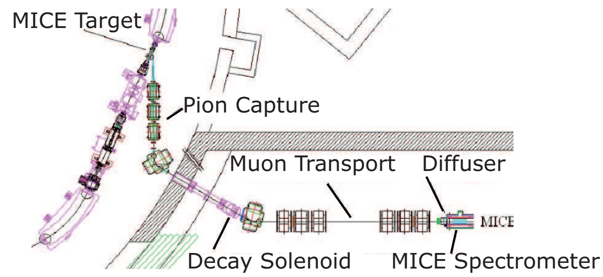

Figure 1: The MICE beamline. The diffuser is located inside the entrance of the first spectrometer solenoid. [9]

THE MICE DIFFUSER

To demonstrate ionisation cooling, the MICE beamline must supply a wide variety of input muon beams for the experiment. The beam is tunable between 140 – 240 MeV/c longitudinal momentum, p_z, and 1 – 12(π)mm·rad normalised transverse emittance, ε_N.

The muon beam is created by dipping a titanium target into the 800MeV proton beam at ISIS, RAL. This produces pions, which are transported down the MICE beamline [10] where they decay into muons. Figure 1 shows the beamline, the position of the diffuser and other key components.

The final component of the MICE beamline is the diffuser. This sits just inside the first spectrometer solenoid. The diffuser is designed to increase the transverse emittance of the muon beam in a controlled manner. The beam is then cooled in the MICE cooling channel.

The diffuser was initially conceived as a selection of lead discs, of different thickness, that could be inserted into the beam path. This design has been studied both with respect to its position within the first spectrometer solenoid, and to matching beams through the diffuser into the tracker region [11]. However, the diffuser must operate in the fringe field of a 4T solenoid magnet. This precludes the use of electric motors and other magnetic components, which made the initial diffuser design impractical to manufacture.

A new diffuser design has recently been approved by the MICE collaboration. This simplifies the mechanisms manufacture and operation, and improves the range of beam emittances provided.

A schematic of the approved design can be seen in Figure 2 . The new MICE diffuser consists of a stainless steel drum which is inserted into the upstream section of the first spectrometer solenoid magnet. The drum contains four irises, whose materials and thicknesses are listed in Table 1.

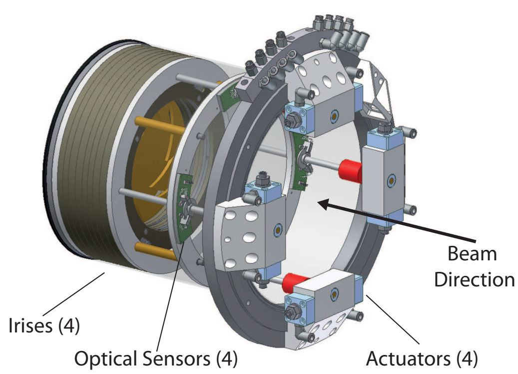

Figure 2: The re-designed MICE diffuser. Four irises are contained within a stainless steel drum, which operate in the fringe field of a 4T solenoid magnet.

Table 1: Diffuser Iris Materials and Thicknesses

Iris	Material	Thickness (mm)
1	Brass	2.97
2	Brass	5.94
3	Tungsten	2.80
4	Tungsten	5.60

These materials were chosen to provide a total of 3 radiation lengths, X_0, of material in steps of $0.2X_0$. Each iris is operated by a non-magnetic, air-driven, actuator and its status is monitored by a set of optical sensors.

An iris consists of two planes of four 'segments', offset with respect to each other, surrounded by a Tufnol ring (Figure 3). When closed, the iris presents a 'solid' piece of material to the muon beam with a radius, $r = 100$ mm. When open, the iris material is stowed outside this radius, within the Tufnol ring.

PHYSICS PERFORMANCE

The impact of a segmented diffuser disc was investigated using a simplified model with the G4MICE software [12]. Although a closed iris presents a solid face to the muon beam, muons follow a helical trajectory in a magnetic field. Hence, a proportion of muons will encounter the diffuser

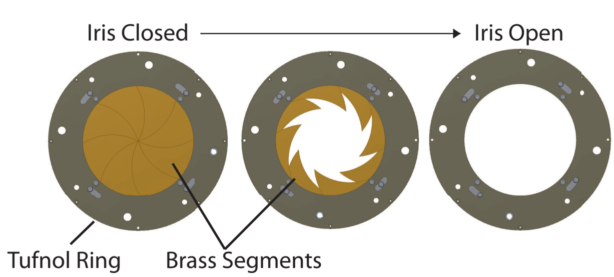

Figure 3: A diffuser iris being opened. When open, all material is stowed within the Tufnol ring.

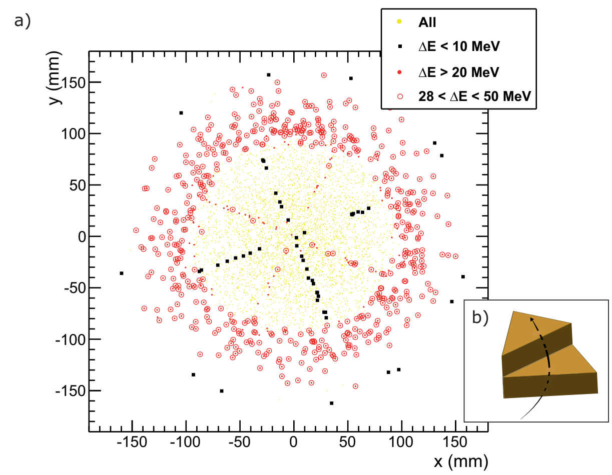

Figure 4: a) Muons passing through one diffuser iris, with all other irises open. The average expected energy loss for this diffuser setting is ≈ 15 MeV. b) A muon crossing two diffuser segments.

iris, and the joints between its segments, at an angle.

Figure 4 demonstrates the amount of energy lost by muons as a function of their position, (x, y), when they traverse an iris. This example shows one iris closed whilst the rest are open with their material stowed in the outer region. The majority of muons crossing the diffuser with $r \leq 100$ mm lose the expected amount of energy. However, about 1% of particles lose significantly more or less energy than expected. This is due to them crossing the area where two sets of segments meet, as illustrated in Figure 4b. This effect is negligible when using multiple irises together.

The overall radius of the diffuser is limited by the aperture size of the spectrometer solenoid. As such, problems can arise when a large, low momentum muon beam is passed through a single iris. In this case, a proportion of the beam lies in the outer region of the diffuser where excess diffuser material is stowed. This is shown by the red points in Figure 4 at $r > 100$ mm. These muons pass through significantly more material than intended, which should be considered when choosing appropriate diffuser settings.

BEAM MATCHING

Introducing material into the beamline changes the optical functions of the beam. As the new diffuser mechanism is made from a series of different materials, previously derived beam matching settings [11] are insufficient. Additionally, the new design provides further flexibility in terms of input emittances for the MICE cooling channel. This raises several questions to be addressed. For example, finding the correct input beam given a fixed diffuser, or finding a diffuser setting that best matches the beam into the MICE cooling channel.

A set of tools are in development that will allow the beam

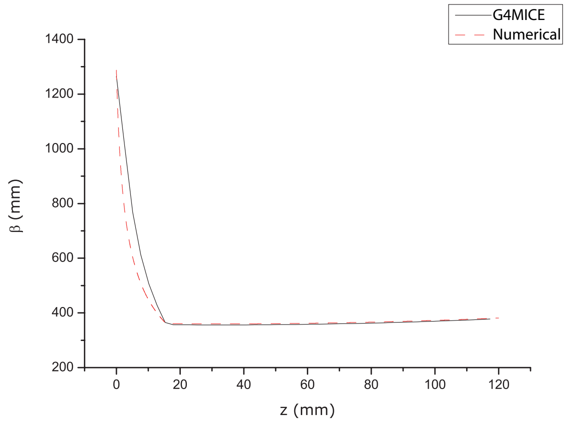

Figure 5: Comparison of beta function evolution between the numerical beam evolver and the G4MICE simulation.

to be matched in real time, based upon the evolution equations of [13]. This assumes that the beam is monochromatic in p_z and cylindrically symmetric. Figure 5 compares the resultant $\beta_\perp$ function through 15.6 mm of lead with a G4MICE Monte Carlo model. There are some small discrepancies between the analytic evolution of the beam optical functions and those found with G4MICE. This is due to the assumption of a constant rate of energy loss, $\frac{dE}{dx}$, as a muon crosses the material. Nevertheless, the evolution of the optical functions provides a good description for any subsequent re-matching of the beam to the MICE cooling channel.

For optimum performance, the MICE cooling channel requires the beam is matched to $\alpha = 0$, $\beta = \frac{p_z}{0.15B_z}$ mm at the centre of the tracker contained in the first spectrometer solenoid module. Given a set diffuser configuration – for example, using only the first and third irises – the upstream optical functions can be derived. The evolution of the β-function of such a re-matched beam through the new diffuser is shown in Figure 6, matching for $\varepsilon_N = 8$mm·rad and $\beta = 333$ mm at the centre of the tracker.

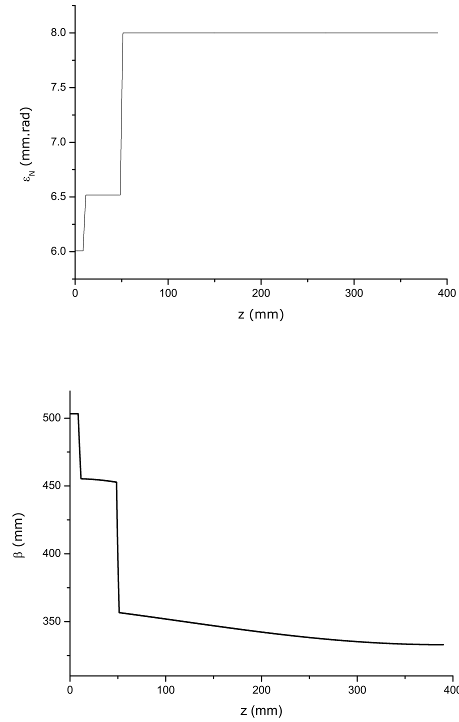

Figure 6: The emittance, ε_N, and β-function evolution of a beam crossing the 1st and 3rd iris of the new MICE diffuser, which is matched into the first spectrometer solenoid module.

CONCLUSION

The new MICE diffuser meets all of its design requirements. It is simpler to manufacture and operate, and also provides greater flexibility to the MICE beamline to match a beam into the cooling channel. Software is in development that will determine the most appropriate diffuser configuration to match the beam into the MICE cooling channel.

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