PROGRESS ON $\mu^+\mu^-$ COLLIDERS

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Abstract

Advantages and disadvantages of muon colliders are discussed. Recent results of calculations of the radiation hazard from muon decay neutrinos are presented. This is a significant problem for machines with center of mass energy of $4\,\mathrm{TeV}$, but of no consequence for lower energies. Plans are outlined for future theoretical and experimental studies. Besides continued work on the parameters of a 4 TeV collider, studies are now starting on a machine near 100 GeV that could be a factory for the s-channel production of Higgs particles. Proposals are also presented for a demonstration of ionization cooling and of the required targeting, pion capture, and phase rotation rf.

1 INTRODUCTION

The first ideas about the use of muon colliders as a potential useful machine for high energy physics were presented by Skrinsky and collaborators[1] and shortly after by D. Neuffer[2]. More recently the concept has further developed and aggressively pursued in a series of collaboration meetings and workshops[3],[4]. A feasibility study of a $4\,\mathrm{TeV}$ muon collider was presented at Snowmass[5] and now studies have started of low energy machines of energy range $500 - 100\,\mathrm{GeV}$.

1.1 Advantages

A muon collider[6] is a class of lepton collider with many of the advantages usually associated with e^+e^- colliders. Unlike protons, the muons are fundamental particles, and when they interact, all the center of mass energy is available for the production of new states.

The possible advantages of muons, compared with electrons, all arise from the formers higher mass. As a result of that:

- Synchrotron radiation ($\propto\ \gamma^4\ \propto\ m^{-4}$) is suppressed, and, as a result, muons can be accelerated to high energies in circular rings that appear to be much smaller than the linear accelerators needed for electrons.
- Since muon collisions can occur in a ring, the bunches collide with one another many (of the order of 1000) times. In a linear e^+e^- collider they can interact only once.
- Synchrotron radiation (beamstrahlung) is also suppressed as the bunches pass through one another, allowing, in principle, very narrow energy spreads ($\rightarrow$ 0.01 %).
- The cross section for the direct production (s-channel) of Higgs particles ($\mu^+\ \mu^-\ \ \rightarrow\ \ h, A, H$), which is $\propto\ \ m^2$ is over 40,000 times higher for muons than electrons.

1.2 Disadvantages

But there are disadvantages, most of which arise from the fact that μ's decay with a life time, at rest, of about $2\,\mu s.$

- Because of their short lifetime it is not possible to cool muons by the conventional methods used for antiprotons (stochastic, or electron cooling). These methods are too slow. And because of the muon's high mass, synchrotron radiation cooling is also ineffective. Instead, ionization cooling [7] can be used, but the minimum emittance achievable by this method is not as low as that achieved for antiprotons or electrons.
- Because of their short lifetime, acceleration must be rapid and conventional synchrotrons would be too slow. A single linac would be good but expensive. A linac would thus only be used at the lowest energies. Recirculating linacs would be cheaper for later stages, and fast pulsed magnet synchrotrons might be desirable for the higher energy accelerators.
- As the muons decay in the collider ring, the electrons from the decay enter the beam pipe walls depositing energy and generating radioactivity. A tungsten liner is required to shield this heating from the superconducting magnets used to form the ring. As a result, these magnets must have relatively large apertures.
- Muons decaying as they approach an experimental area will also direct electrons into the experiment, and these too must be shielded by a tungsten cone that extends down towards the vertex. As a result, the solid angle over which the detector can operate is reduced and experiments must live with a relatively high rate of background tracks.
- Another, and at first surprising, problem from the muon decays is that the flux of decay neutrinos can, at high energies, become a significant radiation hazard. This will be discussed in more detail below.

1.3 Neutrino Radiation Hazard

This problem was first pointed out by Bruce King [8] and has since been calculated in detail by Mokhov[9]. The initial discrepancies between these calculations have now been resolved.

The annual doses from this radiation are given by

$$dose\ \propto\ E^3/length^2\ \propto\ E^3/depth,$$

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where E is the muon beam energy, $length$ is the distance from the ring and $depth$ is the depth of the ring below the ground. Unless straight sections are kept very short, the radiation is dominated by such sections, each of which generates a highly collimated beams of neutrinos.

We take the dose limit, as by FNAL, at 10 mR/year limit (c.f.: The federal limit is 100 mR/year). Then the 4 TeV design (luminosity $10^{35} cm^{-2} s^{-1}$), without straight sections, would meet the requirement if located at a depth of 250 m. If moderate fields are introduced over all straight sections, and/or the orbits are time varied, then various solutions appear possible, at this energy, without major changes to the concept.

The cubic power law means that colliders below 2 TeV present relatively little difficulty, but those significantly above 4 TeV will have serious problems unless:

- Special locations are chosen; or
- Ways are found to cool the muons to lower emittances than now seem possible with ionization cooling. Friction cooling, cooling in crystal lattices, electron cooling, and optical stochastic cooling are being studied. With lower emittances, the required luminosities could be achieved with lower muon currents and thus less neutrino radiation. A very speculative scenario using optical stochastic cooling[10] would achieve the same luminosity with 1/50 th of the muon current and allow colliders up to 15 TeV (and luminosity over 10^{36}) to meet the dose limits. More work is needed.

2 CONTINUED THEORETICAL STUDIES

A lot of progress has been made on the theoretical design of a 4 TeV, luminosity $10^{35} cm^{-2} s^{-1}$ muon collider[5], but much still needs to be done. The highest priority items are:

- Continued study and simulation of all components of a muon collider, with particular emphasis on the ionization cooling system.
- The studies of a 4 TeV collider must continue. In particular, the neutrino radiation problem needs detailed study such a higher energy example.
- Work is also needed on the parameters of lower energy machines that could serve both as technology demonstrations and colliders aimed at specific physics objectives.

In particular the collaboration is studying machine with an energy near 100 GeV that might serve as a Higgs Factory. The final ring of such a machine would only be built after the existence and approximate mass of a light Higgs is known. The muon collider would then be able to make such a particle via the S-channel and set limits or determine its mass, width and branching ratios far better than either a hadron machine, like the LHC, or an electron machine, like LEP or a linear collider. Upgrades of such a machine to energies of 200 and 400 GeV will also be studied.

Table 1: Parameters of a $4\,\mathrm{TeV}$ and $100\,\mathrm{GeV}$ c-of-m energy machines

c of m Energy	GeV	4000	100	
p Energy	GeV	30	24	
p's/bunch	10^{13}	2.5	5	
rep x $n_{bunches}$	Hz	30	5	
p power	MW	7	2	
muons/bunch	10^{12}	2.0	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	.01
rms ϵ_n	π mm mrad	50	85	195
β^*	cm	0.3	4	9
σ_z	cm	0.3	4	9
σ_r	μm	2.8	82	180
tune shift		0.04	0.05	0.02
luminosity	$cm^{-2} sec^{-1}$	10^{35}	5 10^{31}	10^{31}

Tb.1 gives possible parameters of the 4 TeV collider[5] and a 100 GeV "Higgs Factory". In order to minimize the cost, it assumes the use of a proton driver that is an upgraded version of an existing accelerator (in this case the AGS, but it is assumed that similar performance should be possible using upgraded FNAL accelerators). Parameters are given for two modes of operation of the 100 GeV machine:

1. with maximum luminosity, but a relatively large momentum spread; and
2. with momentum spread reduced to 0.01 % for use in precision measurements and S-channel Higgs production, but a somewhat lower luminosity.

3 CURRENT EXPERIMENTAL PROGRAM

Two experiments are now under way:

- The collaboration has joined a BNL nuclear physics experiment E910 that, using a Time Projection Chamber (TPC), is measuring pion production on heavy metal targets at different energies. Data has been taken and is now being analyzed. The results will be essential in establishing a good model of such production and will allow an optimization of the target and capture geometry.
- An AGS accelerator experiment (E932) has been proposed, approved and is scheduled for running in the next few weeks. This experiment will study phase rotation in the accelerator ring, to form the very short proton bunches that our parameters require.

Results from this experiment should indicate if the current parameters are reasonable and what new equipment may be required to achieve them.

4 INITIAL EXPERIMENTAL PROGRAM

It is clear that theoretical studies alone will not establish whether a muon collider is really possible or practical. An experimental program is required. An initial 5 year program is being discussed that would consist of the following items:

4.1 Cooling Demonstration Experiment

The object of this experiment would be:

1. to test the performance of components of the ionization cooling system and establish the technical performance of such subsystems.

2. To compare the performance of these components with computer simulations so that the use of those simulations can be confidently used in the design of the complete system.

It is proposed to build a test facility in which muons from a relatively slow spill beam can be fully characterized (in all 6 dimensions) as they enter and leave a test module. This would be done by the use of counter planes interleaved with spectrometer magnets and rf deflector cavities (see Fig. 1).

The modules that would be tested in this facility would include at least one each of:

- A FOFO Lattice consisting of alternating solenoids surrounding a traveling wave linac with periodic lithium hydride absorbers at the zero axial field nodes. Elements of this type cool in the transverse direction down to modest emittances and would be used for the majority of transverse cooling stages.

- A lattice consisting of one or more current carrying Lithium Rods (lithium lenses) alternating with Linacs. Such a system, being pulsed, is less desirable than the passive FOFO lattice, but has stronger focusing and can cool to smaller emittances. Such elements would be used in the last few transverse cooling stages.

- A lattice with bends and wedges of lithium hydride placed at locations with dispersion to reduce the momentum spread, and thus longitudinal emittance of the muons. Such elements would be interspersed with the above transverse cooling elements.

4.2 Target and RF Demonstration

This experiment, like the cooling, would be performed in stages. A beam is required with the most intense and shortest proton bunches available. The experimental stages would then be:

4.2.1 Phase I (without Solenoid)

Build a target system (probably a liquid metal target) and study shock damage and cooling. Place an rf cavity at different distance from this target and study breakdown in the cavity due to the intense radiation.

4.2.2 Phase II (with Solenoid)

Surround the target with a high field (as near the final proposed 20 T as possible, but, unlike in the real case, it could be pulsed) solenoid to capture the produced pions. Build lower field solenoids to transport those pions to the rf cavity. Study total pion production and capture efficiency, study heat and radiation levels in the solenoid and elsewhere, and study breakdown in a geometry (see Fig. 2) closer to that of the muon collider under study.

4.3 Prototype Pulsed Magnet

A prototype fast pulsed magnet for the final acceleration stage of a 100 GeV machine would be designed and tested. Field precession and time jitter would be determined.

4.4 Prototype SC Magnets

A prototype Nb_3Sn large aperture dipole should be built and tested. It may be noted that the luminosity of a muon ring is inversely to the circumference and thus proportional to the average field in the collider ring. High field is thus of special interest to a muon collider.

A prototype Nb_3Sn large aperture insertion quadrupole is also needed. Field quality is of particular interest for such a magnet.

5 LONG TERM R & D

On a ten year time scale, prior to construction of a First Muon Collider, a more extensive experimental program would be required. But such a program must be conditional on the earlier experimental demonstrations that the basic technical components of a collider can be built.

A major component of this longer term R and D would be a complete demonstration of target, capture, decay channel, phase rotation, and the first stages of cooling of a real high intensity muon bunch. This might form a third phase of the Target and RF Demonstration, discussed above. For this experiment it would be important to achieve, through appropriate accelerator improvements, the actual required proton bunch length and intensity.

This would be a represent a far more realistic demonstration of the required high intensity of muon production and of cooling real, and intense, muon bunches. It would also represent the construction of items that could be used in the First Collider.

Prototype work would also be required on other magnets, rf systems, modulators etc. The definition of such a program would be one of the tasks of the earlier R and D effort.

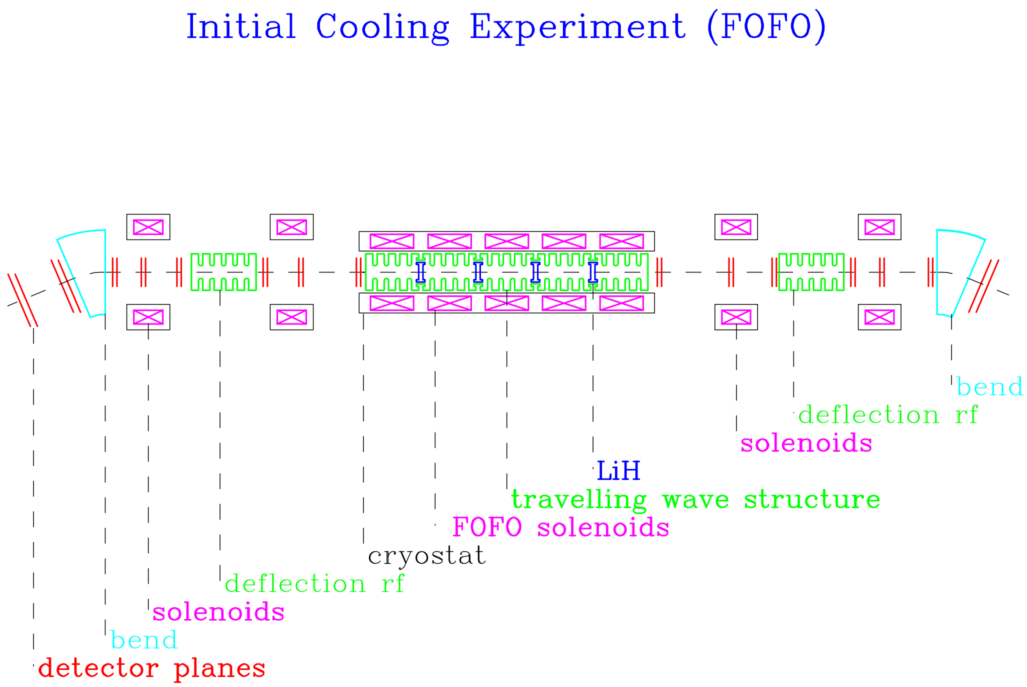

Figure 1: Schematic of the proposed Ionization Cooling Experiment.

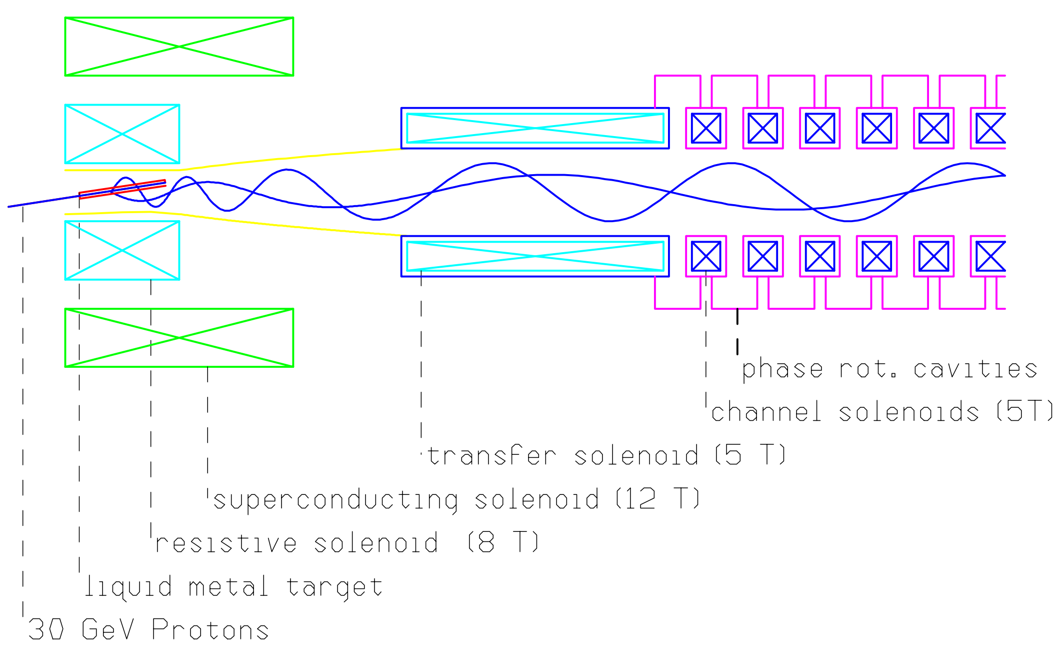

Figure 2: Heavy metal target surrounded by a high field capture solenoid followed by the phase rotation channel.

6 ACKNOWLEDGEMENTS

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