WEDGE ABSORBER DESIGN FOR THE MUON IONISATION COOLING EXPERIMENT*

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Abstract

In the Muon Ionisation Cooling Experiment (MICE), muons are cooled by ionisation cooling. Muons are passed through material, reducing the total momentum of the beam. This results in a decrease in transverse emittance and a slight increase in longitudinal emittance, but overall reduction of 6d beam emittance. In emittance exchange, a dispersive beam is passed through wedge-shaped absorbers. Muons with higher energy pass through more material, resulting in a reduction in longitudinal emittance as well as transverse emittance. We consider the cooling performance of different wedge materials and geometries and propose a set of measurements that would be made in MICE. We outline the resources these measurements would require and detail some constraints that guide the choice of wedge parameters.

EMITTANCE EXCHANGE IN THE MUON IONISATION COOLING EXPERIMENT

Ionisation cooling is achieved in the Muon Ionisation Cooling Experiment (MICE) [1] baseline by the placement of absorbing material in the beamline. The absorbing material reduces beam momentum, which is replaced only in the longitudinal direction by RF cavities, resulting in a net reduction of emittance. Overall, transverse emittance is reduced while longitudinal emittance stays the same or increases slightly due to stochastic processes in the energy loss.

Here we consider using MICE to observe emittance exchange. In emittance exchange a dispersive beam is passed through a wedge-shaped absorber. Muons with higher energy pass through more material and experience greater momentum loss. In this way the longitudinal emittance of the beam can be reduced either in addition to, or even instead of transverse emittance reduction. Emittance exchange is vital for the cooling section of a Muon Collider and has been considered as an upgrade option to the Neutrino Factory.

The measurement of longitudinal emittance reduction in MICE would test the accuracy of the absorber physics models in a different geometry; demonstrate that the physics of emittance exchange is well understood; and demonstrate emittance exchange in a real magnetic lattice.

A first simulation study of wedges in MICE was made in [2], where it was shown that even a large emittance dispersive beam could be passed through MICE step IV with acceptably small non-linear effects given care in the way the beam is selected.

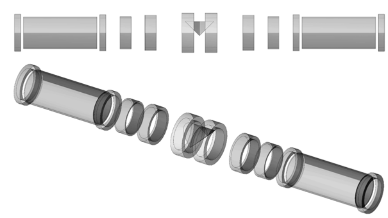

Figure 1: The geometry as simulated in G4MICE: side and 3D view. The wedge absorber and coils are shown. The total length of the Step IV layout is just over 7.5 m; inner radius of the coils is 258 mm.

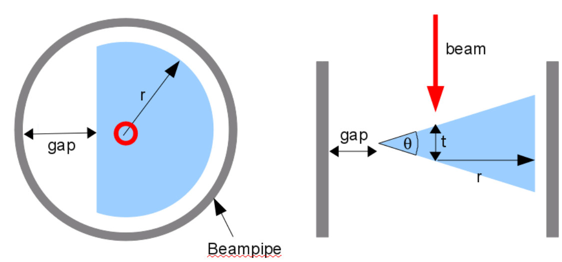

Figure 2: Schematic of the wedge geometry, which is parameterised by the on-axis thickness t, opening angle θ and radius r.

SIMULATION GEOMETRY

In this study a simple wedge-shaped absorber is simulated in a straight solenoid channel. The geometry is shown in Figure 1. The case considered here is MICE Step IV, where MICE is operated in flip mode without RF cavities. The focussing system has symmetry in transverse planes x and y and the absorber is at an optical waist with no beam kinetic angular momentum. The dispersion function is assumed to be at a waist and the dispersion direction aligned with the wedge.

Three materials are considered here, lithium hydride (LiH), beryllium and polyethylene (C_2H_4). LiH is a solid

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with low average Z and low Z/A resulting in less multiple scattering and energy straggling than polyethylene for a given energy loss and hence a generally better cooling performance. LiH is a restricted material due to the nature of its production, making it expensive and difficult to procure. There may also be some handling and safety issues associated with LiH. Polyethylene is readily available and widely used for many industrial applications so is easy to procure and there are no handling issues specific to this material. Beryllium has significant handling and safety issues as beryllium dust is toxic, but it is a material with comparable multiple scattering and energy straggling behaviour to the other materials considered in this article.

The wedge is modeled by the intersection of a triangular prism with a cylinder, as shown in Figure 2. The wedge absorber is parameterised by the thickness on-axis which determines the energy lost by a reference particle, and the opening angle of the wedge, which governs the emittance exchange. For opening angles above about 30° and energy losses typical in MICE, the absorber does not fill the aperture, leaving a gap at the thin end of the wedge. Thus, for larger wedge opening angles part of the beam does not pass through the wedge at all. For example, at 90° about 71$\%$ of the beam passes through the wedge. Overall the 6d cooling performance is better when only muons that traverse the wedge are counted, but the effect of the wedge-aperture gap is not too detrimental.

Wedge Requirements

To demonstrate longitudinal cooling conclusively, it is desirable that the longitudinal and six-dimensional emittance reduction be much greater than any optical beam heating, and this is our primary criterion for the absorber. The second criterion is that the absorber have a good cooling performance, i.e. small equilibrium emittances for a range of beams. In addition, it is desirable to test candidate materials that may be used in a real six-dimensional lattice. And, of course, the beam must have emittances that can be transported by MICE without excessive scraping and that can be generated by the beam line.

Available Beams

The MICE beam line has been shown in simulation to generate matched beams with emittances in the range 6 to 10 mm and momenta in the range 140 to 240 MeV/c. This gives us a good range of parameters with which to populate phase space for beam selection.

Control of dispersion has not been planned for the MICE beam line, and is expected to be challenging. It may be possible to introduce dispersion using a wedge-shaped disc in the diffuser mechanism, but achieving a satisfactory D and D' might be difficult. In this study, it is assumed that dispersion will be introduced using a beam selection algorithm. The parameters of the beam used in simulation, corresponding to a beam matched to the canonical MICE lattice and with typical emittances, are listed in Table 1.

Table 1: Parameters of the simulated beam at the wedge centre. D_i, D'_i are the dispersions and their derivatives.

Parameter	Value
Reference P [MeV/c][1]	200
Transverse emittance [mm][2]	6
Transverse β [mm]	420
Transverse α	0
Longitudinal emittance [mm]	90
Longitudinal β [ns]	10
Longitudinal α	0
RMS Energy Spread [MeV]	25.1
D_x [mm]	200
D_y [mm]	0
D'_x	0
D'_y	0
Number of μ^+	10000

Cooling Signal of Canonical Beam

The main criterion for wedge absorber choice is that a strong cooling signal be observable. The cooling signals for various wedges with the beam described above are shown in Figure 3. Polyethylene, beryllium and LiH materials were simulated with 60.5, 40.2 and 75.4 mm on-axis thicknesses respectively, corresponding to about 12 MeV energy loss at 200 MeV, and various opening angles. 12 MeV energy loss was chosen as it corresponds roughly to the energy loss in the standard MICE absorbers and is typical of ionisation cooling channel designs. In principle thicker absorbers could be used; the advantage is that any cooling signal may be more pronounced; the disadvantage is that this would take the absorber away from the parameter range normally considered for ionisation cooling channels and a significant energy loss may increase non-linear effects.

Longitudinal emittance reduction is more pronounced for larger wedge angles while transverse emittance reduction is more pronounced for lower wedge angles. For higher wedge angles, $\partial/\partial x(dE/dz)$ is more pronounced so that the longitudinal partition function is larger, resulting in more longitudinal cooling. For the same reason, more longitudinal cooling is observed for polyethylene than LiH and more again in beryllium; the relative Z/A in each material may lead to more energy straggling in Be and polyethylene, but this is outweighed by the increased energy loss that leads to greater $\partial/\partial x(dE/dz)$ for a given wedge angle. In most cases the wedges heat in transverse phase space, with more heating for larger opening angles. $\partial/\partial x(dE/dz)$ is larger and in the transverse phase plane this leads to less cooling, while the radiation lengths of polyethylene and beryllium is larger than that of LiH leading to significant heating.

[1] At the lattice start.

[2] The transverse distribution was generated ignoring the effects of dispersion, such that the calculated emittance is different from the nominal emittance listed here.

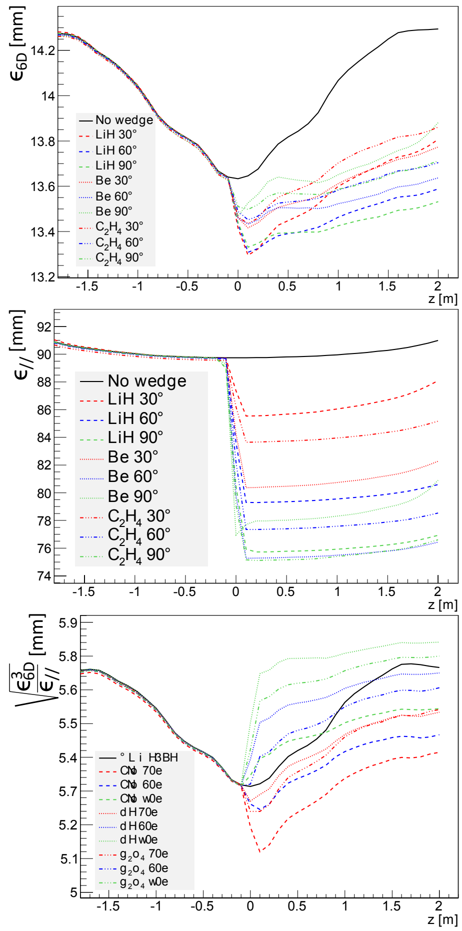

Figure 3: Simulated emittance along the beam line for canonical beam parameters and a dispersion of 200 mm.

The key part of this experiment is to demonstrate longitudinal emittance reduction. In light of this, the 30° wedge is disfavoured for LiH and polyethylene as the longitudinal cooling signal is too weak. On the other hand, the 30° LiH wedge is interesting as there are both a transverse and a longitudinal cooling signal. It may be possible to increase the dispersion to increase the longitudinal emittance reduction but this would take the lattice away from parameters that are currently foreseen in emittance exchange systems.

Minimum Wedge Radius

In this section the effect of a constraint on wedge radius is examined. The inner radius of the MICE absorber focussing coil (AFC) module is 263 mm, the bore of the beam pipe has an inner radius of 235 mm and mounting flanges for the absorbers intrude to an inner radius of 160 mm.

The effect on emittance change of limiting the wedge absorber radius was studied in detail for a 6 mm beam with 200 mm dispersion. The radius of the absorber was lowered from 225 mm, considered to be the largest that could fit inside the bore, and the fractional change in emittance was studied (see Fig. 4). For these simulations, a LiH wedge with 90° opening angle was simulated. Below 150 mm, the cooling performance of the wedge is degraded. This indicates that the aperture of the AFC is sufficient for a 6 mm beam, but that the wedge radius should be kept above about 150 mm.

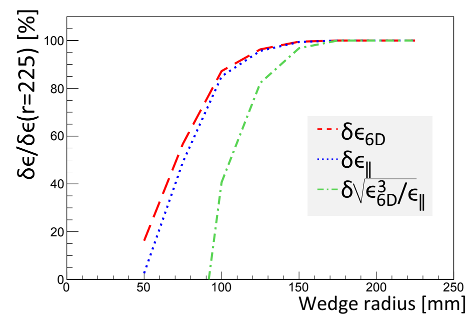

Figure 4: Effect on emittance change of reducing the outer radius of the wedge. Ratio of emittance change at a given radius to the emittance change at R=225 mm is shown.

Wedge Choice

As discussed above, the choice of wedge to operate is determined by the longitudinal emittance change that will be observed and the equilibrium emittance that can be achieved. The 90° LiH wedge is favoured as it shows the largest longitudinal emittance reduction. As demonstrated, the wedge–absorber gap does not significantly affect the overall emittance change; however, it may make some analyses more complicated. The 30° LiH wedge is of interest as it has a good longitudinal equilibrium emittance enabling a broader range of parameters to be studied, and also covers most of the AFC aperture. The 60° LiH wedge would then complete the set. It would also be interesting to study 30°, 60° and 90° polyethylene wedges as a cross-check of the physics process model, dependent on the time available for this experiment.

CONCLUSION

A detailed study has been made to enable choice of a wedge for placement in MICE. The cooling performance for a canonical beam and equilibrium emittance over a range of beam dispersions has been studied. This has led to the choice of, ideally, 30°, 60° and 90° LiH wedges and an equivalent set of plastic wedges. A more detailed technical report has been submitted to the MICE Notes database [3].

REFERENCES

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