Issues and Mitigations for Advanced Muon Ionization Cooling

on behalf of the Muon Collider Collaboration

1 Introduction

There is renewed interest in muon ionization cooling. The Muon Ionization Cooling Experiment has successfully demonstrated ionization cooling for the first time [1]. Also, owing to the excellent potential for physics at a muon collider, the 2020 Update of the European Strategy for Particle Physics recommended that muon beam R&D should be considered a high-priority future initiative [2, 3, 4]. Muon ionization cooling may also be used to generate higher muon beam currents for the muon beamlines to g-2, mu2e and similar facilities [5, 6].

Muon beams can be created by firing protons onto a target, producing pions, kaons and muons. The beams are quite sparse i.e. have high emittance. Muon ionization cooling is required to reduce the emittance to yield the high luminosity desired in a muon collider. In this Letter of Interest 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 [7, 8], muons are passed through an energy absorbing material, reducing the total momentum and normalised transverse beam emittance. Subsequent passage through an RF cavity restores the longitudinal momentum only. Multiple Coulomb scattering weakens 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 mitigating the effect.

Emittance exchange [9] reduces the longitudinal emittance. Dispersion is introduced by bending the beam in a dipole; this is removed by passing the beam through a wedge-shaped absorber. In this way, the high energy portion of the beam passes through more absorber and longitudinal emittance is transferred into transverse emittance, which is reduced in the way outlined above.

A number of cooling channels have been designed. Beams confined in solenoid-dipole combined function magnet lattices [10, 11], helical dipoles [12], cyclotrons [13] and more conventional quadrupole channels [14] have all been proposed. The transverse cooling ideas were tested by MICE. Work is ongoing to study a wedge that was placed in the MICE beamline to make a preliminary test of 6D cooling [15].

3 Possible Issues

The muon collider collaboration has begun to identify issues that may inhibit the performance of a muon cooling scheme.

- Energy loss due to ionisation of atoms in the absorber gives rise to ionisation cooling [16]. 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.
- Transverse cooling is limited by multiple Coulomb scattering of muons off the atomic nucleus [16]. A dedicated study, MuScat, was performed to measure the magnitude of multiple Coulomb scattering and simulation models were updated [17]. MICE is reproducing this validation over a broader range of momenta and materials [18].
- Cooling requires tight focussing of muon beams, despite sometimes large transverse and longitudinal emittance, that is challenging to achieve. Simulations indicate this is possible using large aperture, high field solenoids. The beam physics is well understood. It is noted however that additional design work is required to reach the lowest emittances [19].
- High field magnets are required. The design calls for 30 T solenoids with a 25 mm aperture while lower field solenoids are required with considerably larger apertures. Dedicated prototyping will be necessary to achieve some of the most challenging magnets. It is also noted that muon beam losses may make an adverse radiation environment. Solenoids are coupled throughout the cooling system; attention is required to ensure that a quench does not propagate through the entire magnet system.

- 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: careful surface preparation and coatings; use of Beryllium RF cavity windows which suffer less heating [20]; and suppression of secondary electron emission using high pressure gas-filled cavities [21].
- Further evaluation is needed on the impact of conventional collective effects such as space charge.
- Absorber heating may be an issue, especially for designs employing solid absorbers. Active cooling systems may be required, with appropriate care to avoid disturbing the beam.
- Bulk ionization of material may generate a plasma [22]. Interaction of the plasma with the beam is not expected to affect the beam at higher emittances. Further studies are needed at lower emittances and higher intensities.
- Beam loading of RF cavities may be an issue [23]. Some designs call for high pressure gas to act both as an insulator to suppress breakdown, and a muon energy absorber. The ionization of the gas results in plasma formation which may cause additional loading on the RF cavity.
- Day-to-day operation of the cooling channel will require understanding of beam line tuning and appropriate diagnostics.
- Safety issues surrounding use of high pressure gases and liquid hydrogen must be further explored.

Better understanding of these issues and identification of further challenges will be achieved both by simulation and by constructing and operating test equipment.

4 Mitigations

A cooling test stand based on several tentative concepts is under consideration:

- 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 small proton internal target ring would enable the demonstration of 6D cooling [24]. The physics processes are slightly different; electromagnetic processes would still dominate, but nuclear processes may also be significant. Absorbers would be much thinner due to the shorter proton range in material. 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 easier.
- A muon cooling ring would enable the demonstration of 6D cooling of muons. The cooling signal could potentially be bigger than in a linear cooling channel, but the complexity of the device may also be more challenging.
- 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.
- A flexible muon combined function solenoid-dipole 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 phased scheme could combine several of the options outlined above. Novel concepts may arise during design work and will be integrated into the concepts outlined above.

The test stands may be standalone facilities. However an intriguing possibility is to combine a test stand with an existing or planned muon source, for example nuStorm [25], to provide an intense muon beam and a dedicated test facility.

5 Conclusions

Some of the issues that may inhibit muon cooling schemes have been outlined. Concepts for cooling test stands have been mentioned. The collaboration will seek to improve its understanding of the technical issues and consider construction of appropriate demonstrators, if deemed necessary, to better understand those issues.

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