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Scheme for Ionization Cooling for a Muon Collider

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We discuss a complete scheme for production and cooling a muon beam for three specified Muon Colliders. We outline the parameters for these Muon Colliders. The scheme starts with the front end of a proposed Neutrino Factory that yields bunch trains of both muon signs. Emittance exchange cooling in upward or downward broad helical lattices reduces the longitudinal emittance until it becomes possible to merge the trains into single bunches: one of each sign. Further cooling in all dimensions is applied to the single bunches in further upward climbing helical lattices. Final transverse cooling to the required parameters is achieved in 50 T solenoids that use high temperature superconductor. Preliminary simulations of each element are presented. We discuss known challenges.

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Table 1: Parameters of three Muon Colliders using the proposed cooling scenario.

$E_{c\ of\ m}$	1.5	4	8	TeV
$\mathscr{L}$	1	4	8	10^{34} cm^{2}sec^{-1}
$\Delta\nu$	0.1	0.1	0.1	
μ/bunch	2	2	2	10^{12}
$< B_{ring} >$	5.2	5.2	10.4	T
$\beta^* = \sigma_z$	10	3	3	mm
rms dp/p	0.09	0.12	0.06	%
$N_\mu/N_{\mu o}$	0.07	0.07	0.07	
Rep.	13	6	3	Hz
P_{driver}	$\approx$4	≈ 1.8	≈ 0.8	MW
$\varepsilon_\perp$	25	25	25	pi mm mrad
$\varepsilon_\parallel$	72	72	72	pi mm rad

1. INTRODUCTION

Muon colliders were first proposed in 1981[1] and more detailed studies have followed[2][3][4]. But in none of these references was a complete scheme defined for the manipulation and cooling of the required muons. Muon Colliders would allow the high energy study of point-like collisions of leptons without some of the difficulties associated with high energy electrons, such as the synchrotron radiation requiring their acceleration to be essentially linear, and as a result, long. Muons can be accelerated in smaller rings and offer other advantages, but they are produced only diffusely and they decay rapidly, making the detailed design of such machines difficult. In this paper, we outline a complete scheme for capture, phase manipulation and cooling of the muons, every component of which has been simulated at some level.

2. COLLIDER PARAMETERS

Table 1 gives parameters for Muon Colliders at three energies. Those at 1.5 TeV correspond to a recent collider ring design[5]. The 4 TeV example is taken from a 1996 Feasibility Study[3]. The 8 TeV example is an extrapolation assuming higher bending fields and more challenging intersection parameters. All three use the same muon intensities and emittances, although the repetition rates for the higher energy machines are reduced to control neutrino radiation.

3. PROPOSED SYSTEM

Fig.1 shows a schematic of the components of the system. Fig. 2 shows a plot of the longitudinal and transverse emittances of the muon beams as they progress from production to the specified requirements for the colliders. The subsystems used to manipulate and cool the beams to meet these requirements, are indicated by the numerals #1-#9 on the figures.

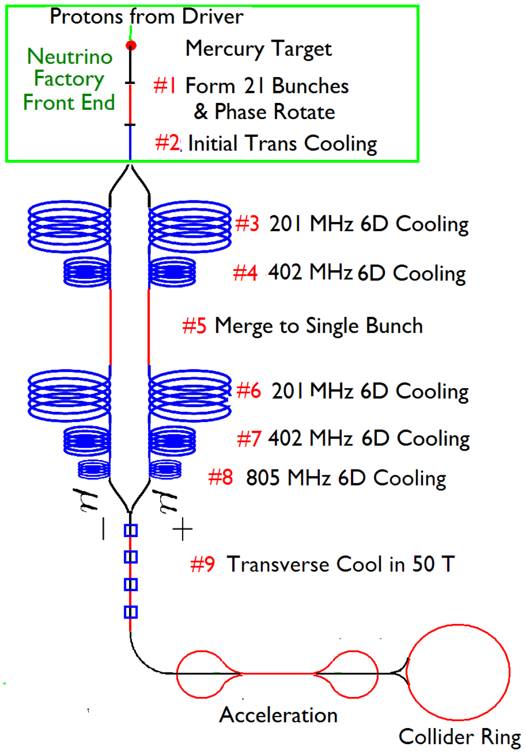

Figure 1: Schematic of the components of the Muon manipulations and cooling.

The muons are generated by the decay of pions produced by proton bunches interacting in a mercury jet target. These pions are captured by a 20 T solenoid surrounding the target, followed by an adiabatic lowering of the field to a decay channel.

The first manipulation (#1), referred to as Phase Rotation[6], converts the initial single short muon bunch with very large energy spread, into a train of 21 bunches with much reduced energy spread. The initial bunch is allowed to lengthen and develop a time energy correlation in a 110 m drift. It is then bunched into a train, without changing the time energy correlation, using rf cavities whose frequency versus location falls from 333 MHz to 234 MHz. Then, by phase and frequency control, the rf accelerates the low energy bunches and decelerates the high energy ones while the frequency falls to 201 MHz. Muons of both signs are captured and then (#2) cooled transversely in a linear channel using LiH absorbers, periodic alternating 2.8 T solenoids, and 201 MHz rf. All the components up to this point are identical to those described in a recent study[7] for a Neutrino Factory.

The next stage (#3) cools simultaneously in all 6 dimensions. The lattice[8] uses 3 T solenoid fields for focusing, weak dipole fields that come from tilting the solenoids to generate dispersion, wedge-shaped liquid hydrogen filled absorbers where the cooling takes place, and 201 MHz rf to replenish the energy lost in the absorbers. The dipole fields cause the lattices to curve, forming a slow upward helix. The following stage (#4) uses a lattice essentially the same as #3, but with twice the fields and half the geometric dimensions. Fig.3 shows the results of a simulation of both systems using ICOOL. Although this simulation was done for circular, rather than the helical

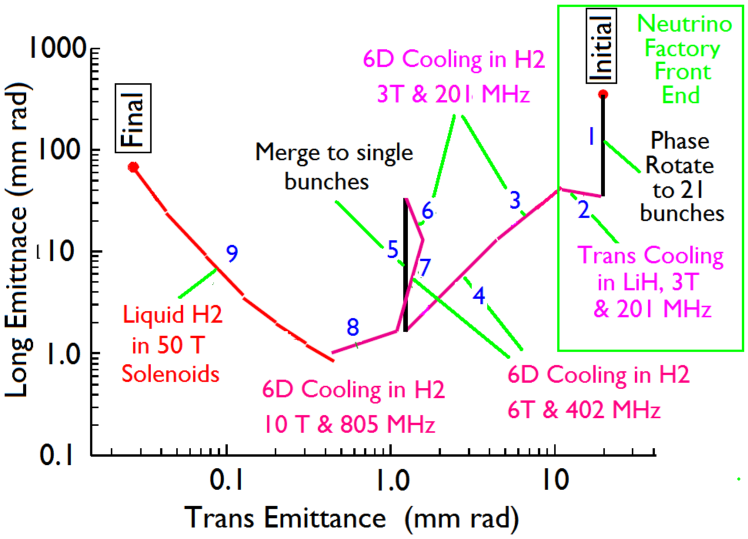

Figure 2: Transverse vs. Longitudinal emittances before and after each stage

geometry, it used realistic coil and rf geometries. Preliminary studies[9] suggest that the differences introduced by the helical, instead of circular geometries will be negligible. The simulation did not include the required matching between the two stages. The simulations also used fields that, while they satisfied Maxwell's equations and had realistic strengths, were not actually calculated from specified coils. Simulations reported in reference[10] using fields from actual coils gave essentially identical results.

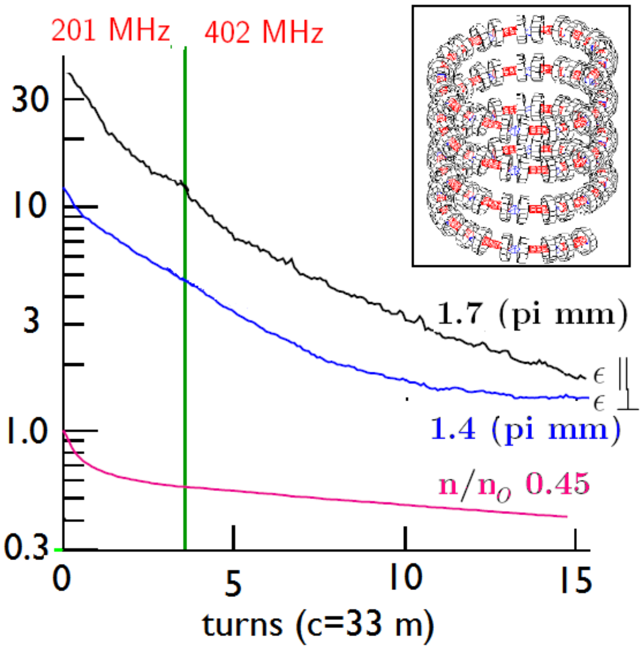

Figure 3: ICOOL Simulation of 6D cooling in stages #3 & #4

Since collider luminosity is proportional to the square of the number of muons per bunch,

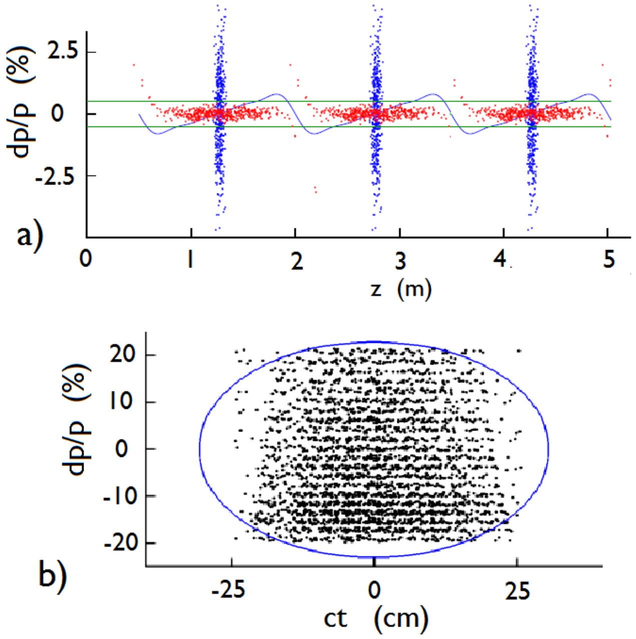

Figure 4: 1D Simulation of merge (#5): a)before and after first rotation, b) after second rotation

it is important to use relatively few bunches with many muons per bunch. However, capturing initial muon phase space into single bunches requires low frequency ($\approx$ 30 MHz) rf, and thus low gradients, resulting in slow initial cooling. It is thus advantageous to capture initially into multiple bunches at 201 MHz and merge them after enough cooling allows them to be recombined into a single bunch at that frequency. This recombination (#5) is done in two stages: a) using a drift followed by 201 MHz rf, with harmonics, the individual bunches are phase rotated to fill the spaces between bunches and lower their energy spread; followed by b) 5 MHz rf, plus harmonics, interspersed along a long drift to phase rotate the train into a single bunch that can be captured using 201 MHz. Results of an initial one-dimensional simulation of this process is shown in fig.4. Work is ongoing on the design and simulation of a system with the low frequency rf separated from the following drift in a wiggler system with greater momentum compaction to reduce the length and decay losses.

After the bunch merging, the longitudinal emittance of the single bunch is now similar to that at the start of cooling. It can thus be taken through the same, or similar, cooling systems as #3 and #4: now numbered #6 & #7 in figs.1 & 2. One more (#8) stage of 6 dimensional cooling has been designed (fig.5) using 10 T magnets, LiH wedge absorbers, and 805 MHz rf. Its ICOOL simulated performance is show in fig.5. Again, the simulation shown used fields that, while they satisfied Maxwell's equations and had realistic strengths, were not actually calculated from specified coils, but defined by fields calculated on the axis of a linear channel.

To attain the required final transverse emittance, the cooling needs stronger focusing than is achievable in the 6D cooling lattices used in the earlier stages. This can be obtained in liquid hydrogen in a strong solenoid, if the momentum is allowed to fall. At the lower momenta the momentum spread, and thus longitudinal emittance, rises relatively rapidly, but, as we see from

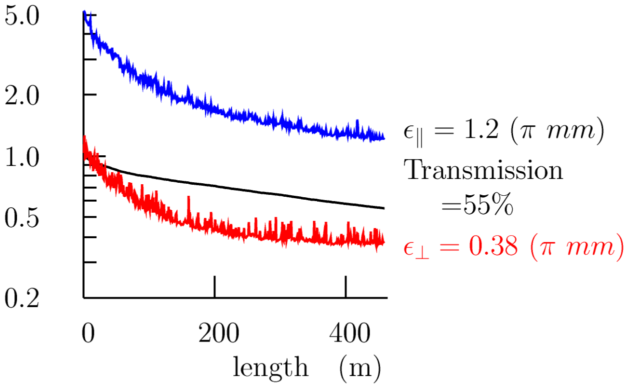

Figure 5: ICOOL Simulation of final 6D cooling lattice (#8).

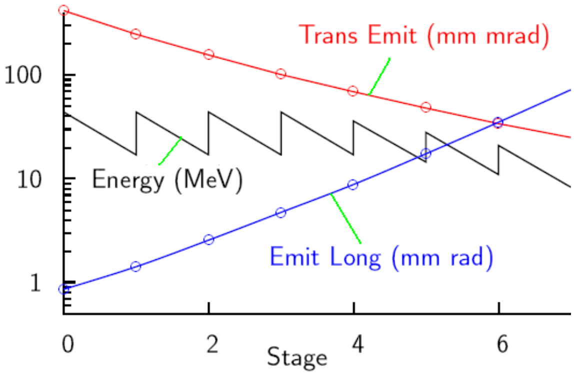

Figure 6: Results of ICOOL simulations of transverse cooling in liquid hydrogen in 7 sequential 50T solenoids

fig.2, the longitudinal emittance after #8 is far less than that required, so such a rise is acceptable. Fig. 6 shows the results of ICOOL simulation of cooling in seven 50T solenoids. The simulation did not include the required matching and re-accelerations between the solenoids.

4. REMAINING CHALLENGES

Experiments suggest that the specified gradients for the vacuum rf cannot be achieved in the specified magnetic fields. Two approaches are being studied to handle this problem:

- Experiments have shown that a high pressure hydrogen gas-filled cavity operated equally well with or without fields of 3 T. Both helical lattices (HCC) and lattices with wedges (as discussed here, but filled with high pressure hydrogen) have been studied. A practical HCC with rf is yet to be established, and adding gas to the lattices with wedges hurts their perfomance somewhat. In either case there is a question of whether gas filled cavities will operate with an intense ionizing beam. An experiment will be performed soon at Fermilab with the linac proton beam. In addition, the lattices with gas seem unable to achieve 6D cooling to the lowest emittances specified.

- It has been proposed that magnetic insulation might be adapted to rf. Cavities would be designed in which all surfaces with significant gradient would be made parallel to the focusing magnetic field lines. Designs seem possible for all stages of 6 D cooling, but no demonstarion has yet been made.

There are also problems in the longitudinal motion of muons in the early, but not the later, 50 T cooling stages. Solutions have been suggested, but not yet simulated. Achieving the required transmission through the many stages and, as the yet unsimulated matching, will also be challenging.

5. CONCLUSION

Although much work remains to be done, the scenario outlined here is a plausible solution to the problems of capturing, manipulating and cooling muons to the specifications for Muon Colliders with useful luminosities and energies even up to 8 TeV in the center of mass. However, there appears to be a technical problem using the specified rf cavities in the required focusing magnetic fields. Use of high pressure gas in the rf cavities may solve the problem in some, but not all 6D cooling stages. Magnetic insulation may be a solution to this problem, but has yet to be demonstrated.

Acknowledgments

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