Issues and Mitigations for Advanced Muon Ionization Cooling

Muon Collider Collaboration

1 Introduction

Authors: I would prefer individual author signatures I think - good to collect list of people directly interested in this effort

TODO: references, proof read for english, collect signatures, finish table, finish words

Muon beams can be created by firing protons onto a target, producing pions, kaons and muons. The short-lived pions and kaons decay resulting in a large number of muons. However, the resultant muon beam has a large 6D emittance making use of the muons challenging. Muon ionization cooling can be used to reduce the 6D emittance of the beam. In this LoI different muon ionization cooling schemes are reviewed and the outstanding technical challenges are identified. Schemes to mitigate the challenges, such as cooling demonstrators, are discussed.

2 Muon Ionization Cooling Schemes

In muon ionization cooling, muons are passed through an absorber, reducing the total momentum and normalised transverse beam emittance. Subsequent passage through an RF cavity can restore the longitudinal momentum resulting in reduced geometric transverse emittance. Multiple Coulomb scattering off the atomic nucleus weakens or ruins the effect. Tight focussing makes the angular spread of the beam large compared to the scattering to counteract this. Use of an absorber having low atomic number increases the amount of energy loss compared to the scattering, also mitigates the effect.

More recent schemes have used an emittance exchange process to reduce the longitudinal emittance. Dispersion can be introduced by bending the beam in a dipole; this can be removed by subsequently passing the beam through a wedge-shaped absorber. In this way, the high energy portion of the beam passes through a thicker absorber and longitudinal emittance is transferred into transverse emittance, which is reduced in the way outlined above.

The parameters of the Muon Accelerator Program muon source cooling scheme are summarised in the table 1

3 Possible Issues

In this section possible issues that may inhibit the realisation of the cooling scheme's full potential are reviewed.

- Energy loss due to ionisation of atoms in the absorber gives rise to ionisation cooling. The physics is well-characterised. Longitudinal cooling is effected by the relative change in energy loss for particles having different momentum, and random noise in the actual energy loss (energy straggling). Further studies are needed to understand the potential impact on longitudinal cooling of uncertainties in the straggling distribution. CHECK - brief literature review required

- Transverse cooling is limited by multiple Coulomb scattering of muons off the atomic nucleus. A dedicated study, MuScat, was performed to measure the magnitude of multiple Coulomb scattering and simulation models were updated. MICE is reproducing this validation over a broader range of momenta.
- Cooling requires tight focussing of muon beams, despite sometimes large transverse and longitudinal emittance. Simulations indicate this can be achieved using large aperture, high field solenoids. The physics is well-characterised. It is noted however that additional design work is required to reach the lowest emittances.
- The cooling systems place significant demands on equipment, requiring combined function solenoids and dipoles or tilted solenoids in the early section and state-of-the-art high field solenoids in the final sections. It is also noted that muon beam losses may make an adverse radiation environment. Solenoids are coupled throughout the cooling system; particular attention is required to ensure that the entire system is not coupled in the event of a quench.
- The cooling performance is limited by the size of the RF bucket and the amount of acceleration that can be provided. High gradient RF cavities are challenging to achieve due to breakdown, particularly in the presence of magnetic fields. Recent success has been achieved in suppressing breakdown by: using Beryllium RF cavity windows which suffer less heating; and suppressing secondary electron emission using high pressure gas-filled cavities.
- Space charge is expected to have a measurable effect on cooling only for the very lowest longitudinal emittances.
- Bulk ionization of material ...
- Absorber heating ...
- Plasma loading of HPRF cavities ...
- Anything else?

4 Mitigations

Several cooling test stands will be considered

- Where possible technical challenges should be avoided by design improvements. Engineering test stands will be used to develop challenging cooling equipment such as high field magnets.
- A flexible muon solenoid-dipole linear channel could enable 6D cooling of muons over a wide range of parameters. Measurement of the small changes in emittance expected from just a few cells would be challenging, although MICE has achieved such a measurement using particle physics style detectors.
- A proton solenoid-dipole linear channel could enable observation of some collective effects. Some effects, such as space charge, accumulate over many cells and may be challenging to observe in just a few.

Section	$\epsilon_\perp$ [mm]	ϵ_l [mm]	$\sigma(x')$	$\sigma(t)$ [ns]	$\sigma(E)$ [MeV]	peak intensity	peak field	magnetic stored energy per length
Initial Cooling Start								
Charge Separation								
HFoFo Start								
Bunch Merge								
Final Cooling Start								
Final Cooling End								
Parametric Ionisation Cooling								
HFoFo gas-filled channel								
Helical channel								

Tab. 1: Summary of the basic parameters; in particular, relate to physics issues.

- A small muon cooling ring would enable the demonstration of 6D cooling of muons. Such a ring would likely be superconducting and several metres in diameter. It would be challenging to reach the design requirements of the full muon collider scheme (e.g. low emittance), but the cooling signal could potentially be bigger than in a linear cooling channel.
- A small proton internal target ring would enable the demonstration of 6D cooling. The physics processes are slightly different; electromagnetic processes would still dominate, but nuclear processes may also be possible. Intensity effects would be more readily measurable due to the higher proton beam currents available. Such a ring could be normal conducting, making the construction a bit easier.

5 Conclusions

The main technical issues for the MAP cooling scheme have been outlined. The Muon Collider Collaboration will continue to update and improve this assessment and use it to guide future studies in order to improve the baseline design.