PROTON CONTAMINATION STUDIES IN THE MICE MUON BEAM LINE

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Abstract

The aim of the international Muon Ionization Cooling Experiment (MICE) is to demonstrate transverse emittance cooling of a muon beam through ionization cooling [1]. However, when the MICE particle beam is created, there exist high levels of proton contamination which swamp pion and muon rates in detectors. Therefore, sheets of polyethylene have been placed into the beam line to remove these protons [2]. It was experimentally determined that for a primary pion/proton beam of 370, 451, and 507 MeV/c, polyethylene sheets of 29, 83, and 147 mm thickness, respectively, were needed to reduce proton contamination to acceptable levels. Comparison with theoretical range plots shows satisfactory agreement.

INTRODUCTION

The MICE experiment, located at Rutherford Appleton Laboratory (RAL) in the United Kingdom, aims to demonstrate transverse emittance reduction of a muon beam. Such a technique is an essential component in the design of a neutrino factory or muon collider. Ionization cooling consists of first passing the muon through liquid-hydrogen absorbers to reduce all three of its momentum components, and then re-accelerating it along the direction of the beam line with RF cavities [6]. In MICE, this process will take place using a cooling channel as shown in Figure 1.

The MICE beam is generated by dipping a titanium target into the proton beam within the ISIS synchrotron. Particles created on each pulse are then transported downstream towards the cooling channel by a magnetic lattice consisting of three triplets of quadrupoles to focus and defocus the beam, two dipoles to select the particles' momenta, and a decay solenoid to enhance the acceptance for decays of pions into muons. The magnetic lattice can operate with either positive or negative polarity settings.

The MICE beam line also contains a number of detectors, as shown in Figure 2, which are used for measuring beam properties and particle information. Of particular interest to this study are three high precision time of flight detectors (TOF0, TOF1, and TOF2), and a scintillation counter named GVA1.

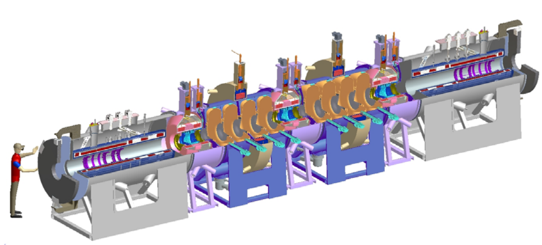

Figure 1: The MICE cooling channel and spectrometers.

TOF0, TOF1, and TOF2 are made of fast scintillation counters, and are used to measure the muons' arrival times with respect to the phasing of the RF cavities, and to provide particle identification information. TOF0 and TOF1 are located upstream of the cooling channel, and can each serve as a trigger for the experiment's data acquisition system. TOF0 is located after the second triplet of quadrupoles and was used as the trigger for this study. TOF1 is located after the last triplet, and TOF2 will be placed downstream of the cooling channel and used to measure particles that have traversed the entire channel [4].

GVA1 is a scintillation counter as well, and is located just after the decay solenoid (DS) and before the second dipole (D2). It is used to measure the charged particle rate exiting the DS in order to optimize the upstream beam line for particle transport.

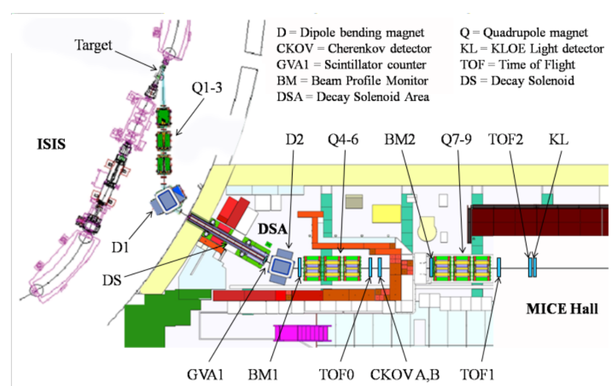

Figure 2: A schematic of the MICE beam line showing the magnetic lattice and detectors. The distance between GVA1 and TOF0 is approximately 6 meters. The proton abosorbers are located just after D1 and before DS.

CHOOSING THE BEAM LINE SETTINGS

The ISIS proton beam's interactions with the target produce a number of secondary particles, among which are pions that are transported by the first triplet of quadrupoles down the MICE beam line. These pions will eventually decay into muons as they travel along the beam line. The magnetic lattice is tuned according to what the momentum of the *muon* beam should be at the center of each absorber in the cooling channel. The muon momentum values

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Table 1: Settings for the MICE Beam Line Used in this Study

	140 MeV/c setting		200 MeV/c setting		240 MeV/c setting	
Magnet	Current (A)	Momentum (MeV/c)	Current (A)	Momentum (MeV/c)	Current (A)	Momentum (MeV/c)
Q1	77.45	361.28	96.77	451.37	127.97	507.39
Q2	141.64	361.05	176.98	451.16	159.97	507.18
Q3	86.70	360.83	108.35	450.94	111.27	506.96
D1	280.33	360.60	370.11	450.72	435.94	506.75
DS	0.00	360.37	0.00	450.49	836.15	506.52
D2	77.46	202.86	96.77	255.87	116.46	296.78
Q4	134.61	201.20	170.17	254.35	197.56	295.31
Q5	180.51	201.19	228.21	254.35	264.94	295.31
Q6	119.62	200.68	151.33	253.88	175.75	294.85
Q7	114.32	174.68	150.93	230.62	178.37	272.57
Q8	172.89	174.35	228.41	230.34	270.00	272.30
Q9	147.52	173.81	195.10	229.87	230.72	271.83

that MICE aims for at this location are 140, 200, and 240 MeV/c. The beam settings used in this study are shown in Table 1.

When the beam line is set to positive polarity, it transports a large number of protons which can potentially saturate the TOF detectors. For the momentum range at which MICE will operate, protons lose energy in material more quickly than pions and muons. Consequently plastic sheets of thicknesses 15, 29, 49 and 54 mm, referred to as the proton absorbers, were placed into the beam line just after D1 to filter out protons while allowing pions and muons to proceed unimpeded [2]. The purpose of this study was to determine the appropriate thickness of proton absorber for each of the MICE beam line settings.

ENERGY LOSS IN MATERIAL

The predominantly pion/proton beams which pass through the proton absorbers have *average* momenta of approximately 370, 451, and 507 MeV/c. For protons of these momenta, Figure 3 shows the expected range in the MICE proton absorbers, assuming a density of 0.89 g/cm^3. According to this figure, approximately 44, 84, and 130 mm of plastic should be enough to stop protons of 370, 452, and 507 MeV/c, respectively. However, there is some spread about the average momentum, and this spread also scales as a function of the beam momentum.

The range for protons was calculated using the continuous-slowing-down-approximation (CSDA), which is found by integrating the "Bethe" equation [5]

$$-\left\langle \frac{dE}{dx} \right\rangle = Z\frac{K}{A}z^2\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]. \quad (1)$$

(See [5] for parameter definitions.)

The calculation of this range assumes that the rate of energy loss along every point of a proton's path is equal to the total stopping power. It is obtained by integrating the reciprocal of Equation 1 with respect to energy [3].

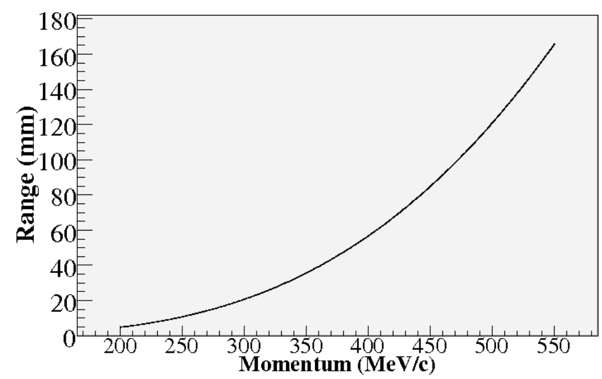

Figure 3: The range for protons in 0.89 g/cm^3 for momentum range of interest to MICE. This range was calculated by dividing the CSDA range, in g/cm^2, obtained from [3] by the density of the MICE proton absorbers.

Considering the momentum spread of the beam, which increases in proportion to the momentum, the range values shown in Figure 3 correspond to the absorber thickness which removes *most* of the protons from the beam, but not all of them. Protons at the higher end of the momentum spread will have a longer range.

REMOVING PROTONS FROM THE MICE BEAM

The proton absorbers have thicknesses of 15, 29, 49 and 54 mm, and can be inserted into the beam line individually or in any combination. For each of the three MICE beam line settings in Table 1, the proton absorbers were placed into the beam with increasing thickness. The time of flight of particles passing between GVA1 and TOF0 was measured by calculating the difference between the trigger, which was TOF0, and the time to digital converter (TDC) signal for GVA1, where the TDC bin width was taken as 25 ps [2]. Because all of the particles in the beam have the

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same average momentum, the protons, having a larger mass than muons and pions, should travel with a smaller velocity between GVA1 and TOF0, and therefore take a longer time.

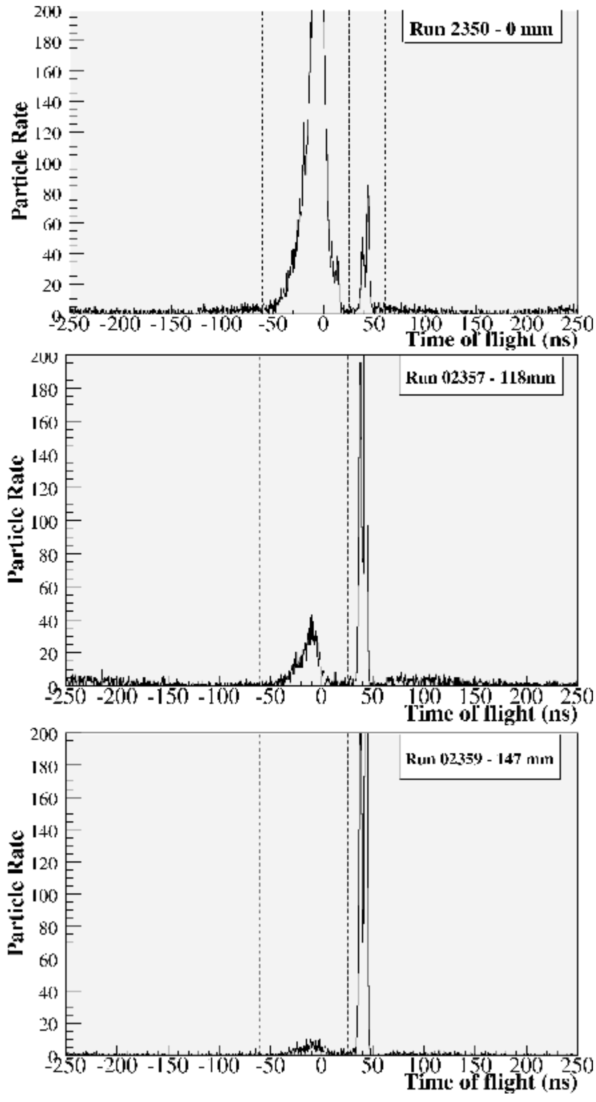

Figure 4: Particle rate for the time of flight between GVA1 and TOF0 for the 240 MeV/c beam line setting. The left population consists of protons, and the right population is muons/pions/positrons. The time of flight appears "negative" for some particles due to an offset between the TOF0 gate and GVA1 TDC. The proton absorber thickness is increased moving from top to bottom.

Figure 4 shows the time of flight of particles measured between GVA1 and TOF0. Because of details of the trigger timing with respect to the GVA1 signal, the TDC actually measures minus the time of flight, so the particles with more positive TDC values (between 25 and 65 ns) correspond to pions/muons,[1] and the population between −65 and 25 ns corresponds to protons. These time cuts were used when integrating the two peaks (separately) in order to determine the number of protons in the beam with respect to the number of muons.

[1] The resolution of GVA1 is not sufficient to distinguish among muons, pions and positrons, so the right-most population represents all of these particles.

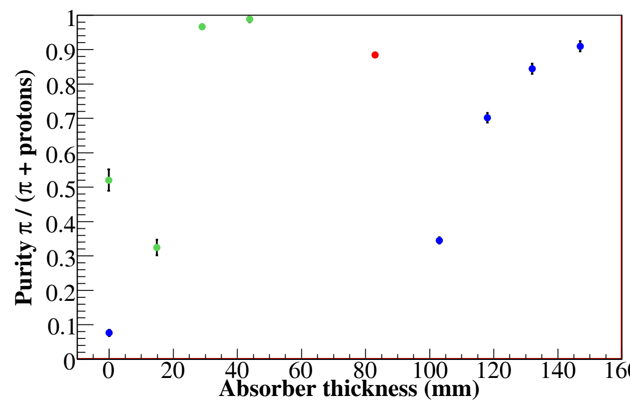

Figure 5: The purity of the beam as a function of absorber thickness for the 140 (green), 200 (red) and 240 (blue) MeV/c beam line settings.

RESULTS

As the protons pass through the proton absorbers, they lose energy through ionization and atomic excitations until they are completely stopped and thus removed from the MICE beam. For predominantly pion/proton beams of 370, 451, and 507 MeV/c at the location of the proton absorbers, 29, 53, and 147 mm of material are necessary to remove most of the protons from the beam. These values are satisfactory when compared with the preliminary theoretical predictions. Thus, the appropriate absorber thickness was determined for each beam momentum at which MICE will operate.

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