The MICE demonstration of ionization cooling

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Abstract. A Neutrino Factory has the potential to make precision neutrino oscillation measurements, which are aided by cooling the muon beam prior to acceleration and decay. The MICE demonstration of ionization cooling adds two accelerating cavities to the existing MICE apparatus in order to show that sustainable cooling is feasible. In order to accomplish this the cooling cell design has been carefully optimised and settings have been found which show a measurable cooling effect for each MICE momentum setting.

1. Introduction
A Neutrino Factory produces high intensity neutrino beams from the decay of stored muons, a technique which has the potential to make precision oscillation measurements. The NuMax+5 GeV factory [1], is optimised for $\delta_{CP}$ studies and uses muon cooling prior to acceleration to reduce the emittance of the muon beam and improve the overall neutrino flux.

Existing cooling technology is incompatible with muon beams due to the short particle lifetime, however a rapid technique called ionization cooling has been proposed. The technique is a repeatedly iterated two step process, where particles are first passed through material, losing energy, and then accelerated to restore the longitudinal momentum. Within the material energy loss reduces the transverse emittance of the beam, while multiple scattering increases the transverse emittance of the beam. The equilibrium emittance is [2]:

$$\varepsilon_{eq} \simeq \frac{\beta_\perp (13.6 \text{ MeV})^2}{2\beta m_\mu X_0} \left\langle \frac{dE}{ds} \right\rangle^{-1}.$$  \hspace{1cm} (1)

where $\beta_\perp$ is the transverse beta function of the beamline, $X_0$ is the absorber materials radiation length and $\frac{dE}{ds}$ is the energy loss in the absorber. For effective cooling, materials with a high $\frac{dE}{ds}$ and $X_0$, such as liquid hydrogen and lithium hydride, are selected. Finally, the beam must be strongly focused within the absorber in order to minimise $\beta_\perp$.

2. The Muon Ionization Cooling Experiment
The Muon Ionization Cooling Experiment (MICE) is hosted at the Rutherford Appleton Laboratory and uses a dedicated beamline from the ISIS synchrotron to provide single muons to the experiment [3]. MICE is in the process of Step IV [4], which will study the cooling process without additional acceleration. The MICE demonstration of ionization cooling adds a pair of radio frequency cavities to the existing cooling cell to re-accelerate the muon beam, as shown in figure 1. This will enable MICE to study the cooling process with re-acceleration and will ultimately enable MICE to demonstrate ionization cooling as a feasible technology.
Before cooling, each particle passes through the upstream instrumentation, which includes a pair of Cherenkov detectors, a pair of time of flight hodoscope stations and a scintillating fibre tracker inside a uniform 4 T field. The fibre trackers measure the position and momentum of each particle, which are then combined to determine the emittance of the beam. In addition the momentum is combined with the velocity measured by the time of flight detectors as a means of particle identification.

At the centre of the experiment is a cooling cell, which contains a central primary absorber surrounded by a pair of radio frequency cavities. Two additional secondary absorbers are used to shield the sensitive detectors surrounding the cooling cell from cavity radiation. The beam is focused using two superconducting solenoid focus coil modules, which are placed each side of the primary absorber.

After cooling the particles are remeasured using a second tracking detector, followed by a third time of flight station, and a tracking calorimeter to confirm particle identification.

3. Performance
In order to maximise the performance of the lattice the beta function, shown in figure 2, has been carefully tuned. Cooling is maximised by minimising $\beta_\perp$ in the absorbers, while the transmission is maximised by limiting the maximum beam size to the apertures of the beamline components. In addition the direction of the focusing field is flipped in the central absorber to cancel the build up of canonical angular momentum in the beam.

The cooling performance of the lattice was studied using the MICE Analysis User Software (MAUS) [5], which uses GEANT4 for simulation. Beams are generated before the upstream tracker and transported through the lattice. The emittance of a 200 MeV muon beam as it propagates through the lattice is shown in figure 3 and shows cooling within the absorbers. Heating of the beam is experienced in regions of high $\beta_\perp$, but overall this is much less than the cooling.

The optimisation process has been repeated for each momentum setting of interest to MICE, and the results are shown in table 1. Each of the settings will produce a measurable cooling effect, with the 140 MeV/c setting producing the largest cooling.

4. Conclusion
The MICE demonstration of ionization cooling builds upon existing apparatus to show re-acceleration of a muon beam during cooling. A lattice design has been found which adds two radio frequency cavities to the cell, and shows cooling for several beam momenta. These settings will enable the MICE demonstration of ionization cooling to study the behaviour of the beam...
Figure 2. The $\beta_\perp$ function for a 200 MeV/c muon beam in the cooling lattice, showing minimised beta in the primary absorber to maximise cooling performance.

Figure 3. The emittance of a 200 MeV/c muon beam transported through the lattice, showing cooling in the absorbers.

Table 1. Cooling performance of the three momentum settings MICE will study.

| Beam momentum (MeV/c) | Initial emittance (mm) | $\Delta \varepsilon/\varepsilon_{in}$ (%) |
|-----------------------|------------------------|----------------------------------------|
| 140                   | 4.2                    | -8.1                                   |
| 200                   | 6.0                    | -5.8                                   |
| 240                   | 7.0                    | -3.0                                   |

during re-acceleration and ultimately show that ionization cooling is a feasible technology for a Neutrino Factory.

References
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