The MINOS Detectors Design Parameter Book

Version 1.3

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The MINOS Collaboration

Overview parameters

LE = low energy beam (baseline), ME = medium energy beam, HE = high energy beam

Measurement	Sensitivity (90% CL)
$\nu_\mu \to \nu_\tau$ limit, high Δm^2, HE	$\sin^2(2\theta) > 2.5 \times 10^{-2}$ (NC/CC test)
$\nu_\mu \to \nu_\tau$ limit, high Δm^2, LE	$\sin^2(2\theta) > 0.1$ (NC/CC test)
$\nu_\mu \to \nu_\tau$ limit, $\sin^2(2\theta) = 1$, LE	$\Delta m^2 > 7.2 \times 10^{-4}$ eV^2 (CC energy)
$\nu_\mu \to \nu_e$ limit, $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2, LE	$U_{e3} > 8.7 \times 10^{-3}$ (ν_e appearance)
$\nu_\mu \to \nu_e$ limit, $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2, ME	$U_{e3} > 7.6 \times 10^{-3}$ (ν_e appearance)
$\nu_\mu \to \nu_\tau$ limit, high Δm^2, HE	$\sin^2(2\theta) > 0.14$ ($\tau \to \pi$ appearance)
Δm^2 measurement precision, LE	3×10^{-4} eV^2 for $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2
$\sin^2(2\theta)$ measurement precision, LE	1×10^{-1} eV^2 for $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2
Limit on admixture of $\nu_\mu \to \nu_s$, LE	$\sin^2(2\theta) < 0.16$ for $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2

Table 1: MINOS physics goals. The baseline detector will achieve these sensitivities in a two year run with 3.7×10^{20} proton per year on target. A beam optimized for lower energy neutrinos extends these sensitivities to lower values of Δm^2. If oscillations are not found, the 90% confidence level limits shown will be achieved. If oscillations are observed with $\Delta m^2 = 10^{-2}$ eV^2, the parameters and modes will be determined with the indicated precisions.

Overview parameters

Parameter	Value
Near detector mass	0.98 (metric) kt total, 0.1 kt fiducial
Far detector mass (2 supermodules)	5.4 (metric) kt total, 3.3 kt fiducial
Steel planes (far detector)	8-m wide, 2.54-cm thick octagons
Magnetic field (far detector)	Toroidal, 1.3 T at 2 m radius
Active detector planes	Extruded polystyrene scintillator strips
Active detector strips	4.1-cm wide, 1-cm thick, ~8-m long
Near detector distance from decay pipe	317 m
Far detector distance from decay pipe	730 km
Cosmic ray rates	270 Hz in near det., 1 Hz in far det.
Neutrino energy range (3 configurations)	1 to 25 GeV
Detector energy scale calibration	5% absolute, 2% near-far
Detector EM energy resolution	$23\%/\sqrt{E}$ (<5% constant term)
Detector hadron energy resolution	$55\%/\sqrt{E}$ (<7% constant term)
Detector muon energy resolution	<12% (from curvature or range)
NC-CC event separation	Efficiency >85%, correctable to 99.5%
Electron/π separation	Hadron rejection $\sim 10^2$ for ϵ_e ~20%
Far det. ν event rate (low-energy beam)	500 ν_μ CC events/kt/yr (no oscillations)
Near det. ν event rate (low-energy beam)	3 events/spill in target region
Far det. ν event rate (high-energy beam)	3000 ν_μ CC events/kt/yr (no oscillations)
Near det. ν event rate (high-energy beam)	20 events/spill in target region
Near-far relative rate uncertainty	2%

Table 2: MINOS experimental parameters (One year running is assumed to give 3.7×10^{20} proton on target.)

Magnet steel and coils

Property	Specification
Tensile strength:	
Ultimate tensile strength	40,000 psi minimum
Yield strength	20,000 psi minimum
Elongation of 2 inches	22% minimum
Chemical composition (% by weight):	
Carbon	0.04% to 0.06%
Manganese	0.40% (max.)
Silicon	0.40% (max.)
Sulfur	0.01% (max.)
Phosphorous	0.07% (max.)
Nitrogen	0.008% (max.)
Aluminum	0.05% (max.)
Chromium	0.05% (max.)
Copper	0.06% (max.)
Nickel	0.06% (max.)
Molybdenum	0.01% (max.)
Vanadium	0.01% (max.)
Niobium	0.01% (max.)

Table 3: Mechanical and chemical specifications for MINOS steel plate material. The chemical composition specifications also include upper limits on the content of possible contaminants such as sulfur, phosphorous and nitrogen.

Dimension (mm)	Far detector	Near detector
Plate thickness	12.7	25.4
Thickness tolerance	$+0.8$, -0.254	$+1.8$, -0.254
Finished plate width	2000	3810
Finished width tolerance	± 0.76	± 0.76
Flatness over any 12 ft length	8.0	14.5
Max. number of waves	8 waves per 8 m	4 waves per 4 m

Table 4: Dimensional tolerances on steel plates for MINOS far and near detectors. All dimensions are in millimeters.

Scintillator detector

Item	Each far plane	Each far supermodule	Full far detector	Near detector	Total
Number of scintillator planes	1	242	484	153	637
Area of scintillator [m^2]	53	12,800	25,600	2,300	27,900
Mass of scintillator [kg]	540	130,680	261,360	24,000	285,360
Number of scintillator strips	192	46,464	92,928	11,616	104,544
Length of scintillator strips [m]	1,293	314,200	628,400	56,000	684,400
Length of WLS fiber [m]	1,485	360,900	721,800	60,000	781,800
Number of 28-wide modules	4	968	1,936	210	2,146
Number of 20-wide modules	4	968	1,936	210	2,146
Number of 16-wide modules	0	0	0	96	96
Number of M16 PMTs	3	726	1,452	0	1,452
Number of M64 PMTs	0	0	0	194	194
Number of PMT pixels	48	11,616	23,232	12,416	35,648
Number of readout channels	48	11,616	23,232	9,240	32,472
Number of MUX boxes	1	242	484	194	679
Number of 8-fold multiplexed pixels	48	11,616	23,232	0	23,232
Number of not-multiplexed pixels	0	0	0	8,448	8,448
Number of 4-fold multiplexed pixels	0	0	0	3,168	3,168
Length of (single) clear fiber [m]	1640	397,000	794,000	30,000	824,000

Table 5: Summary of basic quantities of the MINOS detector components. The values shown are approximations of exact engineering calculations.

Scintillator detector

Overall Parameter	Description/Value	
Photocathode material	bialkali	
Window material	borosilicate glass	
Window thickness	1 mm	
Spectral response	300 to 650 nm	
Wavelength of maximum quantum efficiency	420 nm	
Quantum efficiency at 520 nm	13 %	
Dynode type	metal channel structure	
Number of stages	12	
Anode dark current per channel	$\leq$ 1 nA	
Anode pulse rise time	0.83 ns	
Transit time spread per channel (FWHM)	0.3 ns	
PMT type	M16	M64
Anode		
array of independent pixels	4×4	8×8
Pixel size	4 mm $\times$ 4 mm square	2 mm $\times$ 2 mm square
Maximum high voltage	1000 V	1000 V
Gain at maximum HV	3.9×10^7	3×10^6
Nominal operating gain for MINOS	10^6	10^6
Pulse linearity per channel ($\pm$ 2 % deviation)	0.5 mA	0.5 mA ?
Cross-talk (4×4 mm^2 aperture)	6 %	6 %
Pixel-to-pixel gain variation	1:2	1:3

Table 6: Basic characteristics of the R5900U-00-M16 16-channel photomultiplier and the R5900U-00-M64 64-channel photomultiplier produced by Hamamatsu Photonics.

Electronics (Will ask John Cobb and Keith Ruddick to redo calculations.)

Dark count rate of mm^2 photocathode	3 Hz
Far detector maximum rate/channel	122 Hz
Far detector typical rate/channel	62 Hz
Far detector total rate	1.4 MHz
Near detector maximum rate/channel	173 Hz
Near detector typical rate/channel	55 Hz
Near detector total rate	0.6 MHz

Table 7: Expected singles rates in the MINOS detectors due to radioactivity and photocathode dark counts for a threshold which detects 1 photoelectron. 8-fold optical summing is assumed for the far per-channel rates.

Electronics

Parameter	Near detector	Far detector	Comments
Spill length	10 μs	10 μs	Neutrino spill The far detector must have $> 80\%$ duty cycle for cosmic ray muons out of spill for calibration.
Repetition time	≥ 1.9 s	≥ 1.9 s	
Cosmic muon rate	$\sim$300 Hz	$\sim$1 Hz	Essential for calibration.
Number of channels	9,240	23,232	
Threshold	≤ 0.3 pe	≤ 0.3 pe	
Front end rms noise	≤ 0.05 pe	≤ 0.05 pe	
Charge measurement range	0.005 – 30 pC	0.005 – 30 pC	Assumes PMT gain of 10^6.
Digitization accuracy	5%	5%	
Time resolution (1)	19 ns	—	Resolve overlaps in near detector; not critical for far detector.
Time resolution (2)	—	1.5 ns	For atmospheric ν and upward/downward muon separation in far detector.
Single channel deadtime	0 μs	10 μs	None during spill in near detector; not critical for far detector.
Additional capabilities			
Preamp charge injection	0.005 – 30 pC	0.005 – 30 pC	
Single-channel disable			Remove bad channels from readout.
GPS-based clock	< 1 μs	< 1 μs	Associate events with Main Injector spill.

Table 8: Parameters for the MINOS electronics system.

Component	Near Detector	Far Detector	Comments
PMTs	194	1452	M64 for Near, M16 for Far
Front End Boards	600	484	16 chs N.D. 48 chs F.D.
Readout Crates	8	16	
Read Out Boards	76	41	128 chs N.D., 432 chs F.D.
Front End Processors	8	16	VME single board comp.
FE timing card	8 + 54	16	
Branch readout Processor	4	4	
Farm Processor	<5	<5	
Timing system			
GPS	1	1	
Clock fanout	1	1	

Table 9: Lists the numbers of each component in the readout system

Component	Near Detector	Far Detector	Comments
worst case Detector rate	2.5 MHz	5 MHz	
hit Data size	16 bytes	8 bytes	
detector data	40 Mbytes/s	40 Mbytes/s	
readout crate rate	2.5 Mbytes/s	2.5 Mbytes/s	1 out of 16 in total
network data rate	10 Mbytes/s	10 Mbytes/s	1 out of 4 in total
farm data rates	40 Mbytes/s	40 Mbytes/s	
farm processor rate	8 Mbytes/s	8 Mbytes/s	1 out of 5 used

Table 10: Maximum Rates in the system

Singles Rate (MHz)	Trigger Rate (Level 0, kHz)	Trigger Rate (Level 1, Hz) 3/5 planes	Trigger Rate (Level 1, Hz) 4/5 planes	Max Processors
2	4	6	< 1	1
6	70	26	< 1	3
10	290	130	< 1	5
16	1100	750	< 3	8
20	2000	1500	< 5	10

Table 11: Trigger rates and processor requirements of the trigger farm. The processing power estimates were obtained using an Alpha Server 1000A 5/300, Alpha 21164 chip processor.

Item	Information	Level	Source	Frequency
Construction				
Steel plates	mass	plate	installation	once
	thickness	plate	installation	once
	magnetic properties	plate	mill	once
Scintillator	QC tests (light yield)	batch	extrusion factory	once
WLS Fibers	QC tests (light yield)	batch	module factory	once
Scintillator modules	dimensions	module	module factory	once
	mass	module	installation	once
Photodetectors	QE, uniformity & gain	pixel		once
	operating HV	unit		once
Electronics	modification level	board	factory	as req'd.
	switch settings	board	factory/test rig	as req'd
	calibration constants	channel	factory/test rig	once
Installation and survey				
Steel plates	positions	plate		once
	alignment			once
Scintillator modules	positions	module		once
	alignment		cosmic muons	
Scintillator modules	light yield	strip	source calibration	once
Photodetector	gain	pixel	light flasher	once
Electronics	calibration constants	channel	pulse injection	once
Operation				
Scintillator	calibration constants	strip	muons (software)	weekly
Photodetector	gain	pixel	light flasher	hourly
	replacement history	unit		as req'd.
Electronics	calibration constants	channel	pulse injection	daily
	disabled channels	channel	software	as req'd.
	FPGA & ROM programs	unit	software	as req'd.
	Trigger farm software		software	as req'd.
	high & low voltages	each PSU	software	hourly
	repair history	board	manual	as req.
Magnet	current	each PSU	monitoring systems	hourly
	field	plate	monitoring systems	hourly
General	environmental conditions (temperature etc)		monitoring system	as req'd.

Table 12: Examples of the information that will be recorded in the database during the different phases of the experiment.

Far detector

System	Parameters
MINOS cavern	82.3 m $\times$ 13.8 m $\times$ 11.6 m (height)
Supermodules	2 supermodules, each 2.7 metric kt, 14.4 m long $\times$ 8 m wide
Detector mass	5.14 ktons steel + 261 tons scintillator = 5.4 ktons
Planes/supermodule	243 steel planes and 242 scintillator planes (5.94 cm pitch)
Detector units/plane	192 scintillator strips packaged in 8 modules
Readout	2-ended, with 8 $\times$ multiplexing
Channel count	484 planes $\times$ 192 strips $\times$ 2 $\div$ 8 = 23,232 channels
Photodetectors	1,452 16-channel PMTs in 484 MUX boxes
Installation rate	1 plane/1.85 shifts or 24 planes/month (maximum)
Installation time	12 months for first supermodule, 22.5 months for two
Magnetic field	1.3 T at 2 m radius in steel octagon planes
Magnet coils	15 kA-turns, water-cooled copper wire, 58 kW total
MINOS cavern cooling	270 kW maximum

Table 13: Summary of some of the major parameters of the far detector and its requirements on the infrastructure systems of the MINOS cavern in the Soudan mine.

Near detector

LE = low energy beam (baseline), ME = medium energy beam, HE = high energy beam

System	Parameters
Near hall dimensions	45 m $\times$ 9 m $\times$ 10 m (height)
Detector dimensions	16.6 m long $\times$ 3.8 m high $\times$ 4.8 m wide
Detector mass	955 tons steel + 24 tons scintillator = 980 tons
Steel planes	282 "squashed octagons," 3.4 tons each (5.94 cm pitch)
Steel planes/section	Veto = 20, Target = 40, Shower = 60, Spectrometer = 162
Multiplexing	4 to 1 in Spectrometer, none in other sections
Readout channels	8,448 in forward section, 792 in muon spectrometer
Magnetic field	1.2 T at the neutrino beam location
Magnet coil	8-turn water-cooled aluminum, 40 kA turns, 45.7 kW
Installation time	6 months
Neutrino interactions	1.6 events/spill/0.5 m of steel (LE)
Neutrino interactions	10 events/spill/0.5 m of steel (HE)
Muons from beam	3.2/spill entering detector, 21/spill exiting (LE)
Muons from beam	20/spill entering detector, 130/spill exiting (HE)

Table 14: Summary of the major parameters of the MINOS near detector facility.

System	Parameters
Forward section	
Number of planes	120 steel planes, 120 scintillator planes
Detector units	96 planes $\times$ 64 strips in 3 short modules/plane
	24 planes $\times$ 96 strips in 4 full-length modules
Readout	120 planes: 1-ended, not multiplexed
Channel count	6144 + 2304 = 8448
Photodetectors	144 64-channel PMTs
Spectrometer section	
Number of planes	162 steel planes, 33 scintillator planes
Detector units	33 planes $\times$ 96 strips in 4 full-length modules
Readout	33 planes: 1-ended
Channel count	$(33 \times 96)/4 = 3168/4 = 792$
Photodetectors	50 64-channel PMTs

Table 15: Summary of the major parameters of the near detector. The four strips in each partially instrumented plane (of short modules) which do not overlap the strips of adjacent planes (with orthogonal strip orientation) are not read out. This gives a convenient 64 active strips (4 PMTs) per plane.