From a ν-Factory to μ^+-μ^- Colliders

David Neuffer

Fermilab, PO Box 500, Batavia IL 60510

Abstract. An important feature of a μ-storage ring ν-source is that it can be extended to the possibility of a future high-energy muon collider. The neutrino source provides a useful physics device that initiates key technologies required for future μ^+-μ^- Colliders, but with much less demanding parameter requirements. These technologies include high-intensity μ-production, μ-capture, μ-cooling, μ-acceleration and multiturn μ storage rings. μ^+-μ^- colliders require a similar number of muons, but they require that the muons be cooled to a much smaller phase space and formed into a small number of bunches, and both positive and negative bunches must be simultaneously captured. These differences are discussed, and the extension of the ν-source to μ^+-μ^- collider specifications is described.

INTRODUCTION

For the past 4 years, the possibility of high-energy μ^+-μ^- Colliders has been explored by an international collaboration of physicists. Conventional approaches to high-energy colliders (using protons or electrons) are reaching critical size and performance limitations. Muons (heavy electrons, with $m_\mu = 200m_e$) can provide point-like annihilation interactions, but have negligible radiation and beamstrahlung, and can be accelerated and stored in multiturn recirculating devices or rings. The Muon Collider Collaboration has intensified investigations into the possibilities of high-luminosity muon (μ^+–μ^-) colliders, and critical improvements in collider scenarios have been initiated which promise the possibility of high luminosity. Results of this research are reported in the muon collider Feasibility Study,[1] and the 1998 Status Report,[2] as well as in the collaboration notes, and other associated publications[3].

Table I shows some parameters for possible μ^+-μ^- Colliders, and Figure 1 displays a schematic overview of the μ^+-μ^- collider concept. Each of these cases is based upon the same muon source concept, with further acceleration and higher energy collider rings added to obtain the higher energy cases. The muon source is based on a high-intensity proton synchroton which generates short, high-intensity pulses of protons. These pulses are transported onto a high-Z target, where the pulses produce large numbers of pions. The pions are captured within a high-field solenoid, which is adiabatically matched to a low-field solenoid transport which also contains a low-frequency rf system. The pions decay to muons within the transport, while the rf system rotates the beam in phase space, limiting the energy spread while lengthening the bunches. The muon bunches are cooled by ionization cooling, in which muons lose energy while passing through material (losing transverse and longitudinal momentum) and are reaccelerated (regaining only longitudinal momentum). The cooled μ^+ and μ^- bunches are then accelerated through a sequence of multiturn accelerators to full energy, where they are inserted into a collider ring, where the muons circulate for a muon lifetime ($n_S \cong 1000$ turns), and are focused to collisions within particle detectors. The entire process is repeated at the muon source repetition rate (f_0).

A complete μ^+-μ^- Collider system requires development of a high intensity proton source, an intense π-production targeting system, a high-acceptance $\pi \rightarrow \mu$ decay channel, a μ-cooling system, a rapid-accelerating system and a high-luminosity collider ring, with simultaneous operation for both μ^+ and μ^- bunches. Each of these systems is quite challenging.

A key difficulty identified in these studies is the problem of developing a relatively low-cost low-risk initial μ^+-μ^- collider scenario (with important high-energy physics research goals) to initiate the demanding technologies required for the complete collider concept. Table 1 includes possible parameters for initial low-energy colliders at 100—400 GeV, which would be less expensive than a high-energy collider, but would still require development of all of the difficult technologies, and would also require relatively high luminosities to obtain useful physics results (in presently accepted models), and therefore require immediate high performance in these technologies. An intermediate machine with important physics content which requires only some of these methods (with reduced requirements) would be extremely desirable.

Another potentially important use for stored muons is as a source for neutrinos, obtained from muon decay ($\mu \rightarrow e + \overline{\nu}_e + \nu_\mu$). It has been reported that stored muons can provide a source of neutrinos, and in particular can provide a unique source of high-energy electron neutrinos (or anti-neutrinos).[4, 5, 6, 7] The usefulness of this source depends critically on neutrino properties, as well as the potential for high-intensity. If neutrinos were massless (and therefore oscillation-less), the ν-source would be relatively uninteresting. Several recent physics observations have supported the possibility that neutrinos are massive and oscillate.

These observations require confirmation, and precise follow-up experiments that determine the complete properties of neutrino oscillations will be needed. Conventional high-energy neutrino beams are predominantly μ-neutrino beams from π-decay, and can only indicate ν_μ oscillation parameters. A neutrino beam from muon decay would provide both electron and muon neutrino (and anti-neutrino) beams, and would allow a more complete exploration of the oscillation spectrum. Within presently developing particle physics topics, the exploration of neutrino properties is now a highest priority.

The μ^+-μ^- collider research has developed design concepts for high-intensity muon sources. These sources are also at intensity levels which would enable a μ-storage ring neutrino source with an advanced level of neutrino oscillation measurement sensitivity[8]. However since the neutrino source requires only muon storage and not collisions, the muon beam quality can be somewhat less, and simultaneous production of both μ^+ and μ^- beams is not required. A μ-storage ring ν-source would be an important physics machine which would initiate the technologies of muon production and collection, but at less demanding levels than the μ^+-μ^- collider, and could therefore be the entry level device for the μ^+-μ^- collider program.

In the next section we describe the requirements for a physics-significant μ-storage ring neutrino source. We then describe candidate designs for such a source, including details from a recent design study developed at Fermilab. This source is compared with the requirements of a muon collider, and an upgrade path from an initial neutrino source facility to high-energy μ^+-μ^- colliders is discussed.

PHYSICS REQUIREMENTS FOR A NEUTRINO SOURCE

Recently a study has been completed at Fermilab on the physics potential and requirements of a high-energy neutrino factory, designed primarily for the exploration of ν-oscillations. Much of this section is based on that report[9].

The central question in neutrino physics is whether neutrinos have any mass at all, and, if they do, what is the mass spectrum and mixing properties. The evidence for ν-mass is centered on experimental observations which show strong evidence for neutrino oscillations in a variety of circumstances. Observations of solar neutrinos show a deficit of a factor of 2 or 3 in the observed intensity of electron antineutrinos from the sun, and the most probable explanation of that deficit is neutrino oscillations of electron antineutrinos into another form.[10] Recent measurements of atmospheric muon neutrino (ν_μ) fluxes from the Super—Kamiokande (SuperK) collaboration have shown an azimuth-dependent (→ baseline-dependent) depletion that strongly suggests neutrino oscillations of the type $\nu_\mu \rightarrow \nu_x$[11]. Since the atmospheric ν_e flux is not similarly depleted, ν_x cannot be ν_e and must therefore be either ν_τ, or ν_s (a sterile neutrino). There is also some evidence of $\nu_\mu \rightarrow \nu_e$ at $\delta m^2 \cong 1$ eV^2, $\sin^2(2\theta) \cong 0.01$ from the LSND experiment[12].

While one expects mixing among all three (or more) neutrino types, it simplifies the discussion to assume that in a particular experiment oscillation between only two types is considered. For 2-neutrino oscillations, the oscillation probability can be expressed as:

$$P(\nu_1 \rightarrow \nu_2) = \sin^2(2\theta)\sin^2\left(\frac{1.27\,\delta m^2 L}{E}\right) \qquad (1)$$

where ν_1 and ν_2 are the initial and final neutrino types, θ is the mixing angle, $\delta m^2 = m_2^2 - m_1^2$ is the difference in neutrino masses (squared) in eV^2, L the distance in km and E the neutrino energy in GeV. The Super-K results are consistent with oscillations with $\sin^2(2\theta_{12}) \cong 1$, and $\delta m^2 \cong 0.003$ eV^2, with large error ranges. To identify an oscillation into tau-neutrinos it is desirable to have neutrino energy comfortably above the tau production threshold, which means energies significantly above ~ 5 GeV. Also, to see oscillations at $\delta m^2 \sim 0.003$ eV^2 or less requires L/E ~0.3×10^3 km/GeV, which implies the distance from neutrino source to detector must be ~1000 km or more. Candidate locations for a detector for a Fermilab μ-storage ring are at the Soudan mine (732 km away) or at SLAC/LBL (2900 km), or Super Kamiokande (Japan) or Gran Sasso (Italy) (~7000 km). The Fermilab physics study chose the distance from Fermilab to SLAC/LBL as the reference point for discussion.

An estimate of the neutrino event rate can be obtained by calculating the flux of neutrinos at the detector, and multiplying it by the ν-N cross-section and then by the detector size (in nuclei). The neutrino flux is given by

$$F = \frac{Nf}{\pi\left\langle (L\theta)^2 \right\rangle} \quad , \qquad (2)$$

where N is the number of muons stored in the μ^+-storage ring, f is the fraction of muons which decay in the neutrino source straight section (0.4 in ref. [13]), $\theta^2 \cong (m_\mu/E_\mu)^2$ is the rms angle (squared) of neutrino emission, L is the distance from neutrino source to detector. The ν-N cross section can be estimated as $\sigma_{\nu\text{-}N} \cong 0.7\times10^{-38}\, E_\nu$ cm^2, where E_ν is the neutrino energy in GeV and the average energy of a neutrino reaching the detector (directly downstream) is ~$2/3E_\mu$. A typical detector mass is 10 kT, or ~$6*10^{33}$ nuclei. Using a μ^+-μ^- collider muon source (10^{14} p, 15 Hz, 10^7 s/year, 0.1 μ/p ⇒ 0.5×10^{21} ν/year decays in a 1/3 occupancy straight section) and a 10-GeV storage ring, we obtain ~10^5 events/year at a detector at Soudan (L=732km), and ~10^3/year at Gran Sasso or Kamiokande. This should be more than adequate for a detailed study of neutrino oscillations at $\delta m^2 \sim 10^{-3}$ eV^2.

The physics study has considered variation of the basic parameters of the ν-source system, and has found that an initial μ-storage ring with 20GeV μ's and ~2×10^{19} ν decays per year in a beam line leading to a 10 kTon detector would provide fundamentally important new physics. A much larger detector should be developed; designs of detectors with as much as ~500 kTons have been considered. A ν-source facility design that would include plans for substantial intensity upgrades, as well as detector upgrades, and also possible energy increases would be an extremely desirable physics facility.

COMPARISON WITH μ^+-μ^- COLLIDER REQUIREMENTS

A measure of performance for a ν-source is the rate of events in a detector:

$$R_{\nu-\text{events}} = f_0 N_{\text{neutrinos}}\, W_{\text{detector}}\, N_A\, \sigma_{\nu-N}\, \frac{E_\mu^2}{\pi m_\mu^2 S_{s-d}^2} F(y) \qquad (3)$$

where f_0 is the cycle repetition rate, $N_{neutrinos}$ is the number of neutrinos in the source beam ($N_{neutrinos} = f_{ss} N_\mu$, where N_μ is the number of stored μ's, and f_{ss} is the fraction of the storage ring circumference in the neutrino source straight section), $W_{detector} N_A$ is the number of nucleons in the detector, $\sigma_{\nu\text{-}N}$ is the neutrino-nucleon cross-section (~ $10^{-38} E_\nu$ cm^2), $S_{s\text{-}d}$ is the source to detector distance and F(y) is a factor of order unity determined by the μ-decay spectrum. $S_{s\text{-}d}$ is chosen in order to explore a neutrino oscillation parameter range set by the ration $E_\nu/S_{s\text{-}d}$. For the currently planned experiments, $S_{s\text{-}d}$ is thousands of kilometers for E_ν at 10's of GeV. This event rate can be rewritten as:

$$R_{\nu-\text{events}} = 1.2 \times 10^{-14} f_0 \, N_{\text{neutrinos}} \, W_{\text{det ector}}(\text{kTons}) \frac{E_\mu^3(\text{GeV})}{S_{s-d}^2(\text{km})} \; C(\nu) \quad ,$$

where C(ν) is a reaction-dependent factor of order unity.

For a μ^+-μ^- collider the measure of performance is the luminosity:

$$L = \frac{f_0 n_S N_+ N_- \;\; \beta\gamma}{n_b \, 4\pi\varepsilon_N \beta_\perp} \qquad (4)$$

where f_0 is the cycle repetition rate, N_+, N_- are the number of positive and negative muons per cycle, n_b is the number of muon bunches, n_S is the mean number of storage turns per cycle (~300B, where B is the mean bending field), ε_N is the normalized emittance, $\beta_\perp$ is the betatron function at the interaction point ($\sigma^2 = \varepsilon_N \beta_\perp$ is the beam size), and $\beta\gamma = p_\mu/m_\mu c$.

In comparing these expressions, we note that the neutrino factory requires only one type of stored muon in an experiment. The ν-source event rate depends only on the number of stored muons and not on the quality of the beam; high-luminosity in a collider requires minimizing the beam size σ by minimizing the emittance and $\beta_\perp$ (and therefore the bunch length), and minimizing the number of bunches. Also the ν-event rate can be increased simply by increasing the detector mass (which is somewhat easier than creating more μ's). The beam energy required for a ν-source is relatively limited; for $E_\nu >$ ~100 GeV the required oscillation length becomes greater than the earth's diameter, but a physics-frontier collider may require $E_\mu > 1$ TeV. Thus the ν-factory is relatively easier, and the present perception is that a threshold of important new physics can be more easily reached with a ν-factory.

THE NEUTRINO SOURCE

Fermilab has recently completed a feasibility study on the design of a neutrino source. Much of the discussion in this section is based on that study[13], which is in turn based on concepts developed in the μ^+-μ^- collider research program[14, 15]. Parameters for a μ-storage ring neutrino source from that study are included as the high-intensity 50-GeV case in Table 2, and an overview of a 50 GeV ν-source is displayed in Fig. [2]. Parameters of a lower-energy and –intensity initial source are also included in Table 2.

A μ-storage ring ν-source requires a high-intensity proton source, a target that can accept that high-intensity and produce a large number of π's, a decay channel to collect a maximal number of muons, and phase-space manipulations which may include ϕ-E rotation, beam-cooling, and bunching to capture the μ's into an acceleration system which takes the beam into a high-energy storage ring. μ-decays in that storage ring provide muon and electron neutrino beams directed along those straight sections.

In the feasibility study, a proton source based on Fermilab plans for a high-intensity booster upgrade was proposed[16]. This consists of an upgraded H^- source leading into the Fermilab 400 MeV linac, which would charge-exchange inject into a 16 GeV proton synchrotron with a circumference of 711m. (1.5 × the existing 8 GeV Booster circumference) For the neutrino source this proton driver would provide 4 bunches of ~7.5×10^{12} 16 GeV protons at 15 Hz, with the bunch length at extraction shortened to $\sigma_z \cong 3$ns. (For the μ^+-μ^- Collider this source would be upgraded to provide 10^{14} protons/pulse and $\sigma_z \cong 1$ns.) This beam would be extracted to the π-production target.

A key invention of the μ^+-μ^- Collider effort is the development of high-intensity $\pi\rightarrow\mu$ production and concepts[17], and the ν-source would use similar concepts. The basic structure of the proposed production target is shown in Fig. 3; it consists of a target which is immersed in a high-field solenoid (~20T) with a radius r large enough to trap the transverse momentum of most of the π's produced in the target (r = 7.5cm). Following the target the field is adiabatically reduced to a lower field (~1.25 T) while the radius is increased to r = 30cm.

The optimal target material is a subject of current optimization and research. The largest yield and most compact source is obtained with a heavy metal target. However the difficulty is that the localized energy deposition from the pulsed multi-MW beam will destroy the target. A proposed solution is to use a pulsed liquid-jet target (Hg) (~30cm long, ~1cm diameter pulses). The difficulties in operating such a target in the high-intensity beam environment are a great challenge and are the subject of current research. An alternative strategy presently proposed is to use a graphite target, a low-Z material, (in ~1m long, ~1cm radius cylinders) which has less energy deposition and should be a sufficiently durable material to survive 15 Hz, ~1 MW beam intensity. This has somewhat less π-production (~1/3 less) than a heavy metal target but much easier target handling. Experimental tests of target prototypes to ensure survivability are needed. Other materials, such as Cu-Ni, are also under study.

The beam is continued through a (~50m long) decay line where most of the π's decay. The initial π's, and the product muons, are produced with a very large energy spread. Due to this energy spread, the bunch length increases in the decay transport and a longitudinal position-energy (ϕ-E) correlation develops with the lower energy beam trailing behind the higher energy muons. To reduce this energy spread, the drift is followed by an acceleration system which decelerates the head of each bunch and accelerates the tail, obtaining a long bunch with small energy spread. In the Fermilab ν-source, a 100m induction linac with ΔV = -0.5 to 1.5 MV/m is used, obtaining an ~60m long bunch with $\delta E_{rms} \cong 20$ MeV, $E_{kinetic}$ = 200MeV is obtained. This beam is transported through an absorber and a 200 MHz bunching system, which forms the ~10% energy spread bunch into a string of ~40 200 MHz bunchlets.

Beam cooling for the neutrino source would then occur and the plan is to reduce the μ-beam transverse emittance by ~10× in order to maximize μ-acceptance by the acceleration system and storage ring. A 200MHz rf system (λ=1.5m) was chosen as a wavelength long enough to enable structures that can contain the beam, but also as a frequency high-enough to enable affordable cooling and acceleration at high-gradient. The total length of that system should be ~100m.

Following the cooling section, the beam is inserted into the acceleration system. In the feasibility study this was envisioned as a ~3 GeV 200 MHz linac injecting into a 10 GeV 4-turn 200 MHz reciculating linac, and then into a 50 GeV 5-turn 400 MHz recirculating linac.

Following acceleration, the train of muon bunches is inserted into a racetrack shaped storage ring, with a straight section pointed toward the long base-line detector. A maximal ν-source has a relatively long race-track straight section; racetrack designs with straight sections each as large as 40% of the circumference have been developed. Fig. 4 displays a 50 GeV ν-source as it might be placed on the Fermilab site.

The Fermilab ν-study did not include polarization considerations in its development. The initial μ's from π-decay would have some polarization, which could be preserved through the cycle. A "figure-8" style storage ring (with a net zero bend per full turn) would preserve polarization in the storage ring. Variant storage ring designs with beams directed toward more than one long-baseline detector could also be considered.

m^+-m^- COLLIDER REQUIREMENTS

The ν-source would provide a substantial basis for further extension to a μ^+-μ^- collider. The ν-source would provide the first demonstrations of key technologies needed for a μ^+-μ^- collider. These technologies include :

- Development of a multi-MW medium-energy proton driver, with beam formed into bunches for maximal $\pi \rightarrow \mu$ production.

- Demonstration of a high-intensity target system which can accept the high-intensity beam, and produce a maximal number of π's for acceptance into a following decay transport system.
- Initial operation of a ϕ-E rotation system which would minimize the final energy spread, while maintaining a large acceptance for π-decay muons.
- Development of an initial cooling system, which would provide the first demonstration of ionization cooling with high-intensity μ-bunches.
- Development of efficient, high-acceptance acceleration methods suitable for the large μ-beams, with minimal decay and aperture losses.
- Experience with the use of high-intensity μ-bunches, at levels comparable to collider requirements.

The significant difference between the neutrino source and the collider is that the collider requires the μ^+-μ^- beams to be concentrated in a small number of bunches, cooled to a minimal emittance, and compressed to small beam sizes to obtain high luminosity, and that both μ^+ and μ^- be simultaneously produced.

Thus the initial capture and ϕ-E rotation would be reoptimized to reduce the bunch lengths and number of bunches. In the previous μ^+-μ^- Collider scenarios, this is done by using low-frequency (~30 MHz) rf for ϕ-E rotation (and not ~5MHz induction linacs), followed by ~30 MHz initial cooling systems. Longitudinal cooling systems must be added and integrated with the transverse cooling systems to obtain the 6-D cooling factors needed for the collider. As the beam cools longitudinally the rf frequency can be increased as the beam is shortened. We imagine reaching the cooling needed for the collider ($\varepsilon_\perp$ < ~0.0001m, ε_L < ~0.001m) by a sequence of systems, with rf frequencies increasing from ~30 MHz to 200—800 MHz. The cooling system would be ~600m long.

The cooled bunches would be accelerated, as in the ν-source. The same acceleration system should be useable (up to the ν-source ring energy), and additional acceleration (with acceleration frequency increasing as the beam energy increases) in higher-energy recirculating linacs can be added. As the beam energy (and lifetime) increases, alternative acceleration schemes, such as very rapid cycling synchrotons, could be used.

At full energy the beams would be extracted into a collider ring, which would have very different properties from a ν-source ring, and would be a new device. This ring requires focusing of the colliding beams to small spot sizes at the collision points, detectors surrounding the collision points, and high field magnets.

A significant additional difficulty for the μ^+-μ^- Collider scenarios is that both μ^+ and μ^- bunches must be simultaneously captured, cooled and accelerated. In principle this could be obtained by constructing two (nearly) identical systems for both bunch signs and combining them at the Collider storage ring. In practice, the two systems will combine at some point (perhaps at the beginning of the acceleration), with an appropriate timing shift and orbital dynamics to maintain acceleration for both signs of the colliding beams. It is possible, but perhaps not practical, that the target, capture, and cooling systems could (nearly) simultaneously handle both signs. A cost/practicality optimization for the combined system will be needed.

FROM A n-SOURCE TO A m^{+}-m^{-} COLLIDER

From the previous discussion we can generate a potential scenario for the step-wise development of a high-intensity proton source, an initial μ-storage ring ν-source, an upgraded ν-source, and an initial μ^{+}-μ^{-} collider to be followed by higher-energy μ^{+}-μ^{-} colliders as the physics requirements develop. Each of these steps would be relatively affordable, and would provide fundamental research opportunities.

The first step is development of a proton source at the MW level, with the capacity for upgrades to the multi-MW scale. This is essential for any of the ν-source or μ-collider scenarios which may develop. FNAL, BNL, CERN and JHF are all developing plans for a suitable proton source, all with somewhat different parameters. A MW proton source would have the capacity to support a medium energy physics program at high intensities, similar to that envisioned for the KAON factory project.

The second step would obtain a high-intensity target facility with a following transport that can produce a maximal number of π's and capture them into a transport line. That line would enable physics programs based on high-intensity π and μ beams, as well as the resulting low-energy ν-beams. A similar targetry and capture system (optimized for higher-energy secondaries) would provide high-intensity K, Λ, and other nuclei beams enabling a second-generation of medium-energy physics explorations.

This physics program could also include a low-energy μ-storage ring, which could be used for initial exploration of ν-oscillations at relatively low beam energies, extending the parameters explored by the low-energy neutrino experiments LSND and BooNE.[18] A low-energy μ-storage ring could also provide a test bed for studies of ionization cooling techniques, and could evolve into a "ring cooler" suitable for initial cooling of μ's by ~ an order of magnitude, which would be adequate for a maximal-intensity ν-source.

A low-energy μ-storage ring would not provide enough energy for the production of τ-leptons in ν-interations and hence cannot provide direct evidence for oscillations of ν_e and/or ν_μ into ν_τ, and would not provide adequate interaction rates for extended exploration of the neutrino oscillation regions suggested by the Super-Kamiokande and solar observations. This requires higher μ-energies, and the physics studies suggest a minimum energy of ~20 GeV μ's to provide ν beams of sufficient intensity for these explorations.

Therefore the next logical step would be construction of an acceleration system with a matched storage ring which could raise the μ-beam energy from the phase rotation and/or cooling system to ~20 GeV or more. As in the Fermilab study this accelerator would likely consist of a linac followed by a multi-turn recirculating linac; a 3 GeV Linac followed by a 17 GeV 6-turn RLA (~3GeV/turn) is a possibility.

Following the ~20 GeV program the μ-beam energy could be increased with the addition of more acceleration rf to 50 GeV or more, if the physics requirements (developed from the earlier measurements) require it. Incremental intensity upgrades throughout the system would be implemented.

With completion of the ν-source program, upgrades of specific components to provide μ^+-μ^- collider parameters could then be considered. The proton driver and target system would be upgraded to more beam power, with that beam power initially used to increase ν-source intensity. The experience with beam cooling developed for the ν-source would enable confidence in the design of the much more difficult cooling systems for the μ^+-μ^- collider, and construction of new bunching and cooling systems could be initiated. Systems to simultaneously obtain μ^+ and μ^- bunches would now be needed.

The bunches would be sent into the same acceleration system used for the ν-source, with some transport and phasing modifications to accommodate obtain μ^+ and μ^- bunches. More acceleration would be added if needed, however, a first μ^+-μ^- Collider might not need more energy.

The ν-source storage ring would be replaced by a collider ring, with low-beta (strong focus) interaction region(s), high-field magnets, and the chromatic correction needed for the low-beta regions. Because luminosity increases with the number of circulating turns before decay, the collider circumference will be minimized by using high-field superconducting magnets.

An initial μ^+-μ^- collider would be followed by higher-energy colliders, by adding acceleration systems (recirculating linac or very rapid cycling synchrotron or …) and upgrading the storage ring collider. Incremental improvements in cooling systems would occur with each upgrade. Within presently developed scenarios, a 2×2 TeV μ^+-μ^- accelerator and collider could be constructed entirely on the Fermilab site (see Fig. 5).

CURRENT RESEARCH AND COMMENTS

As discussed above, Fermilab has recently completed detailed studies on the physics potential and the technical feasibility of a μ-storage ring ν-source. These studies conclude that the physics potential of that source is interesting and important, and that the general concept is technically feasible. The technical study identified key “cost drivers” (expensive components and features) that must be studied and minimized; the critical cost drivers included the acceleration and beam cooling systems. Similar design studies, but with somewhat different scope, facility requirements, and some site-dependent constraints are being developed at BNL and CERN.

The central component of any high-intensity facility is a multi-MW proton driver. Fermilab is developing a conceptual design study for a Fermilab-based proton driver; this study is due in October 2000. Similar (somewhat site-dependent) proton source concepts are being developed at BNL, CERN and JHP.

In the μ^+-μ^- Collider collaboration a clear research priority is in the concepts and operational feasibility of the high-intensity target for π-production, and in the high acceptance optics which follows that target. An experiment which is based at BNL has been initiated to test high-intensity target concepts, as well as to provide initial tests of the capture optics [19]. These include tests of prototype carbon, nickel and mercury-jet targets, as well as operation of a target immersed in a 20-T capture solenoid. A demonstration of a target configuration that can accept the MW intensities, and of a capture optics that can obtain more than ~0.1 $(\pi\rightarrow\mu)/p$ would be extremely important accomplishments, which would almost certainly lead to construction of a high-intensity μ-source.

Both the ν-source and the μ^+-μ^- collider concept require development of new acceleration systems and prototypes of such systems are under development. The initial capture and phase-energy rotation system requires low-frequency acceleration systems. An induction linac system is being developed by S. Yu et al.[20] and low frequency rf designs are also being designed. The cooling system and initial acceleration systems require high-gradient ~200 MHz systems and prototype cavity designs are being developed. The acceleration systems require high gradient 200 and 400 MHz SRF systems (~15 MV/m or more) and these are being designed at Cornell and TJNAF.

A clear priority of the current R&D program is the optimization of the $\pi\rightarrow\mu$ capture, φ-E rotation, bunching and initial cooling section to maximize the number of muons delivered to the acceptance of the μ-accelerator [21]. That simulation R&D will specify detailed parameters for the initial cooling experiment. A possible cooling segment would include high gradient 200 MHz rf and liquid hydrogen absorbers; a design configuration is displayed in Fig. 6.

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Table 1: Parameter lists for m^+-m^- Colliders

Parameter	Higgs Factory (Small—Large dE)	Top Source	4TeV
Collision Energy($2E_\mu$)	100	400	4000 GeV
Energy per beam(E_μ)	50	200	2000 GeV
Luminosity($L=f_0 n_s n_b N_\mu^2/4\pi\sigma^2$)	10^{31}—10^{32}	10^{33}	10^{35} $cm^{-2}s^{-1}$
Source Parameters (4 MW p-beam)			
Proton energy(E_p)	16	16	30 GeV
Protons/pulse(N_p)	$4\times2.5\times10^{13}$	$4\times2.5\times10^{13}$	$4\times3\times10^{13}$
Pulse rate(f_0)	15	15	15Hz
μ acceptance(μ/p)	0.2	0.2	.2
μ-survival (N_μ/N_{source})	0.4	0.4	.4
Collider Parameters			
Collider mean radius(R)	50	150	1200m
μ /bunch($N_{\mu\pm}$)	4×10^{12}	2×10^{12}	2.5×10^{12}
Number of bunches(n_B)	1	2	2
Storage turns($2n_s$)	1000	1500	1800
Norm. emittance(ε_N)	0.028– 0.01	10^{-2}	5×10^{-3}cm-rad
μ-beam emittance($\varepsilon_t=\varepsilon_N/\gamma$)	$(5.6– 2)\times10^{-5}$	5.3×10^{-6}	2.5×10^{-7}cm-rad
Interaction focus β_o	13– 4	1	0.3 cm
IR Beam size $\sigma=(\varepsilon\beta_o)^{1/2}$	270– 90	23	2.1μm
δE/E at collisions	0.003– 0.12	0.12	0.12%

Table 2: Parameters for m-Storage Ring n-Sources

Parameter	Entry-Level	Upgrade (?)	
μ Energy(E_μ)	20	50	GeV
Distance to Detector	3000	700–7000	km
(ν_e, ν_μ^*) /ss/year	0.7×10^{20}	1.4×10^{21}	yr^{-1}
Source Parameters (1.2 ® 4 MW p-beam)			
Proton energy(E_p)	16	16	GeV
Protons/pulse(N_p)	$4\times7.5\times10^{12}$	$4\times3\times10^{13}$	
Pulse rate(f_0)	15	15	Hz
μ acceptance(μ/p)	0.05	0.2	
μ-survival (N_μ/N_{source})	0.5	0.5	
Storage Ring Parameters			
Circumference(C)	800	1800	m
Number of bunches(n_B)	4×40	4×50	
Storage turns(n_0)	160	180	
Norm. emittance(ε_N)	0.003	0.0015	m-rad
straight section β_o	100	450 m	
ss Beam size $\sigma=(\varepsilon\beta_o)^{1/2}$	4	4	cm
δE/E - beam	1	0.25	%
Detector Mass	10	100	kTons

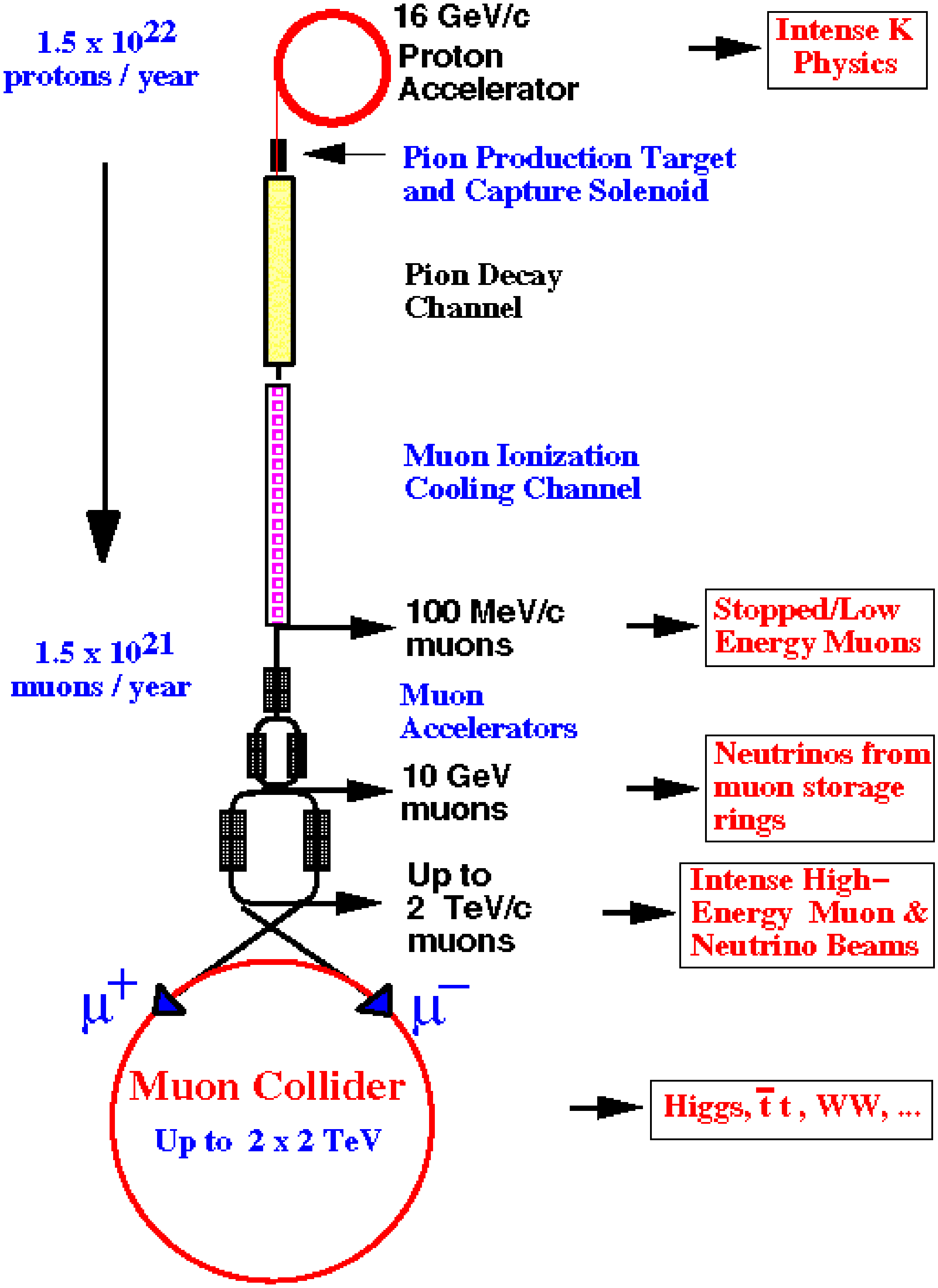
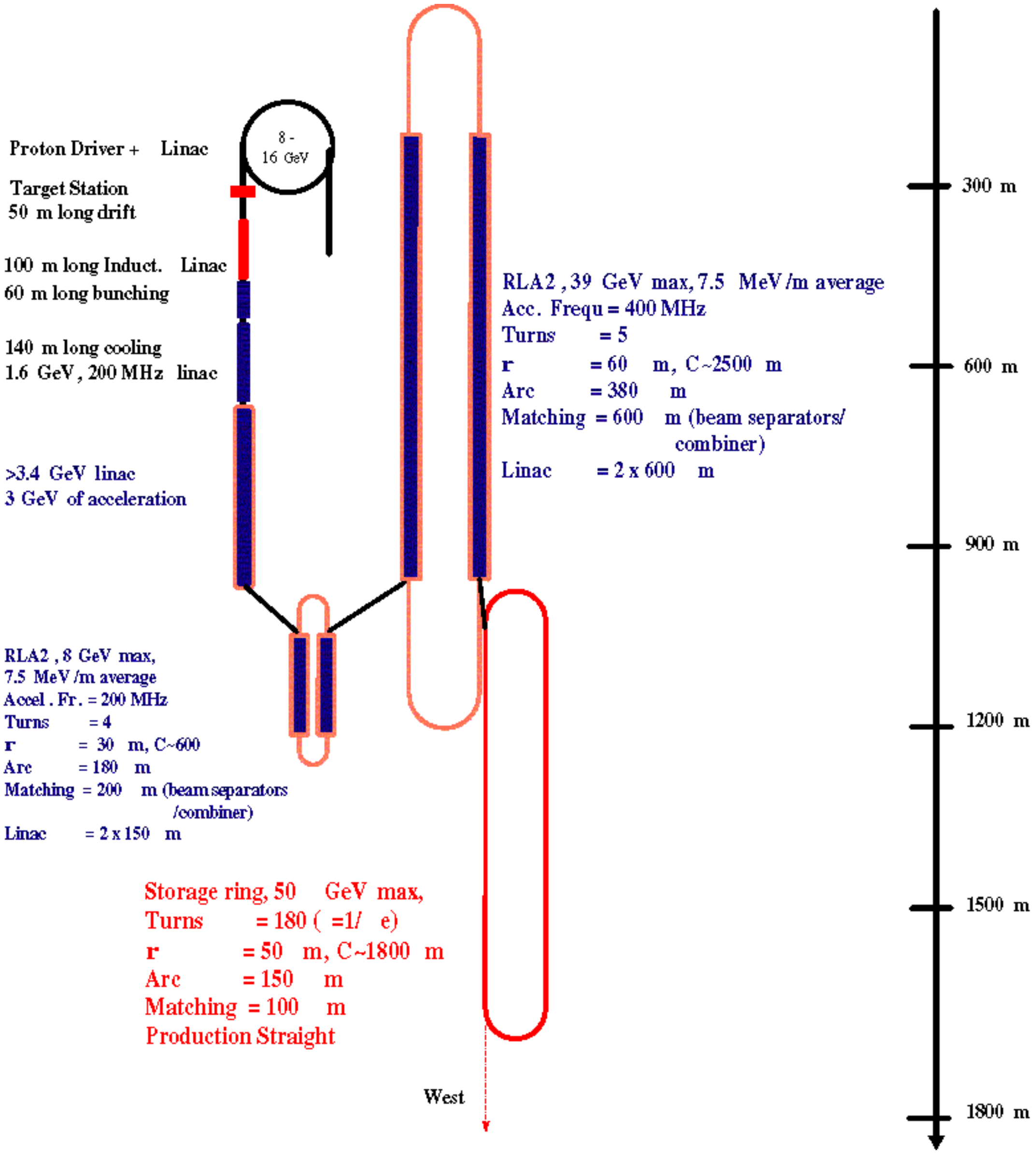


FIGURE 1: Overview of a μ^+-μ^- Collider Facility.

FIGURE 2: Overview of a 50 GeV μ-storage ring ν-source, from ref. [13].



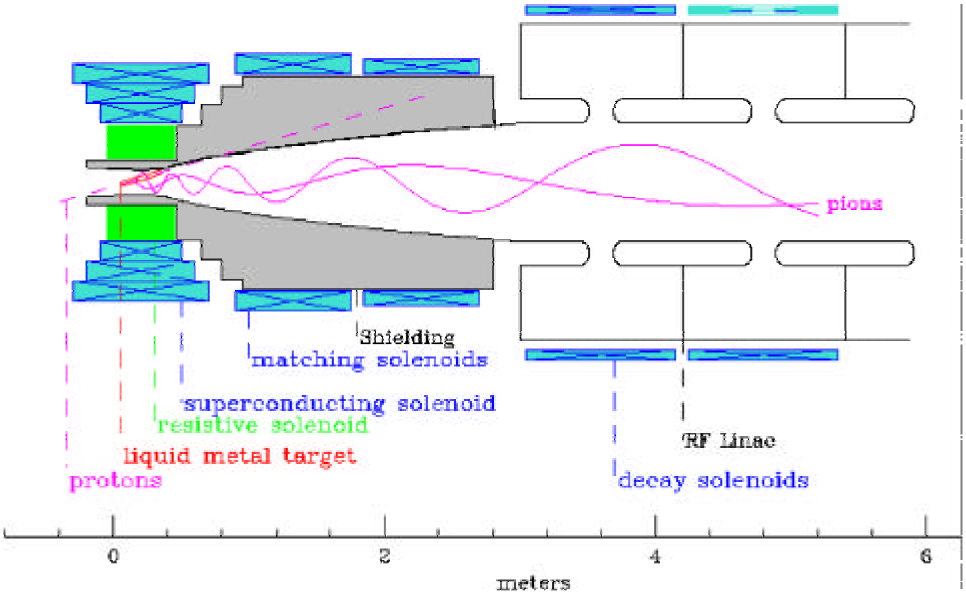


FIGURE 3 Capture solenoid and match to transport for π→μ decay + rf rotation (from ref. 2).

FIGURE 4: 50 GeV neutrino source as it might fit on the Fermilab site inside the existing Tevatron.

FIGURE 5: Photograph of the Fermilab site (with main injector, BOONE and NUMI beam lines, Tevatron, and fixed target areas), with schematic drawings of μ^+-μ^- colliders superimposed.

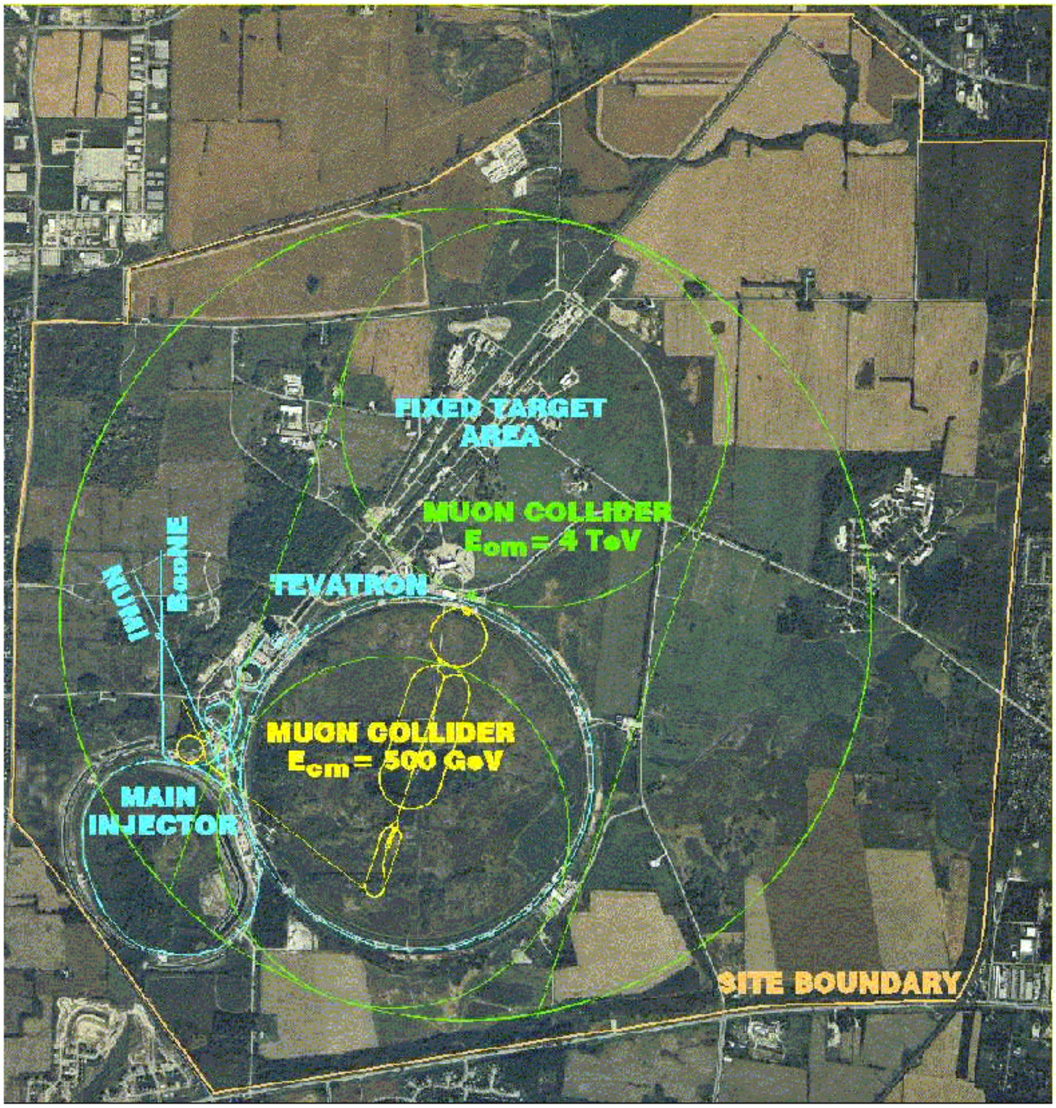


FIGURE 6. Design of a cooling segment, showing rf cavites and liquid hydrogen absorbers within pressure vessels, and solenoidal fields for focussing.