I. CONCLUSION

Unlike protons, muons are point like but, unlike electrons, they emit relatively little synchrotron radiation and can be, therefore, accelerated and collided in rings. As a result, a muon collider with a given energy reach could be smaller than either a proton or electron machine. A 3 TeV muon collider (with effective energy comparable with that of an SSC) would fit on existing sites, such as BNL or FNAL. Another advantage resulting from the low synchrotron radiation is the lack of beamstrahlung and the possibility of very small collision energy spreads. A beam energy spread of ΔE/E of 0.003 % (equivalent to a CoM spread of ΔE/E of 0.002 %) is considered feasible for a 100 GeV machine; and it has been shown that by observing spin precession , the absolute energy could be determined to a small fraction of this width. These features become important in conjuction with the large s-channel Higgs production ($\mu^+\mu^- \to h$, 43000 times larger than for $e^+e^- \to h$), allowing precision measurements of the Higgs mass, width and branching ratios.

Such machines are clearly desirable. The questions are:

- whether they can be built and physics done with them
- what will they cost.

Much progress has been made in addressing the first question and the answer, so far, appears to be yes. It is too early yet to address the second.

We have studied machines with center of mass energies of 100 GeV, 400 GeV and 3 TeV, defined parameters and simulated many of their components. Most recent work has been done on the 100 GeV "First Muon Collider", the exact energy taken to be representative of the actual mass of a Higgs particle.

a. Proton Driver The specification of the proton driver for the three machines is assumed the same: 10^{14} protons/pulse at an energy above 16 GeV and 1-2 ns rms bunch lengths. There have been three studies of how to achieve them. The most conservative, at 30 GeV, is a generic design. Upgrades of the FNAL (at 16 GeV) and BNL (at 24 GeV) accelerators have also been studied. Despite the very short bunch requirement, each study has concluded that the specification is attainable. Experiments are planned to confirm some aspects of these designs.

b. Muon Production Pion production has been taken from the best models available, but an experiment (BNL-E910) that has taken data, and is being analyzed, will refine these models. The assumed 20 T capture solenoid appears to be well within current technology (a coil with the specified field and aperture is now nearing completion at FSU). Capture, decay and phase rotation have been simulated, and have achieved the specified production of 0.3 muons per initial proton. The most serious remaining questions for this part of the machine are:

1. The nature and material of the target: The baseline assumption is that a liquid metal jet will be used, but the effects of shock heating by the beam, and of the eddy currents induced in the liquid as it enters the solenoid, are not yet fully understood.
2. The maximum RF field in the phase rotation. For the short pulses used, the current assumptions would be reasonably conservative under normal operating conditions, but the effects of the massive radiation from the nearby target are not known.

Both these questions can be answered in a target experiment planned to be performed within the next two years at the BNL AGS.

c. Cooling The required ionization cooling is the most difficult and least understood element in any of the muon colliders studied. Ionization cooling is a phenomenon that occurs whenever there is energy loss in a strong focusing environment. Such an environment has existed, for instance, in the iron toroid muon calorimeters of several neutrino experiments, and a Monte Carlo simulation has shown [2] that cooling must have occured there. But achieving the nearly 10^6 reduction required is a challenge. Cooling over a wide range has been simulated using lithium lenses and ideal (linear matrix) matching and acceleration; and examples of limited sections of solenoid lattices with realistic accelerating fields have now been simulated, but the specification and simulation of a complete system has not yet been done. Much theoretical work remains: space charge and wake fields must be included; lattices at the start and end of the cooling sequences must be designed; lattices including liquid lithium lenses must be studied, and the sections must be matched together and simulated as a full sequence. The tools for this work are nearly ready, and this project should be completed within two years.

Technically, one of the most challenging aspects of the cooling system appear to be:

- High gradient RF (e.g. 36 MV/m at 805 MHz) operating in strong (5-10 T) magnetic field, with beryllium foils between the cavities.

An experiment is planned that will test such a cavity, in the required fields, in about two years time. On an approximately six year time scale, a “Cooling Test Facility” is being proposed that could test ten meter lengths of different cooling systems. If they are required, then an urgent need is to develop:

- Lithium Lenses: (e.g. 2 cm diameter, 70 cm long, liquid lithium lenses with 10 T surface fields and a repetition rate of 15 Hz).

The use of 31 T solenoids could avoid their need, at least in a the low energy “First Muon Collider”, which would ease the urgency of this rather long term R & D, but more study is needed. Meanwhile a short lithium lens is under construction at BNIP (Novosibirsk, Russia).

d. Acceleration The acceleration system is probably the least controversial, although possibly the most expensive, part of a muon collider. Preliminary parameters have been specified for acceleration sequences for a 100 GeV and 3 TeV machines, but they need refinement. In the low energy case a linac is followed by three recirculating, or FFAG, accelerators. In the high energy accelerator, the recirculating, or FFAG, accelerators are followed by three fast ramping synchrotrons employing alternating pulsed and superconducting magnets. The parameters do not appear to be extreme, and it does not appear as if serious problems are likely.

e. Collider The collider lattices are challenging because of their required very low intersection betas, high single bunch intensities, and short bunch lengths; however, the fact that all muons will decay after about 1000 turns means that slowly developing instabilities are not a problem. Feasibility lattices have been generated for a 4 TeV case, and more detailed designs for 100 GeV machines studied. In the latter case, but still without errors, 5σ acceptances in both transverse and longitudinal phase space have been achieved in tracking studies. Beam scraping schemes have been designed for both the low energy (collimators) and high energy (septum extractors) cases.

The short bunch length and longitudinal stability problems are avoided if the rings, as specified, are sufficiently isochronous, but some rf is needed to remove the impedance generated momentum spread. Transverse instabilities (beam breakup) should be controlled by rf BNS damping.

The heating of collider ring superconducting magnets by electrons from muon decay can be controlled by thick tungsten shields, and this technique also shields the space surrounding the magnets from the induced radioactivity on the inside of the shield wall. A conceptual design of magnets for the low energy machine has been defined.

Although much work is yet to be done (inclusion of errors, higher order correction, magnet design, rf design, etc), the collider ring do not appear likely to present serious problems.

f. Neutrino Radiation and Detector Background Neutrino radiation, which naturally rises as the cube of the energy, is not serious for machines with center of mass energies below about 1.5 TeV. It is thus not significant for the First Muon Collider; but above 2 TeV, it sets a constraint on the muon current and makes it harder to achieve desired luminosities. However, advances in cooling, and correction of tune shifts may still allow a machine at 10 TeV with substantial luminosity ($> 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$).

Background in the detector was at first expected to be a very serious problems, but after much work, shielding systems have evolved that limit most charged hadron, electron, gamma and neutron background to levels that are acceptable. Muon background, in the higher energy machines, is a special problem that can cause serious fluctuations in calorimeter measurements. It has been shown that fast timing and segmentation can help suppress this background, and preliminary studies of its effects on a physics experiment are encouraging. The studies are ongoing.

g. Summary Much progress has been made since Snowmass, but much still needs to be done. A time scale of two years should allow completion of simulation studies, and the experimental testing of crucial technical challenges. Prototype construction and testing will be required for another 4-6 years. The construction of a "First Muon Collider" by about 2010 does seems possible.

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[1] N. V. Mokhov, *Proceedings of the 1996 DPF/DPB Summer Study on High-Energy Physics, Snowmass'96* (Stanford Linear Accelerator Center, Menlo Park, CA), 1996.

[2] B. King, presentation at the Muon Collider Mini-Workshop: Lattice and Background, UCLA and private communication, 1997, (unpublished).
[3] N. V. Mokhov and A. Van Ginneken, Muon Collider Neutrino Radiation, presentation at the Muon Collider Collaboration Meeting, Orcas Is., Washington, 1997.
[4] C. Johnstone and N. V. Mokhov, presented at the PAC97, Vancouver, Canada (unpublished).
[5] A. Skrinsky, submitted to Proc. of the 4th Int. Conf. on Physics Potential and Development at $\mu^+\mu^-$ Colliders, San Francisco, CA, 1997, (to be published).
[6] A. A. Mikhailichenko and M. S. Zolotorev, Phys. Rev. Lett. **71**, 4146 (1993).
[7] Muon Collider Collaboration, in *Proceedings of the 1996 DPF/DPB Summer Study on High-Energy Physics Snowmass'96,* New Directions for High-Energy Physics (Stanford Linear Accelerator Center, Menlo Park, CA, 1997), for updated information, see the Muon Collider Collaboration WEB page at the URL, http://www.cap.bnl.gov/mumu/.
[8] C. J. Johnstone and N. V. Mokhov, *Optimization of a Muon Collider Interaction Region with Respect to Detector Backgrounds and the Heat Load to the Cryogenic Systems* , Proceedings of the 1996 DPF/DPB Summer Study on New Directions for High Energy Physics (Snowmass'96) and Fermilab-Conf-96/366, 1996., 1996.
[9] G. W. Foster and N. V. Mokhov, in *Physics Potential & Development of* $\mu^+\mu^-$ *Colliders* 2^{nd} *Workshop* (AIP Press, Woodbury, New York, YEAR).
[10] N. V. Mokhov and S. I. Striganov, *Proceedings of the 9th Advanced ICFA Beam Dynamics Workshop* (AIP Press, Woodbury, New York, 1996), Vol. 372, pp. 234–256; also Fermilab–Conf–96/011 (1996).
[11] I. Stumer et al., in *Proceedings of the 1996 DPF/DPB Summer Study on High-Energy Physics, Snowmass'96* (Stanford Linear Accelerator Center, Menlo Park, CA, 1996).
[12] N. V. Mokhov, Nucl. Phys. B **51A**, 210 (1996).
[13] N. V. Mokhov, The MARS Code System Users Guide, Fermilab-FN-628; available at http://www-ap.fnal.gov/MARS/, 1995.
[14] *GEANT manual, v.3.2.1, CERN program Library W5013*, CERN, 1994.
[15] See [7], section 8.5.3.
[16] P. Chen, in *Proceedings of the Symposium on Physics Potential & Development of* $\mu^+\mu^-$ *Colliders*, Vol. 51A of *Proceedings Suppl. Nucl Phy B*, edited by D. Cline (North-Holland, The Netherland, 1996), p. 179.
[17] I. Ginzburg, in *Proceedings of the Symposium on Physics Potential & Development of* $\mu^+\mu^-$ *Colliders*, Vol. 51A of *Proceedings Suppl. Nucl Phy B*, edited by D. Cline (North-Holland, The Netherland, 1996), p. 186.
[18] N. V. Mokhov, Nucl. Phys. B **51A**, 210 (1996).