# THE INTERNATIONAL DESIGN STUDY FOR THE NEUTRINO FACTORY

A. Kurup, Imperial College London, UK / FNAL, Batavia, USA
K. Long, Imperial College London, UK

*Abstract*

The International Design Study for the Neutrino Factory (IDS-NF), which is being carried out by personnel from the Americas, Asia, and Europe, has been established by the Neutrino Factory community to deliver a Reference Design Report for the facility by 2012 [1]. The baseline design, developed from that defined in the ISS [2], will provide $10^{21}$ muon decays per year from 25 GeV stored muon beams. The facility will serve two neutrino detectors; one situated at source-detector distance of between 3000-5000 km, the second at 7000-8000 km. Muon storage rings have also been proposed as the basis of a multi-TeV lepton-antilepton Muon Collider. The R&D required to deliver the Neutrino Factory and that required to realise the Muon Collider have many synergies including: the pion-production target; ionisation cooling; rapid acceleration of large emittance beams; and the provision of high-gradient accelerating cavities that operate in high magnetic fields. The conceptual design of the accelerator facility for the Neutrino Factory and the relation of the IDS-NF to the EUROnu Design Study will be described [3].

## INTRODUCTION

The phenomenon of neutrino oscillations, which is now established, implies that the Standard Model of particle physics is incomplete and hints at the presence of undiscovered particles, forces, and/or symmetries. Precision measurements of the neutrino mixing parameters are therefore essential for the underlying physics to be elucidated. Of the facilities proposed to follow the present generation of long-baseline neutrino-oscillation experiments, the Neutrino Factory, which produces high-energy neutrino beams from the decay of stored muon beams, offers the best sensitivity in the search for CP violation in the leptonic sector and is likely to be able to make the most precise measurements of the neutrino-mixing parameters [1]. Neutrino detectors are required at two baselines: the first, sited between 3000 km and 5000 km from the source, is optimised for the search for leptonic-CP violation; the second, at a source-to-detector distance of between 7000 km and 8000 km, will be used to make a precise measurement of the small mixing angle, $\theta_{13}$, and to resolve parameter degeneracies. The specification for the Neutrino Factory accelerator facility is that it will deliver $5 \times 10^{20}$ neutrinos per $10^7$-second year towards each of the two detectors with a stored-muon energy of 25 GeV [2]. Figure 1 shows a schematic layout of the baseline accelerator facility. The beam requirements for a high-luminosity, multi-TeV Muon Collider are similar to the requirements for the Neutrino Factory. The main difference is that to reach the required luminosity, the Muon Collider requires an aggressive six-dimensional cooling scheme. Therefore, the technology required for the two facilities is common up to and including the first stage of ionisation cooling.

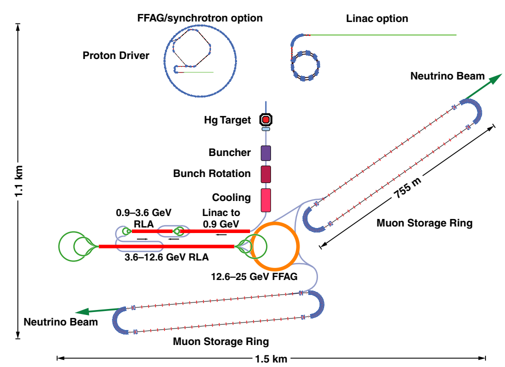


Figure 1: Schematic layout of the baseline accelerator facility that is being developed within the International Design Study for the Neutrino Factory [2].

## PROTON DRIVER

The specification of the Neutrino Factory proton driver was developed through the studies performed by the Accelerator Working Group of the ISS [3]. Some of the key requirements are: 4 MW mean beam power; $10 \pm 5$ GeV energy; 50 Hz pulse repetition frequency; 3 bunches per pulse; and $2 \pm 1$ ns rms bunch length. The main challenge of the proton driver is the production of the desired bunch time structure at the required mean beam power. Several proton-driver designs, including consideration of site-specific and 'greenfield' options, that will meet these requirements are under development. A 5 GeV version of the proposed Superconducting Proton Linac (SPL) at CERN is being considered that utilises accumulator and compressor rings to produce the required time structure. Simulations have been performed to investigate the effect of beam instabilities in the accumulator ring and the effect of space charge in the compressor ring [4]. Project X is being developed as an FNAL-based proton driver for a future long-

[1] The decision point identified by the Strategy Group of the CERN Council.
[2] The International Scoping Study for a future Neutrino Factory and super-beam facility.
[3] Submitted on behalf of the IDS-NF collaboration.

baseline neutrino programme and to serve experiments that study rare particle-physics processes [5]. The current design is for 2 MW mean beam power and a proton energy in the range of $60 - 120$ GeV. Upgrade options are being considered that would make the Project-X proton driver more compatible with the requirements of the IDS-NF. Several 'greenfield' options are being considered that begin with a 200 MeV $H^-$ linac followed by a number of rapid cycling synchrotrons and/or FFAGs [6]. Some of the options being considered allow the proton driver to serve a pulsed neutron spallation source in addition to the Neutrino Factory. Currently, the preferred option for the 0.2-10 GeV acceleration stage is a 0.2-3 GeV rapid cycling synchrotron followed by a 3-10 GeV non-linear, non-scaling FFAG.

## PION-PRODUCTION TARGET

Three technologies are being considered for the Neutrino Factory pion production target: a liquid-mercury jet; a solid; and a fluidised-powder jet. R&D projects are underway to investigate the viability of these alternatives. The MERIT [7] experiment has studied the feasibility of using a free-flowing mercury-jet as the target material. Results have shown that the length of the jet that is disrupted by the passage of the proton beam increases as the proton beam intensity increases. In the presence of a 15 T solenoidal magnetic field, the disruption length reaches a plateau at around 17 cm. On the basis of these results the mercury-jet target has been adopted as the current baseline for the IDS-NF. For beam powers of more than 4 MW it was believed that solid targets would not be able to survive the stress caused by the repeated impacts of a pulsed proton beam. Solid target studies [8] have focused on shock testing materials by pulsing a wire with a large current to simulate the impact of a proton bunch. Initial studies have shown that tungsten is a candidate material for a solid target. A laser interferometer system is now being used to measure the surface velocity of the wire while it is being pulsed. A fluidised powder target has the potential to combine the benefits of a liquid-mercury target and a solid target. However, it is important to ensure that the delivery system is capable of delivering a jet of the required density and speed without suffering from erosion. An experiment based at RAL is underway to study these effects [9]. Investigations of the degree to which pion-production codes reproduce the data from the HARP experiment [10] are being carried out. The incorporation of the HARP data in the particle-production codes is of particular importance and will allow more accurate predictions of pion fluxes and angular distributions to be made.

## MUON FRONT-END

The muon front-end includes the pion capture, bunching, phase-rotation and ionisation cooling sub-systems. The pion capture sub-system uses a solenoid channel in which the magnetic field tapers from 20 T to 1.75 T. This is followed by a series of RF cavities that bunch the beam and reduce its energy spread [12]. The transverse emittance of the beam is then reduced by an ionisation cooling channel composed of a series of lithium-hydride absorbers followed by 201 MHz RF cavities to restore the longitudinal momentum. The bunching, phase-rotation and ionisation cooling sub-systems require the operation of RF cavities within magnetic focussing lattices. However, stray magnetic fields in the RF cavities will cause breakdown to occur at a much lower electric field, therefore reducing the maximum operating electric field within the cavity. This issue is very important for both the Neutrino Factory and the Muon Collider and is being addressed by several experiments and simulation studies. Simulations are being carried out to evaluate whether the impact of a reduced RF gradient on the cooling performance of the Neutrino Factory lattice can be mitigated [11]. Experiments at the MuCool test facility, at FNAL, are looking at different materials and the use of coatings to suppress RF breakdown, therefore increasing the maximum operating electric field [23]. Another method of suppressing RF breakdown is to use high pressure gas-filled RF (HPRF) cavities. Previous results have shown that HPRF cavities do not suffer from a reduction of the maximum operating electric field when a strong external magnetic field is applied [13]. Preparations are now underway to see if this is still the case in the presence of ionising radiation produced by a high intensity 400 MeV proton beam. An alternative muon front-end design that utilises HPRF cavities is being studied [14]. To compare with these experimental results, simulations are being performed to study the mechanism by which RF breakdown occurs in cavities that operate within external magnetic fields [15] [16]. The Muon Ionisation cooling experiment (MICE), based at RAL, will make the first ever measurement of ionisation cooling using a muon beam. This will be a very important step in proving the technology required for the muon front-end of the Neutrino Factory. The status of the MICE experiment is presented elsewhere in these proceedings [17].

## MUON BEAM ACCELERATION

The current baseline design for the Neutrino Factory muon-acceleration system is composed of a linac accelerating the beam from 0.244 GeV to 0.9 GeV, a dog-bone recirculating linear accelerator (RLA) from 0.9 GeV to 12.6 GeV, and a non-scaling FFAG from 12.6 GeV to 25 GeV. RLAs are used for the low energy acceleration of muon beams as they allow multiple passes through the accelerating structure [18]. A design for the lattices of the linac and the RLAs, including the transfer lines and injection chicanes, that allows simultaneous acceleration of $\mu^+$ and $\mu^-$ beams has been completed. Design issues for the RLA that have been addressed include multi-pass optics and phase slippage in the linac, orbit separation at the ends of the linac, compact return-arc lattice design, and chromaticity correction in the arcs. For the final stage of acceleration, a linear non-scaling FFAG is proposed in order to maximise the number of passes made through the RF cavities. Several designs have been studied to optimise the FFAG for transport efficiency and cost [19]. Another important issue with the FFAG is the injection and extraction of the beam. The compact geometry of the non-scaling FFAG places very challenging constraints on the injection and extraction systems. Studies of injection and extraction designs that minimise the kicker and septum strengths are being carried out [20].

## MUON STORAGE RINGS

The main challenge for the storage ring design is to maximise the number of muons that decay in the direction of the detectors. Several geometries for the rings have been studied taking into account not only the beam dynamics, but also geological and engineering construction issues [21]. The baseline design is a racetrack ring for each detector, which can store either $\mu^+$ or $\mu^-$. This was chosen because it allows more flexibility in the choice of detector location. Optimisations of the racetrack design are underway to study chromaticity, resonances and the effect of field and alignment errors [22].

## SUMMARY

Experiments have been carried out or are underway to demonstrate the feasibility of each of the key systems that make up the Neutrino Factory accelerator complex. Taking the results of these experiments and future measurements of $\theta_{13}$ into account, the IDS-NF collaboration will provide the Reference Design Report (RDR) for the facility by 2012. European contributions to the IDS-NF are coordinated through the European Union Framework Programme 7 'EUROnu' Design Study. EUROnu is charged with delivering design reports for super-beam, beta-beam, and Neutrino Factory that will inform the Strategy Group of the CERN Council at the decision point in 2012 when the future of the neutrino programme in Europe will be determined. The IDS-NF collaboration is committed to the timely delivery of the RDR, so making the Neutrino Factory an option for the field.

## REFERENCES


[1] The ISS Physics Working Group, 'Physics at a future Neutrino Factory and super-beam facility', RAL-TR-2007-19, axXiv:0802.4023, to be published in Rep. Prog. Phys.

[2] The IDS-NF Collaboration, "Neutrino Factory: specification of baseline", `https://www.ids-nf.org/wiki/FrontPage/Documentation?action=AttachFile&do=get&target=IDS-NF-002-v1.1.pdf`.

[3] The ISS Accelerator Working Group, "Accelerator design concept for future neutrino facilities", RAL-TR-2007-23, submitted to JInst.

[4] M. Aiba, "Feasibility Study of Accumulator and Compressor for the 6-bunches SPL based Proton Driver", CERN-AB-2008-060

[5] S. Holmes, "Project X at Fermilab", PAC'09, Vancouver(2009)

[6] C. Prior, "Green-Field Proton Drivers for a Neutrino Factory", `https://www.ids-nf.org/wiki/CERN-2009-03-23/Agenda/Accelerator/Files?action=AttachFile&do=get&target=S1-Prior-1-v1.pdf`.

[7] K. McDonald, "The MERIT High-Power Target Experiment at the CERN PS", PAC'09, Vancouver(2009)

[8] G. Skoro, "Solid Target for a Neutrino Factory", PAC'09, Vancouver(2009)

[9] C. Densham, "The Potential of Fluidised Powder Target Technology in High Power Accelerator Facilities", PAC'09, Vancouver(2009)

[10] M. Bonesini, "Particle production vs. energy: how do simulation results match experimental measurements?", Proceedings of Science(Nufact08)092, (2008)

[11] C. Rogers, M. Martini, "Muon Ionisation Cooling in Reduced RF", PAC'09, Vancouver(2009)

[12] D. Neuffer, C. Y. Yoshikawa, "Muon Capture and Bunching in the International Design Study for a Neutrino Factory", PAC'09, Vancouver(2009)

[13] P. Hanlet, M. Alsharo'a, R. E. Hartle, R. P. Johnson, M. Kuchnir, K. Paul, C. M. Ankenbrandt, A. Moretti, M. Popovic, D. M. Kaplan, et al., "High Pressure RF Cavities in Magnetic Fields", EPAC'06, Edinburgh (2006), p. 1364.

[14] D. Neuffer, C. Ankenbrandt, R. P. Johnson, C. Y. Yoshikawa, "Muon Capture, Phase Rotation, and Precooling in Pressurized RF Cavities", PAC'09, Vancouver(2009)

[15] D. Stratakis, J. S. Berg, R. Fernow, J. C. Gallardo,R. B. Palmer, "Effects of External Magnetic Fields on RF Cavity Operation", PAC'09, Vancouver(2009)

[16] A. Zarrebini, A. Kurup, K. Long, J. K. Pozimski, M. Ristic, R. Seviour, "The Effects of Field Emitted Electrons on RF Surface", PAC'09, Vancouver(2009)

[17] V. C. Palladino, "Status of the MICE Muon Ionization Cooling Experiment", PAC'09, Vancouver(2009)

[18] S. A. Bogacz, "Low Energy Stages - 'Dogbone' Muon RLA", Nuclear Physics B, 149 (2005) pp. 309-312.

[19] J. S. Berg, S. Machida, "FFAG Designs for the International Design Study for the Neutrino Factory", PAC'09, Vancouver(2009)

[20] J. Pasternak, J. S. Berg, M. Aslaninejad, D. Kelliher, S. Machida, "Feasibility of Injection/Extraction Systems for Muon FFAG Rings in the Neutrino Factory", PAC'09, Vancouver(2009)

[21] C. Prior, "Muon Storage Rings for a Neutrino Factory", PAC'09, Vancouver(2009)

[22] M. Apollonio, M. Aslaninejad, J. Pasternak, "Beam Dynamics Studies for a Neutrino Factor Decay Ring", PAC'09, Vancouver(2009)

[23] D. Huang, Y. Torun, J. Norem, A. D. Bross, A. Moretti, Z. Qian, R. Rimmer, D. Li, M. Zisman, "RF Studies at Fermilab MuCool Test Area", PAC'09, Vancouver(2009)