Neutrino Factory: specification of baseline
for the accelerator complex and detector systems

1. Introduction

The purpose of this document is to define the baseline for the Neutrino Factory accelerator complex and the detector systems adopted by the International Design Study of the Neutrino Factory (the IDS-NF). The baseline specification will be re-issued from time to time by the IDS-NF Steering Group to reflect improvements made in the course of the IDS-NF. In this, the first definition of the IDS-NF baseline, the baseline developed through the International Scoping Study of a future Neutrino Factory and super-beam facility (the ISS) [1] is adopted. The performance of the facility defined in sections 2 and 3 below is presented in section 4.

1.1 Baseline numbering convention

The various iterations of the IDS-NF baseline will be identified by a version number. The version number will be YYYY/P.s where: YYYY is the year in which the baseline was derived; P is the 'principal version number; and s is the subsidiary version number. A number of parameters are defined below as 'principal interface' parameters. Changes in principal interface parameters directly affect the physics performance of the facility and will trigger a change in the principal version number. Examples of principal interface parameters include the stored muon-beam energy and the fiducial mass of the detector. When the value of a parameter that affects the specification of a sub-system (the proton driver, for example) is changed without affecting any of the principal interface parameters, a change in the subsidiary version number will be triggered.

A change in the IDS-NF baseline version number requires the agreement of the IDS-NF steering group. It is anticipated that changes in the version of the baseline will be made in response to a request from one or more of the working groups. The reasons for the change and the performance implications must be fully documented. Each new version of the baseline will be documented in a baseline specification document.

2. The Neutrino Factory accelerator complex

The specification for the accelerator systems developed by the Accelerator Working Group of the ISS is described in [2]. A schematic diagram of the ISS baseline is shown in figure 1 and the parameters of the various sub-systems are defined in table 1. The principal interface parameters are highlighted and shown in bold face. The baseline for the stored muon energy is 25 GeV and the facility will deliver a total of 10^{21} useful muon decays per year. The baseline for the storage rings is that both signs of muon are stored at the same time. Note that the neutrino-production rates will vary slighting (~±10%) depending on details of the accelerator complex. The fluxes quoted are those used in the performance evaluation in section 4.

The baseline pion-production target is based on a liquid-mercury jet. This implies a 3 proton-driver bunches per bunch train. The baseline target choice, and the consequences to the proton-driver bunch structure will be reviewed by (or at) NuFact08.

Prepared by the IDS-NF Steering Group

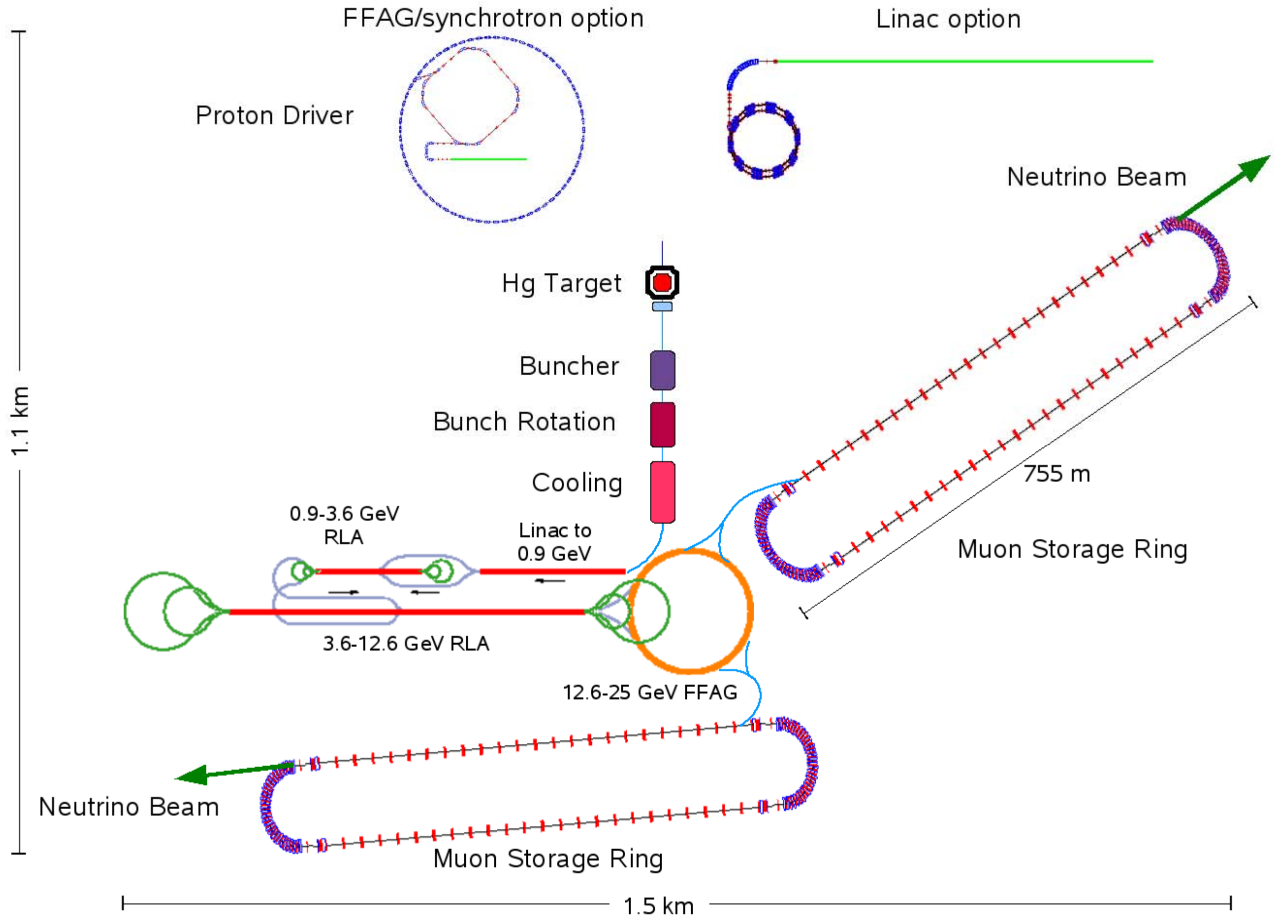

Figure 1: Schematic drawing of the ISS baseline for the Neutrino Factory accelerator complex. The various systems have been drawn to scale.

3. The Neutrino Factory long-baseline neutrino detectors

The baseline for the long-baseline neutrino detectors is the Magnetised Iron Neutrino Detector (MIND) described in [3]. A detector with a fiducial mass of 50 kTonne is located at an intermediate baseline (3,000—5,000 km) and a second detector of fiducial mass 50 kTonne is located at a long baseline (7,000—8,000 km). The detector is optimised for the search for leptonic-CP violation, the determination of the mass hierarchy, and the measurement of θ_{13} through the detection of the 'golden channel' ($\nu_e \rightarrow \nu_\mu$). The ISS baseline includes a Magetised Emulsion Cloud Chamber (MECC, 10 kTonne fiducial mass) for the detection of the 'silver channel' (ν_τ appearance). The silver channel is important in the search for effects beyond the 'Standard Neutrino Model' (SvM). The baseline does not presently include a 'platinum-channel' ($\nu_\mu \rightarrow \nu_e$) detector.

Figure 2 shows a schematic diagram of the MIND and MECC detectors. Table 2 lists the key parameters of the two detectors. The muon-identification efficiency for MIND is shown in figure 3. The energy resolution of MIND was evaluated in [3]. The performance of the baseline Neutrino Factory presented in section 4 has been obtained by taking the neutrino energy resolution to be $55\%/\sqrt{E_\nu}$, where E_ν is the neutrino energy. The systematic uncertainty on the size of the signal and background samples assumed is 2.5% and 20% respectively. These uncertainties are assumed to be uncorrelated between the neutrino and anti-neutrino running and the appearance and the disappearance channels. The efficiency for the detection of golden-channel muons and the fraction of the total number of events contributed by the various background processes in MIND are shown as a function of energy in table 3. The efficiencies (ε_i) in table 3 have been obtained by evaluating:

$$\varepsilon_i = \frac{\text{Events satisfying selectrion criteria with visible energy in bin } i}{\text{Total number of events with visible energy in bin } i}, \qquad (1)$$

where the selection criteria are described in [2]. For the ν_μ-disappearance channel, an efficiency of 0.9 has been assumed from 1 GeV onwards. The charge-misidentification background has not been taken into account. The performance of the MECC is taken to be that quoted by the OPERA collaboration and the Donini et al. papers [4].

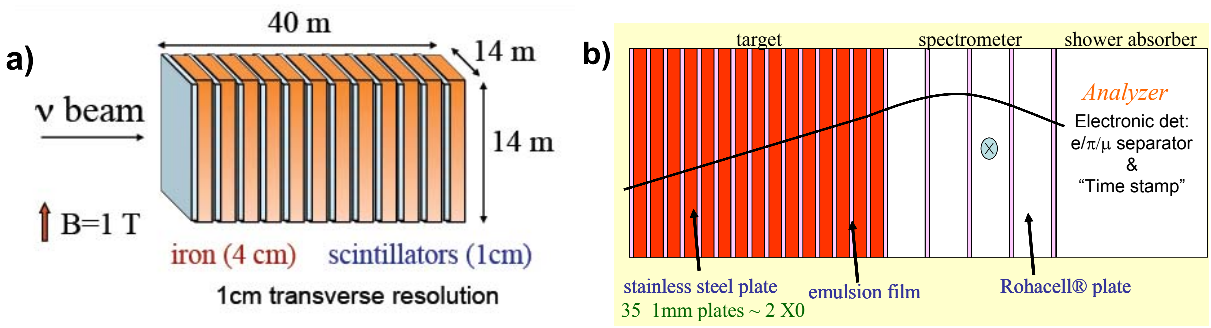

Figure 2: Schematic diagrams of the baseline MIND (a) and MECC (b) detectors.

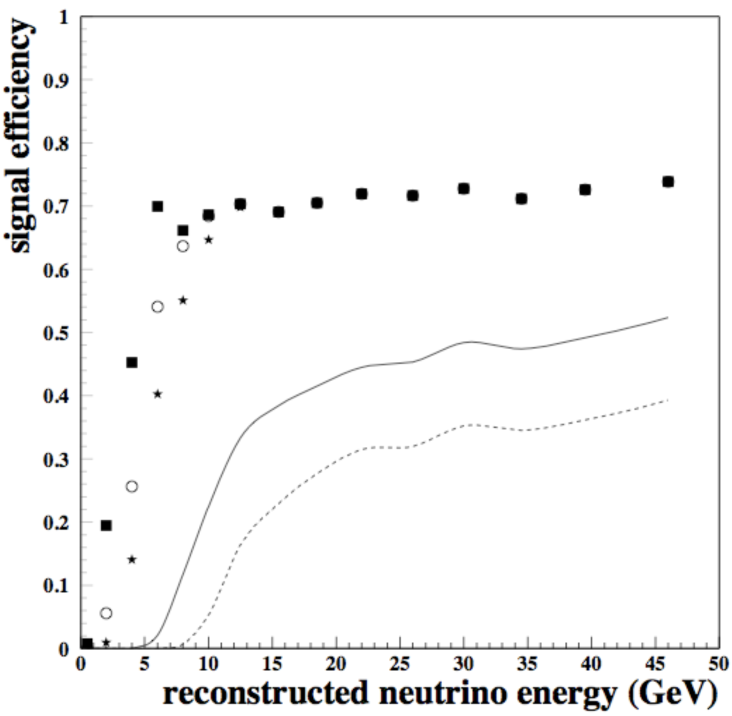

Figure 3: Muon identification efficiency for MIND. The points indicate the efficiency assuming a minimum muon-track-length cut of 75 cm (solid squares), 150 cm (open circles), and 200 cm (stars). The cut used in the baseline analysis (table 3) is 150 cm.

4. Performance of the baseline Neutrino Factory

To evaluate the discovery reach of the Neutrino Factory with the performance defined in sections 2 and 3, the following oscillation parameters have been assumed:

$$\Delta m_{21}^2 = +8\times 10^{-5}\ \text{eV}^2;\quad \Delta m_{31}^2 = +2.5\times 10^{-3}\ \text{eV}^2;\quad \theta_{23} = \frac{\pi}{4};\quad \sin^2\theta_{12} = 0.3;. \qquad (2)$$

In addition, the reference plots presented below correspond to two baselines of 4000 km and 7500 km and a total running time of 10 years. It is assumed that Δm_{31}^2 and θ_{23} are known with an uncertainty of 10% and that Δm_{21}^2 and $\sin^2\theta_{12}$ are known with an uncertainty of 4%. The matter-density uncertainty is assumed to be 2% and to be uncorrelated between the two baselines and to be fully correlated for the two detectors at 4000 km. The sensitivities were evaluated using GLoBES [5].

Figure 4 shows the discovery reach of the facility in $\sin^2 2\theta_{13}$. The figure shows the fraction of all possible values of the true value of the CP phase δ ('CP fraction') for which $\sin^2 2\theta_{13} = 0$ can be excluded at the 3σ confidence level (i.e. a $\Delta\chi^2$ of 9) as a function of the true value of $\sin^2 2\theta_{13}$. Figures 5 and 6 show the discovery reach in $\text{sgn}(\Delta m_{31}^2)$ and δ respectively. The shaded region shows the fraction of all possible values of δ for which $\text{sgn}(\Delta m_{31}^2)$ can be excluded or $\delta = 0$ (or π) can be excluded at 3σ.

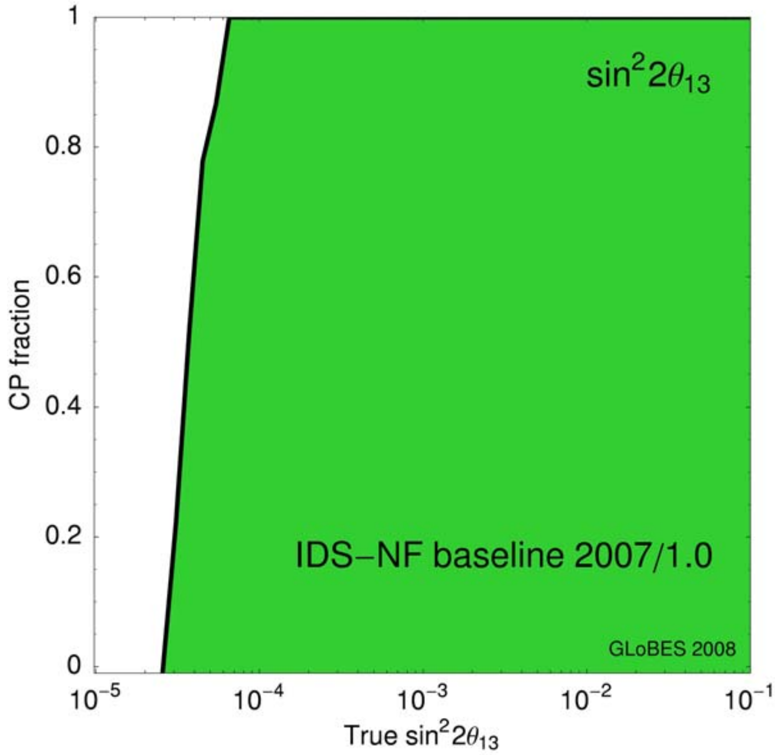

Figure 4: The discovery reach Neutrino Factory defined in sections 2 and 3 in $\sin^2 2\theta_{13}$. In the area to the right of the band, $\sin^2 2\theta_{13} = 0$ can be excluded at the 3σ confidence level. The discovery limit is shown as a function of the fraction of all possible values of the true value of the CP phase δ ('CP fraction') and the true value of $\sin^2 2\theta_{13}$.

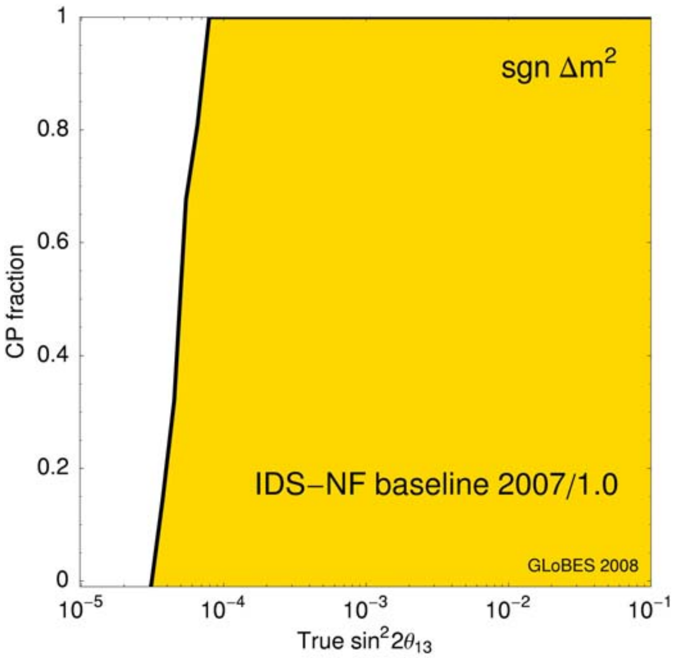

Figure 5: The discovery reach Neutrino Factory defined in sections 2 and 3 in $\mathrm{sgn}\left(\Delta m_{31}^2\right)$*. In the area to the right of the band,* $\mathrm{sgn}\left(\Delta m_{31}^2\right)$ *can be established at the* 3σ *confidence level. The discovery limit is shown as a function of the fraction of all possible values of the true value of the CP phase* δ *('CP fraction') and the true value of* $\sin^2 2\theta_{13}$*.*

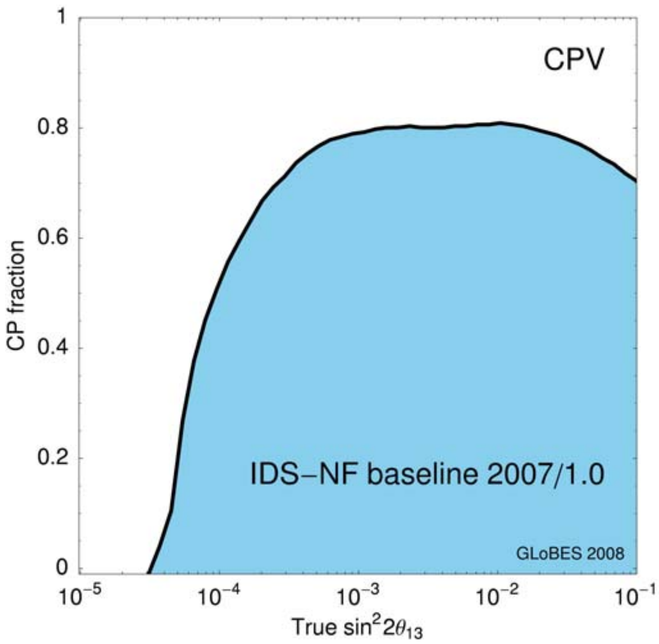

Figure 6: The discovery reach Neutrino Factory defined in sections 2 and 3 in δ*. In the area to the right of the band,* $\delta = 0$ *can be excluded at the* 3σ *confidence level. The discovery limit is shown as a function of the fraction of all possible values of the true value of the CP phase* δ *('CP fraction') and the true value of* $\sin^2 2\theta_{13}$*.*

Table 1: Parameters specifying baseline parameters for the sub-systems that make up the Neutrino Factory accelerator complex. The principal interface parameters are highlighted and shown in bold face.

Baseline specification for the Neutrino Factory accelerator complex			**Version**
Sub-system	**Parameter**	**Value**	**2007/1.0**
Proton driver	Average beam power (MW)	4	
	Pulse repetition frequency (Hz)	50	
	Proton kinetic energy (GeV)	10 ± 5	
	Proton rms bunch length (ns)	2 ± 1	
	Number of proton bunches per pulse	3	
	Sequential extraction delay (μs)	≥ 17	
	Pulse duration, liquid-Hg target (μs)	≤ 40	
Target: liquid-mercury jet	Jet diameter (cm)	1	
	Jet velocity (m/s)	20	
	Solenoidal field at interaction point (T)	20	
Pion collection			
Tapered solenoidal channel	Length (m)	12	
	Field at target (T)	20	
	Diameter at target (cm)	15	
	Field at exit (T)`	1.75	
	Diameter at exit (cm)	25	
Decay channel	Length (m)	100	
Adiabatic buncher	Length (m)	50	
Phase rotator	Length (m)	50	
	Energy spread at exit (%)	10.5	
Ionisation cooling channel	Length (m)	80	
	RF frequency (MHz)	201.25	
	Absorber material	LiH	
	Absorber thickness (cm)	1	
	Input emittance (mm rad)	17	
	Output emittance (mm rad)	7.4	
	Central momentum (MeV/c)	220	
	Solenoidal focussing field (T)	2.8	
Acceleration system	Total energy at input (MeV)	244	
	Total energy at end of acceleration (GeV)	25	
	Input transverse acceptance (mm rad)	30	
	Input longitudinal acceptance (mm rad)	150	
Pre-acceleration linac	Final total energy (GeV)	0.9	
RLA(1)	Final total energy (GeV)	3.6	
RLA(2)	Final total energy (GeV)	12.6	
NFFAG	Final total energy (GeV)	25	
Decay rings	Ring type	Race track	
	Straight-section length (m)	600.2	
	Race-track circumference (m)	1,608.80	
	Number of rings (number of baselines)	**2**	
	Stored muon energy (total energy, GeV)	**25**	
	Beam divergence in production straight (γ^{-1})	**0.1**	
	Bunch spacing (ns)	**≥ 100**	
	Number of $\mu^{\pm}$ decays per year per baseline	**5×10^{20}**	

Table 2: Parameters specifying the baseline for the long-baseline neutrino detectors. The principal interface parameters are highlighted and shown in bold face.

Baseline specification for the Neutrino Factory long-baseline neutrino detectors			**Version**
Sub-system	**Parameter**	**Value**	**2007/1.0**
Configuration	**Number of baselines**	**2**	
	Intermediate baseline (km)	3,000 to 5,000	
	Long baseline (km)	7,000 to 8,000	
	Detectors at intermediate baseline	MECC, MIND	
	Detector at long baseline	MIND	
MIND	**Fiducial mass (kTonne)**	**50**	
	Magnetic field (T)	1	
	Neutrino energy resolution ($GeV^{-0.5}$)	$55\%/E_\nu^{0.5}$	
Background fraction	Charged current (GeV^{-2})	See table 3	
	Neutral current (GeV^{-2})	See table 3	
Efficiency	ν_μ appearance: efficiency	See table 3	
	ν_μ disappearance: efficiency	0.9 (from 1 GeV)	
Systematic uncertainty	Uncertainty on number of events in signal sample	2.50%	
	Uncertainty on number of events in background sample	20%	
MECC	**Fiducial mass (kTonne)**	**10**	
	Magnetic field (T)	**1**	

Table 3: Detection efficiency for signal and the fraction contributed by the various background channels to the data sample recorded in the baseline MIND detector.

Golden-channel signal and background efficiencies for MIND											
Neutrino-energy bin (GeV)		**Signal**		**Charged current (ν_μ CC)**		**Neutral current (ν_μ NC)**		**Charm: (ν_μ CC)**		**Non-charm: (ν_μ CC)**	
Low edge	**High edge**	**Efficiency**	**Uncertainty**	**Efficiency**	**Uncertainty**	**Efficiency**	**Uncertainty**	**Efficiency**	**Uncertainty**	**Efficiency**	**Uncertainty**
0	1	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	3	0.056	0.007	0.00	0.00	6.71E-05	1.43E-05	0.00E+00	0.00E+00	2.59E-05	2.59E-05
3	5	0.256	0.012	1.28E-04	3.85E-05	1.68E-04	2.04E-05	1.28E-04	3.85E-05	3.48E-05	2.01E-05
5	7	0.541	0.019	3.22E-04	5.79E-05	2.23E-04	2.87E-05	3.22E-04	5.79E-05	1.04E-05	1.04E-05
7	9	0.637	0.021	3.26E-04	5.96E-05	1.45E-04	2.90E-05	3.26E-04	5.96E-05	0.00	0.00
9	11	0.684	0.022	3.69E-04	6.33E-05	7.83E-05	2.61E-05	3.69E-04	6.33E-05	0.00	0.00
11	14	0.703	0.018	1.73E-04	3.46E-05	1.21E-04	3.24E-05	1.73E-04	3.46E-05	0.00	0.00
14	17	0.691	0.018	1.18E-04	2.94E-05	1.56E-04	4.33E-05	1.18E-04	2.94E-05	0.00	0.00
17	20	0.705	0.018	2.07E-05	1.19E-05	6.70E-05	3.35E-05	2.07E-05	1.19E-05	0.00	0.00
20	24	0.719	0.016	2.65E-05	1.19E-05	1.71E-05	1.71E-05	2.65E-05	1.19E-05	0.00	0.00
24	28	0.717	0.016	1.04E-05	7.33E-06	0.00	0.00	1.04E-05	7.33E-06	0.00	0.00
28	32	0.727	0.016	5.04E-06	5.04E-06	0.00	0.00	5.04E-06	5.04E-06	0.00	0.00
32	37	0.711	0.014	1.24E-05	7.18E-06	0.00	0.00	1.24E-05	7.18E-06	0.00	0.00
37	42	0.726	0.015	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
42	50	0.739	0.013	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

References

1. http://www.hep.ph.ic.ac.uk/iss/
2. The ISS Accelerator Working Group, 'Summary Report of Accelerator Working Group', http://www.cap.bnl.gov/mumu/project/ISS/ISS-AcceleratorWG-R5.pdf , RAL-TR-2007-23
3. The ISS Detector Working Group, 'Summary Report of the Detector Working Group', http://ppewww.physics.gla.ac.uk/~psoler/iss_det_report_main.pdf, arXiv: 0712.4129
4. OPERA Collaboration, K. Kodama et al., "A long baseline nu/tau appearance experiment in the CNGS beam from CERN to Gran Sasso. Progress report."; CERN-SPSC-99-20;

A. Donini, M. B. Gavela, P. Hernandez, and S. Rigolin, “Neutrino mixing and CP-violation,” Nucl. Phys. B574 (2000) 23–42, hep-ph/9909254;

D. Autiero et al., “The synergy of the golden and silver channels at the Neutrino Factory,” Eur. Phys. J. C33 (2004) 243–260, hep-ph/0305185.

5. P. Huber, J. Kopp, M. Lindner, M. Rolinec, W. Winter, "New features in the simulation of neutrino oscillation experiments with GLoBES 3.0: General Long Baseline Experiment Simulator", Comput.Phys.Commun.177:432-438,2007;

P. Huber, M. Lindner, W. Winter, "Simulation of long-baseline neutrino oscillation experiments with GLoBES (General Long Baseline Experiment Simulator)", Comput.Phys.Commun.167:195,2005.

Appendix: Revision history:

25Jan08: Revision 3 – Final:

With the exception of the proton drive, all energies in table 1 are total energies; table updated. Total number of muon decays per year per baseline noted in table 1 rather. Caption of figure 3 corrected to note track length cut value of 150 cm. Specification of MIND fiducial mass in section 3 clarified. Value of Δm^2_{21} in section 4 corrected. Revision history moved to the end of the document. Definition of efficiency added in section 3. Added comment that all detector masses are fiducial masses. Typos corrected and defintion of mass hierarchy determination clarified. Additional citation added [5].

18Jan08: Typos corrected. Units corrected in table 1. Number of proton bunches per pulse set at 3 in table 1 (mercury target value from ISS report). Beam divergence and bunch spacing added in decay-ring section of table 1. Colour coding (shading) added to tables 1 and 2 to indicate ‘principal interface’ parameters. Changes in the principal interface parameters will trigger a change in the principal version number. Text defining version updating convention added.

17Jan08: IDS-NF baseline: 2007 1.00

Updated to reflect discussion during IDS-NF plenary meeting. The stored-muon energy and the total number of useful muon decays were added in section 2. The fiducial mass of the MECC detector was changed to 10 kTon, inline with the ISS Detector Group’s recommendation (section 3). In section 4, the reference values for the intermediate and far detector locations (4000 km and 7500 km) as well as the total running time (10 years) were noted.

14Jan08: IDS-NF baseline: 2007/0.10:

Adoption of the ISS baseline for accelerator complex and detector systems as IDS-NF baseline 2007/0.10, the first iteration of the baseline specification for the IDS-NF.