International scoping study of a future NEUTRINO FACTORY AND SUPER-BEAM FACILITY

Science & Technology Facilities Council

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Report on the International Design Study

Executive Summary

The ISS Programme Committee

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The ISS – executive summary

Introduction

It is generally recognised that a lepton-antilepton collider will be necessary for detailed examination of phenomena discovered at the LHC and that energies in the TeV region may well be necessary. A Muon Collider, based on a muon storage ring, could provide such high energies, but the short muon lifetime makes it technically highly challenging.

The Muon Collider was under investigation when, around the turn of the century, unambiguous evidence became available that neutrinos had mass and could change flavour as they travelled through free space. This phenomenon, referred to as neutrino oscillation, was the first, and is still the only, experimental evidence for physics beyond the Standard Model. The consequences could be extremely profound for the evolution of the Universe as well as for theories describing the interactions of forces and particles. Measurements of the parameters that govern the neutrino sector are thus of the highest priority. Unfortunately, the exceptionally small neutrino-reaction cross sections make such measurements difficult and extremely intense neutrino and antineutrino beams of different flavours must be produced in the laboratory if the requisite measurements are to be performed. The decay of muons in a storage ring can provide this intensity. This forms the basis of the Neutrino Factory and thus there is a natural synergy between the R&D required for the Muon Collider and the Neutrino Factory. The ISS was set up to look at the possible ways to undertake these future high statistics neutrino experiments with a particular emphasis on generating beams at a Neutrino Factory.

Methods of production of intense neutrino beams

Neutrino super-beam

The conventional method by which neutrino beams are produced at an accelerator is from the decay of pions resulting from bombarding a target with an intense beam of protons. One charge of pion is collected from the target and this determines the nature of the beam: positive pions produce muon-neutrinos; negative pions produce muon-antineutrinos. A small contamination of electron-neutrinos, primarily from K decay, will also be present in the beam. This is the technique used for the NuMI[1] and CNGS[2] beams feeding the MINOS[3] and OPERA[4] experiments at FNAL and CERN, respectively. It is also the basis for the super-beam proposals for T2K[5] in Japan and NOνA[6] in the USA. The T2K and NOνA experiments will dominate high energy neutrino oscillation measurements over the next 5–10 years and investigations are already underway to see how they could be further developed with more powerful super-beams illuminating much larger detectors.

Neutrino Factory

Muon decay yields a muon-neutrino and an electron-antineutrino or vice-versa depending upon the charge of the muon. Thus, neutrino beams can be produced from muons decaying in the straight section of a muon storage ring. This is the basis of the Neutrino Factory[7]. As both neutrinos and antineutrinos are produced from each muon bunch, a detector capable of measuring the particle charge is essential. It is, however, feasible to have both μ^+ and μ^- bunches in the same ring and consequently possible to have both electron- and muon-neutrinos and their anti-particles available within a single experiment.

The Neutrino Factory is easier to realise than the Muon Collider because the requirement for cooling the beam, essentially the reduction of the transverse size, is far less stringent. For the Neutrino Factory it is dictated purely by the acceptance of the muon acceleration system and the storage rings, whereas for the Muon Collider the luminosity, dictating the number of interactions, is inversely proportional to the beam size. Nevertheless, the natural synergy that exists between the Neutrino Factory and the Muon Collider means that, in addition to the wealth of neutrino physics that may be accessible with the beams from a Neutrino Factory, its realisation will also be a significant step in the development of the technology required for a Muon Collider.

Beta-beam

A relatively new approach to the production of a neutrino beam is the beta-beam concept [8]. This makes use of a storage ring containing a β-decaying ion, producing a pure electron-neutrino beam from β^+ decay and a pure electron-antineutrino beam from β^- decay. The beta-beam can therefore, in some ways, be considered complementary to the super-beam; together they yield two flavours of both neutrinos and antineutrinos.

The ISS – the international scoping study of a future Neutrino Factory and super-beam facility

The strong physics case for a future intense neutrino source and the potential viability of the procedures described above have resulted in the inclusion of next-generation neutrino facilities in road maps at the world's major proton accelerator laboratories. With this in mind, John Wood, CEO of CCLRC, the UK Research Council that ran the Rutherford Appleton Laboratory, offered support for a one year scoping study to examine the physics case and the current state of the art for the realisation of a Neutrino Factory. A meeting was subsequently organised at Imperial College in May 2005 to judge interest. Though at short notice, the meeting attracted a large attendance with contributions from the USA and Japan as well as Europe. It was clear that there was a broad desire to establish the current situation and widen the scope of the study from purely the Neutrino Factory. Thus, for the accelerator study, super-beams were added as similar issues are addressed in the proton driver and target areas but beta-beams were not investigated as these share little with the other options and are the subject of a separate design study within the Eurisol project[9]. However, for the physics performance and detector studies the potentialities and requirements of all neutrino production methods were considered.

Structure

At the Imperial College meeting in May 2005, three senior members of the community were charged with defining a structure for the study and finding appropriate people for the organisation. One main principle was to emphasise the international nature. The structure chosen, shown in figure 1, comprises an overall coordinator and three working groups, Accelerator, Detector, and Physics. Each region provided one of the working group convenors, and each of the working groups then formed an executive council to define goals, plan the work, and distribute the effort.

Financial support for the study came primarily from the ECFA/BENE network in Europe, the Japanese NuFact-J collaboration, the US Neutrino Factory and Muon Collider Collaboration, and a special grant to the UK Neutrino Factory collaboration from PPARC and CCLRC.

Meetings and presentations

The study was launched at the NuFact05 workshop in Frascati[10] and gave its conclusions at NuFact06 at Irvine[11]. During the year, plenary meetings were held at CERN in September 2005, KEK in January 2006, RAL in April 2006 and finally at UC Irvine in August 2006, immediately before the NuFact06 workshop. Additionally, the working groups had specialised meetings. Presentations at these meetings and other notes from the study can be found on the ISS website www.hep.ph.ic.ac.uk/iss/.

The scope

The plan was for a one-year programme to lay the foundation, assuming adequate justification, for a more in-depth design study to follow. A significant goal of the ISS, which had been lacking in previous studies, was to have an integrated study including the physics potential and the accelerator and detector possibilities. To do this, it was necessary to bring together experimental and theoretical physicists and accelerator and detector builders under a single umbrella so that the difficulties, importance, and potential could be understood by all. This proved to be very successful and a significant achievement of the ISS.

The work of the accelerator group was directed primarily towards demonstrating the viability of a scheme for a Neutrino Factory and formulating a baseline for a later design study. It built on previous studies in this area, in particular previous US studies, Study I (2001)[12], Study II (2002)[13] and Study IIa (2004)[14], whilst taking into account ideas put forward by studies of prospective muon storage rings at CERN (1999)[15] and Neutrino Factory plans in Japan (2001)[16]. In the super-beam area, the investigations were limited to the proton driver, targetry, and pion capture where evident synergies with the Neutrino Factory programme exist.

The physics group had a broad remit. It investigated the latest theories and models for which accurate measurement of the oscillation parameters were important, and the accuracy that would be needed to make advances. A

Scoping study for a future neutrino complex

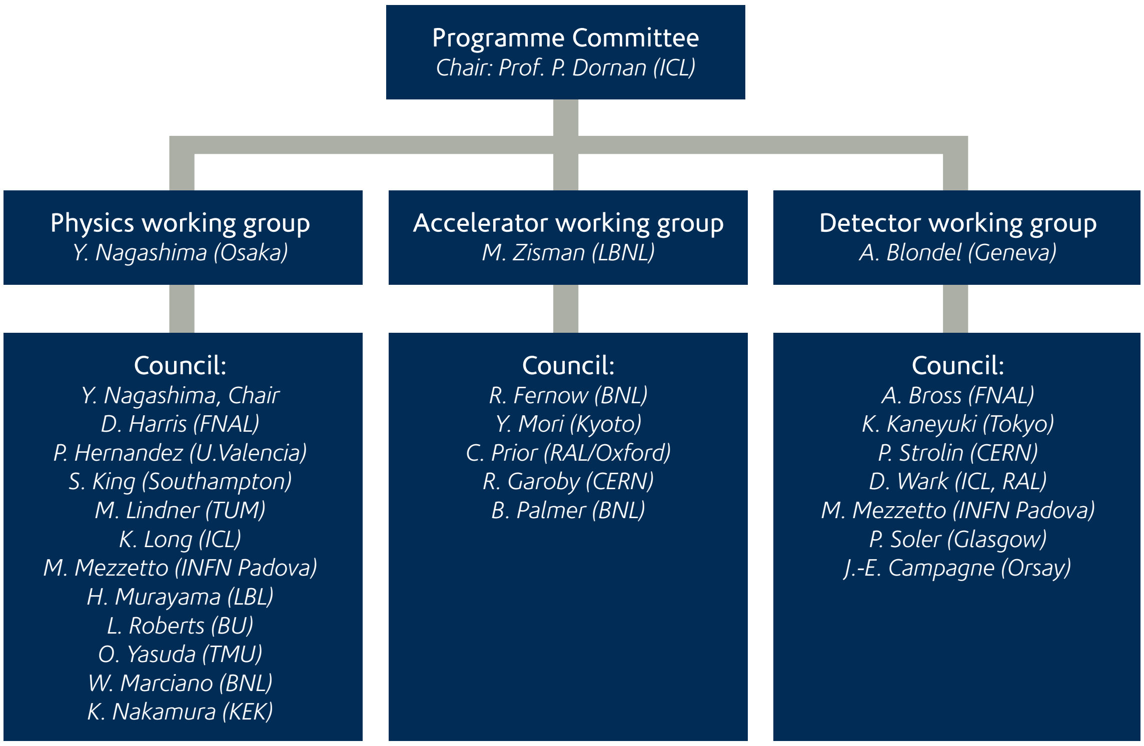

Figure 1: Organisational chart for the ISS.

major activity was to evaluate the relative merits of the Neutrino Factory, beta-beam, and super-beam approaches for the determination of the unknown parameters governing the neutrino sector, the third angle, θ_{13}, the Dirac CP violating phase, δ, and the mass hierarchy.

The detector group surveyed all current, or potential future, neutrino-detection techniques to see how they would perform with beams from a Neutrino Factory, beta-beam, or next-generation super-beam, and established baselines for the different environments. During the study it became obvious that, for an overall cost-performance optimisation, it was essential to consider both the accelerator and the detector(s). Important topics addressed were the magnetisation of large volumes, the detection of tau leptons, and the critical role of the near detectors for accurate experiments.

Summary, baseline, and conclusions

The full conclusions of the ISS are contained in three comprehensive documents, one for each of the working groups[17,18,19]. Each report outlines the status at the start of the ISS, the work undertaken during the year's study, with emphasis on new developments, defines baseline solutions for the follow-up study and an R&D programme for the next few years. A very brief overview is presented here.

The Physics Working Group

The Physics Working Group had four subgroups. The first was to bring together ideas, many speculative, of the importance of neutrino physics for the understanding of forces, particles, and the Universe itself. Neutrinos, although highly abundant, remain very poorly understood, yet so far provide the only direct experimental evidence for a deviation from the Standard Model. They could conceivably hold the major key to the understanding of the basic forces that shape the universe and dictate our existence.

Virtually all theories of physics beyond the Standard Model, such as SUSY, large extra dimensions, and string theory necessarily have consequences in the neutrino area. Additionally, models specific to the neutrino area, such as the see-saw, have evolved to explain the very low neutrino mass. However, the very few constraints currently available give rise to many models and many possible predictions. One approach to discriminate amongst the models involves the use of sum rules, e.g., the combination:

$$\theta_{12} + \theta_{13} \cos \delta,$$

which can be evaluated in various models, was investigated and used to provide an estimation of the accuracy with which θ_{12}, θ_{13}, and δ need to be measured.

The ultimate theory must surely unify the quark and lepton sectors and a number of possibilities in this area were examined, in particular those that relate the CKM and PMNS matrices. Whilst all is speculation at this time, the predominant message is that if neutrinos are to give the needed breakthrough, then as many neutrino parameters as possible will have to be measured as well as possible – at least as well as those in the quark sector.

The second physics subgroup looked at the measurements that could be made in the neutrino sector that would guide the search in a model-independent way for beyond-Standard-Model physics. The aim was to look for results that cannot be accommodated within the standard PMNS theory, including the possible breakdown of CPT, Lorentz invariance, or unitarity. These can be tested in the neutrino sector if measurements of sufficient accuracy, including those involving tau final states, can be performed.

As a Neutrino Factory is based upon a muon storage ring, it can also yield intense muon beams as well as a huge flux of neutrinos. A third working group concentrated on exploiting this, to examine what crucial measurements in the muon sector would be possible at a Neutrino Factory. Muons are probably the best candidates for giving the first evidence for charged-lepton flavour violation and may well also reveal other BSM phenomena. The current value of g–2 for the muon is ~3σ from the expected Standard Model value. However, the study also showed that the desired characteristics of the beams are not the same as those used to produce neutrinos and so compromises may be necessary.

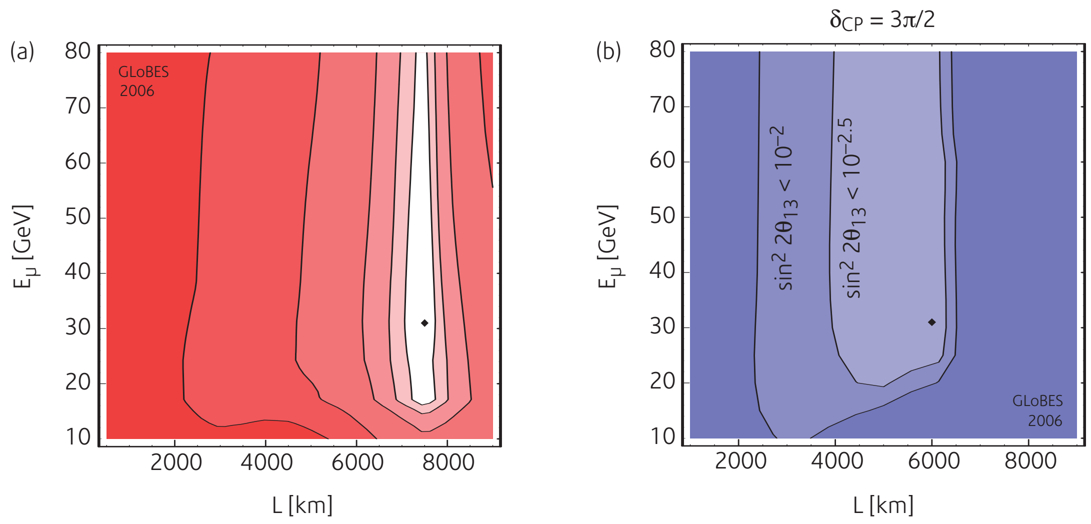

Figure 2: Sensitivity for (a) $\sin^2\theta_{13}$ and (b) δ at a Neutrino Factory as a function of the muon energy in the storage ring and the baseline. Full details are available in the ISS Physics Report[17].

The final group used Monte Carlo simulations to optimise parameters and compare alternatives. For a facility based on a Neutrino Factory, a significant outcome was the appreciation that improvement of the detector sensitivity can result in a less complicated, and consequently less expensive, Neutrino Factory. This is critical in ensuring that the Neutrino Factory design is as cost-effective as possible. Further investigations examined the best baseline in terms of the energy of the muon storage ring and the merits of having two long baselines. Typical results for the best sensitivity for the determination of $\sin^2\theta_{13}$, and δ are shown in figure 2. Figure 2a shows clearly the 'magic baseline' of ~7500 km, where the accurate determination of $\sin^2\theta_{13}$ is rather insensitive to the energy in the muon storage ring. Figure 2b shows that the best sensitivity for δ is about half of the magic baseline; and this provides one of the major justifications for two far detectors.

A second role of this subgroup was to compare the potential of the Neutrino Factory, the beta-beam and next generation super-beams for the determination of θ_{13}, the CP violating phase, δ, and the mass hierarchy. The results are given in detail in the report, but the principal conclusions are presented in figure 3.

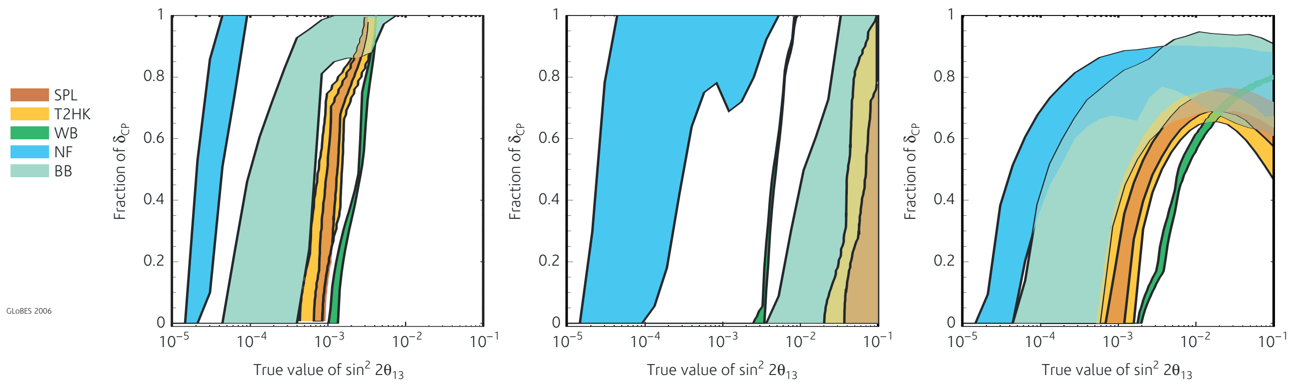

Figure 3: Predicted sensitivities for the determination of (a) $\sin^2\theta_{13}$, (b) the mass hierarchy, and (c) δ. The sensitivities are plotted as a function of $\sin^2\theta_{13}$ for different techniques of neutrino beam production. The bands correspond to configurations ranging from conservative to challenging for each technique. Precise details can be found in the ISS Physics Report[17].

Overall the Neutrino Factory gives the best results, although, if θ_{13} is close to the current limit, the other techniques become competitive. Full details of the configurations used to define the bands are given in the report.

The detectors

The ISS was the first study in which there has been full appreciation that the neutrino detectors are a critical part of the facility. Both far and near detectors require optimisation depending upon the source and the energy of the neutrinos. A basic aim of the study was to define a baseline detector system and for this three scenarios were chosen. The baseline choices are essentially conservative and are based on scaled-up versions of detectors that have already proved to be successful. More ambitious detectors were also considered and are described in the report.

i. **Single flavour sub-GeV neutrino beams: low energy super-beam and beta-beam:**

   This category is appropriate for the off-axis beam from J-PARC, the SPL super-beam, or ^6He and ^{18}Ne beta-beams at CERN. The detectors need not be magnetised, quasi-elastic reactions dominate, and pion production is small. A very massive Water Cherenkov (WC) detector is the baseline option. The small and poorly understood cross sections, and the low Q^2 of the interactions pose considerable systematic problems, which make the design of the near detector critical. The possibility of using a very large Liquid Argon Time Projection Chamber (LArTPC) was considered, but the feasibility and relative merits of this approach require further research.

ii. **Few-GeV beams: wide-band beam, and high energy beta-beam**

   This category is appropriate for a wide-band pion/kaon-decay beam (WBB) from a 20–50 GeV proton beam, or from a high energy beta-beam, employing either high-γ (~350) ^6He or ^{18}Ne ions or by accelerating higher Q (e.g., ^8B or ^8Li) isotopes. Here the situation is more complex, since multi-pion production becomes common and event identification requires more sophistication. This is not an easy energy domain, and no clear baseline has been chosen. The best techniques appear to be the WC, the Totally Active Scintillating Detector (TASD) as in NOνA, or a LArTPC.

iii. **High-energy beams obtained from muon decay in a Neutrino Factory**

   Magnetic detectors are compulsory in this regime, since neutrinos and antineutrinos are present in the detector at the same time. The baseline detector here is the Magnetised Iron Neutrino Detector (MIND). However, full exploitation of the richness of possible oscillation channels strongly motivates the study of other types of detectors. The most promising are magnetised low-Z fine-grain detectors (scintillator or liquid argon) for wrong-sign electron final states and magnetised emulsion detectors (Magnetised Emulsion Cloud Chamber, MECC) enabling tau detection. Combinations have also been examined, a possible one being the combination of MIND and MECC as in figure 4.

These options are all described in the report, together with the development programme required to take full advantage of the possible neutrino sources. In some cases, such as the large Water Cerenkov or the segmented magnetised iron calorimeter, it is mainly a case of maintaining or, ideally, improving performance whilst substantially increasing the detector size and keeping the cost within bounds. For other detector types, substantial R&D is required.

In addition to the baseline choices, other techniques were investigated in considerable detail. The most promising of these are the use of

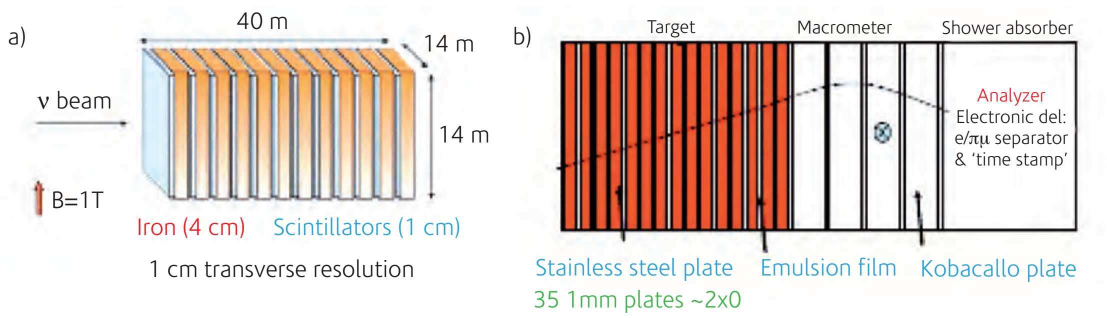

Figure 4: A possible detection system for a high energy neutrino beam from a Neutrino Factory incorporating a MIND (a) followed by a MECC (b) for tau detection[16].

a large totally active scintillating detector or a large liquid-argon TPC. The latter has the capability of detecting all lepton flavours whilst the former is restricted to electrons and muons and so needs to be supplemented by an emulsion detector if the tau channels are an essential part of the programme. Magnetisation of such large detectors is a major issue in the cost-performance optimisation for a Neutrino Factory.

With the increased statistics that result from a next-generation neutrino source, systematic effects become increasingly important and it is essential, when planning the system, that these are minimised. Beam monitoring and the role and effectiveness of the near detector are of major importance and near-detector technologies also require development. Other effects will also become significant, in particular the knowledge of neutrino cross sections and, for very long baselines such as the magic baseline at a Neutrino Factory, the density of the earth. The systematic uncertainty on the earth's density has conventionally been taken to be ~5% but, following discussions with geologists during the study, it is likely that this could be reduced to ~2% if certain terrains are avoided and a geological survey carried out. This is likely to be of particular significance if θ_{13} is close to the present limit, as, in this limit, the matter-density uncertainty becomes a limiting factor for the sensitivity of the Neutrino Factory.

All these topics and a proposed R&D programme are discussed in the Detector Report.

The accelerator

The accelerator report concentrates on the comparison and further development of schemes put forward in previous Neutrino Factory studies in the light of recent advances. The aim is to produce ~10^{21} neutrinos per year, and for this a high power proton driver (~4 MW) is required and, ideally, both signs of pions produced in the target should be employed. Five subgroups were formed to address different areas of the Neutrino Factory accelerator complex. Where appropriate, the relevance for an advanced super-beam was also considered. Baseline choices were made in each area to form the basis of the planned follow-up International Design Study for the Neutrino Factory[20]. The five areas are

i. Proton driver

To reach the target of 10^{21} neutrinos per year, a proton-driver beam power of ~4 MW is required. Such high power proton drivers are planned by virtually all of the major proton-accelerator laboratories as they have many potential uses. Thus, the view was taken that the actual form of proton driver may well be determined by wider considerations and the discussion, within the ISS, was mainly limited to the specific requirements needed for it to be appropriate for a Neutrino Factory. Such input is needed by those laboratories planning a proton driver for which one of the goals is to produce an intense neutrino beam. The parameters the proton driver should satisfy for a Neutrino Factory are given in table 1. As can be seen from the table, the range of proton-driver energies yielding acceptable results is considerable. Measurements of the relevant processes are starting to become available[21] and must be used in future optimisations of the energy.

Table1: Parameters required by a proton driver for it to be suitable for the Neutrino Factory.

Parameter	Value
Average beam power (MW)	4
Pulse repetition frequency (Hz)	50
Proton energy (GeV)	10 ± 5
Proton rms bunch length (ns)	2 ± 1
No. of proton bunches	3 or 5
Sequential extraction delay (μs)	>17
Pulse duration, liquid-Hg target (μs)	< 40
Pulse duration, solid target (ms)	>20

ii. Target

The MERIT experiment[22] at CERN has given a proof-of-principle demonstration that a free mercury jet target is capable of operating with a 4 MW proton beam. A liquid mercury jet target has therefore been chosen as the baseline. Of course, there remain technical and safety issues associated with mercury handling that require further R&D to develop a robust facility design. Other solutions, including solid targets and other liquids, have been considered but, whilst there is potential, there is also need for further R&D. The choice of target has implications for the characteristics of the proton beam, as discussed in the report.

iii. Front end

The term front-end is used to refer to the capture and decay of the pions from the target, the bunching and phase rotation of the muons to minimise the energy spread in each bunch and finally the cooling to produce an emittance acceptable for the acceleration system. For the Neutrino Factory, solenoidal capture is the preferred technique as it retains both positive and negative muons, whilst the horn remains the favoured solution for a super-beam, where only one sign of pion is required at a time unless the detector is magnetised. For the Neutrino Factory, ionisation cooling is assumed, as this is the only known technique to produce the necessary emittance reduction in the short time available before the muons decay. The baseline absorber has been taken to be lithium hydride although liquid hydrogen is an alternative. Ionisation cooling has yet to be demonstrated experimentally; the proof-of-principle will be provided by the MICE experiment[21] at the Rutherford Laboratory.

iv. Acceleration

Again speed is the prime driver, making the ramping of magnets impracticable. The main elements of the acceleration system are therefore RLAs (Recirculating Linear Accelerators) and FFAGs (Fixed Field Alternating Gradient accelerators). Considerable advances were made during the study, in particular in understanding both the potential and difficulties associated with multiple FFAGs. The currently favoured solution involves a linac followed by two dog-bone RLAs and finally one, or possibly two, stages of FFAG acceleration depending on the final energy that is required.

v. Decay ring

As the physics report shows, maximum benefit from a Neutrino Factory will be achieved with two far detectors as well as the near detector. This requires a decay system with two straight sections pointing into the ground and to handle this with both signs of muons, two decay rings are necessary. Two geometrical solutions have been examined during the study, racetrack and triangle. For

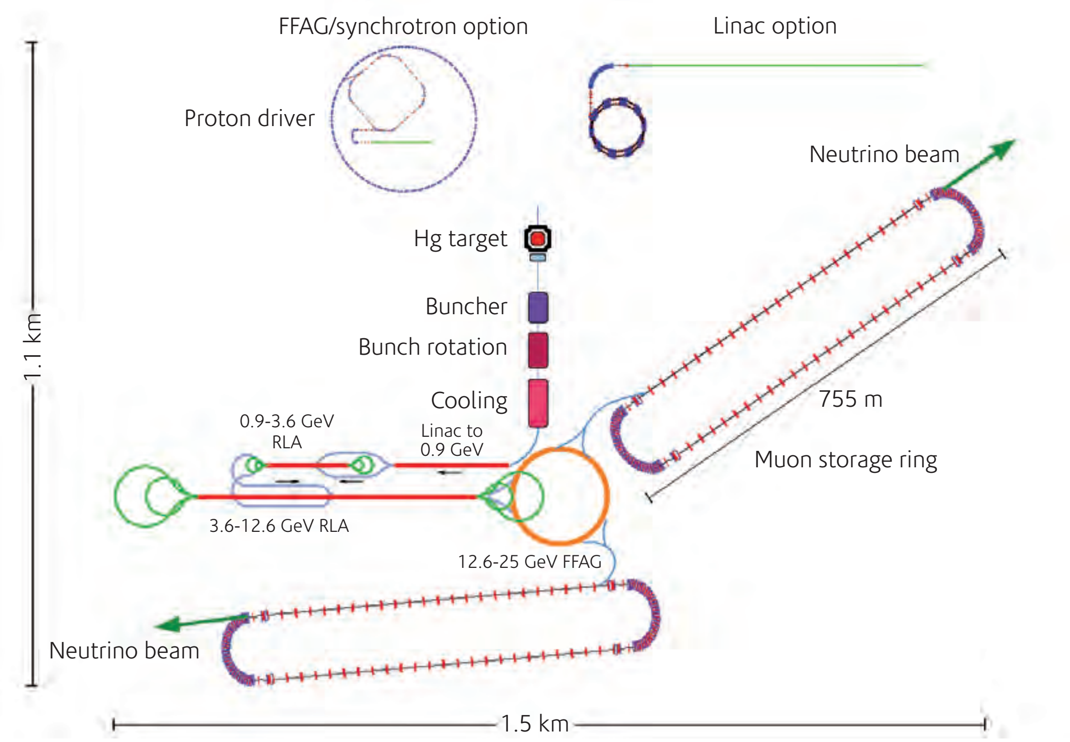

Figure 5: Baseline configuration for the Neutrino Factory resulting from ISS Study[15].

the racetrack, only one straight section produces useful decays unless counter-rotating beams are used. In the case of a triangular decay ring, two sides of the triangle can be used. Typically, for the rings examined, the triangle is somewhat more efficient since the ratio of the length of the production straights to the total decay-ring length is larger for the triangle. This statement is true even for counter-rotating beams in racetrack decay rings. However, for the triangle, where the two rings, one for positives the other for negatives, are in the same inclined tunnel, there are restrictions placed on where the detectors may be positioned. The racetrack scenario, on the other hand, would have the two rings in different tunnels and is therefore more flexible with regard to possible detector sites. Because of the increased flexibility, the racetrack has been chosen for the baseline but this would be reviewed when the actual site for the Neutrino Factory and specific sites for the detectors are defined.

The final conclusion of the ISS, which will become the baseline for the International Design Study for the Neutrino Factory (IDS-NF) is shown in figure 5[20].

Acknowledgements

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