Frictional Cooling

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Abstract. To build a Muon Collider, on the order of 10^{12} muons must be produced and then collected in a small phase space to achieve interesting luminosities. The muons are produced by targeting a bunched proton beam on a target in a region of strong magnetic field. The pions resulting from the proton interactions are constrained to helical trajectories by the magnetic field, and decay to muons in some drift space. The resulting muons occupy very large phase space. They must then be collected and cooled before they can be injected into an accelerator chain. Reducing this phase space of the produced muons, by at least 10^6, is a critical issue in producing a high luminosity Muon Collider. The scheme considered here is based on frictional cooling in gases[1]. This in principle gives the possibility to cool both μ^+ and μ^- to the sufficient emittance.

1. Basic Ideas

The basic idea of frictional cooling is to bring the muons into a kinetic energy range where the energy loss per unit distance increases with kinetic energy. A constant accelerating force can be applied to the muons resulting in an equilibrium energy. A sample dE/dx curve is shown in Fig. 1, where it can be seen that this condition can be met for kinetic energies below a few KeV or kinetic energies beyond about 200 MeV. At the high energy end, the change in dE/dx with energy is only logarithmic, whereas it is approximately proportional to the speed at low energies. Below the dE/dx peak, muons are too slow to ionize the atoms. The processes leading to energy loss: excitation, elastic scattering on nuclei and charge exchange reactions yield differences for μ^+ and μ^-, with significantly large energy loss rates for μ^+[2].

Operating in this energy regime, an electric field can be applied which compensates for the energy loss. Several issues become apparent:

- dE/dx is very large in this region of kinetic energy, so we need to work with a low average density gas in order to have a reasonable electric field strength. 5 MV/m is used in all simulations.
- The electric and magnetic fields must be applied perpendicular to each other or the muons will never get below the dE/dx peak. At the higher energies, the muons follow the magnetic field lines with slow drift and do not pick up energy from the electric field. Once the muons are slow, the electric force is no longer small compared to the magnetic force and the muons will drift out of the volume at a definite Lorentz angle given by the ratio of the magnetic and electric fields.

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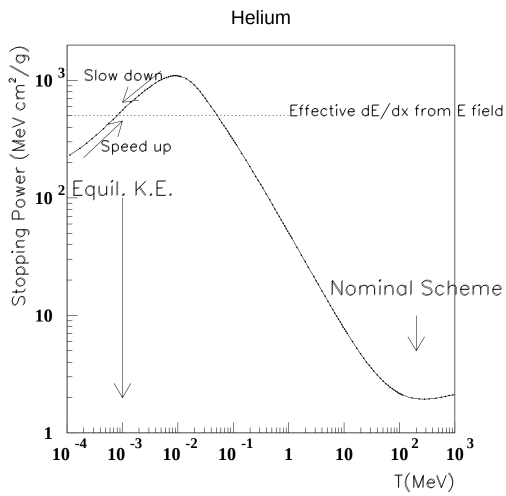

Figure 1. dE/dx in Helium as a function of kinetic energy, T, for μ^+. The effective dE/dx resulting from an external electric field is superimposed. An equilibrium kinetic energy near 1 KeV would result. The nominal scheme discussed for a Neutrino Factory would cool muons near T=200 MeV.

- Muonium formation (μ^+ + Atom $\rightarrow$ Mu) is significant at low μ^+ energies. In fact, the muonium formation cross section dominates over electron stripping cross section in all gases except Helium[3]. Data from Agnello *et al* [4] is parameterized and included in our simulations.
- A possibly fatal problem for μ^- is the loss resulting from muon capture. ($\mu^- +$Atom $\rightarrow \mu$Atom$+e^-$) The cross section for this process has been calculated up to 80 eV[5]. Hydrogen and Helium seem to be the best candidate media.

2. Simulation of Scheme

Given the conditions outlined in the previous section, a scheme was simulated from the production of the pion beam to the extraction of the cooled muons from the cooling section.

The target scheme differs from that of the Neutrino Factory. MARS simulations were performed to optimize the pion production for pions with kinetic energies less than 120 MeV. The pions are extracted transverse to the target. The forward pion production from a proton impinging on a target has tails to large kinetic energies which this scheme will not cool. Moreover, there are roughly equal numbers of π^+ and π^- produced on either side of the target. This allows for both signs to be cooled at the same time by developing a symmetric channel on either side of the production target. To this end a new symmetric magnetic capture section was designed with an initial strength of 20 T tapering down to 5 T for the remaining drift and cooling sections. The drift distance was also maximized to optimize the muon yield. As a result of these investigations the following optimal conditions were determined: a 2 GeV proton driver on a Cu or W target followed by 28m of drift.

Table 1. Emittance Reduction factors for a Ring Frictional Cooling Scheme.

Target	Muon sign	Cooling Medium	Yield (μ/p)	$\epsilon_{6D}/\epsilon'_{6D}(1 \times 10^6)$
Cu	+	He	0.005	22
Cu	-	He	0.002	0.06
Cu	-	H_2	0.003	0.8
W	+	He	0.006	18
W	-	He	0.003	0.06
W	-	H_2	0.004	0.6

At the end of the drift region, there is a correlation between the longitudinal momentum of the muons and the arrival time. This allows for a phase rotation, where time varying electric fields are used to increase the number of muons at lower momenta. The muons are then input into the cooling channel which consists of a series of cooling cells interspersed between solenoids. Due to the repetitive nature of the scheme a ring design was adopted for the cooling section in which the phase rotation would be performed in the solenoidal regions in between the cooling cells. A simple model was used for the phase rotation portion and consisted of a flat 5 MV/m field for some time, t_1, after which the field went linearly to zero at a time, t_2. These parameters were also optimized, as well as the time window for the beam to be accepted into the ring. The cooling cells contained Helium gas for μ^+ and Hydrogen for μ^-. The emittance values were calculated to the edge of the cooling cells, only for those muons which were cooled (see Table 1).

3. Nevis Lab and Ongoing Improvements

The simulations to date have not included thin windows which are required in order to extract the cooled muons from the cooling cells. This will be included in the next iterations. A simpler architecture is being considered; one in which the all the cooling cells are collected into one large cooling volume followed by a region of phase rotation. This phase rotation will reflect those muons which do not cool in the first pass through the cooling volume. This linear channel is more practical to construct and avoids the difficulties of kicker systems needed for injection and extraction into any ring scheme.

A lab has been setup at Nevis in order to address some of the key experimental issues for frictional cooling. Experiments are underway in order to demonstrate the frictional cooling concept using protons at the 4 MV Van der Graaff accelerator located at the Radialogical Research Accelerator Facility located on the Nevis site.

Frictional Cooling has the potential to cool muon beams to the required emittance for use in a Muon Collider.

References

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