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THE NEUTRINO FACTORY; PHYSICS AND ACCELERATOR CONCEPTS*

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After a brief introduction to the Standard Neutrino Model (SNM), the motivation for a programme of high-precision neutrino oscillation measurements is reviewed. The Neutrino Factory, an intense high-energy neutrino source based on a stored muon beam, is widely believed to yield a precision and sensitivity superior to other proposed second-generation facilities. The alternatives are identified and the strengths of the various options is briefly discussed. Highlights of the exciting international R&D programmes which are designed to demonstrate the feasibility of the required techniques are then reviewed. This R&D programme, which covers all aspects of the accelerator complex, positions the Neutrino Factory community to seek to produce a full conceptual design of the facility by around 2012.

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1. Introduction

The Standard Model (SM) [1] has been established over the past forty years through a series of experiments culminating with those at the electron-positron colliders LEP and SLC, the Tevatron proton-antiproton collider, and the HERA electron-proton collider. In the SM, the neutrino is described as a massless, Dirac, fermion. The discovery of neutrino oscillations [2], a phenomenon whereby a neutrino produced in one flavour eigenstate is observed in a different flavour state after travelling some distance, implies that neutrinos are massive and that the mass of each of the three neutrinos is not the same.

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2. The standard neutrino model

The phenomenon of neutrino oscillations is readily described by extending the Standard Model to include three neutrino mass eigenstates; ν_1, ν_2, and ν_3 with masses m_1, m_2 and m_3 respectively [3]. The flavour eigenstates, ν_e, ν_μ, and ν_τ, are obtained by rotating the mass eigenstates using the unitary matrix U which may be written:

$$U = U_{23} U_{13} U_{12} \,, \tag{1}$$

where

$$U_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}, \tag{2}$$

$$U_{13} = \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}, \tag{3}$$

$$U_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{4}$$

the cosines and sines of the three mixing angles θ_{12}, θ_{13}, and θ_{23} are denoted c_{12} *etc.*, and δ is a phase parameter. Measurements of neutrino-oscillation probabilities cannot be used to determine the absolute neutrino-mass scale but, since the probabilities depend on the mass-squared differences, $\Delta m^2_{23} = m^2_3 - m^2_2$ and $\Delta m^2_{12} = m^2_2 - m^2_1$, neutrino oscillations can be used to determine the mass hierarchy. Electron neutrinos produced in the sun undergo elastic scattering with electrons in the material of the sun. This, the MSW effect [3], modifies the effective mass that appears in the electron–neutrino oscillation probability and has been used to determine the sign of Δm^2_{12}. The sign of Δm^2_{23} can be determined in oscillation experiments for which the baseline is sufficiently long ($\gtrsim 1000$ km) and for which the neutrino energy is sufficiently high ($E_\nu \gtrsim 10$ GeV).

Leptonic-CP violation will occur if $\delta \neq 0$ (and $\sin\theta_{13} \neq 0$). Measurements of the difference between the oscillation probabilities for neutrinos and anti-neutrinos can be used to determine δ. Such measurements require large data sets and appropriately chosen baselines and neutrino energies. To obtain the required neutrino-interaction rate requires either a very large detector or a very intense source (or both).

The job of the experimental neutrino community is to measure all the mixing angles of the MNS matrix as precisely as possible, to determine the sign of Δm^2_{23} and to measure precisely Δm^2_{12} and Δm^2_{23}, and, by measuring δ, to discover leptonic-CP violation if it occurs.

2.1. The next generation of long-baseline neutrino oscillation experiments

Data from the Sudbury Neutrino Observatory (SNO) [4, 5] and KamLAND [6, 7] experiments, together with data from Super-Kamiokande [8] 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 $\sin^2\theta_{23}$ and Δm^2_{23} have been determined using atmospheric neutrino data from Super-Kamiokande [9] and verified using an accelerator-based neutrino source by the K2K experiment [10]. With five to seven years of running, the MINOS long-baseline experiment [11, 12], which has begun to take data will determine θ_{23} and Δm^2_{23} with a precision of around 10%. The first results from MINOS [13] are consistent with the results obtained from the atmospheric-neutrino experiments. The two CNGS experiments OPERA [14] and ICARUS [15, 16], which are designed to observe ν_τ appearance and are scheduled to start data taking in 2008, will verify aspects of the mixing formalism outlined above. Two first-generation super-beam experiments, T2K in Japan [17, 18] and NOνA in the US [19], 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 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.

3. Motivation for a high-sensitivity and high-precision neutrino programme

The experimental upper bound on the neutrino mass-scale indicates that neutrino masses are at least two orders of magnitude smaller than the mass of the lightest charged fundamental fermion, the electron. Such a large difference may indicate that the origin of neutrino mass may be different to that which generates the masses of the charged leptons and the quarks.

Measurements of the quark mixing matrix, $U_{\rm CKM}$, have shown that $U_{\rm CKM}$ is essentially diagonal, the off-diagonal terms being very small [1]. By contrast, the matrix elements of U all have approximately the same magnitude. Only the element U_{e3}, which determines the amount of ν_e in ν_3, is small. These observations may indicate that the physics that underlies neutrino mixing may be different to that which results in the mixing among the quarks.

3.1. The case for sensitivity

The high-sensitivity facility must offer the best possibility of observing leptonic CP violation ($\delta \neq 0$) and of determining the mass hierarchy ($\mathrm{sign}\Delta m^2_{32}$). The optimisation of the facility depends on the value of θ_{13}. If θ_{13} is large (such that $\sin^2 2\theta_{13} \gtrsim 0.01$) then it will have been measured, albeit with poor precision, by T2K or NOνA. In this case, the high-sensitivity facility is required to offer the best sensitivity to δ and $\mathrm{sign}\Delta(m^2_{32})$. Electron– and muon–neutrino beams of modest energy ($\sim$ 10–20 GeV) matched to modest baselines (1000–3000 km) will be required. If θ_{13} is small (such that $\sin^2\theta_{13} \lesssim 0.01$) T2K and NO$\nu$A are likely to have provided an upper limit on $\sin^2 2\theta_{13}$ and the facility will, in addition, be required to have the best possible sensitivity to θ_{13}. In this case, high energy ($\sim$ 20–40 GeV) electron– and muon–neutrino beams will be required, matched to very long base lines (2000–7000 km).

3.2. The case for precision

The fundamental importance of the search for leptonic-CP violation is self-evident. Precision measurements of the parameters that govern neutrino oscillations are essential if a complete understanding of the nature of the neutrino is to be obtained. Such measurements will either establish the minimal model outlined above or, by establishing parameter sets inconsistent with it, point to the existence of entirely new phenomena; for example, the three-generation scenario would have to be abandoned should MiniBOONE [20] confirm the presently unexplained LSND result [21–24].

Grand-unified theories typically provide relationships between the neutrino mixing parameters and those of the quarks. For such relationships to be tested requires that the precision with which the neutrino-mixing parameters are determined matches that with which the quark-mixing parameters are known. At present the quark-mixing parameters are known at the percent level. This sets the standard; the high-precision neutrino oscillation programme must deliver measurements of the neutrino oscillation parameters at the percent level. To achieve this goal requires high-energy electron– and muon–neutrino beams and highly sensitive neutrino detection systems.

3.3. Possible facilities for the era of high-sensitivity and high-precision measurements of neutrino oscillations

Three types of facility have been proposed to provide the neutrino beams required to serve the high-sensitivity programme. The Neutrino Factory gives the best performance over almost all of the parameter space and is believed to be the 'facility of choice'. Second-generation super-conventional-beam experiments may be an attractive option in certain scenarios [25, 26].

A beta-beam [27], in which electron neutrinos (or anti-neutrinos) are produced from the decay of stored radioactive-ion beams, in combination with a second-generation super-beam, may be competitive with the Neutrino Factory [28].

Following the feasibility studies that were carried out at the turn of the century, an international programme of R&D into the accelerator complex has grown up, fostered in part by the 'NuFact' (Neutrino Factory, super-beam and beta-beam) workshop series which was initiated in 1999. The programme of hardware development, reviewed below, is now reaching maturity. To put in place the facility (or facilities) required to serve the high-sensitivity programme requires that a conceptual design be prepared by 2012 together with as broad a consensus as possible on the roadmap for its implementation. A step on this road was taken at NuFact05 with the launch of a one-year international 'scoping study' of a future Neutrino Factory and super-beam facility [29]. The objectives of the scoping study are to [30]:

- Evaluate the physics case for a second-generation super-beam, a beta-beam facility and the Neutrino Factory and to present a critical comparison of their performance;
- Evaluate the various options for the accelerator complex with a view to defining a baseline set of parameters for the sub-systems that can be taken forward in a subsequent conceptual-design phase; and to
- Evaluate the options for the neutrino detection systems with a view to defining a baseline set of detection systems to be taken forward in a subsequent conceptual-design phase.

The conclusions of the scoping study will be presented at NuFact06 and published in a written report in September 2006.

4. The Neutrino Factory

4.1. Overview

At the Neutrino Factory, beams of high-energy electron– and muon–neutrinos will be produced from intense stored muon beams [31]. A schematic diagram of the main sub-systems of the accelerator facility is shown in figure 1. The process of generating the stored muon beam starts with the bombardment of a suitable target with a high-power pulsed proton beam of moderate energy ($\sim$ 5–15 GeV). Pions and kaons produced in the target are captured and allowed to decay to produce muons; the muons must be accelerated rapidly to $\sim$ 20–40 GeV before being injected into the storage ring. The muon beam initially occupies a very large phase space, making it necessary to develop fast, affordable, large-aperture acceleration systems and/or a phase-space reduction (cooling) technique that is rapid when compared to the muon lifetime. The feasibility of such a Neutrino Factory has been addressed in a number of studies [32–36]. These studies defined the programme of R&D required to establish technological solutions for each of the key accelerator systems.

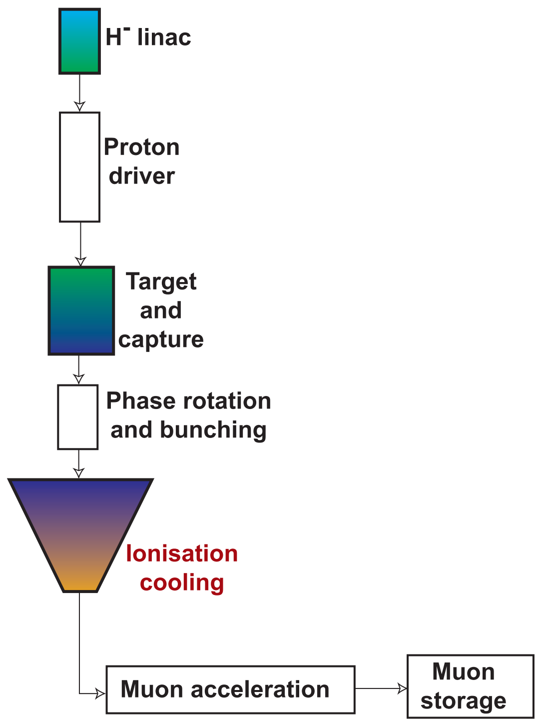

Fig. 1. Schematic drawing showing the major sub-systems in the Neutrino Factory accelerator complex.

It is not possible in a short article such as this to do justice to the Neutrino Factory R&D programmes that are being carried out in Europe, Japan and the US which, together, cover all aspects of the facility. The following paragraphs therefore emphasise the key elements of the programme.

4.2. The proton-driver front-end

The Neutrino Factory proton driver is required to deliver 1–4 MW of proton-beam power at an energy of 5–15 GeV in ~ 1 ns bunches. Machines of similar specification are required to drive a next generation spallation-neutron source, a radioactive heavy-ion facility, and to generate intense 'super-conventional' neutrino beams. Furthermore, high-power proton sources are required to serve applications such as the transmutation of nuclear waste. Such CW sources share many of the technological challenges presented by high-power pulsed proton beams.

The activation of the accelerator elements through the loss of a fraction of the primary beam power is the principal issue for the development of a high-power proton driver. To keep the activation within acceptable limits requires that the beam-loss rate should be no more than 1 W/m [37]. To achieve this challenging specification requires that the beam quality at injection be exceptionally good. Several programmes aimed at developing the technologies required to produce such high quality beams are underway [38]. The programmes emphasise the front end of the accelerator, *i.e.* from the ion source up to energies of a few MeV. For pulsed proton beams, the development of high-quality beam choppers is of particular importance. 'Choppers' are designed to remove unwanted bunches from the beam with 100% efficiency and are required if low-loss injection into accumulator or compressor rings or clean on-off transitions are to be achieved.

Such parallel developments are a strength as they allow the sharing of expertise and information and give confidence that the front-end of the Neutrino Factory accelerator complex will be developed on an appropriate timescale.

4.3. Target and capture

Efficient pion production may be achieved by bombarding a rod-like high-Z material with the primary proton beam. For solid targets, fatigue caused by beam-induced thermal shock is the principal issue that must be addressed in the design of the target [39]. To reduce the effect of shock damage to solid targets may require that the target be replaced every beam pulse. Several solid-target schemes have been proposed [40]. A free-flowing liquid-mercury-jet target is a conceptually simple alternative [40]. Shock-induced processes cause the break-up of the jet, therefore the jet velocity must be chosen such that a new volume of liquid mercury is exposed to the beam every pulse.

Two schemes have been proposed by which the particles produced in the target may be captured. The first uses high-field solenoid magnets to capture both positive and negative particles at the same time [33]. The second calls for a magnetic horn to focus either positive or negative particles into the subsequent transport and decay sections [35]. The horn scheme has the advantage that the focusing element closest to the target itself is relatively simple. The advantage of the solenoid scheme is that an efficiency gain of a factor of two can be achieved if the downstream accelerator complex is designed to manipulate and store μ^+ and μ^- simultaneously [34]. In each case, significant engineering work needs to be carried out to ensure that the target station can be operated safely.

Particle production in the target has been studied [41]. Though particle-production models give significantly different rates and spectra, the results indicate that a proton driver with an energy in the range $\sim$ 5–15 GeV is likely to be suitable. In order to optimise the target and capture system, it will be important to bench-mark the various simulation codes against measured particle distributions. Two experiments, HARP [42] at CERN and MIPP [43] at FNAL have been (or are being) carried out to measure these distributions. The HARP experiment has recently presented results for forward-particle production [44]. The large-angle data, which is expected to be finalised soon, will be important in tuning the particle-production models.

4.3.1. Characterisation of materials

The development of the conceptual design for the Neutrino Factory target station rests on an understanding of the properties of the various proposed materials under extreme conditions. Irradiation studies of solid targets are being carried out at BNL and at CERN [40]. These studies include the investigation of the degree to which the bombarded material can be annealed by baking at high temperature. The intensity, repetition rate, and beam time available for these studies are insufficient to simulate target exposures comparable to long-term (several months to a year) use at the Neutrino Factory. The UK Neutrino Factory collaboration is therefore developing a technique in which a high-current pulse is used to generate, in a sample of tantalum wire, energy densities comparable to those expected in the Neutrino Factory target [45]. The current-pulse technique will be used to mount a 'life-time' test. The numerical techniques needed to extrapolate these measurements to the Neutrino Factory target using LS-DYNA [46] are being developed in parallel.

Measurements of the effect of intense proton-beam pulses on liquid mercury have been carried out at BNL, and studies of the development of mercury jets both with and without magnetic field have been carried out at Grenoble and at BNL respectively [47]. For liquid-jet targets, the energy deposited by the beam can be sufficient to cause voids to be created in the body of the jet by the shock-induced transient pressure waves. This process, referred to as cavitation, is being studied experimentally at CERN using a high-power laser impinging on a jet of water [48]. Numerical studies of the passage of particle beams through mercury-jet targets have been developed and now give a good description of the measured behaviour [49].

4.3.2. The liquid-mercury-jet target

The liquid-metal option for a pion-production target capable of operating with a multi-MW pulsed proton beam at a Neutrino Factory will be tested in the MERIT experiment [50]. MERIT will expose a mercury jet of 1 cm diameter and flowing at 20 m/s in a 15 T solenoidal magnetic field to an intense proton beam from the CERN PS and is scheduled to begin to take data in 2007.

A schematic diagram of the experiment is shown in figure 2. The proton beam from the PS is horizontal and enters the experiment from the right. The experiment is tilted so that the angle between the proton beam and the mercury-jet axis is 100 mrad. Liquid nitrogen will be used to cool the copper coils of the solenoid magnet to 80 K. The magnet, pulsed with a 5 MVA power supply, will deliver a 15 T field for a duration of 1 s. The mercury jet will be injected into the 15 cm diameter warm bore of the magnet and the beam-target interaction will be recorded through viewing ports by high-speed cameras via fibre-optic cables.

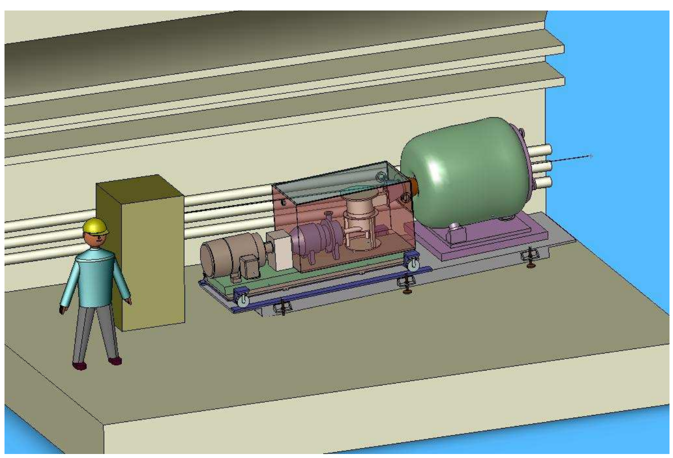

Fig. 2. Schematic diagram of the MERIT experiment at the neutron time-of-flight (nToF) facility at CERN [50].

Short bunch trains containing between one and four bunches of 5–7$\times 10^{12}$ protons will be extracted from the PS. If all four bunches are filled, a total of 28×10^{12} protons will impinge on the target within a 2 μs spill giving a peak energy deposition of 180 J/g. By varying the pattern of filled proton bunches the experiment will also be able to study the effect of cavitation.

4.4. Ionisation cooling

The muon beam that emerges from the decay channel fills a large phase space. For example, in US Study II the transverse emittance at the exit of the decay channel is 12 mm [33]. The spread of the muons in the longitudinal phase space is also very large ($\sim$ 60 mm in Study II). Efficient, cost effective, acceleration of the muon beam requires that the phase space be modified. The phase-rotation and bunching systems that follow the decay channel are required to produce a beam with an energy spread of $\sim$ 60 MeV which is appropriately bunched to match the subsequent cooling sections.

Each of the five Neutrino Factory conceptual design studies have considered the benefit of reducing the emittance of the muon beam (cooling) before injecting it into the acceleration and storage systems. There are two principal motivations for this: to increase the number of muons inside the acceptance of the downstream accelerators; and to keep the cost of the muon acceleration system to a minimum.

At the end of the decay channel, the muons have a momentum of roughly 200 MeV/c. The time-dilated lifetime of the muon is short ($\sim 4.7\mu$s) making it essential that cooling and acceleration take place as rapidly as possible. Ionisation cooling, a process in which the muon beam is caused to pass through an alternating series of liquid-hydrogen absorbers and accelerating RF-cavities, is the technique by which it is proposed to cool the muon beam

TABLE I

Survey of the gain afforded using ionisation cooling in a number of conceptual design studies of the Neutrino Factory.

Design	Number of cooling cells	Gain factor per cell (%)	Cooling	Comment
Study II [33]	26	6	7	Increase in phase-space density in acceptance of downstream accelerator.
Study IIa [34]	26	2	2	Increase in number of muons in acceptance of subsequent muon acceleration section.
CERN [35]	36	10	7	Increase in muon yield at 2 GeV over optimised Neutrino Factory without cooling.
NuFact-J [36]	—	1.5–2	—	Acceleration based on FFAGs. Performance improvement when absorber is included in FFAG ring giving 6D cooling effect.

prior to acceleration. Various 'gain factors' have been defined to quantify the gain in performance due to the cooling channel (see Table I). Systems that give gain factors of between 2 and 10 have been devised. Since a factor of Γ gain in stored muon-beam intensity implies a reduction, by a factor Γ, in the running time required to achieve a particular total neutrino flux, and a decrease in emmitance of the muon beam entering the acceleration section is likely to lead to significantly lower costs for muon acceleration, it will be important to make a careful optimisation, for performance and cost, of the cooling and acceleration systems. The engineering demonstration of the ionisation-cooling technique will be carried out by the international Muon Ionisation Cooling Experiment (MICE) collaboration [51]. The MICE experiment, which has been approved, will take place at the Rutherford Appleton Laboratory (RAL), using muons produced by the ISIS 800 MeV proton synchrotron. The status of the experiment is reviewed in the paragraphs that follow.

4.4.1. The international Muon Ionisation Cooling Experiment

The principal components of the MICE experiment are shown in figure 3. Two, functionally equivalent, spectrometers are placed upstream and downstream of a single lattice cell of the Study II cooling channel. In the Study II design approximately 10^{14} μ/s pass through the channel. The lateral dimensions of the beam are such that space-charge forces can be ignored making it possible to run MICE as a single particle experiment in which the Neutrino Factory bunch is reconstructed offline using an ensemble of particles recorded in the experiment. At the nominal input emittance of $\epsilon_{\rm in} = 6\pi$ mm a cooling effect ($\epsilon_{\rm out}/\epsilon_{\rm in} - 1$, where $\epsilon_{\rm out}$ is the output emittance) of $\sim 10\%$ is expected. The cooling effect will be measured with a precision of 1% (*i.e.* ($\epsilon_{\rm out}/\epsilon_{\rm in} - 1$) will be measured with an absolute precision of 0.1%).

The MICE cooling channel consists of three absorber/focus-coil (AFC) modules and two accelerating-cavity/coupling-coil (RFCC) modules. The AFC modules each contain a 20 l liquid-hydrogen absorber inside a pair of superconducting coils that bring the beam to a focus in the centre of the absorber. Liquid hydrogen is the most efficient ionisation-cooling material because it has a large specific ionisation and a comparatively large radiation length. Safe operation of the system in the presence of liquid hydrogen leads to significant engineering constraints. The AFC modules and the hydrogen system each have both active and passive safety systems. The hydrogen will be stored in the form of metal hydride when the absorber is emptied. A vigorous R&D programme is underway to demonstrate the safe operation of the hydrogen system. The super-conducting coils and the liquid-hydrogen vessel itself are refrigerated using closed-cycle 'cryo-coolers' [52].

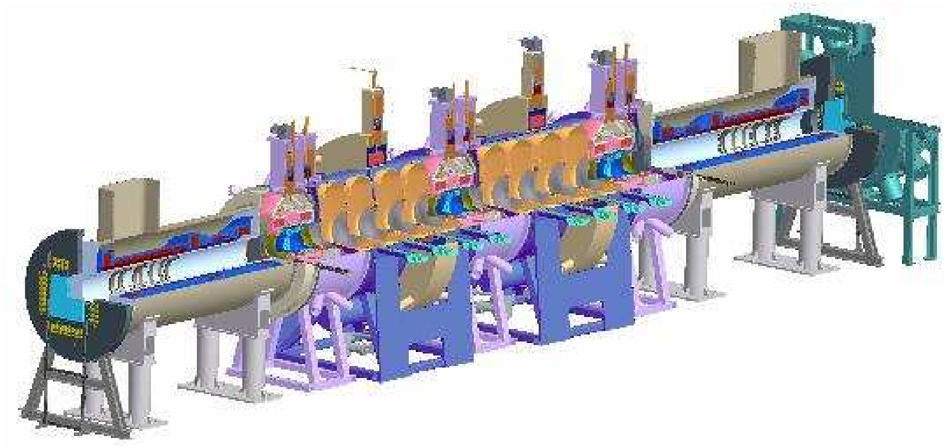

Fig. 3. Drawing of the MICE experiment [51]. The beam enters the experiment from the bottom left-hand corner. The beam first passes through one of the scintillator hodoscopes that form the time-of-flight system. After passing through the upstream spectrometer, the beam passes through three absorber/focus-coil modules and two cavity/coupling- coil modules before it passes through the downstream spectrometer and, a second time-of-flight hodoscope, the downstream Cherenkov counter and is stopped in the electromagnetic calorimeter. The beamline and upstream instrumentation is not shown.

The RFCC module must restore the energy-lost by the muons as they pass through the absorber. The coupling coil, a short, large diameter solenoid, provides the magnetic field that transports the muons through the module. The acceleration is produced by four 201 MHz copper cavities which produce a gradient of 8 MV/m. To produce the required field gradient, the cavities must be electrically closed, yet, to preserve the cooling effect, the amount of material through which the beam passes must be minimised. Thin beryllium windows have been developed for this purpose. The degree of emission from the cavity surfaces is significantly enhanced by the Lorentz force produced by an intense magnetic field [53]. While reducing the field emission in a Neutrino Factory cooling channel, in which the cavities must operate at 16 MV/m, is a challenging problem, it has been estimated that for operation in MICE, the emission can be kept within acceptable bounds.

The muon beam that enters the experiment may contain a small pion contamination. The instrumentation upstream of the cooling channel is therefore required to distinguish pions from muons and to measure the phase space coordinates of the muons entering the channel. Downstream of the cooling channel, the instrumentation is required to identify electrons produced in the channel by muon decays and to measure the muon phase-space coordinates. The upstream particle identification will be performed using a scintillator-based time-of-flight (TOF) system and a threshold Cherenkov counter. The TOF system will also be used to trigger the experiment and to determine the phase of the RF fields in the cavities as the muon traverses the experiment. The upstream and downstream spectrometers are each composed of a 4 T superconducting solenoid instrumented with a scintillating-fibre tracking device. Downstream of the cooling channel a final TOF station, a Cherenkov counter and a calorimeter are used to distinguish muons and electrons.

The MICE collaboration will take enough data to make the uncertainty on the measured cooling effect systematics limited. It is therefore crucial that the systematic errors are understood in detail. To do this, the experiment will be built up in stages. A first measurement of cooling, using the two spectrometers and one AFC module, is scheduled for 2008. The first RFCC module and a second AFC module will then be installed and the full MICE cooling channel will be assembled in 2009.

The MICE experiment will be mounted on ISIS at the CCLRC Rutherford Appleton Laboratory. The preparation of the MICE Muon Beam on ISIS, the MICE Hall and the first phase of the MICE experiment is proceding to schedule. The first data-taking period, in which the muon beam will be characterised, the instrumentation calibrated and the relative systematics of the two spectrometers will be measured, will begin in April 2007.

4.5. Acceleration and storage

The short lifetime of the muon leads to the requirement that the acceleration be as rapid as possible. Past studies have considered re-circulating linear accelerators in various topologies. More recently it has been proposed that fixed field alternating gradient (FFAG) accelerators may offer advantages [54]. Unlike conventional synchrotrons, the magnets within the FFAG are not ramped with the consequence that the radius of the particle orbit increases during acceleration. The radial profile of the magnet pole-pieces is carefully designed to give a field that varies with radius so as to produce the same focusing effect for all momenta. Several 'scaling' FFAGs, in which the magnetic field scales with radius, have been built in Japan [55]. The scaling FFAG programme is reaching maturity with the machine proposed for the PRISM experiment [56]. An alternative to the scaling FFAG is the 'non-scaling' FFAG [57]. In a non-scaling machine the magnets are standard quadrupoles or combined-function dipoles. However, the settings are carefully optimised so as to reduce the radial displacement of the beam during acceleration. An international collaboration (EMMA) is developing a proposal to construct a proof-of-principle non-scaling FFAG [58].

Progress has also been made in developing schemes for the storage ring, the design of which is complicated by the need to serve two or more detectors at different long base-lines [59]. To fully engineer the storage ring will require that the power radiated from the muon beam in the form of decay electrons and bremsstrahlung photons be dealt with using appropriate absorbers.

The experience gained in the construction of PRISM and EMMA and in the design of the storage rings themselves will be important input to a future Neutrino Factory design study in which the cooling, acceleration and storage systems will have to be optimised together for performance and cost.

5. Conclusions

A programme of precision measurement of the properties of the neutrino is important because the measurements may lead to the discovery of CP violation in the lepton sector and of the physical principles that explain the tiny neutrino masses and the very large neutrino mixing angles. It is likely that these measurements will have a profound impact in astro-physics and cosmology, well beyond the confines of particle physics. The Neutrino Factory offers better sensitivity and precision than other second generation facilities, and the accelerator systems required are being developed by an energetic international community. The time is therefore right for the Neutrino Factory community to take the next bold step, to produce a conceptual design report by 2012. If the community is successful in establishing the conceptual design on this timescale and the results of the present generation of experiments confirms that the Neutrino Factory is needed, then the case to expedite the construction of the Neutrino Factory will be very strong indeed.

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