TOWARDS A SYMMETRIC MOMENTUM DISTRIBUTION IN THE MUON IONISATION COOLING EXPERIMENT

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Abstract

The Muon Ionisation Cooling Experiment (MICE) is under development at Rutherford Appleton Labratory (UK). It is a proof-of-principle experiment for ionisation cooling, which is a prerequisite for a future Neutrino Factory (NF) or a Muon Collider. The muon beam will have a symmetrical momentum distribution in the cooling channel of the NF [1]. In the MICE beamline pions are captured by a quadrupole triplet, beam momentum is selected by dipole 1 (D1) before the beam traverses the decay solenoid. After the decay solenoid the beam momentum is selected by dipole 2 (D2), the beam is focused in two quadrupole triplets and characterised by time-of-flight (TOF) detectors TOF0 and TOF1 before entering the cooling channel. By doing a so-called D1-scan, where the optics parameters are scaled according to the upstream beam momentum, the purity and momentum distribution of the decay muons are changed. In this paper simulation results from G4Beamline (G4BL) [2] and data from MICE are presented and compared.

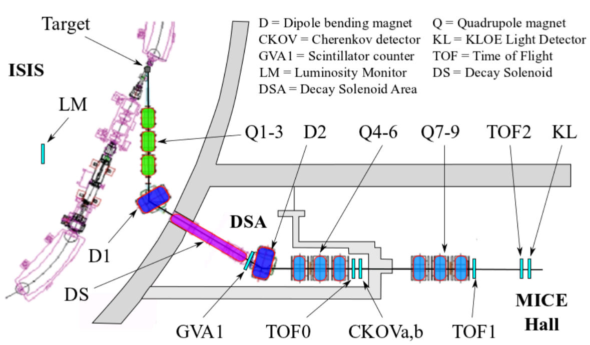

Figure 1: The MICE beamline at step 1.

INTRODUCTION

The short lifetime of muons demands cooling which is several times shorter than the decay time [3]. Ionisation cooling is generated as the muon beam enters and passes through a low-Z absorber in the MICE beam line, losing energy through ionisation [4]. The beam momentum is reduced in the transverse and the longitudinal direction and the longitudinal momentum is restored by acceleration. Ionisation cooling has been proposed for reducing the phase space volume of an intense muon beam for a NF and a Muon Collider. The change in normalised beam emittance ϵ_N in a medium is [5]:

$$\frac{d\epsilon_N}{dX} \approx -\frac{\epsilon_N}{\beta^2 E_\mu}\left\langle\frac{dE}{dX}\right\rangle + \frac{\beta_t(0.014GeV)^2}{2\beta^3 E_\mu m_\mu X_0}, \quad (1)$$

where X is the material thickness, X_0 is the radiation length of the medium, β is the velocity, β_t is the betatron function, E_μ is the muon energy and m_μ is the muon mass. The negative part gives emittance reduction through energy loss of beam particles and the positive part emittance increase through multiple scattering. It is therefore important that the energy loss is dominant to achieve cooling.

SYMMETRICAL MOMENTUM DISTRIBUTION

The MICE cooling channel is based on Feasibility study 2 (ST2)[1]. It consists of liquid hydrogen absorbers and accelerating cavities in a magnetic field. The muon momentum distribution of the beam used in ST2 is symmetrical, with a mean momentum of $\bar{p}$ = 207 MeV/c and momentum standard deviation of s_p = 28 MeV/c, as shown in figure 2.

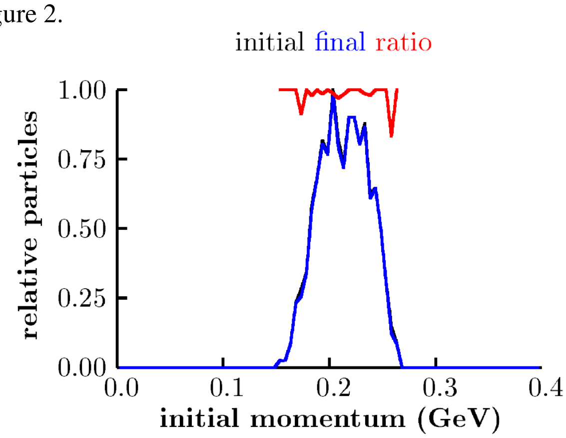

Figure 2: Momentum distribution of the ST2 muon beam [1].

The D1-scan is performed by holding the magnet strengths of D2 and the two quadrupole triplets Q4-Q6 and Q7-Q9 constant, while varying the strengths of the capture quadrupoles Q1-Q3, D1 and the decay solenoid proportionally to the reference pion momentum p_{D1}.

The standard 6 mm - 200 MeV/c beam is used, the magnet currents can be found in [6]. The conversion from currents to fields are done by interpolating values from a magnet data sheet, it can be found in the MICE documentation [7]. D2 is set to select muons with momentum p = 238 MeV/c.

The skewness

$$s = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^3}{(\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^2)^{\frac{3}{2}}}, \quad (2)$$

Table 1: Skewness for the positive and the negative beam calculated from the simulations. The positive/negative beam is on the left/right side of the slash.

p_{D1} +/-(MeV/c)	300/310	325/339	375/375	408/408
s	-0.82/-0.40	-0.13/0.17	0.51/0.45	0.65/0.68

is used to indicate how symmetrical the momentum distribution is. A perfectly symmetric distribution will have $s = 0$. The distribution is negative skew if the left tail is more pronounced than the right, and positive skew if the opposite [8].

SIMULATIONS

D1-scan simulations have been performed for beams of both signs. The skewness is observed to decrease when the ratio between the pion momentum at D1 and muon momentum at D2 p_{D1}/p_{D2} decrease and at some point become 0, such that the beam becomes symmetrical. The momentum distributions after the decay solenoid for $p_{D1} = 310$ and $p_{D1} = 408$ MeV/c are shown in figure 3 and the pion peaks are where one should expect them to be. To get a muon beam with a low pion contamination $p_{D2} < p_{D1}$ can be set to select the muons that decay backwards in the pion reference frame.

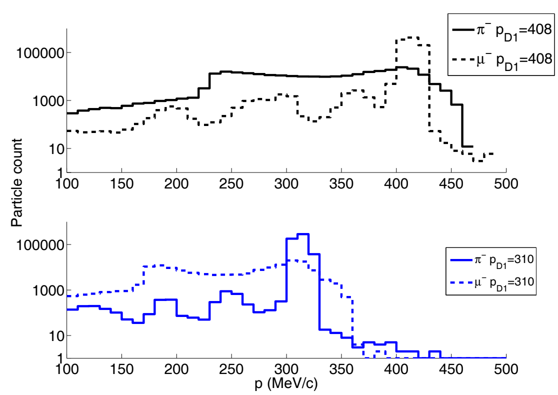

Figure 3: The momentum distribution after the decay solenoid, for the negative beam, with $p_{D1} = 310$ MeV/c and $p_{D1} = 408$ MeV/c.

The skewness values vs. p_{D1} for both signs beams are shown in the table. According to these simulations one would expect the beams to be close to symmetrical when $p_{D1} \approx 325$ MeV/c.

Some pion contamination is expected in the beam, according to the simulations the pion contamination is low in the interval $p_{D1} \in [300, 425]$, shown in figure 4. The worst case is approximately 2.7 %, if one selects the most pessimistic value of the error bar from $p_{D1} = 300$.

The muon momentum distribution from MICE data and G4BL at TOF1 are compared in figure 5 and the agreement is fairly good.

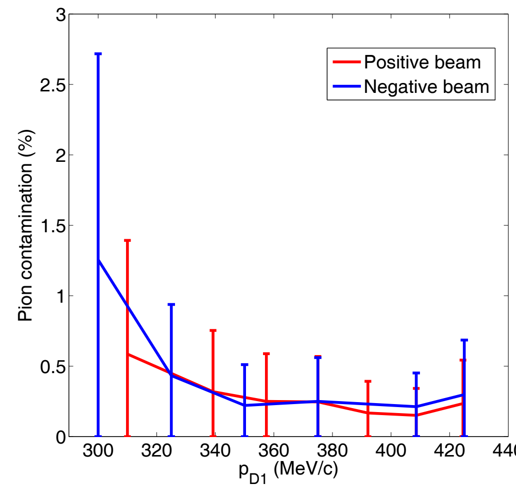

Figure 4: Pion contamination vs. p_{D1} at TOF1, error bars are statistical only.

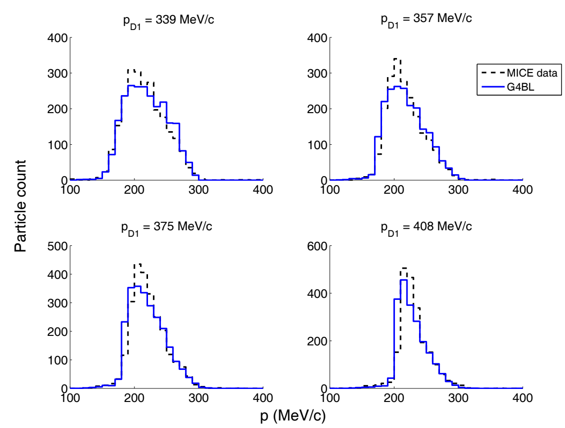

Figure 5: Momentum ditribution vs p_{D1} at TOF1. The distribution get more symmetrical when p_{D1} is lowered, the variance increase and the mean momentum is lowered.

SIMULATIONS AND MICE DATA

The statistics from the MICE data is low and it only exists for the negative beam at the moment, these results are therefore only preliminary. Higher statistics runs are expected to be taken and analysed in the near future. However, the statistics should be high enough to give estimates for the beam mean, skewness and standard deviation with reasonable error calculations.

Cuts are applied to eliminate the longest tails of the momentum distributions, a cut on the particle count was used, eliminating 2.5 % of the particles on each tail. Simulations have been normalised to the MICE data by integration. The cuts are especially important for the higher momenta, which have longer tails.

When analysing the MICE data the momentum distributions are approximated from the time-of-flight between TOF0 and TOF1, removing all particles in the TOF electron

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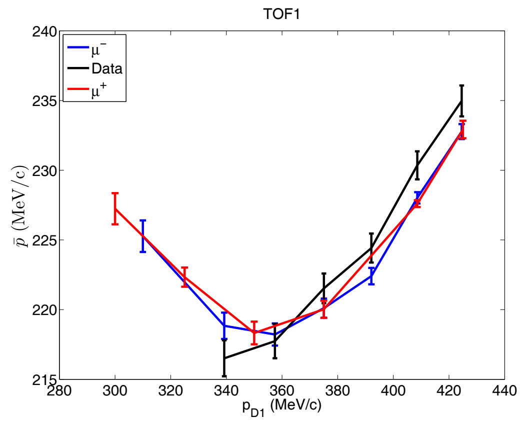

Figure 6: The mean momentum at TOF1 as a function of p_{D1}. The ST2 muon beam has $\bar{p} = 207$ MeV/c.

peak and assuming the rest of the particles to be muons.

The mean momentum at detector TOF1 lies in the interval $p \in [215, 235]$ MeV/c when varing p_{D1}, as shown in figure 6.

The standard deviation of the momentum distribution is shown in figure 7 and the maximum distribution width is found at 325 MeV/c for the simulations, and falls when going to higher momenta. For the MICE data the maximum is found at the lowest p_{D1}.

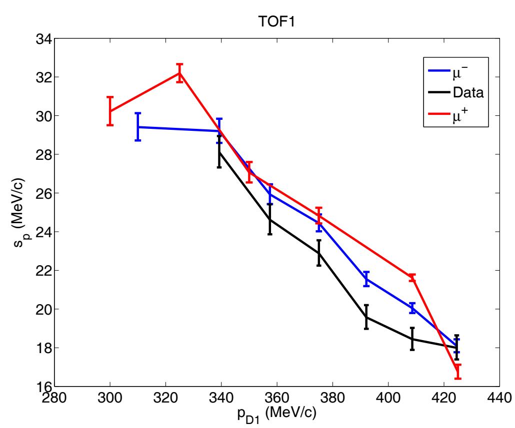

Figure 7: The momentum standard deviation vs p_{D1} at TOF1. The ST2 beam has $s_p = 28$ MeV/c. The error bars correspond to 95 % confidence intervals.

When calculating the skewness of the distribution the cuts are especially important. It is sensitive to outliers and therefore they are eliminated from distribution. The most symmetric distribution is found when $p_{D1} = 330$ MeV/c and for the MICE data the lowest data point has the lowest skewness.

CONCLUSION

If one argues that the MICE data can be extrapolated to agree with the simulations, then a symmetrical momentum

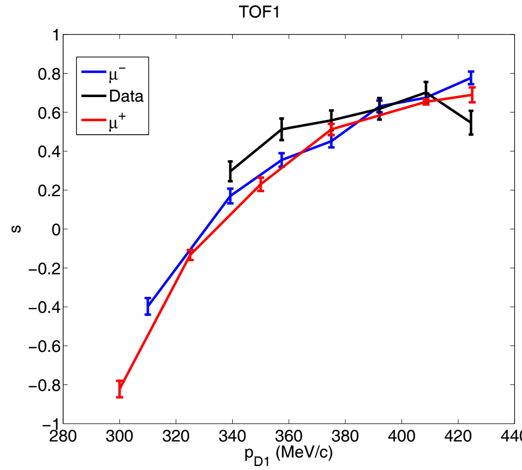

Figure 8: The momentum skewness vs. p_{D1}. The beam is symmetrical when $s = 0$. The error bars are only statistical.

distribution can be found when D1 is set to select pions with $p_{D1} \approx 325$ MeV/c, the standard deviation of that beam is $s_p \approx 30$ MeV/c. The mean momentum is $\bar{p} \approx 225$ MeV/c, but the mean momentum will decrease further between TOF1 and the cooling section, further downstream, where some detector material and a diffuser will be placed.

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