Chapter 1

INTRODUCTION AND OVERVIEW

Contents

1.1 General Considerations

This report describes the theory and technology needed for muon colliders and gives a consistent set of parameters for a 2+2 TeV machine with a luminosity of $10^{35}\,\mathrm{cm}^{-2}s^{-1}$ as well as for a 250+250 GeV collider with luminosity of $10^{33}\,\mathrm{cm}^{-2}s^{-1}$. The higher energy machine would be the upgrade of the lower energy machine since the muon source has common properties. In addition, a *demonstration* machine is discussed, which could serve as a breadboard for exploring the properties of this class of colliders before committing large sums to the construction of the final complex.

The possibility of muon colliders was introduced by Skrinsky et al.[1] and Neuffer[2]. More recently, several workshops and collaboration meetings have greatly increased the level of understanding[3],[4]. After the workshop at Sausalito, in December 1994, a collaboration was formed by BNL and FNAL to study the concept and prepare this document for Snowmass. This effort has expanded to include LBNL, ANL and several other individuals from KEK, DESY and various universities. Subsequently, three mini-workshops were organized and attended by over sixty scientists, to discuss the several technical options and assess the progress and status of the study for a prospective muon collider. Their contributions are gathered in this document.

1.2 Technical Considerations

Hadron collider energies are limited by their size, and technical constraints on bending magnetic fields. At very high energies it will also become impractical to obtain the required luminosities, which must rise as the energy squared. In fact, lepton colliders in general, offer the advantage that the interaction energy is given by twice the machine energy, because they undergo simple, single-particle interactions, compared to the hadron collider where the effective energy is much lower than that of the proton. Even worse, the gluon-gluon background radiation makes it increasingly difficult to sort out the complicated decay schemes envisaged for the SUSY particles. The lepton collider on the other hand offers clean production of charged pairs with a cross section comparable to $\sigma_{\mathrm{QCD}} = 100/s\,\mathrm{fb}$ where s is the energy squared in TeV^2.

Extension of e^+e^- colliders to multi-TeV energies is severely performance-constrained by beamstrahlung, and cost-constrained because two full energy linacs are required[5] to avoid the excessive synchrotron radiation that would occur in rings. Muons ($\frac{m_\mu}{m_e} = 207$) have the same advantage in energy reach as electrons, but have negligible beamstrahlung, and can be accelerated and stored in rings with a much smaller radius than a hadron collider of comparable energy reach, making the possibility of high energy $\mu^+\mu^-$colliders attractive.

The answer to the question of *Why study muon colliders?* is therefore driven by the following two facts:

- Muon colliders can reach much higher energy than e^+e^- colliders due to the much reduced synchrotron radiation. The beamstrahlung and initial state radiation is also smaller leading to better energy definition of the initial state.

- For cases where the coupling is proportional to the mass, as in the case of s-channel Higgs production, muons have an advantages of $\approx (207)^2$ over electrons.

There are however, several major technical problems with muon colliders:

- Muon decay with a lifetime of 2.2×10^{-6} s. This problem is partially overcome by rapidly increasing the energy of the muons, and thus benefiting from their relativistic γ factor. At 2 TeV, for example, their lifetime is $0.044\,\mathrm{s}$ which is sufficient for approximately 1000 storage-ring collisions.

- another consequence of the muon decay is that the decay products heat the magnets of the collider ring and create backgrounds in the detector.

- Since the muons are created through pion decay into a diffuse phase space, some form of cooling is essential. Conventional stochastic or synchrotron cooling is too slow to be effective before they decay. Ionization cooling can be used, but the final emittance of the muon beams will remain larger than that possible for electrons in an e^+e^- collider.

- The machine represents an *untried* technology. It will require an aggressive **R&D** program before a conclusion can be reached. This document should help to define the course of the necessary work.

Despite these problems, it appears possible that high energy muon colliders might have luminosities comparable to or, at energies of several TeV, even higher than those in e^+e^- colliders[5]. Because the $\mu^+\mu^-$machines would be much smaller[6], and require much lower precision (the final spots are about three orders of magnitude larger), they may be significantly less expensive. However, e^+e^- colliders are at a technologically more advanced stage of development and likely will be built before a demonstration muon collider. Hence, it is relevant to ask *what is it that a muon collider may contribute to our understanding of the energy frontier that cannot be achieved with an electron collider?*. That is briefly summarized next and discussed in details in the Physics Chapter.

1.3 Physics Considerations

There are at least two physics advantages of a $\mu^+\mu^-$collider, when compared with an e^+e^- collider:

- Because of the lack of beamstrahlung, a $\mu^+\mu^-$collider can be operated with an energy spread of as little as 0.01 %. It is thus possible to use the $\mu^+\mu^-$collider for precision measurements of masses and widths, that would be very difficult, if not impossible, with an e^+e^- collider.

- The direct coupling of a lepton-lepton system to a Higgs boson has a cross section that is proportional to the square of the mass of the lepton. As a result, the cross section for direct Higgs production from the $\mu^+\mu^-$system is 40,000 times that from an e^+e^- system.

However, there are liabilities:

- It will be relatively difficult to obtain both high polarization and good luminosity in a $\mu^+\mu^-$collider, whereas good polarization of one beam can be obtained in an e^+e^- collider without any loss in luminosity. However, in the muon case moderate polarization could be obtained for both beams which compensate for the lower luminosity.

- Because of the decays of the muons, there will be a considerable background of photons, muons and neutrons in the detector. This background may be acceptable for some experiments, but it cannot be as clean as in an e^+e^- collider.

1.4 Overview of Components

The basic components of the $\mu^+\mu^-$collider are shown schematically in Fig.1.1. Tb.1.1 shows parameters for the candidate designs. Notice that more precisely a factor of π must appear in the dimensions of emittance (i.e. $\pi\,\mathrm{mm\,mrad}$). The emittance ϵ is defined as the *rms* transverse phase space area divided by π and the normalized emittance is $\epsilon^N = \beta\gamma\epsilon$.

A high intensity proton source is bunch compressed and focused on a pion production target. The pions generated are captured by a high field solenoid and transferred to a solenoidal decay channel within a low frequency linac. The linac serves to reduce, by phase rotation, the momentum spread of the pions and of the muons into which they decay. Subsequently, the muons are cooled by a sequence of ionization cooling stages. Each stage consists of energy loss, acceleration, and emittance exchange by energy absorbing wedges in the presence of dispersion. Once they are cooled, the muons must be rapidly accelerated to avoid decay. This can be done in recirculating accelerators (à la CEBAF) or in fast-pulsed synchrotrons. Collisions occur in a separate high field collider storage ring with a single very low beta insertion.

Each one of these components is described in details in the following chapters.

1.5 Discussion

The physics reach of a $\mu^+\mu^-$collider is well outlined by the studies that have been done for a e^+e^- collider. It is reasonably clear that an actual realization of a muon collider has both technical advantages and disadvantages when compared with an e^+e^- machine. Similarly, it has specific physics advantages and disadvantages. Thus, it seems reasonable to consider $\mu^+\mu^-$colliders as complementary to e^+e^- colliders just as e^+e^- colliders are complementary to hadron machines.

It is worthwhile at this point to face some *what if* questions:

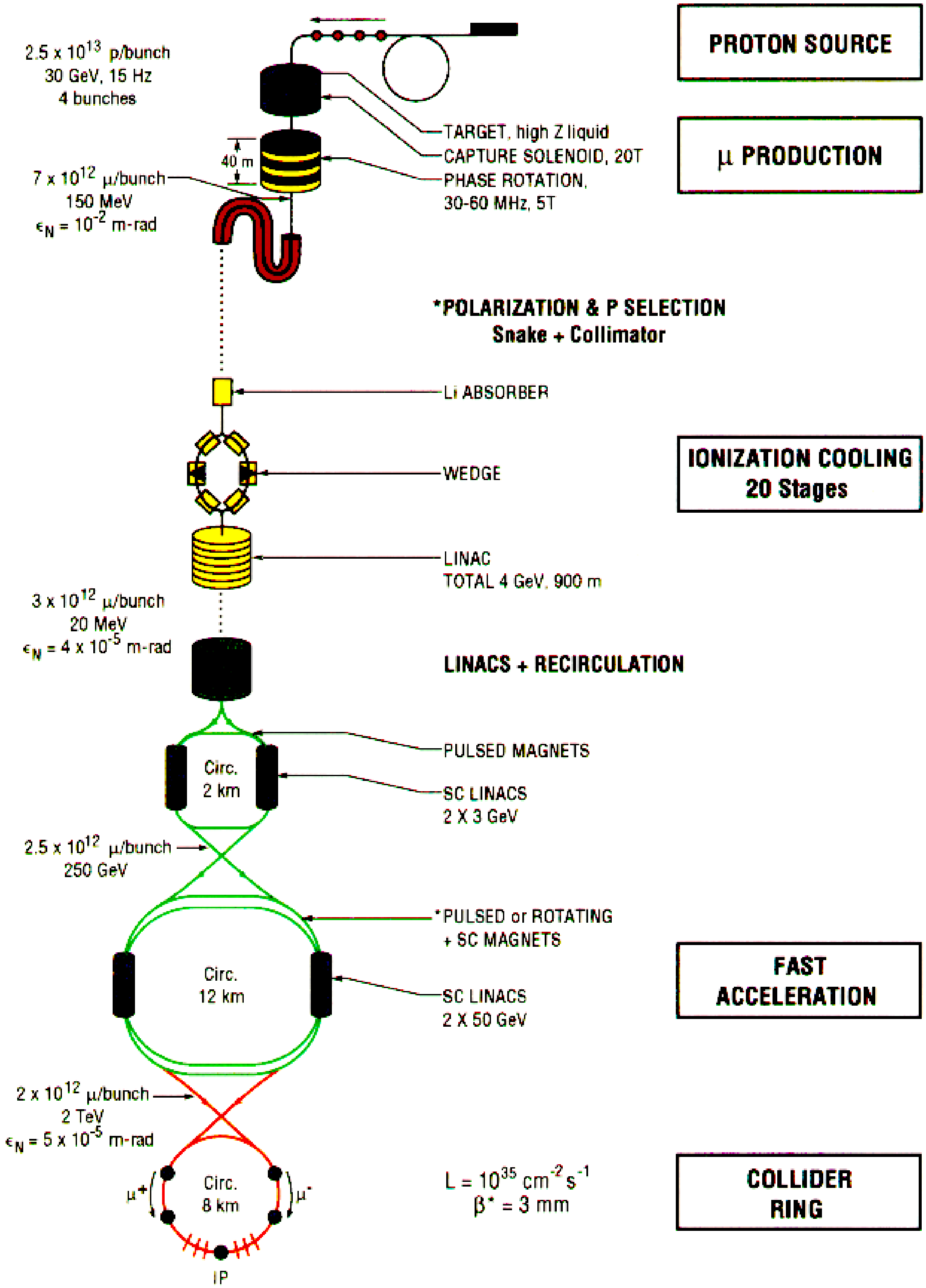

Figure 1.1: Schematic of a muon collider.

Table 1.1: Parameters of collider rings

		4 TeV	.5 TeV	Demo.
Beam energy	TeV	2	.25	.25
Beam γ		19,000	2,400	2,400
Repetition rate	Hz	15	15	2.5
Muons per bunch	10^{12}	2	4	4
Bunches of each sign		2	1	1
Normalized *rms* emittance ϵ^N	$10^{-6}\pi$ m $-$ rad	50	90	90
Bending Field	T	8.5	8.5	7.5
Circumference	km	7	1.2	1.5
Average ring mag. field B	T	6	5	4
Effective turns before decay		900	800	750
β^* at intersection	mm	3	8	8
rms beam size at I.P.	μm	2.8	17	17
Luminosity	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	10^{35}	5×10^{33}	6×10^{32}

- What if the next machine is TESLA or JLC? Clearly, we would support either one of them as good citizens of the international High Energy community. Nevertheless, is there then a complementary machine that could be built in this country?

- What if Nature is different from the scenario presented by SUSY of new physics opening up below 500 GeV and higher energy is required?

- What if the *next machine* is not built for more than ten years? An aggressive muon collider **R&D** during that period may show that it is a natural add-on to existing facilities with rich physics possibilities for an accelerator complex that is affordable in a staged manner.

The studies of the past year are contained in this document which outlines in detail what is known about this class of machine. It appears that many of the problems have been solved or at least have solutions. On the other hand, it is also clear that much more work needs to be done -including experimental work. The present technologies are being pushed to the limit in some cases; on the other hand, new inventions to solve various problems have regularly occurred, showing a healthy tension between challenges and the capacities of the scientists to produce innovations; room exists for more discoveries that can lead to reduced cost, increased luminosity, polarization and simpler configurations.

The present report furnishes a solid base for identifying the main areas of study. The machines described have internally consistent sets of parameters but no optimization of the various components have been attempted. An important part of the optimization procedure involves extensive testing of real components. This is the ultimate objective of the *demonstration machine* and it is hoped that the same collider can also be a useful physics tool, although it is too early to visualize exactly how this would come about. However, even before this, there will have to be an extensive and integrated program of component development.

Finally, the question of the cost of a $\mu^+\mu^-$collider *is not addressed* in this report. Obviously, the next phase of the work will be to optimize the many pieces of the machine in order to minimize the cost. On that regard, the investment in the muon source is the first and most important step. The potential for systematically raising the energy depends on the muon source. A low energy collider ($250 + 250\,\mathrm{GeV}$) with a luminosity of $10^{33}\,\mathrm{cm}^{-2}s^{-1}$ not only has the possibility of interesting physics but also provides the technical base for the higher energy versions in a scenario where the upgrade is achieved by integrating a modest budget over time.

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