Muon Collider and Higgs Factory

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Abstract. Particle physics is at a stage where new, innovative, techniques are required if the push to higher energies is to continue. A Muon Collider facility offers some tantalizing features, but the muon cooling issue must first be solved. An approach based on frictional cooling is discussed here.

1. Introduction

The reasons for interest in a Muon Collider are well known: the large muon mass relative to the electron mass removes the concerns with energy loss due to synchrotron radiation and beamstrahlung, and the point nature of the muon is highly favorable in comparison with a complex proton. We therefore dream of building a high energy Muon Collider. Parameter sets have been considered up to 100 TeV+100 TeV [1]. A lower energy Muon Collider would be interesting as a Higgs Factory, since the Higgs production cross section would be 40000 times higher than at an electron collider. Also, very fine energy scans would be possible since the beam energy is well-defined. Other physics research possibilities stem from the high energy neutrino beams resulting from the decay of stored muons, and low energy neutrinos from the target. There is also a wide range of applications for low energy muons, which could be a by-product of the muon production procedure [2]. The development of a Muon Collider would therefore open up a new realm for physics experimentation, providing opportunities for a broad spectrum of physics topics.

2. Parameters of a Muon Collider

Figure 1 shows a conceptual layout for the Muon Collider facility. Briefly, an intense, bunched, proton beam is directed on a target in a region with strong solenoidal magnetic field. The resulting pions are collected and allowed to decay in a drift region, yielding muons in a large phase space. The muons are squeezed in longitudinal momentum with a phase rotation (time varying electric field). This is followed by a cooling section, intended to reduce the muon 'beam' phase space by 10^6. Once the beams are cooled, they can then be accelerated to high energies. A parameter set for a 3 TeV CoM energy Muon Collider is given in [3], and is summarized in Table 1. The required normalized 6-D emittance for this parameter set is $\epsilon_{6,N} = 1.7 \cdot 10^{-10} (\pi m)^3$. At the end of the drift region the rms dimensions of the muon cloud in x,y,z is approximately 0.05,0.05,10 m, and in P_x, P_y, P_z $50, 50, 100$ MeV/c, yielding $\epsilon_{6,D} = 1.7 \cdot 10^{-4} (\pi m)^3$. The required emittance reduction is therefore of order 10^6, and this must be done with a reasonable efficiency.

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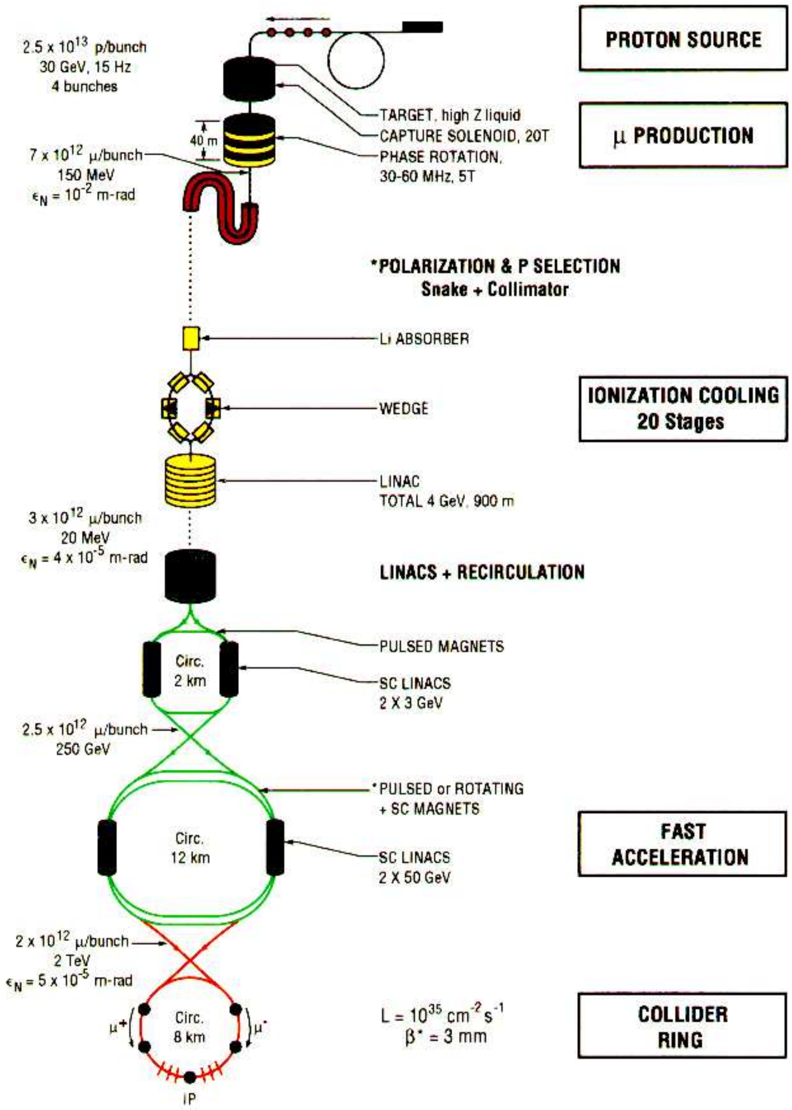

Figure 1. Possible layout for a Muon Collider facility [3].

There are severe difficulties in the way of a Muon Collider:

- Muons are not readily available, requiring a multi-megawatt proton source. In addition to a large starting cost, there are crucial targetry issues.
- Muons decay in $2.2 \cdot 10^{-6}$ s, so the time available for cooling, bunching and accelerating the muons is very limited. New techniques and technologies are needed to address these problems.
- There are large experimental backgrounds resulting from muon decays, so detector design and operation will not be as straightforward as for an e^+e^- collider.

CoM energy (TeV)	3
proton energy (GeV)	16
protons/bunch	$2.5 \cdot 10^{13}$
bunches/fill	4
Rep. rate (Hz)	15
μ/bunch	$2 \cdot 10^{12}$
collider circ. (m)	6000
$\epsilon_{6,N}(\pi m)^3$	$1.7 \cdot 10^{-10}$
Luminosity (cm^{-2}s^{-1})	$7 \cdot 10^{34}$

Table 1. A set of parameters for a 3 TeV CoM energy Muon Collider [3].

- High energy muon beams with large currents will face critical limitations due to radiation resulting from the high neutrino flux. The neutrinos will be strongly beamed, producing regions with high radiation levels.

3. Muon Cooling

Muon cooling is the signature challenge for the Muon Collider. A novel cooling scheme is required to reach the factor 10^6 reduction in emittance required for the desired luminosity. The short time available means no existing scheme is applicable. An even larger emittance reduction is desireable, as cooler beams would allow operation with fewer muons for a given luminosity, thereby reducing the experimental backgrounds and neutrino induced radiation, and would allow for smaller accelerator element apertures, reducing the cost.

The concept of ionization cooling [4] has been studied in some depth [5]. In this scheme, the muons are maintained at ca. 200 MeV while passed successively through an energy loss medium followed by an acceleration stage. Cooling factors of order 20 appear feasible for the transverse emittance, but longitudinal cooling is difficult. In fact, the beam tends to increase in longitudinal phase space during the process. The possibility of exchanging longitudinal and transverse degrees (emittance exchange) has long been studied as a solution to this problem. Recent progress with ring coolers has been reported at this meeting [6], but the goal of 10^6 reduction in emittance still appears far away. Given the importance of cooling for the Muon Collider, it is important that other schemes be consider. One such approach is 'Frictional Cooling' [7]. The rest of this talk is devoted to studies of this alternative.

4. Frictional Cooling Studies

The main idea of frictional cooling is to bring the muons to a velocity regime where the energy loss while traversing a medium increases with velocity. A constant accelerating force on the muons then yields an equilibrium energy, as shown in Fig. 2. This occurs in the kinetic energy range $T < 10$ KeV.

At low kinetic energies, the stopping power is extremely high, such that low average densities are needed for realizeable electric fields. Furthermore, the electric field can only take effect once the muons are at low energies, or the equilibrium regime will never be reached. Given the wide span of muon momenta, even after the phase rotation, the low kinetic energies are reached at very different times and for different

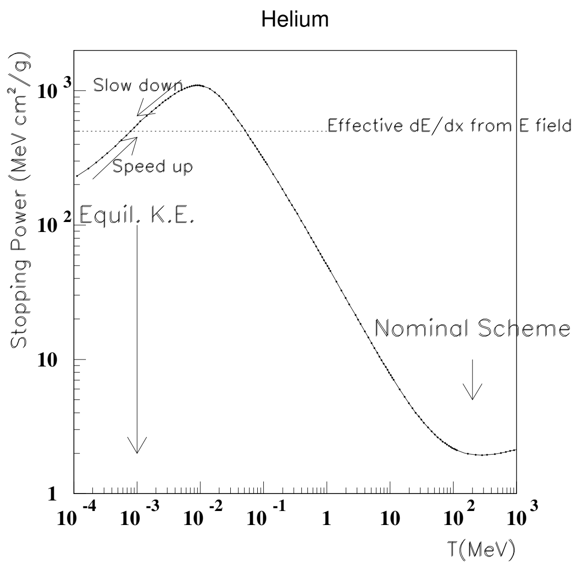

Figure 2. Stopping power for muons in Helium as a function of kinetic energy. Muons with energies below the peak of the dE/dx curve are brought to equilibrium with an external electric field.

ranges, such that a time dependent or local electric field will not work. We therefore consider a crossed electric and magnetic field configuration. The magnetic field guides the muons while they are higher energies, and the electric field extracts them from the slowing medium at small energies. This allows the distance travelled by the muons while at low energies to be small, as discussed below. Other difficuties arise from Muonium formation (μ^+ captures an electron) and muon capture (μ^- is capture in an atomic orbit). Muonium formation is limited by the use of Helium, due to its strong binding of orbital electrons. Muon capture can only be suppressed by keeping the kinetic energy much higher than typical binding energies. Low Z materials are adviseable. We therefore consider using Helium gas as a stopping medium for μ^+ and Helium or Hydrogen gas for μ^-. A muon trajectory in a Helium volume with density $\rho = 1. \cdot 10^{-4}$ gm/cm^3, with $B_z = 5$ T and $E_x = 5$ MV/m is shown in Fig. 3. The main features of the approach can be seen. The muon follows the magnetic field direction, with some drift, while at higher momentum. Once it has reached a low velocity, the magnetic force is considerably reduced and the electric field pulls the muon out of the gas cell. By keeping the transverse dimensions of the cell small, the distance travelled at the small kinetic energies can be kept within an allowable range.

We have performed a detailed simulation of some of the elements needed in a frictional cooling scheme‖. A brief review of some of the results from the simulation (see also the presentation by Rapheal Galea [8]) is given in the following sections.

‖ This work was performed in collaboration with H. Abramowicz, Tel Aviv University, R. Galea, Columbia University, and S. Schlenstedt, DESY/Zeuthen.

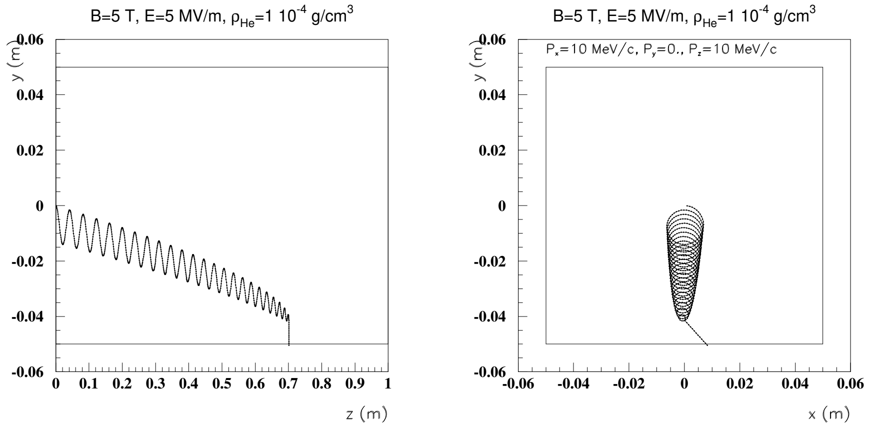

Figure 3. Trajectory for a muon with $P_z = 10$ MeV and $P_T = 10$ MeV in Helium using a continuous energy loss approximation.

4.1. Target System

The proton beam energy as well as the target geometry, orientation, material composition, location in magnetic field, etc. have been studied in detail using a combination of the MARS code [9] and GEANT [10]. We have concluded that a low proton beam energy (ca. 2 GeV) is optimal for our needs. The target is oriented perpendicularly to the magnetic field to allow simultaneous capture of low energy π^+ and π^- in two different channels. This is possible since low energy pions are produced almost isotropically from the target.

4.2. Drift, Phase Rotation, and Cooling Cell

The drift length was optimized to maximize the yield of muons, resulting in a drift region 28 m long. The muons then entered an 11 m long Helium cell (Hydrogen for μ^-) region, where gaps were included to allow flipping of the electric field direction. The muons not stopped by the first pass through the cell were reflected with a time varying electric field, which provided some bunching of muons towards the lower momenta.

A longitudinal and transverse view of the cooling cell is seen in Fig. 4. The cell radius is 20 cm, and the cell resides in a solenoid of radius 1 m. A uniform $E_x = 5$ MV/m field is assumed in the region of the cell, while an additional $E_z = 100$ KV/m field is present outside the cell to provide a first reacceleration of the muons.

The energy loss and scattering simulation in the gas cell included the following effects:

- Electronic energy loss, treated as a continuous process.
- Nuclear scatters, treated as individual events for kinetic energies below 10 KeV as these are critical for reproducing the expected fluctuations in trajectory and energy. A semiclassical approach was used based on algorithms described in [11].
- The Barkas effect [12] (reduced energy loss for μ^- relative to μ^+) was parametrized and included.

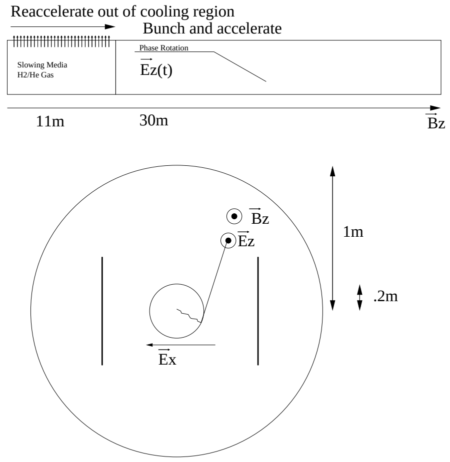

Figure 4. Longitudinal and transverse views of the cooling cell and phase rotation sections.

- The μ^- capture process was implemented using a parametrization of the calculations by Cohen [13].
- The muon lifetime was implemented.

The simulation was cross checked with the NIST tables [11] and found to give excellent agreement.

Some results of the simulation for a single particle are shown in Fig. 5 for illustration. As can be seen in this example, the energy fluctuations resulting from nuclear scatters is substantial.

4.3. Yield and Cooling

A full simulation was performed, starting with 2 GeV protons on target, and simulating all decays, aperture limitations, magnetic field nonuniformities in the target region, etc. All pions were tracked and decayed, and the individual muons were tracked through the gas cell using the full simulation described above. The yield and emittance of the muons coming out after the 11 m cooling cell region was calculated. Note that an initial reacceleration has already taken place in the 11 m region. The yield was $0.002\,\mu^{\pm}$ per 2 GeV proton, or about a factor four smaller than necessary to match the parameters given earlier. The rms of the beam in x,y,z (or rather βct) was 0.015, 0.036 and 30 m, respectively. In momentum space, the rms was 0.18, 0.18, 4.0 MeV/c. These values result in $\epsilon_{6,N} = 5.7 \cdot 10^{-11}$ $(\pi m)^3$, which is somewhat better than the desired value. The results of the simulation are thus far quite encouraging. However, there are many important issues remaining, such as the understanding of the effect of windows, a realistic design of electric and magnetic field configurations in the gas cell region, a concept for the reacceleration and bunching of the muons, and experimental data on muon capture and Muonium formation cross sections. An experimental program is underway to address the latter issues.

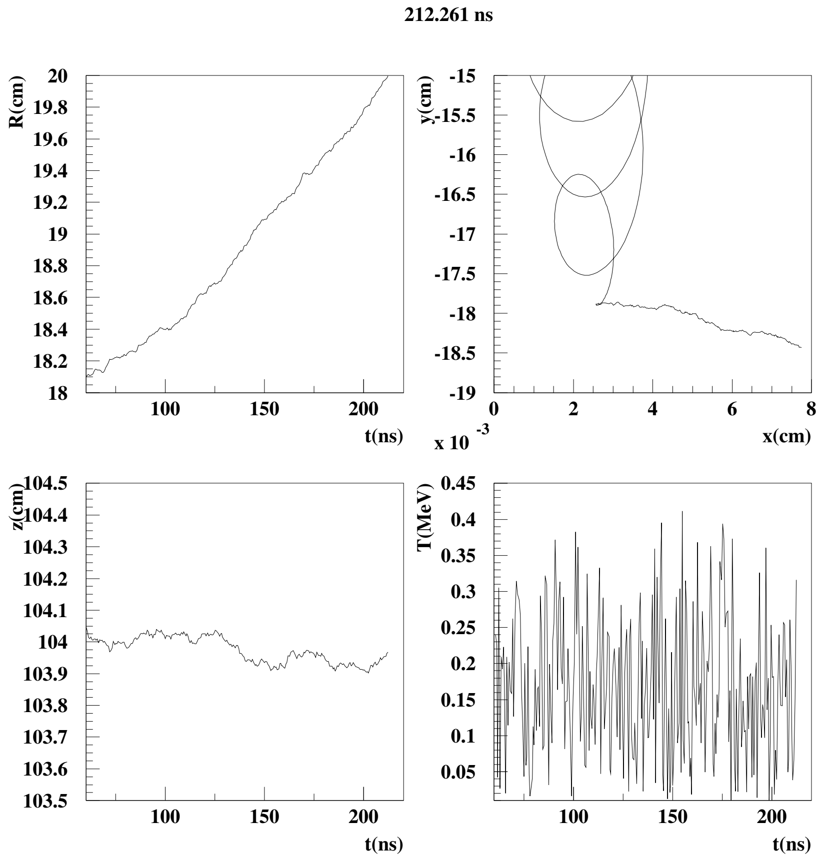

Figure 5. The simulation results for the last stages of one track. The upper left plot shows the radius as a function of time, the upper right the y coordinate as a function of time, the lower left the z coordinate as a function of time, and the lower right the kinetic energy (in KeV) as a function of time. The effect of the individual nuclear scatters are visible, and produce significant fluctuations in the kinetic energy.

5. Conclusions

It is clear that a Muon Collider facility would be a boon for many areas of physics. To build such a complex, including a high energy frontier collider, requires to solve the muon cooling problem. This is the key issue faced by those interested in the Muon Collider, and the importance of the problem dictates that different schemes be investigated. One alternative, frictional cooling, has been discussed in this presentation.

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