3. DESIGN PARAMETERS

This section summarizes the design parameters of the NuMI.

3.1 Extraction and Primary beam

3.1.1 Proton Beam from Main Injector

Proton beam energy	120 GeV
Spill cycle time	1.87 sec
Bunch length	3-8 nsec
Batch length	84 bunches
Bunch spacing	18.8 nsec (53 MHz)
Emittance	40π mm-mr expected 500π mm-mr max
Momentum spread	2 x 10^{-4} δp/p 2σ expected 23 x 10^{-3} δp/p 2σ max
NuMI spill (pbar operation)	5 batches x 84 + 4x3 = 432 bunches = 8.14 μsec
NuMI spill (no pbar operation)	6 batches x 84 + 5x3 = 519 bunches = 9.78 μsec
Maximum intensity	4 x 10^{13} ppp (protons/spill)
Total beam power	404 kW at maximum intensity

3.1.2 Extraction Method and Parameters

Extraction	Single turn
Method	3 traveling wave kicker magnets
Position stability (transport)	± 1 mm max
Beam size @ target	1 mm H x 1 mm V (σ)
Position stability @ target	± 250 μ
Angular stability @ target	± 60 μ-radian max
Max DC beam loss (MI region)	10^{-4} at maximum intensity
Max DC beam loss (Carrier pipe)	10^{-6} at maximum intensity
Max DC beam loss (Pre-target)	10^{-4} at maximum intensity
Max beam loss - accident	5 spills at maximum intensity

3.1.3 Instrumentation

Dynamic range	100 (= $4x10^{13}/4x10^{11}$ protons/spill)
Profile monitors	Multi-wire SEM
Number of wires/plane	48 of 0.003" gold plated tungsten wires
Transport region	3 H + 3 V 1 mm wire spacing, motor-driven
Pre-Target	2 H + 2 V 0.5 mm wire spacing,motor-driven
Position reproducibility	< 50 μ
Intensity range	$2.5x10^{11}$ ppp to $4x10^{13}$ ppp
Channel signal/noise	100x over intensity range
Material in beam	$<10^{-4}$ loss
Beam position monitors	Cylindrical plate BPM
Transport region	6 H + 6 V
Position resolution	0.2 mm rms within ± 20 mm for $3x10^{10}$ to $9.5x10^{10}$ protons/bunch
Intensity resolution	± 3%
Sampling	One sample per batch
Calibration	Electronics charge injection inter-spill
Pre-target	2 H + 2 V
Position resolution	0.05 mm rms within ± 6 mm for $3x10^{10}$ to $9.5x10^{10}$ protons/bunch
Intensity resolution	± 3%
Sampling	One sample per batch
Calibration	Electronics charge injection inter-spill
Toroid intensity monitor	
Intensity resolution	3% absolute for > $1x10^{13}$ppp 30% for > $3x10^{11}$ppp
Stability	< 3% at > $1x10^{13}$ppp
Beam loss monitors	35 Sealed gas ionization chambers
Accuracy	± 30% at $2x10^{8}$ppp
Dynamic range	$2x10^{8}$ to $4x10^{13}$ppp
Monitoring	High voltage status
Function	Sensitive to small localized losses
Total Loss Monitors	4 coax hose ionization, Ar-CO2 purged
Carrier pipe region	1 of 430' long, 2 of 215' long
Pre-target region	1 spanning the entire region
Accuracy	± 30% at $2x10^{8}$ppp
Dynamic range	$2x10^{8}$ to $4x10^{13}$ppp
Monitoring	Radioactive source current inter-spill
Function	Sensitive to large losses

3.2Neutrino Beam Devices

Low Energy Beam Peak at 3 GeV

Baffle/Target Module

Module motion control	
Baffle	
composition	Graphite
aperture	5.4 mm H x 12 mm V
length	2 m
motion control	~10 cm H (manual drive)
cooling	Air or RAW under consideration
Target	
composition	Graphite segments (Poco ZXF-5Q)
length	47 of 20 mm long segments, 0.3mm spacing
density	1.686 ± 0.025 gm/cm^3
width	6.4 mm
height	18 mm
cooling	RAW cooling tubes top/bottom of fin
distance from horn 1	35 cm to Monte Carlo upstream end
motion control	~1 m Z insertion into Horn 1 (manual drive)

Neutrino Horn 1 Module

Horn shape	Double Parabolic
Construction	Nickel plated aluminum inner conductor Anodized aluminum outer conductor
Minimum aperture field-free neck	9 mm radius
Inner conductor thickness	2 mm (min) – 4.5 mm (max at neck)
Outer conductor	11.75 inch I.D. 13.75 inch O.D.
Horn Length	300 cm focus region, 132 inches overall
Current	200 kA
Motion control	±1 cm H x ±1 cm V each end (motor drive)
Horn cooling	RAW spray, 30 gal/min

Neutrino Horn 2 Module

Horn shape	Double Parabolic

Construction	Nickel plated aluminum inner conductor Anodized aluminum outer conductor
Minimum aperture field-free neck	3.9 cm radius
Inner conductor thickness	3 mm (min) - 5 mm (max)
Outer conductor	29.134 inch I.D. 31.134 inch O.D.
Horn Length	300 cm focus region, 143 inches overall
Current	200 kA
Motion control	None
Distance from Horn 1	10 m (upstream end H1 to upstream end H2)
Horn cooling	RAW spray, 30 gal/min

3.3Power Supply Systems

Kicker Power Supply :   Single pulse forming network, drives 2 magnets in parallel

Conventional Power Supplies Regulation requirements

Lam60	200 ppm
V100	400 ppm
HV101	65 ppm
V104	200 ppm
V105	60 ppm
V109	200 ppm
V110	55 ppm
Trims	0.1%
Quadrupoles	400 ppm

Horn Power Supply, current, voltage, Flat top regulation, Pulse width

The design criteria for the horn power supply and stripline are the current, current regulation, and pulse width. Horn 1 and horn 2 are connected in series with the power supply. The voltage is given at the output of the power supply. It is determined by the resistance and inductance of the strip line and horns. When we switched to single turn extraction, the power supply design was modified to give a pulse width of 2.6 msec. The section of stripline to the high energy horn 2 position was later eliminated, shortening the pulse length to 1.7 msec. The "flat-top" regulation is the allowed pulse to pulse variation.

Horn Power Supply : Series connection to Horn 1 and Horn 2

Peak current	240k A
Operating current	200k A average ± 2.5%

Current monitoring	0.4%
Operating voltage	800 V
Repeatability	± 1% pulse to pulse
Pulse width	~half-sine 1.7 ms @ base
Pulse period	1.9 sec

Horn Stripline

Construction	30 cm x 10 cm Aluminum strips, 1 cm spacing
Resistance	10 μΩ/m
Inductance	16 nH/m

3.4 Hadron Decay Pipe

Size	1.98 m inner dia x 677.1 m long
Vacuum	<1 Torr
Upstream vacuum window	4.76 mm thick steel
Downstream vacuum window	6.35 mm thick steel

3.5Hadron Absorber

Primary beam size at Absorber (target out)	5.4 cm H x 7.9 cm V (1 σ)
Primary beam size at Absorber (target in)	29 cm (rms)
Beam power - normal	64 kW (82% primary protons, 18% secondaries)
Beam power - accident	404 kW
Accident condition	1 hour (1900 pulses) mis-targeted primary proton
Absorber core	8 aluminum modules + 10 steel CCSS layers
Aluminum modules	1.29 m H x 1.29 m V x 30 cm Z RAW cooled
Steel CCSS layers	1.29 m H x 1.29 m V x 23 cm Z
Max temperature - normal	60 ^{o}C in aluminum modules 3 and 4 270 ^{o}C in steel module 1
Max temperature - accident	160 ^{o}C in aluminum modules 3 and 4 800 ^{o}C in steel module 1

3.6Neutrino Beam Monitoring

The NuMI beam monitoring system consists of 1 plane of Hadron Monitors (DHM) downstream of the decay pipe and upstream of the Hadron Absorber, 3 planes of Muon monitors located in the Hadron Absorber enclosure (Muon Alcove 0) , Muon Alcove 1 and Muon Alcove 2. The peak charged particle fluxes per spill in the various monitoring locations, assuming $4x10^{13}$ protons per spill**.**

Station	Maximum Flux/spill
DHM	$2.5x10^{9}/cm^{2}$
Alcove 0	$3.2\ x10^{7}/cm^{2}$
Alcove 1	$1.7x10^{7}/cm^{2}$
Alcove 2	$0.22x10^{7}/cm^{2}$

The following table gives the fluxes per spill, and the associated radiation doses per year, expected in the monitoring locations, as a function of particle type. Doses calculated by translating fluxes to Sieverts and then to rads, taking into account spectral information

Station	Particle	Flux (/cm^2/spill)	Dose/year(Rads)
DHM	protons	1.3x10^9	13Grad
DHM	other charged hadrons	2.0x10^9	0.3Grad
DHM	neutrons	3.5x10^9	0.2Grad
Alcove 0	neutrons	10.0x10^7	10Mrad
Alcove 0	muons	1.30x10^7	5Mrad
Alcove 1	muons	0.40x10^7	1.8Mrad
Alcove 1	neutrons	0.04x10^7	0.1Mrad
Alcove 2	muons	0.14x10^7	0.6Mrad
Alcove 2	neutrons	0.04x10^7	0.04Mrad

3.7 Alignment Systems

Alignment tolerances for Low Energy beam

Beam position at target	± 0.45 mm
Beam angle at target	± 0.7 mrad
Target position - each end	± 0.5 mm
Horn 1 position - each end	± 0.5 mm
Horn 2 position - each end	± 0.5 mm
Decay pipe position	± 20 mm
Downstream Hadron monitor	± 25 mm
Muon Monitors	± 25 mm
Near Detector	± 25 mm
Far Detector	± 12 mm

3.8 Water, Vacuum & Gas Systems

CUB = Central Utility Building
CW = Chilled Water
LCW = Low Conductivity Water
PW = Pond Water
RAW = Radioactive Water
SB = Service Building

Power dissipation

Beam transport magnets	628 kW
MI-62 LCW system	700/1200 (kW nominal/max) to MI Pond G
MINOS LCW system	108/200 (kW nominal/max) to MINOS SB CW
Absorber RAW	60/200 (kW nominal/max) to MINOS SB PW
Decay pipe RAW	150/200 (kW nominal/max) to CUB CW (1/2) and MINOS SB CW (1/2)
Target RAW	10/25 (kW nominal/max) to MI62 LCW
Horn 1 RAW	40/200 (kW nominal/max) to CUB CW
Horn 2 RAW	10/50 (kW nominal/max) to CUB CW

Vacuum

Main Injector extraction region	10^{-8} Torr
Primary beam transport vacuum	10^{-6} Torr
Carrier pipe	
Diameter	12”
Vacuum maximum	10^{-5} Torr
Vacuum expected	7×10^{-7} Torr maximum
Hadron Decay Pipe vacuum	0.1 to 1 Torr

Carrier Pipe size, vacuum

The 430' long carrier pipe diameter was determined by an informal cost/benefit analysis. The pipe size is much larger than all magnet apertures, however the consequence of a significant beam loss in the carrier pipe region is severe. The maximum vacuum level is determined by the ground water requirement during normal operation due to interactions with the residual gas. The expected vacuum level is achieved in the middle of the carrier pipe by 3 large ion pumps located at each end of the carrier pipe.

3.9 Installation & Integration

Controls	Power supplies, instrumentation, vacuum, water, beam position & intensity, beam permit, beam loss budget monitor
Beam permit System	Power suppy current & voltage nominal Multi-wire fully inserted/extracted Loss monitors nominal Vacuum valves open Previous Main Injector spill transport nominal BPM positions nominal Target Budal monitor nominal

3.10 Commissioning

Beam intensity	5×10^{12} ppp
Near detector fiducial mass	0.015 kt (40 planes tgt region, 75 cm radius)
Near Detector exposure	2×10^{-6} kt-yr/day