The Neutrino Factory and Related Accelerator R&D

C.R. Prior
STFC Rutherford Appleton Laboratory, Harwell Science & Innovation Campus, Chilton, Oxfordshire OX11 0QX, UK
E-mail: c.r.prior@rl.ac.uk

Abstract. A muon-based neutrino factory, encompassing high power proton accelerators, innovations in rapid acceleration techniques for unstable particles, and initiatives such as ionisation cooling, provides a rich and varied source of high-energy R&D. Over the last ten years, the U.K. has played a leading role in progress towards a large-scale neutrino facility, both at national and international level, and now seeks to move to the next phase with preparation of an International Design Study report for publication in 2010. The basic principles of the project are outlined here, with emphasis on the major problems still to be overcome. Much of the development work relates to other areas of accelerator science - such as spallation neutron sources, used for research in condensed matter physics - and the way in which such projects interact and benefit from each other is also described.

1. Introduction
Apart from the International Linear Collider, the accelerator project of most interest to the high energy particle physics community is the Neutrino Factory (NF). Directed at the Standard Model, the aim of such a facility is to generate sufficient neutrinos from muon decay - set at $10^{21}$ per year - to investigate small values of the mixing angle $\theta_{13}$, determine the mass hierarchy and search for CP violation in the lepton sector.

The first suggestion that an accelerator-based complex might realistically attain these goals was published in 1997 [1], and an intensive international effort has continued over the past ten years, culminating in the International Scoping Study (ISS) in 2006 [2]. ISS carried out a comparative evaluation of previous work, and developed new ideas in certain areas until a self-consistent NF scenario could be identified. A list of topics requiring urgent R&D was also prepared. In August 2007, the follow-up, a full International Design Study...
(IDS), was launched, aimed at detailed analysis, engineering plans and cost estimates, with a Conceptual Design Report due in 2012. The baseline for the study is the ISS recommendation, whose principles are shown in Figure 1.

A high intensity proton driver directs a beam of a few megawatts onto a pion production target. Charged pions are captured in a focussing channel at low energy; they decay to muons, whose phase space is controlled and reduced in size by ionisation cooling. The resulting muon beam is then accelerated rapidly to an energy in the range 20-50 GeV. Finally the muons are stored in designated storage rings with long straight sections, where the neutrinos produced by their decay can be directed through the earth towards the detector sites. Such a facility presents demanding challenges for accelerator R&D, ranging from proton driver development through to rapid muon acceleration, as well as touching on geological and engineering aspects of constructing an almost vertical storage ring several hundred metres below the Earth’s surface.

2. High Intensity Proton Accelerators

The main requirements from the proton driver are high beam power and very short bunch lengths. High beam power is needed to ensure sufficiently many pions are created to achieve the desired annual neutrino flux, and 4 MW is the agreed goal. Short proton bunch lengths are necessary in order that the longitudinal emittance of the muon beam is small, enabling fast acceleration and the establishment of a suitable time structure in the neutrino pulses at the detectors. The ISS study [2] identified 1-3 ns (rms) as a suitable range. To put these demands in perspective, the ISIS accelerators [3] at the Rutherford Appleton Laboratory (RAL), which represent the most powerful pulsed neutron source in the world\(^1\), generate 160 kW of beam power in bunches of ~120 ns duration. The step up to a Neutrino Factory driver is huge and the difficulties to be encountered are not to be taken lightly.

The two projects most likely to enhance our knowledge of high intensity proton accelerators in the world today are mainly designed for the generation of spallation neutrons. These illustrate the possible differences in accelerator architecture, parameters and even aims, but many of the underlying features are essentially the same. In particular, the ways in which difficulties in delivering the required beam power to the target are addressed have been incorporated in theoretical designs for several other projects.

2.1. ORNL Spallation Neutron Source

![Figure 2. The US Spallation Neutron Source at Oak Ridge, Tennessee.](image)

Construction of the US Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory in Tennessee was completed in June 2006 and the focus of attention is now on bringing the machine up to the design operating levels. When fully operational, the proton accelerator will deliver 1.44 MW of proton beam power onto a production target, which is a factor of eight beyond that achieved at ISIS.

The SNS accelerator complex (Figure 2) comprises a 2.5 MeV \( \text{H}^+ \) injector feeding into a linear accelerator that takes the beam to its full energy of 1 GeV. A 1 ms pulse is compressed to about 700 ns in an accumulator.

\(^1\) Since writing, the SNS (q.v.) has exceeded the ISIS beam power, though not on a regular basis, over a sustained period.
ring over 1060 turns, before being transported to a liquid mercury spallation target. An energy of 1.01 GeV has been reached in the linac, making it the highest energy superconducting proton/H$^-$ linac ever built. The main issues being addressed are: improving the output H$^-$ current from the ion source, achieving the design performance in the fast beam chopper, reaching the high intensities needed in the ring via successful operation of the charge exchange injection system, and raising the repetition rate to the 60 Hz design value. The beam chopper is an essential feature of high intensity proton accelerators where beam loss and the need to minimise activation levels are major considerations. Chopping gaps in the train of linac micro-bunches, by deliberately deflecting sections of beam to dedicated dumps, enables almost loss-free injection into the accumulator ring and clean extraction of the beam to the target.

2.2. Japan Proton Accelerator Research Complex, J-PARC

J-PARC, on the other hand, is a much wider ranging research facility and has a different structure for its accelerating system. A 50 mA H$^-$ beam is accelerated to 400 MeV in a 500 µs pulse, and then injected into a 3 GeV rapid cycling synchrotron at a repetition rate of 25 Hz. The design is for a beam power of 1 MW, and the accumulated beam is extracted and transported to an experimental facility for materials and life sciences (see Figure 3). This contains muon and neutron production targets. Every 3.5 s a beam pulse will be transported from the 3 GeV ring to a 50 GeV main synchrotron, producing a 0.75 MW beam that is slow-extracted to a hadron experimental facility. Experiments into kaon rare decays and hyper nuclei will be undertaken. The beam can also be fast-extracted to a neutrino production target and a stream of neutrinos will be sent to the SuperKamiokande detector, which is about 300 km distant. An additional feature of the complex will be a future increase in the linac energy to 600 MeV and the operation of a nuclear waste transmutation facility.

Construction of the linac and the two synchrotrons should be completed by 2008. By August 2007, the linac had been commissioned to an energy of 181 MeV, commissioning of the 3 GeV synchrotron was due to start in September 2007 and of the 50 GeV ring in May 2008.

2.3. CERN SPL and Linac4

J-PARC and SNS illustrate the two different types of proton drivers under construction and study: a full energy linac plus accumulator ring (LAR), and a lower energy linac feeding one or more rapid cycling synchrotrons (RCS) that provide further acceleration. The ISS considered which might be most appropriate for a neutrino factory without making any specific recommendation. Apart from beam power and nanosecond bunches, the demands of the muon acceleration system and requirements at the detector suggest a repetition rate of about 50 Hz in pulses of 3-5 bunches, and the ability to delay transfer to the pion production target so that only a single muon bunch train goes through the system at any one time, to reduce beam loading in the muon accelerators. LAR designs in general produce a high number of bunches per pulse, whereas RCS systems can be envisaged with many fewer, but there are pros and cons in other areas that also need to be taken into account.
At CERN the SPL [4] - a superconducting H− linac at 3.5 or 5 GeV (Figure 4(a)) - has been designed mainly as a new injector to the LHC complex but with the possibility in mind that it might also be used as a driver for a neutrino facility. In the latter case, the beam would be injected into an accumulator ring and bunches sequentially transferred to a compressor ring where the nanosecond bunch durations are achieved. The necessary delays in extraction would be ensured in a scenario illustrated in Figure 4(b). The SPL is currently at the design-study stage; however approval has been given for construction of what is effectively the front end in the form of a new linac injecting into the CERN PS-Booster, known as Linac4. Changes from direct proton injection to H− injection via foil stripping have necessitated substantial modifications to the accelerator complex and will allow greater beam intensity in the PS. Linac4 incorporates a radio frequency quadrupole linac (RFQ), designed in France under the IPHI project, and a fast beam chopper, which has been intensively studied under the EU Framework Project 6. The design energy is 160 MeV.

2.4. Other Proton Drivers

A similar front-end test facility, incorporating ion source, RFQ and chopper, is under development at RAL. This will be the prototype for an H− linac design to an energy of about 200 MeV. Such a linac is at the heart of a series of 4-5 MW proton drivers developed at the laboratory over the past few years. In all cases, the linac injects into a rapid cycling synchrotron booster; beam intensity is built up by multi-turn injection before transfer to, and final acceleration in, a separate ring. Perhaps the most interesting of these is the model incorporating a Fixed Field Alternating Gradient synchrotron (FFAG), shown in Figure 5 and described in [5]. This was specifically designed for a Neutrino Factory and meets the ISS recommendations in terms of a low number (3 or 5) of bunches per pulse and the ability to hold them in a compressed state for the requisite time (17 µs) before transfer to the pion production target. However FFAG technology is very much in its infancy, so a large R&D programme would need to be initiated before such a high intensity proton machine could be built.

Figure 4. CERN’s proposals for a superconducting proton linac

Figure 5. RAL FFAG-based 10 GeV, 4 MW proton driver.
3. Targets
The Neutrino Factory target has often been cited as the single most challenging part of the entire complex. The problems to be overcome relate mainly to heating and thermal shock. There is reasonable confidence that a fixed metallic target would work up to 1 MW, but beyond that one has to think in terms of a moving target, either solid or liquid or even in powder form. SNS has a fixed structure through which mercury flows, but already sees problems with cavitation. For the Neutrino Factory, rotating metal bands have been proposed - so that the proton beam impinges on a different section of target on each pulse - but ISS identified a liquid mercury jet for its baseline. The jet has a speed of 20 m/s and is surrounded by a 20 T solenoid to capture the pions produced. Figure 6(a) shows a possible design, while Figure 6(b) details the MERIT experiment planned for October 2007 using the PS beam at CERN. The experiment focuses a 24 GeV proton beam to a 1.2 mm × 12 mm spot on a mercury jet, with a peak energy deposition of 180 J/g. Because of shock and cavitation problems, a liquid target operates best with short pulses of ≲ 40 µs. Parallel studies of solid targets are being undertaken at RAL, and since such targets have the ability to relax during the deposition, they operate best at longer pulse lengths ≳ 70 µs.

![Image](a) Liquid Mercury Jet Target  
(b) MERIT: the Mercury Intense Target Experiment at CERN

Figure 6. ISS baseline target and associated R&D.

4. Muon Front-End
Pions emanate from the target in all directions, with a range of energies centred roughly on 130 MeV. As many as possible are captured in a solenoid channel, with fields decreasing from 20 T to 1.5 T, and are controlled as they decay to muons. That only about 5% get through explains why so much proton beam power is needed at the production target. The muons pass through an RF phase rotation system that reduces the energy spread of the beam and increases its bunch length. An RF buncher then turns the muon pulse into trains of about 80 interleaved $\mu^\pm$ bunches [6].

4.1. Ionisation Cooling
The muon transverse emittance is however too large for the subsequent accelerating structures, and it needs to be reduced by a process known as ionising cooling. The principle is simple: particles are passed through liquid hydrogen or lithium hydride absorbers and lose momentum in all directions; RF cavities then restore the longitudinal momentum, and although scattering will have adverse transverse effects, the nett effect can be arranged to be a reduction in transverse emittance. The goal is a normalised emittance of $\sim 30,000 \pi \text{mm.mrad}$
(which, though acceptable for the subsequent accelerating systems, is nevertheless enormous compared with the emittances accelerator physicists normally handle). Ionisation cooling is ideal for muons - assuming it works - and a proof-of-principle experiment is under construction at RAL. Known as MICE, the Muon Ionisation Cooling Experiment dips a muon target into the edge of the ISIS proton beam and explores phase space cooling by examining single particle trajectories in a linear cooling channel. Details are shown in Figure 7. In order to control the muons, the RF cavities are surrounded by strong solenoid fields, but these unfortunately have a detrimental effect on the RF gradients available. Techniques to overcome this problem form an active area of accelerator R&D. Other cooling structures are also under study: helical coolers, dogbone coolers, and so-called Guggenheim coolers (after the celebrated museum in New York), some of which also produce longitudinal cooling and are aimed at a future muon collider.

5. Muon Acceleration

Because their half-life in their rest frame is only $2.2 \mu s$, the muons need to be accelerated very rapidly. Conventional synchrotrons, where fields need to be ramped, are unsuitable, and schemes currently in favour are based on combinations of recirculating linear accelerators (RLAs) and FFAGs. In RLAs the beam passes through the same accelerating structure several times, traversing different return loops as its energy increases. Both racetrack and dogbone designs have been considered, with the latter judged to be most economical (see the section following the cooling channel in Figure 1).

FFAGs have fixed magnetic fields and avoid the problem of ramping; they generally have large apertures but until recently presented severe technological problems, for example in building the magnets and supplying the necessary RF power. After intensive research, mainly in Japan, three types are now deemed feasible. Scaling FFAGs have fields varying according to $B \propto r^k$, $k$ constant. Betatron tunes are constant and orbits for different energies are direct copies of each other, but spread over a wide aperture, varying for example over about 0.5 m. This type of machine is most suited to low frequency RF. Scaling FFAGs have been studied at KEK in Japan, where a proof-of-principle (POP) machine has been built and successfully tested. Its successor, a 150 MeV proton machine, has also been commissioned and first results are described in [5].

Non-scaling FFAGs use linear fields and it has been shown that focussing lattices can be constructed to considerably reduce the orbit variation. High frequency RF can be adopted, but there is the drawback that the beam will cross several integer tune resonances during the acceleration. It may well be that the passage is so fast that there are no detrimental effects, but this remains to be confirmed experimentally.

The third type of FFAG, developed at RAL, uses non-linear fields to maintain isochronous motion, so that the time taken to traverse the different orbit paths is constant as the beam accelerates. There is then no phase slip at the RF cavities. There is no restriction on the RF frequency, the vertical tunes are constant; however the horizontal tune does cross one or two resonances and these have resulted in severe beam loss in simulations performed to date. Details of all three types of FFAG are given in [5], which covers their use not only for muons, but for proton accelerators, medical therapy, and ADS.
5.1. EMMA
The early MURA electron machines [7] of the 1950s and the scaling machines in Japan are the only FFAGs ever built. However, non-scaling FFAGs look more promising for muon acceleration in a Neutrino Factory, and detailed study is part of the UK Neutrino Factory programme.

To explore the possibilities, construction of an electron test-model of a non-scaling muon machine is about to begin at the Daresbury Laboratory in Cheshire. EMMA (Electron Model for Muon Acceleration - the original acronym) is 16.7 m in circumference, and has 42 simple cells comprising only $F$ and $D$ quadrupoles whose displacement provides the bends. The energy range is 10-20 MeV. The injector is the linac that feeds the Energy Recovery Linac prototype (ERLP), that is being developed for 4GLS, the fourth generation light source. The ring, shown in Figure 8, will be used to explore non-linear beam dynamics in non-scaling FFAGs, examine resonance crossing, study acceleration (time of flight etc), test theory and benchmark codes. First beam is expected in September 2009.

FFAGs may not be the complete solution to muon acceleration, however. Simulations show that large amplitude particles experience phase slip at the RF cavities and may not be accelerated over the full energy range. If the beam is then put into a second FFAG, the problem gets worse. Remedies using higher harmonics and increased voltages are being investigated, but for the time-being, ISS decided to recommend an acceleration system that uses two dogbone RLAs for the initial stages (to 12.6 GeV) followed by a single FFAG taking the beam to 25 GeV (see Figure 1). If physics considerations demand higher energy, a further FFAG can be added later.

6. Muon Storage Rings
From the accelerators, the muon beam is transferred to storage rings for the decay, and three different geometries have been proposed. Long straight sections are required in which the neutrino beams can be directed to long-baseline detectors at 2500-3500 km and 7000-7500 km.

Since they can be built to point at any chosen detector, the most flexible designs are based on racetrack lattices as shown in Figures 1 and 9. With production straights of 600 m, these are over 750 m in total length and at their lowest point penetrate to a depth of 435 m into the earth, making geological properties of the Neutrino Factory site important. Two such rings could be built, one for each baseline, in separate tunnels, each ring handling either $\mu^+$ or $\mu^-$ (with possible switching between both). The tunnels would slope at an angle between $10^\circ$ and $35^\circ$ into the ground. Since only one of the straights produces usable neutrinos (the other pointing skywards), the efficiency of such rings (production straight/circumference) is only around 37%.

An alternative, based on isosceles triangles (Figure 10), can serve two detectors from the same ring, though there is less flexibility in the choice of site. Two triangles would share the same vertical tunnel, one holding $\mu^+$ and the other $\mu^-$. Bunches could be interleaved in time, so that separated pulses of $\nu$ and $\bar{\nu}$ are received at each detector. Two of the three straights provide useful decays so the efficiency in this case is 48%, and the maximum
depth of construction is 384 m. An example of a scheme with the Neutrino Factory in the UK might have triangular rings pointing at detectors at the Waste Inspection Pilot Plant (WIPP) in Carlsbad, New Mexico (7513 km) and a new detector built in Crete (2750 km).

A development of the triangular ring is a bow-tie structure, with the same length of production straight and efficiency, but with a maximum depth reduced to less than 300 m. In this case the muon polarisation would be preserved, which may affect the sensitivity of the beam instrumentation; however use of a nearby polarisation resonance in the beam optics may alleviate this.

7. Summary
The International Scoping Study has identified a consistent structure for an intense Neutrino Factory as the foundation stage for a full world design study. The proton driver test facilities at CERN and RAL now need to be completed, while MICE and EMMA will provide vital information on ionisation cooling and FFAG acceleration, respectively. An electron model of a proton FFAG is needed to examine the effects of space charge and bunch compression in a possible FFAG proton driver. For the muon front end, work is required on high gradient superconducting cavities that operate in strong solenoid fields; different absorber designs and materials need to be studied, and gas filled cavities are a promising idea that will be pursued. To facilitate rapid acceleration of muons, the use of high frequency RF in scaling FFAGs could be explored; recent new modelling codes need development; and it is hoped that a recent idea of harmonic number jumping during acceleration might be the subject of experimental tests, possibly at Brookhaven National Laboratory. Novel superconducting, combined-function magnets need to be developed for the decay rings, and, because of the enormous muon beam power, heat load and radiation issues need to be addressed. Target R&D is ongoing, with different materials being considered; beam dumps need to be designed and the conceptual/geometric problem of target siting and rotation within a solenoid needs to be solved. In this area, sharing of information with those working on targets for neutron sources such as SNS is important.

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