IDS-NF-Baseline-2007/1.00 17th January 2008

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

Revision history:

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 MTon, 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.

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 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.

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 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.

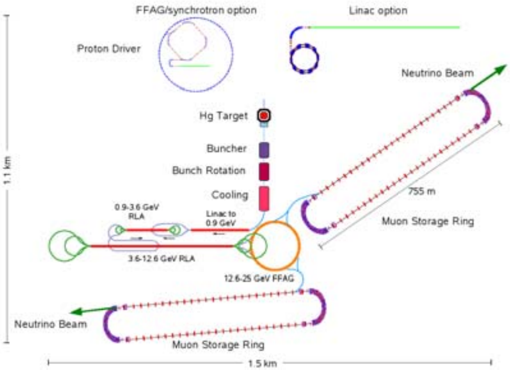

Figure 1: Schematic drawing of the ISS baseline for the Neutrino Factory accelerator complex. The various systems have been drawn to scale.

Table 1: Parameters specifying baseline parameters for the sub-systems that make up the Neutrino Factory accelerator complex.

Baseline specification for the Neutrino Factory accelerator complex

Sub-system	**Parameter**	**Value**
Proton driver	Average beam power (MW)	4
	Pulse repetition frequency (Hz)	50
	Proton energy (GeV)	10 ± 5
	Proton rms bunch length (ns)	2 ± 1
	No. of proton bunches	3 or 5
	Sequential extraction delay (μs)	≥ 17
	Pulse duration, liquid-Hg target	≤ 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	Input energy (MeV)	244
	Final energy (GeV)	25
	Input transverse acceptance (mm rad)	30
	Input longitudinal acceptance (mm rad)	150
Pre-acceleration linac	Final energy (GeV)	0.9
RLA(1)	Final energy (GeV)	3.6
RLA(2)	Final energy (GeV)	12.6
NFFAG	Final energy (GeV)	25
Decay rings	Ring type	Race track
	Number of rings (number of baselines)	2
	Straight-section length (m)	600.2
	Race-track circumference (m)	1,608.80
	Number of μ^- decays per year per baseline	2.5×10^{20}
	Number of μ^+ decays per year per baseline	2.5×10^{20}

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]. The total detector mass (100 kTonne) is split equally between two detectors; one located at an intermediate baseline (3,000—5,000 km) and one 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, 15 kTonne) 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' (SνM). 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 various background processes in MIND are shown as a function of energy in table 3. 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].

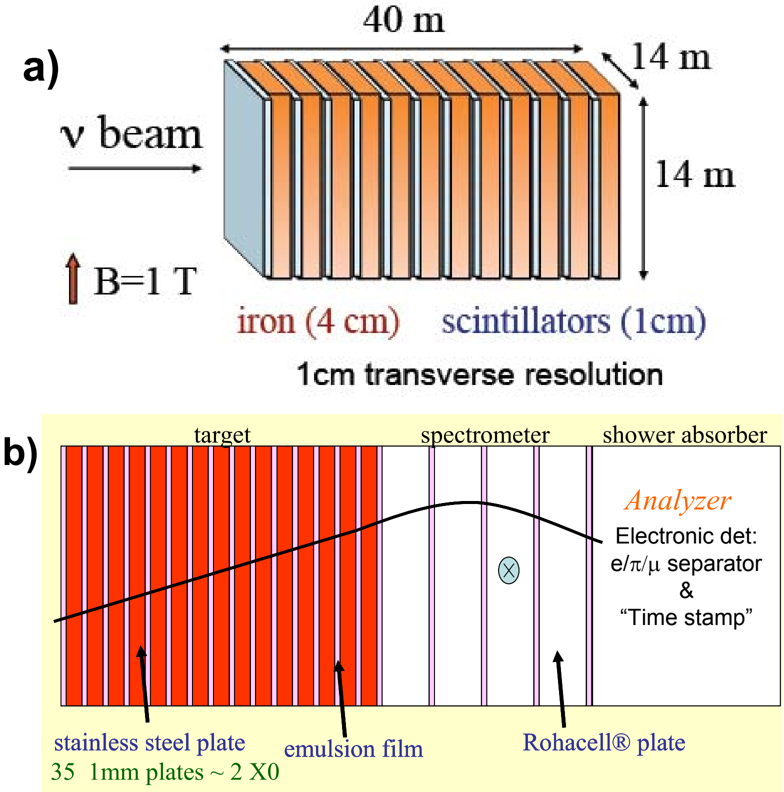

Figure 2: Schematic diagrams of the baseline MIND (a) and MECC (b) detectors.

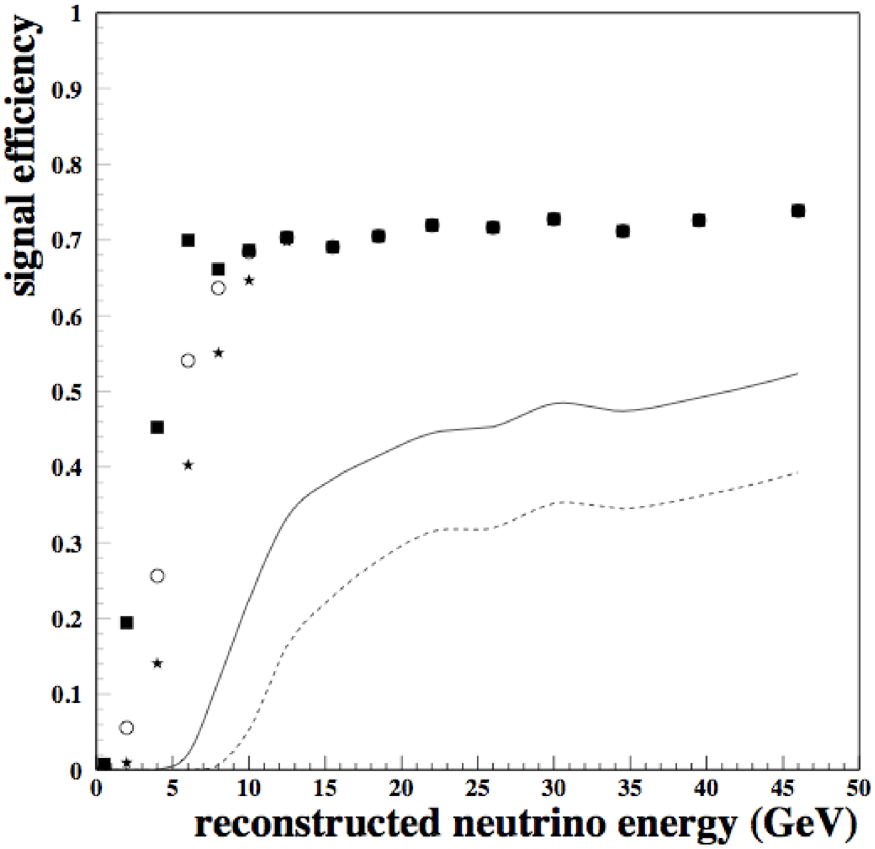

Figure 3: Muon identification efficiency for MIND. The points indicate the efficiency assuming a minimum muon-track-length cut of 75 cm (solid squares), 150 cm (open circles), and 200 cm (stars). The cut used in the baseline analysis (table 3) is 75 cm.

Table 2: Parameters specifying the baseline for the long-baseline neutrino detectors.

Baseline specification for the Neutrino Factory long-baseline neutrino detectors		
Sub-system	**Parameter**	**Value**
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})	0.001/E_ν^{2}
	Neutral current (GeV^{-2})	0.001/E_ν^{2}
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 background channels 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

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:

$$\Delta m_{21}^2 = +8\times10^{-4}\ \mathrm{eV}^2;\quad \Delta m_{31}^2 = +2.5\times10^{-3}\ \mathrm{eV}^2;\quad \theta_{23} = \frac{\pi}{4};\quad \sin^2\theta_{12} = 0.3;. \qquad (1)$$

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.

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 as a function of the true value of $\sin^2 2\theta_{13}$. Figures 5 and 6 show the discovery reach in $\mathrm{sgn}(\Delta m_{31}^2)$ and δ respectively. The shaded region shows the fraction of all possible values of δ for which $\mathrm{sgn}(\Delta m_{31}^2)$ can be determined or $\delta = 0$ (or π) excluded at 3σ.

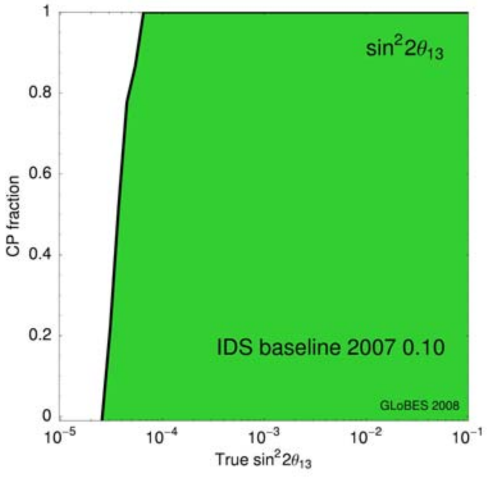

Figure 4: The discovery reach Neutrino Factory defined in sections 2 and 3 in $\sin^2 2\theta_{13}$. In the area to the right of the band, $\sin^2 2\theta_{13} = 0$ can be excluded at the

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 $\sin^2 2\theta_{13}$.

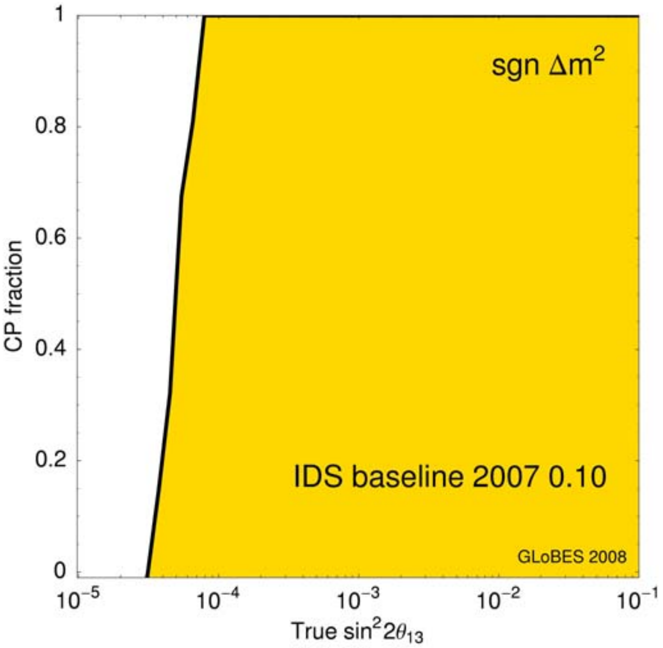

Figure 5: The discovery reach Neutrino Factory defined in sections 2 and 3 in $\text{sgn}\left(\Delta m_{31}^2\right)$. In the area to the right of the band, $\text{sgn}\left(\Delta m_{31}^2\right)$ can be established at the 3σ confidence level. The discovery limit is shown as a function of the fraction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

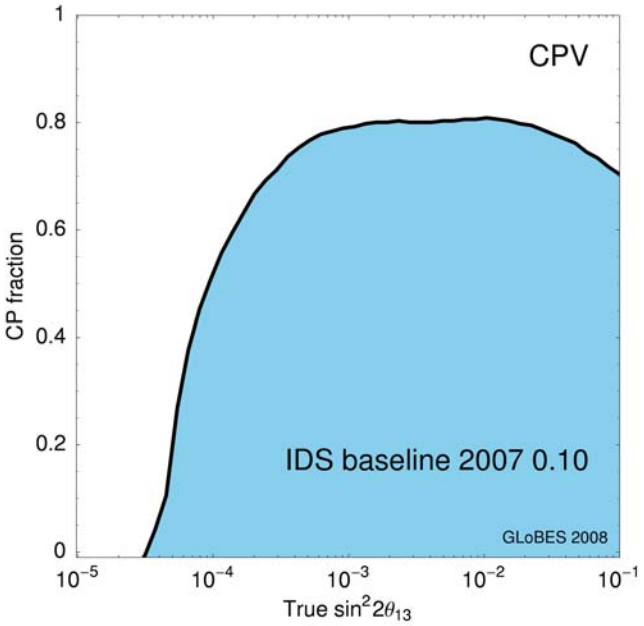

Figure 6: The discovery reach Neutrino Factory defined in sections 2 and 3 in δ. In the area to the right of the band, $\delta = 0$ can be excluded at the 3σ confidence level.

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* $\sin^2 2\theta_{13}$.

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.