FEASIBILITY STUDY OF A NEUTRINO SOURCE BASED ON A MUON STORAGE RING

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ABSTRACT

One of the first applications of an intense muon source could be a muon storage ring. The muon beam is injected into the ring and decays while circulating. The neutrinos from the decay muons form a very intense and well collimated beam (ν_{e},ν_μ) that could be used for future neutrino experiments. The idea for such a neutrino source has been described many times, but only recently with the progress on ionization cooling concepts being made within the muon collider/neutrino source collaboration, such a source seems feasible. With a new proton driver and a target that can withstand the intense radiation and the power density from the impinging proton beam, the source will produce enough muons through pion decay to achieve approximately 2x10^{20} muons decaying into neutrinos in one of the straight sections of the storage ring. In order to achieve this goal very efficient and large aperture focusing and rf accelerating systems have to be developed. The biggest advantage though comes from the fact, that the transverse emittance for a neutrino source has to be reduced by only a factor of approximately ten in both transverse dimensions. The longitudinal emittance coming from the source is of no importance, which makes longitudinal cooling unnecessary. Following the goal of 2x10^{20} muons/year decaying in one straight section an attempt has been made to investigate the technical feasibility of such a facility as a whole.

*The work presented here has been performed by the members of the Muon Collider/Neutrino Source Collaboration coordinated by Fermilab and by many collaborators from different institutes and organizations, like CERN, Thomas Jefferson National Accelerator Facility, Oak Ridge National Laboratory, INP Protvino (Russia), JINR Dubna (Russia), Michigan State University and Cornell University with support from NSF. The author summarizes the results from this study which has been been published in April 2000: FNAL-pub-00/08-E, May 2000

1 Introduction

A muon storage ring as a source of intense neutrino beams supersedes a standard neutrino source in many ways. Classical neutrino sources have long decay channels which are used to generate $\bar{\nu}_{\mu,\tau,\mathrm{e}}$,$\nu_{\mu,\tau,\mathrm{e}}$ beams from pions coming from a target that is hit with an intense proton. In a muon storage ring the muons circulate after injection until they decay. A major fraction of these muons will decay in the straight section, which will produce an intense, very well collimated and clean ν_{e},$\bar{\nu}_{\mathrm{e}}$ beam.

1.1 Physics with a Neutrino Factory

Recent measurements of atmospheric muon neutrino (ν_μ) fluxes from the Super–Kamiokande (SuperK) collaboration have shown an azimuth–dependent ($\rightarrow$ baseline dependent) depletion that strongly suggests neutrino oscillations of the type $\nu_\mu \rightarrow \nu_x$. 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). These observations have inspired many theoretical papers, several neutrino oscillation experiment proposals, and much interest in the physics community. This interest is well motivated. Understanding the neutrino-mass hierarchy and the mixing matrix that drives flavor oscillations, may provide clues that lead to a deeper understanding of physics at very high mass-scales and insights into the physics associated with the existence of more than one lepton flavor. Hence, there is a strong incentive to find a way of measuring the neutrino flavor mixing matrix, confirm the oscillation scheme (three–flavor mixing, four–flavor, n-flavor ?), and determine which mass eigenstate is the heaviest (and which is the lightest). This will require a further generation of accelerator based experiments beyond those currently proposed.

High energy neutrino beams are currently produced by creating a beam of charged pions that decay in a long channel pointing in the desired direction. This results in a beam of muon neutrinos ($\pi^+ \rightarrow \mu^+ + \nu_\mu$) or muon anti–neutrinos ($\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$). In the future, to adequately unravel the mixing matrix, we will need $\nu_{\mathrm{e}}$and $\bar{\nu}_{\mathrm{e}}$ (as well as ν_μ and $\bar{\nu}_\mu$) beams. To illustrate this, consider neutrino oscillations within the framework of three-flavor mixing, and adopt the simplifying approximation that only the leading oscillations contribute (those driven by the largest $\Delta \mathrm{m}^2_{ij}$, defined as $\Delta \mathrm{m}^2_{32} \equiv \Delta \mathrm{m}^2_3 - \Delta \mathrm{m}^2_2$, where m_i is the mass associated with mass eigenstate **i**. The probability that a neutrino of energy E$\approx$GeV and flavor α oscillates into a neutrino of flavor β whilst traversing a distance L $\approx$ (km) is given by:

$$P(\nu_e \to \nu_\mu) = sin^2(\theta_{23})\, sin^2(2\theta_{13})\, sin^2(1.267\Delta m^2_{23}\frac{L}{E}), \quad (1)$$
$$P(\nu_e \to \nu_\tau) = cos^2(\theta_{23})\, sin^2(2\theta_{13})\, sin^2(1.267\Delta m^2_{23}\frac{L}{E}), \quad (2)$$
$$P(\nu_\mu \to \nu_\tau) = cos^4(\theta_{13})\, sin^2(2\theta_{23})\, sin^2(1.267\Delta m^2_{23}\frac{L}{E}). \quad (3)$$

Each of the oscillation probabilities depend on Δm^2_{32} and two mixing angles θ_{ij}. To adequately determine all the θ_{ij} and sort out the various factors contributing to the P($\nu_\alpha \to \nu_\beta$) will require ν_e as well as ν_μ beams. In addition, there is a bonus in using ν_e beams since electron neutrinos can elastically forward scatter off electrons in matter by the charged current (CC) interaction. This introduces a term in the mixing matrix corresponding to $\nu_e \to \nu_e$ transitions that is not present for neutrinos of other flavors. Hence, if electron–neutrinos travel sufficiently far through the Earth, matter effects modify the oscillation probabilities. This modification depends on the sign of Δm^2_{32}, and provides a unique way of measuring which mass eigenstate is heaviest, which is lightest. In conclusion, if one can find a way of producing ν_e beams *of sufficient intensity* a strong motivation exists. The obvious way to attempt to produce high energy ν_e beams is to exploit muon decays. Since muons live 100 times longer than pions, we need to avoid the use of a linear decay channel, which would be impractically long for high energy muons. The solution is to use a muon storage ring with long straight sections, one of which points in the desired direction. This yields a neutrino beam consisting of 50% ν_e and 50% $\bar{\nu}_\mu$ if μ^+ are stored, or 50% ν_μ and 50% $\bar{\nu}_e$ if μ^- are stored. Using a storage ring to produce secondary beams of Koshkarev[2] in 1974. The idea (also ascribed to refs.[3] and[4]) therefore dates back to the early days of the ISR at CERN. The key questions that need to be addressed in order to produce a viable proposal for the production of secondary beams by this method are:

- **How can enough particles be stored ?**
- **How can their phase-space be compressed to produce sufficiently intense beams for physics ?**

The calculated beam fluxes using the proposed scheme were too low to motivate the construction of a secondary beam storage ring. A viable solution to the key question (how to make sufficiently intense beams) was implemented at the beginning of the 1980's for antiproton production, leading directly to the CERN proton–antiproton collider and the discovery of the weak Intermediate Vector Bosons. The solution to the intensity question involved using lithium lenses to collect as many negative particles as possible, and stochastic cooling to reduce the phase-space of the $\bar{\mathrm{p}}$ beam before acceleration. In 1980 it was suggested[4] that the negative particle collection ring (the Debuncher) at the proposed Fermilab antiproton source could be used to provide a neutrino beam downstream of one of its long straight sections. The Debuncher collects negative pions (as well as antiprotons), which decay to produce a flux of captured negative muons. The muon flux in the Debuncher was not considered to be sufficient.

In order to make progress a method of cooling muon beams is required together with an increase in yield for muon production. Stochastic cooling cannot be used since the cooling time is much longer than the muon lifetime. Therefore ionization cooling was proposed as a possible solution.[5] A way of collecting more pions (that subsequently decay into muons) using a very high-field solenoid was proposed[6] in 1989. Thus by the end of the 1980's the conceptual ingredients required for very intense muon sources were in place, but the technical details had not been developed. Beginning with the 1990's the desire to exploit an intense muon source to produce muon beams for a high energy muon collider motivated the formation of a collaboration (back then called *The Muon Collider Collaboration*, subsequently renamed *The Neutrino Factory and Muon Collider Collaboration*). The work going on since has resulted in a more complete technical understanding of the design of an intense muon source.[7] In 1997 it was proposed[8] to use an intense muon source, together with a dedicated muon storage ring with long straight sections, to produce a very intense neutrino source. It was shown that such a **Neutrino factory** would be sufficiently intense to produce thousands of events per year in a reasonably sized detector at large baseline length. In addition, it was shown that if the ring could be tilted at large angles it would provide beams for very long (trans–earth) neutrino oscillation experiments. This proposal came at a time of increasing interest in neutrino oscillation experiments due to the SuperK results.[8] At the same time several articles considering the direction of high physics were published (e.g. Ref. 9). Thus, the neutrino factory concept quickly caught the imagination of the physics community. This interest led to the first NUFACT workshop at Lyon in 1999, a yearly series continuing since then, and to a number of technical feasibility studies investigating several overall schemes to optimize the total muon flux.[10,11] Most of the results presented here have been taken from a study[12] to explore an explicit neutrino factory design and identify the associated R&D issues. Together with a parallel 6 month physics study[13] to explore the physics potential of a neutrino factory as a function of its energy, intensity, and the baseline for oscillation experiments a comprehensive description of the facility and the physics is available.

1.2 The Accelerator Facility

A muon storage ring used to produce very intense and clean neutrino beams is most probably the first application of an intense muon source. After being generated from pion decay and cooled in an ionization cooling channel, the muon beam is accelerated and injected into a storage ring, where the muons decay while circulating. The neutrinos from the decay muons in the storage ring form a very intense and well collimated beam of electron and muon neutrinos ($\nu_{\mathrm{e}}, \nu_{\mu}$). The summary addresses four basic question and the answers are of general interest. They will help to define the R&D program. Specificially defined by the Fermilab directorate, the report tried to answer the following questions.

- **A design concept for a muon storage ring and associated support facilities that could, with reasonable assurance, meet performance goals required to support a compelling neutrino based research program.**
- **Identification of the likely cost drivers within such a facility.**
- **Identification of an R&D program that would be required to address key areas of technological uncertainty and cost/performance optimization within this design, and that would, upon successful completion, allow one to move with confidence into the conceptual design stage of such a facility.**
- **Identification of any specific environmental, safety, and health issues that will require our attention.**

Table 1. Charge for the study of the Neutrino Factory based on a Muon storage ring

If the μ-beam divergence in the straight section is small compared to the decay angle, the opening angle of the neutrino beam is completely dominated by the decay kinematics. Given the energy of the muons this angle basically equals $1/\gamma_{\mathrm{muon}}$. From the requirement to have the divergence of the muon beam in the straight section to be small compared to the divergence of the neutrino beam, a goal emittance for the muon source can easily be defined. The divergence of the muon beam due to beam focusing ($\propto \sqrt{\epsilon/\beta}$ was chosen to be 10 % of the natural divergence and assuming a reasonable maximum β-function of $\approx$400 m, the design emittance the cooling had to produce is

$\approx 2 \times 10^{-3}\pi$ mm rad. This emittance is only a factor of 10 smaller than the typical emittance of the pion beam if it is generated in a 20 T solenoidal field. Transverse emittance requirements (only a factor of ten) and longitudinal emittance requirements (many bunches instead of one or two) are for these two reasons signficantly relaxed in a neutrino factory as compared to a muon collider. Other beam parameters that were chosen for the neutrino factory study are based on various assumptions, some of which are summarized in table 2.

1. Given the experience in the simulations being done for the Muon Collider, and based on an earlier paper on this subject, a reasonable assumption had to be made for the number of muons one could expect per incident proton on target. This would have to include all the decay losses and the beam loss during cooling and acceleration.
2. Because this is a pulsed accelerator, the average current that has to be accelerated to achieve the 2×10^{20} neutrinos/year, critically depends on the total operating time. More operating time reduces the investment cost on the high power rf systems. An optimistic assumption here led to 2×10^{7}sec/year assumed for the purpose of this study.
3. The intense proton source being considered would be based on the results of the design study going on at Fermilab.
4. In the simplest version of a racetrack shaped storage ring with two long straight sections, approximately one third of the muons will decay in each straight.

Table 2. List of basic assumptions being made for the purpose of this feasibility study.

Given the large number of different and technically demanding sub-systems required for such a facility the charge for the feasibility study was focused on basic questions one would have to answer for such an accelerator facility. Given the large variety of possibilities for short (≈500 km), long (≈3000 km) and very long baseline (≈8000 km) experiments and based on somewhat preliminary assumptions in September 1999 on the potential physics goals, a number of boundary conditions had to be taken into account, before a specific set of accelerator parameters was picked. The final list for this study is given in table 3.

This table, together with a number of assumptions that were made (see table 2), defined a set of specifications that were used to start the design of the accelerator complex.

Energy of the storage ring	GeV	50
Number of neutrinos per straight section	1/year	2×10^{20}
Baseline length (FNAL to SLAC/LBN)	km	3000
no polarization		
capability to switch between μ^+ and μ^-		

Table 3. List of basic assumptions being made for the purpose of this feasibility study.

These specifications are given in table 4.

Nevertheless many of these parameters were based on an earlier study[14] and on feasibility considerations that were done in the framework of the muon collider work.[7] It was recognized very early in the study, that because of the comparatively high energy (50 GeV) and high average current with $6\text{x}10^{20}$ muons per year in $2\text{x}10^{7}$ seconds the average beam power would be 240 kW. This would be the highest pulsed power lepton beam in the world, exceeding the SLAC linac by more than a factor of two in its final 1999 run. The basic sketch of such a storage ring, as well as a list of storage ring parameters chosen for this study, is given in figure 1 and table 5.

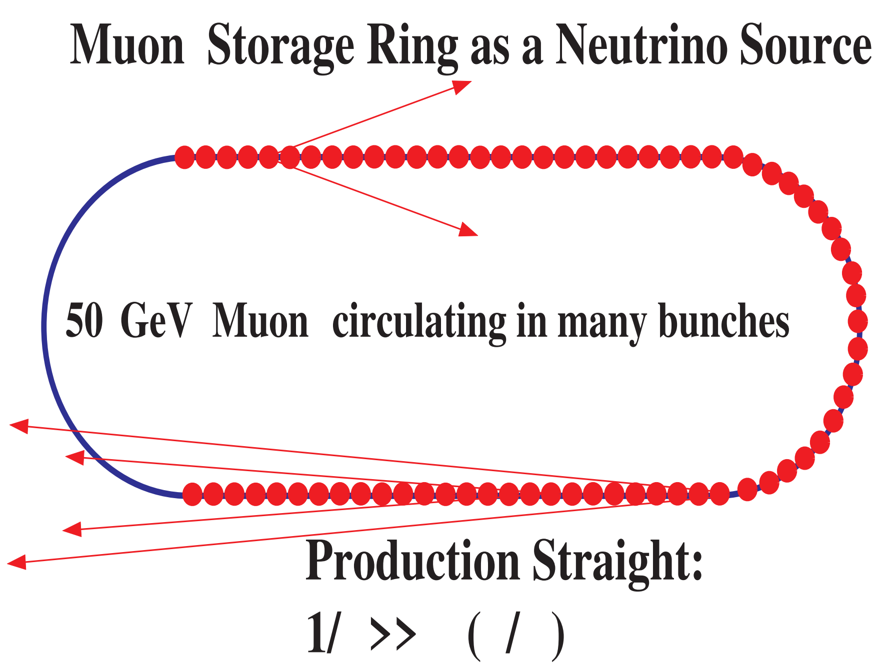

Fig. 1. Sketch of a Muon storage ring with two long straight sections.

The acceptance of the storage ring is designed for 3σ of 3.2 π mm rad. This allows

1. Given the ongoing study at Fermilab for a fast cycling proton synchrotron (15 Hz) with 16 GeV extraction energy, the number of protons per pulse required on target is at least 2×10^{13}. This is approximately 1 MW beam power on target.
2. The transverse emittance of the muon beam after the cooling channel has to be small enough that the beam divergence in the straight section is less then 1/10 of the decay angle, which is $1/\gamma$=2 mrad. At an invariant emittance of $\gamma\cdot\varepsilon$=1.6π mm rad the β-function would be $\approx$ 400m. This seemed reasonable.
3. Following the assumption of having ten protons per one muon injected in the storage ring, 2×10^{12} muons per pulse are required after the cooling channel and have to be accelerated.
4. Abandoning polarization for this study had two advantages. The very low frequency rf system that was proposed directly after the target is not necessary, because forward and backward polarized pions do not have to preserve their correlation in longitudinal phase space. For the same reason the proton bunch length in the proton accelerator could go up to 3 nsec instead of 1 nsec, which is a significant relief.
5. Fermilab to SLAC/LBNL with a distance of $\approx$3000 km defines the slope of the storage ring with respect to the earth surface, which is 22% or 13 deg in our case. This slope is gentle enough to think of conventional installation methods.

Table 4. Parameters for the facility following from table 2 and table 3.

a total emittance growth of approximately a factor of 2 in the accelerating systems once the muon beam has been cooled down to the goal value of 1.6 π mm rad. The straight section pointing towards the west coast would have the large β-functions to provide the smallest possible opening angle for neutrino beam. The upward pointing straight section would feed a surface experiment with a very intense neutrino beam. In order to correct the nonlinear and off-energy beam dynamics, the β-function is significantly smaller ($\approx$ 150m).

Energy	GeV	50
decay ratio per straight	%	39
Designed for inv. emittance	π·m·rad	0.0032
Emittance at cooling exit	π·m·rad	0.0016
β in straight	m	440
N_μ/pulse	10^{12}	6
typical decay angle of μ (= 1/γ)	mrad	2.0
Beam angle ($\sqrt{\epsilon/\beta} = \sqrt{\epsilon \cdot \gamma}$) $\gamma = (1-\alpha^2)/\beta$	mrad	0.2
Lifetime (c γ τ)	m	$3\text{x}10^5$

Table 5. Parameters for the 50 GeV storage Ring.

2 The General Layout of the Facility

The footprint of the total facility is comparatively small and fits easily under several existing laboratory sites. This is considered a big advantage compared to other large scale accelerator studies going on. A sketch which is basically made to scale is shown in figure 2. The largest subsystems are the accelerating linacs and recirculating accelerators (RLA1 and RLA2).

The total area required in order to provide a 50 GeV muon beam to a storage ring is approximately 1.0 km$\times$2.0 km only. In contrast to other High Energy physics programs proposed, the site constraints can hardly be a limitation. The philosophy behind the given geometric layout is that bending between the different subsystems is minimized, which will minimize muon loss because of the large transverse emittance of the beam. The same number of passes through each linac (both sides) of the RLA's is another criterion that was applied to make the beam loading and the rf system requirement the same for both sides. Coming out of the last RLA, the muon beam would be gently bent downwards into the storage ring tunnel and injected into the straight section pointing to the long baseline experiment. Although this might take up a certain fraction of the main decay straight, injecting in this direction is much easier than injecting into the upward arm.

Another remarkable result of this layout, given the earlier boundary conditions, is that the direction the proton beam hits the target defines the direction of the neutrino beam going to the experiment. Therefore once the location of the detector is fixed, the

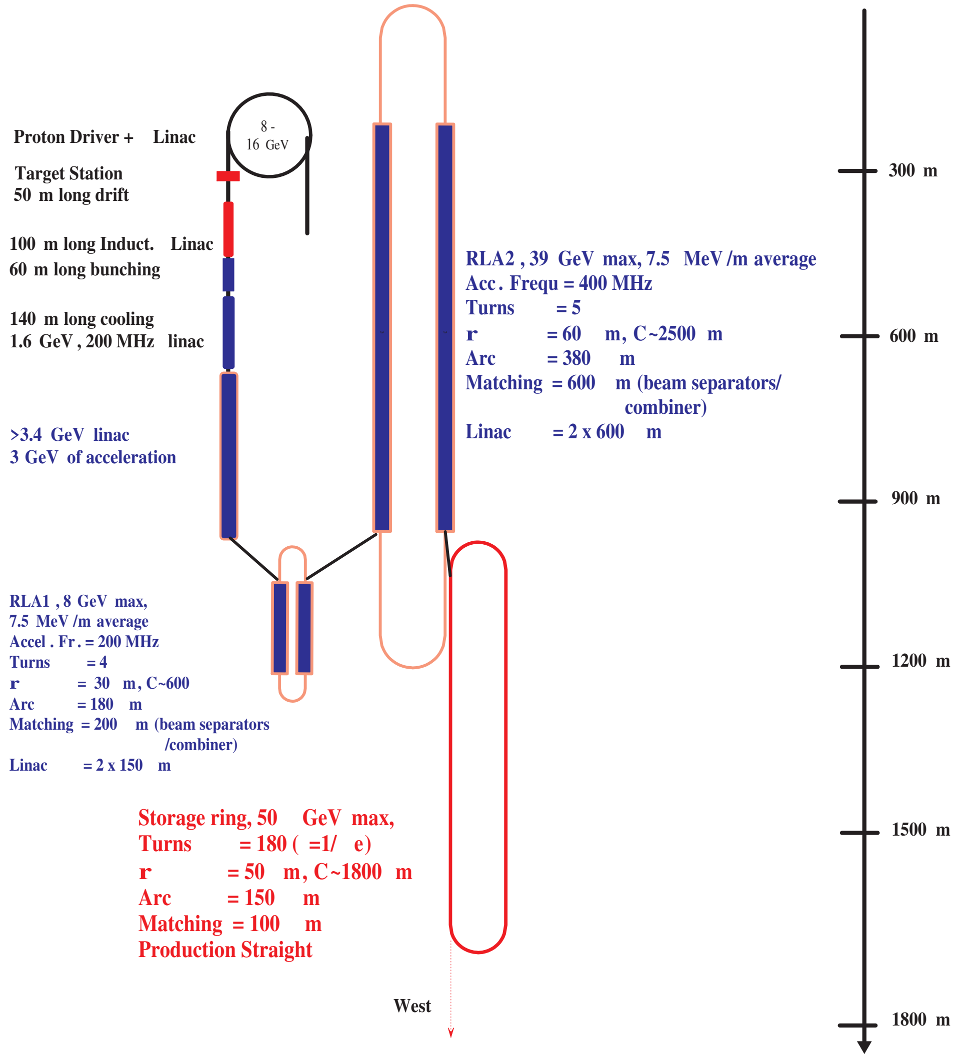

Fig. 2. Footprint (approximately to scale) of the whole facility.

layout is constrained, or else one of the boundary conditions have to be given up, which will most probably increase cost or decrease performance.

3 The subsystems of a the Neutrino Factory

The different subsystems of such a Neutrino Factory are in principle very similar to what is required for a Muon Collider, although they are not identical and in many ways not as demanding. The relaxation of having the muons in each pulse distributed over many bunches, together with the reduced transverse emittance cooling required, are the most obvious ones. The beam dynamics and performance of these subsystems, as well as their technical feasibility, are now described further.

3.1 The Proton Driver

The design of an intense proton source as part of a possible upgrade within the baseline program at Fermilab is under investigation.[15] A fast cycling synchrotron operating at 16 GeV is under study. It would produce a high power proton beam, with four bunches per pulse at a repetition rate of 15 Hz. Given the infrastructure at Fermilab, the existing linac in combination with a minor upgrade program would be capable of providing enough protons for injection. In the course of the study two things became evident:

- The required proton intensity is more likely to be 3×10^{12} per pulse due to smaller efficiency of the low Z target.
- This intensity can be distributed over four bunches but not many more, given the limitation of the induction linac (used later in in the accelerator chain) which has to produce a number of high voltage pulses within one acceleration cycle of the synchrotron ($\approx$2 μsec).

Given the advantages of a low Z target (see later in this paragraph) the optimization showed in addition that there is a 15-20% advantage in the pion yield per unit proton beam power as the energy of the protons drop. From the engineering point of view and given the higher yield, a lower energy proton driver operating at 6-8 GeV would therefore be preferable. It became also quite clear that a proton synchrotron that is capable of delivering a 4 MW proton beam is one of the larger consumers of wall plug power within the facility.

3.2 The Target

Extensive studies on target yield[16] as well as on radiation damage have been performed. The basic system considered as a first generation target consists of a strained graphite rod, which would operate at approximately 2200C°.[17] The advantages of graphite are the lower atomic number and the capability of withstanding very high thermal and mechanical stress. While the power deposited in the target per incident beam power goes down by a factor of five, the yield only drops by $\approx$1.5. The target would be radiation cooled and based on present knowledge would have to be exchanged every 3 months. An intense R&D program together with the collaborating institutions is necessary to justify these statements. The design of the 20 Tesla capture solenoid is a technical enterprise by itself. The combination of a 11 Tesla superconducting coil with an 8 Tesla normal conducting coil set additional constraints on feasibility. The normal conducting coil requires approximately 10 MW dc power and the lifetime is limited to about 2500 hours because of erosion due to excessive cooling requirements.[18] A sketch of the target set-up can be seen in figure 3. The approximately one meter long grpahite rod is mounted within the normal conducting Bitter solenoid. In addition to this massive copper device more shielding is added around and the super-conducting target solenoid can be seen in the outer shell. The radiation level during operation at the target is of the order of $10^{10} - 10^{11}$ Gray.

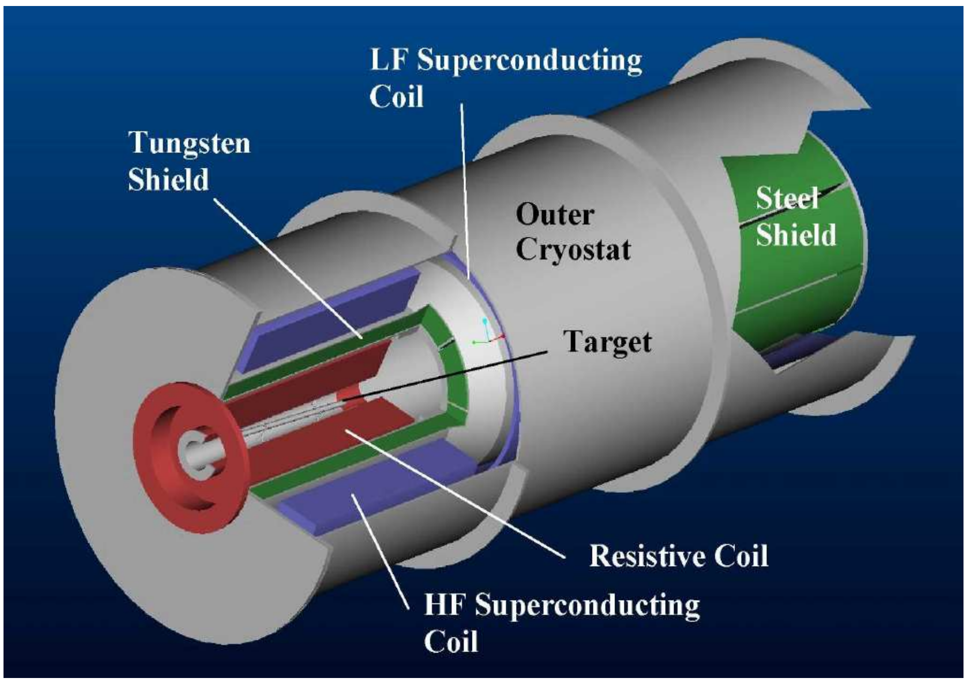

Fig. 3. Sketch of the target set-up: the graphite rod placed within the normal conducting magnet, the shielding, and in the outer shell the sc-solenoid.

The target area, remote handling procedures and facilities are very similar to what has been proposed for the **Spallation Neutron Source** in Oak Ridge. Having a solid target even reduces the operational risk according to the experts. The target hall itself on the other hand is impressive. Remote handling procedures, shielding and target and component exchange has to be integrated into the design to make it viable.

3.3 The Phase Rotation

In order to reduce the energy spread of the muon beam, the muons have to be rotated in phase space. The fifty meter long decay channel is not only used to let the pions decay into muons but also to develop a correlation between the energy of the muons and their longitudinal position along the muon bunch. With a total length of more than 200 nsec per bunch, each of the four bunches coming from the target should be de-accelerated at the head and accelerated at the tail[19] to reduce the energy spread before rebunching. An induction linac naturally provides voltage pulses of that order, while rf cavities with a low enough frequency either become excessively large or too power intensive. A 100 meter long induction linac operating at 15 Hz with 4 pulses per cycle and a not yet achieved gradient of -1 to 1 MV/m (2MV/m total) would be required. A sketch of an induction cell together with a superconducting coil operating at 1.3-3 Tesla is shown in figure 4. Coming out of the decay channel the required beam aperture is 60 cm, which dominates the core size of the induction cell.

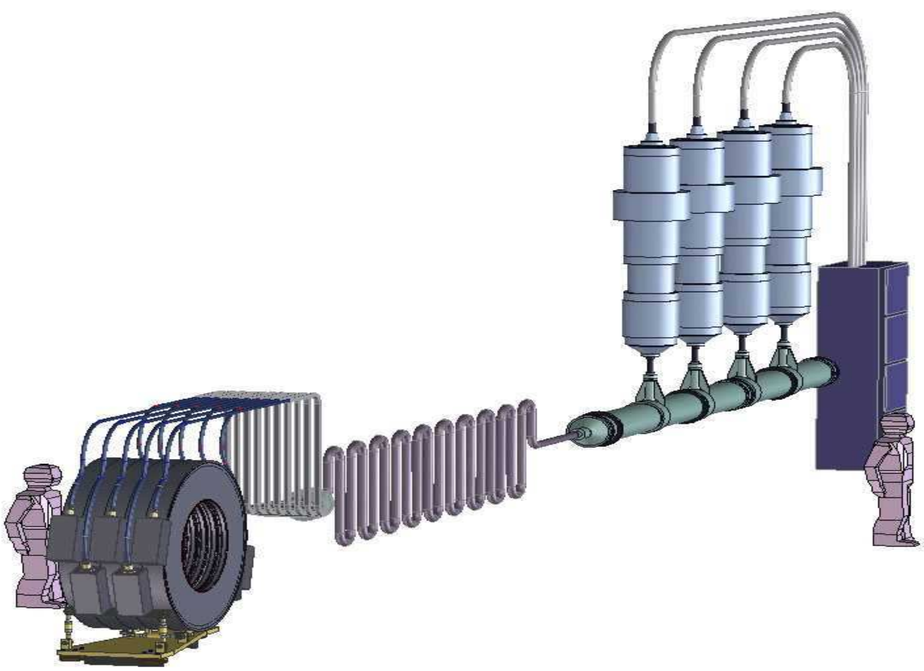

Fig. 4. Sketch of an induction cell with integrated superconducting 3 T coils for muon focusing. A delay line pulser with switches to produce four pulses per cycle is connected to a single one meter long induction cell.

Each unit is approximately one meter long and driven by an individual power supply.[19,20] The accelerating gradient is large compared to existing induction linacs and is certainly an R&D item. Technical feasibility on the other hand is less of a concern than investment cost, power consumption and reliability.

3.4 Mini Cooling, Bunching and the Cooling Channel

Mini cooling and re-bunching of the muon beam after the phase rotation is the first intrinsically non-efficient step. Four muon pulses with a length of $\approx$200 nsec each drift through an approximately two meter long liquid hydrogen absorber into high gradient cavities and then further on into the cooling channel. While so called mini-cooling reduces the transverse emittance by $\approx$30% the cooling channel has to reduce the emittance by almost an order of magnitude. The high gradient 200 MHz cavities have to reaccelerate and longitudinally focus the growing muon bunch while strong alternating solenoids with a field of 3.6 Tesla on axis produce small enough β-functions for transverse cooling.[21] The performance of the cooling channel is shown in figure 5. Significant beam loss occurs immedeately at the entrance of the cooling channel. The main reason is that the energy spread reduction in the phase rotation section is far from perfect and after rebunching the rf-bucket is already completely filled. Any further disturbance, like straggling and scattering in the cooling cells, will increase the longitudinal emittance and cause particles to fall out of the bucket. For the channel shown here the cooling channel increases the number of particles that would fit into the acceptance of the accelerators by only a factor of 2, while for an ideal beam coming (small energy spread) this factor is more like 6-8. New designs that are being explored come much closer to this number.[11]

The main challenges here are certainly the unrivaled gradient in normal conducting cavities at 200 MHz and the rf source that is necessary to provide enough peak power at this frequency.[23] The high field superconducting coils on the other hand are more than challenging due to the very large stored energy and the enormous forces (2000 tons) they have to sustain. A rule of thumb correlates the achievable current density (J) with the field at the coil (B) and the radius (R): $B \times J \times R < 350\,\mathrm{MPa}$. As a result, the coils used for focusing in the cooling channel become rather large and expensive.[22] A sketch of the cooling channel segment, with the hydrogen absorber, the cavity and the solenoids is shown in figure 6.

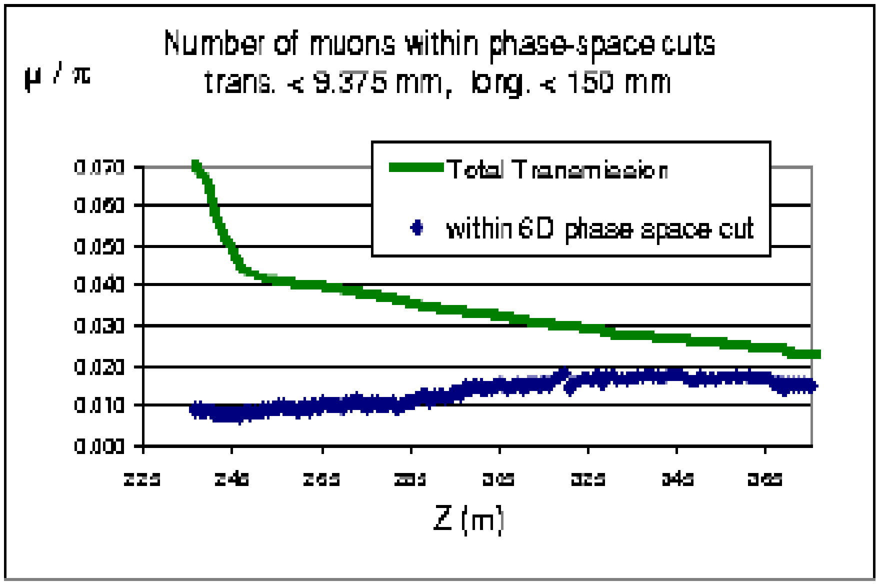

Fig. 5. Cooling performance of the cooling channel being used in this study.

3.5 The Acceleration

Coming out of the cooling channel, the muons have a kinetic energy of ≈ 110 MeV and have to be accelerated to 50 GeV. The transverse invariant emittance is ideally $1.6\,\pi$ mm rad. The longitudinal phase space is diluted due to scattering in the cooling channel as well as energy and position dependent drift differences. In order to capture the beam the first part of the acceleration can only be done in a low frequency high gradient rf system operating far off crest to form a stable bucket. 200 MHz is the maximum possible frequency because that is the bunching frequency used early on after phase rotation and in the cooling channel. The main difference between this linac and the cooling channel is that distributed focusing (solenoids or quads) can be used, which makes possible the use of superconducting rf cavities between the focusing elements. Shown in figure 2 is a 3 GeV superconducting linac in which the phase angle for acceleration is gradually increased to capture and stabilize the beam. Afterwards two cascaded recirculating linacs (RLAs) boost the energy to 50 GeV, with the first RLA having four recirculations and the second RLA having five. The large energy spread of the beam in combination with the large beam size requires long matching sections in order to go into and out of the arcs, which are normal conducting for the first RLA and superconducting in the second. The aperture that is required in the arc cells is

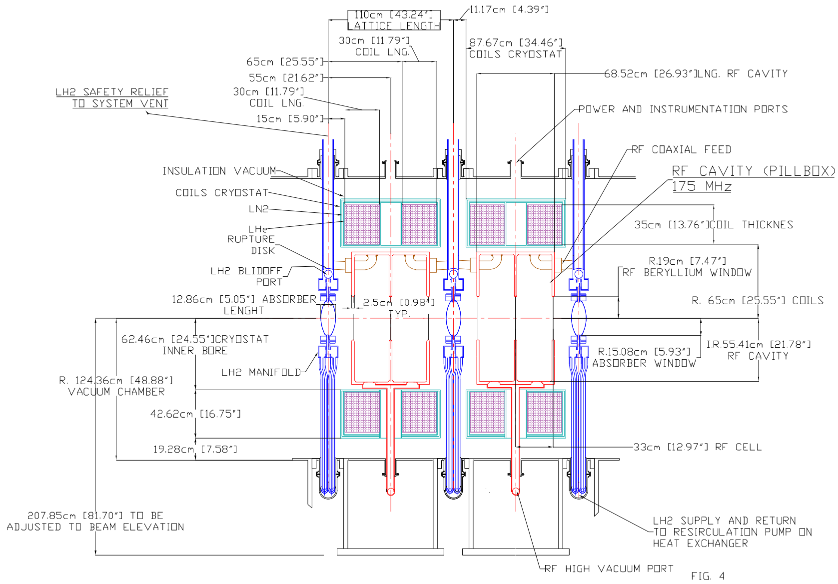

Fig. 6. Sketch of a cooling cell showing one period of the magnetic channel, the hydrogen absorber and the 200 MHz cavities mounted inside.

dominated by the off energy particle orbits (given $\sim 10\%$ energy rms spread coming from the cooling channel) and goes up to several tenths of centimeters. The number of recirculations is limited by the fact that the separation from turn to turn becomes more difficult as the number of turns increases, and also by balancing the cost of the arcs with the cost of the rf systems.

For these reasons the second RLA, with five turns and 8 GeV/turn, certainly dominates the required real estate requirement. Developing the low frequency high gradient superconducting cavities for these accelerators is clearly a high priority R&D item. Based on the technology at CERN, where sputtered niobium on copper cavities are used for acceleration at 350 and 400 MHz, this seems feasible, but has not been demonstrated yet. The first linac as well as RLA1 is based on 200 MHz rf. RLA2 though would have twice the frequency (400 MHz) in order to save investment and operational cost. The rf power sources that would be used to drive these cavities have to be developed as well. Providing peak power at low frequency using standard technology leads to excessively large structures. Multi-beam klystrons are one possibility to avoid such pitfalls.[25]

3.6 The Storage Ring

The muon storage ring represents neither a cost driver not a real technological issue, given the boundary conditions from table 5. The racetrack shape with the superconducting 6 T arcs brings the efficiency per straight to almost 40%. The circumference is ≈1800 meters and given the angle of 13°, the ring dips 260 m into the earth on one side. The available depth for reasonably good tunneling conditions is the only real site-dependent part of this study. A sketch of the geology under the Fermilab site demonstrates the boundary conditions. Starting almost at the surface of the earth, the ring goes down to the top of the underlying aquifer which should be avoided due to largely increased tunneling cost (see figure 7).

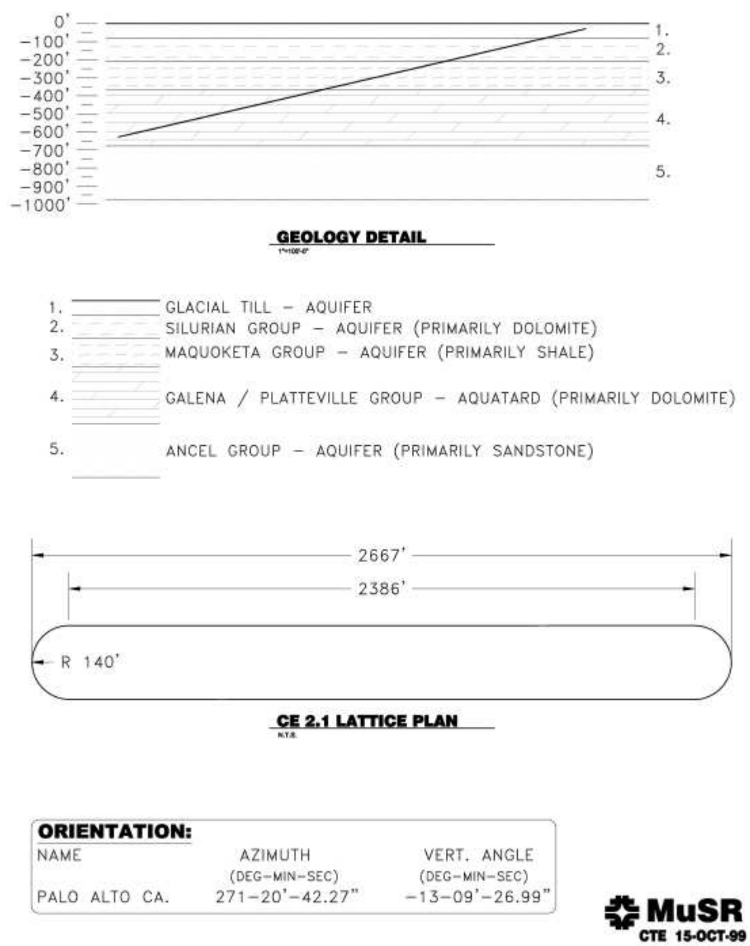

Fig. 7. Location of the storage ring under the Fermilab site tilted at an angle of 13 degree. The geological layers determine the available depth for tunneling under reasonable conditions.

Maximizing the yield from each straight section on the other hand requires maximum circumference. The gain that can be made by following this philosophy is shown in figure 8. Bending magnets with a field larger than 6 Tesla do not significantly increase the yield but are technically more challenging, given the fact that a large aperture is required: a) for the beam due to the large emittance, b) due to the tungsten shield to protect the magnet from decay electrons. Normal conducting dipoles on the other hand (1.8 T) would reduce the muon yield per straight from 39% to 28%. The production of the muon beam is much too expensive and too difficult to accept such a large factor for the ring design. As a result of this study, the storage ring certainly seems not to be much of an R&D issue[26] compared to the other subsystems.

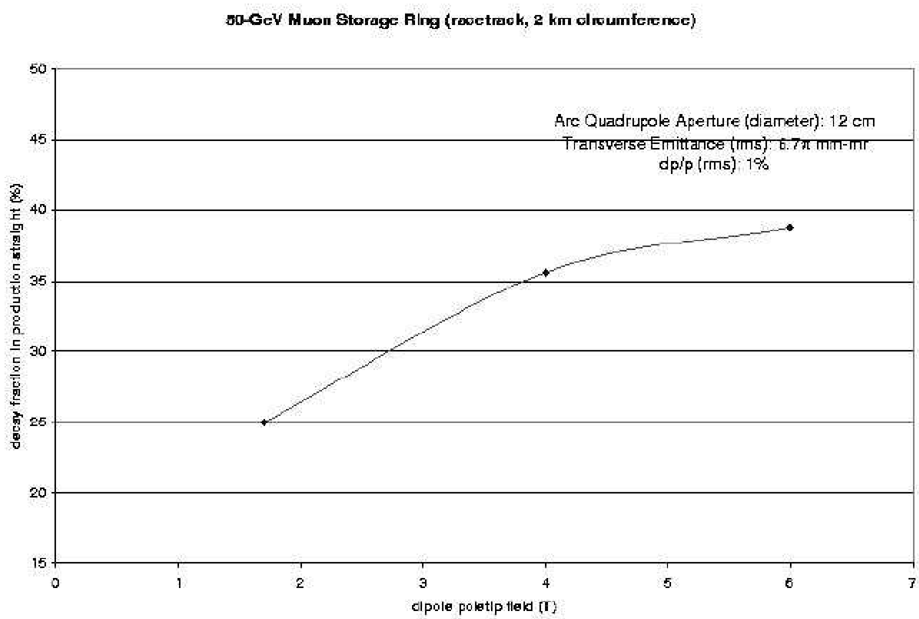

Fig. 8. Muon yield versus bend strength assuming the maximum depth to be used for the storage ring tunnel at an angle of 13°.

3.6.1 Environment, Safety and Health Issues

For the Muon Storage ring there are four major subsystems where significant ES&H issues have to be addressed. Some of them are very common, others are not. For the proton source, a 16 GeV synchrotron, 4 MW of average proton beam power is produced. Residual radiation, etc., will be a major design, and later on operational, issue. The target, the place where 4 MWatts of proton beam are dumped, is the second area where remote handling, radiation environments and operational aspects have to be part of the design. Both areas though are not uncommon, and the procedures being in place for the Spallation Neutron Source project in Oak Ridge will provide a lot of input on how to handle those. The same is true for the operation of cryogens for the different superconducting systems, magnets and rf cavities. Again, this is a familiar subject.

On the other hand, the large amount of neutrino radiation produced by an intense neutrino beam coming from the straight section of a storage ring is very uncommon. The well collimated neutrino beam, with an opening angle of 2 mrad, and the intense flux of neutrinos into this cone produces enough interaction with matter, so that 100 mrem per year can be achieved being close to the ring. In order to avoid any legal matter discussion on this subject, a boundary condition applied by the project team was to design the ring so that by the time the neutrino beam exits the west boundary (the down-going beam) or the east boundary (the up-going beam), the integrated radiation per year will not exceed this amount. Given the integrated design flux per year (2×10^{20} ν's), this determines the location of the storage ring with respect to the site boundaries. For the Fermilab site this boundary can be seen in figure 9.

For the east boundary, a large (so far nonexistent) building with a height of 600 feet was assumed. The neutrino beam, if it hit the walls, would produce radition for the same reason as in the soil. Three boundaries for different conditions (30 GeV, 50 GeV, 10 mrem/y, 100 mrem/y) have been plotted. The final location of the storage ring can be seen as well.

3.7 Summary

Presented here is a preliminary summary of the feasibility study on a muon storage ring used as a new intense source for long baseline neutrino beams. The study was done in close collaboration with the Neutrino Source/Muon Collider collaboration and has focused much more closely on the engineering aspects of such a facility. As a result, many R&D issues have been identified. All of them seem solvable if an aggressive R&D program could be started, but it would have to happen almost simultaneously. All of these solutions are extrapolations of existing and well understood technologies. One of the real challenging subjects, the beam diagnostics, which will be crucial for the performance especially of the cooling channel, has not been addressed. Here really new inventions are required. Given the results from this study it certainly seems feasible to build a Neutrino Source if intensity and energy can be compromised for the first step.

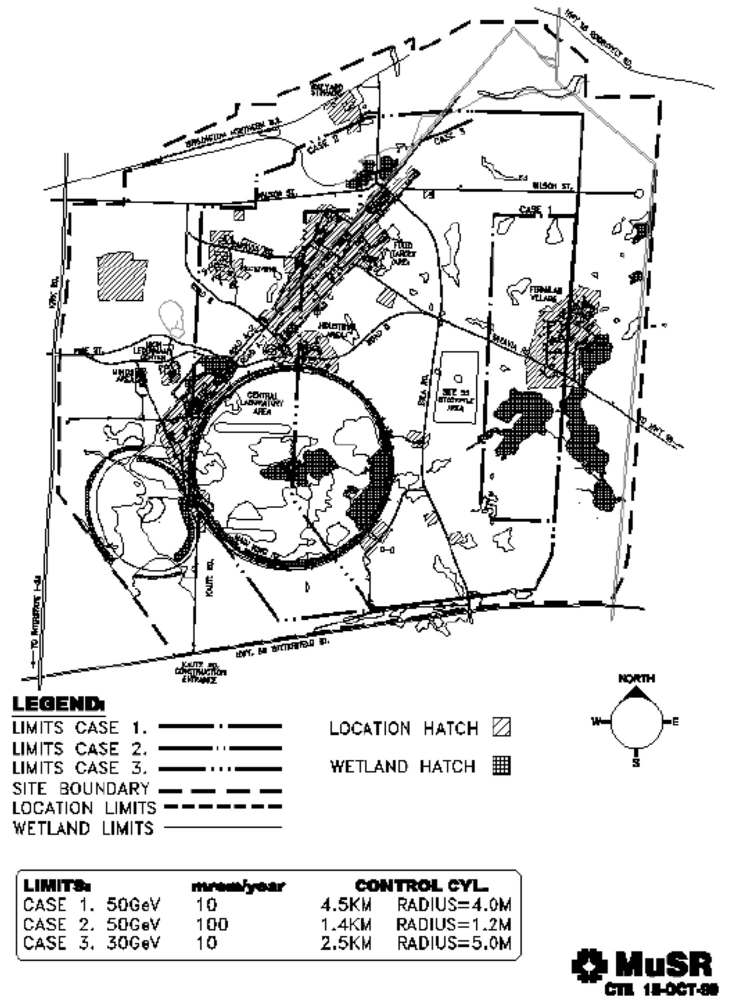

Fig. 9. Fermilab site boundaries and possible locations for the muon storage ring, without exceeding exposure limits outside the Fermilab boundary.

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