Status of Muon Collider Research and Development and Future Plans

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The status of the research on muon colliders is discussed and plans are outlined for future theoretical and experimental studies. Besides continued work on the parameters of a 3-4 and 0.5 TeV center-of-mass (CoM) energy collider, many studies are now concentrating on a machine near 100 GeV

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(CoM) that could be a factory for the s-channel production of Higgs particles. We discuss the research on the various components in such muon colliders, starting from the proton accelerator needed to generate pions from a heavy-Z target and proceeding through the phase-rotation and decay ($\pi \to \mu\,\nu_\mu$) channel, muon cooling, acceleration, storage in a collider ring and the collider detector. We also present theoretical and experimental R & D plans for the next several years that should lead to a better understanding of the design and feasibility issues for all of the components. This report is an update of the progress on the R & D since the Feasibility Study of Muon Colliders presented at the Snowmass'96 Workshop [R. B. Palmer, A. Sessler and A. Tollestrup, *Proceedings of the 1996 DPF/DPB Summer Study on High-Energy Physics* (Stanford Linear Accelerator Center, Menlo Park, CA, 1997)].

29.27.-a,29.27.Bd,29.20.-c,29.20.Dh,29.25.-a,41.85.-p,41.75.Lx,41.75.-i,13.35.Bv,13.10.+9,14.60.Ef

I. INTRODUCTION

Our present theoretical prejudice is that new physics *beyond the Standard Model* will emerge in particle-antiparticle collisions at or approaching the TeV energy scale. Both hadron-hadron and lepton-antilepton colliders will be required to discover and make precision measurements of the new phenomena. The next big step forward in advancing the hadron-hadron collider energy frontier will be provided by the CERN Large Hadron Collider (LHC), a proton-proton collider with a center-of-mass (CoM) energy of 14 TeV (for which the effective energy reach of collisions of fundamental constituents will be about 1.5 TeV) which is due to come into operation in 2005. The route towards TeV-scale lepton-antilepton colliders is less clear.

The lepton-antilepton colliders built so far have been e^+e^- colliders like the Large Electron Positron collider (LEP) at CERN and the Linear Collider (SLC) at SLAC. In a circular ring like LEP the energy lost per revolution in keV is $88.5 \times 10^4/\rho$, where the electron energy E is in GeV, and the radius of the orbit ρ is in meters. Hence, the energy loss grows rapidly as E increases. This limits the center-of-mass energy that would be achievable in a LEP-like collider. The problem can be avoided by building a linear machine (the SLC is partially linear), but with current technologies, such a machine must be very long (30-40 km) to attain the TeV energy scale. Even so, radiation during the beam-beam interaction (beamstrahlung) limits the precision of the CoM energy [1].

For a lepton with mass m the radiative energy losses are inversely proportional to m^4. Hence, the energy-loss problem can be solved by using heavy leptons. In practice this means using muons, which have a mass ≈ 207 times that of an electron. The resulting reduction in radiative losses enables higher energies to be reached and smaller collider rings to be used [2,3]. Estimated sizes of the accelerator complexes required for 100-GeV, 0.5-TeV and 4-TeV muon colliders are compared with the sizes of other possible future colliders and with the FNAL and BNL sites in Fig. 1. All of muon colliders considered, 100 GeV, 0.5 TeV and 3-4 TeV, would fit on the existing laboratory sites. Although the cost of building a muon collider is still unknown, since it would be relatively small and contained within the boundary of an existing laboratory, muon-collider proponents believe that cost will be lower than for alternative machines.

Since muons decay quickly, large numbers of them must be produced to operate a muon collider at high luminosity. Collection of muons from the decay of pions produced in proton-nucleus interactions results in a large initial phase volume for the muons, which must be reduced (cooled) by several orders of magnitude for a practical collider. The technique of ionization cooling is proposed for this [4–7], in which muons lose both transverse and longitudinal momentum when passing through matter, and only longitudinal momentum is restored by acceleration in rf cavities. This technique is uniquely applicable to muons because of their minimal interaction with matter.

Muon colliders also offer some significant physics advantages. The small radiative losses permit very small beam-energy spreads to be achieved. For example, momentum spreads as low as $\delta P/P = 0.003\%$ are believed to be possible for a low-energy collider. By measuring the time-dependent decay asymmetry resulting from the naturally polarized muons, it has been shown [8] that the beam energy could be determined with a precision of $\delta E/E = 10^{-6}$. The small beam-energy spread together with the precise energy determination would facilitate measurements of the masses and widths of any new resonant states scanned by the collider.

In addition, since the cross-section for producing a Higgs-like scalar particle in the s-channel (direct lepton-antilepton annihilation) is proportional to m^2, this extremely important process could be studied at a muon collider but not at an e^+e^- collider [9].

The decaying muons will produce copious quantities of neutrinos. Even short straight sections in a muon-collider ring will result in neutrino beams of several orders of magnitude higher intensity than presently available [10].

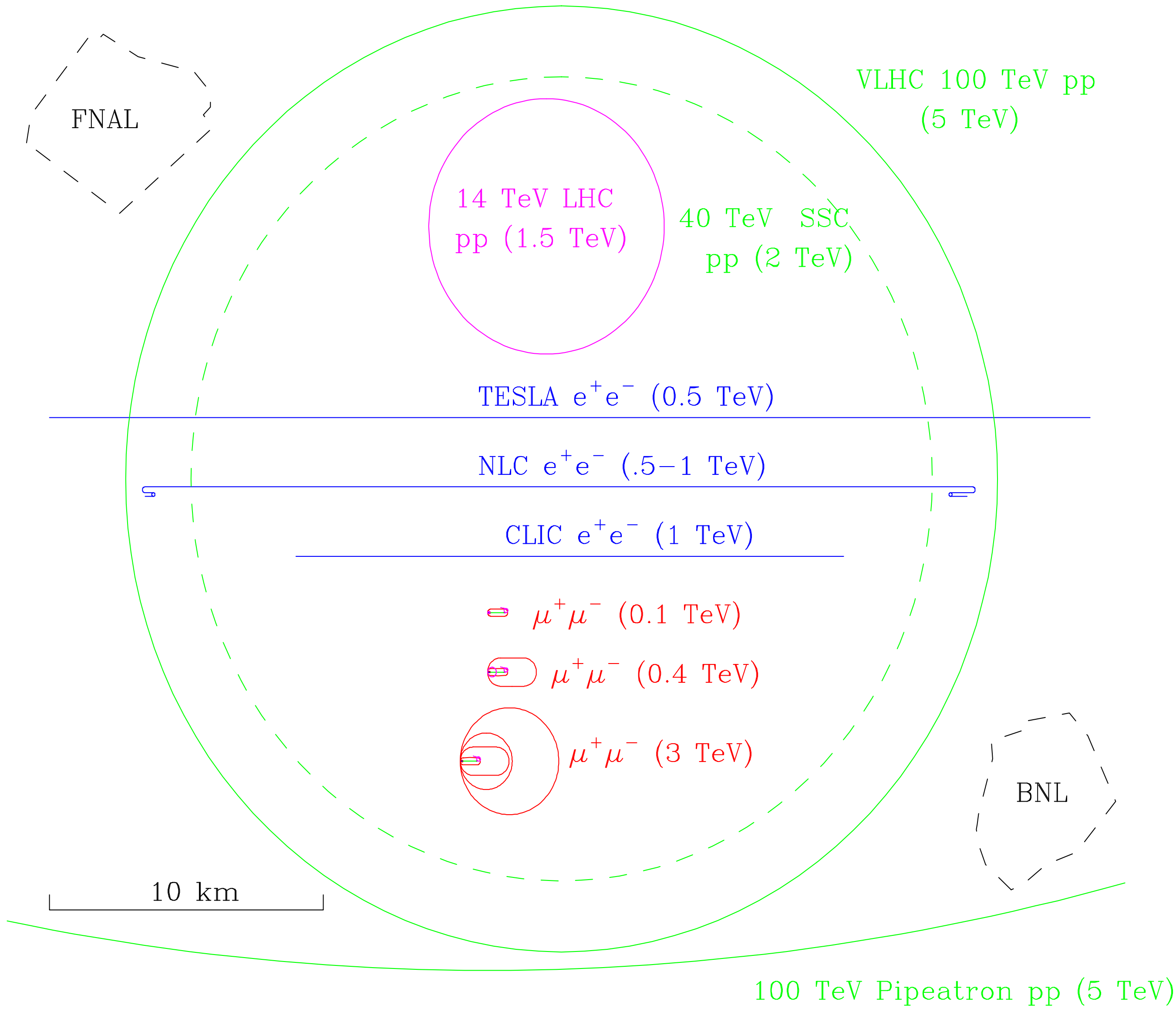

FIG. 1. Comparative sizes of various proposed high energy colliders compared with the FNAL and BNL sites. The energies in parentheses give their approximate energy reaches.

The possibility of muon colliders was introduced by G. I. Budker [2,3], A. N. Skrinsky *et al.* [11–18] and D. Neuffer [9,10,19,20]. They pointed out the significant challenges in designing an accelerator complex that can make, accelerate, and collide μ^+ and μ^- bunches all within the muon rest lifetime of $2.2\,\mu$s ($c\tau = 659$ m). Concentrated study of muon-collider design has been underway in the U.S. since 1992 in a series of workshops [21–48]. By the Sausalito workshop [25] in 1995 it was realized that with new ideas and modern technology, it may be feasible to make muon bunches containing a few times 10^{12} muons, compress their phase space and accelerate up to the multi-TeV energy scale before more than about 3/4 of them have decayed, Later, it was also found that with careful design of the collider ring and shielding it appears possible to reduce to acceptable levels the backgrounds within the detector that arise from the very large flux of electrons produced in muon decays.

These realizations led to an intense activity which resulted in the muon-collider feasibility study report [49,50] prepared for the 1996 DPF/DPB Summer Study on High-Energy Physics (the Snowmass'96 workshop). Since then, the physics prospects at a muon collider have been studied extensively [51–53], and the potential physics program at a muon collider facility has been explored in recent workshops [44] and conferences [45]. Studies [54–61] have been made for muon colliders at 3-4 TeV, 0.4-0.5 TeV and ≈ 100 GeV.

One year after Snowmass'96, encouraged by further progress in developing the muon-collider concept, together with the growing interest and involvement of the high-energy-physics community, the *Muon Collider Collaboration* became a formal entity in May of 1997. The collaboration now has over 100 members, and is led by an executive board with members from Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), Lawrence Berkeley National Laboratory (LBNL), Budker Institute for Nuclear Physics (BINP), University of California at Los Angeles (UCLA), University of Mississippi and Princeton University. The goal of the collaboration is to complete within a few years the R&D needed to determine whether a Muon Collider is technically feasible, and if it is, to design the First Muon Collider.

TABLE I. Baseline parameters for high- and low-energy muon colliders. Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV; 1 year = 10^7 s.

CoM energy	TeV	3	0.4		0.1	
p energy	GeV	16	16		16	
p's/bunch		2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill		4	4		2	
Rep. rate	Hz	15	15		15	
p power	MW	4	4		4	
μ/bunch		2×10^{12}	2×10^{12}		4×10^{12}	
μ power	MW	28	4		1	
Wall power	MW	204	120		81	
Collider circum.	m	6000	1000		350	
Ave bending field	T	5.2	4.7		3	
Depth	m	500	100		10	
Rms $\Delta P/P$	%	0.16	0.14	0.12	0.01	0.003
6d ϵ_6	$(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
Rms ϵ_n	π mm-mrad	50	50	85	195	290
β^*	cm	0.3	2.6	4.1	9.4	14.1
σ_z	cm	0.3	2.6	4.1	9.4	14.1
σ_r spot	μm	3.2	26	86	196	294
σ_θ IP	mrad	1.1	1.0	2.1	2.1	2.1
Tune shift		0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)		785	700	450	450	450
Luminosity	cm^{-2}s^{-1}	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/year				1.9×10^3	4×10^3	3.9×10^3

Table I gives the parameters of such colliders, and Figs. 2 and 3 show possible outlines of the 3-TeV and 100-GeV machines. In the latter case, parameters are given in the table for operation with three different beam-energy spreads: $\Delta P/P = 0.12$, 0.01, and 0.003%.

In all cases, proton bunches containing 2.5-5 $\times 10^{13}$ particles are accelerated to energies of 16-24 GeV. The protons interact in a target to produce $\mathcal{O}(10^{13})$ charged pions of each sign. A large fraction of these pions can be captured in a high-field solenoid (for example, a 20-T coaxial solenoid with an inner radius of 7.5 cm). Muons are produced by allowing the pions to decay into a lower-field solenoidal channel. To collect as many particles as possible within a useful energy interval, rf cavities are used to accelerate the lower-energy particles and decelerate the higher-energy particles (so-called phase rotation). With two proton bunches every accelerator cycle, the first used to make and collect positive muons and the second to make and collect negative muons, there are about 10^{13} muons of each charge available at the end of the decay channel per accelerator cycle. If the proton accelerator is cycling at 15 Hz, then in an operational year (10^7 s), about 10^{21} positive and negative muons would be produced and collected.

The muons exiting the decay channel populate a very diffuse phase space. The next step in the muon-collider complex is to *cool* the muon bunch, *i.e.*, to turn the diffuse muon cloud into a very *bright* bunch with small longitudinal and transverse dimensions, suitable for accelerating and injecting into a collider. The cooling must be done within a time that is not long compared to the muon lifetime. Conventional cooling techniques (stochastic cooling [62] and electron cooling [12]) take too long. The technique proposed for cooling muons is called ionization cooling [4,6,7], and will be discussed in detail in sec. V. Briefly, the muons traverse some material in which they lose both longitudinal and transverse momentum by ionization losses (dE/dx). The longitudinal momentum is then replaced using an rf accelerating cavity, and the process is repeated many times until there is a large reduction in the transverse phase space occupied by the muons. The energy spread within the muon beam can also be reduced by using a wedge-shaped absorber in a region of dispersion (where the transverse position is momentum dependent). The wedge is arranged so that the higher-energy particles pass through more material than lower-energy particles. Initial calculations suggest

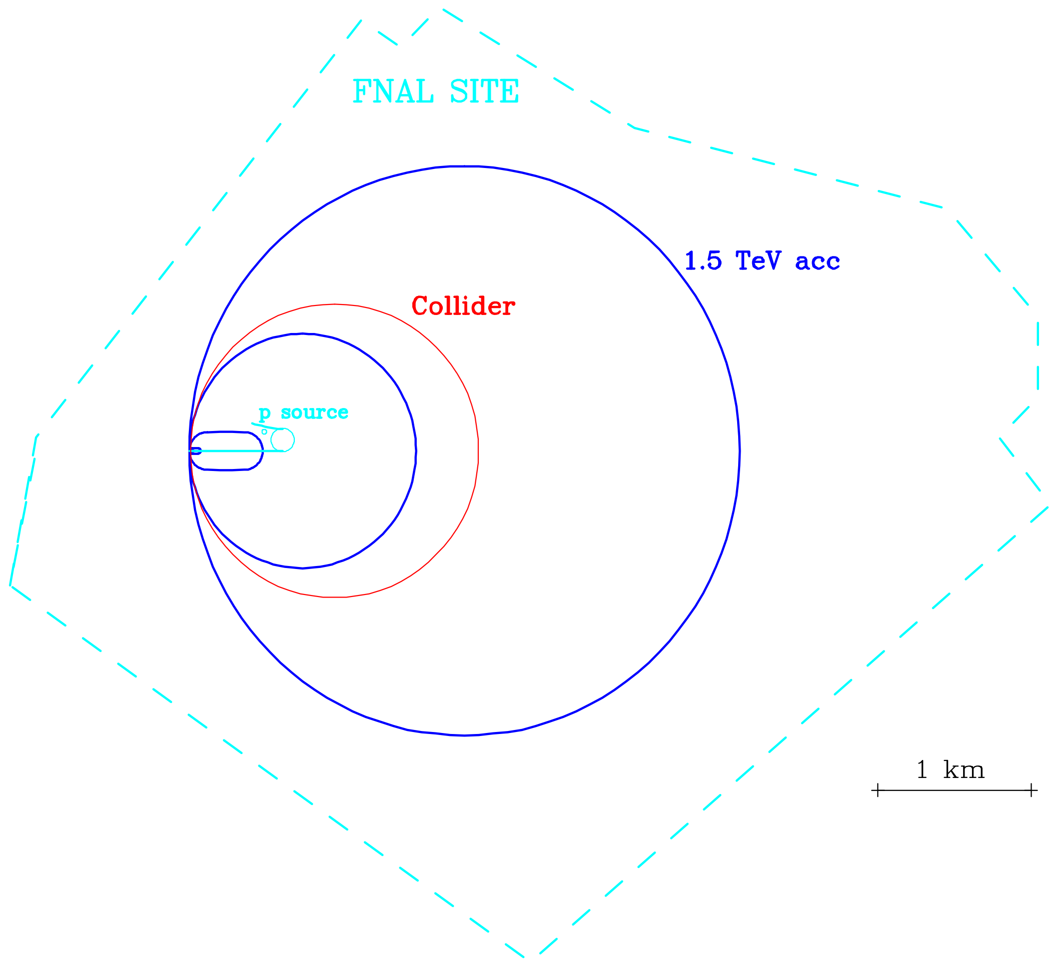

FIG. 2. Plan of a 3-TeV-CoM Muon Collider shown on the Fermi National Laboratory site as an example.

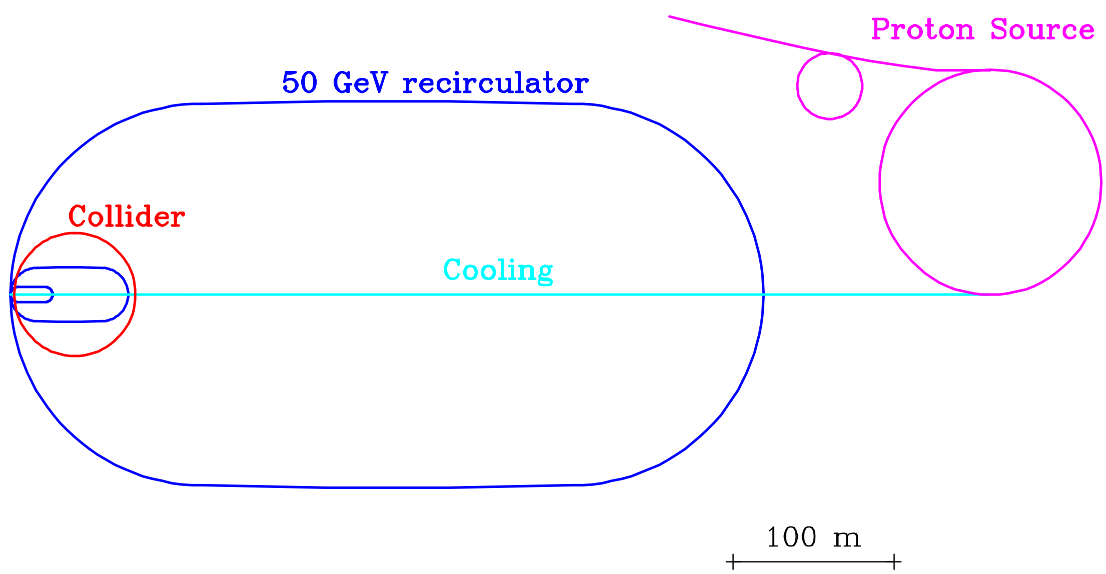

FIG. 3. Plan of a 100-GeV-CoM Muon Collider.

that the six-dimensional phase space occupied by the initial muon bunches can be reduced by a factor of 10^5-10^6 before multiple Coulomb scattering and energy straggling limit further reduction.

Rapid acceleration to the collider beam energy is needed to avoid excessive particle loss from decay. It can be achieved, initially in a linear accelerator, and later in recirculating linear accelerators, rapid-cycling synchrotron, or fixed-field-alternating-gradient (FFAG) accelerators. Positive and negative muon bunches are then injected in opposite directions into a collider storage ring and brought into collision at the interaction point. The bunches circulate and collide for many revolutions before decay has depleted the beam intensities to an uninteresting level. Useful luminosity can be delived for about 1000 revolutions independent of the beam energy, since the muon laboatory-frame lifetime and storage-ring circumference both scale with energy for a given strength of storage-ring magnetic field of order a few Tesla.

There are many interesting and challenging problems that need to be resolved before the feasibility of building a muon collider can be demonstrated. For example, (i) the heating from the very intense proton bunches may require the use of of a liquid-jet target, and (ii) to attain the desired cooling factor in the ionization-cooling channel may require the development of rf cavities with thin beryllium windows operating at liquid-nitrogen temperatures in high solenoidal fields. In addition, the development of long liquid-lithium lenses may be desirable to provide stronger radial focusing for the final cooling stages.

This article describes the status of the associated muon-collider feasibility studies, and is organized as follows. Section II gives a brief summary of the physics potential of muon colliders, including physics at the accelerator complex required for a muon collider. Section III describes the proton-driver specifications for a muon collider, and two site-dependent examples that have been studied in some detail. Section IV presents pion production, capture, and the pion-decay channel, and sec. V discusses the design of the ionization-cooling channel needed to produce an intense muon beam suitable for acceleration and injection into the final collider. Sections VI and VII describe the acceleration scenario and collider ring, respectively. Section VIII discusses backgrounds at the collider interaction point and associated detector issues. A summary of the conclusions is given in sec. IX.

II. THE PHYSICS POTENTIAL OF MUON COLLIDERS

The physics opportunities and possibilities of muon colliders have been well documented in the Feasibility Study [50] and other works [51–53]. This section begins with a brief overview of the current theoretical and experimental status of high-energy physics, then summarizes the contributions that muon colliders could make to extending our knowledge of elementary-particle physics.

A. Brief Theoretical Overview

The observed pattern of properties of all known elementary particles has been accurately characterized 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 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 – the quantum of the Higgs field thought to be directly responsible for particle masses – still eludes detection. Hence, we do not know whether EWSB is accomplished via a single Higgs particle as in the SM.

In contrast, the most-popular class of alternative theories, known as supersymmetry (SUSY), suggests a new and rich spectrum of particles at the mass scale of 0.1-1 TeV, including perhaps 5 types of Higgs bosons [53].

B. Potential Capabilities of Current Colliders

The discovery of the Higgs particle, if its mass is low enough, might be possible in the next few years at the LEP collider at CERN or at the FNAL Tevatron. Beyond this, the most-powerful collider currently under construction is the Large Hadron Collider (LHC) at the European laboratory CERN. The LHC is a proton-proton collider at 14-TeV CoM energy. It is scheduled for completion in 2005 and will probably discover the Higgs boson and/or prominent signals for physics beyond the SM (if such exist and have not already been discovered elsewhere).

The LHC and other proton colliders offer the most-established technology for reaching the high-energy frontier of elementary-particle physics. However, the physics potential of proton colliders is somewhat compromised because protons themselves are not elementary particles. The basic physics interactions take place between their quark and gluon constituents, 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 rare production of heavy particles must be disentangled from a huge pile-up of soft events. This problem becomes more acute at higher energies where the falling fundamental cross sections dictate higher luminosities leading to even-higher event rates and radiation levels.

C. The Role of Muon Colliders

Because of the experimental difficulties associated with proton colliders and the potential for other physics processes not explored in proton collisions, a strong case can be made for the complementary, precision physics studies that can be done at high-energy lepton colliders – either muon or linear electron-positron colliders.

The physics reach of the two types of lepton colliders has a large overlap. The general theme is the detailed characterization of the couplings of particles associated with electroweak symmetry breaking. But there are also differences, some of which result from differences in the physics processes, while others result from the completely different technical specifications of the lepton colliders. Thus, their 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 linear electron collider were built.

An example of this is the direct production of Higgs-like particles for which the rate varies as the square of the mass of beam particles, hence favoring muons. Furthermore, 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 100 GeV and above. The crispness of the muon initial state remains to much higher energies than for electrons, where beam radiation leads to significant degradation of the beam quality.

D. Additional Physics Possibilities at a Muon Collider

Further types of hybrid colliders are possible with the addition of muons to the menu of high-energy particle beams [44]. A muon-proton collider becomes a natural extension when a muon-collider complex is built at a site already including a high-energy proton machine, such as CERN, DESY or FNAL. Other options 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 [44]. Studies of rare muon decays can be pursued at such a facility, and precision observations of the muon anomalous magnetic moment will be both a research topic and a beam diagnostic [8]. Neutrino beams will be several orders of magnitude stronger than existing beams, permitting greatly extended studies of neutrino oscillations, nucleon structure functions, the CKM matrix, and precise indirect measurements of the W-boson mass [10,63–67].

Thus, a muon collider offers both precision studies at high energies associated with a leptonic initial state plus the flexibility for physics in secondary beams as presently found at hadron accelerators.

III. PROTON DRIVER

The overview of the required parameters is followed by a description of designs that have been studied in some detail. The section concludes with a discussion of the outstanding open issues.

A. Specifications

The proton-driver requirements are determined by the design luminosity of the collider, and the efficiencies of muon collection, cooling, transport and acceleration. The baseline specification is for a 4(7)-MW, 16(30)-GeV proton driver, with a repetition rate of 15 Hz and 10^{14} protons per cycle in 2 bunches (for the 100-GeV machine) or 4 bunches (for the higher energies) of 5×10^{13} or 2.5×10^{13} protons, respectively. Half the bunches are used to make μ^- and half for μ^+.

The total beam power is several MW, which is larger than that of existing synchrotrons. However, except for bunch length, these parameters are similar to those of Kaon factories [73] and spallation neutron sources [74]. As in those cases, the proton driver must have very low losses to permit inexpensive maintenance of components.

The rms bunch length for the protons on target has to be about 1 ns to: 1) reduce the initial longitudinal emittance of muons entering the cooling system, and 2) optimize the production of polarized muons. Although bunches of up to 6×10^{13} protons per cycle have been accelerated, the required peak current is 2000 A, which is unprecedented.

Since the collection of highly polarized μ's is inefficient (sec. IVG), the proton driver should eventually provide an additional factor of two or more in proton intensity to permit the luminosity to be maintained for polarized muon beams.

B. Possible Options

Accelerator designs are site, and to some extent, time dependent, and there have been three studies at three different energies (30 GeV [68], 16 GeV [69] and 24 GeV [70,71]; see also [72]). In general, if the final energy is higher, the required currents are lower, bunch manipulation and apertures are easier, and the final momentum spread and space-charge tune shifts are less. Lowering the final energy gives somewhat more π's/Watt, a lower rf requirement ($V_{rf} \sim E^2$) and perhaps a lower facility cost.

In the low-energy muon collider, where two bunches of 5×10^{13} are required on target, two bunches can be merged outside the driver. Two bunches would be extracted simultaneously from two different extraction ports, and fed by different transmission lines to the same target. By arranging the path lengths of the two lines appropriately, the two bunches can be exactly merged.

1. A Generic Design

A 7-MW collider-driver design based on parameters originally proposed in the Snowmass Feasibility study [68] consists of a 600-MeV linac, a 3.6-GeV booster and a 30-GeV driver. Both linac and booster are based on the BNL Spallation Neutron Source design [74], using a lower repetition rate and a lower total number of protons per pulse. For the 4-bunch case (2.5×10^{13} protons per bunch), the (95%) bunch area is assumed to be 2 eV-s at injection and < 4.5 eV-s at extraction. The driver lattice is derived from the lattice of the JHF driver using $90°$ FODO cells with missing dipoles in every third FODO cell, allowing a transition energy that is higher than the maximum energy, or perhaps imaginary.

2. FNAL Study

If a muon collider is built at an existing laboratory, then possibilities abound for symbiotic relationships with the other facilities and programs of that laboratory. For example, the proton driver for a muon collider might result from an upgrade of existing proton-source capabilities, and such an upgrade could then also enhance other future programs that use the proton beams.

Fermilab has conceived such a proton-source development plan [75] with three major components: an upgraded linac and two rapid-cycling (15 Hz) synchrotrons: a prebooster and a new booster. The two synchrotrons operate in series; the four proton bunches for the muon collider are formed in the prebooster and then accelerated sequentially in the prebooster and the booster. The plan could be implemented in stages, and other programs would benefit from each stage, but all three components are required to meet the luminosity goals of the muon colliders that have been considered so far.

Table II presents the major parameters of the two rings. Whenever the needs of the muon collider itself allow some flexibility, the parameters have been chosen to optimize the resulting facility as a proton source for the rest of the future program at Fermilab. For example, the machine circumferences and rf-harmonic numbers result in bunch trains that are compatible with the existing downstream proton machines.

A muon collider requires proton bunches that are both very intense and, at the pion-production target, very short. Strong transverse and longitudinal space-charge forces might disrupt such bunches in the synchrotrons unless measures to alleviate those effects are incorporated in the design. The Laslett incoherent-space-charge tune shift quantifies the severity of the transverse effects. A useful approximation for the space-charge tune shift $\Delta\nu_{sc}$ at the center of a round Gaussian beam is

TABLE II. Baseline proton-driver parameters of the FNAL study.

	Linac	Booster	Driver
Energy range	1 GeV	3 GeV	16 GeV
Rep. rate	15 Hz	15 Hz	15 Hz
RF voltage per turn		0.15 MV	1.5 MV
Circumference		158 m	474 m
Protons per bunch		2.5×10^{13}	2.5×10^{13}
Beam emittance [95%]		200π mm-mrad	240π mm-mrad
Bunch area [95%]		1.5 eV-s	< 2.0 eV-s
Incoherent tune shift @ Inj.		0.39	0.39

$$\Delta\nu_{sc} = -\frac{3r_p N_{\rm tot}}{2\epsilon_n \beta\gamma^2 b} \tag{1}$$

In this expression $r_p = 1.535 \times 10^{-18}$ m is the so-called electromagnetic radius of the proton, $N_{\rm tot}$ is the total number of protons in the ring, ϵ_n is the 95% normalized transverse emittance, β and γ are the usual Lorentz kinematical factors, and $b \leq 1$ is the bunching factor, defined as the ratio of the average beam current to the peak current.

The approximation (1) implies that for a given total number of protons, here 10^{14}, the factors in the denominator are the only ways to reduce the tune shift to a specified maximum tolerable value, taken as 0.4. The bunching factor can be raised somewhat by careful tailoring of beam distributions, but here a typical value of 0.25 is conservatively assumed. Achieving the desired beam intensity then requires a combination of high injection energy, here taken as 1 GeV into the first ring, and large transverse normalized emittances, here assumed to be about 200π mm-mrad. The corresponding required aperture is about 13 cm in the first ring and about 10 cm in the second ring. With such large apertures in rapid-cycling synchrotrons, careful design of the beam pipes for both rings is required to manage eddy-current effects. Two approaches are under consideration. One is a thin Inconel pipe with water cooling and eddy-current coil corrections integrated on the pipe, as in the AGS Booster. The other is a ceramic beam pipe with a conductor inside to carry beam-image currents, as in ISIS.

The Fermilab linac presently delivers a 400-MeV beam, and is capable with modest modifications of accelerating as many as 3×10^{13} protons per cycle at 15 Hz [76]. A significant upgrade is required in order to deliver 10^{14} protons at 1 GeV. The energy can be raised by appending additional side-coupled modules to the downstream end of the linac. Increasing the linac beam intensity probably means increasing both the beam current and the duration of the beam pulse. Injection into the first ring is by charge stripping of the H^- beam; the incoming beam will be chopped and injected into pre-existing buckets to achieve high capture efficiency.

The circumference of the second ring is set equal to that of the existing Fermilab Booster. This choice provides several advantages. First, the new booster could occupy the same tunnel as a relocated Booster; secondly, the beam-batch length from a full second ring matches that of the present Booster, which simplifies matching to downstream machines for other programs. The output energy of 16 GeV then results from an assumed dipole packing fraction of 0.575 and a peak dipole field of 1.3 T, which is the highest dipole field that is consistent with straightforward, nonsaturating design of magnets having thin silicon-steel laminations. Driving such magnets into saturation would cause significant heating of the magnet yoke as well as potential problems with tracking between the dipoles and quadrupoles.

The prebooster also has 1.3-T dipole fields, and its circumference is one third that of the new booster; it operates at an rf harmonic number $h = 4$. The strategy for achieving the required short bunches at the target while alleviating space-charge effects in the rings is to start with four bunches occupying most of the circumference of the first small ring in order to keep the bunching factor large, and to do a bunch-shortening rotation in longitudinal phase space just before extraction from the second synchrotron. The four bunches are accelerated in the first ring to 3 GeV, then transferred bunch-to-bucket into the second ring with its harmonic number $h = 12$. At that energy, the kinematic factor in the tune-shift formula (1) is large enough to compensate for the smaller bunching factor in the second ring. The transfer energy of 3 GeV between the two rings roughly equalizes their space-charge tune shifts.

Both rings employ separated-function lattices with flexible momentum compaction in order to raise their transition energies above their respective extraction energies. This not only avoids having to accelerate beam through transition but also provides other advantages. Intense beams are not subject to certain instabilities such as the negative-mass instability below transition and empirically seem less susceptible to other instabilities such as microwave instability. Also, the negative natural chromaticity is beneficial for stabilizing the beam below transition, thereby perhaps obviating the need for sextupole correctors, especially in the first ring. Having transition not too far above extraction also provides substantial bucket area in which to accomplish beam-shortening rf manipulations.

Several potential sources of instabilities in the rings have been examined [77], as well as the possibility of compensating the latter effect by inductive inserts in the rings. Space charge is the main factor affecting the stability of the beams; the rings appear to be safe from longitudinal- and transverse-microwave instabilities. Of course, standard stabilizing methods such as active dampers are necessary to counteract some of the instabilities. Flexible momentum-compaction lattices would be useful not only to raise the transition energy above the extraction energy, but also to allow fast changes in the slip factor to facilitate bunch-narrowing manipulations at extraction time. Compensation of longitudinal space-charge effects by means of ferrite-loaded inductive inserts would be useful, especially for the first ring.

The magnet-power-supply circuit for each ring is a 15-Hz resonant system like that of the existing Booster, with dipoles and quadrupoles electrically in series. This implies that the second ring will accelerate only one batch at a time from the first ring, which is all that the muon collider needs. Adding about 15% of second harmonic to the magnet ramp reduces the required peak accelerating voltage by about 25%, which is probably worth doing, especially for the second ring with its large voltage requirement.

One of the advantages of a two-ring system is that the two rings divide the work of accelerating the beam. The rf system of the first ring is relatively modest because of its small circumference and small energy gain; that of the second ring is simplified because its high injection energy means a small rf-frequency swing [78].

ESME simulations of longitudinal motion show that the rms bunch length is 2 nsec as desired after the bunch rotation that occurs just before extraction from the second synchrotron [79]. The bunch rotation creates momentum spreads of about 2% with longitudinal emittances of about 2 eV-s per bunch. Such spreads would contribute a few cm in quadrature to the beam size for a short period before extraction. This is thought to be tolerable, given the large apertures that are required in any case. High injection energies help to alleviate these longitudinal effects, which result from space-charge voltages having the same $1/\beta\gamma^2$ kinematic dependence as the transverse tune shifts.

3. AGS Upgrade

The third study [70] is of an upgrade to the BNL AGS, which should produce bunches larger than those required for the muon collider, but at a lower repetition rate. The AGS presently produces 6×10^{13} protons in eight bunches at 25 GeV and 0.6 Hz. A 2.5-GeV accumulator ring in the AGS tunnel and AGS power-supply upgrade to 2.5-Hz operation would match the repetition rate to the 10-Hz repetition rate of the booster. This would generate 11MW beam power. With an additional upgrade of the linac energy to 600 MeV, an intensity of 2×10^{14} protons per pulse in four bunches of 5×10^{13} at 25 GeV and 2.5 Hz could be reached, raising the power to 2 MW. Other options are also under consideration, such as the addition of a second booster and 5-Hz operation, that would reach the baseline specification of 4 MW.

The AGS momentum acceptance of $\pm 3\%$ requires that the longitudinal phase space occupied by one bunch be less than 4.5 eV-s. This high bunch density in turn generates stringent demands on the earlier parts of the accelerator cycle. In particular, Landau damping from the beam momentum spread may guard against resistive wall instabilities during injection and longitudinal microwave instabilities after transition. Beam stability can be restored with a more-powerful transverse-damping system and possibly a new low-impedance vacuum chamber. The transverse microwave instability is predicted to occur after transition crossing unless damped by Landau damping from incoherent tune spread or possibly high-frequency quadrupoles.

C. Progress and Open Issues

Conventional rf manipulations appear able to produce 1- to 2-ns proton bunches if enough rf voltage to overcome the space-charge forces is used, and the beam energy is far enough from transition so the final bunch rotation is fast. Both simulations and experimental work have been directed at demonstrating that a short pulse can be produced easily.

An experiment at the AGS has shown that bunches with $\sigma = 2$ ns can be produced near transition from bunches with $\sigma \sim 8$ ns by bunch rotation [80,81]. In this experiment, the AGS was flattoped near transition (~ 7 GeV) while the γ_t-jump system was used to bring the transition energy suddenly to the beam energy, letting the bunch-energy spread expand and bunch length contract. The experiment also demonstrated that bunches are stable over periods of 0.1 s. In addition, the data were used to measure the lowest two orders of the momentum-compaction factor.

The AGS bunch area, 1.5 eV-s, was comparable to that expected in the proton driver, but the bunch charge (though large as 3-5 $\times 10^{12}$ protons) was only about one tenth of that required by the muon target. The proton driver would use an FMC lattice which would give much better control of the transition energy, permitting a very fast final bunch rotation. In addition, the rf frequency would be higher than that of the AGS so the buckets (and bunches) would initially be only half as long. Thus bunch rotation could be expected to be easier with the new machine, which should compensate for the larger charge.

Simulations with the ESME code have also shown that 1-2 ns bunches of 5×10^{13} can be produced at extraction in a 16-GeV ring with the rf and emittance shown in Table II.

The efficiency of capturing and accelerating beam may be increased by compensation of 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 of the opposite sign to the capacitive space charge). Initial experiments at the KEK proton synchrotron [82] and Los Alamos PSR [83] with short ferrite inserts appear to show a reduction in the synchrotron oscillation frequency shift caused by space charge and a decrease in the necessary rf voltage to maintain a given bunch intensity. Further experiments are needed to demonstrate this technique fully.

The high rf voltage and beam power and the relatively small size of the machine require high-gradient, high-power rf cavities. Fermilab, BNL and KEK are collaborating on research and development of such type of cavities **give reference**. This work includes the study of magnet alloys and hybrid cavities using both ferrite and new magnet alloys, high-power amplifiers and beam-loading compensation.

The employment of barrier-bucket rf cavities can effectively generate and manipulate a gap in the beam and reduce the space-charge effect. Two barrier cavities have been built by BNL and KEK and will be installed on the AGS for test **give reference**. Another high-gradient barrier cavity using magnet alloys is under study at Fermilab **give reference**.

IV. PION PRODUCTION, CAPTURE AND PHASE-ROTATION CHANNEL

This section first discusses the choice of target technology, optimization of the target geometry, and then describes design studies for the pion capture and phase-rotation channel. Prospects for polarized muon beams are discussed in detail. The section concludes with an outline of an R&D program into target and phase-rotation issues.

Figure 4 gives an overview of the configuration for production of pions by a proton beam impinging on a long, thin target, followed by capture of low-momentum, forward pions in a channel of solenoid magnets with rf cavities to compress the bunch energy while letting the bunch length grow: thus rotating the bunch in longitudinal phase space.

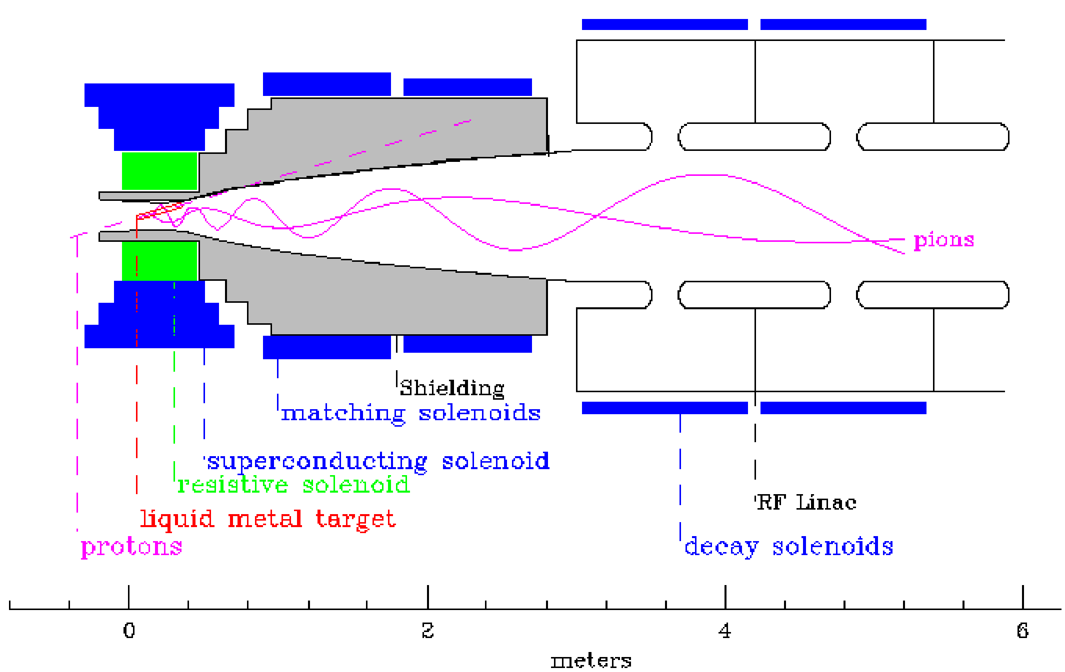

FIG. 4. Schematic view of pion production, capture and initial phase rotation: A pulse of 16-30 GeV protons is incident on a skewed target inside a high-field solenoid magnet followed by a decay and phase-rotation channel.

A. Pion production

To achieve the luminosities for muon colliders presented in Table I, 2×10^{12} (or 4×10^{12} in the 100-GeV CoM case) muons of each sign must be delivered to the collider ring in each pulse. We estimate that a muon has a probability of only 1/4 of surviving the processes of cooling and acceleration, due to losses in beam apertures or by decay. Thus, 0.8×10^{13} muons (1.6×10^{13} at 100 GeV) must exit the phase-rotation channel each pulse. For pulses of 2.5×10^{13} protons (5×10^{13} for 100 GeV), this requires 0.3 muons per initial proton. Since the efficiency of the phase-rotation channel is about 1/2, this is equivalent to a capture of about 0.6 pions per proton: a very high efficiency.

The pions are produced in the interaction of the proton beam with the primary target. Extensive simulations have been performed for pion production from 8-30 GeV proton beams on different target materials in a high-field solenoid [50,84,85]. Three different Monte Carlo codes [86–89] predict similar pion yields despite significant differences in their physics models. Some members of the Collaboration are involved in an AGS experiment [90] to measure the yield of very low momentum pions, which will validate the codes in the critical kinematic region.

The pion yield is greater for relatively high-Z materials, and for these, the pion yield is maximal for longitudinal momenta of the same order as the average transverse momentum (≈ 200 MeV/c). Targets of varying composition ($6 < Z < 82$), radii (0.2-3 cm) and thicknesses (0.5-3 nuclear interaction lengths (λ_I)) have been explored [85]. For a fixed number of interaction lengths, the pion yield per proton rises almost linearly with proton energy, and hence almost proportional to the energy deposited in the target. The yield is higher for medium- and high-Z target materials, with a noticeable gain at $Z > 26$ for 30-GeV proton beams, but with only a minor effect for $E \leq 16$ GeV, as shown in Fig. 5 where results of detailed MARS13(98) [87] simulations are presented. The curves show the meson yield $(\pi + K)$ from the targets in the momentum interval $0.05 \leq P \leq 0.8$ GeV/c (labeled Y) and the number of mesons that are both captured in the high-field solenoid and transported into the decay channel (labeled YC). The typical statistical error is a few percent.

B. Target

The target should be 2-3 interaction lengths long to maximize pion production. A high-density material is favored to minimize the size and cost of the capture solenoid magnet. Target radii larger than about 1 cm lead to lower pion rates due to reabsorption, while smaller-diameter targets reduce the added production from secondary interactions. Tilting the target by 100-150 mrad minimizes loss of pions by absorption in the target after one turn on their helical trajectory [56,91]. Another advantage of the tilted target geometry is that the high-energy and neutral components of the shower can be absorbed in a water-cooled beam dump to the side of the focused beam (see Fig. 4).

About 30 kJ of energy is deposited in the target by each proton pulse (10% of the beam energy). Hence, the target absorbs 400 kW of power at the 15-Hz pulse rate. Cooling of the target via contact with a thermal bath would lead to unacceptable absorption of pions, and radiative cooling is inadequate for such high power in a compact target. Therefore, the target must move so as to carry the energy deposited by the proton beam to a heat exchanger outside the solenoid channel.

Both moving-solid-metal and flowing-liquid targets have been considered, with the latter as the currently preferred solution. A liquid is relatively easy to move, easy to cool, can be readily removed and replaced, and is the preferred target material for most spallation neutron sources under study. A liquid flowing in a pipe was considered, but experience at ISOLDE with short proton pulses [92] as well as simulations [93,94] suggest serious problems in shock damage to the pipe. An open liquid jet is thus proposed.

A jet of liquid mercury has been demonstrated [93] but not exposed to a beam. For our application, safety and other considerations favor the use of a low-melting-point lead alloy rather than mercury. Gallium alloys, though with lower density, are also being considered. Experimental and theoretical studies are underway to determine the consequences of beam shock heating of the liquid. It is expected that the jet will disperse after being exposed to the beam. The target station must survive damage resulting from the violence in this dispersion. This consideration will determine the minimum beam, and thus jet, radius.

For a conducting liquid jet in a strong magnetic field, as proposed, strong eddy currents will be induced in the jet, causing reaction forces that may disrupt its flow [95,96]. The forces induced are proportional to the square of the jet radius, and set a maximum for this radius of order 5-10 mm. If this maximum is smaller than the minimum radius set by shock considerations, then multiple smaller beams and jets could be used; *e.g.*, four jets of 5-mm radius with four beams with $2.5\ 10^{13}$ protons per bunch. Other alternatives include targets made from insulating materials such as liquid PtO_2 or Re_2O_3), slurries (*e.g.*, Pt in water), or powders [97].

A moving solid-metal target is not the current baseline solution, but is a serious possibility. In this case,the target could consist of a long flat band or hoop of copper-nickel that moves along its length (as in a band saw) [98]. The

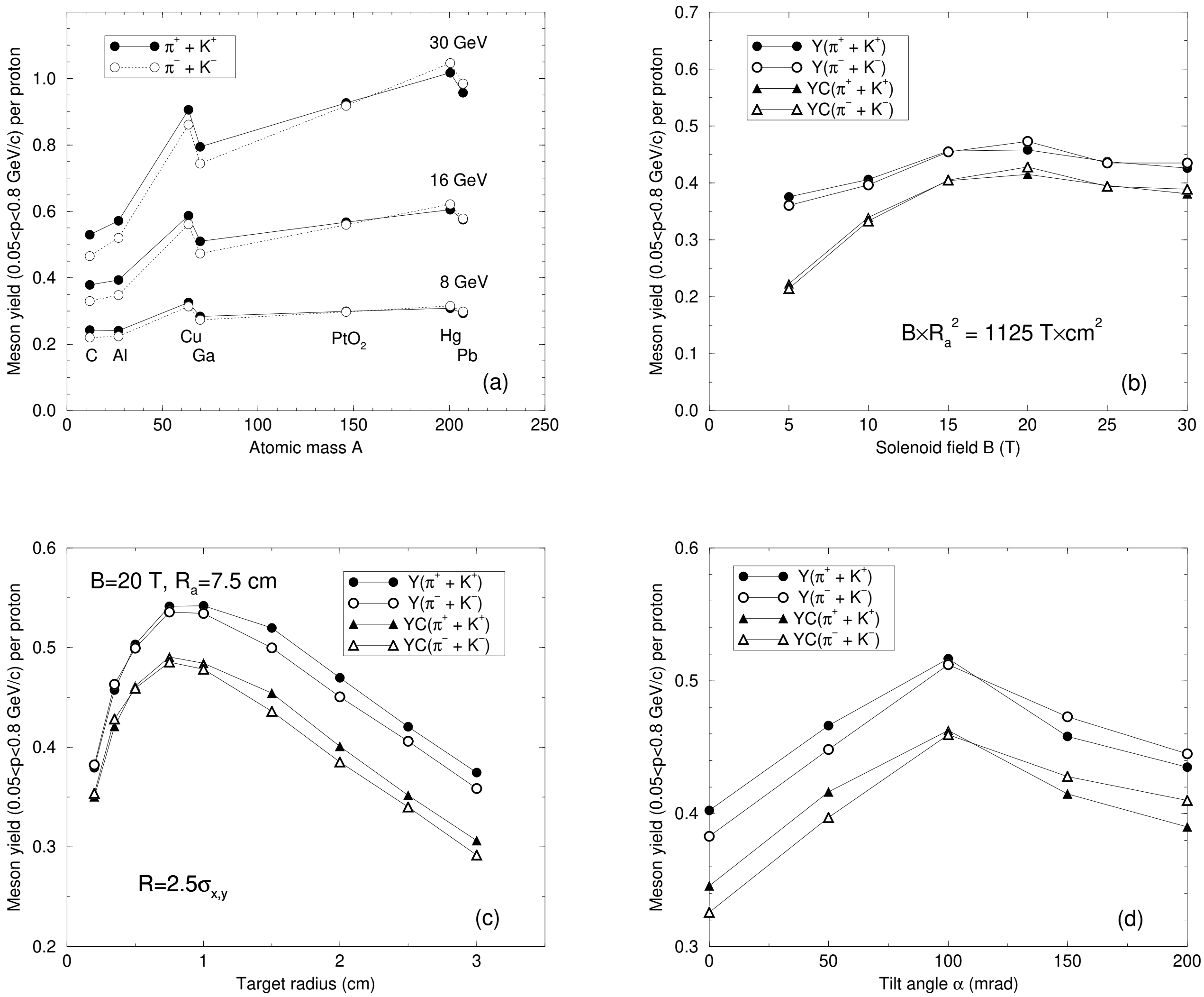

FIG. 5. Meson yield $(\pi + K)$ from different targets tilted by angle α in a solenoidal field B of aperture R_a as calculated with the MARS13(98) code. The target is aligned along the beam. The curves labeled YC show mesons that are transported into the decay channel. (a) Yield from a 1.5-λ_I, 1-cm-radius target irradiated with 8-, 16- and 30-GeV proton beams ($\sigma_x = \sigma_y = 4$ mm) as a function of target atomic mass ($B = 20$ T, $R_a = 7.5$ cm, $\alpha = 0$); (b) Yield from a 3-λ_I, 1-cm-radius gallium target tilted at $\alpha = 150$ mrad in a 16-GeV proton beam ($\sigma_x = \sigma_y = 4$ mm) *vs.* solenoid field for a fixed adiabatic invariant BR_a^2; (c) Yield as a function of radius of a 3-λ_I gallium target in a 16-GeV proton beam ($\sigma_x = \sigma_y = 4$ mm, $B = 20$ T, $R_a = 7.5$ cm, $\alpha = 100$ mrad); (d) Yield from a 3-λ_I, 1-cm-radius gallium target *vs.* tilt angle between the axis of the capture solenoid and the proton beam for a 16-GeV proton beam ($\sigma_x = \sigma_y = 4$ mm, $B = 20$ T, $R_a = 7.5$ cm).

band would be many meters in length, would be cooled by gas jets away from the target area, and would be supported and moved by rollers, as shown in Fig. 6.

The choice and parameters of the target are a critical question that needs resolution. Only an experiment in a magnetic field and in a beam will settle it, as discussed in sec. IVH.

C. Capture

To capture all pions with transverse momenta $P_\perp$ less than their typical value of 200 MeV/c, the product of the capture solenoid field B and its radius R_a must be greater than 1.33 T-m. The use of a high field and small radius is preferred to minimize the corresponding transverse emittance, which is proportional to BR^2: for a fixed transverse-

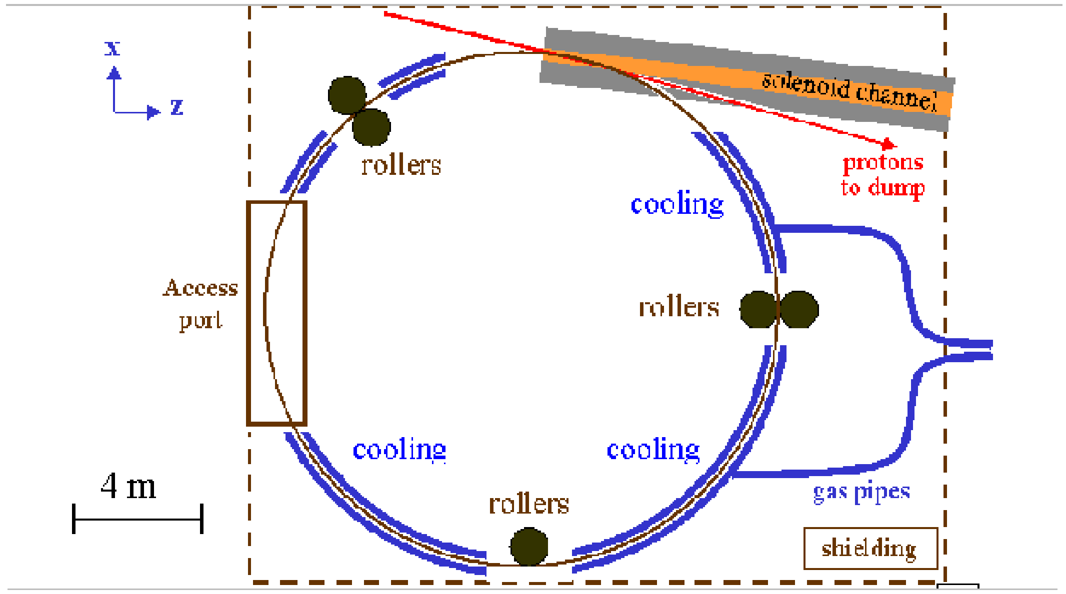

FIG. 6. Alternative concept of a solid metal target in the form of a rotating Cu-Ni band.

momentum capture, this emittance is thus proportional to R. A field of 20 T and 7.5 cm radius was chosen on the basis of simulations described below. This gives $BR = 1.5$ T-m, $BR^2 = 0.1125$ T-m^2 and a maximum transverse-momentum capture of $P_\perp = 225$ MeV/c.

A preliminary design [99] of the capture solenoid has an inner 6-T, 4-MW, water-cooled, hollow-conductor magnet with an inside diameter of 24 cm and an outside diameter of 60 cm. There is space for a 4-cm-thick, water-cooled, heavy-metal shield inside the coil. The outer superconducting magnet has three coils, with inside diameters of 60 to 80 cm. It generates an additional 14 T of field at the target and provides the required tapered field to match into the decay channel. Such an hybrid solenoid has parameters compatible with those of existing magnets [100].

The 20-T capture solenoid is matched via a transfer solenoid [84] into a decay channel consisting of a system of superconducting solenoids with the same adiabatic invariant $BR^2 \propto RP_\perp$. Thus, for a 1.25-T decay channel, B drops by a factor of 1/16 between the target and decay channel, R and $P_\perp$ change by factors of 4 and 1/4, respectively. This permits improved acceptance of transverse momentum within the decay channel, at the cost of an increased spread in longitudinal momentum. Figure 5(b) shows the meson yield as a function of field in the capture solenoid, with the radius of the capture solenoid adjusted to maintain the same BR_a^2 as in the decay channel. The optimum field is 20 T in the capture solenoid.

If the axis of the target is coincident with that of the solenoid field, then there is a relatively high probability that pions re-enter the target after one cycle on their helical trajectory and are lost due to nuclear interactions. When the target and proton beam are set at an angle of 100-150 mrad with respect to the field axis [85], the probability for such pion interactions at the target is reduced, and the overall production rate increased by 60%, as shown in Fig. 5(d).

In sum, the simulations indicate that a 20-T solenoid of 16 cm inside diameter surrounding a tilted target will capture about half of all produced pions. With target efficiency included, about 0.6 pions per proton will enter the pion decay channel [85].

D. Phase-Rotation Linac

The pions, and the muons into which they decay, have a momentum spread with an rms value of approximately 100% and a peak value at about 200 MeV/c. 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. Several studies have been made of the design of this system, using differing ranges of rf frequency, delivering different final muon momenta, and differing final bunch lengths. In all cases, muon capture efficiencies of close to 0.3 muons per proton are obtained. Until the early stages of the ionization cooling have been designed, it is not yet possible to choose between them. Independent of the above choices is a question of the location of the focusing solenoid coils and rf cavity design, as discussed below in the sec. IVF.

1. Lower-Energy, Longer-Bunch Example

This example captures muons at a mean kinetic energy of 130 MeV. Table III gives parameters of the linacs used. Monte Carlo simulations [58], with the program MUONMC [101], were done using pion production calculated by ARC [86] for a copper target of 1-cm radius at an angle of 150 mrad. A uniform solenoidal field was assumed in the phase rotation, and the rf was approximated by a series of kicks.

TABLE III. Parameters of the Lower-Energy Phase-Rotation Linacs

Linac	Length (m)	Frequency (MHz)	Gradient (MeV/m)
1	3	60	5
2	29	30	4
3	5	60	4
4	5	37	4

Figure 7 shows the energy *vs.* ct at the end of the decay and phase-rotation channel. The abscissa ct is a measure of bunch length at the end of the channel: the total transit time of each π/μ is multiplied by the velocity of light with total length of the channel subtracted. Thus a photon at the center of the proton bunch at the target arrives at $ct = 0$ m. A loose final bunch selection was defined with an energy 130 ± 70 MeV and bunch ct from 3 to 11 m. With this selection, the rms energy spread is 16.5%, the rms ct is 1.7 m, and there are 0.385 muons per incident proton. A tighter selection with an energy 130 ± 35 MeV and bunch ct from 4 to 10 m gave an rms energy spread of 11.7%, rms ct of 1.3 m, and contained 0.305 muons per incident proton.

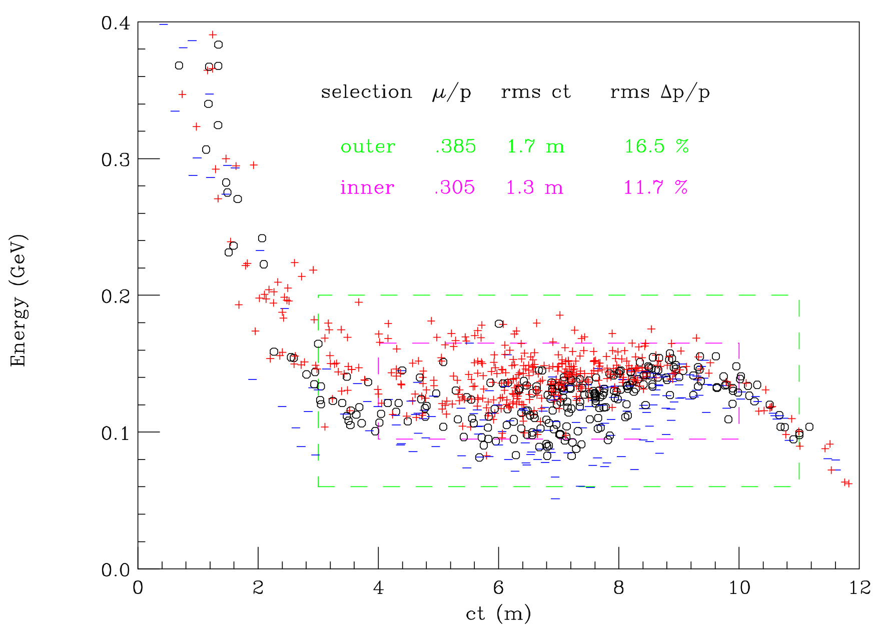

FIG. 7. Energy *vs.* ct of μ's at end of the lower-energy phase-rotation channel. The symbols +, o and $-$ denote muons with polarization $P > \frac{1}{3}$, $-\frac{1}{3} < P < \frac{1}{3}$ and $P < -\frac{1}{3}$, respectively.

In this example the captured muons have a mean kinetic energy close to 320 MeV. It is based on a Monte Carlo study [102] which uses the updated MARS pion production model [88] to generate pions created by 16-GeV protons on a 36-cm-long, 1-cm-radius coaxial gallium target. Figure 8 shows the longitudinal phase space of the muons at the end of an 80-m-long channel with cavities of frequency in the 30-90 MHz range and acceleration gradients of 4-18 MeV/m. A total of 0.33 muons per proton fall within the indicated cut (6 m$\times$300 MeV). The rms bunch length inside the cut is 148 cm and rms energy spread is 62 MeV. The normalized 6-D emittance is 217 cm^3 and the transverse part is 1.86 cm.

A sample simulation with lithium hydride absorbers regularly spaced in the last 60 m of a 120-m decay channel and with compensating acceleration provided captures 0.297 muons with mean kinetic energy of about 380 MeV in a (6 m$\times$300 MeV) cut. The longitudinal phase space is about the same as in the previous example but the transverse part shrinks to 0.95 cm due to ionization cooling which reduces the 6-D phase space to 73.5 cm^3.

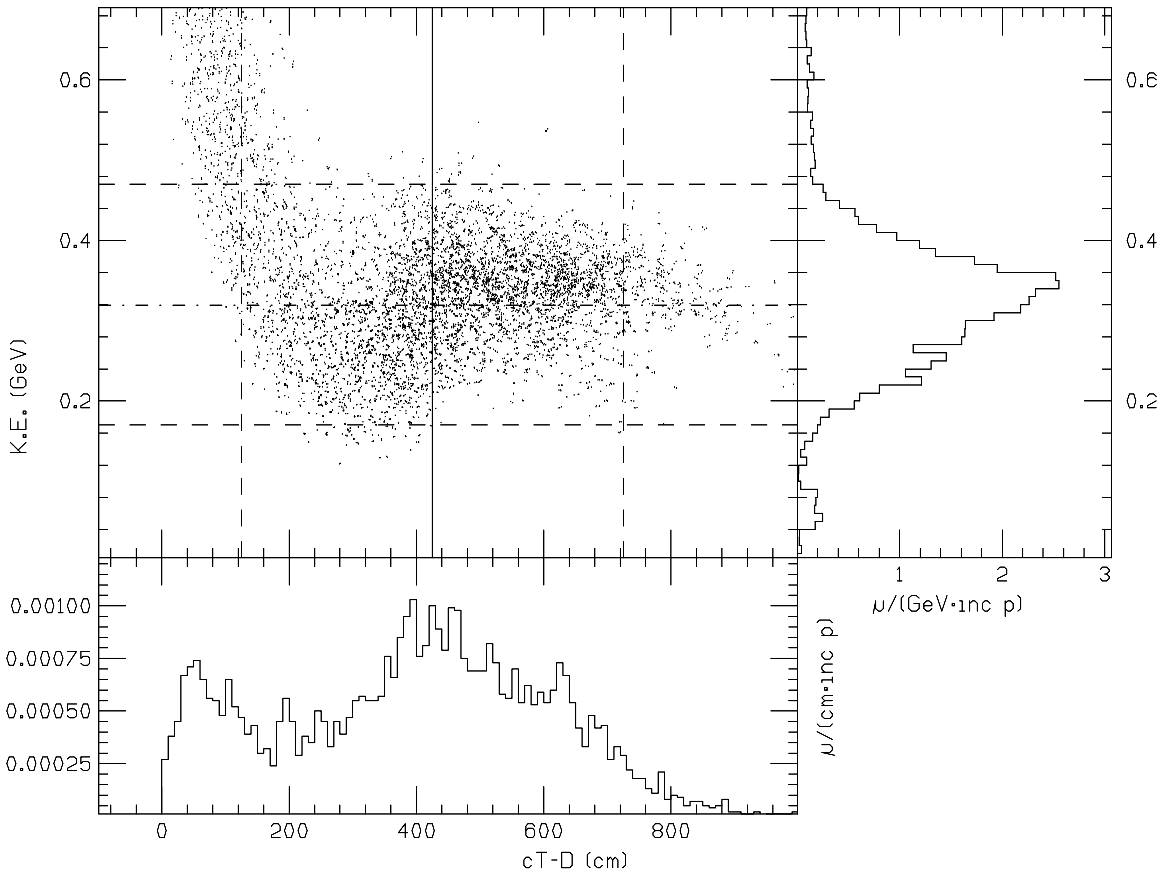

FIG. 8. Longitudinal phase space at the end of decay channel with projections onto time and energy axes. The four dashed lines delineate the region deemed acceptable for the cooling channel.

E. Use of Both Signs

Protons on the target produce pions of both signs, and a solenoid will capture both, but the subsequent rf systems will have opposite effects on each sign. The proposed baseline approach uses two separate proton bunches to create separate positive and negative pion bunches and accepts the loss of half the pions/muons during phase rotation.

If the pions can be charge separated with limited loss before the phase-rotation cavities are reached, then higher luminosity may be obtained. The separation of charged pions in a curved solenoid decay line was studied in [84]. Because of the resulting dispersion in a bent solenoid, an initial beam of radius R with maximum-to-minimum momentum ratio F will require a large beampipe of radius $(1+F)R$ downstream to accommodate the separated beams. A septum can then be used to capture the two beams into separate channels. Typically the reduction in yield for a curved solenoid compared to a straight solenoid is about 25% (due to the loss of very low and very high momentum pions to the walls or septum), but this must be weighed against the fact that both charge signs are captured for an overall net gain. A disadvantage is that this charge separation takes place over several meters of length during which time the beam spreads longitudinally. This makes capture in an rf phase-rotation system difficult, although a large-aperture cavity system could be incorporated in the bent solenoid region to alleviate this. The technique deserves further study and may be useful to consider as an intensity upgrade to a muon-collection system.

F. Solenoids and RF

As noted above, capture using higher frequencies appears to be less efficient, and most studies now use frequencies down to 30 MHz. Such cavities, when conventionally designed, are very large (about 6.6 m diameter). In the Snowmass study [103] a reentrant design reduced this diameter to 2.52 m, but this is still large, and it was first assumed that the 5-T focusing solenoids would, for economic reasons, be placed within the irises of the cavities (see Fig. 9).

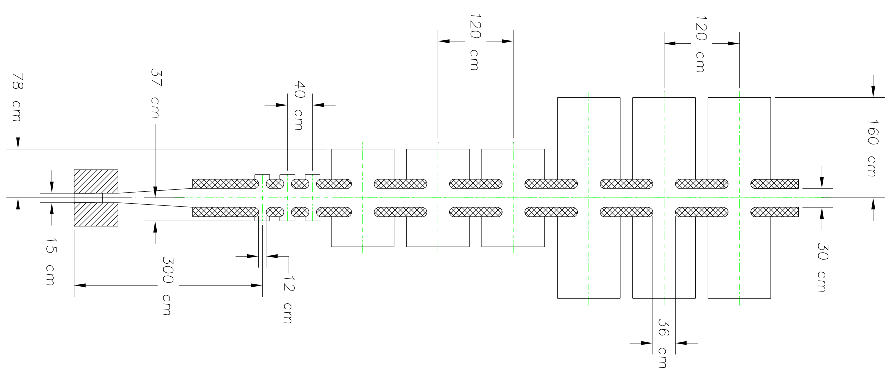

FIG. 9. Schematic of capture and phase rotation using rf cavities with superconducting solenoids (hatched) inside the irises. Only three sections each are shown for cavities operating at 90, 50, and 30 MHz.

A study [104] of transmission down a realistic system of iris-located coils revealed betatron resonant excitation from the magnetic-field periodicities, leading to significant particle loss. This was reduced by the use of more complicated coil shapes [103], smaller gaps, and shorter cavities, but remained a problem.

An alternative is to place continuous focusing coils outside the cavities (as shown in Fig. 4). In this case, cost will be minimized with lower magnetic fields (1.25-2.5 T) and correspondingly larger decay channel radii (21-30 cm). Studies are underway to determine the optimal solution.

G. Polarization

Polarization of the muon beams presents a significant physics advantage over the unpolarized case, since signal and background of electroweak processes usually come predominantly from different polarization states.

1. Polarized Muon Production

In the center of mass of a decaying pion, the outgoing muon is fully polarized ($P = -1$ for μ^+ and $+1$ for μ^-). In the lab system the polarization depends on the decay angle θ_d and initial pion energy [105–107]. For pion kinetic energy larger than the pion mass, the average polarization is about 20%, and if nothing else is done, the polarization of the captured muons after the phase-rotation system is approximately this value.

If higher polarization is required, some selection of muons from forward pion decays ($\cos\theta_d \to 1$) is required. Figure 7, above, showed the polarization of the phase-rotated muons. The polarization {P$> \frac{1}{3}$, $-\frac{1}{3} < P < \frac{1}{3}$, and P$< -\frac{1}{3}$} is marked by the symbols +, **o** and − respectively. If a selection is made on the minimum energy of the muons, then greater polarization is obtained. The tighter the cut, the higher the polarization, but the less the fraction $F_{\rm loss}$ of muons that iremain. Figure 10 gives the results of a Monte Carlo study.

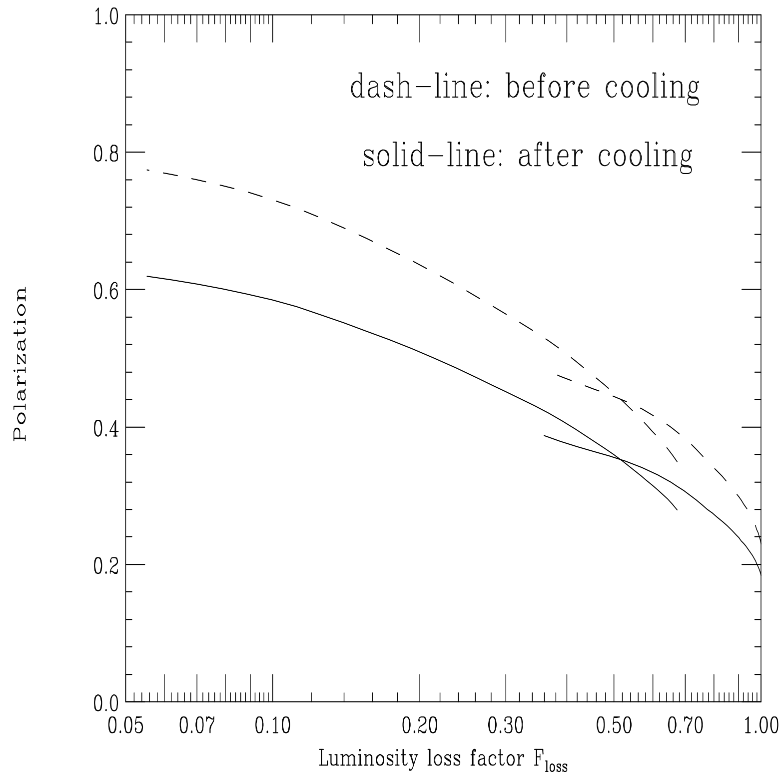

FIG. 10. Polarization *vs.* fraction F_{loss} of μ's accepted.

If this selection is made on both beams, and if the proton-bunch intensity is maintained, then each muon bunch is reduced by the factor $F_{\rm loss}$ and the luminosity would fall by $F_{\rm loss}^2$. But if, instead, proton bunches are merged so as to obtain half as many bunches with twice the intensity, then the muon-bunch intensity is maintained and the luminosity (and repetition rate) falls only as $F_{\rm loss}$.

The luminosity could be maintained at the full unpolarized value if the proton-source intensity could be increased. Such an increase in proton-source intensity in the unpolarized case might be impractical because of the resultant excessive high-energy-muon beam power, but this restriction does not apply if the increase is used to offset losses in generating polarization.

Thus, the goal of high muon-beam polarization may shift the parameters of the muon collider towards lower repetition rate and higher peak currents in the proton driver.

2. Polarization Preservation

The preservation of muon polarization has been discussed in some detail in [108]. During the ionization-cooling process the muons lose energy in material and have a spin-flip probability $\mathcal{P}$,

$$\mathcal{P} \approx \int \frac{m_e}{m_\mu} \beta_v^2 \frac{dE}{E}, \tag{2}$$

where dE/E is the fractional loss of energy due to ionization. In our case, the integrated energy loss is approximately 3 GeV and the typical energy is 150 MeV, so the integrated spin-flip probability is close to 10%. The change in polarization $\Delta P/P$ is twice the spin-flip probability, so the reduction in polarization is approximately 20%. This loss is included in Fig. 10.

During circulation in any ring, the muon spin, if initially longitudinal, will precess by $\gamma(g-2)/2$ turns per revolution, where $(g-2)/2$ is 1.166×10^{-3}. A given energy spread $\Delta\gamma/\gamma$ will introduce variations in these precessions and cause dilution of the polarization. But if the particles remain in the ring for an exact integer number of synchrotron oscillations, then their individual average γ's will be the same and no dilution will occur.

In the collider, bending can be performed with the spin orientation in the vertical direction, and the spin rotated into the longitudinal direction only for the interaction region. The design of such spin rotators appears relatively straightforward, but long. This might be a preferred solution at high energies but is not practical in the 100-GeV machine. An alternative is to use such a small energy spread, as in the Higgs factory, that although the polarization vector precesses, the beam polarization does not become significantly diluted.

H. R&D Program

An R&D program is underway to continue theoretical studies (optimization of pion production and capturing up to the cooling channel) and to clarify several critical issues related to targetry and phase rotation [109]. A jet of the room-temperature eutectic liquid alloy of Ga-Sn will be exposed to nanosecond pulses of 1.5×10^{13} 24-GeV protons at the F.E.B. U-line of the Brookhaven AGS to study the effect of the resulting pressure wave on the liquid. The same jet will also be used in conjunction with a 20-T, 20-cm-bore resistive magnet at the National High Magnetic Field Laboratory (Tallahassee, FL) to study the effect of eddy currents on jet propagation. Then, a pulsed, 20-T magnet will be added to the BNL test station to explore the full configuration of jet, magnet and pulsed proton beam. Also, a 70-MHz rf cavity will be exposed to the intense flux of secondary particles downstream of the target and 20-T magnet to determine viable operating parameters for the first phase-rotation cavity. The complete configuration of the targetry experiment is sketched in Fig. 11.

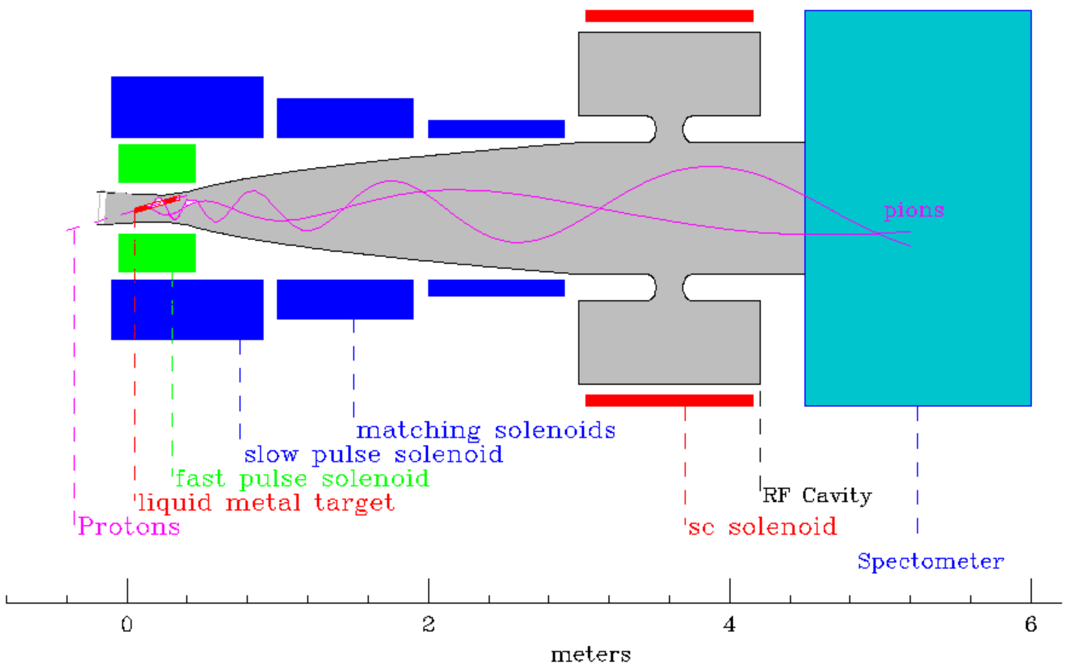

FIG. 11. Layout of the targetry experiment including liquid-metal jet target, pulsed 20-T solenoid, rf cavity inside a 1.25-T superconducting magnet, and diagnostic particle spectrometer.

The first two studies should be accomplished during 1999, and the third and fourth in the years 2000/01.

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