MUON COLLIDER PROGRESS *

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Abstract

A complete scheme for muon production, cooling, acceleration and storage in a collider ring is presented. Parameters for two muon colliders are given. Both start with pion production on a mercury target. A capture and phase rotation yields bunch trains of both muon signs. Six dimensional cooling reduces the longitudinal emittance until it becomes possible to merge the trains into single bunches, one of each sign. Further cooling in 6 dimensions is applied in lattices followed by final linear transverse cooling in 50 T solenoids. Experiments suggest that there are rf breakdown problems with the focusing magnetic fields. Possible solutions are discussed.

Table 1: Parameters of two muon colliders.

C of m Energy (TeV)	1.5	4
Luminosity (10^{34} cm^{2}sec^{-1})	1	4
Beam-beam Tune Shift	0.1	0.1
Muons/bunch (10^{12})	2	2
Ring circumference (km)	3	8.1
Beta at IP = σ_z (mm)	10	3
rms mom. spread (%)	0.1	0.12
Required depth for ν rad (m)	13	135
Muon survival	0.07	0.07
Repetition Rate (Hz)	12	6
Proton Driver power (MW)	≈4	≈ 2
Trans Emittance (π mm mrad)	25	25
Long Emittance (π mm mrad)	72,000	72,000

INTRODUCTION

This work is part of two collaborations: The Neutrino Factory and muon Collider Collaboration[1] (NFMCC), and the FNAL Muon Collider Task Force[2] (MCTF).

Muon colliders were first proposed by Budker in 1969 [3], and later discussed by others [4]. A more detailed study was done for Snowmass 96 [5], but none of these proposed a complete scheme for the manipulation and cooling of the required muons. This report will address the current approaches to such a scheme.

Muon colliders would allow the high energy study of point-like collisions without some difficulties associated with high energy electron colliders. e.g. synchrotron radiation requiring their acceleration to be linear and 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. The baseline scheme for pion production, capture, decay to muons, acceleration, and collider rings will be outlined. The scheme[6] for phase manipulation and muon cooling will be described, followed by a discussion of observations of rf breakdown in the presence of magnetic fields, and possible ways of overcoming the problem.

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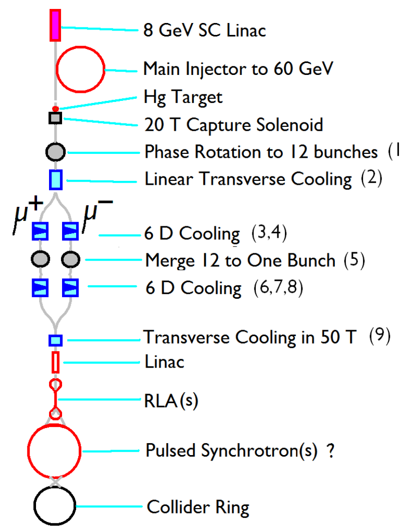

Figure 1: Schematic of Muon Collider components.

CONVENTIONAL COMPONENTS

Table 1 gives parameters for muon colliders at two energies. Those at 1.5 TeV correspond to a recent collider ring design [7]. The 4 TeV example is taken from the 96 Study [5]. Both use the same muon intensities and emittances, although the repetition rates for the higher energy machines are reduced to control neutrino radiation.

Fig. 1 shows a schematic of the components of the system. The proton source is assumed here to be an 8 GeV proton linac feeding a 50-60 GeV main Injector (an upgraded version of that proposed at FNAL). In this case, the required proton intensity per bunch is 40 Tp, and the required rms bunch length is 3 ns. Alternatives using 8 GeV protons accumulated from the linac, or 20 GeV protons from a fast cycling synchrotron are also being studied.

Muon production

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 use of a free mercury jet has been demonstrated in a recently run experiment MERIT[8] experiment

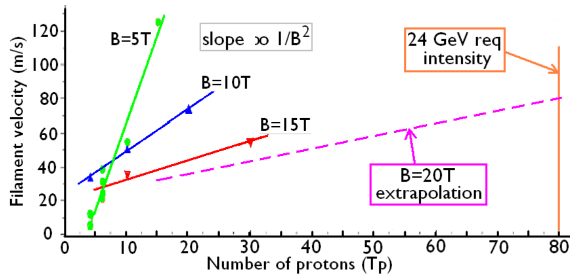

Figure 2: MERIT observed filament velocities vs. proton intensity at B=5, 10, 15 T, & dashed extrapolation to 20 T.

at CERN. In this experiment 24 GeV protons with intensities up to 30 Tp intersected a mercury jet inside a pulsed 15 T solenoid magnet. Fig. 2 shows the observed filament velocities vs. proton intensity and magnetic field. It is seen that the velocities, which could be damaging at a few 100 m/s, are suppressed by the damping effects of the magnetic field. Extrapolating from this data one can conclude that at 60 GeV, proton intensities of 40 Tp should not be damaging in the presence of the 20 T field.

Required manipulations and cooling

Following the target, the pions drift and decay into muons in a solenoid focused channel. The captured muons, with peak momenta of $\approx$ 200 MeV/c, and momentum spread of the order of 70 % have longitudinal emittance ($\beta\ \gamma\ dp/p\ \sigma_z$) of approximately 0.5 ($\pi$ m rad) and transverse emittance ($\beta\ \gamma\ \sigma_\theta\ \sigma_r$) of approximately 20 ($\pi$ mm rad). These must be cooled to the specified emittances of 72 π mm rad (a factor of $\approx 10^3$), and 25 π μm rad (a factor of $\approx$ 10) respectively. The required manipulations and cooling will be discussed in the following section.

Acceleration

The initial acceleration after cooling would be in a sequence of linacs with frequencies increasing as the energy rises and bunch lengths decrease. After the linacs there would be one or more Recycling Linear Accelerators (RLAs). Such RLAs could be used for all the remaining acceleration, but a lower cost solution would be to do the later stages in rapidly field ramped synchrotrons[9]. In order to avoid high field pulsed bending magnets or excessive diameters, fixed super conducting magnets would be alternated with pulsed magnets swinging from -1.8 T to +1.8T. The super-conducting rf frequency might be 1.3 GHz, but 805 MHz is probably preferred to reduce wake fields.

Collider Rings

The 1.5 TeV center of mass collider parameters are based on the "dipole first" lattice[7] that gives a 3 sigma acceptance for the 25 π mm mrad emittance. The parameters for the 4 TeV center of mass collider are based on the Oide[5] lattice designed for the 1996 Snowmass study.

PHASE MANIPULATION AND COOLING

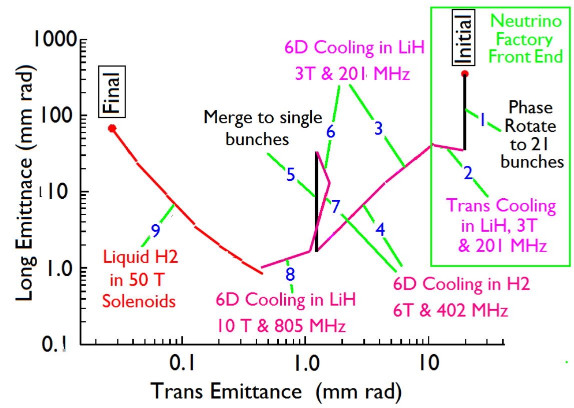

Figure 3: Transverse vs. longitudinal emittances before and after each stage.

Fig. 3 shows a plot of the longitudinal vs. transverse emittances of the muons 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 figures 1 and 3. The general baseline scheme was presented at PAC07[6], and will be described again here with comments on the more recent work.

Phase Rotation (1)

The first step is to phase rotate each single muon burst into strings of bunches with lower momentum spreads. Earlier designs yielded approximately 21 bunches, but a recent redesign[10] has achieved efficient rotation into only 12 bunches, greatly easing the required later bunch merging.

First the muon burst, in a 57 m drift, is allowed to lengthen and develop a time energy correlation. It is then, over a distance of 31 m, bunched into a train, without reducing the time energy correlation, using rf cavities whose frequencies varies with location (from 333 to $\approx$ 220 MHz). Then, over 36 m, by phase and frequency control, the rf accelerates the low energy bunches and decelerates the high energy ones, to form a mono-energetic train. Muons of both signs are captured into interleaved bunches.

Initial transverse cooling (2)

The next stage cools the muons transversely in a linear channel. The current baseline uses LiH absorbers, periodic alternating 2.8 T solenoids, and 201 MHz rf. All the components up to this point are similar to those described in a recent study [11] for a Neutrino Factory. But an alternative would use the more efficient cooling channel similar to that to be tested by the MICE[12] experiment at RAL in the UK.

6D cooling before merge (3 & 4)

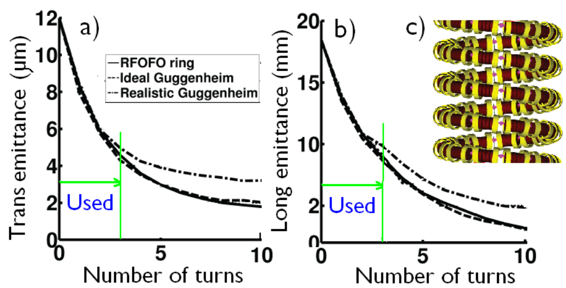

Figure 4: Simulation of a) transverse, & b) longitudinal, cooling in RFOFO 6D lattice; c) Cooling geometry.

The next two stages cool simultaneously in all 6 dimensions. The base-line RFOFO (Reverse FOcus FOcus) lattice [13] uses (fig. 4c) two 2 T solenoids per cell for focus, a weak dipole field (generated by tilting the solenoids) to generate dispersion, wedge shaped liquid hydrogen filled absorbers, and rf to replenish the energy lost in the absorbers. The dipole fields cause the lattices to curve, forming a slow upward or downward helix. The first of these two 6D cooling lattices uses 201 MHz rf and has been fully simulated[14] (fig. 4a & b) using G4Beamline[15]. The second uses 402 MHz rf, twice the magnetic fields and half the cell length and other dimensions and has only been simulated assuming a ring geometry. Possible problems with operating the rf in the required fields will be discussed later.

Instead of the slow helices, a planar wiggler lattice is being studied that would cool both muon signs simultaneously, thus greatly simplifying the system.

6D cooling might also be achieved in high pressure gas filled helical cooling channels (HCC)[16]. Such channels achieve emittance exchange by having longer path lengths for higher momentum particles, thus lowering their energy more. An advantage is that rf breakdown in high pressure gas is not affected by the magnetic fields. But it is not yet known whether the gas will breakdown of become excessively lossy in the presence of the ionizing muon beam. Integrating the rf and waveguides into the helical magnets will also be difficult.

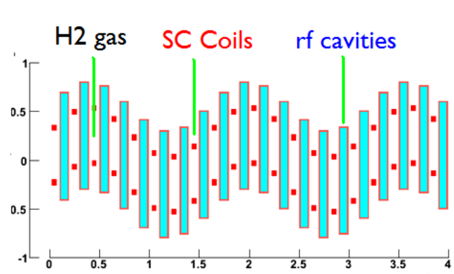

Figure 5: An example of a Helical Cooling Channel.

Bunch merge (5)

Since collider luminosity is proportional to the square of the number of muons per bunch, it is desirable to use few bunches with many muons per bunch. it is thus important to merge the bunches into one prior to there use in the collider. In the baseline, this is done as soon as longitudinal cooling is sufficient to allow all the bunches to be merged into one. This recombination is done in two stages: a) using a drift followed by 201 MHz rf, with harmonics, the individual bunches are phase rotated to minimize 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.

6D cooling after merge (6, 7, & 8)

After the bunch merging, the longitudinal emittance of the single bunch is now similar to that at the start of cooling, and it can be taken through the same, or similar, cooling systems as 3 and 4: now numbered 6 & 7. One more (8) RFOFO lattice has been designed and simulated, using 10 T magnets, and 805 MHz rf.

After stage 8 the transverse emittance is 300 π mm mrad (a factor of 12 greater than that specified). But the longitudinal emittance is only $\approx$ 1000 π mm mrad, compared with 72,000 π mm mrad specified (a factor of 72 less). Thus the final cooling of the transverse emittance need not cool in all dimensions. Indeed it can allow the longitudinal emittance to grow.

Final cooling in high field solenoids (9)

To attain the required final transverse emittance, the cooling needs stronger focusing than is achievable in the 6D cooling lattices. But, if the momentum is allowed to fall below 60 MeV/c, it can be obtained in liquid hydrogen in long 50T solenoids. At this low momentum the energy spread, and thus longitudinal emittance, rises, but, as we noted above, this is acceptable.

Fig. 6a shows ICOOL[18] simulations of cooling in individual 50 T channels, without the required matching and re-accelerations between the solenoids. Cooling from 300 to 25 (π mm mrad) is achieved in 7 stages. Matching and re-acceleration has been simulated only between the last two stages. Fig. 6b shows the longitudinal vs. transverse emittances through these last two stages including the matching and re-acceleration between them. Very little emittance dilution is observed.

The calculated space charge tune shifts are moderate, but space charge is not yet in the simulations.

RF IN MAGNETIC FIELDS

The MuCool collaboration has tested two pillbox cavities with beryllium windows at 805 MHz (to 4 T)[19] and 201 MHz (to 0.7 T)[20]. Both broke down at significantly

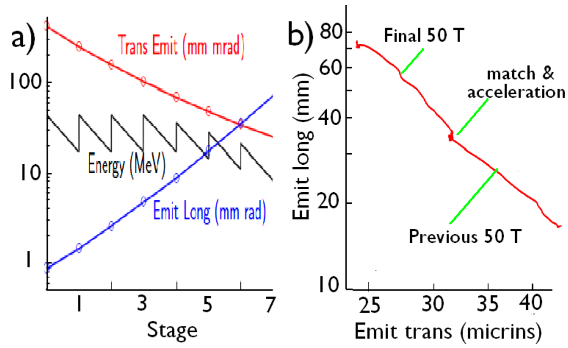

Figure 6: a) Energy, longitudinal, and transverse, emittances for 7 stages of final cooling; b) Long. vs. trans. emittances through the last two stages including matching and re-acceleration.

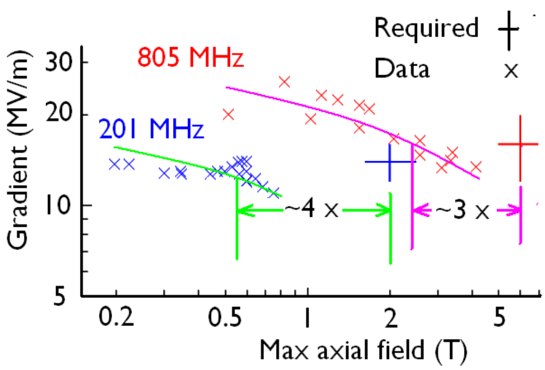

Figure 7: Observed breakdown gradients vs maximum axial fields on cavities, together with approximate required gradients: 201 MHz in blue, 805 MHz in red.

lower gradients as the magnetic field was increased (see fig.7. This figure also shows the gradients and magnetic fields required for the baseline scenario. It is seen that at both frequencies breakdown was observed at gradients below those specified.

A qualitative theory[21] supposes that the breakdown occurs after focused electrons from a field emission site damage a surface with high electric fields. Such damage would be caused by fatigue from cyclical strains induced by local heating by the electrons. Qualitative agreement with the data is possible, but quantitative calculations require more knowledge of the electron sources and the influence of space charge.

Several approaches to a solution to this problem are being considered. Only further experiments will determine which solution is best.

Atomic Layer Deposition (ALD)

Atomic Layer Deposition (ALD) has allowed superconducting cavities to reach higher fields, and could suppress the field emission that may be causing the damage. Other surface treatments might reduce the emitted currents by raising the work function. MuCool is studying these

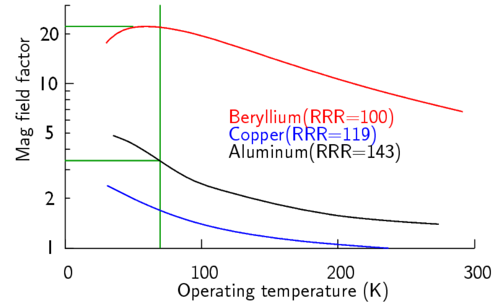

Figure 8: Relative increase in allowable axial field vs. initial temperature for Copper, Aluminum, and Beryllium.

possibilities.

Cold Beryllium, or Al cavities

If it is assumed that the damage is caused by fatigue then one can study the sensitivity to magnetic field as a function of the thermal conductivity, specific heat and coefficients of expansion, including their temperature dependence. Assumes that the electron beamlets are not significantly increased in diameter by space charge effects, then fig. 8 shows the calculated relative increases in magnetic field for the same gradient as a function of material and its initial temperature. This analysis suggests that room temperature cavities built of, or coated with, beryllium could operate in 7 times higher fields (probably sufficient), and an aluminum cavity cooled to 77 Kelvin could operate in 3.5 times higher fields (possibly sufficient). But in view of the needed assumptions, only an experimental program could establish whether either would be sufficient.

Magnetic Insulation

Assuming again that the breakdown in magnetic fields is triggered by emitted electrons accelerated and focused on other surfaces, the process could be stopped if the magnetic fields were parallel to all emitting surfaces. Instead of focusing the electrons, the field would now return them, with little energy, to near their points of origin. It has been shown that cavities can be designed with this condition (fig. 9).

Fig. 10 shows a) two cells of a conventional RFOFO lattice, b) a magnetically insulated version of the same, and c) the magnetic fields vs length in the two cases. Unfortunately, magnetically insulated cavities have open irises leading to lower shunt impedances and lower acceleration for given surface fields. They also have richer longitudinal harmonics of the axial fields that result in greater particle loss.

High pressure gas

rf cavities filled with high pressure hydrogen gas tolerate high surface gradients and are unaffected by magnetic

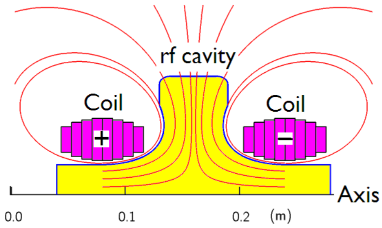

Figure 9: Magnetically insulated cavity with magnetic fields parallel to surfaces.

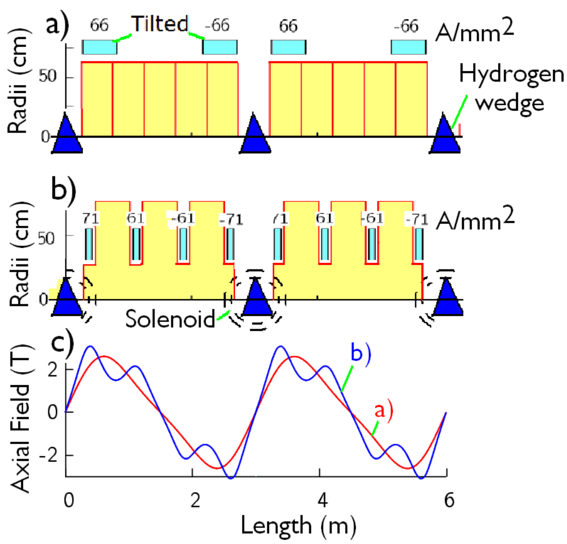

Figure 10: a) Two cells of a conventional RFOFO lattice; b) a magnetically insulated version of the same; and c) the magnetic fields vs length in the two cases.

fields[22]. The presence of hydrogen everywhere in the lattice excludes the use, as is possible in the RFOFO lattices, of having the absorber placed at focii where the $\beta_\perp$ is much lower than the average.

Emittance exchange, for 6D cooling, could be achieved with dispersion and wedges of LiH. Alternatively, helical cooling channels (HCC) [16] might be used.

CONCLUSION

If a solution is found for the rf breakdown in magnetic fields, then the scenario outlined here appears to be 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 4 or more TeV in the center of mass. But much work remains to be done. The Neutrino Factory and muon Collider Collaboration (NFMCC)[1], together with the FNAL Muon Collider Task Force (MCTF)[2] have submitted a proposal to DoE for a 5 year program of R&D to produce a Feasibility Study together with first cost estimate.

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