Progress Toward A High-Energy, High-Luminosity μ^+-μ^- Collider

David V. Neuffer, *CEBAF, 12000 Jefferson Avenue, Newport News VA 23606*

Robert B. Palmer, *SLAC, Stanford University, Stanford CA 94305 and Brookhaven National Laboratory, Box 5000, Upton NY 11973*

Abstract. In the past two years, considerable progress has been made in development of the μ^+-μ^- collider concept. This collider concept could permit exploration of elementary particle physics at energy frontiers beyond the reach of currently existing and proposed electron and hadron colliders. As a benchmark prototype, we present a candidate design for a high-energy high-luminosity μ^+-μ^- collider, with $E_{cm} = 4$ TeV, $L = 3\times10^{34}$cm^{-2}s^{-1}, based on existing technical capabilities. The design uses a rapid-cycling medium-energy proton synchrotron, producing proton beam pulses which are focused onto two π-producing targets, with two π-decay transport lines producing μ^+'s and μ^-'s. The μ's are collected, rf-rotated, cooled and compressed into a recirculating linac for acceleration, and then transferred into a storage ring collider. The keys to high luminosity are maximal μ collection and cooling, and innovations with these goals are presented. Possible variations and improvements are discussed. Recent progress in collider concept development is summarized, and future plans for collider development are discussed.

I. INTRODUCTION

Recent discussions, beginning with the 1992 Port Jefferson Advanced Accelerator Concepts Workshop,[1] have indicated that the presently emphasized approaches in high-energy accelerators are reaching critical size and performance constraints. It appears that hadronic colliders (p-p) are reaching critical cost and size limitations with the CERN Large Hadron Collider (LHC, with up to 14-TeV collisions), and are performance-constrained in that they produce complicated many-particle collisions, with a rapidly-diminishing fraction (in numbers and energy) of the interactions in point-like new-particle-state production. Lepton(e^+-e^-) colliders produce simple interactions, and this magnifies the effective energy of collisions by more than an order of magnitude over hadron colliders. Extension of e^+-e^- colliders to multi-TeV energies (effectively beyond the LHC) is constrained by "beamstrahlung" and synchrotron radiation effects, which increase as $(E_e/m_e)^4$, limiting performance as well as forcing the use of two costly full-energy linacs[1], with impractically large size requirements and power demands (GW or more).

However, muons (heavy electrons, with $m_\mu = 200m_e$) have negligible radiation and beamstrahlung, and can be accelerated and stored in recirculating devices or rings. The liabilities of muons are that they decay, with a lifetime of 2.2×10^{-6}

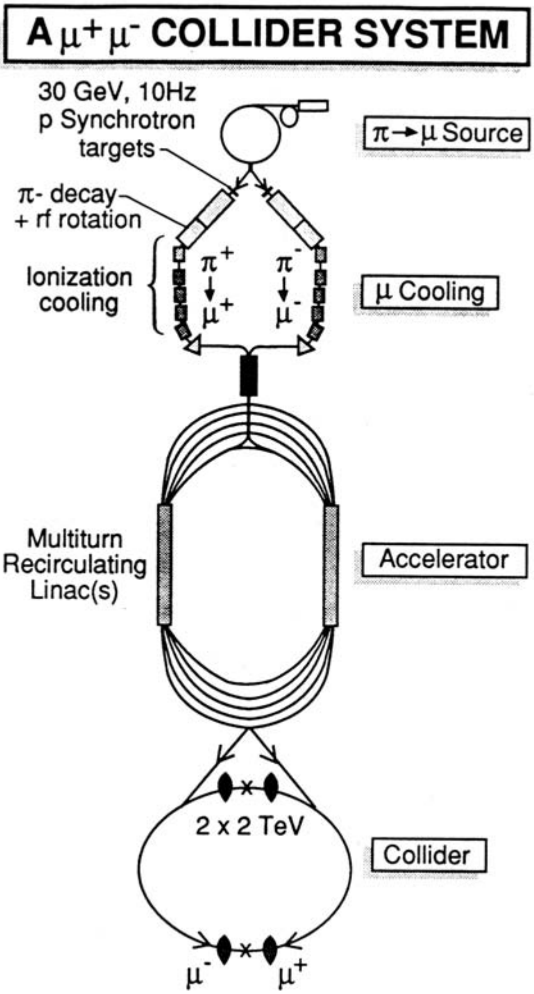

Figure 1: Overview of the μ^+-μ^- collider system, showing a muon (μ) source based on a high-intensity rapid-cycling proton synchrotron, with the protons producing pions (π's) in a target, and the μ's are collected from subsequent π decay. The source is followed by a μ-cooling system, and an accelerating system of recirculating linac(s) and/or rapid-cycling synchrotron(s), feeding μ^+ and μ^- bunches into a superconducting storage-ring collider for multiturn high-energy collisions. The entire process cycles at 10 Hz.

E_μ/m_μ s, and that they are created through decay into a diffuse phase space. But the phase space can be reduced by ionization cooling, and the lifetime is sufficient for storage-ring collisions. (At 2 TeV, τ_μ = 0.044 s.) The μ^+-μ^- collider concept had been previously introduced by Skrinsky et al.[2] and Neuffer[3]. More substantial investigations of the possibility of muon (μ^+-μ^-) colliders were initiated at the Port Jefferson meeting,[4] resulting in the first μ^+-μ^- Collider Workshop in Napa, Ca. (December, 1992)[5] This workshop and several following mini-workshops have greatly increased the level of discussion,[6, 7] stimulating the present developments and improvements which have transformed the concept into a plausible possibility, and leading to the increased degree of interest and many contributions represented in the Second Workshop on μ^+-μ^- Colliders (Sausalito, Ca., November, 1994).[8]

As a prototype, we present a design for a high-energy high-luminosity $\mu^+\mu^-$ collider, with an energy of E_{cm}=$2E_\mu$= 4TeV, and a luminosity of L = 3×10^{34}cm^{-2}s^{-1}, which uses only existing technical capabilities.[9, 10] In this design, we have introduced improvements, particularly in muon collection and cooling, and develop a complete scenario for a high-luminosity high-energy collider, which demonstrates that the μ^+-μ^- collider is a practical possibility. We use this example as a basis for discussion of the features and requirements of a collider system. We discuss variations and potential improvements in the various components and requirements. We then summarize the recent accomplishments in μ^+-μ^- collider development, and discuss future directions for investigation and improvement.

II. A μ^+-μ^- COLLIDER DESIGN

A. Design Overview

In this section we present details of a prototype design for a E_{cm}=$2E_\mu$= 4TeV, L = 3×10^{34}cm^{-2}s^{-1}, μ^+-μ^- collider. The effective energy reach of this collider is beyond that of the LHC or proposed e^+-e^- linear colliders, and the luminosity is sufficient for general-purpose high-energy physics. Table 1 shows parameters for the candidate design, which is displayed graphically in fig. 1. The design consists of a muon source, a muon collection, cooling and compression system, a recirculating linac system for acceleration, and a full-energy collider with detectors for multiturn high-luminosity collisions.

B. Muon Production

The μ-source driver is a high-intensity rapid-cycling synchrotron at KAON[11] proposal parameters (30 GeV, 10 Hz), which produces beam which is formed into two short bunches of 3×10^{13} protons. Combination of the accelerated beam bunches into two short bunches at full energy (possibly in a separate extraction

Table 1: Parameter list for a 4 TeV μ^+-μ^- Collider

Parameter	Symbol	Value
Energy per beam	E_μ	2 TeV
Luminosity	$L=f_0 n_s n_b N_\mu^2/4\pi\sigma^2$	3×10^{34} cm^{-2}s^{-1}
Source Parameters		
Proton energy	E_p	30 GeV
Protons/pulse	N_p	$2\times3\times10^{13}$
Pulse rate	f_0	10 Hz
μ-production acceptance	μ/p	.15
μ-survival allowance	N_μ/N_{source}	.33
Collider Parameters		
Number of μ /bunch	$N_{\mu\pm}$	1.5×10^{12}
Number of bunches	n_B	1
Storage turns	n_s	900
Normalized emittance	ε_N	3×10^{-5} m-rad
μ-beam emittance	$\varepsilon_t=\varepsilon_N/\gamma$	1.5×10^{-9} m-rad
Interaction focus	β_0	0.3 cm
Beam size at interaction	$\sigma = (\varepsilon_t\beta_0)^{1/2}$	2.1 μm

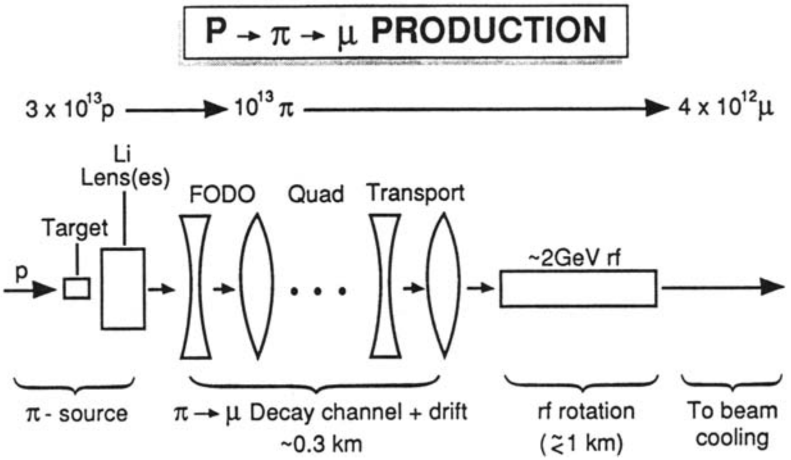

Figure 2: Overview of the $\pi\to\mu$ production transport line. Each proton bunch collides into a target, producing large numbers of π's (~1 π/interacting p) over a broad energy and angular range (E_π =0-4 GeV, $p_\perp$ < 0.5 GeV/c). The target is followed by a Li lens, which collects the π's into a transport line, which accepts a large energy width (2±1 GeV) and has a large transverse acceptance($p_\perp$< 0.4 GeV/c). This line is sufficiently long to insure $\pi\to\mu$ decay, plus rf rotation, which reduces the energy spread. The μ-beam is then matched into a beam-cooling system.

ring) simplifies the subsequent longitudinal phase space manipulations. The two proton bunches are extracted into separate lines for μ^+ and μ^- production. (Separate lines permit use of higher-acceptance, zero-dispersion $\pi \rightarrow \mu$ capture lines.) Each bunch collides into a target, producing π's (~1 π/interacting p) over a broad energy and angular range ($E_\pi = 0.2$—4 GeV, $p_\perp < 0.5$ GeV/c). The target is followed by Li lenses, which collect the π's into a large-aperture high-acceptance transport line (an r = 0.15m, B= 4T FODO transport with a 0.8m period in a current scenario), designed to accept a large energy width (2±1 GeV) and have a large transverse acceptance($p_\perp < 0.4$GeV). This array is sufficiently long (~300 m) to insure $\pi \rightarrow \mu$ decay, plus debunching, in which the energy-dependent particle speeds spread the beam longitudinally to a full width of ~6 m, while reducing the local momentum spread.

This is followed by an rf debuncher, a nonlinear rf system (3 harmonics are sufficient) which flattens the momentum spread.[12] We have conservatively assumed that rf gradients at these frequencies (~10—30 MHz) are limited to less than ~2 MeV/m; this implies a total rf debuncher length of ~1.4 km. The resulting μ-beam is then matched into a beam cooling system. Figure 2 shows a schematic overview of the production and collection system.

A Monte Carlo program (MCM - Monte Carlo Muon) has simulated the muon production and cooling.[13] The generation of π's in the target is calculated using a thermodynamic model or the Wang distribution,[14] validated by comparisons with production data. (The Wang distribution can be approximated by the following empirical formula, useful for initial estimates:

$$\frac{d^2 N}{dP\, d\Omega} \cong A P_p X(1-X) e^{-BX^C - DP_t} \; \frac{\text{pions}}{\text{sr}-\text{GeV/c}} / \text{interacting proton} \qquad (1)$$

where P_p is the incident proton momentum, $X = P_\pi / P_p$ is the pion/proton momentum ratio, P_t is the pion transverse momentum and A = 2.385 (1.572), B = 3.558 (5.732), C = 1.333 (1.333), and D = 4.727 (4.247) for positive (negative) pions. In this formula, pions are produced with a mean transverse momentum of ~D^{-1} or ~0.2 GeV.) In the MCM simulations, the π's are tracked through decay to μ's, and through phase-energy rotation, into the cooling system. We obtain ~0.15 captured μ's per inital proton, with $\varepsilon_N = 0.01$ m-rad, an rms bunch length of 3m, and energy width of 0.15 GeV with an average energy of 1 GeV.

The μ capture efficiency (0.15μ/p) is larger than estimated in previous scenarios[2, 3, 4], and this is a result of the use of a high acceptance decay transport with a larger momentum acceptance. The transport is followed by a linac-based rf rotation, which reduces the momentum spread to a level acceptable by the subsequent transport and cooling system, while lengthening the beam bunch.

Previously, Noble[4] has noted that $\mu^+\mu^-$ collider luminosity increases with the energy spread acceptance ΔE_A by as much as $\Delta E_A{}^4$, with factors accumulating from the production and the decay acceptances of both beams. The high-acceptance transport plus rf rotation has increased that acceptance by almost an order of magnitude above previous estimates. Also, for the first time, the production has been directly calculated in a realistic simulation, and not simply estimated.[13]

C. Beam Cooling

For collider intensities, the phase-space volume must be reduced by beam-cooling and the beam size compressed, within the μ lifetime. Much of the needed compression is obtained through adiabatic damping in acceleration from GeV-scale μ collection to TeV-scale collisions. Beam cooling is obtained by "ionization cooling" of muons ("μ-cooling"), in which beam transverse and longitudinal energy losses in passing through a material medium are followed by coherent reacceleration, resulting in beam phase-space cooling.[2,3,15] Figure 3 shows a schematic view of the cooling process. (Ionization cooling is not practical for protons and electrons because of nuclear scattering (p's) and bremstrahlung (e's) effects, but is for μ's and the necessary energy losses are easily obtained within the μ lifetime.) In this section we present the equations for μ-cooling, use these to deduce optimal cooling conditions, and generate a practical cooling scenario.

The equation for transverse cooling is:

$$\frac{d\epsilon_N}{ds} = -\frac{dE}{ds}\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp}{2}\frac{(0.014)^2}{E_\mu m_\mu}\frac{1}{L_R} \qquad (2)$$

(with energies in GeV), where ε_N is the normalized emittance, $\beta_\perp$ is the betatron function at the absorber, dE/ds is the energy loss, $E_\mu = \gamma m_\mu c^2$ is the muon energy and L_R is the material radiation length. The first term in this equation is the coherent cooling term and the second term is heating due to multiple scattering. This heating term is minimized if $\beta_\perp$ is small (strong-focusing) and L_R is large (a low-Z absorber). (We have anticipated the eventual optimization at relativistic energies by using relativistic approximations (v/c=1). In a more complete derivation, factors of v/c would appear. Momentum p_μ rather than E_μ would be a preferred variable.)

The equation for energy cooling is:

$$\frac{d\langle(\Delta E)^2\rangle}{ds} \approx -2\frac{\partial\frac{dE_\mu}{ds}}{\partial E_\mu}\langle(\Delta E)^2\rangle + \frac{d\langle\Delta E_\mu^2\rangle}{ds} \tag{3}$$

Energy-cooling requires that $\partial(dE_\mu/ds)/\partial E > 0$. The energy loss function, dE_μ/ds, is rapidly decreasing with energy for $E_\mu < 0.2$ GeV (and therefore heating), but is slightly increasing (cooling) for $E_\mu > 0.3$ GeV. This small natural cooling is ineffective, because of the relatively large rms energy straggling; but $\partial(dE_\mu/ds)/\partial E$ can be increased by placing a transverse variation in absorber density or a wedge absorber where position is energy-dependent. (This variation is used in two modes: a weak variation to balance cooling rates, or a thick wedge to transfer phase space.) The sum of cooling rates is invariant:

$$\frac{1}{E_{cool,x}} + \frac{1}{E_{cool,y}} + \frac{1}{E_{cool,\Delta E}} = \text{Constant} \approx \frac{2}{E_\mu}\ , \tag{4}$$

where E_{cool} is the total energy loss needed to obtain an e-folding of cooling and E_μ is the μ energy.

In the long-pathlength Gaussian-distribution limit, the heating term or energy straggling term is given by:[16]

$$\frac{d(\Delta E_\mu)^2}{ds} \cong 4\pi(r_e m_e c^2)^2 N_0 \frac{Z}{A}\rho\gamma^2(1-\beta^2/2)\ , \tag{5}$$

where N_0 is Avogadro's number and ρ is the density. Since this increases as γ^2, and the cooling system size scales as γ, cooling at low energies is desired.

To obtain energy cooling and to minimize energy straggling, we require cooling at low relativistic energies ($E_\mu \sim 300$ MeV). For optimum transverse cooling, the ideal absorber is itself a strong focussing lens which maintains small beam size over extended lengths, and a low-Z material. In this design, we use Be ($Z=4$) or Li ($Z=3$) current-carrying rods, where the high current provides strong radial focussing. For Be, $Z=4$, $A=9$, $dE_\mu/dx = 3$ MeV/cm, and $\rho = 1.85$ gm/cm^3.

The beam cooling system reduces transverse emittances by more than two

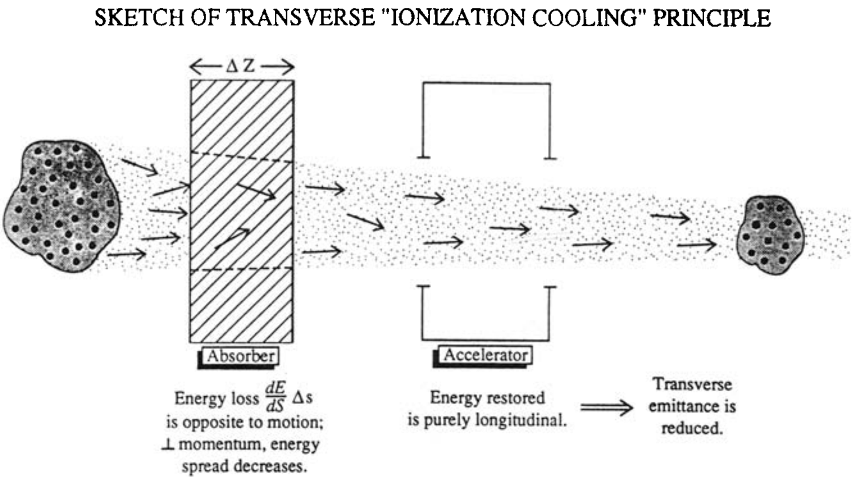

Figure 3: Schematic view of transverse "ionization cooling". Energy loss in an absorber occurs parallel to the motion; therefore transverse momentum is lost with the longitudinal energy loss. Energy gain is longitudinal only; the net result is a decrease in transverse phase-space area. Statistical beam heating by random multiple scattering opposes the coherent cooling.

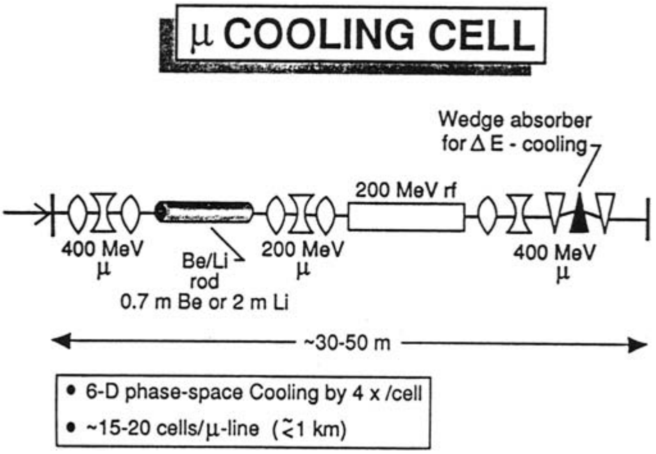

Figure 4: Overview of a μ-cooling (ionization cooling) cell. A typical cooling cell consists of a focusing cooling rod which reduces the central energy from 400 to 200 MeV, followed by a ~200 MeV linac, with appropriate optical matching. Cooling by a 3-D factor of ~4 is obtained in each cell, and 15-20 such cells (~1 km) are needed in the complete machine. For energy cooling, we introduce a dispersion (position-dependence on momentum), and use an absorber with a density gradient or wedge shape. This arrangement permits enhancement of energy-cooling[2, 3, 15], and the parameters are adjusted to obtain optimal transverse and longitudinal cooling.

orders of magnitude (from 0.01 to 3×10^{-5} m-rad), and reduces longitudinal emittance by more than an order of magnitude. This cooling is obtained in a series of cooling cells, with the initial cells reducing the energy toward the cooling optimum of 300 MeV. A typical cooling cell consists of a focusing cooling rod (~0.7 m long for Be, ~2.1 m for Li) which reduces the central energy by ~200 MeV, followed by a ~200 MeV linac (20—40 m at 10—5 MeV/m), with optical matching sections (~40–60 m total cell length) (see fig. 4). Small angle bends introduce a dispersion (position-dependence on energy), and wedge absorbers (or density gradients) introduce an energy loss dependence on beam energy. Bends are also used to provide path length dependence on momentum, in order to compress the bunch lengths. The cell parameters are adjusted to obtain optimal transverse and longitudinal cooling rates, and cooling by a 6-D factor of ~4 is obtained in each cell. ~15–20 such cells (~800 m) are needed in the complete machine.

From equation 1, we find a limit to transverse cooling when the multiple scattering balances the cooling, at $\varepsilon_N \approx 10^{-2}\,\beta_\perp$ for Be. The value of $\beta_\perp$ in the Be rod is limited by the peak focusing field to $\beta_\perp$~0.01 m, obtaining $\varepsilon_N \sim 10^{-4}$ m-rad. This is a factor of ~3 above the emittance goal of Table 1. The additional factor can be obtained by cooling more than necessary longitudinally and exchanging phase-space with transverse dimensions in a thick wedge absorber. MCM simulations have demonstrated that the desired cooling and phase-space exchange can be obtained.

D. Acceleration and Collisions

Following cooling and initial bunch compression to ~.1–.3m bunch lengths, the beams are accelerated to full energy (2 TeV). A full-energy linac would work, but it would be costly and does not use our ability to recirculate μ's. A recirculating linac (RLA) like CEBAF[17] can accelerate beam to full energy in 10—20 recirculations, using only 200—100 GeV of linac, but requiring 20—40 return arcs. The μ-bunches would be compressed on each of the return arcs, to a length of 0.003m at full energy. A cascade of RLAs (i. e., 1–10, 10–100 and 100–2000 GeV), with rf frequency increasing as bunch length decreases, may be used. The cooling and acceleration cycle is timed so that less than ~half the initial μ's decay. (In Table 1, we allow a factor of 3 in total losses.)

After acceleration, the μ^+ and μ^- bunches are injected into the 2-TeV superconducting storage ring (~1-km radius), with collisions in one or two low-β^* interaction areas. The beam size at collision is $r = (\varepsilon_N\,\beta_0/\gamma)^{1/2} \sim 2\mu$m, similar to hadron collider values. The bunches circulate for ~300B turns before decay, where B is the mean bending field in T. (This is 150B luminosity turns, a factor of two smaller since both beams decay.) The design is restricted by μ decay within the rings ($\mu \rightarrow e\,\nu\nu$), which produces 1/3-energy electrons which radiate and travel to the inside of the ring dipoles. This energy could be intercepted by a liner inside the magnets, or specially designed C-dipoles could be used and the electrons intercepted in an external absorber. The design constraints may limit B; we have chosen $B = 6T$ (900 turns) in the present case. μ-decays in the interaction areas will also provide some background levels in detectors. The limitations in detector design are being studied.

III. VARIATIONS AND IMPROVEMENTS

A. Design Overview

We have presented a candidate scenario for a high-energy high-luminosity μ^+-μ^- collider. In this section we discuss variations in the scenario, both in outline and details, which should be considered and studied. This discussion should not be considered complete. The most important innovations have probably not been invented yet, and will result from the thoughts and investigations of our future research, including the μ^+-μ^- workshops.

The luminosity estimate of the scenario should not be considered as an absolute limit. Luminosity could be readily increased by reducing losses, or by increasing the source repetition rate (increasing the source to above KAON-class intensity). In the workshop,[8] potential difficulties and possible improvements were identified. Within present uncertainties in implementation (μ-production, cooling, possible improvements or regressions, etc.), the achieved luminosity could be as much as two orders of magnitude larger or smaller. More precision is needed.

The 4 TeV energy was set as a benchmark; however it is at a size and scope similar to existing facilities. Higher or lower energy colliders are possible, and we are not near absolute luminosity limitations. The μ^+-μ^- collider concept naturally increases in luminosity with energy. One factor of E_μ increase results from transverse emittance adiabatic damping. Since the beam also decreases in size longitudinally by adiabatic damping, smaller interaction-region β^* should also be possible, permitting further enhancement. If the injector intensity/cost is also allowed to increase (beyond KAON-class) in proportion to E_μ, then beam intensities increase as E_μ, and luminosity increases by at least another factor of E_μ. These increases of luminosity with energy, by at least factors of E_μ^2, should be followed up to the 100 TeV scale, beyond which μ synchrotron radiation becomes large. (Radiation damping would then initially permit further improvements.)

Lower energy machines (100–400 GeV Higgs, top factories, etc.) are also possible, particularly if there are strong physics motivations.[18] Lower-energy machines could also be a useful step toward a high-energy machine. These would have lower luminosity, because of the adiabatic damping factors. However, if a

KAON-class muon source is also used, a relatively high luminosity ($L \sim 10^{33}cm^{-2}s^{-1}$) is possible. (The source intensity need not decrease with decreasing E_μ.)

B. Muon Production

The scenario for production and collection of muons needs much further study and development. Production calculations should be more precisely calibrated with experimental observations. Many options for targetting, collection and, transport, as well as variations on the rf debunching and compression scenario, should be explored.

In the present scenario the entire beam of the proton accelerator ring has been compressed into two short bunches before delivery onto target. While this appears possible (extrapolating from AGS experience and using a separate bunching ring), it is difficult, and it has not been demonstrated that bunches that are short enough for the subsequent rf rotation are readily obtained. Scenarios with a larger number of initial bunches (possibly shorter) may be preferable. As discussed in the previous workshop, bunch combination in π-decay or in the cooling system will be possible.

In the present scenario, the debunching process obtains relatively long bunches (up to 10m long), and therefore relatively low frequency rf (10–30 MHz) is required in the debunching rf. (An induction linac rather than resonant-cavity rf could also be used.) Acceleration gradients at these frequencies are currently relatively limited; research enabling gradient increase would permit a more compact facility and better performance. The μ-bunch length also implies that low-frequency-rf must be used in the initial cooling, and complicates subsequent bunch compression. Scenario variations with shorter bunches may be more readily implemented, and should be explored.

Variations on initial proton beam and π collection energies should be considered. Sources based on existing accelerators (AGS, Fermilab booster and main injector) could be developed, and used in initial colliders. A high-energy primary beam could obtain amplified production by using multiple interactions through a cascade of production targets. A lower energy proton beam may be more efficient in single π production. A GeV p-beam (π-factory, similar to LAMPF) could enable use of low-energy stopped π sources, where the μ-beam would be naturally cooler at production.

C. Beam Cooling

In the present scenario, we cool only with ionization cooling in conducting Be (or Li) rods, along with phase space exchange, and that is sufficient for high luminsosity. While portions of the process have been Monte Carlo simulated, the complete scenario has not been specified and studied. Longitudinal damping with wedge absorbers, and bunch compression, has not been fully integrated with transverse cooling.

The ionization cooling scenario needs to be optimized in full detail, and verified by more complete simulations. The detailed design will be dependent on bunch lengths, rf gradients, and optics optimization.

Previous active conductor lenses have been Li lenses, and that experience can be extended into the present case. Be is much denser, has higher electrical and thermal conductivity (permitting higher fields), and has similar multiple scattering, but has had safety problems in other applications. Research leading to validation of Be for rod cooling would be desirable.

Other techniques (such as ionization cooling in focussing transports or rings, or using plasma lenses, or high-frequency "optical" stochastic cooling[19]) may permit improvements, and are being studied. Also, with a low-energy source, μ-cooling at low (thermal) energies, which has somewhat different behavior, could be implemented.[20] Study of low-energy sources, with low-energy cooling, is needed.

D. Acceleration and Collisions

The bunch-compression and acceleration scenario also needs to be optimized and simulated. A detailed scenario including all stages of bunch compression has not yet been specified. Variations such as rapid-cycling synchrotrons and fixed-field alternating gradient (FFAG) machines should be considered. Hybrid recirculating-linac rapid-cycling devices are possible, in which each arc of the recirculating linac contains rapid cycling magnets, permitting multiturn passes within each recirculating arc. (A low-cost scenario requiring only 20 GeV of rf, using an injector and three RLA stages with rapid-cycling in the last stage, has been generated.)

Complete lattices are needed for the accelerator(s) and for the full-energy collider, where the low-β^* interaction region must be integrated with the high-field arcs, and modifications must be included to accomodate μ-decay in the arcs and near the IR's. Tracking of complete lattices for a muon lifetime should be investigated, and any instability limits should be identified.

It would be desirable to collide polarized beams. Muons are naturally polarized when produced in π-decay; however, polarization selection may reduce intensity, and we do not yet know if that polarization can be maintained through a debunching, cooling, acceleration and collision cycle. Further study is needed.

IV. SUMMARY AND CONCLUSIONS

A. Recent Accomplishments

In this section we recount some highlights of the progress in the past two years in development of the μ^+-μ^- collider, most of which are described in greater detail in the μ^+-μ^- collider workshop proceedings:[8]

The concept of a high-energy collider has been greatly improved, and a reasonable first scenario for a high-luminosity collider has been developed, based only on existing technical capabilities.

Since this scenario is confined to existing technology, first approximate estimates of the size and scope of a facility can be made. While, remembering the SSC, we would not like to state a crude cost number, the size and scope of the concept are within that of existing and planned facilities, and within plausibly estimated high-energy physics resources.

rf rotation immediately following $\pi \rightarrow \mu$ production has been incorporated into that scenario.[12] This greatly enhances μ acceptances; and therefore greatly increases luminosity. For the first time, the muon source has been simulated in a Monte Carlo simulation, with particle tracking from the π-production target through the decay transport, and followed by rf rotation. Relatively large μ-acceptance is obtained (~0.2 μ/p).

Also, for the first time, Monte Carlo simulations of the ionization cooling process have been initiated, by Palmer and Gallardo, and by van Ginnekin. These simulations have included increasingly complicated, and hopefully more realistic, models of the multiple scattering and energy straggling effects. Initial results are in reasonable agreement with the the rms cooling model.

For the first time, serious plans toward initial ionization cooling experiments have been developed. Proposals for initial experiments at TRIUMF, Fermilab and BNL are being developed, and collaborations are forming for their implementation.

Detailed studies of stochastic cooling of muons have been developed, by Ruggiero, and Barletta and Sessler. While conventional stochastic cooling is relatively ineffective because of the short muon lifetime, very-high-frequency cooling, such as proposed in "optical stochastic cooling", shows some promise of eventual utility.

Studies of alternative sources (photoproduction, or low-energy stopped-π) have been initiated.

As is also discussed in ref. 8, the underlying physics motivation for a muon collider has been more clearly formulated. The simple single-particle interactions characteristic of lepton-antilepton collisions are obtained, with the important advantage that the collisions occur within a small energy width (without the large energy broadening due to beamstrahlung expected in e^+-e^- linear colliders). The possibility of s-channel Higgs production is being studied. Also, the detector complications implied by μ-decay have also been studied, and initial detector configurations have been developed.

B. Future Directions

In this section, we outline some of the effort which we hope will be accomplished in the near future, before the next workshop.

The present scenario is a first proof-of-principle design concept. Much further optimization and design and concept development will be implemented, and the enlarged μ^+-μ^- collider collaboration developed at the collider workshops will enable this. One goal of the research will be complete source to collider simulations. These detailed calculations will identify key difficulties and potential improvements in the present scenario. We also hope to have a complete design concept for the μ^+-μ^- collider detector, and that the detector is integrated into the collider ring design.

Other scenarios, with substantial differences in source, cooling, and acceleration, will be developed, to a level that reasonable comparisons and optimizations can be made.

The presently developing experimental collaborations should have made substantial progress in experimental design and construction. A first demonstration of ionization cooling should be obtained. Other experiments may be needed. More accurate measurements of π-production under the same conditions used in the collider would be useful, and could be important in developing an accurately optimized scenario. rf acceleration development would also be desirable, both in the low-frequency rf systems needed in the debuncher and cooling, and in the high-frequency rf needed in the accelerator and collider.

The most important innovations cannot, of course, be predicted, but we expect substantial inventions and dramatic changes in the future. The progress over the past two years has transformed the μ^+-μ^- collider concept into a credible possibility. A similar degree of progress over the next two years could be the basis for the next-generation collider, which would enable particle-physics exploration at energy frontiers beyond the reach of existing and proposed accelerators.

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