FEASIBILITY STUDY-II OF A MUON-BASED NEUTRINO SOURCE

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Preface

Executive Summary

The concept of using a muon storage ring to provide a well characterized beam of muon and electron neutrinos (a Neutrino Factory) has been under study for a number of years now at various laboratories throughout the world. The physics program of a Neutrino Factory is focused on the relatively unexplored neutrino sector. In conjunction with a detector located a suitable distance from the neutrino source, the facility would make valuable contributions to the study of neutrino masses and lepton mixing. A Neutrino Factory is expected to improve the measurement accuracy of $\sin^2(2\theta_{23})$ and Δm^2_{32} and provide measurements of $\sin^2(2\theta_{13})$ and the sign of Δm^2_{32}. It may also be able to measure CP violation in the lepton sector.

In the U.S., a formal collaboration of some 140 scientists, the Neutrino Factory and Muon Collider Collaboration (MC), has undertaken the study of how to design such a machine. The MC has three "sponsoring" national laboratories, Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL or Fermilab), and Lawrence Berkeley National Laboratory (LBNL), and receives funding primarily from the U.S. Department of Energy (DOE).

Recently, the MC has gained from the addition of NSF-sponsored university groups, coordinated by Cornell University, and of various universities in Illinois sponsored by the Illinois Consortium for Accelerator Research (ICAR), coordinated by Illinois Institute of Technology.

In 1999, the MC aimed to define the scope of a Neutrino Factory facility by doing an end-to-end study of the entire complex. This led, in late 1999, to a request from the Fermilab Director, Michael Witherell, to carry out a Feasibility Study, in cooperation with the MC, of a Neutrino Factory sited at Fermilab. That initial Study (denoted here as "Study-I"), organized by Norbert Holtkamp and David Finley (Fermilab), demonstrated the feasibility of an entry-level machine, and outlined the features of the various systems needed to build it. However, the performance reached in that effort, characterized in terms of the number of muon decays aimed at a detector located 3000 km away from the muon storage ring, $N = 2 \times 10^{19}$ decays per "Snowmass year" ($\equiv 10^7$ s) per MW of protons on target, was lower than anticipated.

In June 2000, a request was made by the BNL Director, John Marburger, for the MC to participate in a second Neutrino Factory Feasibility Study (denoted here as "Study-II"), this time focused on a machine sited at BNL. Study-II was to aim at a high-performance machine, with an intensity an order of magnitude higher than achieved in Study-I. Study-II was co-organized by the MC and BNL. The Study Leaders (see below for the organization of the work) were Satoshi Ozaki and Robert Palmer (BNL) and Michael Zisman (LBNL). This document contains the results of Study-II.

In this report we first describe the exciting physics program that can be carried out at a Neutrino Factory. The context of the experimental program is defined in terms of the enhanced knowledge we expect to have at the time such a facility is anticipated to come on line, roughly 2013. Then we describe the Neutrino Factory facility, which comprises the following systems:

- Proton Driver (providing 1 MW of protons on target from an upgraded AGS)
- Target and Capture (a mercury-jet target immersed in a 20-T superconducting solenoidal field to capture pions, product of the proton-nucleus interactions)
- Decay and Phase Rotation (three induction linacs, with internal superconducting solenoidal focusing, to contain the muons from pion decays and provide nearly non-distorting phase rotation; a minicooling absorber section is included after the first induction linac)
- Bunching and Cooling (a solenoidal focusing channel with high-gradient rf cavities and liquid-hydrogen absorbers that bunches the 247 MeV/c muons into 201.25-MHz rf buckets and cools their transverse normalized emittance from 12 mm·rad to 2 mm·rad)
- Acceleration (a superconducting linac with solenoidal focusing to raise the muon beam energy to 2.48 GeV, followed by a four-pass superconducting recirculating linear accelerator to provide a 20 GeV muon beam)
- Storage Ring (a compact racetrack-shaped superconducting storage ring in which 35% of the stored 20 GeV muons decay toward a detector located 2900 km from the ring)

In addition to the Neutrino Factory facility, we describe the features of a possible neutrino detector that could carry out the appropriate physics program.

Performance estimates for the facility show that an intensity of $N = 1.2 \times 10^{20}$ decays per "Snowmass year" per MW of protons on target is feasible—a factor of 6 improvement over the Study-I result, though somewhat less than the original Study-II goal. Upgrade plans that increase the proton driver power from 1 to 4 MW would permit a corresponding increase in the overall intensity per year to $N = 4.8 \times 10^{20}$ decays. R&D to develop a target capable of handling this beam power would be needed. Taking the two Feasibility

Studies together, we conclude that a high-performance Neutrino Factory could easily be sited at either BNL or Fermilab.

Reaching the facility performance estimated here will require an intensive R&D program; an outline of the needed activities is included in this report. To assess the cost range of a Neutrino Factory, a top-down cost estimate has been carried out for the major components. This estimate represents an initial look at what is needed, and should not be construed as the kind of detailed estimate that would result from a Conceptual Design Report. With that caveat, we find that the cost of such a facility is about $1.9 B in today's dollars. This value represents only direct costs, not including overhead or contingency allowances. Lastly, we describe a phased approach to arriving at the complete facility. At each step, we outline the capabilities of the facility and the corresponding scientific program that can be pursued. We also comment on the time scales and costs that would be implied by this approach. Such an "evolutionary" approach to the facility may represent the most effective way to achieve the ultimate goal of a high-performance Neutrino Factory, even if it stretches out the overall time line.

It is worth noting that the Neutrino Factory facility described here can be viewed as a first critical step on the path toward an eventual Muon Collider. Such a collider offers the potential of bringing the energy frontier in high energy physics within reach of a moderate sized machine. The very fortuitous situation of having an intermediate step along this path that offers a powerful and exciting physics program in its own right presents an ideal opportunity, and it is hoped that the high energy physics community will have the resources and foresight to take advantage of it.

Acknowledgment

We would like to thank the management of the Brookhaven National Laboratory, Dr. John Marburger and Dr. Peter Paul, for their support, interest and foremost for the commissioning of the Study. We would like also to express our gratitude to Dr. A. Sessler, spokesperson for the Neutrino Factory and Muon Collider Collaboration, for his continuous encouragement and technical guidance. Finally, our most sincere thanks to all the contributors, especially those who were not members of the Collaboration. Their technical expertise was crucial for the completion of this report.

Charge to the Study Group

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DATE: June 13, 2000
TO: Robert Palmer, Satoshi Ozaki
CC: Thomas Kirk, Peter Paul, Andrew Sessler
FROM: John Marburger
SUBJECT: Muon device studies

I am writing to request that you organize, in cooperation with the Muon Collider Collaboration, a BNL site-specific study on the feasibility of a 'high performance' muon storage ring neutrino source.

The study would complement the recently completed 'entry level' study commissioned by the Fermilab director and carried out together with the Muon Collider Collaboration.

The scope and parameters for this study have been developed and approved by the Muon Collider Collaboration Spokesperson, Andy Sessler, and Project Manager, Mike Zisman. The Muon Collaboration will participate in the study.

The study will also complement the AGS Targetry Experiment, E951, that will study two crucial components of the high performance version of the muon storage ring.

The study should consist of two components:

A. A BNL site specific part, led by S. Ozaki and including:

1. a technical description of upgrades to the AGS to reach an average beam power of 1 MW (e.g. 10^{14} pps at 24 GeV at 2.5 Hz), together with a preliminary cost estimate for this upgrade;
2. a design, layout and preliminary cost estimate for a muon storage ring with the requirement that it be sufficiently above the water table to minimize environmental impacts;
3. magnet studies for the above ring.

B. A generic part, led by the collaboration management, funded by DOE MCC Collaboration funds, and including:

1. the design and technical description of the non-AGS components of a high performance muon storage ring neutrino source, including liquid metal target, muon capture, cooling, acceleration and storage;
2. determination of cost drivers in these systems where not already covered in the Fermilab study;
3. areas for potential cost reduction;
4. continued physics and detector studies as needed.

The study should consider a facility with the following characteristics:

1. a muon storage ring energy of approximately 20 GeV;

2. a neutrino beam aimed at an optimized 50 kT detector located approximately 1800 km from BNL;

3. 2 10^{20} muons per (10^{7} sec) year decaying in the detector direction; this is approximately one order of magnitude higher than the 'entry level' machine.

The written report on this new study should be submitted to me by April 30, 2001.

Organization of the Study

The organization chart of the Study is shown in the figure

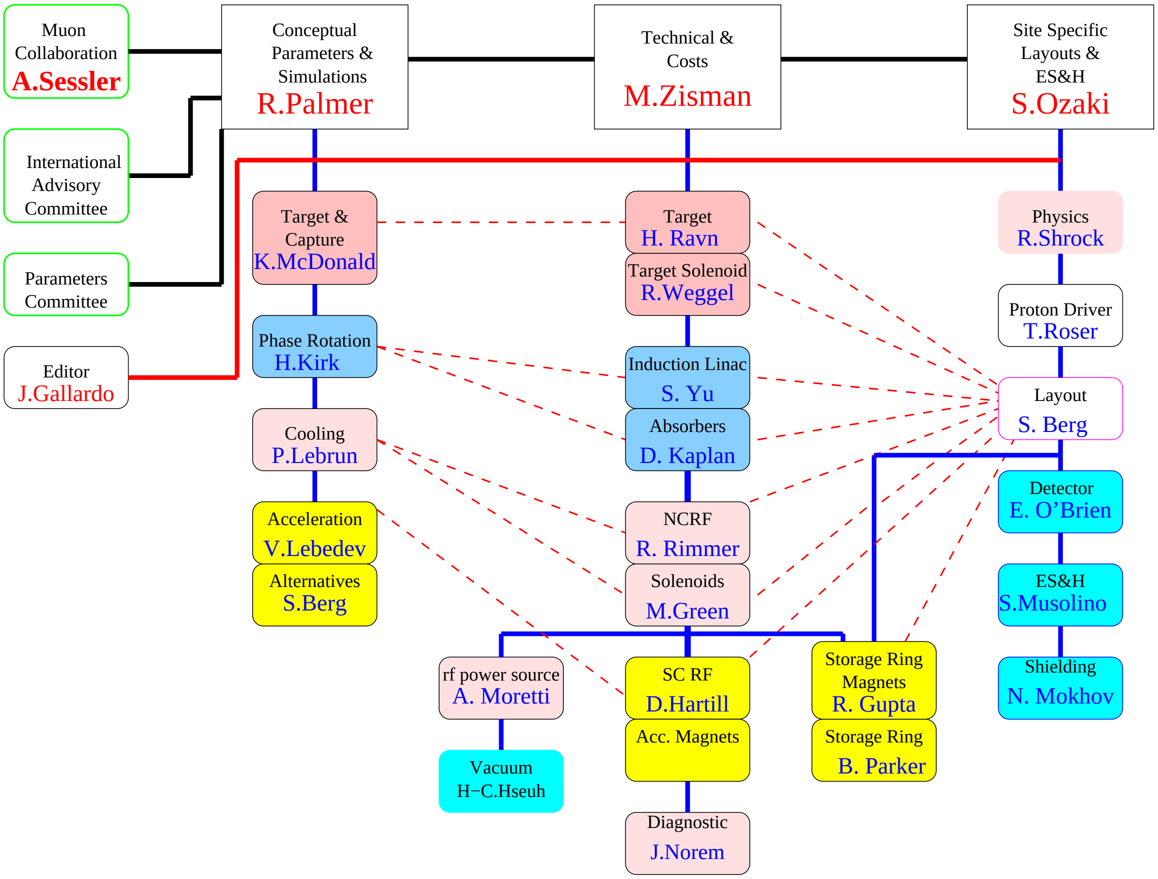

Figure 1: Organization chart for Study-II.

Summary of Parameters and Performance

In this section, we briefly summarize the overall parameters and predicted performance of the Neutrino Factory concept developed for Study-II and described in this document. The majority of the concepts developed here are generic, in the sense that they do not depend upon specifics of the BNL site. A few details, of course, do depend on the particular site chosen for this Study.

The proton driver on which this Study is based is the BNL Alternating Gradient Synchrotron (AGS). This machine delivers 24 GeV protons and presently holds the world's intensity record for proton accelerators. To create a 1 MW proton beam, the properties of the AGS dictate a ramp cycle of 150 ms up, 100 ms flat-top, and 150 ms down, with six proton bunches extracted sequentially at 20-ms intervals during the 100-ms flat-top. This cycle is repeated at 2.5 Hz, leading to an average pulse rate of 15 Hz, that is, 6 bunches per cycle at 2.5 Hz. Note that the instantaneous repetition rate is 50 Hz (20 ms bunch separation) even though the average rate is lower. Individual proton bunches have an rms length of 3 ns.

The other site-specific aspect of the Study-II design concerns the elevation of the facility. Local policy requires that no part of the Neutrino Factory complex that produces radiation lie below the local BNL water table elevation. This is not an issue for most of the facility, but it does constrain the location of the storage ring. Because the ring must be tilted vertically by 13.1° to aim at the Waste Isolation Pilot Plant (WIPP) site in Carlsbad, NM, some 2900 km distant, this vertical location requirement placed a premium on having a compact storage ring, and dictated using an above-ground berm to shield the ring.

The general design approach we follow is an outgrowth of the previous Feasibility Study ("Study-I"). However, we have made many technical changes from the previous design—in some cases simply to explore alternative design options, and in other cases to specifically enhance performance. As in the previous Study, we have chosen not to consider muon beam polarization as a design criterion. This avoids the need to place high-gradient rf cavities in the high-radiation environment very close to the target. The overall layout of the facility is presented in Fig. 2. Lengths of the various systems that comprise the facility are summarized in Table 1.

The specific changes made in Study-II to enhance facility performance include:

- Use of a liquid mercury target
- Use of three induction linac units, separated by suitable drift lengths, to achieve nearly non-distorting phase rotation

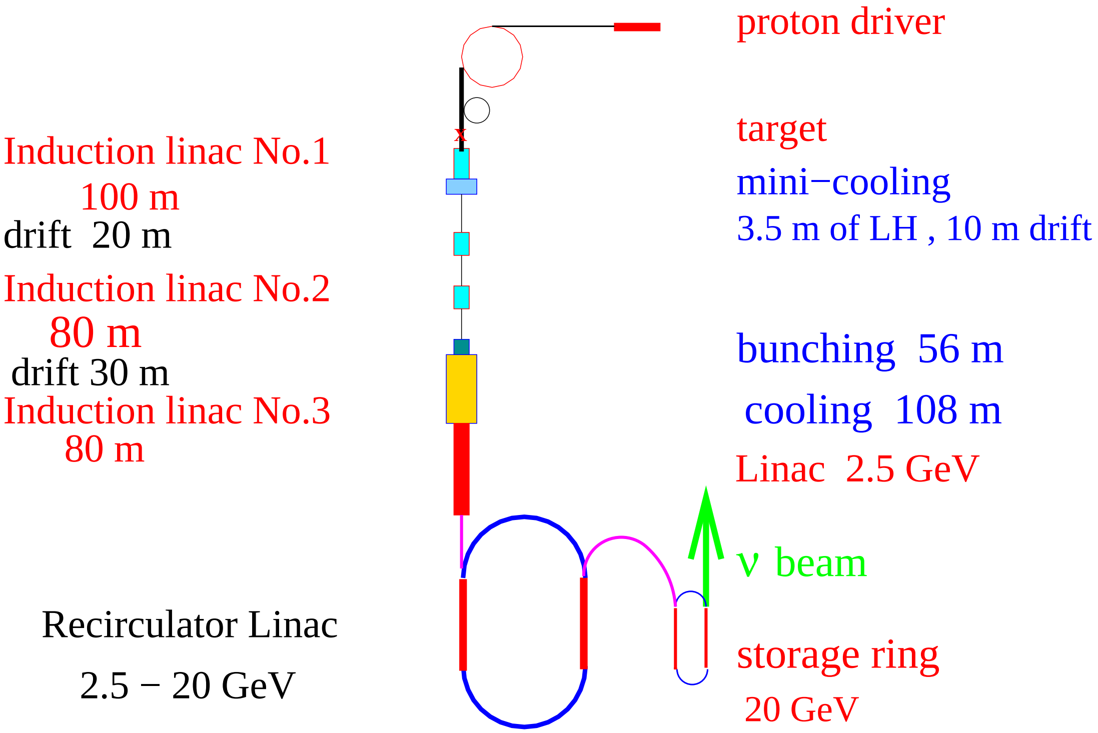

Figure 2: Schematic of the Neutrino Factory facility

Table 1: Length of the main components of a Neutrino Factory.

Component	Length (m)	Total (m)
Target	0.45	0.45
Taper	17.6	17.6
Drift	18	35.6
Induction 1	100	135.6
Drift	3.3	138.9
Mini-Cool	13.5	152.4
Drift	23.2	175.6
Induction 2	80	255.6
Drift	30	285.6
Induction 3	80	365.6
Match to Super FOFO	12	377.6
Buncher	$20 \times 2.75 = 55$	432.6
Cooling part 1	$16 \times 2.75 = 44$	476.6
Match	4.4	481.0
Cooling part 2	$36 \times 1.65 = 59.4$	540.4
Match	22.04	562.4
Linac	433	
RLA arcs min.	2×310	
RLA linacs	2×363.5	
Storage ring arcs	2×53	
Storage ring straights	2×126	

- Use of a graded focusing strength along the cooling channel to keep the beam angular spread nearly constant as the emittance decreases

As will be seen later, taken together these changes improved the overall performance of Study-II by a factor of 6 compared with Study-I.

Other changes in the present Study that differ from Study-I include:

- Use of a hollow-conductor resistive magnet insert at the target, in place of a Bitter magnet insert

- Use of a Super-FOFO ("SFOFO") cooling channel, in place of a FOFO channel

- Use of a large-acceptance superconducting linac for the initial acceleration after the cooling channel, in place of a conventional linac
- Use of a combined-function compact storage ring, in place of a conventional separated-function ring

These changes, as noted above, enhance our knowledge base by giving an expanded understanding of the parameter space available to the designers of a Neutrino Factory.

Key parameters for the overall facility are summarized in Table 2.

Table 2: Muon beam parameters along the length of the facility.

Location (end of)	σ_r (cm)	$\sigma_{r'}$ (mrad)	σ_p (MeV/c)	σ_t (ns)	$\langle p \rangle$ (GeV/c)
IL3	8.6	95	118		0.237
Matching	5.8	114	115		0.247
Buncher	5.7	134	110	0.84	0.247
2.75 m cooling lattice	3.0	87	72	0.55	0.222
1.65 m cooling lattice	2.4	109	32	0.51	0.204
Matching	10	29	27	0.97	0.270
Pre-accelerator			81	0.26	2.583
RLA			134	0.27	20.105
Storage Ring			134	0.27	20.105

Based on simulation results, we expect that the facility described herein will provide 1.2×10^{20} muons decays, per "Snowmass year" ($10^7 s$) and per MW of proton beam incident on the target, aimed at a detector some 3000 km distant from the storage ring. This value corresponds to our baseline case of a 1-MW proton driver.

For the enhanced case of a 4-MW proton driver, discussed in Section B.1, the muon decay rate would increase to 4.8×10^{20} muons decays, per "Snowmass year".