

# Status of the Neutrino Factory accelerator design studies

**Gersende Prior**<sup>1</sup>

CERN, 1211 Geneva 23, Switzerland

E-mail: [gersende.prior@cern.ch](mailto:gersende.prior@cern.ch)

**Abstract.** This document is a review of the present status of the Neutrino Factory design study, after the publication of the Interim Design Report and before the publication of the Reference Design Report. The different components of the accelerator as well as their current design stage and future tasks are described here.

## 1. Introduction

In March 2011, the Interim Design Report (IDR) [1] was published. It documents in details the Neutrino Factory design study and progresses made, since the Accelerator Working Group (AWG) of the International Scoping Study (ISS) identified in 2006, the baseline design as well as the required R&D activities and issues to address. Details of the work performed by the ISS AWG group have been published [2]. Following up this publication the International Design for a Neutrino Factory (IDS-NF) collaboration was born, whose mandate is to complete the design study by addressing the current technical issues and working on possible mitigation options for the publication of the Reference Design Report (RDR), foreseen at the beginning of 2013. At present 134 authors and 47 institutes are members of the IDS-NF collaboration. In Europe, the Neutrino Factory design study is funded by the EU FP7 contract EUROnu, which also encompasses the design study of two other accelerator options: the Super Beam and the Beta Beams.

## 2. The Neutrino Factory: wish-list and constraints

The next generation of neutrino facilities will perform precision measurements of the last unknown mixing angle  $\theta_{13}$ , search for CP-invariance violation in neutrino oscillations, determine the sign of  $\Delta m_{31}^2$  and measure all the oscillation parameters with an unprecedented precision. It requires intense (4 MW,  $10^{21}$  neutrinos/year), high-energy ( $> 20$  GeV) neutrino and anti-neutrino beams. This puts a number of constraints on the target and accelerator systems. The most important important ones being:

- the target should be able to withstand beam-induced shocks
- the muon beam should be bunched, rotated and cooled over a small distance
- a rapid muon acceleration system able to transport the muons beam to two decay rings with minimum beam losses is needed

<sup>1</sup> on behalf of the EUROnu and IDS-NF collaborations.

The Neutrino Factory buncher allows both muon signs transport in different radio-frequency (RF) buckets, whereas the rotator will permit a reduction of the energy spread and the cooler a reduction of the beam emittance.

The feasibility study will determine if we can overcome its technical challenges, identify the cost driving factors and detail possible risk mitigation solutions.

In addition, if one considers building in the future a muon collider, a detailed reference design of the Neutrino Factory is necessary as it is a key component of the muon collider complex [3].

### 3. Proton driver and annexes

A schematic layout of the Neutrino Factory is shown on Figure 1. Three options have been identified for the proton driver which are described in more details below.

#### 3.1. CERN SPL-based scenario

As part of the upgrade of the CERN accelerator complex, a Super Proton Linac (SPL) will be built in the future. It is an  $H^-$  linac, with a bunch frequency of 352.2 MHz and a repetition rate of 50 Hz. It comprises a high-speed chopper permitting to form bunches less than 2 ns wide, including rise and fall times. It could serve as a proton driver [4] for the Neutrino Factory and two working options have been identified which are summarized in Table 1.

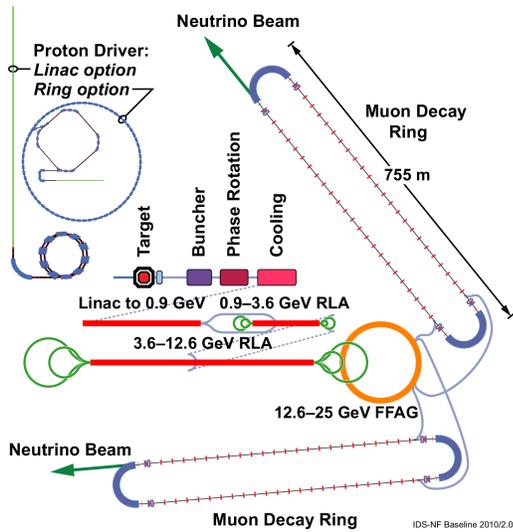
**Table 1.** CERN SPL configuration options for the Neutrino Factory and beam energies (a) = 2.5 GeV and (b) = 5 GeV.

	Option 1	Option 2
Power (MW)	2.25 (a) or 4.5 (b)	5 MW (a) and 4 MW (b)
Number of protons/pulse	$1.1 \times 10^{14}$	$2.14 \times 10^{14}$ (a) and $1 \times 10^{14}$ (b)
Pulse current (mA)	20	40
Pulse duration (ms)	0.9	1 (a) and 0.4 (b)

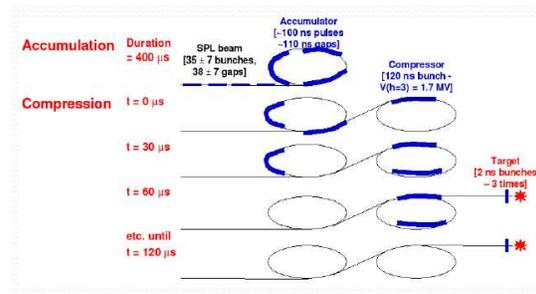
The SPL is then followed by an accumulator and compressor rings, where the proton beam is transformed into three bunches aimed at the target. Figure 2 shows the transformation of the bunch structure from the SPL to the output of the compression ring. A study of the beam instabilities in the accumulator for the case of three bunches has been performed. MADX [5] simulations of the accumulator and compressor rings are available for the case of three bunches. The components of the accumulator and compressor rings are being listed for costing purposes.

#### 3.2. Fermilab scheme and the upgrade to Project X

The proton driver based on the upgrade of the Fermilab Project X acceleration complex (see Figure 3) would provide 4 MW power at 8 GeV. By increasing the 3 GeV CW linac average current to 5 mA, its duty factor to  $\sim 10\%$  (Project X is  $\sim 5\%$ ) and the number of particles per linac bunch, one could reach the Neutrino Factory proton driver requirements. An additional accumulator and a compressor rings (as in the CERN scenario) would be necessary. In the present design, the accumulator has a circumference of  $\sim 250$  m aiming at forming  $14 \times 100$  ns-long bunches with  $1.3 \times 10^{13}$  protons/bunch. The use of a stripping foil or a novel laser-stripping technique are under consideration. The compressor would get at its entrance  $\sim 50$  ns bunches needing to be shortened into few ns long bunches. Detailed studies of the instabilities and space charge have to be completed. An optimization study of the beam size and angle at target is also under way.



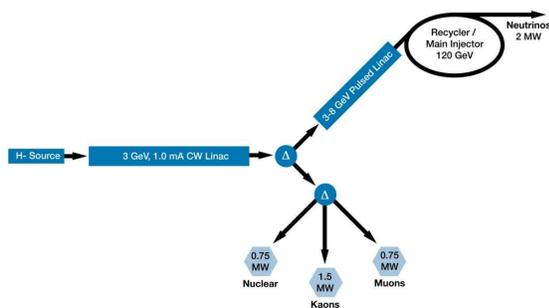
**Figure 1.** Schematic layout of the Neutrino Factory.



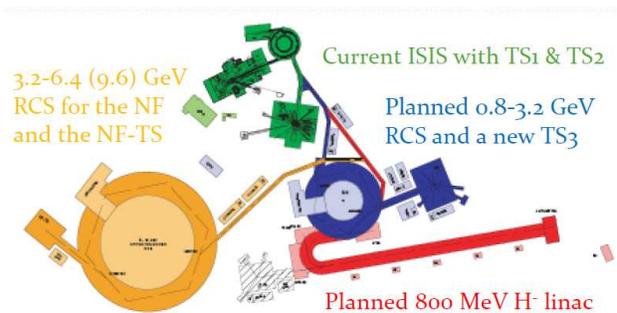
**Figure 2.** Bunches accumulation and compression in the CERN accumulation and compression rings.

### 3.3. RAL scenario and the upgrade to ISIS

The third option consists of an upgrade of the Rutherford Appleton Laboratory (RAL), neutron spallation source ISIS, to provide beam powers of 2-5 MW in the few GeV energy range. The facility could be shared between a short pulse spallation neutron source and the Neutrino Factory. A layout of the proposed accelerator complex is shown in Figure 4. It would require an additional Rapid Cycling Synchrotron (RCS) or a Fixed Field Alternating Gradient (FFAG) booster in order to bring the proton beam to the necessary energy and perform the appropriate bunch compression. Several studies are underway, including a high-intensity  $\sim 3.3$  GeV booster synchrotron and beam lines, a 800 MeV high-intensity linac and the RCS and FFAG options for the main ring accelerator. The study of a high-power Front End Test Stand (FETS), RF systems, stripping foils options, diagnostics and kickers will be addressed in future R&D experiments.



**Figure 3.** Project X layout.



**Figure 4.** RAL accelerator complex layout.

## 4. Target system

### 4.1. Hg-jet target developments

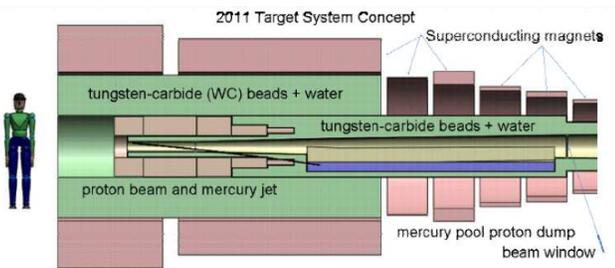
The Neutrino Factory baseline target is made of a Hg-jet target surrounded by a solenoid field of 20 T followed by an adiabatic taper to 1.5 T, to allow for optimal secondaries capture. Previous

simulations using MARS 15 [6] and FLUKA [7] showed high levels of energy deposition in the magnets, requiring the shielding to dissipate about 2.4 MW. Also the Hg-jet and proton beam are sent to a Hg pool and disrupting it, showing the need for a study of splash mitigation. During a redesign campaign [8] a better shielding of the Super Conducting (SC) magnets from radiation was identified. Splash mitigation options are under study [9] and the design of the mechanical support has been improved. The layout of the new target design is shown in Figure 5. The R&D experiment MERIT [10] whose analysis of data was completed in 2007, validated 4 MW proton beam operation in mercury. Further work on the target station infrastructure, including outer shielding, remote handling, mercury cooling loop, the design of the beam windows and the beam dump are required.

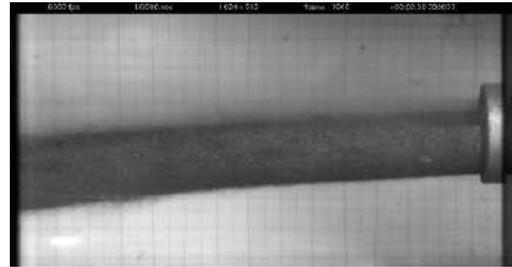
#### 4.2. Alternative/mitigation options

A few alternative target systems [11] are under consideration, made either of a metal-powder jet or a system of solid tungsten bars that would be exchanged between pulses.

A test rig has been built at RAL where 100 kg of W powder with grain size  $< 250 \mu\text{m}$  could be operated continuously for about 20 min. A coherent free flow jet at  $P \sim 2$  bars was produced and the results were validated with simulations. A photograph of the jet is shown in Figure 6. For the solid target options, shock studies were performed using high-currents in thin W and Ta



**Figure 5.** Hg-jet target system layout.



**Figure 6.** Photograph of the W powder jet.

wires. The results obtained are in agreement with LS-DYNA [12] simulations. The preliminary design for the target change system is underway.

Future R&D will include the study of flow improvement by mitigation of the flux breakdown or phase separation for the powder target. An irradiation experiment of tungsten powder and tungsten pebble bed will be performed at the CERN HiRadMat facility [13].

## 5. Front-end system

The front-end system is located after the target system. It comprises a buncher, a rotator and a cooling sections.

### 5.1. Front-end status

The baseline lattice described in the IDR has undergone an optimization study [14] identifying possible options to get rid of the unwanted particles in the accelerator, as early as possible. A proton absorber is under consideration in order to remove the low-momentum protons. The design of a chicane (see Figure 7) is underway to remove the high-momentum particles. Finally a transverse collimation system will take care of the remaining particles.

The reference lattice parameters have started to be listed in order to provide a detailed engineering study, where possible, and provide an accurate costing.

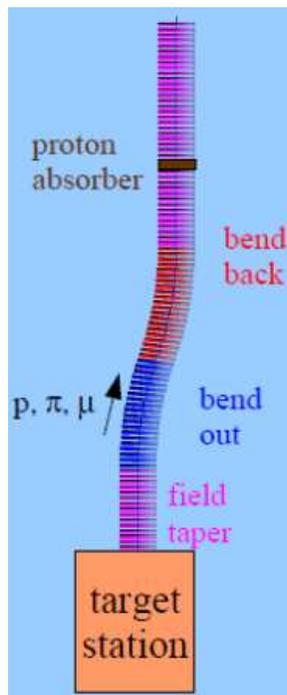
A realistic operational RF gradient limit has still to be determined and future R&D experiments

[15] will be performed at the Fermilab Muon Testing area (MTA). There is also a need to assess in details, and mitigate, the energy deposition from particle losses. An optimization of the lattice matching sections need also to be done. Finally a complete engineering design for the magnets, RF and absorbers is required.

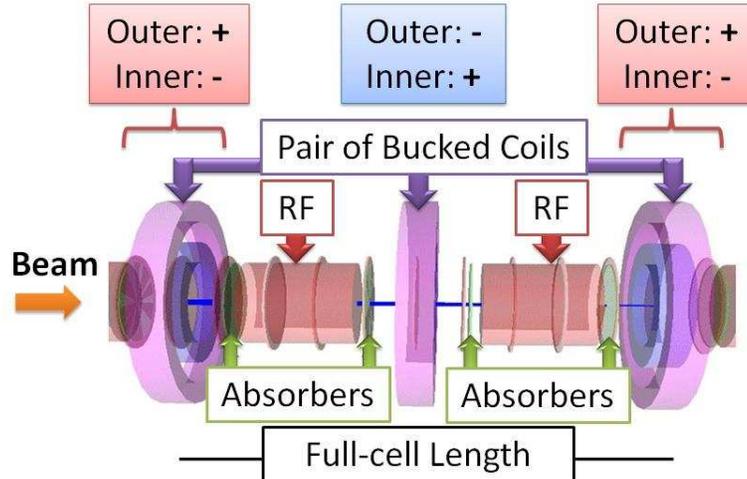
### 5.2. Alternative/mitigation cooling options

Efficient bunching/rotation and cooling of the muons beam requires high (9-16 MV/m) RF cavity gradients in high (1-3 T) magnetic fields. This increases the risk of breakdown as suggested by experiments performed at the MTA. Three scenarios are under study, as alternative to the breakdown problem. A bucked coil lattice, a magnetically insulated lattice and a high-pressure gas RF (HPRF) lattice.

The bucked coil lattice provides a reduced magnetic field in the RF. It is made of 1.8 or 2.1 m long cells (see Figure 8). Three different solenoid current configurations for two cooling cells



**Figure 7.** Layout of the front-end chicane and proton absorber.



**Figure 8.** Schematic of a pair of bucked coils and RF cavities.

were simulated in G4MICE [17]. These configurations have been tested with both a reduced ( $\sim 1000$  muons) and full statistics. This lattice shows a good transmission in comparison with the ISS lattice.

The magnetically insulated lattice [18] has a configuration where the electric field is perpendicular to the magnetic field in the cavity. Simulations results are giving similar performance to the ISS lattice. In addition the behavior of a pillbox cavity in presence of electric field having a small angle with the magnetic field was tested at the MTA. The drawback of such a design is that the tolerance to coils misalignment is reduced to below 2 mm. Additional issues such as multipactoring and power consumption have still to be addressed.

The HPRF lattice comprises a cavity filled with high-pressure  $H_2$  gas [19]. LiH absorber disks will be used on the windows as in the IDR configuration to provide muons cooling. Studies of windows

material and windows thickness for different pressure configuration have been performed. In addition, tests with a gas-filled cavity were done at the MTA.

## 6. Muon acceleration

The acceleration system [20] is made of a linac for low-energies (below 0.9 GeV), followed by two Recirculating Linac Accelerators (RLA's) allowing multiple passes (to 12.6 GeV). Final acceleration to 25 GeV is provided by a FFAG (see Figure 9).

### 6.1. Linac and RLA's

The linac is made of short (3 m, 3.8 MV/m), medium (5 m, 5.1 MV/m) and long (8 m, 6.4 MV/m) cells containing SC RF cavities. Focusing is provided with solenoids which are better for low-energy and large-emittance beams. As the beam goes in the linac, the acceleration is increased by moving the RF phase toward the crest.

The RLA's have a dogbone shape providing greater separation at the switchyard (over a racetrack shape). They are made of SC RF and quadrupoles. The beam injection is done at the center of the linac. The muons are going for 4.5 passes per linac before beam extraction.

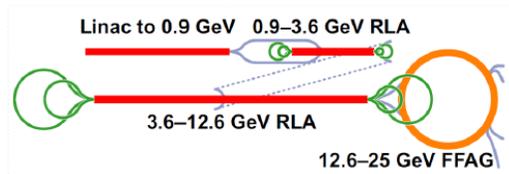
The validation of the switchyard design for the RLA's needs to be completed, as well as the lattice design, including the matching sections, injection system and the overall layout. A tracking through all the subsystems with realistic errors needs to be performed. The engineering design for all the components (including magnets and RF) needs also to be completed.

### 6.2. FFAG rings

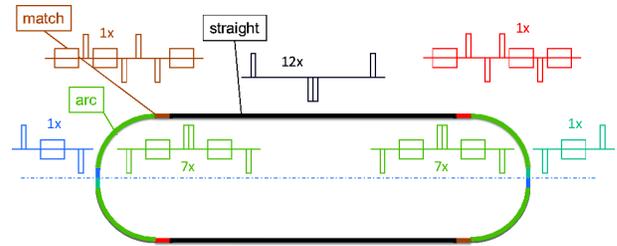
The FFAG system [21] is a linear non-scaling ring made of a single arc with a large energy acceptance. It consists of identical FDF triplets. Almost all drifts contain SC cavities or injection/extraction hardware. For the injection and the extraction, the kickers are shared for both muons signs. The injection is made from inside and the extraction to outside. The magnet apertures are slightly bigger in the injection and extraction regions. The remaining tasks are to finalize the chromatic correction scheme, determine the optimal longitudinal phase space matching, design the matching to upstream and downstream systems. In addition a complete 6D tracking with errors need to be performed. A complete design for the main components (magnets, RF, injection and extraction) will also be provided. Finally a cost comparison with an equivalent RLA solution has to be done.

### 6.3. Decay rings

As the goal of the Neutrino Factory is to measure all together  $\delta$  the CP violation phase,  $\theta_{13}$  and the neutrino mass hierarchy, two distinct baselines working in combination would permit an optimum measurements of these parameters. At a so-called "magic" [23] distance of 7500 km, the matter effects cancel out the CP-violation effects allowing a clean measurement of  $\theta_{13}$  and the sign of  $\Delta m_{31}^2$  with the help of a 50 kT fiducial mass Magnetised Iron Neutrino Detector (MIND) [22]. In combination with the magic baseline, a second baseline set at 4000 km, allows the measurement of  $\delta$  with a 100 kT fiducial mass detector based on the MIND technology. The Neutrino Factory contains two racetrack shaped rings (see Figure 10), one per detector. Three trains of 50 bunches at 25 GeV enter the rings. The muons decay in the straight section which represents a large fraction of the total circumference. Both muons signs are stored simultaneously. The beam divergence from the lattice is at most  $0.1/\gamma$ . The rings circumference is 1609 m with 599 m-long (not including the matching cells) straight sections. The rings tilt angles are large,  $36^\circ$  for the detector located at 7500 km and  $18^\circ$  for the detector located at 4000 km. This places the decay ring tunnels lower points at a depth of 445 m and 234 m respectively. The  $\beta$  of the beam is 150 m in the straights and 13 m in the arcs.



**Figure 9.** Layout of the muon acceleration systems linac and RLA's.



**Figure 10.** Layout of the muon decay ring.

Beam diagnostics [24] are necessary and the use of a polarimeter to measure the decay electrons is under consideration. It is based on measurements of the g-2 muon spin precession. It can also measure precisely the beam energy and the energy spread.

Measurements of the beam divergence can be provided by in-beam devices. Two options are under consideration, a cherenkov He-gas detector and an optical transition radiation (OTR) device. It still has to be demonstrated if the desired precision level can be reached by these devices, as the natural beam divergence is 4 mrad.

The remaining tasks include the design of the injection system, to assess the need for chromatic corrections and a beam abort scheme. The design of the diagnostics and the identification of their specifications has to be completed. Means to measure the neutrino flux spectrum at the far detectors will also have to be identified.

## 7. Conclusion: from the IDR to the RDR

The European Committee for Future Accelerator (ECFA) Review Panel was mandated to review the EUROnu mid-term report and the IDS-NF IDR in May 2011. The remaining steps toward the RDR include the development of a complete and technically feasible design with the required performance. An end-to-end tracking of the entire facility has been carried out to validate the performance estimate. A cost estimate of the whole facility has to be performed. After completion of these steps the reference design will be published in the RDR.

## Acknowledgments

We acknowledge the financial support of the European Community under the European Commission Framework Programme 7 Design Study: EUROnu, Project Number 212372. The EC is not liable for any use that may be made of the information contained herein.

## References

- [1] Choubey S *et al.* (The IDS-NF collaboration) 2011 *Interim Design Report* IDS-NF-020
- [2] Berg J S *et al.* (The ISS Accelerator Working Group) 2007 *Accelerator design concept for future neutrino facilities* RAL-TR-2007-23
- [3] Shiltsev V *Toward a Muon Collider* these proceedings
- [4] Garoby R *Proton drivers for Neutrino beams and other high-intensity applications* these proceedings
- [5] Schmidt F 2002 *MADX user's guide* CERN-T5001
- [6] Mokhov N and Striganov S I 2007 *MARS15 Overview* Fermilab-Conf-07-008-AD
- [7] Battistoni G *et al.* 2007 *The FLUKA code: description and benchmarking* AIP Proc. Conf. 896 31
- [8] McDonald K *Simulation of dynamic interaction of the Neutrino Factory mercury jet with the mercury collection pool/beam dump* these proceedings
- [9] McDonald K *Multi-MW target and capture design for NF* these proceedings
- [10] McDonald K *et al.* 2009 *The MERIT high-power target experiment at the CERN PS* IPAC10 Conf. Proc. WEPE078
- [11] Densham C *Target option for NF* these proceedings

- [12] LS-DYNA <http://www.lstc.com/>
- [13] Efthymiopoulos I *et al.* *Feasibility experiment of granular target options for future neutrino facilities* these proceedings
- [14] Neuffer D *Neutrino factory front-end and extensions* these proceedings
- [15] Yonehara K *Commissioning and status of the MTA* these proceedings
- [16] Alekou A *Performance comparison between FSIIA and bucked coils for the Neutrino Factory cooling* these proceedings
- [17] G4MICE <http://www.mice.iit.edu/software/>
- [18] Stratakis D *et al.* 2011 *Numerical study of a magnetically insulated front-end channel for a neutrino factory* PRSTAB 14 011001
- [19] Zisman M *Accelerators for future neutrino facilities: strength and challenges* these proceedings
- [20] Beard K *Linac & RLA design status and simulations* these proceedings
- [21] Pasternak J *Recent development on the muon non-scaling FFAG for the Neutrino Factory and its subsystems* these proceedings
- [22] Abe T *et al.* *Preprint* arXiv:0712.4129 [physics.ins-det]
- [23] Huber P and Winter W 2003 *Phys. Rev. D* **68** 037301
- [24] Blondel A *Neutrino flux monitoring in the Neutrino Factory* these proceedings