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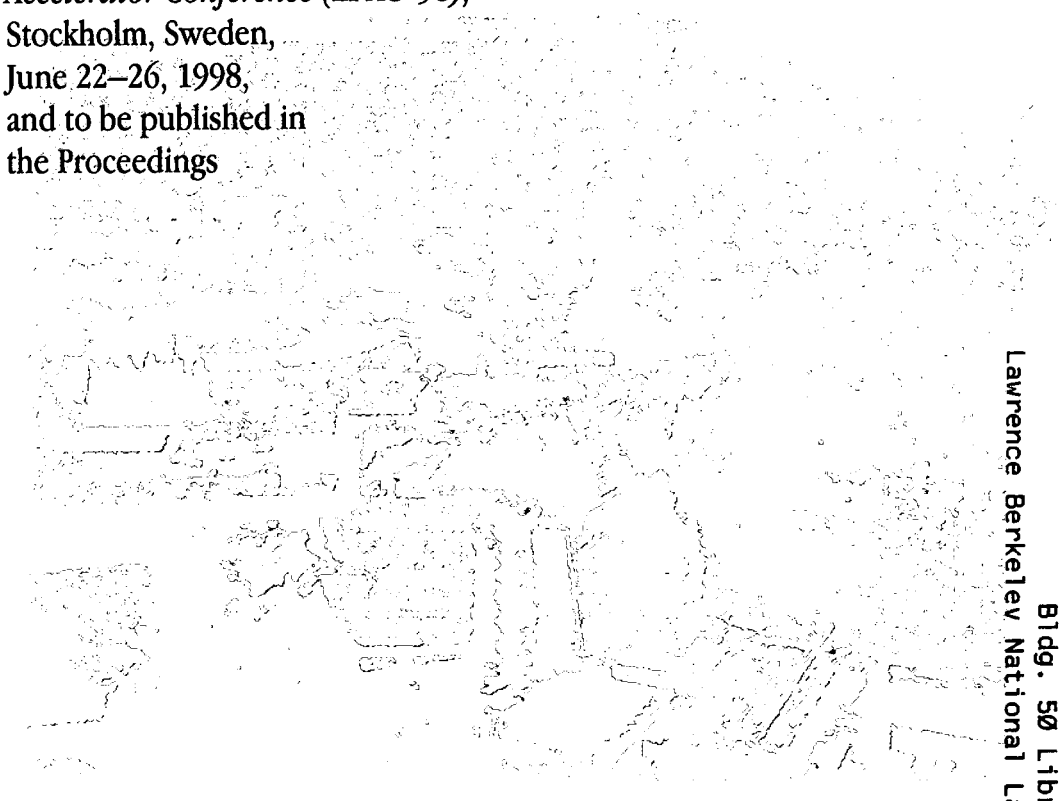

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Muon Collider Overview: Progress and Future Plans

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Abstract

Besides continued work on the parameters of a 3-4 and 0.5 TeV center of mass (CoM) collider, many studies are now concentrating on a machine near 100 GeV (CoM) that could be a factory for the s-channel production of Higgs particles. We mention the research on the various components in such muon colliders, starting from the proton accelerator needed to generate pions from a heavy-Z target and proceeding through the phase rotation and decay ($\pi \rightarrow \mu \nu_\mu$) channel, muon cooling, acceleration, storage in a collider ring and the collider detector. We also mention theoretical and experimental R & D plans for the next several years that should lead to a better understanding of the design and feasibility issues for all of the components. This note is a summary of a report[1] updating the progress on the R & D since the Feasibility Study of Muon Colliders presented at the Workshop Snowmass'96.[2]

1 INTRODUCTION

Unlike protons, muons are point like but, unlike electrons, they emit relatively little synchrotron radiation and therefore, can be 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 (see Figs.1, 2). 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 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 ($\mu^+\mu^- \rightarrow h$, 43000 times larger than for $e^+e^- \rightarrow h$), 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 positive. 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 (see Tb.1). Most 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.

2 COMPONENTS

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 have been done and are planned to confirm some aspects of these designs.[3]

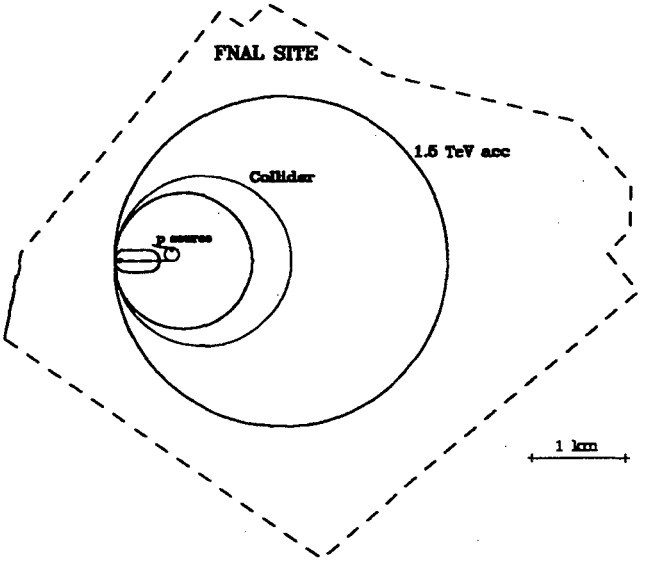

Figure 1: Plan of a 3 TeV Muon Collider shown on the FNAL site as an example.

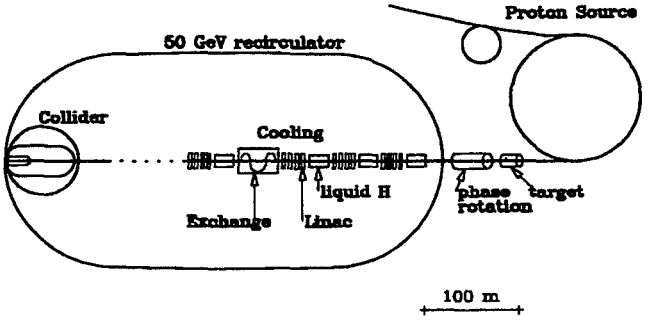

Figure 2: Plan of a 100 GeV CoM Muon Collider.

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.[4] 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 the National High Magnetic Field Laboratory, Florida State University). 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 AGS.[5]

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[6] 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 designed and 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.[7]

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.[8] If they are required, there is the need 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).

They may not be needed for the low energy "First Muon Collider", which would ease the urgency of this rather long term R & D. Meanwhile a short lithium lens is under construction at BINP (Novosibirsk, Russia).

Acceleration The acceleration systems are 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 accelerators. In the high energy accelerator, the recirculating 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.

Collider The collider lattices are challenging because of their required very low intersection betas, high single bunch intensities, and short bunch lengths (see Tb.1); however, the fact that all muons will decay after about 1000 turns means that slowly developing instability 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.

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.

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

Table 1: Baseline parameters for high and low energy muon colliders.

CoM energy (TeV)	3	0.4	0.1		
p energy (GeV)	16	16	16		
p's/bunch	2.5×10^{13}	2.5×10^{13}	5×10^{13}		
Bunches/fill	4	4	2		
Rep. rate (Hz)	15	15	15		
p power (MW)	4	4	4		
μ/bunch	2×10^{12}	2×10^{12}	4×10^{12}		
μ power (MW)	28	4	1		
Wall power (MW)	204	120	81		
Collider circum. (m)	6000	1000	300		
Depth (m)	500	100	10		
Rms $\frac{\Delta p}{p}$ (%)	0.16	0.14	0.12	0.01	0.003
6d ϵ_6 $((\pi\mathrm{m})^3)$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
Rms ϵ_n (π mm mrad)	50	50	85	195	280
β^* (cm)	0.3	2.3	4	9	13
σ_z (cm)	0.3	2.3	4	9	13
σ_r spot (μm)	3.2	24	82	187	270
Tune shift	0.043	0.043	0.05	0.02	0.015
Luminosity ($cm^{-2}s^{-1}$)	5×10^{34}	10^{33}	1.2×10^{32}	2×10^{31}	10^{31}
CoM $\frac{\Delta E}{E}$	8×10^{-4}	8×10^{-4}	8×10^{-4}	7×10^{-5}	2×10^{-5}
Higgs/year			1.6×10^3	4×10^3	4×10^3

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 ($> 10^{35}$ cm^{-2}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 expected to be 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.[9]

3 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 seem to be possible.

4 ACKNOWLEDGMENTS

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