The Fermilab Feasibility Study of a Neutrino Source Based on a Muon Storage Ring

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The study of the muon and/or electron neutrino oscillations requires intense neutrino sources (10^{20} to 10^{21} per year). Such neutrino beams are used for long baseline experiments ($\approx$ 5,000 km). The accelerator complex required to produce and accelerate the muon beams consist of an intense proton driver, capable of delivering 1 to 4 MW on target, a pion and decay capture channel followed by a longitudinal phase rotation of the emerging muon beam to reduce its momentum spread, a 200 MHz buncher, a transverse cooling channel, the 20 to 50 GeV muon accelerator and, finally, the muon storage ring.

1. Introduction

Neutrino Oscillations have been studied for a long time. Such phenomena are clearly beyond our long-standing Standard Model of particle Physics. One experiment, Super-K has recently reported evidence for $\nu_\mu \rightarrow \nu_X$ oscillation. Obviously, more experimental data is required. While conventional neutrino sources (i.e. based on pion beams) are in operation or under construction, new designs based on the use of muon storage ring must be studied, given the rate limitation and the lack of electron neutrinos of these conventional sources.

The goal of this study was to investigate and document the technical feasibility of an intense neutrino source based on the use of a muon storage/decay ring. Colleagues from several national and international laboratories with expertise in the different areas were asked to work closely together with the study group at Fermilab and the *Neutrino factory and Muon Collider Collaboration.* What is the design concept and can it meet the performance goals? Those were set by the neutrino physics community, organized in a different study group [1]. Our mission was to determine the R&D required for such a machine, and what are the likely cost drivers and the potential technical risks. Safety and Health issues also had to be addresses.

A unique characteristic of this program arises from the fact that the cost of the total facility can be balanced between the neutrino detector and the accelerators. Over a wide range the measure of the quality of the physics is proportional to the product of $E.I.M$, where E is the energy of the muon beam, I is the intensity of the muon beam and M is the fiducial mass of the detector. Minimizing the cost for the product requires investment in to accelerator (energy), the cold muon source (intensity) and the detector ("instrumented mass"). Balancing $E.I$ with M will minimize the total cost and will require the development of accelerators as well as detector technologies. This study addresses only the accelerator part.

Our complete report is available on the web [2]. In this write-up, only a brief summary is given. I'll also draw heavily on the paper recently written by our spokesperson on the topic [4], and on the excellent talk presented by N. Holtkamp at the recent SLAC summer School [6]

2. The Neutrino Factory Complex

A neutrino factory design based on a muon storage ring is dominated by two considerations. First, the muon decays (when at rest) in 2.2 microseconds. Event with time dilation (ranging from 2 to 500), everything must be done very fast, and therefore, many of the "tricks" commonly used in accelerator physics, such as a adiabatic capture, or stochastic cooling, cannot be employed. The second consideration is that the muon produced via pion decay are very dilute, and therefore a great deal of cooling must be considered.

The neutrino factory complex can be (somewhat arbitrarily) divided into three distinct parts: the front-end, the acceleration and the compact muon storage ring. The layout of such a facility is shown on figure 1. All components have distinct challenges, and associated cost-drivers. While the design of the muon accelerator and the storage ring requires advanced, albeit established, accelerator technologies (such as superconducting r.f.), the optimization of the front-end demands new techniques, such as efficient pion production and ionization cooling Therefore, particle physics plays an essential role [3].

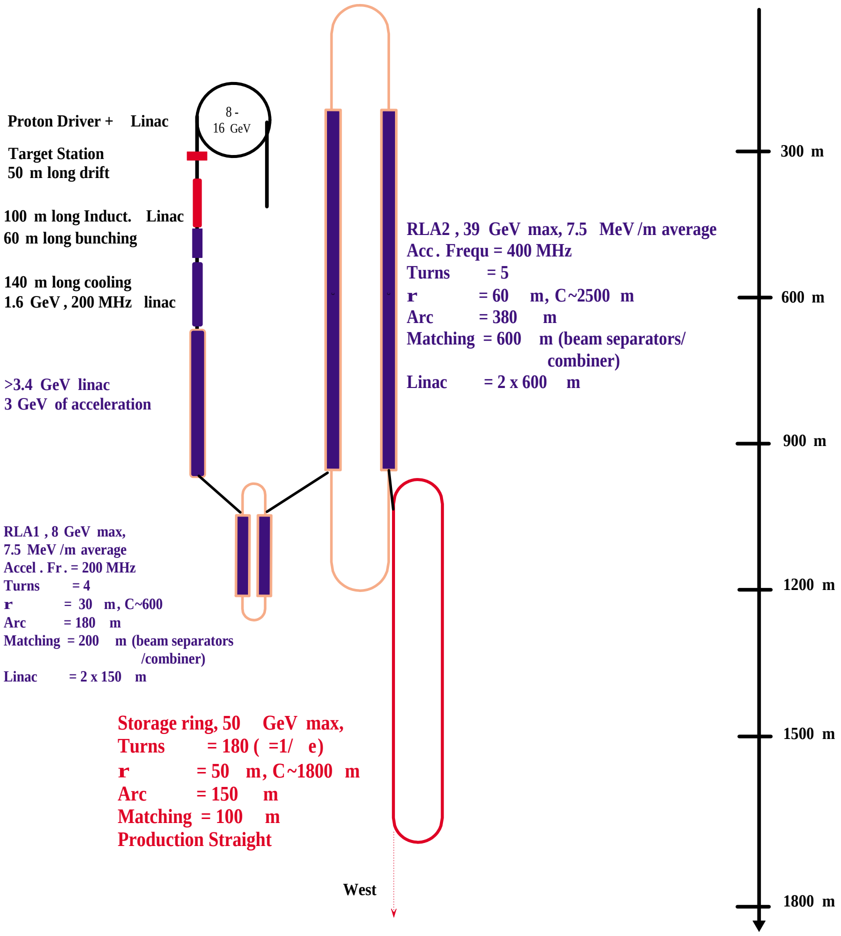

Figure 1: A schematic of a neutrino factory.

2.1. The Front-End: Production of a 200 MeV/c Intense Muon Beam

2.1.1. The proton source

As muon are produced from pion decay[1], an intense proton beam is required to produce this pion beam. While existing muon facilities use a rather low incident proton kinetic energy (550 to 800 MeV), generated by a Linac or cyclotron, we do propose a 16 GeV synchrotron, or "booster", as a proton source. This increased in energy is required for two distinct reasons:

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[1] All other processes, such as muon pair production in electromagnetism cascade, have too small of a cross section.

- As only relatively low energy pions ($\approx$ 300 MeV) are collected, these pions are produced by the excitation of Δ resonances in the target nucleus. In this regime, the yield is almost directly proportional to the incident proton energy, if a 2 to 3 interaction length target is used.
- These intense proton beams are space charge dominated. Raising the energy allows us to reach smaller longitudinal emittance prior to phase rotating the proton beam. This gives us a very short proton bunch at the target($\approx$ 1 to 3 ns). This is required in order to obtain a longitudinal emittance for the emerging pion beam small enough, such that the resulting muon beam can be phase rotated at a later stage, yielding a small $\Delta P/P$ for cooling and acceleration.

In order to produce enough pions, a 1 to 4 MW proton beam power is required.

2.1.2. The target system and support facility

An 80 cm long solid carbon target is proposed. A liquid mercury jet would give and enhanced flux by about 50%, but would be clearly more difficult to operate. Our collaboration plans to study such advanced targets at BrookHaven [5] This target is embedded in a high magnetic field (20 T) to capture the maximum amount of pions, about 0.6 pion per incident protons. A combination of normal, resistive, and superconducting coils is proposed. Stronger magnetic fields have been achieved. However, our coils will be exposed to a very high radiation field: The annual hadron flux ($E > 0.1$ MeV) and dose in the hottest spot of the inner resistive coil are $1.2 \cdot 10^{20}\, cm^{-2}$ and $3 \cdot 10^{10}$ Gy. The field tapers down to about 1.25 T., which is then held constant over 48 m, the length of the pion decay channel.

2.1.3. Muon Phase Rotation, Bunching and Cooling

The energy spread on the muon beam emerging from the decay channel is quite large, of the order of 50 to 100 GeV. In addition, the average energy of the muon beam at the end of the decay channel is a bit too high. Therefore, the beam goes though a 2 m. long hydrogen absorber. As describe later, transverse cooling occurs as well. A correlation develops between the time of flight in the drift section (or in the decay channel) and the muon energy. An induction Linac allows us to selectively correct this energy based on the position (or time of flight) of the muon. The maximum electric field is about ±1 MV/m (bipolar mode) and the required pulse length is about 250 ns. At the end of this last phase rotation, the nominal muon kinetic energy is now about 110 MeV/c, with a spread of about 5%.

The cooling channel and the first Linac used to start accelerating the muon use 200 MHz r.f. cavities. At such a frequency, a 15 MV/m peak field is achievable, allowing to capture and accelerate most of the bunch with a remaining energy spread mentioned above (5 to 15 MeV). Thus, a 200 MHz based buncher immediately follows the induction Linac.

The transverse emittance of the beam is also quite large, even after scraping off a substantial fraction of the pion or muon beam at the end of capture and decay system: about 13 π mm Rad (normalized). A transverse cooling channel is required for two distinct reasons:

- Evidently, the divergence of the neutrino beam must be kept as small as possible in order to maximize the neutrino flux at the detector located thousands of km from the source. However, the smallest obtainable divergence of this neutrino beam is set by the muon decay process: the neutrinos will received of the order of 30 to 60 MeV/c momentum transfer, corresponding to about a few mRad emission angle in the long straight section of the muon storage ring. Thus, for reasonable beta function and aperture in the storage rings, there is little gain at reducing the transverse emittance below $\approx$ 1.6 mm Rad.

- The muon accelerator aperture required to accelerate such a large beam would simply be too large: it would prohibit us to use relatively high frequency (400 MHz) r.f. with relatively high gradient (7.5 MeV/m). Other aperture problems in the re-circulators arcs and the kickers would be also truly difficult to solve.

Therefore, ionization cooling is employed to reduce the normalized transverse emittance to about 2 mm. Further reduction would be helpful, as some this emittance will grow somewhat during the acceleration. In ionization cooling, the beam loses both transverse and longitudinal momentum by ionization energy loss, while passing through the absorber. The longitudinal momentum is then restored to the beam in the accelerating cavities. This sequence, repeated many times, results in a reduction of the angular spread of the beam particles, and thereby reduces the normalized transverse emittance. Ionization cooling is limited by heating of the beam due to multiple scattering in the absorber as well as windows required in the high gradient, low Q, r.f. cavities. This effect can be reduced if the angular spread of the beam is always kept higher than the average multiple scattering angle.

To obtain this strong focusing needed for optimal cooling, several lattice configurations have been considered. Solenoids can be used to focus a large transverse emittance beam to small $\beta_\perp$, in both plane simultaneously. Two designs have been pursued, one in which a periodic lattice (FoFo) and one where the longitudinal magnetic field is flipped only once[7]. In the FoFo case, lower value of $\beta_\perp$ can be reached at the absorber, due to the relative proximity a strong betatron resonance. However, such betatron resonances are themselves a nuisance if the particle momenta stays too close to such a resonance for too many betatron wave length. The beam optics in the Single Flip is a bit more stable. The performance of this cooling channel is shown in figure 2. Significant beam loss occurs in the cooling channel. The main reason is that the energy spread reduction in the phase rotation section is far from perfect and after re-bunching the r.f.-bucket is already completely filled. Any further disturbance, like straggling and scattering in the cooling cells will increase the longitudinal emittance and particles fall out of the bucket. For the channel shown here the cooling channel increase the number of particles that would fit into the acceptance of the accelerators by only a factor of ≈ 3.5, while for an ideal beam coming (small longitudinal emittance) this factor is more like 6-8.

The main challenges here are certainly the unrivaled gradient in normal conducting cavities at 200 MHz and the r.f. source that is necessary to provide enough peak power at this frequency [8]. 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): $\mathrm{B}\times\mathrm{J}\times\mathrm{R} < 350\,\mathrm{MPa}$. As a result, the coils used for focusing in the cooling channel became rather large and expensive [2].

2.2. The Acceleration

Coming out of the cooling channel, the muons have a kinetic energy of $\approx$110 MeV and have to be accelerated to 50 GeV. The transverse invariant emittance is ideally 1.6π 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 r.f. 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 quadrupoles) can be used, which makes the use of superconducting r.f. cavities between the focusing elements possible. Shown in 1 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.

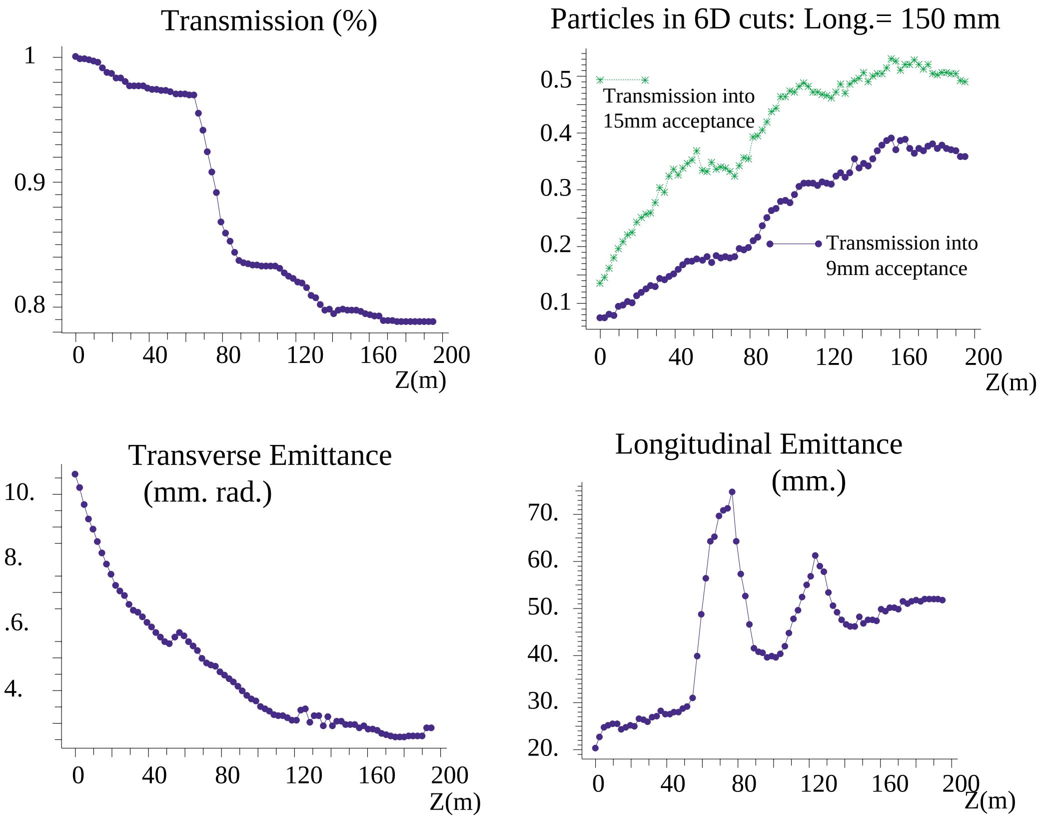

Figure 2: Cooling performance of the cooling channel being used in this study.

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 dominated by the off energy particle orbits (given 10% energy rms spread coming from the cooling channel) and goes up to several tenth 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. An other consideration in optimizing the number of recirculation is the overall cost, which is most likely obtained by balancing the cost of the arcs with the cost of the rf systems.

For these reasons the certainly the second RLA, with five turns and 8 GeV/turn 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 use 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 on possibility to avoid such pitfalls [9].

2.3. The Storage Ring

The muon storage represents neither a cost driver not a real technological issue, given the boundary conditions from table 1. 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, as the straight section points the emerging neutrino beam towards the SLAC site. The available depth for reasonably good tunneling conditions in that sense is the only real site dependent part of this study. 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.

Maximizing the yield from each straight section on the other hand requires to maximize the length of the straight sections, with respect to the length of the arcs. This in turns means short bends, e.g., strong dipole fields in the arcs. However, 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 to expensive and to 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 [10] compared to the other subsystems.

Table 1: Parameters for the 50 GeV storage Ring.

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 ($= 1/\gamma$	mrad	2.0
Beam angle $(\sqrt{\epsilon/\beta}) = (\sqrt{\epsilon\,\gamma}$ $\gamma = (1-\alpha^2)/\beta$	mrad	0.2
Lifetime	c $\gamma\tau$ / m	$3\text{x}10^5$

2.3.1. Environment, Safety and Health Issues

For the Muon Storage ring there is 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 after all 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 Neutron Spallation Source project in Oak Ridge will provide a lot of input how to handle those. The same is true for the operation of cryogens for the different super-conducting systems, magnets and rf cavities. Again, this is a familiar subject to our field.

On the other hand, substantial radiation produced by an intense neutrino Beam coming from the straight section of a storage ring is a very uncommon problem. The well collimated (opening angle of 2 mrad), and intense, beam of neutrinos produces enough interaction with matter, such that a 100 mrem per year dose can be reached close to the ring. 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 (down going beam) or the east boundary (up going beam), the integrated radiation per year will not exceed a dangerous 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. The final location of the storage ring meets the these requirements.

2.4. Summary

A summary of the Fermilab Neutrino Factory Feasibility study has been presented. The study is 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 with an aggressive R&D program in place. All of these solutions are extrapolations of existing and well understood technologies. In fact, this study can be criticized for rejecting truly challenging options, such the use of liquid mercury target to enhance the pion yield or low frequency r.f. placed at the entrance of the decay channel to preserve or enhance the muon polarization.

As conventional neutrino sources (K2K, NUMI program, for instance) are or soon will confirm (or challenge) the Super-K results, our task is to refine, certify and improve our designs, via computer simulation, engineering work, and hardware R&D. More information on the optimum muon storage energy will be available by the time a Conceptual Design Report can be written. In any event, more work is needed to optimize the front-end. One of the real challenging subjects, the beam diagnostics will be crucial for the performance of the front-end (especially the cooling channel), and has not yet been addressed[2]. Here really new inventions are required. In addition, other designs of the front-end, or other constraints coming from a different siting of the facility are being considered [11]. Such studies are an ongoing effort undertaken by our collaboration. Given the price range (more than a billion dollars) of such a facitility, such studies are evidently required.

3. Acknowledgment

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