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Superconducting Muon Collider Concepts

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Introduction

High energy colliding beam machines for elementary particle research have grown so costly that funding for them has become problematical. The physics they would explore, however, remains compelling, so that new methods must be found to reach high energy if this physics is to be studied. One such new approach is the muon collider. This machine could reach multi-TeV collision energies with good luminosity at an affordable cost.

Muons belong to the same family of elementary particles, leptons, as do electrons and positrons. Thus collisions between muons would have similar, intense physics interest as collisions between electrons and positrons. The linear machine SLC at SLAC in California and the circular machine LEP at CERN in Switzerland collide electrons and positrons at multi-GeV energies per beam. Linear machines become very costly as their energy and therefore their length is increased, and circular machines, because of intense synchrotron radiation by electrons and positrons, become unmanageable at higher energy. The synchrotron radiation problem does not plague muons because of their large mass ($m_\mu=207m_e$). Thus muons offer the possibility of colliding leptons with multi-TeV energies at an affordable cost. There are no other leptons in the spectrum of elementary particles that could be used.

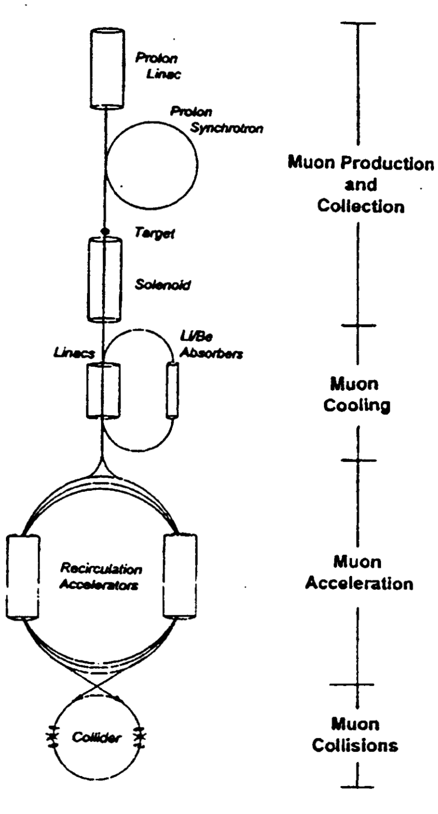

Figure 1 The muon collider, showing the principle subsystems required to produce and collect, cool, accelerate and collide muons.

The major problem with using muons is that they are unstable: they decay with a characteristic lifetime of 2.2 μs in the reaction $\mu\rightarrow e+\nu+\nu$. However, the relativistic time dilation factor extends this lifetime so that the production and collection, cooling, acceleration and collision of muons are still possible. The decay electrons must be shielded for they spread energy (about 35% the muon energy) around the collider, heating machine components and making unwanted background in the experiment.

A further problem is that muons must be made via collisions of accelerated beams with targets, e.g. $p+\text{nucleon}\rightarrow\pi^{\pm}+\ldots$, $\pi^{\pm}\rightarrow\mu^{\pm}+\nu$. This adds considerable complexity but appears feasible. An analogous though easier process is the routine production of positrons via the reaction $e^{-}+\text{nucleon}\rightarrow e^{+}+\ldots$ for use in electron-positron colliders.

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Overview

The scenario for producing $\mu^+\mu^-$ collisions is shown schematically in Fig. 1. A high intensity proton synchrotron delivers protons ($2.5*10^{13}$) in sharply defined bunches onto a stationary target with an energy of 30 GeV. Many pions are produced that decay into muons; both are collected in a solenoid magnet system with useful energies in the range 0.1-1.0 GeV. The muons ($\sim 8*10^{12}$) are then cooled, i.e. their transverse momentum as well as the spread in their longitudinal momentum is reduced. In this way, a bunch of protons is turned into a bunch of positive or negative muons ($\sim 3*10^{12}$) suitable for acceleration and collision. The energy of the muons at this stage is only 0.02 GeV.

Acceleration is accomplished in a series of recirculating linac accelerators, similar to the approach used in CEBAF. Conventional accelerators require too much time with attendant muon loss for this application. Upon reaching 2000 GeV (2 TeV) of energy, the muons ($\sim 2*10^{12}$) are transferred into a ring where positive and negative muons, transferred in successive bunches, collide and the collisions studied in a suitable detector. About 25% of the muons originally collected survive into the collider ring, and here they live for an average of ~1000 revolutions. At this point, the surviving muons are dumped and new bunches are injected.

Muon colliders were first discussed by Skrinsky et. al.[1], Neuffer[2], and others. More recently, Robert Palmer has led a nationwide effort to make a more comprehensive assessment of their possibilities. A recent report[3] and a conceptual design study[4] for the 1996 Snowmass Summer Study summarize the work, and detailed descriptions, technical parameters, and options for the required subsystems can be found there and in the references therein. Although many difficult technical challenges have been identified, no insurmountable technical hurdles have been found to date. This paper describes in abbreviated form the main features and parameters of the presently envisioned muon collider, most of it taken from the latter two reports.

Muon Production

A 30 GeV proton synchrotron operating at 15 Hz with four bunches per cycle provides protons for making muons. The protons hit a target inside a high field solenoid, Fig. 2. Positive and negative pions are produced in all directions with a wide range of momenta. Those with a forward component of momentum are transmitted as the solenoidal field curves the transverse momentum components, thereby keeping such pions from hitting the wall. A high field improves the efficiency of the process: a 20 T field is suitable, generated by superconducting coils surrounding a water-cooled Bitter magnet. The inner diameter of the channel is initially 15 cm, then expands to 30 cm as the field drops to 5 T. Pions decay

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[1] E. A. Perevedentsev and A. N. Skrinsky, Proc. 12th Int. Conf. on High Energy Accelerators, F. T. Cole and R. Donaldson, Eds., (1983) 485; A. N. Skrinsky and V. V. Parkhomchuk, Sov. J. of Nucl. Physics **12**, (1981) 3; *Early Concepts for $\mu^+\mu^-$ Colliders and High Energy Storage Rings,* Physics Potential & Development of $\mu^+\mu^-$ Colliders, 2nd Workshop, Sausalito, CA, Ed. D. Cline, AIP Press, Woodbury, NY, (1985).

[2] D. Neuffer, Colliding Muon Beams at 90 GeV, Fermilab Physics Note FN-319 (1979), unpublished; D. Neuffer, Particle Accelerators, 14, (1983) 75; D. Neuffer, Proc. 12th Int. Conf. on High Energy Accelerators, F. T. Cole and R. Donaldson, Eds., (1983) 481.

[3] R. B. Palmer, A. Sessler, A. Skrinsky, A. Tollestrup, et. al., *Muon Collider Design*, BNL Report Num. 62949, March, 1996.

[4] In preparation.

to muons throughout this channel, which is some 3.5 m long. The emerging pions and muons have energies up to 3 GeV, peaked at 0.1 GeV, and with an energy spread (rms/mean) of 100%.

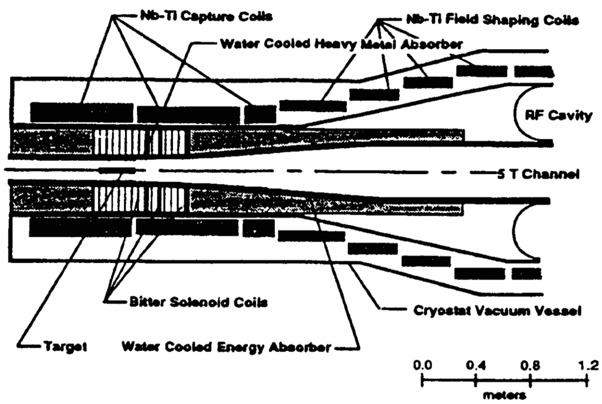

Figure 2 A high solenoid field traps low momentum pions and muons produced in a bunch in the target by a proton beam.

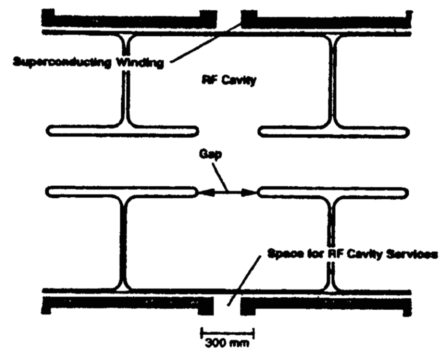

Figure 3 In the phase rotation linac, RF cavities are phased to accelerate the slower muons and slow the faster muons in the bunch.

The longitudinal momentum spread of the pions and muons is next reduced in a series of phase rotation linacs. Here, the faster particles in the bunch are slowed down and the slower ones speeded up by adjusting the phase of the RF voltage relative to the bunch of particles. Successive linacs have frequencies of 60 and 30 MHz. The channel diameter is still 30 cm and its length is ~50 m. Solenoid fields generated by superconducting coils surrounding the RF cavities control the transverse motion of the particles. Fig. 3 shows a typical section of this linac system. Muons emerge with an energy vs. position profile as shown in Fig. 4 (right). Considerable bunching has occurred relative to the straight-through case, Fig. 4 (left). The core of this spectrum is selected for transmission. Its parameters are typically 0.15 GeV mean energy, energy spread 20%, and length of bunch several meters.

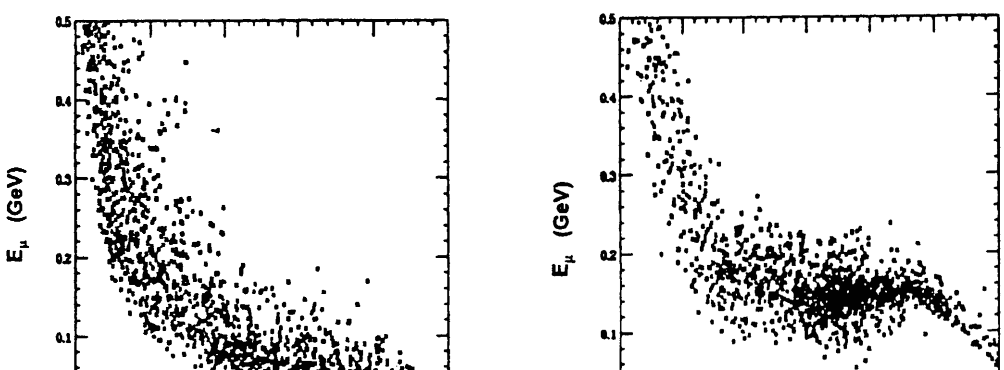

Figure 4 The left plot is the spectrum of muon energy vs. position in the bunch at the end of the phase rotation linac with the RF turned off, the right plot with it turned on. The horizontal scales are quite different. With the RF on, the muons have coalesced into a tighter bunch.

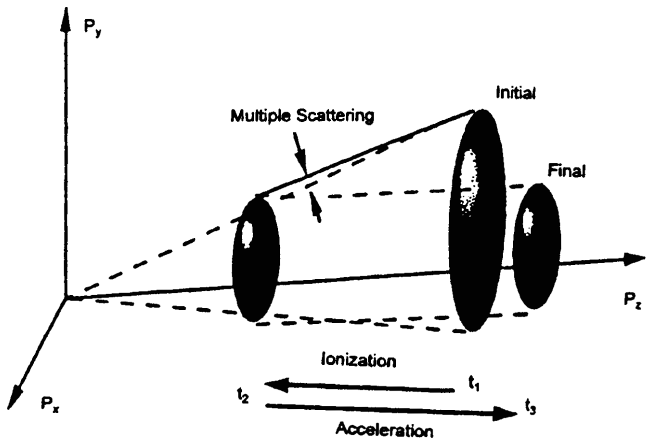

Figure 5 In ionization cooling, the three momentum components are reduced by scattering in material and only the wanted longitudinal component is restored by acceleration.

Cooling

This muon bunch is next cooled using ionization cooling, i.e., the spread in its transverse and longitudinal momentum components, or emittance, is reduced. The principle of ionization cooling to reduce transverse emittance is illustrated in Fig. 5. As the muons of this bunch pass through material, they lose momentum by ionization (desirable) slightly more quickly than they increase momentum spread by multiple scattering (undesirable). The longitudinal component of momentum is regularly restored by RF cavities. This process is repeated many times in a series of stages with lithium hydride for material and solenoid fields for focusing. Only muons can be cooled in this relatively straightforward way; all other charged particles would interact too much in the material.

The longitudinal emittance is further reduced by introducing stages with dispersion. The principle is illustrated in Fig. 6. Muons with higher momentum are passed through the thicker part of a wedge-shaped piece of material (lithium hydride) thereby losing more of their longitudinal momentum than those with lower momentum.

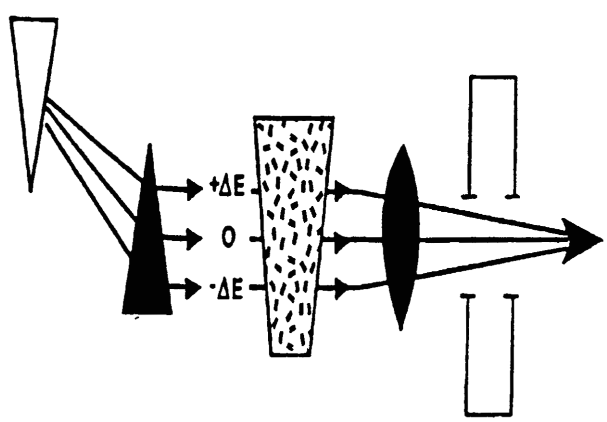

Figure 6 Bending magnets disperse the bunch so that the high momentum muons can be passed through more material in order to slow them relative to the lower momentum muons.

The design of the cooling system has some 25 stages totaling ~900 m in length with many (>100) magnets. Magnet apertures are large (>100 mm) in the beginning but get smaller (<100 mm) near the end of this section. Fields range from 7 T at the beginning to 10 T at the end.

Acceleration

From the cooling section, the muon bunch is accelerated in an injection linac operating at 100 MHz. It raises the muon energy to 1 GeV in a length of 160 m. This is followed by a sequence of four recirculating accelerators, Fig. 7 and Table 1.

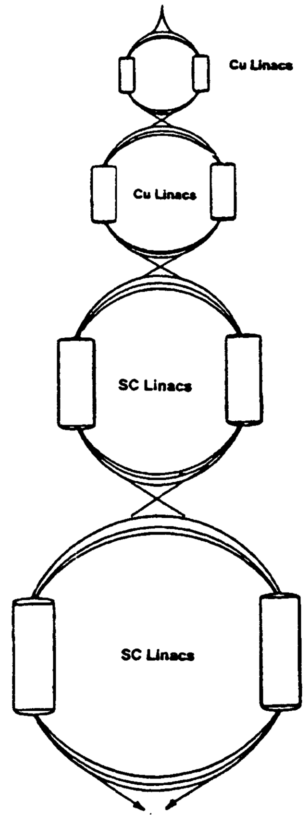

Figure 7 A sequence of recirculating accelerators raises the energy of the muon bunch (not to scale).

Table 1 Parameters for four recirculating accelerators to raise the energy from 1 GeV to 2000 GeV.

Accelerator	1	2	3	4
E_{in}, GeV	1	9.6	70	250
E_{out}, GeV	9.6	70	250	2000
RF type	Cu	SC, 4.5 K	SC, 1.8 K	SC, 1.8 K
RF frequency, MHz	100	350	800	1300
RF gradient, MV/m	5	10	15	20
Linac length, total of two, m	100	300	533	2800
Magnet field, T	3.4	4.2	5.2	6.0
Length of bending field, m	59	349	1006	6978
Number of passes	9	11	12	16

In a recirculating accelerator, the muon bunch is accelerated repeatedly in the linacs in two straight sections and switched to an arc of magnets with successively higher field after each pass through a linac. A multi-aperture magnet for the final accelerator is shown in Fig. 8. Similar magnets could be used in the other three accelerators. Such magnets are expensive, and a lower cost option for the magnets of the first three accelerators is a pulsed magnet design, Fig. 9. Only one ring of pulsed magnets, with the field ramped to follow the gain of energy in the linacs, is required in each accelerator.

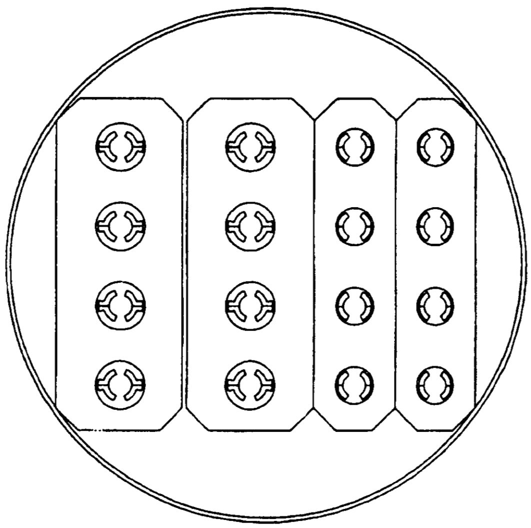

Figure 8 A multi-aperture magnet with highest field at the top left and the lowest field at the bottom right. The diameter is ~1 m.

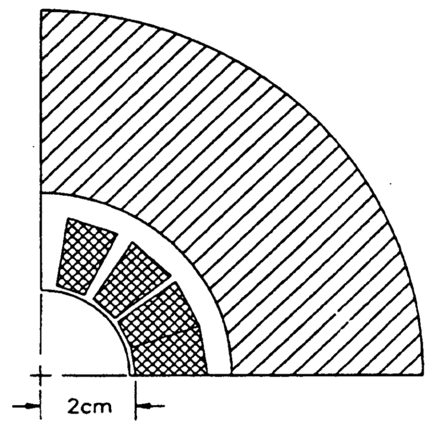

Figure 9 A quarter section of a pulsed magnet made with heavy copper conductor that could ramp to 4 T in <0.5 ms.

Upon emerging from this sequence of accelerators, the muon bunch has the full energy of 2000 GeV, an energy spread of 0.2%, and a bunch length $\sigma = 3$ mm.

<u>Collider</u>

The muon bunch is injected into the collider ring, Fig. 10, where it circulates for approximately 1000 turns with useful intensity. Close behind, a second muon bunch of opposite sign is injected to circulate in the opposite direction. Collisions occur and could be studied in two experimental regions, although only one experiment is planned initially. It is desirable to have the highest possible magnetic field in the dipole magnets of the collider ring because this shortens the path length around the ring and thus allows more collisions before decay. A minimum field of 8.5 T is specified for these magnets. The collider ring is ~8 km long and has a warm bore beam aperture of 2 cm.

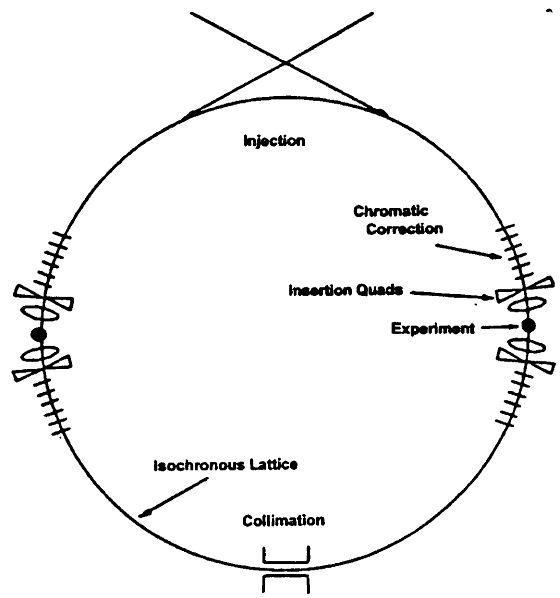

Figure 10 The collider ring with two collision regions. The highest possible fields are desirable in the bending arcs to shorten the ring, and high gradient, large aperture quads are required in the insertions to bring the muons to a tight focus. The collider ring has a circumference of 8 km for 8.5 T magnets filling 60% of the ring.

The decaying muons produce electrons with about 35 % the energy of the circulating muons. These muons are lost from the ring and produce heating in the magnets (~1 kW per meter) and troublesome background in the detector. To absorb this energy, the aperture of the magnets is lined with 6.5 cm of cooled tungsten, which reduces the heat into the magnets by ~1000. A drawing of the magnet

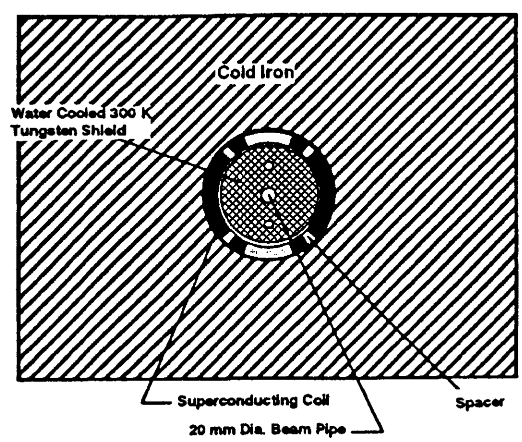

Figure 11 A dipole magnet with a thick tungsten shield inside the coil aperture. The iron yoke would be made round in practice.

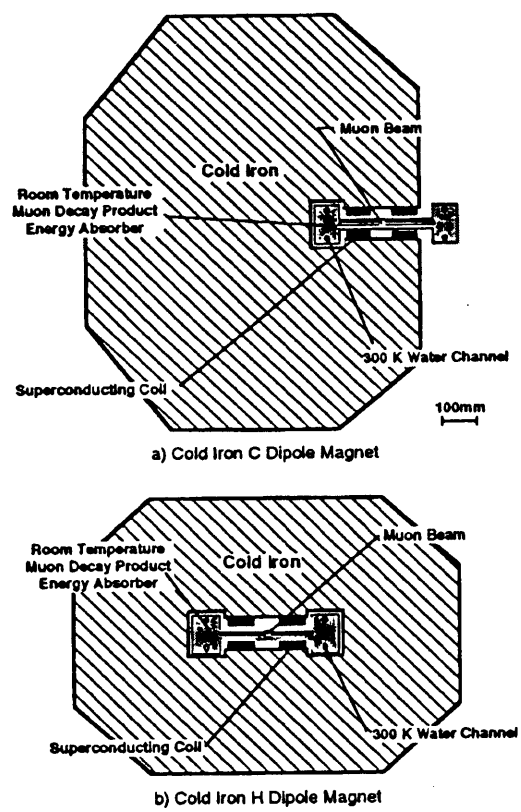

Figure 12 Alternative dipole magnet designs for the collider ring.

is shown in Fig. 11. Several alternative designs are shown in Fig. 12. In these designs, the electron energy is absorbed in a cooled dump outside the beam region.

The luminosity for collisions is $\mathscr{L} = 10^{35}\text{cm}^{-2}\text{s}^{-1}$. This rivals that of other colliders and is sufficient to carry out many interesting and significant experiments.

Summary

Work to date indicates that collisions between muons at high energy are quite possible. Many options for producing the desired beams in a cost effective way must still be evaluated in detail. A demonstration collider operating at ~1/10 the energy (250 GeV per beam) would validate the required technology while producing much interesting physics and is being discussed as a first step. The overall size of the 2000 GeV collider is small enough to fit onto the sites of existing national laboratories. This relatively modest size indicates that the overall cost would be less than that of other recent and current projects, e.g. SSC and LHC, although thorough cost estimates remain to be done. A period of R&D is needed to more completely understand the technical problems of this promising concept.