MUON COLLIDER PROGRESS

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Abstract

Recent progress in the study of muon colliders is presented. An international collaboration consisting of over 100 individuals is involved in calculations and experiments to demonstrate the feasibility of this new type of lepton collider. Theoretical efforts are now concentrated on low-energy colliders in the 100 to 500 GeV center-of-mass energy range. Credible machine designs are emerging for much of a hypothetical complex from proton source to the final collider. Ionization cooling has been the most difficult part of the concept, and more powerful simulation tools are now in place to develop workable schemes. A collaboration proposal for a muon cooling experiment has been presented to the Fermilab Physics Advisory Committee, and a proposal for a targetry and pion collection channel experiment at Brookhaven National Laboratory is in preparation. Initial proton bunching and space-charge compensation experiments at existing hadron facilities have occurred to demonstrate proton driver feasibility.

1 INTRODUCTION

The possibility of muon colliders was introduced by G.I. Budker[1], Skrinsky and Parkhomchuk[2] and Neuffer[3]. More recently, a collaboration of over 100 members, led by Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), Lawrence Berkeley National laboratory (LBNL), Budker Institute for Nuclear Physics (BINP), University of Mississippi, Princeton University and University of California at Los Angeles (UCLA) has been formed to coordinate studies on specific designs. Work has been done on designs at center-of-mass (CM) energies of 3-4 TeV, 0.4-0.5 TeV and 100 GeV[4, 5]. A detailed feasibility study for a 4 TeV muon collider was presented at the SNOWMASS'96 workshop[6]. A detailed status report on muon collider research is in preparation by the Collaboration[7].

The reason for interest in muon colliders comes from consequences of the muon behaving like a *heavy electron*. As for an electron, the full center-of-mass energy is available in an interaction. But because of the large mass, there is essentially no synchrotron radiation from the muon (in comparison to electrons). Consequently, the machine can be circular and much smaller than the current design of linear electron colliders. Of course, a muon collider requires successful solutions of many difficult physics and technical questions, and the hope is that the sum of development and construction costs will not be so high as to make the realization unaffordable.

The short muon lifetime and large initial beam emittance determines the essential character of a muon collider, namely, a rapid-cycling complex in which large numbers of muons are generated and cooled for each accelerator cycle. A muon collider facility has two basic parts consisting of a muon source and an accelerator/collider. Figure 1 shows a possible outline of a 100 GeV machine. Tables 1 and 2 give the parameters of some muon colliders considered to date within the collaboration study. The luminosities for the low energy machine are given in the table for three different energy spreads: $\mathcal{L}$=$1.2, 0.2, 0.1 \times 10^{32}$cm^{-2}s^{-1} for σ_p/p= $0.12, 0.01, 0.003 \times 10^{-2}$, respectively.

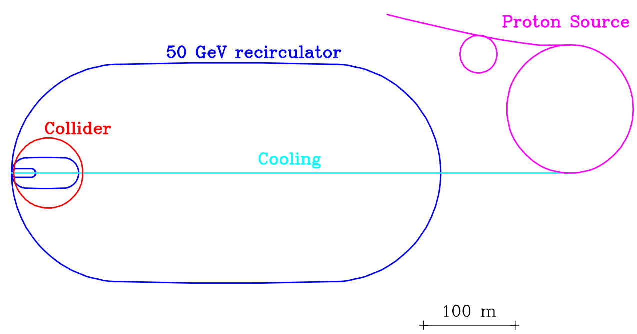

Figure 1: Plan of a 100 GeV Muon Collider.

Table 1: Baseline parameters for a 100 GeV muon collider with different momentum spreads.

CM energy (TeV)		0.1	
p energy (GeV)		16	
p's/bunch		5×10^{13}	
Bunches/fill		2	
Rep. rate (Hz)		15	
p power (MW)		4	
μ/bunch		4×10^{12}	
μ power (MW)		1	
Wall power (MW)		81	
Collid. Circum.(m)		300	
Depth (m)		10	
σ_p/p ($\times 10^{-2}$)	0.12	0.01	0.003
$\epsilon_{n,6d}$(mm^3)	0.17	0.17	0.17
$\epsilon_{n,rms}$(mm-mrad)	85	195	280
β^*(cm)	4	9	13
σ_z(cm)	4	9	13
σ_r^*(μm)	82	187	270
Tune shift	0.05	0.02	0.015
Lumin.(cm^{-2}s^{-1})	1.2×10^{32}	2×10^{31}	10^{31}
CM $\Delta E/E$	8×10^{-4}	7×10^{-5}	2×10^{-5}
Higgs/year	1.6×10^3	4×10^3	4×10^3

Table 2: Baseline parameters for high and medium energy muon colliders.

CM energy (TeV)	3	0.4
p energy (GeV)	16	16
p's/bunch	2.5×10^{13}	2.5×10^{13}
Bunches/fill	4	4
Rep. rate (Hz)	15	15
p power (MW)	4	4
μ/bunch	2×10^{12}	2×10^{12}
μ power (MW)	28	4
Wall power (MW)	204	120
Collid. Circum.(m)	6000	1000
Depth (m)	500	100
σ_p/p ($\times 10^{-2}$)	0.16	0.14
$\epsilon_{n,6d}$(mm^3)	0.17	0.17
$\epsilon_{n,rms}$(mm-mrad)	50	50
β^*(cm)	0.3	2.3
σ_z(cm)	0.3	2.3
σ_r^*(μm)	3.2	24
Tune shift	0.043	0.043
Lumin.(cm^{-2}s^{-1})	5×10^{34}	10^{33}
CM $\Delta E/E$	8×10^{-4}	8×10^{-4}

2 PROTON SOURCE

The muon survival budget through the chain of production, collection, cooling and acceleration is of critical importance for determining the expected luminosity in a collider. The expected muon survival fractions at each stage when multiplied together determine the nominal proton bunch intensity at the source. The final muon survival fraction is calculated to be about 0.08 muon per proton on target. The basic specification is for a 4 to 7 MW, 16 to 30 GeV proton driver, with a repetition rate of 5 to 15 Hz and 10^{14} protons per cycle in 2 bunches (for the 100 GeV machine) or 4 bunches (for the higher energies) of 5×10^{13} or 2.5×10^{13} protons, respectively. Half the bunches are used to make μ^- and the other for μ^+.

There are several accelerator designs that in principle can achieve the above specifications for a muon source since the raw characteristics of the pion beams produced are insensitive to the details of the proton acceleration chain. Designs have been studied based on final proton kinetic energies of 8, 16, 24 and 30 GeV, with the lower energies, higher repetition rate being preferred for a Fermilab Booster Upgrade and the higher energies, lower repetition rate for a Brookhaven AGS Upgrade.

Independent of the details of the proton acceleration chain, the key requirement of the proton driver is to produce the ultra-short, high-intensity proton bunches on the pion production target. The rms bunch length for the protons on target has to be about 1 ns to: 1) reduce the initial longitudinal emittance of muons entering the cooling system and, 2) optimize the separation of the muon populations of the two polarizations off the target. Conventional rf manipulations appear able to produce 1 to 2 ns proton bunches if enough rf voltage to overcome the space charge forces is used, and the beam energy is far enough from transition so the final bunch rotation is fast. Both simulations and experimental work have been directed at demonstrating that a short pulse can be produced. An experiment at the AGS has shown that bunches with $\sigma \sim 2$ ns can be produced near transition from $\sigma \sim 8$ ns bunches using an rf frequency of 3 MHz (which would be comparable to 1 ns in a 7.5 MHz system for a hypothetical proton driver)[8]. This experiment was done with bunches of 4×10^{12} protons. Simulations with the ESME longitudinal particle simulation code have also shown that 1 to 2 ns bunches of 5×10^{13} can be produced at extraction in a 16 GeV ring with a 1.5 MV rf voltage capability at 7.5 MHz and a 95% bunch emittance of 2 eV-sec[9].

Space charge forces in the proton driver increase rf voltage requirements and oppose any attempt to create ultrashort bunches. The use of tunable inductive inserts in the ring vacuum chamber may permit active control and compensation of the longitudinal space charge below transition (since the inductive impedance is the opposite sign from the capacitive space charge). Initial experiments at the Los Alamos PSR and KEK proton synchrotron with short ferrite inserts appear to show a decrease in the necessary rf voltage to maintain a given bunch intensity and a reduction in the synchrotron oscillation frequency shift caused by space charge[10]. Further experiments are needed to fully demonstrate this technique.

3 PION PRODUCTION, CAPTURE AND PHASE ROTATION CHANNEL

The pions are produced by the interaction of the proton beam with the primary target. Capture of low-momentum, forward pions occurs in a 20 T solenoid field surrounding the target which adiabatically leads into a channel of 5 T solenoid magnets with rf cavities to compress the bunch energy spread while letting bunch length grow (thus rotating the phase of the bunch).

Extensive simulations have been performed for pion production from 8 to 30 GeV proton beams on different target materials in a high-field solenoid [5, 6]. The yield is higher for medium and high-Z target materials, and targets of 2 to 3 interaction lengths maximize pion production. Tilting the target by 100 to 150 mrad minimizes loss of pions by absorption in the target after one turn on their helical trajectory, and allows the proton beam to be absorbed off to the side of the collection channel. Simulations indicate that a 20 T solenoid of 16 cm inside diameter surrounding a tilted target will capture about half of all produced pions. With target efficiency included, about 0.6 pions per proton will enter the pion decay channel [11].

The choice and parameters of the target are a critical question that needs resolution. Only a beam experiment in a magnetic field will settle it, and this is being planned for the targetry/capture experiment at Brookhaven National Laboratory. The target absorbs 400 kW of power at the 15 Hz pulse rate or about ten percent of the beam power. A moving target is preferred to carry the energy deposited by the proton beam to a heat exchanger outside the solenoid channel. An open jet is favored for a moving liquid target to avoid shock damage to a pipe carrying a liquid. For a conducting liquid jet in a strong magnetic field, strong eddy currents will be induced in the jet, causing reaction forces that may disrupt its flow. Alternatives include targets made from insulating materials (such as liquid PtO_2 or Re_2O_3), slurries (*e.g.*, Pt in water), or powders. A moving solid metal target is another possibility. In this case the target would consist of a long flat band or hoop of copper-nickel that moves along its length (as in a band saw). The band would be many meters in length, would be cooled by gas jets away from the target area, and would be supported and moved by rollers.

The pions, and the muons into which they decay, have an energy spread of hundreds of MeV and a peak momentum value at about 200 MeV/c. A linac is introduced along the decay channel, with frequencies and phases chosen to deaccelerate the fast particles and accelerate the slow ones. The linac radio frequency is reduced as the bunches get longer. Several studies have been made of the design of this system, and muon capture efficiencies of about 0.3 muons per proton are obtained. Capture and rotation using higher radio frequencies appears somewhat less efficient with a frequency set of 90, 50 and 30 MHz now being used in many studies. Focusing solenoids can be placed within the irises of the cavities or outside the linac structure.

Fig. 2 shows simulation results for the kinetic energy *vs.* c t at the end of a decay and phase rotation channel. A loose final bunch selection was defined with an energy 130 +/- 70 MeV and bunch ct from 3 to 11 m. With this selection, the rms energy spread is 16.5 %, the rms ct is 1.7 m, and there are 0.385 muons per incident proton. A tighter selection with an energy 130 +/- 35 MeV and bunch ct from 4 to 10 m gave an rms energy spread of 11.7 %, rms ct of 1.3 m, and contained 0.305 muons per incident proton.

4 IONIZATION COOLING

The muon beam at the end of the decay channel is very intense, but diffuse in phase space. For a high luminosity collider, the phase-space volume of the muon beam must be reduced within a time of the order of the muon lifetime (about 2 μs if done at 100 to 200 MeV). Only ionization cooling of muons seems to be fast enough, though other methods like optical stochastic cooling may become viable in the future. Ionization cooling involves passing the beam through some material in which the muons lose both transverse and longitudinal momentum by ionization loss (dE/dx). The longitudinal muon momentum is then restored by reacceleration, leaving a net loss of transverse momentum (transverse cooling). The process is repeated many times to achieve a large cooling factor. The energy spread can also be reduced (longitudinal emittance exchange) by introducing a transverse variation in the absorber density or thickness (e.g. a wedge) at a location where there is dispersion (the position is energy dependent). This results in a corresponding increase of transverse emittance and is thus not true cooling, but rather an exchange of longitudinal and transverse emittance.

Ionization cooling of muons will require extensive simulation studies and hardware development for its realization. Several tracking codes have either been written or modified to study the cooling process in detail (SIMUCOOL by A. Van Ginneken, ICOOL by R. Fernow, a double precision version of GEANT by P. Lebrun et al and a modified version of PARMELA, the linac simulation code, by H. Kirk et al). A proposal for a muon cooling experiment has been presented at Fermilab, and the design of prototype cavities and solenoids has begun. The experiment would use 100 to 300 MeV/c muons. The phase-space volume occupied by the population of muons upstream and downstream of the cooling sections would be measured sufficiently well to enable cooling to be established, the calculations used to design the cooling system to be tested, and optimization of the cooling hardware to be studied[12].

A muon collider requires the 6-D normalized emittance to be reduced by about a factor of 10^5 to 10^6 relative to the initial muon beam. A complete cooling channel is envisioned to consist of 20 to 30 cooling stages, each stage yielding about a factor of two in phase-space reduction. The total length of the system would be of the order 500 m, and the total acceleration would be approximately 6 GeV. The fraction of muons remaining at the end of the cooling system is estimated to be about 0.6.

The baseline solution for transverse cooling involves the use of liquid hydrogen absorbers in strong solenoid focus-

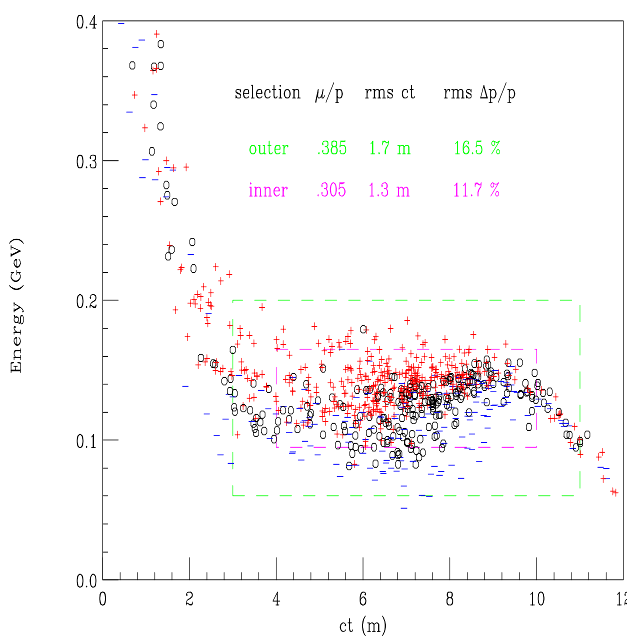

Figure 2: Kinetic energy *vs.* *ct* of muons at end of phase rotation channel. The symbols +, o and $-$ denote muons with polarization $P > \frac{1}{3}$, $-\frac{1}{3} < P < \frac{1}{3}$ and $P < -\frac{1}{3}$, respectively.

ing fields, interleaved with short linac sections. The radio frequency starts low in the cooling line to accomodate the long muon bunches from the decay/phase rotation channel. The solenoidal fields in successive absorbers are reversed to avoid build up of the canonical angular momentum. The focusing magnetic fields are not large (about 1 T) in the early stages where the emittances are large, but must increase (up to 15 to 30 T) as the emittance falls. The preferred solution for emittance exchange involves the use of bent solenoids to generate dispersion and wedges of hydrogen or LiH to reduce the energy spread.

A detailed and complete simulation of an entire cooling channel is close to being realized and is expected within a year. Individual sections of the cooling line have been simulated. Figure 3 shows the cross section of one cell of such a system, together with the magnetic field along the axis and the beta function. The lattice in this example, which is toward the end of the cooling line, consists of 11 identical 2 m long 'cells'. In each cell there is a liquid hydrogen absorber (64 cm long, 10 cm diameter) in the 15 T solenoid focusing magnet (64 cm long, 12 cm diameter). Between the end coils there are magnetic matching sections (1.3 m long, 32 cm inside diameter) where the field is lowered and then reversed. Inside these matching sections are short 805 MHz high gradient (36 MeV/m) linacs. To realize maximum acceleration gradients within the acceleration cavities, thin berylium windows (about 100 μm thick, which muons penetrate easily) are placed between each rf cell, thereby creating an accelerating structure closely approximating the classic pill-box cavity. This permits operating conditions in which the axial accelerating field is equal to the maximum wall field and gives a high shunt impedance.

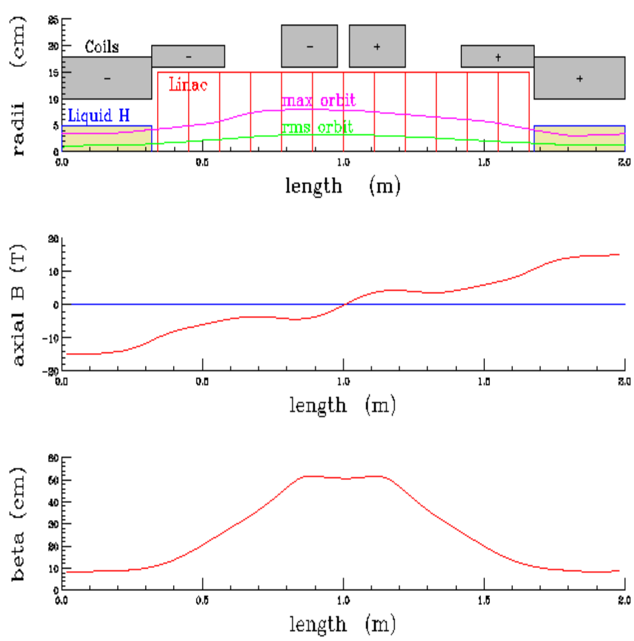

Figure 3: a) Cross section of one cell (2 m) of an alternating solenoid cooling system; b) axial magnetic field *vs.* z; c) beta function *vs.* z.

5 ACCELERATION

Following cooling and initial bunch compression, the beams must be rapidly accelerated. Since muons radiate much less than electrons, some form of circulating acceleration is preferred. To avoid excessive muon decay, the average acceleration gradient in any machine should be ≥ 5 MV/m. At the lowest energies ($<$ 700 MeV) the momentum spread and beam sizes are so large that only a linac is possible. At intermediate energies (to about 200 GeV) the acceleration time is so short (of order 10^{-4} sec) that any form of magnet ramping is impractical. The conservative option here is to use a sequence of recirculating accelerators (similar to that used for the electron beam facility at TJNL), but Fixed Field Alternating Gradient (FFAG) accelerators are also being studied. At higher energies, the acceleration rate is slow enough that fast rise-time, pulsed magnets are possible, and a rapid-cycling synchrotron is an option.

Far less work has gone into the accelerator study than other parts of the muon collider. No complete lattices have been designed, and the only significant simulations done have been in the longitudinal dynamics of recirculating linacs[13]. Table 3 gives some relevant accelerator parameters for a 100 GeV Higgs factory.

Table 3: Accelerator parameters for 100 GeV collider

Accel. type	linac	linac	recirc	recirc	recirc
Magnet type			warm	warm	warm
Cavity type	Cu	Cu	Cu	Cu	Cu
E_{init}(GeV)	0.10	0.20	0.70	2	7
E_{final}(GeV)	0.20	0.70	2	7	50
Circ.(km)	0.04	0.07	0.07	0.19	1.74
Turns	1	1	8	10	11
Loss($\times 10^{-2}$)	2.3	4.0	7.3	7.9	14.0
B_{arc}(T)			2	2	2
Disper. (m)			1	1.50	3
σ_z^{init} (cm)	2.71	2.22	1.42	1.64	0.90
RF (MHz)	200	200	200	200	400
E/turn (GeV)	0.10	0.50	0.17	0.50	4
$T_{acc}(\mu s)$	0.13	0.23	1.9	6.3	64
E_{acc} (MV/m)	8	8	8	10	10
T_{rf} (msec)	0.17	0.17	0.17	0.18	0.13
P_{rf}(peak,GW)	0.05	0.10	0.05	0.26	4.71
P_{rf}(avg,MW)	0.14	0.24	0.13	0.68	9.54
P_{wall}(MW)	0.64	1.16	0.46	2.42	28.1

6 COLLIDER STORAGE RING

After acceleration, both μ^+ and μ^- bunches are injected into a separate storage ring. The highest possible average bending field is desirable, to maximize the number of revolutions before decay, and thus maximize the luminosity. Collisions would occur in one, or perhaps two, low-beta interaction regions (IR). Parameters of the rings were given earlier in Tables 1 and 2. A large body of work has been done on collider ring design, and recent Collaboration status reports contain complete descriptions of the various options including the expected backgrounds in the detectors due to muon beam decay[6, 7].

In order to maintain the required short bunches without excessive rf voltage, the ring must be approximately, or fully, isochronous. The required focusing beta functions at the intersection point (IP) are small for a 3 TeV collider ($\beta^* = 3\,\mathrm{mm}$), and the quadrupoles needed to generate them are large (20 to 30 cm beam-pipe diameter). At 100 GeV, the beta functions at the IP are not as small, and the quadrupoles are more conventional, but in both cases it has been found that local chromatic correction is essential.

The rings are racetracks, with two circular arcs separated by an experimental insertion, on one side, and a utility insertion for injection, extraction, and beam scraping, on the other. The experimental insertion includes the interaction region followed by a local chromatic correction and a matching section. The chromatic correction section is optimized to correct the ring's linear chromaticity, which is almost completely generated by the IR. The bending magnets would be superconducting. The magnets must be shielded from the electrons emitted by decay of the beam. Fields of 8 T have been assumed in the 100 GeV lattices, but higher field dipoles would reduce the ring diameters and increase luminosity. Studies of higher field dipoles have been started. The problem of neutrino-induced radiation for multi-TeV beam energies will require special lattice design and special siting considerations, but is apparently not an issue for low-energy colliders[14].

The rf requirements depend on the lattice momentum compaction and bunch parameters. For the very low momentum spread Higgs collider parameters, synchrotron motion does not occur, and rf voltage is used solely to correct impedance generated momentum-spread in the bunch. For the higher momentum-spread cases, there are two options. If the momentum compaction can be corrected to high order, then synchrotron motion can still be eliminated, and the rf is again only used for energy-spread correction. Alternatively, if some momentum compaction is retained, then significant rf voltage is needed to maintain the specified short bunches. In either case rf quadrupoles will be required to generate BNS damping of the transverse head-tail instability (beam breakup).

7 OUTLOOK

Since the resurgence of interest in the muon collider concept in 1995, several tens of man-years of effort by over a hundred people internationally have gone into feasibility, simulation and design studies. The concept has survived considerable scrutiny and appears to have no fundamental flaws. However being a new machine concept from source to collider, its realization will likely take more than a decade of research and development at resource levels comparable to recent electron-positron linear collider work. The demonstration of muon cooling is viewed as an essential first step on this path.

8 ACKNOWLEDGEMENTS

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