INTENSE MUON SOURCES FOR MUON STORAGE RINGS AND COLLIDERS

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Abstract

Muon colliders have been discussed as an alternate route to very high energy lepton colliders. As a by-product such a collider would produce very intense neutrino beams because of the decaying muons circulating in the storage ring. In a dedicated storage ring these neutrino beams could be produced in long straight sections which would point towards long, medium or short baseline detectors, opening up a whole new class of neutrino physics experiments because of the enormous neutrino flux that in principle could be achieved in such a facility as compared to more standard fixed target sources. Intense pion sources in combination with powerful emittance cooling strategies for the comparatively large muon emittance are necessary to make this type of Neutrino Source as well as a Muon Collider feasible for a possible future high energy physics facility. The Neutrino Factory and Muon Collider collaboration studies the different subsystems being required and presently focuses on the layout of a Neutrino Source based on a 50 GeV Muon Storage Ring.

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 $\nu_{\mu,e},\bar{\nu}_{\mu,e}$ beams from pions coming from a target that is hit with an intense proton beam. In a muon storage ring the muons circulate after injection until they decay. A certain fraction of these muons will decay in the straight section, which will produce an intense, well collimated neutrino beam. If the muon 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 $1/\gamma_{muon}$. Because the divergence of the muon beam in the straight section should be small compared to the divergence of the neutrino beam, an emittance goal for the muon source and the cooling channel can easily be defined (compare Table 3).

After being generated from pion decay and cooled in an ionization cooling channel, the muon beam is accelerated and injected into a storage ring. The principal idea for such a neutrino source has been described several times[1][2][3], but only recently with the progress being made on ionization cooling concepts, does an intense source seem feasible. With an intense proton beam and a target that can withstand the power density and the intense radiation from the impinging proton beam, the source will produce enough muons to achieve 2×10^{20} muons or more 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 solenoids and rf accelerating systems must be developed for the ionization cooling channel. On the other hand, the transverse emittance that has to be achieved in this channel, to be sufficient for a neutrino source, has to be reduced by only a factor of approximately ten in both transverse dimensions, orders of magnitude less than for a muon collider. The longitudinal emittance coming from the source is almost of no importance, which makes longitudinal cooling and emittance exchange unnecessary. It also represents a basic difference between the neutrino source and the muon collider, where the Luminosity is proportional to the number of particles per bunch squared. Following a Neutrino Factory workshop in Lyon in July 1999, an attempt has been made to investigate the technical feasibility of such a facility as a whole. Initiated by a charge from the Fermilab directorate two dedicated studies, one on the physics and one on the accelerator facility were finished and published recently[4][5]. Given the large number of different and technically demanding sub-systems required for such a

1. 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.
2. Identification of the likely cost drivers within such a facility.
3. 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.
4. Identification of any specific environmental, safety, and health issues that will require our attention.

Table 1: Charge for the feasibility study.

This work that is presented here has been performed by the members of the Neutrino Factory and Muon Collider Collaboration, the Fermilab staff and 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 as well as several NSF funded universities and organizations.

facility the charge for the feasibility study was focused on basic questions one would have to answer for such an accelerator facility (see Table 1). The parameters that were chosen for the study are given in Table 2. This paper as well as the report focus on the question of technical feasibility throughout. The results of the study are reported here and a second study carrying on the identified issues based at BNL will follow.

Energy of the Storage Ring	50	GeV
Number of muons/straight section	$2x10^{20}$	1/year
no polarization		
Possibility to switch μ^+ and μ^-		
Baseline for facility: FERMI to SLAC/LBNL		

Table 2: Parameters chosen for the feasibility study.

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 assumption in September 1999 on the potential physics goal, a number of boundary conditions had to be taken into account, before a specific set of accelerator parameters was picked. The baseline length, the energy as well as the intensity per year have a strong impact on the design and were both driven by an early assessment of technical feasibility. Intensity because of the beam power on target to produce enough muons, energy because of the accelerating systems involved and baseline length because of the inclination angle with respect to the surface of the earth for the storage ring and the civil construction involved therein. As a result the result the achieved intensity in this study falls short by about a factor of four as compared to the goal

2 GENERAL FACILITY LAYOUT

Given the experience in the simulations being done for the Muon Collider and based on an earlier paper [6] on this subject a reasonable assumption had to be made for the number of muons one could expect per incident proton on target and the goal was to achieve 0.1μ/p. 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 as approximately 1 MW beam power on target that will deliver 2×10^{12} μ's per pulse into the storage ring. This would have to include all the decay losses and the beam loss during cooling and acceleration. Because this is a pulsed accelerator the average current that has to be accelerated to achieve the 2×10^{20} μ/year, critically depends on the total operating time. More operating time reduces the investment cost on the high power rf systems. Based on the experience of other pulsed accelerators an optimistic assumption here led to 2×10^{7} sec/year. The intense proton source being considered would be based on the results of the design study going on

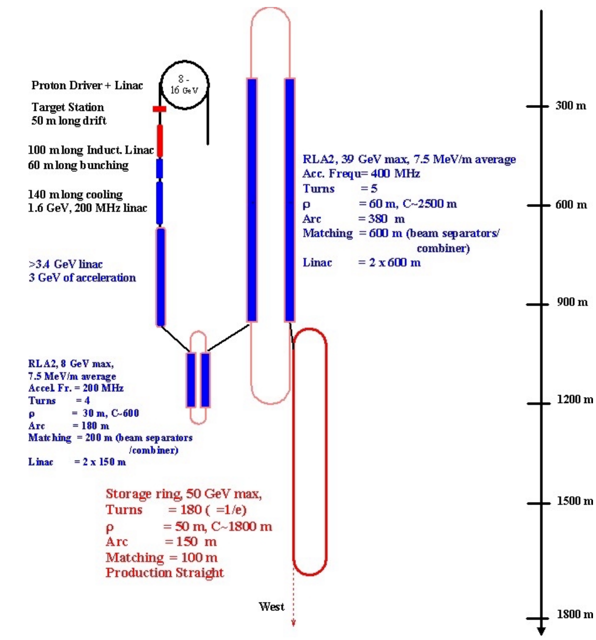

Figure 1: Footprint of the Facility, approximately to scale.

at Fermilab and in the simplest version of a racetrack shaped storage ring with two long straight sections, almost one third of the muons will decay in each straight.

Avoiding polarization allows the absence of high gradient low frequency rf right behind the target (6MV/m @ ~ 60 MHz). In addition the required bunch length in the proton driver can be increased and relaxes the design. Finally, with the fixed baseline length (FNAL to West Coast) the distance becomes 2800 km and the angle of the ring with respect to the earth is 13° (=22%), which is gentle enough to allow conventional installation.

In Figure 1 a footprint of the whole facility is shown which shows the different subsystems to scale on a site which is approximately 2 km by 1 km. Small enough to fit on several existing laboratory sites. Given the relatively high energy (50 GeV), the average power in the muon beam is 240 kW. This would be one of the highest pulsed power lepton beams in the world with acceleration dominating the site layout and being certainly one of the

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_0 in straight	m	440
N_μ/pulse	10^{12}	2
decay angle of $\mu = 1/\gamma$	mrad	2.0
Beam angle $(\sqrt{\varepsilon/\beta}) = (\sqrt{\varepsilon\, \gamma_\perp})$	mrad	0.2
Lifetime $c*\gamma*\tau$	m	$3x10^5$

$\gamma_\perp = (1-\alpha^2)/\beta_0$

Table 3: Final Parameters for the Muon Storage Ring.

cost drivers. The combination of Table 2 and the assumptions made above did allow the specification of most of the critical parameters for the study. The acceptance of the storage ring is designed for 3 σ of 3.2 π*mm*rad. This allows 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 (≈150 m).

3 THE MAIN SUBSYSTEMS

The different subsystems of such a Neutrino Factory in principle are very similar to what is required for a Muon Collider, although 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 cooling being required, are the most obvious ones.

3.1 The Proton Driver

An intense proton source is an integral part of the design of a neutrino factory. At Fermilab a 16 GeV proton synchrotron is under investigation, while at Brookhaven an upgrade scenario for the AGS operating at 24 GeV is developed and at CERN a low energy design based on the LEP cavities is being discussed [7]. All of these approaches have in common that the average proton beam power on target is 1 MW with upgrade scenarios to 4 MW and more. All these designs a mature enough that they will meet most probably their performance specifications.

Given the results from our simulations of a low Z target (see later in this paragraph) the optimization showed 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 would be preferable while for high Z targets the yield is proportional to beam power and the energy of the proton beam does not have such a significant impact. .

3.2 The Target Station

Extensive studies on target yield as well as on radiation damage were performed. The basic system considered as a first generation target consists of a strained graphite rod, which would operate at approximately 2200 C°. 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 ≈1.5. The target would be radiation cooled and based on present knowledge would have to be exchanged every

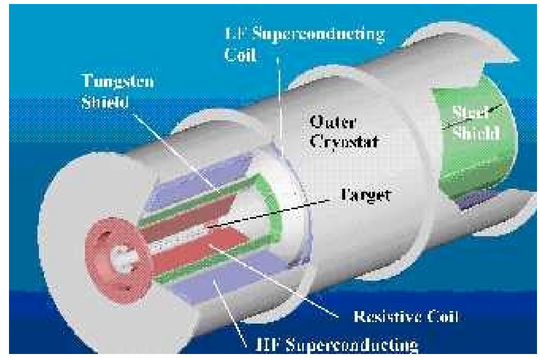

Figure 2: Target insert with sc coil and normal conducting 10 T insert.

3 month. An intense R&D program together with the collaborating institutions is necessary to justify these statements.

At the same time a liquid jet mercury target is under development and both target systems will ultimately be tested in the target experiment at BNL. In the present design an 11 Tesla superconducting coil with a 9 T normal conducting coil insert is used to produce 20 Tesla in the target region tapering off to 1.25 Tesla in the decay channel. The nc coil requires approximately 10 MW dc power and the lifetime is limited to about 2500 hours because of erosion due to excessive cooling requirements. The target area, remote handling procedures and the facilities are very similar to what has been proposed for the **Spallation Neutron Source** in Oak Ridge.

3.3 Phase Rotation and Induction Linac

In order to reduce the energy spread of the muon beam, the muons have to be rotated in phase space. The 50 meter long decay channel is not only used to let the pions decay into muons but also to develop a correlated energy spread 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. An induction linac (compare Figure 3) 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 2 MV/m would be required. Coming out of the decay channel the required beam aperture is 60 cm, which dominates the core size. Each unit it approximately one meter long and driven by an individual power supply. The accelerating gradient is

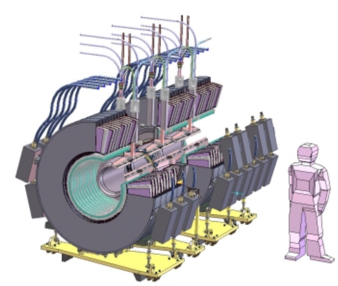

Figure 3: Sketch of an induction cell with integrated sc 3 T coils.

certainly an R&D item as well as the pulsing system. Technical feasibility on the other hand is less of a concern than investment cost, power consumption and reliability, because a very similar induction linac is under construction at present.

3.4 Mini Cooling, Bunching, 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 ≈200 nsec each drift through a long liquid hydrogen absorber into high gradient cavities and then further on into the cooling channel. While so called "mini-cooling", a ~2 m long hydrogen absorber cell, reduces the transverse emittance by ≈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 focus the longitudinally growing muon bunch while strong alternating solenoids with up to 3.6 Tesla on axis produce small enough β-functions to ensure transverse cooling. The main challenge here is certainly the unrivaled gradient in a normal conducting cavity at 200 MHz and the source that is necessary to provide enough peak power at this frequency . 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***): $B \cdot J \cdot R < 350$ MPa. As a result, the coils used for focusing in the cooling channel became rather large and expensive. A sketch of the cooling channel segment, with the hydrogen absorber, the cavity and the solenoids is shown in Figure 4. The typical performance of the cooling channel with the beam coming from the front end described before can be seen in Figure 5. Due to the too large incoming energy spread, the channel basically scrapes and increase the number of particles into the accelerator acceptance by only a factor of 2.

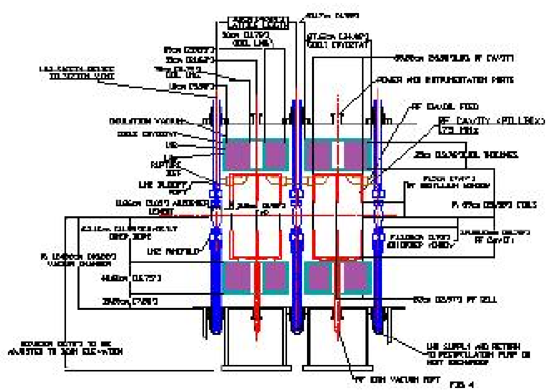

Figure 4: Sketch of a FOFO cooling cell with two 2-cell cavities and LH_2 absorbers in between.

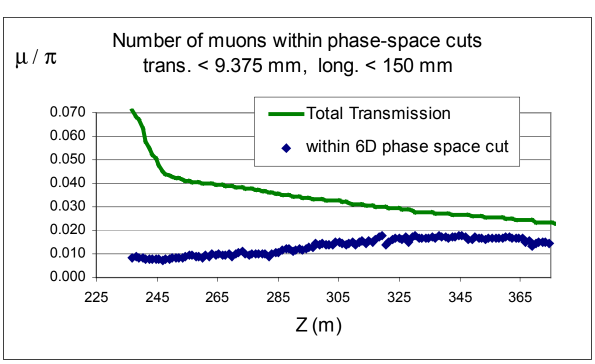

Figure 5: Performance of cooling channel with beam having a too large energy spread coming in.

3.5 The Accelerators

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 π*mm*rad at this point. The longitudinal phase space is diluted due to scattering 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 minimum possible frequency because it is the bunching frequency used early in the phase rotation and cooling. The main difference from the cooling channel is, that distributed focusing (solenoids or quads) can be used, which makes the use of superconducting rf possible. Investigated has been a 3 GeV linac, which gradually increases the phase angle for acceleration. Afterwards two cascaded recirculating linacs boost the energy to 50 GeV. 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. For this reason the second RLA dominates the required real estate (compare Figure 1 for details). 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.

Stage	Voltage (GeV)	#cells	F (MHz)	U_{sto}/cell (J)
Linac	3.6	320	200	1000
RLA1	2.6	231	200	1000
RLA2	8.5	1079	400	125

Table 4: Voltage installed in the accelerating systems and stored energy per cell for an operating gradient of 15 MV/m.

Table 4 summarizes the installed voltage per accelerating susbsystem. 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 stored energy per cell at low frequency and high gradient is large. The beam extracts ~0.3 % per turn at 200 MHz and ~1 % at 400 MHz. Given the number of recirculations, the acceleration can be done based on the stored energy and the feed power does not have to be matched to the circulating current. This allows a very long filling time and comparatively small peak power per cell (<800kW @ 200 MHz) but has the disadvantage of small coupling and high sensitivity to Lorentz force detuning and vibration. After all only 5 % of the power is extracted by the beam which makes the acceleration very intrinsically inefficient

Developing the low frequency high gradient superconducting cavities for these accelerators is clearly a high priority item. Based on the technology developed at CERN, where sputtered niobium on copper cavities are used for acceleration, this seems feasible. Providing peak power at low frequency using standard technology leads to excessively large structures for high gain devices. Multi-beam klystrons are one possibility.

3.6 The Storage Ring

This part is the only really site dependant part of the study. The 50-GeV storage ring for neutrino production has been designed using a racetrack configuration. This design is simple, containing a downward straight, (production straight) and a return straight pointed towards the surface with a second detector and two arcs with their associated matching and dispersion suppression sections.

One of the parameter constraints of the design arises from the underlying geology of the site as shown in Figure 6. The vertical distance between the surface of the site and the bottom of the Galena Platteville rock layer is approximately 680 feet. Below this dolomite layer is a sandstone layer, which must be avoided. This vertical constraint is a limitation because at least part of the ring must be tilted at a vertical angle to direct the neutrino beam through the earth to a long-baseline detector.

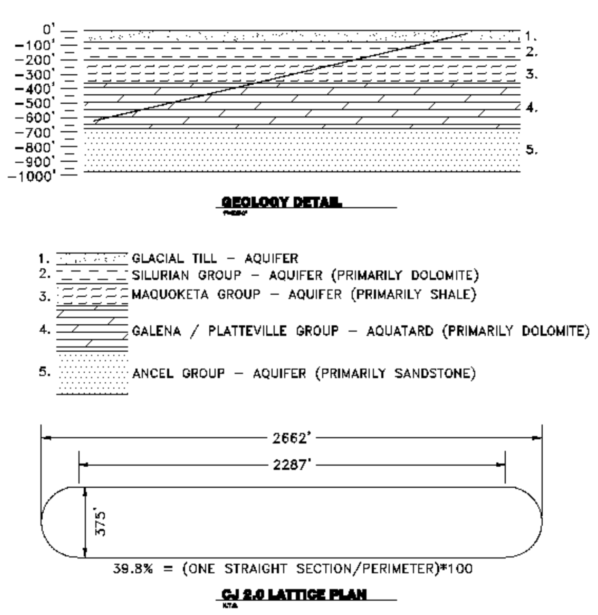

Figure 6:Sketch of the geological layers at Fermilab. The bottom of the Galena Platteville determines the maximum height available for the storage ring.

In the production straight 38 %of the muons decay. With a 240 kW average beam power that leaves ~ 80 kW going into the electrons from which ~20% decay in the arcs. The superconducting magnets have to be shielded from the 70 W/m power deposition which requires a tungsten liner of 1 cm thickness to reduce the loss into the cryogens to ~7 W/m. Using normal conducting magnets would reduce the neutrino yield by almost a factor of two and was not an option. Although the sc magnet can be comparatively simple, after all the beam does only 200 turns, the aperture is large (12.0x9.3 cm^2). The cryogens and the power will be transmitted to an alcove 230 m under ground. Unlimited access is possible because of the low radiation level. In the present configuration the ring is not a cost driver and technically certainly feasible.

4 SUMMARY

The study performed by the Neutrino Factory and Muon Collider collaboration has demonstrated the feasibility of an intense Muon Source based on a Muon Storage Ring. Nevertheless this a difficult accelerator complex making use of a large variety of technologies, which all have to be further developed and therefore require substantial R&D. I parallel a second study, lead by S. Ozaki and R. Palmer from BNL together with the collaboration, will take place over the next 12 month with the goal to improve the muon flux by an order of magnitude. CERN plans to come up with another study on the same time scale.

Several reasons are in favor of such a facility. It is a worldwide unique facility, it is comparatively small and it can be staged (in acceleration and in flux). In addition for the same physics, detector cost and accelerator cost can be balanced and it has attracted a large community nationally and internationally with several funding agencies involved already, certainly in the US.

After all I want to thank the collaboration and all the laboratories involved as well as the Fermilab management for their support during the study.

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A more detailed citation list can be found in [4,5] which would be too long for this report.