First Draft (6 August, 1997): Status of Muon Colliders and Future Research and Development Plans

The Muon Collider Collaboration

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I Contents

ABSTRACT

The status of research into muon colliders is discussed and plans are outlined for future theoretical and experimental studies. Besides continued work on the parameters of a 4 TeV collider, many studies are now concentrating on a machine near 100 GeV that could be a factory for the s-channel resonance production of Higgs particles. We discuss the research on the various components in such muon colliders, starting from the proton accelerator needed to generate the muons and proceeding through muon cooling, acceleration, storage in a collider ring and the collider detector. Finally, we present theoretical and experimental R & D plans for the next several years that should lead to a high level of understanding of the design and feasibility issues for all of the components of muon colliders.

II INTRODUCTION

The muon collider is a new type of accelerator for the high energy physics (HEP) study of elementary particles. The possibility of muon colliders was introduced by Skrinsky et al.[2] and Neuffer[3] and has been aggressively developed over the past three years in a series of collaboration meetings and workshops[4, 5, 6, 7]. A detailed feasibility study for a 4 TeV muon collider was presented at Snowmass96 [1] and, since then, progress has continued both on this collider and on others at lower energies. This paper updates the status report that was submitted to the Snowmass96 proceedings [**?**].

The workforce involved in muon collider studies is becoming progressively larger and better organised and we have recently become a formal collaboration. This currently consists of [number] physicists and engineers, concentrated mainly in the U.S.A. and largely at three U.S. national laboratories: Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL) and Lawrence Berkeley National Laboratory (LBNL).

The paper is organized as follows. Section ?? gives an overview of muon colliders and their physics potential, then section ?? follows with an overview of collider design studies that have been performed for various center of mass (CoM) energies and section ?? describes studies for their various components. Finally, section ?? presents an outline of the collaboration's R and D plans for the next several years.

III THE PHYSICS POTENTIAL OF MUON COLLIDERS

The physics opportunities and possibilities of muon colliders have been well documented in the Feasibility Study[1] and other papers [8]. The section begins with a brief overview of the current theoretical and experimental status of HEP, then summarizes the contributions that muon colliders could make to extending our knowledge of elementary particles.

A Brief Theoretical Overview

To summarize the current status of HEP, the observed pattern of properties of all known elementary particles has been accurately characterised by the standard model (SM), a well tested but cumbersome phenomenological theory containing 19 independent experimentally determined parameters. However, the SM is known to be an incomplete theory that gives inconsistent predictions when extrapolated to experimentally inaccessible mass scales, and even its predictions for the next generation of collider experiments are uncertain.

Today's colliders have reached the threshold of an extremely interesting and fundamental mass scale in the SM: the electroweak symmetry breaking (EWSB) scale – at masses of order 100 GeV to 1 TeV. In the SM this is associated with the origin of the masses of all elementary particles through the so-called Higgs mechanism.

Recent collider experiments have already discovered and studied two of the three particles predicted by the SM at the EWSB mass scale, namely, the W and Z bosons that are the carriers of the weak force. However, the Higgs boson itself – the particle thought to be directly responsible for particle masses – still eludes detection.

Because the SM is known to be only an incomplete and phenomenological theory, we simply do not know if its prediction of a single Higgs particle at the EWSB scale is correct. In contrast, the most popular class of alternative theories, known as supersymmetric theories (SUSY), predict the possibility of an entirely new and rich spectrum of particles at this mass scale, including perhaps 5 types of Higgs boson.

B Potential Capabilities of Current Colliders

The discovery of the Higgs particle in the next few years is possible at the LEP collider at CERN or, possibly, at the FNAL TeVatron. Both of these colliders are currently taking data. Beyond this, the most powerful collider currently under construction is the Large Hadron Collider (LHC) at the European laboratory CERN, a proton-proton collider at 14 TeV center-of-mass (CoM) energy. The LHC is scheduled for completion in 2005 and will probably discover the Higgs boson if it exists and hasn't already been discovered.

The LHC and other proton colliders offer the most established technology for reaching the high energy frontier of elementary particles. However, the physics potential of proton colliders is somewhat compromised because protons themselves are not elementary particles. The interesting physics interactions take place between their quark and gluon sub-components, so only a fraction of the CoM energy is available in each interaction and the interpretation of the interaction is more difficult. Further, the very large proton-proton cross section for soft interactions – of order 100 millibarns – produces an enormous event rate, so the interesting physics events must be disentangled from a huge pile-up of uninteresting background events.

C The Need for Muon Colliders

Because of the experimental difficulties associated with proton colliders and the potential for other physics processes not explored at proton collisions, a strong case can be made for the complementary physics studies that can be done at high en-

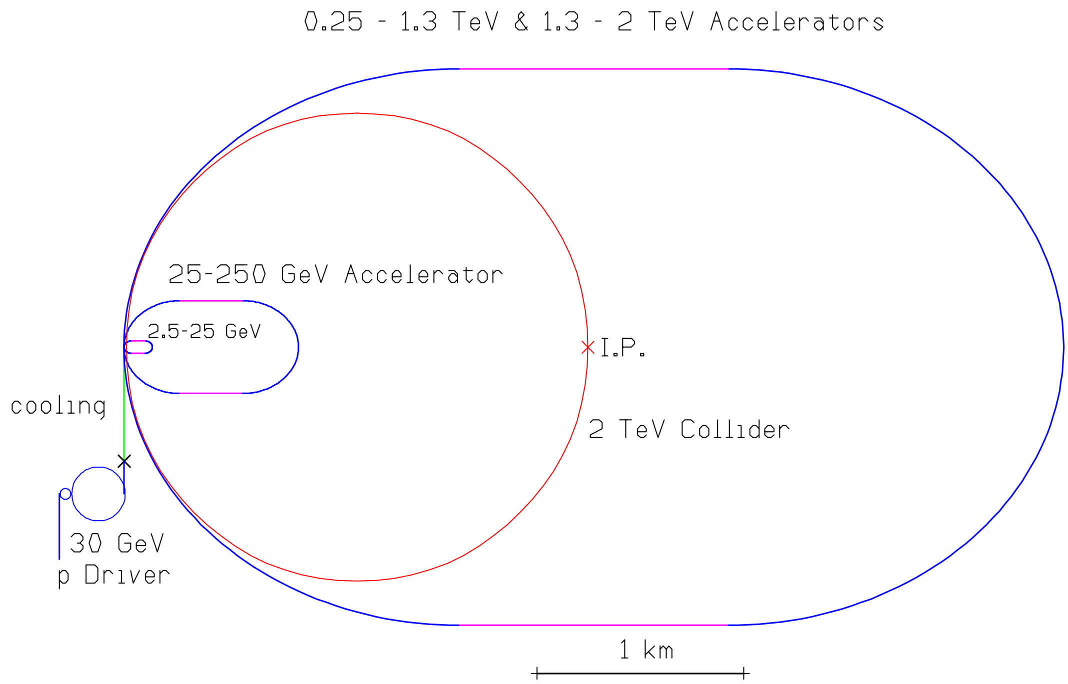

Figure 1: Possible layout of accelerators

ergy lepton colliders – either muon colliders or linear electron-positron colliders.

The physics reach of the two types of lepton colliders has a large overlap but there are also differences. Some of these difference result from differences in the physics processes while others result from the completely different technical specifications of electron and muon colliders. Thus, their potential roles are also somewhat complementary, and studies at a muon collider would be able to provide important additional information even if a new high energy electron collider was built.

One of the main advantages of muon colliders is that they can reach the high energy frontier of HEP without the technical problems associated with the small electron mass. In contrast to e+e- colliders, the synchrotron radiation is small in muon colliders, even for energies up to tens of TeV, so muons can be accelerated and stored in small circular rings containing high-field bending magnets. Also, the beamstrahlung radiation at collisions is much less so, unlike e+e- colliders, the CoM collision energy is not smeared out by energy lost to photons.

As well as exploring physics at the energy frontier, the unique potential of muon colliders for very narrow CoM energy spreads makes them particularly suited for both resonance production and threshold studies of elementary particles at energy scales of around 100 GeV and above. An exciting example is the resonant s-channel production of Higgs bosons. (See section ??.) The potential to study this process is unique to muon colliders, due to the relatively strong coupling strength of muons to the Higgs channel – approximately 40 000 times that for electrons.

D Additional Physics Possibilities with Muon Beams

Further types of hybrid colliders become possible with the addition of muons to the menu of high energy particle beams. One possibility which is generating increased interest is muon-proton colliders [**?**]. This becomes a natural extension when a muon collider complex is built at a site already including a high energy proton machine, such as FNAL, CERN or DESY.

Additional collider possibilities that have been considered are same-sign muon colliders ($\mu^-\mu^-$ or $\mu^+\mu^+$) [**?**] or even muon-electron colliders.

The intense beams of muons and neutrinos in the complex also offer many opportunities for new physics. Rare muon decay experiments would be ideally suited for such a facility while the neutrino beams might be several orders of magnitude stronger than existing beams.

Neutrino studies that could be greatly extended with such uniquely powerful beams include [**?**] searches for neutrino oscillations, precise indirect measurements of the W boson mass and measurements of nucleon structure functions and the parameters of the CKM matrix.

IV DESCRIPTION AND GENERAL FEATURES OF MUON COLLIDERS

This section gives an introduction to the basic components and general features of muon colliders. The discussion is limited to an overview of the important features that are characteristic to muon colliders; details on specific design possibilities for the collider and its components will be deferred to the two following sections.

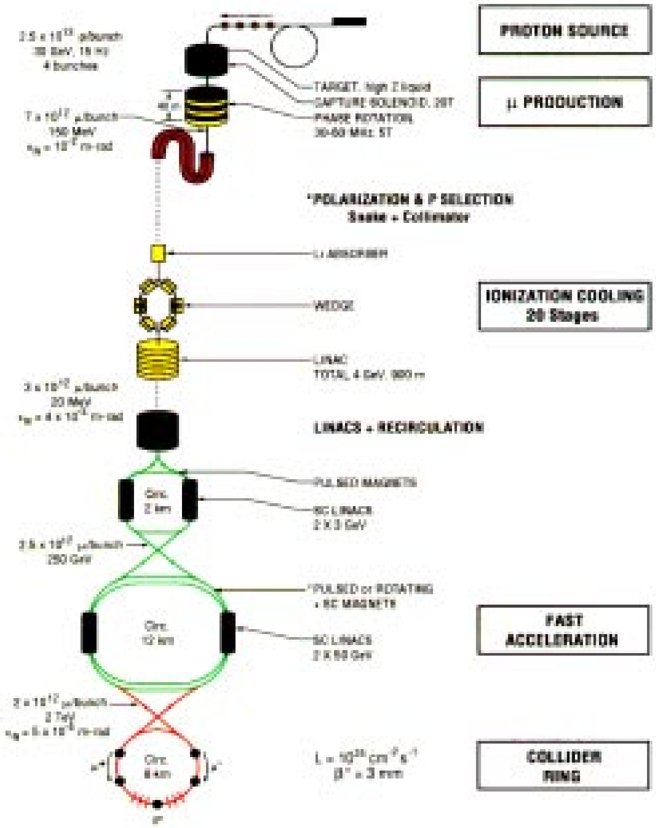

Figure 2: Schematic of a Muon Collider.

Table I: Parameters of a 4 TeV and 100 GeV c-of-m energy machines

c of m Energy	GeV	4000	100	
p Energy	GeV	16	16	
p's/bunch	10^{13}	2.5	5	
rep x $n_{bunches}$	Hz	30	15	
p power	MW	4	4	
muons/bunch	10^{12}	2	4	
collider circ	m	8000	260	
ℓ^* at IP	m	6.5	5	
4 x σ_θ at IP	mrad	3.5	8	
dp/p	%	.12	.12	.003
rms ϵ_n	π mm mrad	50	85	280
β^*	cm	0.3	4	13
σ_z	cm	0.3	4	13
σ_r	μm	2.8	82	270
tune shift		0.04	0.05	0.015
luminosity	$cm^{-2}sec^{-1}$	10^{35}	1.2×10^{32}	10^{31}

A Overview

The basic components of the $\mu^+\mu^-$collider are shown schematically in Fig.2. The muons travel through the components in order from top to bottom of the figure. Initially, large bunches of low energy muons are produced by targeting proton bunches from a high intensity proton source onto a pion production target inside a solenoidal capture and decay channel. The relatively diffuse muon bunches from the decay channel then enter an ionization cooling channel which shrinks them down to a suitable emittance for fast acceleration and injection, at full energy, into a collider storage ring.

The ionization cooling channel is the most novel and characteristic feature of a muon collider. As a general outline of the cooling process, the muons in each bunch lose both transverse and longitudinal momentum in passing through a material medium then are reaccelerated in r.f. cavities, restoring the longitudinal momentum but leaving a reduced transverse momentum spread in the bunch. The momentum spread of the bunch can also be reduced, by separating the momentum components in a dispersive section of a magnet lattice then passing the bunch through a wedge of material oriented to preferentially reduce the momenta of the high momenta muons. A large amount of cooling is required – perhaps a factor of 10^6 reduction in the invariant 6-D phase space – so the cooling channel will probably be a repetitive structure with perhaps 20 to 30 stages.

Because of the short muon lifetime – 2.2 microseconds in the muon rest frame – the muon cooling and acceleration must be done very quickly. Current scenarios envisage about a 50% decay loss in the cooling channel and a 25% loss of the remaining muons during acceleration either with fast ramping pulsed magnets or in a recirculating linac. Also, the muons only survive for of order 1000 turns in the collider ring (almost independent of the collider energy) so the muon bunches must be frequently replenished.

B Beam Properties

Only moderately small 6-dimensional emittances are envisaged at the current level of optimization of the cooling scenario. High luminosities seem to be achievable for these luminosities, but only by using large muon bunches, perhaps with 2 to 4×10^{12} muons per bunch. Note that these bunch sizes are probably not practical for other types of collider: the event pile-up would probably be unacceptable for proton-proton colliders while the beamstrahlung would be prohibitive at electron-positron colliders.

As explained in section ???, it is possible that advances in the design of the muon cooling channel may result in similar or higher luminosities but with smaller bunch charges.

C Electrons from Muon Decays

An undesirable consequence of the large bunches of muons decaying to electrons is a large and difficult background in the detector.

The instantaneous density of background hits in the central tracker is expected to be comparable to that for the LHC hadron collider. (See section ?? for details.) However, a crucial difference is that most of the detector backgrounds in the LHC will come from event pile-up – real background tracks and particles emerging from the I.P. – whereas essentially all the detector hits in muon colliders can be treated essentially as random noise and can, in principle, be removed from the event reconstruction by using tracking redundancy and fast timing information. In fact, the number of background tracks emerging from the I.P. will be even smaller than at high energy electron colliders.

The electrons from muon decays will also cause a radiation heat load on the magnets around the collider ring which will require the use of a tungsten liner – see section ??? for details. The heat load will be smaller in the cooling channel and acceleration rings, where each muon bunch makes no more than a few passes.

D Polarization

Beam polarization of approximately 20 percent is natural for both muon signs with the current collection scenario, with prospects for higher polarization. See section ??? for details. The polarization is relatively robust compared to other types of circular colliders because the precession frequency is much less. This is true relative to electron rings because the relativistic boost factor, γ, is 200 times smaller for the same energy, and relative to proton colliders because the anomalous magnetic moment, $g-2$, is much smaller.

E Ease of Upgrade

A nice feature of muon colliders is the easy upgrade path to add additional collider rings. The source of cooled muons represents a fairly sizable investment in a muon collider facility, while the acceleration and collider rings would be relatively small compared with other types of accelerator with comparable physics potential and, hopefully, might be correspondingly cheaper. This makes it natural to consider a progressive physics program, where a FMC facility would be upgradable to higher center of mass energies by adding further acceleration and collider rings.

As an example scenario, the FMC might be a Z factory or an s-channel Higgs factory operating at around 100 GeV CoM energy. A natural upgrade possibility might be a ring at 162 GeV CoM to study threshold production of W pairs. A further ring at around 350 GeV CoM would produce top quark pairs at threshold and could also study Z-Higgs associated production if a relatively light Higgs particle exists. The new collider rings could either replace the first ring or operate simultaneously, sharing the available luminosity by alternating use of the muon bunches.

V FEASIBILITY AND DESIGN STUDIES

A Overview

1 Motivation

This section describes some relatively detailed design scenarios that are in progress for muon colliders at several different CoM energies.

These studies serve several purposes. Firstly, they test the feasibility of various collider parameters such as, for example, the very low beam energy spreads that might be required for a Higgs factory. If successful, the studies should also act as proofs-by-example that these collider parameters are reasonable.

As well as assessing the overall potential at various energies the detailed scenarios allow detailed optimizations of the components that depend on the energy of the collider – the acceleration and collider rings and the detector and its shielding – and an understanding of how their design will evolve with energy. The optimizations of the individual components will be reported in the following section.

2 Scope of the Studies

The main study at high energy is the study at 4 TeV that was presented at Snowmass96 [**?**]. This book also included some studies at 500 GeV CoM energy. Work has progressed further for these energies and, since then, detailed studies have also been performed for a 100 GeV collider for s-channel Higgs production (described further in section ????) and another 100 GeV collider with a broader energy spread of 0.12%. The machine parameters for the 4 TeV and Higgs factory studies are given in table 1.

It should be recognised that these design scenarios are not yet particularly optimized for performance or cost and, indeed, many of the parameters and design assumptions might be expected to change as our understanding improves.

3 Front End Scenario

Since the design of the front end is essentially independent of the collider energy, all the studies are done using similar parameters for the front end.

In all of the design scenarios it is assumed that the collider is fed at 15 Hz with either one bunch per sign of 4×10^{12} muons or two bunches per sign of 2×10^{12}. The invariant 6-dimensional emittance of the bunches is assumed to be [????? - value] and it assumed that this emittance can be distributed optimally within the 6-dimensional phase space to maximize the collider luminosity and/or to minimize backgrounds in the detector.

These assumptions are consistent with our current understanding of muon production and cooling, as detailed in sections ???.?? through ???.???.

4 Observations from the Studies

The studies indicate that muon colliders can probably achieve very good luminosities, particularly at higher energies. It was found that the luminosity (L) naturally rises rather quickly with increasing energy (E).

The scaling law $L = E^{5/3}$ is obtained in a simple scaling analysis [**?**] which assumes the front end scenario of the preceding subsection.

As another encouraging general feature, it was found that, as with proton storage rings, the level of technical difficulty in building a muon collider does not increase markedly with increasing CoM energy.

B Energy Constraints from Neutrino-Induced Radiation

A serious and unexpected problem that has arisen for multi-TeV colliders is the potential radiation hazard posed by neutrinos emitted from muon decays in the collider ring [**?**].

1 Characterization of the Potential Hazard

The neutrinos are emitted in a direction highly correlated to the direction of the parent muon, resulting in a neutino radiation disk emanating out from the plane of the collider ring and with a very small characteristic half-height given by $1/\gamma$, where gamma is the normal relativistic boost factor: $\gamma \equiv E_\mu/M_\mu$.

The hazard results from the charged products of occasional neutrino interactions in the soil and other objects. Although the neutrino cross-section is tiny, this is greatly compensated by the enormous number of tightly collimated high energy neutrinos produced at the collider ring: of order 10^{21} per year in current design scenarios.

The neutrino flux is typically expected to be very non-uniform in different directions around the radiation disk. The dose is largest along the direction of those straight sections with little angular divergence of the muon beam, since these produce highly collimated neutrino beams.

Quantitatively, a radiation hot spot on the neutrino disk with approximately twice the average intensity would be produced by such a straight section subtending an angle of $2/\gamma$ at the center of the collider ring. This length is less than a meter for a typical muon collider ring.

As a detail, the caveat that the straight section has a low angular divergence is included because the conclusions of the preceding paragraph do not apply for straight sections with beam angular divergences greater than of order $1/\gamma$, since the radiation hot spot from these straight sections is more dispersed. The obvious example is the long straight section around the interaction point (I.P.), for which the radiation hot spot would be much dispersed.

2 Energy Dependence

The off-site radiation dose scales as

$$\mathrm{dose} \propto \frac{\mathrm{E}^3}{\mathrm{length}^2} \propto \frac{\mathrm{E}^3}{\mathrm{depth}} \tag{1}$$

where E is the energy of the muons in the collider ring, “length” is the distance from the ring and “depth” is the corresponding underground depth assuming the ground follows average curvature of the Earth.

The cubic dependence of the dose on energy means that neutrino radiation is not a significant problem for lower energy muon colliders but quickly rises to become serious for multi-TeV colliders, as can be seen from the following numerical examples.

3 Numerical Examples

As a low energy example, the radiation dose from the 100 GeV CoM Higgs factory of table 1 would everywhere remain below about one thousandth of the U.S. Federal off-site limit (1 mSv/year) if it was located 10 meters underground and had low divergence straight sections up to 10 meters long. Thus the radiation dose appears to be satisfactorily low at this energy without the need for any modifications to the collider siting or design.

For contrast, a 4 TeV muon collider with the parameters given in table 1 would, if located 250 m underground, give surface doses of approximately 10% of the federal off-site limit even without allowing for the increased dose along the direction of straight sections. The dose would be considerably higher in some directions for any realistic lattice design unless great care was taken to minimize the length of all straight sections.

4 Strategies for Minimizing the Hazard

Various strategies for minimizing the neutrino radiation hazard are being investigated using detailed Monte Carlo simulations [**?**] of the collider magnet lattice, muon beams and neutrino production, propagation and interactions.

Possible options include, for example, using combined function bending magnets for the quadrupole and sextupole magnets, introducing bending magnetic fields over straight sections and varying the muon orbits.

The obvious way to reduce the neutrino hazard at multi-TeV colliders, aside from using a custom designed magnet lattice or building the collider in a special location, is to reduce the muon currents in the collider ring. It is hoped that advances in muon cooling will allow a reduction from the presently assumed muon currents without a corresponding decrease in luminosity – see section ??.

C Studies for an S-channel Higgs Factory

1 A Possible First Muon Collider

If a Higgs boson was discovered at another accelerator then an s-channel Higgs factory would become a natural choice for the first muon collider (FMC). In principle, such a Higgs factory would be particularly useful in the mass region where the Higgs is predicted to have a vary narrow width in the SM, in the approximate range 70 to 150 GeV. (The low end of this range is the approximate current experimental lower limit for the SM Higgs mass.)

We have chosen a CoM energy of 100 GeV for our detailed design scenario. The results of the study should be relatively easy to scale to any other energy within this range.

2 Physics Motivation

A Higgs boson in the region that is interesting for muon colliders appears quite likely on both experimental and theoretical grounds. Experimentally, precision electroweak data from LEP and SLC favor, but do not require, a relatively light SM-like Higgs boson. Rather indirect theoretical arguments also favor a relatively light Higgs boson in the context of the SM, while if nature turns out to be describable by a supersymmetric model then a SM-like Higgs boson is predicted with a mass below 150 GeV.

Because of its unique s-channel production mechanism, a muon collider would be able to determine the mass and width of a light Higgs far better than any other type of collider, and could also contribute to knowledge of the branching ratios to various decay modes [**?**]. These are expected to include decays to pairs of bottom or charm quarks, and decays to final states proceeding through production of Z or W pairs (where, in general, at least one of the Z's or W's is off its mass-shell).

The combination of the width and branching ratio measurements give measurements of the absolute coupling strengths of the Higgs boson to the final state particles. This, in turn, allows one to distinguish between a SM Higgs and the SM-like Higgs that occur in, e.g., supersymmetric theories.

As emphasized in reference [**?**], the full potential of the possible measurements at a muon collider would be realized by combining them with measurements from other types of colliders at the high energy frontier.

Whether a light Higgs particle exists or not, a muon collider facility in this energy range can still be used, at 91 GeV CoM energy, as a factory for the production of Z bosons – the neutral carrier of the weak interaction.

A Z factory would not need the extremely narrow momentum spreads used for the Higgs factory, so it can be designed with a higher luminosity. A suitable magnet lattice for the collider ring has been designed with a 0.12% momentum spread, as outlined in section ???. The estimated luminosity of $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ might produce roughly 30 million Z's per year. This is larger than the entire existing world sample of Z's. Also, the muon beams might each have 20% or more polarization, while only a very small fraction of the current Z sample has polarization.

As mentioned in section ??, such a complex would also allow for physics studies with both muon and neutrino beams. For example, very large improvements in searches for neutrino oscillations could result from the neutrino beams at these lower energies.

3 Colliders with Low Energy Spread

The study also explores the limits in beam energy spread. An energy spread of 3×10^{-5}, or 1.5 MeV per beam at 100 GeV, is matched to the expected Higgs width in the SM at this energy of 2 or 3 MeV.

The luminosity decreases slowly when the beam energy spread is reduced, since the beam extent in the other dimensions of 6-D phase space must be increased to conserve overall 6D emittance. However, for studies of narrow resonances it is found to always be advantageous to reduce the beam energy spread until it becomes comparable to the resonance width. This is because the resonant production of the particle is actually proportional to the specific luminosity – i.e. the luminosity divided by the energy spread – while the production of backgrounds is proportional to the luminosity itself. Further, the measurement of the width of a Higgs resonance gains enormously when the energy spread is reduced to close to the natural resonance width.

It appears feasible to prepare beams with the required 1.5 MeV energy spread in the cooling channel. The biggest problem appears to be maintaining the stability of such a beam over 1000 turns in the collider ring. (Normally, the finite energy spread of particle beams helps to avoid resonant blow-up.) Beam-tracking computer simulations have already found some lattice parameters that will give the required stability, but only with unrealistically low integral tune shifts. Study continues on this issue. A back-up solution [**?**] is to accept a bigger beam spread in the collider ring but to introduce dispersion at the I.P. so that the higher energy particles of one bunch collide with the lower energy particles of the others. This might effectively reduce the CoM energy spread at collision to the desired value.

4 Conclusions from the Feasibility Study

Our current example parameter set would produce of order 10^4 Higgs per year for the SM cross section, which is adequate for many of the physics studies[**?**]. The physics potential would become even better with higher luminosity. It is hoped that ongoing studies to optimize muon production, capture and cooling might increase the potential yield of Higgs particles, perhaps by up to an order of magnitude or more – see section ????.

VI PROGRESS ON COMPONENTS

A Proton Driver

Proton driver design has recently shifted to the study of machines that can serve the hadron physics program at an existing laboratory and potentially act as a source for a future muon collider. In particular studies at Fermilab have looked at replacing the 8 GeV Booster with a 15 Hz, 10^{14} protons per pulse complex consisting of a 1 GeV linac, 4.5 GeV pre-Booster and a final 16 GeV synchrotron. The pre-Booster would operate at harmonic number two in order to produce the two bunches needed for muon operation, but could be bypassed to allow direct H^- filling of the 16 GeV machine from the linac for the hadron program. This high energy synchrotron would likely have a 50 MHz rf system compatible with the Main Injector which would also facilitate the production of short bunches ($\sigma_t \sim 1$ nsec) for muon operation. Another option being considered is a three-ring complex ending with a 24 GeV synchrotron which has the advantage of higher pion production for the muon collider and beam injection above transition for the Main Injector.

The production of very short and intense proton bunches is the most difficult aspect of the muon source design. Longitudinal space charge forces can prevent the desired bunch shortening, and excessive longitudinal emittance will produce large momentum spreads in the proton synchrotron when bunches are rotated. Designs for the proton driver assume a high transition energy so that transition does not need to be crossed, and longitudinal emittance can be preserved. Conventional rf bunch manipulations appear able to produce 1 to 2 nsec proton bunches by using enough rf voltage to overcome the space charge forces. Simulations with the ESME code have shown that 1-2 nsec bunches of 5×10^{13} protons can be produced at extraction in a 16 GeV ring with less than 200 kV per turn of rf voltage while maintaining the emittance at about 2 eV-sec.

The amount of rf voltage needed to shorten proton bunches may be reduced by compensating the space charge forces in the proton driver. 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 KEK Proton Synchrotron and Los Alamos PSR with short ferrite inserts appear to show a reduction in the incoherent synchrotron oscillation frequency caused by space charge and a decrease in the necessary rf voltage to maintain a given bunch intensity. Further experiments are needed to fully demonstrate this technique, but it seems promising.

Another method to facilitate bunch rotation is to purposely introduce an energy shear to a bunch near transition (to limit bunch spreading), quickly move the transition energy away from the beam energy and let the mismatched bunch undergo a quarter of a synchrotron revolution to shorten itself. Flexible momentum compaction (FMC) lattices can be used to move the transition energy in this way. Some experimental progress has been made to understand bunch rotation near transition. The AGS experiment E-932 has demonstrated that bunches with 1.5 eV-sec emittance could be rotated from 10 to 3 nsec rms and remain stable near transition for 10 to 100 msec. It is thought that if the transition energy can be rapidly moved away with a transition jump system, shorter bunches can be produced.

B Pion Production, Capture and Decay Channel

This subsection discusses the choice of target technology and optimization of the target geometry.

1 Pion Production Target

The pion production target needs to withstand the heat load and thermal shock stress from a proton beam with an average power of several Megawatts. The thermal shock is comparable to that at existing proton targets for neutrino experiments. However, the heat load is considerably larger, and is more comparable to that at proposed neutron spallation facilities. For this reason, liquid target targets have been studied most extensively (since the heat energy can be removed along with the liquid) but solid targets are still under consideration.

Further, we have been considering the option of pulsed liquid metal jet targets, in order to avoid shock damage to a container. These might be patterned after a liquid mercury jet target that has been built and tested at CERN (although not exposed to a proton beam).

Predictions of nuclear Monte-Carlo(MC) programs[13, 14, 15, 16] suggest that π production is maximized by the use of heavy target materials, and that the production is large at a relatively low pion energy, substantially independent of the initial proton energy. An experiment E910[17], currently running at the AGS, should calibrate the MC programs, and settle at which energy the capture should be optimized – see section ??.

The optimal target length has been found to be roughly 1.5 to 2 proton interaction lengths, and reabsorbtion of pions within the target can be minimized by using a thin cylindrical target. It has recently been discovered that reabsorbtion can be further reduced by tilting the axis of the target and proton beam with respect to the axis of the capture solenoid.

2 Capture and Decay Channel

Pions are captured from the target by a high-field (20 T, 15 cm inside diameter) hybrid magnet: superconducting on the outside, and a water cooled Bitter solenoid on the inside. A preliminary design[19] has an inner Bitter magnet with an inside diameter of 24 cm (space is allowed for a 4 cm heavy metal shield inside the coil) and an outside diameter of 60 cm; it provides half (would consume approximately 8 MW. The superconducting magnet has a set of three coils, all with inside diameters of 70 cm and is designed to give 10 T at the target and provide the required tapered field[20] to match into the decay channel.

Protons produce an average of approximately 1 pion of each sign. These then decay to muons in a long solenoid with a branching ratio of essentially 100%. Muon capture efficiency in current Monte Carlo simulation is estimated at about 15%. However, this assumes that can only collect one muon charge for each bunch. We are investigating a possible factor-of-two improvement by using a curved solenoid to separate the charges.

The decay channel consists of a periodic system of superconducting solenoids ($5\,\mathrm{T}$ and radius $= 15\,\mathrm{cm}$). If a simple channel is used then the pions, and the muons into which they decay, will have an energy spread with an rms/mean of $\approx 100\%$, and a peak at about a few hundred MeV. It would be difficult to handle such a wide spread in any subsequent system. A linac is thus introduced along the decay channel, with frequencies and phases chosen to deaccelerate the fast particles and accelerate the slow ones; i.e. to phase rotate the muon bunch. After this phase rotation, a bunches are selected with mean energy 150 MeV, rms bunch length $1.7\,\mathrm{m}$, and rms momentum spread $20\,\%$ ($95\,\%$, $\epsilon_{\mathrm{L}} = 3.2\,\mathrm{eVs}$).

3 Polarization Selection

The muon from the pion decay is fully polarized in the rest frame of the pion which, in the lab frame, correlates the muon polarization to the decay angle θ_d and initial pion energy. For pion kinetic energies larger than the pion mass, the dependence on pion energy becomes negligible and the polarization is given approximately by [21]:

$$P_{\mu^-} \approx \cos\theta_d + 0.28(1 - \cos^2\theta_d) \tag{2}$$

The current collection scenario naturally results in a polarization of approximately 20% for both muon signs. Higher polarization could, in principle, be obtained by either collimating or partitioning the beam according to muon momentum, and these options are currently under investigation.

C Muon Cooling Channel

The very intense muon beams needed for a high-luminosity muon collider will require the development of a new method for beam cooling. The technique that has been proposed is called ionization cooling, and 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 cooling) 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). Theoretical studies have shown that, assuming realistic parameters for the cooling hardware, ionization cooling can be expected to reduce the phase-space volume occupied by the initial muon beam by a factor of $10^5 - 10^6$.

Ionization cooling[**?**] is a new technique that has not yet been demonstrated. Specialized hardware must be developed to perform transverse and longitudinal cooling. Initial theoretical design studies have shown that a complete cooling channel might consist of 20 – 30 cooling stages, each stage yielding about a factor of two in phase-space reduction. The early cooling stages focus the beam using a FOFO lattice, which consists of solenoids with alternating field directions, and lithium hydride absorbers placed in spaces between the solenoids. To minimize the final transverse emittances that can be achieved, the later cooling sections require a stronger focusing than can be provided by the solenoids. The last few cooling stages therefore consist of current carrying lithium rods. Both the FOFO and the lithium rod sections will require some R&D before a cooling channel can be fully designed. It is recognized that understanding the feasibility of constructing a muon ionization cooling channel is on the critical path to understanding the feasibility of the whole muon collider concept.

In the following parts of this section we will briefly describe the physics underlying the process of ionization cooling. We will then discuss the most promising technological systems for efficiently accomplishing the cooling. We then describe our current thinking on what a complete cooling system for the muon collider would look like. Finally, we discuss our R&D program for experimentally demonstrating that ionization cooling works in practice.

1 Ionization Cooling

To achieve sufficiently intense muon beams for a high luminosity muon collider the phase-space volume must be reduced by about a factor of 10^5 –10^6. The appropriate figure of merit for the muon cooling is the final value of the 6D relativistically invariant emittance, i.e., the area in the 6-dimensional phase space x-y-z-px-py-pz. The way the 6D emittance is shared among the various components can be changed, within reasonable bounds, using wedge absorbers, etc. To a fairly good approximation, the invariant emittance is preserved during acceleration of the beam and storage in the collider ring. We require a reduction of the normalized horizontal and vertical emittances by two orders of magnitude together with a reduction of the longitudinal emittance by one to two orders of magnitude. The technical challenge is to design a system that can reduce the initial muon phase-space on a timescale that is short or comparable to the muon lifetime ($\tau_\mu = 2\mu$s). This time-scale is much shorter than the cooling times that can be achieved using ordinary stochastic cooling or electron cooling.

Fig. **??** shows a conceptual schematic of ionization cooling. The beam is passed 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 equation describing transverse cooling (with energies in GeV) is:

$$\frac{d\epsilon_n}{ds} \;=\; -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\;\frac{\epsilon_n}{E_\mu} \;+\; \frac{1}{\beta^3}\frac{\beta_\perp(0.014)^2}{2\,E_\mu m_\mu\,L_R}, \tag{3}$$

where $\beta =$ v/c, ϵ_n is the normalized emittance, $\beta_\perp$ is the betatron function at the absorber, dE_μ/ds is the energy loss, and L_R is the radiation length of the material. The first term in this equation is the cooling term, and the second is the heating term 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). Thus, low Z materials, like H, Li, Be and LiH, are most useful for ionization cooling.

The energy spread (longitudinal emittance) is given by:

$$\frac{d(\Delta E)^2}{ds} = 2\,\frac{d\left(\frac{dE_\mu}{ds}\right)}{dE_\mu} \;<(\Delta E_\mu)^2> \;+\; \frac{d(\Delta E_\mu)^2_{\rm straggling}}{ds} \tag{4}$$

where the first term is the cooling (or heating) due to energy loss, and the second term is the heating due to straggling. The heating term (energy straggling) is given by [**?**]

$$\frac{d(\Delta E_\mu)^2_{\rm straggling}}{ds} \;=\; 4\pi\,(r_e m_e c^2)^2\,N_o\,\frac{Z}{A}\,\rho\gamma^2\left(1-\frac{\beta^2}{2}\right), \tag{5}$$

where N_o is Avogadro's number and ρ is the density.

The energy spread is reduced 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). The concept is illustrated in Fig. **??**. The use of such wedges will reduce the energy spread and simultaneously increase the transverse emittance in the direction of the dispersion. Thus, longitudinal cooling is accomplished by the exchange of emittance between the longitudinal and transverse directions.

Ionization cooling of muons seems relatively straightforward in theory, but will require extensive simulation studies and hardware development for its optimization. There are practical problems in designing lattices that can transport, and focus the large emittances without exciting resonances that blow up the emittance and attenuate the beam. There may also be problems with space charge and wake field effects.

2 *Cooling Components*

A complete muon ionization cooling channel might consist of 20 – 30 cooling stages. The optimum muon momentum for ionization cooling appears to be in the range 100–300 MeV/c. Each stage would contain systems for transverse and longitudinal cooling and yield about a factor of 2 in 6D phase-space reduction. The channel that has been investigated most thoroughly [**?**] uses a FOFO (focusing-drift-focusing-drift) lattice of alternating sign, short superconducting solenoidal magnets. The final stages of cooling are accomplished using liquid lithium lenses. The superior focusing strength of lithium lenses can hold the muon bunches at a small size while ionization cooling takes place in the lithium, thus quickly achieving the invariant emittance value required for the collider.

A FOFO lattice can be used to provide transverse cooling. It consists of alternating direction solenoids with lithium hydride absorbers placed between them, in spaces where the $\beta_\perp$'s are minimum (see Fig. **??**). It is reasonable to use FOFO lattices in the earlier cooling stages where the emittances are large. To obtain smaller transverse emittances as the muon beam travels down the FOFO cooling sections, the minimum $\beta_\perp$'s must decrease. This is accomplished by increasing the focusing fields and/or decreasing the muon momenta. We envision using solenoids with strengths up to 8 T in the lattice, thereby producing $\beta_\perp$ values down to about 10 cm.

In the FOFO scheme the rf reacceleration cavities would be embedded within the solenoid coils (Fig. **??**).

Computer simulations have shown that significant transverse cooling and net 6D cooling can be achieved in single sections of FOFO transverse cooling lattice. Fig. **??** shows the expected cooling for a FOFO lattice with an initial transverse normalized emittance of 1500 mm-mrad. The transverse emittance is reduced by a factor of 2 in a distance of about 13 m.

Current carrying lithium rods would be used for transverse cooling in the last few cooling stages (see Fig. **??**). The magnetic field generated by the current provides the focusing, and the liquid lithium provides the absorber. These lenses provide a much stronger radial focusing and minimize the final achievable emittances. Li lenses, which are currently under development, may be able to produce $\beta_\perp$ values down to about 1 cm. Similar lithium rods, with surface fields of 10 T , were developed at Novosibirsk and have been used as focusing elements at FNAL and CERN[25]. It is hoped[26] that liquid lithium columns can be used to raise the surface field to 20 T and improve the resultant cooling.

Longitudinal cooling can be provided by a lattice which includes bending magnets to generate dispersion, and wedges of lithium hydride to lower the energies of the more energetic particles. This results in an exchange of longitudinal and transverse emittance. Rf acceleration must be provided to restore the energy lost in the absorbers.

We are investigating several variations on this ionization cooling channel, including making use of lithium lenses earlier in the cooling channel or doing much of the cooling inside of a long solenoidal channel beginning from the initial capture solenoid. It is interesting to note that, although ionization cooling is fast and conceptually simple, the performance of muon colliders could potentially be improved still further if even cooler muon bunches could be obtained. In that case higher luminosities could be achieved with smaller bunches, which has many advantages for the project. Many ideas for cooling have been proposed, such as optical stochastic cooling, electron cooling in plasmas, and cooling in crystals. It is recognized that these alternative cooling schemes are currently all very speculative. They are not assumed in any of the parameters presented in this paper and are certainly not required to reach high luminosities.

3 *Cooling System*

We require a reduction of the normalized transverse emittance by almost three orders of magnitude (from 15000 to 50mm-mrad), and a reduction of the longitudinal emittance by one order of magnitude. We have developed a scenario for achieving this emittance reduction using analytic calculations that take into account most important processes. Parts of the scenario have been checked using 4 independent tracking codes.

The cooling is obtained in a series of cooling stages. The transverse and longitudinal emittances are shown as a function of stage number in Fig.**??**, together with the beam energy. In the first 15 stages, relatively strong wedges are used to rapidly reduce the longitudinal emittance, while the transverse emittance is reduced relatively slowly. The object is to reduce the bunch length, thus allowing the use of higher frequency and higher gradient rf in the reacceleration linacs. In the next 10 stages, the emittances are reduced close to their asymptotic limits. In the last stages, the emittance is further reduced in current carrying lithium rods. In order to obtain the required very low equilibrium transverse emittance, the energy is allowed to fall to 15 MeV, thus increasing the focusing strength and lowering the $\beta_\perp$. The result is an effective exchange of longitudinal and transverse emittances, with little change in the overall six dimensional phase space. The total length of the system is 750 m, and the total acceleration used is 4.7 GeV. The fraction of muons that have not decayed and are available for acceleration is calculated to be $55\,\%$.

As an interesting example, in Fig. **??** results are shown from a simulation of a cooling channel constructed entirely from lithium lenses plus reacceleration. The cooling channel consists of twelve 2 m long lithium lenses with reacceleration at the end of each lens. The gradient is increased from lens to lens, following the reduction in beam size as the beam is cooled. The calculation predicts a reduction in the normalized rms transverse emittance from $\sim 10000\pi$ mm-mrad to 80π mm-mrad. The parameters of the simulated cooling setup have not been optimized. However, the predicted final transverse emittance is already consistent with the requirements for a high-luminosity muon collider.

The Monte Carlo studies to date demonstrate convincingly that a single lithium lens can effectively reduce the emittance. However, the angular divergence of the muons entering and leaving the lens has to be large, and more detailed simulations are needed to test the feasibility of focusing the beam into the rod and capturing it as it leaves, all without emittance growth.

4 Recent Progress and Outlook

Although our current cooling scenario represents a plausible method for achieving the required muon cooling by a factor of 10^6, much work remains to be done in order to flesh out all of the details. Simulations have demonstrated that single sections of FOFO lattice with LiH absorbers or single Li lenses can produce transverse cooling by a factor of 2 and that single Li wedges can produce longitudinal cooling. Simulation work is now addressing the important issue of matching the beam between the various cooling components.

To achieve efficient and cost effective cooling we are proposing a number of new technological developments that must be tested experimentally. For example, the FOFO lattice we are proposing uses pillbox rf cavities. This gives the maximum possible electric field gradient on the axis, but, since the cavity does not have irises, requires the beam to cross the cavity walls. The rf cavities have to operate inside a strongly varying solenoidal field. To reduce the required rf power we are proposing to operate the cavity at liquid nitrogen temperature. For the lithium lens we are proposing longer and smaller diameter lenses than any previously built. We are also requiring the lens system to operate for significantly more pulses than current lenses.

For theses reasons we intend to design and prototype critical sections of the muon ionization cooling channel. The measurements that are needed to demonstrate the cooling capability and optimize the design of the FOFO and lithium lens cooling stages will require the construction and operation of a new Ionization Cooling Test Facility [**?**], which is described in section ???.

D Acceleration

The accelator for the muons is physically the largest component of a muon collider and is also expected to be the most expensive component for higher energy colliders.

1 Acceleration Options

The muons must be rapidly accelerated to avoid decay. However, a single linac, such as those required for electron-positron colliders, is a very expensive option. Instead, one can economize on the expensive r.f. cavities by instead using a recirculating linac similar to that used at CEBAF.

2 Possible Alternatives to a Recirculating Linac

While a recirculating linac appears to be the logical choice for muon colliders at CoM energies of order 100 GeV, two other less conventional options are being investigated to see if they might be cheaper for higher energy accelerators: either fast ramping dipole magnets interspersed with r.f. cavities or combined function (dipole-plus-quadrupole) magnets in a recirculating lattice.

3 Fast Ramping Dipole Magnets

Of these two options, the fast ramping dipole magnets have been investigated in more detail. Special materials are needed to minimize the eddy currents in the magnets. Options include silicon steel (BNL) or metglass (Univ. Mississippi) laminations or finemet laminated tape or powdered solid (both from NIRS, Japan).

For the final acceleration stages in high energy machines, the power consumed by a ring using only pulsed magnets would be excessive, but if rings of alternating pulsed and superconducting magnets[28, 29] are used, then the power consumption can be made reasonable.

4 Performance of an Example Acceleration Scenario

Computer simulations[27] tracking particles through a sequence of recirculating accelerators similar to fig. 1 found a dilution of longitudinal phase space of the order of $15\,\%$, with a particle loss of approximately 33%, due almost entirely to decays.

E Collider Storage Ring

1 Introduction

A ring design for a high-luminosity, 2-TeV muon collider is particularly challenging with its low beta, isochronicity, and heavy shielding requirements [**?**]. A preliminary design of an entire collider ring has been completed which meet the constraints, including the technical ones, of such a collider.

Because of the beam's large emittance and beam size, as compared with linear colliders, for example, the β^* at the IP must be exceptionally small; i.e. $3x10^{-3}\,\mathrm{m}$, in order to reach the design luminosity given the specifications. The ring design is further complicated by an additional requirement, that of isochronicity. To prevent the short $3\,\mathrm{mm}$ bunch from spreading in time, without applying substantial rf, implies that the momentum compaction factor must be in the range $10^{-5} to 10^{-6}$. The resulting highly nonlinear Interaction Region (IR) combined with the isochronicity condition make designing a lattice for a muon collider exceptionally challenging.

2 Lattice

The lattice for a 2-TeV on 2-TeV muon collider must satisfy three major design constraints. The first and most difficult of these is provision of an Interaction Region (IR) with an extremely low β^* ($\sim$ 3 mm) consistant with an acceptable dynamic aperture. This requirement is complicated by the necessity to incorporate considerable shielding in and around the superconducting magnets to protect them from the high muon-decay backgrounds [**?**]. Second, the ring must exhibit a high degree of isochronicity in order to preserve short $3\,\mathrm{mm}$ long bunches with a modest rf system. Lastly, there must be small corrected chromaticity, so that the momentum-dependent tune spread of the beam does not severely restrict the momentum aperture. The following sections describe a lattice, which is intended to meet the above requirements.

The ring has a roughly oval shape, with reflection symmetry about the vertical axis. The lattice has two circular arcs, separated by the experimental insertion and a utility insertion for injection, extraction, and beam scraping. The two arcs are identical; each contains 14 periodic cells or modules. One additional arc module located at the experimental-insertion end of each arc can be perturbed and rematched to allow adjustment of the machine tunes without impacting lattice functions in the rest of the ring. Consequently the ring structure, both geometrically and optically, has a single superperiod, and reflection symmetry about the line joining the centers of the two insertions.

Arc module In order to have very short $3\,\mathrm{mm}$ bunches in the 2-TeV muon collider, the storage ring must be quasi-isochronous, which requires that the momentum compaction α be very close to zero. Furthermore, the lattice must be designed so that over the required momentum range, the momentum compaction remains small. Since the experimental insertion has bending regions with positive contributions to α, the contributions of the arcs must be negative.

A negative value of α in the arcs is obtained by invoking the approach used in flexible momentum compaction (FMC) modules[**?**]; where two FODO cells are connected by a matching region with horizontal phase advance of nearly π (low β_x). This drives the dispersion η to a negative value at the ends of the module and makes $\eta_{bends} \sim 0$.

The specific module used for this muon collider lattice (Fig. **??**) has been modified by including an insertion with a vertical phase advance of nearly π (low β_y) at the end of the module. This modification has several advantages compared to the standard FMC module. Firstly, the negative dispersion region has been flattened and lengthened so that the value of α is mainly determined by the bends placed in the dispersion plateaus–making it much less sensitive to η', and thus providing a wider range of quadrupole settings and corresponding lattice functions which satisfy the negative or low-α criterion. In fact, α can be tuned with a sensitivity of 10^{-5} to 10^{-7} through the use of paired trim dipoles in these two regions alone; thereby preserving both lattice functions and closure. Over a range in α of -10^{-4} to $+10^{-4}$ the impact on the lattice functions in the rest of the ring is negligible.

Secondly, the vertical phase advance of the module is no longer nearly an integer, but is identical to the horizontal phase advance, 1.5π. This is particularly important, because when the corresponding sextupoles in successive modules are separated by odd multiples of π in both planes, one obtains partial cancellation of their geometrical effects. (The near π vertical phase advance caused off-momentum particles to experience integer-related resonances in the long arc strings when sextupole correctors were on.)

Thirdly, the regions of high-β_x, low-β_y and low-β_x, high-β_y in this arc module are ideal locations for sextupoles for chromatic correction of the arcs and reduction of the variations of α with momentum. A pair of horizontal sextupoles adjacent to the center doublets are especially effective in eliminating the dependence of α on momentum offset. With these two sextupoles the variation of α over the momentum range of $\pm.004$ can be restricted to less than 10^{-6}, cancelling the dependence to approximately third order.

Experimental insertion The design of an insertion with an extremely low-beta interaction region for a muon collider presents a challenge similar to that encountered for the Next Linear Collider (NLC)[**?**]. The design used here for each half of the symmetric low-beta insertion follows the prescription proposed by Brown[**?**]; it consists of two telescopes with a chromatic correction section between. Therefore, the experimental insertion consists of three parts: the Final Focus Telescope (FFT) or IR, a Chromatic Correction Section (CCS), and a Matching Telescope (MT). Fig.**??** shows the right half of the insertion beginning at the IP. From left to right, the figure shows the FFT, CCS, and MT.

The low beta-function values at the IP are mainly produced by four strong superconducting quadrupoles in the FFT with NbSn coils. Their poletip fields range from 9.5 to 12 T depending on the apertures, which determines the size of the coils and sustainable currents [**?**]. The first of the four quadrupoles begins $4\,\mathrm{m}$ away from the IP, they all have 2-cm thick tungsten liners and are interleaved with tungsten collimators to protect them from the intense backgrounds from muon decay [**?**]. Systematically positioning tungsten collimators before superconducting elements is also effective in the arcs and has eliminated the need for thick, 6-cm tungsten liners in the ring magnets.

The IR quadrupoles are followed by a pair of 15-m long bucked superconducting dipoles which sweep background particles produced by muon decays away from the IR. A long space follows without quadrupoles but with a substantial length of bending magnets in order to make an efficient transition into the CCS; matching η and η' from their zero values at the IP into the CCS. In this IR design, β_{max} in both planes is $145\,\mathrm{km}$. A more detailed description of the experimental insertion, especially the FFT, can be found in the Snowmass proceedings[**?**].

The extremely high beta values in the FFT quadrupoles produce large chromaticities, which must be corrected locally with sextupoles. The natural chromaticity of the FFT is -1500 in the horizontal and -2200 in the vertical. The purpose of the CCS is to correct these large first-order chromaticities locally, relatively close to the IP, by using interleaved sextupole pairs. These sextupole pairs are located at positions with large values of the dispersion and of the beta function corresponding to the chromaticity to be corrected by that pair.

In this design, these β values are $10\,\mathrm{km}$ in the plane being corrected and $.5 - .7\,\mathrm{m}$ in the opposite plane. The dispersion is $3.4\,\mathrm{m}$ at the horizontal sextupoles and $1.5\,\mathrm{m}$ at the vertical ones. The sextupoles which comprise each pair are separated by betatron-phase intervals of $\phi = \pi$. Additionally, they are located at positions where the phase interval from the IP is an odd multiple of $\pi/2$. The vertical-correction sextupole is closest to the IP, since the vertical chromaticity is the largest.

This sextupole arrangement cancels the second-order geometric aberrations of the sextupoles, which reduces the second order tune shift by several orders of magnitude. The large ratio between the beta functions allows the sextupoles to be interleaved and still maintain the delicate higher-order cancellation. Shortening the chromatic correction section–especially with respect to the number of maxima and minima included for sextupoles–proves to be very important in improving the dynamic aperture. Placement of sextupoles at minima in the plane not being corrected reduces significantly the aberrations arising from sextupole length and cross-plane correlations.

Utility insertion The utility insertion has been specifically designed with high-beta regions to facilitate beam scraping and extraction of unwanted beam, and injection and extraction. A detailed discussion of this insertion can be found in following sections [**?**].

Work on improving the experimental insertion at first concentrated on reducing its chromaticity by altering the FFT, but it t proved necessary also to optimize the CCS and and the global phase advance to improve the dynamic aperture. When the peak beta functions in the CCS were lowered from 100 to 50 km, the dispersion raised in the insertion sextupoles, and the working point optimized using the phase trombones, the dynamic aperture increases from 1 to 5 sigma. Further studies indicated that a $10\,\mathrm{km}$ version of the CCS with the same final focus structure had an even more improved dynamic aperture due to a much reduced tuneshift with amplitude created by the strong chromatic correction sextupoles.

In a sextupole-dominated ring, as is the muon collider, either the large and negative tuneshift with amplitude must be corrected or a working point must be chosen which is just below the integer or half integer to provide the maximum displacement from these resonances as a function of beam amplitude. The tuneshift with amplitude can be corrected using sextupoles in dispersion-free regions. These sextupoles are generally rotated from the standard sextupole orientation which is set to cancel chromatic aberrations in regions of positive dispersion. Including nonstandard orientations of sextupoles has not been implemented in some of the beam optics codes being used in the design work and this is presently being addressed.

The chromaticity must be corrected in order to provide a reasonable momentum aperture. The overall momentum bandwidth of the system is limited by third-order aberrations and residual second-order amplitude-dependent tune shifts. These aberrations arise from small phase errors between the sextupoles and the final quadruplet, and from the finite lengths of the sextupoles. Presently, the entire ring has a dynamic aperture of greater than 5 sigma and a momentum acceptance larger than $\pm.15\%$. The base working design stands to be improved further by raising the dispersion in the utility sections (from .6 m at the sextupoles) and by implementing higher-order correction schemes; as was done in another collider lattice design by K. Oide [**?**], which has many good features and performance.

F Detector and Shielding of Interaction Region

1 Background Environment

Background in the detector comes from 3 main sources: 1) muon decays near the detector, 2) muon halo and 3) beam-beam interactions. We will discuss these 3 background contributions in turn.

Table II gives the fluxes of different particles at a radius of 10 cm from the vertex, obtained by one of the Monte Carlo studies[38].

The beam pipe must be surrounded by a tungsten shield that is extended, as a cone, down towards the vertex. Designs have been studied in which this cone had a half angle of between 10 and 20 degrees, and extended to within 6 to 15 cm of the vertex. Different dimensions and shapes have been tried, and the optimum design is yet to be determined. In addition, careful design of beam collimators approaching the intersection point is required, and boron or other neutron absorbing materials must be used.

With such shields, the backgrounds estimated from Monte Carlo studies, indicate that a suitable detector should be able to operate and physics be analyzed. Recent optimization of the shielding for the 4 TeV design has reduced the background levels by roughly an order of magnitude from the levels reported in Snowmass96, down to a level comparable to those expected in the LHC detectors. Studies on a 0.5 TeV design yield similar background levels, while initial studies on the 100 GeV Higgs factory show a somewhat worse situation. Further shielding optimization is expected to improve the situation, particularly for the 100 GeV design.

There could be a very serious background from the presence of even a very small halo of near full energy muons in the circulating beam[40]. These muons can pass through the calorimeter and deposit significant clumps of energy from deep-inelastic scattering processes.

The beam will need careful preparation before injection into the collider, and a collimation system will have to be designed to be located on the opposite side of the ring from the detector.

There is also a small background from incoherent electron-positron pair production in the 4 TeV Collider case[41]. The cross section is estimated to be 10 mb[42], which would give rise to a background of $\approx 3\,10^4$ electron pairs per bunch crossing. However, most of these electrons are curled up by the solenoidal magnetic field of the magnet and do not escape into the detector, so this background does not appear to be a particularly serious problem. Coherent pair production has also been shown not to create a problem for the detector.

Table II: Background rates at a 10 cm radius. ** needs Iulio/Mokhov update **

			Silicon Drift		Micro TPC	
	flux cm^{-2}	$< E >$ MeV	hits cm^{-2}	Occup. %	hits cm^{-2}	Occup. %
γ	10000	1	20	2	.5	10*
n	3000	10	3	0.3	.06	.01
$e^{\pm}$	20	1	20	2	20	4
$\pi^{\pm}$	10	240	10	1	10	2
p	2	30	2	0.2	2	0.4
$\mu^{\pm}$	1	24000	1	0.1	1	0.2
total			56	6	34	17*

2 *Current Status and Outlook*

The choice of detectors must take into account the requirements of the physics and their ability to operate in the background environment. A major design goal is to be able to place the inner layer of the vertex detector close enough to the interaction point to allow effect separation of charm from bottom quarks.

The effect of these backgrounds in the electromagnetic calorimeter, assumed to have 2 x 2 cm towers, would be to introduce pedestals of about 100 MeV and fluctuations of about 50 MeV: neither serious. In the hadron calorimeter, the effect of all backgrounds, except the muons, would be to introduce a 2 GeV pedestals with 300 MeV fluctuations: also acceptable. But the muons, arising from Bethe-Heitler pair production in EM showers or from a halo in the machine, though modest in number, have high average energies. They would not be a problem in the tracking detectors. But in the calorimeters, they would occasionally induce deeply inelastic interactions, depositing clumps of energy deep in the absorbers. If a calorimeter is not able to recognize the direction of such interactions (they will be pointing along the beam axis) then they would produce unacceptable fluctuations in hadron energy determination. It has been suggested that segmenting the calorimetry in depth would allow these interactions to be subtracted.

VII RESEARCH AND DEVELOPMENT PLAN

This section gives an outline of our current research and development (R and D) studies and our plans for the next few years. Currently, our R and D largely consists of theoretical design studies, involving heavy use of computer simulations.

Theoretical studies are expected to remain a large part of our R and D over the next few years, but they will be increasingly augmented with an experimental program to test and develop critical components and concepts, in preparation for the detailde design and, hopefully, construction of a first muon collider facility.

The first subsection describes the current and planned scope of our theoretical studies. In the following two subsections, plans are presented for two proposed experimental R & D facilities, one to study ionization cooling and the other to study the production and capture of large bunches of pions. Smaller experiments are then discussed, before summarizing the expected logistical requirements of our experimental program.

A Theoretical Studies

1 Overview

Theoretical studies involve verification, design and optimization of muon colliders. They are expected to progress over the next few years from rather general studies to more detailed design and a full exploration of options for each of the components.

2 Theoretical R and D on Cooling

With the recent successes in reducing the expected detector backgrounds to a manageable level (see section ??) the most critical item for theoretical R and D is now the muon cooling channel.

Since all of the physics involved in cooling is well understood and relatively straightforward to model, the design of the muon cooling channel will come largely from computer simulations rather than hardware demonstrations These computer simulations can be developed on a somewhat shorter timescale than required for experiments. Our goal for the coming year is to have a relatively complete simulation for a cooling channel design that meets our 6-D emittance goal, and we can already expect to have a rather high level of confidence in our design when the R & D eperiments come online in about 3 years time.

The only part of the computer simulation that will not be directly calibrated by the R & D experiments is collective effects on the muon bunches when cooled to low emittance. There are established techniques for calculating these collective effects in which essentially, the model of the bunch is partitioned into ”macroparticles” which are then subjected to the forces predicted by Maxwell's equations. As detailed in section ???, collective effects have already been partially installed in our computer simulations and should be fully modelled in the near future.

Optimization of the muon cooling channel could lead to faster cooling and smaller final emittances, which should lead directly to increased luminosity with smaller bunch sizes and more relaxed technical specifications.

For example, it is quite conceivable that big gains in the cooling might come from adding final cooling stages to slow the muon bunches to well below the speed of light. Both the 6-dimensional cooling rates and the equilibrium emittances can improve enormously at these lower momenta if we work out how to deal with the larger angular spreads and the blow-up in longitudinal emittance. More speculative alternative cooling methods also have a chance of improving the muon cooling. Alternatives that are beginning to be looked at include optical stochastic cooling and various schemes with very low energy muons. We expect to have detailed evaluations of all alternative methods for cooling, including cooling at lower momenta, in about 1 year's time.

B Ionization Cooling Facility (ICF)

The experiments required to demonstrate ionization cooling and to develop and optimize the cooling hardware will not be trivial. They will require an ionization cooling test facility[**?**] with the following capabilities:

- Injection of single muons with momenta in the range 100 - 300 MeV/c into a test cooling setup of length up to ~ 50 m.
- Measurement of the six-dimensional phase-space volume occupied by the populations of the incoming and outgoing muons with a precision of a few %.
- Measurement of the non-decay loss of muons traversing the cooling setup with a precision corresponding to O(10%) for a full cooling stage. Since the non-decay losses are expected to be $\sim$1%, each measurement will require O(10000) muons within the phase-space acceptance of the cooling apparatus.

To provide these capabilities the facility will need to have a low energy muon beamline, the infrastructure to operate the cooling prototypes to be tested (services, shielding, overhead crane coverage, refrigerants for superconducting magnets, rf power for accelerating cavities including modulators, klystrons, etc), and instrumentation to identify incoming and outgoing muons and determine their positions, directions, momenta, and their entrance and exit times with respect to the rf acceleration cycle. Work on an initial design of the required facility is proceeding.

We propose to design and prototype critical sections of the muon ionization cooling channel. These sections would be tested by measuring their performance when exposed to single incoming muons with momenta in the range 100 – 300 MeV/c. 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 demonstrated, the calculations used to design the cooling system to be tested, and optimization of the cooling hardware to be studied. Our goal is to develop the muon ionization cooling hardware to the point where a complete ionization cooling channel can be confidently designed for the First Muon Collider.

The required FOFO R&D consists of:

- Developing an appropriate rf reacceleration structure. Both traveling wave and standing wave structures are being considered. To reduce the power requirements (by a factor of 2) the rf cells would be operated at liquid nitrogen temperatures, and to maximize the accelerating field on axis the aperture that would be open in a conventional rf cell will be closed by a thin beryllium window. The rf structure must therefore be prototyped and tested at liquid nitrogen temperatures before a complete cooling stage can be developed.
- Prototyping complete transverse and longitudinal (wedge) cooling stages and measuring their performance in a muon beam of the appropriate momentum.

The required lithium lens R&D consists of:

- Developing 1 m long liquid lithium lenses. Note that the muon collider repetition rate of 15 Hz would result in a thermal load that would melt a solid lithium rod. Long lenses are required to minimize the number of transitions between lenses.
- Developing lenses with the highest achievable surface fields, and hence the maximum radial focusing, to enable the minimum final emittances to be achieved.
- Prototyping a lens–rf–lens system and measuring its performance in a muon beam of the appropriate momentum.
- Developing, prototyping, and testing a longitudinal cooling system.

This facility will need a muon beam with a central momentum that can be chosen in the range 100 – 300 MeV/c, an experimental area that can accommodate a cooling and instrumentation setup of up to 50 m in length, and instrumentation to precisely measure the positions of the incoming and outgoing particles in six-dimensional phase-space and confirm that they are muons. In an initial design, the instrumentation, consists of identical measuring systems before and after the cooling apparatus. Each measuring system consists of (a) an upstream time measuring device to determine the arrival time of the particles to with one quarter of an rf cycle ($\sim\ \pm 300$ ps), (b) an upstream momentum spectrometer in which the track trajectories are measured by low pressure TPC's on either side of a bending magnet, (c) an accelerating rf cavity to change the particles momentum by an amount that depends on its arrival time, (d) a downstream momentum spectrometer which is identical to the upstream spectrometer and together with the rf cavity and the downstream spectrometer forms a precise time measurement system with a precision of a few ps. The entire measuring apparatus is 6 m long, and is contained within a 5 T solenoid to keep the beam particles within the acceptance of the cooling apparatus. The R&D program can be accomplished in a period of about 6 years. At the end of this period we believe that it will be possible to assess the feasibility and cost of constructing an ionization cooling channel for the First Muon Collider, and begin a detailed design of the complete cooling channel.

C Target and Capture Facility (TCF)

This subsection presents plans for an experimental facility at the BNL AGS accelerator which will study the production and capture of large bunches of pions. Further details on this facility can be found in reference [**?**].

To generate the 20 tesla, 15 cm bore solenoidal magnetic field to capture pions of transverse momentum up to 400 MeV/c, we have designed systems of three types. To minimize cost, each system employs hardware that BNL already has, or is working to obtain. Common to all systems is Brookhaven's "MPS" power supply, which delivers 4 MW at 16 kA. Magnet systems of the first type employ a large superconducting magnet that generated over 11 teslas for the High Field Test Facility (HFTF) at Lawrence Livermore National Laboratory (LLNL). BNL is negotiating with LLNL for loan of the magnet. To bring the power consumption within the 4 MW capability of the MPS power supply, magnets of the second and third types are cryogenic. Magnets of the second type receive continuous cooling, while those of the third type are adiabatic, with recooling between pulses.

Figure 1 shows the winding cross section of the first type of magnet system, known as a "hybrid". It consists of three sets of coils: 1) the HFTF superconducting magnet, 2) a compact water-cooled insert, and 3) field-shaping coils. The HFTF magnet and resistive insert combine to generate at least 15 T throughout the region of the proton beam target, which is about 25 cm long. Were the HFTF magnet cooled to 1.7 K instead of 4.2 K, it might generate as much as 14 T, giving a total field of 18 T. The insert is of hollow conductor, reinforced with stainless steel of very high strength. The field shaping coils, from approximately 40 cm to 100 cm downstream from the target, gradually lower the field from its central strength, $B(0)$, to $B(0)/4$, to retain the captured pions as they speed toward the phase rotation and cooling hardware. These coils are to be superconducting (of surplus SSC wire); otherwise they would require an additional 3 to 5 MW. The gently flaring horn in the figure shows the radial limits of pion capture and retention, defined by $r(z) = r(0) \times \sqrt{B(0)/B(z)}$.

The second type of system employs a long cryogenic Bitter coil of about seven tons to generate most of the field. To minimize cooling passage length and maximize cooling surface area, cooling is radial. For ease of fabrication, the Bitter coil is nowhere larger than about 80 cm in diameter. To augment its field throughout the target region is a large bore hollow conductor coil of about three tons. For efficiency the bore of Bitter coil is conical, for which we derived the needed equations for field and power. As presently designed, the conductor is copper, and the cryogen is liquid nitrogen, which one throws away after it has vaporized. However, the operating cost of such a mode of operation is very high–about $7,000 per hour at 4 MW. More economical for many months of operation at a modest duty cycle would be a magnet of ultrapure aluminum, reinforced to limit strain, and cooled by liquid neon, liquid hydrogen or high-density helium gas. Each of these cryogens one would draw from a reservoir, and then regenerate with a refrigerator.

The second figure shows the winding cross section of a pulse magnet for pion capture and retention. To bring the power demands of the magnet within the capability of the MPS power supply, one precools the windings to 77 K. Furthermore, one energizes the coils sequentially, rather than all at once. Specifically, one employs the outer set of four coils to energize the inner set. One first energizes the outer set of four coils at full voltage for 15 to 20 seconds, to reach the current limit of the power supply. The outer set then generates a central field of about 10 T and stores about 20 MJ. By discharging this set through a room-temperature resistor, one generates a terminal voltage of a few kilovolts – an order of magnitude greater than that of the power supply. In about a third of a second, the outer coil has discharged from 16 kA to about 13 kA and has charged the inner set of coils to about 11 kA. The inner set then contributes about 12 T to the central field. The total field throughout the region of the target is at least 20 T. Like the cryogenic systems, the pulse systems described here need about ten tons of copper, some as hollow conductor and some in the cheaper form of solid conductor. These latest designs should allow a duty cycle of many pulses per hour. The operating cost for liquid nitrogen is only ten dollars per pulse. Note that coils are conical in both bore and outer diameter. Once again we needed to derive the equations for field and power.

The cost of the hybrid magnet systems we estimate to be about two million dollars. The cryogenic magnet systems should cost only about a third as much. However, they either are expensive to run, or else generate pulses that last only a fraction of a second. Therefore, the preferred system, despite its higher capital cost, is the hybrid.

D Other Experimental R & D

Prototype work would also be required on other magnets, r.f. systems, modulators etc. The definition of such a program will be one of the tasks of the near-term R & D effort.

[[status: rewrite this paragraph]]

1 *Accelerator Experiments*

An accelerator experiment has already been conducted to study the preparation of short proton bunches suitable for the pion production target at a muon collider. Other experiments are underway to study the reduction of space charge in proton storage rings.

Experiment E-932 at the AGS has shown one can reduce the bunch length from 10 ns to 3 ns for 1.5 eV-sec bunches by operating close to transition, and the bunches are stable for usefully long times. It should be possible to demonstrate proton bunches with sigma = 1 - 2 ns using either bunch rotation far from transition, possibly using a harmonic cavity to control nonlinear effects, or rotation near transition, followed by rotation far from transition. Experiments at the AGS, the Fermilab Booster and the KEK proton synchrotron are being considered. The transition jump system would be used to change the machine lattice as required.

Longitudinal space charge effects can be troublesome both at injection and during the final bunching process. The use of tunable inductive inserts in the vacuum chamber could permit active control and compensation of the longitudinal space charge voltage below transition. Experiments underway at the PSR at Los Alamos using biased ferrite rings to modify and control the wall impedance have shown that longitudinal space charge effects can be modified. Preliminary experiments have also been done at KEK which indicate that the technique should be useful [**?**].

2 *Measurement of Pion Production Cross Sections*

The collaboration has joined a BNL nuclear physics experiment, E910 [17, 18], that is measuring pion production from protons at different energies striking various heavy metal targets. The data is currently being analyzed, and should allow more realistic Monte-Carlo calculations of total pion yield and capture in a solenoid.

3 *Lithium lenses*

Ionization Cooling to minimal transverse emittance requires strong focusing at the absorber, and that can obtained over extended lengths by using a metal conductor absorber, where the energy loss is within the metal itself and the active current focuses the beam radially. For minimal multiple scattering, a low-Z material such as Li is desired, and Li lens conductors have been developed (for antiproton and positron collection) at BINP, Fermilab and CERN, and this technology can be extended for beam-cooling applications. For beam-cooling, we would want somewhat longer lenses (¿ 1m/ unit) and 15-Hz Collider operation would raise Li lenses to liquid temperatures.

Currently a three-year plan for design, construction, and testing of a liquid Li lens has been initiated by BINP and Fermilab. The initial plan is for a 13T, 1cm radius, 20 cm long lens for antiproton collection. That experience can be readily extended to the 1m length needed for a cooling Li lens, and an initial design for a 1m lens has been presented by Silvestrov of BINP.

The cooling plan would be to extend the Liquid Li lens experience to build and test a 1-m long module suitable for cooling (13T, 1 cm radius, 1m long), with the assistance of Hartouni et al. of Lawrence Livermore National Laboratory. This module would be bench-tested, and then inserted in the muon initial cooling experiment.

Obtaining minimal emittances requires stronger lenses, which can be obtained by increasing the surface field to 20T, while lens radii are reduced from 1 cm toward 1mm. In a cooling sequence, the reducing emittance will enable smaller and smaller lens radii. The R & D program would continue by producing these higher gradient lenses, adding them to the cooling channel for further cooling (with beam reacceleration rf), and eventually testing the limits of the cooling technology.

4 *Magnet Experimental R & D*

Superconducting dipoles, quadrupoles and solenoids are used from the target station to the final interaction region. In almost all cases they will be exposed to high radiation, and the design is dominated by the desire for high field, low cost, and radiation hardness.

Magnets containing niobium-tin (Nb_3Sn) suerconductor offer great advantages and this option needs to be explored. LBNL has already succeeded in constructing an accelerator style dipole using Nb_3Sn and have contributed greatly to the development of conductor technology, but the technique used (wind, react, and then vacuum impregnate) would not provide adequate cooling for muon collider applications. Luckily, most of the magnets for the muon collider, being large, are natural candidates for the use of either cable and conduit construction, or react-and-wind; either of which should allow adequate cooling. But no accelerator magnets using cable and conduit, and few using react-and-wind, have been built.

The IR quadrupoles are probably the most critical superconducting magnet program to work on. The design and performance of the collider lattice is strongly dependent on their gradients and field quality, particularly for higher energy muon colliders.

They will be very large, with apertures up to 50 cm diameter, and will thus require very high pole tip fields, if reasonable gradients are to be achieved. Nb_3Sn is clearly desired. The cost for the IR quad research is 500k$ in FY98.

The insertion quadrupoles need urgent R & D because the lattice design work depends on the gradients that are achieved. Nb_3Sn, or other higher field conductor will be prefered. Since the magnets operate at a constant field, metallic insulation is probably acceptable, which would obviate the need for impregnation and thus provide better cooling. High T_c materials should be considered. A program of at least 1 M$ per year is needed.

The dipole magnets, if of cosine theta design, would probably develop excessive mid plane compression in their coils. Block conductor arrangements will need to be developed. The use of $\mathrm{Nb_3Sn}$ will again be prefered for its high field capability. A program at about the 1 M$ per year level is required.

If pulsed magnets turn out to be needed after a comparative evaluation of the proposed acceleration methods (see section ?) then some pulsed magnet construction and testing will be needed to follow up on the theoretical work that has already been done.

5 *Radiofrequency Cavities*

Some R & D work is also needed to determine the performance of the required superconducting cavities when excited for the relatively short pulse durations required. Studies of their sensitivity to electrons from muon decays may also be needed. It is hoped that such studies will be undertaken within the context of more general superconducting cavity development.

6 *Detector Experimental R & D*

As is the case for the LHC collider project, the detectors will likely be the most technically challenging component. However, we will benefit from a much longer lead-in time for R & D than the LHC project and will also benefit directly from the LHC detector development and from several extra years of improved technology for the electronics, DAQ, computing etc. Thus it is likely that the detector R & D effort in the near future will concentrate more on computer simulations rather than committing to a significant experimental R & D program.

E Five Year R & D Plan

We hope to have vigorously tested the feasibility of muon colliders and have relatively detailed designs for the components within the next 5 years. If this is the case then the experimental R & D beyond 5 years can be limited to small projects for fine-tuning some components. Hopefully, this will be concurrent with the approval and construction of the FMC.

The total yearly costs of the R & D work described above is 5 M$ per year, plus a total of 26 M$'s in equipment money for the two major demonstration projects.

It is estimated (see table III) that the current effort is about 27 full time equivalents, but only a few of these are funded specifically for such work. The most serious need of the project is for increased support for dedicated personnal committed to the muon collider project. The required manpower cost has been estimated at 7 M$ per year.

Table III: Required Base Manpower. ** needs update **

	Now	Required
ANL	1	2
BNL	8	16
FNAL	7	16
LBNL	4	8
BINP	1	3
Other US	1	3
	—	—
Total FTE's	22	48
M$/year	3	7

It is estimated that if the above level of funding were available, then about 5 years of R & D should be required. A prefered profile of the required funding is shown in table IV and Fig.3. It must be emphasised that these figures are no more than our best current guess at what would be needed, and which would lead to a relatively early start on the next phase: the design and construction of the FMC.

Table IV: R & D Funding Needs in M$'s. *** needs update ***

FY	96	97	98	99	00	01
Base	3	5	7	7	7	7
Capture			1	2	2	1
Cooling				2	8	10
R & D		1	2	4	5	5
Total	3	6	10	15	22	23

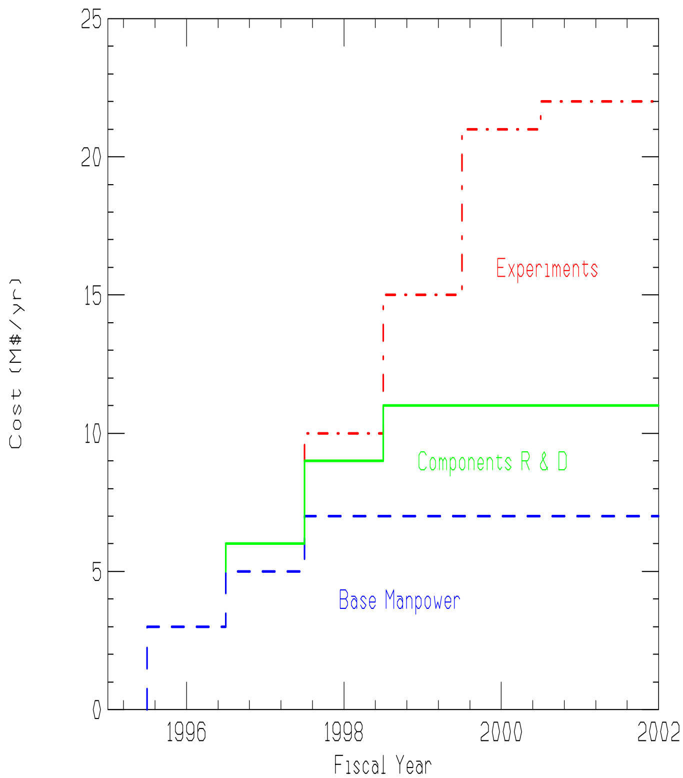

Figure 3: Required Funding Profile. *** needs update ***

VIII SUMMARY

A Physics Potential of Muon Colliders

Section ?? shows that the physics case for muon colliders is very strong, particularly for the study of the fundamental Higgs mechanism that is thought to determine the masses of all the elementary particles. It is hoped that muon colliders will help to give a deeper understanding and unification of the elementary forces and particles that underlie all physical processes.

A muon collider complex is expected to be considerably smaller than other types of colliders at the high energy frontier, and it is hoped that it will also be correspondingly relatively cheaper. It is envisioned that a muon collider facility could be easily upgradable, perhaps with several collider rings feeding off the same source of cooled muons.

B Design Scenarios

The emphasis of our theoretical studies has shifted to lower energy colliders that might be good choices for first muon collider (FMC). If a Higgs boson is discovered with a mass below about 150 GeV then the FMC would probably be a factory for its resonant production.

Detailed design scenarios have advanced in the past year, particularly with the addition of detailed studies for an s-channel Higgs factory at around 70 to 150 GeV. These studies have increased our confidence in the feasibility of muon colliders from relatively low energies up to multi-TeV colliders.

The understanding of the components' performance and optimization at energies around 100 GeV is new, while the studies for the 4 TeV collider have made good progress, particularly in the areas of detector shielding and magnet lattice design. [in summary?] Combining these studies now gives us a much better understanding of the feasibility and design issues for muon colliders spanning the range from 100 GeV up to 4 TeV.

The one serious problem that has emerged in the past year is the surprising potential for a radiation hazard from the copious neutrino flux emerging from the collider. This has been found to be not a serious problem for lower energy colliders such as an s-channel Higgs factory. However, the radiation dose rises as the cube of the CoM energy, and quickly becomes a problem at higher energies. It appears certain to force major constraints on the design and, possibly, siting of any proposed multi-TeV muon colliders. Studies are underway to further assess and reduce this problem.

C Progress on Components

There has been progress in our understanding of all of the components of a muon collider, particularly on the two components that we consider to be the most critical: the cooling channel and the detector shielding.

The muon cooling channel is the most novel part of a muon collider complex. Steady progress has been made both in improving the design of the channel and in adding detail to the computer simulations. We are now much closer to the goal of having a detailed and complete simulation of an entire cooling channel. Further, a vigorous experimental program is beginning to verify and benchmark the computer simulations.

Coping with the large backgrounds in the detector was presented last year as perhaps the worst problem facing muon colliders. By optimization of the detector shielding, this problem has already been reduced by an order of magnitude from last year's 4 TeV design, and the feasibility of shielding the detector has now also been demonstrated at lower energies, including for a 100 GeV Higgs factory.

D Experimental R and D Program

The collaboration is now embarking on a vigorous effort to initiate an experimental R and D program to complement the theoretical studies and computer simulations. Section ??? presents an outline of the anticipated R and D program over the next several years. This includes the construction of two fairly major experimental facilities, one to test ionization cooling and the other to verify the production and capture of large pion bunches.

IX CONCLUSIONS

The muon collider is a new type of proposed accelerator that has considerable potential for contributing to the future program of experimental high energy physics.

Our collaboration is making good progress in establishing the feasibility of muon colliders. With our current level of understanding we believe it likely that muon colliders will be able to achieve both high luminosities and manageable experimental conditions. Although the designs are novel, the technologies required seem to be nowhere more than modest extrapolations from what is available today.

[[status: needs rewrite: 5 paragraphs]]

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