STATUS OF DESIGN OF 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 present design for the muon beamline, and the plans for its implementation at RAL.

INTRODUCTION

A Neutrino Factory based on a muon storage ring, is the ultimate tool for studying neutrino oscillations, however one of the challenges posed is the control of the large emittances possessed by muons from pion decay produced at the proton driver target. Ionisation cooling is a proposed mechanism to reduce this on a suitably short timescale. This involves passing through a sequence of absorbers and RF-cavities, replenishing only the longitudinal motion. The MICE collaboration has designed an experiment [1] in which a section of ionisation cooling channel could be exposed to a muon beam, and hence 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. It has been proposed to replace the old High Energy Physics (HEP) beamline, and install MICE on a new beamline at the facility. The HEP beamline consisted of an internal target on the ISIS synchrotron, together with dipole and quadrupole elements from the former NIMROD accelerator. For the new muon beam, it is proposed to make use of these magnets, together with a superconducting solenoid contributed by PSI in Switzerland, and a set of large aperture quadrupoles presently in storage at RAL.

BEAMLINE FUNCTIONS

The muon beamline must supply a muon beam with particular qualities in momenta, emittance, muon purity and rate. MICE is designed for reference momenta 140-240MeV/c. To allow for energy loss mechanisms, and tests with long cooling channel correlations, muon momenta of up to 300Mev/c must be supplied. For each case the momentum spread must be as large as possible. The MICE apparatus is designed to cool beams down to a normalised transverse rms equilibrium emittance of 2.5π mm rad, and it is desirable to supply beams with emittances from this level up to 6 π mm rad, and possibly beyond. Both of the above must also be supplied as a high purity muon beam, with high enough rates for good statistics to be accumulated in a reasonably short time.

DESCRIPTION

The proposed MICE muon beamline is based on a conventional pion-muon decay channel, similar to those used for condensed matter studies[2], but tuned for higher muon momenta, and with provision for emittance tuning and matching into the experiment. The beamline begins with a target dipped into the edge of the ISIS beam, after which the layout falls naturally into four main sections:

- Particles (mainly pions and protons) are captured by a first quadrupole triplet, tuned for as large an acceptance as possible.
- The accepted beam is momentum analysed by a rectangular dipole magnet and injected into a solenoid decay channel, where muons accumulate from pion decay.
- A second dipole is used to select the muon momentum, and separate them from the remaining pions and protons. The muons are then transported down a large acceptance transport channel.
- Beam is finally focussed onto a beam scatterer for emittance generation and matching 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.

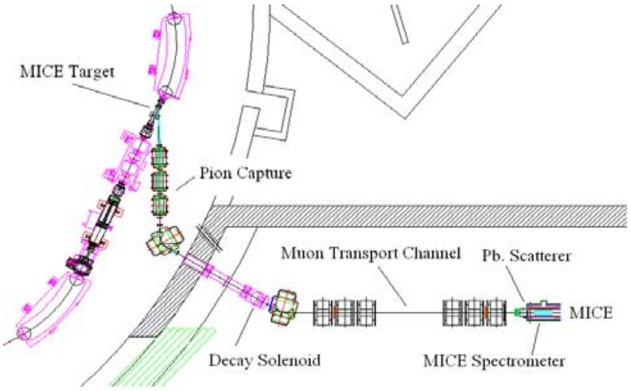

Figure 1: Current layout of MICE muon beamline.

The codes TRANSPORT [3] and DECAY TURTLE [4] have been used to design the beamline optics, supplemented by G4beamline [5], a simulation package based on version 4 of CERN's GEANT package. [6]

Target

A titanium target 1mm thick and 10mm long is dipped 2-5mm into the halo of the ISIS proton beam at 1Hz, providing the initial source of pions. The target is dipped at ~ 800MeV. This provides pions with at least 350MeV/c which will decay to muons over the required momentum range. Studies with LAHET [7], GEANT4 and MARS[8] have been undertaken to estimate particle production, using the smallest practical capture angle of 25°.

The ultimate performance will depend upon target heating and beamloss limitations. The latter constitutes one of the uncertainties in calculating the production rates, and it is hoped to undertake a series of measurements in 2005/06 to quantify this further.

Pion Injection and Decay Section

The first two sections of the beamline are designed for a pion momentum of 350Mev/c, and a momentum spread of 2.5%. The first section contains a quadrupole triplet, placed as close as possible to the target, and tuned to maximise the pion acceptance. The beam is then transported and focussed through a large aperture rectangular dipole, deflecting the central trajectory by 60°. The pion transmission efficiency is ~ 65% which compares favourably with similar beamlines [9].

The decay section consists of a 5m superconducting solenoid, used to collect as many muons from pion decay as possible. The solenoid, from the former μE4 beamline at PSI can reach fields of 5Tesla. High field operation decreases the diameter of the helical spiral of the decay muons, increasing the capture rate, and a field of 4.7Tesla has been found to be optimal in the current design. The full-width pion beam profile for the first two sections is illustrated in Figure 2.

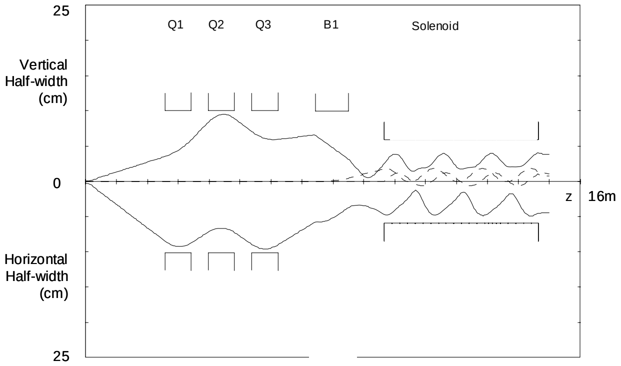

Figure 2: TRANSPORT beam profile for the pion injection and pion-muon decay section.

A 5cm polyethylene absorber will also be placed at the end of the decay section. The purpose of this element is to absorb background protons transported from the target.

Muon Extraction

This section consists of a large aperture dipole, and two sets of large aperture quadrupole triplets. The dipole bend angle is 30° which bends the beam parallel to the length of the experimental hall. Vacuum chambers are omitted in this section, in view of the low muon-air interaction cross sections, and the larger transmissions thus derived.

The current design provides a muon beam with a central momentum of 250Mev/c. The shallow bend of the second dipole keeps dispersion to a minimum and a large muon momentum spread is achieved. These combine to allow a momentum-transverse amplitude correlation expected in a Neutrino Factory [10] to be constructed by offline particle selection.

The transport line incorporates the upstream part of the MICE detector system, and the layout has been influenced by the requirements for time-of-flight particle identification. The distance between the last quadrupole and the MICE lattice has been set to minimise the effects of the strong fringe field of the MICE spectrometer solenoid on this element.

The muon beam profile for this section is shown in Figure 3. This shows the rms vertical profile for 250MeV/c muons which reach the lead scatterer, together with the horizontal profile of the same emittance. The final beam focus is discussed in the following section.

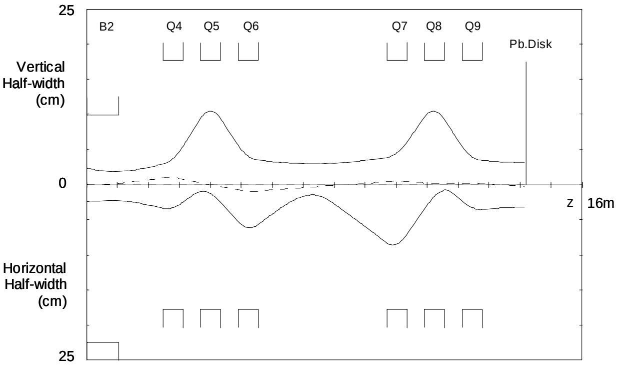

Figure 3: TRANSPORT beam profile for muon extraction.

Emittance Preparation & Matching

The transport line typically supplies a normalised rms vertical emittance of ~ 1π mm rad, at the momentum of interest, and slightly larger in the horizontal due to the present quadrupole optics.

MICE plans to cool beams of at least 6π mm rad, and to generate such large emittances, it is planned to use multiple scattering in a lead disk just before the experiment, to boost the angular spread of the beam.

For a thin scatterer, and to first order, the effect on the geometric emittance ε and Twiss parameters (α,β) can be summarised as [11]:-

$$\Delta\varepsilon = \frac{1}{2}\beta_0\langle\theta^2\rangle \qquad \alpha = \frac{\varepsilon_0\alpha_0}{\varepsilon_0+\Delta\varepsilon} \qquad \beta = \frac{\varepsilon_0\beta_0}{\varepsilon_0+\Delta\varepsilon} \tag{1}$$

where $\sqrt{\langle\vartheta^2\rangle}$ is the rms scattering angle, and the subscript refers to incoming beam parameters.

In addition to increasing the emittance, it is important to ensure that the muon beam is matched into the experiment, which requires control over the two Twiss parameters α and β. The upstream MICE spectrometer solenoid has been designed with a set of end coils, which aim to provide a uniform 4T longitudinal field. The beam profile is designed to be constant within this, and this can be achieved with a beam with optical properties:-

$$\alpha = 0 \qquad \beta = \frac{2p}{qB} \tag{2}$$

These two conditions of emittance tuning and matching can be achieved simultaneously by focussing the beam at the lead scatterer with an appropriate beamsize, and adjusting the scatterers length to achieve the required matched distribution. This process is illustrated in Figure 4 below:-

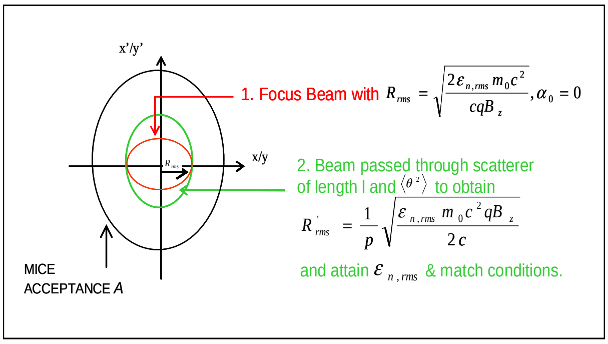

Figure 4: Use of scatterer and beamline for emittance-tuning and matching.

The effect of the energy loss in the material can be accommodated by a small iteration on the resulting thickness of the lead.

Performance

The above scheme has been applied to the beamline at the incoming central momentum of 250Mev/c and for a normalised emittance of 6π mm rad, resulting in the beam profile shown in Figure 3. The scheme is driven by the smaller vertical emittance, with the result that the horizontal distribution covers a slightly larger area in phase space. A lead thickness of 0.8cm was found appropriate, placed immediately upstream of the first MICE end-coil, and resulting in a final central momentum of 236.5Mev/c. The overall momentum spread is large. Current assessments based on tracking with G4beamline, and modelling of the MICE target, indicates 200 useful muons/ms, with a pion contamination approaching 0.1%.

Beamline Diagnostics and Control

Beam diagnostics to identify particle species, and measure beam profiles are in development. These will be based on segmented scintillators together with photomultiplier tubes. A system for beam steering and optic control based on these devices is under consideration.

FUTURE PLANS

Work is ongoing across a number of areas, and with suitable funding, beam is anticipated at the end of the proposed ISIS 2005/06 long shutdown. Immediate plans include prototyping and performing system tests on the new MICE target, and developing the beamline diagnostics described above.

A number of features exist in the full beam distribution which still remain to be explored. Simulations of the beamline will continue, incorporating the full MICE lattice, to develop and optimise its performance for different emittances and momenta.

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