Title
International scoping study: accelerator working group report

Author
Zisman, M.S.

Publication Date
2008-09-03

International scoping study: accelerator working group report

Michael S. Zisman[1], for the ISS Accelerator Working Group

Center for Beam Physics, Accelerator & Fusion Research Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, U.S.A.

E-mail: mszisman@lbl.gov

Abstract. During the past several years, an International Scoping Study (ISS) of a Neutrino Factory was carried out, with the aim of developing an internationally accepted baseline facility design. Progress toward that goal will be described. Many of the key technical aspects of a Neutrino Factory facility design are presently being investigated experimentally, and the status of these investigations will be mentioned. Plans for the recently launched International Design Study (IDS), which serves as a follow-on to the ISS, will be briefly described.

1. Introduction

The mission of the International Scoping Study [1] involved two aspects. First, it was to evaluate the physics case for a next-generation neutrino facility. Second, it was to study options for the accelerator complex and the required neutrino detection systems.

The principal objective is to lay the foundations for a full conceptual design of such a facility. The study was conceived from the outset as an international endeavor, with effort provided by the ECFA BENE network [2] and the UK Neutrino Factory group [3] in Europe, the NuFact-J collaboration [4] in Japan, and the Neutrino Factory and Muon Collider Collaboration (NFMCC) [5] in the U.S.

The basic design requirements for the facility are:

- a muon beam energy of 20 GeV, upgradeable to 50 GeV
- 10^{21} muon decays per year directed toward the detectors
- neutrino and antineutrino pulses separated by ≥100 ns at the detectors, which are located at distances of 3000 km and 7500 km from the source

It should be obvious from the distances quoted that a Neutrino Factory is intrinsically an international project.

2. Neutrino Factory ingredients

The ingredients of a Neutrino Factory are summarized pictorially in figure 1. The process begins with a high-intensity proton driver, which generates the primary beam and sends it to a production target, where pions are created and then rapidly decay into muons. Following the creation of the muon beam, it must be "conditioned" to create a usable beam for the downstream systems. First the beam is bunched with an RF system having frequencies that vary along the beam line, and then it is phase rotated in longitudinal phase space, that is, the bunch train is made longer but with a lower energy spread. Thereafter, the transverse emittance of the muon beam is quickly reduced by a process known as

[1] To whom all correspondence should be addressed.

"ionization cooling." In a nutshell, the muons lose energy in LH_2 absorbers in all three planes (p_x, p_y, p_z) via dE/dx, after which the longitudinal component of momentum, p_z, is restored with high-gradient RF cavities. Repeated application results in a decrease in p_x/p_z and p_y/p_z, thus reducing the transverse emittance. These processes all take place at a muon momentum of roughly 200 MeV/c. After cooling, the beam must be accelerated to its final energy of 20–50 GeV. The acceleration scheme is multi-stage, and involves a linac, several stages of dog-bone recirculating linear accelerators (RLAs), and one or more stages of fixed-field, alternating gradient (FFAG) acceleration. Lastly, the beam is stored in one or more decay rings, with long straight sections aimed at the detectors.

Constructing such a facility is challenging. Firstly, muons have a short lifetime (2.2 μs at rest). This puts a substantial premium on rapid beam manipulations. In particular, we require high-gradient RF cavities for the cooling channel, a fast, large acceptance acceleration system, and the presently untested technique of ionization cooling. Secondly, muons are created as a tertiary beam ($p \rightarrow \pi \rightarrow \mu$). This has two consequences—a rather low production rate, which necessitates a target that can withstand a multi-MW proton beam, and a beam created with a large transverse phase space and energy spread, which necessitates a high acceptance acceleration system and decay ring.

3. Accelerator working group aims

The study had three main aims. First, we examined alternative configurations for a Neutrino Factory to arrive at a set of baseline specifications for a system to pursue further. Approaches with and without ionization cooling were examined, as both have been proposed as candidate Neutrino Factory designs. The choices made, discussed later in this paper, will serve as the starting point for the follow-on International Design Study for a Neutrino Factory (IDS-NF) [6], which is just getting under way.

A second aim was to develop the computational tools we would need to carry out end-to-end simulations of the alternative facility concepts. In this regard, we made less progress than hoped for. Though tools for dealing with individual pieces are available, the ability to follow the beam from the target through to the decay ring is not yet available. Such end-to-end simulations are ultimately needed, as correlations in the beam and the details of the particle distribution have a significant effect on the transmission at the interfaces between systems, i.e., the muons have "memory."

The third aim was to develop and maintain a list of key R&D topics as we proceeded with the study. This list identifies the activities that must be accomplished to develop confidence in the particle physics community that we have arrived at a design that is both credible and cost-effective.

4. Neutrino Factory baseline design

4.1. Proton driver

For the design of the proton driver, we examined suitable operating parameters, including repetition rate, beam energy, and bunch length. For all of the cases we looked at, 50 Hz appeared to be a reasonable compromise and was adopted for our baseline. To assess the optimum proton beam energy, we carried out calculations of pion and muon production using the code MARS [7]. Our results [8], shown in figure 2, indicate a rather broad optimum. We adopted 10±5 GeV as a representative range for both signs.

Investigations of proton bunch length dependence were carried out using the Study 2a [9] channel. The results showed a decrease in intensity beyond a 1 ns rms bunch length. Using 3 ns bunches decreases the throughput by about 10% compared with 1 ns. Thus, 1 ns is preferred, but 2–3 ns is acceptable.

There are a number of proton driver options being considered, including those based on synchrotrons [10], on FFAG rings [11], and on linacs [12]. In our estimation, all these can deliver the required beam, though the ability to produce short bunches gets progressively harder as the beam energy decreases. For this reason, we did not specify a particular hardware configuration, but only a set of parameters, summarized in table 1.

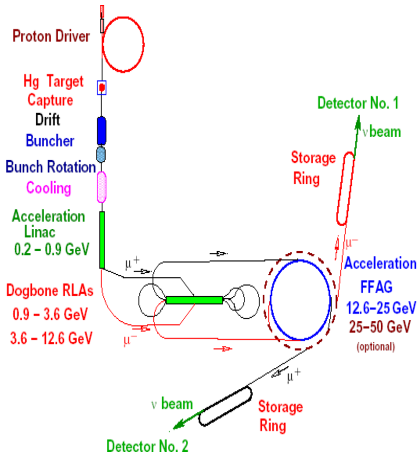

Figure 1. Schematic layout of ISS base configuration for a Neutrino Factory.

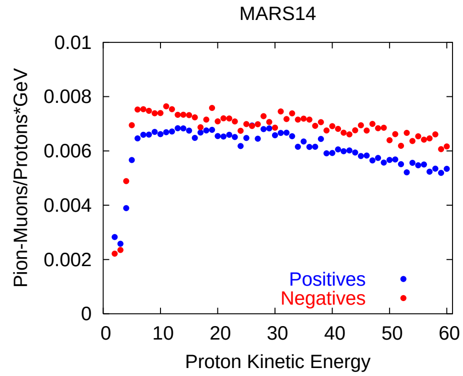

Figure 2. Calculated pion and muon production a function of proton beam energy for a target of Hg.

Table 1. Baseline proton driver parameters.

Parameter	Value
Energy (GeV)	10 ± 5
Beam power (MW)	4
Repetition rate (Hz)	≈50
No. of bunch trains	3,5[a]
Bunch length, rms (ns)	2 ± 1
Beam duration (μs)	≈40

[a]Values from 1–5 possibly acceptable

4.2. Target and capture

Our simulation studies compared both high- and low-*Z* targets. We found [8] that a Hg target with a proton beam energy of 10 GeV was optimal. At a low beam energy, 5 GeV, a carbon target gives good production, but Hg at 10 GeV gave better performance, by about 20%, compared with C at 5 GeV.

We use a solenoidal capture system, based on the system used in Studies II [10] and IIa [9]. A 20 T hybrid magnet is employed immediately surrounding the target . The 15 cm diameter device has a superconducting outer coil and a conventional solenoid insert. It also uses an iron plug to improve field uniformity at the target location. Downstream, the field tapers adiabatically from 20 T to 1.75 T over a 20 m distance.

4.3. Front end

We carried out two main tasks in this area. First, we evaluated the trade-offs between the amount of cooling provided and the downstream acceptance. Our findings are summarized in figure 3, which shows curves of the μ/p ratio as a function of cooling channel length for various assumptions about the downstream acceptance. For 30 π mm acceptance, it takes 79 m of cooling channel to reach the value of μ/p = 0.17 found in Study IIa [9]. If the downstream acceptance increases to 35 π mm, the required length of cooling channel is roughly halved. At an acceptance of 45 π mm, no cooling at all is needed to provide the desired throughput. Based on our present studies of acceleration systems, however, 30 π mm seems like a practical limit.

Comparison of the various cooling channel concepts proposed to date showed that the system described in Study IIa [9] had the best performance, and was the only system that (using both signs of muon simultaneously) gave the desired 10^{21} neutrinos per year aimed at the far detector.

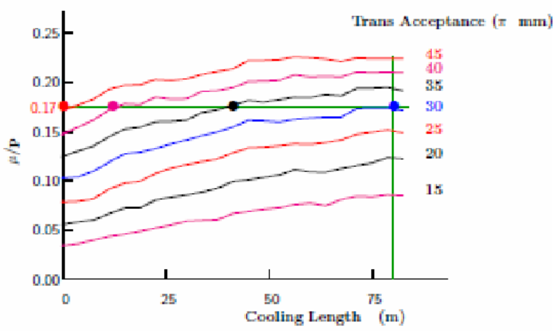

Figure 3. Number of muons per proton into specified downstream acceptance, as a function cooling channel length. The Study IIa channel assumed. The horizontal line at $\mu/p = 0.17$ represents performance found in Study IIa.

4.4. Acceleration system

We looked at various schemes and optimized performance using several different subsystems. As indicated in figure 4, our baseline scenario uses an initial linac to reach 0.9 GeV, followed by two stages of dog-bone RLA and one or more non-scaling FFAG rings. This system is capable of delivering both μ^+ and μ^- simultaneously. While the proposed system delivers the beam with minimal losses and emittance dilution, it is not necessarily cost-optimized. In particular, there are operating cost implications of such a heterogeneous system that need to be evaluated.

In looking at the implications of increasing the acceptance of the acceleration system, a beam dynamics problem was discovered with the non-scaling FFAGs. At very large emittance values, the path length differences associated with different amplitudes give rise to sufficiently large time variation that particles slip out of phase with the RF and are not fully accelerated. The present conclusion is that 30 π mm acceptance is reasonable, but is already difficult. Moreover cascading several FFAG rings looks difficult, as the phase slippage is exacerbated in going into the second ring. Two FFAG rings in series may be possible, but more than this presently looks impractical.

4.5. Decay ring

Both triangle and racetrack geometries have been studied [13]. Triangle rings (see figure 5) would be stacked side-by-side in a common tunnel. One ring would store each muon sign, since the two beams must circulate in the same direction to illuminate the detectors. This geometry is more efficient than the racetrack shape in optimizing useful muon decays, but requires that the two sites lie in opposite directions with respect to the ring.

For a single detector site, or for two sites in the same direction, a racetrack design is preferred. In the absence of specific site information, we chose the racetrack geometry as the baseline, with the proviso that this must be revisited when specific detector and source locations are defined. The racetrack design (illustrated schematically in figure 1) is very flexible, in that the detector sites can be anywhere. Moreover, if only one detector is operating, all of the muon decays (from both μ^+ and μ^-) can in principle be directed toward that location, which cannot be done for the triangle geometry. The price for this flexibility is the need for two tunnels rather than one, the need for two injection lines for each ring (one for each sign) and probably the need for two near detectors per ring to monitor each straight section separately.

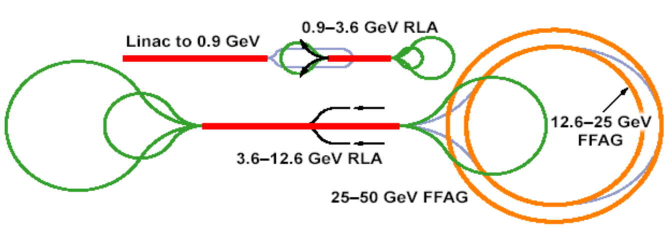

Figure 4. Neutrino Factory baseline acceleration scenario.

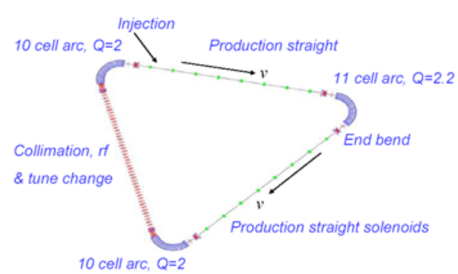

Figure 5. Layout of triangle decay ring.

5. R&D program

MERIT [14], scheduled to take data this fall, will test the performance of a Hg-jet target in a 15 T solenoid using a 24 GeV proton beam from the CERN PS. Optical diagnostics will observe the behavior of the jet after being hit by a beam intensity corresponding to a single pulse of a 4 MW beam.

MICE [15] involves a muon beam test of one cell of a realistic muon ionization cooling channel, comprising liquid-hydrogen absorbers, high-gradient 201-MHz RF cavities, and large aperture, high-field solenoid magnets. Muons will be provided parasitically by the ISIS accelerator at Rutherford Appleton Laboratory. Upstream and downstream of the cooling channel cell will be spectrometer solenoids with scintillating-fiber trackers and time-of-flight detectors. Cherenkov detectors will be located upstream and an electromagnetic calorimeter will be downstream for particle identification. The experiment will be staged to ensure adequate control over possible systematic errors. Components are presently being fabricated in preparation for first beam early in 2008.

The EMMA experiment [16] at Daresbury Laboratory will test an electron model of a non-scaling FFAG ring. It will study FFAG beam dynamics (e.g., longitudinal dynamics, transmission, emittance growth, influence of resonances) and will serve to demonstrate the non-scaling FFAG concept.

6. Summary

With the ISS, the Neutrino Factory community has made good progress toward consensus on a single optimized scenario. The IDS-NF will carry forward and expand upon the ISS design process.

An ongoing R&D program is a key ingredient in the Neutrino Factory design process; synergy with Muon Collider R&D is considered an advantage. Operation of high-gradient RF cavities in a strong axial magnetic field is presently viewed as the most critical R&D issue.

Acknowledgments

This work was supported by the U.S. Department of Energy, Office of High Energy Physics, under contract number DE-AC02-05CH11231.

References

[1] See http://www.hep.ph.ic.ac.uk/iss/

[2] A Baldini, *et al.* (eds.), "BENE midterm scientific report," CARE-2006-009-BENE, CERN-2006-005, ECFA/06/242; see http://people.na.infn.it/~ palladin/BeneMidtermReport.pdf.

[3] See http://hepunx.rl.ac.uk/uknf/

[4] See http://www-prism.kek.jp/nufactj/index.html

[5] See http://www.cap.bnl.gov/mumu/mu_home_page.html

[6] See http://www.hep.ph.ic.ac.uk/ids/

[7] N V Mokhov *et al.*, Fermilab-Conf-98/379; LANL report LA-UR-98-5716 (1998); see http://www-ap.fnal.gov/MARS

[8] H G Kirk, 2006 private communication

[9] J S Berg *et al.*, 2006 *Phys. Rev. Special Topics-AB* **9** 011001

[10] S Ozaki, R Palmer, M Zisman and J Gallardo (eds.), "Feasibility study-II of a muon-based neutrino source," BNL-52623, June, 2001, see http://www.cap.bnl.gov/mumu/studyii/final_draft/The-Report.pdf.

[11] G H Rees, 2006 *Nucl. Phys.* B **155** 301

[12] F Gerigk (ed.), "Conceptual design of the SPL II—a high power superconducting H^- linac at CERN," CERN report CERN-2006-006.

[13] G Rees, C Johnstone, and F Méot, in Proc. of 2006 European Particle Accelerator Conf., Edinburgh, Scotland, June 26–30, 2415

[14] H. G. Kirk *et al.*, in Proc. 2007 Particle Accelerator Conf., Albuquerque, June 25–29, 646

[15] P. Drumm (ed.), "MICE: an international muon ionization cooling experiment, Technical design report," http://www.isis.rl.ac.uk/accelerator/MICE/TR/MICE_Tech_ref.html

[16] R. Edgecock, in Proc. 2007 Particle Accelerator Conf., Albuquerque, June 25–29, 2624