Proposal for Participation in the T2K Long-baseline Neutrino Oscillation Experiment

Presented to NuSAG
June 28, 2005

The T2K US B280 Collaboration
The T2K US B280 Collaboration

Brookhaven National Laboratory,  Upton, New York, U.S.A.
   S. Bellavia, M. Goldhaber, M. Harrison, H. Kirk, N. Simos, P. Wanderer

University of Colorado, Boulder, Boulder, Colorado, U.S.A.
   L. Bartoszek, R. Nelson, E. D. Zimmerman

Louisiana State University, Baton Rouge, Louisiana, U.S.A.
   J. Goon, S. Hatakeyama, T. Kutter, B. Svoboda

State University of New York at Stony Brook, Stony Brook, New York, U.S.A.
   Whitehead, C. Yanagisawa

University of Rochester, Rochester, New York, U.S.A.
   Sakumoto, J. Steinman

University of Washington, Seattle, Washington, U.S.A.
   H. Berns, R. Gran, J. Wilkes
# Contents

1 Executive Summary .......................... 1

2 Introduction .................................. 4
   2.1 Theoretical Framework and Experimental Status .................. 4
      2.1.1 Current Experimental Status ................................ 5
   2.2 The Global Neutrino Roadmap .................................. 7
   2.3 The T2K Experiment ...................................... 8

3 Proposed Experimental Arrangement .......... 9
   3.1 The Primary Beam .................................. 9
   3.2 Target and Horns .................................. 11
   3.3 The Off-Axis Angle ................................ 12
   3.4 The Neutrino Flux ................................ 16
      3.4.1 The $\nu_e$ Flux ................................ 16
      3.4.2 The $\nu_e$ Background ............................ 18
   3.5 The 280m Near Detector (ND280) .......................... 18
      3.5.1 The ND280 On-Axis Detector Baseline Design ............ 19
      3.5.2 The ND280 Off-Axis Detector Baseline Design .......... 19
   3.6 The Intermediate (2 km) Detector ......................... 28
      3.6.1 Motivation for an Intermediate Detector ............... 28
      3.6.2 Physics with the Intermediate Detector ................ 30
   3.7 The Far Detector (Super-Kamiokande) ....................... 31
      3.7.1 Systematics for a Measurement of $\Delta m^2_{23}$ and $\sin^2 2\theta_{23}$ .......................... 31
      3.7.2 Systematics for a Measurement of $\theta_{13}$ ................. 32

4 Neutrino Oscillation Sensitivity .......... 32
   4.1 Expected Yields of Neutrino Interactions ...................... 32
   4.2 Electron Neutrino Appearance ................................ 33
   4.3 Muon Neutrino Disappearance ................................ 35

5 The U.S. B280 Contributions ............... 36
   5.1 Introduction ....................................... 36
   5.2 Neutrino Beamline Elements ............................ 36
      5.2.1 Superconducting Corrector Coils ......................... 38
      5.2.2 Proton Beam Intensity Monitor: Current Transformer (CT) ........ 44
      5.2.3 DAQ Electronics for the Beamline Monitor System ........... 48
      5.2.4 Proton Beam Target ................................ 51
      5.2.5 Horns and Target ................................ 58
5.3 The ND280 Off-axis Sub-detectors ................................................. 63
  5.3.1 The PØD Fine-Grained Detector ............................................ 63
  5.3.2 The Side Muon Range Detector (SMRD) .................................... 83
5.4 GPS Time Synchronization System ................................................ 91

6 Implementation and Management Plan ........................................... 92
  6.1 The T2K International Collaboration and the Status of the Experiment . 92
  6.2 The US B280 Collaboration Structure and Project Management Plan .... 95

7 Estimated Costs and Schedule ....................................................... 97
  7.1 Estimated Project Costs and Justification .................................... 97
  7.2 Schedule .................................................................................. 101
1 Executive Summary

We propose to participate in the T2K (Tokai to Kamioka) long baseline neutrino oscillation experiment at the J-PARC facility in Tokai, Japan. We are especially interested in participating in the R&D, design and construction of the T2K neutrino beamline and 280 m near detector. The participating U.S. groups, hereafter called T2K US B280 Collaboration, are from six institutions: Brookhaven National Lab; University of Colorado, Boulder; Louisiana State University; State University of New York at Stony Brook; University of Rochester; and University of Washington, Seattle.

T2K is a second generation long baseline neutrino oscillation experiment, designed to probe the mixing of the muon neutrino with other species, and the neutrino mass scale. It is the first long baseline neutrino oscillation experiment proposed and approved to explicitly look for the electron neutrino appearance from the muon neutrino, thereby measuring $\theta_{13}$, the last unknown mixing angle in the lepton sector.

T2K physics goals include the precision measurement of the $\nu_\mu \rightarrow \nu_e$ oscillation parameters with precision of $\delta(\Delta m^2_{23}) \sim 10^{-4}$eV$^2$ and $\delta(\sin^2 2\theta_{23}) \sim 0.01$, and achieving a factor of 20 higher sensitivity compared to the current best limit on $\theta_{13}$ from the CHOOZ experiment through the search for $\nu_\mu \rightarrow \nu_e$ appearance ($\sin^2 \Delta m^2_{\mu e} \sim \frac{1}{2} \sin^2 2\theta_{13} > 0.003$ for CP violating phase $\delta = 0$). In addition to neutrino oscillation studies, the T2K neutrino beam (with $E_\nu \sim 1$GeV) will enable a rich fixed-target physics program of neutrino interaction studies at energies covering the transition between the resonance production and deep inelastic scattering regimes.

T2K is similar to the K2K experiment in that it uses Super-Kamiokande as the far detector to measure neutrino rates at a distance of 295 km from the accelerator and near detectors to sample the unoscillated beam. The proposed experiment requires construction of a neutrino beam line, a near detector complex at 280 m (ND280) and, if possible, an intermediate detector at 2 km from the proton beam target, with Super-Kamiokande, which will be upgraded and rebuilt in 2005-6, serving as the far detector.

The T2K neutrino beam will be generated using the new high intensity proton synchrotron at J-PARC, which has a Phase-I design beam power of 0.75 MW. The narrow-band neutrino beam will be centered 2.5$^\circ$ off-axis, with its direction adjustable within $\pm 0.5^\circ$ with respect to the Super-Kamiokande/J-PARC baseline direction, allowing variation of the peak neutrino energy.

The near detector site at 280 m from the target will house on-axis and off-axis detectors. The on-axis detector will measure the neutrino beam direction and profile. A modestly sized fine-grained off-axis detector will serve to measure the flux, energy spectrum and electron neutrino contamination in the direction of the far detector, along with measuring rates for exclusive neutrino reactions. This will characterize signals and backgrounds in the Super-Kamiokande detector.

The baseline design of the ND280 detector, established at a T2K collaboration meeting
in March, 2005, calls for an on-axis detector composed of an array of iron-scintillator sandwiches, and an off-axis detector composed of a π^0 detector (POD) followed by a TPC-Fine Grained Detector (FGD) sandwich, which are in turn surrounded by an electromagnetic calorimeter (ECAL). The whole off-axis detector is placed in a 0.2 T magnetic field provided by the recycled UA1 magnet, which also serves as part of a side muon range detector (SMRD). The US B280 collaboration has led the effort to design the POD and SMRD detectors, and naturally these are the main areas of interest for US contributions. The POD detector plays a critical role by measuring the π^0 background with a water target. The SMRD detector catches about 40% of the muons emanating from the POD and FGD detectors, providing a larger acceptance for muons and dramatically improving the response at neutrino energies near the expected oscillation maximum.

The Japanese government approved the T2K experiment in 2003. The total approved budget for the five-year construction plan is ¥16B (~$160M), which includes funds for the neutrino beam line and the ND280 detector. The 2km detector has not been approved at this time. Construction of the neutrino beam line started in Japanese FY04, which began on April 1, 2004. The experiment will begin commissioning and data taking in 2009.

The following items, which are all part of the T2K scope approved by the Japanese government, represent the specific interests of the T2K US B280 collaboration. The overall philosophy adopted in selecting our contributions to the T2K experiment is to identify critical components that match our expertise and experience. All items we propose here have been approved by the T2K international collaboration as desirable US contributions to the T2K experiment. We have made a conscious effort to keep our overall cost under 5M.

- **T2K Beam Line:** The BNL superconducting magnet division has contributed to development of combined-function (dipole-quadrupole) superconducting magnets for the arc section of the primary proton line. When successfully built, this will be the first application of superconducting combined function magnets in the world. In order to provide fine-tuning capability, we propose to build four superconducting corrector “trim” coils. One functional prototype trim coil has been built and tested at BNL using US-Japan cooperative research funds.

The University of Colorado (CU) group will work on the neutrino horn system. The system will consist of a series of three horns, with the target residing inside Horn 1. CU will construct Horn 2 as a major hardware contribution. In addition, CU is performing R&D, engineering, and physics studies of the target station, target, and all three horns.

The Louisiana State University (LSU) group participates in R&D on the CT (Current Transformer) proton intensity monitors. We propose to provide four operating CTs and one spare.

The University of Washington (UW) group will construct the GPS system for T2K, providing precise time synchronization between J-PARC and Super-Kamiokande. UW
will also provide electronics for the proton beam monitors.

- **280 m Off-axis Detector:** The PØD design is based on collaborators’ experience with the DØ pre-shower detector (Stony Brook Group), the K2K SciBar detector (Stony Brook Group) and the proposed MINERνA detector (Rochester Group). We propose to supply the “target mass” portion of the PØD (scintillator layers, wavelength shifting fibers, thin lead foils and water target containers, etc.) and part of the electronics. The SMRD detector also uses scintillators for detecting charged particles, and shares much common technology with the PØD detector. We propose to provide scintillators for the SMRD detector.

Stony Brook, Rochester, and UW will share responsibility for constructing the target mass portion of PØD, UW will share responsibility for supplying the PØD electronics with the T2K UK collaboration, and LSU will be responsible for the US portion of the SMRD.

The scheduled date for the first proton beam on target and completion of the ND280 on-axis detector is April 1, 2009. The ND280 off-axis detector will be constructed in stages: the magnet will be installed in 2008, the innermost sections of the detector, such as PØD, FGD and TPC, are to be completed by April 1, 2009, and most of the remaining detector components are expected to be ready by September 1, 2009. Depending on the funding situation in various participating countries, final completion of the ND280 detector system may stretch to April 1, 2010. Thus, all of the proposed US contributions to the beamline system must be delivered to Japan by 2008, while our contributions to the PØD and SMRD may be completed in the summer of 2009.

The T2K US B280 Collaboration is composed of institutions and individual physicists with rich experience and a record of accomplishments in contemporary neutrino experiments such as K2K, MiniBooNE, NuTeV, SNO and Super-Kamiokande. Over the years, through K2K and Super-Kamiokande, many of the members have developed strong partnerships with the Japanese T2K collaborators and we are eager to continue that fruitful collaboration to participate in the forefront science of the T2K experiment.

**Contact Person:**

*Chang Kee Jung*
*Dept. of Physics and Astronomy*
*The State University of New York at Stony Brook*
*Stony Brook, New York 11794-3800*
*Tel: 631-632-8108, Fax: 631-632-8101*
*e-mail: alpinist@nngroup.physics.sunysb.edu*
2 Introduction

In this section, we summarize the current interpretation of neutrino oscillation data in the three generation mixing model. We discuss the exciting future goals of neutrino oscillation experiments, and we describe the ability of the T2K program to contribute to these goals.

2.1 Theoretical Framework and Experimental Status

Based on the recent observations by neutrino experiments, a model of three generation neutrino mixing has been accepted as a new Standard Model. This mixing can be described by a unitary matrix (often referred to as the MNSP matrix) that is analogous to the CKM matrix in the quark sector. The weak flavor eigenstates, $\nu_e$, $\nu_\mu$, and $\nu_\tau$ are related to the mass eigenstates by the unitary mixing matrix $U$:

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
=
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{bmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
$$

(1)

where the matrix is commonly parameterized as

$$
U = \begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{bmatrix}
\begin{bmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{bmatrix}
\begin{bmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix}
$$

(2)

with $c_{ij}$ ($s_{ij}$) representing $\cos \theta_{ij}$ ($\sin \theta_{ij}$) where $\theta_{ij}$ is the mixing angle between the mass eigenstates $i$ and $j$. There is one relative complex phase $\delta$, allowed in a unitary 3x3 mixing matrix. The oscillation probabilities which follow from this involve numerous competing processes:

$$
P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i=1}^{3} \sum_{j=i+1}^{3} U_{\alpha i} \cdot U_{\beta i} \cdot U_{\alpha j}^* \cdot U_{\beta j}^* \sin^2 \left( \frac{1.27 \text{ GeV}}{\text{km} \cdot \text{eV}^2} \frac{\Delta m^2_{ij} \cdot L}{E_\nu} \right).
$$

(3)

$L$ is the path length traveled by the neutrinos, $E_\nu$ is the energy of the neutrino, and $\Delta m^2_{ij}$ is the difference of the neutrino masses squared. These transition probabilities are further modified by the presence of interactions of neutrinos with surrounding matter as they travel from their point of creation to observation. Interference between multiple terms in this transition probability can lead to CP violation in neutrino mixing if $\delta$ is non-zero.

By convention, solar neutrino oscillations are attributed to mixing between the first and second generation, and atmospheric neutrino oscillations are attributed to mixing between the second and third generation. This formulation leads to the standard neutrino oscillation parameterization of two independent mass-squared splittings, $\Delta m^2_{12}$ and $\Delta m^2_{23}$, the “solar mixing angle” $\theta_{12}$, the “atmospheric mixing angle” $\theta_{23}$, $\theta_{13}$ and the complex phase $\delta$. 

4
Figure 1: Left: The current K2K I & II neutrino oscillation fit overlain with the 90% C.L. region from the Super-Kamiokande oscillation analysis.

2.1.1 Current Experimental Status

The experimental study of neutrino oscillations has made remarkable progress in recent years and a coherent picture is emerging. The data from a wide variety of experiments are consistent with two different mass scales, $\Delta m^2_{\text{sol}} \sim 8 \times 10^{-5} \text{ eV}^2$ and $\Delta m^2_{\text{atm}} \sim 2.5 \times 10^{-3} \text{ eV}^2$ (see [1] and [2] for detailed references). Further, the observed mixing is close to maximal for atmospheric neutrinos, while solar neutrino mixing is large, but not maximal. In addition, experiments using reactor neutrinos have placed stringent limits on $\nu_e \rightarrow \nu_x$ oscillations for $\Delta m^2 > 7 \times 10^{-4}$.

The evidence for $\nu_\mu \leftrightarrow \nu_\mu$ neutrino oscillations presented by atmospheric neutrino experiments shows a high degree of consistency between various independent neutrino samples [1]. In addition to the Super-Kamiokande detector, supporting evidence is provided by the earlier water Cherenkov experiments, IMB and Kamiokande, and by the underground tracking calorimeters, Soudan-2 and MACRO. Figure 1 shows the result of a recent Super-
Table 1: Best-fit values, 2σ, 3σ, and 5σ intervals (1 d.o.f.) for the three-flavor neutrino oscillation parameters from global data including solar, atmospheric, reactor (KamLAND and CHOOZ) and accelerator (K2K) experiments[2].

<table>
<thead>
<tr>
<th></th>
<th>best fit</th>
<th>2σ</th>
<th>3σ</th>
<th>5σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta m_{21}^2) [10^{-5} eV^2]</td>
<td>6.9</td>
<td>6.1–8.4</td>
<td>5.4–9.4</td>
<td>2.1–29</td>
</tr>
<tr>
<td>(\Delta m_{31}^2) [10^{-3} eV^2]</td>
<td>2.3</td>
<td>1.4–3.0</td>
<td>1.1–3.4</td>
<td>0.68–4.4</td>
</tr>
<tr>
<td>(\sin^2 \theta_{12})</td>
<td>0.30</td>
<td>0.25–0.35</td>
<td>0.23–0.39</td>
<td>0.16–0.47</td>
</tr>
<tr>
<td>(\sin^2 \theta_{23})</td>
<td>0.52</td>
<td>0.36–0.66</td>
<td>0.32–0.70</td>
<td>0.26–0.78</td>
</tr>
<tr>
<td>(\sin^2 \theta_{13})</td>
<td>0.005</td>
<td>(\leq 0.037)</td>
<td>(\leq 0.061)</td>
<td>(\leq 0.13)</td>
</tr>
</tbody>
</table>

Kamiokande fit to atmospheric neutrino oscillations along with the K2K allowed region. The 90% C.L. allowed region favors \(\sin^2 2\theta_{23} > 0.92\) and \(0.0015 \text{ eV}^2 < \Delta m_{23}^2 < 0.0034 \text{ eV}^2\). The \(\nu_\mu\) disappearance data have been found to be consistent with \(\nu_\mu \rightarrow \nu_\tau\) oscillations, but Super-Kamiokande strongly excludes \(\nu_\mu \rightarrow \nu_s\) as the dominant oscillation mode and has recently presented indications of \(\nu_\mu\) regeneration [3].

The K2K experiment is a combination of a neutrino beam line, a near detector at the KEK site and the Super-Kamiokande detector 250 km west of KEK. The characteristics of the neutrino beam are monitored and studied using the near detectors allowing a reliable prediction of the expected event rate and energy spectrum in the Super-Kamiokande detector[4, 5]. The K2K experiment has accumulated data corresponding to an exposure of \(8.9 \times 10^{19}\) protons on target. A total of 108 beam associated neutrino events have been observed in the Super-Kamiokande detector compared to an expectation of 150.9^{+11.6}_{-10.0} events. The observed event rate and energy spectrum are consistent with neutrino oscillation with \(\Delta m^2=0.0017–0.0035 \text{ eV}^2\) and the probability for null oscillation is less than 0.005% excluding that hypothesis by about 4σ[6].

In the near future, the MINOS experiment at the FNAL-NuMI beamline will expand upon the work of K2K. With much larger statistics than K2K and a similar broadband beam, MINOS will be able to provide a precision measurement of \(\Delta m_{23}^2\) by the time of the next generation neutrino oscillation experiments which may be useful for optimizing beam energies in these experiments.

Data from solar, atmospheric, reactor and accelerator neutrino experiments have been combined into a single global fit by several groups. Table 1 gives the allowed region for the three-flavor neutrino oscillation parameters[2].
2.2 The Global Neutrino Roadmap

Future neutrino oscillation studies are not merely an exercise in improving the precision of the measurements of the parameters in Table 1. Neutrino oscillation experiments offer us the opportunity to answer three qualitative questions about the nature of neutrinos and their role in the Standard Model.

1. Is there direct mixing between all neutrino generations, i.e., is $\theta_{13}$ zero or non-zero?
2. What is the hierarchy of masses, i.e., is $\Delta m^2_{23}$ positive or negative?
3. Is there CP violation in neutrino mixing, i.e., is $\delta$ non-zero?

All three questions have important consequences for understanding the lepton flavor sector of the Standard Model. The answer to the last and most challenging question may contribute to a circumstantial case for identifying leptogenesis as the source of the baryon asymmetry in the visible Universe.

The importance of this experimental program was recently highlighted in the APS Multi-Divisional Study of the Physics of Neutrinos, completed in late 2004. One of the two “high priority” programs recommended in the study is

“...a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum and to search for CP violation among neutrinos.”

The report goes on to define this comprehensive program as one that consists of

“...an experiment built a few kilometers from a nuclear reactor, a beam of accelerator-generated neutrinos aimed towards a detector hundreds of kilometers away, and, in the future, a neutrino superbeam program utilizing a megawatt-class proton accelerator. The interplay of the components makes possible a decisive separation of neutrino physics features that would otherwise be commingled and ambiguous.”

Finally, the report addresses the possibility of multiple accelerator experiments, the T2K experiment proposed here, and NOvA at the NuMI beamline, running on similar timescales. It concludes that these two are “complementary” because the different baselines of T2K Phase I and NOvA provide different sensitivities to matter effects in neutrino mixing.

“With both the U.S. and international programs, we may confidently anticipate a thorough understanding of neutrino mixing.”

We submit this proposal for U.S. involvement in the T2K experiment because we believe that a modest U.S. participation helps the international part of this equation to be successful. The potential differences in timescales, physics sensitivities and future upgrades of the planned NOvA and T2K programs ensure that these two efforts will not be redundant.
2.3 The T2K Experiment

T2K is a second generation long baseline neutrino experiment to measure neutrino oscillation parameters \([7, 8]\). Like the K2K experiment, it uses Super-Kamiokande to measure neutrino rates at a distance of 295 km from the accelerator. The T2K neutrino beam will be generated using the high intensity 50 GeV proton synchrotron at J-PARC in Tokai, Japan, which has a Phase-I design beam power of 0.75 MW with the most recent designs calling for a neutrino beam centered 2.5° off-axis, variable between 2.0–3.0°. This produces a flux of neutrinos at the Super-Kamiokande site which is peaked near the energy of maximum oscillation predicted by atmospheric neutrino observations and the K2K long base-line experiment.

The primary goal of T2K is to search for \(\nu_\mu \rightarrow \nu_e\) appearance at a \(\Delta m^2\) consistent with the atmospheric neutrino oscillation parameters. If \(\nu_e\) appearance is found, it can be interpreted as mixing between the first and third generations of neutrinos. The T2K experiment will be sensitive to \(\sin^2 2\theta_{13} > 0.006\) for the CP violating phase \(\delta = 0\), which is 20 times smaller than the present limit. The angle \(\theta_{13}\) is the only angle in the three neutrino mixing matrix which has not been measured, and if it is non-zero, this result opens the possibility of CP violation in the leptonic sector. In addition to searching for a positive \(\nu_e\) appearance signal, the physics goals of T2K include the precision measurement of the \(\nu_\mu \rightarrow \nu_e\) oscillation parameters \((\delta(\Delta m_{23}^2) \sim 10^{-4}\text{eV}^2\) and \(\delta(\sin^2 2\theta_{23}) \sim 0.01)\).

T2K possesses some important technical assets that will enhance its discovery potential. To run at the first oscillation maximum, it will produce a beam of low energy neutrinos, 0.6–0.9 GeV. At these energies the neutrino reactions are dominated by the experimentally simple quasi-elastic process, \(\nu_n n \rightarrow \ell^- p\). The beam itself is steerable, as described in Section 3.3, and thus can be tuned to run at an energy near the oscillation maximum when \(\Delta m_{23}^2\) has been precisely measured by the wideband MINOS oscillation experiment. The beamline has been optimized using a relatively low proton energy and short decay volume to reduce backgrounds to \(\nu_e\) appearance from muon decays in flight and interactions of higher-energy neutrinos. This also implies a relatively short baseline, and therefore, smaller matter effects on the transition rates than would be seen in appearance experiments at higher energies and longer baselines. This is both a liability and an asset in that the matter effects themselves are the tool to untangle the mass hierarchy but at the same time make discerning the effects of possible CP violation more difficult.

T2K is envisaged as a phased experiment. In Phase-I, T2K will have as its source a 0.75 MW proton beam and the 50 kTon Super-Kamiokande as a target. In later phases, this proton beam power is proposed to be upgraded to 4 MW, and new detector sites are being explored either near Super-Kamiokande or South Korea where the same beam could produce interactions in a future 10^3 kTon class detector. If such a detector is built, it will provide rich physics beyond neutrino oscillations, and likely be unique. Thus, by ensuring a US involvement in T2K in this first phase, we prepare for the possibility of these upgrades occurring at one of the candidate facilities.
Figure 2: Site plan for the J-PARC facility at Tokai-mura.

3 Proposed Experimental Arrangement

3.1 The Primary Beam

The T2K beam begins with a fast-extracted primary proton beam from the J-PARC 50 GeV synchrotron\textsuperscript{1} (Figure 2). The beam will arrive in 4.2 $\mu$s pulses, one pulse per 3.5 s. Each pulse will consist of 8 bunches with 58 ns full width and a separation of 598 ns. The 50 GeV accelerator group is investigating the possibility of operations with a doubled harmonic number and 15 bunches. The average primary beam power will be 0.75 MW, or about $3 \times 10^{14}$ protons per pulse and $10^{21}$ protons-on-target per year. This power presents a major challenge for the construction and operation of all beamline elements, but especially the superconducting magnets, the proton target, and the horns.

Protons will be directed to the target through the Primary Beamline (Figure 3). This consists of three sections, labeled from upstream: the preparation section, the arc, and the final focus region.

The preparation section is 54 m long and contains 12 normal conducting magnets and

\textsuperscript{1}In the initial running phase, the primary proton energy will be restricted to 40 GeV pending construction of a flywheel-based energy storage system.
Figure 3: T2K primary and secondary beamlines.
collimators. The arc section will bend the beam by approximately 80° with a turning radius of 104 m. This will require the use of 28 high-field superconducting combined-function (dipole-quadrupole) magnets. Brookhaven National Laboratory is working with KEK on development of these magnets (see Sec. 5.2.1). In 50 GeV operation, the dipole and quadrupole components of the magnets will be 2.587 T and 18.62 T/m respectively.

Losses must be tightly controlled in both the preparation section and the arc, to minimize activation and in particular to minimize heating of the superconducting coils. The arc section will have losses below 1 W/m, and the total loss in the preparation section will be below 750 W.

At the end of the final focus section, the beam will pass into the target station, through a graphite collimator called the “baffle,” whose purpose is to protect the horns from mis-steered beam.

### 3.2 Target and Horns

Protons from the primary beam strike a 90 cm long graphite target, producing short lived hadrons with a typical transverse momentum of 0.3 GeV/c. The hadrons are focused by the magnetic fields generated from a series of magnetic horns. A horn system was chosen because it gives higher angular and momentum acceptances than other focusing systems. It can also be made to withstand high radiation levels, has cylindrical symmetry, and gives sign selection (which will be important when antineutrino running is conducted for CP violation searches). The T2K horn system has been optimized to focus pions in a broad momentum band around 2 GeV/c.

A horn contains a pulsed toroidal magnetic field in the volume between two coaxial conductors. Current flows along the inner (small radius) conductor and back along the outer (large radius) conductor. There is no field inside the inner conductor, nor outside the outer conductor. In the volume between the inner and outer conductors, the magnitude of the field is given by $B(\text{kG}) \approx 0.2 \cdot I(\text{kA})/R(\text{cm})$, and its direction is azimuthal (the field lines are toroidal, encircling the inner conductor). Typical horn currents are in the range 150-350 kA (320 kA in the case of T2K). To avoid catastrophic resistive heating, horn currents are pulsed. The pulse width is generally chosen to balance the resistive heating with the large inductive EMF associated with a very short pulse. The current is brought from a capacitor-bank power supply to the horn via a set of flat conducting plates called striplines, which are connected to the horn conductors.

The T2K neutrino source will use a series of three horns (Figure 4). The target is located within the first horn, which is essentially a cylinder designed to surround the target as close to it as possible. Horn 1 provides rough focusing of particles coming out of the target at large angles. Horn 2 is contoured to correct under- and over-focused particles emerging from Horn 1, especially at large radii. Horn 3 is larger and about 10 m downstream, and is designed to make a final correction to the remaining charged particles. The inner conductor shapes and
currents are being optimized using GEANT [9] simulations at Colorado and KEK.

The horns will be located inside a steel cave called the target station, where they will hang from steel shielding modules. The striplines will be routed through penetrations in the shielding and connect to the horns. Colorado is working with KEK on optimizing the locations and shapes of these connections. The entire target station will be in a helium atmosphere in order to minimize interactions, scattering, and air activation.

After focusing, the hadron beam exits the target station and enters the decay region (Figure 5). This beam consists mainly of unscattered and scattered primary protons and mesons. The decay channel is 115 m long. It is flared in both $x$ (horizontal) and $y$ (vertical), in order to contain the diverging beam. In $y$, the channel is flared all the way to the downstream end, to allow the beam to be steered either to the upper or lower end for control of the off-axis angle (see Sec. 3.3).

Most of the kaons and about one-fourth of the pions decay before reaching the end of the decay channel. At the end of the channel, 130 m from the target, is a beam absorber which stops all the hadrons and low-energy muons. Muon monitors in and behind the absorber will be used to measure the beam direction and profile.

### 3.3 The Off-Axis Angle

The key feature (besides the high beam power) of the T2K beam is the off-axis angle, which exploits the kinematics of pion decay to enhance the yield of neutrinos in a selected narrow energy range. At a given pion energy and lab frame decay angle, there are only two solutions
for the neutrino energy from the two-body $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay. The lower-energy solution corresponds to nearly-backward decays in the $\pi^+$ rest frame. The higher-energy solution dominates the population of neutrinos at small angles from the forward direction. This solution has the property that the neutrino energy is not strongly dependent on the pion energy for a fixed decay angle in the lab frame (see Figure 6). Therefore, a broad pion energy spectrum will yield a highly peaked neutrino spectrum if off-axis decays at a particular angle are selected.

A narrow-band beam is desired for two reasons. First, it is important to maximize the flux at energies near the first oscillation node. This energy will be known more precisely as measurements of $\Delta m^2_{\text{atm}}$ improve. Second, higher-energy neutrinos are a major source of neutral current $\pi^0$ production. Super-Kamiokande’s water Cherenkov design is sensitive to misidentification of these events as $\nu_e$ from oscillations if the $\pi^0 \rightarrow \gamma \gamma$ decay is particularly energy-asymmetric.

A very important feature of T2K is that the off-axis angle can be tuned between 2° and 3° by moving the primary beam, target, and horns. This will allow us to vary the energy of the neutrino beam at Super-Kamiokande, for systematic studies or to reoptimize the experiment toward a different value of $\Delta m^2_{\text{atm}}$. Traditionally, this has been very difficult in other proposed off-axis beamlines. T2K is building in flexibility by the construction of an oversized decay channel (Note the flare in the elevation view in Figure 5). The nominal angle for “standard running” beam studies is 2.5°.
Figure 6: Neutrino vs. pion energy for various decay angles.
Figure 7: Neutrino flux at Super-Kamiokande for three choices of the off-axis angle
3.4 The Neutrino Flux

The neutrino flux has been calculated with a full GEANT simulation of the target, horns, decay region, and all apertures. The GCALOR/GFLUKA [10] model was used to simulate hadronic interactions. Checks have been done with the MARS [11] model as well, and the results are consistent.

3.4.1 The $\nu_\mu$ Flux

The $\nu_\mu$ flux at Super-Kamiokande for a 2.5° off-axis beam is shown in Figure 8. As desired, it is narrowly peaked in the energy region of interest, between 0.5 and 0.8 GeV. This corresponds to a peak oscillation sensitivity for $\Delta m^2$ between 2.1 and $3.3 \times 10^{-3}$ eV$^2$, which is the region for $\Delta m^2_{\text{atm}}$ indicated by Super-Kamiokande data [3]. The neutrino spectrum has a tail extending to higher energies; these events are predominantly due to kaon decays (see Figure 9).
Figure 9: Kaon contribution to $\nu_\mu$ and $\nu_e$ flux at T2K. Crosses indicate total $\nu_\mu$ (above) and $\nu_e$ (below) flux; shaded histograms indicate combined $K^\pm$ and $K^0_L$ decay contributions.
3.4.2 The $\nu_e$ Background

A $\nu_e$ background is inevitable in this experiment. What is important is that the $\nu_e$ background be as small as possible and be well understood. In addition, one wants the energy dependence of the $\nu_e$ background to be significantly different from that of the signal. This will allow us to use the energy distribution of $\nu_e$ candidate events in a fit to signal and background hypotheses.

The $\nu_e$ background arises from two main sources: $\pi \to \mu \to e$ decay chains and $K^+/K_L^0$ decays in flight. The former events are peaked at lower energies, while the latter are spread out over all energies. In the peak of the $\nu_\mu$ energy distribution, the $\nu_e$ background is below 0.4%. The integrated $\nu_e$ flux is about 1% of the $\nu_\mu$ flux, but it is clear that removing high-energy events will be an effective background reduction tool.

3.5 The 280m Near Detector (ND280)

The main purposes of the 280 m near detector are as follows.

1. Measurement of the neutrino flux to estimate the flux at SK.

2. Measurement of the neutrino energy spectrum. The spectrum measurement as a function of the distance from the beam center provides a constraint on the estimation of the far/near ratio (see section 3.6.1).

3. Measurement of neutrino cross sections for various interaction modes, such as charged current quasi-elastic, charged current non quasi-elastic, and neutral current interactions.

4. Measurement of the $\nu_e$ contamination for the $\nu_e$ appearance search.

5. Measurement and monitoring of neutrino beam direction.

For these purposes and for neutrinos with energies below 1 GeV, fully active detectors, such as a water Cherenkov and a fine grained scintillator detector satisfy the requirements.

Because of typically high event rates in the 280 m detector of 0.06 events per spill per ton for an off-axis beam it is hard to use a water Cherenkov detector like the 1kt detector of K2K. A fully active scintillator tracker as used in K2K [12] could be operated at high event rates. However, the difference in the neutrino target material between H$_2$O and CH$_2$ must be understood.

The physics capabilities and the design of the 280 m detector will be discussed in the following sections.
3.5.1 The ND280 On-Axis Detector Baseline Design

With an off-axis beam configuration, neutrino energy is strongly correlated with angle relative to the beam direction, and thus precise knowledge of the neutrino beam direction is indispensable. A change of 1 mrad in the neutrino beam direction corresponds to about 25 MeV shift in the peak neutrino energy. This translates into a systematic uncertainty of $10^{-4}$ eV$^2$ in the measured value of $\Delta m^2_{23}$, which is comparable in magnitude to the desired precision of T2K, $\delta(\Delta m^2) \approx 10^{-4}$ eV$^2$.

In order to address this issue, the ND280 on-axis detector provides the means to accurately monitor the direction of the neutrino beam, and the neutrino beam profile. The conceptual design of the on-axis detector is illustrated in Figure 10. One detector module is also shown. Thirteen of these detector modules, each a sandwich of iron blocks and scintillator hodoscope layers, are placed in a symmetrical, cross-shaped array. With this system, the center position of the neutrino beam will be measured continuously, with an accuracy of 0.18 mrad. The on-axis detector will be constructed by T2K collaborators in Japan.

3.5.2 The ND280 Off-Axis Detector Baseline Design

The conceptual design for the 280 m off-axis detector resulted from a number of Monte Carlo studies carried out within the collaboration, and was optimized to address the physics issues listed in Section 3.5. Figure 11 shows an overview of the 280 m off-axis detector. The specific
Figure 11: The conceptual design of the T2K 280 m near detector. The neutrino beam is directed from the left to the right. The main purpose of the left most fine grained detector is to detect $\pi^0$ from neutral current interactions. Hence it is also referred to as the Pi-Zero Detector (P0D).
dimensions of various detector components, and in particular, the size of the electromagnetic calorimeter and side muon range detector, have not yet been finalized. It was also found that a magnetic field is very desirable for forward muon momentum measurements, and to better characterize secondary particles in inelastic reactions.

The UA1 Magnet The magnet previously used in the UA1 and NOMAD experiments was made available to the T2K collaboration by CERN. Figure 12 shows the magnet in the 'open' position along with the core of the detector which is anticipated to be mounted in a cage. The various components of the detector core are indicated. Although the magnet is capable of supplying a magnetic field intensity of 0.67 T, in the case of the T2K-280m off-axis detector a field strength of about 0.2 T or less is anticipated, due to power restrictions (<0.6 MW).

Figure 12 shows the detector position relative to the magnetic coils and the iron yokes. The magnet consists of four coils, and eight pairs of C-shaped iron yokes, which are shown in Figure 14. The dimensions of an individual yoke are indicated in figure 13. The yokes themselves will be instrumented and serve as the side muon range detector (SMRD). Each yoke has 12 groups of gaps suitable for insertion of detectors. The gaps are 17 mm high and are spaced 50 mm apart.
Figure 13: Dimensions and specs of a single magnet yoke. The individual iron plates are 48 mm thick and are partly welded and bolted together. Each C-shaped iron yoke weighs 53 tons.

Figure 14: The yokes are currently stored on the CERN property.
Figure 15: This figure shows the magnet in its open and closed configuration inside the cylindrically shaped 280 m experimental hall.
The yokes will be lowered one by one into the detector hall, and mounted on a support structure. The latter is in turn mounted on a rail car which allows the magnet to be opened (see Figure 12) for installation of the inner detector components and possible later maintenance access. With the yokes in the open position there will be very limited space available, so detector installation logistics will have to be carefully planned. Figure 15 shows a plan view of the magnet in the 280m hall and illustrates the space constraints. The hatched area represents a drop off to a lower floor level.

The $\pi^0$-Detector (PD)  One of the main limitations facing the T2K electron neutrino search will be the understanding of backgrounds which are dominated by two distinct sources with roughly equal contributions. The first crucial source of background is the result of $\nu_e$ events from the primary beam which cannot be removed from the event selection. Fortunately, the electron neutrino flux is suppressed relative to the $\nu_\mu$ flux and has an energy spectrum which differs from that of the expected $\nu_e$ appearance signal. The other significant source of background results from neutral current $\pi^0$ production by muon neutrinos where the $\pi^0$ is not reconstructed in Super-Kamiokande. It is expected that the statistical uncertainty on these backgrounds will approach 10% during the first phase of T2K. The $\pi^0$-detector (PD) has been optimized to address these backgrounds.

The PD is primarily intended to measure events that contain electrons and gamma-rays. The particular goals of the PD are to measure the inclusive $\pi^0$ production rate by $\nu_\mu$ on oxygen, as well as partially inclusive neutral and charged current production rates. In addition to an accurate determination of the inclusive rate, it will be important to measure rates for various exclusive $\pi^0$ production channels, such as $\nu_\mu p \rightarrow \mu \pi^0$ and $\nu_\mu N \rightarrow \nu_\mu N \pi^0$. The PD will provide new data for these and other relatively poorly known partial cross sections in the energy range below 1 GeV. Finally, the PD will provide a measurement of the intensity and energy spectrum of the beam-associated electron neutrino flux by directly searching for $\nu_e$ quasi-elastic events.

These goals require that the PD meet several criteria in terms of mass and event reconstruction ability. First, the PD is intended to study processes with relatively small partial cross sections compared to the total neutrino cross section so it must have relatively large mass as well as high reconstruction efficiencies (see section 4.1). Further, since the expected $\pi^0$ momentum distribution peaks near 300 MeV/c, the PD must have a threshold to reconstruct gamma-rays that is below 100 MeV. Finally, the total PD target mass will be significantly smaller than the total mass of the surrounding ECal and magnet so it must have adequate vertex resolution to eliminate background events from outside of its fiducial volume.

A fine grained scintillating detector that is several radiation lengths deep has the capability to meet all of these requirements.
The Fine Grained Detector (FGD) and the Time Projection Chamber (TPC)  It is important to measure the neutrino spectrum as accurately as possible in the near detector, and to be able to measure differences in the spectrum as a function of time and location within the detector. The most accurate estimate of neutrino energies comes from the momenta and angles of muons produced in quasi-elastic charged-current neutrino interactions. At the peak of the neutrino spectrum in the near detector, approximately 750 MeV, the neutrino energy resolution is limited to approximately 10% due to Fermi motion within the struck nucleus. In order to reach this fundamental limit in the neutrino energy determination, the momentum resolution of the TPC should be better than 10% for muons with momenta below 1 GeV/c.

The charge sign of neutrino interaction products must also be determined unambiguously in order to distinguish the charge of pions produced in inelastic events and to determine the anti-neutrino component in the beam. This will be most challenging for high energy neutrinos, primarily arising from kaon decays. Given the limited curvature of tracks in the relatively weak magnetic field in which the TPC will operate (0.2 T), good spatial resolution will be needed to meet these goals.

Good measurements of the ionization energy loss will be useful to help distinguish electrons and protons from muons and pions. It will also be important to distinguish the products from neutrino interactions inside the fiducial volume of the near detector from other beam related activity. In particular, neutrino interactions in the magnet iron will produce many charged particles that will enter the FGD fiducial volume. The excellent 3D resolution of TPCs will allow these to be distinguished more easily than in a projective 2D tracker.

A large fraction of low energy neutrino-nucleus interactions involve the production of very low energy hadrons. Monte Carlo simulations of these processes involve empirical models which have not been well tested, owing to the fact that it is difficult to detect and measure the low energy particles within dense target material. The gas of the TPC will provide additional target nuclei, and neutrino interactions within the gas could provide excellent samples of a few thousand events per year to improve our understanding of neutrino-nucleus interactions, since all of the charged particles produced can be tracked in the TPC.

Thus the role of the fine grained detector (FGD) and the time projection chamber (TPC) are to provide complementary information to the data collected in the P0D.

The Electromagnetic Calorimeter (ECal)  The electromagnetic calorimeter will play a crucial role to characterize the backgrounds to $\nu_e$ appearance and is complementary to the FGD, TPC and P0D. The latter have been designed to detect electron neutrino interaction vertices. However, due to their small size and low mass, they will have relatively poor electromagnetic shower containment. For this reason, they are surrounded by an electromagnetic shower calorimeter.

In order to identify electrons and $\pi^0$s, the detector must have good energy and angular resolution. The geometry and design of this detector, as well as the physical size of its
Table 2: Simulated muon acceptance for the conceptual 280 m near detector configuration.

<table>
<thead>
<tr>
<th>Components of the Detector</th>
<th>CC - QE</th>
<th>Non - QE</th>
</tr>
</thead>
<tbody>
<tr>
<td>no. of evts generated in FV</td>
<td>7624</td>
<td>6357</td>
</tr>
<tr>
<td>evts stopping in FGD</td>
<td>694</td>
<td>9%</td>
</tr>
<tr>
<td>evts hit in TPC</td>
<td>4017</td>
<td>53%</td>
</tr>
<tr>
<td>TPC and SMRD</td>
<td>2104</td>
<td>28%</td>
</tr>
<tr>
<td>FGD and SMRD</td>
<td>797</td>
<td>10%</td>
</tr>
</tbody>
</table>

components still need to be studied, however, it must meet several very general requirements. First, in order to study the direct $\nu_e$ component of the beam using the inner detectors, the ECAL should have high efficiency as well as be hermetic. Showers detected in the calorimeter will be matched to charged particles measured in the TPC to separate electrons from muons and gaps in the ECAL could significantly reduce the identification efficiency for regions of phase space. In addition, the ECAL will need to have good energy, position and direction resolution to reduce confusion between showers from $\pi^0$ decay.

The Side Muon Range Detector (SMRD) One of the main goals of the 280 m detector is the measurement of the neutrino spectrum. For charged current quasi-elastic (CC-QE) processes the neutrino energy is closely related to the muon energy. The relation between neutrino energy and muons from CC-QE reactions is described in Section 3.7. The neutrino energy can be reconstructed for CC-QE events using the muon momentum and its scattering angle if the Fermi motion is ignored. A full spectral measurement of the neutrino beam must include muons with large angles relative to the neutrino beam direction.

The momentum of muons with large angles relative to the beam direction can be measured if the detector is instrumented with a side muon range detector. The total fraction of muons from CC-QE reactions that is expected to intersect the SMRD amounts to nearly 40%. For non-QE reactions about 15% of all muons are expected to intersect the SMRD. A more detailed accounting of CC-QE and non-QE events is given in Table 2. Muon events are split into 4 different categories. Each event category is characterized by the detector components that the muon tracks intersect. The 4 categories are:

1. Events with muons that stop inside the FGD.
2. Events for which the muons escape in the forward direction and consequently intersect the TPC.
3. Events with muons that penetrate the FGD and TPC, then enter the SMRD.
Figure 16: Muon momentum and momentum-acceptance distributions for the ND280 default design.

Figure 17: Muon angle and angle-acceptance distributions for the ND280 default design.
4. Events for which the muon travels in the FGD and then only intersects the SMRD. For each category in Table 2 the fraction of charged current quasi elastic (CC-QE) and non-quasi-elastic (Non-QE) events are specified. A significant fraction of muons are expected to be detected by the SMRD. Monte Carlo studies indicate that the mean momentum of the muons that would have to be ranged out in the SMRD is on the order of 400 MeV/c. The muon momentum and angular distribution as well as the muon acceptance distributions as function of muon momentum and muon angle are shown in Figures 16 and 17, respectively. In addition to measuring muons which would otherwise escape unseen from the inner detectors the SMRD will also significantly reduce the systematic uncertainties in the muon detection efficiency in the momentum range around 500 MeV/c.

The SMRD will also serve to veto particles entering the detector from outside, and secondary particles from beam neutrino interactions in the iron of the magnet yokes.

3.6 The Intermediate (2 km) Detector

3.6.1 Motivation for an Intermediate Detector

The Phase-I plan for T2K as approved by Japanese funding agencies provides only for construction of the neutrino beamline, with its associated set of beam monitors and facilities, and the near detector suite, on the J-PARC site at 280 m from the neutrino production target. At time of writing, the Japanese agencies cannot commits to construction of an intermediate detector facility. Nonetheless, a number of physicists in Japan, Europe and the USA (including some co-investigators on this proposal) are developing a design for an intermediate detector suite, so that this potentially valuable source of additional physics data can be constructed as soon as possible, if and when appropriate facilities are approved on the Japanese side.

As described above, T2K will use an off-axis neutrino beam. Since the part of the neutrino beam observed by Super-Kamiokande is only a small, non-central portion of the beam exiting the decay pipe, the energy spectrum sampled at Super-Kamiokande will not be the same as the energy spectrum observed when integrating over a large fraction of the entire beam emittance, as is necessarily the case at a near site. The J-PARC site boundary limits the near detector distance to 280 m, where the target is effectively a short line source rather than a point source, as viewed by the near detectors. The analysis of T2K data would be significantly enhanced by construction of an intermediate detector sited an order of magnitude farther from the production target, at about 2 km. A suitable site has been identified at about 2 km, in Tokai Village.

An intermediate detector would be particularly useful in the search for $\nu_e$ appearance. The background for the $\nu_e$ search comes from both electron neutrinos that are intrinsically in the beam at production and misidentified events at Super-Kamiokande that were produced by $\nu_\mu$ interactions. To increase the potential reach of the experiment, one should carefully
Figure 18: (left) The near/far neutrino flux ratio as a function of energy 280 m from the T2K target. (right) The near/far neutrino flux ratio as a function of energy 2 km from the T2K target.

measure the expected neutrino spectrum for both $\nu_\mu$ and $\nu_e$ in a place where the spectrum is as similar to Super-Kamiokande as possible.

The differences in flux as measured at 280 m and 295 km can be seen by looking at the ratio of near $\nu_\mu$ flux to far flux (N/F ratio) as a function of energy. The left and right panels of Figure 18 show this ratio at 280 m and 2 km respectively. Because the energy of peak positions are shifted at 280 m relative to that at Super-Kamiokande, the N/F ratio changes rapidly in the region where the oscillation maximum takes place. On the other hand, at 2 km the N/F ratio is flat to about 2%. Thus, a 2km detector would help to predict the $\nu_e$ background and $\nu_\mu$ flux at Super-K, with much reduced dependence on Monte Carlo simulations.

Because Super-Kamiokande is a water Cherenkov detector, having a similar near detector would help eliminate common systematics. However, the high event rate at 280 m makes it an unsuitable location for a water Cherenkov detector. On the other hand, the event rate 2 km from the neutrino source is low enough that a moderately large unsegmented water Cherenkov detector could be built there.

The design of the water Cherenkov detector is driven by two factors. First, it must contain most of the muons which are produced inside the fiducial volume. At the same time the detector must not have more than one neutrino interaction per spill on average. While the event rate at 2 km is low enough, this criterion sets a size limit of approximately 14 m
with a 9 meter diameter and a 100 ton fiducial volume. To measure any muons that leave the water tank, and better match the acceptance of Super-Kamiokande, a separate muon range detector is also planned.

Both quasi-elastic(QE) and non-quasi-elastic(non-QE) neutrino interactions must be measured at 2km, since the nonQE interactions serve as a source of background both to the \( \nu_e \) appearance and \( \nu_\mu \) disappearance searches. K2K experience showed that the more finely grained and lower the energy threshold of the detector, the better one can do at measuring pions and other particles produced in non-QE interactions and characterizing both the intrinsic \( \nu_e \) in the beam and misidentified \( \nu_e \) background. For this reason a liquid argon TPC is being considered by European collaborators, to supplement the water Cherenkov detector. The LAr TPC would be placed in front of the water Cherenkov tank.

A muon range detector will be located following the water Cherenkov detector. As currently planned, it will consist of 9 tracking layers (scintillator X-Y hodoscopes, with 4 cm wide strips), interleaved with steel plates, with absorber thicknesses stepped from 2.5 cm in front to 20 cm in back. The total thickness will be about 2200 gm/cm\(^2\), corresponding to the range for a muon with energy about 3.5 GeV.

### 3.6.2 Physics with the Intermediate Detector

When searching for \( \nu_e \) appearance in Super-Kamiokande there will be both an irreducible intrinsic \( \nu_e \) background and a background due to event misidentification. If there is no observed signal, or the signal is quite small, the error or sensitivity will be dominated by how well one can determine the background to the search. If the total background uncertainty is allowed to approach 20\% the \( \theta_{13} \) sensitivity flattens out after 5 years of T2K running as the result becomes systematics limited. Therefore our goal is to control the total uncertainty to 10\% and individual uncertainties to 5\%.

The leading uncertainty is in the rate of NC single-\( \pi^0 \) interactions on water which fake a single-ring electron. The 2KM water Cherenkov detector will provide a direct measurement of these interactions using a detector with nearly identical response. A lesser contribution to \( \nu_e \) appearance background is due to \( \nu_e \) interactions from the intrinsic \( \nu_e \) flux component of the T2K beam. The background from misidentification of CC-\( \nu_\mu \) interactions is smallest. Although these interactions should look very different than \( \nu_e \) interactions, there is a very high rate of CC-\( \nu_\mu \) interactions. Single-ring \( \mu \)-like events are distinguished from single-ring \( e \)-like events by a particle identification algorithm as used in Super-Kamiokande. The intermediate detector will again allow direct observations of this background.

The background for \( \nu_e \) analysis at Super-Kamiokande, may be extrapolated from the measurement at 2 km using a simple scaling method:

\[
N_{SK} = N_{2km} \times \left( \frac{L_{SK}}{L_{2km}} \right)^2 \times \frac{M_{SK}}{M_{2km}} \times \frac{\epsilon_{SK}}{\epsilon_{2km}},
\]

(4)
where \( L \) is the distance from the detector the neutrino source and \( M \) the fiducial mass used in the analysis. For CC-\( \nu_\mu \) it is necessary to include the oscillation “survival” probability in the estimate (thereby reducing the background from misidentified \( \nu_\mu \) CC events). A preliminary, simple, and conservative estimate of the systematic errors on this measurement predicts a total error of approximately 7.5\%, assuming 5-year exposure of the T2K beam with \( 10^{21} \) protons-on-target per year. After one year of exposure the total error using the same estimation would already be approximately 8.7\%.

3.7 The Far Detector (Super-Kamiokande)

The purpose of the far detector in T2K is to measure the neutrino flux after a flight distance roughly equal to one oscillation length. The Super-Kamiokande detector, at a distance of 295 km from the J-PARC neutrino beam line is ideally suited. At this baseline, the oscillation maximum will occur below 1 GeV within the energy range Super-Kamiokande provides an excellent combination of large mass, and event reconstruction (See [13], [6], [14] for details about the detector and analysis).

As the far detector for the T2K Experiment, the Super-Kamiokande detector is used to measure the shape and normalization of the muon neutrino flux, as well as the shape and normalization of the electron neutrino flux. These fluxes will be measured using single ring muon (electron) events, and by assuming that the events result from quasi-elastic neutrino interactions. In this case, the neutrino energy can be inferred using

\[
E_\nu = \frac{m_n E_l - \frac{1}{2} m_l^2}{m_n - E_l + P_l \cos \theta_l}
\]

where \( m_n \) and \( m_l \) are the masses of the neutron and lepton (\( e \) or \( \mu \)), and, \( E_l, P_l, \) and \( \theta_l \) are the energy, momentum, and angle of the lepton relative to the neutrino beam.

3.7.1 Systematics for a Measurement of \( \Delta m_{23}^2 \) and \( \sin^2 2\theta_{23} \)

The measurement of \( \Delta m_{23}^2 \) and \( \sin^2 2\theta_{23} \) will require detailed knowledge of the \( \nu_\mu \) flux at Super-Kamiokande, and the uncertainty will be dominated by several important contributions. The T2K measurement of \( \Delta m_{23}^2 \) will be made by finding the location of the maximum suppression with respect to the expected neutrino flux. This requires a good understanding of the shape of the \( \nu_\mu \) flux at SK, as well as excellent energy calibrations. The \( \nu_\mu \) spectrum will be determined by the pion kinematics in the beam decay pipe, as well as the off axis angle. Since the uncertainty in the energy spectrum will enter directly into the uncertainty in \( \Delta m_{23}^2 \), particular attention has been paid to measuring the shape of the neutrino flux at the ND280 site. The T2K measurement of \( \sin^2 2\theta_{23} \) is made by measuring the amount of suppression observed at the oscillation maximum and requires good knowledge of the total flux normalization.
Since the $\nu_\mu$ flux will be determined by assuming that all single-ring $\mu$-like events result from quasielastic interactions, the contribution from non-QE events must be subtracted, and introduces systematic uncertainty. Non-quasielastic events which are reconstructed as single-ring $\mu$-like result from events where particles such as pions are below the Cherenkov threshold. This leads to an incorrect estimation of the neutrino energy, and partially reduces the $\nu_\mu$ suppression at the oscillation maximum. Further, since the non-QE background varies as a function of energy, it will introduce uncertainty in the value of $\Delta m_{23}^2$.

In addition to flux related uncertainties, there are significant contributions to the total systematic error from SK detector related effects. For instance, the systematic uncertainty in the Super-Kamiokande energy scale will enter directly into the uncertainty in $\Delta m_{23}^2$. Event reconstruction, and $\mu$ identification will have a negligible effect.

### 3.7.2 Systematics for a Measurement of $\theta_{13}$

The search for electron neutrino appearance at Super-Kamiokande will be limited by the understanding of the background. This background is relatively large when compared to the expected signal and has two significant contributions. The first contribution is a result of direct $\nu_e$ produced in the decay pipe. This contribution will be measured by the near detector, and can be largely inferred from the high-energy tail of the on-axis $\nu_\mu$ flux which results from kaon decay. In addition to the $\nu_e$ background, neutral current events are a particular problem. This background is dominated by events containing a single $\pi^0$ where only a single $\gamma$ is found. Given the importance of this background, it will be studied using several corroborating methods, and can be constrained using the single $\pi^0$ event rate measured at Super-Kamiokande; however, this requires that we know the expected total $\pi^0$ rate. The background subtraction will be helped by a precise knowledge of $\Delta m_{23}^2$ so uncertainties in the $\nu_\mu$ flux discussed above will also contribute to the $\nu_e$ appearance uncertainty.

### 4 Neutrino Oscillation Sensitivity

#### 4.1 Expected Yields of Neutrino Interactions

In a typical run year ($10^7$ s) the T2K neutrino beam is expected to produce between 100,000 and 130,000 events/ton at the ND280 off-axis detector site. This assumes a beam power of approximately 0.75 MW. Approximately 88% of the recorded events will result from charged current interactions with about 43% of the events being from QE interactions. Single pion interactions will contribute approximately 21% of the charged current rate, and an additional 15% of events will result from multi-pion production. Neutral current interactions contribute about 30% of the total interaction rate, however the majority do not produce a signal in our detectors. Only 12% of the events are expected to be from neutral current interactions. Most of these events (7%) will be from single $\pi^0$ production.
Particles produced in neutrino interactions are expected to have a mean momentum of approximately 500 MeV/c (see Figure 19). It can be seen that while the majority of particles will have relatively low momentum, a significant number will have momenta of more than 1 GeV/c.

4.2 Electron Neutrino Appearance

T2K will be sensitive to values of $\sin^2 2\theta_{\mu e}$ down to 0.003 at 90% confidence level at the optimal $\Delta m^2_{23}$ after $5 \times 10^{21}$ protons on target, or approximately five years running at the nominal intensity. As the $\Delta m^2_{23}$ accuracy is improved by MINOS in the next few years, T2K will adjust the planned off-axis beam angle to optimize its sensitivity.

The T2K sensitivity to $\nu_e$ appearance is shown in Figure 20. The left hand panel shows the 90% C.L. sensitivity to measure $\theta_{13}$ if an electron appearance signal is interpreted as mixing between the first and third neutrino generations. The solar mixing parameters are taken to be $\Delta m^2_{12} = 8.2 \times 10^{-5}$ and $\tan^2 \theta_{12} = 0.4$. The sensitivities have been calculated assuming a 10% systematic uncertainty in the background subtraction which will require detailed measurements of the neutrino flux and cross sections near to the production point of the T2K neutrino beam. The sensitivity is shown for three values of $\theta_{23}$, which will be independently measured by MINOS, and at T2K by muon neutrino disappearance. Note that T2K will measure the electron neutrino appearance probability and the inferred value...
Figure 20: The left plot shows the expected T2K 90% sensitivity after $5 \times 10^{21}$ protons on target (5 years of nominal intensity). The right plot shows the 90% C.L. sensitivity contours for $\sin^2 2\theta_{13}$ after $5 \times 10^{21}$ protons on target as a function of the CP violating phase $\delta_{CP}$. 

\[ m^2_{21} = 8.2 \times 10^{-5} \text{ eV}^2 \]
\[ \tan^2 \theta_{12} = 0.4 \]
\[ \sin^2 2\theta_{13} = 1 \]

\[ m^2_{13} = 2.5 \times 10^{-3} \text{ eV}^2 \]
\[ m^2_{13} = 1.9 \times 10^{-3} \text{ eV}^2 \]
\[ m^2_{13} = 3.0 \times 10^{-3} \text{ eV}^2 \]
Figure 21: The expected statistical uncertainty after a five year exposure to $\sin^2 2\theta_{23}$ (left) and $\Delta m_{23}^2$ (right) as a function of the true $\Delta m_{23}^2$. The solid line shows the sensitivity for a $2^\circ$ off-axis beam, and the dashed line shows sensitivity for a $3^\circ$ off-axis beam.

of $\theta_{13}$ depends on the CP violating phase $\delta_{CP}$ which is taken to be zero in this panel. The right hand panel in Figure 20 shows the dependence of the T2K $\sin^2 2\theta_{13}$ sensitivity on $\delta_{CP}$ for three different values of $\Delta m_{13}^2$.

4.3 Muon Neutrino Disappearance

Muon neutrino disappearance will be measured at Super-Kamiokande using the event selection pioneered in the Super-Kamiokande sub-GeV atmospheric neutrino measurement, and the K2K neutrino flux shape analysis [14, 6]. In this selection, fully contained single ring muon-like events have been estimated to have a QE purity of approximately 80% allowing the neutrino flux to be estimated. Figure 21 shows the expected statistical uncertainty for $\Delta m_{23}^2$ and $\sin^2 2\theta_{23}$ after an exposure of $5 \times 10^{21}$ protons on target [7]. The total systematic error is estimated to be less than $\sim 1\%$ for $\sin^2 2\theta_{23}$ and $\sim 1 \times 10^{-4} eV^2$ for $\Delta m_{23}^2$. The significant contributions are $10\%$ uncertainty in the far/near flux ratio, $4\%$ uncertainty in the energy scale, and $20\%$ uncertainty in the non-QE background subtraction [7].
5 The U.S. B280 Contributions

5.1 Introduction

The T2K US Beamline and 280 m detector (T2K US B280) collaboration proposes to participate in the R&D, design and construction of the T2K beamline and 280 m near detector.

The items we propose to contribute (listed in Table 4) are all part of the T2K scope approved by the Japanese government. The overall philosophy that defines our contributions to the T2K experiment is to concentrate on critical components of the experiment that match our expertise and experience. All items we propose here have also been approved by the T2K International collaboration as possible US contributions to the T2K experiment pending approval by the US funding agencies.

We have made a conscious effort to keep our overall cost under $5M. As the host country the Japanese are contributing on the order of $160M, which includes most of the beam line elements, the beam extraction system, and civil construction for the beam line and the ND280 detector hall. Other countries are also expected to make contributions to the beamline elements and the ND280 detector sub-systems. Table 3 summarizes the general areas of contributions to the approved portion of the T2K experiment to be made by the participating countries.

We expect that a relatively modest hardware contribution from the US side will have a very large impact on the success of the project. Besides the hardware contributions, we will continue making strong contributions to the intellectual and organizational aspects of the project based on our extensive experience in the field and the long-standing successful partnership with the Japanese leadership.

The T2K US B280 Collaboration is comprised of institutions and individual physicists with rich experiences and accomplishments in neutrino physics, such as: K2K, MiniBooNE, NuTeV, SNO and Super-Kamiokande. Over the years, through K2K and Super-Kamiokande, many of the members have developed strong partnership and working relationship with the Japanese T2K collaborators. We are eager to continue that fruitful collaboration to make the T2K experiment a success. With T2K, we have an opportunity to participate as full partners in a project in which U.S. financial contributions amount to only a few percent of the total cost, but will reap rich scientific rewards.

Table 4 summarizes the proposed US B280 contributions to T2K and the institutions responsible for each subsystems.

In the following sections, the details of our proposed contributions will be described.

5.2 Neutrino Beamline Elements

The T2K neutrino beamline project will rely heavily on international contributions. KEK and the collaboration are strongly encouraging participation from all regions. The collabora-
Table 3: List of the proposed contributions to the beamline and ND280 detector from the participating countries other than Japan, the host country.

<table>
<thead>
<tr>
<th>Country</th>
<th>Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>Beamline (extraction), ND280 Off-axis (FGD, TPC, ECAL)</td>
</tr>
<tr>
<td>France</td>
<td>ND280 Off-axis (FGD, TPC, Magnet)</td>
</tr>
<tr>
<td>Italy</td>
<td>ND280 Off-axis (Magnet, SMRD)</td>
</tr>
<tr>
<td>S. Korea</td>
<td>ND280 On-axis (Electronics)</td>
</tr>
<tr>
<td>Poland</td>
<td>TBA</td>
</tr>
<tr>
<td>Russia</td>
<td>ND280 Off-axis (ECAL, SMRD)</td>
</tr>
<tr>
<td>Spain</td>
<td>ND280 Off-axis (FGD, TPC, Magnet)</td>
</tr>
<tr>
<td>Switzerland</td>
<td>ND280 Off-axis (TPC, Magnet)</td>
</tr>
<tr>
<td>UK</td>
<td>Beamline (Beam dump), ND280 Off-axis (PØD, ECAL, SMRD, Magnet)</td>
</tr>
<tr>
<td>USA</td>
<td>Beamline (Beam monitors/electronics, Horn, Proton target, Superconducting magnets, GPS system), ND280 Off-axis (PØD, SMRD)</td>
</tr>
</tbody>
</table>

Table 4: List of US B280 contributions to T2K

<table>
<thead>
<tr>
<th>Institution</th>
<th>Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL</td>
<td>Beamline (Proton target, Superconducting Corrector coils)</td>
</tr>
<tr>
<td>U. of Colorado, Boulder</td>
<td>Beamline (Neutrino Horns/target)</td>
</tr>
<tr>
<td>Louisianna State U.</td>
<td>Beamline (CT Proton beam monitor), ND280-off-axis (SMRD)</td>
</tr>
<tr>
<td>SUNY at Stony Brook</td>
<td>Beamline (Proton target), ND280-off-axis (PØD)</td>
</tr>
<tr>
<td>U. of Rochester</td>
<td>ND280-off-axis (PØD)</td>
</tr>
<tr>
<td>U. of Washington</td>
<td>Beamline (Proton beam monitor electronics/DAQ, GPS system ND280-off-axis (PØD electronics/DAQ, Water Target)</td>
</tr>
</tbody>
</table>
tion spokesperson and the KEK directorate have both emphasized that the beam is an area of the experiment where outside contributions are particularly critical. The US participation in the beamline will be substantial, and takes advantage of the expertise at several institutions: BNL on superconducting magnets and high-radiation targets, LSU and Washington on beam monitoring devices, and Colorado on target and horn systems.

5.2.1 Superconducting Corrector Coils

The T2K beamline that transports protons from the 50-GeV Proton Synchrotron to the proton target must use superconducting magnets in order to achieve the required change in the beam direction towards Super-Kamiokande in the available space. Collaboration between the KEK cryogenics group and the BNL superconducting magnet division on the T2K beamline superconducting magnets initiated by the Stony Brook group led to an agreement to do R&D and construct combined-function superconducting magnets instead of constructing separate conventional dipole and quadrupole superconducting magnets as originally planned. The combined-function magnet option provides a cheaper solution to the T2K neutrino beam line and saves space. When successfully built, this will be the first application of superconducting combined-function magnets in the world.

Since these combined-function magnets, however, intrinsically couple dipole fields and quadrupole fields, it is expected that fine-tuning of the beam will be difficult. In order to provide a fine-tuning capability, the beam line then requires vertical and horizontal dipole corrector magnets. We propose to contribute these needed superconducting corrector “trim” coils. The BNL Superconducting magnet division has developed an unique automatic coil winding method that winds coils directly on the beam pipe [15]. A proto-type magnet has been already constructed and tested successfully using the Japan-U.S. cooperative research funds. We propose to provide three operating corrector coils and one spare. The principal combined-function magnets are being made in Japan, under the supervision of KEK.

A photograph of the BNL coil winding machine in operation is shown in Figure 22. The machine uses ultrasound to bond the insulated wire to the substrate that has been previously wrapped on the support tube. The coils will be wound on a copper support tube using NbTi/copper wire 0.33 mm in diameter to produce an integral field of 0.1 Tm with an operating current of 43 A. The slot length in the beam line is 800 mm, the magnetic length of the corrector is 522 mm, and the coil inner diameter is 150 mm. The peak field in the coil is 0.2 T, well below the quench limit of the superconductor, which is greater than 6 T. This will give the magnet substantial temperature margin for beam loss.

Each corrector will consist of vertical and horizontal dipoles wound on the same support tube, one over the other. Each dipole will have two layers. The winding pattern for a single layer is shown in Figure 23. The winding patterns for the two layers are shown in Figure 24. Because the coil aperture is a significant fraction (~ 30%) of its length, the harmonics of the end windings can be an important part of the field integral. However, by winding in
the novel pattern shown in the figure ([16]), the harmonics due to the coil ends essentially cancel. That is, the harmonics of the left end of the bottom layer cancel those of the right end of the upper layer. Similarly, the right end of the bottom layer cancels the left end of the upper layer. This method of winding also permits each layer of the dipole to be wound as a single unit. Traditionally, a dipole is wound from two separate units which are then spliced together. This is one example of several production-oriented features that reduce the cost of the correctors.

After the coils have been wound, they are over-wrapped with epoxy-loaded fiberglass under tension to prevent conductor motion due to Lorentz forces. The units will be quench-tested and have magnetic field measurements made at Brookhaven and then be shipped to KEK for finishing work. When installed in the beam line, the correctors will be placed in the low-field region between the main magnets in order to reduce interaction between the main magnets and the correctors. The inner diameter of the corrector support tube is chosen so that it fits around the beam tube with a small clearance. The temperature of the cold mass will be kept near 4.5 K by running thin sheets of high-conductivity aluminum between the correctors and a 4.5 K helium transport line. (This is done because the correctors will not be in the helium flow that keeps the main magnets at operating temperature.) Finishing work at KEK will include a yoke, a superinsulation blanket, and attachment of the superconducting leads to the leads that make the transition to room temperature.

Development of this design has been underway for more than two years, funded by the U.S.-Japan Collaboration. A prototype corrector coil was made and successfully tested at BNL in the spring of 2005. It can serve as a spare. The prototype has been sent to Japan to be completed and mounted with a prototype main beam line magnet. Figure 25 shows the completed corrector magnet.

The BNL cost is $513k, including all overheads. A reduced overhead has been assumed for the budget. Reduced overheads have been obtained for similar projects in the past. A reduced overhead has been requested for this work.

The major component of the cost is corrector production ($286k for labor, $141k for material). The cost of cryogenic testing is $26k for labor, $19k for material. The cost of shipping and documentation is $35k. The processes of magnetic design, mechanical design, and semiautomatic winding are highly integrated, so the cost of coil design is small, $7k. Because the coil is wound directly on its support tube, no tooling is needed.

The cost is based on production of the prototype corrector (February and March, 2005) plus production of similar magnets on the semi-automatic winding machine. The prototype magnet has the same design as the production magnets, and will be suitable for use as a spare, so the budget is for the cost of making, testing, and shipping four correctors. Based on this experience, a 15% contingency has been assigned to this work.

The schedule for the magnet system for the proton transport line calls for installation in the summer of 2008. The correctors need to be at KEK in early April of 2008 in order to meet the installation schedule.
Figure 22: The photograph shows the winding machine as it lays down the dipole layer of one of the magnets for the BEPC upgrade project.
Figure 23: The figure shows the winding pattern for a single layer of a dipole corrector, presented as a flat pattern. If the corrector is oriented to produce a vertical field, the midplane will be at $0^\circ$ and $180^\circ$. 
Figure 24: The figure shows the winding patterns for the two layers that make up a single dipole corrector.
Figure 25: The photograph shows the completed corrector magnet.
5.2.2 Proton Beam Intensity Monitor: Current Transformer (CT)

The main goal of the beam intensity monitor is to count the number of protons in each section of the primary beam line with a relative accuracy at the 1% level. Measurements of section-to-section beam loss allow tuning the beam, and measurement of the absolute beam intensity is critical to calculate the number of protons on target which will directly feed into the calculation of the neutrino beam intensity. CTs are commonly used to measure the proton beam intensity since they are non-destructive, simple, and reliable.

Operating Principle of CTs  The CT is made of a toroidal magnetic core and a coil wound around the core (see Figure 26).

For a suitably chosen frequency range the output voltage induced in the CT is proportional to the beam current \( I_b \). In the desired operating region

\[
\omega_L < \omega < \omega_H
\]

(6)

the output voltage is independent of the frequency and linearly proportional to the beam current. Here \( \omega_L = R/L \) is the lower cut-off frequency and R and L represent the load resistance and the self inductance of the coil, respectively. The higher cut-off frequency is given by \( \omega_H = 1/CR \), where C is the capacitance. Hence, in the desired operating region one finds

\[
V \simeq \frac{1}{N} R I_b.
\]

(7)

This implies that the best choice for a CT coil has high self-inductance and low capacitance. In addition, most materials saturate at a high induction fields, which would limit the dynamic range.
Table 5: Typical CT core materials.

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Finemet(FT-3M)</th>
<th>Permalloy(TMH-0.05)</th>
<th>Ni-Zn ferrite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components</td>
<td>Fe-based Si,B</td>
<td>Fe,Ni amorphous</td>
<td>Ni,Zn</td>
</tr>
<tr>
<td>Structure</td>
<td>strip-wound</td>
<td>strip-wound</td>
<td>solid</td>
</tr>
<tr>
<td>Saturation flux density (*)</td>
<td>1.23 (T)</td>
<td>0.70 (T)</td>
<td>0.38 (T)</td>
</tr>
<tr>
<td>Relative permeability (**)</td>
<td>25000</td>
<td>2000</td>
<td>5300</td>
</tr>
<tr>
<td>Curie temperature</td>
<td>570(°C)</td>
<td>-</td>
<td>200(°C)</td>
</tr>
<tr>
<td>Electrical resistivity</td>
<td>1.1×10⁻⁶ (Ω·m)</td>
<td>6×10⁻³ (Ω·m)</td>
<td>1 (Ω·m)</td>
</tr>
</tbody>
</table>

(*) 20°C, (**) 100kHz

The toroidal core Commonly used core materials are magnetic metals such as ferrite or other amorphous alloys. Since J-PARC will operate with very high beam intensity, of 3.3×10¹⁴ ppp, the core must be chosen carefully to match the constraints. A large relative permeability allows for a larger radius, which reduces the potential interactions with the beam. A larger saturation flux density allows for a larger linear dynamic range. Table 5 shows the specification of some core candidate materials. Currently, the preferred candidate is Finemet(FT-3M), produced by Hitachi Metal Co. The advantage of this core is its high saturation flux density which is larger by a factor of two compared to Permalloy and a factor of three relative to ferrite. Table 5 lists the characteristics of these core materials.

Prototype CT A prototype CT core, supplied by KEK, was used for suitability tests. It consisted of a Finemet core with a strip-wound structure, an inner diameter of 190mm, an outer diameter of 220mm, and a thickness of 25mm.

The left panel of Figure 27 shows the calculated N-turn dependence of the inductance for various frequencies. The number of turns was chosen to be N = 16 since it places the coil in the middle of the desirable frequency range.

A test setup is used to measure the linearity of the CT response as a function of the input wire voltage. The left panel of Figure 28 shows the results of a measurement on a 16-turn CT. The horizontal axis is the input pulse height and the vertical axis is CT’s output pulse height measured by an oscilloscope. The error bars of each plot are simply the estimated reading errors of the oscilloscope. The fitting result 0.06308 agrees well with the expectation of 1/16=0.0625 based on equation 7 with \( V_{p.g.} = I_b R \).

In principle, the location of the wire inside the loop should not affect the result. In reality, response of the coil might be expected to be slightly non-linear, and this might lead to a position dependence. The right panel of Figure 28 shows the position dependence of the CT’s output as the wire position is varied. The horizontal axis is the distance from the center.
Figure 27: The inductance is shown as function of the number of turns of the coil (left panel). The right panel shows the CT response as function of the number of turns of the coil. The operating range should be chosen to fall in the linear regime.

of the CT to the wire, and the vertical axis is the output voltage. Within uncertainties, the output is independent of position, as expected.

**Beam test in 12GeV PS** In December 2004, the prototype CT was installed in the K2K proton beam line. The location was at a 10cm air gap of the beam pipe between two magnets. (see Figure 29). In this case \( N = 10 \), and one turn of wire was also wound around the CT for calibration purposes.

The output signal went through 40 m of coaxial cable, a delay module, an attenuator module, and finally to a FADC. The CT used for K2K near the aforementioned magnet was used as reference. Figure 30 shows the integrated charge as a function of the spill number for both the prototype CT and the q31 and vd1 K2K CT. The measured charge is relatively stable, and fluctuations are clearly correlated between the instruments. The lower panel of Figure 30 shows the linear correlation between CT-Finemet and CT-q31 with single and 9-bunch spills. The lowest two panels are just an expanded view of the upper figure. There is a clear correlation between two CT, with a relative deviation from linear of about 1 \( \sim 2\% \).

**Further R&D** There are still a number of tests to be made before the design is finalized:

- more precise testing with a precision pulse generator and 12-bit FADC
Figure 28: The response for a 16 turn coil is shown as function of the input pulse size. The right panel shows the CT readout voltage as function of the core position relative to the test pulse. The position independence can be seen clearly.

Figure 29: Prototype CT in the K2K beamline.
the K2K beam is only 1% the intensity of the J-PARC beam. We need to check the radiation hardness of the core, cables, and connectors.

- high current test

The necessary funds for these tests are included in this proposal.

Installation plan and milestone  In our current plan, four CTs will be installed at the following locations: (1) input of the magnet PH1 just after the beam extraction point, (2) input of magnet PH3 just before the arc section, (3) input of FV2 near the end of the arc, and (4) at the input or output of FV2 near the target. We would like to finish the R&D and decide the final design by the end of 2006. Production will be done in FY 2007 at LSU, and installation would be in mid-2008. We plan to make one spare CT along with the four operational ones.

5.2.3 DAQ Electronics for the Beamline Monitor System

The J-PARC neutrino beamline will require highly precise monitoring to ensure maximum efficiency for neutrinos delivered to the far detector per pot. Steering, targeting and intensity of the proton beam must be constantly measured, and appropriate alarms sent to operators and shift physicists when beam parameters drift out of acceptable limits. To the extent
Figure 31: Overview of the J-PARC neutrino beamline monitor system.

Loss monitors are placed along the beam line.

Beam Monitor
I: Intensity
C: Center position
P: Profile
possible, corrective adjustments will be applied by automated controls; this in turn depends upon rapid and continuous acquisition of monitor data. Construction and operation of major beamline elements and monitor components will not be part of the US commitment to T2K, but we have been asked to contribute to part of the beamline monitor DAQ system, due to the specific expertise and experience of US groups. The overall neutrino beamline layout is outlined in Figure 31, where the locations and types of the main monitoring components are indicated:

- **CT**: Current transducers are simple devices that non-destructively measure beam current by induction.

- **BPM**: Beam position monitors (Figure 32) determine beam coordinates nondestructively by comparing signals induced on 4 electrodes surrounding the beam.

- **SSEM**: Segmented Secondary Emission Monitors determine the beam profile by collecting secondary-emission electrons from a lattice of metal strips. Since these devices interfere with the beam, the monitors must be inserted and removed as needed.

After discussion with Japanese physicists working on the beamline design, and careful analysis of the signals and accuracy requirements of the various monitor types, we were asked to provide a low-cost readout system for the BPM elements. The basic front-end design, based on a commercial chip, is already done, but we will need to carry out some development and prototyping to ensure the final board delivers the required performance.
Since the number of channels involved is relatively small (about 100), the total cost of this contribution is modest. The DAQ board development effort is centered at UW, led by Hans Berns, a research engineer with extensive experience on DAQ systems for neutrino experiments.

The analog BPM signals will be sent to the custom front-end boards to be constructed by UW. These boards, as currently under development, are based on the Texas Instruments ADS5410 (12-bit, 80 MSPS) A/D chip, although higher-performance chips may be substituted later. FPGA techniques will be used for fast control and readout, and CPLD devices will be used for slow control and interfacing. An onboard MCU will allow all control functions to be downloadable, so the board can be readily adapted to different specific functional requirements as and if needed (Figure 33).

Front-end boards will be housed in standard VME crates, interfaced to the overall beamline data system via commercially available memory-mapping VME-PCI adaptor cards. The recorded data will be pre-processed by PC-based workstations and sent to the beamline control network.

It is possible that the same boards may be needed for a much large number of channels, for the SSEM monitors. At present, the Japanese side is studying the option of commercially available high-performance DAQ components, but at time of writing, it is possible that after prototype testing, these will be found to be either too expensive, or have inappropriate features. In that case, the specifications of the UW board are adequate (if not ideal) for the SSEM DAQ task, and additional numbers of boards, for a total of 3200 channels, will be produced. This possibility is not reflected in the attached budget since such additional production would be paid for by the Japanese side. However, their request to keep this option open indicates an important additional motivation for the work proposed here.

5.2.4 Proton Beam Target

The T2K target design concept shown in Figure 34 is based on a 90 cm long graphite target cooled by forced helium that flows in a double annulus made of graphite and titanium alloy. The integrated target-cooling channel assembly is placed within the inner conductor of the first horn. The success and longevity of the target concept in intercepting the protons and generating pions depends on the ability of the selected materials to resist irradiation damage and maintain their intended function. Key to maintaining target system integrity is the ability of the target material to withstand beam-induced thermal shock and thermomechanical fatigue as well as resist the long term exposure to irradiation and maintain the physical properties, such as conductivity and heat capacity, that allow for the removal of the beam deposited heat load. While the above issues are common to all target systems and they tend to grow with increasing beam intensities, they are of special importance in the T2K target design where the path to the heat sink depends on maintaining conduction between surfaces and bonding between dissimilar materials.
Figure 33: Monitor DAQ front-end card block diagram.
The importance of making a determination of how well the material resists irradiation damage is clearly depicted in Figure 35 where irradiation-induced changes on the conductivity of graphite are dramatic. While the data shown have been derived from neutron-irradiation exposure, the changes in a key property that controls the heat removal from the target are hard to ignore.

BNL has been addressing high-power target issues through a series of experimental studies in support of the Muon Collider and Neutrino Superbeam initiatives. These studies include beam-induced thermal shock on graphite and carbon-carbon composite targets and irradiation damage assessment of different materials some of which are relevant to the T2K target concept (such as the graphite and Ti-6Al-4V alloy). Extension of the on-going BNL irradiation studies to assess irradiation-induced changes on material properties directly affecting the performance of the T2K target concept (such as conductivity, volumetric change, bonding with Ti-alloy, etc.) is considered to be a valuable contribution to the T2K initiative. An integral part of the current BNL irradiation study is the evaluation of the graphite material considered in the T2K target and it involves active participation of T2K collaborators Y. Hayato (KEK) and K. Yoshimura (KEK). The post-irradiation study of the T2K target material is focusing on stress-strain relations, the coefficient of thermal expansion, conductivity and volumetric change.

Assessment of other target and target system materials (such as carbon-carbon composite, Albemet, etc.) resulting from the extension of the current BNL studies will provide options during the process of finalizing the target design.
Figure 35: Effects of neutron irradiation on the conductivity of graphite. The figure shows the dramatic reduction of conductivity with low levels of irradiation expressed in terms of displacements-per-atom (dpa).
The BNL contributions to the target design of T2K can be summarized as follows:

- Experimental validation of the baseline target material (graphite) as well as of alternative materials such as carbon-carbon composite through a comprehensive effort that focuses on target-governing properties such as diffusivity, thermal expansion, volumetric change, fatigue strength and shock resilience.

- Experimental confirmation of the feasibility of the special bonding of dissimilar materials in the T2K target scheme (graphite and Ti-6Al-4V) and assessment of how such bond survives irradiation.

- Integrated simulation of the baseline target scheme while taking into account the results of the R&D effort on target materials. BNL has extensive experience with large scale simulations that involve energy deposition, heat transfer and shock response.

- Design of an integrated target system based on the T2K requirements.

With the ever-increasing demand for higher accelerator power the pool of materials that can potentially survive the demanding conditions has been dramatically reduced. The challenge stems from the compounded uncertainties associated with the long-term survival of the highly irradiated target and other integrated materials within the target station that play key roles in the generation and capturing of secondary particles. The ever greater beam deposited energy and its consequences on the affected materials (such as shock and thermo-mechanical fatigue) are the reason for the limitations. Efforts are underway looking for materials that are potentially up to the challenge. These efforts focus on three fronts, namely, the conceptualization of smart target designs, the identification of new alloys and composites that can support these designs, and finally, actual experimentation on these materials through which their resilience to irradiation damage and degradation of their key properties are assessed.

An extensive R&D study on high-power targets has been under way at BNL in support of the Muon Collider and the Neutrino Superbeam initiatives. The study is focusing on both the beam-induced shock and also the irradiation damage on different materials that can potentially support a high-power target. During the first phase of the study, graphite and carbon-carbon composite targets were exposed to high intensity 24 GeV proton pulses in an effort to assess whether the carbon composite is a viable alternative to graphite. Figure 36 is a representation of the actual target responses and it reveals that carbon-carbon is a far better candidate than graphite in absorbing beam-induced shock. However, the level of irradiation damage that the two materials will experience is still an open issue and further studies were needed.

The current phase of the BNL irradiation study utilizes the 200 MeV, 70 μA proton beam of the BNL Linac to irradiate a host of different materials that exhibit favorable properties in their un-irradiated state.
Figure 36: Comparison of graphite and carbon-carbon composite response to 24 GeV proton pulses obtained during the BNL E951 Experiment on Muon Collider/Neutrino Factory targets. The figure shows the level of strain recorded with fiber-optic strain gauges attached to the targets.[Ref. [17]]
The materials under study for irradiation effects on mechanical and physical properties include:

**Carbon-Carbon composite**: Experiments have shown that this composite can minimize thermal shock and thus survive high intensity pulses. The effect of proton irradiation on key physical and mechanical properties is being assessed.

**Graphite (IG43)**: Different grades of graphite may respond differently to irradiation. While neutron irradiation experience shows considerable changes in key physical properties of graphite, proton irradiation effects on certain grades of this material are important to be established.

- **Titanium Ti-6Al-4V alloy**: The fracture toughness changes due to irradiation are of interest regarding this particular alloy that combines good tensile strength and relatively low Coefficient of Thermal Expansion (CTE).

- **Toyota’s Gum Metal**: This super alloy exhibits, in its un-irradiated state, ultra-low elastic modulus, high strength, super-elastic like nature and near-zero linear expansion coefficient for the temperature range -200 °C to +250 °C.

- **Vascomax**: High-strength, high-Z alloy. Irradiation effects on thermal expansion, fracture toughness and ductility loss are sought.

- **Beryllium**: Low-Z material with potential use as a target but with environmental/handling issues.

- **AlBeMet**: A low-Z composite or alloy that combines the good properties of Beryllium and Aluminum.

- **Super-Invar**: A nickel-based alloy that exhibits very low thermal expansion in the range of 0-200 °C.

- **NuMI Horn Material (Ni-plated aluminum)**: The effects of irradiation, combined with the effects of oxidation from contact with cooling water, of the nickel-plated NuMI horn materials are being evaluated.

Preliminary, post-irradiation results of the BNL experimental study have been obtained and have provided some understanding of how prone these materials are to experience degradation of their properties due to irradiation. The post-irradiation analysis has focused thus far on thermal expansion and stress-strain relation changes in the listed materials. A significant portion of the post-irradiation analysis of the material matrix is being performed by Le P. Trung of SUNY Stony Brook who has been working closely with the BNL team during both the experimental and the data analysis phases. Studies on other properties such as conductivity and volumetric change, also relevant to T2K target, are being planned.
5.2.5 Horns and Target

The horn system is critical to delivering the neutrino beam to Super-Kamiokande. The Colorado group will design and build Horn 2 as a major hardware component of the beam. In advance of this, we are also performing a series of Monte Carlo studies of the neutrino flux, to define the tolerances and refine the geometry of the horns and target station. In addition, we are consulting on and contributing to the design of all aspects of the target station, target, and horn systems.

A key part of the US contributions to the T2K neutrino source is our partnership with Bartoszek Engineering, Inc. Larry Bartoszek, who operates the company, is a former Fermilab engineer who designed the MiniBooNE horn system and is well known in the neutrino beam community. He worked on MiniBooNE as an independent contractor to Fermilab, and has designed and built projects for several other university and laboratory-based groups. The MiniBooNE horn operated stably for two years and saw five times more pulses than any previous neutrino horn. Zimmerman was a leader of that project as a postdoc at Columbia, and has worked closely with Larry Bartoszek for many years.

Horn 2

Horn 2 will have an outer conductor with a radius of 35 cm and a length of 2 m, and will operate with a current of 320 kA. The inner conductor will have a double-paraboloid shape, although studies are ongoing to see if a conical shape (which would be easier to build) can be designed without significantly reducing the flux. A conceptual design with the paraboloid is shown in Figure 37. The conductors will be constructed of 6061-T6 aluminum, a well-understood alloy with a long history of use in neutrino horns.

Horn 2 will be a challenging device to design. The current will be nearly twice MiniBooNE’s 170 kA. This is very high but not unprecedented. The beam power, however, is an order of magnitude higher than in previous experiments (and a factor of three higher than NuMI), and is concentrated in relatively few pulses with very high proton intensity ($0.6 \times 10^{14}$ protons/$\mu$s). Thus, thermal shock and radiation damage will be paramount concerns in the design.

The heat loads for the K2K and MiniBooNE horns were all dominated by resistive heating. At T2K, however, the horns will be exposed to much more severe radiation heating. Horn 2 will see 3.8 kJ resistive heat deposited from a 2 ms full width current pulse. However, the inner conductor will see 6.7 kJ and the outer conductor 12.3 kJ deposited by radiation (from a MARS calculation). Pre-prototype tests with a heated conductor and a mockup of the proposed water cooling geometry will be performed at CU in order to verify the adequacy of the water flow.

Full finite-element analyses of the Lorentz force, thermal stress, and vibration modes will be performed before finalizing the design of the conductors and support structures.

---

Information about Bartoszek Engineering can be found at [http://www.bartoszekeng.com](http://www.bartoszekeng.com).
Figure 37: A conceptual view of Horn 2 with stripline connections. The outer conductor is rendered pseudo-transparent. Image by Bartoszek Engineering.
The helium environment of the target station creates a complication for horn designs, because the breakdown voltage for helium is much lower than for air; horn components therefore need to be designed with more stringent corona protection. We plan to build a facility at Colorado to test various part shapes at high voltage in humid and dry helium environments.

The scope of the construction project for Horn 2 is a good match to existing capabilities at Colorado. CU has a skilled designer/technician as well as the physics group’s experience from MiniBooNE. The Physics Department’s machine shop is available for fast-turnaround of pieces we anticipate needing for prototype testing. The department has a large high-bay hall, formerly the home of a nuclear physics cyclotron, that is well suited as assembly space for the horn. The horn will weigh about 900 pounds, making it reasonable to assemble in Colorado and ship to Japan. Bartoszek will work with Colorado physicists and technicians on pre-prototype tests of cooling and high-voltage corona, and then complete the engineering design of the horn. Bartoszek and the Colorado physics group will supervise the construction and assembly of the horn. Mechanical tests will be performed at Colorado, after which the horn will be shipped to Japan where Colorado physicists will complete full-current testing and installation.

In order for this type of international collaboration to work, close coordination is essential. The US groups are working with KEK to determine the exact boundaries and interfaces between our project and KEK responsibilities. Our current plan is to design and build the inner conductor, outer conductor, stripline connections, and all assembly fixtures and cooling hardware. Power supplies and water recirculation systems will be provided by KEK and/or J-PARC. We anticipate building a production horn, and retaining the capability to build spare horns as operating contributions as needed by the experiment. Project funds will be used for the engineering and pre-prototype work as well as the construction of the production horn.

Design and Engineering Contributions

We view the neutrino source as an integrated system. In addition to construction of Horn 2, the Colorado and BNL groups are involved in many aspects of designing the remainder of the system. At this early stage, we have contributed work on the Horn 1 stripline and support structure, and have consulted on the target support design. We plan to share much of the engineering work on Horns 2 and 3, as they have some basic features in common (though their different sizes make for many differences in stress, heating, and fabrication methods).

Bartoszek Engineering is currently researching the method to produce the insulator separating the inner and outer conductors for Horn 3. Recent horn designs (including MiniBooNE and K2K) have called for alumina ceramic due to its good insulation and radiation resistance. However, the large radius (133 cm) of Horn 3 will likely preclude the use of a ceramic ring. Bartoszek is looking at new insulating materials such as plasma-sprayed ceramic coatings.
over metal, and granite. We are also looking at novel clamping methods for the water-tight connection between the inner and outer conductors to simplify the design of this insulator.

Using experience gained from MiniBooNE and NuMI, Bartoszek has designed a new upstream end connection for the striplines that should guarantee good uniformity in the current flow around the outer conductor during pulsing. Work is currently proceeding on designing the water system around Horn 1.

Work is also proceeding on the design of a remote system for inserting and extracting the target from Horn 1. Bartoszek Engineering and Colorado are reviewing the target cooling system design in light of recent problems with the NuMI target cooling. Support and alignment for Horn 1 is also being worked on by Bartoszek Engineering. The target replacement system needs to be well integrated with this support above the horn because of the tight space constraint, so KEK has asked Bartoszek to begin the design of a fully integrated horn support system that satisfies all the support, alignment and horn replacement design criteria. Bartoszek has participated design reviews of the NUMI horn support modules, and this experience will be translated to the J-PARC horn modules.
Figure 39: A detail of the PØD target region. The green represents the scintillating bar tracking planes. The water target region is located in the first two thirds of the detector and is indicated by blue. The down stream portion of the detector is constructed from a series of tracking planes without the interleaved water target.
5.3 The ND280 Off-axis Sub-detectors

5.3.1 The PØD Fine-Grained Detector

To meet the T2K physics goals the neutral current $\pi^0$ rate must be measured at the J-PARC site using the ND280 off axis detector. Due to conflicting requirements faced by this detector, it has been divided into two sub-detectors that have different emphasis. The Pizero Detector (PØD) which sits at the upstream end of the ND280 off axis detector has been designed to make a high precision measurement of neutrino interactions which contain electromagnetically showering particles using a water target, and the tracking detector which sits downstream of the PØD (see Figure 38 and Section 3.5). The PØD detector consists of an instrumented target region surrounded by an electro-magnetic calorimeter. The calorimeter is shared with the down stream tracking detector and is discussed elsewhere. This section will primarily describe the instrumented target region (which will be referred to as the PØD for convenience). The PØD is a scintillating bar detector that is similar to the successful K2K SciBar [12] and the approved MINER$\nu$A detectors. A diagram of the detector is shown in Figure 39.

Scintillating bar tracking planes are the primary component of the PØD. The baseline design has 76 tracking planes position along the beam direction. The design is centered around a simple modular component that can be constructed away from the T2K site and later assembled in the detector hall. Remote construction will also allow quality control and survey to be done during the tracking module assembly phase.

The tracking planes are constructed of polystyrene triangular scintillating bars that are fabricated by co-extruding with a reflective layer TiO$_2$ and a central hole for a WLS fiber. The nominal bar has a 3 cm base and a 1.5 cm height and has a length of 180 cm or 210 cm. Tracking planes have thin layer of lead (nominally 0.06 cm) sandwiched between $X$ and $Y$ layer of interlocked scintillating bars to increase the efficiency to detect gamma rays from $\pi^0$ decay. The light seal for the tracking plane is maintained by light manifolds which collect the WLS fibers into optical connectors. Light will be transported to the photo-sensors using clear optical fibers.

Because of the large number of scintillating bars ($\sim$20,000) and available space limitations, it is impractical route the fibers to photo-sensors outside of the magnetic volume. For this reason, the photo-sensors will be located within the inner detector basket. The Stony Brook group has identified a candidate photo-sensor, Micro-Channel Plate based Multi-Anode PMT (MCP-MAPMT) that is similar to devices that have been shown to operate in magnetic fields of approximately 1.5 T. This specific MCP-MAPMT (see Figure 40), however, has not yet been tested in a magnetic field. The manufacturer of this device, Burle, kindly agreed to loan a sample of 64-channel MCP-MAPMT to Stony Brook this summer so that we can test this device carefully to determine if it is truly a good candidate. Other candidate photo-sensors that are being investigated are Geiger-mode SiPM and MA-HPD.
One of the constraints facing the PØD is that the neutrino interactions must be measured on a oxygen target. In the baseline design, this is achieved by interleaving water target planes between the 30 upstream scintillating bar tracking planes. Oxygen cross section measurements will be made by comparing the interaction rate for events vertices in the upstream and downstream portions of the detector. This introduces a certain level of complexity into the design not present in either the SciBar or MINERνA detector, and affects track reconstruction efficiency. Care is taken to assure that the composition and detection efficiencies in the upstream and downstream detector regions are well controlled. The oxygen target is provided by a $\sim 3$ cm thick water target. Candidate containers have been identified and are expected to introduce an additional $0.06 \text{ g/cm}^2$ of material.

The baseline detector design has a total mass of approximately 12 tons with a fiducial mass of 1.7 tons of water, 3.6 tons of plastic scintillator, and 0.8 tons of lead. Based on the expected event rates, we expect to collect a total sample of approximately 60,000 neutral current single-$\pi^0$ events for an exposure of $10^{21}$ pot (approximately one year), of which approximately 17,000 occur in the water target. This number will be reduced by the reconstruction efficiency. As discussed below, this large sample of $\pi^0$ events is required to predict the $\pi^0$ production rate at Super-Kamiokande as a function of momentum and direction.

**PØD event reconstruction capabilities** The capabilities of the PØD have been studied using a detailed detector simulation and track pattern recognition. Where the results depend on the behavior of the photo-sensor, the light collection has been tuned to match the MINERνA vertical slice test and corresponds to approximately 22 pe/layer/MIP.

The PØD has been designed to have the largest possible target mass, while maintaining a
Figure 41: The figure shows the fraction of the fully contained 200 MeV gamma ray energy measured in the scintillator after applying corrections for the P0D energy response.

Table 6: The efficiency to reconstruct a gamma ray as a function of the true gamma ray energy.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Overall Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MeV</td>
<td>68%</td>
</tr>
<tr>
<td>100 MeV</td>
<td>81%</td>
</tr>
<tr>
<td>200 MeV</td>
<td>85%</td>
</tr>
<tr>
<td>400 MeV</td>
<td>85%</td>
</tr>
</tbody>
</table>
Figure 42: The top figures show the efficiency as a function of the Z position to reconstruct photons with 50 MeV, 100 MeV, 200 MeV and 400 MeV of energy inside the P̃ÕD. The bottom figures show the efficiency to reconstruct photons as a function of the photon direction. The solid histograms show the efficiency to reconstruct photons using a specialized photon tracking program. The dashed line shows efficiency to reconstruct a photon using standard tracking.
large efficiency to reconstruct low energy gamma rays. The baseline active target described in this proposal has not been fully optimized, but we believe it sufficiently demonstrates the potential for this detector.

The primary goal for the P0D active target is to measure neutral current single $\pi^0$ production where in the typical case, all particles traveling further than a few centimeters from the interaction vertex without a hit will be neutral. For this reason, it is quite important that the P0D have high efficiency to detect gamma rays leaving the fiducial volume. By requiring a localized cluster of energy deposition in either the X or Y projection, the active target will detect $85\%$ of gamma rays with $E_\gamma > 100$ MeV that originate more than 30 cm from the edge of the detector. The detection efficiency drops to $68\%$ for $E_\gamma = 50$ MeV. The efficiency as a function of energy is shown in Table 6. Gamma rays which leave the target without depositing energy are likely to be detected in the P0D EM calorimeter which is discussed elsewhere.

Without accounting for photon-counting statistics of the light collected from the scintillating bars, the energy resolution for events fully contained in the active target is approximately $\sigma_E = 10\% + 3.5%/\sqrt{\text{GeV}}$. Including the effect of real light detectors worsens the statistical component of the energy resolution to approximately 5%. Figure 41 shows the fraction of energy detected in the scintillator for fully contained 200 MeV gamma rays after correcting for the effects of light attenuation in the WLS fiber and inactive material in the P0D.

Figure 42 shows the efficiency to reconstruct photons as a function of the Z position in the P0D (top plots), and direction (bottom plots). In these figures, the water target is located between -170 cm and -340 cm. For photons with more than approximately 100 MeV the efficiency as a function of position is quite uniform, but the efficiency for 50 MeV photons drops to approximately 60% in the water target region while remaining above 75% in the carbon target region. The efficiency is also relatively uniform as a function of the photon angle, although the planar nature of the P0D give a moderate reduction perpendicular to the neutrino beam direction.

Figure 43 shows two examples of $\pi^0$ events as simulated in the P0D. The left figure shows an X and Y projection of a neutral current $\nu_\mu p\rightarrow p\pi^0$. The proton track, and the $\gamma$-rays from the $\pi^0$ is clearly visible in both projections. The proton can be identified based on the charge deposition as a function of length, while the $\gamma$-ray tracks show a clear E&M shower signature. All tracks can be projected back to a single vertex within the detector which corresponds to the start of the proton track. The right figure shows an X and Y projection of a $\nu_\mu n\rightarrow n\pi^0$ event where the $\gamma$-rays from the $\pi^0$ are clearly visible. The $\gamma$-ray tracks can be projected back to a single position along the Z axis, and show a clear E&M shower signature.

Table 7 gives the efficiency to reconstruct the neutral current $\pi^0$ production rate which has been estimated using a sample of events preselected by the following criteria: 1) There must be at least one $\pi^0$ produced in the event. 2) There must be no muon or charged pion with more than 250 MeV/c. 3) The event must have originated more than 25 cm from
Figure 43: Typical neutral current single $\pi^0$ production events. The left panels shows a 983 MeV/c proton and a 495 MeV/c $\pi^0$. The right panels shows a single 473 MeV/c $\pi^0$ that was accompanied by a neutron. The upper (lower) panels show a projection of the Y-Z (X-Z) hits. The various colors (red, green, etc.) show the results of a track reconstruction applied to these events. The axes are labeled in centimeters.

Table 7: The efficiency and background to reconstruct neutral current $\pi^0$ events.

<table>
<thead>
<tr>
<th>Momentum</th>
<th>Efficiency</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 – 300 MeV/c</td>
<td>52% ± 3%</td>
<td>18%</td>
</tr>
<tr>
<td>300 – 400 MeV/c</td>
<td>54% ± 4%</td>
<td>19%</td>
</tr>
<tr>
<td>400 – 600 MeV/c</td>
<td>59% ± 4%</td>
<td>22%</td>
</tr>
<tr>
<td>600 – 800 MeV/c</td>
<td>47% ± 6%</td>
<td>8%</td>
</tr>
<tr>
<td>&gt; 800 MeV/c</td>
<td>62% ± 4%</td>
<td>7%</td>
</tr>
</tbody>
</table>
the edge of the PD. These events are then reconstructed using automated algorithm and considered to contain a $\pi^0$ if: 1) There are at least two reconstructed tracks of any type. 2) At least two tracks start from different points. 3) The reconstructed vertex is inside the PD. To calculate the final efficiency, the reconstructed vertex was required to be within 30 cm of the true vertex. The efficiency presented in Table 7 is consistent with a uniform $\pi^0$ reconstruction efficiency of 55\%±5\%.

Predicting the number of $\pi^0$ inclusive events at Super-Kamiokande as a function of $\pi^0$ momentum is one of most important roles of PD.

Although the neutrino spectrum at 280 m is different from that at Super-Kamiokande, the $\pi^0$ momentum distribution at 280 m and at Super-Kamiokande are quite similar. This is seen in Figure 44 where the ratio of $\pi^0$ yield at Super-Kamiokande to that at 280 m as a function of $\pi^0$ momentum (far/near ratio of $\pi^0$ momentum) where scale is arbitrary just to compare the shape.

As shown elsewhere, the far/near ratio of the neutrino energy spectrum varies by more than 50\%, especially in the energy region between 400 MeV and 700 MeV. The far/near ratio of the $\pi^0$ momentum, on the other hand, is quite flat. This indicates that the $\pi^0$ momentum spectrum from neutral current inclusive $\pi^0$ production does not depend very
much on the neutrino energy spectrum. Therefore we do not need to know precisely the cross section for these events as a function of the neutrino energy, although good knowledge of energy resolution is essential. A measurement of the $\pi^0$ momentum distribution at the 280 m off-axis detector is a good prediction of the neutral current $\pi^0$ production rate at Super-Kamiokande.

In the following we will consider sources for systematic error on the prediction of inclusive neutral current $\pi^0$ events produced at Super-Kamiokande using the measurement on the same neutral current inclusive $\pi^0$ events at P0D. These sources come are:

- Uncertainty arising from the statistical errors on the measurement at P0D.
- Uncertainty arising from the detection efficiency for the neutral current inclusive $\pi^0$ events (signal events).
- Uncertainty arising from the detection efficiency from non neutral current events (background events).

Here the uncertainty in the detection efficiency should be understood in a broader sense than usual. It includes uncertainties in the estimate of the number of target nucleons and in the knowledge of event migration due to $\pi^0$ energy resolution. Further, the detection efficiency uncertainty includes systematic uncertainty associated with the subtraction that is required to obtain the event rate on oxygen. A particularly important component will come from the uncertainty in the relative efficiency of different portions of the P0D.

Using the number of neutral current inclusive $\pi^0$ events observed by P0D, we can estimate how many $\pi^0$ will be produced at Super-Kamiokande. Figure 45 summarizes the statistical errors for several $\pi^0$ momentum ranges assuming a 1.7 ton fiducial mass.

The systematic error on the number of NC inclusive $\pi^0$ events produced arises from uncertainties in the estimation of the signal and background detection efficiency, and in the estimation of the cross section ratio for background to signal. For simplicity, the neutrino flux is assumed to be known, but will also contribute to the systematic error.

Table 8 is a summary of the contribution from each type of uncertainty as a function of $\pi^0$ momentum. The $\pi^0$ flux uncertainty is dominated by the statistical error and the error on signal detection efficiency (in the broad sense as explained above). Since we aim to control this systematic error to under 10%, we need to control the detection efficiency error to approximately 9%, considering the maximum statistical error of 5% for $\pi^0$ momentum of up to 1.0 GeV/c. The uncertainty in the relative cross section of the background to the signal can be quite large. In the extreme case of a relative cross section uncertainty approaching 30%, the contribution to the systematic error is 5% at a $\pi^0$ momentum of 250 MeV/c.

Figure 46 shows two typical quasi-elastic neutrino events as measured in the P0D. The P0D has not been optimized to measure events containing only heavy charged particles, but contains a large fully active target. In fact, the target mass for the P0D will be significantly
Figure 45: The percent statistical error as a function of $\pi^0$ momentum after one accelerator year of a 1.7 ton of fiducial volume.
<table>
<thead>
<tr>
<th></th>
<th>Uncertainty vs. $\pi^0$ Momentum (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>250</td>
</tr>
<tr>
<td>Statistical (1 yr)</td>
<td>2%</td>
</tr>
<tr>
<td>“Signal” Efficiency</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>4%</td>
</tr>
<tr>
<td>“Background” Efficiency</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>7%</td>
</tr>
<tr>
<td>Relative Cross Section</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>7%</td>
</tr>
</tbody>
</table>

Table 8: Summary of contributions to the systematic error on the number of $\pi^0$ events in a particular energy band at the 280 m detector from different sources. The first column gives the achieved systematic uncertainty on the parameter. The remaining columns give the effect of that systematic error on the number of $\pi^0$ events.
Figure 46: The left panel shows a quasi-elastic neutrino interaction with a 275 MeV/c muon and a 690 MeV/c proton. The right panel shows a quasi-elastic interaction with a 420 MeV/c muon and a 696 MeV/c proton. The colors represent the result of pattern recognition applied to these events. The axis is labeled in centimeters.
larger than that of the FGD detector. For this reason, the P0D will provide an excellent verification of measurements made with the much more precise FGD+TPC combination, and can provide access to processes with small partial cross-sections.

Mechanical structure and construction plan The P0D is a solid scintillator strip detector using water to provide a large oxygen content and is based on K2K SciBar experience and MINERνA design. The P0D target is constructed of water layers between X-Y scintillator modules which provide the charged particle tracking. The scintillator modules are constructed with a 22% lead by mass so that γs have a high probability of creating an electromagnetic shower. The P0D has a total target mass of approximately 14 tons and a fiducial mass of approximately 6 tons.

Figure 47 shows the schematic view of a P0D target. The tracking layers consist of X and Y extruded scintillator planes (white) with a 0.6 mm foil (red) sandwiched between them. The scintillator planes are made light tight with layers of mylar on the large faces (not shown), and end caps (dark green). The end caps serve the dual purposes of providing a manifold to bring WLS fibers (cyan) out of the scintillating bars, and keeping the ends of the scintillator light tight. A water cell is placed between half of the scintillator modules to provide oxygen target. Figure 48 shows the schematic view of the assembled P0D layers.

The water cells consist of semi-flexible pillow bladders, nominal dimensions 3 cm × 1.8 m
Figure 48: The schematic view of assembled PØD layers. White shows extruded scintillators; red shows lead foil; yellow shows water cell; green shows polypropylene plate.

× 2.1 m, holding about 100 kg of water each. They are provided with fill tubes at top and drain tubes at bottom. The drain tubes will run through a simple manifold outside the magnet, and thus serve as sight tubes for checking water levels. The bladders are made from rubberized cloth or polyethylene-coated EVAL plastic. Similar in construction to inflatable boats or industrial fluid storage bladders, such bags have a well-established engineering history of toughness and long-term reliability. (Similar bags have been used for decades to waterproof balloon flight packages in Japan, where scientific balloon flights typically land in the sea.) The proposed budget includes prototypes for testing, and spares.

Figure 49 shows a plan view of the whole PØD detector. The size of the target volume is 1.8 m × 2.1 m × 3.3 m, which is obtained by minimizing the space needed (35 cm in thickness) for PMT box mounting and clear fiber routing. The PMTs and front-end boards are installed in boxes for optically shielding.

Particle tracking is done using extruded scintillators similar to that used in the K2K SciBar detector and is in the MINERνA design. The PØD design calls for triangular scintillator bars that are 1.5 cm in height and 3.0 cm in base that are co-extruded with a TiO₂ surface treatment (see Figure 50). The bar length is 1.8 m for an X-plane and 2.1 m for a Y-plane. Each scintillator module is constructed from 120 (140) bars oriented in the X (Y) direction and there are a total of 76 scintillator planes in the baseline design. In total we have 19,760 scintillator strips. Each scintillator module is optically shielded by mylar and...
Figure 49: The schematic view of the PØD. Right and left figure shows front and side view, respectively. Pink shows PMT box; dark green shows end-cap; blue shows support structure; orange shows clear fiber.

Figure 50: Prototype MINERνA scintillator bars with WLS fibers. The size of each bar is 33 mm in base and 17 mm in height. The PØD will use bars with similar size and shape, but with a co-extruded TiO$_2$ surface treatment.
four end-caps. We expect the scintillator will be produced by the northern Illinois Center for Accelerator and Detector Development (NICADD) at Northern Illinois University (NIU). NIU physicists and mechanical engineers have formed a collaboration to support development of the next generation of detectors at the Fermilab Scintillator Detector Development Laboratory (FSDDL). NICADD and Fermilab have significant scintillator extrusion experience and are expected to produce MINERvA triangular bars, which is similar to our design. The quantity of scintillator required by the P0D is well matched to the FSDDL production capacity. An important point in producing extruded scintillators is the development of the die used to shape the final scintillator cross-section. A triangular die has been developed by MINERvA similar to that required by the P0D. The scintillator strips are made of polystyrene doped with PPO (1% by weight) and POPOP (0.03% by weight) and co-extruded with a reflective coating of TiO$_2$. The total 7.2 tons of extruded scintillators included in the full P0D design will require a production run of approximately six weeks.

Wavelength shifting (WLS) fiber (Kuraray Y11) is inserted into the hole of each scintillator strip. The light will be read out from only one end of each fiber. In K2K SciBar and MINERvA, 1.2 mm and 1.5 mm diameter fibers have been tested. 1.5 mm fibers deliver more light than 1.2 mm fibers; however, we use 1.2 mm fibers which have a smaller bending radius, because the available space for the P0D is limited. To increase the light collection, unread end of each fiber is mirrored. Mirroring consists of polishing the end to be mirrored, depositing a 99.999% chemically pure aluminum reflective surface on the fiber, and with a coat of epoxy.

The WLS fibers are connected to clear fibers using an optical connector from Fujikura/DDK. This connector was originally developed for the CDF Plug Upgrade by DDK, in consultation with Tsukuba University and has been used by several other experiments. Figure 51 shows the DDK connector embedded in a boot that was developed by the MINERvA collaboration. The DDK connector consists of a ferrule, clip, and box. They snap together without screws or pins. Bundles of eight WLS fibers will be connected to a single DKK connector. The remaining light collection system consists of clear fiber bundles which take the light from the scintillator module to the PMT box, and a clear fiber “pigtail” which distributes the light to individual PMT pixels inside of the PMT box. The clear fiber cables are kept light-tight by an opaque sheath. There is an RTV silicon rubber boot around the end of the sheath and connector to maintain a light-tight seal. This has been proto-typed and tested for MINERvA. This DDK connector is installed in the end-cap (dark green in Figure 47). WLS fibers and scintillators are fully light-shielded. The thickness of the end-cap is 16 cm which is determined by the bending radius of the WLS fibers (10 cm). The other end of the clear fiber cables are inserted into an acrylic cookie for connection to a PMT in the PMT box.

The P0D modules are assembled from an X and Y plane of scintillator. To assemble an X-plane, we put 70 triangular bars (base down) on a frame-table. After applying glue to the upper faces of these bars, we place a second set of bars (base up) on top of the first.
We assemble Y-planes in the same way as X-planes. The X-plane, lead foil, and Y-plane are glued together one by one, and we attach end-caps to the sides of the layer. After the scintillator and end-caps are assembled, WLS fibers with optical connectors are inserted into all the scintillator strips in the layer and the layer is fully light-shielded by closing the end-caps. Assembled layers are tested to assure the quality of the light shield, WLS fibers, and optical connectors.

After the modules have been fully assembled, the energy response as a function of position will be scanned using a $^{137}$Cs source mounted on a movable frame. Approximately 10 measurements will be taken along each fiber so that the attenuation can be accurately determined.

After assembly and quality control, all modules, water cells and polypropylene plates will be shipped to J-PARC for installation into the ND280 off-axis detector. Installation will be done one module at a time by lifting it into a pre-installed support structure inside of the magnetic coil. The PMT boxes are then installed around the outside of the PØD. After all of the modules and PMT boxes are installed, we connect clear fiber bundles to the optical connectors in the end-caps and PMT boxes which are attached at a support frame. This procedure is very similar to that used to install the K2K SciBar detector.

**Expected Light Yield for a MIP** Since the PØD detector has been designed to be very similar to the K2K SciBar detector and MINER$\nu$A, we use the measured performance of these detectors to estimate the expected PØD light yield. The PØD bars will be instrumented
using WLS fiber that is read on one end using a MCP-MAPMT, the uninstrumented end will be mirrored.

The SciBar detector used for the K2K experiment is made of scintillator bars read by a wavelength shifting (WLS) optical fiber. Each scintillator has dimension of 2.5 cm × 1.3 cm × 300 cm. Only one end of the fiber is read by a MAPMT, and the opposite end is not mirrored. The observed light yield at the center is 10.8 pe/MIP/cm with a 1.5 mm Kuraray Y11(200) WLS fiber that is 3.5 m long. Without accounting for mirroring, assuming a linear relationship between fiber diameter and correcting for the relative efficiency of the SciBar MAPMT and the proposed MCP-MAPMT, the light yield in the center of the PÔD is estimated to be 8.0 pe/MIP/cm (this includes corrections for the clear fiber and the optical connectors).

The MINERvA experiment uses triangular scintillator bars with a similar dimension as proposed for PÔD: 3.3 cm (base) × 1.6 cm (height). The WLS fiber is 1.2 mm in diameter and is made of s-35 multi-clad Kuraray fiber with 175 ppm Y11. The MINERvA collaboration conducted a light yield test with 3.5 m WLS fiber without aluminum coating on the far end. The average light yield was measured using cosmic ray muons and was found to be 6.3 pe/MIP/cm. Applying corrections similar as used for the SciBar, this corresponds to 5.2 pe/MIP/cm.

Based on the relatively low light yield expected based on the SciBar and MINERvA measurements, we propose to mirror the PÔD WLS fibers. This will increase the light yield at the center by approximately 50%, but also flattens the response over the length of the bar. Using light yield measured in the MINERvA cosmic ray test, we expect that the PÔD light response will vary between 7.3–9.2 pe/MIP/cm. This increases to 11.3–14.1 pe/MIP/cm for the SciBar measured values. The expected light yield for a PÔD layer then is between 11 pe and 21 pe. This is sufficient light yield for our purpose.

**DAQ Electronics for the PÔD subsystem** Currently we have a workable design for the PÔD detector electronics, mostly based on the MINERvA experiment electronics, assuming that we will use MCP-MAPMTs as the photo-sensors for the PÔD. This is also used to cost the electronics budget presented in the budget section. The electronics design, however, cannot be finalized at this time because of the uncertainty in the choice of a photo-sensor that will perform satisfactorily in a 0.2 T magnetic field. Thus, at this time, the T2KUK collaboration and the T2K US B280 collaboration have agreed to collaborate in this project in order to come up with a final electronics design that is appropriate for the choice of photo-sensor and cost-effective. In the following we present the current baseline of the PÔD electronics.

The PÔD will have a total of 19,760 channels, from 309 MCP-MAPMTs, each with 64 independent anode channels serving individual scintillator bars. The data acquisition (DAQ) system must digitize pulse edge arrival times to within a few nanoseconds, and pulse charge
to 0.25 photo-electron (pe) equivalent.

To reduce costs and eliminate the need for lengthy R&D, the PØD could adopt readout electronics components currently under development for MINERνA if the final choice of the PØD photo-sensor characteristics match the MINERνA electronics. The key elements of the MINERνA electronics design have already reached the advanced prototype stage, and successful cosmic-ray tests at Fermilab have demonstrated performance well-matched to the needs of the ND280. Design, fabrication and testing of production prototypes for both custom boards in the system (front-end digitizers, and VME readout modules) is supported as part of MINERνA’s approved FY’05 R&D budget.

The front-end boards mounted outside the light-tight photosensor housings will digitize timing and pulse-height signals, provide high-voltage for the photo-sensors, and communicate with VME-resident readout controller modules over an LVDS token-ring. Pulse-heights and latched times will be read from all channels at the end of each spill. The cost of the proposed readout electronics and data acquisition system, including contingency, is approximately $25 per channel.

The front-end board is designed around the D0 TRiP ASIC, which is a redesign of the readout ASIC for the D0 fiber tracker and preshower. Its analog readout is based on the SVX4 chip design. Each TRiP chip supports 32 channels for digitization, but only half that number of channels for discrimination and timing.

The pre-amplifier gain is controlled by jumper and has two settings which differ by a factor of four. The gain of the second amplifier stage is controlled by three additional jumpers. The amplified analog signal goes into a pipeline 48 cells deep. To gain dynamic range, we will increase the input range of the electronics by passively dividing charge from a single pixel among two TRiP analog channels with a ratio of a factor of 10. The “high range” channel, then, will allow energy depositions many times greater than minimum ionizing to be recorded without saturation. Each TRiP channel will be digitized by a 12-bit ADC.

Only one of every two input channels to the TRiP chip has a latched discriminator output useful for timing information. The lower range channels will feed the latch whose output is presented to an FPGA. With appropriate firmware, internal logic of the FPGA can be used measure timing with a granularity of 5 ns. To measure the time of the latch firing accurately, a 25 MHz reference clock is multiplied by four in a PLL and phase shifted by 90 deg to form a quadrature clock that is used inside the FPGA to form a digital TDC with least bit resolution of 2.5 ns. This feature has been tested on the prototype board and timing resolution better than 2.5 ns least count has been achieved. The reset time for the latch is only 15 ns, so inside a spill the latch will be in the ready state by default. After the signal exceeds a threshold and the latch fires, it is reset incurring minimal deadtime.

Each board includes its own high-frequency phase-locked oscillator, which provides a local clock signal for the FPGA logic. Global synchronization is provided using an external counter-reset reference signal distributed over the LVDS interface from the VME readout boards once every second, and originating with a timing module which is, in turn, synchro-
nized to the beam.

A resonant mode Cockroft-Walton high-voltage generator, mounted on a daughter card, will provide power to each board's PMT. The daughter-card design will allow a malfunctioning high-voltage supply to be easily replaced without changing the main readout board. A controller based on the Fermilab RMCC chip will allow the PMT voltage to be monitored, adjusted or disabled under computer control, using the LVDS interface to the board.

The internal behavior of the front-end board is supervised by an FPGA operating as a finite-state machine, making the system programmable and highly flexible. The most mission-critical and demanding elements of the firmware (controlling the TRiP chip’s buffering and TDC functionality) have already been developed and tested, during commissioning of the first prototype in 2004. Logic to interpret commands and exchange data over the LVDS interface, and control the on-board Cockroft-Walton high-voltage supply has since been written and is now being tested. Persistent storage for the firmware is provided by an onboard flash PROM, which is read by the FPGA on power-up and can be re-written under computer control. As such, it will be possible, if necessary, to reprogram the FPGA logic of all boards remotely, even after installation.

The front-end digitizer boards are daisy-chained into 27 LVDS token rings of 12 boards each. Both ends of a chain terminate in a custom built VME Chain Read Out Controller (CROC) module.

LVDS signals will be transmitted around a ring on standard, commercially-available fire-resistant and halogen-free CAT-5e network cable approved by for safe underground use. The LVDS chains will also be used to transmit configuration and slow-control messages to the cards.

Each CROC module will control four LVDS chains, requiring a total of 7 CROCs (plus spares) for the entire detector. These modules will reside in a VME crate alongside a crate controller and a custom-built timing distribution module.

The readout controller modules have the following functions:

1. Prior to the arrival of a spill, as signaled by the VME-resident timing module, to reset the timing counters of each front-end board and open a 10\mu sec gate to collect data from the spill.

2. Upon completion of a spill, to initiate readout of front-end digitizer data over the four associated LVDS rings, into internal RAM.

3. Upon completion of the parallel readout of all four chains, to raise an interrupt with the main DAQ computer, indicating that event data is available. The PVIC/VME interface/crate controller allows VME interrupts to be received directly by the main computer.

4. The internal RAM of each CROC is memory-mapped to the host computer’s PCI bus, allowing block transfer of event data via the PVIC/VME interface/crate controller.
Table 9: Tasks required to construct the P0D and the institutions with primary responsibility

<table>
<thead>
<tr>
<th>2.1</th>
<th>ND280 P0D</th>
<th>Responsible Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.1</td>
<td>Water Target Materials and Labor</td>
<td>U. Washington</td>
</tr>
<tr>
<td>2.1.2</td>
<td>Lead Absorbers</td>
<td>Stony Brook</td>
</tr>
<tr>
<td>2.1.3</td>
<td>Clear Fiber Cables</td>
<td>Rochester</td>
</tr>
<tr>
<td>2.1.4</td>
<td>WLS Fiber Materials and Labor</td>
<td>Rochester</td>
</tr>
<tr>
<td>2.1.5</td>
<td>Scintillator Production</td>
<td>Rochester</td>
</tr>
<tr>
<td>2.1.6</td>
<td>Module Assembly</td>
<td>Stony Brook</td>
</tr>
<tr>
<td>2.1.7</td>
<td>Modules Scanner Construction</td>
<td>Rochester/Stony Brook</td>
</tr>
<tr>
<td>2.1.8</td>
<td>Module Scanning</td>
<td>Stony Brook</td>
</tr>
<tr>
<td>2.1.9</td>
<td>Electronics</td>
<td>T2KUK/U. Washington</td>
</tr>
<tr>
<td>2.1.10</td>
<td>Shipping and Installation in Japan</td>
<td>All Institutions</td>
</tr>
<tr>
<td>2.1.11</td>
<td>Photo-Sensors</td>
<td>T2KUK</td>
</tr>
</tbody>
</table>

The relatively long machine duty cycle and low data rate ensures that no deadtime will be associated with the readout itself.

5. Once per second, to globally synchronize the detector’s TDCs over LVDS using a high-precision refresh signal from the timing distribution module. The need for this synchronization drives the choice of LVDS for the readout chains, as opposed a less performant alternative such as Ethernet.

6. Upon command of the main data acquisition computer, to control and monitor the Cockroft-Walton high-voltage power-supplies on the front-end digitizer boards, and to configure the firmware of these boards at run-startup.

Communication between the main data acquisition computer will be via commercially available PVIC/VME link, allowing block data transfers to and from VME and interrupts to be received by the computer in response to the spill gate.

The main DAQ and slow-control computer will be located near the VME electronics, with high-speed TCP/IP links (one for data, one for monitoring and control messages) to the laboratory network. A relatively modest, dual-CPU server model will be more than adequate for our purposes. One CPU will be dedicated to real-time data acquisition, and the other will handle control messages and monitoring. An on-board, RAID-5 disk cluster with sufficient capacity to store several weeks of data will serve as a buffer for the data, pending transfer to offline processing nodes and permanent storage.
Figure 52: Left plot: muon momentum for CC-QE muons reaching the SMRD with $cos\theta < 0.8$. Right plot: muon momentum for CC-QE muons reaching the SMRD versus $|cos\theta|$.

**Tasks to Construct the PØD** Table 9 gives the top level WBS for the PØD, as well as the responsible institutions. Several groups outside of the U.S. expect to make contributions to construction.

**5.3.2 The Side Muon Range Detector (SMRD)**

The muon momentum distribution for CC-QE interactions is shown in Figure 52. The vast majority of large angle muons, namely 91% of all muons not escaping in the forward direction (e.g. $cos\theta < 0.8$) has momenta of less than 600 MeV/c.

As can be seen in Figure 53 muons with energies less than 600 MeV will range out within less than 35 cm of iron. Since the iron plates in the previously described yokes (Section 3.5.2) are 4.8 cm thick it would be sufficient to instrument 6 radial layers in order to completely range out 95% of all muons that are not escaping in the forward direction. Table 10 lists the range of muons in iron and the corresponding number of layers, as functions of energy along with the fraction of muons that is represented. First energy resolution estimates from a crude GEANT 3 based Monte Carlo study are shown in Figure 54. This Monte Carlo assumed a set of 5 cm thick parallel iron plates onto which a sample of 200 MeV to 1 GeV muons impinge at angles in the range from 0 to 90 deg.

The study indicates that a muon energy resolution of less than 10% can be achieved. As expected the energy resolution is best for muons emitted at large angles (e.g. perpendicular to the beam direction) and worsens for muons emitted at smaller angles with respect to the
Figure 53: Relation between muon energy and range in iron as seen in data from Monte Carlo study [18].
Table 10: Maximum detected muon momentum and corresponding fraction $f$ of muons originating from CC-QE reactions with $|\cos \theta| < 0.8$. The penetration depth in iron and the corresponding number of layers in the SMRD are specified in the two right-hand columns.

<table>
<thead>
<tr>
<th>$P_{\mu}^{\text{max}}$ (GeV)</th>
<th>$f$ (%)</th>
<th>Range (cm)</th>
<th>Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>79</td>
<td>24</td>
<td>5</td>
</tr>
<tr>
<td>0.6</td>
<td>91</td>
<td>31</td>
<td>6</td>
</tr>
<tr>
<td>0.7</td>
<td>96</td>
<td>37</td>
<td>7</td>
</tr>
<tr>
<td>0.8</td>
<td>98</td>
<td>44</td>
<td>9</td>
</tr>
<tr>
<td>0.9</td>
<td>99</td>
<td>51</td>
<td>10</td>
</tr>
<tr>
<td>1.0</td>
<td>99</td>
<td>57</td>
<td>12</td>
</tr>
<tr>
<td>1.1</td>
<td>100</td>
<td>65</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 54: The muon energy resolution as function of muon momentum (left) and as a function of angle with respect to the beam (right) [18].
beam direction.

In order for the 280m detector to reliably identify CC-QE interactions and identify background events originating from the cavity and the iron yokes, the SMRD is required to identify minimum ionizing particles (MIP) with very good efficiency. Hence the active detector medium has to provide uniform and high light yield. It is also required to have sufficient inter-layer timing resolution to distinguish inward from outward going particles.

The neutrino beam will consist of 8 bunches with a time spread of about 60 ns each and a separation of about 360 ns between bunches. In order to clearly identify events with individual bunches in the beam a time resolution of at least some tens of nanoseconds is required. However, more stringent timing is required in order to resolve event times within a single bunch, achieve good position resolution, and obtain directional information. Monte Carlo studies are currently in progress to address granularity and background issues. The scintillator segmentation and electronics requirements will be derived from these studies.

Detector Design and Technology  The baseline detector technology was chosen based on its ability to satisfy the minimum physics requirements, reliability, cost effectiveness, and availability. LSU has played a leading role in identifying this baseline design which is described in the following section.

Scintillators and Wavelength Shifting Fibers  The active component of the SMRD will consist of slabs of 1 cm thick scintillator. The scintillators will be sandwiched between the iron plates of the magnet yokes. Equidistant wavelength shifting fibers will be immersed into the scintillators in order to achieve good light yield and consequently high detection efficiencies of traversing minimal ionizing particles (MIP). The WLS fiber will also serve to guide the light into the photo-detectors. Depending on the light yield which is determined by the characteristics and thickness of the scintillator, the quality of the wavelength shifting (WLS) fibers, and their relative spacings, the fibers can be read out on both sides or mirrored on one side and read out on the other. The scintillators will be coated with a chemical reflector to enhance the light yield. Similar combinations of scintillator slabs and WLS fibers have been used as muon or photon veto detectors in other experiments such as ZEUS [20], KOPIO [21], and E949 at BNL [22]. Furthermore, extensive R&D of this technology has been carried out for the SSC [23]. Figure 55 shows long slabs of extruded scintillators with immersed fibers spaced at 2 cm and 1 cm, respectively. Figure 56 displays preliminary results from light yield measurements in response to traversing MIPs of the scintillators shown in Figure 55.

An alternative to the baseline design would be a slightly modified technology. A combination of extruded scintillators with embedded WLS fibers coupled to wavelength shifter bars or light guides is conceivable. The advantage would be to minimize the risk of fiber damage due to bending or interference with cables in the gaps between individual iron yokes. The
Figure 55: The picture shows 210 cm long, 17 cm wide, and 1 cm thick scintillators with embedded WLS fibers (Y11) of 240 cm length. The spacing between the fibers is 2 cm and 1 cm, respectively. The fibers are glued into 2 mm deep grooves and the scintillators are coated with a chemical reflector.
Figure 56: Preliminary ADC spectra from light yield measurements for cosmic muons intersecting the center of the scintillator slab [19]. The various panels correspond to different scintillator and fiber configurations.

Wavelength shifter bars or light guides are more robust than the fibers. This option would come with the disadvantage of an additional interface which is estimated to cause a 10% light loss.

We propose to provide the active components of the SMRD detector. LSU has ample experience with scintillators read out through embedded WLS fibers. The experience spans the fabrication process in the local workshop, testing with local test stands, and the installation and operation of scintillator detectors.

Even though the final budget of the Japanese groups for contributions to the 280m off-axis detector has not yet been made public, the Japanese groups, in particular Kyoto and Tokyo, are interested to provide WLS fibers for the 280m off-axis detector. Our colleagues at INR Moscow, Russia have committed to contribute $150k and one full time employee to the SMRD project over a period of 3 years. In addition, there are good prospects that a group of 8 to 10 technicians at INR will become available in early 2006. This group of technicians is highly experienced in the production and testing of scintillator detectors with embedded WLS fibers.

**Multi-anode PMTs** Bundles of fibers will be read out by conventional but magnetically shielded multi-anode PMTs (MA-PMTs) or micro-channel plate photo-multiplier tubes (MCP-PMTs) which will be connected to transient waveform recorders (FADCs). MCP-
PMTs have the advantage to allow unshielded operation in magnetic fields without significant loss in performance. The left panel of Figure 40 illustrates the basic functioning of a MCP-PMT and the right panel shows pictures of an actual device. However, only limited experience with MCP-PMTs exists and further suitability studies are required to look at gain stability and dead time issues. Choice of photo-sensor which will work inside a 0.2 T magnetic field is a common task for all ND280-offaxis detector components that use scintillator technology.

**Readout Electronics and Data Acquisition** The principal aim of the electronic system is to digitize the electric signal from the photo-detectors. Moreover, it can also supply the high voltages to the photo-detectors and provide monitor and control functions. The electronics has to measure and digitize the signal from each photo-detector exceeding a threshold, recording hit times with a relative accuracy at the sub-nanosecond level, and to flag hits potentially corrupted by pileup from a previous hit. The electronics is required to have no dead time during a spill so as not to miss any events during a spill. All events shall be zero suppressed and only channel data above a programmable threshold shall be read-out.

Our Japanese collaborators from Kobe University have ample experience in building electronics for the SciFi detector in the K2K experiment and are committed to provide the electronics with support from the Kyoto group. The Kobe group consists of three faculty and their students.

**Detector Trigger** The main event trigger will be formed from a coincidence of the overall spill trigger with individual scintillator panel triggers. Each scintillator panel will self trigger if a signal exceeds a set pulse threshold. Based on these self trigger signals coincidence triggers between two or more scintillator panels separated by iron layers can be constructed. This type of trigger can be used for calibration purposes as the constant flux of cosmic ray muons penetrates the detector.

**Detector Calibration** Three different calibration systems, each aiming at a different task, are planned. These three systems are a light-injection system, cosmic ray muons, and a radioactive source system.

The baseline design of the light-injection system is based upon pulsed blue light-emitting diodes (LEDs) and aims to map the gain curve of the photo-multipliers, monitor short-term gain drifts, and to confirm the optical path integrity (e.g. check that no fibers are broken). We anticipate a system very similar to what is currently used for the SciBar [12] detector of the K2K experiment or in the MINOS [24] experiment.

The intensity of vertical muons above 1 GeV at sea level is \(I \sim 1 \text{ cm}^{-2}\text{min}^{-1}\) [25]. Given a detector surface of \(760 \times 560 \text{ cm}^2\), a total of 425,000 muons per minute, or 7,000 muons per second hit the detector. This constant flux of MIPs can be used to continuously monitor the
response of the horizontally oriented scintillator slabs. If the position of individual cosmic muons can be derived accurately with the inner detector components, the attenuation of the WLS fibers can be measured and compared to measurements before installation.

A radioactive source system allows an absolute calibration of each scintillator-WLS-fiber unit. Short stainless steel tubes can be attached at either end of the scintillator slab and serve as a guide track for a radioactive source. This technique has been used by BaBar [26] and MINOS [27] where it helped to reduce the systematic uncertainties significantly.

Our collaborators in the UK, in particular the group at Queen Mary University London and potentially a small group at Rutherford Appleton Laboratory are actively working on the various calibration systems and are pursuing the idea of approaching the 'Particle Physics and Astronomy Research Council' (PPARC) for resources to supply these systems.

**Installation of active SMRD components** The mechanical implementation of the SMRD will allow access to each scintillator slab after the start of the experiment, so that repairs and adjustments can be accomplished. It is anticipated to place the scintillator slabs into thin aluminum drawers. Each of the drawers will fit into a gap in the iron yokes and individual drawers will be connected to each other with flexible but sturdy spacers. This will allow installation and access for repair to all scintillator slabs despite the limited detector access space and space constraints imposed by the iron yokes. Figure 57 shows a sketch of

---

Figure 57: Illustration of the drawer system which will allow deployment and retrieval of the scintillator slabs.
such a drawer configuration. The drawers will also serve to protect the light tight wrapping from tear during installation and the retrieval mechanism allows full access for repair. It is anticipated that wavelength shifting fibers would exit the detector in between each (or every other) iron yoke. The MA-PMTs would be mounted at a distance from the iron yokes to minimize the impact of the magnetic field on their performance.

The Italian groups on the T2K project have provided the magnet, including refurbishing and engineering support. In addition to this already important contribution the Italian groups are presently discussing the possibility to submit a proposal to INFN to participate in the SMRD component of the detector. The SMRD is closely intertwined with the already provided magnet and would enhance the already substantial contribution of the Italian groups.

5.4 GPS Time Synchronization System

A unique DAQ requirement for long baseline experiments is the need to accurately and reliably timestamp event triggers at the far detector, for later comparison with timestamps of accelerator beam spills. For the K2K experiment, we developed and successfully employed a highly reliable system using duplicate GPS-based systems, providing synchronized UTC time at the near and far detectors with 20 ns precision and 50 ns absolute accuracy.

We propose to reproduce the K2K system for T2K, taking advantage of eight years of operational experience to introduce minor improvements. The new system will have 10 ns precision, and about 50 ns absolute accuracy. The system maintains time accuracy within these limits as long as it has at least one GPS satellite in range, and its rubidium-stabilized oscillator allows it to maintain time accuracy within 100 ns for periods up to about 5000 seconds if there is a temporary loss of all satellite data (which never actually happened throughout K2K running).

At each site, Ru-stabilized oscillators provide a stable local time base that is regularly calibrated and aligned with UTC using GPS data from two independent commercial GPS receivers (Figure 58). Since the time synchronization function is critical to the success of T2K, we propose to provide full on-site swappable backups for all specialized system components, to minimize downtime in case of component failure.

The GPS time synchronization system will consist of identical installations at each site (J-PARC and Super-Kamiokande). At J-PARC, the GPS equipment will be housed at the same location as the beamline monitor DAQ hardware. At Super-Kamiokande, new equipment will replace existing but outdated components in the external “Radon Hut” building and in the “Central Hut”, on top of the detector, where trigger electronics are housed. The 2km fiber optic cable between the radon hut and central hut at Super-Kamiokande will be reused. Current models of the GPS receivers offer improved reliability and more efficient firmware, which the 10-year old receivers used in K2K cannot be upgraded to match.

Each site will be equipped with the following:
Two independent commercial GPS receivers:

1. TrueTime rack-mounted XL-DC GPS receiver;
2. Motorola M12-plus OEM GPS receiver card (mounted on LTC).

- Weatherproof, lightning-protected antennas for each GPS receiver.
- Local Time Clock (LTC) board (custom VME board with rubidium-stabilized oscillator).
- VME crate with power supply.
- VME FIFO module to buffer GPS data.
- VME-PCIbus interface, to link PC to VME crate.
- PC workstation (typical 2 GHz, 512 MB RAM, 80 GB disk, ethernet ports, etc) with Linux OS.

As noted, we will provide on-site spares for each item above, ready for swap-in replacement if needed.

The total cost per site for the equipment listed will be $80K, including spares. Realtime software, and web-accessible tools for monitoring and control of the system, will be prepared by the UW group under the direction of H. Berns, who designed the corresponding systems for K2K.

6 Implementation and Management Plan

6.1 The T2K International Collaboration and the Status of the Experiment

In September 2002, at the NP2002 conference in Kyoto, Japan, a call was issued for official LOIs for possible experiments using J-PARC facility by the J-PARC Project Director Dr. S. Nagamiya. An LOI was submitted by K. Nishikawa et. al. to do a neutrino oscillation experiment (T2K) using the J-PARC 50 GeV PS (JHF), neutrino beam-line, near detector complex and the Super-Kamiokande detector. The LOI was signed by 150 physicists from 52 institutions in 12 countries. From U.S., 28 physicists from 14 institutions signed the document as shown in Table 11.

The LOI received a high priority mark from two J-PARC committee deliberations in March 2003. Encouraged by this recommendation, an international T2K collaboration was formed in May 2003. K. Nishikawa of Kyoto University, the current K2K international collaboration spokesperson, was elected as the spokesperson. Working groups and other minimally
Figure 58: Schematic overview of the GPS time synchronization system for T2K.

Table 11: Numbers of signers for Letter of Intent

<table>
<thead>
<tr>
<th></th>
<th>Number of signers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Countries</td>
<td>12</td>
</tr>
<tr>
<td>Institutions</td>
<td>52</td>
</tr>
<tr>
<td>Physicists</td>
<td>150</td>
</tr>
<tr>
<td>US Institutions</td>
<td>14</td>
</tr>
<tr>
<td>US Physicists</td>
<td>28</td>
</tr>
</tbody>
</table>
Table 12: List of the working groups and their conveners

<table>
<thead>
<tr>
<th>Working group</th>
<th>Names of the conveners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam line</td>
<td>T.Kobayashi(KEK)</td>
</tr>
<tr>
<td>Proton beam monitor</td>
<td>M.Iwasaki(Tokyo)</td>
</tr>
<tr>
<td>Target and Horn</td>
<td>A.K.Ichikawa(KEK)</td>
</tr>
<tr>
<td>Beam line control/electronics</td>
<td>Y.Hayato(KEK)</td>
</tr>
<tr>
<td>Muon monitor, ND280</td>
<td>T.Nakaya(Kyoto), A.Konaka(TRIUMF)</td>
</tr>
<tr>
<td></td>
<td>F.Sanchez(Barcelona), K.McFarland (Rochester)</td>
</tr>
<tr>
<td>2 km detector</td>
<td>T.Kajita(ICRR), M.Sakuda(KEK)</td>
</tr>
<tr>
<td></td>
<td>F.Pierre(Saclay)</td>
</tr>
</tbody>
</table>

Table 13: List of the Intrin/International Board of regional Representatives (IBR)

<table>
<thead>
<tr>
<th>Region</th>
<th>Name of the regional representative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>A.Konaka, J.M.Poutissou</td>
</tr>
<tr>
<td>France</td>
<td>F.Pierre</td>
</tr>
<tr>
<td>Italy</td>
<td>M.Mezzeto</td>
</tr>
<tr>
<td>Korea</td>
<td>S.B.Kim</td>
</tr>
<tr>
<td>Poland</td>
<td>D.Kielczewska</td>
</tr>
<tr>
<td>Russia</td>
<td>Y.Kudenko</td>
</tr>
<tr>
<td>Switzerland</td>
<td>A.Blondel</td>
</tr>
<tr>
<td>UK</td>
<td>D.Wark</td>
</tr>
<tr>
<td>USA</td>
<td>C.K.Jung (Chair), K. McFarland, H.Sobel</td>
</tr>
<tr>
<td>Japan</td>
<td>K.Nishikawa</td>
</tr>
<tr>
<td>(Spokesperson)</td>
<td></td>
</tr>
<tr>
<td>(KEK: Host Institution)</td>
<td>K.Nakamura</td>
</tr>
<tr>
<td>(ICRR: Host Institution)</td>
<td>Y.Suzuki</td>
</tr>
</tbody>
</table>
necessary collaboration structures were instituted as well as an Interim/International Board of regional Representatives (IBR) and convenors of the working groups were designated. Table 12 shows the list of working groups and their convenors and Table 13 summarizes the list of IBR. The IBR plays role of interim executive committee of the collaboration and represents the T2K experiment in their respective countries. The working group convenors organize and lead the respective working groups. The collaboration council is comprised of all collaborators with a Ph.D. degree and makes final decisions on the crucial matters to the collaboration by consensus or by vote if necessary. Jung serves as the Chair of the T2K IBR. This collaboration is interim in nature until an International Collaboration Agreement (ICA) is drafted and signed. (Currently an ICA is being drafted by a committee chaired by Jung and it is expected be in effect sometime this year.)

The T2K experiment was approved by the Japanese Ministry for Science and Technology in March 2004 for funding beginning in fiscal 2004. The total approved budget for the five-year construction plan is 16B-yen ($160M), which provides funds for the neutrino beam line and the 280 m near detector. With this addition of the neutrino project, the entire budget for the J-PARC project is now 151B-yen.

The construction of the neutrino beam line started on April 1, 2004. A baseline design of the all beamline elements and the ND280 detector was established in March this year, and a general agreement on the further R&D, construction and the institutional and regional responsibilities was also made. Presently, the pion decay tunnel construction is proceeding. There are many T2K activities at the working group level. Many video conferences both locally and internationally are being held almost every week.

6.2 The US B280 Collaboration Structure and Project Management Plan

The T2K US B280 Collaboration is composed of members from six institutions: Brookhaven National Lab; University of Colorado, Boulder; Louisiana State University; State University of New York at Stony Brook; University of Rochester; and University of Washington, Seattle. A complete list of the members can be found on the back page of the front cover of this document.

C. K. Jung is the Spokesperson of the collaboration and the PI of this proposal. He provides leadership for the collaboration and makes day-to-day decisions on behalf of the collaboration. He also represents the T2K US B280 Collaboration to the US funding agencies. He discusses any significant matters with the Institutional Board (IB) and receives advices from the Board. The IB is composed of one representatives from each participating institutions (see Table 14) and acts as an executive committee. The board will discuss all financial matters and the board members will represent individual institution’s opinions and interests.
Table 14: List of the US B280 Collaboration Institutional Board (IB) Members

<table>
<thead>
<tr>
<th>Institution</th>
<th>Representative</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL</td>
<td>P. Wanderer</td>
</tr>
<tr>
<td>U. of Colorado, Boulder</td>
<td>E. Zimmerman</td>
</tr>
<tr>
<td>Louisiana State U.</td>
<td>T. Kutter</td>
</tr>
<tr>
<td>SUNY at Stony Brook</td>
<td>C. McGrew</td>
</tr>
<tr>
<td>U. of Rochester</td>
<td>K. McFarland</td>
</tr>
<tr>
<td>U. of Washington</td>
<td>J. Wilkes</td>
</tr>
</tbody>
</table>

The Collaboration Council is composed of all members with a Ph.D. degree in the Collaboration and all Ph. D. graduate students who are involved in the T2K related research. The council makes major decisions by consensus whenever possible or by vote if necessary including vote on Collaboration policies and directions, and on election of the Spokesperson.

T2K US B280 proposal will be submitted to DOE through Stony Brook University. The entire budget request will be categorized as “Capital Equipment”, which bears no overhead charges from the University. (Stony Brook University has a simple policy of charging no overhead on all capital equipment related funds including contingency and sub-contracts.) When the proposal is approved, the base cost of each sub-project will be sent to the corresponding sub-project leader’s institution following any applicable DOE rules and regulations.

Stony Brook Research Foundation, as the PI institution, will manage the funds and hold all contingency funds. Jung will serve as the Project Manager (PM) and will be assisted by Prof. Peter Paul (as an Assistant PM) and Joan Napolitano (Stony Brook HEP/X-ray group grant manager). The PM will oversee progress of all sub-projects and frequently communicate with the sub-project institutional leaders (see Table 15).

The Assistant PM will support the PM in all aspects of managing the project, which includes tracking the timelines of project components and deliverables, and the adherence to DOE project guidelines and operational rules. He will also assist in writing progress reports and preparing for project reviews to the agencies. Prof. P. Paul’s extensive experience as a senior manager at BNL is a very appropriate background for these tasks.

All of the sub-projects will have separate accounts, and are expected to send quarterly financial reports to PM. There will be semi-annual progress reviews of the sub-projects.

When needed, after a review, the contingency funds will be awarded to a sub-project by either a purchase order or a subcontract to that institution. We will follow any applicable DOE guidelines and rules such as Change Control Action limits on contingency. Details of these procedures will be discussed with DOE when the project is approved.
Table 15: List of the US B280 Collaboration Institutional Sub-project leaders

<table>
<thead>
<tr>
<th>Sub-project/Institution</th>
<th>Leader</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrector Coils/BNL</td>
<td>P. Wanderer</td>
</tr>
<tr>
<td>Proton Beam CT Monitor/Louisiana State U.</td>
<td>R. Svoboda</td>
</tr>
<tr>
<td>Proton Beam Monitor Electronics/U. of Washington</td>
<td>J. Wilkes</td>
</tr>
<tr>
<td>Neutrino Horn/U. of Colorado, Boulder</td>
<td>E. Zimmerman</td>
</tr>
<tr>
<td>GPS Time Synchronization System/U. of Washington</td>
<td>J. Wilkes</td>
</tr>
<tr>
<td>PØD/SUNY at Stony Brook</td>
<td>C. McGrew</td>
</tr>
<tr>
<td>PØD/U. of Rochester</td>
<td>K. McFarland</td>
</tr>
<tr>
<td>PØD Electronics/U. of Washington</td>
<td>J. Wilkes</td>
</tr>
<tr>
<td>SMRD/Louisiana State U.</td>
<td>T. Kutter</td>
</tr>
</tbody>
</table>

7 Estimated Costs and Schedule

The T2K US B280 Collaboration proposes to contribute significant hardware subsystems to the T2K neutrino beamline and the ND280 Off-axis detector (see Table 4). These subsystems have been described in detail in the preceding sections. Here we present project cost estimates and justifications, and schedules for each of these subsystems. The total amount of funding requested for this project is $\sim$4.7M in FY2005$, including 39% contingency, over the period FY06–FY09. No overall escalation is included.

We must begin the initial stage of the construction very soon to keep up with the experiment’s schedule.

7.1 Estimated Project Costs and Justification

A summary of the project cost in a Work Breakdown Structure (WBS) format is shown in Figure 59. The costs presented are all capital equipment costs and do not include project management costs, operating costs or the offline computing costs.

The cost estimates are based on either actual cost of prototype production, a vendor quote, engineer’s estimate or physicist’s estimate, in order of the highest confidence level to the lowest. This level of confidence in the cost estimates are reflected in the contingencies.

We do not expect in general that there will be any overhead charges on the funds by the participating University institutions since these are entirely categorized as capital equipment funds. Some small amount of overhead charges could occur due to complications in university rules and regulation in case of sub-contracting a private consultant. We have included such anticipated overhead charges in our costing. Work done at BNL will incur the standard BNL overhead charges.
<table>
<thead>
<tr>
<th>WBS</th>
<th>Item Description</th>
<th>Base Cost (in $)</th>
<th>Overhead (in $)</th>
<th>Contingency (in $) (in %)</th>
<th>Subtotal (in $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Beam Line</td>
<td>1,187,872</td>
<td>112,120</td>
<td>322,736</td>
<td>1,622,729</td>
</tr>
<tr>
<td>1.1</td>
<td>SC Corrector Coils</td>
<td>335,220</td>
<td>102,739</td>
<td>72,370</td>
<td>513,329</td>
</tr>
<tr>
<td>1.1.1 Magnet Design</td>
<td>4,080</td>
<td>1,599</td>
<td>852</td>
<td>6,531</td>
<td></td>
</tr>
<tr>
<td>1.1.2 Tooling Design</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1.1.4 Production</td>
<td>288,191</td>
<td>87,284</td>
<td>55,721</td>
<td>427,196</td>
<td></td>
</tr>
<tr>
<td>1.1.5 Cold Testing</td>
<td>30,275</td>
<td>8,626</td>
<td>5,835</td>
<td>44,736</td>
<td></td>
</tr>
<tr>
<td>1.1.6 Shipping</td>
<td>19,674</td>
<td>5,230</td>
<td>9,562</td>
<td>34,865</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>CT Proton Beam Monitor</td>
<td>110,100</td>
<td>948</td>
<td>26,721</td>
<td>131,769</td>
</tr>
<tr>
<td>1.2.1 Equipment</td>
<td>86,200</td>
<td>0</td>
<td>20,040</td>
<td>106,240</td>
<td></td>
</tr>
<tr>
<td>1.2.2 Test Stand</td>
<td>12,500</td>
<td>0</td>
<td>3,825</td>
<td>16,325</td>
<td></td>
</tr>
<tr>
<td>1.2.3 Fabrication and Testing</td>
<td>4,120</td>
<td>948</td>
<td>2,260</td>
<td>7,348</td>
<td></td>
</tr>
<tr>
<td>1.2.4 Installation</td>
<td>1,200</td>
<td>0</td>
<td>576</td>
<td>1,786</td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>Proton Beam Monitor Electronics</td>
<td>25,100</td>
<td>0</td>
<td>10,040</td>
<td>35,140</td>
</tr>
<tr>
<td>1.3.1 ADC Card Construction</td>
<td>10,840</td>
<td>0</td>
<td>4,335</td>
<td>15,176</td>
<td></td>
</tr>
<tr>
<td>1.3.2 Data Readout System</td>
<td>6,460</td>
<td>0</td>
<td>2,584</td>
<td>9,044</td>
<td></td>
</tr>
<tr>
<td>1.3.3 Integration and Testing</td>
<td>5,800</td>
<td>0</td>
<td>2,320</td>
<td>8,120</td>
<td></td>
</tr>
<tr>
<td>1.3.4 Mobilization and Shipping</td>
<td>2,000</td>
<td>0</td>
<td>800</td>
<td>2,800</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>2nd Neutrino Horn</td>
<td>632,302</td>
<td>8,433</td>
<td>195,475</td>
<td>836,210</td>
</tr>
<tr>
<td>1.4.1 Prototype tests</td>
<td>44,000</td>
<td>0</td>
<td>13,200</td>
<td>57,200</td>
<td></td>
</tr>
<tr>
<td>1.4.2 Fabrication and Assembly Fixtures</td>
<td>91,100</td>
<td>0</td>
<td>27,330</td>
<td>118,430</td>
<td></td>
</tr>
<tr>
<td>1.4.3 Engineering Design and Production Horn</td>
<td>475,768</td>
<td>6,500</td>
<td>144,680</td>
<td>626,948</td>
<td></td>
</tr>
<tr>
<td>1.4.4 Shipping</td>
<td>5,000</td>
<td>0</td>
<td>2,000</td>
<td>7,000</td>
<td></td>
</tr>
<tr>
<td>1.4.5 Travel expenses</td>
<td>7,434</td>
<td>1,933</td>
<td>4,215</td>
<td>13,582</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>GPS System for Time Synchronization</td>
<td>88,150</td>
<td>0</td>
<td>16,130</td>
<td>104,280</td>
</tr>
<tr>
<td>1.5.1 GPS Receivers</td>
<td>25,000</td>
<td>0</td>
<td>5,000</td>
<td>30,000</td>
<td></td>
</tr>
<tr>
<td>1.5.2 Local Timing Clock System</td>
<td>18,950</td>
<td>0</td>
<td>3,790</td>
<td>22,740</td>
<td></td>
</tr>
<tr>
<td>1.5.3 Data Readout System</td>
<td>30,590</td>
<td>0</td>
<td>6,188</td>
<td>36,708</td>
<td></td>
</tr>
<tr>
<td>1.5.4 Integration and Testing</td>
<td>11,110</td>
<td>0</td>
<td>2,222</td>
<td>13,332</td>
<td></td>
</tr>
<tr>
<td>1.5.5 Mobilization and Shipping</td>
<td>2,500</td>
<td>0</td>
<td>1,000</td>
<td>3,500</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>280 m Near Detector (ND280)</td>
<td>2,072,532</td>
<td>0</td>
<td>1,009,393</td>
<td>3,081,925</td>
</tr>
<tr>
<td>2.1</td>
<td>POD</td>
<td>1,850,782</td>
<td>0</td>
<td>911,618</td>
<td>2,762,400</td>
</tr>
<tr>
<td>2.1.1 Water Target Materials and Labor</td>
<td>33,706</td>
<td>0</td>
<td>13,482</td>
<td>47,188</td>
<td></td>
</tr>
<tr>
<td>2.1.2 Lead Absorbers</td>
<td>89,928</td>
<td>0</td>
<td>26,976</td>
<td>116,906</td>
<td></td>
</tr>
<tr>
<td>2.1.3 WLS Fiber Materials and Labor</td>
<td>331,745</td>
<td>506</td>
<td>179,442</td>
<td>510,639</td>
<td></td>
</tr>
<tr>
<td>2.1.4 Sidestream Scintillators</td>
<td>237,783</td>
<td>0</td>
<td>126,625</td>
<td>364,408</td>
<td></td>
</tr>
<tr>
<td>2.1.5 Scintillator Bar Production</td>
<td>195,524</td>
<td>0</td>
<td>99,717</td>
<td>295,241</td>
<td></td>
</tr>
<tr>
<td>2.1.6 PDOM Assembly</td>
<td>499,291</td>
<td>0</td>
<td>199,716</td>
<td>699,007</td>
<td></td>
</tr>
<tr>
<td>2.1.7 Scanner Construction</td>
<td>87,406</td>
<td>0</td>
<td>34,962</td>
<td>122,368</td>
<td></td>
</tr>
<tr>
<td>2.1.8 PDOM Scanning</td>
<td>57,365</td>
<td>0</td>
<td>22,530</td>
<td>80,005</td>
<td></td>
</tr>
<tr>
<td>2.1.9 Electronics</td>
<td>135,723</td>
<td>0</td>
<td>127,723</td>
<td>272,446</td>
<td></td>
</tr>
<tr>
<td>2.1.10 Installation in Japan (including shipping)</td>
<td>102,290</td>
<td>0</td>
<td>72,540</td>
<td>174,839</td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>SNRD</td>
<td>221,750</td>
<td>0</td>
<td>97,775</td>
<td>319,525</td>
</tr>
<tr>
<td>2.2.1 Sidestreams</td>
<td>180,000</td>
<td>0</td>
<td>81,000</td>
<td>261,000</td>
<td></td>
</tr>
<tr>
<td>2.2.2 Light Tight Wrapping</td>
<td>2,000</td>
<td>0</td>
<td>900</td>
<td>2,900</td>
<td></td>
</tr>
<tr>
<td>2.2.3 Chemical Reflector/Tyvek</td>
<td>2,000</td>
<td>0</td>
<td>900</td>
<td>2,900</td>
<td></td>
</tr>
<tr>
<td>2.2.4 Optical Lens</td>
<td>6,750</td>
<td>0</td>
<td>2,025</td>
<td>8,775</td>
<td></td>
</tr>
<tr>
<td>2.2.5 Fabrication and Testing</td>
<td>0</td>
<td>0</td>
<td>2,250</td>
<td>2,250</td>
<td></td>
</tr>
<tr>
<td>2.2.6 Shipping</td>
<td>20,000</td>
<td>0</td>
<td>8,000</td>
<td>28,000</td>
<td></td>
</tr>
<tr>
<td>2.2.7 Installation and Travel</td>
<td>6,000</td>
<td>0</td>
<td>2,700</td>
<td>8,700</td>
<td></td>
</tr>
<tr>
<td><strong>Total Project Cost</strong></td>
<td><strong>3,260,404</strong></td>
<td><strong>112,120</strong></td>
<td><strong>1,332,129</strong></td>
<td><strong>4,704,653</strong></td>
<td></td>
</tr>
</tbody>
</table>

Figure 59: Summary of the T2K US B280 project cost estimates in a WBS format in FY05$
The Total Project Cost (TPC) for the proposed T2K US B280 project is then $4,705k including 39% overall contingency in FY05.

In the following we provide brief descriptions of the our cost estimate bases and justifications for each sub-project.

**Corrector Coils**  The cost is based on the production of the prototype corrector (February and March, 2005) plus production of similar magnets on the semi-automatic winding machine. The prototype magnet has the same design as the production magnets, and will be suitable for use as a spare, so the budget is for the cost of making, testing, and shipping four correctors. Based on this experience, a low (15%) contingency has been assigned to this work.

**CT Proton Beam Monitor**  The cost is based on the production of a prototype monitor. The equipment listed represents materials to construct 5 CT proton beam monitors. In order to finalize the design a test stand is required to perform necessary R&D. Fabrication and initial testing will take place at LSU. Installation and further testing will be performed by an experienced LSU technician in Japan.

**Proton Beam Monitor DAQ Electronics**  Basis of cost estimates are: vendor quotes for Commercial electronics, and physicist estimate (experience from previous experiments) for custom board construction, and for mobilization and shipping. The budget includes purchase of commercial electronics, 1 month FTE research engineer time for integration, installation, and testing, construction of custom FADC boards, mobilization and shipping, and 40% contingency due to new design for custom board.

**Neutrino Horn 2**  Basis of cost estimates are: Physicist and engineer estimate (experience from previous experiments) for part production, assembly, and labor costs; vendor quotes for shipping and travel.

The budget covers R&D, fixtures and hardware necessary to construct Horn 2, the horn itself, and shipment and testing. Most WBS items include engineering labor, which will be contracted to Bartoszek Engineering, Inc.

Pre-prototype testing equipment will include corona test equipment and a heated mockup of the inner conductor and cooling setup, for testing the cooling system to ensure adequate heat transfer. Assembly hardware will include fixtures for crane handling of the fragile inner conductor and insulating ring, temporary horn support and handling fixtures, and a portable hoist to supplement the building crane for more delicate manipulation of horn components.

The horn production budget include: the full engineering design; modeling of the design with finite element calculations of magnetic forces, vibration modes, and heat load; procurement of all parts for the horn; and assembly of the horn.
Travel funds are included for Bartoszek to travel to Boulder and Japan for work on the project.

**GPS Time Synchronization System** Basis of cost estimates are: vendor quotes for Commercial electronics, and physicist estimate (experience from previous experiments) for custom board construction, and for mobilization and shipping. The budget includes: purchase of commercial GPS receivers, antennae, and associated DAQ electronics; 2 months FTE research engineer time for integration, installation and testing construction of custom Local Time Clock boards for precision timing; and mobilization and shipping. A very low 20% contingency due to direct prior experience with similar task for the K2K experiment.

**POD**

- Water Target Materials and Labor: Basis of cost estimates are: vendor quote (Fujikura Co. Tokyo) for the bladders, and physicist estimate for engineering design, installation and commissioning. The budget includes: purchase of 35 custom-made prototype bladders (28 for POD, 3 for testing and 4 spares); 2.5 months FTE research engineer time for prototype testing and evaluation, integration and testing, and installation; 100 hours of shop time; and shipping.

- Lead Absorbers Base of cost estimate is vendor quote (Vulcan Lead).

- Clear Fiber Cable construction: Supplies and materials are estimated from vendor quotes (notably Kuraray fiber) or engineering designs. Production waste and labor required is based on direct extrapolation from as-realized costs in similar cable construction from CDF endplug (Rochester), STAR (Michigan State) and the CMS HCAL (Rochester). Labor estimates scaled from these projects varied by a significant amount, and accordingly an average of the projects was used with a contingency inflated to cover all projects. Labor rates are current Rochester Barnes shop rates, scaled for expected escalation.

- WLS Fiber preparation: Costs are based on vendor quotes (notably Kuraray fiber), and as-realized production costs for nearly identical project (CMS HCAL, Rochester/FNAL). The facility used for vacuum deposition mirroring of the WLS fiber ends is that of FNAL Lab 7. Labor rates come from a technician with added FNAL G&A.

- Scintillator production: Costs are based on vendor quotes for materials (Dow Styron and Curtiss Labs) and labor rates estimated by Anna Pla for use of the NICADD/FNAL extrusion facility and include appropriate G&A. Production rates, die tuning time and die development costs are based on prototype production for the MINERvA experiment.
• PDule Assembly: Time-Motion estimates and as-realized costs are extrapolated from similar MINOS module production.

• PDule Scanner Construction: The scanner estimates of labor times and equipment costs are based on as-realized costs for the MINOS module scanner constructed by Argonne. Labor rates are current Rochester Barnes shop rates, scaled for escalation.

• PDule Scanning: Time-Motion estimates are based on physicist design.

• Electronics: The budget requested here for the PD electronics is our anticipated contribution of 30% of the base cost with 100% contingency, which reflects the uncertainty in the final design. The costing is based on the MINERvA experiment electronics costing.

• Installation in Japan Including Shipping: The shipping costs are estimated based on as-realized costs from the shipping of the US contribution to the Super-Kamiokande and K2K detectors. The installation costs are estimated based on the as-realized costs for the K2K SciBar detector.

SMRD  The cost is based on estimates, which in turn are extrapolations from purchases of similar items in small quantities and catalogue pricing.

The items listed in the budget are the active component of the side muon range detector (scintillators), and the components to assemble the SMRD (optical cement) and guarantee its proper operation (light tight wrapping). Additional items listed represent work associated with the testing, assembly, and mechanical installation of the SMRD scintillators.

The items will be assembled and tested in conjunction with the lab equipment (including computers and software) that are available in the PIC-s experimental neutrino physics group and the common high energy laboratory resources at LSU. The work associated with the project will be supported by the electronics and mechanical workshops at LSU.

7.2 Schedule

The project schedule is driven by the schedule of the T2K project in Japan. The first proton beam is scheduled to be delivered on target on April 1, 2009. Accordingly, the completion of the ND280 On-axis detector, which monitors neutrino beam direction and the profile, is scheduled for April 1, 2009. The ND280 Off-axis detector will, however, be constructed in stages: The detector magnet will be installed in 2008, the inner-most sections of the detector such as the FGD and TPC should be completed by April 1, 2009, and the majority of the other detector components should be completed by August 31, 2009. Depending on the funding situations in various participating countries, the full completion of the ND280 detector may stretch to March 31, 2010. Thus, all of the proposed US contributions to the
Figure 60: The schedule of the beam related construction.

<table>
<thead>
<tr>
<th>Facility Final Design</th>
<th>Primary Beam Tunnel</th>
<th>NC mag (Prep. Sect.)</th>
<th>1st Util. Build.(NU1)</th>
<th>Installation Build.(NC)</th>
<th>50GeV Beam Comm.</th>
<th>SC/FF NC mags</th>
<th>Cryogenics</th>
<th>Intrlock/Ctrl</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Primary line</th>
<th>Secondary line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay Volume I</td>
<td>TS (underground)</td>
</tr>
<tr>
<td>TS building</td>
<td>TS instrumentation</td>
</tr>
<tr>
<td>Target &amp; Horns</td>
<td>2nd Util. Build.(NU2)</td>
</tr>
<tr>
<td>Beam dump Civil</td>
<td>Beam dump Instrum.</td>
</tr>
<tr>
<td>3rd Util. Build.(NU3)</td>
<td>Near det. Hall</td>
</tr>
</tbody>
</table>

Figure 61: The schedule for construction of the ND280.
<table>
<thead>
<tr>
<th>Item Description</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Line</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC Correctors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrector Production</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold Testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipping to Japan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation and Testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off Proton Beam Monitor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RDG</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production and Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation and Testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutrino Monitors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production Horn 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipping</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation and Testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPS System for Time Synchronization</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construct Custom Electronic Board</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchase Commercial Equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integration and Testing at UW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipping to Japan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation and Testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>280 m Near Detector (ND280)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RDG</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Target Materials and Labor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead Absorbers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clear fiber cables construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WLS fiber preparation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scintillator Bar Production</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMT tube assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scannable construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMT tube scanning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electronics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipping</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMID</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production and Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Testing in LSU</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipping to Japan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 62: The schedule of the T2K US B280 Sub-Projects.
beamline elements must be delivered to Japan by 2008. On the other hand, our contributions to the P0D and SMRD could be completed as late as by the summer of 2009.

Figure 60 shows the schedule for the T2K beamline construction and Figure 61 shows the ND280 construction schedule. In the latter figure, we have shown the best estimate of the initial neutrino beam and accelerator schedules. Figure 62 shows the schedule for the US B280 project. We assume a decision on this proposal will be made within six months of the submission and our work can begin starting January 1, 2006. Obviously, much of the R&D, designing and engineering studies of the sub-projects will continue until the project is approved.

We set our target date for completion of the construction to be April 1, 2009. We reserve 5 months as our contingency in the schedule making September 1, 2009 as our final target date for the completion of the US B280 project.

References


