Neutrino Factory roadmap 2006

Executive summary

Science-driven timescale

The international scientific community has recognised the fundamental importance of the observation of neutrino oscillations. The next generation of long-baseline neutrino-oscillation experiments will be nearing completion around 2015. Therefore, the facility that will serve the era of high-precision, high-sensitivity neutrino-oscillation measurements must be brought into operation in the second half of the next decade. The international consensus is that the Neutrino Factory is the facility of choice. Based on the length of the SNS build phase (six years), and that projected for J–PARC (seven years), a reasonable estimate for the build phase of the Neutrino Factory is six to seven years. A conceptual design for the facility must therefore be produced by 2012.

International Design Study initiative

An international collaboration is required to carry out the conceptual-design work and the associated hardware R&D programme. The one-year 'international scoping study of a future Neutrino Factory and super-beam facility' (the ISS), together with the international R&D collaborations MICE, MERIT, and EMMA, form the basis upon which the International Design Study (IDS) collaboration can be built.

The ISS was launched in July 2005 at NuFact05 and will conclude in August 2006 at NuFact06. The IDS will then be required to deliver the full conceptual design over the five-year period 2007/08 to 2011/12. The UK Neutrino Factory (UKNF) collaboration has established a world-leading Neutrino Factory R&D activity, encompassing both conceptual design and hardware development, and is therefore ideally positioned to play a leading role in the IDS effort. Over the coming year resources to support the UK contributions to the IDS will be sought from PPARC in the forthcoming rolling-grant round and in the UKNF bid for continuation. To enhance the UKNF activity, and to cement the European Neutrino Factory collaboration, a bid (or bids) will be made against the EU Framework Programme 7 (FP7) call for proposals that it is anticipated will be issued in the autumn of 2006. Ideally, the IDS initiative will be launched at NuFact06 with the mandate to assemble an IDS collaboration and define the programme required to deliver a conceptual design by 2012.

Resources to support the UK Neutrino Factory collaboration in the IDS phase

Over the past three years, CCLRC, PPARC and the OST have supported the MICE-UK and UKNF activities at the level of £13.2M. To develop the UKNF activity to the point at which the UK can make a successful bid to host the facility requires sustained investment that ramps up slowly over the five-year IDS period. The UKNF R&D programme has many aspects in common with that required for the development of a future neutron spallation source; the proposed programme of work will therefore be of benefit to both communities. An investment of £21M, plus a design team building to 20 staff, over the first three year period followed by a further investment of £23M, plus an increase in the design team by a further 30 staff, over the subsequent two-year period will allow the UKNF collaboration to:

- Complete the initial conceptual design of the facility in the context of the IDS activity;
- Implement the Front End Test Stand at RAL;
- Deliver the UK contributions to the construction of the MICE cooling channel (Phase 2 of the MICE experiment);
- Develop prototypes of key elements of the H^- injection linac;
- Support detailed engineering studies of the Neutrino Factory target station;
- Construct the non-scaling FFAG proof-of-principle machine EMMA;

- Carry out an appropriate neutrino detector R&D programme; and
- Further develop the phenomenological studies required to determine the physics performance of the facility.

Near-term decision points and resource implications

The UKNF collaboration has created the opportunity for the UK to lead the IDS and thus position the UK to bid to host the facility or to make a significant contribution wherever it is sited. The decisions that CCLRC and PPARC must take in the near future are to:

- Take the lead in the preparation of the International Design Study by which an agreed conceptual design report will be produced by 2010 and a first technical design report by around 2012. The formal launch of the IDS initiative should take place at NuFact06; and
- Decide that CCLRC should seek to 'host' the Design Study and/or the Integrating Infrastructure Initiative bid/s to EU Framework Programme 7.

These decisions have resource implications:

- Since the production of a complete conceptual design by 2012 is of great strategic importance to the UK, it will be necessary to establish a baseline resource for the design-study period;
- Matching funds will be required for the proposed bids to FP7 to be successful. The UKNF and MICE-UK collaborations will seek these matching funds through the UKNF bid for continuation and the MICE-UK Phase 2 bid. It will be necessary for such resources to have been identified at the time the FP7 bid, or bids, are submitted; and
- The preparation of a successful bid (or bids) to FP7 requires a significant effort. Though some of the resources required to prepare the bid can be provided through the FP6 funded BENE Networking Activity, the UKNF award, and the resources granted to support the ISS, additional staff effort from CCLRC and/or the Universities is required to carry out the negotiations with prospective European partners and, subsequently, to prepare the bid itself.

1. Science driver, context, and assumptions

1.1 Science driver

In the Standard Model (SM) of particle physics [1], there are three types, or flavours, of neutrino, each of which has no mass. As a consequence, the SM does not allow a neutrino of a certain flavour, for example a muon neutrino (ν_μ), to change – or oscillate – into another flavour, for example a tau neutrino (ν_τ), as it propagates. The observation of neutrino oscillations in atmospheric, solar, reactor, and long-baseline neutrino oscillation experiments [2 – 5] therefore implies that the SM is incomplete and that the neutrino has a small but non-zero mass.

The SM may readily be extended to describe neutrino oscillations through the introduction of three neutrino mass states and a mixing mechanism analogous to that known to occur among the quarks [6]. This mechanism implies that the matter-anti-matter symmetry (the 'CP' symmetry) may be violated ('CP violation') in the interactions of neutrinos. Theories that purport to explain neutrino masses and mixing often postulate that the neutrino is its own antiparticle – a property which the neutrino alone among the fundamental fermions may possess as it has no conserved quantum numbers [7]. Such theories offer a natural explanation of both the very small neutrino mass and the observation that the neutrino mixing parameters are substantially different to those of the quarks.

It is clearly of fundamental importance to particle physics to establish the true nature of the neutrino, whether CP-violation occurs in neutrino oscillations, to measure the mass of the various neutrino states, and to determine the parameters that govern neutrino oscillations. Precise measurements are required to establish the correct theoretical description of the neutrino. Equally important are the implications of neutrino oscillations in other fields. For example: CP violation in neutrino interactions may underpin the mechanism by which all antimatter was removed from the early universe [8]; the neutrinos produced by the Big Bang (the 'relic' neutrinos) may make a contribution to the mass of the Universe as big as that of the stars and planets [9]; and the large number of relic neutrinos, combined with the fact that neutrinos interact only weakly, may allow the neutrino to play a crucial role in the formation of large-scale structure in the Universe [10]. Furthermore, in particular models, the neutrino, or its 'super-partner' the sneutrino, may be responsible for inflation [11].

The science driver is, therefore, for an energetic programme of precise measurements of the properties of the neutrino. The experimental programme must address:

- The absolute neutrino-mass scale and the mass hierarchy;
- Whether the neutrino is its own anti-particle;
- Whether matter-antimatter symmetry is violated in neutrino oscillations; and
- The precision determination of the neutrino-mixing parameters.

1.2 Context

The importance of the discovery of neutrino oscillations in 1998 [2] was immediately recognised by the international particle-physics community and led to a rapid and sustained growth in interest in neutrino physics. Evidence of this trend may be found in the rate of publication [12], the citation index [13], the growth in the number of international meetings dedicated to neutrino physics [14], and the increase in the number of delegates at the bi-annual Neutrino conference [15].

There is now an international consensus that a novel, accelerator-based, facility is required to satisfy the science driver [16]. The facilities that have been proposed to serve the programme of precision measurement fall into three classes: the Neutrino Factory [17], an intense high-energy neutrino source based on a stored muon beam, gives the best performance over almost all of the parameter space; second generation 'super-conventional-beam' experiments [18] may be attractive in certain scenarios;

and a beta-beam, in which electron neutrinos (or anti-neutrinos) are produced from the decay of stored radioactive-ion beams [19], in combination with a second-generation super-beam, may be competitive with the Neutrino Factory. The one-year 'international scoping study of a future Neutrino Factory and super-beam facility' [20] that was initiated by CCLRC with the support of PPARC will make a critical review of the physics performance of each of the proposed facilities and define the R&D programme that is required to deliver a conceptual design for the Neutrino Factory by the end of the decade.

1.3 Assumptions

The Neutrino Factory will be required.

The international consensus is that, of the three classes of proposed future facilities, the Neutrino Factory will give the best performance, both in terms of the range of parameter space over which leptonic-CP violation can be discovered and in terms of the precision with which the parameters governing neutrino oscillations can be measured. It is therefore reasonable to assume that the Neutrino Factory will be required.

The Neutrino Factory will be built.

The Neutrino Factory physics programme is complementary to that of the Large Hadron Collider (the LHC) and the International Linear (electron-positron) Collider (the ILC) and can not be carried out at any existing or planned facility. It is therefore reasonable to assume that the Neutrino Factory will be built.

It is cost effective to develop the techniques required and to build the Neutrino Factory.

Various incremental, staged, scenarios to satisfy the science driver have been proposed [19]. In each of these scenarios it is recognised that the Neutrino Factory is required but it is only implemented after a second generation super-beam and/or a beta-beam facility has taken data. Such an incremental approach requires that the R&D, construction, commissioning, and exploitation phases of each of the facilities in turn be funded. It is therefore reasonable to assume that the integral of the investment required to carry out the incremental approach is significantly larger than that required to develop and then to build the Neutrino Factory. This assumption is being evaluated through the ISS and will continue to be reviewed through the annual Neutrino Factory, super-beam and beta-beam (NuFact) workshops [16].

2. The Neutrino Factory is required in the second half of the next decade

Neutrino oscillations are described using five parameters: three 'mixing angles' (θ_{12}, θ_{13}, and θ_{23}); one phase parameter (δ), CP violation occurs if δ (and θ_{13}) are non-zero; and two mass-squared differences ($\Delta m^2_{12} = m^2_2 - m^2_1$ and $\Delta m^2_{23} = m^2_3 - m^2_2$, where m_1, m_2, and m_3 are the masses of the three neutrino states).

Data from the Sudbury Neutrino Observatory (SNO) [21] and KamLAND [22] experiments, together with data from Super-Kamiokande [23] and elsewhere have been used to determine θ_{12} with a precision of around 10% and Δm^2_{12} with a precision of 10% – 20%. The parameters θ_{23} and Δm^2_{23} have been determined using atmospheric neutrino data from Super-Kamiokande [24] and verified using an accelerator-based neutrino source by the K2K experiment [25]. With five to seven years of running, the MINOS long-baseline experiment [26], which has begun to take data, will determine θ_{23} and Δm^2_{23} with a precision of around 10%. The two CNGS experiments OPERA [27] and ICARUS (T600) [28], which are designed to observe ν_τ appearance and are scheduled to start data taking in 2008, will verify aspects of the neutrino-mixing formalism. Two first-generation super-beam experiments, T2K in Japan [29] and NOνA in the US [30], are being mounted with the objective of demonstrating that $\sin^2 2\theta_{13}$ is greater than zero. The T2K experiment will start in 2009 and, after five years of data taking, will be sensitive to $\sin^2 2\theta_{13}$ down to about 0.005 at 90% C.L. NOνA, which has recently been granted scientific approval by the FNAL PAC, will yield a comparable sensitivity. Both T2K and NOνA will improve the determination of θ_{23} and Δm^2_{23} to the level of a few percent after five years of data taking. However, neither T2K (Phase I) nor NOνA will have the sensitivity required to discover leptonic-CP violation or to deliver the precision measurements of the parameters that are required for a full understanding of neutrino oscillations.

To take the study of neutrino oscillations further requires a second-generation facility ready to begin operation in the second half of the next decade. This facility must be capable of making high-precision measurements of the mixing angles and mass-squared differences and of making searches for leptonic-CP violation of great sensitivity. The precision of the measurements must be such that sensitive tests of the consistency of the theoretical framework can be made.

The timescales for the various aspects of the experimental programme outlined above are summarised in figure 1. The experiments that are in the data-taking phase, or that are currently being planned, will become systematics limited during the first half of the next decade. To take the study of neutrino oscillations further requires that the best possible second generation facility (the Neutrino Factory) be brought into operation in the second half of the next decade.

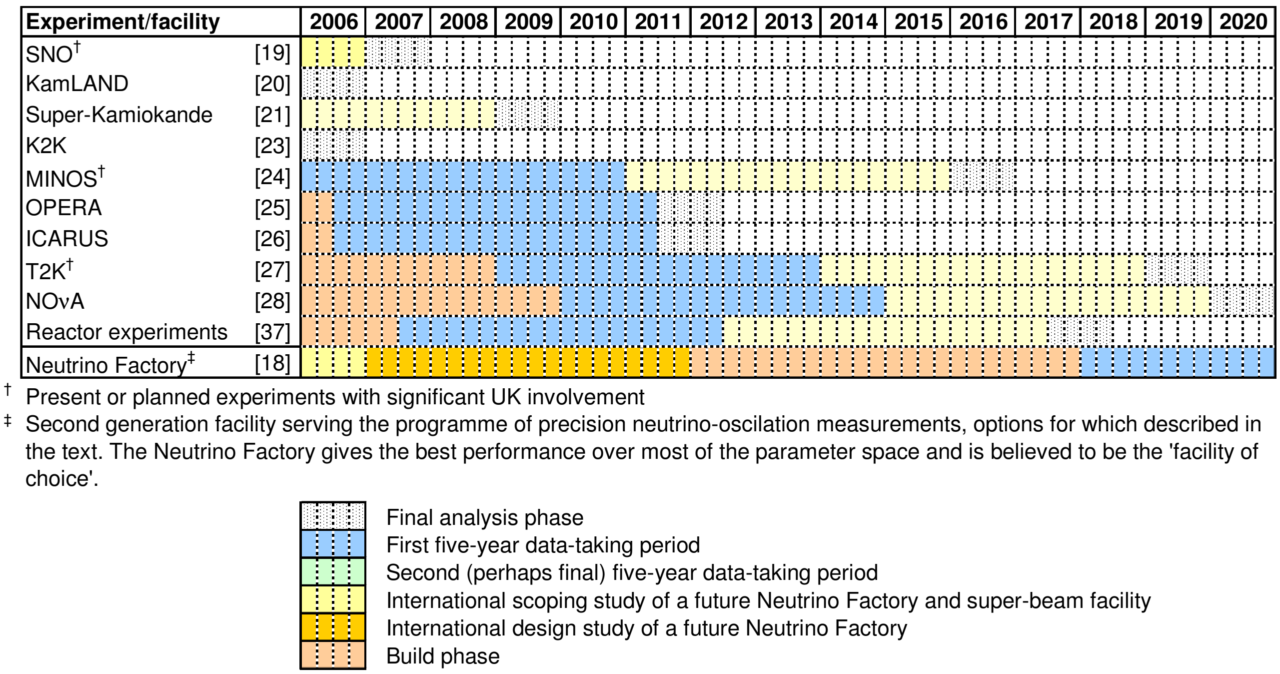

Figure 1: Development of the programme of long-baseline neutrino-oscillation experiments. The ISS, IDS, and Neutrino Factory build-phase periods are also indicated. An indication of the time scale on which the next generation reactor-based neutrino-oscillation experiments will be implemented is also shown.

3. Key dates and decision points

A reliable estimate of the length of time required to build and commission the Neutrino Factory requires the results of the full design study. A reasonable estimate can be obtained by comparison with the length of the build phase of comparable facilities. The length of time taken to build the Spallation Neutron Source (the SNS) (construction start to completion) was approximately six years [31]. Construction work on the Japanese Proton Accelerator Centre (J-PARC) started in 2001 and commissioning is scheduled to start in 2007 – a build phase of approximately seven years [32]. Therefore, a six or seven year construction phase may be taken as a reasonable estimate for the time required to build the Neutrino Factory.

Bearing in mind the need for a five-year design-study phase, a reasonable target date for the completion of the Neutrino Factory facility is 2018. This achieves the science-driven requirement of bringing the second-generation facility into operation in the second half of the next decade and implies that the conceptual-design report is required by 2010 and a first technical-design report by 2012.

To deliver the conceptual design by 2012 requires an intensive five-year period of conceptual-design and technical-design work backed up by a hardware R&D programme by which prototypes of key components of the accelerator complex and detector systems are proved. The results of the hardware-development programme will be used in the final stages of the design study to optimise the performance of the facility. An international collaboration is required to carry out the five-year design study. This schedule is indicated in figure 1.

The foundations for the five-year 'International Design Study' (IDS) phase are being developed through the ISS. Proof-of-principle demonstrators of several of the key accelerator sub-systems are being developed though international collaborations:

- MICE: the international Muon Ionisation Cooling Experiment [33] collaboration will provide an engineering demonstration of a section of an ionisation cooling channel. The experiment is being prepared on ISIS at the Rutherford Appleton Laboratory;
- MERIT: the MERcury Intense Target experiment [34] will demonstrate the operation of a mercury-jet target in an intense magnetic field exposed to the intense proton beam delivered by the CERN PS; and
- EMMA: the Electron Model of Muon Acceleration [35] collaboration seeks to build a proof-of-principle non-scaling fixed field alternating gradient (FFAG) accelerator of the type proposed for the rapid acceleration of muons in a Neutrino Factory.

The ISS is likely to lead to further international efforts to develop engineering demonstrations of the techniques required to implement the neutrino detectors.

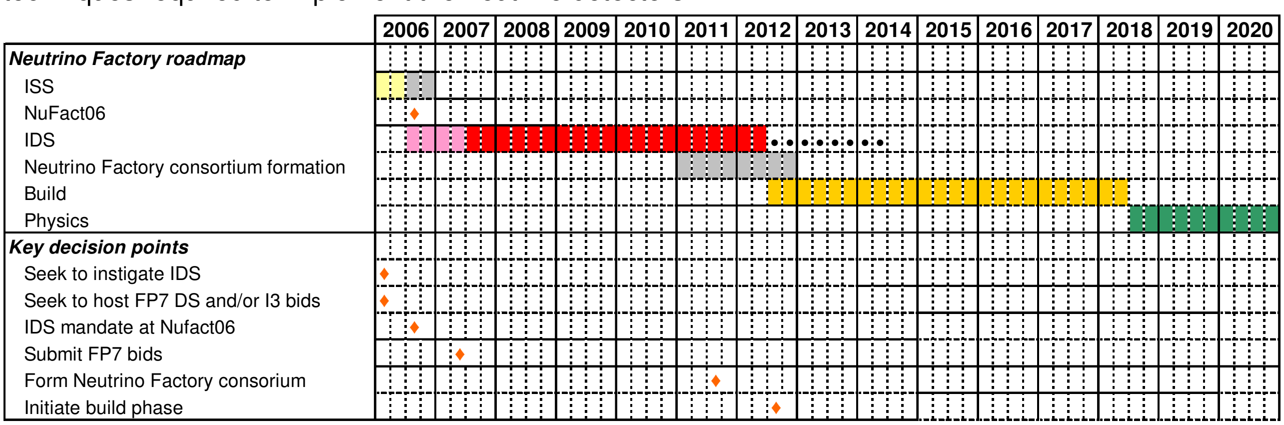

Figure 2: Neutrino Factory roadmap and the key decision points it implies.

Figure 2 shows the development of the international Neutrino Factory activity required to satisfy the science driver. For the IDS collaboration to begin work on the conceptual design from the beginning of financial year 2007/08 requires that a mandate to form the IDS collaboration is obtained at NuFact06. For the UK to initiate the discussions required to generate the required mandate, CCLRC and PPARC must decide to:

1. Take the lead in the preparation of the International Design Study activity with the objective of producing a conceptual design for the facility by 2010 and a first technical design report by 2012. Negotiations with potential partners must be initiated to allow an International Design Study Steering Group with the mandate to assemble the IDS collaboration and to define the IDS programme to be proposed to, and endorsed by, the community at NuFact06;

2. Take the lead in the preparation of the Design Study and/or the prototype development bids to Framework Programme 7 that are required to provide the resources for the European IDS collaboration.

The medium-term decision points that follow from the decision to put the UK at the forefront of the drive to produce a conceptual design on the timescale implied by the science driver are shown in figure 2.

4. Indicative resource estimate

An indication of the resources required in the five-year IDS period is presented below. Both the conceptual design and the hardware development programmes must be carried out in an international context, therefore an estimate of the resources required across the international collaboration is presented before an estimate of the resources required to put the UK at the heart of the activity.

4.1 International Design Study – indicative resource estimate

The IDS activity must encompass:

- *Conceptual design*:
  - Physics performance optimisation: Systematic evaluation of the physics-performance implications of the various options for the accelerator and detector systems will be required to allow the facility to be optimised for performance and cost. Members of the international Neutrino Factory community will seek to contribute to the evaluation of the physics performance making a core team of around 12 theoretical, phenomenological, and experimental physicists sufficient to carry out the relevant calculations;
  - Accelerator complex: The IDS is likely to be broken down into a conceptual-design phase, in which concepts for each of the accelerator systems are developed, and a technical-design phase, in which detailed technical designs for the various components are completed. The technical-design phase may overlap the conceptual-design phase as shown in figure 3. Over the course of the IDS, a team of between 30 and 40 accelerator physicists must be recruited to carry out the conceptual-design work and to oversee the technical-design effort. Towards the end of the technical-design phase, a team of between 30 and 40 engineers and draftsmen will be required. Therefore, over the course of the study a design team (physicists, engineers, and draftsmen) of around 80 must be assembled. In addition, a core team of around half the total must be established at the laboratory hosting the design effort. It will be essential to establish such a core group if the effort provided through the broad international collaboration is to be used effectively;
  - Detector systems: Options for the neutrino detection systems are being evaluated through the ISS. It is likely that a number of technologies will be required to allow detectors to be optimised for the different appearance and disappearance channels. A high-performance near detector capable of making precision measurements of the appropriate cross sections will be required. In addition, instrumentation will be required to measure the properties (flux, energy, direction, etc.) of the neutrino beams. The complexity of the instrumentation required implies conceptual- and technical-design activities of a similar magnitude to that required for the accelerator complex, i.e. over the course of the study it will be necessary to establish a team of a round 60 physicists, engineers, and draftsmen.
- *Accelerator R&D*:
  - Proton driver front end: The development of the techniques required to produce intense, high-quality H^--ion beams for injection into the proton driver (high-current ion sources, high-gradient RFQs, fast beam-choppers) must be carried through. In addition, prototypes of the structures required in the injector linac must be constructed, and a section of linac built and

commissioned using the beam from the front-end test stand. The Neutrino Factory requirements in this area are very similar to those of other applications using intense, pulsed proton beams and there are several parallel initiatives at proton laboratories in Europe and in the US [36]. It is likely that, to maintain and generate expertise the various proton-accelerator based laboratories will seek to establish a programme in this area. A five-year programme of hardware development in this area is likely to require resources at the level of £7M;

	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	
ISS							
IDS							
Conceptual design phase							140‡
Technical design phase							
Mangement and coordination							5‡
Development of key accelerator systems							
Proton driver							
Proton driver front end							£15M
Proton-injector linac prototypes							
Target and capture							
Proof-of-principle experiment: MERIT							£15M
Engineering demonstrators							
Bunch-rotation and cooling							
Engineering demonstration: MICE							
Demonstration of components: MuCool							£15M
Second phase ionisation cooling development							
Rapid acceleration							
Non-scaling FFAG proof of of principle: EMMA							£7M
Storage ring							
Component R&D and site investigations							£3M
Generic technology development							
RF							
Power sources							
Accelerating structures							
Magnets							£15M
Large apperture, high field							
High-current, rapid rise-time power supplies							
High-T_C conductor development							
Development of neutrino detector systems							
High-resolution/high-granularity option							
Development of liquid argon or other techniques							£15M
High-mass, large volume option							
Development of tracking calorimeter option							
Total capital R&D							**£85M**

Figure 3: Indicative resource estimates for the International Design Study period. The table shows the resources required to support the international collaboration.

– Target and capture: The results of the MERIT experiment and the conclusions of the studies of shock-induced damage in solid targets are required for a decision to be made on the target material. Therefore, these programmes must be brought to a timely conclusion. The engineering of the target station for a Neutrino Factory presents significant challenges, many of which have features in common with high-power targets for neutron-spallation sources. The principal challenge that the targetry R&D programme must address is the safe operation of the target station. The establishment of a target test stand over the IDS period is desirable. A baseline targetry programme at the level of £5M will be required to address the engineering and safety issues, the provision of a target test stand would require additional investment at the level of £10M;

– Phase-rotation and bunching, ionisation cooling: Phase 2 of the MICE experiment must be brought to a timely conclusion so that the experience gained in engineering a section of an ionisation-cooling channel, as well as the measured performance of the system, can be used in the optimisation of the facility. In addition, the prototypes of elements of phase rotation and bunching systems must be built and shown to operate to specification. An investment of £10M is required to complete Phase 2 of MICE. The development of large-aperture magnets and cavities of the type used in the phase-rotation and bunching sections will require additional investment at the level of £5M over the IDS period;

- Rapid acceleration: Recent design work indicates that non-scaling fixed field alternating gradient (FFAG) accelerators are particularly well suited to the rapid acceleration of the muon beam that is essential in the Neutrino Factory. A proof of principle machine should be constructed. Such machines have wide application and have been proposed to serve a wide variety of applications including hadron-therapy facilities. The investment of the £7M required to construct the non-scaling FFAG proof-of-principle machine EMMA is required to establish the design of the Neutrino Factory and is likely to yield a significant return in terms of the development of rapid acceleration techniques that are broadly applicable;
- Storage ring: The storage ring components are not regarded as requiring a significant hardware R&D programme. However, the depth of the ring and the slope of the various straight sections may present significant engineering and safety challenges. A modest programme of component R&D supported by site investigations costing in the region of £3M is therefore required to manage some of the risks of the construction phase;
- Generic technology: In parallel to developing the conceptual design for the Neutrino Factory and carrying out the system-specific hardware R&D programmes, it is necessary to develop capability in the techniques required to build the various components. Examples include, the development of manufacturing techniques by which high-gradient normal and super-conducting cavities can be produced reliably, and the development of cost-effective solutions to the large aperture magnets required in many of the Neutrino Factory sub-systems. An investment in the region of £15M is likely to be required. This investment will yield results that will benefit many future accelerator-based projects.

- *Detector R&D*: The various detector technologies that have been proposed for the detectors at a Neutrino Factory are being evaluated in the ISS. Magnetic segmented detectors typically use scintillator interspersed with an inactive material such as iron immersed in a magnetic field. Very high resolution is offered by detectors based on liquid-argon time-projection chambers and hybrid emulsion detectors. A ‘near detector’ will be required to make the precise cross section measurements required for the analysis of the far-detector data and to carry out a deep inelastic neutrino-nucleon scattering programme. Instrumentation will also be required to determine the flux and energy spectrum of the neutrino beam.

  An important output of the ISS will be the R&D required to implement the Neutrino Factory detector systems. A network of R&D programmes will be required, perhaps modelled on the ‘Research and Development’ (RD) experiment programme established to develop prototypes of the LHC detectors. Over the IDS period, an investment at the level of £15M is likely to be required to carry out this work.
- *Management and coordination*: A core management team of around five people will be required at the host laboratory to manage the R&D programme outlined above.

A summary of the R&D programme required in the IDS phase is presented along with a summary of the indicative resource estimates given above in figure 3.

	2007/08	2008/09	2009/10	2010/11	2011/12	
Concept development (CCLRC, Universities)						
Conceptual design phase						50 SY‡
Technical design phase						
Management and coordination						3 SY‡
Development of key accelerator systems						
Proton driver						
Proton driver front end						£6M
Proton injector linac prototypes						£6M
Beam dynamics, haloes, minimising beam losses						
High intensity proton rings						
Beam dynamics, space charge, instabilities						£3M
Target and capture						
Targets and moderators for neutron spallation sources						£2M
Proof-of-principle experiment: MERIT						£4M
Engineering demonstrators						
Bunch-rotation and cooling						
Engineering demonstration: MICE						
Demonstration of components: MuCool						£5M
Second phase ionisation cooling development						
Rapid acceleration						
Non-scaling FFAG proof of principle: EMMA						£5M
Storage ring						
Component R&D and site investigations						£1M
Generic technology development						
RF						
Power sources						£6M
Accelerating structures						
Magnets						
Large aperture, high field						
High-current, rapid rise-time power supplies						£4M
High-T_C conductor development						
Development of neutrino detector systems						
High-resolution/high-granularity option						
Development of liquid argon or other techniques						£3M
High-mass, large volume option						
Development of tracking calorimeter option						
Development of neutron instruments						
High rate, large solid angle developments						£1M
Total capital R&D						**£45M**

‡ Manpower estimate, person years 2007 - 2012.

Figure 4: The five-year programme of R&D that is required to support the UK contributions to the international efforts to establish conceptual designs for the second generation neutron spallation source and the Neutrino Factory.

4.2 UK Neutrino Factory collaboration – indicative resource estimate

The synergy between the R&D required to realise the second generation neutron spallation source and the Neutrino Factory is strong; both require multi-megawatt pulsed proton beams, high-power target stations for secondary particle production, sophisticated diagnostic equipment, and instrumentation that is well beyond the present state of the art. The Neutrino Factory requires in addition pion-capture and muon phase-space manipulation systems. To bid to host either facility, or both of them, requires that a strong team of highly skilled scientists and engineers be established. The collaborations presently developing the Front End Test Stand at RAL, the targetry work package of the UK Neutrino Factory collaboration, and the MICE experiment clearly demonstrate the synergies noted above. The key elements of the five-year R&D programme together with an indicative estimate of the resources required to support the UK activity in the various areas as part of international efforts to develop conceptual designs of the next generation neutron spallation source and the Neutrino Factory are presented in figure 4. The UK activity defined in figure 4 is well matched to that of the IDS shown in figure 3.

Over the past three years, CCLRC, PPARC and the OST have supported the MICE-UK and UKNF activities at the level of £11.7M, the division of the support by funding agency and sub-project is shown in figure 5. These resources have allowed the UKNF and MICE-UK collaborations to establish an internationally recognised R&D activity into the conceptual design of the Neutrino Factory accelerator complex, the development of a test facility for the front end of the proton driver, the effect of beam-induced shock on solid targets, and ionisation cooling through the international Muon Ionisation Cooling Experiment (MICE) which will be hosted on ISIS at RAL.

The UKNF and MICE-UK collaborations are now preparing plans that will be presented in the UKNF bid for continuation and the MICE-UK bid for resources to carry out Phase 2 of the MICE programme. The collaborations will seek the resources to complete the first phase of the programme, i.e. to complete the conceptual design of the facility, to implement the Front End Test Stand at RAL, and to deliver the UK contributions to the construction of the MICE cooling channel. In addition, resources will be requested to develop prototypes of key elements of the H^- injection linac, to support detailed engineering studies of the Neutrino Factory target station, to construct the non-scaling FFAG proof-of-principle machine EMMA, to carry out an appropriate neutrino detector R&D programme, and to further develop the phenomenological studies required to determine the physics performance of the facility. To achieve these goals will require a modest ramp of the support for the UK Neutrino Factory programme. Over the first three years of the five-year period, it is likely that support at the level of £21M will be required. To deliver the programme over the remaining two years, and to establish the team that will complete the conceptual design for the Neutrino Factory in the IDS framework and is capable of developing a successful bid to host the facility, will require a further £23M. Figure 5 shows the modest ramp required to achieve this level of activity.

The various funding opportunities being considered by the UKNF collaboration to support the continuation of the research programme are also shown in figure 5. The collaboration proposes to make appropriate use of funding opportunities provided by CCLRC, PPARC, and the OST Basic Technology Fund. A bid (or several bids) will be made to the EU Framework 7 programme to enhance the UK activity and to cement the European Neutrino Factory programme. Aspects of the research programme are of direct benefit to scientific disciplines at present supported by the EPSRC, BBSRC and the MRC. The collaboration recognises the importance of engaging with as broad a range of funding bodies as is required to allow the programme to be carried out.

5. Benefits to the UK

The programme being prepared by the UK Neutrino Factory collaboration, and outlined above, is designed to establish UK leadership in the international Neutrino Factory community. This will position the UK to bid to host the facility or to make a leading contribution wherever it is built. Much of the R&D programme is directly relevant to the development of other accelerator-based facilities such as a second generation neutron spallation source. The development of the basic accelerator systems has an even broader application. For example the development of the FFAG programme is strongly supported by a consortium that includes the MRC, Cancer Research UK, TESLA Engineering, and E2V. To have successfully carried out the programme will clearly greatly benefit the UK science and technology base and significantly enhance the UK's reputation in the high-energy physics and accelerator communities.

In areas of the programme where it is appropriate, the UKNF and MICE-UK collaborations are working closely with industry through the High Power RF Faraday Partnership. The close cooperation of manufacturing industry is necessary from the early stages of the development of technological solutions to ensure that the constraints of reliability and cost of bulk production are taken into account. In addition, the construction of a large scientific infrastructure in the UK, or the provision of significant sub-systems to a facility overseas, yields significant opportunities for UK industry to win contracts of significant value to provide systems at the cutting edge of technology. The benefits of this in terms of employment in high-added value, high-tech jobs within the UK will be significant and will be important in making the case for the substantial investment required to construct the facility in the UK or overseas.

		Resource allocations (2004/05 – 2006/07) and indicative estimate (2007/08 – 2011/12)								
		£k	**2004/05**	**2005/06**	**2006/07**	**2007/08**	**2008/09**	**2009/10**	**2010/11**	**2011/12**
MICE-UK/UKNF first phase	UKNF	CCLRC	500	500	500					
		PPARC	414	700	808					
		UKNF total	*914*	*1200*	*1308*					
	MICE-UK	CCLRC	500	500	500					
		OSF LFF	1200	1500	2000					
		PPARC	366	504	417					
		Sub-total	2066	2504	2917					
		Working margin	207	250	292					
		Contingency	413	501	583					
		MICE-UK total	*2686*	*3255*	*3792*					
	Total		***3600***	***4455***	***5100***					
MIEC-UK/UKNF second phase	R&D indicative resource estimate					6	7	8	10	13
	Total R&D									***44***
	Core design team (SY)					10	15	20	35	50
		Funding opportunities for second-phase programme								
PPARC call for accelerator science proposals					Call					
OST Basic Technology Fund				Call						
EU Framework programme 7					Call					

Anticipated funding period

Figure 5: Indicative funding profile for the UK neutron spallation source and Neutrino Factory R&D activities over the coming five-year period. The hardware R&D programme and the development of the core design team are shown separately. The funding sources presently targeted by the UKNF collaboration are indicated.

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12. The average rate of publications related to the properties of the neutrino was 600 publications per year in the eight year period 1990 – 1997. Following the Super-Kamiokande collaboration's measurement of the atmospheric neutrino anomaly rose dramatically. In the eight-year period 1998 to 2005, the average annual rate of neutrino-related publications was 1005 publications per year. Source, the SPIRES data base.

13. Citation ranking of experimental papers, source SPIRES.

	Experiment	Paper title	Reference	Number of citations
1	Super-Kamiokande	Evidence for oscillation of atmospheric neutrinos	Phys. Rev. Lett. 81, 1562-1567 (1998)	2539
2	CDF	Observation of top quark production in anti-p p collisions	Phys. Rev. Lett. 74, 2626-2631(1995)	1239
3	DØ	Observation of the top quark	Phys. Rev. Lett. 74, 2632-2637 (1995)	1195
4	SNO	Measurement of the rate of íe + D -> p + p + e- interactions produced by 8B solar neutrinos at the Sudbury Neutrino Observatory	Phys. Rev. Lett. 87, 071301 (2001) [nucl-ex]	1167
5	CHOOZ	Limits on Neutrino Oscillations from the CHOOZ Experiment	Phys. Lett. B466, 415-430 (1999)	1088
6	SNO	Sudbury-SNO, "Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory	Phys. Rev. Lett. 89, 011301 (2002) [nucl-ex]	1125
7	KamLAND	First Results from KamLAND: Evidence for Reactor Anti-Neutrino Disappearance	Phys. Rev. Lett. 90, 021802 (2003)	1045
8	CHOOZ	Initial Results from the CHOOZ Long Baseline Reactor Neutrino Oscillation Experiment	Phys. Lett. B420, 397-404 (1998)	847
9	Super-Kamiokande	Solar 8B and hep Neutrino Measurements from 1258 Days of Super-Kamiokande Data	Phys. Rev. Lett. 86, 5651-5655 (2001)	747
10	Super-Kamiokande	Measurement of a small atmospheric nu_mu/nu_e ratio	Phys. Lett. B433, 9-18 (1998)	711
11	LSND	Evidence for îì to íe Oscillations from the LSND Experiment at	Phys. Rev. Lett. 77, 3082-3085 (1996) [nucl-ex]	671
12	Super-Kamiokande	Study of the atmospheric neutrino flux in the multi-GeV energy	Phys. Lett. B436, 33-41 (1998)	665
13	SNO	Measurement of Day and Night Neutrino Energy Spectra at SNO and Constraints on Neutrino Mixing Parameters	Phys. Rev. Lett. 89, 011302 (2002) [nucl-ex]	717
14	LSND	Evidence for îì -> íe Neutrino Oscillations from LSND	Phys. Rev. Lett. 81, 1774-1777 (1998) [nucl-ex]	664
15	LEPS	Evidence for a narrow S = +1 baryon resonance in photoproduction from the neutron"	Phys. Rev. Lett. 91, 012002 (2003)	629
16	Super-Kamiokande	Tau Neutrinos Favored over Sterile Neutrinos in Atmospheric Muon Neutrino Oscillations	Phys. Rev. Lett. 85, 3999-4003 (2000)	609
17	Super-Kamiokande	Measurement of the flux and zenith-angle distribution of upward through-going muons by Super-Kamiokande	Phys. Rev. Lett. 82, 2644-2648 (1999)	568
18	BaBar	The BaBar detctor	Nucl. Instrum. Meth. A479, 1-116 (2002)	564
19	CDF	Evidence for top quark production in anti-p p collisions at root(s) = 1.8 TeV	Phys. Rev. Lett. 73, 225-231 (1994)	550
20	Muon g-2	Precise measurement of the positive muon anomalous magnetic moment	Phys. Rev. Lett 86, 2227-2231 (2001)	529

Note: Citation counts listed here are as of Jan 18, 2006 (original list from Symmetry May 05 (http://www.symmetrymag.org/cms/?pid=1000122).

14. The average number of international neutrino-related meetings rose from 4 per year in the period 1992 to 1997 to 13 per year in the period 1998 to 2005. Source, the SPIRES data base.

15. The number of delegates at the bi-annual Neutrino Conference has been steadily growing over the years. In 2002, 410 delegates attended the conference, in 2004 538 delegates attended. In the forward planning for the bid to host the 2010 Neutrino Conference at Imperial College, provision will be made to accommodate between 600 and 700 delegates.

16. The international Neutrino Factory community meets annually at the Neutrino Factory and Superbeam (NuFact) Workshop. NuFact05 will take place from the 21st June to the 26th June 2005 in Frascati. The NuFact05 web site, http://www.lnf.infn.it/conference/2005/nufact05/, contains links to the preceding six workshops in the series.

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